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2. MIDDLE MIOCENE TO PLEISTOCENE DIATOM BIOSTRATIGRAPHY OF THE NORTHWEST PACIFIC AT SITES 1150 AND 1151[1]

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ABSTRACT

Late Neogene biostratigraphy of diatoms has been investigated from two sites occupied during Ocean Drilling Program (ODP) Leg 186 off the coast of northeast Japan. A unique aspect of ODP Leg 186 was the installation of two permanent borehole geophysical observatories at the deep-sea terrace along the Japan Trench. The Neogene subsidence history of the forearc was documented from both Sites 1150 and 1151, and Quaternary to middle Miocene (16 Ma) sediments represent a nearly continuous stratigraphic sequence including numerous ash records, especially during the past 9 m.y. Diatoms are found in most samples in variable abundance and in a moderately well preserved state throughout the sequence. The assemblages are characterized consistently by age-diagnostic species of *Denticulopsis* and *Neodenticula* found in regions of high surface water productivity typical of middle to high latitudes. The Neogene North Pacific diatom zonation divides the Miocene to Quaternary sequences fundamentally well, except that the latest Miocene through early Pliocene *Thalassiosira oestrupii* Subzone is not applicable. Miocene and late Pliocene through Pleistocene diatom datum levels that have been proven to be of great stratigraphic utility in the North Pacific Ocean appear to be nearly isochronous within the level of resolution constrained by core catcher sample spacing. The taxonomy and stratigraphy of previously described species determined to be useful across the Miocene/Pliocene boundary have been investigated on the basis of the evolutionary changes within the *Thalassiosira trifulta* group.

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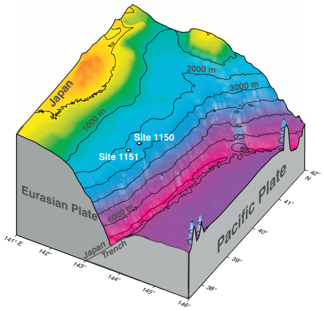
The biostratigraphically important forms belonging to the genus *Thalassiosira* have been illustrated with scanning electron micrographs.

INTRODUCTION

The Japan Trench area is probably the best investigated island arc-trench system on the planet, where two borehole geophysical observatories were installed at ~1100 meters below seafloor (mbsf) on the deep-sea terrace during Ocean Drilling Program (ODP) Leg 186. The borehole geophysical observatories were planned to monitor the ongoing tectonic processes at two sites (Sites 1150 and 1151) ~25 km north and south of 39°N (Fig. **F1**). A forearc basin developed in the deep-sea terrace and trench upper slope, which extends from the coast of Hokkaido >600 km to the south and is filled with Cretaceous and Cenozoic sediments as much as 5 km thick. Sites 1150 and 1151 on the deep-sea terrace, located ~100 km west of the Japan Trench, are on the eastern edge of the forearc basin, where the Neogene section is ~1.5 km thick (Sacks, Suyehiro, Acton, et al., 2000).

F1. Location of Leg 186 sites, p. 21.



Previous drilling in the forearc area took place during Deep Sea Drilling Project (DSDP) Legs 56, 57, and 87, which transected the Japan Trench at ~39.8°N–40.7°N. During DSDP Legs 56 and 57, five sites were drilled along across the trench at 39°45′N. Sites 438 and 439 during Leg 57 were drilled across the trench at 40°40′N, where Site 584 was also drilled during DSDP Leg 87 (Shipboard Scientific Party, 1980; Kagami, Karig, Coulbourn, et al., 1986). These legs focused on the study of the mechanism and dynamics of plate convergence and their effects on sedimentation because the Japan Trench has the dynamic properties of one of the world's most active plate subduction zones, where the oldest oceanic plate (>100 Ma) is subducting at a high rate (~90 km/m.y.). It is presently widely accepted that little tectonic accretion is occurring. A surprise finding from Site 439 was the unexpected presence of andesitic volcanic rocks only 90 km west from the trench axis (Shipboard Scientific Party, 2000a).

These legs established not only the concept of tectonic erosion along a subduction zone but also provided a biostratigraphic standard applicable to the middle to high latitudes in the North Pacific Ocean. The sedimentation rates between Sites 1150 and 1151 are broadly similar after 8 Ma and are consistent with those reported at DSDP Leg 57 Site 438 and Leg 87 Site 584, but differ before 8 Ma (Sacks, Suyehiro, Acton, et al., 2000). Extensional tectonics continued from the middle Miocene until the early Pliocene. Numerous ash layer records from all the DSDP and ODP sites suggest that onshore volcanic activity increased during the latest Miocene and continued through the early Pliocene (Shipboard Scientific Party, 1980; Kagami, Karig, Coulbourn, et al., 1986).

Sites 1150 (39°11′N, 143°20′E) and 1151 (38°45′N, 143°20′E) are located in areas with contrasting seismic characteristics at water depths of 2681 and 2182 m, respectively. The Neogene subsidence history of the forearc was documented, and numerous ash records were obtained that span the past 9 m.y. The ages of the recovered sediments are 10–0 Ma at Site 1150 and 16–0 Ma at Site 1151 (Shipboard Scientific Party, 2000a). Biostratigraphic research objectives for the forearc basin-floor drilling focus on a few major threads. These are (1) documenting the succession of surface ocean floras and faunas in the Japan Trench area, (2) investigating the longer-term linkage between the oceanographic evolution of the North Pacific and continental records of mainly volcanic activities, and (3) defining age frameworks for deep-sea sediment sequences.

The sediments collected during Leg 186 provide a unique opportunity to enhance current biostratigraphies and to improve the temporal biochronologic framework for refined paleoceanographic analysis. The authors had to do their diatom work within 4 months before the second postcruise meeting because they were unable to join the shore-based scientific party until the late spring of 2001.

In the near future it is expected that drilled sediments shall contribute to the understanding the oceanographic and climate histories along the North Pacific rim, along with drill sites from the eastern and western equatorial Pacific (Legs 138 and 130, respectively), through the eastern and western somewhat temperate mid-latitude margins (Legs 167 and 186, respectively), and toward the high-latitude North Pacific (Leg 145). Scientific goals must be to link the evolution of the North Pacific climate and the development of the tectonic events in the Northern Hemisphere and, finally, to resolve the teleconnections responsible for the Miocene through Pleistocene diatom records (Barron, 1989, 1992b, 1995, 1998).

The purpose of this paper is (1) to document the diatom stratigraphy at Sites 1150 and 1151, (2) to test the reliability of diatom datum levels and zones for integration with radiolarian biostratigraphy and magnetostratigraphy, and (3) to reexamine a diatom zonation associated with the Miocene/Pliocene boundary. The emphasis of this paper is to substantiate the practical age assignment of the North Pacific Miocene through Pleistocene diatom datums given that most of these events have been previously calibrated to paleomagnetic stratigraphy (Koizumi and Tanimura, 1985; Barron and Gladenkov, 1995; Yanagisawa and Akiba, 1998).

METHODS

Zonation

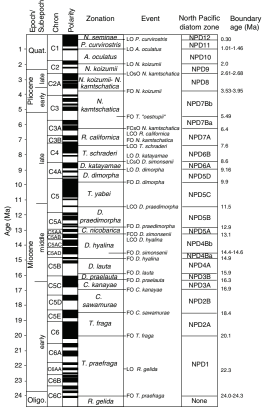
The Neogene through Quaternary diatom sequences of the North Pacific Ocean have been the subject of investigation since the pioneering work of Donahue (1970), Schrader (1973a), and Koizumi (1973a, 1973b). These authors established the fundamental basis for the Neogene biochronostratigraphic zonation. Successive revision and refinement of the North Pacific diatom stratigraphy have been developed rapidly by subsequent studies including those by Koizumi (1975a, 1975b, 1975c, 1975d, 1977, 1980), Burckle and Opdyke (1977), and Akiba (1977, 1979).

Barron (1980) presents a major advance toward the understanding of the timing of Neogene paleoclimatic and paleoceanographic evolution of the North Pacific Ocean based on diatom biostratigraphy. Later investigators (e.g., Barron [1981, 1985], Barron and Baldauf [1986], Akiba [1982b, 1983], Akiba et al. [1982a, 1982b], Akiba and Ichinoseki [1983], Maruyama [1984b], Koizumi [1985], Koizumi and Tanimura [1985], and Oreshkina [1985]) extended and modified the biostratigraphic framework of Barron (1980). These studies documented the late Neogene diatom biostratigraphy for a number of North Pacific deep-sea sites drilled that have provided data necessary to correlate the Neogene marine sequences exposed on land in Japan with those elsewhere in the North Pacific Ocean.

A significant advance in Neogene biochronostratigraphy was achieved by Akiba (1986), whose paper is conceivably the best summary of the Miocene to Pleistocene North Pacific diatom stratigraphy, and his proposed stratigraphic zonation has been widely accepted as a standard practicable scheme (Koizumi, 1992; Barron, 1992a; Barron and Baldauf, 1995, Yanagisawa, 1996; Watanabe and Takahashi, 1997). For the high-latitude North Pacific transect (ODP Leg 145), Barron and Gladenkov (1995) succeeded in directly correlating diatom stratigraphic events with magnetostratigraphy and in supplying precise ages for the Neogene zonal markers. Furthermore, Gladenkov and Barron (1995) presented an early Miocene through Oligocene diatom zonation based on a near-continuous stratigraphic record.

Recently, minor modifications to the Neogene North Pacific diatom zonation of Akiba (1986) were proposed in order to adjust the differences between the previously existing zonations (Yanagisawa and Akiba, 1998; Maruyama, 2000) and to integrate the diatom zonation with the radiolarian zonation (Motoyama and Maruyama, 1998). The ages of the primary diatom events are updated based on the revised geomagnetic polarity timescale of Cande and Kent (1995) by extrapolation of each horizon within each magnetic chron. Among the geomagnetic polarity timescales (Cande and Kent, 1992, 1995; Baksi, 1993; Wei, 1995; Berggren et al., 1995a, 1995b), the severe variance in age calibration points is relatively well known.

F2. Diatom zonation, primary zonal markers, and zonal code numbers, p. 22.



The diatom zonation (Fig. **F2**) used for the late Cenozoic closely follows the zonation of Yanagisawa and Akiba (1998) proposed for the northwest Pacific Ocean. There are small changes in zonal boundaries. For example, the top of the *Denticulopsis katayamae* Zone is marked by the last consistent occurrence (LCsO) of *Denticulopsis simonsenii* as suggested by Akiba (1986) and the base of the *Neodenticula kamtschatica* Zone is decided not by the last common occurrence (LCO) of *Rouxia californica,* but by the first consistent occurrence (FCsO) of *N. kamtschatica*. Moreover, the base of the *Neodenticula koizumii* Zone is recognized by the LCsO of *N. kamtschatica* instead of the strict last occurrence (LO) of *N. kamtschatica*. A consistent occurrence (CsO) is important for determining a taxon's stratigraphic consistency in comparison to a common occurrence (CO) by placing special emphasis on a change in relative abundance. Code numbers of Neogene North Pacific diatom (NPD) zones were also modified. Relationships between the zone name, code label, and definition are shown in Table **T1.**

T1. North Pacific diatom zonation and stratigraphic markers used during Leg 186, p. 24.

Although the Neogene datum levels, particularly Miocene datum levels, were not directly calibrated with the magnetostratigraphy, they occur in the proper stratigraphic sequence and apparently at the proper intervals, thus suggesting that they may be isochronous with other parts of the North Pacific Ocean. In addition to the ODP Leg 186 zonation, exceptional diachronism across latitude has been well known for a number of diatom events such as the first occurrence (FO) of *N. kamtschatica,* the FO of *N. koizumii,* the LO of *N. kamtschatica,* the LO of *N. koizumii,* and the LO of *Actinocyclus oculatus*.

Taxonomic studies, especially on a group commonly accepted as "marine *Denticula*" (Simonsen and Kanaya, 1961) or the genus *Denticulopsis* (Simonsen, 1979), resulted in a remarkable advance in the Neogene North Pacific diatom biostratigraphy. The three dominant genera, *Denticulopsis, Crucidenticula,* and *Neodenticula* (Akiba and Yanagisawa, 1986), which consist of various short-ranging species, provide many stratigraphically useful biohorizons (Schrader, 1973a, 1973b; Maruyama, 1984a, 1992; Akiba, 1977, 1979, 1982a, 1986; Tanimura, 1989; Yanagisawa and Akiba, 1990).

The taxonomy used in this study follows that of Koizumi (1980, 1992), Akiba (1986), Yanagisawa and Akiba (1990, 1998), Fenner (1991), Harwood and Maruyama (1992), and Akiba et al. (1993). However, several groups are defined because it is not clear how to correctly separate taxa of *Crucidenticula* and *Denticulopsis* and because it is uncertain whether a number of secondary diatom biohorizons proposed by Yanagisawa and Akiba (1998) are applicable in the North Pacific Ocean.

Crucidenticula nicobarica group = *Crucidenticula paranicobarica* vars. and *C. nicobarica.*
Denticulopsis lauta group = *D. lauta, Denticulopsis ichikawae, Denticulopsis okunoi,* and *Denticulopsis tanimurae.*
Denticulopsis hyalina group = *Denticulopsis praehyalina* and *D. hyalina.*
Denticulopsis simonsenii group = *D. simonsenii* and *Denticulopsis vulgaris.*
Denticulopsis katayamae group = *Denticulopsis praekatayamae* and *D. katayamae.*
Denticulopsis praedimorpha group = *D. praedimorpha* v. *minor, Denticulopsis barronii, D. praedimorpha* v. *intermedia, D. praedimorpha* v. *praedimorpha,* and *D. praedimorpha* v. *robusta.*
Denticulopsis dimorpha group = *D. dimorpha* v. *dimorpha* and *D. dimorpha* v. *areolata.*

Moreover, on the basis of the available taxonomic studies by Shiono (2000, 2001), and Shiono and Koizumi (2000, 2001), an identification and an age assignment of the *Thalassiosira trifulta* group were carefully conducted for documenting the taxon ranges accurately from the northwest Pacific deep-sea holes.

Techniques

On board the *JOIDES Resolution*, supplementary smear slides were prepared from appropriate core intervals for determining placement of zonal boundaries and for calibrating sedimentation rates (Sacks, Suyehiro, Acton, et al., 2000). Postcruise observations are based on examination of core catcher samples that were newly processed in the shore-based laboratory. Sample material was placed in an oven at 60°C for 24 hr, ~1–2 g of dried material was boiled in a 200-mL beaker with ~30–50 mL of hydrogen peroxide solution (H_2O_2, 5%) for a few minutes, and 10 mL of hydrochloric acid (HCl, 5%) was added in small portions. Acid-treated material was made pH neutral by repeatedly filling and decanting the beakers with distilled water and allowing 1 hr for settling. Strewn slides were prepared by spreading the pipette suspension onto a cover glass (22 mm × 22 mm), drying on a hot plate, and mounting in photocuring adhesive DB-855.

Diatoms are present throughout the sites but with varying abundance and preservation. Strewn slides were examined in their entirety at a magnification of 600×, and identifications were checked routinely at 1000× for stratigraphic markers and paleoenvironmentally sensitive taxa. Semiquantative estimates were made of the relative abundance of stratigraphically important taxa for each sample. These abundances were recorded as follows:

A = abundant; two or more specimens per field of view.
C = common; one specimen per two fields of view.
F = few; one specimen per each horizontal traverse.
R = rare; one specimen per a few horizontal traverses.
T = trace; one specimen per several or more horizontal traverses.

