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Diatom assemblages of sediments from the estuary of Fukuda River in Kobe along the northwestern coast of Osaka Bay with special reference to the Holocene sedimentary history

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Diatom assemblages of sediments obtained from the estuary (Tarumi site) of Fukuda River in Kobe were analyzed in order to clarify the local Holocene sedimentary history. The results were as follows: 1) the lowermost sediment was a brackish environment at around 7000 yr B. P. 2) the first marine diatom zone (MD_1 Zone) was alternated three times by three transitional zones ($Tr_{1-1, 1-2, 1-3}$ Zone) probably caused by the developments of three sand bars across the estuary of paleo-Fukuda River during the period between 7000 and 6000 yr B. P.

Key Index Words: diatom assemblages—Fukuda River estuary—Holocene transgression—sand bar development.

The diatoms occur in virtually all bodies of water exposed to light and contain easily recognized taxa characteristic of many different environments between truly marine conditions and potable freshwater and at widely varying temperatures, salinities, pH, and chemical composition. Similar fossil forms are found in sediments that were deposited under such environmental conditions. So the diatoms have many advantages as microfossils to clarify the local paleoecological factors.

Previously we have analyzed the diatom assemblages of sediments obtained from the estuary along the Osaka Bay (Kumano and Miyahara, 1981; Kumano and Fujimoto, 1982; Sato et al., 1983), Kutcharo Lake (Kumano et al., 1984, Sekiya and Kumano, 1983) and Kushu Lake (Kumano et al., 1990a).

In Osaka Bay area, the Marine Diatom Zone (MD_1 Zone) coincided with the peak of the first Holocene transgression at about 6000 yr B.P. at several sites along the coast of Osaka Bay.

In Kutcharo Lake and Kushu Lake, deposition of the Marine Diatom Zone (MD_1 Zone) and the Transitional Zone (Tr_2 Zone) finished at about 6000 yr B.P. and 5000 yr B.P., respectively, because of the sand bar development prior to the first Holocene regression at about 4500 yr B.P., the "Middle Jomon minor regression" named by Ota et al. (1982).

In the present study, diatom assemblages of sediments obtained from the estuary (Tarumi site) of Fukuda River in Kobe were analyzed in order to clarify the local Holocene sedimentary history.

Materials and Methods

Sampling Sites

Fukuda River is about 7 km in length and Tarumi site is located at the estuary in Kobe along the northwestern coast of the Osaka Bay, at altitude about 4 m, latitude 34°35′38″ N and longitude 135°3′40″E (Fig. 1).

