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Biostratigraphic and palaeoecologic evaluation of the Japan Sea's Joetsu Basin based on the study of foraminifera

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Abstract. Foraminiferal assemblage distribution was used to reconstruct the palaeoenvironmental conditions that prevailed during the deposition of the core MD179-3312 in the eastern margin of the Japan Sea. One hundred six benthic foraminifera species belonging to 50 genera and seven planktonic foraminifera species belonging to three genera were identified in this core. Cluster analyses of both benthic and planktonic foraminifera data led to the identification of seven biofacies which demonstrate the palaeoceanographic history of the Japan Sea since 130 cal kyr BP. Species diversity, evenness and dominance were measured to understand effects of environmental changes on benthic foraminifera distribution. The results indicate that changes in organic matter and oxygen content throughout the core clearly influence community structure of benthic foraminiferal assemblages and species diversity. The light colored non-laminated layers found in particular at the lowermost and uppermost core areas indicate both high diversity and equitability, corresponding to high vertical mixing and good ventilation of subsurface water which would produce suitable living environments for most species; conversely, the dark colored thinly laminated layers (TL layers), in particular TL-1 and TL-2, indicate both low diversity and equitability, corresponding to dysoxic conditions caused by a severe decrease in bottom water oxygenation which would produce unsuitable living environments for most species, with only a few species adapted to this depleted oxygen condition able to survive.

Key words: biostratigraphy, cluster analysis, foraminifera, Japan Sea, late Quaternary, palaeoceanography

Introduction

Studies on the palaeoceanography of the Japan Sea started in the late 1960's based on a small number of short cores (e.g. Ujiié and Ichikura, 1973). In the early 1980's, the first comprehensive multidisciplinary project was organized by Oba (1984) and Oba *et al.* (1991), and since then, the many cores obtained have allowed an increasing number of studies. Among these, the study of late Quaternary sediments has been of the major interest.

late Quaternary sediments of the Japan Sea are mainly composed of clay or silty clay and are characterized by the occurrence of centimeter- to decimeter-scale alterations of non-laminated, strongly bioturbated, organic-poor light-colored layers and finely laminated, organic-rich dark-colored layers which are observed basin-wide and are considered to reflect changes in bottom water oxygenation (e.g. Tada *et al.*, 1999). The centimeter- to decimeter-scale alternations of dark- and light-colored layers in the sediments of the Japan Sea are thought to be associated with the Dansgaard–Oeschger (D–O) cycles, with dark-colored layers corresponding to interstadials and light-colored layers corresponding to stadials (e.g. Tada *et al.*, 1999; Tada, 2004). Watanabe *et al.* (2007) reported on the origin of dark layers in the hemipelagic sediments of the Japan Sea covering the last 130 kyrs, mostly based on the comparison of the sedimentary fabrics that reflect bottom-water oxygenation levels between the intermediate and deep water depths. Their results suggest that dark layers deposited during glacial lowstands were formed under stratified conditions, whereas those deposited during interglacial highstands were formed under upwelling conditions.

The palaeoenvironments of the Japan Sea during late Quaternary time have been documented by studies on such various topics as stable isotopes of planktonic foraminifera (e.g. Oba *et al.*, 1991), radiolarian assemblages (e.g. Itaki *et al.*, 2004), diatom assemblages (e.g. Tada *et al.*, 1999), alkenone SST reconstructions (e.g. Ishiwatari *et al.*, 2001), benthic foraminifera (e.g. Ujiié *et al.*, 1983; Oba *et al.*, 1991), and geochemical analysis (e.g. Masuzawa and Kitano, 1984; Crusius *et al.*, 1999; Tada *et al.*, 1999). For example, Oba *et al.* (1991) showed that palaeoccanographic conditions of the Japan Sea changed drastically during the last 85 kyrs, later dividing environmental changes into five distinct chronological stages as follows (Oba *et al.*, 1995): (1) cold, low-saline surface water mixed with the Yellow Sea and East China Sea and was supplied to the Japan Sea from 85–30 cal kyr BP; (2) surface water was freshened and distinctly stratified from 30–14 cal kyr BP, with salinity reaching a minimum at 15 cal kyr BP; (3) Oyashio Cold Water (OCW) entered the Japan Sea from 14–10 cal kyr BP; (4) Tsushima Warm Current (TWC) temporally formed from 10–8 cal kyr BP; and (5) the modern oceanographic regime, Japan Sea Proper Water (JSPW), appeared after 8 cal kyr BP. In particular, Oba *et al.* (1991) discovered a positive excursion of the δ^{18}O of planktonic foraminifera during the Last Glacial Maximum (LGM), which suggests that surface water salinity had dropped significantly, probably due to the isolation of the sea in response to the glacioeustatic sea level drop and consequent decrease in the influx of the TWC during the LGM (e.g. Oba *et al.*, 1991; Matsui *et al.*, 1998). Tada *et al.* (1999) examined variations in the assemblage and number of diatoms in the Japan Sea sediments during the last 150 kyrs. They paid particular attention to warm water diatoms as indicative of the TWC and a coastal water diatom (*Paralia sulcata* (Ehrenberg) Cleve) as indicative of the East China Sea Coastal Water (ECSCW). Millennial-scale variations in the abundance and relative ratio of these diatom types were found, which they interpret as reflecting variation in the relative contribution of the ECSCW to the total influx. They further speculated that deposition of the dark layers during the last glacial period, closely associated with glacioeustatic sea level changes, reflected the expansion of the ECSCW to the mouth of the Tsushima Strait, which was caused by increased discharge from the Huanghe and Changjiang rivers due to the shift towards a wet climate in Central to East Asia. Furthermore, they recorded four distinct modes of surface and deep circulation in sediments of the Japan Sea in response to different sea level changes during the late Quaternary: The first mode corresponds to the periods of maximum sea level lowstands such as the LGM, when near-isolation of the Japan Sea led to low-saline surface water, inhibited deep water production, and created euxinic bottom water conditions. The second and third modes correspond to the periods of intermediate to low sea levels, when deep water circulation within the Japan Sea grew sensitive to the relative contribution of low-saline ECSCW to the influx, consequently causing oscillation of bottom water oxygenation levels during these periods. Finally, the fourth mode corresponds to the interglacial highstands such as the present, with the high-saline TWC flowing strongly into the Japan Sea, enhancing ventilation of its deeper parts. On the basis of these studies, the depositions of dark- and light-colored layers in the Japan Sea are thought to be well understood. However, there remains need for further research on water mass characteristics and ocean circulation of the Japan Sea through the late Quaternary.

The Joetsu area at the eastern margin of the Japan Sea has been investigated as part of a gas hydrate exploration research project since 2004. Studies conducted since that time include seafloor topography (e.g. Matsumoto, 2005), acoustic and seismic surveys (e.g. Aoyama and Matsumoto, 2009), sediment geochemistry (e.g. Freire *et al.*, 2009), pore water chemistry (e.g. Tomaru *et al.*, 2007), and foraminifera assemblages (e.g. Nakagawa *et al.*, 2009); these have provided a large amount of information about this area. In this research, the biostratigraphy of the Japan Sea during the late Quaternary is reconstructed based primarily on the vertical distribution of foraminifera at core MD179-3312 to elucidate palaeoenviromental conditions of the Japan Sea through the late Quaternary and to provide a biostratigraphic framework to the study area.

Geographic and oceanographic setting

The Japan Sea is a marginal sea of the western Pacific Ocean between the Asian mainland, the Japanese archipelago and Sakhalin. The sea has an approximately oval shape, vertically oriented from southwest to northeast. It is about 750 km long and 180 km wide with average and maximum water depths of 1350 m and 3700 m, respectively. In the northern part of the sea lies the Japan Basin, a flat-floored area between 3000 and 3500 m in depth with an oceanic crust (Murauchi, 1972; Ludwig *et al.*, 1975), while the floor of the southern half is very rough. The Yamato Rise is located in the central part of the sea, with the Yamato and Tsushima basins on its eastern and western sides. The sea is connected to the Pacific Ocean and adjacent marginal seas by four shallow straits: Tsushima Strait in the southwest, Tsugaru Strait in the northeast between Honshu and Hokkaido, Soya Strait between Hokkaido and Sakhalin, and Mamiya Strait in the north. Of these, Tsushima and Tsugaru straits are deep at approximately 135 m, while Soya and Mamiya straits are very shallow at 55 m and 12 m, respectively (Figure 1).

In contrast to other marginal seas, the circulation of

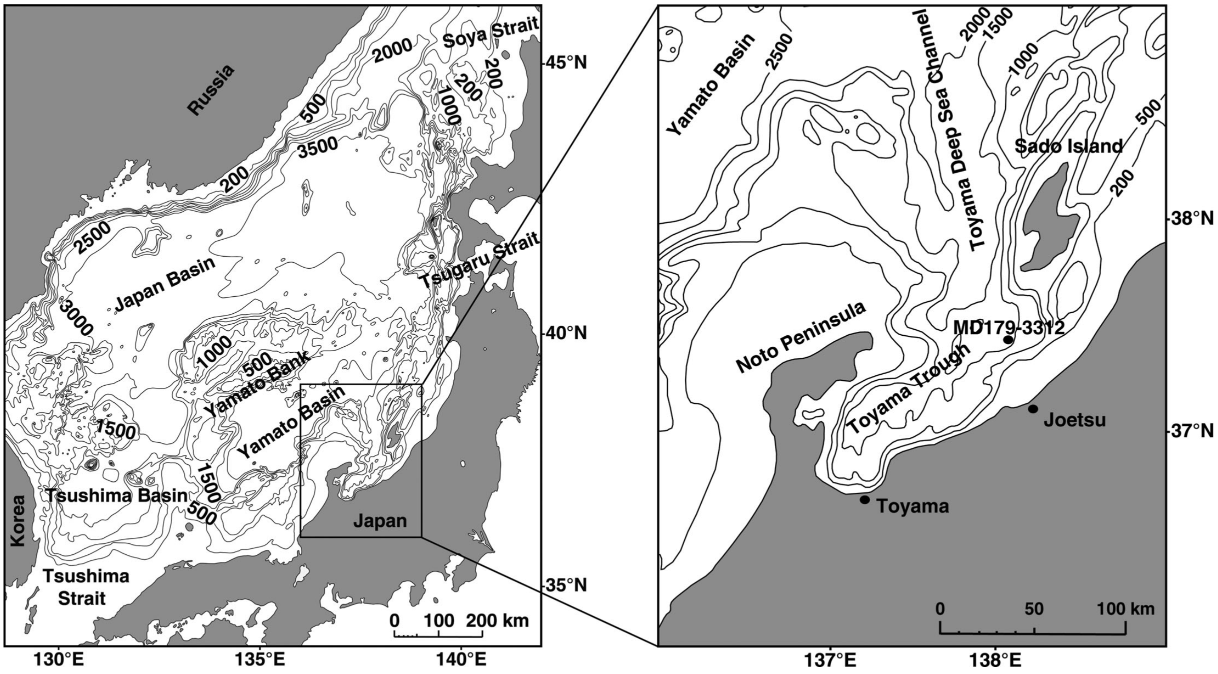

Figure 1. Bathymetric map of the Japan Sea showing the location of the study area in the Joetsu Basin, in the eastern margin of the Japan Sea and southwest of Sado Island (Maritime Safety Agency of Japan).

deep water in the Japan Sea is specific, and very well ventilated at all depths from the surface to the bottom. The Okhotsk, Bering, and East China Seas contain sills deep enough to allow the inflow of Pacific Deep Water (PDW); conversely, the sills of the Japan Sea are so shallow as to block inflow of PDW. With water exchange between adjacent seas restricted to surface water, deep water (that below 300 to 400 m) in the Japan Sea is generally homogeneous, with a low temperature (0–0.5°C), low salinity (34.0–34.1‰), and high dissolved oxygen content of about 5.0–5.5 ml/l (Moriyasu, 1972). Therefore, a special vertical circulation occurs within the sea, and a peculiar water mass is formed. This deep, cold and highly dense water is called the Japan Sea Proper Water (Uda, 1934; Gamo and Horibe, 1983; Matoba, 1983).

In the southern part of the Japan Sea, the JSPW is covered by the warm surface water of the TWC. The TWC, a branch of the Kuroshio Current (KC), mixes with ECSCW (Lim, 1971; Sawara and Hanzawa, 1979), and enters the Japan Sea through the Tsushima Strait. It differentiates inside the Japan Sea by a variety of meanders and eddies. The TWC diverges into two branches in the southwest of the Tsugaru Strait, flowing mainly into the Pacific through the Tsugaru Strait and partly to the Okhotsk Sea through the Soya Strait (Figure 2). The rest of the current cools down by mixing with cold water in the northwestern part of the Japan Sea and flows southwestward as the Liman Current (LC). The boundary between both currents forms a subpolar front at latitude 39°N to 40°N (Domitsu and Oda, 2005).

The study area is located in the Joetsu Basin, in the eastern margin of the Japan Sea and southwest of Sado Island (Figure 1). The Joetsu area (Umitaka spur and Joetsu knoll) is a proven gas hydrate field as evidenced by geochemical anomalies and the presence of a bottom simulating reflector (BSR). This area is located at the southern end of the tectonic mobile zone corresponding to the incipient convergent boundary between the eastward moving Amurian Micro-Plate, the eastern edge of the Eurasian Plate, and the North American Plate (Sato, 1994). Formation of a series of ridges, troughs and basins was initiated by tectonic inversion of the stress-field from extension to compression at around 2–3 Ma. The Joetsu knoll is regarded as uplifted antiforms bounded by eastward dipping reverse faults (Matsumoto and Kakuwa, 2011). Several large pockmarks 50 to 500 m in depth and mounds 10 to 50 m high have been observed on the seafloor on the crest of NNE-SSW trending ridges at a water depth of 900–1000 m. (Freire *et al.*, 2011; Matsumoto *et al.*, 2011). According to Matsumoto (2005), these mounds were formed by the crystallization of gas hydrates, while the pockmarks are the result of intense gas hydrate dissociation during the LGM, when the sea level dropped 120 m below that of the present

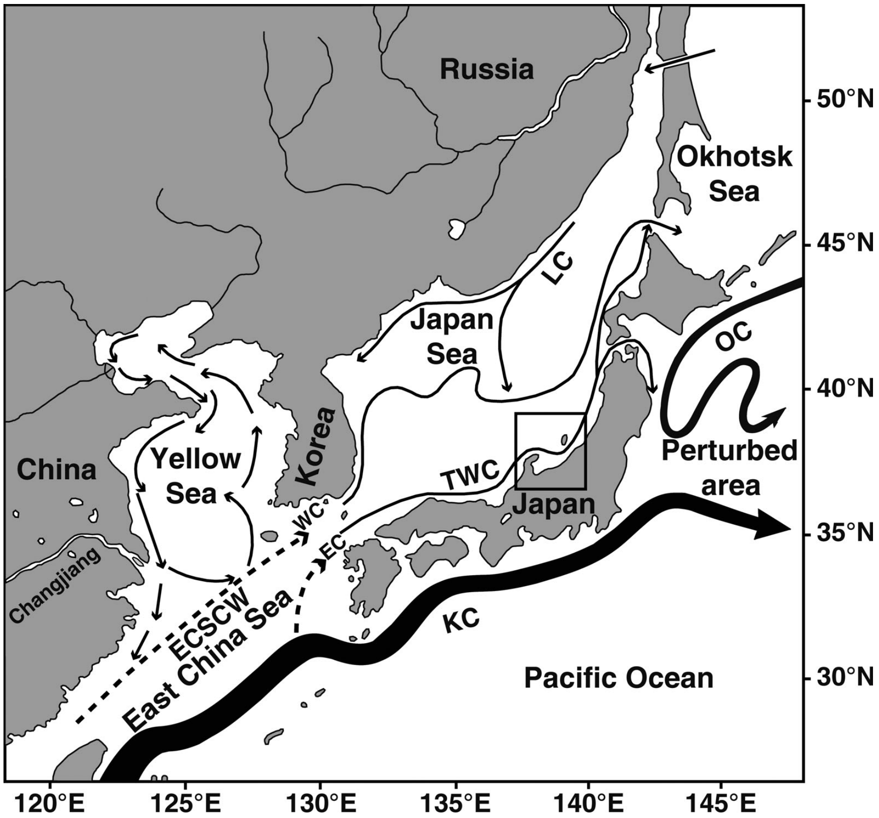

Figure 2. Map of the Japan Sea with schematic of major surface currents (Domitsu and Oda, 2005). Abbreviations: EC, Eastern Channel; ECSCW, East China Sea Coastal Water; KC, Kuroshio Current; LC, Liman Current; OC, Oyashio Current; TWC, Tsushima Warm Current; WC, Western Channel.

