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# Paleohydrography of the Kuroshio Extension in the Tohoku Area based on fossil diatoms

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**Abstract** The most complicated hydrographic conditions are encountered in the Perturbed Area, where numerous eddies and thermohaline fronts are irregularly distributed between the Kuroshio Extension and Oyashio Fronts at Lat. 38° to 41°N. These features brought the abundance of fishery resources on the northern side of the Kuroshio Extension due to the multiplication of phytoplankton by upwelling. The paleohydrography of the Tohoku Area since 150 ka was reconstructed based on the high-resolution analyses of fossil diatom assemblages in seven cores. Diatom assemblages in the southern margin of the Perturbed Area have been controlled mainly by the Kuroshio and Kuroshio Extension, but in the northern margin they changed in responding to the expansion of the warm-water eddies detached from the Kuroshio Extension and of the southward Oyashio Intrusion. Diatom abundances are higher in the area near shore than in the area off shore, and the diatom assemblages were affected more seriously by the environmental changes in the area near shore. The abundances of extinct diatoms increase in the glacial phase, and diatom abundances and *Td'* values increase in the interglacial phase. The variation of oceanic diatom abundance is pronounced at 41-kyr and 23-kyr periods, and also *Td'* values predominating at 60-kyr, 30-kyr, and 23-kyr periods. The seawater mixing during the interval from glacial to interglacial transition induced by orbital-obliquity cycles played an important role in the primary production of oceanic diatoms. The predominant occurrences of extinct diatom species *Melosira albicans* are accompanied by that of *Pseudopodosira elegans* throughout the cores.

**Keywords**: Kuroshio Extension, Oyashio Intrusion, Perturbed Area, diatom temperature (*Td'*) values, glacio-eustatic sea-level change, obliquity (tilt), precession

## 1. Introduction

The Kuroshio Extension is characterized by being far away from the continental shelf and encountering Oyashio cold water which flows along the southeast coast of Hokkaido down to approximately Lat. 41°N, and also by very complicated hydrographic conditions with distorted meanders of its path and numerous eddies especially on its north side. The Tsugaru Warm Current flows southward to approximately Lat. 38°N and occasionally comes in contact with the Oyashio Intrusion which forms a tongue-like shape. The Oyashio Intrusion water subsides as the North Pacific Intermediate Water, which is characterized with a salinity minimum (Kawai, 1972; Yasuda et al., 1996).

The water in the Tohoku Area, where is the northern portion of the sea along the Pacific coast of Japan, is crucial to the hydrographic relationship between the subtropical North Pacific Ocean and subarctic North Pacific Ocean. The water is hydrographically divided into three areas, which are the Kuroshio Area, the Perturbed Area and the Oyashio Area, by eastward Kuroshio Front at Inubo-zaki, which is the stream axis of the Kuroshio Extension in the surface, and southward Oyashio Front. The studied area involves the most complicated hydrographic conditions in the Perturbed Area (Fig. 1).

The research vessel “Mirai” (the meaning of “future”) belonging Japan Agency for Marine-Earth Science and Technology (JAMSTEC) systematically collected many piston cores from 1997 to 2002. The hydrographic history was reconstructed based on fossil diatoms in the cores recovered in the Kuroshio Extension off Joban coast from Inubo-zaki to about 38°N (Koizumi et al., 2004; Koizumi and Yamamoto, 2005) and in the northern margin of the Perturbed Area off Sanriku coast located the Pacific coast of the northern Tohoku District of about 38°N (Koizumi

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and Yamamoto, 2007).

Diatom abundances were higher in near shore area than in offshore area, and diatom assemblages were affected by the serious changes in the area near shore. The diatom assemblages also showed the fluctuations in its species composition at the intervals of 23-kyr corresponding to the precession, 41-kyr to the obliquity (tilt) band variations among the Earth's orbital parameters, and 30-kyr intervals found in equatorial Indo-Pacific paleoproductivity records (Beaufort et al., 2001) and 60-kyr intervals suggesting changes in the sea-level by glaciation or deglaciation (Birchfield and Gurmbine, 1985).

This paper aims to document paleohydrographic records since 150 ka (cal kyr BP) of the Kuroshio Extension in the Perturbed Area, where the most complicated hydrographic conditions gather together, based on high-resolution analysis by fossil diatoms.

## 2. Core materials and age model

Three piston cores were recovered in the area beneath the Kuroshio Warm Core off Joban coast (Fig. 1, Table 1). The diatom assemblages from the core MD01-2421 were described in Koizumi et al. (2004), but they were slightly modified in this paper. The core MR02-03-2 is composed of dark olive colored clay to silty clay with ash layers and yellowish green bands. The age model for the core was obtained by the correlation between the paleomagnetic intensity (NRM15/ARM15) of the core and the global changes in intensity of the Earth's magnetic field SINT800 (Guyodo and Valet, 1999); core depth 379 cm is assigned to age 54 ka, 813 cm to 130 ka, 884 cm to 146 ka, and 1259 cm to 190 ka (Koizumi et al., 2003). The core MR99-04-3 consists of the alternation of grayish olive and olive black colored massive clay with dark greenish gray laminated layers, burrows, and ash layers. The core contains two marker tephra layers; Shikotsu-Daiichi (Spfa-1) tephra at 329-314 cm (center depth 321.5 cm) is assigned to 39.8 ka and Aso-4 tephra at 537-533 cm (535 cm) to 88.0 ka (Aoki et al., 2000).

