Title.

Pliocene and Pleistocene paleoceanography in the western subarctic Pacific based on diatom analyses of ODP Leg 145 Hole 884B and IODP Expedition 323 Holes U1341B and U1343E

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Abstract

Late Pliocene-Pleistocene fossil diatom assemblages from Ocean Drilling Program (ODP) Leg 145 Hole 884B in the western subarctic Pacific were investigated to improve the diatom biostratigraphy. Moreover, the paleoceanographic records at Hole 884B were compared with those in Integrated Ocean Drilling Program (IODP) Expedition 323 Holes U1341B and U1343E in the Bering Sea for the time interval of 2.5-0 Ma in order to clarify the differences in the diatom assemblage fluctuations and the history of past ocean circulations around the subarctic Pacific. In Hole 884B, five diatom zones from the *Neodenticula koizumii*-*N. kamtschatica* Zone to the *N. seminae* Zone were identified. The decreases in the relative abundance of temperate-water species were recognized at ca. 1.9 Ma in Hole U1343E, ca. 2.1 Ma in Holes 884B and U1341B. The decreases of the temperate-water species at these sites indicate that a widespread cooling event must have occurred over the subarctic Pacific at ~2 Ma. In addition, the continuous low occurrences of the sea-ice related species from around 2 Ma onward, which indicate the presence of sea-ices, were observed in Sites 884 and U1341. We also point out that the age differences in decrease of temperate-water species at the three sites (i.e., delay in response of the temperate-water species at Site U1343) may be related to changes of seawater inflow from the North Pacific to Sites U1341 and U1343 and of the East Kamchatka Current from the Bering Sea to Site 884.

Keywords: diatom, paleoceanography, subarctic Pacific, Bering Sea, East Kamchatka Current, Aleutian passes, Pleistocene, Pliocene

1. Introduction

Large areas of the seafloor in the subarctic Pacific and the Bering Sea are covered thickly with siliceous sediments containing siliceous microfossils such as diatoms, radiolarians and silicoflagellates (Lisitzin, 1971). In particular, diatoms are the most abundant microfossils found in the sediments of these areas (Sancetta, 1982).

Investigations on fossil/recent diatom species in surface sediments in the subarctic Pacific and the Bering Sea have clarified the correspondence between biogeographic distribution and present-day oceanographic conditions in the overlying upper water masses (Jousé et al., 1971; Kanaya and Koizumi, 1966; Sancetta, 1981, 1982). These studies have brought about advances in paleoceanography based on firm classification of fossil diatom assemblages. Diatom-based paleoceanographic studies can provide useful information for the interpretation of past oceanographic changes. For example, Koizumi (1985) discussed the late Neogene paleoceanographic history in the western North Pacific on the basis of Td (diatom temperature) values defined by Kanaya and Koizumi (1966) for Deep Sea Drilling Project (DSDP) Sites 579 and 580 and showed there were distinct surface water cooling events at 2.5, 2.0, and 1.6 Ma. In addition, Sancetta and Silvestri (1986) analyzed diatom assemblages in six cores spanning the entire Pleistocene and extending to 2.5 Ma beneath different water masses (the subarctic and transitional zones) and looked into the process of development of the subarctic water masses from the late Pliocene to the Pleistocene.

Later on, Ocean Drilling Program (ODP) Leg 145 obtained core samples in the subarctic Pacific, which contain well-preserved fossil diatoms throughout the Miocene to the Pleistocene sections (Shipboard Scientific Party, 1993; Barron and Gladenkov, 1995). However, there are only a handful of Plio-Pleistocene paleoceanographic reports based on fossil diatom analyses from the North Pacific (Barron, 1998; Shimada et al., 2009). Barron (1998) showed that the fluctuation of diatom mass accumulation rates in the North Pacific during the late Neogene underwent major changes in response to high-latitude cooling and changes in surface and deep-water circulation. On the other hand, Shimada et al. (2009) presented high-resolution data on changes in diatom assemblages, including the *Neodenticula* complex, from the North Pacific subarctic gyre in the late Pliocene. They indicated that the diatom assemblages were affected by the convection leading to the supply of nutrients and the onset of the Northern Hemisphere Glaciation (NHG). However, their papers did not include a detailed

interpretation of how and whether the changes in oceanic circulation influenced the diatom assemblages of the Bering Sea and North Pacific. Moreover, there is a need to correlate the latest datums to reconstruct the past surface current system because the age control, based on magneto- and biostratigraphy, has been updated by Gradstein et al. (2004, 2012).

In this paper, we discuss the paleoceanographic changes in the western subarctic Pacific from the Pleistocene to the Pliocene^{*1} based on the fossil diatom analyses at ODP Leg 145 Site 884 located on the Detroit Seamount, southeast of the Kamchatka Strait (**Fig. 1**). Although diatom biostratigraphy in the region was established by Barron and Gladenkov (1995), some of their datums defined by several diatom bioevents in core-catcher samples separated by large intervals (usually ca. 9.5 m). Therefore, a higher-resolution sampling (~3 to 0.75 m intervals) was undertaken in this study in order to provide more detailed biohorizons in the cores from Site 884.

In addition, the paleoceanographic reconstruction at Site 884, based on diatom assemblage analysis, is compared with those of Integrated Ocean Drilling Program (IODP) Expedition 323 Site U1341 on the Bowers Ridge (Takahashi et al., 2011a, b; Onodera et al., this issue) and Site U1343 on the Bering Sea Shelf (Takahashi et al., 2011a, b; Teraishi et al., this issue). Based on this comparison, we discuss the fluctuations of ocean water mass structures between the subarctic Pacific and the Bering Sea. These regions are of particular interest since water exchanges between the subarctic Pacific and the Bering Sea through the Aleutian Passes, and may have played an important role in the global water circulation and climate change (e.g., Ezer and Oey, 2010; Stabeno et al., 1999, 2005).

