九州大学学術情報リポジトリ
Kyushu University Institutional Repository

Diatom paleoceanography during the last 340 kyr in the Bering Sea and the western subarctic Pacific

Katsuki, Kota
Department of Earth and Planetary Sciences, Graduate School of Sciences, Kyushu University

Takahashi, Kozo
Department of Earth and Planetary Sciences, Graduate School of Sciences, Kyushu University

Matsushita, Kiyoka
Department of Earth and Planetary Sciences, Graduate School of Sciences, Kyushu University

https://hdl.handle.net/2324/12451

出版情報：Proceedings of the International Diatom Symposium. 17, pp.147-159, 2004. Biopress
バージョン：
権利関係：

SEVENTEENTH INTERNATIONAL DIATOM SYMPOSIUM 2002
Ottawa, Canada (M. Poulin, ed.), pp. 147–159
© Biopress Limited, Bristol, 2004

Diatom paleoceanography during the past 340 kyr in the Bering Sea and the western subarctic Pacific

K. Katsuki, K. Takahashi & K. Matsushita

Department of Earth and Planetary Science, Graduate School of Science, Kyushu University, 6–10–1 Hakozaki, Higashi-ku, Fukuoka, 812–8581, Japan [1]

Abstract

Based on quantitative analyses of fossil diatom assemblages in four Piston Cores, the paleoceanographic changes during the last 340 kyr in the southern Bering Sea and western subarctic Pacific have been reconstructed. The total diatom accumulation rate (DAR) in each core is influenced by cold low-salinity surface waters. The cold low-salinity surface waters covered all over the southeast Bering Sea throughout the past 100 kyr, whereas such water masses expanded in the southwest Bering Sea and western subarctic Pacific during the glacial periods. Moreover, based on the changes in major diatoms, a model that predicts a flow through the Aleutian Island is proposed. The flow of the Alaskan Stream waters heads northward through the Aleutian Islands at present. As the climate became colder in the glacials, the shallow eastern and central passes were possibly eliminated or restricted due to sea level drop. Therefore, the southeast Bering Sea was isolated from the North Pacific and the southwest Bering Sea was influenced by the Alaskan Stream during the glacial periods.

Introduction

The Bering Sea (Fig. 1) is one of the most biologically productive areas of the hemipelagic realm in the world (e.g. Berger *et al.* 1987). Furthermore, the Bering Sea plays a significant role in the global material balance as heat, salt and various chemical properties are transported with water circulation. This is because of its pivotal location between the Pacific and the Arctic oceans (Takahashi 1999). Today, Pacific water is transported into the Arctic Ocean through the Bering Sea and eventually exits into the Atlantic Ocean through the Fram Strait. This one-way flow of water from the Pacific to the Atlantic through the Bering Sea and the Arctic Ocean accounts for contrasting chemistry of deep and bottom waters between the Pacific and the Atlantic. According to Honjo (1990), this process of water mass movement is partially responsible for the Pacific to be a silica ocean and the Atlantic to act as a carbonate ocean. Moreover, water masses of the Bering Sea mix with that of the North Pacific. Much of the Pacific water masses entering the Bering Sea leave through passes in the Aleutian Islands (Fig. 1). The Alaskan Stream, which is an extension of the Alaskan Current flowing westward along the Aleutian Islands in the subarctic Pacific, mostly enters the Bering Sea (Favorite *et al.* 1976). A part of the Subarctic Current also joins the northward flow coming from the Alaskan Stream (Stabeno & Reed 1994; Stabeno *et al.* 2002). In contrast, the Bering water

[1] e-mail: katuki@geo.kyushu-u.ac.jp

mass also flows out to the Pacific region. For example, the Bering Sea is a source region for western subarctic Pacific water, which plays a major role in the circulation of the western subarctic Pacific (Ohtani *et al.* 1972). In brief, the Bering Sea is an important area as to the movement of water masses. Hence intensive studies have been conducted on this area in recent years from various perspectives. The paleoceanography of the Bering Sea and the subarctic Pacific has been advanced on the basis of these studies (e.g. Keigwin 1995, 1998; Sancetta 1983).

Diatoms are the most abundant microfossils found in the sediments of the Bering Sea and the western subarctic Pacific (Sancetta 1982). The remains of these important primary producers can be used as proxies for the environmental conditions prevailing in the upper water column of the ocean. Kanaya & Koizumi (1966) defined diatom assemblages that are characteristic of major water masses in the North Pacific. In addition, Sancetta (1982) who discussed taxonomic and morphological problems related to some diatom taxa, also pointed out the significance of studing the distribution of certain species in respect to oceanographical or ecological conditions in the Bering Sea.

Although a considerable number of studies in these regions have been performed, few are known about the past water circulation. Especially, there are few reports on the diatom accumulation rate. In this paper, we discuss past water circulation and oceanographic condition on the basis of the study of quantitative accumulation changes of major diatom species in the southern Bering Sea and the western subarctic Pacific during the last 340,000 years.

Materials and Methods

Core samples

Four piston cores were raised in the southern Bering Sea and western subarctic Pacific during the R/V Hakuho-maru Cruise KH99-3, August 1999 (Fig. 1). Two of these cores were collected from the Bowers Ridge in the southern Bering Sea (BOW-8A: 54° 46' 99"N, 76° 54' 99"E, water depth: 884 m; BOW-12A: 53° 23' 47"N, 179° 33' 47"W, water depth: 2391 m) (Table 1). Another core was drilled at the Umnak Plateau in the southeastern Bering Sea (UMK-3A: 54° 25' 22"N, 170° 13' 38"E, water depth: 1892 m). The last core was taken from Emperor Seamount in the western subarctic Pacific (ES: 49° 44' 07"N, 168° 18' 93"E, water depth: 2388 m). The recovered sediment cores consisted mainly of a dark green-grey or olive-grey diatom silt, together with several volcanic ash layers and calcareous oozes. Furthermore, Core BOW-12A has slumping beds in the upper section, and Core UMK-3A has a lamina structure (Fig. 1). Slumping is afflux of sedimentary layer from other place(s).

An age model for Cores ES and BOW-12A were determined on the basis of planktonic foraminiferal $\delta^{18}O$ and comparison of magnetic susceptibilities between ES and neighboring ODP Site 883, the ages of which have been precisely determined based on benthic foraminiferal $\delta^{18}O$ (Kiegwin 1995) and ^{14}C dating (Kiefer *et al.* 2001). Stable oxygen isotope ratios of Cores ES and BOW-8A were measured on samples of planktonic foraminifera *Neogloboquadrina pachyderma* sinistral coiling, at Shizuoka University and JAMSTEC (Japan Marine Science and Technology Center) Mutsu Laboratory (Katsuki *et al.* in press; Okada & Takahashi 2003). The age models for Cores BOW-12A and UMK-3A were made by comparison of magnetic susceptibilities between these cores and Core BOW-8A (Okada & Takahashi 2003).