(Oba *et al.*, 1991). He proposed that pockmarks were the final stage after mound formation, when gas hydrate stability conditions severely dissipated during the low stand of the LGM. Piston coring and ROV dives have identified visible gas hydrates in the form of layers, platy and nodular concentrations, or fracture filling veins both in surface sediments and on the mounds located on the spur and knoll. Gigantic methane plumes, 600–700 m high, and gas venting have been observed from and around the mounds in close association with bacterial mats, carbonate crusts and concretions (Matsumoto and Kakuwa, 2011).

Material and methods

Coring and sampling

During the 2010 R/V *Marion Dufresne* expedition, a total of 19 piston coring operations were carried out in the Joetsu area. Among the recovered sediment cores, the core MD179-3312 was obtained from a terrace of an unnamed ridge in the northeastern part of the Umitaka Spur (37°32.09′N, 138°08.30′E) to provide a reference lithostratigraphy and biostratigraphy core of the study area (Figure 2). This core, with a total length of 31.135 m, was retrieved from a water depth of 1026 m using the giant piston corer Calypso with a weight of 4.5 tons, diameter of 10 cm, and length of 36.68 m.

The core was divided into 22 sections. Each section was about 150 cm in length and 10 cm in diameter. All sections were split into a working half and an archive half; the working half was temporary sampled onboard the ship by pressing a 50 cm-long, rectangular tube called a u-channel into the cut surface of the entire section half to provide materials for micropalaeontological studies, while the archive half was stored in the repository of the Kochi Core Center of Kochi University/JAMSTEC. Kumamoto University later obtained a total of 631 cube samples at depth intervals of 2.5 cm for further analyses of foraminifera, diatoms, and radiolarians.

This core was chosen as our study target because it is one of the longest apparently undisturbed records of the Joetsu Basin apart from the main area of methane seeps.

Although a few signs of gas hydrates were observed in the core, they were insufficient to cause disturbances in the foraminifera records. Also, Sub Bottom Profiler (SBP) images of this core show well developed stratification with few disturbances of deformations (Kakuwa *et al.*, 2013). This core is thus well suited to elucidate the palaeoenvironmental history of the Joetsu Basin in the Japan Sea and may also be used as a biostratigraphy standard to correlate with other cores which were extracted from methane seeps and have been influenced by gas hydrates.

Core sedimentology and chronological framework

The core was preliminarily described using on-board laboratory facilities and then measured, photographed and microscopically analyzed in detail at the Kochi Core Center of Kochi University/JAMSTEC (Matsumoto and Kakuwa, 2011; Kakuwa *et al.*, 2013). The core is composed of non-laminated, bioturbated, light-colored silty clay alternating with thinly laminated dark-colored silty clay with occasional intercalation of regional and local tephra layers (Figure 3). The thinly laminated dark-colored layers, called TL layers (Tanaka, 1984), are a well known and ubiquitous feature that extend over the basins of the Japan Sea (e.g. Nakajima *et al.*, 1996), and are useful stratigraphic markers for the Japan Sea. Twenty-five TL layers were identified in this core, numbered from TL-1 to TL-25 in ascending order (Kakuwa *et al.*, 2013). Each TL layer was identified by its occurrence with the help of widespread tephra (Kakuwa *et al.*, 2013) and was separated by bioturbated layers. Seven well known tephra layers, namely, Aira-Tanzawa Ash (AT), Ontake-Nagawa Ash (On-Ng), Aso-4 Ash (Aso-4), Ontake-Katamachi Ash (On-Kt), Kikai-Tozurahara Ash (K-Tz), Sanbe-Kisuki Ash (SK), and Toya Ash (Toya), were identified in this core on the basis of the shape of glass shards and the chemical composition of volcanic glass in correlation with land or marine tephra layers of known age (Nakamura *et al.*, 2013). Two unknown tephra layers, Joetsu 1 (Jo-1) and Joetsu 2 (Jo-2), were also identified (Nakamura *et al.*, 2013), confirming them as new marker tephras in the eastern margin of the Japan Sea (Freire, 2010).

The chronology of this core was reconstructed through radiocarbon dating of the tests of planktonic foraminifera and wood fragments, TL layers, stable isotope analysis, and marker tephra layers (Ishihama *et al.*, 2014). Based on age-depth correlation, this core covers approximately the age between 0 to 130 cal kyr BP; the sedimentation rate for 130 to 88 cal kyr BP was 25.1 cm/kyr, gradually decreasing to 22.7 cm/kyr for the last 88,000 years.

Foraminiferal processing

Foraminiferal faunal processing was conducted on 110 cube samples throughout the core. The samples generally consisted of 15.3 cm^3 sediments. In order to remove water content without greatly altering the physical structure of the sediments, all samples were first frozen in a laboratory freezer to convert the water content of the sediments to ice. The frozen samples were then placed into a vacuum chamber to remove the unbound or free ice through sublimation. This process reduces foraminifera breakage resulting from contraction of the sediment due to drying and also prevents carbonate reprecipitation, which may change the isotopic composition of the foraminifera. Next, freeze-dried samples were wet-sieved with a mesh openings of 63 μm using a water jet. Each washed residue was then oven-dried at 40°C and microsplit down to an amount containing almost 150–300 specimens for identification and census count of benthic foraminifera, while for planktonic foraminifera analyses, the samples were dry sieved once more with mesh openings of 125 μm. Figure 4 shows the number of total benthic and planktonic foraminifera at this core. Foraminifera were identified at the generic level largely using the taxonomy of Loeblich and Tappan (1988). Allocation of the foraminiferal taxa into morphogroups of species was largely performed following Asano (1950–1952), Ujiié *et al.* (1983), and Jones (1994).

Analysis of foraminiferal faunas

Raw numerical data of both benthic and planktonic species counts were standardized by calculating relative abundance in all samples (Figure 5). Benthic foraminiferal abundance data were then used to calculate species diversity in terms of Shannon index (H') and species evenness (J'). The Shannon index was calculated using:

$$H' = -\Sigma \left((n_i / N) \times \log (n_i / N)\right)$$

Where n_i is the number of individuals of the i-th species and N is the total number of individuals in each sample.

Species evenness (J') was calculated using the following equation:

$$J' = H' / \log S$$

Where H' is the Shannon index and S is the number of species.

Cluster analyses of benthic and planktonic foraminifera were performed to compare the composition of foraminifera assemblages and their distribution through the core material of MD179-3312 (Figures 6–8). Benthic foraminifera cluster analysis was adopted to study bottom water conditions, while planktonic foraminifera analysis was used to reconstruct sea-surface hydrology. Both R-mode and Q-mode cluster analyses were under-

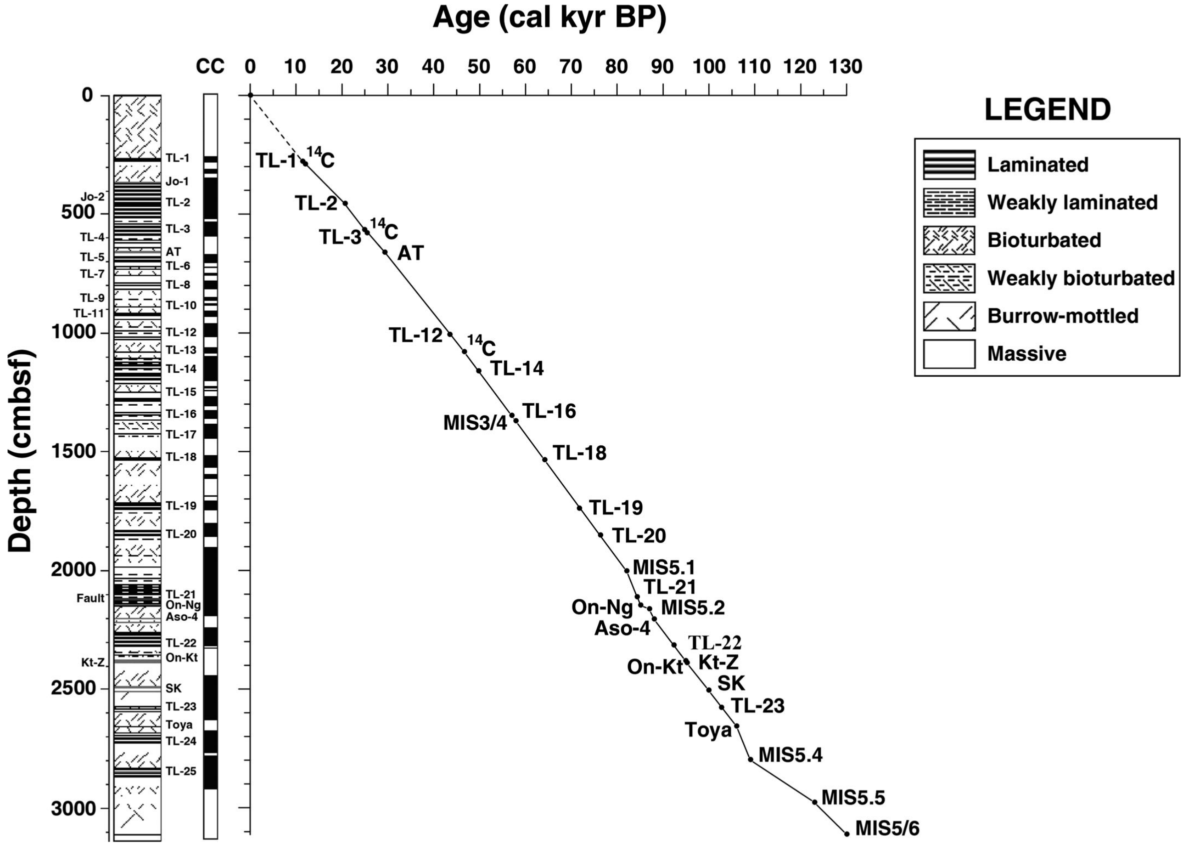

Figure 3. Lithology and age model for the core MD179-3312. Data are from Kakuwa *et al.* (2013) and Ishihama *et al.* (2014). Abbreviations: cal kyr BP, calibrated kiloyear (thousand years) Before Present; cmbsf, centimeters below the sea floor; CC, Color Changes (black bars display dark layers).

taken in this study. R-mode analysis was used to group taxa into clusters with similar patterns of distribution, whereas Q-mode analysis was conducted to group samples into clusters that share similar foraminifera assemblages. Cluster analysis was conducted using a program written by Hasegawa (1988). The similarity index of cluster analysis in this program is adopted using Horn's modification of Morishita's overlap index (Horn, 1966). It is intensified from Shannon's information function, and is given by the following equation:

$$\text{Overlap} = R_o = (\Sigma\ (x_i+y_i)\log(x_i+y_i) - \Sigma\ x_i \log x_i - \Sigma\ y_i \log y_i) / ((X+Y)\log(X+Y) - X\log X - Y\log Y)$$

Where x_i, and y_i are the individual number of the i-th species in samples X and Y, respectively. For both R-mode and Q-mode cluster analyses, samples were required to contain a minimum of 50 specimens if more than 3 species were present.

In addition, benthic foraminifera data used to calculate the Benthic Foraminifera Oxygen Index (BFOI) following Kaiho (1994):

$$\text{BFOI} = [O / (O + D) \times 100]$$

Where O is the number of oxic species and D is the number of dysoxic species.

Results

Foraminifera data and general features of foraminifera specimens

From the 110 samples studied of this core, 56,523 specimens were examined, allowing discrimination of a total of 106 benthic foraminifera species belonging to 50 genera and 7 planktonic foraminifera species belonging to 3 genera (Appendixes 1 and 2). Scanning electron microscope (SEM) images of the most important foraminifera species are displayed in Figures 9–11. Benthic assemblages contain diverse mixtures of taxa that inhabit epifaunal to deep infaunal microhabitats. Calcareous forms (as opposed to agglutinated forms) dominate benthic assemblages, accounting for 90% or more of the benthic populations in this core. In terms of maximum

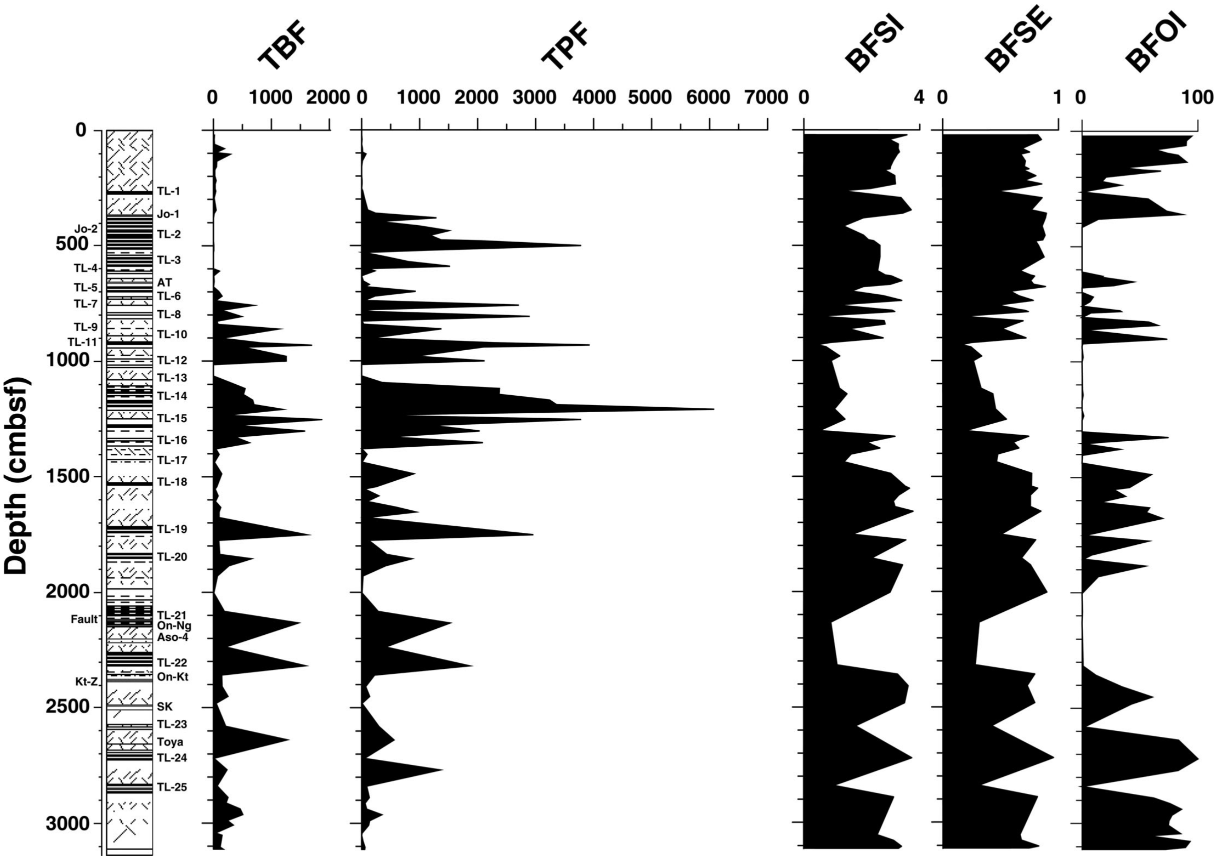

Figure 4. Number of total benthic and planktonic foraminifera, species diversity (*H*′), species evenness (*J*′), and benthic foraminifera oxygen trend from the core MD179-3312. Abbreviations: BFOI, Benthic Foraminifera Oxygen Index; BFSE, benthic foraminifera species evenness; BFSI, benthic foraminifera Shannon index; TBF, total benthic foraminifera; TPF, total planktonic foraminifera.

percentages of individual species in a given sample, *Brizalina pacifica* (Cushman and McCulloch) (94%), *Stainforthia loeblichi* (Feyling-Hanssen) (50.4%), *Pseudoparrella takayanagii* (Iwasa) (50%), and *Eilohedra rotunda* (Husezima and Maruhasi) (48%) are the most abundant taxa. Of the planktonic population, *Neogloboquadrina pachyderma* (Ehrenberg) is the most dominant species with maximum percentage greater than 99.5%; *Globigerina bulloides* d'Orbigny and *Globigerina quinqueloba* Natland are secondary dominant species with maximum percentages of 84 and 71 percent, respectively; while *Neogloboquadrina incompta* (Cifelli) (86%) and *Globigerina umbilicata* Orr and Zaitzeff (44%) are occasionally abundant on the top and bottom of the core and between 550.75 to 361.25 cmbsf, respectively.