2. Materials and methods

ODP Leg 145 Site 884 was drilled and an 850 m-long sequence from the early Eocene to the Pleistocene sediments was obtained in five holes. The 640 m-thick Miocene to Pleistocene sediments are composed of diatomites, claystones, and clayey diatom ooze. Diatoms are abundant and well preserved throughout the sections (Shipboard Scientific Party, 1993; Barron and Gladenkov, 1995).

^{*1} In this paper we opt to continue using the last major published time scale, in which the base of the Pleistocene is defined by the GSSP of the Calabrian Stage at 1.806 (1.8) Ma (Gradstein et al., 2004a,b).

Eighty microslides were prepared for the late Pliocene to Pleistocene diatom analyses. The microslides contained abundant and well-preserved fossil diatom assemblages. To prepare the microslides, silty to clayey sediment samples containing fossil diatoms were selected, within an interval ranging from Cores 145-884B-24X-3W, 10-11 cm (202.5 m below the sea floor (mbsf)) to 1H-1W, 10-11 cm (0.1 mbsf). Samples were picked every ca. 3 m (average temporal resolution of ~40 kyr) for the 3.94 to 0 Ma interval and also collected every ca. 0.75 m (~10 kyr on average) adjacent to the diatom biohorizons reported in Barron and Gladenkov (1995).

Methods of sample treatment are after Koizumi (1968). Approximately 1.0 g of each wet sample was mixed with ~30 ml of hydrogen peroxide (H_2O_2 , 10–15%) to remove organic matter in a 200 ml beaker. Then, ~30 ml of hydrochloric acid (HCl, 30%) were added and boiled using a Bunsen burner at ca. 100 °C to dissolve calcareous material. After boiling for ~5 minutes, the beaker was filled with distilled water and allowed to stand for 8 hours and the residue was separated by decanting off the acidic water. In order to remove the clay fraction, ~200 ml of solution of peptizer sodium pyrophosphate ($\text{Na}_4\text{P}_2\text{O}_7$, 0.01 N) was added to the beaker and allowed to stand for 8 hours. The residue was separated by decanting the water and the beaker was filled again with the sodium pyrophosphate solution. These processes of removing the clay fraction by decantation were repeated until the supernatant liquid became clear.

Microslides for light microscopic (LM) observation were prepared with the cleaned samples in the following way. One hundred milliliter of distilled water was added to the treated sample in order to suspend the sample in the beaker and after a few seconds 0.7 ml of the solution was picked by a micropipette and settled on an 18 × 18 mm cover glass. After it had dried on a hot plate for one hour at 50-60 °C, the cover glass was mounted on a slide glass using Pleurax.

The counting method for fossil diatom valves follows that of Akiba (1986). A single valve of a centric diatom was counted as one when greater than a half of a whole valve was observed. Broken specimens of pennate diatoms were counted as one valve when both apices were observed, and those only with the other side of apex were counted as 0.5 valves and were later converted to number of valves. Other criteria for the identification of genera and species were taken from the references listed in **Appendix Table 1**. To determine the fluctuation of diatom assemblages, 100 diatom valves of vegetative stages were counted at the species level for each sample. After

counting, the slides were scanned to record the presence of species missed in the original tally. Diatom species occurrences and presence (indicated by a “+” in **Appendix Table 2**) in Hole 884B are representative of the taxa recognized in a tally of over 100 valves in separate scanning line (s), given in **Appendix Table 2**.

For the diatom biostratigraphic assignments of ODP Hole 884B, the diatom bioevents which define or characterize certain horizons are mainly based on the North Pacific diatom zonation by Barron and Gladenkov (1995) and Yanagisawa and Akiba (1998). The age model of Hole 884B in this paper was based on diatom biohorizons and geomagnetic polarity datums updated by Lourens et al. (2004a, b) (**Figs. 2, 3 and Table 1**) for those indicated in Barron and Gladenkov (1995), while the established ages by Barron and Gladenkov (1995) were based on the geomagnetic polarity time scale of Cande and Kent (1992). The age model for diatom-based paleoceanographic study at IODP Site U1341 (Onodera et al., this issue) is based on geomagnetic polarity events, astronomically-tuned age curves of Si/Al and $\delta^{18}\text{O}$ foraminifers and that for IODP Site U1343 is based on astronomically-tuned age curves of $\delta^{18}\text{O}$ benthic foraminifers (Asahi et al., this issue; Teraishi et al., this issue).

In addition, we examined the abundance of closed and open copulas of *Neodenticula* spp. in order to confirm the reliability of their datums and appearances (i.e., closed copula = *N. seminae*; open copula = *N. koizumii* and/or *N. kamtschatica*) (Yanagisawa and Akiba, 1990). The *Neodenticula* copula abundance is defined here as the numbers of copula encountered during a count of 100 vegetative cell valves.

3. Modern oceanographic setting of the subarctic Pacific

The modern general circulation in the subarctic Pacific is characterized by a large anticlockwise gyre (subarctic gyre) and two subgyres (Alaska Gyre in the east, Western Subarctic Gyre in the west). The circulation in the Bering Sea basin is also described as a cyclonic gyre, with the southward flowing East Kamchatka Current as a western boundary current and the northwestward flowing Bering Slope Current (BSC) as an eastern boundary current (Stabeno et al., 1999, **Fig. 1**).

