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Late Pleistocene–Holocene paleoenvironmental changes inferred from the diatom record of the Ulleung Basin, East Sea (Sea of Japan)

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Abstract

The diatom floral record from two piston cores (00GHP-01 and 00GHP-07) taken from the southwestern margin of the Ulleung Basin, East Sea (Sea of Japan) reveals a series of well-defined changes in glacio-eustatic sea level and paleoceanographic conditions during the late Pleistocene–Holocene. Six assemblage zones and two barren zones in 00GHP-01 and four assemblage zones in 00GHP-07 are erected respectively on the basis of frequency of variations in, and occurrences of, biostratigraphically significant diatom species. All assemblage zones have been strongly influenced by the Tsushima Warm Current (TWC). The TWC has an important affect on controlling the distribution and composition of diatom flora, which in turn, reveal the history of the TWC in this area. The distribution pattern of diatoms in the diatom assemblages reveals sea surface temperature and salinity affected by the sediments type and terrigenous material input. Diatom temperature (Td) values show that the site of 00GHP-01 in the Ulleung Basin has been influenced by a relatively enhanced TWC twice during the deposition of lowermost and uppermost intervals. A relatively weak TWC was recorded in the middle interval since the latest Pleistocene. The diatom assemblages of 00GHP-07 represent an apparently continuous Late Quaternary record, spanning the Last Glacial Maximum, Bølling-Allerød, Younger Dyras and Holocene. High abundance of a low-salinity, coastal water diatom *Paralia sulcata* may reflect the influx of the East China Sea water through the Korean Strait to the East Sea (Sea of Japan). During the Last Glacial Maximum, the sea level was low enough that selected basin with shallow sills along the margin of the East Sea (Sea of Japan) became isolated from the Pacific Ocean. Salinity also decreased due to increased freshwater input from rivers draining the surrounding lands. The density-stratified water column may have prevented vertical mixing and resulted in anoxic bottom-water conditions.

Keywords: late Pleistocene–Holocene; diatom; paleoceanography; Ulleung Basin; East Sea (Sea of Japan)

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1. Introduction

The East Sea (Sea of Japan) is a semiclosed marginal sea connected not only with the Pacific Ocean and the Sea of Okhotsk, but also with the East China Sea by four narrow, shallow straits including the Tartarskiy Strait (15 m deep), Soya Strait (55 m deep), Tsugaru Strait (130 m deep) and Korean Strait (140 m deep). The Tsushima Warm Current (TWC), a branch of the Kuroshio Current, enters the sea through the Korean Strait, and then flows out through the Tsugaru and Soya Strait (Fig. 1a). In the Okhotsk and Bering seas, the sill is deep enough to allow the inflow of Pacific Deep Water, whereas the sill in the East Sea (Sea of Japan) is so shallow that the Pacific Deep Water cannot flow into the East Sea (Sea of Japan). Therefore, a special vertical circulation occurs within East Sea (Sea of Japan), and a peculiar water mass called the East Sea (Sea of Japan) Proper Water is formed (Hidaka, 1966).

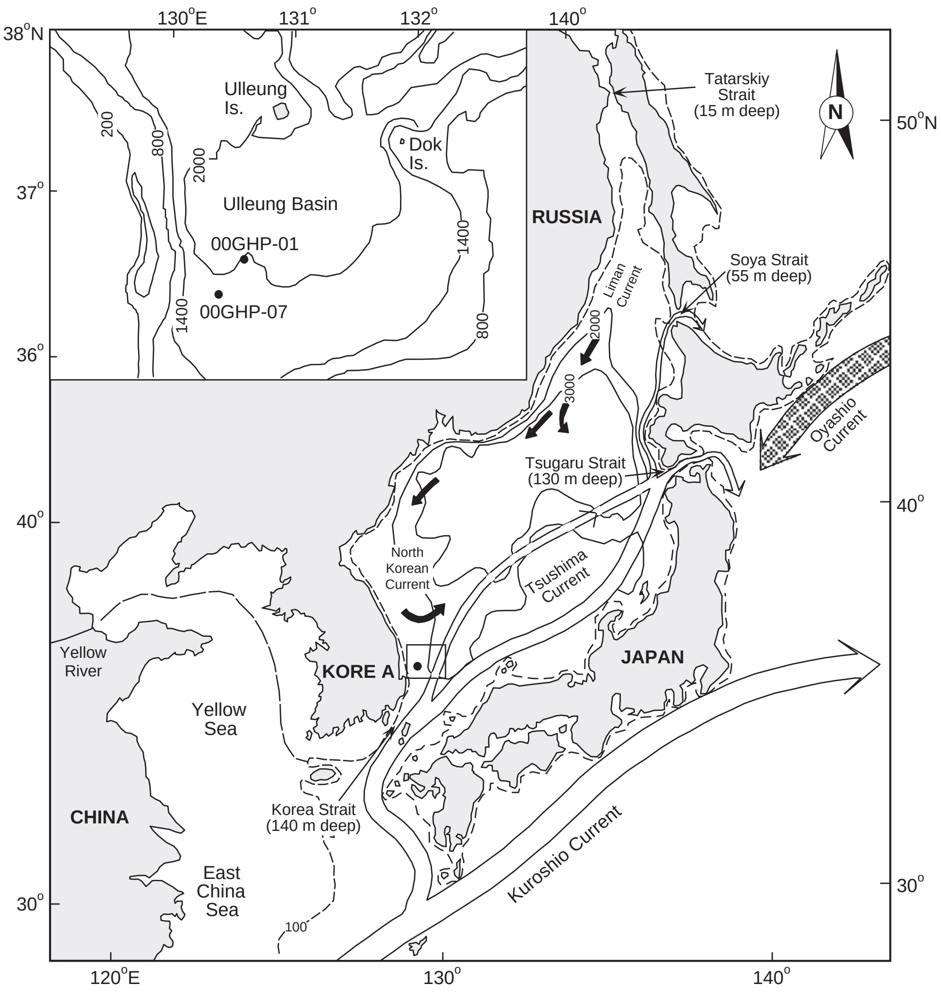


Fig. 1. a: Location map showing the sites of piston cores 00GHP-01 and 00GHP-07 in the Ulleung Basin, East Sea (Sea of Japan) with simplified dominant currents system (modified from Oba et al., 1991). Open arrow (Tsushima Warm Current) indicates high salinity warm current originated from equatorial of western Pacific Ocean. Hatched arrow (Oyashio Cold Current) represents low saline cold current come from the Bering Sea. Black closed arrow indicates cold longshore current along the eastern side of Russia and Korean Peninsula. Inset figure shows the isobath (contours is in meter) and core sites. b: Physiography of the East Sea (Sea of Japan) showing the Japan, the Yamato and the Ulleung basins and other major physiographic features. Contour intervals in meters (modified from Lee and Suk, 1998).

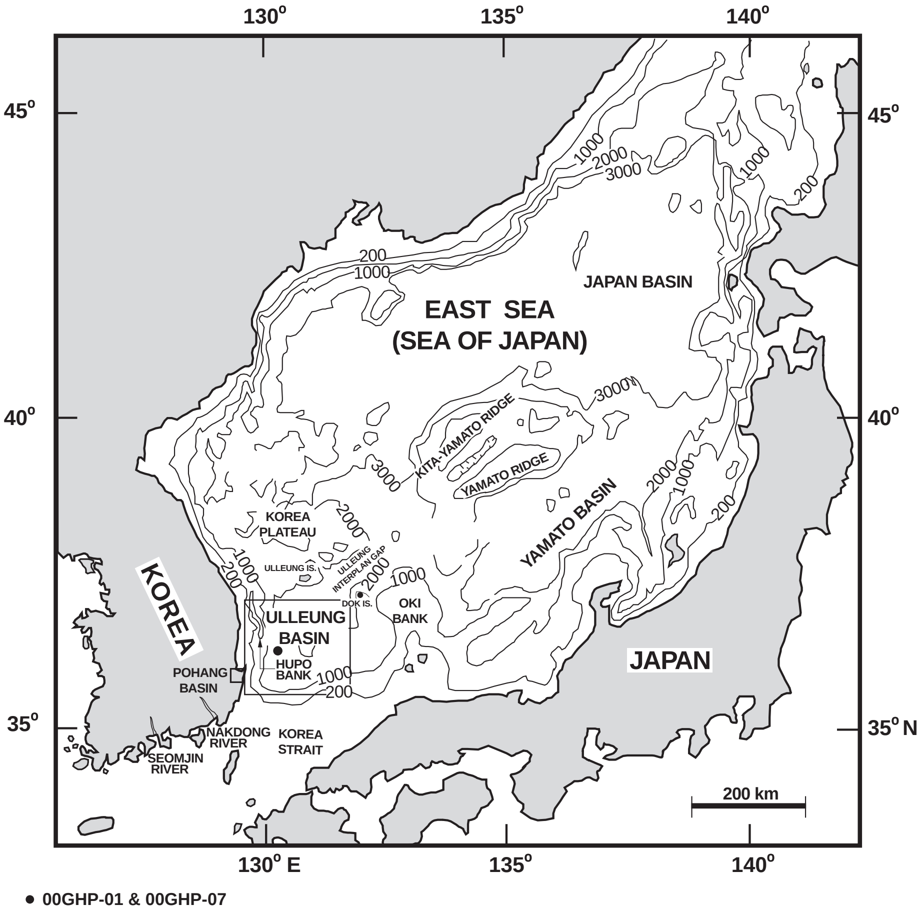


Fig. 1 (*continued*).

The circulation of modern surface water in the East Sea (Sea of Japan) is dominated by the inflow of warm and high saline water of TWC through the Korean Strait, and the inflow of cold and low saline water from the north, i.e. the Oyashio Cold Current (Fig. 1a). The paleoenvironmental conditions of the East Sea (Sea of Japan), however, changed dramatically during late Pleistocene to Holocene times. The very shallow depths of sills imply that paleoenvironmental conditions were strongly influenced by glacio-eustatic sea-level changes in the Late Quaternary. Paleontological and oxygen isotope studies from the East Sea (Sea of Japan) have revealed that during the last glacial period the bottom water was poorly oxygenated beneath a strongly density-stratified water column (Oba et al., 1991; Gorbarenko, 1993; Crusius et al., 1999; Gorbarenko and Southon, 2000; Itaki et al., 2004). The intensified density stratification has been attributed to freshwater input from rivers or excess precipitation in the nearly isolated East Sea (Sea of Japan) at that time (Oba et al., 1991; Keigwin and Gorbarenko, 1992; Gorbarenko and Southon, 2000). The paleoceanography of the East Sea (Sea of Japan) has been discussed principally based on the studies of the late Pleistocene to Holocene in Japan (e.g., Matoba, 1984; Kitamura, 1991; Oba et al., 1991; Tada et al., 1999; Kitamura and Ubukata, 2003). In contrast, the study of the latest Quaternary paleoceanography of the East Sea (Sea of Japan) of the Korean Peninsula side is limited (Chough et al., 1984, 1985; Chough and Bahk, 1984–1985; Bahk et al., 2000; Lee and Nam, 2003). There are few previous micropaleontological studies aimed at the

Quaternary environmental reconstruction of the Ulleung Basin. Even those micropaleontological researches conducted so far have been restricted to the Japanese basins, these being the Yamato Basin and Japan Basin (e.g., Ujiie and Ichikura, 1973; Tanimura, 1981; Muza, 1992; Ling, 1992; Burckle, 1992; Koizumi, 1992; Itaki et al., 2004), excluding the Ulleung Basin. In addition, a preliminary diatom study has been made from sediments of the southwestern Ulleung Basin (Ryu et al., 2003). The purpose of this study is to reconstruct the paleoenvironments of the East Sea (Sea of Japan) during the late Pleistocene and Holocene based on diatom floras from two piston cores 00GHP-01 and 00GHP-07, obtained in the southwestern of the Ulleung Basin.