The absolute abundance of both benthic and planktonic foraminifera of this core was calculated as the number of specimens per gram of dry sediment (Figure 4). The benthic foraminifera absolute abundance varies between 0 to 1,870, while planktonic foraminifera numbers are much higher ranging from 0 to 6,080 specimens per gram of dry sediment. From the bottom to the middle of the core (3113.5 to 1402.75 cmbsf), excepting tephra and TL layers, both benthic and planktonic foraminifera numbers are moderate, 1,606 in benthic and 2,963 in planktonic foraminifera population. The highest values of benthic and planktonic foraminifera abundances occur in sediments deposited from 1402.75 to 550.75 cmbsf at 1,869 in benthic and 6,079 in planktonic foraminifera population. Benthic foraminifera decrease in number abruptly from very high values to 5 specimens per gram of dry sediment from 550.75 to 361.25 cmbsf; however, the absolute abundance of planktonic foraminifera remains relatively high at about 3,785 specimens per gram of dry sediment through this interval. In the uppermost segment of the core (361.25 cmbsf to top), both benthic and planktonic numbers are absolutely low at 289 and 239 specimens per gram of dry sediment, respectively.

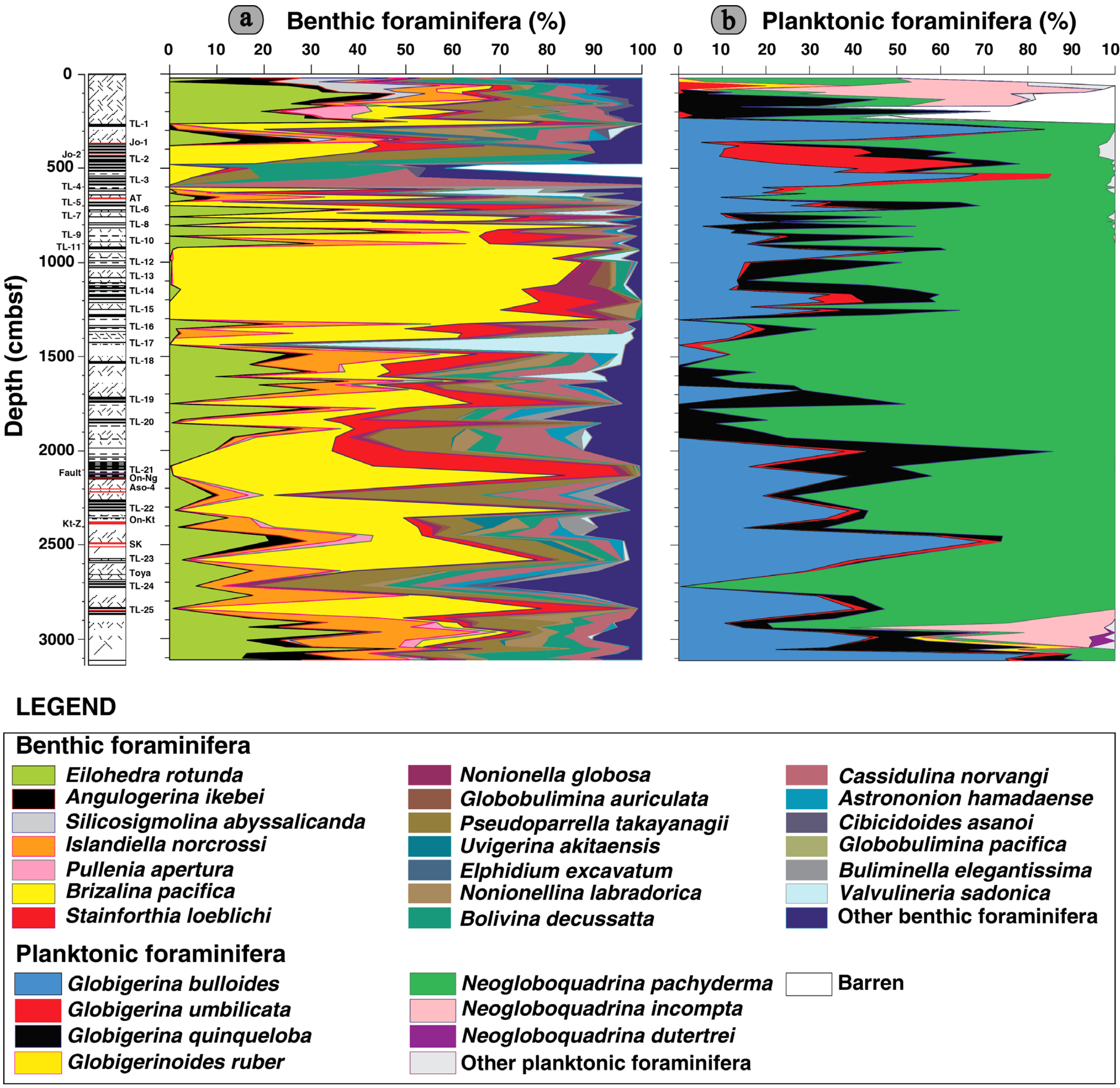

Figure 5. Relative abundance of benthic (a) and planktonic foraminifera (b) from the core MD179-3312.

Benthic foraminifera species diversity and equitability

Figure 4 shows species diversity evaluated by Shannon index (H') and species evenness (J'). Species distribution pattern and diversity is clearly related to changes in the texture of the sediments due to oxygen availability throughout the core. The curves representing the H' and J' values are at minimums in thinly laminated dark-colored layers and peak in non-laminated light-colored layers. Relationships between species diversity, equitability, and species number were utilized to graph two groups of this core (Figure 6). The first group is characterized by high diversity (greater than 2) and high equitability (greater than 0.5) and in particular represents samples from 3113.45 to 1303.25 cmbsf, and 921.75 cmbsf to top, excluding the TL-2 and TL-1 layers. The second group is dominated by low diversity and low equitability, representing samples from 1303.25 to 921.75 cmbsf as well as the TL-2 and TL-1 layers.

Discussion

Benthic foraminifera cluster analysis

R-mode cluster analysis of benthic foraminifera assemblages was conducted on the faunal data set con-

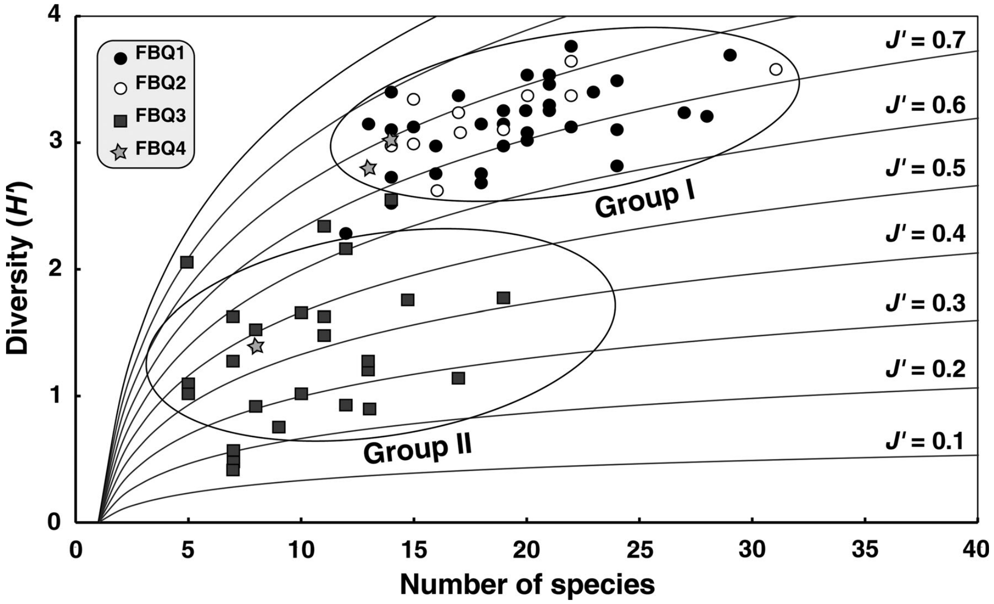

Figure 6. Benthic foraminifera Q-mode clusters and their relation with species diversity and equitability from the core MD179-3312. FBQ1–FBQ4, clusters identified through Q-mode cluster analyses (see text in details).

sisting of a census count of 33 foraminiferal species in a set of 92 samples which produced a dendrogram differentiate of four groups of species (Clusters FBR1 to FBR4) and five outliers (*Valvulineria sadonica* Asano, *Uvigerina akitaensis* Asano, *Cushmania striatopunctata* (Parker and Jones), *Buliminella elegantissima* (d'Orbigny), and *Elphidium excavatum* (Terquem)). To elucidate biofacies based on similarities among the samples, Q-mode cluster analysis was also conducted utilizing the same data set, resulting in the identification of four clusters (clusters FBQ1 to FBQ4). Results of the R-mode and Q-mode cluster analyses are illustrated in Figures 7 and 8. Clusters of R-mode analysis and their distribution through the core (Q-mode clusters) are described as follows:

Cluster FBR1 is dominated by *Angulogerina ikebei* Husezima and Maruhasi, *Islandiella norcrossi* Cushman, *Bolivina decussata* Brady, *Astrononion hamadaense* Asano, *Cassidulina norvangi* Thalmann, *E. rotunda*, *P. takayanagii*, *Pullenia apertura* Cushman, *Nonionellina labradorica* (Dawson), *Fissurina* spp., *Pyrgo* spp., *Quinqueloculina* spp., *Triloculina* spp., *Evolvocassidulina* sp., *Lagena* spp., *Procelolagena* spp., *Astrononion* spp., *Entosolenia* spp., and *Karreriella baccata japonica* Asano. Samples containing assemblages of cluster FBR1 are grouped in the Q-mode clusters FBQ1 and FBQ2, which are distributed through non-laminated, light-colored layers; its foraminifera, though, are particularly abundant in the lowermost (3113.5 to 2889.25 cmbsf, 130-114.5 cal kyr BP) and uppermost (263.25 cmbsf to top, 10.5 cal kyr BP to present) of the core. Among foraminifera of this cluster, *A. ikebei*, *I. norcrossi*, *B. decussata*, *A. hamadaense*, *C. norvangi*, *E. rotunda*, and *P. takayanagii* share the greatest similarity (0.8–1). In the present Japan Sea, these species are mostly distributed in offshore water regions of outer sublittoral to upper bathyal zones (Akimoto and Hasegawa, 1989), and they are usually common in the present JSPW (Ujiié *et al.*, 1983; Matoba and Nakagawa, 2009).

P. apertura of this cluster can be found in recent sediments of upper offshore water regions of the upper bathyal zone (Akimoto and Hasegawa, 1989). In the northern part of the Okhotsk Sea, this species is distributed in the intermediate area with the same physical conditions as JSPW, but a less saline status (Oi, 2011).

N. labradorica, which is distributed in offshore water regions of the middle sublittoral zone of the recent Japan Sea (Akimoto and Hasegawa, 1989), is an important indicator of warming conditions after the last glaciation in North Atlantic shelf areas (Scott *et al.*, 2004), which generally occurs during the latter stages of deglaciation. Recent distribution studies from the Barents and Kara seas (Hald and Steinsund, 1992) show a clear relationship between *N. labradorica* abundance maxima and the position of the polar front. The connection between the polar front and the high amounts of organic carbon that were input to the sediment may be related to enhanced productivity at these regions. Therefore the proximity of

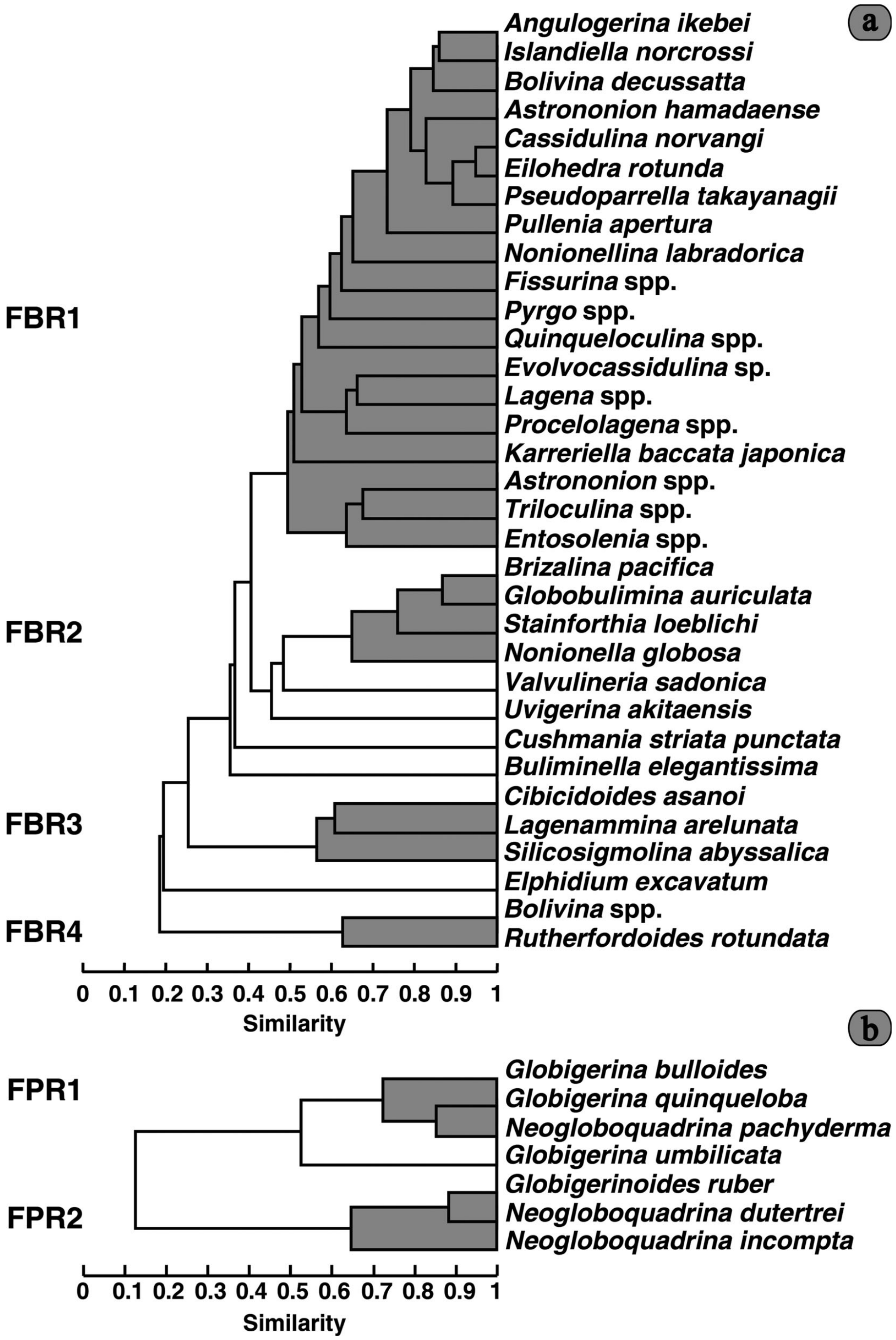

Figure 7. R-mode cluster analysis of benthic (a), and planktonic foraminifera (b) from the core MD179-3312. Shading indicates four and two distinct assemblages for benthic and planktonic foraminifera, respectively.

the polar front might be one of several possible explanations for *N. labradorica*'s relative abundance peak in glaciomarine sequences (Andrews *et al.*, 1996). The infaunal life mode of *N. labradorica* (Corliss, 1991; Corliss and van Weering, 1993; Hunt and Corliss, 1993) further suggests the affinity of this species for environments with at least seasonally elevated concentrations of food in sediment, although *N. labradorica* is also capable of surviving prolonged starvation (Cedhagen, 1991).