The Alaskan Stream, the western boundary current of the Alaska Gyre, flows along the Alaska Peninsula and Aleutian Island arc. Some portion of the Alaskan Stream flows northward through passages in the Aleutian Island arc and enters into the Bering Sea (Stabeno et al., 2005), participating in the cyclonic circulation of the Bering Sea

(Cokelet et al., 1996). After entering into the Bering Sea through the Aleutian passes such as Amchitka Pass and Amukta Pass, they flow eastward along the north slope of the Aleutian arc as the Aleutian North Slope Current (ANSC) (Stabeno et al., 2009). Eastward of 167°W, the ANSC turns northwestward, forming the BSC. Finally, the combination of the westward flow from the BSC and the northward flow entering into the Bering Sea through the Near Strait (Stabeno et al., 1994) forms the East Kamchatka Current.

Thus, the circulation in the Bering Sea is strongly influenced by the Alaskan Stream. In addition, the inflow into the Bering Sea is balanced by the outflow through the Kamchatka Strait (Stabeno et al., 1999) and Near Strait (Panteleev et al. 2012). Therefore, the cold East Kamchatka Current and the main flow of the Alaskan Stream appear to have a major influence on the environment around Site 884 (Kinney and Maslowski, 2012).

In addition, the surface water temperature in the modern eastern subarctic Pacific is slightly higher than that in the western subarctic Pacific. Mean annual sea surface temperatures (SSTs) are ~5.4°C and ~7.2°C for around Site 884 (the western subarctic Pacific) and Site 887 (the eastern subarctic Pacific), respectively (Locarnini et al., 2010). A similar east-west temperature gradient in the subarctic Pacific might have already existed around 2 Ma because the present domains of sea surface water masses in the North Pacific had already developed by 2.7 Ma (e.g., Kamikuri et al., 2007).

4. Results

4.1. Diatom biostratigraphy in Hole 884B

Seven diatom datums were recognized in this study. **Table 1** shows the age and depth interval of each datum. The higher-resolution sampling (~3 to 0.75 m intervals) accomplished in this study enabled a more detailed description of biohorizons in the cores of Hole 884B, in comparison to Barron and Gladenkov (1995) who determined diatom bioevents using core-catcher samples that are usually ca. 9.5 m apart (**Table 1**). In addition, ages of the datums that we observed were calculated using the astronomically tuned Neogene time scale (ATNTS) of Lourens et al. (2004a, b), while Barron and Gladenkov (1995) employed the geomagnetic timescale of Cande and Kent (1992). These datums indicate that the core materials investigated in this study correspond to five diatom zones with the Neogene North Pacific Diatom zone codes

(NPD) of Yanagisawa and Akiba (1998): the *Neodenticula koizumii*-*N. kamtschatica* (NPD 8; 3.86-2.60 Ma), *N. koizumii* (NPD 9; 2.60-2.00 Ma), *Actinocyclus oculatus* (NPD 10; 2.00-0.96 Ma), *Proboscia curvirostris* (NPD 11; 0.96-0.30 Ma), and *N. seminae* (NPD 12; 0.30-0.0 Ma) Zones (**Fig. 2, Table 1**). The age-depth plot of ODP Hole 884B based on these diatom datums as well as paleomagnetic events are also shown in **Fig. 3**.

Although the last occurrence (LO) datums of *Stephanopyxis horridus* and *Pyxidicula zabelinae* were given ages of 1.8-2.0 Ma and 2.0-2.2 Ma, respectively, by Barron and Gladenkov (1995), these datums were not clearly identified in the present study. Therefore, these datums are not included in the age models of our study. In addition, the FO datum of *N. seminae* and the LO datum of *N. koizumii* coincided with the FO datum of closed copula and the LO datum of open copula, respectively (**Fig. 2**).

4.2. Diatom paleoenvironmental indicators from Hole 884B

Eighty-two species of fossil diatoms are recognized (**Appendix Tables 1, 2**) and most of them are marine planktonic species. Marine diatoms are divided into five ecological groups according to Teraishi et al. (this issue): cold-water (C), temperate-water (T), sea-ice related (S), neritic (N), and open-ocean (O) species (**Table 2** and **Appendix Table 2**). The percent relative abundance of these groups was calculated in each core intervals sampled (**Appendix Table 2**). “Miscellaneous” species were omitted in these calculations.

Figure 4 shows the relative abundance (%) in diatom assemblages of selected paleoenvironmental indicators in Hole 884B at depths ranging from 120 to 0 mbsf, which corresponds to ages spanning 2.5 to 0 Ma. In general, the cold-water and open-ocean species display high abundances throughout Hole 884B, while the temperate-water and neritic species have lower abundances. The temperate-water species show relatively high abundances (up to ~20%) between 2.5 and 2.1 Ma. Generally consistent (sometimes intermittent) occurrences with low abundances of the sea-ice related and neritic species are recognized from ca. 2.1 Ma onward.

5. Discussion

5.1. Diatom-based paleoceanography of Hole 884B

The high relative abundance the cold-water species recognized throughout Hole

884B (**Fig. 4**) suggests that cold environmental conditions analogous to the modern western subarctic Pacific have persisted from at least 2.5 Ma to the present. The temperate-water species show relatively high abundances (up to ~20%) between 2.5 and 2.1 Ma and decrease after 2.1 Ma (**Fig. 4**). Moreover, the continuous low occurrences of the sea-ice related species (living in ice margin waters) from around 2 Ma onward were observed, although there is almost no sea-ice distribution around Site 884 region today, indicating that the region around Site 884 has experienced conditions with a little sea-ice from ca. 2 Ma.