2. Physiographic and paleoceanographic setting

2.1. East Sea (Sea of Japan)

The East Sea (Sea of Japan) is a semi-enclosed back-arc basin with a distinctive physiographic configuration, which is crucial to its oceanographic regime, and is one of several marginal seas of the western Pacific Ocean (Fig. 1b). The sea is about 750 km long and 180 km wide and its maximum depth exceeds 3700 m. The East Sea (Sea of Japan) is surrounded by open seas such as the Pacific Ocean and the Okhotsk Sea into which the water of the East Sea (Sea of Japan) flows through four narrow and shallow straits such as Tartarskiy, Soya, Korea and Tsugaru Straits. The East Sea (Sea of Japan) is also characterized by influx of a large amount of freshwater from the Nakdong, the Seomjin and the Yellow rivers.

The paleoceanography of the East Sea (Sea of Japan) is mainly governed by TWC, a branch of the Kuroshio Current originating from the equatorial western Pacific Ocean. This northward-flowing TWC enters the East Sea (Sea of Japan) through the Korean Strait and is forced eastwards (Fig. 1a). However, the southwestern East Sea (Sea of Japan) is divided into three different surface water masses: high salinity warm water mass, low salinity warm water mass and low salinity cold water mass. The transition region water is derived from off the coast of Japan, where the Oyashio Cold Current, originating in the Bering Sea and the Okhotsk Sea, converges with the TWC, originating in the central water mass. These currents affect the salinity and temperature of the East Sea (Sea of Japan), producing warmer and higher salinity water. Additionally, glacio-eustatic oscillations of sea level and consequent opening and closure of the Korean Strait have caused surface waters to oscillate between warm and cold conditions (Tada and Iijima, 1992; Takei et al., 2002).

Surface water conditions in the East Sea (Sea of Japan) vary depending on the region. This is mainly due to surface currents and to the influx of fresh water such as from the Yellow River. For example, the surface water temperature in the northern part of the East Sea (Sea of Japan) is low because it is affected by the Oyashio Cold Current, whereas that in the southeastern part is warm due to inflow from the TWC. Moreover, the temperature and salinity of the surface water fluctuate seasonally. Unlike the surface waters, the temperature and salinity of waters below 300 m deep are quite uniform due to convective circulation with the East Sea (Sea of Japan) Proper Water, a deep water mass that originates in the northwestern part of the sea by excessive cooling of surface during winter (Hidaka, 1966). The convective circulation induced by these seasonal and constant processes maintains conditions that are low in temperature and salinity, and high in dissolved oxygen. This water mass characterizes the present East Sea (Sea of Japan) at all depths below 300 m. This deep water has a temperature of 1 °C and a salinity of 34.07‰. It is also notable that the concentrations of dissolved oxygen are particularly high, exceeding 5 ml/l at almost all depths (Gamo et al., 1986; Kim et al., 1996). Accordingly, the organic carbon content of the surface sediments is unusually low because the high oxygen content causes organic materials to oxidize easily (Ingle, 1975). The local calcium carbonate compensation depth (CCD) is situated at about 2000 m (Ickikura and Ujiie, 1976), much shallower than in the adjacent Pacific Ocean (Kato et al., 2003). These geochemical data strongly demonstrate that the East Sea (Sea of Japan) is a well-mixed environment.

As mentioned earlier, the paleoenvironmental conditions of the East Sea (Sea of Japan) were dramatically different in the late Pleistocene and Holocene. The East Sea (Sea of Japan) may have been completely isolated from the Pacific Ocean during glacial intervals (Tada and Iijima, 1992)

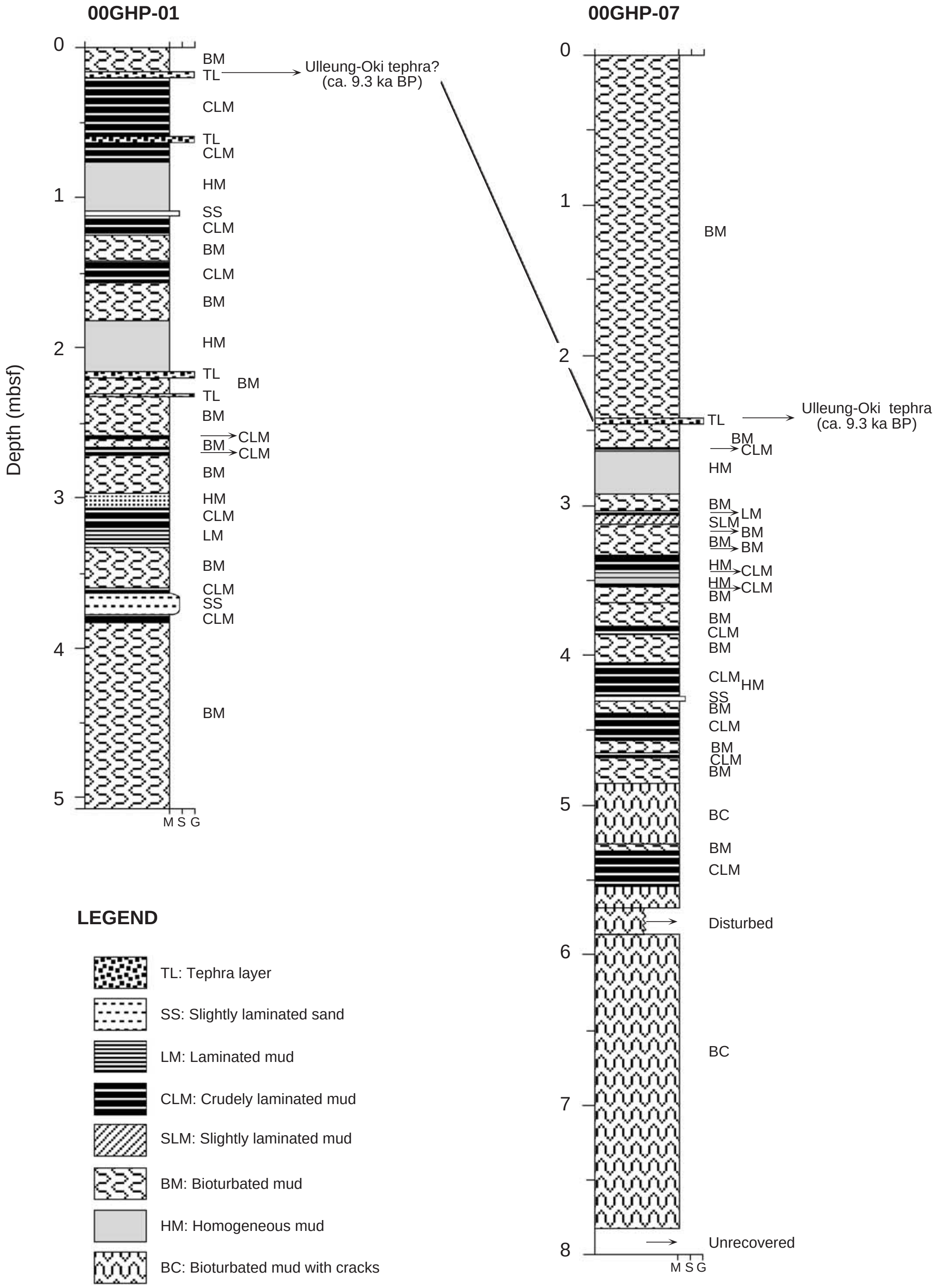


Fig. 2. General lithologic sections of 00GHP-01 and 00GHP-07 (after Park et al., 2002).

because of ice-sheet expansion, lowered sea level and greatly decreased water exchange with open seas (Morley et al., 1986). As a consequence, convective water circulation remained static during the LGM. These conditions may have resulted in anoxic deep-water conditions that allowed the formation of framboidal pyrite and organic-carbon-rich sediments (Ujiie and Ichikura, 1973; Ingle, 1975; Oba, 1983; Oba et al., 1991). These climate-controlled environmental changes in the East Sea (Sea of Japan) have influenced such physical and chemical conditions as temperature and salinity, which, in turn, affected sedimentation processes and the distribution of marine organisms including diatoms (Cremer, 1999).

2.2. Ulleung Basin

The Ulleung Basin was formed by an extension of the continental crust accompanied by a progressive southward drift of the Japanese Arc during the late Oligocene to early Miocene (Yoon and Chough, 1995). Since the late Miocene, the southern margin of the Ulleung Basin has experienced compressive deformation (Jolivet et al., 1995; Yoon and Chough, 1995). The Ulleung Basin is a deep, bowl-shaped, back-arc basin bounded by the steep continental slope of the eastern Korean Peninsula to the west and the Korea Plateau to the north (Lee and Suk, 1998) (Fig. 1b). In the south and east, the basin is bordered by a gentle slope (1–2°) and broad shelf (30–150 km wide) of the Japanese Arc and the Oki Bank. The continental shelf of the eastern Korean Peninsula is narrow (<25 km wide) and flanked by a steep slope (4–6°). Slopes as steep as 10° occur locally around the topographic highs such as the Korea Plateau and the Hupo Bank. The basin deepens progressively toward the northeast until it reaches the 2 km isobath which marks the rim of the flat basin floor. It is connected to the deeper Japan Basin by the Ulleung Interplain Gap, which is approximately 3 km deep and 70 km wide, and runs northeastward connecting the Ulleung Basin to the Japan Basin (Bahk et al., 2001) (Fig. 1b). Slope failures occurred frequently on the Ulleung Basin Slopes during the late Pleistocene. The failures have been attributed to degradation of regional slope stability by glacial eustatic sea-level lowering because no significant deltas and submarine fans were observed on the basin margin (Lee et al., 1996). In addition, a wide variety of mass-movement deposits were identified; slide and slump deposits occur mainly on the upper slope region, debris flow deposits on the lower slope and turbidites in the deeper area. These mass flow deposits are overlain by 1–2 km thick, hemipelagic/pelagic muds (Chough et al., 1985, 1997). Chough et al. (1984) and Chough and Bahk (1984–1985) documented several types of fine-grained turbidites and bottom-current deposits, but a distinction between laminated turbidite and hemipelagic laminated mud was not made (Bahk et al., 2000).

3. Materials and method

Sediments from the late Pleistocene and Holocene were recovered from two piston cores obtained in the southwestern Ulleung Basin: 00GHP-01 (latitude 36°35′N, longitude 130°34′E, 1975 m water depth) and 00GHP-07 (36°04′N, 130°08′E, 1484 m water depth) (Fig. 1a). The cores consist mainly of mud interbedded with ash layers. The layers are characterized by thinly laminated mud, homogeneous mud, crudely laminated mud, thick bioturbated mud and silty laminated sand. The upper and lower parts of the cores are dominated by hemipelagic facies, whereas the fine-grained turbidite facies is mainly present in the middle part of the cores. The bioturbated mud facies is characterized by various types of burrow structures (Fig. 2). Many crack and horizontal void structures, particularly, were identified at depths between 573 and 591 cmbsf in 00GHP-07. These structures may suggest dissociation of gas-hydrate and gas expansion (Kim et al., 2003). Several tephra layers also occur. The lapilli tephra and ash layers were observed at depths of 16–18.5, 59.5–61, 220–235.6 and 378–382 cmbsf in 00GHP-01, and 242–244.5 and 432–434 cmbsf in 00GHP-07. The lapilli tephra at depths of 16–18.5 cmbsf in 00GHP-01 and 242–244.5 cmbsf in 00GHP-07 is correlated with the U-Oki layer originating from Ulleung Island (Machida and Arai, 1992; Chun et al., 1998; Park et al., 2002) (Fig. 2). The U-Oki layer consists of milky pumice, mica, scoria and fine-grained ashes. The fine ash consists mainly of massive-type glass shards. The chemical composition of glass shards is very similar to that of glass shards occurring in the adjacent areas (Kim et al., 2003). The U-Oki layers were observed over the darker sections of the core at changes of sedimentary facies. The bioturbated mud layer in the Ulleung Basin is 1.5–2.5 m thick in Core 00GHP-07 (Fig. 2), whereas it is only ca. 15 cm thick in Core 00GHP-01. It does not seem to represent a natural sedimentary sequence in the Ulleung Basin (J.J. Bahk, personal communication). It is possible that the uppermost parts of the bioturbated interval in Core 00GHP-01 were lost by gas expansion or during the piston core recovery processes. The samples were released from Korea Institute of Geoscience and Mineral Resources that carried out the methane hydrate from the same cores.