The excavation for the construction of

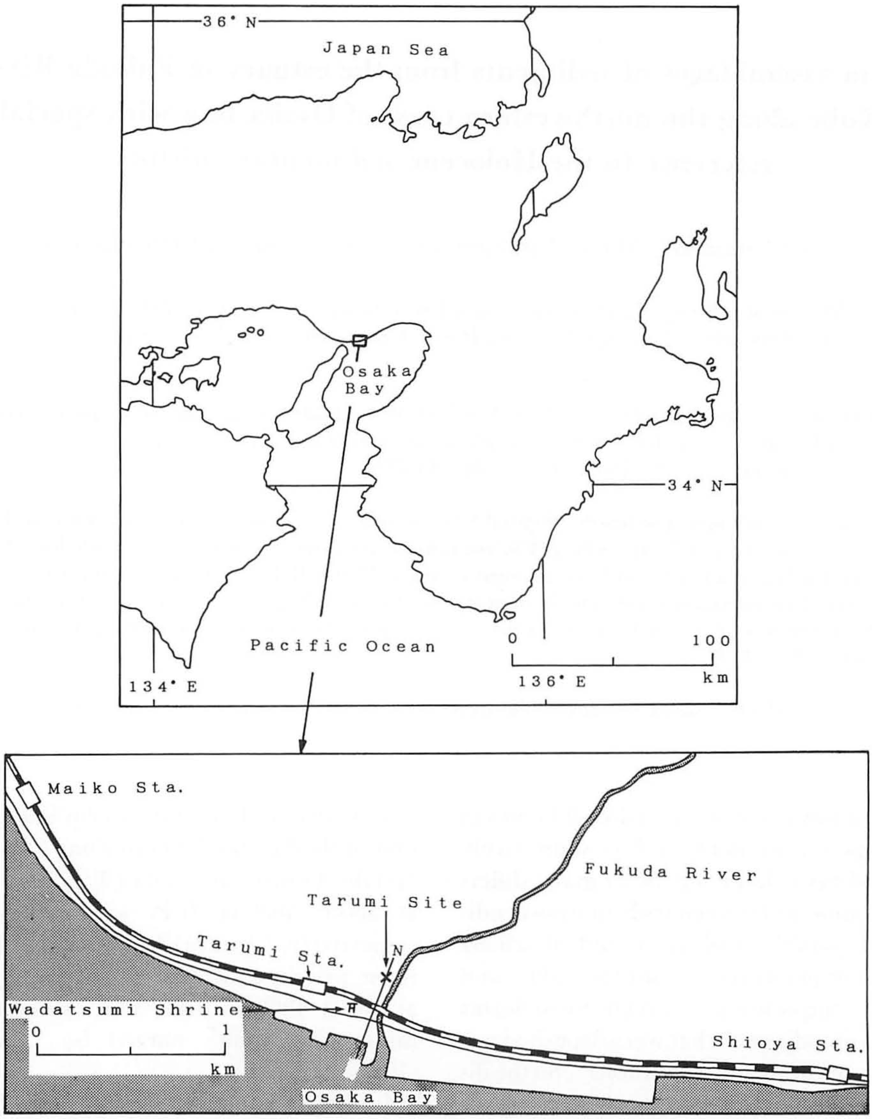

Fig. 1. The estuary (Tarumi site) of Fukuda River at altitude about 4 m is located at latitude 34°35′38″N and longitude 135°3′40″E in Kobe along the northwestern coast of Osaka Bay, central Japan.

buildings at the estuary (Tarumi site) of Fukuda River offered us outcrops of Holocene deposits, from which samples of Site A (-0.2 m to $+1.4$ m) and Site B ($+0.8$ m to $+2.7$ m) were collected in 1988, those of Site C ($+1.0$ m to $+2.2$ m) were collected in 1988 and those of Site D ($+2.4$ m to $+3.7$ m), were collected in 1990, respectively (Fig. 2).

^{14}C Dates and Akahoya Tephra

The ^{14}C dates were measured by Dr. Kigoshi (1992) and Akahoya tephra was identified by Dr. Danhara (1992). The ^{14}C and tephra dates from Site A to Site C are shown in the second column from Fig. 3 to 5, respectively. The plant remains at the -0.1 m horizon of Site A gave a ^{14}C age of 7220 ± 110 yr B.P., those at the $+0.1$ m horizon gave a ^{14}C age of 7210 ± 120 yr B.P., those at the $+1.6$ m horizon of Site C gave a ^{14}C age of 6340 ± 110 yr B.P. and Akahoya tephra at the $+1.8$ m horizon showed about

