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# Revision of the upper Pliocene - Pleistocene diatom biostratigraphy for the northern belt of the Southern Ocean

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**ABSTRACT:** Previous diatom biostratigraphic results for the southern high-latitude late Pliocene and Pleistocene are revised. Considering new biostratigraphic results and the ranges of acme intervals, an improved diatom zonation for the last ca. 2.6 Ma is proposed. Guided by magnetostratigraphic events, the diatom zonation provides a time resolution of ca. 200 - 300 kyrs. Considering the latitudinal control on diatom distribution during the last 2.6 Ma in the Southern Ocean, the zonation should only be used in sediments deposited north of the present Polar Frontal Zone. The paper also includes the taxonomic transfer of stratigraphically useful Southern Ocean diatom taxa from the genus *Nitzschia* Hassal to *Fragilariopsis* Hustedt, and the description of *Fragilariopsis matuyamae* Gersonde et Bárcena sp. nov. and *F. matuyamae* var. *heteropola* Gersonde et Bárcena var. nov.

## INTRODUCTION

Recent research improved the Cenozoic diatom biostratigraphic zonations for the southern high-latitudes based on core materials recovered in the Atlantic and the Indian sectors of the Southern Ocean during ODP Legs 113, 114, 119 and 120. The studies of Gersonde and Burckle (1990), Fenner (1991), Baldauf and Barron (1991), and Harwood and Maruyama (1992) provided new information on diatom ranges, abundance patterns and taxonomic review. These works revised and improved earlier biostratigraphic and taxonomic investigations, especially those by McCollum (1975), Schrader (1976), Weaver and Gombos (1981) and Ciesielski (1983). New biostratigraphic zonations for the Southern Ocean were proposed that are directly correlated with other microfossil zonations and with the geomagnetic time scale for absolute age assignment (Gersonde et al. 1990; Barron et al. 1991; Harwood et al. 1992). More details on the scientific development of southern high-latitude diatom biostratigraphy were compiled by Baldauf and Barron (1991).

The occurrence and abundance patterns of stratigraphically useful Neogene and Quaternary diatom taxa are not uniformly distributed in different latitudes of the Southern Ocean even though they are endemic to the southern high-latitudes. This latitudinal differentiation of certain diatom taxa can be interpreted as a signal of (1) steepening of latitudinal gradients within the Southern Ocean, (2) the establishment of zonal hydrographic frontal systems characterized by distinct thermohaline and nutrient gradients, and (3) the occurrence of seasonal sea ice, covering parts of the Southern Ocean. The recently developed Neogene and Quaternary biostratigraphic zonations are mainly based on ODP holes drilled south of the Polar Front (text-fig. 1) and do not consider fully the occurrence and abundance patterns of taxa in the northern belt of the Southern Ocean.

In this paper we review previous biostratigraphic results for the late Pliocene and Pleistocene obtained from the northern portion of the Southern Ocean. A refined biostratigraphic zonal scheme is proposed for the areas located under relatively warmer surface waters in the northern belt of the Southern

Ocean. New biostratigraphic results obtained from piston and gravity core studies in this area provide new data to develop this zonation. The stratigraphic ages are according to the geomagnetic time scale proposed by Cande and Kent (1992). Published diatom datums were recalculated using the formula of Wei and Peleo-Alampay (1993). Considering recent nomenclatural changes in diatom taxonomy we propose the transfer of several taxa from the genus *Nitzschia* Hassal to *Fragilariopsis* Hustedt and describe two new upper Pliocene diatom taxa.

## MATERIALS AND METHODS

Additional stratigraphic results were obtained by the study of gravity cores PS1435-1, PS1442-4, PS1751-7, PS2074-1, and PS2083-3 recovered during RV "Polarstern" cruises ANT-IV/4 (Fütterer 1987), ANT-VIII/3 (Gersonde and Hempel 1990) and ANT-IX/4 (Bathmann et al. 1992), and ODP Site 697 drilled during Leg 113 (Barker et al. 1988), all located in the Atlantic sector, as well as piston core E13-3 obtained with RV "Eltanin" in the eastern Pacific sector (tab. 1, text-fig. 1). In cores PS1435-1 and E13-3 only the sections representing the time interval of the lower Matuyama Chron (latest Pliocene) were studied quantitatively. For estimation of absolute diatom numbers microscope slides were prepared to obtain random distribution of microfossils. The cleaning of the sediment samples, preparation of permanent mounts for light microscopy (using the resin Mountex) and SEM-investigations were accomplished according to routine methods established at the Alfred-Wegener-Institute. Counting of specimen followed the method described by Schrader and Gersonde (1978). In general, more than 200 diatom valves per sample were counted. If the number of diatoms preserved in the sediment was low, more than one slide was studied. Zonal boundary ages and ages of species ranges were calculated assuming constant sedimentation rates between the various geomagnetic and biostratigraphic data points. The core depths of zonal boundaries, species ranges and unconformities were calculated as the midpoint between the core depths of samples below and above these events or boundaries. Light microscope investigations were made with a Zeiss Axioskop microscope with apochromatic optics. Microphotographs were taken with an automatic Zeiss camera. The scanning electron

microscope investigations were carried out with a Philips SEM 515. The paleomagnetic data and its interpretation were taken from Abelmann et al. (1990) for Core PS1435-1, from Bárcena et al. (submitted) for Core PS2074-1 and from Hays and Opdyke (1967) for Core E13-3.

## RESULTS AND DISCUSSION

In a paper on the abundance patterns of biostratigraphically useful upper Pliocene and Quaternary diatom taxa recovered from ODP Leg 114 sites 699, 701 and 704 Fenner (1991) noted that some taxa are not uniformly distributed in the Southern Ocean. Species abundance patterns from ODP sites 699 and 701, south of, or within the Polar Frontal Zone of the Antarctic Circumpolar Current (ACC) and from Site 704 near the boundary between the Subantarctic and Polar Frontal Zone, show that taxa such as *Thalassiosira kolbei* (Jousé) Gersonde 1990, *Proboscia barboi* (Brun) Jordan et Priddle 1991, *Fragilariopsis weaveri* (Ciesielski) Gersonde et Bárcena comb. nov., and *Hemidiscus karstenii* Jousé in Jousé et al. 1963 are more abundant and have more continuous occurrence in the northern zone of the Southern Ocean, which is characterized by warmer surface water conditions.

*Hemidiscus karstenii* was reported by Ciesielski (1983) from DSDP sites 513 and 514, which are located in the southern Subantarctic Zone of the western South Atlantic (text-fig. 1), to range consistently from the upper Miocene to the upper Pliocene *Coscinodiscus vulnificus* Zone in the lowermost Matuyama Chron (text-fig. 2). At DSDP Site 514 the youngest occurrence of *H. karstenii* within the Pliocene is marked by an abundance maximum occurring in the lowermost Matuyama Chron (C2r). At this age an abundance peak of the taxon, reaching more than 10% of the total assemblage, was also marked in Core PS2074-1 in the Southern Cape Basin (text-fig. 3). Rare to few occurrences of *H. karstenii* are reported from the upper Miocene and lower to upper Pliocene by Baldauf and Barron (1991) and Harwood and Maruyama (1992) from ODP sites 736, 737, 744, 745, 747, 748, and 751 drilled on or at the Kerguelen Plateau in the Indian sector of Southern Ocean, and by Schrader (1976) from DSDP Site 278 in the Pacific sector (text-fig. 1). The latter author proposed *H. karstenii* as the nominate taxon of an upper Miocene diatom zone, however this was not used in subsequent biostratigraphic zonations. This indicates that *H. karstenii* was widespread in the Southern Ocean during the late Miocene to the mid - late Pliocene. It apparently declined in the latest Pliocene. *Hemidiscus karstenii* reappears in abundance in the late Pleistocene (Burckle et al. 1978; Burckle 1982) where its occurrence is associated with interglacials between the isotopic stages 11 and 7, thus between ca. 0.42 Ma and 0.19 Ma (Imbrie et al. 1984). Pleistocene abundance maxima of *H. karstenii* reaching values between 10 and 50% of the total assemblage are noted only in cores located in the Subantarctic and northern Polar Frontal Zone of the Southern Ocean (Burckle 1982; Fenner 1991; Bárcena et al. 1992; Bárcena et al., submitted; Gersonde unpubl.). In the more southerly areas of the Southern Ocean this taxon was found only rarely at very low numbers (e.g. Fenner 1991; Baldauf and Barron 1991; Gersonde unpubl.). Abbott (1974) employed the Pleistocene occurrence range of *H. karstenii* to define the *Hemidiscus karstenii* Zone (text-fig. 2).