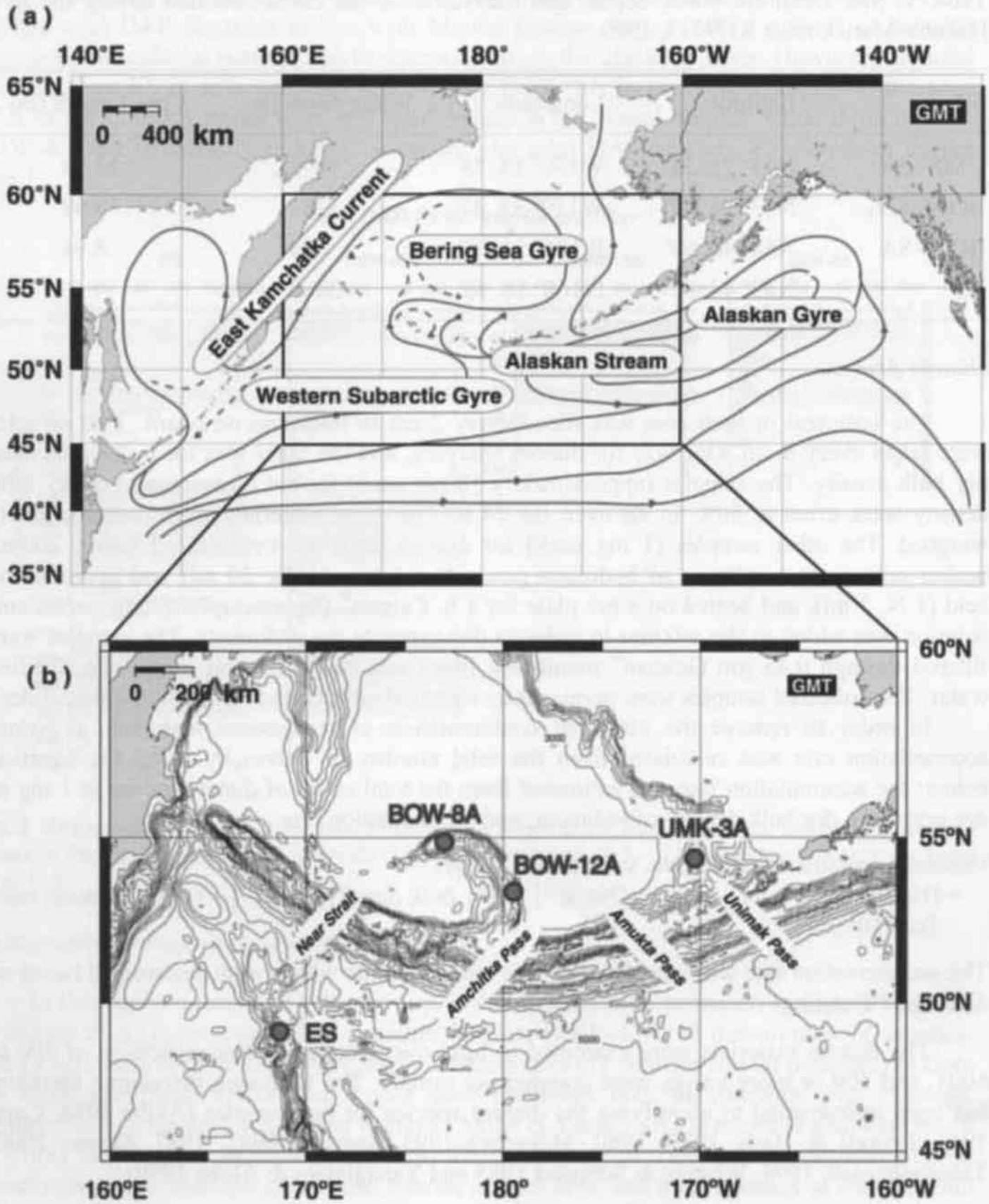

Fig. 1. (a) Map showing the modern surface circulation system in the North Pacific Ocean (Modified from Dodimead *et al.* 1963). (b) Sampled locations of Piston Cores UMK–3A, BOW–12A, BOW–8A, and ES which were collected during R/V Hakuho-maru KH99–3 Cruise in 1999. The bathymetric contour intervals are every 200 m up to 1000 m and then they are every 1000 m below.

Table 1. Site locations, water depths and recoveries of the cores obtained during the R/V Hakuho-Maru Cruise KH99–3, 1999.

Site	Latitude	Longitude	Water depth (m)	Core Length (m)
UMK–3A	N54° 25. 22'	W170° 13. 38'	1892	13.35
BOW–12A	N53° 23. 47'	W179° 33. 47'	1287	8.99
BOW–8A	N54° 46. 99'	E 176° 54. 99'	884	8.94
ES	N49° 44. 07'	E 168° 18. 93'	2388	8.7

Diatom Analysis

The sediment in each core was sliced every 2 cm in thickness on board. Two samples were taken every 8 cm. One was for diatom analyses, and the other was for measurement of dry bulk density. The samples (approximately 10 mg each) for the measurement of dry bulk density were dried at 50°C in an oven for 24 h. The dried materials were then accurately weighed. The other samples (1 mg each) for diatom analyses were placed into a 200-ml beaker containing a mixture of hydrogen peroxide solution (10%, 20 ml) and hydrochloric acid (1 N, 3 ml), and heated on a hot plate for 1 h. Calgon® (hexametaphosphate, surfactant) solution was added to the mixture in order to disaggregate the sediments. The samples were filtered through 0.45 μm Gelman® membrane filters and rinsed several times with distilled water. The collected samples were permanently mounted with Canada Balsam on microslides.

In order to remove the effect of contamination of terrigenous materials, a diatom accumulation rate was calculated from the total number of valves by using the equation below: the accumulation rate was estimated from the total count of diatom valves in 1 mg of dry materials, dry bulk density of sediment, and sedimentation rate.

Diatom Accumulation Rate [No. valves cm^{-2} 10^3·yrs^{-1}]
= (No. valves g^{-1} dry sediment)[No. g^{-1}] × (dry bulk density)[g cm^{-3}] × (sedimentation rate) [cm 10^3 yrs^{-1}]

The sedimentation rate was calculated by age control points which were determined based on $\delta^{18}O$ and ^{14}C dating.

The diatom materials were examined in light microscopy of a magnification of 400 to 600×, and 500 or more valves were counted per sample. The following taxonomic literature has been instrumental to identifying the diatom species for our samples (Akiba 1986, Cupp 1943, Fryxell & Hasle 1979, 1980, Makarova 1993, Sancetta 1982, 1987, Shiono 2000, Takahashi *et al.* 1994, Whiting & Schrader 1985 and Yanagisawa & Akiba 1990).