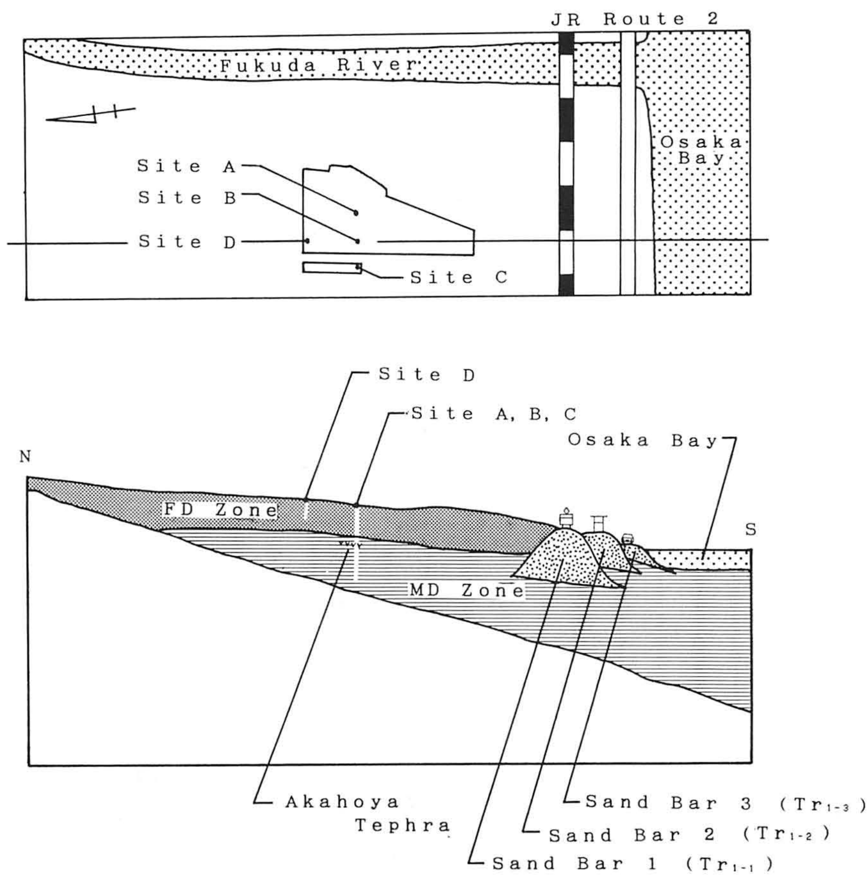

Fig. 2. Four sampling sites (site A, site B, site C and site D) and three rows of sand bars are shown (Takahashi, 1992). Sand bar 1: the innermost row of sand bars located on the track of Japanese Railway. Sand bar 2: the middle sand bar on the grounds of Wadazumi Shrine. Sand bar 3: the outermost sand bar on the national road of Rout No. 2.

6300 yr B.P..

Preparation of Samples

For diatom analysis, approximately 1 g d.w. of each sample was dispersed with 10% H_2O_2 and $Na_4P_2O_7$ and the clay fraction removed by decanting. The fraction containing diatom frustules was boiled with conc. HCl and then cleaned and washed about 5 times with distilled water by centrifugation. An appropriate amount of each washed sample was then mounted with Pleurax. About 200 diatom frustules were identified and counted along a transect chosen at random on each sample slide.

The marine diatom zone (MD Zone) is considered as the zone which comprised more than 80% marine and brackish-water diatoms. The transitional zone (Tr Zone) is considered as the zone, in which marine diatoms accounted for less than 30% of the total count.

Results

The successive changes in the ecological spectra are shown in Fig. 3-5 and the successive changes in the predominant diatoms in Fig. 6-8.

Site A (−0.1 m to +1.4 m):