Preservation of diatoms was determined qualitatively as follows:

G = good; finely silicified forms present and no alteration of frustules observed.
M = moderate; finely silicified forms present with some alteration.
P = poor; finely silicified forms absent or rare and fragmented, and the assemblage is dominated by robust forms.

Diatom analysis on board the *JOIDES Resolution* presumed the Miocene/Pliocene boundary to be expected between Samples 186-1150B-5R-CC and 15R-CC and 186-1151A-50R-CC and 60R-CC, respectively. Particular attention was focused on morphology and stratigraphic distribution of the *T. trifulta* group. In an effort to resolve the diatom biostratigraphy for the epoch boundary interval, 11 core catcher samples were picked for analysis of this group from each site, respectively. Not only light microscope (LM) observations but also scanning electron microscope (SEM) observations were made on selected samples in order to settle the Miocene/Pliocene epoch boundary in both Holes 1150B and 1151A.

Samples were boiled in a solution of hydrogen peroxide (H_2O_2, 15%) and hydrochloric acid (HCl, 15%), which washed the organic matter from the diatom skeleton, and then the residue was suspended in a solution of sodium diphosphate decahydrate ($Na_4P_2O_7 \cdot 10H_2O$, 0.02%–0.03%) for reducing the clay minerals. The LM pictures were taken using a Pixera camera system, and the SEM pictures were produced using an S-2250N Hitachi SEM and Quartz PCI image management system. Diatom valves of all species including the genus *Chaetoceros* were counted in each sample under the LM until the number of valves totaled 1000 or 1000.5. Whenever we encountered valve specimens, each end of a pennate diatom was taken as a half valve (0.5). With regard to centric diatoms, the central area was taken as one valve (1).

RESULTS

The tabulated occurrences of stratigraphically important taxa are shown in Tables T2 and T3, including the sample depth in meters below seafloor. Table T4 provides the sample interval and meters below seafloor depth, which are constrained to stratigraphic events identified for Sites 1150 and 1151.

T2. Age diagnostic diatoms, Site 1150, p. 25.

T3. Age diagnostic diatoms, Hole 1151A, p. 28.

T4. Middle Miocene through Quaternary diatom datum levels, Leg 186, p. 31.

Site 1150

Site 1150 is located at a water depth of 2681 m in the deep-sea terrace on the landward side of the Japan Trench. An apparently continuous sequence of upper Miocene through Pleistocene sediments and sedimentary rocks was recovered from Site 1150 (Shipboard Scientific Party, 2000b). The 1181-m-thick section consists mainly of diatomaceous silty clay and diatomaceous clay. Diatoms are generally common to abundant and moderately well preserved throughout. In the upper Miocene section, however, abundance of diatoms slightly decreases because of the increase in clay content and probably siliceous diagenetic alteration.

Diatom assemblages from all samples consist almost entirely of oceanic species, which are typical of the subarctic North Pacific Ocean. Diatoms are represented by open-ocean forms not characteristic of coastal upwelling regions. Sparse occurrences of temperate taxa, such as *Fragilariopsis doliola, Hemidiscus cuneiformis, Nitzschia reinholdii,* and *Nitzschia marina,* indicate the influence of temperate water masses from the south during the Neogene through Quaternary.

The Shipboard Scientific Party (2000b) reported that a significant difference in the sedimentation rate is observed between Site 1150 and nearby areas such as Holes 438A and 584. The Neogene basin around Site 1150 is called the Kitakami Basin and is situated at ~38°–40°N; on the other hand, the Ishikari-Hidaka Basin around Sites 438 and 584 extends northward. Oceanic diatoms have been deposited continuously in the vicinity of Site 1150 since at least the late Miocene, whereas in Holes 438A and 584 some hiatuses are recorded as the result of a slightly shallower condition during the paleoceanographic history.

The boundary between the late Quaternary *Neodenticula seminae* and *Proboscia curvirostris* Zones (NPD12/NPD11) is indicated by the LO of *P. curvirostris* (0.30 Ma) between Samples 186-1150A-5H-CC and 6H-CC. The biostratigraphic interval through Zone NPD12 and the uppermost part of Zone NPD11 corresponds well to positive magnetic inclinations above Section 186-1150A-10H-1 (84.18 mbsf), representing Chron C1n (Brunhes).

The LO of *A. oculatus* immediately above Sample 186-1150A-12H-CC marks the boundary between the *P. curvirostris* and *A. oculatus* Zones (NPD11/NPD10). This boundary is estimated to be between 1.01 and 1.46 Ma in the subarctic region by Barron and Gladenkov (1995), based on its LCO. The FO of *P. curvirostris,* with an age of 1.58 Ma, is recognized between Samples 186-1150A-14H-CC and 15H-CC.

Koizumi (1992) proposed that the LO of *N. koizumii* clearly defines the base of the *A. oculatus* Zone (NPD10) and the top of the underlying *N. koizumii* Zone (NPD9). This latest Pliocene event, at ~2.0 Ma, falls between Samples 186-1150A-15X-CC and 16X-CC. The occurrence of *F. doliola* (= *Pseudoeunotia doliolum*) in Sample 186-1150A-13X-CC supports the recognition of the NPD10/NPD9 zonal boundary because the FO of that warm-water species has an estimated age of 1.9 Ma in the eastern equatorial Pacific Ocean (Baldauf and Iwai, 1995).

The LCsO of *N. kamtschatica* (2.61–2.68 Ma) between Samples 186-1150A-21X-CC and 22X-CC marks the top of the *N. koizumii–N. kamtschatica* Zone (NPD8). The FO of *N. koizumii* (3.53–3.95 Ma), which defines the boundary between the *N. koizumii–N. kamtschatica* Zone and the underlying *N. kamtschatica* Zone (NPD8/NPD7B), is clearly identified between Samples 186-1150A-27X-CC and 28X-CC.

Shipboard Scientific Party (2000b) reported that the FO of *Thalassiosira "oestrupii"* sensu amplificato (that notation has been generally written as sensu lato or s.l.), denoting the Miocene/Pliocene boundary from a standpoint of diatom biostratigraphy, is detected between Sample 186-1150A-56X-CC and Section 57X-1 and is useful to subdivide the NPD7B Zone. Based on recent progress in taxonomy of the *Thalassiosira* group (Shiono and Koizumi, 2000, 2001), the FO of *T. "oestrupii"* s. ampl. (5.49 Ma) is not suitable for a datum plane in the Neogene diatom zonation. We cannot help discarding the name of the *T. oestrupii* Subzone from the North Pacific diatom zones and reconstructing the subzonal framework during the uppermost Miocene through lower Pliocene series.

Drilling in Hole 1150A stopped in Core 186-1150A-76X, and the lowest stratigraphic sample (186-1150A-76X-CC) at 722.85 mbsf remained in Zone NPD7B. Drilling continued in Hole 1150B with the topmost core catcher (Sample 186-1150B-1R-CC) still remaining in the same NPD7B Zone at 708.22 mbsf. The top of the upper Miocene *R. californica* Zone (NPD7A) is defined by the FCsO of *N. kamtschatica* (6.4 Ma) between Samples 186-1150B-21R-CC and 22R-CC.

A complete sequence of diatom zones from the middle upper Miocene *Thalassionema schraderi* Zone (NPD6B) to the lower upper Miocene *Thalassiosira yabei* Zone (NPD5C) was penetrated in the lower part (>1044.73 mbsf) of Hole 1050B. The LCO of *T. schraderi* (7.6 Ma), just above Sample 186-1050B-36R-CC, marks the boundary between the NPD7A Zone and the underlying the *T. schraderi* Zone (NPD6B). From Zones NPD7A through NPD6B, both characteristics of *R. californica* and *T. schraderi* occur consistently but not abundantly. The LCsO of *D. simonsenii* (8.6 Ma) is assigned between Samples 186-1050B-40R-CC and 41R-CC, where the NPD6B/NPD6A boundary is obviously placed. The LO of *D. katayamae* was not determined clearly because of the presence of a poorly preserved horizon at ~1070 mbsf in Hole 1150B.

Assemblages in Samples 186-1150B-43R-CC through 48R-CC (1111.28 to 1157.71 mbsf) containing *D. dimorpha* are assigned to the lower upper Miocene *D. dimorpha* Zone (NPD5D). Within Zone NPD5D, Sample 186-1150B-45R-CC records the FO of *D. katayamae* and Sample 186-1150B-46R-CC contains the FO of *T. schraderi*.

At the bottom of Hole 1150B, the *T. yabei* Zone (NPD5C) lies in Samples 186-1150B-49R-CC through 50R-CC. Neither *D. praedimorpha* nor *D. dimorpha* persist through Zone NPD5C, so the evolutionary lineage from *D. praedimorpha* to *D. dimorpha* is disrupted in the midlatitude northwestern Pacific Ocean. It is surely indicated that the base of Hole 1150B lies between 9.9 and 11.5 Ma, although on board the ship a much older age of 11.6 Ma was given for the bottom sediments from an extrapolation of the sedimentation rate.

Site 1151

The sedimentary sequence recovered from Site 1151 consists of an apparently continuous 1113-m-thick interval of lower middle Miocene (<16.3 Ma) to Pleistocene sediment. Site 1151 is located on the deep-sea terrace at 2681 m water depth, ~100 km west of the Japan Trench axis. The geologic setting at Site 1151 is similar to that at Site 1150, which is 48 km north from Site 1151 on the eastern edge of the forearc basin.

Four holes were completed at Site 1151 to a maximum depth of 1113.6 mbsf. Dominant lithologies are diatomaceous silty clay. Diatoms are generally common to abundant and moderately to well preserved throughout the section cored with the exception that some ash and dolomite layers contain few to rare diatoms. Diatom assemblages are typical of hemipelagic sedimentary sequences of temperate middle latitudes, and the standard North Pacific diatom zonation has been adapted for use in Hole 1151A (Table T3). Reworked forms and neritic assemblages are not significant at this site. Sparse occurrences of subtropical taxa including *H. cuneiformis, Nitzschia fossilis,* and *N. reinholdii* suggest the influence of relatively warmer waters.

The top of Hole 1151A contains *P. curvirostris,* indicating that the age of Sample 186-1151A-2R-CC is older than 0.3 Ma. Because the late Pleistocene diatom *N. seminae* is also continuously present, the top of Hole 1151A apparently corresponds to the *P. curvirostris* Zone (NPD11). The

LO of *A. oculatus* (1.01–1.46 Ma), which defines the boundary between the middle Pleistocene *P. curvirostris* Zone and the lower Pleistocene *A. oculatus* Zone (NPD11/NPD10), is identified between Samples 186-1151A-3R-CC and 4R-CC. The beginning of a consistent occurrence of the Pleistocene diatom *P. curvirostris* lies between Samples 186-1151A-4R-CC and 5R-CC, and its ancestral form already appeared in the upper Pliocene NPD9 Zone.

The base of the *A. oculatus* Zone (NPD10) and the top of the underlying *N. koizumii* Zone (NPD9) is defined by the LO of *N. koizumii*. This latest Pliocene event occurs between Sample 186-1151A-5R-CC and 6R-CC. The LCsO of *N. kamtschatica* (2.61–2.68 Ma) between Samples 186-1151A-11R-CC and 12R-CC marks the top of the *N. koizumii–N. kamtschatica* Zone (NPD8). The FO of *N. seminae* is detected in the upper part of this zone from Sample 186-1151A-12R-CC. The FO of *N. koizumii* (3.53–3.95 Ma), which defines the boundary between the upper Pliocene *N. koizumii–N. kamtschatica* Zone and the lower Pliocene through upper Miocene *N. kamtschatica* Zone (NPD8/NPD7B boundary), is clearly identified between Samples 186-1151A-14R-CC and 15R-CC.

The FO of *T. oestrupii* s. ampl. (5.49 Ma) is accepted as the top of the upper Miocene *N. kamtschatica* Zone of Koizumi (1992). Also Yanagisawa and Akiba (1998) used this event as the zonal marker at the Subzone NPD7Bb/NPD7Ba boundary. The Leg 186 *Initial Reports* volume reported that this datum exists between Sections 186-1151A-38R-1 and 38R-CC (Sacks, Suyehiro, Acton, et al., 2000). Recent rapid progress of taxonomic study on the genus *Thalassiosira* (Shiono and Koizumi, 2000, 2001) prohibits the FO of *T. oestrupii* s. ampl. from defining the subzonal boundary between NPD7Bb and NPD7Ba and indicates the reexamination of diatom biostratigraphy covering the Miocene/Pliocene boundary in the North Pacific Ocean.

The top of the upper Miocene *R. californica* Zone (NPD7A) was originally defined by the LCO of *R. californica* (Akiba, 1986; Maruyama, 2000), but its stratigraphic occurrence is not continuous and its abundance is rare in Hole 1151A. Thus, the top of the NPD7A Zone is recognized as the FCsO of *N. kamtschatica* (6.4 Ma) between Samples 186-1151A-77R-CC and 79R-CC. Within the NPD7A Zone, the FO of *N. kamtschatica* (7.3–7.4 Ma) is also an important event as a zonal marker, but the actual distinction of *N. kamtschatica* from its ancestor *Nitzschia rolandii* (based on broader spacing of pseudosepta or costae) is difficult because of their gradual evolutionary change (Yanagisawa and Akiba, 1990, 1998). We should stress the biostratigraphic importance of the FCsO of *N. kamtschatica* rather than its FO datum in the upper Miocene.

The LCO of *T. schraderi* (7.6 Ma) is detected sharply between Samples 186-1151A-79R-CC and 80R-CC and marks the top of the upper Miocene *T. schraderi* Zone (NPD6B). In the Leg 186 *Initial Reports* volume, the *D. katayamae* Zone (NPD6A) is observed from the short interval between Sections 186-1151A-91R-5 and 91R-CC and, moreover, is conformably overlain by the *T. schraderi* Zone (NPD6B) from beyond Section 91R-3 (Sacks, Suyehiro, Acton, et al., 2000). Both datums of the LCsO of *D. simonsenii* (8.6 Ma) and the LO of *D. dimorpha* (9.16 Ma), however, simultaneously appear between Samples 186-1151A-90R-CC and 91R-CC from our shore-based analysis. These events without the observation of the LO of *D. katayamae* suggest that the NPD6A Zone is missing or compressed in the interval between Sections 186-1151A-91R-4 and 91R-5.

The *D. dimorpha* Zone (NPD5D) extends consistently from Sample 186-1151A-91R-CC down through 95R-CC, with the FO of *T. schraderi* encountered between Samples 186-1151A-92R-CC and 93R-CC. The FO of *D. dimorpha* (9.9 Ma), which defines the top of *T. yabei* Zone (NPD5C), is clearly identified between Samples 186-1151A-95R-CC and 99R-CC. The stratigraphic horizon of this FO event agrees with the result in the Leg 186 *Initial Reports* volume between Sections 186-1151A-95R-CC and 96R-1, and also with the extent of the *T. yabei* Zone from Sections 186-1151A-96R-1 down to 99R-CC (979.32 to 1009.53 mbsf). On the other hand, only one sample (186-1151A-99R-CC) represents the NPD5C Zone based on the intermittent sample interval in our analysis.