A total of 68 samples were collected from two piston cores (518 cm long in 00GHP-01, 782 cm long in 00GHP-07) at 2–10 cm intervals in order to study fossil diatoms. To examine detailed changes across lithostratigraphical contacts, samples were taken at intervals closer than 2 cm. These samples were prepared using standard procedures; 1 g of dry sediment was treated with 10% HCL to remove the calcareous matter and then treated with 30% H_2O_2 in order to destroy the organic materials. The residue was washed repeatedly with distilled water until clean. The residue was then mounted in Hyrax for permanent slides. Four hundred diatom frustules were counted in each sample (excluding *Chaetoceros* resting spores), although at some levels the limited amount of diatoms in the sediments prevented this figure from being reached. A total 193 species were identified and their frequency expressed as an individual (Figs. 3 and 5). Diatoms were categorized as marine planktonic, tychopelagic and benthic, freshwater and extinct species (Koizumi, 1992).

4. Results

4.1. Diatom assemblages in Core 00GHP-01

4.1.1. General characteristic

Core 00GHP-01 samples yielded abundant and diverse diatom taxa, and a total of 186 diatom species have been recognized. Most of the fossil diatoms recovered are well preserved. The highest abundance with moderate preservation was recorded in the samples at lower interval (502–400 cm), but in some samples at upper interval of 100–40 cm a few poorly preserved specimens were observed. The predominant taxa are *Paralia sulcata* (7–60%), *Thalassiothrix longissima* (1–47%), *Thalassionema nitzschioides* (3–29%), *Cyclotella striata* (1–26%), *Pseudoeunotia doliolus* (1–18%), *Rhizosolenia hebetata* var. *hiemalis* (1–13%) in combination with common to few *Actinocyclus curvatulus, Actinocyclus octonarius, Actinoptychus senarius, A. splendens, Diploneis bombus, D. smithii, Delphineis surirella, Thalassiosira oestrupii, T. eccentrica, Azpeitia nodulifera, Coscinodiscus asteromphalus, Coscinodiscus radiatus, Coscinodiscus marginatus, C. oculus-iridis* and *Rhizosolenia setigera* (Figs. 3 and 4). The majority of diatoms are marine planktonic, marine benthic and tychopelagic sublittoral species; some freshwater and extinct species are also present in the sediments, and these are believed to have been transported or reworked. The extinct species such as *Actinocyclus ingens, Denticulopsis dimorpha, Denticula hustedtii, Denticula lauta* and *Neodenticula kamtschatica* attain values below 2% of the entire diatom assemblage. The percentage value of the freshwater forms is not significant (1–2%). The marine tychopelagic species (e.g., *Cyclotella striata* and *P. sulcata*), benthic species (e.g., *Delphineis surirella* and *Diploneis bombus*) and sublittoral-neritic species (*A. octonarius* and *A. senarius*) are present throughout the whole section, showing a high abundance. *Azpeitia nodulifera, C. radiatus, C. oculus-iridis, Nitzschia marina, R. setigera, Roperia tesselata* and *T. oestrupii* predominate among the oceanic species.

4.1.2. Assemblage zone

A total of six assemblage zones together with two barren zones, are established from the whole section of Core 00GHP-01, based on critical species occurrences such as *Paralia sulcata, Pseudoeunotia doliolus, Cyclotella striata, Rhizosolenia hebetata* var. *hiemalis, Thalassionema nitzschioides* and *Thalassiothrix longissima*. The assemblage zones and their characteristic are described in ascending order.

The *Pseudoeunotia doliolus* Assemblage Zone (502–410 cm) is characterized by the predominance of *P. doliolus, Coscinodiscus asteromphalus, Azpeitia nodulifera, Coscinodiscus radiatus, C. oculus-iridis, Actinocyclus curvatulus, Thalassiosira oestrupii* and *Thalassionema nitzschioides*. This assemblage zone

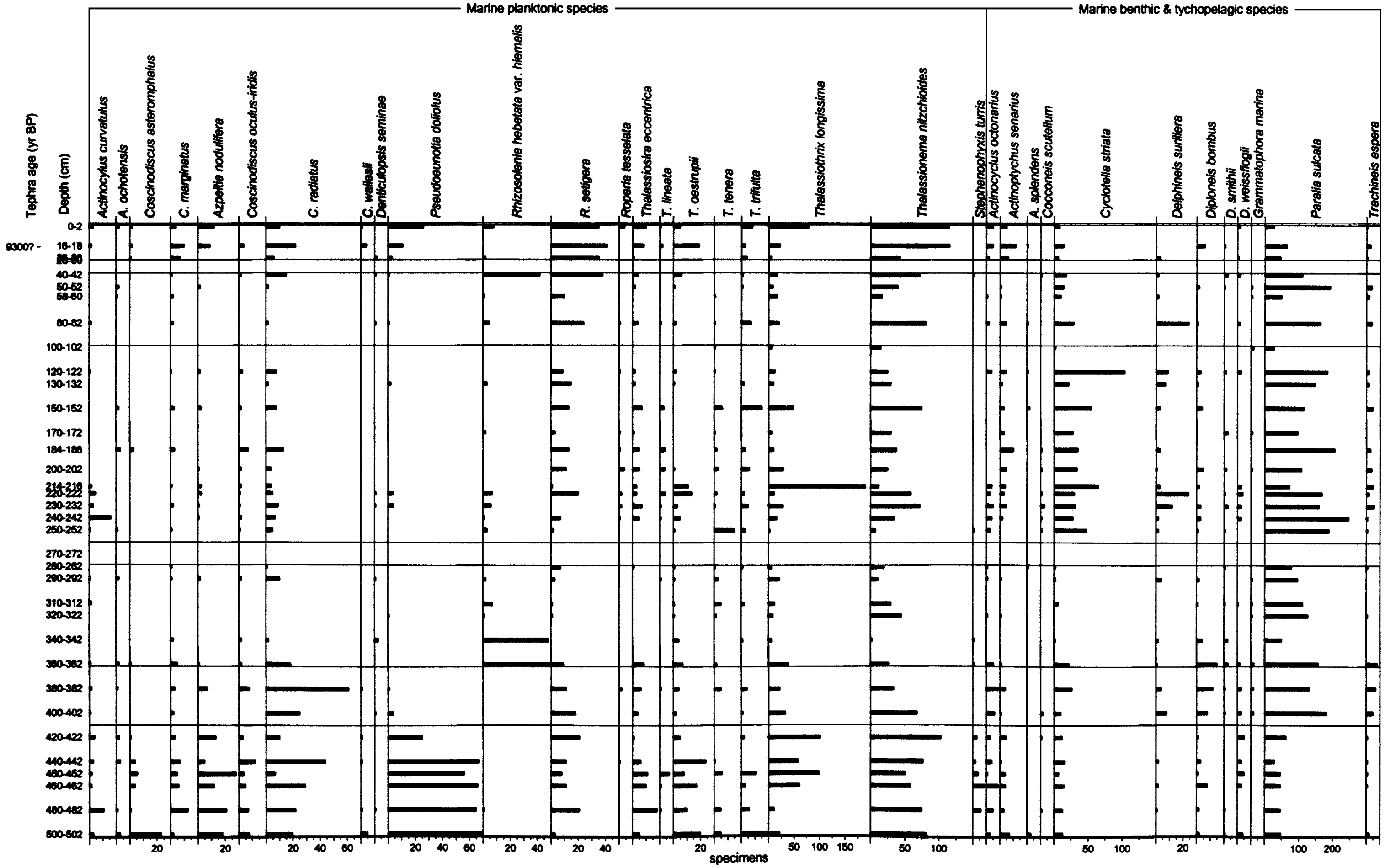
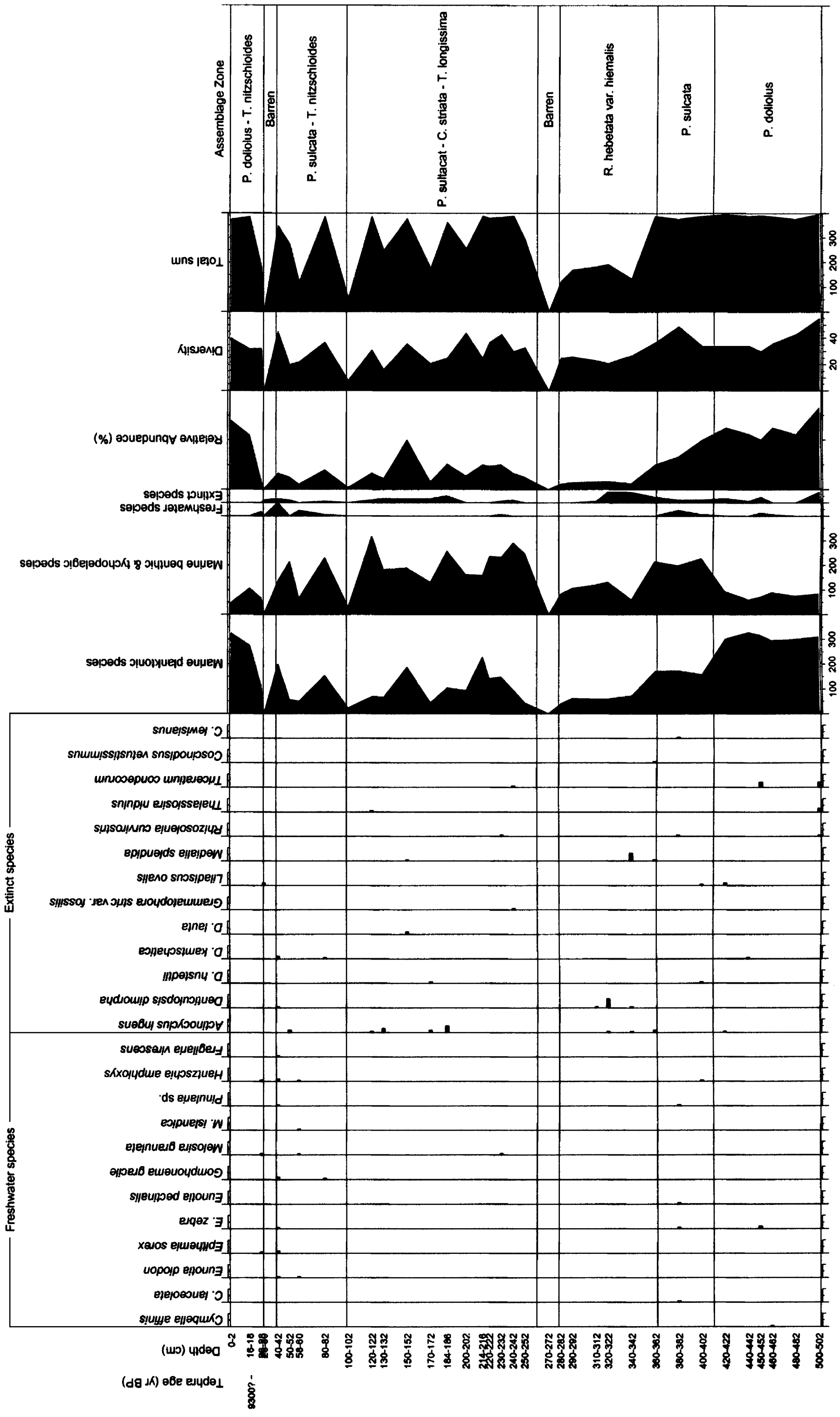


Fig. 3. Relative abundance of the dominant diatom taxa with assemblage zones in 00GHP-01. Species variations of marine planktonic and benthic–tychopelagic species, and freshwater and extinct species and total abundance and diversity are also given in right column. Six assemblage zones are named by representative species.