Three marker tephra layers were reported for the Pleistocene sequence at ODP Hole 1150A; Towada-Hachinohe (To-H) tephra at 505 cm to 14.83 ka, Spfa-1 tephra at 1507 cm, and Aso-4 tephra at 2681 cm (Motoyama et al., 2004). Three piston cores were recovered along the transect running east-west at about 40°N (Fig. 1, Table 1). The diatom assemblages in the core MR97-04-1 were previously analyzed (Koizumi et al., 2006). The marine isotope chronology based on the benthic $\delta^{18}$O record suggested that the sediment of 25.16 cm thick corresponding to 7.8 kyr was not recovered at the topmost of main piston core (Oba et al., 1999; Yamamoto, 1999). Three tephra layers, Aso-4 tephra at 436.1 cm, Towada-Ofudo (To-Of) tephra at 154 cm age assigned to 31.27 ka and To-H tephra at 19 cm, were newly used in this paper (Table 2). The core MR00-05-2 is composed of gray olive colored siliceous clay, mottled with abundant

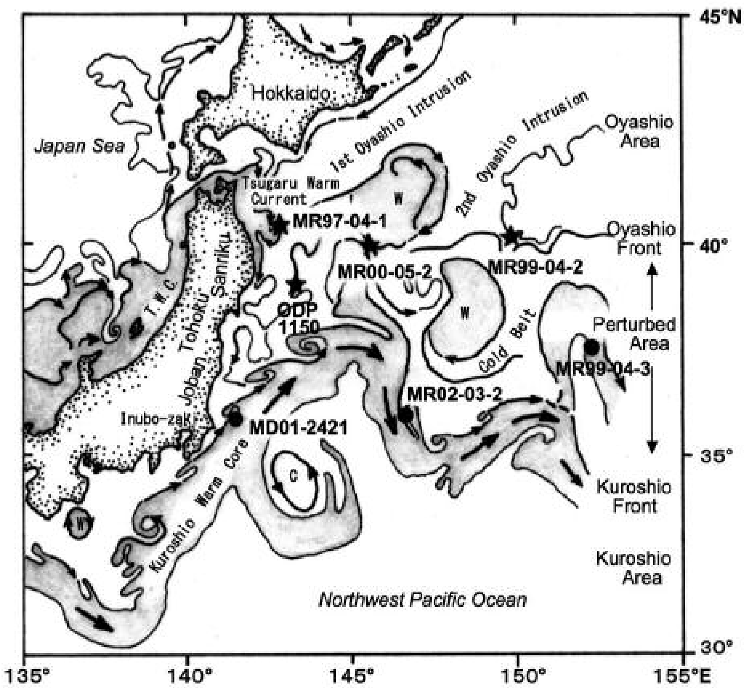


Figure 1: Locations of seven cores in this report. Black circles indicate core sites off Joban coast and black stars off Sanriku coast. Arrows indicate the currents and contour interval for the boundary between water masses (Kawai, 1991). T.W.C. =Tsushima Warm Current, W=warm-water eddy, C=cold-water eddy.

Table 1: Locations of seven cores studied in the Tohoku Area.

| Locations Cores | Latitude (° N) | Longitude (° E) | Water depth (m) | Core length (cmbsf) | Studied length (cmbsf) |
|---|---|---|---|---|---|
| Off Joban coast: | | | | | |
| MD01-2421 | 36.014 | 141.468 | 224 | 4582 | 4522 |
| MR02-03-2 | 36.007 | 146.000 | 5712 | 1818.5 | 1300 |
| MR99-04-3 | 37.500 | 152.000 | 5848 | 1876 | 970.25 |
| Off Sanriku coast: | | | | | |
| ODP 1150A | 39.183 | 143.333 | 2681 | 72260 | 2680 |
| MR97-04-1 | 40.555 | 142.927 | 1520 | 683.8 | 683.8 |
| MR00-05-2 | 40.000 | 146.000 | 5177 | 1988 | 1380 |
| MR99-04-2 | 40.083 | 149.850 | 5608 | 1813 | 950 |

Table 2: Chronostratigraphic framework (depth vs. calendar age) in seven cores studied.

| Age controls | Age (cal kyr BP) | MD01-2421 (cmbsf) | MR02-03-2 (cmbsf) | MR99-04-3 (cmbsf) | ODP 1150A (cmbsf) | MR97-04-1 (cmbsf) | MR00-05-2 (cmbsf) | MR99-04-2 (cmbsf) |
|---|---|---|---|---|---|---|---|---|
| AMS$^{14}$C | 0.31 | 8 | | | | | | |
| AMS$^{14}$C | 1.79 | 158 | | | | | | |
| AMS$^{14}$C | 3.62 | 308 | | | | | | |
| AMS$^{14}$C | 5.57 | 456 | | | | | | |
| AMS$^{14}$C | 7.57 | 606 | | | | | | |
| MI Event 2.0 | 12.05 | | | | | 38.2 | | |
| AT tephra | 29.24 | 1210 | | | | | | |
| To-H tephra | 14.83 | | | | 505.0 | | 221.0 | 77.5 |
| MI Event 2.2 | 17.85 | | | | | 54.4 | | |
| MI Event 3.0 | 24.11 | | | | | 64.7 | | |
| To-Of tephra | 31.27 | | | | | | 540.5 | 297.0 |
| Spfa-1 tephra | 39.80 | | | 321.5 | 1507.0 | | 661.0 | 392.0 |
| MI Event 3.3 | 50.21 | | | | | 247.7 | | |
| SINT800 | 54.00 | | 379 | | | | | |
| MI Event 4.0 | 58.96 | 2005 | | | | 267.7 | | |
| MI Event 5.0 | 73.91 | 2427 | | | | 344.7 | | |
| MI Event 5.1 | 79.25 | 2775 | | | | 365.7 | | |
| MI Stage 5.1/5.2 | 85.22 | 2827 | | | | | | |
| Aso-4 tephra | 88.00 | | | 535.0 | 2681.0 | | 1151.5 | 679.0 |
| MI Event 5.2 | 90.94 | 2960 | | | | 410.4 | | |
| MI Stage 5.2/5.3 | 94.06 | 3117 | | | | | | |
| MI Event 5.3 | 99.38 | 3328 | | | | 448.4 | | |
| Kc-Hb | 110.73 | | | | | | 1237.5 | |
| MI Event 5.4 | 110.79 | | | | | 491.4 | | |
| MI Stage 5.4/5.5 | 117.30 | 3648 | | | | | | |
| MI Event 5.51 | 122.56 | 4027 | | | | 552.7 | | |
| MI Event 6.0 | 129.84 | 4241 | | | | 598.8 | | |
| SINT800 | 130.00 | | 813 | | | | | |
| Above MI Event 6.2 | 132.81 | 4329 | | | | | | |
| MI Event 6.2 | 135.10 | | | | | 634.0 | | |
| MI Event 6.3 | 141.33 | 4479 | | | | | | |
| SINT800 | 146.00 | | 884 | | | | | |
| MI Event 6.4 | 152.58 | | | | | 674.0 | | |
| MI Event 6.41 | 161.34 | | | | | 698.0 | | |
| SINT800 | 190.00 | | 1259 | | | | | |
| Top *P. curvirostris* | 300.00 | | | | | | | 1575.0 |