Other species of this cluster such as *Quinqueloculina*

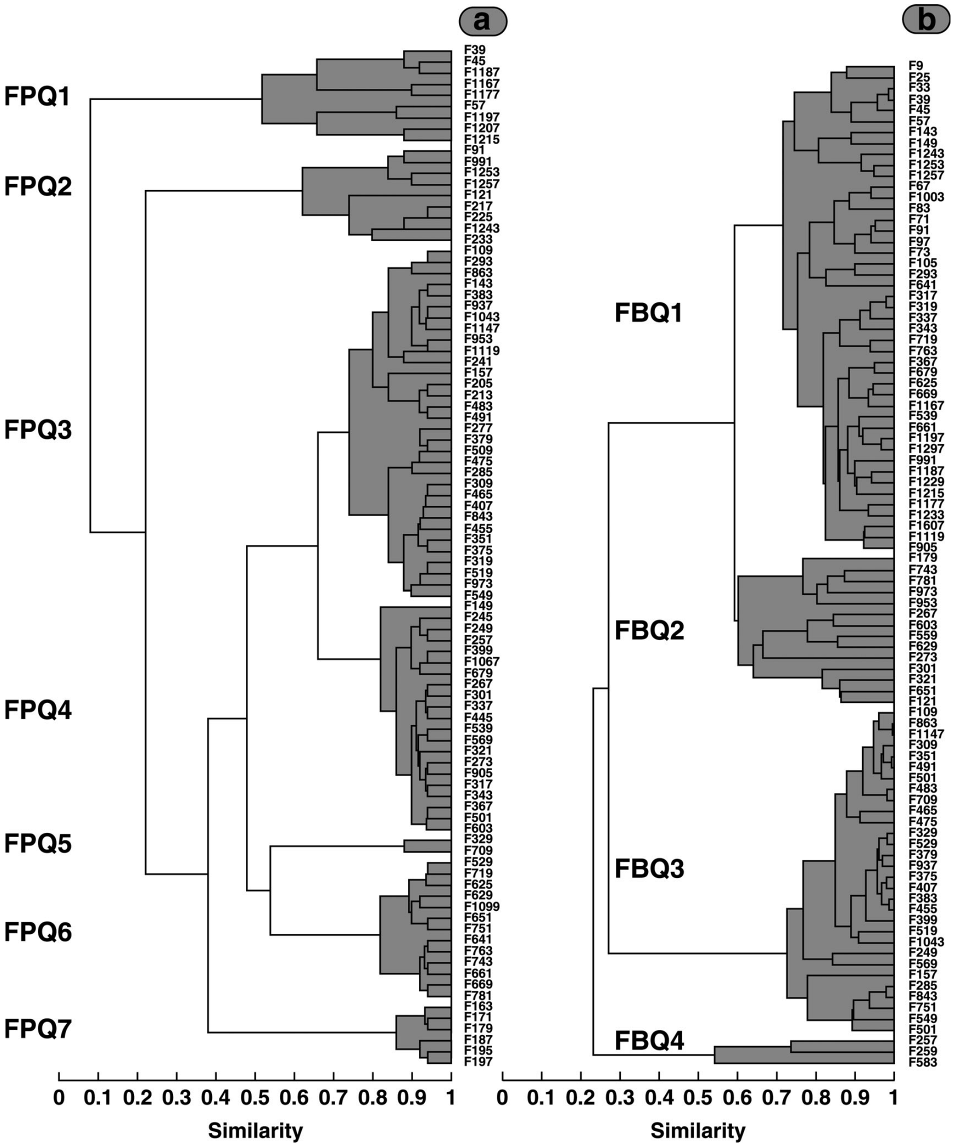

Figure 8. Q-mode cluster analysis of planktonic (a), and benthic foraminifera (b) from the core MD179-3312. Shaded areas indicate major sample groups.

spp., *Triloculinella* spp., and *Pyrgo murrhina* (Schwager) are distributed in the offshore regions of the inner- to middle-sublittoral zone of the modern Japan Sea (Akimoto and Hasegawa, 1989) and are usually abundant under high-oxygen bottom-water conditions (Kaiho, 1994).

Fissurina spp., *Lagena* spp., *K. japonica*, *Evolvocassidulina* sp., *Astrononion* spp., and *Entosolenia* spp. have the least similarity among foraminifera of this cluster. They appear in minor amounts of about 3 to 5 specimens per sample and are irregularly distributed in the core; however, they are especially abundant through warm stages. Excepting *P. apertura*, whose occurrence does not extend to the uppermost Pleistocene, other foraminifera of cluster FBR1 are mostly prominent in the Holocene portion and correspond to a well ventilated, highly oxic environment (Ujiié *et al.*, 1983; Matoba and Nakagawa, 2009).

Cluster FBR2 is represented by a very thin wall and elongated or flattened benthic foraminifera species, including *B. pacifica*, *Nonionella globosa* Ishiwada, *Globobulimina ariculata* (Bailey), and *S. loeblichi*. Samples including this assemblage are grouped in FBQ3 of Q-mode cluster, and its foraminifera are mainly abundant in dark-colored layers. In the modern Japan Sea, the for-

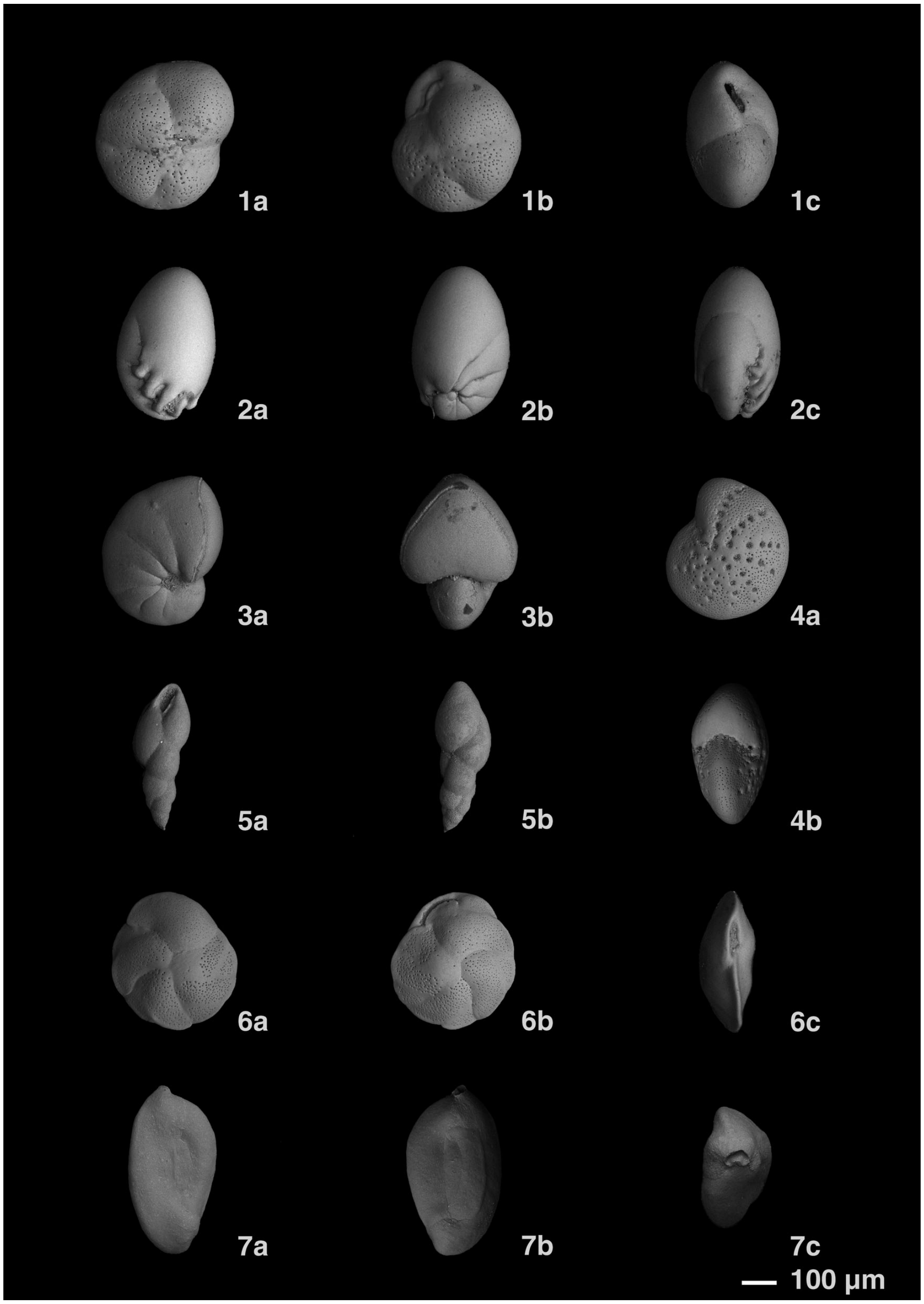

Figure 9. Scanning electron microscope (SEM) images of benthic foraminifera from the core MD179-3312, Joetsu Basin, eastern margin of the Japan Sea. **1,** *Cassidulina norvangi* Thalmann; 1a, side view; 1b, opposite side; 1c, edge view; **2,** *Nonionella globosa* Ishiwada; 2a, side view; 2b, opposite side; 2c, edge view; **3,** *Nonionellina labradorica* (Dawson); 3a, side view; 3b, edge view; **4,** *Elphidium excavatum* (Terquem); 4a, side view; 4b, edge view; **5,** *Stainforthia loeblichi* (Feyling-Hanssen); 5a, side view; 5b, opposite side; **6,** *Islandiella norcrossi* Cushman; 6a, side view; 6b, opposite side; 6c, edge view; **7,** *Silicosigmolina abyssalica* Inoue; 7a, side view; 7b, opposite side; 7c, edge view.

aminifera of this cluster can be found within the outer sublittoral to upper bathyal zone (Akimoto and Hasegawa, 1989). Many researchers have reported evidence of these species in depleted oxygen environments (Phleger and Soutar, 1973; Kato, 1992; Kaiho, 1994; Ohkushi *et al.*, 2003; Matoba and Nakagawa, 2009); however, they also

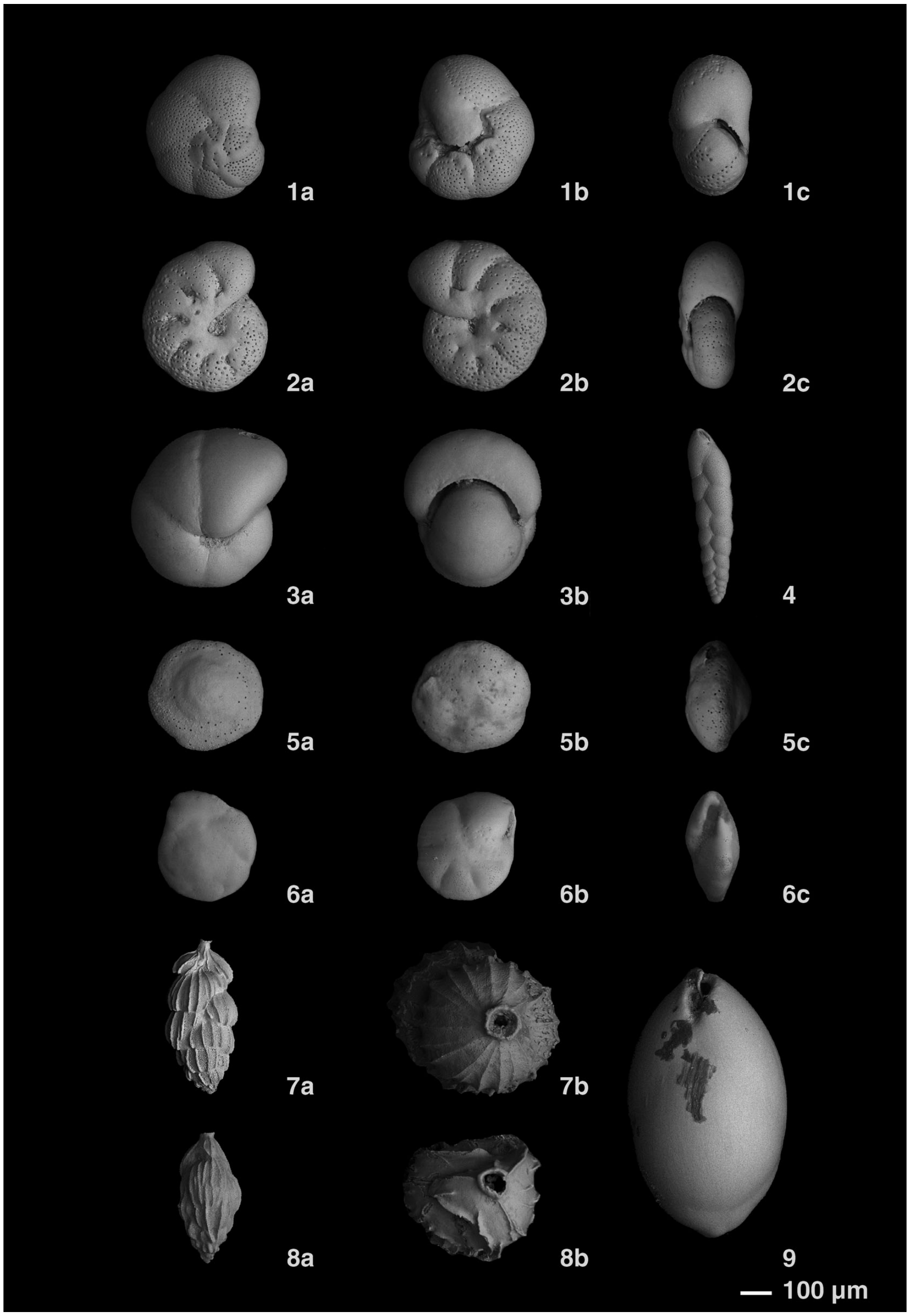

Figure 10. Scanning electron microscope (SEM) images of benthic foraminifera from the core MD179-3312, Joetsu Basin, eastern margin of the Japan Sea. **1,** *Valvulineria sadonica* Asano; 1a, dorsal view; 1b, ventral view; 1c, edge view; **2,** *Astrononion hamadaense* Asano; 2a, side view; 2b, opposite side; 2c, edge view; **3**, *Pullenia apertura* Cushman; 3a, side view; 3b, edge view; **4,** *Brizalina pacifica* (Cushman and McCulloch), side view; **5,** *Eilohedra rotunda* (Husezima and Maruhasi); 5a, dorsal view; 5b, ventral view; 5c, edge view; **6,** *Pseudoparrella takayanagii* (Iwasa); 6a, dorsal view; 6b, ventral view; 6c, edge view; **7,** *Uvigerina akitaensis* Asano; 7a, side view; 7b, apertural view; **8**, *Angulogerina ikebei* Husezima and Maruhasi; 8a, side view; 8b, apertural view; **9,** *Globobulimina auriculata* (Bailey), side view.