Koizumi (1985) estimated the surface water temperature on the basis of Td values at DSDP Sites 579 (38°37.7'N, 153°50.2'E) and 580 (41°37.5'N, 153°58.6'E) in the western North Pacific and showed that distinct and large drops in surface water temperature occurred at about 2.1 Ma^{*2} at Sites 579 and 580. In addition, estimations of the sea surface temperature (SST) based on planktonic foraminiferal assemblage in the North Pacific (DSDP Sites 296, 310, 173) and western Pacific (DSDP Sites 62, 200, 289, 292, 296, 445, 451, 577) also showed a cooling event around 2 Ma (Keller, 1979; Wang, 1994). The decrease in the relative abundance of temperate-water species at Site 884 after 2.1 Ma is consistent with the above observations. Moreover, Keigwin (1979) suggested that a glaciation or bottom-water cooling event occurred at ~2 Ma on the basis of a significant variation observed in $\delta^{18}\text{O}$ record at DSDP Sites 157 and 158 in the easternmost equatorial Pacific (Panama Basin) and Site 310 in the central Pacific (Hess Rise).

Koizumi (1985) also indicated that the surface water temperature initially fell below the present day level at 3.0 Ma^{*2} at Site 579 and at 2.6 Ma^{*2} at Site 580. Later on, the surface water temperature reached to the present level, except at 2.2 Ma^{*2} when a slightly warmer surface water temperature was recognized at both sites (Koizumi, 1985). Combining these results, the SST at Site 884 during ca. 2.5-2.1 Ma seems to have been similar to the present level and a cooling event likely occurred at ca. 2.1 Ma.

In addition, the existences of the sea-ice related species at ca. 1.0-0.8 and 0.4 Ma and the neritic species at ca. 1.2 and 0.9 Ma may be related to the changes of the oceanographic conditions mentioned by Sancetta and Silvestri (1986) (**Fig. 4**). Sancetta

^{*2} The ages are recalculated using the ATNTS 2004 geological timescale, Lourens et al. (2004a, b)

and Silvestri (1986) analyzed diatom assemblages in six cores spanning the entire Pleistocene and extending to 2.5 Ma beneath different water masses (the subarctic and transitional zones) and discussed the developmental process of the subarctic water masses from the late Pliocene to the Pleistocene including the southward migration of the Subarctic Front (i.e., cooling in the transitional zone). They showed that the subarctic sites record fluctuations between times of cold surface waters and strong seasonal contrast (extreme winter cooling) with times of cool and fresh conditions in the interval between 1.1 and 0.9 Ma^{*2}. They also showed the change in diatom assemblages at 0.4 Ma^{*2} suggesting an increase in severity of glacial conditions (Sancetta and Silvestri, 1986). In this study, the occurrences of sea-ice related and neritic taxa suggest the cooling sea surface temperature and intensified influence of coastal waters along the eastern Kamchatka, respectively. Based on the above, we would like to point out a possibility that the occurrences of the sea-ice related and neritic species at Site 884 are related to the developmental process of the subarctic water masses mentioned by Sancetta and Silvestri (1986).

5.2. Comparison with Holes U1341B and U1343E in the Bering Sea

Paleoceanographic analyses using fossil diatom assemblages from IODP Expedition 323 were also carried out for Hole U1341B by Onodera et al. (this issue) and for Hole U1343E by Teraishi et al. (this issue) (**Fig. 1**). Holes U1341B (54°2.0'N, 179°0.5'E, water depth 2139.5 m, total core recovered 594.98 m at Site U1341) and U1343E (57°33.4'N, 175°49.0'W, 1956.0 m, 700.27 m at Site U1343) were drilled on the western flank of the Bowers Ridge and northeastern shelf slope in the Bering Sea, respectively (Takahashi et al., 2011a, b). The results of Hole 884B are compared with those of the Bering Sea in order to clarify the differences in the diatom assemblage fluctuations, especially those of the temperate-water species, and to document the history of past ocean circulations around the subarctic Pacific from 2.5 Ma to the Pleistocene (**Fig. 4**).

A decrease in the relative abundance of temperate-water species was observed around ~2 Ma at each site, suggesting a widespread cooling or glaciation event occurred at ~2 Ma in the subarctic Pacific region. The increases in the relative abundance of sea-ice related species (**Fig. 4**) also indicate that further cooling seems to have begun around ~2 Ma. It should be noted that sea-ice related species were observed not only at

Site U1343 but also at Sites 884 and U1341, although there is no sea-ice distribution around Sites 884 and U1341 today.

As mentioned above, some previous studies also refer to a cooling event at ~2 Ma (e.g., Koizumi, 1985; Keigwin, 1979), there are, however, not so many reports that discuss on this widespread cooling event at ~2 Ma, while there are a lot of reports on other climatic events such as the NHG and the Mid-Pleistocene transition (e.g., Haug et al., 2005; Clark et al., 2006).

5.3. The age difference in the decreases of the temperate-water species between Holes 884B, U1341B and U1343E

More specifically, the decreases in the temperate-water species abundances at the three sites had different ages. The decrease was initially recognized at ca. 2.1 Ma in Holes 884B and U1341B and in Hole U1343E at 1.9 Ma (**Fig. 4**). Note that Hole U1343E is located in the area further north of Holes 884B and U1341B (**Fig. 1**), which has a bearing on the age difference. Although the sampling resolution at Hole 884B (up to ~0.05 Myr) is not sufficient to discuss on the detailed temporal differences (order of 0.1 Myr), we would like to point out the delay in response of the temperate-water species occurrences at Hole U1343E in comparison to Holes 884 and U1341B.