glassy ash layers. Such composition is recognized in Kutcharo-Haboro (Kc-Hb) tephra at 1237.5 cm to age assigned to 110.73 ka, Aso-4 tephra at 1151.5 cm, Spfa-1 tephra at 661 cm, To-Of tephra at 540.5 cm, and To-H tephra at 221 cm (Yamamoto and Kanamatsu, 2001; Yamamoto and Aoki, 2002). The core MR99-04-2 is mainly composed of dark olive gray colored clay with abundant glassy ash layers as recognized in Aso-4 tephra at 679 cm, Spfa-1 tephra at 392 cm, To-Of tephra at 297 cm, and To-H tephra at 775 cm (Yamamoto et al., 2000; Aoki et al., 2000).

The age model (depth vs. calendar age) for seven cores is shown in Table 2 and Figure 2. In the interval from 950 cm to 679 cm of the core MR99-04-2, the sedimentation rates (depth vs. calendar age) were taken an average both the extrapolation between 88.0 ka of Aso-4 tephra at 1151.5 cm and 39.8 ka of Spfa-1 tephra at 392 cm, and 300.0 ka of the last occurrence of *Proboscia curvirostris* at 1575.0 cm and 88.0 ka of Aso-4 tephra at 1151.5 cm (Fig. 2).

## 3. Method of Study

The average sampling interval in ODP Hole 1150A is 30 cm corresponding to 0.95 kyr and in MD01-2421 20 cm corresponding to 0.6 kyr throughout the cores. The sampling interval in four MR cores is 10 cm corresponding to ~1.0-1.7 kyr, but in the core MR97-04-1, 10 cm corresponds to 3.1 kyr in average. The sampling interval during the Holocene in the cores MR99-04-3, MR97-04-1, and MR99-04-2 is 5 cm.

The procedures of slide preparation and microscopic examination follow Koizumi et al. (2004). Paleoceanogarphic analyses were conducted through calculations of diatom abundance, relative abundance of extinct diatoms, ecological and biogeographical categories based on the habitats of diatom species, living warm-water and cold-water species, and diatom temperature estimates using the following relationship; ($Td'=[(Xw+XW)/(Xw+XW+Xc+XC)]\times100$), where $Xw$ is the frequency of warm-water species and $Xc$ is that of cold-water species originally proposed by Kanaya and Koizumi (1966). XW and XC are supplemented species. $Td'$ values reflect more precisely oceanic holoplanktonic associations than originally proposed $Td$ (Koizumi et al., 2004).

## 4. Results and discussion

### 4.1. Extinct species

The relative abundances of extinct species occupy less than 10 % of the total diatom flora in the cores located off shore, with the peaks of occurrences at 135-130 ka, exceptionally of 115 ka, 85-75 ka, 40-35 ka and 25 ka (Fig. 3). Those peaks of high abundances are synchronously correlated with the peaks of the large fluctuations recognized in ODP 1150A and MR97-04-1 located at continental slope, and MR00-05-2 at the mixed between the warm-water eddy detached from the Kuroshio Extension and 2nd Oyashio Intrusion (Fig. 1). The abundances of extinct species was increased during the lowered sea-level phase, which indicates contribution of reworked and displaced diatoms derived from the sea bottom exposed the strata including such extinct diatoms, since freshwater and littoral species rarely occur. The relative abundances decrease characteristically since ~20-15 ka due to the deglaciation.