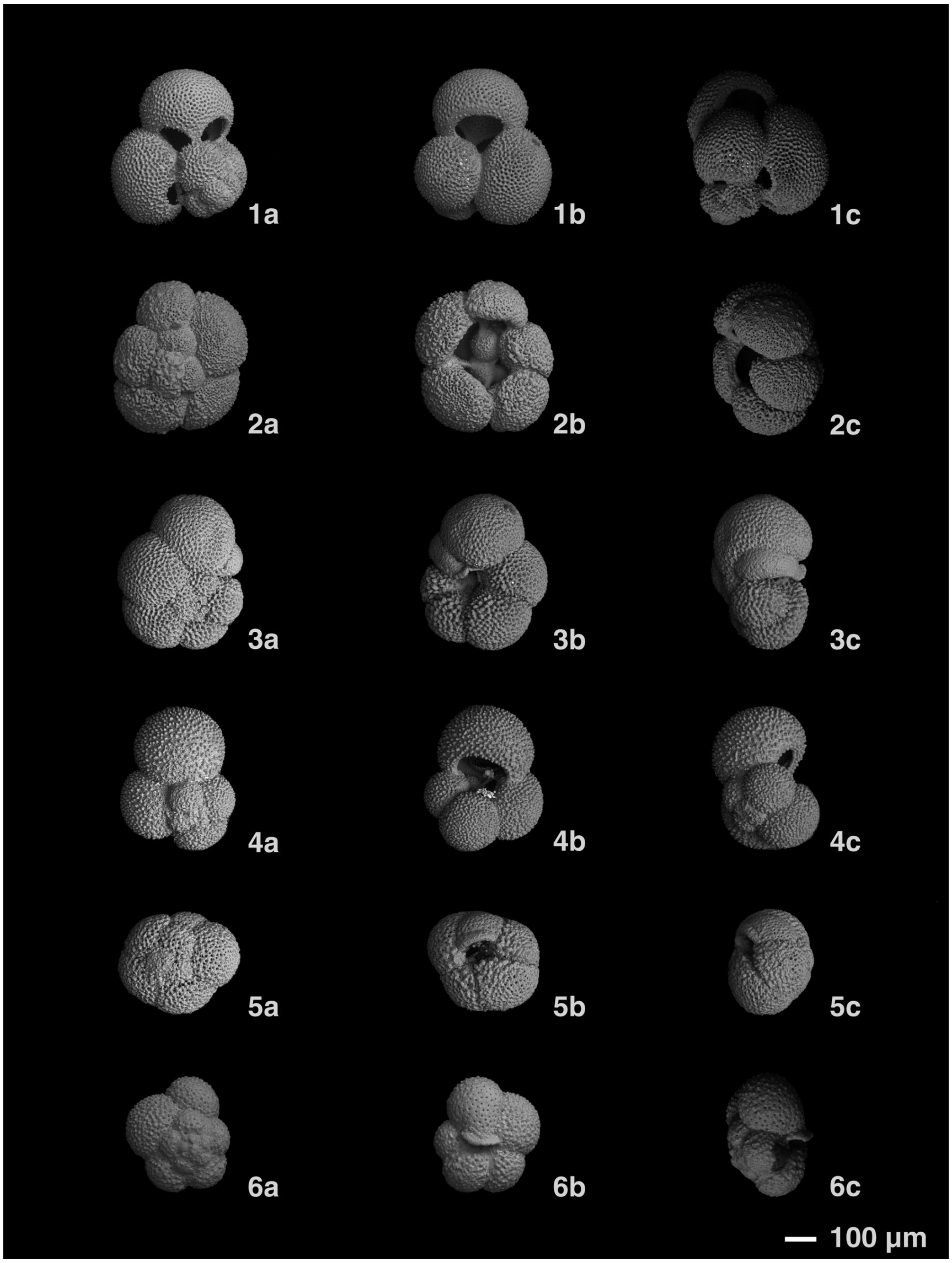

Figure 11. Scanning electron microscope (SEM) images of planktonic foraminifera from the core MD179-3312, Joetsu Basin, eastern margin of the Japan Sea. **1,** *Globigerinoides rube*r (d'Orbigny); 1a, oblique view; 1b, ventral view; 1c, edge view; **2,** *Globigerina umbilicata* Orr and Zaitzeff; 2a, oblique view; 2b, ventral view; 2c, edge view; **3,** *Neogloboquadrina incompta* (Cifelli); 3a, oblique view; 3b, ventral view; 3c, edge view; **4,** *Globigerina bulloides* d'Orbigny; 4a, oblique view; 4b, ventral view; 4c, edge view; **5,** *Neogloboquadrina pachyderma* (Ehrenberg); 5a, oblique view; 5b, ventral view; 5c, edge view; **6,** *Globigerina quinqueloba* Natland; 6a, oblique view; 6b, ventral view; 6c, edge view.

can live as infauna in high-oxygen bottom water conditions. That these species are common in dysoxic environments may be due to the difficulty of secreting carbonate in such harsh conditions (Rhoads and Morse, 1971).

Cluster FBR3 is represented by *Cibicidoides asanoi* Matsunaga, *Lagenammina arenulata* (Skinner), and

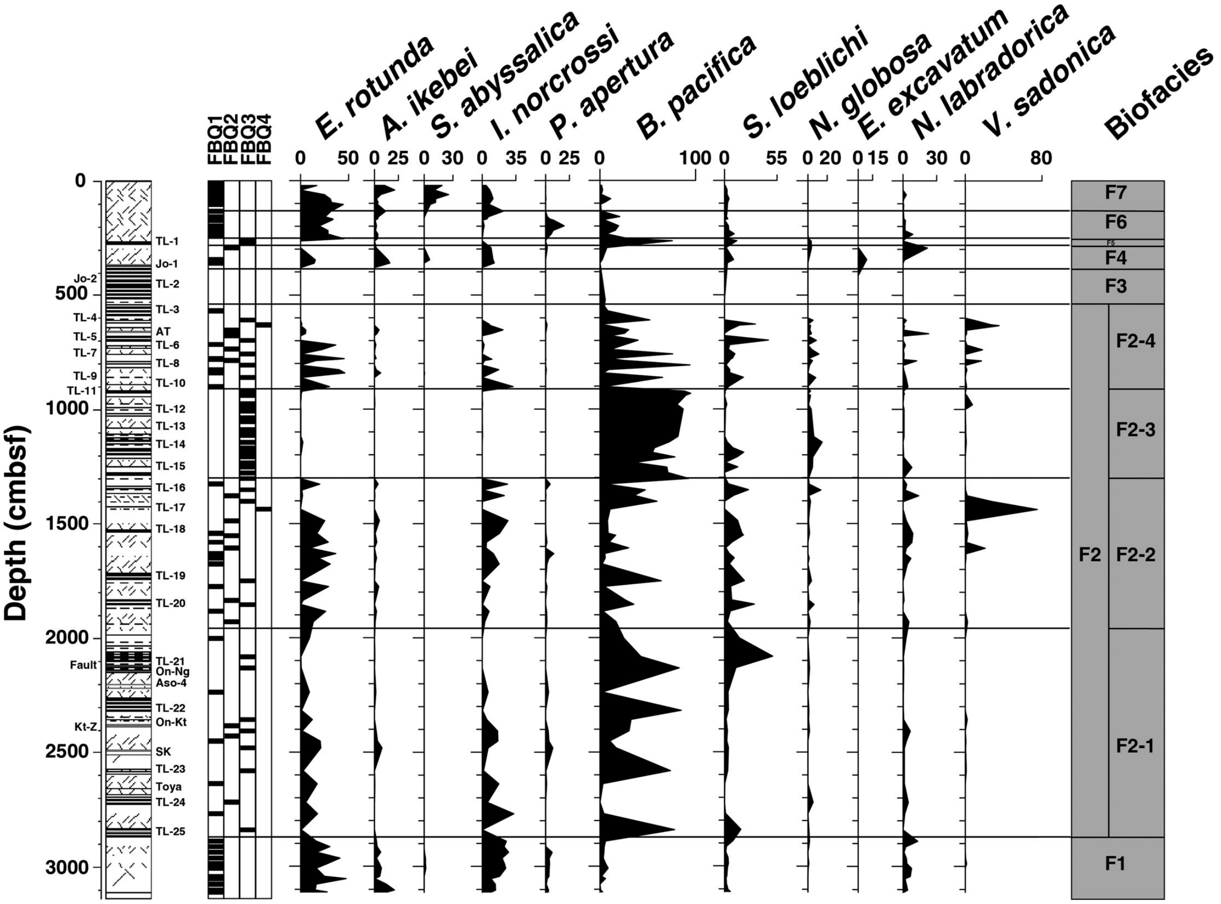

Figure 12. Biofacies and the relative abundance of the main species of benthic foraminifera from the core MD179-3312.

Silicosigmolina abyssalica Inoue. Samples containing assemblages of cluster FBR3 are grouped in FBQ1 of Q-mode cluster. In the present Japan Sea, *Lagenammina* and *Silicosigmolina* can be found in the offshore water regions of the upper bathyal zone (Akimoto and Hasegawa, 1989). Excepting *C. asanoi,* which is a calcareous form, the other species of this cluster are arenaceous forms, with their tests being composed of sandy material agglutinated to a chitinous base. They are easily distorted by pressure, and only appear in the uppermost segment of the core.

Cluster FBR4 is dominated by *Bolivina* spp. and *Rutherfordoides rotundata* (Parr). Both *Bolivina* and *Rutherfordoides* are infaunal taxa which have been reported by many researchers from different methane-rich marine settings and have proved good indicators of methane eruptions (Montagna *et al.*, 1989; Akimoto *et al.*, 1994; Sen Gupta and Aharon, 1994; Sen Gupta *et al.*, 1997; Rathburn *et al.*, 2000, 2003; Bernhard *et al.*, 2001). These species feed on rich bacterial food sources at methane seeps, indicating their potential as a proxy for methane fluxes in geological records. Akimoto *et al.* (1994) reported *Rutherfordoides cornuta* (Cushman) with *Calyptogena* clam communities from cold seepages at Sagami Bay. Kitazato (1996) suggested that the mentioned species host sulfide oxidizing bacterial symbionts, or are an anaerobic species able to respire in anoxic environments. Bernhard *et al.* (2001) reported *R. rotundata* as methanophilic taxa in clam flats of Monterey Bay. *R. rotundata* has also been reported as characteristic to CH4-enriched and low oxygen environments during the LGM at methane seepage areas of the Joetsu Basin in the eastern margin of the Japan Sea (Nakagawa *et al.*, 2009; Matsumoto and Kakuwa, 2011). Samples containing these species are grouped in FBQ4 of Q-mode cluster, where these species appear in small amounts below and in the lower part of the TL-2 layer.

In addition, five outliers, *V. sadonica*, *U. akitaensis*, *C. striatopunctata*, *B. elegantissima*, and *E. excavatum*, appear in the R-mode dendrogram. *V. sadonica* is a marker species in the sediments of the Japan Sea that dis-

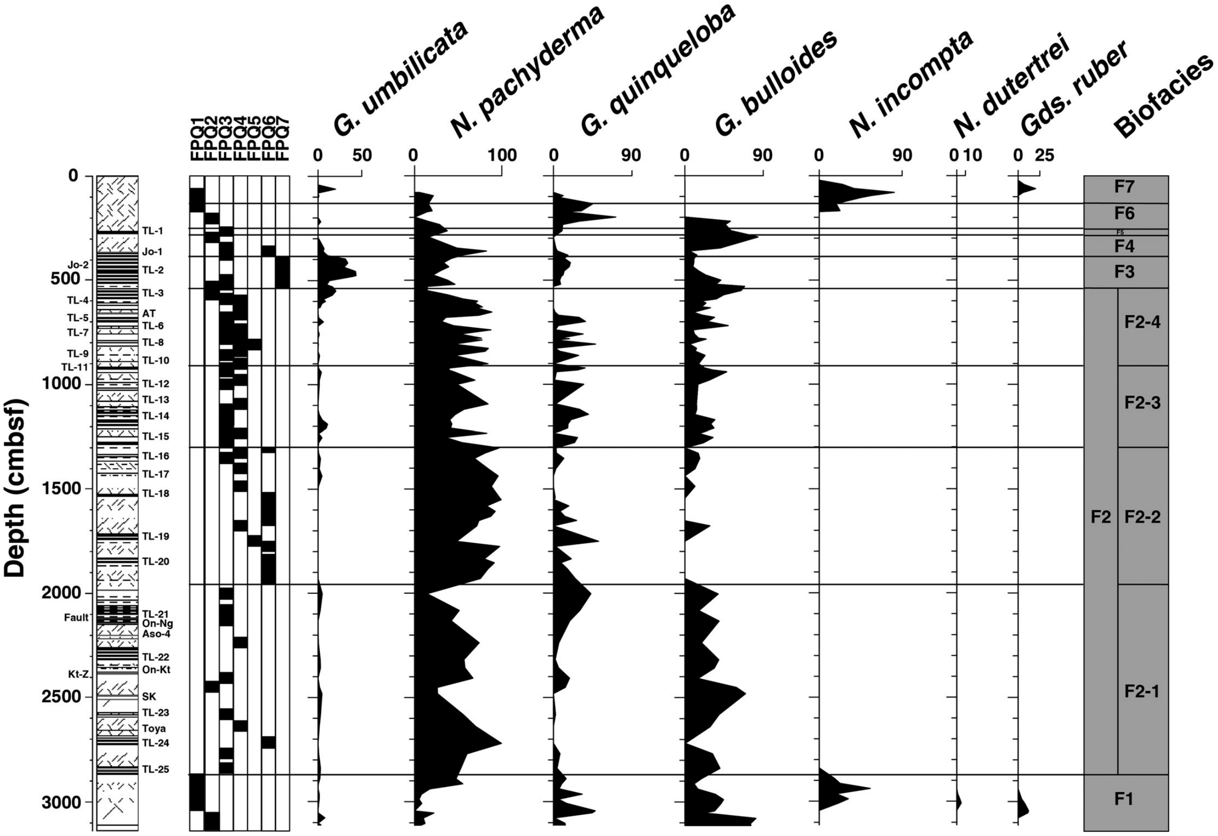

Figure 13. Biofacies and the relative abundance of the main species of planktonic foraminifera from the core MD179-3312.

appears just prior to the LGM (Ujiié *et al.*, 1983; Kato, 1992). In the study area, samples containing this species are grouped in FBQ4 of Q–mode cluster, with the species becoming extinct below the TL-2 layer. *U. akitaensis* is an infaunal species whose existence in the sediments of the Japan Sea is limited to the lower Pleistocene (Ujiié *et al.*, 1983). However, in the study area, it also appears in minor amounts in the Holocene portion. *B. elegantissima* is an infaunal, detritivore species (Murray, 1991) normally rare in tide pool deposits and locally common in shallow estuaries near the open ocean (Andrews *et al.*, 1996) such as Berkeley Harbor and Tomales Bay (both in northern California); it may also be locally abundant in polluted environments (Bandy *et al.*, 1964). Murray (2006) reported this species from less turbulent areas of marginal marine environments. In the present Japan Sea, the bathymetric distribution of this species is mostly restricted to an inner sublittoral zone above 45 m (Akimoto and Hasegawa, 1989). In the study area, this species together with *C. striatopunctata* are in low number, one to five specimens per sample, and irregularly distributed throughout the core. Finally, *E. excavatum* is a marker species of cold, shallow water less than 200 m in the northwestern part of the Pacific Ocean (Saidova, 1961). This species, along with *A. hamadaense*, is commonly found in relatively cold waters often associated with proximal glaciomarine conditions (Osterman and Nelson, 1989; Hald and Korsun, 1997; Korsun and Hald, 2000; Husum and Hald, 2004). It has been reported in the modern Japan Sea from the offshore water region of the inner sublittoral zone above 45 m (Akimoto and Hasegawa, 1989). In the core MD179-3312, it appears in samples that are distributed above the TL-2 layer from 585.75 to 545.75 cmbsf.