As mentioned in chapter 3, the cold East Kamchatka Current and main flow of the Alaskan Stream (Kinney and Maslowski, 2012) appear to have had a major influence on the environmental conditions around Sites 884, U1341, and U1343 since the modern ocean circulation in the subarctic Pacific is characterized by the Subarctic Gyre. Therefore, it is possible that the delay in the response of the temperate-water species between Sites 884, U1341 and U1343 may be related to changes of seawater inflow from the North Pacific to Sites U1341 and U1343 and of the East Kamchatka Current from the Bering Sea to Site 884.

Therefore, we propose that the decreases in the relative abundance of temperate-water species in Holes 884B and U1341B at ca. 2.1 Ma (**Fig. 4**) may be linked to a cooling and strengthening of the colder East Kamchatka Current and the relative weakening of the warmer Alaskan Stream to the western subarctic Pacific. As a result, the abundance of the temperate-water species in Holes 884B and U1341B decreased at ca. 2.1 Ma.

When the flow of colder East Kamchatka Current was intensified, the water

inflow into the Bering Sea from the eastern subarctic Pacific through the Aleutian passes must have increased because the inflow to the Bering Sea is balanced by an equivalent outflow (Stabeno et al., 1999; Ezer and Oey, 2010). The increases of the inflow include water masses via the Amchika and the Amukta Passes originating from the warmer Alaskan Stream, which feeds the ANSC and BSC (Stabeno et al., 2009). Since the original waters of Alaskan Stream provide relatively fresh surface and warm subsurface waters to the Bering Sea (Stabeno et al., 1999), there has been a supply of warmer water to the Bering Slope region near Site U1343 until 1.9 Ma. Consequently, the continuous supply of warmer water to the Bering Slope region might have delayed the decrease of the temperate-water species at Hole U1343E compared to Holes 884 and U1341B (**Fig. 4**).

In order to evaluate the scenario, further investigations on diatom assemblage fluctuations with higher resolution sampling over the subarctic Pacific and the Bering Sea are needed. In addition, future studies in the eastern subarctic Pacific such as ODP Site 887 may help to prove it because our proposed scenario is based on the fact that warmer water supply to the subarctic Pacific or the Bering Sea is derived from the Alaskan stream.

6. Conclusions

In this study, we investigated the late Pliocene-Pleistocene fossil diatom assemblages from ODP Leg 145 Hole 884B and improved diatom biostratigraphy. The results of the paleoceanographic analysis of Hole 884B were compared with those of the Bering Sea at Holes U1341B (Onodera et al., this issue) and U1343E (Teraishi et al., this issue) to clarify the differences in the diatom assemblage fluctuations and the history of past ocean circulations around the subarctic Pacific from 2.5 Ma to the Pleistocene.

In Hole 884B, seven diatom datums and five biostratigraphic diatom zones were recognized: *Neodenticula koizumii*-*N. kamtschatica* (NPD 8; 3.86-2.60 Ma), *N. koizumii* (NPD 9; 2.60-2.00 Ma), *Actinocyclus oculatus* (NPD 10; 2.00-0.96 Ma), *Proboscia curvirostris* (NPD 11; 0.96-0.30 Ma), and the *N. seminae* (NPD 12; 0.30-0 Ma) Zones. The higher-resolution sampling accomplished in this study enabled a more detailed description of biohorizons in the cores of Hole 884B, in comparison to Barron and Gladenkov (1995). The datum ages were calculated using ATNTS geological timescale

(Lourens et al., 2004a, b).

A decrease in the relative abundance of temperate-water species was observed around ~2 Ma at Sites 884, U1341 and U1343, which suggests that a widespread cooling or glaciation event must have occurred at ~2 Ma over the subarctic Pacific region. The increases in the relative abundance of sea-ice related species also indicate that further cooling seems to have begun around ~2 Ma although there is no sea-ice distribution around Sites 884 and U1341 today. In addition, it is possible that the age differences (Sites 884 and U1341 at 2.1 Ma and Site U1343 at 1.9 Ma) in decrease of temperate-water species were related to changes of surface water circulation.

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Legends

Fig. 1. Map illustrating the sites drilled during Ocean Drilling Program (ODP) Leg 145 (Sites 881-884 and 887) and the Integrated Ocean Drilling Program (IODP) Expedition 323 (Sites U1339-U1345), with the surface water circulation modified after Stabeno et al. (1999). The black square and circles indicate the sites investigated in this study. The Alaskan Stream, East Kamchatka Current, Bering Slope Current (BSC), Aleutian North Slope Current (ANSC), Alaskan Coastal Current (ACC), Near Strait (N), Amchitka Pass (Amc), Amukta Pass (Amk), Unimak Pass (U), and Kamchatka Strait (K) are indicated. The lower panel shows the depth of the passes in the Aleutian Arc after Stabeno et al. (2005).

Fig. 2. Relative abundance (%) of diatom biostratigraphic markers from ODP Leg 145 Hole 884B. Diatom zones and NPD codes are after Yanagisawa and Akiba (1998). The abundances of the *Neodenticula* copulas refer to the relative copula numbers in counts of 100 diatom vegetative valves, excluding *Neodenticula* copulas.

Fig. 3. Age-depth plot for Hole 884B applied in this study based on diatom events and paleomagnetic events. Ages of diatom datums are calculated using the ATNTS 2004 geological timescale (Lourens et al., 2004a, b). NPD (Neogene North Pacific Diatom zone) codes are after Yanagisawa and Akiba (1998). Paleomagnetic datums are updated to Lourens et al. (2004a, b).