The predominant occurrence of extinct species *Melosira albicans* are accompanied by that of *Pseudopodosira elegans* throughout the cores. *M. albicans* and *P. elegans* were described originally at the Pliocene in Sakhalin and Kamchatica (Sheshukova-Porentzkaya, 1964), and also found in the Pliocene Tatsunokuchi Formation in Fukushima and Miyagi Prefectures (Koizumi, 1972, 1973b). On the other hand, their last occurrences are at the Pleistocene *Proboscia* (=*Rhizosolenia*) *curvirostris* Zone by the diatom biostratigraphy in the DSDP (Deep Sea Drilling Project)

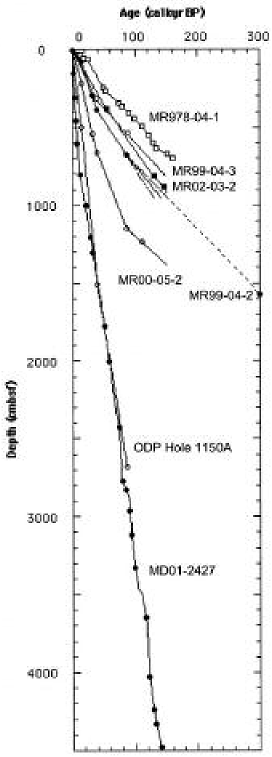


Figure 2: Age (cal kyr BP)-depth (cm) models for seven cores. In the interval of 950-679 cm of MR99-04-2, the sedimentation rate was taken an average both the extrapolated rate of 87.0-39.8 ka at 1151.5-392.0 cm and the rate of 300-87 ka at 1575.0 -1151.5 cm.

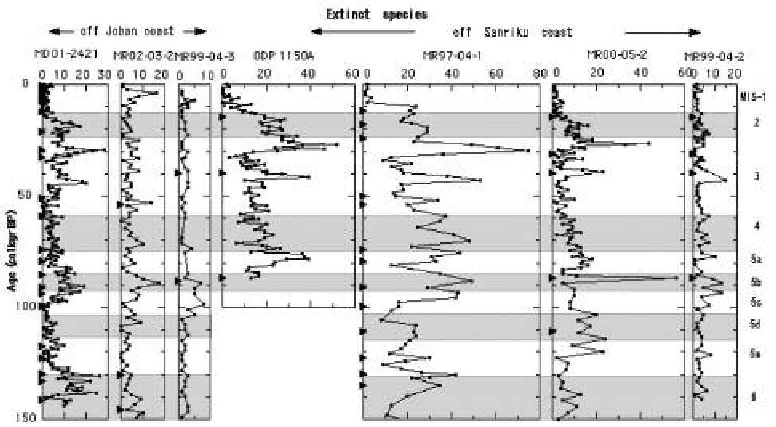


Figure 3: Chronostratigraphic variations in the relative abundances (valves/200 valves) of extinct species in seven cores. High abundances of extinct species are correlated within the lowered sea-level phase estimated from normalized $\delta^{18}$O curve (Martinson et al., 1987) in each core recovered from the area near shore. Black triangles on the left side of each column indicate the age control points for age model.

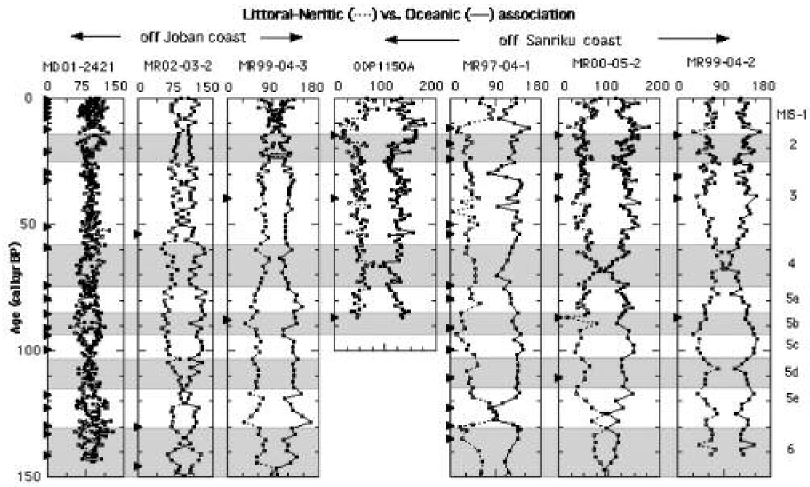


Figure 4: Chronostratigraphic variations in the relative abundances (valves/200 valves) of littoral-neritic and oceanic species in seven cores. They are almost mirror image in the relative abundances curves. Black triangles on the left side of each column indicate the age control points for age model.

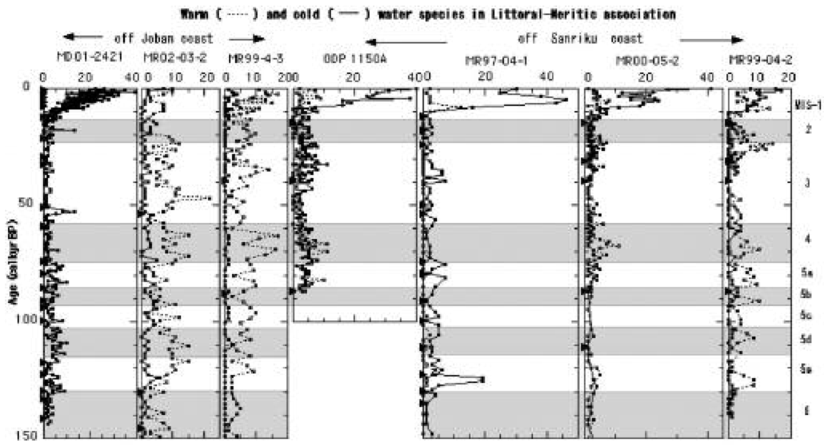


Figure 5: Chronostratigraphic variations in the relative abundances (valves/200 valves) of the warm-water and cold-water species in littoral-neritic association in seven cores. High abundances of cold-water species increase suddenly from about 10 cal kyr BP. Black triangles on the left side of each column indicate the age control points for age model.