Planktonic foraminifera cluster analysis

R-mode and Q-mode cluster analyses of planktonic foraminifera assemblages were carried out based on a faunal data set consisting of seven foraminiferal species in a set of 92 samples. The R-mode dendrogram comprises two main clusters (clusters FPR1 and FPR2) and one outlier (*G. umbilicata*), illustrated in Figure 7. The Q-mode cluster (Figure 8) consists of seven clusters (clusters FPQ1 to FPQ7), each corresponding to groups of samples containing a similar planktonic foraminiferal assemblage. Clusters of R-mode analysis and their distribution through the core (Q-mode clusters) are described as follows:

Cluster FPR1 is dominated by *N. pachyderma*, *G. quinqueloba*, and *G. bulloides*. At present, *N. pachyderma* is a dominant cold-water species in polar and subpolar regions (Bé, 1977) which is not only able to survive but also to reproduce in the high latitudes (Darling *et al.*, 2004). It is highly prevalent from the central to northern Japan Sea and is a typical marker species of the cold OC in the northwestern Pacific (Takayanagi and Oda, 1983; Oda and Takemoto, 1992). In the study area, samples containing this species are grouped in FPQ3, FPQ6, and FPQ4 of Q-mode clusters; in particular, samples in cluster FPQ6, which are distributed from 550.75 to 361.25 cmbsf (24 to 17.5 cal kyr BP), display a very high percentage (99.5%) of this species. *G. quinqueloba* and *G. bulloides* are abundant in areas under the effects of less saline, nutrient-rich fresh water (e.g. Wang *et al.*, 1988; Hama *et al.*, 1997; Xu and Oda, 1999; Domitsu and Oda, 2005). In the East China Sea, *G. quinqueloba* and *G. bulloides* occur abundantly near the mouth of the Changjiang (Wang *et al.*, 1988; Xu and Oda, 1999) and in surface sediments of the continental shelf (Xu and Oda, 1999), where the surface temperature is low and primary productivity is prominently high due to large amounts of dissolved inorganic nutrients from the Changjiang (Hama *et al.*, 1997). In the Japan Sea, these species are in high abundance in the western channel of the Tsushima Strait, where salinity decreases significantly due to inflow of low-saline and nutrient-rich fresh water from the Changjiang (Domitsu and Oda, 2005). In the study area, samples containing these species are grouped in FPQ3 and FPQ2 of Q-mode cluster.

Cluster FPR2 is represented by *Globigerinoides ruber* (d'Orbigny), *Neogloboquadrina dutertrei* (d'Orbigny), and *N. incompta*. Presently, *Gds. ruber* and *N. dutertrei* are widely distributed in tropical and subtropical regions (Bé, 1977; Saito *et al.*, 1981). In the modern Japan Sea, they are known as typical indicators of TWC and reported in high abundance in the eastern channel of the Tsushima Strait, which is not strongly affected by low-saline, high-nutrient fresh water from the Chiangjang, unlike the western channel (Domitsu and Oda, 2005). *N. incompta* is a typical species in the marginal areas of the southeastern part of the present Japan Sea from the Oki Islands up to central Hokkaido. It is reported from the middle to downstream regions of the TWC, where the transitional water is formed by the mixing of the TWC and cold waters in the Japan Sea (Domitsu and Oda, 2005). In addition, this species is in high abundance in the western Pacific Ocean between the Kuroshio and Oyashio fronts (Oda and Takemoto, 1992). In the study area, samples containing this assemblage are grouped in FPQ1 of Q-mode cluster and are especially abundant in the lowermost (313.5 to 2889.25 cmbsf, 130–114.5 cal kyr BP) and uppermost (263.25 cmbsf to top, 10.5 cal kyr BP to present) of the core.

One outlier exists among the above-mentioned clusters illustrated in the Q-mode dendrogram and is labeled as *G. umbilicata* (Figure 6). Insufficient published data exists regarding the modern distribution of this species in the present Japan Sea or adjacent regions. However, a few studies have reported this species as a marker species of cold and low-salinity surface water that increased during the LGM in the Japan Sea (Ujiié *et al.*, 1983; Oi, 2011). In the study area, samples containing this species are grouped in FPQ7 of Q-mode cluster and distributed through TL-2 layer of the core MD179-3312.

Biofacies

Fossil sample clusters of the current study and the foraminiferal assemblages that characterize them have been integrated with their corresponding palaeoecological parameters (species diversity, equitability, BFOI, and the occurrence of marker species) and used to separate the sequence of this core into seven distinct biofacies, biofacies F1 to F7, in stratigraphic ascending order (Figures 12, 13).

Biofacies F1—Biofacies F1 is defined as the biostratigraphic interval from 3113.5 to 2889.25 cmbsf. This biofacies corresponds to samples of FBQ1 and FPQ1 of Q-mode cluster, which are overwhelmingly dominated by assemblages belonging to clusters FBR1 and FPR2 of R-mode cluster analysis. In benthic communities, *E. rotunda*, *I. norcrossi*, and *P. takayanagii* are the dominant species. Other common species include *N. labradorica*, *C. norvangi*, and *B. decussata*. Samples of this biofacies exhibit high diversity and high equitability, suggesting a low level of ecological stress. In addition, the benthic foraminifera oxygen trend (Figure 4) displays a higher value through this interval that corresponds with a well ventilated deep-sea environment. In planktonic populations, *Gds. ruber*, *N. dutertrei*, and *N. incompta* are dominant. *Gds. ruber* appears from 3053.25 to 2963.25 cmbsf of this biofacies, and corresponds to MIS5e.

Biofacies F2—Bifacies F2 is defined as the biostratigraphic interval from 2889.25 to 550.75 cmbsf and is divided into four sub-biofacies, F2-1 to F2-4, in stratigraphic ascending order:

Sub-biofacies F2-1 includes the interval between 2889.25 to 1929.25 cmbsf. This sub-biofacies corresponds to samples of FBQ1, FBQ2, and FBQ3, which oscillate through this interval, and FPQ3 of Q-mode cluster, and is dominated by assemblages of clusters FBR1, FBR2, and FPR1 of R-mode analysis. In benthic assemblages, it is characterized by the appearance of both thin-walled, elongated, flattened infaunal species such as *B. pacifica*, *G. auriculata*, *S. loeblichi*, *N. globosa*, and oxic to suboxic epifaunal species such as *E. rotunda*, *V. sadonica*, and *P. takayanagii*. The species diversity and benthic foraminifera oxygen trend reveal different values through this subzone, which oscillate between low and high. In planktonic communities, this sub-biofacies is dominated by *G. quinqueloba* and *G. bulloides*.

Sub-biofacies F2-2 is defined as the interval from 1929.25 to 1303.25 cmbsf. In benthic communities, this sub-biofacies is characterized by oscillation between dysoxic and oxic species, which is similar to sub-biofacies F2-1. Species diversity, equitability and benthic foraminifera oxygen trend display the same pattern as well, fluctuating between low and high through this interval (Figure 4). However, in the planktonic population, this sub-biofacies is dominated by a great abundance (99%) of *N. pachyderma*. The high positive value of this species through this interval (samples of cluster FPQ6) corresponds to cold surface water and probably can be correlated with MIS4.

Sub-biofacies F2-3 includes the biostratigraphic standard from 1303.25 to 921.75 cmbsf. This sub-biofacies corresponds to samples of FBQ3 and FPQ3 of Q-mode clusters, which are dominated by foraminifera assemblages that belong to clusters FBR2 and FPR1 of R-mode analysis. In benthic population, this sub-biofacies consists mostly of infaunal foraminifera, particularly a high percentage of *B. pacifica*. Samples of this sub-biofacies have low diversity and equitability, corresponding to a less stable environment. The benthic foraminifera oxygen trend display very low values, suggesting depleted bottom water oxygenation through this interval (Figure 4). In planktonic communities, this sub-biofacies is characterized by *G. quinqueloba* and *G. bulloides*, similar to sub-bfacies F2-1.

Sub-biofacies F2-4 is defined as the biostratigraphic interval from 921.75 to 550.75 cmbsf. The benthic and planktonic foraminifera assemblages of this sub-biofacies are similar to F2-1. In benthic communities, *V. sadonica* disappears from the core through this interval.

Biofacies F3—This biofacies is defined as the biostratigraphic interval from 550.75 to 361.25 cmbsf, corresponding to samples of FPQ7 of Q-mode clusters. In benthic communities, this biofacies is characterized by the very low number of benthic foraminifera (Figure 4). Oxic species are entirely absent through this interval, and infaunal taxa such as *B. pacifica* appear in an extremely low percentage through this interval. The benthic foraminifera oxygen curve displays a low value during this period (Figure 4). In addition, *R. rotundata* occurs in a very low abundance at the lowermost end of this interval. In planktonic population, this interval is dominated by high percentage values of *G. umbilicata*.

Biofacies F4—Biofacies F4 includes the biostratigraphic interval from 361.25 to 293.25 cmbsf. This biofacies corresponds to samples of FBQ1 and FPQ2 of Q-mode clusters and is characterized by foraminifera assemblages that belong to FBR1 and FPR1 of R-mode analysis. In benthic population, it is dominated by *E. rotunda*, *A. ikebei*, *I. norcrossi*, *B. decussata*, *N. labradorica*, *A. hamadaense*, and *E. excavatum*. The benthic foraminifera assemblage of this biofacies display high benthic foraminifera oxygen values, demonstrating a highly oxygenated environment (Figure 4). In planktonic communities, this biofacies is dominated by a high abundance value (nearly 100%) of *G. bulloides*.

Biofacies F5—Biofacies F5 includes the biostratigraphic interval from 293.25 to 263.25 cmbsf. This biofacies corresponds to samples of FBQ3 of Q-mode cluster, which are characterized by foraminifera assemblages that belong to cluster FBR2 of R-mode analysis. In benthic communities, it is dominated by the presence of potentially infaunal species, suggesting the occurrence of a dysoxic period. The frequency of *B. pacifica* increases (76%), while other species such as *E. rotunda*, *A. ikebei*, *I. norcrossi*, *B. decussata* and *N. labradorica*, which were previously quite common, disappear or display an abrupt decrease. Samples of this biofacies have low diversity and low equitability, indicating less stable environmental conditions. In addition, the benthic foraminifera oxygen trend displays low oxygen values in this biofacies (Figure 4). Planktonic communities are dominated by a moderate abundance of *G. bulloides*, *G. quinqueloba* and *N. pachyderma*.

Biofacies F6—Biofacies F6 is defined as the biostratigraphic interval from 263.25 to 133.75 cmbsf. This biofacies corresponds to samples of FBQ1, FPQ1, and FPQ2 of Q-mode clusters, which are identified by foraminifera assemblages of clusters FBR1, FPR1 and FPR2 of R-mode analysis. Benthic foraminifera oxygen values are moderate during this interval (Figure 4). Oxygen content, although moderate, was sufficient to sustain communities of predominantly suboxic and dysoxic foraminifera such as *E. rotunda*, *P. apertura*, and *B. pacifica*. *P. apertura* is found in the intermediate area of the northern part of the Sea of Okhotsk, an area with similar physical conditions to the JSPW but a less saline environment (Oi, 2011). This species disappears from the core through this interval. Planktonic communities are characterized by *G. bulloides,* which is a characteristic species of low surface temperature, less saline, and nutrient-rich fresh water (e.g. Wang *et al.*, 1988; Hama *et al.*, 1997; Xu and Oda, 1999; Domitsu and Oda, 2005), and *N. incompta*, which is presently reported from the middle to downstream regions of the TWC, where transitional water is formed by the mixing of the TWC and cold waters in the Japan Sea (Domitsu and Oda, 2005), and also in the western Pacific Ocean between the Kuroshio and Oyashio fronts (Oda and Takemoto, 1992).

Biofacies F7—Biofacies F7 includes the biostratigraphic interval from 133.75 cmbsf to the top of the core. This biofacies corresponds to samples of FBQ1 and FPQ1 of Q-mode clusters and is characterized by foraminifera assemblages that belong to clusters FBR1 and FPR2 of R-mode analysis. Its benthic population is dominated by both large- and small-sized oxic species such as *A. ikebei*, *E. rotunda*, *C. asanoi*, *S. abyssalica*, *Quinqueloculina* spp., *Triloculinella* spp., *B. decussata*, *C. norvangi*, *P. takayanagii*, and *A. hamadaense*. Dysoxic forms are either absent or in quite low percentages. Another characteristic of this biofacies is the occurrence of *Islandiella japonica* (Asano and Nakamura), which appears in low abundance through this interval. The samples of this biofacies have high diversity and equitability, indicating an environment of low stress and stability. Benthic foraminifera assemblages recovered from this interval reveal high benthic foraminifera oxygen values (Figure 4). Planktonic communities are dominated by *Gds. ruber* and *N. incompta*.

Temporal palaeoceanographic changes

Study of Joetsu area water mass characteristics is necessary to determine their potential influence on the composition of foraminifera assemblages. Nakagawa *et al.* (2009) have investigated biostratigraphic records and palaeoenvironmental conditions of the late Quaternary from 11 sediment cores recovered from the Umitaka Spur of the Joetsu area, which were used as reference in this research. However, their research focused on foraminifera assemblages of the last 32,000 years and thus only supports analysis of foraminiferal assemblages of the upper part of the core MD179-3312. Therefore, in order to better understand the relationships between foraminifera distribution and overlying water masses, other published data (e.g. Oba *et al.*, 1995; Tada *et al.*, 1999) was also applied to this study so as to aid palaeoenvironmental interpretations. The overall distribution of the biofacies along the sequence of the core MD179-3312 reveals seven major periods:

The period from 130 to 114.5 cal kyr BP consists of sedimentary facies of non-laminated, bioturbated, light-colored silty clay with greenish blue lenses and burrow-mottled extensions. However, it changes to dark-colored bioturbated silty clay at its top (Figure 3). The common feature of sediments through this interval is the absence of primary sedimentary structures. The occurrence of burrow mottling indicates the presence of abundant and active benthic fauna during sediment deposition. Sediments contain highly diversified benthic foraminifera assemblages that belong to biofacies F1 (Figure 12). The absence of stratification due to bioturbation, as well as burrows and color mottling are diagnoses of oxygenated benthic conditions at the time of deposition (Rhoads and Morse, 1971; Savrda *et al.*, 1984; Wetzel, 1991). The benthic foraminifera oxygen trend value is also high, corresponding to a well ventilated deep-sea environment (Figure 4). Planktonic foraminifera during this period are similar to those of the present TWC (Figure 13). This period corresponds to a rising sea level and inflow of TWC through the Tsushima Strait (Tada *et al.*, 1999). The inflow of high-temperature, high-salinity, low-nutrient TWC (Hasegawa, 1988; Domitsu and Oda, 2005) during this period increased the ventilation of the deep-sea environment and created a depleted nutrient and high oxic condition similar to the present Japan Sea (Tada *et al.*, 1999).

The period from 114.5 to 24 cal kyr BP consists of light-colored silty clay alternating with dark-colored silty clay (Figure 3). This period is dominated by biofacies F2. The light-colored layers are non-laminated, bioturbated, and commonly have texture or color mottling. They contain oxic epifaunal species, particularly a large amount of *E. rotunda* (Figure 12) and show a high value of bottom water oxygenation (Figure 4). These characteristics are indicative of a continuously oxic bottom water condition through light layer deposition (Rhoads and Morse, 1971; Savrda *et al.*, 1984; Wetzel, 1991). In contrast, the dark-colored layers vary among laminated, weakly laminated, bioturbated, and weakly bioturbated. In spite of variations in pattern, dark sediments display low diversity and oxygen values (Figure 4) and contain infaunal species, especially a high abundance of *B. pacifica*. These observations suggest an oxygen-deficient environment (Rhoads and Morse, 1971; Savrda *et al.*, 1984; Wetzel, 1991). Bioturbated and weakly bioturbated dark-colored layers probably represent an environment sufficiently oxygenated to support benthic life, but not so well oxygenated to dissipate reducing condition within the sediments. Planktonic foraminifera typical of warm surface water disappear from the core through this period. Instead, *G. bulloides* and *G. quinqueloba*, presently abundant in the low surface temperature, low-salinity, and rich-nutrient fresh water from the Changjiang (Wang *et al.*, 1988; Xu and Oda, 1999), occur through this interval. This period corresponds to periodic changes in surface water due to the influence of ECSCW (Oba *et al.*, 1995). As a result, bottom water conditions fluctuated between dysoxic and suboxic to oxic from time to time corresponding to increases and decreases of nutrients supplied by the low-saline ECSCW through the Tsushima Strait (Tada *et al.*, 1999).