*Thalassiosira elliptipora* (Donahue) Fenner 1991 occurs primarily in sediments deposited in an area between the northern Antarctic Zone (south of the Polar Front) and the northern Subantarctic Zone, based on the findings of Fenner (1991), Ciesielski (1983), Baldauf and Barron (1991), and the lack of the

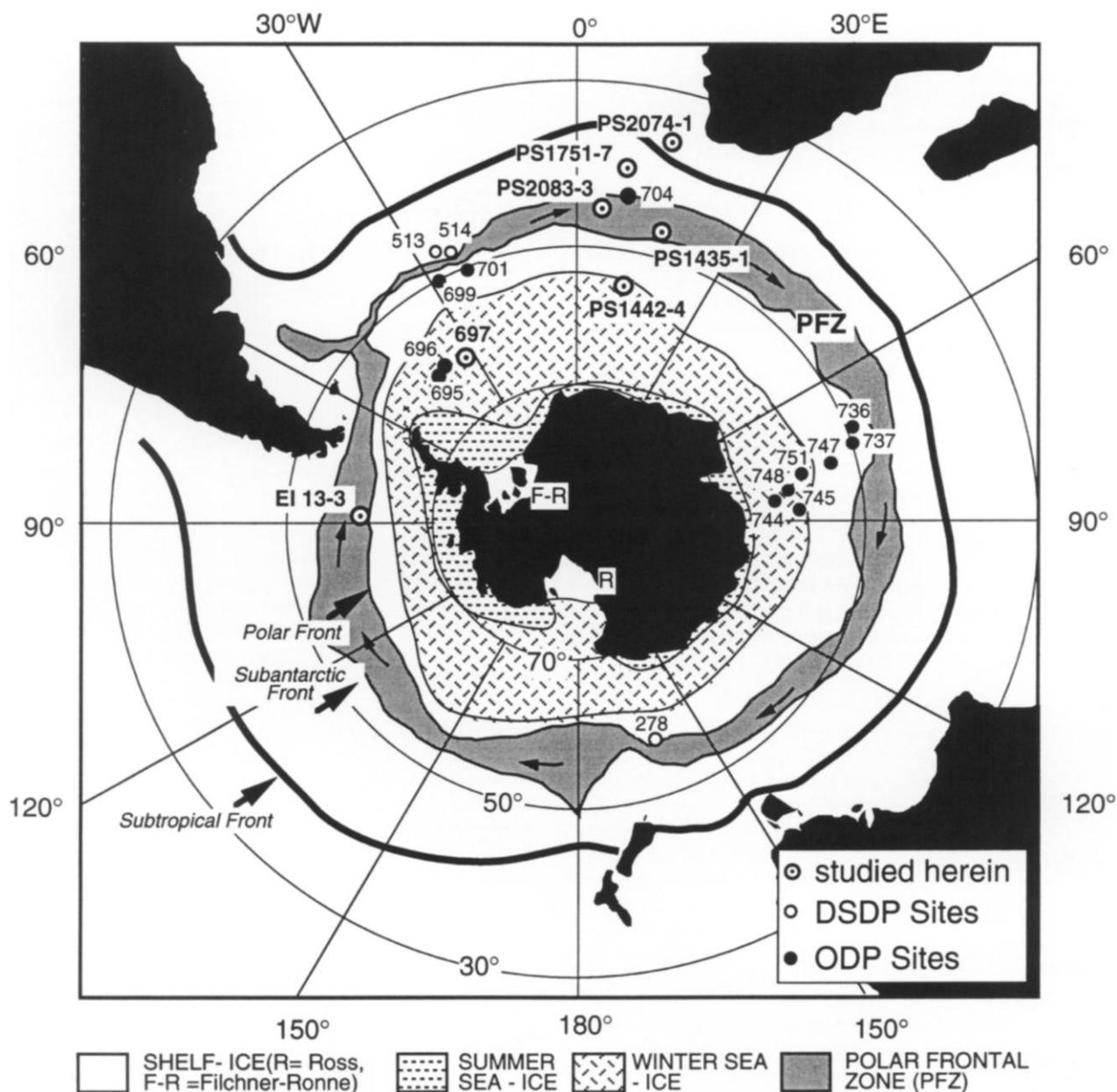
TABLE 1

Location, core length and water depth of studied cores.

Core	Core length (m)	Latitude (S)	Longitude	depth (m)
PS2074-1	13.03	39°40.0'	14°31'E	4644
PS1435-1	8.40	49°09.6'	15°02'E	4320
PS 2083-3	10.61	46°21.8'	07°02.3'E	1936
PS1751-7	10.03	44°29.6'	10°28.1'E	4760
PS1442-4	8.78	54°00.0'	11°05.0'E	3550
E13/3	16.03	57°00'	89°29'W	5090
ODP Site 697	304.9	61°48.6'	40°17.7'W	3480

sielski (1983), Baldauf and Barron (1991), and the lack of the taxon in Core PS2074-1 (southern Cape Basin). The FAD of *T. elliptipora* seems to be strongly controlled by environmental conditions and was observed over a wide range of stratigraphic levels in the Matuyama Chronozone (Ciesielski 1983). Fenner (1991) reported abundance peaks reaching values of more than 20% of the total assemblages from ODP sites 699 and 701 from below the Jaramillo Event (C1r.1n) into the lowermost portion of the Brunhes Chron (C1n) (FAAD 1.11 - 1.04 Ma, LAAD 0.8 - 0.75 Ma), but with lower abundance at ODP Site 704. In our cores from the Subantarctic Zone the taxon was found consistently but also at low percentages (text-figs. 4, 5). The LAD of *T. elliptipora* occurs within the lowermost part of the Brunhes Chronozone slightly below the LAD of *Actinocyclus ingens* Rattray 1890, which is at 0.65 Ma, as reported by Ciesielski (1983) and Fenner (1991), and as documented in cores PS1751-7 and PS2083-3 (text-figs. 4, 5).

*Proboscia barboi*, which has its first appearance in the late middle Miocene (Baldauf and Barron 1991, Harwood and Maruyama 1992), is another taxon occurring during the latest Pliocene predominantly in relatively warmer waters of the northern zone of the Southern Ocean. At ODP Site 704 it makes up between 10 and 50% of the total assemblages in the lower part of the Matuyama Chron (Fenner 1991), as well as in the cores PS2074-1 (text-fig. 3) and E13-3 (text-fig. 6). Also, Ciesielski (1983) reports an abundance maximum of *P. barboi* during this time period from DSDP Site 514. The LAD of *P. barboi* was placed close to the upper boundary of the Olduvai Event in the Matuyama Chron by Ciesielski (1983) and Fenner (1991) and in this study in cores PS2074-1 and E13-3 (text-figs. 3, 6). This converts to an age around 1.8 Ma, marking the Pliocene-Pleistocene boundary, as recognized by Harland et al. (1989). Conforming data were also reported by Baldauf and Barron (1991) from ODP Sites drilled at the Kerguelen Plateau. However, in the areas south of the Subantarctic Zone, *P. barboi* occurs only sparsely during the late Pliocene (Gersonde and Burckle 1990; Fenner 1991; Baldauf and Barron 1991) and does not represent a useful stratigraphic marker. The LAD of *P. barboi* was used by McCollum (1975) to define the top of the *Rhizosolenia barboi/Nitzschia kerguelensis* Zone which range into the latest Pliocene. This zone was renamed the *Rhizosolenia barboi* Zone (NSOD Zone 19) by Baldauf and Barron (1991).