The base of the *T. yabei* Zone (NPD5C) is determined by the LCO of *D. praedimorpha* (11.5 Ma), but that event is not found in the course of our shore-based analysis. Moreover, the *D. praedimorpha* Zone (NPD5B) starts with the FO of *D. praedimorpha* (12.9 Ma) and is characterized by the consistent occurrences of that species, but the NPD5B Zone is not detected in our studies of Hole 1151A. On board the *JOIDES Resolution,* however, a 10-m-thick sequence (1017.66 to 1027.31 mbsf) containing middle Miocene Zone NPD5B was recorded in Samples 186-1151A-100R-1, 66–69 cm, through 101R-1, 71–73 cm. The Shipboard Scientific Party (2000c) suggested some probabilities of coring gap or a hiatus of <1 m.y. between Sections 186-1151A-99R-CC and 100R-1.

The authors put great emphasis upon the coincidence among the following events; the FCO of *D. simonsenii* (13.1 Ma), the FO of *D. simonsenii* (14.4–14.6 Ma), and the LCO of *D. hyalina* (13.1 Ma) between Samples 186-1151A-99R-CC and 101R-CC (1009.53 to 1028.78 mbsf). The absence of the *C. nicobarica* Zone (NPD5A) and the deficiency of the acme of *D. hyalina* being assignable to the NPD4Bb Subzone (the upper part of the *D. hyalina* Zone) fairly characterized the diatom assemblages from ~1027 mbsf in Hole 1151A. Although the NPD4Bb Subzone was established for the 9-m-thick interval from Sample 186-1151A-101R-1, 90–91 cm, to 102R-1, 69–72 cm (1027.5 to 1036.89 mbsf), on board the *JOIDES Resolution,* the placement of Zone NPD5A is not at all as certain; neither is that in our onshore analyses. It is likely that the NPD5A interval, exhibiting the whole span of 0.2 Ma, is compressed or absent within Section 186-1151A-101R-1, close to 1027 mbsf.

The underlying *D. hyalina* Zone (NPD4Ba) is characterized by the continuous occurrence of *D. hyalina* and rare *D. lauta,* and its base is marked by the FO of *D. hyalina* (14.9 Ma) between Samples 186-1151A-103R-CC and 104R-CC. Within the *D. lauta* Zone (NPD4A), the group abundance of diatom assemblages decline from common to few, with sporadic intervals of poor preservation. Regardless of group abundance and preservation, the lowest occurrence of the index *D. lauta* in Sample 186-1151A-107R-CC defines the bottom of Zone NPD4A. Consistent distribution of *D. praelauta* without the presence of *D. lauta* in the bottom interval from Samples 186-1151A-108R-CC through 109R-CC designates the *D. praelauta* Zone (NPD3B) as the oldest sedimentary sequence at Site 1151, exhibiting an age between 15.9 and 16.3 Ma.

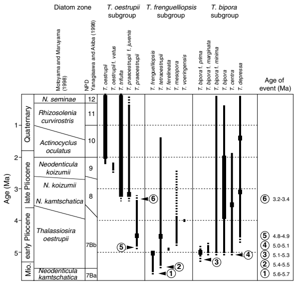
DISCUSSION

Drilling during ODP Leg 186 provided a high-quality suite of upper Cenozoic cores from the Japan Trench area. Sedimentary sequences containing a relatively continuous record of diatoms have been satisfactory for determining, at relatively high stratigraphic resolution, a biostratigraphic zonation. Based on the available taxonomic studies by Shiono (2000, 2001) and Shiono and Koizumi (2000, 2001), however, we have to examine whether diatom assemblages from the lower Pliocene are treated in conformity with the desirable biostratigraphic rules. Tables T5 and T6 document the stratigraphic occurrences of important taxa belonging to the genus *Thalassiosira,* including the sample depth in meters below seafloor. The stratigraphic ranges and events on the Pliocene and Quaternary key species in the *T. trifulta* group are shown in Figure F3, basically following the framework of Shiono and Koizumi (2001). New taxonomic revisions of *Thalassiosira* require a fresh look at the lower Pliocene.

T5. Pliocene key species belonging to the genus *Thalassiosira,* Hole 1150B, p. 32.

T6. Pliocene key species belonging to the genus *Thalassiosira,* Hole 1151A, p. 33.

F3. Stratigraphic ranges of key species in the *Thalassiosira trifulta* group, p. 23.



Thalassiosira trifulta Group

The *T. trifulta* group consists of centric marine diatoms forming chainlike colonies that mainly range from the early Pliocene to the Holocene. The *T. trifulta* group is composed of three subgroups, the *T. oestrupii* subgroup, *Thalassiosira frenguelliopsis* subgroup, and *Thalassiosira bipora* subgroup; their taxonomic and biostratigraphic characteristics were vigorously examined by Shiono and Koizumi (2000, 2001). Based on Shiono and Koizumi's work on the *T. trifulta* group, taxonomic grouping of taxa and their stratigraphic ranges are summarized in Figure F3.

Thalassiosira praeoestrupii appears at 4.8–4.9 Ma and disappears at 3.2–3.4 Ma in the middle part of Zone NPD8. This is the oldest taxon in the *T. oestrupii* subgroup. Both the FOs of *T. praeoestrupii* f. *juvenis* and *T. trifulta* occur at the same horizon of the LO of *T. praeoestrupii.* A species representative of the subgroup is *T. oestrupii,* extending the range from 2.2 Ma to the Holocene. Unfortunately, the previously used FOs of both *T. praeoestrupii* and *T. oestrupii* are inaccurate.

A representative of the *T. frenguelliopsis* subgroup is *T. frenguelliopsis,* whose total range is restricted from 5.6–5.7 to 4.9–5.0 Ma, is compactly confined within only 700 k.y., and crosses over the Miocene/Pliocene epoch boundary in the Northern Hemisphere. Slightly below the epoch boundary, the FO of *Thalassiosira tetraoestrupii* is apparently recognizable at 5.4–5.5 Ma. In the *T. frenguelliopsis* subgroup, these are remarkable features detected from the northwest Pacific Ocean.

Near the epoch boundary, *T. bipora* f. *prima,* as the most primitive taxon of the *T. bipora* subgroup, first occurs at 5.1–5.3 Ma and becomes suddenly extinct after a short lifespan of <500 k.y. in the early Pliocene. It is a particularly characteristic event of the subgroup that at least four taxa appear simultaneously at 5.0–5.1 Ma, namely the FOs of *T. bipora* f. *marginata, T. bipora* f. *minima, T. bipora* s. str., and *Thalassiosira centra* coincide with each other immediately above the epoch boundary.

The lower Pliocene NPD7Bb Subzone corresponds to the upper subzone of NPD7B and is also named as *T. oestrupii* Subzone. However, diatom assemblages from the NPD7Bb Subzone neither include any specimens of *T. oestrupii* nor document the taxon's first appearance datum. The biostratigraphic unit of the *T. oestrupii* Subzone should be abandoned from the Pliocene zonal framework in the North Pacific diatom biochronostratigraphy, and we should replace both datums of the FO of *T. oestrupii* s. ampl. (5.49 Ma) and the FO of *T. praeoestrupii* (6.1 Ma) with a more reliable stratigraphic indicator as soon as possible.

Miocene/Pliocene Boundary in Holes 1150B and 1151A

Because of a consistent occurrence of *T. frenguelliopsis* and a complete absence of *T. bipora* f. *prima* during the Pliocene interval in Hole 1150B, the stratigraphic span between Samples 186-1150B-11R-CC and 15R-CC (802.82 to 837.15 mbsf) can be compressed into the short age-assignment of 5.1–5.7 Ma (Table T5). *T. bipora* f. *prima* first occurs in Sample 186-1150B-10R-CC with an age estimate of 5.1–5.3 Ma, and this form shows a somewhat continuous occurrence upward to Sample 186-1150B-5R-CC. Both the FO of *T. bipora* (5.0–5.1 Ma) and the FO of *T. praeoestrupii* (4.8–4.9 Ma) are simultaneous with the FO of *T. bipora* f. *prima* (5.1–5.3 Ma) between Samples 186-1150B-10R-CC and 11R-CC. An age of 5.1–5.3 Ma is assigned to the stratigraphic interval just below Sample 186-1150B-10R-CC.

Although the FO of *T. frenguelliopsis* at 5.6–5.7 Ma or the FO of *T. tetraoestrupii* at 5.4–5.5 Ma should be an effective means to determine the Miocene/Pliocene boundary in the northwestern Pacific Ocean, neither of these events are recognized in Hole 1150B. It is indicated that the Miocene/Pliocene boundary probably lies somewhere at a deeper horizon than Sample 186-1150B-10R-CC (791.04 mbsf).

In Hole 1151A, the lowest sample (186-1151A-60R-CC) analyzed for the genus *Thalassiosira* contains such important taxa as *T. frenguelliopsis, T. bipora* f. *prima,* and *T. bipora* (Table T6). Their first occurrences are indirectly calibrated at 5.6–5.7, 5.1–5.3, and 5.0–5.1 Ma, respectively, so the age of Sample 186-1151A-60R-CC should be younger than 5.1 Ma.

The coincidence of the two events, the FO of *T. tetraoestrupii* (5.4–5.5 Ma) and the FO of *T. praeoestrupii* (4.8–4.9 Ma), is detected between Samples 186-1151A-57R-CC and 58R-CC, and the stratigraphic horizon immediately below Sample 186-1151A-57R-CC is estimated at 4.8–4.9 Ma based on the latter younger event. The interval between Sample 186-1151A-58R-CC and 60R-CC is well dated and has an age between 4.8 and 5.1 Ma. Because of the uncertainty of the FO datums among *T. frenguelliopsis, T. tetraoestrupii, T. bipora* f. *prima,* and *T. bipora,* we failed to determine the Miocene/Pliocene boundary, which is assuredly situated on a deeper horizon than Sample 186-1151A-60R-CC (640.76 mbsf).

The authors tried to detect the Miocene/Pliocene boundary derived from the diatom biostratigraphic zonation; they missed it after all because of their improper sample selection at both sites. It is practically impossible to divide the *N. kamtschatica* Zone (NPD7B) into the two subzones based upon the definition shown in Table T1 and Figure F2.

Early Pliocene Problem Subzone

Koizumi (1985) introduced the *Thalassiosira oestrupii* Zone as an interval zone into the Neogene North Pacific diatom zonation. The zonal base is defined by the FO of *T. oestrupii* s. ampl., and the top is marked by the FO of *N. koizumii* (= *Denticulopsis seminae* var. *fossilis*). Yanagisawa and Akiba (1998) adopted the zone as a subzone representing the upper part of the *N. kamtschatica* Zone (NPD7B) and supplied the subzone with the code NPD7Bb in their framework. It has been described that diatom assemblages in the NPD7Bb Subzone are characterized by abundant *N. kamtschatica* with very rare *T. oestrupii.* The base event is dated at 5.49 Ma by Motoyama and Maruyama (1998) and at 5.5 Ma by Yanagisawa and Akiba (1998), respectively. The top event exhibits latitudinal dischronity in the North Pacific Ocean, which is calibrated at 3.53–3.95 Ma or 3.5–3.9 Ma (Motoyama and Maruyama, 1998; Yanagisawa and Akiba, 1998).

However, in the northwestern Pacific Ocean, the FO of *T. oestrupii* is recognized at 2.2 Ma. *T. oestrupii* f. *vetus* is inferred as an early form of *T. oestrupii,* and its FO is estimated at 2.4–2.5 Ma by Shiono and Koizumi (2001). The total range of *T. oestrupii* s. ampl., including the two taxa as mentioned above, is restricted to the upper Pliocene NPD9 Zone through the Quaternary NPD12 Zone, apparently. The name of *T. oestrupii* is unsuitable for the biostratigraphic unit corresponding to the NPD7Bb (= *T. oestrupii*) Subzone, because the nominative taxon *T. oestrupii* s. ampl. is lacking within this interval. In addition, the base of the subzone also should be replaced by another biohorizon.

T. bipora is easily identified based on the characteristic two central porelike structures (occluded areola and central fultoportula) and occupies the solid situation of evolutionary speciation in the *T. bipora* subgroup. The FO of *T. bipora* at 5.0–5.1 Ma can be correlated with the lower part of the NPD7Bb Subzone in the early Pliocene. *T. bipora* f. *prima* is inferred as an preexisting taxon of *T. bipora* and first appears at 5.1–5.3 Ma, immediately above the Miocene/Pliocene boundary. But it is almost impossible to classify the two taxa with each other by means of the LM observations. We are able to take a realistic view of *T. bipora* sensu amplificato including *T. bipora, T. bipora* f. *prima,* and other forms and to indicate the FO of *T. bipora* sensu amplificato as a tentative biodatum, which is at ~5.0–5.3 Ma in the earliest Pliocene.

According to Shiono and Koizumi (2001), *T. tetraoestrupii* has a long range extending from the early Pliocene to the Quaternary, and its FO can be correlated with the base of the NPD7Bb Subzone, which is dated at 5.4–5.5 Ma. Unfortunately, *T. tetraoestrupii* occurs too rarely through the interval representing Subzone NPD7Bb to be nominated as representative of the subzone. The FO of *T. frenguelliopsis* is also very close to the base of the NPD7Bb Subzone, which is calibrated at 5.6–5.7 Ma (Shiono and Koizumi, 2001). It is actually difficult, however, to distinguish *T. frenguelliopsis* in LM observations from *T. praeoestrupii* because there are many morphologic similarities between two species.

Although stratigraphic distributions of *T. tetraoestrupii* and *T. frenguelliopsis* are evidently observed from Holes 1150B and 1151A (Tables **T5, T6**), further research into potential candidates for representation needs to be done for the North Pacific Ocean. Dumont et al. (1986) reported that the FO of their *T. praeoestrupii* was tied to the top of paleomagnetic event C3An.1n (or 5.9 Ma) at Santa Cruz in California and also that those typical specimens occurred below the FO of *T. oestrupii* s. ampl. in upper Miocene sediments. It is highly probable that their *T. oestrupii* s. ampl. includes specimens of both our *T. tetraoestrupii* and *T. frenguelliopsis*. Shiono and Koizumi (2000) perceived that *T. tetraoestrupii* and *T. frenguelliopsis* may have been confused with *T. oestrupii* in previous studies because their FOs are close to the FO of *T. oestrupii* previously described.

Although *T. bipora* is very rare in relative abundance, it shows successive occurrences during the Pliocene through Quaternary in the northwest Pacific Ocean (Shiono and Koizumi, 2001). Similarly, the appearance of *T. praeoestrupii* ordinarily typifies the early Pliocene interval, but its abundance is also very rare. Because of the presence of the characteristic trifultate fultoportula, it is easy to identify *T. praeoestrupii* in the SEM observations. The FO of *T. praeoestrupii* is recognized near the base of the NPD7Bb Subzone, which is well dated at 4.8–4.9 Ma, considerably younger than the Miocene/Pliocene boundary. The LO is estimated at 3.2–3.4 Ma from the middle part of the NPD8 Zone above the FO of *N. koizumii* (3.53–3.95 Ma).

We would like to modify the *T. oestrupii* Subzone toward the new *T. bipora* Subzone, the base of which is definable at 5.0–5.3 Ma by the FO of *T. bipora* sensu amplificato including *T. bipora, T. bipora* f. *prima,* and other forms. The authors did not succeed in the establishment of precise biostratigraphy across the Miocene/Pliocene boundary in Holes 1150B and 1151A, and therefore they refrain from making a new proposal based on *T. bipora* sensu amplificato. The problem subzone still remains to be solved and is beyond our biostratigraphic study on Sites 1150 and 1151.