1. The first Transitional Zone (Tr_{1-1} Zone) (−0.1 m to +0.18 m)

a) Tr_{1-1}-a subzone

Brackish-water diatoms were dominated in

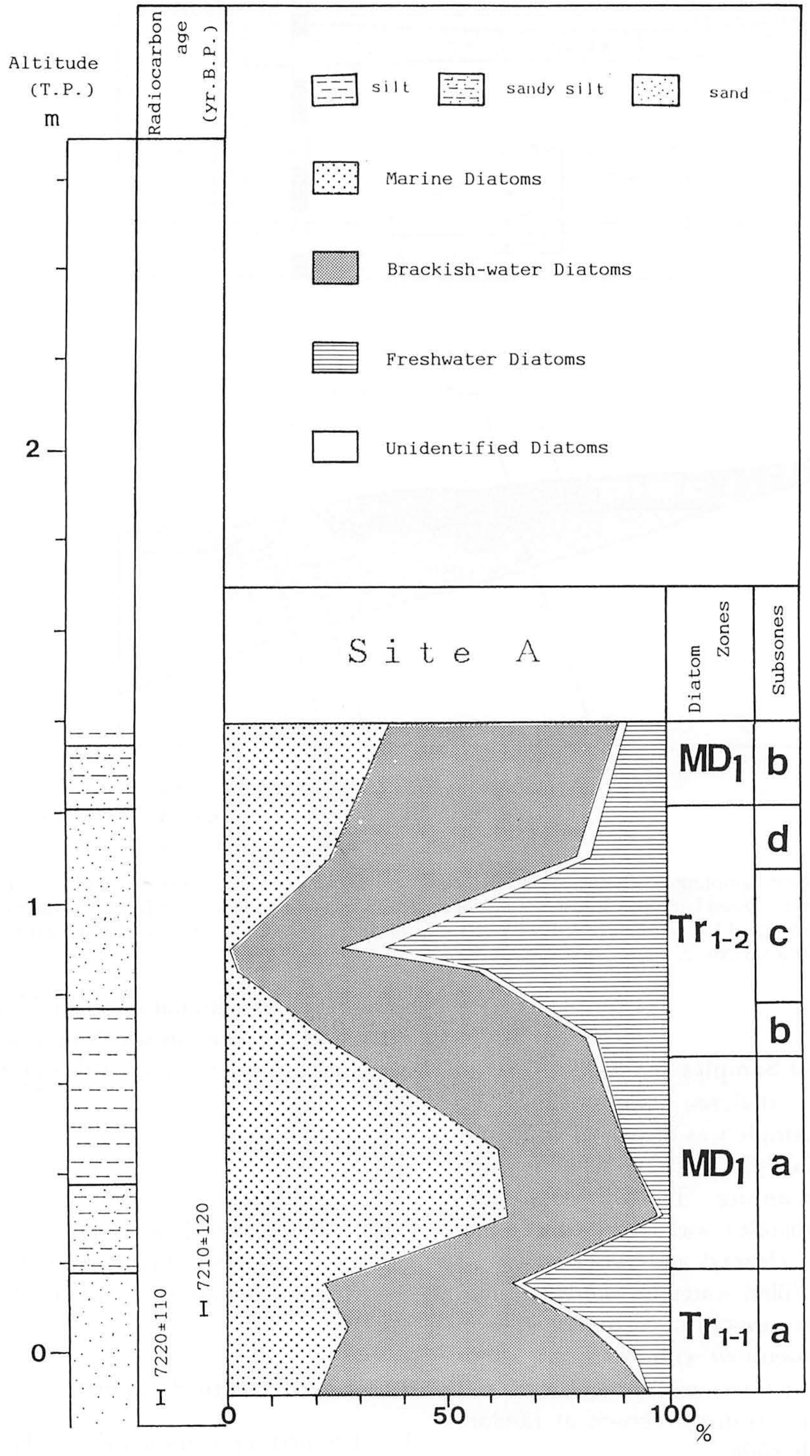

Fig. 3. Stratigraphic profile in Site A, the Fukuda River and the successive changes in the ecological spectrum. Facies of the sediments are shown in the first column, the ^{14}C dates in the second column, proportions of marine, brackish-water and freshwater diatoms in the third column, diatom zones in the fourth column and subzones in the fifth column.