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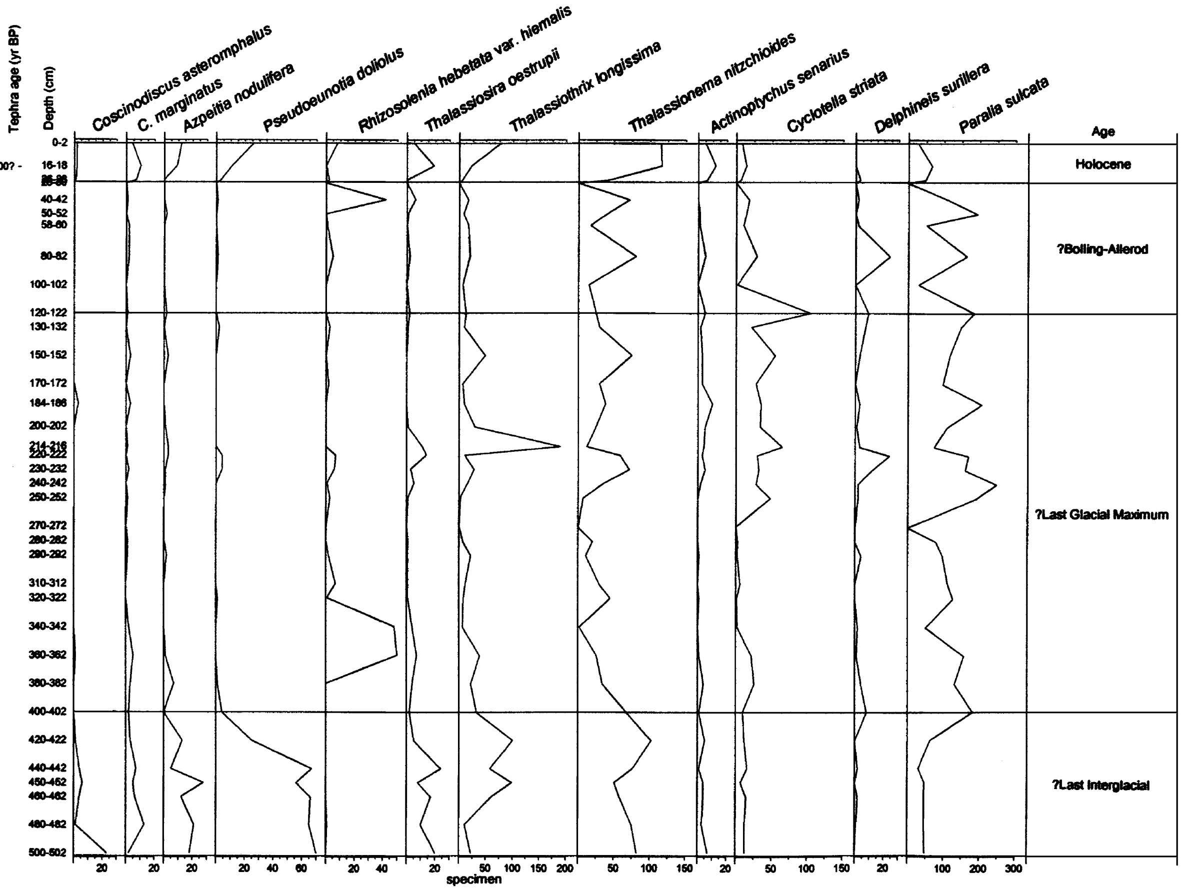


Fig. 4. Occurrence variation of selected critical taxa with inferred geologic age in 00GHP-01.

shows high species diversity and abundance and is predominated by *P. doliolus* (up to 18%).

The *Paralia sulcata* Assemblage Zone (410–360 cm) is dominated by benthic and tychopelagic species such as *P. sulcata, Cyclotella striata, Delphineis surirella, Diploneis bombus* and *Diploneis weissflogii,* and is characterized by an overwhelming abundance of the low salinity species, *P. sulcata* (up to 46%). The admixture of the displaced marine-littoral diatoms *Trachyneis aspera, Biddulphia tuomeyi, Navicula hennedyi* and *Triceratium antediluvium* is almost as constant as the admixture of freshwater species (e.g., *Melosira granulata, Epithemia sorex, E.* zebra, *Eunotia diodon* and *E. pectinalis*).

The *Rhizosolenia hebetata* var. *hiemalis* Assemblage Zone (360–280 cm) has low diatom abundance, but is characterized by relatively high frequencies of *R. hebetata* var. *hiemalis* (up to 13%). *Paralia sulcata* also occurs abundantly and a few specimens of *Denticula seminae* are present only at 340 cm (1%).

The *Paralia sulcata–Cyclotella striata–Thalassiothrix longissima* Assemblage Zone (260–100 cm) is characterized by the predominance of *P. sulcata* (47–62%), *C. striata* (5–26%), *T. longissima* (1–18%) and *Thalassionema nitzschioides* (3–20%). Moreover, many marine tychopelagic and benthic species including *Actinocyclus octonarius, Actinoptychus senarius* and *Diploneis bombus* are continuously present throughout the section. Interestingly, a small number of *Pseudoeunotia doliolus, Coscinodiscus asteromphalus, Azpeitia nodulifera, Actinocyclus curvatulus* and *Thalassiosira oestrupii*, which are found within the interval 502–410 cm, reoccur in this zone. A tropical species, *Hemidiscus cuneiformis* appears for first time only within the interval 250–220 cm and *Hemidiscus cuneiformis* is generally very rare throughout its total range.

The *Paralia sulcata–Thalassionema nitzschioides* Assemblage Zone (100–40 cm) shows relatively low species diversity and abundance, and is characterized by a significant amount of *Delphineis surirella* compared with other intervals. Valves are poorly preserved and generally small in size. The marine tychopelagic species *P. sulcata* (47–62%) and cold water species *Rhizosolenia hebetata* var. *hiemalis* are the most commonly encountered diatoms, but marine planktonic species including *Pseudoeunotia doliolus, Coscinodiscus asteromphalus, Azpeitia nodulifera, Actinocyclus curvatulus* and *Thalassiosira oestrupii* are minor components within this interval. Reworked extinct diatoms (e.g., *Actinocyclus ingens, Denticulopsis dimorpha, Denticula hustedtii, Denticula lauta* and *Neodenticula kamtschatica*) are more abundant than in the overlying sections. Some displaced fresh-water species including *Hantzschia amphioxyes, Fragilaria virescens* and *Eunotia monodon* together with the river-mouth taxon *Cyclotella striata* var. *bipunctata* occur in this assemblage zone.

The *Pseudoeunotia doliolus–Thalassionema nitzschioides* Assemblage Zone (28–0 cm) is dominated by *P. doliolus, Azpeitia nodulifera, Coscinodiscus asteromphalus, Coscinodiscus radiatus, C. oculus-iridis, Actinocyclus curvatulus, T. nitzschioides*, *Thalassiosira oestrupii* and *Thalassiothrix longissima.* This zone is characterized by significant increase in abundance and diversity.

Barren Zone: Two barren zones (2 cm thickness) are observed at depths of 30 cm and 270 cm below the sea floor. Neither diatoms nor any organic remains are found in these two zones.

4.2. Diatom assemblage in Core 00GHP-07

4.2.1. General characteristic

A total of 193 diatom species have been identified in Core 00GHP-07, showing a close similarity in abundance and diversity to those of Core 00GHP-01. Species diversity and preservational state both vary with depth (Figs. 5 and 6). The assemblage characteristics of 00GHP-07 are an abundant occurrence of both marine tychopelagic (*Actinoptychus senarius, Paralia sulcata* and *Cyclotella striata*) and benthic species including *Delphineis surirella*, *Diploneis bombus* and *D. smithii.* In particular, a tychopelagic species, *P. sulcata*, occurs dominantly throughout the whole section.

The percentage of marine tychopelagic–benthic species is higher in 00GHP-07 than in 00GHP-01. They occur abundantly at middle and lower interval (775–150 cm), whereas marine planktonic species are abundant in the upper interval (150–0 cm). At a depth of 775–150 cm, however, a diagnostic subtropical warm water species, *Pseudoeunotia doliolus,* is scarcely found. There are a few displaced fresh-water species at some levels in the middle and bottom portions of the core. A few reworked Miocene diatoms (e.g., *Actinocyclus ingens, Denticulopsis dimorpha, Denticula hustedtii,* and *Grammatophora stricta* var. *fossilis*) occur at various levels, having maximum abundance in the middle part of the section (440–270 cm). At 160–150 cm interval, the curve show a planktonic and benthic assemblage shift change (Fig. 5). The distribution and relative frequency of the planktonic, benthic–tychopelagic groups of diatoms are shown in Fig. 5. In general, the preservational state of diatom valves is poor, although heavily silicified species (e.g., *Thalassionema nitzschioides, Paralia sulcata* and *Cyclotella striata*) occur elsewhere throughout the section (as far as 150 cm below the sea floor). Various stages of dissolution and extensive diagenetic alteration are clearly visible in most frustules. Particularly, the most poorly preserved specimens are concentrated at the middle of the interval where *D. smithii* shows maximum dissolution.

4.2.2. Assemblage zone

On the basis of benthic and planktonic species, and relative abundance of specific species (e.g., *Paralia sulcata, Pseudoeunotia doliolus, Cyclotella striata, Rhizosolenia hebetata* var. *hiemalis, Thalassionema nitzschioides,* and *Thalassiothrix longissima*) the following four assemblage zones are recognized from lower to upper horizons.

The *Paralia sulcata–Cyclotella striata* Assemblage Zone (775–440 cm) is distinguished by the predominance (up to 80%) of tychopelagic and benthic diatom genera including *Navicula, Diploneis, Delphineis* and *Cocconeis*. In contrast, marine planktonic species are minor components. Dominant