Results

Total diatom accumulation rate

Diatom frustules are generally well preserved throughout these cores. The total diatom accumulation rate (DAR) amounts to 40.3 x 10^6 valves cm^{-2} kyr^{-1} on the average for Core UMK–3A, 7.4 x 10^6 valves cm^{-2} kyr^{-1} for Core BOW–12A, 1.5 x 10^6 valves cm^{-2} kyr^{-1} for Core BOW–8A and 36.8 x 10^6 valves cm^{-2} kyr^{-1} for Core ES (Fig. 2). In the core UMK–3A, total DAR shows the highest value between 15 kyr and 8 kyr. In Core BOW–12A, total DAR

tends to increase with the lapse of time except on slumping point. In the cores BOW–8A and ES, the total DAR fluctuate in line with Marine Isotope Stages (MIS): it tends to increase during the interglacial periods and to decrease during the glacial periods. However, the total DAR in Core ES is different from that in Core BOW–8A in two respects. Firstly, the total DAR in the Core ES shows relatively small values in the glacial periods, while those in Core BOW–8A are remarkably reduced. Secondly, the total DAR in Core ES decreases during MIS 1.

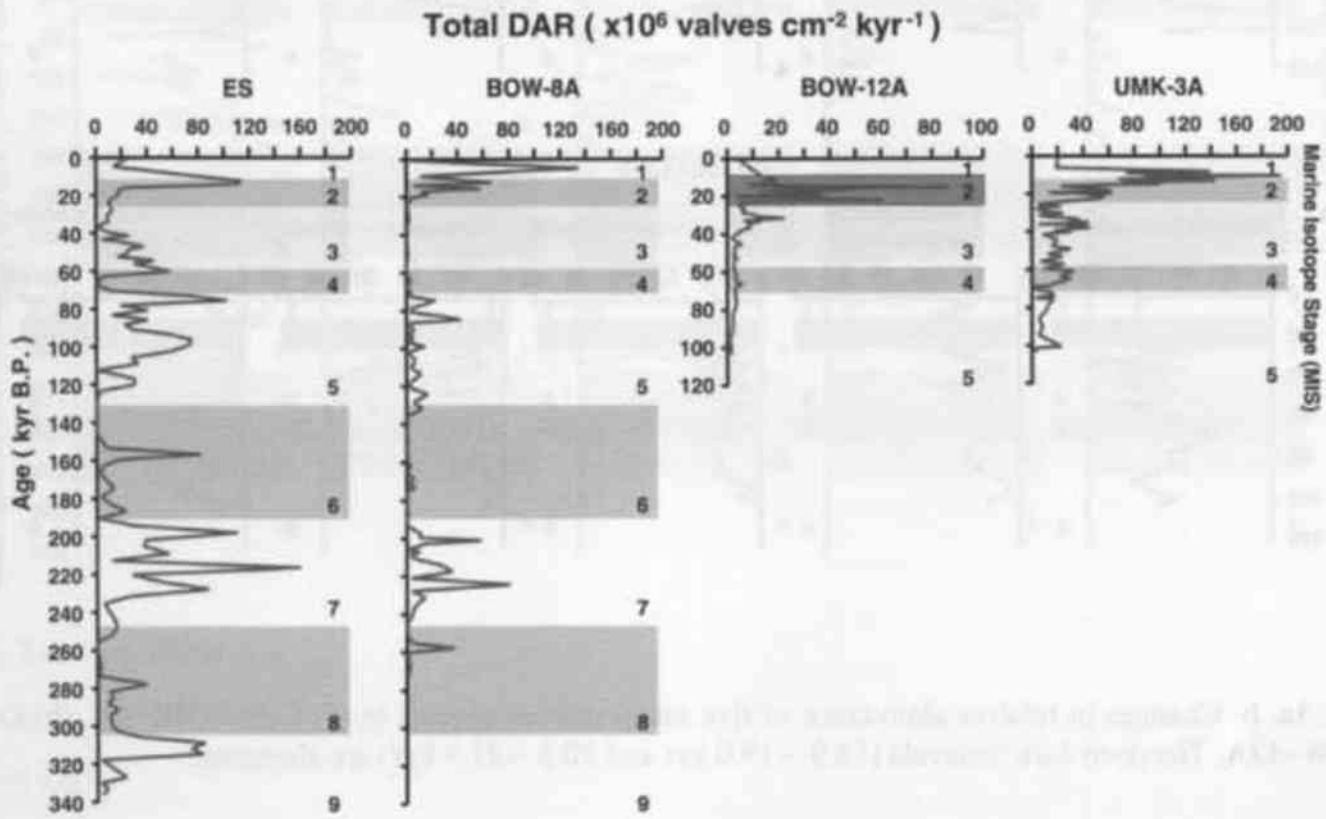

Fig. 2. Stratigraphic changes of the total DAR in four piston cores from the Bering Sea and the western subarctic Pacific. The deep dark intervals (13.9 ~ 19.0 kyr and 20.5 ~ 21.9 kyr) are slumping for Core Bow-12A.

Stratigraphic change of the diatom assemblages

In this study, a total of 52 diatom taxa (38 centrics and 14 pennates) in Core UMK–3A, 45 diatom taxa (31 centrics and 14 pennates) in Core BOW–12A, 43 diatom taxa (30 centrics, and 13 pennates) in Core BOW–8A, and 72 diatom taxa (52 centrics and 20 pennates) in Core ES were identified. These four cores have dominant taxa in common. For example, *Neodenticula seminae* (Simonsen et Kanaya) Akiba et Yanagisawa is the most abundant taxon in Cores BOW–12A, BOW–8A, and ES. The frequency of *Thalassiosira trifulta* Fryxell constitutes greater than 5% of the total species in each core, and the frequency of *Rhizosolenia hebetata* f. *hiemalis* (Baily) Gran and *Thalassiosira gravida* Cleve constitutes greater than 5% of the total species in three cores.

Core UMK–3A

In this core, the species dominance changes rapidly between MIS 1 and the other periods (Fig. 3 a). *Neodenticula seminae* dominated during MIS 1, whereas *Thalassiosira gravida* dominated during the other periods. The abundance of *Thalassiosira trifulta* increased during MIS 3, however, it did not make its appearance during MIS 2. *Odontella aurita* (Lyngbye) Agardh increased between 35 kyr and 15 kyr.