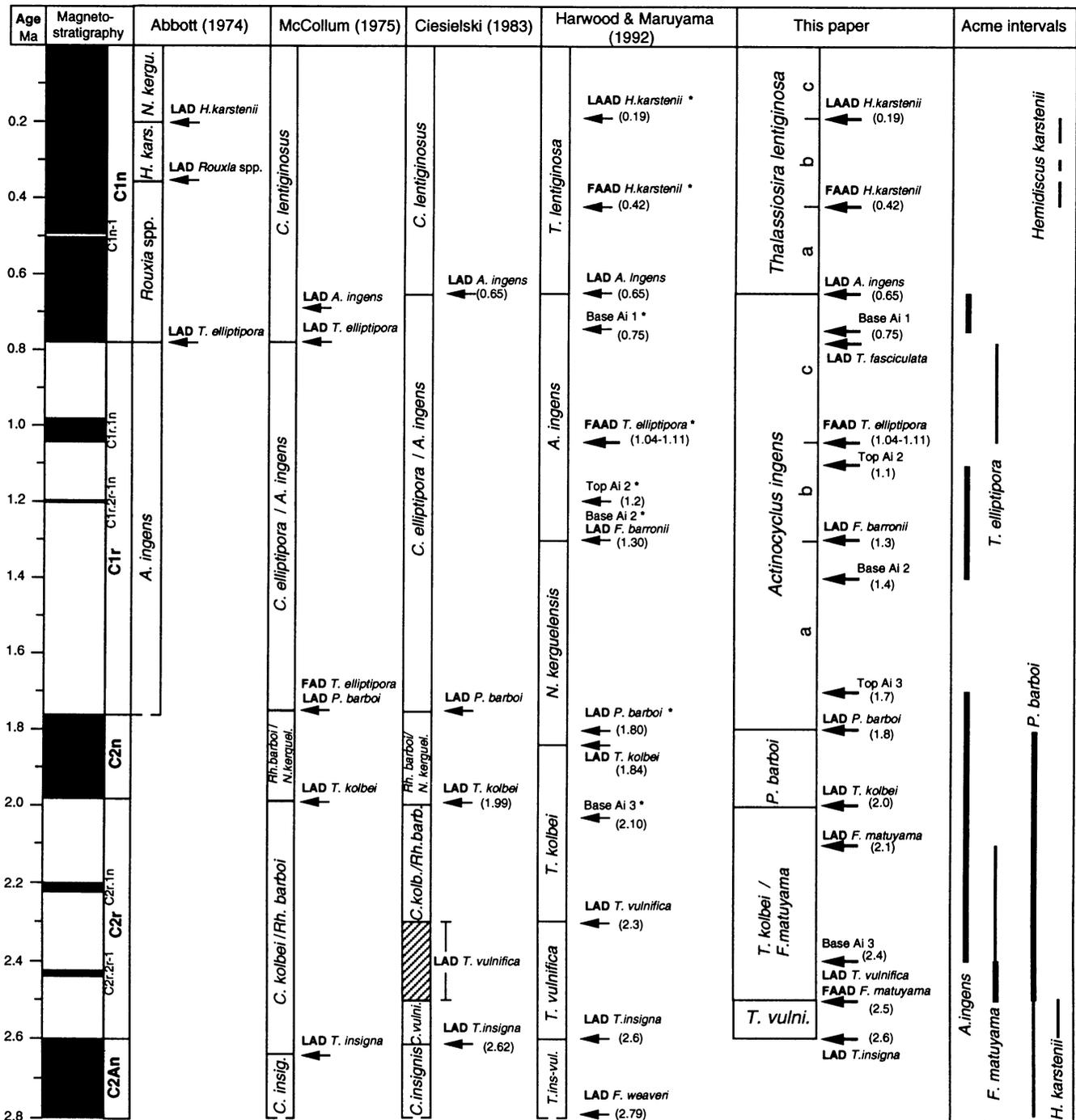


**TEXT-FIGURE 1**  
Schematic representation of the Southern Ocean, its present oceanographic frontal systems, sea ice distribution (according to Whitworth 1988, and other sources), the locality of previous DSDP and ODP sites used for the establishment of southern high-latitude zonations and localities of piston and gravity cores studied in this paper.

*Thalassiosira kolbei* has a LAD slightly older than that of *P. barboi*. Ciesielski (1983), Gersonde and Burckle (1990), Fenner (1991), and Baldauf and Barron (1991) place its LAD at the base or into the lowermost portion of the Olduvai Event of the Matuyama Chron, which corresponds to an age between 1.9 and 2 Ma. Similiar to *P. barboi*, *T. kolbei* is prominent in upper Pliocene sediments recovered in the area of the Polar Front Zone and the Subantarctic Zone. However, in Core PS2074-1 located in the Southern Cape Basin it occurs only rarely. The same is true for sediments recovered from the area south of the Polar Front. This suggests, that *T. kolbei* preferred water temperatures slightly colder than those preferred by *P. barboi*. The LAD

of *T. kolbei* marks the top of the *Coscinodiscus kolbei/Rhizosolenia barboi* Zone of McCollum (1975), which was emended by Ciesielski (1983). Baldauf and Barron (1991) renamed this zone as the *T. kolbei* Zone (NSOD Zone 18).

*Thalassiosira vulnifica* (Gombos) Fenner 1991 has its FAD at 3.1 Ma according to Harwood and Maruyama (1992), or at 3.24 Ma if converted to the Cande and Kent (1992) time scale. It contributes between 10 and 25% of the total diatom assemblages in lower Matuyama sediments recovered between the Subtropical Front (Core PS2074-1, text-fig. 3) and northern Antarctic Zone as documented by Fenner (1991) from ODP sites 699, 701 and 704, and cores E13-3 and PS1435-1 presented herein (text-figs.

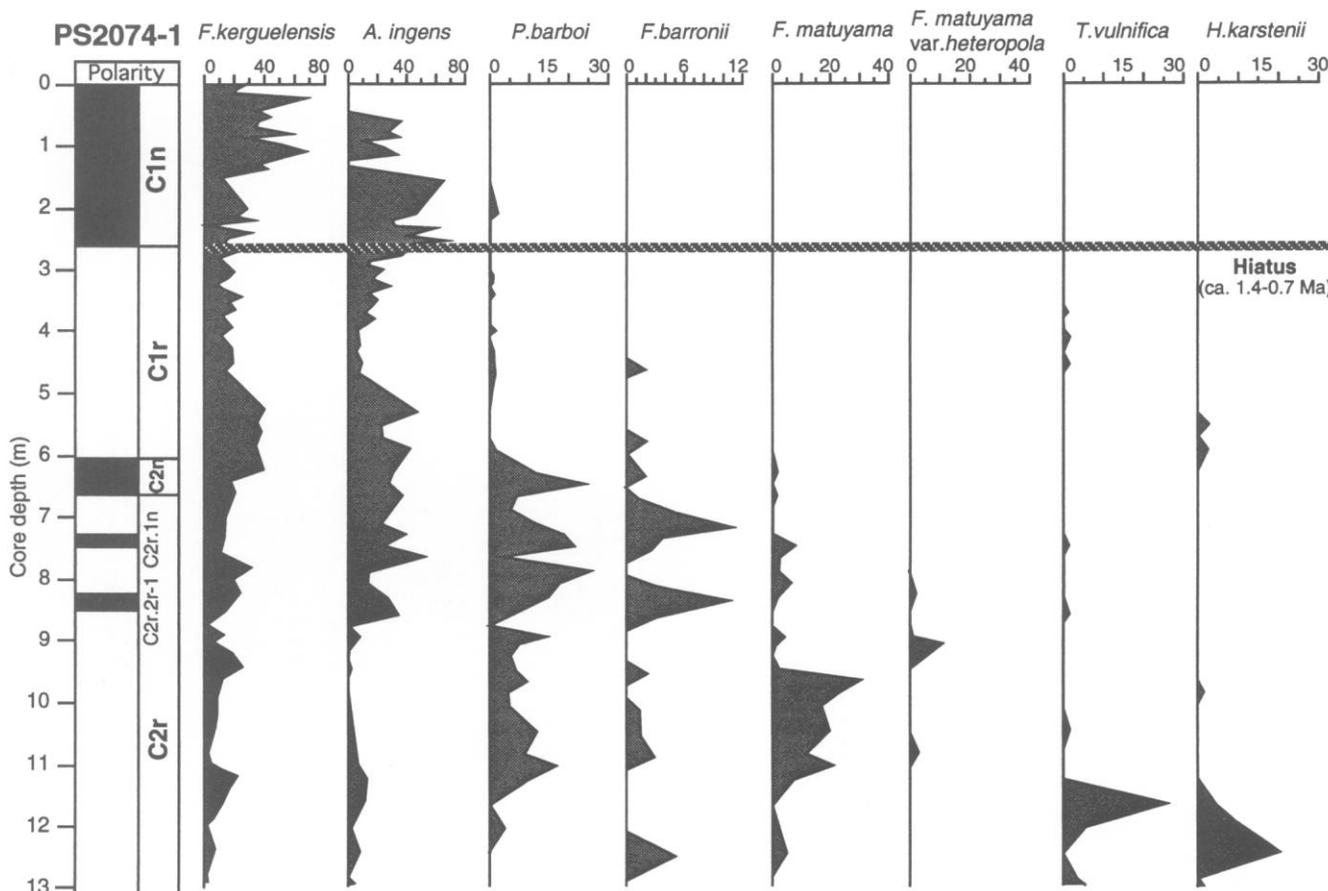


TEXT-FIGURE 2

Correlation of Late Pliocene and Quaternary diatom zonations and occurrence events from previous studies in the Southern Ocean with that proposed herein. The LAD of *T. vulnifica* defined by Ciesielski (1983) is presented as a range because of the uncertainty of the age assignment. Asterisks indicate data from other authors (Fenner 1991, Burckle 1982).

6, 7). Common to few occurrences have also been reported by Ciesielski (1983) from DSDP sites 513 and 514, and by Baldauf and Barron (1991) from ODP Site 736. In sequences recovered from the southern Antarctic Zone e.g. at ODP sites 693, 695, 696 in the Weddell Sea (Gersonde and Burckle 1990) and ODP Site 745 in the southern Indian sector (Baldauf and Barron 1991) it was only reported in low numbers. *Thalassiosira vulni-*

*fica* has also been reported from a 3 myr old diamicite recovered in the CIROS-2-drillhole located at the margin of the Antarctic continent (Barrett et al. 1992) and from the late Pliocene Sirius Formation in the Transantarctic Mountains (Harwood 1983). Both reports together with other Pliocene diatoms were interpreted to document a mid-late Pliocene deglaciation event of the Antarctic continent allowing marine invasion of



TEXT-FIGURE 3  
Abundance pattern of stratigraphically useful datoms in Core PS2074-1 (southern Cape Basin). Magnetostratigraphy from Bárcena et al. (submitted).