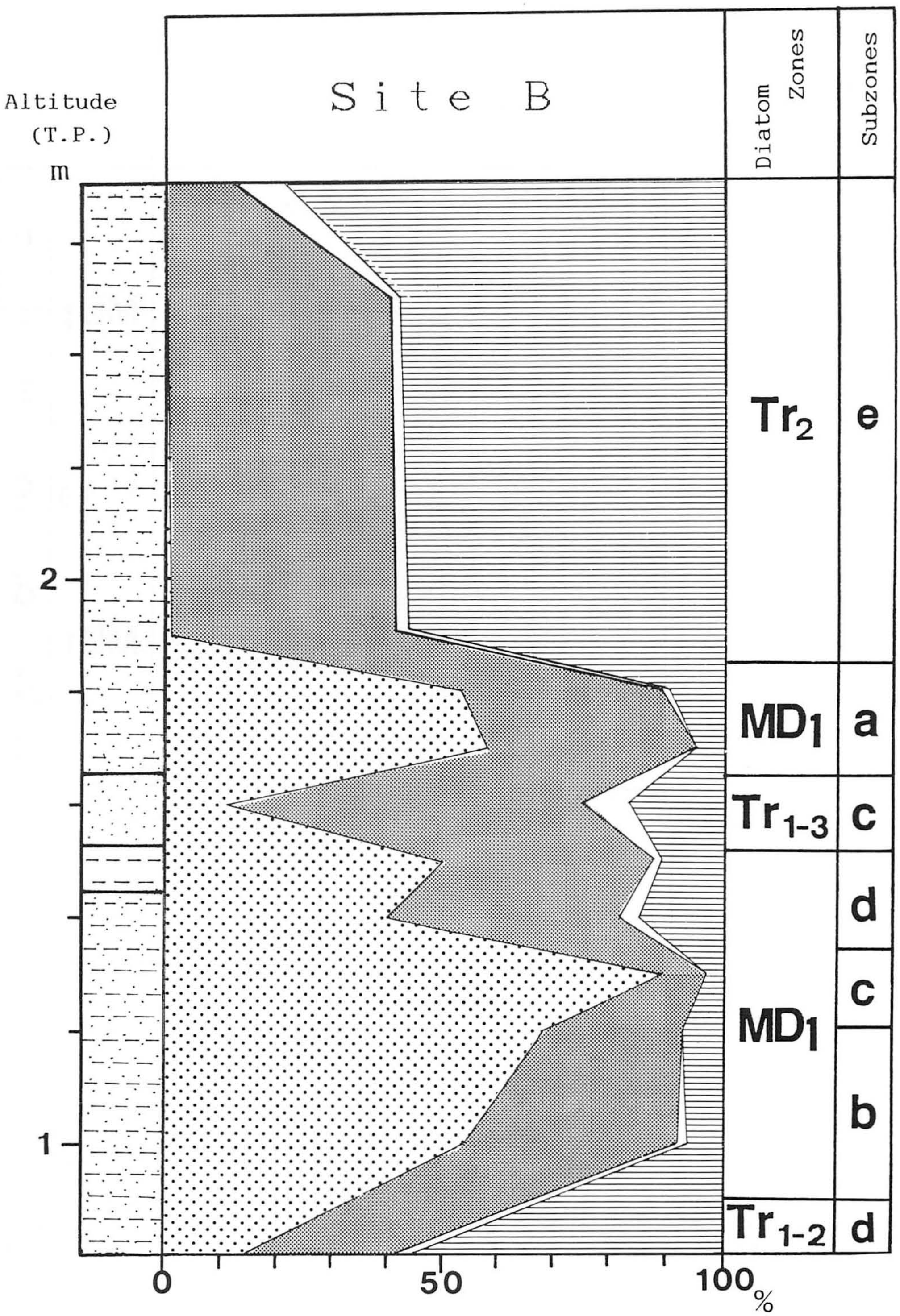

Fig. 4. Stratigraphic profile in Site B, the Fukuda River and the successive changes in the ecological spectrum. Facies of the sediments are shown in the first column, proportions of marine, brackish-water and freshwater diatoms in the second column, diatom zones in the third column and subzones in the fourth column. The other marks and symbols are the same as those in Fig. 3.