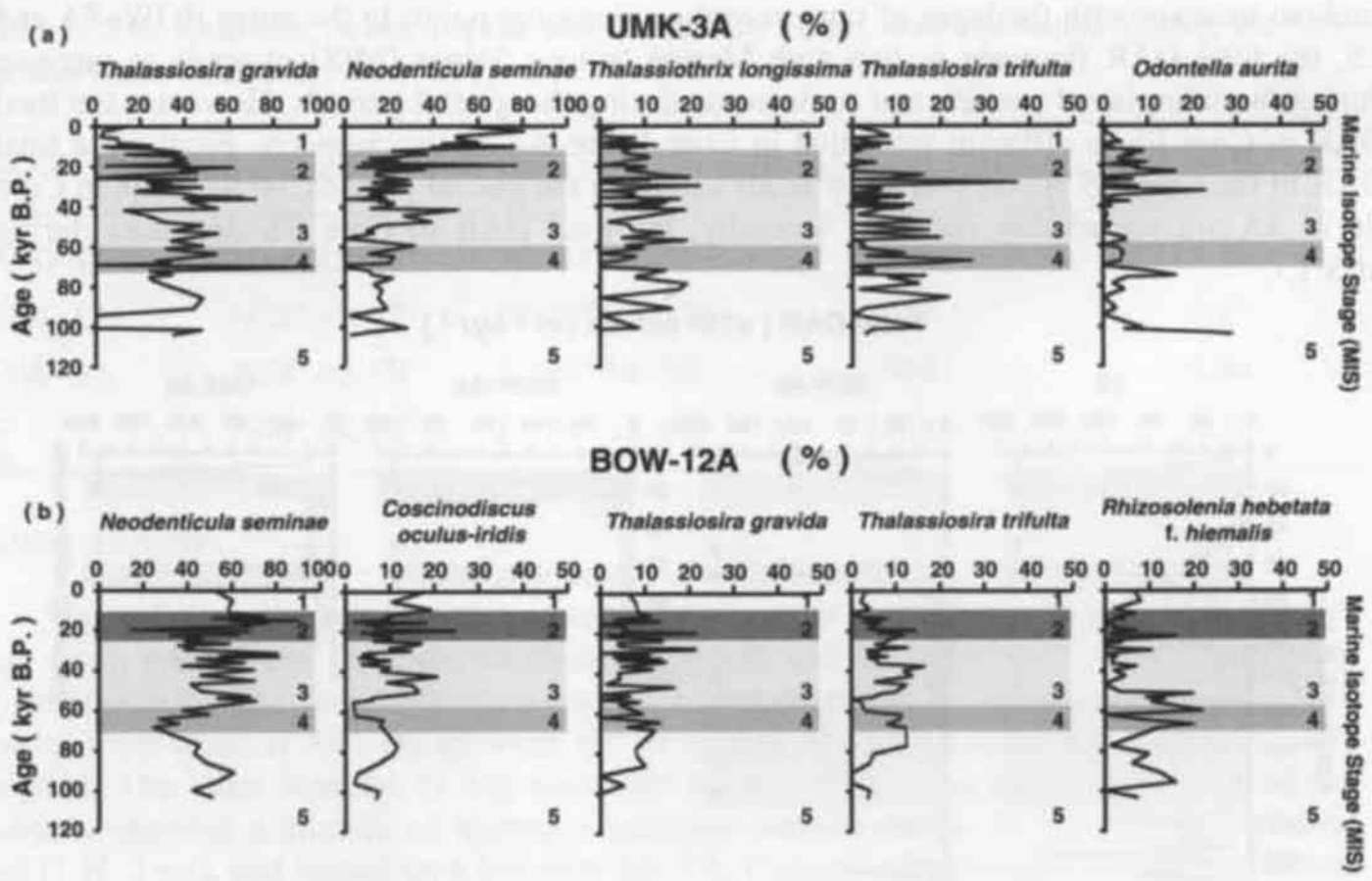

Fig. 3a, b. Changes in relative abundance of five major diatom species in (a) Core UMK–3A, (b) Core BOW–12A. The deep dark intervals (13.9 ~ 19.0 kyr and 20.5 ~ 21.9 kyr) are slumping.

Core BOW–12A

Neodenticula seminae dominated throughout this core (Fig. 3b), with a mean relative abundance of 50%, while *Thalassiosira gravida* is almost constantly represented with minor fluctuations throughout the core. The relative abundance of *Thalassiosira trifulta* shows constant fluctuations between 80 kyr and 60 kyr and between 55 kyr and 20 kyr, but its abundance is low during other periods. *Coscinodiscus oculus-iridis* Ehrenberg shows a similar fluctuation pattern as *Neodenticula seminae*, but with a lower mean relative abundance. *Rhizosolenia hebetata* f. *hiemalis* accounted for a significant proportion of the assemblage before 50 kyr and decreased thereafter.

Core BOW–8A

Neodenticula seminae dominated throughout this core, with a mean relative abundance of 70% (Fig. 3c). The abundance of this species became especially high at the peaks of the glacial and interglacial periods. On the other hand, other dominant species such as *Actinocyclus curvatulus* Janisch, *Rhizosolenia hebetata* f. *hiemalis* and *Thalassiosira trifulta* tended to increase during the relatively warm part of the glacial periods and the relatively cool part of the interglacial periods. The abundances of sea ice species (e.g. *Thalassiosira gravida*) were generally low.

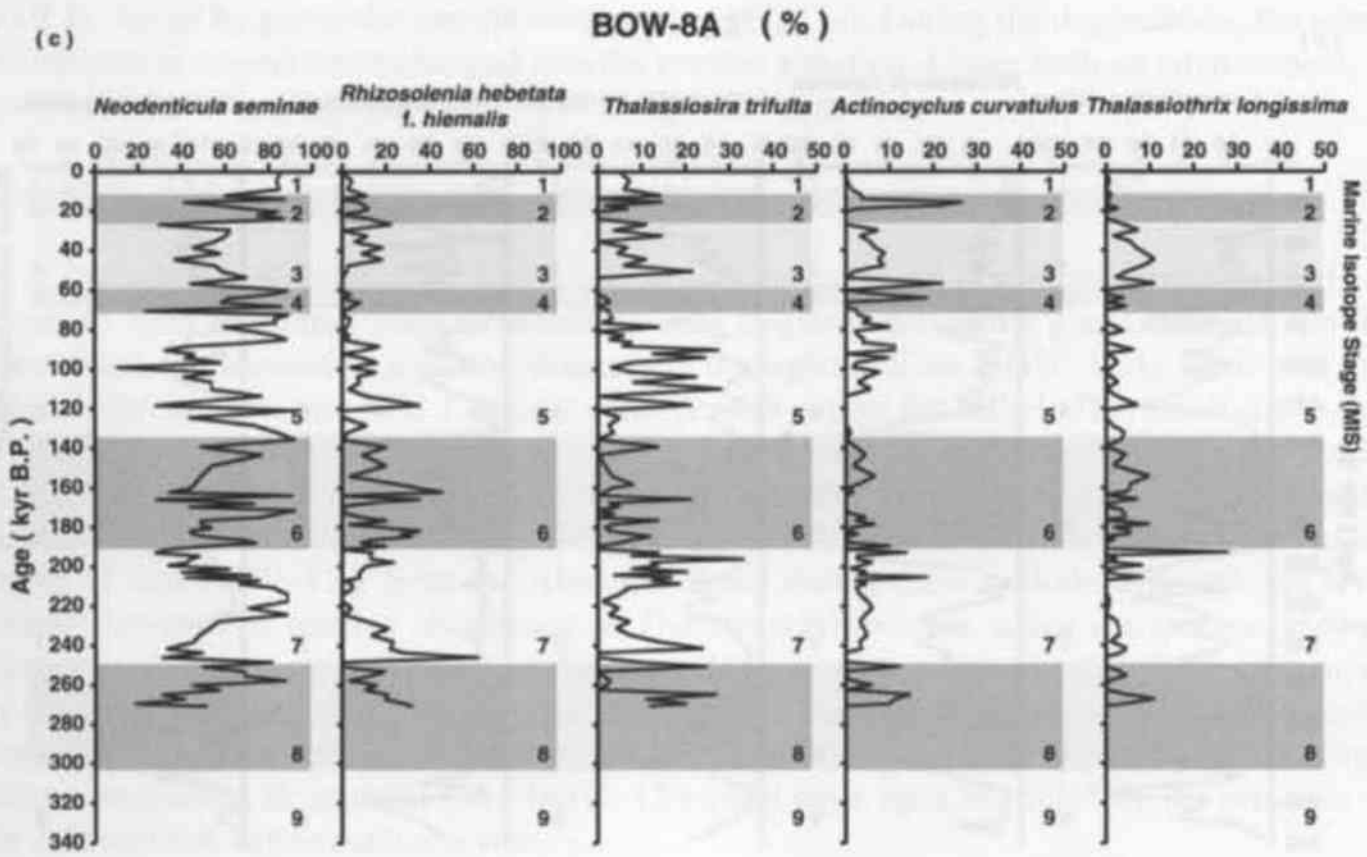

Fig. 3 c. Core BOW–8A.