(Koizumi, 1973a) and ODP (Ocean Drilling Program) (Koizumi, 1992) in the middle-to-high latitudes. They occur regularly, however, throughout the Pleistocene to Holocene sediments exclusively recovered by piston coring of the North Pacific Ocean (Koizumi et al., 2001, 2004; Shimada and Hasegawa, 2001). Since their last occurrences are much more younger off shore sediments than on land sections, those species need to be checked taxonomically.

### 4.2. Littoral-neritic and oceanic species

The relative abundances of littoral-neritic association are almost a mirror image of those of oceanic association (Fig. 4). Three cores taken in the area beneath the Kuroshi-Kuroshio Extension off Joban coast contain abundant littoral-neritic species reaching to ~25-50 % of the total diatom flora. But they become smaller in quantities in four cores off Sanriku coast in the Perturbed Area. It suggests that the Kuroshio flowing toward the northeast along the coast of southwest Japan absorbed littoral-neritc species near shore area.

The relative abundances of littoral-neritic association gradually decrease from 150 ka to 15 ka with gentle undulations made of the rapid and short cyclicities of several kyr duration. The abundances increase during the Holocene.

In littoral-neritic association, the relative abundances of such warm-water species as *Hemiaulus sinensis*, *Odontella reticulum* and *Thalassionema nitzschioides* var. *parva* dominate over those of cold-water ones in MR02-03-2 and MR99-4-3 off Joban coast, and MR99-04-2 off Sanriku coast (Fig. 5). The relative abundances of warm-water and cold-water species in littoral-neritic association are almost even in MD01-2421 and ODP Hole 1150A located at near shore except since 8 ka. On the other hand, the relative abundances of cold-water species are slightly over than warm-water ones in MR97-04-1 located at the southern end of the First Oyashio Intrusion off Sanriku coast. Sudden increases of exclusive littoral-neritic cold-water *Odontella aurita* occur from ~8 ka. The relative abundances of *O. aurita* since 8 ka in the cores recovered near shore are two times as much that in the cores recovered off shore.

The relative abundances of oceanic association increase as the locations of the cores become far from near shore area with large fluctuations. In three cores from off Joban coast, the relative abundances at ~60-kyr intervals are following secondary and smaller fluctuations at the ~20-kyr intervals. In the four cores off Sanriku coast, large fluctuations occur at the intervals of ~40-kyr with secondary and smaller fluctuations at ~20-kyr intervals. The peaks of high abundances of oceanic association, therefore, are correlated with each other in the interglacial phases throughout the cores (Fig. 4).

### 4.3. Cold-water and warm-water species in oceanic association

The relative abundances of warm-water species in oceanic association are slightly over than those of cold-water species in the interglacial phases of MIS 5e and Holocene. The abundances of warm-water and cold-water species are almost even in MD01-2421, MR02-03-2, and MR99-04-3 located in the warm tongue along the Kuroshio Extension off Joban coast (Figs. 1 and 6). In the four cores off Sanriku coast, the abundances of warm-water species increase as the locations of the cores become far from near shore area. The relative abundances of cold-water species dominate over those of warm-water ones with large fluctuations throughout the cores. It suggests that the cores near shore is exactly located within the first Oyashio Intrusion, but the cores from off shore were affected by the warm-water eddies detached from the Kuroshio Extension.

The repeating ~40-kyr intervals in the relative abundances of cold-water species correlate each other among the cores, except MR02-03-2 where ~60-kyr cyclicity dominates. Remarkable decreases in the relative abundances of cold-water species are recognized at 145 ka, 115-105 ka, 65 ka, 25 ka and 8 ka. In these levels, the relative abundances of such cold-water species as *Fragilariopsis cyclindrus*, *Fragilariopsis oceanicus* and *Thalassiosira gravida* decrease, and those of warm-water species such as *Azpeitia nodulifera*, *Azpeitia tabularia*, *Fragilariopsis doliolus* and *Roperia tesselata* generally increase.

Since *T. gravida* (=*T. antarctica*) is associated with sea-ice in coastal waters of arctic and boreal seas (Shiga and Koizumi, 2000), the relative abundances of *T. gravida* decrease as the cored area becomes away from near shore. The large fluctuations at ~40-kyr intervals with secondary and smaller fluctuations at ~20-kyr intervals typically occur throughout the cores from near shore. The peaks of high abundances are in glacial phases. *F. doliolus* is one of the most common plankton species in subtropical-tropical areas in the World Ocean (Hasle, 1976). And the relative abundances of it increase in the MIS 5e and 1 indicating characteristic interglacial phase. The increase of this species in the cores from off shore suggested the influences of the warm-water eddies, being resistant to dissolution of the valves and keeping the valves away from terrigenous materials.

### 4.4. Diatom temperature (*Td'*) values

The *Td'* values in the cores located along the Kuroshio

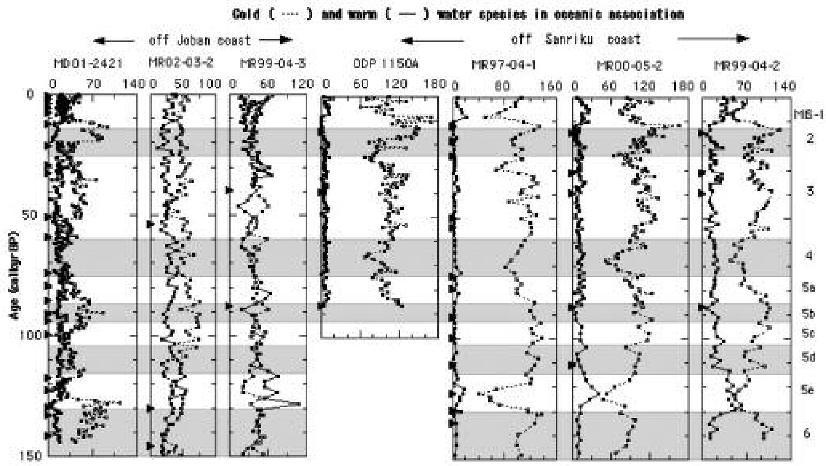


Figure 6: Chronostratigraphic variations in the relative abundances (valves/200 valves) of the cold-water and warm-water species in oceanic association in seven cores. High abundances of warm-water species are correlated each other among seven cores in interglacial phase. Black triangles on the left side of each column indicate the age control points for age model.