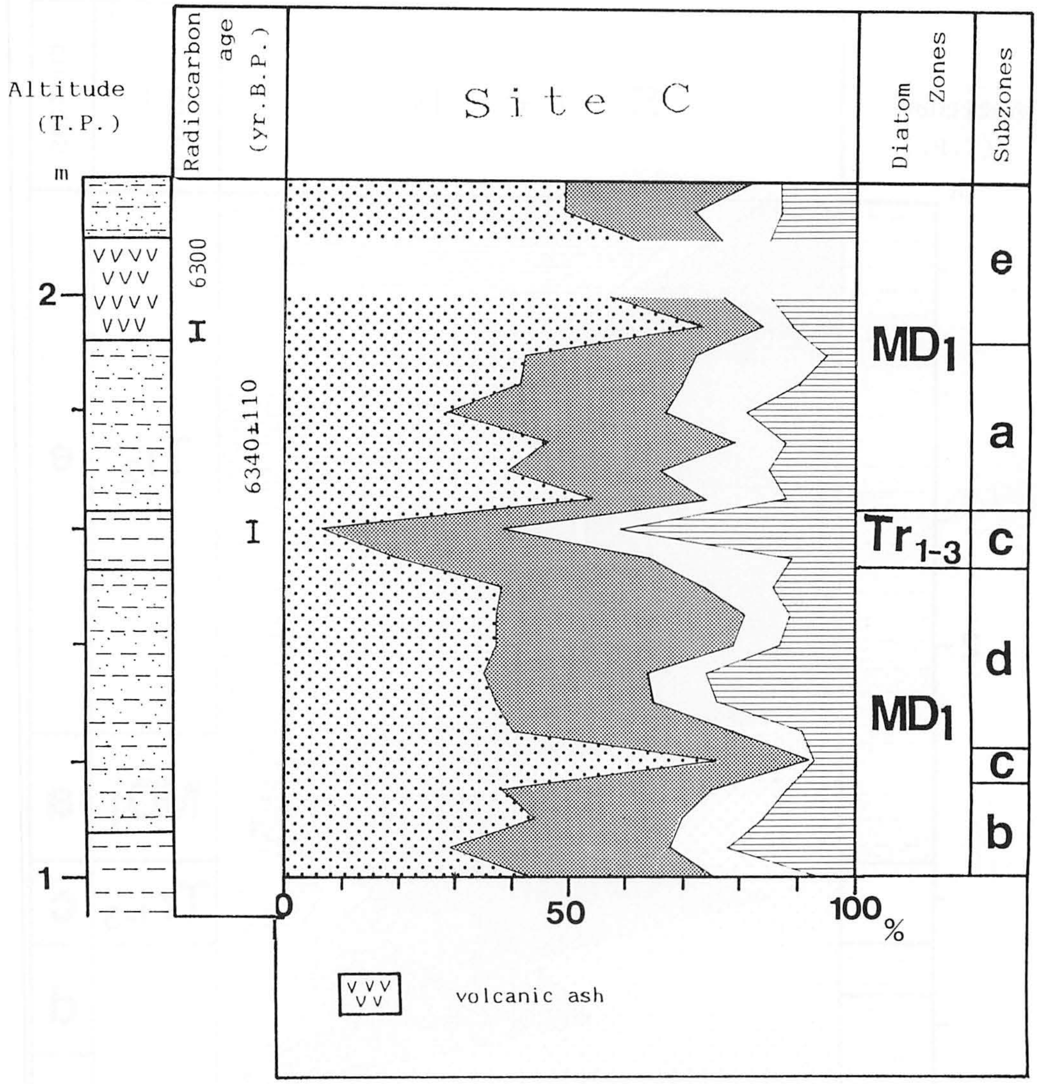

Fig. 5. Stratigraphic profile in Site C, the Fukuda River and the successive changes in the ecological spectrum. Facies of the sediments are shown in the first column, the ^{14}C and tephra dates in the second column, proportions of marine, brackish-water and freshwater diatoms in the third column, diatom zones in the fourth column and subzones in the fifth column. The other marks and symbols are the same as those in Fig. 3.

this subzone (Fig. 3): the dominant diatom at the lower horizon of this subzone was the brackish-water *Achnanthes hauckiana*, while those at the upper horizon were the brackish-water *Bacillaria paradoxa* in addition to the brackish-water *Rhopalodia gibberula*, the marine *Nitzschia granulata* and *Nitzschia punctata* (Fig. 6).

2. The Marine Diatom Zone (MD_1 Zone) (+0.18 m to +0.65 m)

a) MD_1-a subzone

In the MD_1-a subzone, marine diatoms were increased and occupied 30-60% of the total count, and brackish-water diatoms occupied 30-50% of the total throughout this subzone. Freshwater diatoms occupied less than 30% of the total (Fig. 3).