Core ES

The major five species (*Neodenticula seminae*, *Rhizosolenia hebetata* f. *hiemalis*, *Actinocyculus curvatulus*, *Thalassiosira trifulta* and *Thalassiosira gravida*) accounted for 70% of the total species on the average throughout the core (Fig. 3d). In particular, the mean abundance of *N. seminae* amounted for 25% throughout the core. Species dominance in the diatom assemblages changed rapidly between the glacial and the interglacial periods. *Neodenticula seminae* dominated during the interglacial periods, whereas the other four species were in high abundance in the glacial periods. *Thalassiosira gravida* was in high abundance in MIS 2, 3 and 5 (Katsuki *et al.* in press).

Discussion

Chronological change of diatom assemblage in each core

Core UMK–3A

The diatom assemblages between 100 kyr and 10 kyr in Core UMK–3A were mostly represented by *Thalassiosira gravida*. Some workers have proposed that the abundance of *T. gravida* exhibits a positive correlation with sea ice concentration (Karpuz & Schrader 1990; Sancetta 1982; Shiga & Koizumi 2000). The relative abundance of *Neodenticula seminae* was low between 100 kyr and 10 kyr, but this taxon became dominant after 10 kyr, changing place with *T. gravida*. *Neodenticula seminae* is the highly abundant species in the subarctic Pacific and its marginal seas in the Quaternary, and it can be a good tracer of waters of the Alaskan Stream (Sancetta 1982; Sancetta & Silvestri 1984). The Alaskan Stream water flows into the

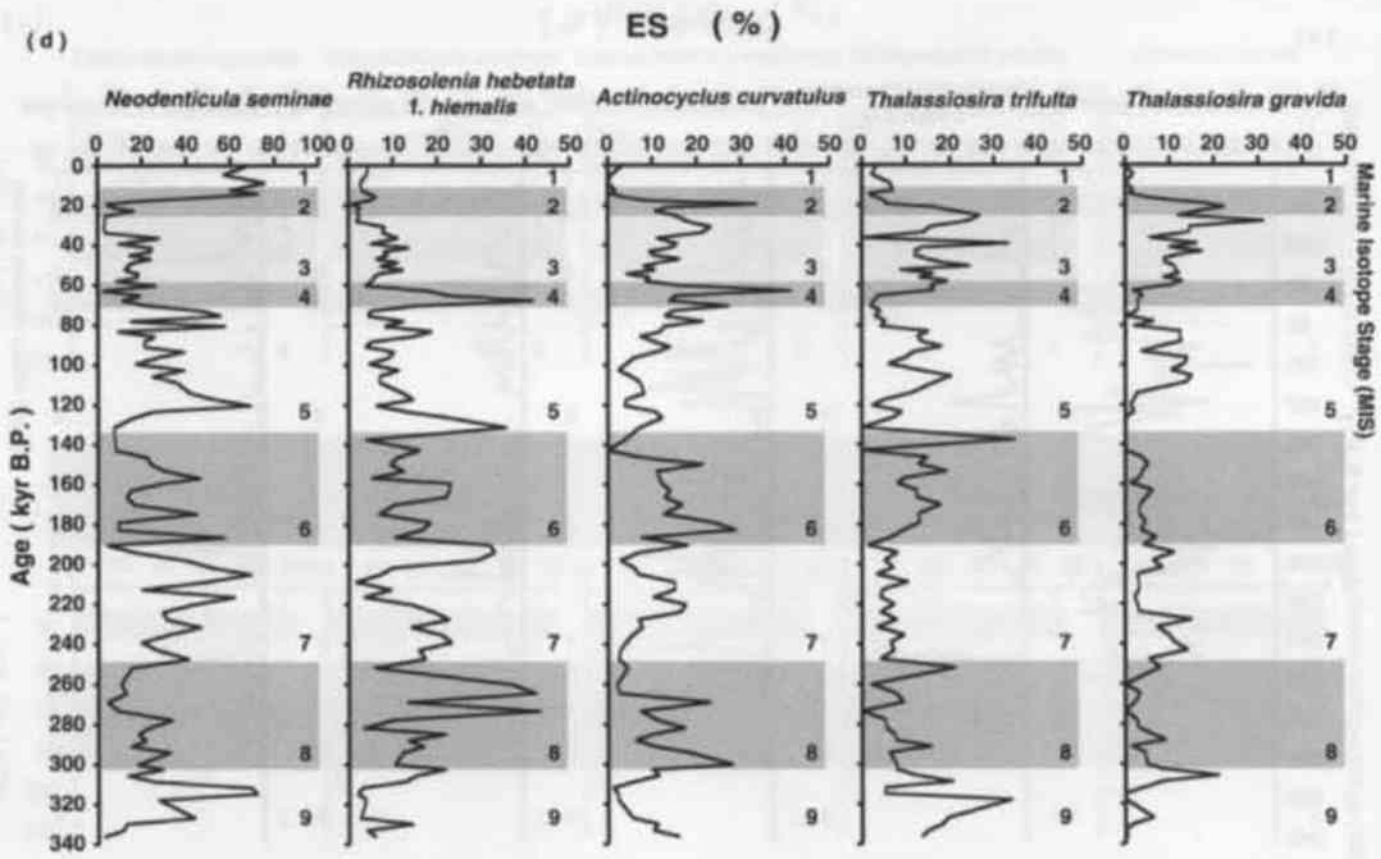

Fig. 3 d. Core ES.

southeastern Bering Sea through Unimak Pass at present (Stabeno *et al.* 2002). It is likely that decrease of the relative abundance of *N. seminae* indicates the diminution of water masses from the North Pacific through Unimak Pass. Thus, this area was semi-closed and strongly influenced by sea ice before 10 kyr. The semi-closure and the diminution of water masses were caused by a decrease of the sea level. According to Chappell (1996), the sea level has been lower by 50–120 m than present between 100 kyr and 20 kyr. The Unimak Pass is relatively shallow and narrow; its maximum depth is 160 m. Therefore, we can safely say that the inflow of water masses from the North Pacific has been restricted between 100 kyr and 20 kyr (Fig. 4) which is consistent with the proposal by Sancetta & Robinson (1982).