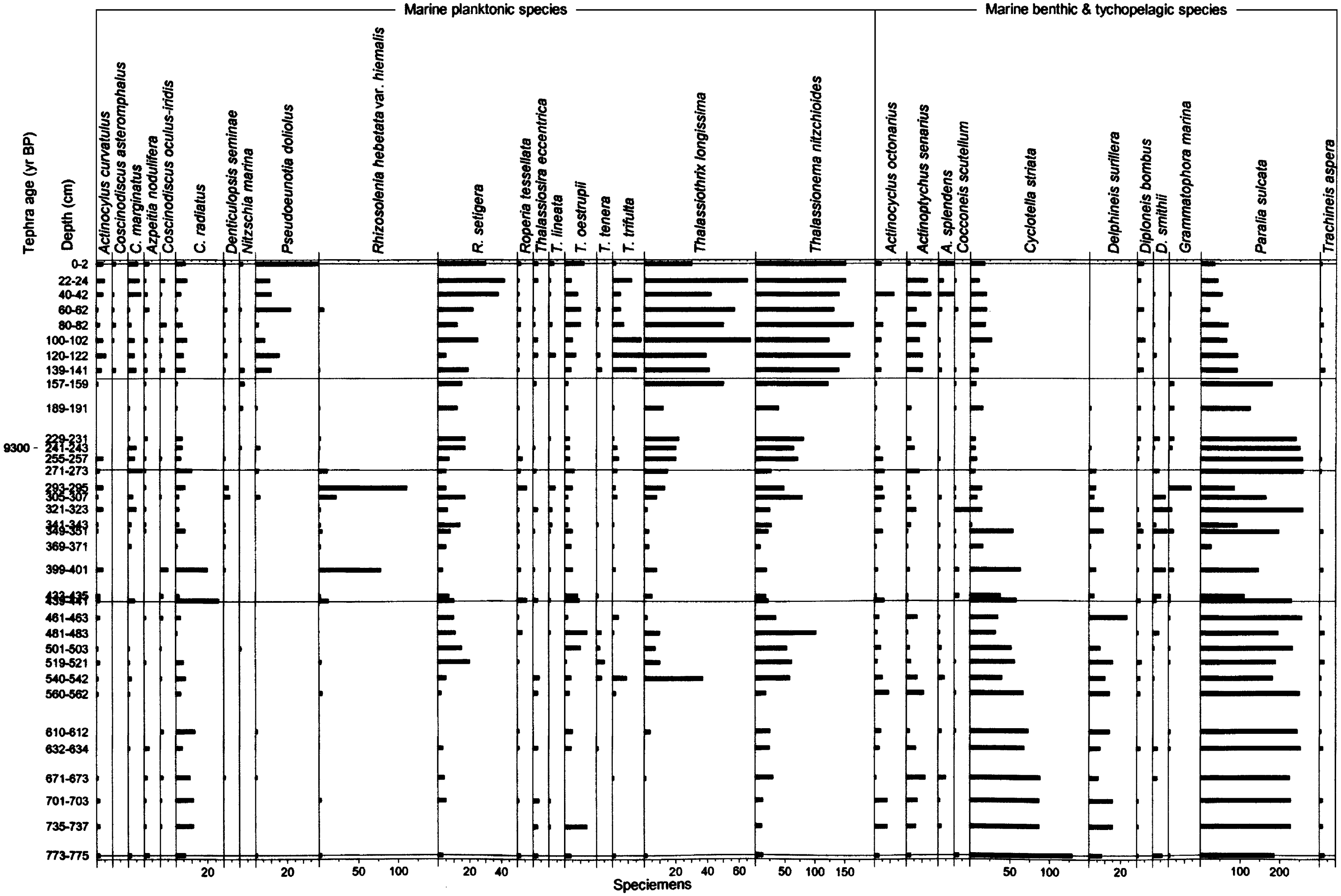


Fig. 5. Relative abundance of the dominant diatom taxa with assemblage zones in 00GHP-07. Species variations of marine planktonic and benthic–tychopelagic species, and freshwater and extinct species and total abundance and diversity are also given in right column. Four assemblage zones are named by representative species.

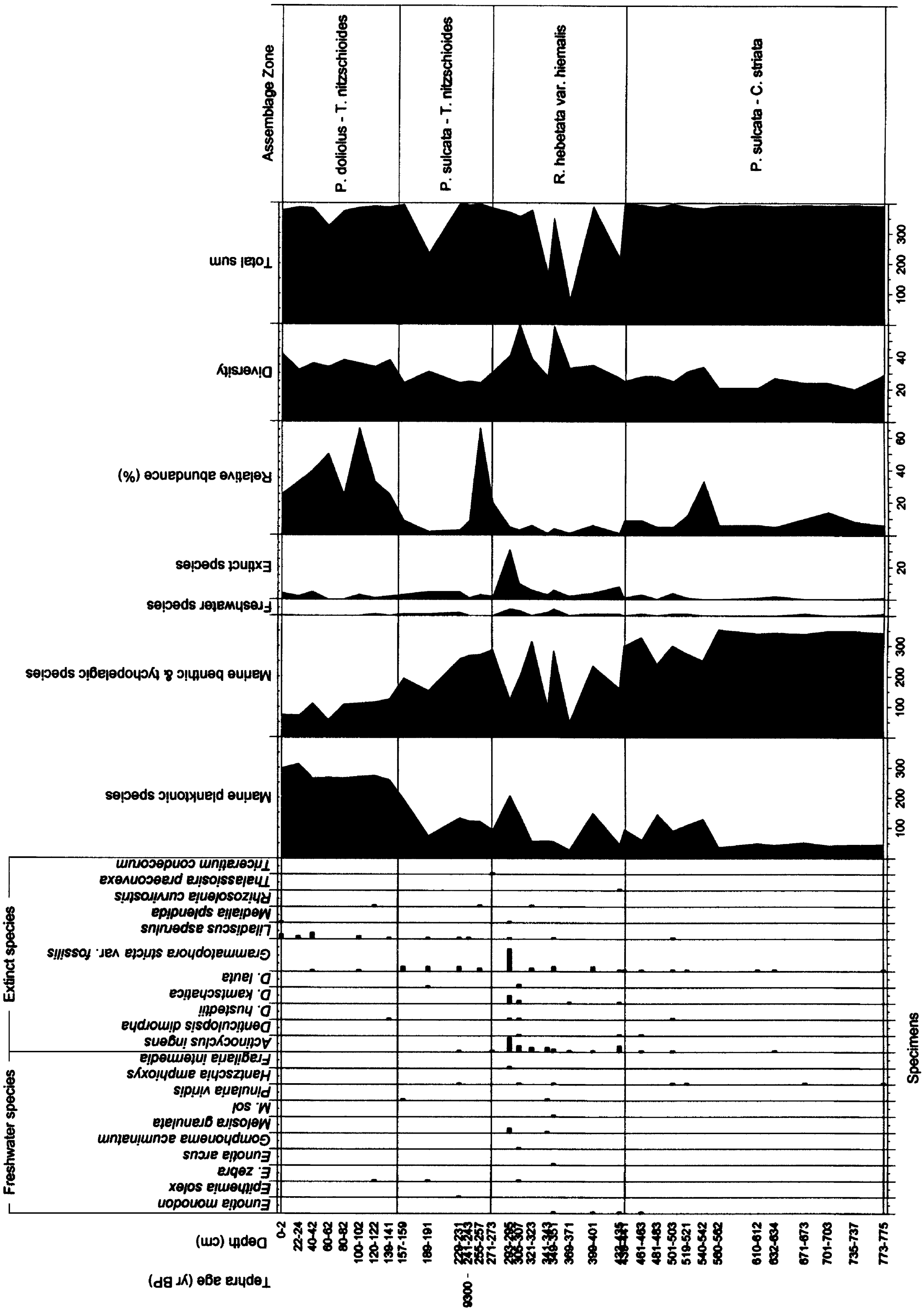


Fig. 5 (continued).

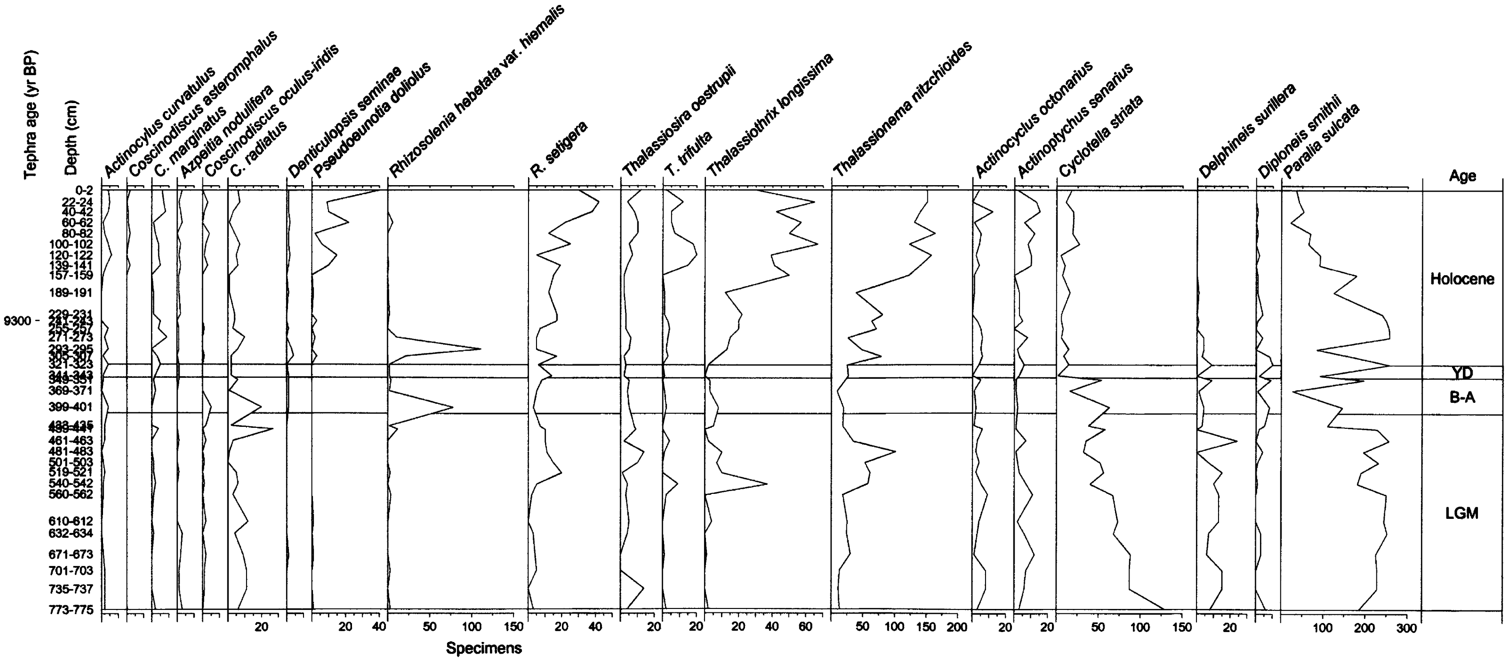


Fig. 6. Occurrence variation of selected critical taxa with inferred geologic age in 00GHP-07. YD: Younger Dryas, B-A: Bølling-Allerod, LGM: Last Glacial Maximum.

species also include *Thalassionema nitzschioides* (up to 26%), *Thalassiothrix longissima* (up to 9%), *Rhizosolenia setigera* (up to 5%), *Coscinodiscus radiatus* (up to 7%) and *Actinoptychus senarius* (up to 3%). At a depth of 775 cm, *C. striata* (up to 32%) is found abundantly. Dominant floras involving *C. striata* and *P. sulcata* in this assemblage zone are interestingly robust and heavily silicified.

The *Rhizosolenia hebetata* var. *hiemalis* Assemblage Zone (440–270 cm) is characterized by low diversity and abundance, a relatively large proportion of reworked specimens and poor preservation. Dominant taxa are *Rhizosolenia hebetata* var. *hiemalis, Thalassionema nitzschioides, Paralia sulcata, Cyclotella striata, Diploneis bombus, D. smithii* and *Actinoptychus senarius*. Among them, *R. hebetata* var. *hiemalis* is the predominant species and its abundance reaches a peak at depths of 293 cm (38%) and 400 cm (20%). In spite of low species diversity and abundance, this assemblage zone contains more displaced species including freshwater diatoms than other assemblages. The reworked diatom fossils are *Actinocyclus ingens, Denticulopsis dimorpha, Denticula hustedtii, Denticula lauta* and *Neodenticula kamtschatica.* Freshwater diatoms encountered in this assemblage zone include *Hantzschia amphioxyes, Fragilaria virescens* and *Eunotia* spp.

The *Paralia sulcata–Thalassionema nitzschioides* Assemblage Zone (270–140 cm) is predominated by *P. sulcata* (up to 64%) and *T. nitzschioides* (up to 40%), together with common *Rhizosolenia setigera* (up to 5%), *Thalassiothrix longissima* (up to 5%), *Thalassiosira oestrupii, Thalassiosira trifulta, Roperia tesselata* and *Coscinodiscus radiatus. Plagiogramma staurophorum* is also found more abundantly in this zone than other intervals.