SUMMARY

Ocean floor drilling during Leg 186 furnishes an opportunity to examine the diatom assemblages from almost-continuous stratigraphic sequences from the northwestern Pacific margin. Miocene through Pleistocene reference sections show that the standard diatom zonation of Yanagisawa and Akiba (1998) is of great use for North Pacific diatom biostratigraphy. When compared with one another and with published data, most of the middle through late Miocene diatom datum levels that have been widely accepted in the North Pacific for biostratigraphy appear to be isochronous within the level of resolution constrained by sample spacing. Reliable Miocene diatom datum levels proved in Leg 186 include the FO of *D. lauta* (15.9 Ma), the FO of *D. hyalina* (14.9 Ma), the FO of *D. dimorpha* (9.9 Ma), the LO of *D. dimorpha* (9.16 Ma), the LCsO of *D. simonsenii* (8.6 Ma), the LCO of *T. schraderi* (7.6 Ma), and the FCsO of *N. kamtschatica* (6.4 Ma). Such datum levels as the FO of *D. simonsenii* (14.4–14.6 Ma), the FCO of *D. simonsenii* (13.1 Ma), the FO of *D. praedimorpha* (12.9 Ma), and the LCO of *D. praedimorpha* (11.5 Ma) are compressed into a narrow stratigraphic interval because of a low sedimentation rate or hiatuses. The somewhat rare and inconsistent occurrence of *R. californica* in Leg 186 materials precluded the complete approval for its LCO as the base of the *N. kamtschatica* Zone (NPD7B).

Within the early Pliocene, there is nothing reliable among datum levels off northeast Japan covered by Leg 186. The rapid progress of taxonomic study on the *T. trifulta* group prohibits the FO of *T. oestrupii* (5.49 Ma) from dividing the *N. kamtschatica* Zone (NPD7B) into two subzones, and the authorization of the upper unit, named the *T. oestrupii* Subzone (NPD7Bb), lapses from the North Pacific zonal framework entirely. An incomplete biostratigraphy around the FO of *T. bipora* sensu amplificato precluded the replacement both of the *T. oestrupii* Subzone and the FO of *T. oestrupii* as the base datum in Leg 186 samples.

At least five of the late Pliocene through Pleistocene diatom datum levels allow precise correlation along the northwestern Pacific margin between Sites 1150 and 1151. The stable adoptions of datum levels are established on the FO of *N. koizumii* (3.53–3.95 Ma), the LCsO of *N. kamtschatica* (2.61–2.68 Ma), the LO of *N. koizumii* (2.0 Ma), the LO of *A. oculatus* (1.01–1.46 Ma), and the LO of *P. curvirostris* (0.3 Ma) during Leg 186. They are widely used as a zonal markers in the North Pacific Ocean; however, diachroneity across latitude is also documented for the FO of *N. koizumii,* the LCsO of *N. kamtschatica,* and the LO of *A. oculatus.*

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APPENDIX

Floral List

Floral list and taxonomic remarks on the genus *Thalassiosira* species are as follows: original and amended descriptions portrayed through figures and detailed descriptions can be traced through Johansen and Fryxell (1985), Dumont et al. (1986), Bodén (1993), Shiono (2000, 2001), and Shiono and Koizumi (2000, 2001). Examples are show in Plates **P1, P2, P3, P4.**

Thalassiosira baldaufii Bodén, 1993.

Thalassiosira bipora Shiono, 2000 (Pl. **P1,** figs. 1–7).

Thalassiosira bipora f. *prima* Shiono, 2001 (Pl. **P2,** figs. 1–7).

Thalassiosira centra Shiono, 2000.

Thalassiosira depressa Shiono, 2000.

Thalassiosira exceptiuncula Shiono, 2001 (Pl. **P4,** fig. 9).

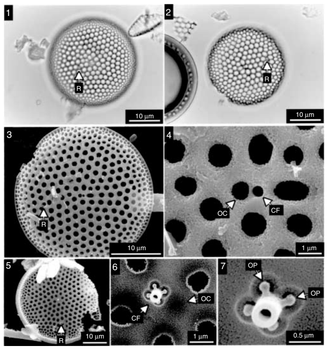
Thalassiosira frenguelliopsis Fryxell and Johansen, 1985 in Johansen and Fryxell (Pl. **P4,** figs. 4–7, 10, 11).

Thalassiosira praeoestrupii Dumont, Baldauf, and Barron, 1986 (Pl. **P3,** figs. 1–7; Pl. **P4,** figs. 1–3).

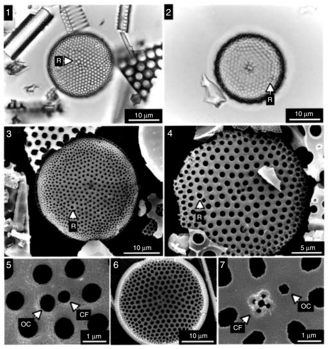
Remarks: A specimen on Pl. **P4,** figs. 1–3, which possesses a trifultate fultoportula with four trifultate structures and four operculate structures, is found in Sample 186-1150B-6R-CC. In this study, we identify the specimen as *Thalassiosira* cf. *praeoestrupii* because *T. praeoestrupii* also has the trifultate fultoportula with two kinds of structures. However, *T. praeoestrupii* sensu stricto possesses the trifultate fultoportula with three trifultate structures and three operculate structures. As an operculate fultoportula with four operculate structures represents a common structure in the genus *Thalassiosira,* this specimen is recognizable as a primitive form among several taxa with trifultate fultoportula.

Thalassiosira tetraoestrupii Bodén, 1993 (Pl. **P4,** figs. 8, 12).

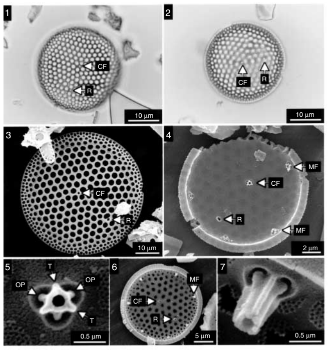
P1. *Thalassiosira bipora* Shiono, p. 34.



P2. *Thalassiosira bipora* f. *prima* Shiono, p. 35.



P3. *Thalassiosira praeoestrupii* Dumont, Baldauf, and Barron, p. 36.



P4. Species of the *T. trifulta* group, *T. frenguelliopsis, T. tetraoestrupii,* and *T. exceptiuncula,* p. 37.

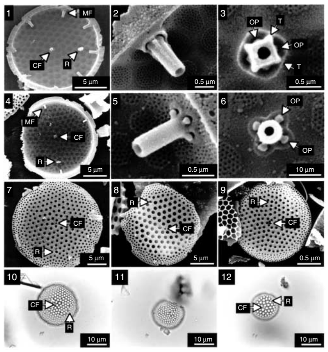


Figure F1. Location of Leg 186 sites. Contours shown at 1000-m intervals. Sites 1150 and 1151 are situated at the deep-sea terrace landward of the Japan Trench (from Sacks, Suyehiro, Acton, et al., 2000).

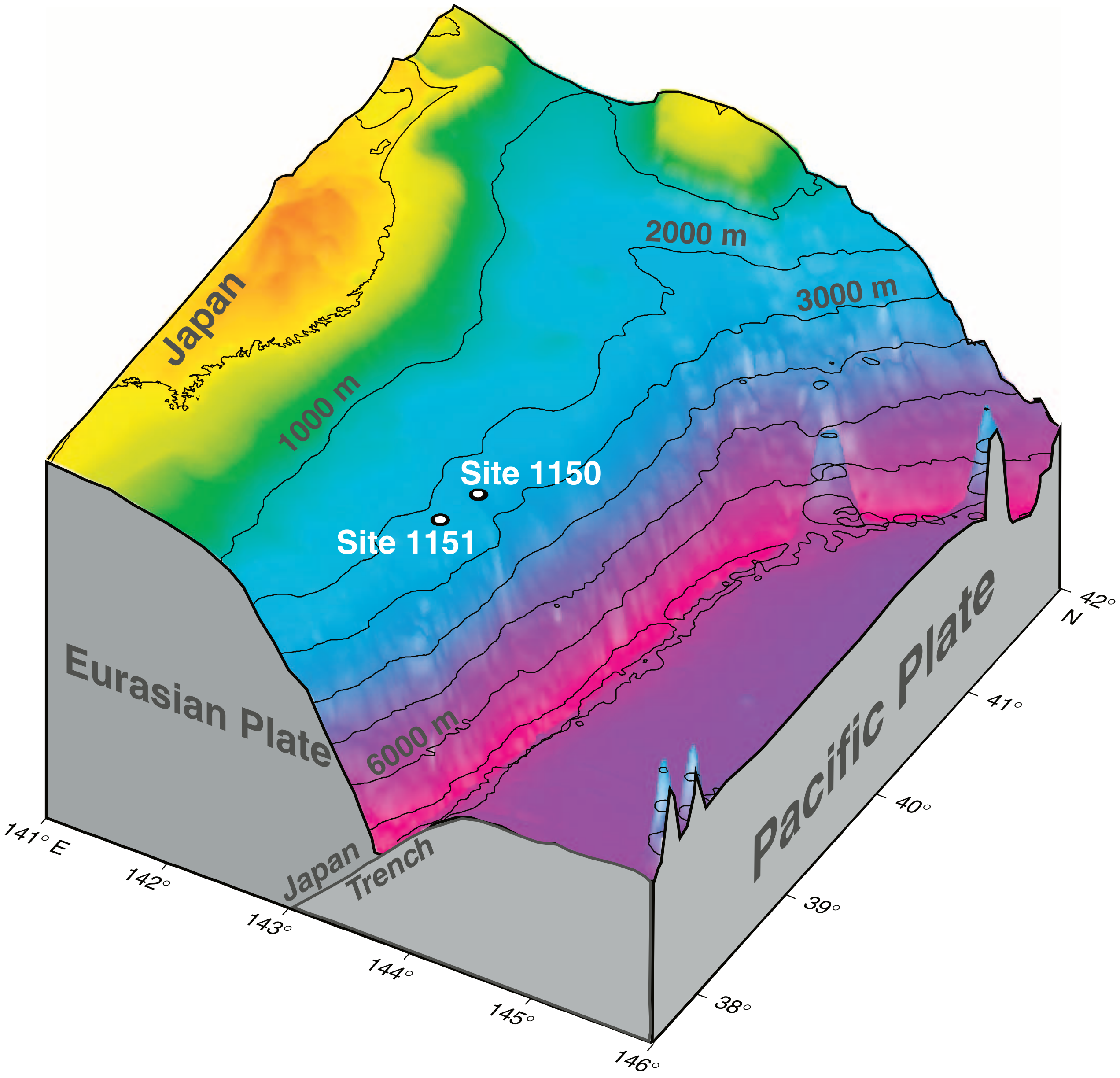


Figure F2. Correlation of diatom zonation, primary zonal markers, and zonal code numbers used during Leg 186. Zone limits have been calibrated to the geochronology of Cande and Kent (1995). FO = first occurrence, LO = last occurrence, FCO = first common occurrence, LCO = last common occurrence, FCsO = first consistent occurrence, LCsO = last consistent occurrence.

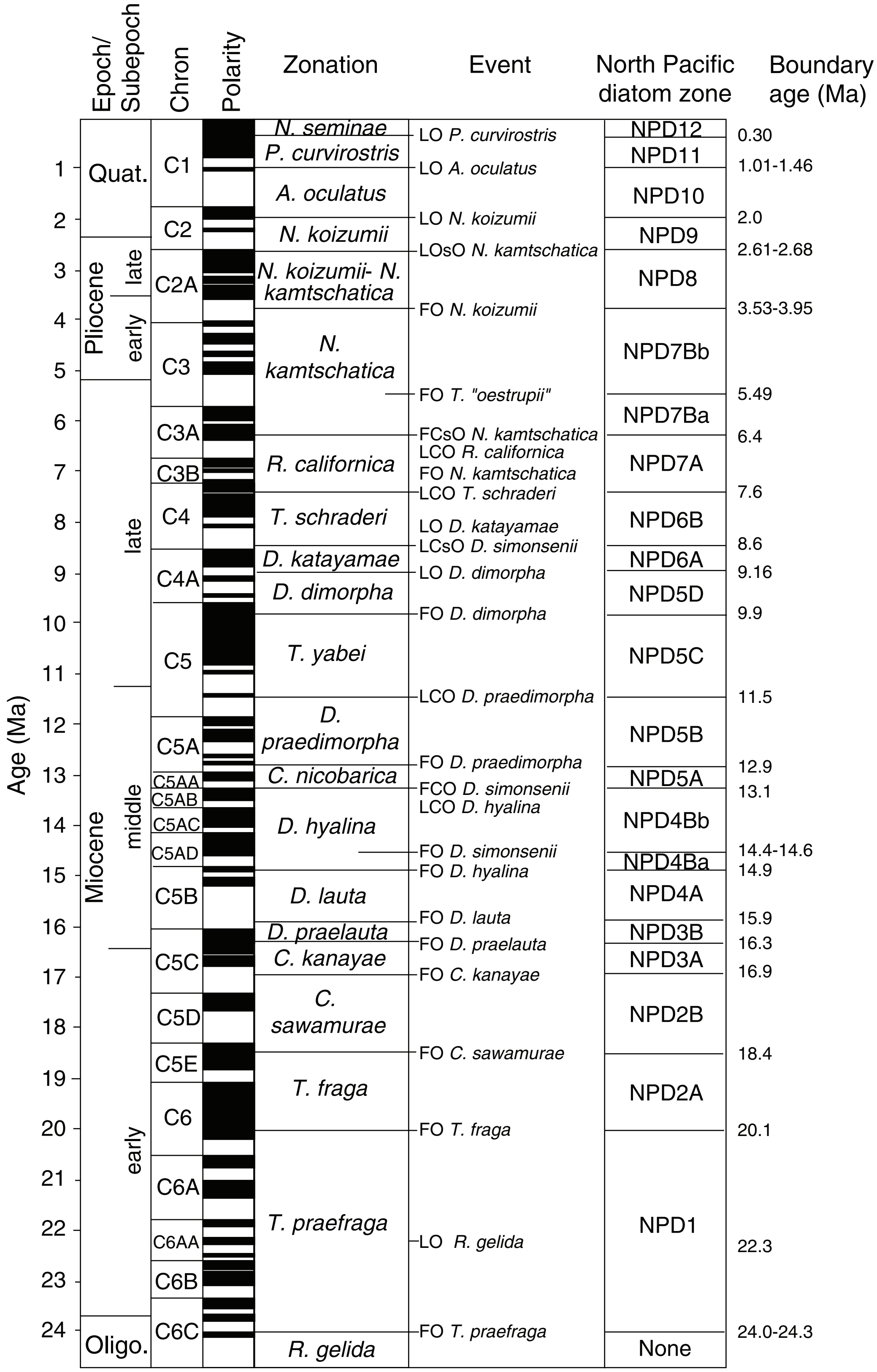


Figure F3. Stratigraphic ranges of key species in the *Thalassiosira trifulta* group in the northwest Pacific Ocean. Dashed lines represent range extensions based on rare or sporadic occurrences (modified from Shiono and Koizumi, 2001). NPD = North Pacific diatom zone.