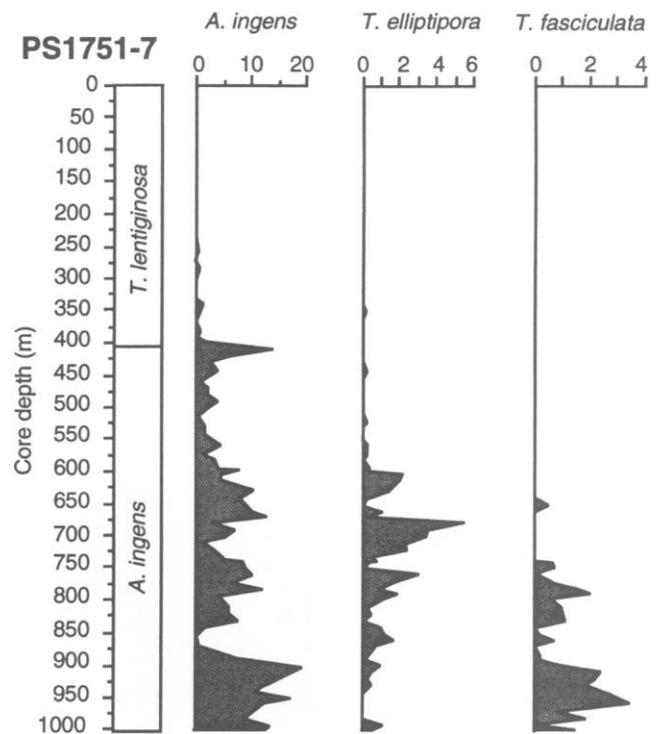
Antarctic intracratonic basins as proposed by Harwood (1985). This indicates that the species occurs over a broad range of latitudes in the Southern Ocean. Its main occurrence area however is located in the northern belt of the Southern Ocean. The LAD of *T. vulnifica* was placed in the lower portion of the Matuyama Chron (C2r) and defines the top of the *Coscinodiscus vulnificus* Zone (Ciesielski 1983). This zonal assignment was also used by Baldauf and Barron (1991) and Harwood and Maruyama (1992). In his zonation Ciesielski (1983, fig. 3) placed the top of the *C. vulnificus* Zone below the lower Reunion Event (C2r.2r-1). He, however, states that the definitive placement of the LAD of *T. vulnifica* awaits more detailed studies. Since then no detailed reevaluation of this date was made, probably due to the fact that the lowermost Matuyama sediment record is disturbed widespread in the Southern Ocean by disconformities (Ledbetter and Ciesielski 1986; Abelmann et al. 1990). The geomagnetic record in Core PS2074-1 reflects a continuous sedimentation during the early Matuyama time period and documents the two Reunion events. The last consistent occurrence of *T. vulnifica* was noted below the lower Reunion Event (text-fig. 3). A reinterpretation of the magnetostratigraphic data presented from ODP Hole 745B (Sakai and Keating 1991) in combination with the biostratigraphic data of Baldauf and Barron (1991) also leads to a LAD of *T. vulnifica* below the lower Reunion Event. The magnetostratigraphic polarity record shows three normal polarity events in the lower Matuyama that,

in contrast to the general high sedimentation rates of the Matuyama sediments at Site 745, are short-termed. The last occurrence of *T. vulnifica* was placed below the lowermost event. The two lower events could be reinterpreted to represent the two Reunion Events and the uppermost event to be the lowermost portion of the Olduvai Event (C2n) partly omitted by a hiatus. This interpretation would be in accordance with the diatom biostratigraphic data of Baldauf and Barron (1991) who place the last occurrence of *T. kolbei* and *P. barboi* around 90 mbsf (meters below sea floor), thus at the level of the uppermost of the three short-termed events. Based on the findings in Core PS2074-1, the reinterpretation of the ODP Hole 745B magnetics and considering the interpretation of Ciesielski (1983) the LAD of *T. vulnifica* and thus the zonal boundary between the *T. vulnifica* and the *T. kolbei* Zone can be placed between the top of the Gauss Chron (C2An) and the lower Reunion Event (C2r.2r-1), around 2.5 Ma (text-fig. 2). Fenner (1991) however, reported *T. vulnifica* to have a diachronous LAAD around 2 Ma, which converts to 2.1 Ma according to Cande and Kent (1992). The LAAD in ODP Site 701 located south of the present Polar Frontal Zone (text-fig. 1) occurs ca. 0.1 my. earlier than the LAAD at Site 704, located in the northern Polar Frontal Zone. However, the available magnetostratigraphy in these sequences (Hailwood and Clement 1991) cannot be interpreted clearly. Fenner (1991) also reports that the occurrence range of *T. vulnifica* continues at low abundances into the lower Brunhes Chron at ODP

sites 699, 701 and 704. The study of Subantarctic cores recording the species composition in the upper portion of the *A. ingens* Zone, which falls in the uppermost Matuyama and lowermost Brunhes Chrons, shows the presence of a taxon bearing prominent labiate processes scattered over the valve face, thus having some affinities to *T. vulnifica*. This taxon has been described as *Thalassiosira fasciculata* Harwood and Maruyama 1992 and differs from *T. vulnifica* by larger size, finer areolation, closer packing of areolae and the presence of a higher number of smaller strutted processes scattered over the valve face. It can be speculated that Fenner (1991) reporting *T. vulnifica* ranging into the lower Brunhes combined taxa belonging to *T. fasciculata* with *T. vulnifica*. The LAD of *T. fasciculata* falls in Subantarctic sediments in the uppermost *A. ingens* Zone, close to the LAD of *T. elliptipora* (text-figs. 4, 5). This LAD is significantly younger than that reported by Harwood and Maruyama (1992) from ODP Leg 120 Sites (1.6 Ma).

The study of the upper Pliocene - Pleistocene sediment cores PS2074-1, PS1435-1 and E13-3 recovered in the southern Cape Basin immediately north of the present Subtropical Front and in the Polar Front Zone of the Atlantic and Pacific sectors of the Southern Ocean, respectively (text-fig. 1), revealed new taxa of the genus *Fragilariopsis*. *Fragilariopsis matuyamae* sp. nov. and *F. matuyamae* var. *heteropola* var. nov. are described herein from the lower portion of the Matuyama Chron. *Fragilariopsis matuyamae* ranges in Core PS2074-1 from the core base (ca. 2.5 - 2.6 Ma) to the uppermost portion of the lower reversed Matuyama C2r between 2.0 and 2.1 Ma (text-fig. 3). A similar range was noted in cores E13-3 and PS1435-1 (text-figs. 6, 7). In these cores *F. matuyamae* makes up to 35% of the total diatom assemblages. *Fragilariopsis matuyamae* var. *heteropola* occurs in lower abundance making up to 11% of the total (PS2074-1, E13-3). The first stratigraphic occurrence of *F. matuyamae* cannot be defined herein because the cores studied here do not extend into the middle portion of the Pliocene or older strata. Because *F. matuyamae* occurs synchronously in significant numbers in three cores located in the Atlantic and Pacific sector of the Southern Ocean, we propose to use the occurrence of this species for further refinement of southern high-latitude upper Pliocene biostratigraphic zonation. Investigations of lower Matuyama sediments deposited south of the Polar Front (Core PS1442-4, ODP Site 697) did not recover *F. matuyamae* and its variety and indicate that these taxa predominantly occur in upper Pliocene southern high-latitude sediments deposited north of the Polar Front.

*Actinocyclus ingens* is a prominent taxon in uppermost Pliocene and Pleistocene southern high-latitude sediments. *Actinocyclus ingens* first occurs in the lower Miocene with a cosmopolitan distribution (Barron 1985). While it is excluded from low-latitudes in the middle Miocene and from middle- to northern high-latitudes during the latest Miocene (Barron 1985), this taxon ranges in the southern-high latitudes until the middle Pleistocene at 0.65 Ma (Ciesielski 1983; Fenner 1991; Harwood and Maruyama 1992). The occurrence during the late Pliocene and Pleistocene is marked by distinct acme intervals, which are reported from areas close to the Antarctic continent to the southern Cape Basin (Abelmann et al. 1990; Fenner 1991; Bárcena et al. submitted). This indicates that *A. ingens* was broadly distributed in the Southern Ocean during the Pleistocene. Its stratigraphic occurrence pattern, however, reveals that *A. ingens* preferred relatively warm surface waters. Fenner (1991) identified three acme intervals which are not exactly synchronous in the area north and south of the Polar Front.



TEXT-FIGURE 4

Abundance pattern of *A. ingens*, *T. elliptipora* and *T. fasciculata* in Core PS1751-7 (southern Subantarctic Zone, Atlantic sector).

Acme horizons of *A. ingens* recorded in a composite late Pliocene-Pleistocene section from the southern Cape Basin can be correlated with those reported by Fenner (1991). Their diachronous occurrence can be related to paleoceanographic changes (Bárcena et al. submitted). This indicates that the three acmes have some limited stratigraphic value, at least in the Atlantic sector of the Southern Ocean. The extinction of *A. ingens* may be related to the onset of drastic glacial/interglacial cyclicity with severe cooling periods (isotopic stage 16, Williams et al. 1988). It can be speculated that steep thermal gradients between the cold Antarctic surface waters and the adjacent subtropical waters did not permit a northward invasion of *A. ingens* into warmer waters of the middle latitudes. The LAD of *A. ingens* defines the base of the *Coscinodiscus lentiginosus* Zone of McCollum (1975), a zonal definition that was accepted by all subsequent authors of southern high-latitude diatom biostratigraphic zonation (see Harwood and Maruyama 1992).

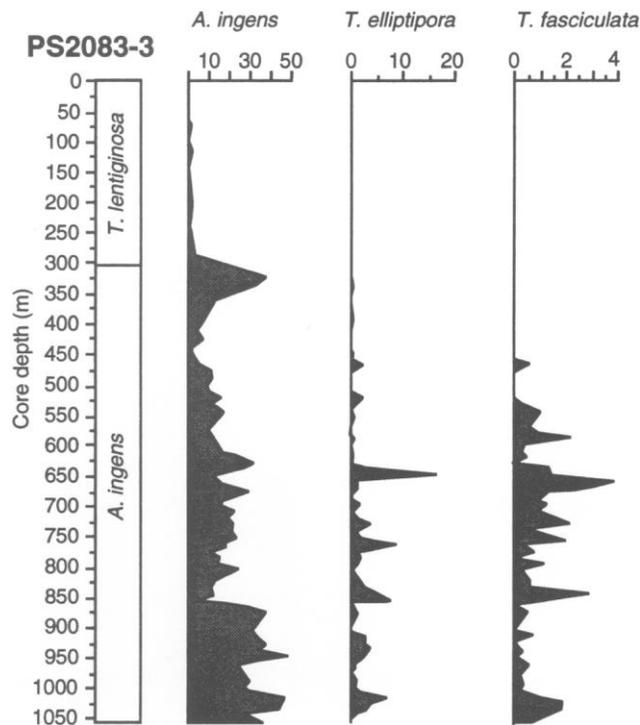
The stratigraphic ranges and the abundance patterns of the diatom taxa discussed allows the definition of a refined upper Pliocene and Pleistocene diatom zonation which is applicable for sediment sequences deposited in the northern belt of the Southern Ocean (north of the Polar Front) (text-fig. 2).