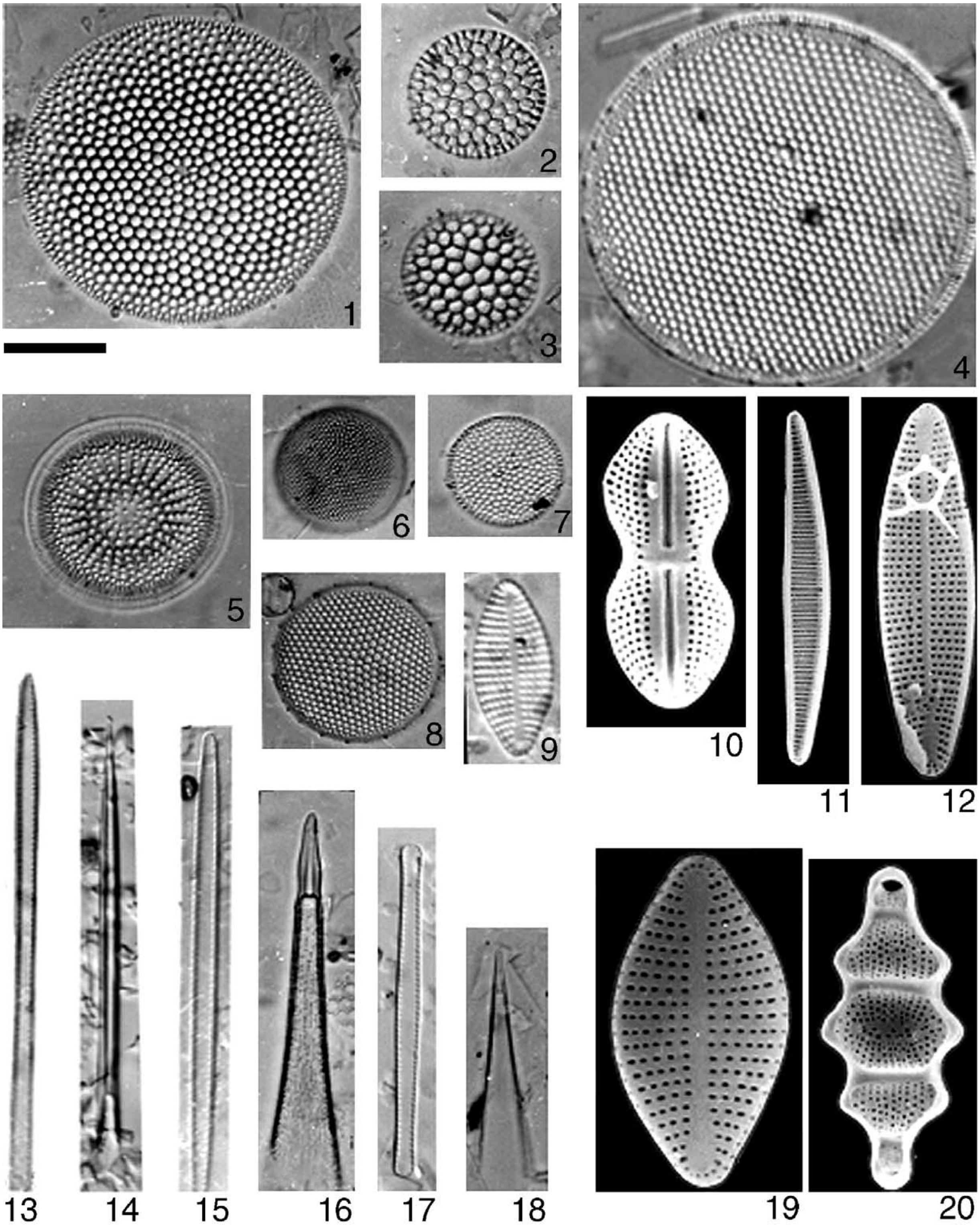
The *Pseudoeunotia doliolus–Thalassionema nitzschioides* Assemblage Zone (140–0 cm) is distinguished by high species diversity and abundance, in which *P. doliolus* (up to 10%), *T. nitzschioides* (up to 40%), *Thalassiothrix longissima* (up to 14%), *Paralia sulcata* (up to 23%), *Rhizosolenia setigera* (up to 11%) and *Thalassiosira trifulta* (up to 5%). *Roperia tesselata, Azpeitia nodulifera, Coscinodiscus marginatus, Coscinodiscus radiatus, Cyclotella striata, Diploneis bombus, Actinoptychus senarius* and *A. splendens* are commonly present throughout the interval. Preservation of frustules is moderate to good (Plates I and II).

5. Discussion

5.1. Age model

An absolute age was obtained only on the Ulleung-Oki tephra, by means of radiometry. The lapilli tephra layers from the interval 242–244.5 cm in core 00GHP-07 is correlated with the U-Oki layer originated from the Ulleung Island (Park et al., 2002; Kim et al., 2003) (Fig. 2). The sedimentation rate at the interval of 242 cm were also determined by using correlatable ash layers including the Ulleung-Oki tephra (9.3 ka) and by sedimentological analysis (Park et al., 2002; Kim et al., 2003). Sedimentation rates, in general, correlate with the relative amounts of pelagic sediments, hemipelagic sediments and terrigenous debris-bearing sequences in the core. As mentioned above, only one radiometric age is known and therefore absolute ages throughout the core are unavailable. However, relative or approximate ages may be calculated using an absolute age of the tephra layer, a thinly laminate layers sedimentation rate of the core and a presence or absence of certain diatoms in the core. The most characteristic feature of the sedimentology was the presence of dark colored layers, most of which showed thin lamination (TL), these layers being a well-known and ubiquitous feature of basins in the East Sea (Sea of Japan) (Tada et al., 1999). In addition, diatom assemblages showed apparent depth-related changes. The sedimentary sequences of 00GHP-07 show an apparently continuous Late Quaternary record, spanning the LGM, Bølling-Allerød, Younger Dyras, and Holocene (Fig. 6).

The Ulleung-Oki tephra (9.3 ka) occurs at 242–244.5 cm depth in 00GHP-07, suggesting an average sedimentation rate of 25.8 cm/ky. Extrapolating this rate downcore implies that the first continuous downcore occurrence of *Pseudoeunotia doliolus* at about 321–323 cm would be at 11.3 ka, or about the base of the Holocene (Fig. 6). In addition, a reversal of the dominant taxa at this interval suggests the location of the Pleistocene/Holocene boundary. From this boundary upwards, the amount of displaced marine planktonic diatoms increases compared to the underlying section, which may be attributed to sea level rise. This means that Pleistocene/Holocene boundary marks a period of change in the character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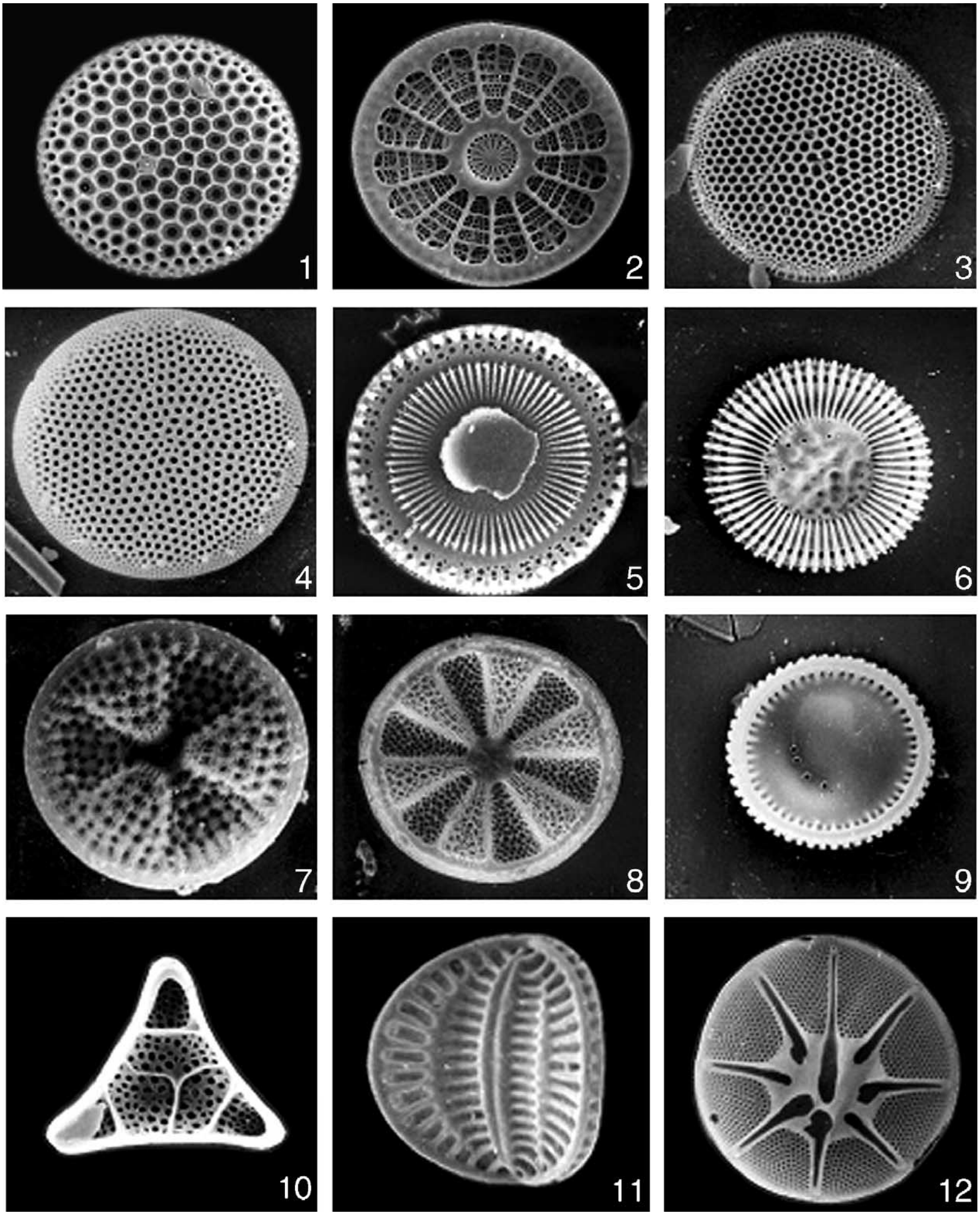
of the diatom assemblage as suggested by Koizumi (1984). In addition, *Cyclotella striata*, which is a tychopelagic taxon living in coastal areas, is reduced in relative abundance above this interval, suggesting that it might be a good marker for the base of the Holocene. The cold surface-water diatom, *Rhizosolenia hebetata* var. *hiemalis*, indicates that a southward migration of the Oyashio Cold Current took place in the East Sea (Sea of Japan). The first down core occurrence of laminated mud at 345–355 cm would be at 12.1 to 12.4 ka, corresponding to the circum-Atlantic Younger Dyras chronology (Gorbarenko and Southon, 2000). The thicker laminated muds begin at 410 cm, corresponding to the base of the Bølling-Allerød (14.4 ka). The laminated sediments in the East Sea (Sea of Japan) occur prior to 15 ka and indicate water column stratification (Crusius et al., 1999). Deposition of this dark layer probably reflects enhanced preservation of organic matter under the euxinic conditions caused by isolation of the East Sea (Sea of Japan) during the LGM, and increased relative contribution of the low salinity East China Sea water (Tada et al., 1999). Deep water circulation within the East Sea (Sea of Japan) became sensitive to the relative contribution of low salinity East China Sea Water to the influx, and bottom water oxygenation levels oscillated during low to intermediate sea levels (Tada et al., 1999). The high abundance of *Paralia sulcata* and *Delphineis surirella* at 440–775 cm represents low sea-level and weakly oxic conditions. In the East Sea (Sea of Japan), the distribution of *P. sulcata* is generally restricted to the southern part of the sea under the influence of low salinity water. Furthermore, large increases in sedimentation rates in core 00GHP-07 occurred at the time of lowest salinity.