Fig. 4. Selected paleoenvironmental diatom indicators in total diatom assemblages from ODP Leg 145 Hole 884B and IODP Exp. 323 Holes U1341B and U1343E. Decreases in the temperate-water species abundances are observed at the three sites (Holes 884B, U1341B: 2.1 Ma, Hole U1343E: 1.9 Ma). From ~2 Ma, the occurrences of the sea-ice related species are observed not only at Hole U1343E but also at Sites 884 and U1341B.

Fig. 5. Photomicrographs of selected diatoms (biostratigraphic markers) from ODP Leg 145 Hole 884B. The jointed photomicrographs show the different focus for one specimen. Scale bar = 10 μ m. **1, 2.** *Neodenticula seminae* (Simonsen & Kanaya) Akiba & Yanagisawa, (1) Sample 145-884B-1H-3, 10-11 cm, (2) Sample 145-884B-2H-3, 10-11 cm. **3, 4.** *N. koizumii* Akiba & Yanagisawa, (3) Sample 145-884 B-16X-3, 10-11 cm. (4) Sample 145-884B-16X-1, 85-86. **5, 6.** *N. kamtschatica* (Zabelina) Akiba & Yanagisawa, (5) Sample 145- 884B-16X-3, 10-11 cm, (6) Sample 145-884B-18X-5, 10-11 cm. **7, 8.** closed copula of

601 *Neodenticula* (7) Sample 145-884B-1H-5, 10-11 cm. (8) Sample 145-884B-6H-6,
 602 85-86 cm. **9, 10.** open copula of *Neodenticula* (9) Sample 145-884B-16X-5,
 603 10-11 cm. (10) Sample 145-884B-22X-5, 10-11 cm. **11.** *Proboscia curvirostris*
 604 (Jousé) Jordan & Priddle, (11) Sample 145-884B-6H-5, 85-86 cm. **12.**
 605 *Thalassiosira jouseae* Akiba, (12) Sample 145-884B-18X-3, 10-11 cm. **13.**
 606 *Actinocyclus oculatus* Jousé, (13) Sample 145-884B-9H-3, 10-11 cm.

607 **Table 1.** Diatom datums determined in Hole 884B. FO: the first occurrence, LO: the last
 608 occurrence.

609 **Table 2.** Diatom taxa divided into five ecological groups: cold-water (C),
 610 temperate-water (T), sea-ice related (S), neritic (N), and open-ocean (O) species
 611 (after Teraishi et al., this issue).

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613 **Downloadable Appendix Table 1.** Taxonomic list of fossil diatoms from ODP Leg 145
 614 Hole 884B.

615 **Downloadable Appendix Table 2.** Stratigraphic occurrences of fossil diatom valves
 616 from ODP Leg 145 Hole 884B.

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Fig.1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Table 1. Diatom datums determined in Hole 884B. FO: the first occurrence, LO: the last occurrence.

Datums	this study			Barron and Gladenkov (1995)		
	Calculated Age (Ma)	Samples (top / bottom samples)	Depth (mbsf)	Defined / Proposed Age (Ma)	Samples (top / bottom samples)	Depth (mbsf)
LO <i>Proboscia curvirostris</i>	0.30±0.01 ^a	3H-1, 10-11 / 3H-1, 85-86	16.48±0.38	0.3	1H-CC / 2H-CC	11.25±4.75
LO <i>Thalassiosira jouseae</i>	0.38±0.03 ^a	3H-3, 10-11 / 3H-5, 10-11	20.11±1.50	0.3-0.4	1H-CC / 2H-CC	11.25±4.75
LO <i>Actinocyclus oculatus</i>	0.96±0.01 ^a	6H-6, 10-11 / 6H-6, 85-86	52.49±0.38	0.9-1.0	5H-CC / 6H-CC	49.25±4.75
FO <i>Proboscia curvirostris</i>	1.43±0.03 ^a	9H-1, 10-11 / 9H-3, 10-11	74.60±1.50	1.58	11H-CC / 12X-CC	90.30±3.00
LO <i>Neodenticula koizumii</i>	2.00±0.05 ^a	13X-4, 54-55 * / 14X-1, 10-11	100.73±2.38	2.0-2.2	13X-4, 54-55 / 14X-4, 47-48	103.67±5.32
LO <i>Neodenticula kamtschatica</i>	2.60±0.01 ^a	16X-1, 10-11 / 16X-1, 85-86	122.72±0.38	2.6-2.7	15X-CC / 16X-CC	127.00±4.80
FO <i>Neodenticula koizumii</i>	3.86±0.01 ^a	23X-5, 85-86 / 23X-6, 10-11	197.04±0.38	3.7-3.8	23X-5, 25-26 / 23X-CC	197.73±1.68

a: calculated in ATNTS 2004 geological timescale (Lourens et al., 2004 a, b), *: after Barron and Gladenkov (1995)

Table 2. Diatom taxa divided into five ecological groups: cold-water (C), temperate-water (T), sea-ice related (S), neritic (N), and open-ocean (O) species (after Teraishi et al., in this volume).