The period from 24 to 17.5 cal kyr BP consists of the thickest thinly laminated, dark-colored silty clay which is known as TL-2. Laminae are parallel from base to top, have continuous boundaries, and are well preserved, indicating an extremely oxygen-deficient bottom water condition (Savrda *et al.*, 1984; Watanabe *et al.*, 2007). This period is dominated by Biofacies F3. Benthic foraminifera decreases abruptly during this period (Figure 4). Oxic species are totally absent, and infaunal taxa are present in very low amounts through this interval. Instead, the planktonic foraminifera *G. umbilicata* is highly abundant during this period. This period corresponds to the LGM, when the sea level dropped below the sill depth of the Tsushima Strait, nearly isolating the Japan Sea from the open ocean (Tada *et al.*, 1999; Nakagawa *et al.*, 2009). The low diversity and low oxygen concentration in the sediments (Figure 4) represent severely dysoxic conditions in the bottom water, suggesting effects of a restricting factor, possibly reduced salinity in surface waters. The development of low salinity in the upper part of the water column can be explained by large freshwater discharge to the sea from the extensive adjacent land areas (Nakagawa *et al.*, 2009). The most possible source of fresh water is the Huang He River in China (Oba, 1983). During the Last Glacial Maximum, the mouth of this river shifted from the west side of Cheju Island to the east due to sea level fall (Chang and Cheong, 1987), causing an inflow of fresh water into the Japan Sea through the Tsushima Strait (Oba *et al.*, 1991). As a result, low salinity surface water during the LGM stratified the water column. Simultaneously, the stratification of the water column caused a severe decrease in the ventilation of the subsurface water and limited upwelling of nutrients (Ishiwatari *et al.*, 1999; Nakagawa *et al.*, 2009). Oxidation of organic matter in the water column and on the seafloor consumed all of the dissolved oxygen in the bottom water, resulting in extremely dysoxic environments and forming the thickest thinly laminated layers (TL-2) in the sediments (Masuzawa and Kitano, 1984; Oba *et al.*, 1991; Tada *et al.*, 1999; Nakagawa *et al.*, 2009). Such a harsh environment thus made it difficult even for infaunal species to sustain communities during this period. Nakagawa *et al.* (2009) reported the occurrence of *R. rotundata* during the LGM from active methane seeps of the Joetsu area. They suggested that the sea level fall during the LGM may have caused instability and massive dissociation of subsurface gas hydrate, which led to the formation of pockmarks. At the core MD179-3312, the mentioned species appears in a small amount in the lowermost segment of this interval.

The period from 17.5 to 12 cal kyr BP consists of non-laminated, bioturbated, light-colored silty clay with greenish blue lenses and burrow-mottled structures. The occurrence of burrows indicates high activity by benthic fauna and suggests the change from dysoxic to oxic conditions at the end of the LGM. This period is dominated by biofacies F4. It is characterized by the occurrence of a well oxygenated foraminifera assemblage, the first appearance of *E. excavatum*, and the presence of the characteristic fauna related to warming conditions after glaciation such as *A. hamadaense* and *N. labradorica* (Figure 12). In addition, *G. umbilicata* displays an abrupt decrease, with only few juveniles appearing through this interval (Figure 13). These circumstances all suggest that the sea level rose during this period due to deglaciation (Oba *et al.*, 1995; Nakagawa *et al.*, 2009). As a result, the more saline OCW flowed from the north through the Tsugaru Strait into the Japan Sea, mixed with the surface water, and sank to the deeper parts of the sea, regenerating vertical circulation and leading to a rise in primary productivity (Oba *et al.*, 1991; Ishiwatari *et al.*, 1999).

The period from 12 to 10.5 cal kyr BP consists of the last thinly laminated layers, which is known as TL-1. This period is dominated by biofacies F5 and is characterized by a great abundance value of *B. pacifica*, the absence of oxic epifaunal species (Figure 12), and a sudden decrease in benthic foraminifera oxygen trend (Figure 4). The absence of species belonging to aerobic morphogroups and the significant increase of infaunal species indicates that the water was severely dysoxic. The origin of this depleted oxygen environment might be associated with changes due to displacement of the Tsushima-Oyashio Currents, which caused interruption of water circulation in the Japan Sea and consequently deposition of the last thinly laminated layer (Oba *et al.*, 1991).

The period from 10.5 to 5 cal kyr BP consists of non-laminated light-colored silty clay with burrow-mottled extensions. This period is dominated by biofacies F6. The main characteristics of this period include the first and last occurrence of *P. apertura*, the moderate value of bottom water oxygenation (Figure 4), the appearance of suboxic and dysoxic species such as *E. rotunda* and *B. pacifica*, and the occurrence of *N. incompta*. The appearance of *N. incompta*, which is a typical species of relatively warm surface water and is presently abundant in the middle to downstream of the TWC in the Japan Sea (Domitsu and Oda, 2005), indicates the temporary inflow of TWC into the Japan Sea through the Tsushima Strait (Oba *et al.*, 1995; Nakagawa *et al.*, 2009). However, planktonic foraminifera during this period include the mixture of cold (*G. bulloides*) and warm (*N. incompta*) surface water species. All these phenomena indicate this period as a transitional stage from dysoxic or suboxic to completely oxic modern conditions of the Japan Sea

(Oba *et al.*, 1995).

Finally, the period after 5 cal kyr BP consists of non-laminated, bioturbated, light-colored silty clay with greenish blue lenses at its lower part. The lack of primary sedimentary structure and the presence of bioturbation indicate stabilization of oxic conditions (Rhoads and Morse, 1971; Savrda *et al.*, 1984; Wetzel, 1991). This period is dominated by biofacies F7 and is characterized by the first occurrence of *I. japonica*, a large amount of oxic epifaunal species that are presently common in the modern JSPW, very few or an absence of dysoxic infaunal species, and high benthic foraminifera oxygen value, corresponding to strong subsurface water ventilation. These are evidenced by the occurrence of *Gds. ruber* as a marker species of TWC (Domitsu and Oda, 2005) and a change of dominant species from *G. bulloides* to *N. incompta* in planktonic assemblage, suggesting permanent inflow of the TWC into the Japan Sea. The regeneration of deep water followed the initiation of the TWC inflow into the Japan Sea, and the modern JSPW with high oxygen was generated (Oba *et al.*, 1995; Nakagawa *et al.*, 2009).

Conclusion

Palaeoceanographic changes of the Japan Sea off the Joetsu area were reconstructed from the core MD179-3312 over the period since 130 cal kyr BP. The core is mainly composed of light-colored silty clay alternating with dark-colored silty clay. This sedimentary sequence has an essentially continuous foraminiferal record, composed almost entirely of calcareous taxa. A total of 106 benthic foraminifera species belonging to 50 genera and seven planktonic foraminifera species belonging to three genera were identified in this core. Based on cluster analyses of both benthic and planktonic foraminifera assemblages and occurrence of marker species, seven biofacies and four sub-biofacies were distinguished in this core. These biofacies and their association with distinct water masses within the Joetsu area provide significant information on the foraminiferal distributions within the Japan Sea, particularly the Joetsu region. This study confirms that distribution of foraminifera was strongly influenced by changes in organic matter, oxygen content, and major water masses in the Japan Sea. The light-colored layers are mainly dominated by oxic epifaunal species such as *A. ikebei*, *I. norcrossi*, *B. decussata*, *A. hamadaense*, *C. norvangi*, *E. rotunda*, and *P. takayanagii*. They always display high diversity and high oxygen value, suggesting a low level of ecological stress and a well ventilated environment; otherwise, the dark-colored layers generally show low diversity and high abundances of the infaunal dysoxic species, such as *B. pacifica*, *N. globosa*, *G. ariculata*, and *S. loeblichi*, indicating dysoxic bottom water conditions. The distribution of the biofacies along the sequence of the core MD179-3312 reveals seven major periods: (1) inflow of TWC into the Japan Sea from 130 to 114.5 cal kyr BP; (2) periodic changes in surface water productivity due to influence of high nutrient ECSCW from 114.5 to 24 cal kyr BP; (3) sea level fall and near isolation from open ocean from 24 to 17.5 cal kyr BP; (4) inflow of OCW through Tsugaru Strait from 17.5 to 12 cal kyr BP; (5) interruption of water circulation in the Japan Sea from 12 to 10.5 cal kyr BP; (6) temporary inflow of TWC into the Japan Sea through Tsushima Strait from 10.5 to 5 cal kyr BP; and (7) permanent inflow of TWC into the Japan Sea and regeneration of modern JSPW since 5 cal kyr BP.

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Appendix 1. Census count of benthic foraminifera.

Sample Number	9	17	25	33	39	45	57	67	71	73	83	91	97	105	109	121	143	149	157	171	179	187	195	197	205	213	225	233	241	245	249
Depth (cmbsf)	21.25	41.25	61.25	81.25	96.25	103.75	133.75	158.75	168.75	173.25	198.25	218.25	233.25	253.25	263.25	293.25	346.25	361.25	381.25	416.25	436.25	456.25	476	480.75	500.75	520.75	550.75	570.75	590.75	600.75	610.75
Ammodiscus sp.																															
Angulogerina ikebei	13	8	9	12	9	7	27	10	9	1	2	5	4	5		1	56	10								1					
Astacolus insolitus	1			2																											
Astrononion hamadaense	6		11	11	10	5	12	2	2								18	2					3	1				2			
Buccella tenerrima																															
Bolivina decussata	2	10	7	29	22	16	12	6	13	5		19	7	11	6	7	9	7			4	5	3	5	8	6	4	5			8
Bolivina pseudodifformis																															11
Bolivina sp. 1																										1					
Bolivina sp. 2																											1				
Bolivina sp. 3																						1									
Bolivina sp. 4																															
Bolivina sp. 5																															
Bolivina sp. 6																															
Bolivina sp. 7																															
Bolivina sp. 8																															
Brizalina pacifica	2	1	2	60	11	2	3	50	20	8	19	75	8	41	134	4	9		4	4	2	3	2		3	1	1	2			79
Bulimina aculeata																															
Buliminella elegantissima												1					1							1						1	
Cassidulina norvangi	5			34	15	11	5	5	35	22	7	50	11	7		6	45	8	1				2			3	3	2	1		
Cibicides sp. 1																															
Cibicides sp. 2																															
Cibicidoides asanoi	12	2	3	5	1	2	9	3	10	14	1	3	5			2	1	1							1	1					
Cushmania striatopunctata										1																					
Dentalina guttifera																															
Eilohedra rotunda	21		35	168	68	105	73	62	94	59	19	135	34	65			63	9			2							3			
Elphidium excavatum																	36	2	1												
Entosolenia lucida												3																			
Eoeponidella pulchella									1																						
Evolvocassidulina sp.				3	2	5	1					1	1				1							1							1
Fissurina cucurbitasema	1				1	4	1										3														
Fissurina echigoensis	1		2														4	1													
Fissurina lagenoides																															
Fissurina marginata				3		3	1	2		1							1								1	1		1			
Fissurina marginata ß			3			1	1	1																							
Fissurina marginata α	1		1	1		1																									
Fissurina milletti																															
Fissurina sp. 1					1																										
Fissurina sp. 2					1																										
Fissurina sp. 3						1																									
Fissurina sp. 4																										1					
Fissurina sp. 5																												1			
Fissurina sp. B		1			2	2	1		1								2														
Glandulina laevigata				3		1											1														
Globobulimina auriculata			1		1							1		2	4	1															4
Globobulimina pacifica						1			1						1																2
Guttulina sp.								1																							
Haplophragmoides sp.	2		2	2				2			2			1																	1
Haynesina sp.				1		2					2	16		2			2	7			1		1	1	5	1	7				2
Islandiella japonica	2		2	2	3	6	3																								
Islandiella norcrossi	5	3	13	62	18	17	51	16	13	1	2	4	1			5	46	8								1		5			
Karreriella baccata japonica		1		2		1						1																			
Laevidentalina inflexa																	1														
Lagena apiopleura																															
Lagena clavata																	1														
Lagena laevis																															
Lagena nebulosa				2						1																					
Lagena perlucida																															
Lagena sp. 1						1																									
Lagena sp. 2																															
Lagena sp. 3																															
Lagena striata																1															
Lagena substriata				1																											
Lagena tricaritortuosa	1			2																											
Lagena trigonoelliptica								1																							
Lagenammina arenulata	13	6		1	1								1																		
Lagenosolenia inflatiperforata											2															1					
Marginulina obesa																															
Nonionella globosa														1	6	2	3											1			8
Nonionellina labradorica			5	4		2	1	2	3	4	2	10	12	3		14	6														5
Oolina baukalionilla																															
Oolina felsinea					1																										
Oolina hexagona																															
Oolina melo	1									1																					
Oolina ovum																															
Parafissurina lateralis							1																								
Parafissurina sp. 1												1					1														
Parafissurina sp. 2																															
Patellinella hanzawai			1																												
Planoglabratella opercularis																				1	1										
Procerolagena gracilis	1			1													1														
Procerolagena gracillima			1																												
Pseudoparrella takayanagii	9		2	14	7	10	14	60	52	46	15	73	16		3		23	2		5	5	2			1		3	2			
Pullenia apertura				1				4	12	14	19	37	7	2		1															
Pyrgo murrhina																															
Pyrgo sp.																															
Pyrgo vespertilio						1																									
Pyrgoella sphaera					2	1						5												1			1				
Quinqueloculina lamarckiana																1		1				1									
Quinqueloculina seminula												1																			
Quinqueloqulina hasimotoi					1														1					1	3						
Quinqueloqulina sp. 1																	1														
Quinqueloqulina sp. 2																											1				
Quinqueloqulina sp. 3																															
Rutherfordoides rotundata																															11
Silicosigmolina abyssalica	23	4	36	65	25	15	7	1									24														
Stainforthia loeblichi	1	1	4	26	8	7	6	5	9		4	21	12	3	23	1	39	3	2						2						3
Stainforthia sp.							1																								
Triloculina tricarinata									1		1	1					2														
Triloculina trigonula												3																			
Triloculinella tegminis						3																									
Trioculinella sp.						2				1																					
Uvigerina akitaensis		1					1	8		1	1					7	1	2													
Uvigerina sp.				1																											
Valvulineria sadonica																2															15
Valvulineria sp.1																															
Valvulineria sp.2																															1
Total number of specimens	123	38	140	518	210	235	231	241	276	180	98	466	119	143	177	55	401	63	9	10	15	12	11	11	24	18	21	24	1	1	151

Appendix 1. *Continued*.