As mentioned earlier, the missing in uppermost interval in 00GHP-01 can be inferred. On the basis of the diatom frequency distributions (Figs. 3 and 4) and the lithologies (Fig. 2), the tephra at 16–18.5 cm in 00GHP-01 might be U-Oki tephra (9.3 ka). This tephra layer is overlying a laminated layer (20–70 cm). Moreover, an abrupt decline in *Rhizosolenia hebetata* var. *hiemalis* and the first occurrence of *Pseudoeunotia doliolus* at base of these intervals, probably corresponds to the Pleistocene/Holocene boundary. *P. doliolus* is the key species in calculating the relative age of core 00GHP-01. The first occurrence of *P. doliolus* was reported from the Olduvai Subchron (2 Ma) in the Equatorial Pacific, but this species first appeared in East Sea (Sea of Japan) at 10 ka according to Koizumi (1989). *P. doliolus* indicates that present-day TWC did not flow into the East Sea (Sea of Japan) between 85 and 11 ka (Oba et al., 1991). Instead of the TWC, warm and low salinity surface water mixed with the Yellow Sea and East China Sea was supplied to the

Plate I. Specimens are identified by core and sample depth (cm). Scale bar: 20 μm. Figures 10–12, 19–20 are SEM photos; others are transmitted microscopic photos.

1. *Coscinodiscus radiatus* (00GHP-07, 701–703).
2–3. *Coscinodiscus marginatus* (00GHP-07, 632–634), same species in different foci.
4. *Thalassiosira leptopus* (00GHP-01, 500–502).
5. *Actinocyclus ingens* (00GHP-07, 305–307).
6. *Roperia tesselata* (00GHP-07, 341–343).
7. *Azpeitia nodulifera* (00GHP-07, 293–295).
8. *Thalassiosira trifulta* (00GHP-07, 229–231).
9. *Delphineis surirella* (00GHP-07, 369–371).
10. *Diploneis bombus* (00GHP-07, 0–2) (×1300).
11. *Pseudoeunotia doliolus* (00GHP-07, 0–2) (×800).
12. *Delphineis surirella* (00GHP-01, 500–502 cm) (×700).
13. *Thalassiothrix longissima* (00GHP-01, 500–502).
14. *Rhizosolenia setigera* (00GHP-01, 480–482).
15. *Thalassionema nitzschioides* (00GHP-01, 500–502).
16. *Rhizosolenia hebetata* var. *hiemalis* (00GHP-07, 399–401).
17. *Thalassionema nitzschioides* (00GHP-01, 0–2).
18. *Rhizosolenia bergonii* (00GHP-01, 120–122).
19. *Delphineis surirella* (00GHP-07, 369–371) (×500).
20. *Biddulphia tuomeyi* (00GHP-07, 481–483) (×500).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East Sea (Sea of Japan) from 85 to 27 ka. However, high abundance of *P. doliolus* and warm water diatoms (e.g., *Coscinodiscus asteromphalus*, *Thalassiosira oestrupii* and *Azpeitia nodulifera*) at the base (about 420–502 cm) of 00GHP-01 suggests a strong inflow of TWC into the East Sea (Sea of Japan). It might be indicative of the last interstadial, around 30–35 ka (Morley et al., 1986) (Fig. 4).

More detailed foraminiferal studies and stable-isotope records of sediment in the Ulleung Basin are needed to constrain our interpretation of this part of the Late Quaternary.

5.2. Significance of high abundance of Paralia sulcata in Late Quaternary sediments of the East Sea (Sea of Japan)

Diatom assemblages have been used frequently as qualitative indicators of paleoproduction (Sancetta, 1992) and less often as quantitative one of individual parameters such as temperature (Karpuz and Schrader, 1990) and salinity (Fritz et al., 1991). However, the accuracy of paleoreconstructions depends on how well the sediment record reflects the plankton and the sensitivity of organisms to the environmental variables to be reconstructed (Mcquoid and Hobson, 2001).

Paralia sulcata is one of the most useful diatom species for inferring past environmental conditions. The tychoplanktonic nature of *P. sulcata* must be taken into account when interpreting its usefulness as a paleoindicator of environmental change, because this species is plentiful and cosmopolitan, and more resistant to dissolution than other diatom species. During the LGM, when sea level was 130 m lower than today (Fairbanks, 1989), oceanographic conditions in the East Sea (Sea of Japan) were different from present-day conditions. A falling sea level would have resulted in a greatly increased littoral area, and more area suitable for *P. sulcata* growth. *P. sulcata* is a good marker for low-salinity, river-derived water generally shallower than 100 m (Sancetta, 1982; Koizumi, 1984; Tanimura, 1981), and is especially abundant in fine-grained, organic-rich sediments (Zong, 1997). Sancetta (1982) used high abundances of *P. sulcata* as an indicator of the shelf-slope break in the Bering Sea. In sediments deposited below the shelf break (ca. 200 m depth), increased relative numbers of *P. sulcata* reflect increased downslope transport, typical of periods of lowered sea level. In the East Sea (Sea of Japan), this species has been used as an indicator of the East China Sea coastal water (Koizumi, 1984; Tada et al., 1999). High abundance of *P. sulcata* in core sediments (4–67%) is considered to reflect the relative contribution of the East China Sea coastal water to the influx through the Korean Strait (Tanimura, 1981; Tada et al., 1999), and influx of amount of terrestrial material brought from the Korean Peninsula. Such tendency is probably caused by the intensifying influence of freshwater discharged from the Korean (Nakdong and Seomjin) and Chinese (Yellow and Yangtze) rivers. When a continuous influx of high-salinity TWC occurred during sea level rise, *P. sulcata* decreased. A sudden decrease of *P. sulcata* in the upper (30–0 cm) and lower (500–400 cm) part of the 00GHP-01, and the upper (150–0 cm) part of the 00GHP-07 coincides with the period of sea level rise which greatly reduced littoral areas and increased salinity, thus reducing areas suitable for *P. sulcata*.

Plate II. Specimens are identified by core and sample depth (cm). All figures are SEM photos.

1. *Coscinodiscus marginatus* (00GHP-01, 500–502) (×1700).
2. *Arachnoidiscus japonicus* (00GHP-01, 500–502) (×700).
3. *Thalassiosira eccentrica* (00GHP-01, 250–252) (×1200).
4. *Roperia tesselata* (00GHP-01, 500–502) (×600).
5. *Paralia sulcata* (00GHP-01, 500–502) (×2000).
6. *Cyclotella striata* (00GHP-07, 439–431) (×1400).
7. *Actinoptychus heliopelta* (00GHP-07, 0–2) (×1500).
8. *Actinoptychus splendes* (00GHP-01, 250–252) (×1500).
9. *Paralia sulcata* (00GHP-01, 250–252) (×2000).
10. *Triceratium alternans* (00GHP-01, 250–252) (×1300).
11. *Campylodiscus brightwelli* (00GHP-01, 500–502) (×500).
12. *Asteromphalus hookeri* (00GHP-07, 0–2) (×1200).

Thalassionema nitzschioides is also the main species in the two cores of the Ulleung Basin (Figs. 3 and 5). Both species (*Paralia sulcata* and *T. nitzschioides*) are closely related to the East China Sea water flowing into the East Sea (Sea of Japan). They are mainly found in the surface sediments southern and western sides of Korean Peninsula, where the East China Sea has a strong impact (Lee, 1991; Lee et al., 1994, 1995, 1997). In addition, *P. sulcata* is abundant in upwelling areas (Karpuz and Schrader, 1990; Schrader, 1993; Lange et al., 1998) and in estuarine or lagoonal environments (Cahoon and Laws, 1993; Hemphill-Haley, 1995). However, relatively high abundance of this species is also recorded from deep seas where salinity is less than 30% and water depth is more than 100 m (Karpuz and Schrader, 1990). This may explain cosmopolitan species of *P. sulcata* or easy tendency of detachment from the bottom after winter storm (Hendey, 1964; Sherrod, 1999), making this species to live as plankton (Crawford, 1979; Lange et al., 1998). Valves of *P. sulcata* could also be transported from the continental shelf to the deep ocean by winds, surface ocean currents, deep ocean currents, or turbidity currents. It appears likely that *P. sulcata* valves are subject to downslope movement, perhaps in turbidity currents traveling down to the steep continental slope of that region. In short, valves of neritic diatoms appear to be transported substantial distances. This possibility is particularly strong for the more heavily silicified taxa such as *Delphineis,* which are most likely to survive dissolution during the transportation.

Owing to the persistent presence of *Paralia sulcata* in the sediments, and its resistance to dissolution and the general state of preservation (Abrantes, 1988, 1991), caution needs to be kept in mind when one interprets paleoenvironments or true abundance of this species. For example, the relative frequency and abundance of *P. sulcata* in assemblages can be regarded as useful criteria in understanding sediment conditions. Such an ecological context for *P. sulcata* hinders paleoenvironmental interpretation when fossil assemblages are dominated by this species.

5.3. Paleoproductivity estimations from the diatom record

5.3.1. Upwelling component

In general an upwelling area is characterized by the dominance of diatoms and the development of a succession of species around the upwelling core, since water circulation brings nutrient-enriched bottom water to the surface (Estrada and Blasco, 1985). In such coastal upwelling regions, the distribution of species is thus defined by the constant presence of neritic assemblages in areas close to the coastline. As a result, variations observed in fossil diatom assemblages and presence or absence of certain fossil diatoms can be used to differentiate conditions of strong/permanent upwelling from conditions of occasional upwelling and/or production from river discharge (Sancetta, 1982; Abrantes, 1991). In general, the phytoplankton of an upwelling area is characterized by the dominance of diatoms (Estrada and Blasco, 1985). *Paralia sulcata* is indicated as an upwelling-related species and has been widely used as an indicator of high primary production (Abrantes, 1988, 1991). Vertical turbulence can re-suspend *P. sulcata* cells from the littoral and sublittoral zones up into the water column. Once in plankton, these cells may spread horizontally within the surface waters over deeper parts of the basin and may be deposited where cores 00GHP-01 and 00GHP-07 were collected. The variations observed in diatom assemblages can be used to differentiate conditions of strong/permanent upwelling from those of occasional upwelling and/or production from river discharge (Abrantes, 1991).

The following observations of the diatom assemblage through the whole section of the cores are of interest: 1) a great number of *Paralia sulcata*, 2) well-preserved *Thalassionema nitzschioides* in all sections and 3) the occurrence of small species of the genus *Thalassiosira*. These species are present in areas of persistent upwelling where availability of nutrients is more consistent and higher. The abundance of *T. nitzschioides* suggests that there was high surface primary productivity caused by the strong vertical circulation associated with upwelling or river discharge (Blasco et al., 1980; Abrantes, 1988, 1991). *Thalassiosira* is also found but the frustule size of this species is consistently small. *Delphineis surirella* is also of particular interest as it may be a specific indicator of coastal upwelling. This species occurs more than 6% in relative abundance at lower intervals within core 00GHP-07 (Fig. 6). Schuette and Schrader (1979) showed the distribution of a species of genus *Delphineis* as a monitor of coastal upwelling off the west coast of South America. It occurs only in active coastal upwelling regions of the present and in deposits representing locations affected by very productive coastal surface waters of the past. *Cyclotella striata* is also frequently recognized in sediments of upwelling zones (Jousé, 1972; Mukina, 1976; Schuette and Schrader, 1979). Under present-day conditions this species inhibits near-shore waters of relatively low salinity. Consequently, the consistent occurrence of *T. nitzschioides, P. sulcata, C. striata*, *D. surirella* and *Coscinodiscus* spp. in the core sediments may indicate that upwelling has persisted in the East Sea (Sea of Japan) and productivity was high.