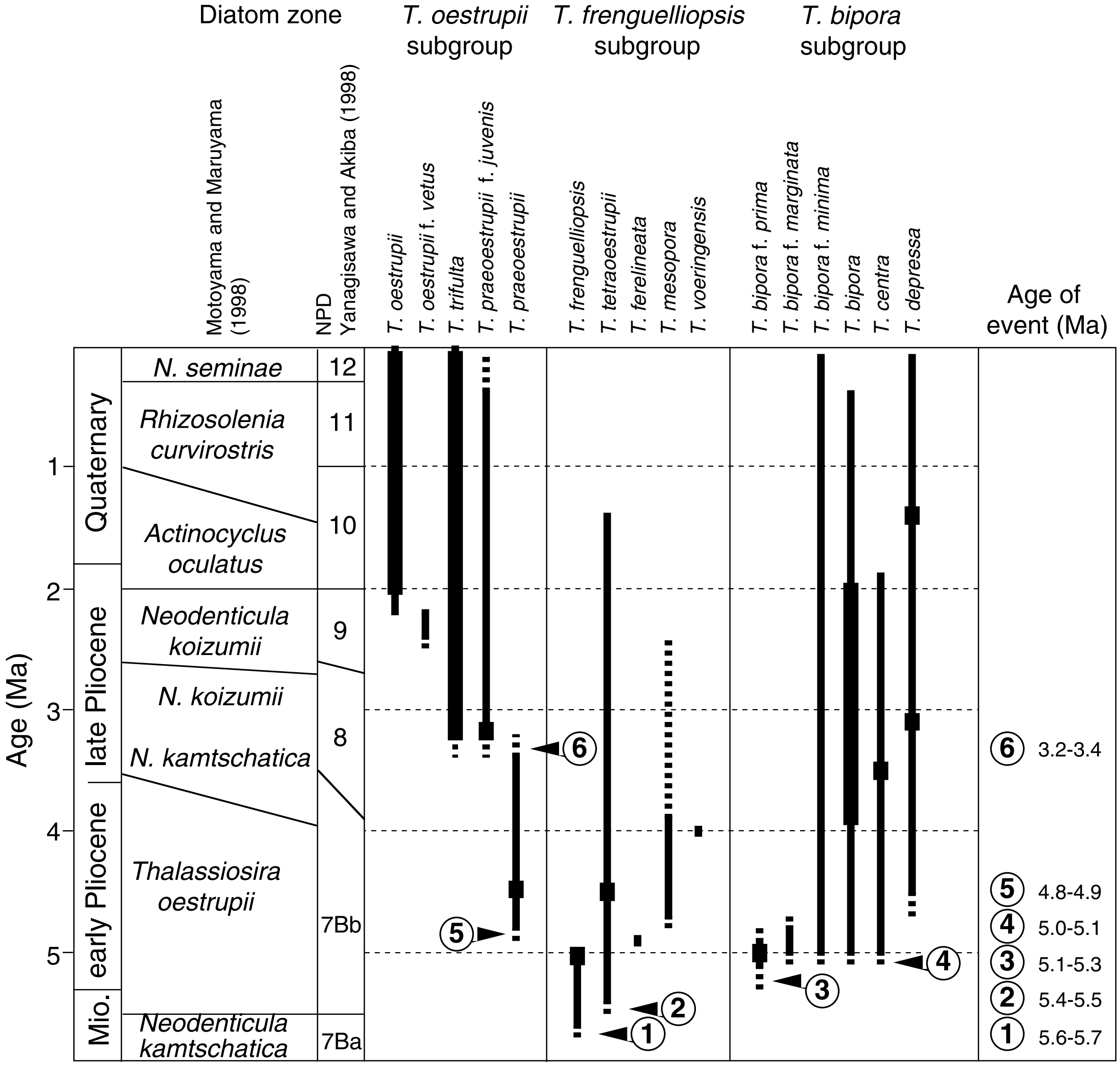


Table T1. North Pacific diatom zonation and stratigraphic markers used during Leg 186.

Code	Zone/Subzone	Category	Reference	Base	Top
NPD12	*Neodenticula seminae*	Interval zone	Donahue (1970)	LO *Proboscia curvirostris*	Present
NPD11	*Proboscia curvirostris*	Interval zone	Donahue (1970)	LO *Actinocyclus oculatus*	LO *Proboscia curvirostris*
NPD10	*Actinocyclus oculatus*	Interval zone	Donahue (1970)	LO *Neodenticula koizumii*	LO *Actinocyclus oculatus*
NPD9	*Neodenticula koizumii*	Interval zone	Koizumi (1973a)	LCsO *Neodenticula kamtschatica*	LO *Neodenticula koizumii*
NPD8	*N. koizumii-N. kamtschatica*	Concurrent range zone	Koizumi (1973a)	FO *Neodenticula koizumii*	LCsO *Neodenticula kamtschatica*
NPD7Bb	*N. kamtschatica*-b	Interval zone	Koizumi (1973a, 1973b, 1985)	FO *Thalassiosira "oestrupii"* s. ampl.	FO *Neodenticula koizumii*
NPD7Ba	*N. kamtschatica*-a	Interval zone	Koizumi (1973a, 1973b, 1985)	FCsO *Neodenticula kamtschatica*	FO *Thalassiosira "oestrupii"* s. ampl.
NPD7A	*Rouxia californica*	Interval zone	Akiba (1986)	LCO *Thalassionema schraderi*	FCsO *Neodenticula kamtschatica*
NPD6B	*Thalassionema schraderi*	Interval zone	Akiba (1982a)	LCsO *Denticulopsis simonsenii*	LCO *Thalassionema schraderi*
NPD6A	*Denticulopsis katayamae*	Interval zone	Maruyama (1984b)	LO *Denticulopsis dimorpha*	LCsO *Denticulopsis simonsenii*
NPD5D	*Denticulopsis dimorpha*	Taxon range zone	Maruyama (1984b), Akiba (1979)	FO *Denticulopsis dimorpha*	LO *Denticulopsis dimorpha*
NPD5C	*Thalassiosira yabei*	Interval zone	Maruyama (1984b), Akiba (1979)	LCO *Denticulopsis praedimorpha*	FO *Denticulopsis dimorpha*
NPD5B	*Denticulopsis praedimorpha*	Taxon range zone	Akiba et al. (1982b)	FO *Denticulopsis praedimorpha*	LCO *Denticulopsis praedimorpha*
NPD5A	*Crucidenticula nicobarica*	Interval zone	Akiba et al. (1982b)	FCO *Denticulopsis simonsenii*	FO *Denticulopsis praedimorpha*
NPD4Bb	*Denticulopsis hyalina*-b	Interval zone	Maruyama (1984b)	FO *Denticulopsis simonsenii*	FCO *Denticulopsis simonsenii*
NPD4Ba	*Denticulopsis hyalina*-a	Interval zone	Maruyama (1984b)	FO *Denticulopsis hyalina*	FO *Denticulopsis simonsenii*
NPD4A	*Denticulopsis lauta*	Lineage zone	Koizumi (1973a)	FO *Denticulopsis lauta*	FO *Denticulopsis hyalina*
NPD3B	*Denticulopsis praelauta*	Lineage zone	Akiba (1983, 1986)	FO *Denticulopsis praelauta*	FO *Denticulopsis lauta*
NPD3A	*Crucidenticula kanayae*	Interval zone	Akiba (1977)	FO *Crucidenticula kanayae*	FO *Denticulopsis praelauta*
NPD2B	*Crucidenticula sawamurae*	Interval zone	Gladenkov and Barron (1995)	FO *Crucidenticula sawamurae*	FO *Crucidenticula kanayae*
NPD2A	*Thalassiosira fraga*	Interval zone	Barron (1985a)	FO *Thalassiosira fraga*	FO *Crucidenticula sawamurae*
NPD1	*Thalassiosira praefraga*	Interval zone	Gladenkov and Barron (1995)	FO *Thalassiosira praefraga*	FO *Thalassiosira fraga*
None	*Rocella gelida*	Partial range zone	Gladenkov and Barron (1995)	FO *Rocella gelida*	FO *Thalassiosira praefraga*

Notes: Modified from Maruyama, 2000. The boundary between Subzone NPD4Bb and Zone NPD5A can be also recognized by the LCO *Denticulopsis hyalina*. FO = first occurrence, LO = last occurrence, FCO = first common occurrence, LCO = last common occurrence, FCsO = first consistent occurrence, LCsO = last consistent occurrence.

Table T2. Distribution and relative abundances of age diagnostic diatoms, Site 1150. (See table notes. Continued on next two pages.)

Core, section	Depth (mbsf)	Diatom zone	NPD	Geologic age	Group abundance	Preservation	*Actinocyclus oculatus*	*Crucidenticula nicobarica*	*Denticulopsis dimorpha*	*Denticulopsis hyalina*	*Denticulopsis katayamae*	*Denticulopsis praedimorpha*	*Denticulopsis simonsenii*	*Fragilariopsis doliola*	*Hemidiscus cuneiformis*	*Koizumia tatsunokuchiensis*	*Neodenticula kamtschatica*	*Neodenticula koizumii*	*Neodenticula seminae*	*Nitzschia fossilis*	*Nitzschia marina*	*Nitzschia reinholdii*	*Nitzschia rolandii*	*Proboscia barboi*	*Proboscia curvirostris*	*Rouxia californica*	*Thalassionema schraderi*
186-1150A-																											
1H-CC	7.68	*N. seminae*	12	late Pleistocene	A	M								T			r	r	R								
2H-CC	17.69	*N. seminae*	12	late Pleistocene	A	G													R								
3H-CC	27.45	*N. seminae*	12	late Pleistocene	C	G								R					T								
4H-CC	36.65	*N. seminae*	12	late Pleistocene	C	M													R								
5H-CC	46.33	*N. seminae*	12	late Pleistocene	C	G													R		R						
6H-CC	55.73	*P. cuvirostris*	11	middle Pleistocene	C	M	r						r	T			r	r	R		R				R		
7H-CC	65.30	*P. cuvirostris*	11	middle Pleistocene	A	M								T					F		R			R	F		
8H-CC	74.45	*P. cuvirostris*	11	middle Pleistocene	C	M													R		F				R		
9H-CC	84.53	*P. cuvirostris*	11	middle Pleistocene	A	M								T							R	R			R		
10H-CC	94.09	*P. cuvirostris*	11	middle Pleistocene	A	M								R					R		R	R			R		
11H-CC	102.66	*P. cuvirostris*	11	middle Pleistocene	C	M								T					R			F			R		
12H-CC	112.15	*A. oculatus*	10	early Pleistocene	A	M	C												A					R	R		
13X-CC	117.37	*A. oculatus*	10	early Pleistocene	A	G	R							T				r	C			R		R	R		
14X-CC	124.71	*A. oculatus*	10	early Pleistocene	C	G	F								R				F		R				T		
15X-CC	130.20	*A. oculatus*	10	early Pleistocene	C	M	R																	R			
16X-CC	139.58	*N. koizumii*	9	late Pliocene	A	G	C											C	R		R	R		F			
17X-CC	154.53	*N. koizumii*	9	late Pliocene	A	M	R											A				R		F			
18X-CC	162.11	*N. koizumii*	9	late Pliocene	C	M	R											C		T		R		F			
20X-CC	174.00	*N. koizumii*	9	late Pliocene	A	G	R											A		R				R			
21X-CC	192.01	*N. koizumii*	9	late Pliocene	A	G	R								R			C						F			
22X-CC	202.94	*N. koizumii–N. kamtschatica*	8	late Pliocene	A	G			r				r		R		R	R									
23X-CC	212.84	*N. koizumii–N. kamtschatica*	8	late Pliocene	A	G									F		C										
24X-CC	213.22	*N. koizumii–N. kamtschatica*	8	late Pliocene	C	M	R								R		C	R						R			
25X-CC	232.14	*N. koizumii–N. kamtschatica*	8	late Pliocene	A	G									R		R	R		R				R			
26X-CC	239.55	*N. koizumii–N. kamtschatica*	8	late Pliocene	A	G											A	T									
27X-CC	251.16	*N. koizumii–N. kamtschatica*	8	late Pliocene	A	G									R		A	T									
28X-CC	260.33	*N. kamtschatica*	7B	early Pliocene–late Miocene	A	G											R										
29X-CC	269.34	*N. kamtschatica*	7B	early Pliocene–late Miocene	A	G											R										
30X-CC	280.11	*N. kamtschatica*	7B	early Pliocene–late Miocene	A	M											R										
31X-CC	289.80	*N. kamtschatica*	7B	early Pliocene–late Miocene	A	M											A			R		T		R			
32X-CC	298.83	*N. kamtschatica*	7B	early Pliocene–late Miocene	C	G									R		F			F							
33X-CC	305.57	*N. kamtschatica*	7B	early Pliocene–late Miocene	A	G											F										
34X-CC	318.94	*N. kamtschatica*	7B	early Pliocene–late Miocene	A	G				r							A										
35X-CC	328.85	*N. kamtschatica*	7B	early Pliocene–late Miocene	A	G											A										
36X-CC	338.43	*N. kamtschatica*	7B	early Pliocene–late Miocene	A	G											A										
37X-CC	347.37	*N. kamtschatica*	7B	early Pliocene–late Miocene	C	G											A										
38X-CC	357.39	*N. kamtschatica*	7B	early Pliocene–late Miocene	C	G											A										
39X-CC	366.98	*N. kamtschatica*	7B	early Pliocene–late Miocene	C	M											C			R							
40X-CC	376.41	*N. kamtschatica*	7B	early Pliocene–late Miocene	C	M						r					C										
41X-CC	378.61	*N. kamtschatica*	7B	early Pliocene–late Miocene	C	M							r		R		C										
42X-CC	395.62	*N. kamtschatica*	7B	early Pliocene–late Miocene	C	G									F		C										

Table T2 (continued).