Sample Number	257	259	267	273	277	285	293	301	309	317	319	321	329	337	343	351	367	375	379	383	399	407	445	455	465	475	483	491	501	509	519	529	539
Depth (cmbsf)	629.25	633.75	653.75	668.75	678.75	698.75	718.75	738.75	758.75	778.75	782.25	786.75	806.75	826.75	841.75	861.75	901.75	921.75	931.75	939.75	979.75	999.75	1094.25	1119.25	1144.25	1169.25	1189.25	1209.25	1234.25	1253.25	1278.25	1303.25	1328.25
Ammodiscus sp.																																	
Angulogerina ikebei			7	2			10	1		5				3	30						1												9
Astacolus insolitus																	1																
Astrononion hamadaense	2		11				4	3		13	11	3		3	18		3					1	2		1	1			2		1		1
Buccella tenerrima																													1				
Bolivina decussata		6	4	2	4	2	15	17	1	5	5	6	1					1	1	2	9	7	10	5	5	2	1		7	3	7	3	4
Bolivina pseudodifformis			2							1					1																		
Bolivina sp. 1																																	
Bolivina sp. 2																																	
Bolivina sp. 3																																	
Bolivina sp. 4																																	
Bolivina sp. 5																																	
Bolivina sp. 6																																	
Bolivina sp. 7																																	
Bolivina sp. 8																																	
Brizalina pacifica		5	43	20	1	94	204	24	175	35	37	78	160	15	16	122	8	224	141	155	315	188	61	261	125	126	104	134	325	175	175	238	14
Bulimina aculeata																																	
Buliminella elegantissima					1																	1	1				1		1				1
Cassidulina norvangi	3	1	1		2	2	52	30		14	15	6	1	3	51	1	16	2				1	24				1		10		5		44
Cibicides sp. 1											1																						
Cibicides sp. 2																					1				1								2
Cibicidoides asanoi			1											1																			
Cushmania striatopunctata													1		1						1												
Dentalina guttifera			2																														
Eilohedra rotunda	1		8	4			294	48		129	92	51		65	215		49	4	1	1		1	47	3	4				21		11		48
Elphidium excavatum																																	
Entosolenia lucida																																	
Eoeponidella pulchella																																	
Evolvocassidulina sp.	7	1	6				16	5		6	5	10		4	7		3	5	1	1	15	2	8	5					8		3		
Fissurina cucurbitasema																																	
Fissurina echigoensis																																	
Fissurina lagenoides																																	
Fissurina marginata	1							1				1	1		1		1												1				1
Fissurina marginata ß												2												1									
Fissurina marginata α																																	
Fissurina milletti																																	
Fissurina sp. 1																																	
Fissurina sp. 2																																	
Fissurina sp. 3																																	
Fissurina sp. 4																																	
Fissurina sp. 5																																	
Fissurina sp. B												1																					
Glandulina laevigata			1												1																		
Globobulimina auriculata		5	2	10		4	6	8		1		1		1	1	3	3	3		4		3	1	15		9	18	4		2	5	9	1
Globobulimina pacifica		2		3														1			1					1	3						
Guttulina sp.																																	
Haplophragmoides sp.																																	
Haynesina sp.								3				1											1		2								
Islandiella japonica																																	
Islandiella norcrossi	5	6	31	8			17	2		24	25	8		28	47		52	1			2		6	1					3				63
Karreriella baccata japonica																																	
Laevidentalina inflexa																																	
Lagena apiopleura										1																							
Lagena clavata																																	
Lagena laevis															1																		
Lagena nebulosa	1		1				3				1				3																		
Lagena perlucida																																	
Lagena sp. 1																																	
Lagena sp. 2																																	
Lagena sp. 3										1		1				1							1						1			1	
Lagena striata	5	1						4			1																						
Lagena substriata											1																						
Lagena tricaritortuosa																																	
Lagena trigonoelliptica																																	
Lagenammina arenulata																																	
Lagenosolenia inflatiperforata							1																										
Marginulina obesa																																	
Nonionella globosa		2	3	3		21		9	27	2	6	15	3	1		15		7		5	3	7	3	20	26	58	19	9	305	12	8	2	3
Nonionellina labradorica		1	1	21			19	1	2	2	5	48		1	8	6	8	1	2	1		2	8	3		3		1	147	23			9
Oolina baukalionilla																																	
Oolina felsinea																																	
Oolina hexagona															2																		
Oolina melo								1																									
Oolina ovum																																	
Parafissurina lateralis																																	
Parafissurina sp. 1							2																										
Parafissurina sp. 2																								1									
Patellinella hanzawai																																	
Planoglabratella opercularis																																	
Procerolagena gracilis			3				6	1			1				1																		
Procerolagena gracillima											1																						
Pseudoparrella takayanagii			2		1	2	90	6		18	13	10		21	25		6	2	2	1	2	1	14	3	1				4		5		11
Pullenia apertura	1	1	1								1			1	1								1										11
Pyrgo murrhina														2																			
Pyrgo sp.																																	
Pyrgo vespertilio																																	
Pyrgoella sphaera				1											1																		
Quinqueloculina lamarckiana								1				1																					2
Quinqueloculina seminula			3																														
Quinqueloqulina hasimotoi											2				1	1							1										1
Quinqueloqulina sp. 1																																	
Quinqueloqulina sp. 2																									1								
Quinqueloqulina sp. 3																																	
Rutherfordoides rotundata	1	6		1																													
Silicosigmolina abyssalica															2														2				
Stainforthia loeblichi	22	12	8			108	43	9	25	23	16	17	3	9	26	37	8	2	1		10	2	4	1	5	19	38	23	10	35		3	10
Stainforthia sp.							1																										
Triliculina tricarinata				1																													
Triloculina trigonula																																	
Triloculinella tegminis																																	
Trioculinella sp.				1																													
Uvigerina akitaensis	1									1											2								2		15	1	2
Uvigerina sp.																	1																
Valvulineria sadonica	18	27	2	1			13	38		1	2	60		3	3		2	1		3	30		8	2	2				62		12		
Valvulineria sp.1																							1										
Valvulineria sp.2																																	
Total number of specimens	68	76	143	78	9	233	796	212	230	282	241	320	170	161	463	186	161	254	149	173	392	216	202	321	173	219	185	171	912	250	247	257	237

Appendix 1. *Continued.*

Sample Number	549	559	569	583	603	625	629	641	651	661	669	709	719	751	763	811	863	937	953	973	1003	1043	1099	1147	1167	1233	1243	1253	1257
Depth (cmbsf)	1353.25	1378.25	1402.75	1437.75	1487.75	1542.75	1552.25	1582.25	1607.25	1632.25	1652.25	1750.75	1775.75	1854.25	1884.25	2002.75	2132.75	2317.75	2357.75	2407.75	2481.25	2581.25	2719.25	2839.25	2889.25	3053.25	3078.25	3103.25	3112.5
Ammodiscus sp.				2																									
Angulogerina ikebei		2			9	2	5	5		2	3		7		4					6	21				4	1	76	39	39
Astacolus insolitus																											2		
Astrononion hamadaense	1	1			11	2	1		3	2	2		14		16			1		3	8	1	1				5		
Buccella tenerrima																													
Bolivina decussata		9	9	5	6	12	13	8	31	8	3		6	3	3	2		2	12	5	16	9	1	1	4	16	157	24	51
Bolivina pseudodifformis																											1		
Bolivina sp. 1																							1						
Bolivina sp. 2																													
Bolivina sp. 3																													
Bolivina sp. 4															1														
Bolivina sp. 5																						1							
Bolivina sp. 6																						1							
Bolivina sp. 7																							1						
Bolivina sp. 8																							1						
Brizalina pacifica	104	146	301	12	14	21	25	21	65	10	8	107	7	78	6	8	224	230	63	117	44	222		252	11	14		1	8
Bulimina aculeata											1														1				
Buliminella elegantissima						1						1	9		2			1	9	28		1							
Cassidulina norvangi	10	3			1	14	7	38	7	22	16	1	7	1	31	6			5	19	12	2	1	1	21	15	48	17	19
Cibicides sp. 1						1																							
Cibicides sp. 2											1								5			1							
Cibicidoides asanoi																							1						
Cushmania striatopunctata								1	1									1									3		
Dentalina guttifera								1													1								
Eilohedra rotunda	3	8	5		44	42	11	63	21	70	28		46	1	54	3	2	3	24	7	56	8	1	2	32	118	101	29	80
Elphidium excavatum																													
Entosolenia lucida																													
Eoeponidella pulchella																													1
Evolvocassidulina sp.	3	4	9	2	3	5	8	3	5	4	10		7		6				6	7	2	2				2	7	6	5
Fissurina cucurbitasema							3													2									3
Fissurina echigoensis																												2	2
Fissurina lagenoides							1																						
Fissurina marginata						1	4	1		1	4		1		2			1	1	2							3		2
Fissurina marginata ß						1	1		1										1	1	1						1	2	1
Fissurina marginata α																													
Fissurina milletti																		1											
Fissurina sp. 1																													
Fissurina sp. 2																													
Fissurina sp. 3																													
Fissurina sp. 4																													
Fissurina sp. 5																													
Fissurina sp. B																													
Glandulina laevigata																													1
Globobulimina auriculata	4	13	5	4	1	4	1	1	4	1	2	9		24	1		2	5		7		4		1	4				
Globobulimina pacifica						2														1									
Guttulina sp.																													
Haplophragmoides sp.																													
Haynesina sp.							1		4	5	2	3	2	12	8	1	1	3	9	11		3	1	1	2	2	2	9	4
Islandiella japonica																													
Islandiella norcrossi	2	95	1		47	45	16	10	9	22	21		13	2	15			1	9	61	16	4	1		49	23	86	26	27
Karreriella baccata japonica															2					3	1								
Laevidentalina inflexa																													
Lagena apiopleura																													
Lagena clavata																											2		
Lagena laevis																													
Lagena nebulosa		1																			2						2		
Lagena perlucida																				1				1					
Lagena sp. 1																													
Lagena sp. 2															1														
Lagena sp. 3																													
Lagena striata							1						1							1									
Lagena substriata													1							1									
Lagena tricaritortuosa																													
Lagena trigonoelliptica																													
Lagenammina arenulata																													
Lagenosolenia inflatiperforata																							1						1
Marginulina obesa																											1		
Nonionella globosa	30	4	14	2	2	4					2	6		14			5	3	1	7			1	3	3				
Nonionellina labradorica	5	67			7	25	13	27	7	4	12	1				1	2	1	1	29	4	4	1		30	5	21	10	3
Oolina baukalionilla																				1									
Oolina felsinea																												1	
Oolina hexagona							1																						
Oolina melo																													
Oolina ovum														1															
Parafissurina lateralis																													
Parafissurina sp. 1																							1			3			
Parafissurina sp. 2																													
Patellinella hanzawai																													
Planoglabratella opercularis																											1		
Procerolagena gracilis													1			2												1	
Procerolagena gracillima																													
Pseudoparrella takayanagii	1	1	1		2	8	1	2	4	9	5	1	17	10	34	3	2	4	19	27	37	19	4	4	14	41	81	7	10
Pullenia apertura		2				1	1	3		16	5		2		2					11	20	1				4	4	6	8
Pyrgo murrhina								2			1		2		1					1	1								
Pyrgo sp.																					1								
Pyrgo vespertilio																													
Pyrgoella sphaera						1															1						1		
Quinqueloculina lamarckiana							2		2				1		2					1									3
Quinqueloculina seminula						1		2		2	4		1		1			1							1				
Quinqueloqulina hasimotoi					2	1		5	4		2	3			1														
Quinqueloqulina sp. 1																													
Quinqueloqulina sp. 2																													
Quinqueloqulina sp. 3																											1		
Rutherfordoides rotundata																													
Silicosigmolina abyssalica																													
Stainforthia loeblichi	55	42	1		24	45	30	18	3	9	15	35	10	74	13	5	32	11	3	12	11	10		55	18	4	12	7	18
Stainforthia sp.																													
Triloculina tricarinata										2										1							1	1	
Triloculina trigonula																				2									
Triloculinella tegminis																													
Trioculinella sp.																													
Uvigerina akitaensis			14	1		2		4					1		1			2	22	8	9	6							
Uvigerina sp.																													
Valvulineria sadonica	1	10	144	85	2	7	6	3	45	1	1								4		1	3							
Valvulineria sp.1																													
Valvulineria sp.2																1				1									1
Total number of specimens	219	408	504	111	175	248	152	218	216	190	148	167	156	220	207	32	270	271	194	384	265	302	18	321	194	248	619	188	287

Appendix 2. Census count of planktonic foraminifera

Appendix 2. *Continued.*

Sample Number	Depth (cmbsf)	*Globigerinoides ruber*	*Globigerina bulloides*	*Globigerina quinqueloba*	*Globigerina umbilicata*	*Neogloboquadrina dutertrei*	*Neogloboquadrina incompta*	*Neogloboquadrina pachyderma*	Other planktonic foraminifera	Total number of specimens
9	21.25		3					3		6
17	41.25	1	3				4	7		15
25	61.25	1			1		2		1	5
33	81.25	2	1				31	2		36
39	96.25		7	11	1		58	21		98
45	103.75	2	5	16			156	48	12	239
57	133.75		4	35			25	12	1	77
71	168.75		6	8			6	5		25
73	173.25		5	1				1		7
83	198.25		2	5						7
91	218.25		34	19	2			10		65
97	233.25		13	3				8	4	28
109	263.25		38	7				27		72
121	293.25		187					36		223
143	346.25		94	6	16			112	3	231
149	361.25		8	7	9			128	3	155
157	381.25		64	77	50			252	18	461
163	396.25		23	28	69			93	8	221
171	416.25		40	77	135			131	14	397
179	436.25		27	52	86			113	11	289
187	456.25		73	56	198			133	1	461
195	476		94	43	172			82	4	395
197	480.75		97	33	143			88		361
205	500.75		118	21	37			109	2	287
213	520.75		65	15	18			85		183
217	530.75		136		33			29		198
225	550.75		223		71			50	3	347
233	570.75		256		94			218	6	574
241	590.75		103		17			158	6	284
245	600.75		64		28			241		333
249	610.75		80		15			229	7	331
257	629.25		32		4			130	1	167
259	633.75		7					17		24
267	653.75		38	7				348		393
273	668.75		42	12	1			154		209
277	678.75		114	98	2			119		333
285	698.75		78	112	19			94		303
293	718.75		80	9				72		161
301	738.75		23	6				210	1	240
309	758.75		25	77	3			117	4	226
317	778.75		30	14				146		190
319	782.25		39	29				87	3	158
321	786.75		73	6				268		347
329	806.75		14	123	1			114	2	254
337	826.75		12	2				77		91
343	841.75		22	13				148		183
351	861.75		53	66	4			105	1	229
367	901.75		27					145		172
375	921.75		80	129	2			142		353
379	931.75		110	95	7			134		346
383	939.75		172	12	13			162		359
399	979.75		80	4	4			197		285
407	999.75		55	126	5			178		364
445	1094.25		33	6				208		247
455	1121.75		48	103				197		348
465	1144.25		23	80	3			93		199
475	1169.25		91	53	13			106		263
483	1189.25		68	38	25			97		228
491	1209.25		146	72	40			180		438
501	1234.25		81		3			406		490
509	1253.25		82	70	11			90		253
519	1278.25		80	91	2			205		378
529	1303.25			10				322		332
539	1328.25		46	10	2			243		301
549	1353.25		32	22	5			128		187
569	1402.75		56	14	6			409		485
583	1437.75				1			22		23
603	1487.75		32		1			244		277
625	1542.75		1	6				281		288
629	1552.25			2				236		238
641	1582.25			37				173		210
651	1607.25			44				537		581
661	1632.25			29				197		226
669	1652.25			92				256		348
679	1677.25		143					357		500
709	1750.75			160				148		308
719	1775.75			5				196		201
743	1835.75			430				1686		2116
751	1854.25			25				266		291
763	1884.25			26				136		162
781	1929.25			64				194		258
811	2002.75		8	9	1			3		21
843	2082.75		254	481	38			808	1	1582
863	2132.75		110	53				118		281
905	2237.75		385	125	10			1480		2000
937	2317.75		62	3	4			90		159
953	2357.75		51	9	4			87		151
973	2407.75		26	32				117		175
991	2451.25		130	30	4			57		221
1003	2481.25		16		1			6		23
1043	2581.25		83	5	6			118		212
1067	2639.25		68		3			164		235
1099	2719.25		1					247		248
1119	2769.25		80	19	2			152		253
1147	2839.25		168	17	12			220		417
1167	2889.25		38	30	4		35	96		203
1177	2913.25		30	27	1		68	157	2	285
1187	2938.25		36	16			141	42	6	241
1197	2963.25	10	162	154	6	5	92	37		466
1207	2988.25	6	68	9	2	5	51	8	4	153
1215	3008.25	13	72	26	1	9	39	14		174
1229	3043.25	12	34	48					6	100
1233	3053.25	1	2	4				2		9
1243	3078.25		83	1	8			10		102
1253	3103.25		146	26				23		195
1257	3112.5		140	25	6			14		185