5.3.2. Reworked older species

Microfossils tend to be eroded from older strata and redeposited along with the remains of newly dead organism in younger sediments. Such reworked fossils may be easily detected by differences in the state of preservation. These reworked microfossils can sometimes be used not only to determine the source of sediment, but also to give information on erosional processes of the source rock, transportation, sedimentation and preservation, each of which influences the recycled assemblage and change in atmospheric transportation (Pokras, 1986). Consequently, paleoenvironmental and paleobiological interpretation based on fossil diatom assemblages needs to be carried out with caution. But, it is not always easy to identify reworked fossils by their state of preservation, because transportation may occur with little damage or alteration. In particular, paleoenvironmental reconstructions based on higher proportions of benthic diatoms should be interpreted very carefully. In general, most reworked thanatocoenoses were strongly affected by chemical and mechanical factors, and thus only heavily silicified frustules are remained in such mixed assemblages.

Many reworked forms, including old and extinct diatoms and freshwater diatoms, were contained in this core samples. Frequently encountered old species in younger sediments include *Actinocyclus ingens* (Miocene–Pliocene), *Denticula hustedtii* (late Middle Miocene–Early Pliocene), *D. kamtschatica, Rhizosolenia barboi* (Miocene–Early Pleistocene), and *Grammatophora stricta* var. *fossilis* and *Medialia splendida* (Miocene). The existence of recycled forms suggests that there is possibility of Miocene–Pliocene exposures in deeper parts of the shelf. These species, including *A. ingens, G. stricta* var. *fossilis* and *M. splendida*, have been reported frequently from Neogene sedimentary strata of the Pohang Basin (Lee, 1991). These reworked diatoms were probably transported from adjacent areas through the submarine channels to the continental slope or by slumping. The occurrence of these Miocene diatoms in sediments could be the result of reworking sediments from the Pohang Basin which is several hundreds km southwest of the Ulleung Basin (Fig. 1b). Freshwater diatoms are also found in the core sediment assemblages, indicating a strong freshwater input and coastal sedimentation in the region of river mouths and deltas. The influence of the Nakdong and Seomjin river discharges in the study area could explain the presence of freshwater diatoms. Two rivers are located on the southern tip of the Korean Peninsula (Fig. 1b). Furthermore, the relative abundance of freshwater diatoms in coastal sediments may give evidence of the mixing intensity of river water with saline shelf waters.

5.3.3. Interpretation of Td value and relative frequency of planktonic and benthic species

Td (diatom temperature) values proposed by Kanaya and Koizumi (1966) are adopted here to estimate surface water temperature during the accumulation of sediments in the lower levels of a core sequence. Td is defined as follows:

$$Td = Tw \times 100/(Tw + Tc)$$

where Tw is the number of warm-water species and Tc is the number of cold-water species.

Td value ranges from 0 to 100: Td values 50–100, warm biofacies; Td value 20–50, temperate biofacies; and Td value 0–20, cold biofacies. Temperate to warm-water species used for Td analysis include *Pseudoeunotia doliolus*, *Nitzschia marina*, *Thalassionema nitzschioides*, *Rhizosolenia styliformis*, *Coscinodiscus radiatus*, *Thalassiosira oestrupii*, *Hemidiscus cuneiformis* and *Azpeitia nodulifera*, whereas the cold-water taxa used for Td analysis are *Biddulphia aurita*, *Denticula seminae*, *Cosinodiscus marginatus*, *Thalassiothrix longissima*, *Rhizosolenia hebetata* var. *hiemalis*, *R. curvirostris* and *Rhizosolenia barboi* (Kanaya and Koizumi, 1966).

The general trend appears to be upward lowering of Td values in 00GHP-01 (Fig. 7). The increases in 502–400 cm, 230–200 cm and 30–0 cm are correlated with the increase in paleotemperature and a rising sea-level. These intervals obviously indicate synchronous events in the East Sea (Sea of Japan) related to the strong and rhythmic inflow of the TWC (Fig. 7). At the 400–260 cm and 200–30 cm intervals, the Td values drop sharply due to the appearance in abundance of cold water taxa (particularly *Rhizosolenia hebetata* var. *hiemalis*). The unstable minor fluctuations in the lower Td values in the intervals correspond to lowering sea-level. The greater variations at both intervals occur in the numbers of the Xw, whereas those of Xc are more stable. These shifts in Td values may indicate the climatic fluctuations comparable to LGM. Owing to high abundance of benthic and tychopelagic species and a minor occurrence of planktonic species, a sequence of oscillations in Td values cannot be reconstructed for core 00GHP-07. The relative frequency of planktonic/benthic species is shown in Fig. 3.

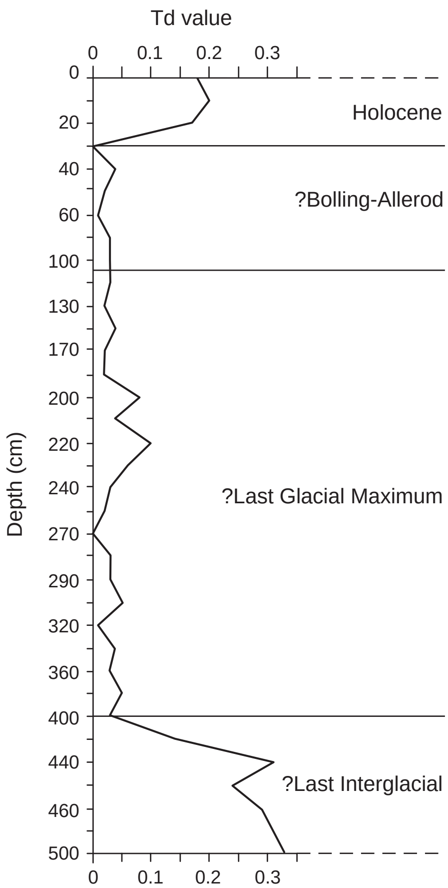

Fig. 7. Td (diatom temperature) value curve in 00GHP-01. Td=Xw/(Xw+Xc) (Xw: frequency of warm water species, Xc: frequency of cold water species). High Td values are recognized three times (502–400 cm, 230–200 cm and 30–0 cm) in core section, which seems to be correlated with the influence of the Tsushima Warm Current.

5.4. Paleoenvironmental implications of East Sea (Sea of Japan) diatoms

Paleoceanographic modes in the East Sea (Sea of Japan), during the Late Quaternary, developed in response to global sea level changes (Tada, 1994; Gorbarenko and Southon, 2000). Consequently, diatom analyses from the cores may correlate with global sea level change, and each assemblage in the core may reflect the environmental conditions influenced by sea level fluctuations. Fortunately, many diatoms recovered in the East Sea (Sea of Japan) sediments have specific ecological tolerance that can be used to make paleoclimatic and paleoceanographic interpretation of the East Sea (Sea of Japan). Cores are situated beneath the pathway of the Tsushima Warm Current (TWC), and thus sedimentation and diatoms recorded from the cores are strongly influenced by the TWC. For example, occurrence of warm water species in lower part of 00GHP-01 indicates that the Tsushima Warm Current flowed into the East Sea (Sea of Japan) during the late Pleistocene. The relative frequencies of *Pseudoeunotia doliolus* (dominant in highly saline areas) and *Paralia sulcata* (dominant in low salinity areas) provide a useful clue to estimate the degree of influence of low salinity water on the upper surface water of the southern part of the East Sea (Sea of Japan). *P. doliolus* flourishes in open sea under the influence of high salinity warm water, and is rarely present in cold glacial intervals (Oba et al., 1991). In the lower part of Core 00GHP-07, *P. doliolus* is rare. Absence or such a minor presence in 00GHP-07 may reflect the minor influence of the Tsushima Warm Current since that time.

Epiphytic genera such as *Cocconeis* and *Diploneis* and presumably *Delphineis* recorded here reflect close proximity to the coast, whereas thick-shelled genera including *Biddulphia, Diploneis, Grammatophora* and *Hemiaulus* are representative of relatively shallow neritic environments. Since the species indicative of low salinity are benthic, they must be autochthonous rather than allochthonous. Moreover, the presence of freshwater and river-mouth dwelling species indicates a considerable influx of freshwater taxa into a landlocked basin at the time of late Pleistocene. The high abundance of *Rhizosolenia hebetata*, ranging from Miocene to present-day, suggests that the interval represented by this species was under extremely cold conditions, because this species occurs in modern sediments of the Bering Sea (Sancetta, 1982). This hypothesis has been supported by the fact that the form of *R. hebetata* recorded here is the winter phenotype (forma *hiemalis*, Gran, 1904). *R. hebetata* var. *hiemalis* was probably preadapted for extreme glacial condition and reached a very high abundance during glacial intervals within the late Pleistocene. The change in occurrence of *R. hebetata* var. *hiemalis* is recorded respectively in both two horizons (295 cm and 400 cm) in 00GHP-07 and two horizons (360–340 cm and 60–40 cm) in 00GHP-0l. These horizons reflect a longer duration of the cold winter seasons during the glacial times.

The most striking peculiarity of the diatom assemblages is the presence of *Cyclotella striata* that is abundant of 30% at 120 cm horizon in Core 00GHP-01 and 33% at 775 cm horizon in 00GHP-07, respectively. This brackish water species inhibits low salinity areas of the seas, such as river-mouths (Jousé, 1972; Mukina, 1976; Schuette and Schrader, 1979). The predominance of benthic species at the lower and middle part of Core 00GHP-07 indicates a shallow marine environment (Fig. 5). Although the exact sea level in the East Sea (Sea of Japan) at the time of deposition is unknown, such an increase in benthic species may indicate that the sea level at Pleistocene/Holocene boundary was lower than that at present. In addition, the core samples contain a great number of reworked species including displaced freshwater and benthic diatoms, which may have been brought in by turbidity currents. This also means that the glacial lowering sea level occurred between 10 and 20 ka. During the rise of sea level, fewer displaced benthic diatoms were transported to the basin. However, the salinity and temperature of surface waters are considered to increase when sea level rises, and thus the number of marine planktonic species increases (Fig. 5). Finally such an analysis on the basis of reworked species throughout the section indicates that there were several sea level fluctuations.

6. Conclusion

Diatom assemblages recorded in two piston cores from the Ulleung Basin reflect a series of glacio-eustatic sea level fluctuations and associated paleoceanographic changes during the Late Quaternary. These changes appear to have been driven largely by changes in surface water salinity, which in turn arose from reduction in the Tsushima Warm Current (TWC) water input due to sea level falls and the ensuing increased role of fresh water in the salinity balance. The TWC plays an important role in controlling the distribution and species composition of diatom fauna. Also the diatom assemblages reflect the intensity of the TWC and Oyashio Cold Current. Correspondingly, there was a reduced inflow of TWC water to the East Sea (Sea of Japan) shelf, but a strong East China Sea influence to the East Sea (Sea of Japan) shelf was in existence. Only minor changes occurred in the general sea-surface circulation system in the Ulleung Basin during the Late Holocene. During the LGM, a lowered sea level was enough to close the shallow sills of the East Sea (Sea of Japan), thereby isolating it from the Pacific Ocean. The salinity became decreased owing to freshwater input from adjacent rivers of the surrounding lands. As a result, the density-stratified water column may have prevented vertical mixing and resulted in an anoxic bottom-water conditions. Td values in Core 00GHP-01 suggest that the East Sea (Sea of Japan) was influenced by a relatively strong TWC twice during the lowermost and uppermost intervals and relatively weak TWC since the latest Pleistocene. Diverse marine tychopelagic–benthic species recorded in 00GHP-07 are considered to have been deposited in shallow water condition. Older diatom fossils encountered here may have been incorporated as a result of reworking. Such species may have been transported by turbidity flows on the slope. High abundance of a low salinity coastal water diatom, *Paralia sulcata*, may reflect the relative contribution of influx of East China Sea water through the Korean Strait, and reflects not only its preferential preservation in increased downslope transport but also the distinct effects of upwelling along the coast.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.marmicro.2005.03.004.

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