Core, section	Depth (mbsf)	Diatom zone	NPD	Geologic age	Group abundance	Preservation	*Actinocyclus oculatus*	*Crucidenticula nicobarica*	*Denticulopsis dimorpha*	*Denticulopsis hyalina*	*Denticulopsis katayamae*	*Denticulopsis praedimorpha*	*Denticulopsis simonsenii*	*Fragilariopsis doliola*	*Hemidiscus cuneiformis*	*Koizumia tatsunokuchiensis*	*Neodenticula kamtschatica*	*Neodenticula koizumii*	*Neodenticula seminae*	*Nitzschia fossilis*	*Nitzschia marina*	*Nitzschia reinholdii*	*Nitzschia rolandii*	*Proboscia barboi*	*Proboscia curvirostris*	*Rouxia californica*	*Thalassionema schraderi*
43X-CC	405.28	*N. kamtschatica*	7B	early Pliocene–late Miocene	A	G											A										
44X-CC	414.48	*N. kamtschatica*	7B	early Pliocene–late Miocene	C	M									R		C										
45X-CC	424.33	*N. kamtschatica*	7B	early Pliocene–late Miocene	A	G											A					R					
46X-CC	428.83	*N. kamtschatica*	7B	early Pliocene–late Miocene	A	M											R										
47X-CC	443.68	*N. kamtschatica*	7B	early Pliocene–late Miocene	A	G									R		C							R			
48X-CC	453.35	*N. kamtschatica*	7B	early Pliocene–late Miocene	A	M										R	C										
49X-CC	463.14	*N. kamtschatica*	7B	early Pliocene–late Miocene	A	M									R	R	R										
50X-CC	462.99	*N. kamtschatica*	7B	early Pliocene–late Miocene	R	M										T	R										
51X-CC	480.58	*N. kamtschatica*	7B	early Pliocene–late Miocene	R	M										T											
52X-CC	482.50	*N. kamtschatica*	7B	early Pliocene–late Miocene	A	G										R	F			R							
53X-CC	492.25	*N. kamtschatica*	7B	early Pliocene–late Miocene	C	M										T	F			R			R				
54X-CC	511.46	*N. kamtschatica*	7B	early Pliocene–late Miocene	A	G										T	C						R	R			
55X-CC	520.80	*N. kamtschatica*	7B	early Pliocene–late Miocene	A	G											A										
56X-CC	527.49	*N. kamtschatica*	7B	early Pliocene–late Miocene	C	G											C										
57X-CC	531.67	*N. kamtschatica*	7B	early Pliocene–late Miocene	A	G										T	C			R			R				
58X-CC	540.50	*N. kamtschatica*	7B	early Pliocene–late Miocene	C	M											F						R				
60X-CC	563.74	*N. kamtschatica*	7B	early Pliocene–late Miocene	C	M											F										
61X-CC	571.58	*N. kamtschatica*	7B	early Pliocene–late Miocene	R	M											R										
62X-CC	588.49	*N. kamtschatica*	7B	early Pliocene–late Miocene	A	M											F										
63X-CC	589.91	*N. kamtschatica*	7B	early Pliocene–late Miocene	A	M											F										
64X-CC	601.35	*N. kamtschatica*	7B	early Pliocene–late Miocene	C	G											R					R					
65X-CC	609.96	*N. kamtschatica*	7B	early Pliocene–late Miocene	C	M											F					R	R				
66X-CC	627.05	*N. kamtschatica*	7B	early Pliocene–late Miocene	C	M							r				F										
67X-CC	636.73	*N. kamtschatica*	7B	early Pliocene–late Miocene	A	G											R										
68X-CC	645.68	*N. kamtschatica*	7B	early Pliocene–late Miocene	A	G											R			R							
69X-CC	655.49	*N. kamtschatica*	7B	early Pliocene–late Miocene	C	M											F							R			
70X-CC	663.16	*N. kamtschatica*	7B	early Pliocene–late Miocene	C	G										T	R										
71X-CC	674.46	*N. kamtschatica*	7B	early Pliocene–late Miocene	A	G											R						R				
72X-CC	684.23	*N. kamtschatica*	7B	early Pliocene–late Miocene	A	G											R			R							
73X-CC	686.55	*N. kamtschatica*	7B	early Pliocene–late Miocene	C	M											R			R							
74X-CC	702.84	*N. kamtschatica*	7B	early Pliocene–late Miocene	C	M											F			R							
75X-CC	713.12	*N. kamtschatica*	7B	early Pliocene–late Miocene	C	G										T	C										
76X-CC	722.85	*N. kamtschatica*	7B	early Pliocene–late Miocene	C	G											C						R				
186-1150B-																											
1R-CC	708.22	*N. kamtschatica*	7B	early Pliocene–late Miocene	A	G							r				C						R				
2R-CC	711.93	*N. kamtschatica*	7B	early Pliocene–late Miocene	C	G											C						R				r
3R-CC	720.11	*N. kamtschatica*	7B	early Pliocene–late Miocene	A	M										T	C			R							
4R-CC	732.49	*N. kamtschatica*	7B	early Pliocene–late Miocene	A	G											C										
5R-CC	740.07	*N. kamtschatica*	7B	early Pliocene–late Miocene	A	G											C					R					
6R-CC	756.54	*N. kamtschatica*	7B	early Pliocene–late Miocene	A	G									R		F						C				
8R-CC	770.05	*N. kamtschatica*	7B	early Pliocene–late Miocene	A	M											F						R				
9R-CC	781.47	*N. kamtschatica*	7B	early Pliocene–late Miocene	C	G										T	R			R			R				

Table T2 (continued).

Core, section	Depth (mbsf)	Diatom zone	NPD	Geologic age	Group abundance	Preservation	*Actinocyclus oculatus*	*Crucidenticula nicobarica*	*Denticulopsis dimorpha*	*Denticulopsis hyalina*	*Denticulopsis katayamae*	*Denticulopsis praedimorpha*	*Denticulopsis simonsenii*	*Fragilariopsis doliola*	*Hemidiscus cuneiformis*	*Koizumia tatsunokuchiensis*	*Neodenticula kamtschatica*	*Neodenticula koizumii*	*Neodenticula seminae*	*Nitzschia fossilis*	*Nitzschia marina*	*Nitzschia reinholdii*	*Nitzschia rolandii*	*Proboscia barboi*	*Proboscia curvirostris*	*Rouxia californica*	*Thalassionema schraderi*
10R-CC	791.04	*N. kamtschatica*	7B	early Pliocene–late Miocene	C	M							r				R						R				
11R-CC	802.82	*N. kamtschatica*	7B	early Pliocene–late Miocene	C	G											R						F				
12R-CC	811.91	*N. kamtschatica*	7B	early Pliocene–late Miocene	F	M											R					T					
13R-CC	819.78	*N. kamtschatica*	7B	early Pliocene–late Miocene	C	M							r				R						R				
14R-CC	830.48	*N. kamtschatica*	7B	early Pliocene–late Miocene	A	G									R		R						F				
15R-CC	837.15	*N. kamtschatica*	7B	early Pliocene–late Miocene	F	M											R					T	F				
16R-CC	852.22	*N. kamtschatica*	7B	early Pliocene–late Miocene	A	G											R					R	R				
17R-CC	859.53	*N. kamtschatica*	7B	early Pliocene–late Miocene	C	M							r														
18R-CC	868.08	*N. kamtschatica*	7B	early Pliocene–late Miocene	C	G							r				R			R		T					
19R-CC	877.53	*N. kamtschatica*	7B	early Pliocene–late Miocene	C	M				r							R										
20R-CC	893.02	*N. kamtschatica*	7B	early Pliocene–late Miocene	C	M				r							R					R	F				
21R-CC	898.32	*N. kamtschatica*	7B	early Pliocene–late Miocene	C	M			r								R					T	F	R		R	
22R-CC	910.67	*R. californica*	7A	late Miocene	R	M										T							F			R	
23R-CC	919.73	*R. californica*	7A	late Miocene	R	M																T	R			R	
24R-CC	923.46	*R. californica*	7A	late Miocene	R	P																T	F			T	
25R-CC	939.07	*R. californica*	7A	late Miocene	R	P										T				T			R			R	r
26R-CC	950.30	*R. californica*	7A	late Miocene	R	P											T										
27R-CC	957.41	*R. californica*	7A	late Miocene	C	P				r													T			R	r
28R-CC	968.83	*R. californica*	7A	late Miocene	C	P											T						T			R	
29R-CC	978.02	*R. californica*	7A	late Miocene	C	P							r							T			T			R	
30R-CC	987.85	*R. californica*	7A	late Miocene	C	P							r														T
31R-CC	992.31	*R. californica*	7A	late Miocene	F	M				r																R	
32R-CC	1007.82	*R. californica*	7A	late Miocene	C	M																					R
33R-CC	1009.47	*R. californica*	7A	late Miocene	A	M							r							R				R		R	R
34R-CC	1019.99	*R. californica*	7A	late Miocene	C	M				r			r											F		F	R
35R-CC	1031.50	*R. californica*	7A	late Miocene	C	M							r							F						R	
36R-CC	1044.73	*T. schraderi*	6B	late Miocene	C	M																					C
37R-CC	1050.51	*T. schraderi*	6B	late Miocene	C	M					r		r													R	C
38R-CC	1058.56	*T. schraderi*	6B	late Miocene	C	M																		R			C
39R-CC	1070.80	*T. schraderi*	6B	late Miocene	F	P																					R
40R-CC	1079.21	*T. schraderi*	6B	late Miocene	C	M					T													R			R
41R-CC	1094.47	*D. katayamae*	6A	late Miocene	C	M					R	r	R														
42R-CC	1103.87	*D. katayamae*	6A	late Miocene	C	M					R		F														
43R-CC	1111.28	*D. dimorpha*	5D	late Miocene	C	M			R		R		C		R												R
44R-CC	1115.76	*D. dimorpha*	5D	late Miocene	C	G		r	F		C		C														R
45R-CC	1129.85	*D. dimorpha*	5D	late Miocene	C	M		r	F		R		R														
46R-CC	1138.94	*D. dimorpha*	5D	late Miocene	C	M			R	r			R											R			R
47R-CC	1147.36	*D. dimorpha*	5D	late Miocene	C	M			R				F														
48R-CC	1157.71	*D. dimorpha*	5D	late Miocene	C	M			T				F														
49R-CC	1170.57	*Thalassiosira yabei*	5C	late Miocene	C	P						r	R														
50R-CC	1180.23	*Thalassiosira yabei*	5C	late Miocene	C	P							T											T			

Notes: NPD = North Pacific Diatom zones. Abundance: A = abundant, C = common, F = few, R = rare, T = trace, r = reworked. Preservation: G = good, M = moderate, P = poor.

Table T3. Distribution and relative abundances of age diagnostic diatoms, Hole 1151A. (See table notes. Continued on next two pages.)

Core, section	Depth (mbsf)	Diatom zone	NPD	Geological age	Group abundance	Preservation	*Actinocyclus oculatus*	*Crucidenticula nicobarica*	*Denticulopsis dimorpha*	*Denticulopsis hyalina*	*Denticulopsis katayamae*	*Denticulopsis lauta*	*Denticulopsis praedimorpha*	*Denticulopsis praelauta*	*Denticulopsis simonsenii*	*Hemidiscus cuneiformis*	*Ikebea tenuis*	*Kieselviella carina*	*Koizumia tatsunokuchiensis*	*Neodenticula kamtschatica*	*Neodenticula koizumii*	*Neodenticula seminae*	*Nitzschia fossilis*	*Nitzschia reinholdii*	*Nitzschia rolandii*	*Proboscia barboi*	*Proboscia curvirostris*	*Rouxia californica*	*Thalassionema schraderi*
186-1151A-																													
2R-CC	82.08	*P. curvirostris*	11	middle Pleistocene	A	G																C					R		
3R-CC	92.50	*P. curvirostris*	11	middle Pleistocene	A	G															r	R					R		
4R-CC	99.51	*A. oculatus*	10	early Pleistocene	A	G	R															C		R		R	R		
5R-CC	105.90	*A. oculatus*	10	early Pleistocene	C	G	R									R						F	R	F					
6R-CC	118.07	*N. koizumii*	9	late Pliocene	A	G	R									R				r	C	C	T	T		R	R		
7R-CC	126.45	*N. koizumii*	9	late Pliocene	A	M	F													r	R	F	R	T		F	T		
8R-CC	136.78	*N. koizumii*	9	late Pliocene	A	G	R														C	R		T		R			
9R-CC	147.17	*N. koizumii*	9	late Pliocene	C	M	R														C	R		T		R			
10R-CC	158.64	*N. koizumii*	9	late Pliocene	A	M															F	F		T		C			
11R-CC	168.86	*N. koizumii*	9	late Pliocene	A	M	R														C	R		T		F			
12R-CC	179.96	*N. koizumii–N. kamtschatica*	8	late Pliocene	A	G	R									R				F	C	R		T		R			
13R-CC	187.11	*N. koizumii–N. kamtschatica*	8	late Pliocene	C	G									r					R	C			R		R			
14R-CC	199.19	*N. koizumii–N. kamtschatica*	8	late Pliocene	A	G										F				F	T			T					
15R-CC	208.87	*N. kamtschatica*	7B	late Miocene–early Pliocene	C	G										R				R			R	T					
16R-CC	218.64	*N. kamtschatica*	7B	late Miocene–early Pliocene	C	G										F				R				R					
17R-CC	222.75	*N. kamtschatica*	7B	late Miocene–early Pliocene	A	G														R						T			
18R-CC	237.89	*N. kamtschatica*	7B	late Miocene–early Pliocene	C	G														R						R			
19R-CC	244.96	*N. kamtschatica*	7B	late Miocene–early Pliocene	A	G														R						R			
20R-CC	252.50	*N. kamtschatica*	7B	late Miocene–early Pliocene	C	G														C						R			
21R-CC	266.69	*N. kamtschatica*	7B	late Miocene–early Pliocene	A	G														C			R			R			
22R-CC	276.14	*N. kamtschatica*	7B	late Miocene–early Pliocene	C	G													R	A			R			R			
23R-CC	285.05	*N. kamtschatica*	7B	late Miocene–early Pliocene	A	M														C			R						
24R-CC	295.17	*N. kamtschatica*	7B	late Miocene–early Pliocene	C	G										R				C						R			
25R-CC	305.39	*N. kamtschatica*	7B	late Miocene–early Pliocene	C	M														C			T	R		R			
26R-CC	312.54	*N. kamtschatica*	7B	late Miocene–early Pliocene	C	M														C				R		R			
27R-CC	321.44	*N. kamtschatica*	7B	late Miocene–early Pliocene	C	M														C						R			
28R-CC	333.38	*N. kamtschatica*	7B	late Miocene–early Pliocene	A	G														C						R			
29R-CC	344.01	*N. kamtschatica*	7B	late Miocene–early Pliocene	A	M														C									
30R-CC	353.56	*N. kamtschatica*	7B	late Miocene–early Pliocene	A	G														C						F			
31R-CC	360.99	*N. kamtschatica*	7B	late Miocene–early Pliocene	A	G														C						F			
32R-CC	367.05	*N. kamtschatica*	7B	late Miocene–early Pliocene	C	M														C						F			
33R-CC	377.61	*N. kamtschatica*	7B	late Miocene–early Pliocene	A	G														C						R			
34R-CC	388.11	*N. kamtschatica*	7B	late Miocene–early Pliocene	C	M													R	C						R			
35R-CC	396.01	*N. kamtschatica*	7B	late Miocene–early Pliocene	F	M														F						R		T	
36R-CC	406.49	*N. kamtschatica*	7B	late Miocene–early Pliocene	C	G									r					C								T	
37R-CC	415.43	*N. kamtschatica*	7B	late Miocene–early Pliocene	A	G							r		r					C				T	T			T	
38R-CC	426.21	*N. kamtschatica*	7B	late Miocene–early Pliocene	C	M														C			R		R	R		R	
39R-CC	433.64	*N. kamtschatica*	7B	late Miocene–early Pliocene	C	G														C			R		R				
40R-CC	445.36	*N. kamtschatica*	7B	late Miocene–early Pliocene	F	M			r			r								C									
41R-CC	455.01	*N. kamtschatica*	7B	late Miocene–early Pliocene	C	G														C									
42R-CC	464.46	*N. kamtschatica*	7B	late Miocene–early Pliocene	A	M					r									A			R			R		T	

Table T3 (continued).