Ecological group		Taxa
proxy of sea surface temperature	Cold-water species (C) ^{a, b, c}	<i>Actinocyclus curvatulus</i> Janisch <i>Actinocyclus ochotensis</i> Jousé <i>Asteromphalus robustus</i> Castracane <i>Bacterosira fragilis</i> (Gran) Gran <i>Coscinodiscus marginatus</i> Ehrenberg <i>Fragilariopsis oceanica</i> (Cleve) Hasle <i>Neodenticula kamtschatica</i> (Zabelina) Akiba et Yanagisawa <i>Neodenticula koizumii</i> Akiba et Yanagisawa <i>Neodenticula seminae</i> (Simonsen et Kanaya) Akiba et <i>Porosira glacialis</i> (Grunow) E. Jørgensen <i>Rhizosolenia hebetata</i> J.W. Bailey <i>Shionodiscus trifultus</i> (G. Fryxell) Alverson et al. <i>Thalassiosira gravida</i> Cleve <i>Thalassiosira sancettae</i> Akiba
	Temperate-water species (T) ^d	<i>Stephanopyxis</i> spp. <i>Thalassiosira convexa</i> Muchina <i>Thalassiothrix</i> spp.
proxy of sea-ice margin	Sea-ice related species (S) ^{c, e, f}	<i>Bacterosira fragilis</i> (Gran) Gran <i>Fragilariopsis oceanica</i> (Cleve) Hasle <i>Thalassiosira antarctica</i> Comber <i>Thalassiosira gravida</i> Cleve
proxy of sea-surface water origin	Neritic species (N) ^a	<i>Ellerbeckia sol</i> (Ehrenberg) Crawford et Sims <i>Paralia</i> spp. <i>Porosira glacialis</i> (Grunow) E. Jørgensen
	Open-ocean species (O) ^a	<i>Actinocyclus ochotensis</i> Jousé <i>Rhizosolenia hebetata</i> J.W. Bailey <i>Shionodiscus trifultus</i> (G. Fryxell) Alverson et al.

a: Sancetta (1982), b: Yanagisawa and Amano (2003), c: Koizumi (2008), d: Hasle and Syvertsen (1996), e: Barron et al. (2009), f: Expedition 323 Scientists (2011)

Appendix table 1. Taxonomic list of diatoms from the ODP Leg 145 Hole 884B.