The relative abundance of *Thalassiosira trifulta* was absent or negligible during MIS 2, whereas the percentages became nearly 10% or greater during other periods. *Thalassiosira trifulta* is common in the area characterized by winter ice cover and a summer vertical stratification similar to the modern central Okhotsk Sea (Sancetta 1983). The low occurrence of *T. trifulta* during MIS 2 would represent the existence of sea ice in the early summer or spring in this region.

MIS 1 is different from other MISs in terms of composition of diatom assemblages. This is attributable to a difference caused by sudden temperature and sea level rises between MIS 1 and 2. These changes will bring a reduction in sea ice effect and, concurrently, an increase of the inflow of the North Pacific waters.

Total DAR has increased rapidly between 18 kyr and 8 kyr. This period falls within the deglaciation. This result is consistent with the proposal by Nakatsuka *et al.* (1995) that the retreat of the sea ice front closer to the continental shelf areas and the prevailing summer conditions of the surface water might have stimulated phytoplankton production in the surface waters during the deglaciation. This high production can be attributed to high nutrient utilization rate during that period. *Thalassiosira gravida* is a sea ice species and *N. seminae* is a oceanic species. It might be, however, inferred from the composition of diatom assemblages, the high relative abundance of *N. seminae* and *T. gravida* that a significant factor of high total

DAR is caused by particular marine environment (Fig. 3a). During the deglaciation, the semi-closed marine environment changed into the present situation. Under such an environment, *T. gravida* and *N. seminae* were able to live in the same area.

Core BOW–12A

The relative abundance of *Thalassiosira trifulta* increased during the glacial periods. It means to form a summer vertical stratification in this area during the glacial periods. On the other hand, *Neodenticula seminae* dominated throughout Core BOW–12A; there was not much difference between MIS 1 and the other periods except for MIS 4. This result shows that inflow to this area from the Alaskan Stream have little changed or increased during the glacial periods, as compared to the extent of the current inflow (Fig. 4a, b). This is because the diminution of water masses flowing through Unimak Pass should increase water masses to the region of Site BOW–12A from the Alaskan Stream during these periods, although sea level became lower. The relative abundance of *Thalassiosira gravida*, a sea ice species, showed relatively constant values throughout this core. It suggests that this area has been influenced by sea ice at a similar extent throughout. Melt water from the sea ice might contribute to cold, low-salinity surface water. The melt water prevents vertical mixing (Sancetta 1983). Thus, diatom production throughout Core BOW–12A must have been restricted by the presence of the cold and low-saline surface waters.

Core BOW–8A

The sea ice species, *Thalassiosira gravida*, and *Nitzschia* species have not been ubiquitous throughout Core BOW–8A. Therefore, Site BOW–8A has not been immediately influenced by the sea ice. However, total DAR changed with the MIS intervals; it tended to decrease during the glacial periods. Namely, it has been affected by cold and low-saline surface waters coming from sea ice during the glacial periods. The relative abundance of *Neodenticula seminae* decreased and *Thalassiosira trifulta* increased during the relatively warm part of glacial periods and the relatively cool part of interglacial periods. This result indicates that the component of the diatom assemblage is affected by low-salinity water at Site BOW–8A during these periods. In this regard, we agree with Sancetta *et al.* (1985) who reported that a large amount of melt water was discharged from alpine glaciers into southern Aleutian Basin during the deglaciation. It is noteworthy that the total DAR has been still low during the glacial peaks. Accordingly, it is not reasonable to suppose that the low-salinity melt water has retreated far off Core BOW–8A during glacial peaks. Thus, it appears that the resemblance of the component of diatom assemblage between glacial peaks and the present time is caused by the massive inflow to Site BOW–8A from Alaskan Stream through Near Strait during glacial peaks (Fig. 4c). As discussed above, diminution of water masses through Amuchitka Pass is considered to provoke the increase of water masses through Near Strait. Another possibility is that a terminal branch of the Alaskan Stream, which does not enter the Bering Sea at present, entered the Bering Sea during the glacial peaks. However, the evidence supporting this hypothesis is exiguous now.

Core ES

Total DAR shows generally higher values during the interglacial periods than in the glacial ones. This temporal trend roughly accords with the change in the concentration of biogenic opal (Narita *et al.* 2002). It strongly suggests that primary productivity increased during the interglacial periods. Several investigators have reported that the DAR and/or the

concentration of biogenic opal also tended to increase during the interglacial periods in other areas of the northern North Pacific and the marginal sea regions (Gorbarenko *et al.* 2002, Narita *et al.* 2002, Shimada & Hasegawa 2001). Accordingly, these changes should be attributed to a common origin. On the other hand, primary productivity is restricted by a depletion of major nutrients in the euphotic zone because the northwest Pacific produces low-salinity surface water which spreads over the northwestern Pacific during the glacial periods and contained only low concentrations of nutrients (Gorbarenko 1996, Keigwin 1998, Keigwin *et al.* 1992). Our present observation on diatom assemblage change supports these proposals (for a more thorough discussion of mechanism, see Katsuki *et al.* in press).

In the light of the relative abundance of *Neodenticula seminae* which tended to oscillate with the MIS intervals, the influence of the Alaskan Stream appeared at Site ES during the interglacial periods, whereas it was small during the glacial periods. Instead of the Alaskan Stream, the East Kamchatka Current is considered to give a major influence near the site of Core ES during the glacial periods. Closure of the Bering Strait forming the landmass of Beringia (Hopkins 1973) stops the transport of the Bering water mass into the Arctic Ocean. Moreover, winter wind stress in the northwest Pacific from the northwest Siberia during the glacial periods must have been at least as strong as that of the present and probably stronger (Gate 1976). It is inferred from these papers that the East Kamchatka Current became stronger during the glacial periods than the present (Fig. 4c). Site ES was affected by sea ice during the glacial periods, especially during MIS 2 and 3. The sea ice might have been transported by the East Kamchatka Current.