#### REVISED DIATOM ZONATION

##### *Thalassiosira lentiginosa* Partial Range Zone

Author: McCollum (1975), renamed informally by Kellogg and Kellogg (1986), formally renamed by Gersonde and Burckle (1990), subzoned herein.

Top: Present.



TEXT-FIGURE 5  
Abundance pattern of *A. ingens*, *T. elliptipora* and *T. fasciculata* in Core PS2083-3 (northern Subantarctic Zone, Atlantic sector).

Base: LAD of *Actinocyclus ingens*.

Age and paleomagnetic correlation: 0.65 Ma (early isotopic stage 16) - present.

The *T. lentiginosa* Zone ranges from the lower portion to the top of the Brunhes Chronozone (C1n).

Subzones: Three subzones are distinguished within the *T. lentiginosa* Zone, defined by the Pleistocene occurrence range of *Hemidiscus karstenii*. The lower Subzone "a" ranges between the LAD of *A. ingens* and the Pleistocene FAAD of *Hemidiscus karstenii* in the lower portion of isotopic stage 11 (0.42 Ma) (Burckle 1982). The middle Subzone "b" covers the Pleistocene range of *H. karstenii* between 0.42 Ma and the upper portion of isotopic stage 7 (0.19 Ma) (Burckle 1977), while the upper Subzone "c" ranges above the LAAD of *H. karstenii* from 0.19 Ma to present.

Remarks: The LAD of *A. ingens* in ODP Hole 704A can be placed between Samples 704A-2H-7,40 - 42cm and 704A-2H-6, 120cm (Shipboard Scientific Party 1988; Ciesielski 1991), which converts to an age between 0.659 Ma and 0.643 Ma, according to Hodell (1993), thus in the lower portion of isotopic stage 16 (Imbrie et al., 1984). The Pleistocene range of *H. karstenii* between isotopic stages 11 and 7 is confirmed by the isotopic results of Hodell (1993) obtained at ODP Hole 704A.

#### *Actinocyclus ingens* Partial Range Zone

Author: Gersonde and Burckle (1990), base modified herein, subzoned herein.

Top: LAD of *A. ingens*.

Base: LAD of *Proboscia barboi*.

Age and paleomagnetic correlation: 1.8 - 0.65 Ma (early isotopic stage 16).

The *A. ingens* Zone ranges from the uppermost portion of the Olduvai Event (C2n) in the Matuyama Chronozone to the lower portion of the Brunhes Chronozone (C1n).

Subzones: The *A. ingens* Zone is divided into three subzones. The boundary between the lower Subzone "a" and the middle Subzone "b" is defined by the LAD of *Fragilariopsis barronii* (Gersonde) Gersonde et Bárcena comb. nov., which can be placed at 1.3 Ma in the upper portion of the Matuyama Chron (C1r). In Subzone "a" is the top of an acme of *A. ingens* spanning ca 700 kyr between 2.4 and 1.7 Ma (Acme Ai 1), and the base of another *A. ingens* acme spanning between ca. 1.4 and 1.1 Ma (Acme Ai2). The middle Subzone "b" is marked by the top of Acme Ai2 at ca. 1.1 Ma. The boundary between Subzone "b" and the upper Subzone "c" is defined by the FAAD of *Thalassiosira elliptipora* which occurs between at 1.04 and 1.11 Ma, according to Fenner (1991). The LAD's of *T. fasciculata* and *T. elliptipora* are in the uppermost portion of Subzone c around the Brunhes/Matuyama boundary or just above it. In this Subzone is the base of an *A. ingens* acme spanning between 0.75 Ma and the LAD of *A. ingens* (Fenner 1991; Bárcena et al. submitted).

Remarks: The LAD of *F. barronii* was placed in the upper portion of the Matuyama Chron (1.3 Ma) by Harwood and Maruyama (1992). These authors proposed the use of the LAD of *F. barronii* for definition of the base and top of the middle Pleistocene *A. ingens* and *Nitzschia kerguelensis* zones, respectively. The use of the LAD of *F. barronii* as a zonal boundary marker is not supported herein because early Pleistocene specimens of *F. barronii* can be confused with specimens of *Fragilariopsis kerguelensis* (O'Meara) Hustedt 1952 or other lower Pleistocene specimen belonging to the genus *Fragilariopsis*. To avoid possible problems with the identification of lower Pleistocene diatom zones we propose to use the LAD of *F. barronii* only for definition of subzones within the *A. ingens* Zone, at the present state of knowledge. More biometric and morphological studies have to be carried out to understand the evolutionary linkages between early Pleistocene *Fragilariopsis* taxa and for more accurate definition of the morphological variability of the Plio-Pleistocene taxa which gave rise to the modern *Fragilariopsis* taxa.

#### *Proboscia barboi* Partial Range Zone

Author: Ciesielski (1983), renamed herein.

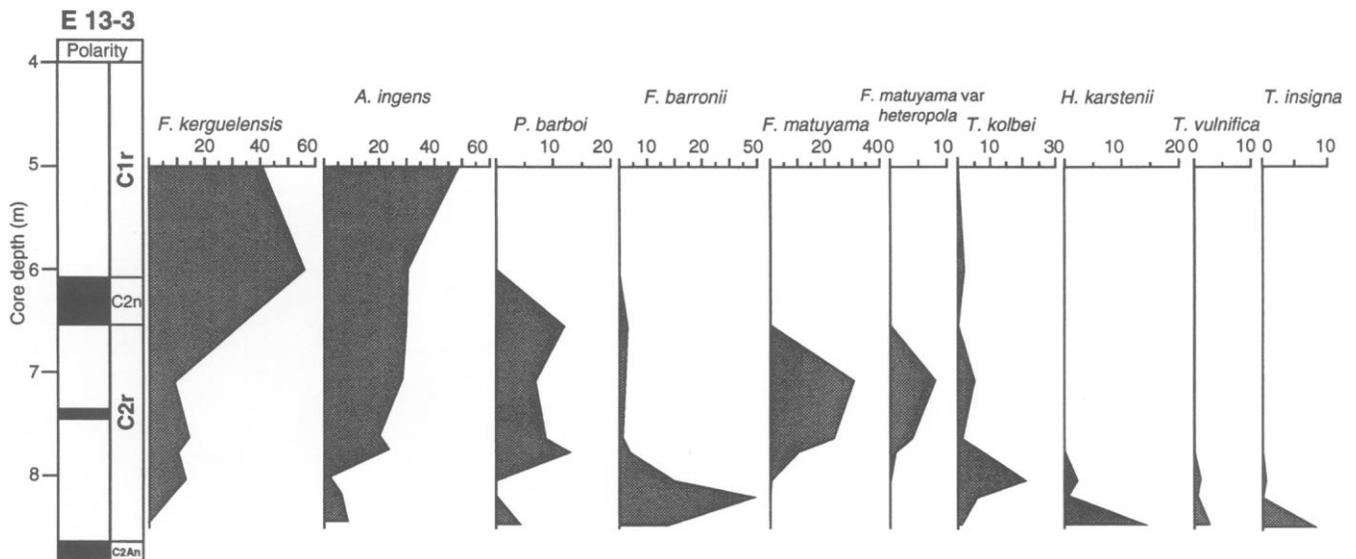
Top: LAD of *Proboscia barboi*.

Base: LAD of *T. kolbei*.

Age and paleomagnetic correlation: 2.0 - 1.8 Ma.

The *P. barboi* Zone ranges from the lower boundary to the uppermost portion of the Olduvai Event (C2n).

Remarks: The *P. barboi* Zone occurs within an acme of *A. ingens* spanning ca 300 kyr between 2.1 and 1.7 Ma. The LAD of *T. kolbei* is noted at the lower boundary of the Olduvai Event (ca. 2.0 Ma), according to Ciesielski (1983) and Baldauf and Barron (1991), while Fenner (1991) reports a 100 - 200 kyr



TEXT-FIGURE 6  
Abundance pattern of stratigraphically useful diatoms in Core E13-3. (Polar Front Zone, Pacific sector). Magnetostratigraphy from Hays and Opdyke (1967).

younger datum. We follow the age determinations of Ciesielski (1983) and Baldauf and Barron (1991) because the paleomagnetic control in the critical intervals of the sections studied by Fenner is not clear and because the data obtained from Cores PS2074-1 and E13-3 support the assignment of the older datum (text-figs. 3, 6). *Thalassiosira kolbei* is rare in the northernmost part of the Southern Ocean (northern Subantarctic Zone), which does not allow the use of this zonal marker in this area. It can be replaced in this area, in certain limits, by the occurrence of the LAD of *F. matuyamae*, which is noted below the LAD of *T. kolbei* between around 2.1 Ma.