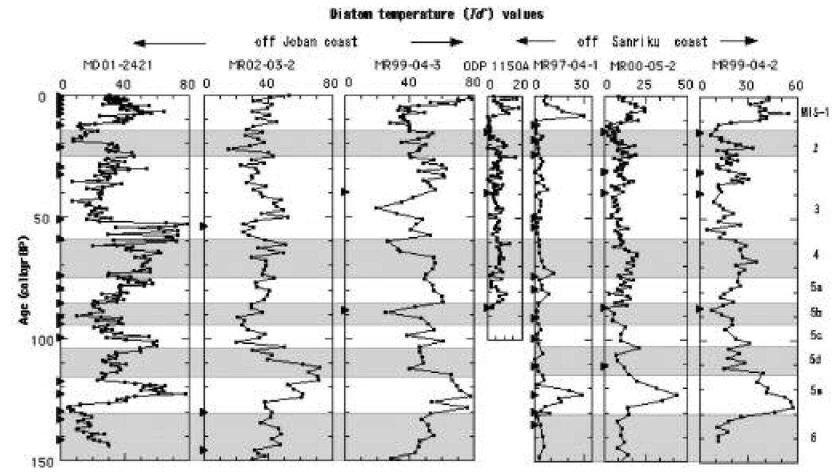


Figure 7: Chronostratigraphic variations of diatom temperature (*Td'*) values in seven cores. *Td'* values in the cores along the Kuroshio Front are high and largely fluctuated in interglacial phase. Black triangles on the left side of each column indicate the age control points for age model.

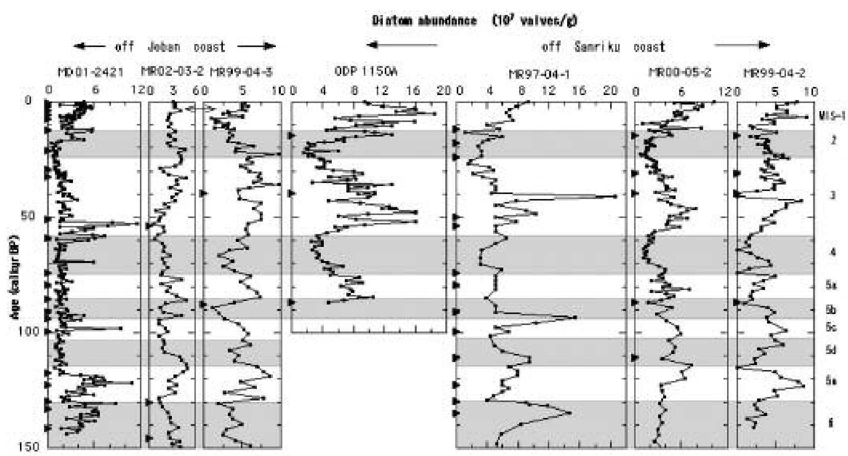


Figure 8: Chronostratigraphic variations of diatom abundances ($10^7$/g of dried sediment) in seven cores. High diatom abundances are correlated within each core among seven cores. Diatom abundances increase generally in interglacial phase. They are larger in the cores near shore area off Sanriku coast. Black triangles on the left side of each column indicate the age control points for age model.

Front in the Kuroshio Extension are high and largely fluctuated (Fig. 7). On the other hand, the *Td'* values in the cores from near shore off Sanriku coast are smaller than those from off shore. Locations of the cored sites account for this (Fig. 1). ODP Hole 1150A locates in the 1st Oyashio Intrusion, and MR97-04-1 is at the outer margin of the Tsugaru Warm Current. Both MR00-05-2 and MR99-04-2 are under the influence of the warm-water eddies, and particularly they are considered to have lesser influence of the cold-water.

High *Td'* values occur at MIS 5e, 5d/c boundary, 4, the base-middle of MIS 3 and 1, all situating in the interglacial phase (Fig. 7). The correspondence of the high *Td'* values to the periods turning toward interglacial phases is recognized common among the cores investigated.

Spectral analysis of *Td'* values (Irino, personal information 2007) indicates that the variation during the last 150 kyr is pronounced at 60-kyr corresponding to isostatic balance between the crust and advance retreat of continental ice sheet on Northern Hemisphere (Birchfield and Gurmbine, 1985), 30-kyr suggesting of the long-term variation of El Niño-Souhtern Oscillation (ENSO) (Clement et al., 1999), and 23-kyr corresponding with precession. Beaufort et al. (2001) showed that variations in equatorial productivity have reflected precession-controlled long-term variation of ENSO changes in the east-west thermocline slope of the Indo-Pacific, and Yamamoto et al. (2005) also found the precession-controlled east-west seesaw-like change of alkenone SST in mid-latitude North Pacific margins.