Core, section	Depth (mbsf)	Diatom zone	NPD	Geological age	Group abundance	Preservation	*Actinocyclus oculatus*	*Crucidenticula nicobarica*	*Denticulopsis dimorpha*	*Denticulopsis hyalina*	*Denticulopsis katayamae*	*Denticulopsis lauta*	*Denticulopsis praedimorpha*	*Denticulopsis praelauta*	*Denticulopsis simonsenii*	*Hemidiscus cuneiformis*	*Ikebea tenuis*	*Kieselviella carina*	*Koizumia tatsunokuchiensis*	*Neodenticula kamtschatica*	*Neodenticula koizumii*	*Neodenticula seminae*	*Nitzschia fossilis*	*Nitzschia reinholdii*	*Nitzschia rolandii*	*Proboscia barboi*	*Proboscia curvirostris*	*Rouxia californica*	*Thalassionema schraderi*
43R-CC	473.30	*N. kamtschatica*	7B	late Miocene–early Pliocene	A	G														C					R	R		T	
44R-CC	487.25	*N. kamtschatica*	7B	late Miocene–early Pliocene	C	G														C						R			
45R-CC	492.21	*N. kamtschatica*	7B	late Miocene–early Pliocene	A	G			r											A						R			
46R-CC	505.75	*N. kamtschatica*	7B	late Miocene–early Pliocene	A	G														C					R	R		T	
47R-CC	516.13	*N. kamtschatica*	7B	late Miocene–early Pliocene	A	G														A						R		T	
48R-CC	524.49	*N. kamtschatica*	7B	late Miocene–early Pliocene	A	M		r											R	F				R	F			T	
49R-CC	533.52	*N. kamtschatica*	7B	late Miocene–early Pliocene	A	G				r									R	C								T	
50R-CC	541.94	*N. kamtschatica*	7B	late Miocene–early Pliocene	A	M										T				C					R	R			T
51R-CC	554.63	*N. kamtschatica*	7B	late Miocene–early Pliocene	A	M									r					C									T
52R-CC	563.99	*N. kamtschatica*	7B	late Miocene–early Pliocene	A	G														F								R	
53R-CC	573.28	*N. kamtschatica*	7B	late Miocene–early Pliocene	A	G														C			R		R				
54R-CC	582.76	*N. kamtschatica*	7B	late Miocene–early Pliocene	C	M														C									R
55R-CC	584.38	*N. kamtschatica*	7B	late Miocene–early Pliocene	A	G														C			R						
56R-CC	596.47	*N. kamtschatica*	7B	late Miocene–early Pliocene	C	M														C						R			
57R-CC	609.84	*N. kamtschatica*	7B	late Miocene–early Pliocene	C	M										R				C				R					
58R-CC	622.95	*N. kamtschatica*	7B	late Miocene–early Pliocene	C	M										R			T	R				R		T			
59R-CC	631.34	*N. kamtschatica*	7B	late Miocene–early Pliocene	C	G									r				R	R						R			
60R-CC	640.76	*N. kamtschatica*	7B	late Miocene–early Pliocene	C	M													T	R									
61R-CC	649.03	*N. kamtschatica*	7B	late Miocene–early Pliocene	C	M													R	R									
62R-CC	652.80	*N. kamtschatica*	7B	late Miocene–early Pliocene	F	M									r					R			T			R			
63R-CC	664.31	*N. kamtschatica*	7B	late Miocene–early Pliocene	F	M				r										R			R			F			
65R-CC	688.40	*N. kamtschatica*	7B	late Miocene–early Pliocene	C	G									r					R						R			
66R-CC	693.43	*N. kamtschatica*	7B	late Miocene–early Pliocene	C	M														R									
67R-CC	705.63	*N. kamtschatica*	7B	late Miocene–early Pliocene	F	M														F			R						
68R-CC	718.84	*N. kamtschatica*	7B	late Miocene–early Pliocene	C	G									r	R				C				T		T		R	
69R-CC	725.77	*N. kamtschatica*	7B	late Miocene–early Pliocene	C	M					r						R			F									
70R-CC	732.14	*N. kamtschatica*	7B	late Miocene–early Pliocene	C	G					r						R			R						R		R	
71R-CC	747.10	*N. kamtschatica*	7B	late Miocene–early Pliocene	F	M					r									R					R				
72R-CC	755.44	*N. kamtschatica*	7B	late Miocene–early Pliocene	A	M				r						T				R					R				
73R-CC	767.11	*N. kamtschatica*	7B	late Miocene–early Pliocene	F	M									r					R			T		R				
74R-CC	774.79	*N. kamtschatica*	7B	late Miocene–early Pliocene	C	M		r		r							R			R									
75R-CC	784.18	*N. kamtschatica*	7B	late Miocene–early Pliocene	C	M									r					R					R				
76R-CC	794.56	*N. kamtschatica*	7B	late Miocene–early Pliocene	F	M									r		R			R					R				
77R-CC	800.62	*N. kamtschatica*	7B	late Miocene–early Pliocene	C	M											R			R			R		R				
79R-CC	816.95	*R. californica*	7A	late Miocene	R	P																				R			
80R-CC	834.47	*T. schraderi*	6B	late Miocene	C	M																							R
81R-CC	836.94	*T. schraderi*	6B	late Miocene	C	P											R									R			R
82R-CC	850.93	*T. schraderi*	6B	late Miocene	C	M											R												R
84R-CC	872.05	*T. schraderi*	6B	late Miocene	C	M											R												C
85R-CC	882.45	*T. schraderi*	6B	late Miocene	F	M											R									R			R
86R-CC	886.60	*T. schraderi*	6B	late Miocene	C	M							r			T												R	F
87R-CC	897.70	*T. schraderi*	6B	late Miocene	C	M									T											T			C

Table T3 (continued).

Core, section	Depth (mbsf)	Diatom zone	NPD	Geological age	Group abundance	Preservation	*Actinocyclus oculatus*	*Crucidenticula nicobarica*	*Denticulopsis dimorpha*	*Denticulopsis hyalina*	*Denticulopsis katayamae*	*Denticulopsis lauta*	*Denticulopsis praedimorpha*	*Denticulopsis praelauta*	*Denticulopsis simonsenii*	*Hemidiscus cuneiformis*	*Ikebea tenuis*	*Kieselviella carina*	*Koizumia tatsunokuchiensis*	*Neodenticula kamtschatica*	*Neodenticula koizumii*	*Neodenticula seminae*	*Nitzschia fossilis*	*Nitzschia reinholdii*	*Nitzschia rolandii*	*Proboscia barboi*	*Proboscia curvirostris*	*Rouxia californica*	*Thalassionema schraderi*
88R-CC	911.06	*T. schraderi*	6B	late Miocene	C	P									T													R	C
89R-CC	920.99	*T. schraderi*	6B	late Miocene	C	P									T								R			R			F
90R-CC	926.10	*T. schraderi*	6B	late Miocene	C	P			r						T		R		T							R		T	R
91R-CC	939.54	*D. dimorpha*	5D	late Miocene	C	M			R						R	R										R			R
92R-CC	948.09	*D. dimorpha*	5D	late Miocene	C	G			F						F											R			R
93R-CC	953.73	*D. dimorpha*	5D	late Miocene	A	M			F		T				C	R													
94R-CC	962.76	*D. dimorpha*	5D	late Miocene	C	M			F						F														
95R-CC	970.00	*D. dimorpha*	5D	late Miocene	A	G			F						F		T												
99R-CC	1009.53	*Thalassiosira yabei*	5C	late Miocene	F	P									F														
101R-CC	1028.78	*D. hyalina*	4Ba	middle Miocene	C	P		F		F		R																	
102R-CC	1039.51	*D. hyalina*	4Ba	middle Miocene	C	P		R		F		R					R												
103R-CC	1048.85	*D. hyalina*	4Ba	middle Miocene	F	M				F		R																	
104R-CC	1061.21	*D. lauta*	4A	middle Miocene	C	P		R										r											
105R-CC	1074.44	*D. lauta*	4A	middle Miocene	C	M		R				R		r												R			
106R-CC	1083.11	*D. lauta*	4A	middle Miocene	F	P												r											
107R-CC	1093.97	*D. lauta*	4A	middle Miocene	F	M						R		R			R												
108R-CC	1104.08	*D. praelauta*	3B	middle Miocene	F	M								F			R												
109R-CC	1113.46	*D. praelauta*	3B	middle Miocene	F	P								R															

Notes: NPD = North Pacific Diatom zones. Abundance: A = abundant, C = common, F = few, R = rare, T = trace, r = reworked. Preservation: G = good, M = moderate, P = poor.

Table T4. Age and stratigraphic position of middle Miocene through Quaternary diatom datum levels, Leg 186.

Event Datum	North Pacific Diatom zone boundary	Age (Ma)*†	Age (Ma)‡	Interval	Depth (mbsf)	Interval	Depth (mbsf)	Interval	Depth (mbsf)
				186-1150A-		186-1150B-		186-1151A-	
LO *P. curvirostris*	NPD11/12	0.30	0.3	5H-CC/6H-CC	46.33/55.73	ND	ND	ND	ND
LO *A. oculatus*	NPD10/11	1.01–1.46	1.0	11H-CC/12H-CC	102.66/112.15	ND	ND	3R-CC/4R-CC	92.50/99.51
LO *N. koizumii*	NPD9/10	2.0	2.0	15X-CC/16X-CC	130.20/139.58	ND	ND	5R-CC/6R-CC	105.90/118.07
LCsO *N. kamtschatica*	NPD8/9	2.61–2.68	2.6–2.7	21X-CC/22X-CC	192.01/202.94	ND	ND	11R-CC/12R-CC	168.86/179.96
FO *N. koizumii*	NPD7Bb/8	3.53–3.95	3.5–3.9	27X-CC/28X-CC	251.16/260.33	ND	ND	14R-CC/15R-CC	199.19/208.87
FO *T. oestrupii*	NPD7Ba/7Bb	5.49	5.5	ND	ND	ND	ND	ND	ND
FCsO *N. kamtschatica*	NPD7A/7Ba	6.4	6.4	ND	ND	21R-CC/22R-CC	898.32/910.67	77R-CC/79R-CC	800.62/816.95
LCO *T. schraderi*	NPD6B/7A	7.6	7.6	ND	ND	35R-CC/36R-CC	1031.50/1044.73	79R-CC/80R-CC	816.95/834.47
LCsO *D. simonsenii*	NPD6A/6B	8.6	8.5	ND	ND	40R-CC/41R-CC	1079.21/1094.47	90R-CC/91R-CC	926.10/939.54
LO *D. dimorpha*	NPD5D/6A	9.16	9.2	ND	ND	42R-CC/43R-CC	1103.87/1111.28	90R-CC/91R-CC	926.10/939.54
FO *D. dimorpha*	NPD5C/5D	9.9	10.0	ND	ND	48R-CC/49R-CC	1157.71/1170.57	95R-CC/99R-CC	970.00/1009.53
LCO *D. praedimorpha*	NPD5B/5C	11.5	11.5	ND	ND	Below 50R-CC	Below 1180.23	ND	ND
FO *D. praedimorpha*	NPD5A/5B	12.9	12.9	ND	ND	ND	ND	ND	ND
FCO *D. simonsenii*	NPD4Bb/5A	13.1	13.1	ND	ND	ND	ND	99R-CC/101R-CC	1009.53/1028.78
FO *D. simonsenii*	NPD4Ba/4Bb	14.4–14.6	14.5–14.9	ND	ND	ND	ND	99R-CC/101R-CC	1009.53/1028.78
FO *D. hyalina*	NPD4A/4Ba	14.9	14.9	ND	ND	ND	ND	103R-CC/104R-CC	1048.85/1061.21
FO *D. lauta*	NPD3B/4A	15.9	15.9	ND	ND	ND	ND	107R-CC/108R-CC	1093.97/1104.08
FO *D. praelauta*	NPD3A/3B	16.3	16.3	ND	ND	ND	ND	Below 109R-CC	Below 1113.46

Notes: * = Motoyama and Maruyama (1988), † = Maruyama (2000), ‡ = Yanagisawa and Akiba (1998). FO = first occurrence, LO = last occurrence, FCO = first common occurrence, LCO = last common occurrence, FCsO = first consistent occurrence, LCsO = last consistent occurrence. ND = no data. The boundary between Subzone NPD4Bb and Zone NPD5A can be also recognized by the LCO *Denticulopsis hyalina*. A taxonomic problem prohibits the FO *T. oestrupii* from defining the subzonal boundary between NPD7Ba and NPD7b among all of three holes. Indefinite zones of NPD4Bb, 5A, 5B, 5C, and 6A in Hole 1151A indicate the low sedimentation rate or the presence of some hiatuses in a stratigraphic sequence.

Table T5. Stratigraphic occurrence of the Pliocene key species belonging to the genus *Thalassiosira*, Hole 1150B.

				T. frenguelliopsis subgroup			*T. bipora* subgroup				*T. oestrupii* subgroup					
Core, section	Depth (mbsf)	*Thalassiosira* cf. *baldaufii*	*Thalassiosira baldaufii*	*T.* cf. *frenguelliopsis*	*Thalassiosira frenguelliopsis*	*Thalassiosira tetraoestrupii*	*Thalassiosira bipora* f. *prima*	*Thalassiosira bipora*	*Thalassiosira centra*	*Thalassiosira depressa*	*Thalassiosira praeoestrupii*	*Thalassiosira* cf. *praeoestrupii*	*Thalassiosira* sp.	In the *T. trifulta* group	*Thalassiosira trifulta* group	Others
186-1150B-																
5R-CC	740.07	1					(S1)	17 (S1)			17(L2, S3)				34	465.5
6R-CC	756.54	2(L1)	9		6	3	(S1)	11			13(L2, S3)	(S1)	(S1)		33	456.5
7R-1	767.60		4		1	4		10		3(L1)	4				22	474.5
8R-CC	770.05		2		1(L1)			9(L1)	1	1	6(L2)				18	480
9R-CC	781.47		7		7		(S3)	9(L1, S1)			10(L1, S3)				26	463
10R-CC	791.04		2		(S1)		2(L1, S3)	6			9(L4, S2)				17	481.5
11R-CC	802.82		9		6(L2, S1)										6	485.5
12R-CC	811.91		20(L1)		2(L2)										2	498
13R-CC	819.78		12		4(L3)										4	496
14R-CC	830.48		16		9(L1, S5)										9	491
15R-CC	837.15		58	1(L1)	(S2)										1	499.5

Note: The number of photographed specimens used for the observation of features are shown in parentheses (L = light microscope, S = scanning electron microscope).

Table T6. Stratigraphic occurrence of the Pliocene key species belonging to the genus *Thalassiosira*, Hole 1151A.

			T. frenguelliopsis subgroup				*T. bipora* subgroup					*T. oestrupii* subgroup		
Core, section	Depth (mbsf)	*Thalassiosira baldaufii*	*Thalassiosira* cf. *frenguelliopsis*	*Thalassiosira frenguelliopsis*	*Thalassiosira* cf. *tetraoestrupii*	*Thalassiosira tetraoestrupii*	*Thalassiosira bipora* f. *prima*	*Thalassiosira* cf. *bipora*	*Thalassiosira bipora*	*Thalassiosira depressa*	*Thalassiosira exceptiuncula*	*Thalassiosira praeoestrupii*	*Thalassiosira trifulta* group	Others
186-1151A-														
50R-CC	541.94	5						2	1			1(L1)	4	496.5
51R-CC	554.63	7				1			3			3	7	493
52R-CC	563.99	22							7(L1)			2(L1)	9	491.5
53R-CC	573.28					1			1	1		1	4	496
54R-CC	582.76	9		(S1)		4(L1)			15(L1, S2)		(S1)	2(L2, S3)	21	479
55R-CC	584.38	24			1(L1)	1			4	1		6(L3)	13	487
56R-CC	596.47	5							7(L2)			3(L2)	10	490
57R-CC	609.84			14(L1, S1)	(S1)	1	1(L1, S3)	4(L1)	2(L1)			9(L1, S1)	31	469
58R-CC	622.95	7	7(L1)	1(L1)			1						9	491
59R-CC	631.34	12											0	500
60R-CC	640.76	27		2(L1, S5)			1(L1)		3				6	494

Note: The number of photographed specimens used for the observation of features are shown in parentheses (L = light microscope, S = scanning electron microscope).