The MD_1-a subzone was dominated by the littoral *Nitzschia granulata* (about 15-50%) accompanied with the littoral *Nitzschia punctata* (about 5-20%) and the brackish-water

Achnanthes hauckiana (about 5-15%) (Fig. 6). Toward the upper horizon of this subzone, the marine diatoms were decreased, while the brackish *Rhopalodia gibberula* was increased.

3. The second Transitional Zone (Tr_{1-2} Zone) (+0.65 m to 1.21 m)

The Tr_{1-2} Zone is divided into three subzones according to the dominant diatoms.

a) Tr_{1-2}-b subzone

Marine diatoms decreased up to less than 30%, and brackish-water and marine ones counted for more than 70% of the total count (Fig. 3). The dominant diatom of this subzone was the brackish *Rhopalodia gibberula* (Fig. 6).

b) Tr_{1-2}-c subzone

At the middle horizon of this subzone, brackish-water diatoms decreased to less than 30% and only a few marine diatoms were counted, while freshwater diatoms increased up to about 60% of the total count (Fig. 3). Dominant diatoms in this subzone were the freshwater *Navicula contenta* and *Achnanthes lanceolata* accompanied with the brackish-water *Nitzschia hungarica* and *Achnanthes hauckiana* (Fig. 6).

c) Tr_{1-2}-d subzone

In the Tr_{1-2}-d subzone, marine and brackish diatoms increased up to 20-30% and about 50%, respectively, whereas freshwater ones decreased to about 20% (Fig. 3). The dominant diatoms were the brackish *Rhopalodia gibberula* and the marine *Nitzschia granulata*, and a few freshwater diatoms such as *Navicula contenta* were counted (Fig. 6).

4. The Marine Diatom Zone (MD_1 Zone) (+1.21 m to +1.4 m)

a) MD_1-b subzone

In the MD_1-b subzone, marine diatoms increased and occupied about 30-40% of the total count and brackish ones about 50% of the total count, whereas freshwater ones decreased to about 10% (Fig. 3). In this subzone, the dominant diatom was the brackish-water *Rhopalodia gibberula* accompanied with the littoral *Nitzschia granulata* and *Nitzschia punctata* (Fig. 6).

Site B (−0.8 m to +2.7 m):

1. The second Transitional Zone (Tr_{1-2} Zone) (−0.8 m to −0.9 m)

a) Tr_{-1-2}-d subzone

The Tr_{-1-2}-d subzone was occupied by about 40-70% of marine and brackish-water diatoms among which marine diatoms occupied about 15-40% of the total count (Fig. 4). Dominant diatom in this subzone was the littoral *Nitzschia granulata* and *Nitzschia punctata* accompanied with the brackish-water *Rhopadoria gibberula* and *Achnanthes hauckiana* (Fig. 7).

2. The Marine Diatom Zone (MD_1 Zone) (+0.9 m to +1.54 m)

The MD_1 Zone is divided into three subzones according to the dominant diatoms.

a) MD_1-b subzone

In the MD_1-b subzone, marine diatoms occupied about 40-70% of the total count, and brackish-water diatoms occupied about 30%. Freshwater diatoms occupied about 10-30% of the total throughout this subzone (Fig. 4). The lower horizon of this subzone was dominated by the littoral *Nitzschia punctata* accompanied with the brackish-water *Rhopalodia gibberula* and *Achnanthes hauckiana*, while at the upper horizon the dominant diatom was changed to the littoral *Nitzschia granulata* (Fig. 7).

b) MD_1-c subzone

In the MD_1-c subzone, marine diatoms increased and occupied about 70-90% of the total count, whereas brackish-water and freshwater ones occupied about 10-30% (Fig. 4). In this subzone, the dominant diatom was the littoral *Nitzschia granulata* (Fig. 7).

c) MD_1-d subzone

In the MD_1-d subzone, marine and brackish diatoms occupied about 40-70% and 20-40% of the total count, respectively, while freshwater ones less than 20% (Fig. 4). At the lower horizon of this subzone the dominant diatoms were the marine *Nitzschia punctata* and the brackish-water *Rhopalodia*