***Thalassiosira kolbei* / *F. matuyamae* Zone**

Author: Gersonde and Bárcena (this paper).

Top: LAD of *T. kolbei*.

Base: LAD of *T. vulnifica*.

Age and paleomagnetic correlation: 2.5 - 2.0 Ma.

The *T. kolbei* / *F. matuyamae* Zone ranges from the lowermost portion of the lower Matuyama Chronozone C2r to the lower boundary of the Olduvai Event (C2n). Both Reunion events, C2r.2r.1 and C2r.1n occur in this zone.

Remarks: Ciesielski (1983) first used the LAD of *T. kolbei* and the LAD of *T. vulnifica* for the definition of his *Coscinodiscus kolbei* / *Rhizosolenia barboi* Zone, which was renamed the *Thalassiosira kolbei* Zone (NSOD Zone 18) by Baldauf and Barron (1991). The definition of the base of this zone is now augmented by the FAAD of *F. matuyamae*. The LAD of *F. matuyamae* occurs within the *T. kolbei* / *F. matuyamae* Zone around 2.1 Ma presenting an additional stratigraphic datum in the lower Matuyama Chronozone, which has important stratigraphic significance in sediments originating in the northern Subantarctic Zone where *T. kolbei* occurs in low numbers. In ODP Hole 704A (Fenner 1991) and in Cores PS2074-1 and E13-3 (text-figs. 3, 6) the base of the *T. kolbei* / *F. matuyamae* Zone is also marked by the lower boundary of an acme (FAAD) of *P. barboi*.

***Thalassiosira vulnifica* Partial Range Zone**

Author: Ciesielski (1983), formally renamed herein.

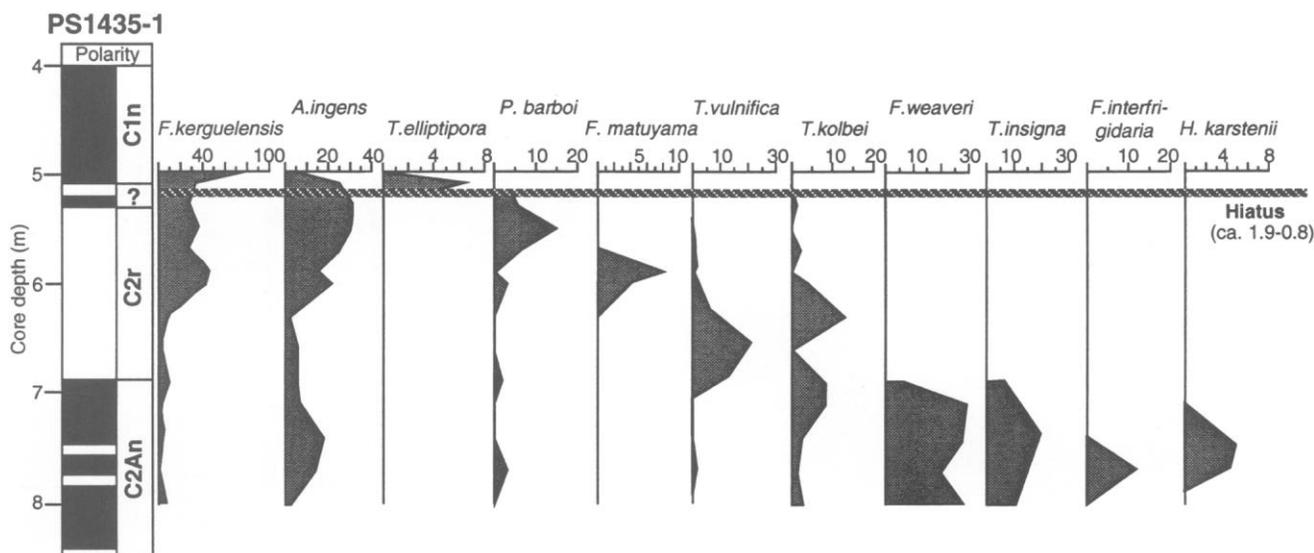
Top: LAD of *T. vulnifica*.

Base: LAD of *Thalassiosira insigna* (Jousé) Harwood et Maruyama 1992.

Age and paleomagnetic correlation: 2.6 - 2.5 Ma.

The *T. vulnifica* Zone ranges from the uppermost portion of the Gauss Chronozone (C2An) to the lowermost portion of the lower Matuyama Chronozone (C2r) below the lower Reunion Event C2r.2r.1.

Remarks: The LAD of *T. insigna* was placed close to the upper boundary of the Gauss Chronozone by McCollum (1975), Ciesielski (1983) and Baldauf and Barron (1991), which converts to an age of ca. 2.6 Ma according to Cande and Kent (1992). The study of PS1435-1 and E13-3 supports this age determination, as well as the studies of Burckle et al. (1990). However, the studies of Burckle et al. (1990) also indicate that the LAD of *T. insigna* occurred in areas at present located south of the Polar Frontal Zone several 100 kyrs earlier in the upper Gauss Chronozone. Fenner (1991) also reports a sharp drop in the abundance pattern of *T. insigna*, however she places the LAD of *T. insigna* into the lower portion of the Matuyama Chronozone (C2r) around 2.1 to 2.2 Ma. This discrepancy might be caused by confusions of *T. insigna* with occurrences of *Thalassiosira inura* Gersonde 1991 or early precursors of *Thalassiosira oliverrana* (O'Meara) Makarova et Nikolaev 1983. The lowermost portion of the *T. vulnifica* Zone is marked in areas located north of the Polar Frontal Zone by an abundance maximum of *H. karstenii*, as documented by Ciesielski (1983) from DSDP Hole 514 and recorded in Core PS2074-1 (text-fig. 3). A supplemental marker to approximate the top of the *T. vulnifica* Zone is the FAAD of *F. matuyamae*.



TEXT-FIGURE 7  
Abundance pattern of stratigraphically useful diatoms in Core PS1435-1 (Polar Front Zone, Atlantic sector). Magnetostratigraphy from Abelmann et al. (1990).

## CONCLUSION

Revising the diatom biostratigraphic zonations and stratigraphic age assignments of diatom events according to the time scale of Cande and Kent (1992) we propose a refined diatom zonation for the last 2.6 Ma. This zonation has application in sequences deposited in the northern belt (north of present Polar Frontal Zone) of the Southern Ocean. Additional diatom datums and the consideration of acme intervals in the definition of subzones allowed the establishment of a refined diatom biostratigraphy with an average time resolution of 0.2 - 0.3 Ma based on control from the geomagnetic time scale. This zonation can be the base for further improvement of Southern Ocean biostratigraphy in the future, relying both on the study of additional marker taxa that have not yet been treated taxonomically, and the recovery of other sediment sequences collected by piston coring or deep sea drilling.

## TAXONOMY

### Transfer of Taxa

Round et al. (1990) proposed to reinstate the genus *Fragilariopsis*, established by Hustedt (1913) separating taxa belonging to *Fragilariopsis* from the genus *Nitzschia* in order to provide greater taxonomic resolution within a complex and broad group of taxa. Hasle (1993) gave an emended diagnosis of the genus *Fragilariopsis*, which can be summarized for the treatment of fossil diatoms as follows, considering comments of Medlin and Sims (1993) and Round et al. (1990): The valve outline of *Fragilariopsis* taxa ranges from linear-lanceolate to elliptical with isopolar or heteropolar apices. The valve face is generally flat and well separated from the steep mantle. The striae are in general parallel and can be curved towards or at the apices. They are mono- to multiserial and separated by interstriae that are well developed on the inner valve. *Fragilariopsis* has a canal raphe system located in strictly eccentric position at the junction of valve face and mantle, not raised above the gen-

eral level of the valve. The raphe lacks terminal fissures but may be separated by a central nodule. The number of fibulae is approximately the same as the number of interstriae.

Considering this generic description we follow the strategy proposed by Round et al. (1990) and propose to transfer taxa belonging to the genus *Nitzschia*, that are important Neogene and Quaternary biostratigraphic markers in the Southern Ocean, to the genus *Fragilariopsis*.

*Fragilariopsis arcula* (Gersonde) Gersonde et Bárcena, comb. nov.  
Basionym: *Nitzschia arcula* Gersonde 1991, p. 143-144, pl. 2 fig. 4; pl. 4, fig. 4; pl. 5, figs. 1-6.

*Fragilariopsis aurica* (Gersonde) Gersonde et Bárcena, comb. nov.  
Basionym: *Nitzschia aurica* Gersonde 1991, p. 144-145, pl. 1, figs. 18-25; pl. 3, fig. 5; pl. 4, figs. 5, 6; pl. 7, fig. 6.

*Fragilariopsis barronii* (Gersonde) Gersonde et Bárcena, comb. nov.  
Basionym: *Nitzschia barronii* Gersonde 1991, p. 146-147, pl. 3, fig. 6; pl. 4, figs. 1-3; pl. 5, figs. 1-17.

*Fragilariopsis interfrigidaria* (McCollum) Gersonde et Bárcena, comb. nov.  
Basionym: *Nitzschia interfrigidaria* McCollum 1975, p. 535, pl. 9, figs. 7-9; Ciesielski 1983, p. 655, pl. 1, figs. 11-18.