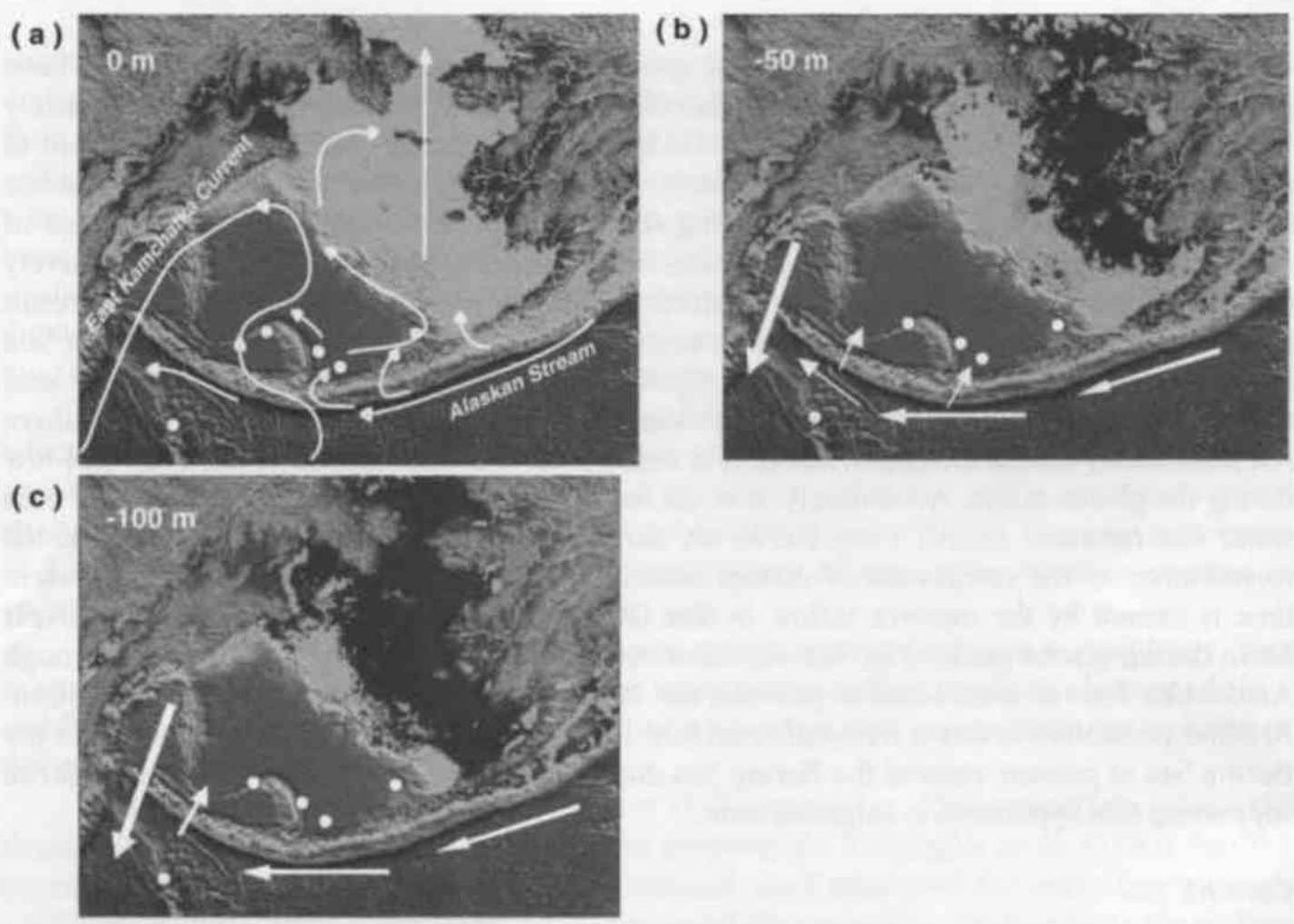

Fig. 4. Maps showing the modern and past surface circulation systems in the Bering Sea and the subarctic Pacific. (a) today (b) the past when the sea level dropped 50 m below the modern level; and (c) the past when the sea level dropped 100 m. The topographical map used as the background was taken from GEOMER HOME PAGE.

Paleoceanography of the Bering Sea and the western subarctic Pacific

The difference in the total DAR among these cores may be reflected in the extent of the low-salinity surface water. The change in total DAR in the Cores BOW–8A and ES tended to fluctuate with the MIS intervals, whereas the total DAR in Cores UMK–3A and BOW–12A did not exhibit such a trend (Fig.2). An explanation for this difference is that the low-salinity surface water has existed in the southeastern Bering Sea at Sites UMK–3A and BOW–12A during the interglacial periods, while it has hardly influenced the southwestern Bering Sea and western subarctic Pacific at Sites BOW–8A and ES. Moreover, the total DAR values of Core BOW–8A are different from that of Core ES: the total DAR values in Core BOW–8A are very low during the glacial periods, while those of Core ES are moderate. The cause of this difference is probably due to the difference in areal extent of the low-salinity surface water masses. In summary, the southeast Bering Sea has been influenced by low-salinity surface water almost always, while the Bowers Ridge area has been influenced only during the glacial periods and the western subarctic Pacific has been influenced during some parts of the glacial periods. However, we should not overlook the fact that the total DAR of Core UMK–3A is relatively high throughout and the total DAR of Core ES decreased in the Holocene. The cause of the former seems to be an effect of some factors originating from the coastal regions. Most of the Bering continental shelf was exposed during glacial periods. As the consequence, Core UMK–3A became closer to the landmass. However, we do not have an reasonable explanation for the latter at present.

The change in the relative abundance of *Neodenticula seminae* in each core represents the influence of the Alaskan Stream. The flow of the Alaskan Stream waters heads northward through Aleutian Islands at present (Favorite *et al.* 1976, Stabeno *et al.* 2002) (Fig. 4a). As the climate became colder, the shallow eastern and central passes were probably eliminated or restricted due to lowered sea level (Sancetta 1983). Consequently, the more water masses of the Alaskan Stream would enter into the Southwestern Bering Sea through the western passes like Near Strait as climate became colder (Fig. 4b, c). This hypothesis is consistent with the result that the abundances of sea ice species (e.g. *Thalassiosira gravida*) were generally low in Core BOW–8A. Sea ice did not reach this area due to the presence of the Alaskan Stream flowing northward.

Acknowledgements

The authors would like to thank Dr M. Okada (Ibaraki University) for kindly allowing use of his age models of the pistons cores, and Dr R. W. Jordan (Yamagata University) for his instruction on the taxonomy of diatoms. We also thank Dr H. Asahi (Kochi University), Y. Okazaki and all other graduate students in this laboratory for technical assistance. Shipboard scientists and crew who took part in Cruise KH99-3 of the University of Tokyo R/V Hakuho-Maru are acknowledged for contribution to core sampling. This study was supported by the following research programs: Ministry of Education, Culture, Sports, Science and Technology Grants-in-Aid-for Scientific Research B2 Project No. 10480128 to K. Takahashi and B1 Project No. 13440152 to R. W. Jordan and K. Takahashi, and Tatsuro Matsumoto Scholarship Funds.

References

AKIBA, F. (1986). Middle Miocene to Quaternary diatom biostratigraphy in the Nankai Trough and Japan Trench, and modified lower Miocene through Quaternary diatom zones for middle-to-high latitudes of the North Pacific. *Initial Reports of the Deep Sea Drilling Project*, **87**, 393–481.

BERGER, W. H., FISCHER, K., LAI, C. & WU, G. (1987). Ocean productivity and organic carbon flux. Part I: Overview and maps of primary production and export production. *Scripps Institution of Oceanography* SIO Ref. **67**, 87–30.

CHAPPELL, J., OMURA, A., ESAT, T., MCCULLOCH, M., PANDOLFI, J., OTA Y. & PILLANS, B. (1996). Reconciliation of late Quaternary sea levels derived from coral terraces Huon Peninsula with deep sea oxygen isotope records. *Earth and Planetary Science Letters*, **141**, 227–236.

CUPP, E. E. (1943). Marine plankton diatoms of west coast of North America. *Bulletin of the Scripps Institution of Oceanography of the University of California*, **5**, 1–238.

FAVORITE, F., DODIMEAD, A. J. & NASU, K. (1976). Oceanography of the subarctic Pacific region, 1960–1971. *International North Pacific Fisheries Commission*, **33**, 1–187.