Species	References
<i>Actinocyclus curvatulus</i> Janisch in Schmidt et al.	Sancetta (1982), pp. 222-224, pl. 1, figs. 1-3
<i>A. ellipticus</i> Grunow in Van Heurck	Akiba (1986), pl. 16, fig. 5
<i>A. ingens</i> Rattray	Akiba (1986), pl. 16, figs. 6, 9
<i>A. ochotensis</i> Jousé	Sancetta (1982), pp. 224-225, pl. 1, figs. 4-6
<i>A. octonarius</i> Ehrenberg	Kanaya (1959), pp. 95-96, pl. 7, fig. 1 Akiba (1986), pl. 29, fig. 3
<i>A. oculatus</i> Jousé	Akiba and Yanagisawa (1986), p. 494, pl. 46, figs. 15, 16
<i>Actinoptychus senarius</i> (Ehrenberg) Ehrenberg	Sancetta (1982), p. 225, pl. 1, fig. 7 Akiba (1986), pl. 29, fig. 2
<i>Asteromphalus brookei</i> J.W. Bailey	Sancetta (1982), p. 226, pl. 1, fig. 9
<i>A. robustus</i> Castracane	Sancetta (1982), p. 226, pl. 1, fig. 10
<i>Azpeitia endoi</i> (Kanaya) P.A. Sims et G. Fryxell in Fryxell et al.	Kanaya (1959), pp. 76-77, pl. 3, figs. 8-11 Akiba (1986), pl. 2, fig. 2
<i>A. nodulifera</i> (Schmidt) G. Fryxell et P.A. Sims	Akiba (1986), pl. 3, fig. 6
<i>A. tabularis</i> (Grunow) G. Fryxell et P.A. Sims in Fryxell et al.	Gladenkov and Barron (1995), pl. 3, figs. 9, 11
<i>A. vetustissima</i> (Pantocsek) P.A. Sims in Fryxell et al.	Sims et al. (1989), p. 303, pl. 2, figs. 11-13, pl. 3, fig. 10
<i>Bacterosira fragilis</i> (Gran) Gran	Akiba (1986), pl. 4, figs. 1-4
<i>Cavitatus jouseanus</i> (Sheshukova-Poretzkaya) Williams	Akiba (1986), pl. 21, fig. 9
<i>Cocconeis antiqua</i> Tempère & Brun in Brun et Tempère	Akiba (1986), pl. 30, fig. 6
<i>C. costata</i> Gregory	Akiba (1986), pl. 30, fig. 1
<i>C. formosa</i> Brun	Kanaya (1959), pp. 109-110, pl. 10, figs. 4, 5
<i>C. scutellum</i> Ehrenberg	Akiba (1986), pl. 30, figs. 2, 3, 11
<i>Coscinodiscus marginatus</i> Ehrenberg	Baldauf and Barron (1982), p. 69, pl. 5, figs. 2, 3 Akiba (1986), pl. 1, figs. 1-4
<i>C. obscurus</i> Schmidt in Schmidt et al.	Baldauf and Barron (1982), p. 69, pl. 3, fig. 1
<i>C. oculus-iridis</i> Ehrenberg	Baldauf and Barron (1982), p. 69, pl. 5, fig. 1
<i>C. volutus</i> Baldauf	Baldauf and Barron (1982), pp. 66-67, pl. 2, figs. 1-4, pl. 3, fig. 2
<i>Cymbella cistula</i> (Ehrenberg) Kirchner	Ando (1990), fig. 30
<i>C. minuta</i> W. Gregory	Kosugi (1988), pl. 5, fig. 4
<i>Delphineis sachalinensis</i> (Sheshukova-Poretzky) Barron et Baldauf	Akiba (1986), pl. 20, fig. 18
<i>Diploneis smithii</i> (Brébisson in W. Smith) Cleve	Akiba (1986), pl. 30, fig. 8
<i>Ellerbeckia sol</i> (Ehrenberg) Crawford et Sims	Kanaya (1959), pp. 63-64, pl. 1, fig. 3
<i>Fragilariopsis oceanica</i> (Cleve) Hasle	Akiba (1986), pl. 24, figs. 19-21
<i>Kisseleviella carina</i> Sheshukova-Poretzkaya	Akiba (1986), pl. 19, figs. 17, 18
<i>Navicula salinarum</i> Grunow	Ando (1990), figs. 24, 25
<i>Neodenticula kamtschatica</i> (Zabelina) Akiba et Yanagisawa	Akiba (1986), pl. 25, figs. 7-27
<i>N. koizumii</i> Akiba et Yanagisawa	Yanagisawa and Akiba (1990), pp. 262-263, pl. 7, figs. 38-41
<i>N. seminae</i> (Simonsen et Kanaya) Akiba et Yanagisawa	Akiba (1986), pl. 25, figs. 28-32
<i>Odontella aurita</i> (Lyngbye) Agardh	Sancetta (1982), pp. 224-225, pl. 3, figs. 11, 12
<i>Porosira glacialis</i> (Grunow) E. Jørgensen	Schrader and Fenner (1976), p. 993, pl. 16, figs. 1-4, 13, pl. 17, fig. 1 Sancetta (1982), pp. 235-236, pl. 3, figs. 16-18
<i>Proboscira barboi</i> (Brun) Jordan et Priddle	Akiba (1986), pl. 18, fig. 2
<i>P. curvirostris</i> (Jousé) Jordan et Priddle	Akiba (1986), pl. 18, fig. 3
<i>Pyxidicula marginata</i> (Grunow) Strelnikova et Nikolaev	Schrader and Fenner (1976), p. 1000, pl. 20, fig. 3
<i>P. zabelinae</i> (Jousé) Makarova et Moiseeva	Akiba (1986), pl. 8, figs. 6, 7, 9, 10
<i>Rhizosolenia hebetata</i> f. <i>hiemalis</i> Gran	Akiba (1986), pl. 18, figs. 9, 10
<i>R. hebetata</i> f. <i>semispina</i> (Hensen) Gran	Akiba (1986), pl. 18, fig. 8
<i>R. styliformis</i> Brightwell	Akiba (1986), pl. 18, fig. 4
<i>Rocella vigilans</i> Fenner	Gladenkov and Barron (1995), pl. 1, figs. 1, 2
<i>Shionodiscus oestrupii</i> (Ostenfeld) A.J. Alverson et al.	Akiba (1986), pl. 4, figs. 1-6
<i>S. trifultus</i> (G. Fryxell) A.J. Alverson et al.	Sancetta (1982), pp. 244-245, pl.5 ,figs. 10-12, pl. 6, figs. 1, 2 Akiba (1986), pl. 10, figs. 5, 6
<i>Stephanopyxis horridus</i> Koizumi	Yanagisawa (2010), pl. 2, fig. 25
<i>S. hyalomarginata</i> Hajós	Schrader and Fenner (1976), p. 1000, pl. 19, figs. 6, 9
<i>S. turris</i> (Greville et Arnott) Ralfs in Pritchard	Sancetta (1982), pp. 238-239, pl. 4, figs. 9, 10
<i>T. nitzschoides</i> (Grunow) Mereschkowsky	Sancetta (1982), pp. 239-240, pl. 4, figs. 11-13 Akiba (1986), pl. 21, figs. 11, 12, 19
<i>Thalassiosira antarctica</i> Comber	Sancetta (1982), pp. 240-241, pl. 4, figs. 14, 15
<i>T. antiqua</i> (Grunow) Cleve-Euler	Akiba (1986), pl. 12, figs. 1, 3, 4
<i>T. convexa</i> Muchina	Akiba (1986), pl. 8, fig. 1
<i>T. decipiens</i> (Grunow in Van Heurck) E. Jørgensen	Akiba (1986), pl. 15, figs. 5, 6 Schrader and Fenner (1976), p. 1001, pl. 17, fig. 9
<i>T. eccentrica</i> (Ehrenberg) Cleve emend. Fryxell et Hasle	Akiba (1986), pl. 14, figs. 10, 11, 13, pl. 15, fig. 2
<i>T. gravida</i> Cleve	Schrader and Fenner (1976), p. 1001, pl. 16, figs. 5, 6, pl. 17, fig. 2 Akiba (1986), pl. 10, figs. 1-4
<i>T. jacksonii</i> Koizumi et Barron in Koizumi	Akiba (1986), pl. 11, figs. 1, 2, 5
<i>T. jouseae</i> Akiba	Akiba (1986), pl. 6, figs. 8-10
<i>T. leptopus</i> (Grunow in Van Heurck) Halse et Fryxell	Akiba (1986), pl. 14, fig. 12
<i>T. marujamica</i> Sheshukova-Poretzkaya	Akiba (1986), pl. 13, figs. 1-7, pl. 15, figs. 3, 4
<i>T. nidulus</i> (Tempère et Brunn in Brun et Tempère) Jousé	Schrader and Fenner (1976), p. 1002, pl. 17, fig. 13, 16 Akiba (1986), pl. 6, figs. 4-7
<i>T. punctata</i> Jousé	Akiba (1986), pl. 9, figs. 5, 6
<i>T. sancettae</i> Akiba	Akiba (1986), pl. 7, figs. 1-3
<i>Thalassiothrix longissima</i> Cleve et Grunow in Grunow	Akiba (1986), pl. 21, fig. 18