*Fragilariopsis lacrima* (Gersonde) Gersonde et Bárcena, comb. nov.  
Basionym: *Nitzschia lacrima* Gersonde 1991, p. 148, pl. 1, fig. 1-6, 26; pl. 2, figs. 1-3.

*Fragilariopsis praecurta* (Gersonde) Gersonde et Bárcena, comb. nov.  
Basionym: *Nitzschia praecurta* Gersonde 1991, p. 148-149, pl. 1, figs. 7-17; pl. 2, fig. 5, 6; pl. 3, fig. 3, 4; pl. 10, fig. 7.

*Fragilariopsis praeinterfrigidaria* (McCollum) Gersonde et Bárcena, comb. nov.  
Basionym: *Nitzschia praeinterfrigidaria* McCollum 1975, p. 535, pl. 10, fig. 1; Ciesielski 1983, p. 655, pl. 2, figs. 1-8, 13-16; pl. 3, fig. 5.

*Fragilariopsis weaveri* (Ciesielski) Gersonde et Bárcena, comb. nov.  
 Basionym: *Nitzschia weaveri* Ciesielski (1983) p. 655, pl. 1, figs. 1 - 10.

**Description of new taxa**

*Fragilariopsis matuyamae* Gersonde and Bárcena sp. nov.  
 Plate 1, figures 1–9, 13–16; plate 2, figures 1, 4–5, 7–9

**Description:** Valve flat, isopolar, with rounded apices. Apical axis ranges from 12 to 40µm, transapical axis from 3 - 7µm. Interstriae straight and heavily silicified on the valve inside. The heavy silicification can lead to a junction of the interstriae on the valve inside (pl. 2, fig. 7). Interstriae next to apices can be slightly curved, 10 - 13 interstriae in 10µm. Striae in general biseriate, the areolae regular spaced and located adjacent to the interstriae (40 - 50 in 10µm). Central transapical part of the striae can be perforated by additional areolae that are irregular spaced (pl. 2, fig. 8). Raphe located at the junction between valve face and valve mantle. Central nodule is present (pl. 1, fig. 14, 15). Number of fibulae and interstriae are identical. Basal portion of the mantle heavily silicified (pl. 1, fig. 16, pl. 2, fig. 7)

**Holotype:** Deposited in the Friedrich-Hustedt Collection No. Zu4-60 (pl. 1, fig. 2)

**Type locality:** Core PS2074-1, southern Cape Basin (tab. 1, text-fig. 1).

**Type level:** Marine, upper Pliocene, Sample PS2074-1, 988cm.

**Paratype:** Deposited in the Friedrich-Hustedt Collection No. Zu4-61 (pl. 2, fig. 5) from Sample PS2074-1, 968cm.

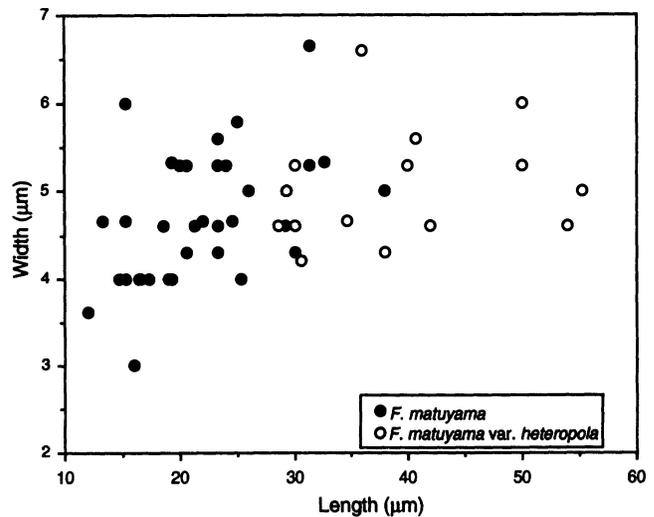
**Stratigraphic occurrence:** In the upper Pliocene of the northern Southern Ocean. Known range from the *T. vulnifica* Zone into the uppermost *T. kolbei* /*F. matuyamae* Zone (LAD ca. 2.1 Ma). Acme occurs in the lower *T. kolbei* /*F. matuyamae* Zone. Base of acme (FAAD of *F. matuyamae*) is at the base of the *T. kolbei* /*F. matuyamae* Zone and represents additional stratigraphic marker, besides the LAD of *T. vulnifica*.

**Derivation of name:** After the Matuyama Geomagnetic Chronozone, which has been named after the Japanese geophysicist Motonori Matuyama.

**Discussion and remarks:** *F. matuyamae* has affinities to *Fragilariopsis arcuata* (Gersonde) Gersonde et Bárcena comb. nov. (this paper), a taxon which ranges from the late Miocene to the early Pliocene in southern high-latitudes (Gersonde 1991). *F. matuyamae* differs from *F. arcuata* by the presence of a central nodule and generally more heavily silicified interstriae that can merge with each other.

***Fragilariopsis matuyamae* var. *Heteropola*** Gersonde and Bárcena var. nov.  
 Plate 1, figures 10–12; plate 2, figures 2–3, 6

**Description:** Valve flat, heteropolar, with rounded apices. Apical axis ranges from 25 to 60µm, transapical axis from 4 - 7µm. Interstriae straight and heavily silicified on the valve inside. The heavy silicification can lead to a junction of the interstriae on the valve inside (pl. 2, fig. 6). Interstriae next to apices can be slightly curved, 10 - 13 interstriae in 10µm. Striae in general biseriate, the areolae regular spaced and located adjacent to the interstriae (40 - 50 in 10µm). Central transapical part of the striae can be perforated by additional areolae that are irregular



TEXT-FIGURE 8  
 Length - width ratio of *Fragilariopsis matuyamae* sp. nov. and *F. matuyamae* var. *heteropola* var. nov.

spaced. Raphe located at the junction between valve face and valve mantle. Central nodule is present. Number of fibulae and interstriae are identical. Basal portion of the mantle heavily silicified (pl. 2, fig. 6).

**Holotype:** Deposited in the Friedrich-Hustedt Collection No. Zu4-62 (pl. 2, fig. 2).

**Type locality:** Core PS2074-1, southern Cape Basin (tab. 1, text-fig. 1).

**Type level:** Marine late Pliocene, Sample PS2074-1, 908cm.

**Paratype:** Deposited in the Friedrich-Hustedt Collection No. Zu4-63 (pl. 2, fig. 3) from Sample PS2074-1, 948cm.

**Stratigraphic occurrence:** In the upper Pliocene of the northern Southern Ocean. Ranges in the *T. kolbei* /*F. matuyamae* Zone.

**Derivation of name:** heteropolar outline.

**Remarks:** Abundance lower than that of *F. matuyamae* (text-fig. 3).

**List of other taxa**

*Actinocyclus ingens* Rattray (1890); Gersonde (1990), p. 791-792, pl. 1, figs. 1, 3–5; pl. 3, figs. 8–9; pl. 4, fig. 1.

*Hemidiscus karstenii* Jousé in Jousé et al. (1963), p. 78, pl. 2, figs. 7–9.

*Fragilariopsis kerguelensis* (O'Meara) Hustedt (1952); Hasle (1965), p. 14–18, pl. 3, figs. 4–5; pl. 4, fig. 11–18; pl. 5, fig. 1–11; pl. 6, figs. 2–4; pl. 7, fig. 9; pl. 8, fig. 10; pl. 16, figs 3–5.

*Proboscia barboi* (Brun) Jordan and Priddle (1991), p. 56; Schrader (1976), p. 635, pl. 9, figs 11–13 as *Rhizosolenia barboi*; Fenner (1991), p. 108, pl. 3, fig. 1, 3 as *Simonseniella barboi*.

*Thalassiosira elliptipora* (Donahue) Fenner (1991), p. 108, pl. 1, fig. 3, pl. 3, fig. 2.

*Thalassiosira fasciculata* Harwood and Maruyama (1992), p. 707, pl. 15, figs. 4–6.

*Thalassiosira insigna* (Jousé) Harwood and Maruyama (1992), p. 707, pl. 14, figs. 3–5.

Remark: One reviewer, D. Harwood, stated that according to unpublished investigations the basionym of *T. insigna*, which was originally described by Jousé (1961) from northern latitude Neogene as *Cosmioliscus insignis*, cannot be attributed to the genus *Thalassiosira* due to its valve morphology. However, the valve morphology of the taxon occurring in southern high-latitudes Neogene sediments, and which has been related by Harwood and Maruyama (1992) to *C. insignis*, includes this taxon to the genus *Thalassiosira*. Thus, this taxon represents a new species which should be described after acquisition of additional SEM-information on the valve morphology of both, *C. insignis* Jousé and *T. insigna* sensu Harwood and Maruyama.

*Thalassiosira inura* Gersonde (1991), p. 151, pl. 6, figs. 7–14; pl. 8, figs. 1–6.

*Thalassiosira kolbei* (Jousé) Gersonde (1990), p. 793; pl. 1, fig. 2; pl. 5, figs. 3, 5, 6.

*Thalassiosira oliverana* (O'Meara) Makarova et Nikolaeva (1983); Fenner et al. (1976), p. 779, pl. 14, figs. 1–5 as *Schimperella antarctica* Karsten.

*Thalassiosira vulnifica* (Gombos) Fenner (1991), p. 108, pl. 2, fig. 2.