FRYXELL, G. A. & HASLE, G. R. (1979). The genus *Thalassiosira*: *T. trifulta* sp. nova and other species with tricolumnar supports on strutted processes. *Beihefte zur Nova Hedwigia*, **64**, 13–32.

FRYXELL, G. A. & HASLE, G. R. (1980). The marine diatom *Thalassiosira oestrupii*: structure, taxonomy and distribution. *American Journal of Botany*, **67**, 804–814.

GATE, W. L. (1976). Modeling the ice-age climate. *Science*, **191**, 1138–1144.

GORBARENKO, S. A., KHUSID, T. A., BASOV, I. A., OBA, T., SOUTHON, J. R. & KOIZUMI, I. (2002). Glacial Holocene environment of the southeastern Okhotsk Sea: evidence from geochemical and palaeontological data. *Palaeogeography, Palaeoclimatly, Palaeoecology*, **177**, 237–263.

HONJO, S. (1990). Particle fluxes and modern sedimentation in the polar oceans. In: *Polar Oceanography, Part B. Chemistry, Biology, and Geology* (W.O. Smith, ed.), 687–739. Academic Press, New York.

HOPKINS, D. M. (1973). Sea level history in Beringia during the past 250,000 years. *Quaternary Research*, **3**, 520–540.

KANAYA, T. & KOIZUMI, I. (1966). Interpretation of diatom thanatocoenoses from the North Pacific applied to a study core V20–130. (Studies of a deep-sea core V20–130). *Tohoku University, Science Report, 2nd series*, (*Geology*), **37**, 89–130.

KARPUZ, K. N. & SCHRADER, H. (1990). Surface sediment diatom distribution and Holocene paleotemperature variations in the Greenland, Iceland and Norwegian Sea. *Paleoceanography*, **5**, 557–580.

KATSUKI, K., TAKAHASHI, K. & OKADA, M. (in press). Diatom assemblage and productivity changes during the last 340,000 years in the subarctic Pacific. *Journal of Oceanography*.

KEIGWIN, L. D. (1995). Stable isotope stratigraphy and chronology of the upper Quaternary section at Site 883, Detroit Seamount. *Proceedings of the Ocean Drilling Program, Science Results*, **145**, 257–264.

KEIGWIN, L. D. (1998). Glacial-age hydrography of the far northwest Pacific Ocean. *Paleoceanography*, **13**, 323–339.

KEIGWIN, L. D., JONES G. A. & FROELICH P. N. (1992). A 15,000 year paleoenvironmental record from Meiji Seamount, far northwestern Pacific. *Earth and Planetary Science Letters*, **111**, 425–440.

KIEFER, T., SARNTHEIN, M., ERLENKEUSER, H., GROOTES, P. M. & ROBERTS, A. P. (2001). North Pacific response to millennial-scale changes in ocean circulation over the last 60 kyr. *Paleoceanography*, **16**, 179–189.

MAKAROVA, V. I. (1993). Morphology of some species of the genus *Coscinodiscus* Ehrenberg. *Nova Hedwigia*, **106**, 185–196.

NAKATSUKA, T., WATANABE, K., HANDA, N., MATSUMOTO, E. & WADA, E. (1995). Glacial to interglacial surface nutrient variations to Bering deep basins recorded by $\delta^{13}C$ and $\delta^{15}N$ of sedimentary organic matter. *Paleoceanography*, **10**, 1047–1061.

NARITA, H., SATO, M., TSUNOGAI, S., MURAYAMA, M., IKEHARA, M., NAKATSUKA, T., WAKATSUCHI, M., HARADA, N. & UJIIE, Y. (2002). Biogenic opal indicating less productive northwestern North Pacific during the glacial ages. *Geophysical Research Letter*, **29**, 22–1–22–4.

OHTANI, K., AKIBA,Y. & TAKENOUCHI, A. Y. (1972). Formation of western subarctic water in the Bering Sea. *Canadian Special Publication of Fisheries and Aquatic Sciences*, **121**, 87–95.

OKADA, M. & TAKAHASHI, K. (2003). On the age models of cores recovered from Cruise KH99–3 of R/V Hakuho-maru. *Kaiyo Monthly*, **35**, 381–386. (In Japanese).

SANCETTA, C. (1982). Distribution of diatom species in surface sediment of the Bering and Okhotsk seas. *Micropaleontology*, **28**, 221–257.

SANCETTA, C. (1983). Effect of Pleistocene glaciation upon oceanographic characteristics of the North Pacific Ocean and Bering Sea. *Deep-Sea Research*, **30**, 851–869.

SANCETTA, C. (1987). Three species of *Coscinodiscus* Ehrenberg from North Pacific sediment examined in the light and scanning electron microscopes. *Micropaleontology*, **33**, 230–241.

SANCETTA, C. & ROBINSON, S. W. (1987). Diatom evidence on Wisconsin and Holocene events in the Bering Sea. *Quaternary Research*, **20**, 232–245.

SANCETTA, C. & SILVESTRI, S. (1984). Diatom stratigraphy of the late Pleistocene (Brunhes) subarctic Pacific. *Marine Micropaleontology*, **9**, 263–274.

SHIGA, K. & KOIZUMI, I. (2000). Late Quaternary paleoceanographic changes in the Okhotsk Sea based on diatom records. *Marine Micropaleontology*, **38**, 91–117.

SHIMADA, C. & HASEGAWA, S. (2001). Paleoceanographic implications of a 90,000 year long diatom records in piston core KH94-3, LM–8 of NE Japan. *Marine Micropaleontology*, **41**, 153–166.

SHIONO, M. (2000). Three new species in the *Thalassiosira trifulta* group in the Late Neogene sediments from the northwest Pacific Ocean. *Diatom Research*, **15**, 131–148.

STABENO, P. J. & REED, R. K. (1994). Circulation in the Bering Sea basin observed by satellite-tracked drifters: 1986–1993. *Journal of Physical Oceanography*, **24**, 848–854.

STABENO, P. J., REED, R. K. & NAPP, J. M. (2002). Transport through Unimak Pass, Alaska. *Deep-Sea Research II*, **49**, 5919–5930.

TAKAHASHI, K. (1999). Paleoceanographic changes and present environment of the Bering Sea. In: *Dynamics of the Bering Sea* (T.R. Loughlin & K. Ohtani, eds), 365 pp. University of Alaska Sea Grant, Fairbanks.

TAKAHASHI, K., JORDAN, R. & PRIDDLE, J. (1994). The diatom genus *Proboscia* in subarctic water. *Diatom Research*, **9**, 411–428.

YANAGISAWA, Y. & AKIBA, F. (1990). Taxonomy and phylogeny of the three marine diatom genera, *Crucidenticula*, *Denticulopsis* and *Neodenticula*. *Bulletin of the Geological Survey of Japan*, **41**, 197–301.

WHITING, M. C. & SCHRADER, H. (1985). Late Miocene to early Pliocene marine diatom and silicoflagellete floras from the Oregon coast and continental shelf. *Micropaleontology*, **31**, 249–270.