### 4.5. Diatom abundance

Diatom abundances ($10^7$ valves per 1 g of dried sediment) increase generally in interglacial phases than in glacial phases (Fig. 8). They are larger in the cores recovered near shore off Sanriku coast, where diatoms fertile due to the mixing of the Tsugaru Warm Current and the Oyashio Intrusion in the northwestern margin of the Perturbed Area, with exceptions of spike-like increases at the horizons 135.10 ka, 93.38 ka and 41.15 ka in MR97-04-1 (Fig. 8). Diatom abundances of MD01-2421 in the Kuroshio Warm Core off Joban coast, however, are very low caused by the dilution with terrigenous and organic materials due to the shallow depth of core location (Table 1), but show rapid increases at three horizons 121.67 ka, 98.20 ka and 52.84 ka.

The fluctuations of diatom abundances are larger in the cores recovered near shore, where affected more serious environmental changing near shore, than that off shore. Oceanic abundance, excluded such local environmental noise, predominate at 41-kyr intervals corresponding to the obliquity (tilt) band and 23-kyr to the precession. This implies that seawater mixing during the interval from glacial to interglacial transition induced by orbital cycles played an important role in the primary production of oceanic diatoms.

## 5. Conclusions

1. The reworked and/or displaced extinct species derived from sea bottom dominantly occur when the sea level lowered during glacial phase near shore in the northern area of the Perturbed Area.
2. The extinct species *Melosira albicans and Pseudopodosira elegans* should be checked taxonomically, because their last occurrences are much more younger off shore sediments than on land sections.
3. The relative abundances of littoral-neritic species, particularly warm-water species, are higher in the cores beneath the Kuroshio Extension than in the cores in the northern margin of the Perturebed Area, because the Kuroshio flowing northeast along the near shore of southwest Japan transports littora-neritic species into the southern margin of the Perturbed Area.
4. The littoral-neritc cold-water species *Odontella aurita* increases suddenly since ~8 ka, and the relative abundances also increases along the frontal zone in the northern margin of the Perturbed Area because this species flourishes most in arctic and boreal seas during April and May.
5. The relative abundances of cold-water species in oceanic association dominate over those of warm-water ones throughout the cores in the Perturbed Area. However, the abundances of warm-water species increase in MR99-04-3 and MR99-04-2 located in the warm-water tongue and eddies along the Kuroshio Extension.
6. The diatom temperature (*Td'*) values are controlled by the fluctuations at 60-kyr intervals suggesting glacial-eustatic sea-level changes with secondary and smaller fluctuations 30-kyr intervals corresponding to long-term variation of El Niño-Southern Oscillation, and at 23-kyr intervals corresponding to precession.
7. The diatom abundances in the northern margin of the Perturbed Area are twice as high as those beneath the stream axis of the Kuroshio Extension because streaky structures due to mixing of Oyashio Intrusions and warm-water eddies along the Kuroshio Extension developed in the northern margin area.
8. The oceanic diatom abundance was attributed mainly to the effect of orbital-scale changes at 41-kyr and 23-kyr periods.