Plate P1. *Thalassiosira bipora* Shiono. **1.** Whole valve showing rimoportula (R) (Sample 186-1151A-56R-CC); light microscope (LM). **2.** Whole valve showing R (Sample 186-1151A-52R-CC); LM. **3, 4.** Sample 186-1150B-5R-CC; scanning electron microscope (SEM); (3) external view of whole valve showing opening of R; (4) central area showing external openings of occluded areola (OC) and central fultoportula (CF). **5, 6, 7.** Sample 186-1151A-54R-CC; SEM; (5) internal view of whole valve showing broken process of R; (6) central area showing OC and internal process of CF; (7) internal process of CF with four operculate structures (OP).

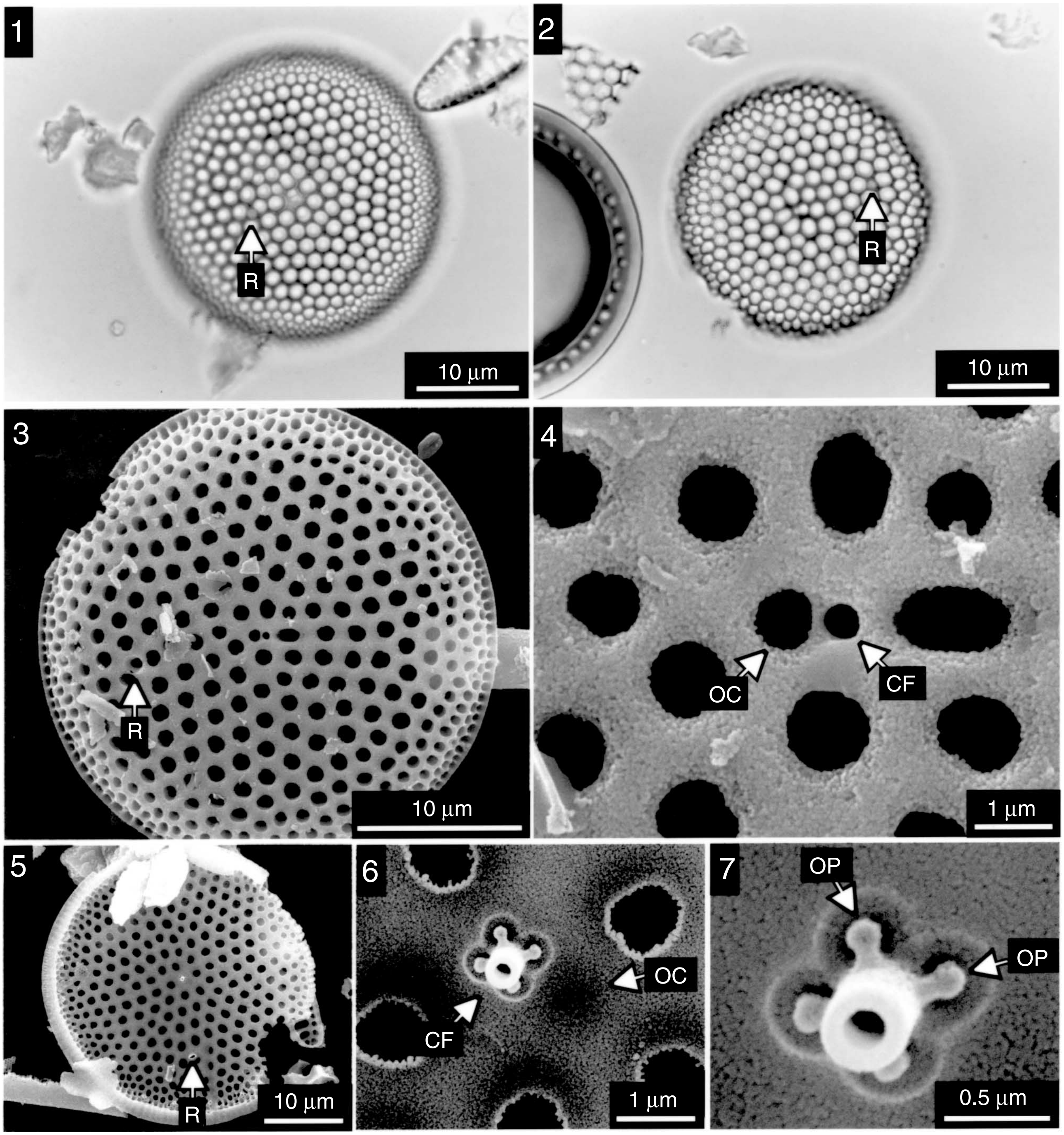


Plate P2. *Thalassiosira bipora* f. *prima* Shiono. **1.** Whole valve showing rimoportula (R) (Sample 186-1151A-60R-CC); light microscope (LM). **2.** Whole valve showing R (Sample 186-1150B-10R-CC); LM. **3.** External view of whole valve showing opening of R (Sample 186-1150B-6R-CC); scanning electron microscope (SEM). **4, 5.** Sample 186-1151A-57R-CC; SEM; (4) external view of whole valve showing opening of R; (5) central area showing external openings of occluded areola (OC) and central fultoportula (CF). **6, 7.** Sample 186-1151A-57R-CC; SEM; (6) internal view of whole valve; (7) central area showing internal openings of OC and broken CF.

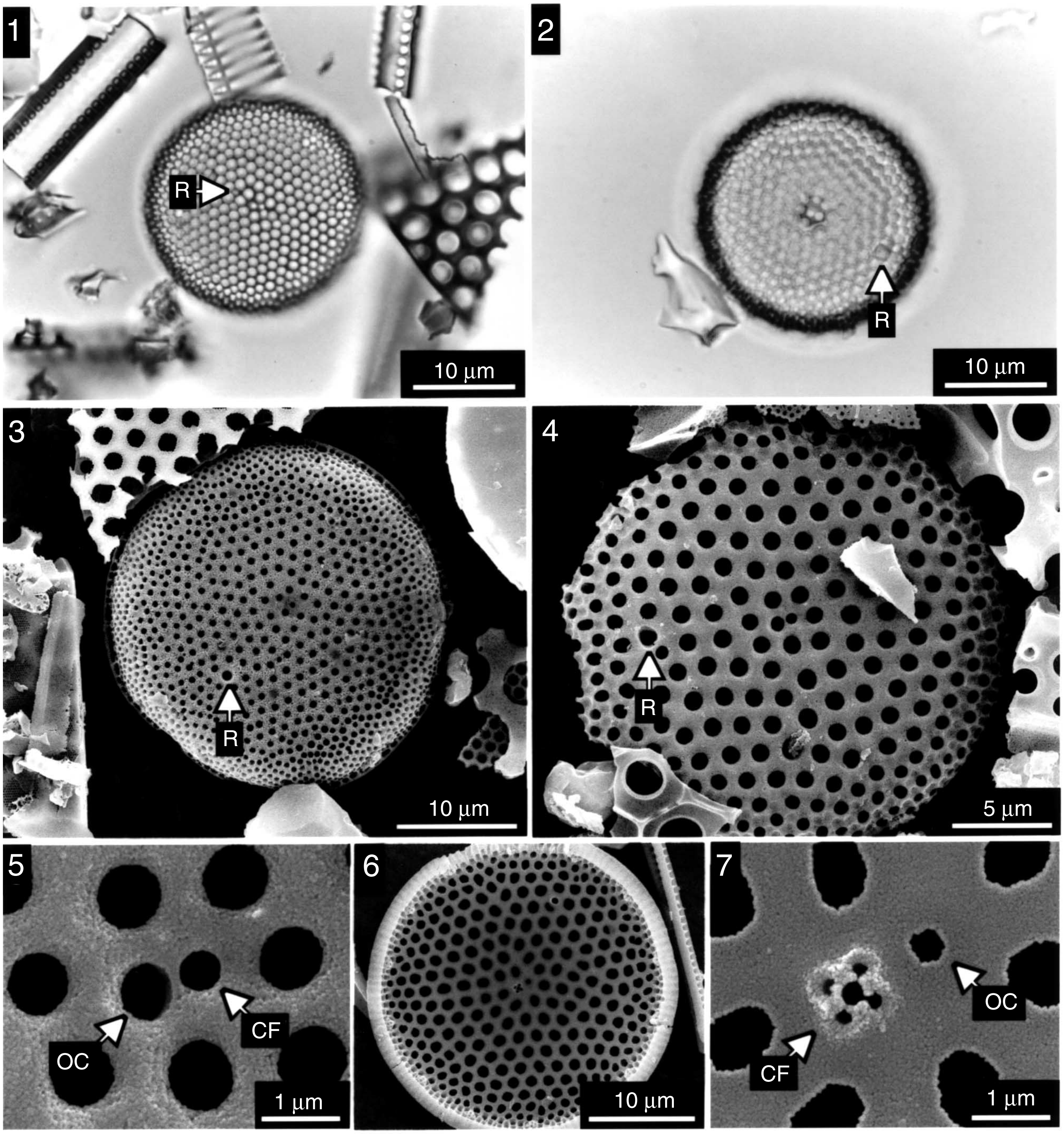


Plate P3. *Thalassiosira praeoestrupii* Dumont, Baldauf, and Barron. **1.** Whole valve showing rimoportula (R) and central fultoportula (CF) (Sample 186-1150B-6R-CC); light microscope (LM). **2.** Whole valve showing R and CF (Sample 186-1150B-5R-CC); LM. **3.** External view of whole valve showing openings of R and CF (Sample 186-1151A-54R-CC); scanning electron microscope (SEM). **4, 5.** Sample 186-1150B-9R-CC; SEM; (4) internal view of whole valve showing broken R, broken processes of marginal fultoportulae (MF), and internal process of CF; (5) internal process of CF with three operculate structures (OP) and three trifultate structures (T). **6, 7.** Sample 186-1151A-54R-CC; SEM; (6) internal view of whole valve showing broken R, internal processes of MF and CF; (7) internal process of MF.

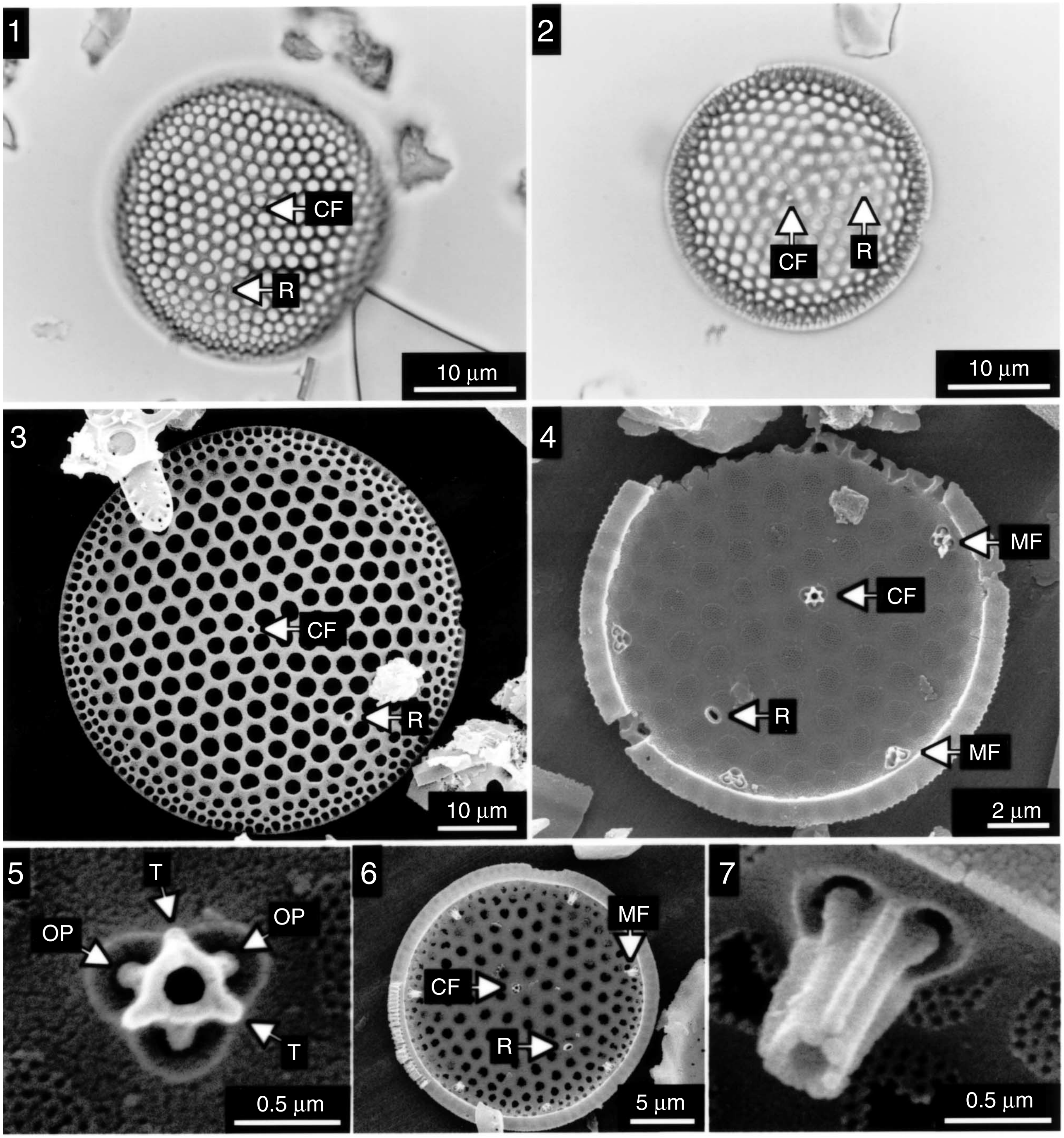


Plate P4. Species of the *Thalassiosira trifulta* group. **1–3.** *Thalassiosira* cf. *praeoestrupii* Dumont, Baldauf, and Barron (Sample 186-1150B-6R-CC); scanning electron microscope (SEM). (1) Internal view of whole valve showing internal processes of rimoportula (R), marginal fultoportulae (MF), and central fultoportula (CF). (2) Internal process of MF. (3) Internal process of CF with four operculate structures (OP) and four trifultate structures (T). **4–6.** *Thalassiosira frenguelliopsis* Fryxell and Johansen (Sample 186-1151A-54R-CC); SEM. (4) Internal view of whole valve showing internal processes of R, MF, and CF. (5) Internal process of MF. (6) Internal process of CF with four OP structures. **7.** *Thalassiosira frenguelliopsis* Fryxell and Johansen. External view of whole valve showing openings of R and CF (Sample 186-1150B-14R-CC); SEM. **8.** *Thalassiosira tetraoestrupii* Bodén. External view of whole valve showing openings of R and CF (Sample 186-1151A-57R-CC); SEM. **9.** *Thalassiosira exceptiuncula* Shiono. External view of whole valve showing openings of R and CF (Sample 186-1151A-54R-CC); SEM. **10–11.** *Thalassiosira frenguelliopsis* Fryxell and Johansen. (10) Whole valve showing R and CF (Sample 186-1150B-14R-CC); light microscope (LM). (11) Whole valve (Sample 186-1150B-11R-CC); LM. **12.** *Thalassiosira tetraoestrupii* Bodén. Whole valve showing R and CF (Sample 186-1150B-6R-CC); LM. **(Figure shown on next page.)**

Plate P4 (continued). (Caption shown on previous page.)