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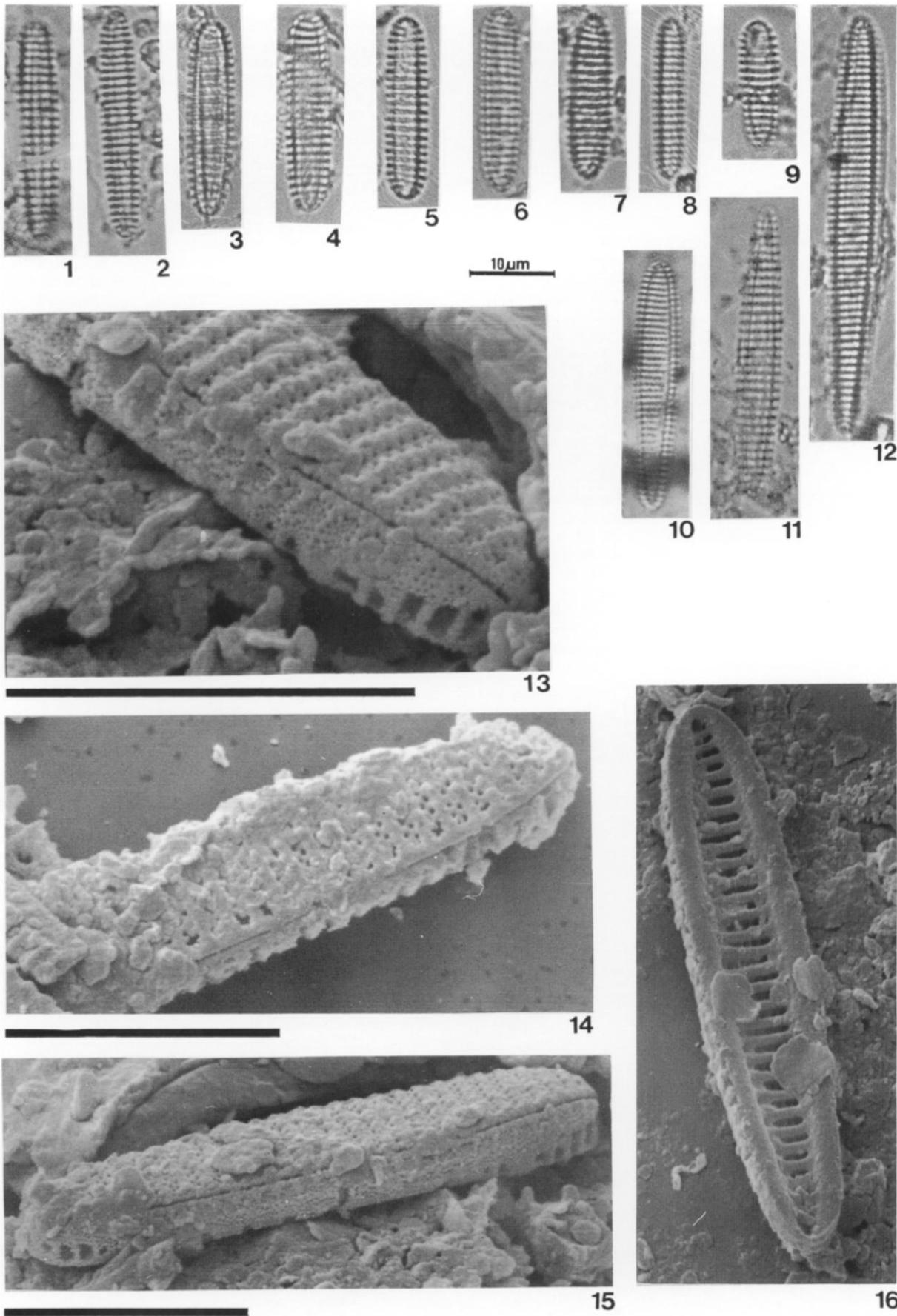
#### PLATE 1 Scale bar = 10µm.

1-9 *Fragilariopsis matuyamae* sp. nov.; (1) Sample E13/3, 708–711.5cm; (2) holotype, Sample PS2074-1, 988cm; (3-4) Sample PS1435-1, 560cm; (5-6, 9) Sample PS2074-1, 1008cm; (7) Sample PS2074-1, 988cm; (8) Sample PS2074-1, 908cm.

10-12 *Fragilariopsis matuyamae* var. *heteropola* var. nov.; (10, 12) Sample PS2074-1, 1008cm; (11) Sample E13/3, 764–767cm.

13-15 *Fragilariopsis matuyamae* sp. nov. outside view of valve face, marginal raphe and central nodule well discernable, Sample PS 2074-1, 908cm.

16 *Fragilariopsis matuyamae* sp. nov. inside view of valve face, Sample PS 2074-1, 908cm.



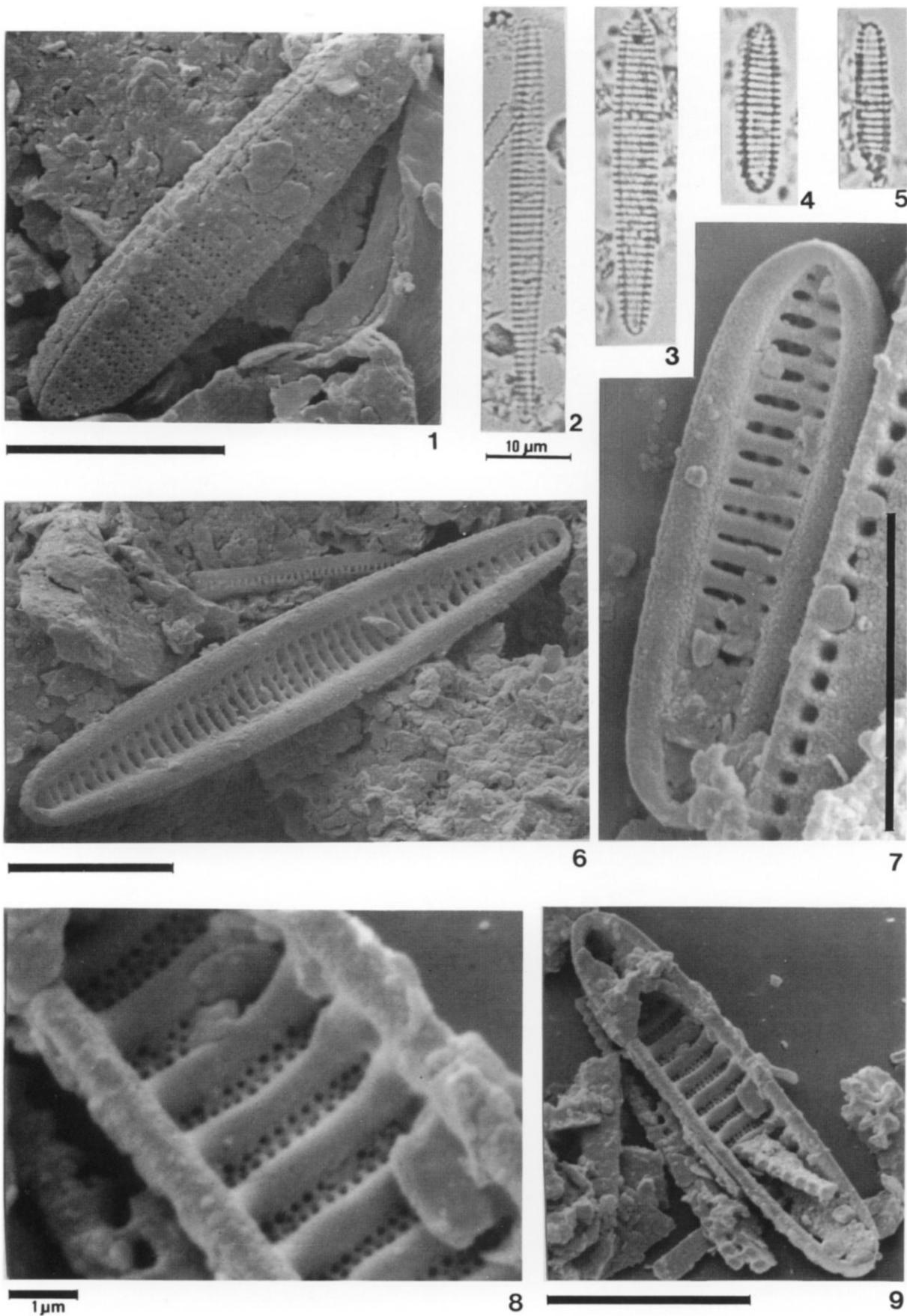
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## PLATE 2

Scale bar = 10µm, unless otherwise indicated.

- 1 *Fragilariopsis matuyamae* sp. nov., outside view of valve face, marginal raphe and central nodule well discernable, Sample PS 2074-1, 908cm.
- 2-3 *Fragilariopsis matuyamae* var. *heteropola* var. nov.; (2) holotype, Sample PS2074-1, 908cm; (3) paratype, Sample PS2074-1 948cm.
- 4-5 *Fragilariopsis matuyamae* sp. nov.; (4) Sample PS2074-1, 988cm; (5) paratype, Sample PS2074-1, 968cm.
- 6 *Fragilariopsis matuyamae* var. *heteropola* var. nov. inside view of valve face, Sample PS 2074-1, 908cm.
- 7-9 *Fragilariopsis matuyamae* sp. nov. inside view of valve face; (7) Sample PS2074-1, 908cm; (8-9) stria structure, Sample E13-3, 703cm.



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