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## References


1) K. Aoki, H. Yamamoto, and M. Yamauchi, “Late Quaternary tephro-stratigraphy of marine cores collected during “Mirai” MR98-03 and MR99-K04 cruises”. JAMSTECR **41**, 49-56 (2000) (Japanese with English abstract).
2) L. Beaufort, T. de Garidel-Thoron, A.C. Mix, and N.G. Pisias, “ENSO-like forcing on oceanic primary production during the late Pleistocene”. Science **293**, 2440-2444 (2001).
3) G.E. Birchfield, and R.W. Gurmbine, ““Slow” physics of large continental ice sheets, the underlying bedrock and the Pleistocene Ice Ages”. J. Geophys. Res. **90**, 11294-11302 (1985).
4) A.C Clement, R. Seager, and M.A. Cane, “Orbital controls on the El Niño/Southern Oscillation and the tropical climate”. Paleoceanography **14**, 441-456 (1999).
5) Y. Guyodo, and P. Valet, “Global changes in intensity of the Earth’s Magnetic field during the past the past 800 kyr”. Nature **399**, 249-252 (1999).
7) G.R. Hasle, “The biogeography of some marine planktonic diatoms”. Deep-Sea Research 23, pp. 319-338 (1976).
8) T. Kanaya, and I. Koizumi, “Interpretation of ditom thanatocoenoses from the North Pacific applied to a study of core V20-130 (studies of a deep-sea core V20-130, part _)”. Sci. Rep. Tohoku Univ., 2nd ser. (Geol.) **37**, 89-130 (1966).
9) H. Kawai, “Hydrography of the Kuroshio Extension”. In: Stommel, H., and Yoshida, K. (Eds.) Kuroshio-Its Physical Aspect. Univ. of Tokyo Press, Tokyo, 235-352 (1972).
10) H. Kawai, “The existing conditions of research on the relationship current and biology”. In: Kawai, H. (Ed.) Existing Conditions of Researches into Currents and Biology—Fisheries Oceanography--. Kyoto Uni. Press, Kyoto, 2-4 (1991) (in Japanese).
11) I. Koizumi, “Marine diatom flora of the Pliocene Tatsunokuchi Formation in Fukushima Prefecture, northeast Japan”. Trans. Proc. Paleontol. Soc. Jpn., No. 86, 340-359 (1972).
12) Koizumi, I., “The late Cenozoic diatoms of Sites 183-193, Leg 19 Deep Sea Drilling Project”. In: Creager, J.S., Scholl, D.W., et al. (Eds.), Init. Repts. 19, Washington (U.S. Govt. Printing Office), 805-855 (1973a).
13) I. Koizumi, “Marine diatom flora of the Pliocene Tatsunokuchi Formation in Miyagi Prefecture”. Trans. Proc. Paleontol. Soc. Jpn., N.S., No. 79, 126-136 (1973b).
14) I. Koizumi, “Diatom biostratigraphy of the Japan Sea: Leg 127”. In: Ingle, J.C., Jr., von Breymann, M.T., Barron, J., et al. (Eds.) Proc. ODP, Sci. Res. 127/128, Pt.1, College Station, TX (Ocean Drilling Program), 249-289 (1992).
15) I. Koizumi, and H. Yamamoto, “Paleohydrography of the Kuroshio-Kuroshio Extension based on fossil diatoms”. JAMSTEC Rep. Res. Dev. **1**, 57-68 (2005).
16) I. Koizumi, and H. Yamamoto, “Paleohydrography of the Kuroshio-Kuroshio Extension off Sanriku coast based on fossil diatoms”. JAMSTEC Rep. Res. Dev. **5**, 1-8 (1977).
17) I. Koizumi, T. Irino, and H. Yamamoto, “Changes in the warm water Kuroshio Current system from the ending period of the last glacial to the present interglacial based on diatom fossils in the western North Pacific Ocean sampled on the R/V Mirai cruise [MR00-K05]”. JAMSTECR **44**, 29-40 (2001) (Japanese with English abstract).
18) I. Koizumi, T. Irino, T. Mishima, T, Kanamatsu, and H. Yamamoto, “Changes in the warm water Kuroshio Cyrrent system during the past 200 thousand years based on diatom fossils in the sediment core PC-2 sampled on the R/V Mirai cruise [MR02-K03]”. JAMSTECR **48**, 1-9 (2003) (Japanese with English abstract).
19) I. Koizumi, T. Irino, and T. Oba, “Paleoceanography during the last 150 kyr off central Japan based on diatom floras”. Mar. Micropaleontology **53**, 293-365 (2004).
20) I. Koizumi, R. Tada, H. Narita, T. Irino, T. Aramaki, T. Oba, and H. Yamamoto “Paleoceanographic history around the Tsugaru Strait between the Japan Sea and the Northwest Pacific Ocean since 30 cal kyr BP”. Palaeogeogr. Palaeoclimatol. Palaeoecol. **232**, 36-52 (2006).
21) D.G. Martinson, N.G. Pisias, J.D. Hays, J. Imbrie, T.C. Moore, Jr., and N.J. Shackleton, Age dating and the orbital theory of the Ice Ages: development of a high-resolution 0 to 300,000-year chronostratigraphy. Quat. Res. **1**, 1-29 (1987).
22) I. Motoyama, N. Niitsuma, T. Maruyama, H. Hayashi, S. Kamikuri, M. Shiono, T. Kanamatsu, K. Aoki, C. Morishita, K. Hagino, H. Nishi, and M. Oda, “Middle Miocene to Pleistocene magneto-biostratigraphy of ODP Sites 1150 and 1151, northwest Pacific: Sedimentation rate and updated regional geological timescale”. The Island Arc **13**, 289-305 (2004).
23) T. Oba, M. Murayama, M. Yamauchi, M. Yamane, S. Oka, and H. Yamamoto, “Oxygen isotopic ratio of Foraminiferal tests in marine sediment cores collected during “Mirai” MR97-04 cruise”. JAMSTECR 39, 41-45 (1999) (Japanese with English abstract).
24) V.S. Sheshukova-Poretzkaya, “New and rare marine diatoms in the Neogene of Sakhalin and Kamchatka”. Akad. Nauk SSSR, Bot. Inst., Novitates Systematicae Plantaru non Vascularum **10**, 69-72 (1964) (Russian with English abstract).
25) K. Shiga, and I. Koizumi, “Latest Quaternary oceanographic changes in the Okhotsk Sea based on diatom revords”. Mar. Micropaleontology 38, 91-117 (2000).
26) C. Shimada, and S. Hasegawa, “Paleoceanographic implica-

tions of a 90,000 year long diatom record in piston core KH94-3, LM-8 off NE Japan". Mar. Micropaleontol. **41**, 153-166 (2001).

27) H. Yamamoto, Kuroshio warm current changes during the past 20 thousand years in marine sediment cores collected during "Mirai" MR97-04 cruise. JAMSTECR 39, 95-109 (1999) (Japanese with English abstract).

28) H. Yamamoto, and T. Kanamatsu, "Lithology of piston cores recovered from the northwestern Pacific Ocean on R/V Mirai cruise [MR00-K05]". JAMSTECR **44**, 55-72 (2001) (Japanese with English abstract).

29) H. Yamamoto, and K. Aoki, "Late Quaternary tephrostratigraphy in piston cores collected during _Mirai" MR00-K05 cruise". JAMSTECR **46**, 29-37 (2002) (Japanese with English abstract).

30) H. Yamamoto, M. Yamauchi, K. Aoki, M. Horii, and T. Sugawara, Lithology of piston cores recovered from the deep sea floor in the western North Pacific during the R/V Mirai cruise [MR99-K04]. JAMSTEC **41**, 37-48 (2000) (Japanese with English abstract).

31) M. Yamamoto, R. Suemune, and T. Oba, "Equatorialward shift of the subarctic boundary in the northwestern Pacific during the last deglaciation". Geophy. Res. Lett. **32**, L05609, doi:10.1029/2004GL021903 (2005).

32) I. Yasuda, K. Okuda, and Y. Shimizu, "Distribution and modification of North Pacific Intermediate Water in the Kuroshio-Oyashio interfrontal zone". J. Phys. Oceanography **26**, 448-465 (1996).

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