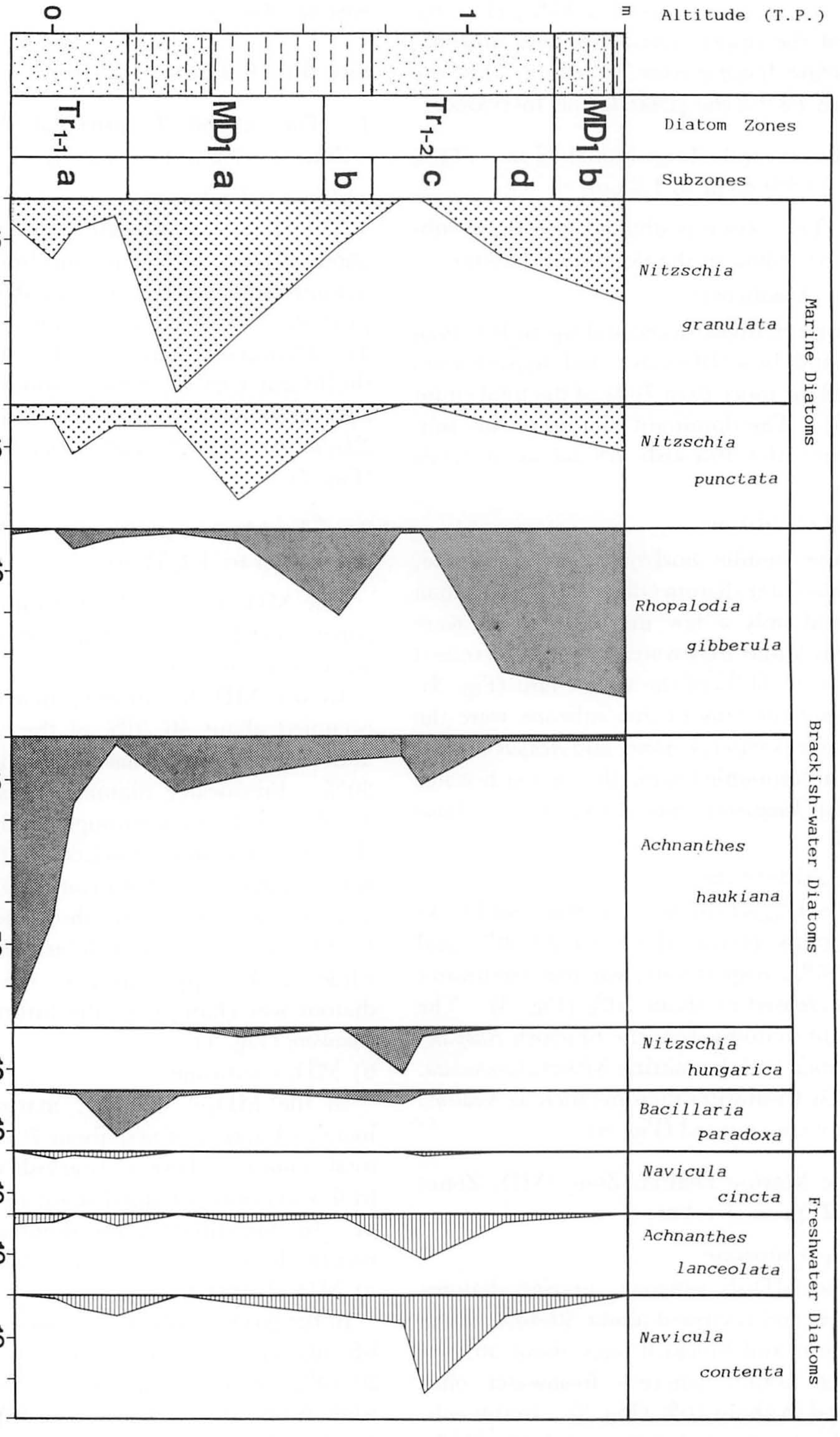

Fig. 6. Diatom diagrams of Site A showing the occurrence of the prominent taxa. Facies of the sediments are shown in the first column, diatom zones in the second column, subzones in the third column, marine diatoms in the fourth column, brackish-water ones in the fifth column, and freshwater ones in the sixth column.

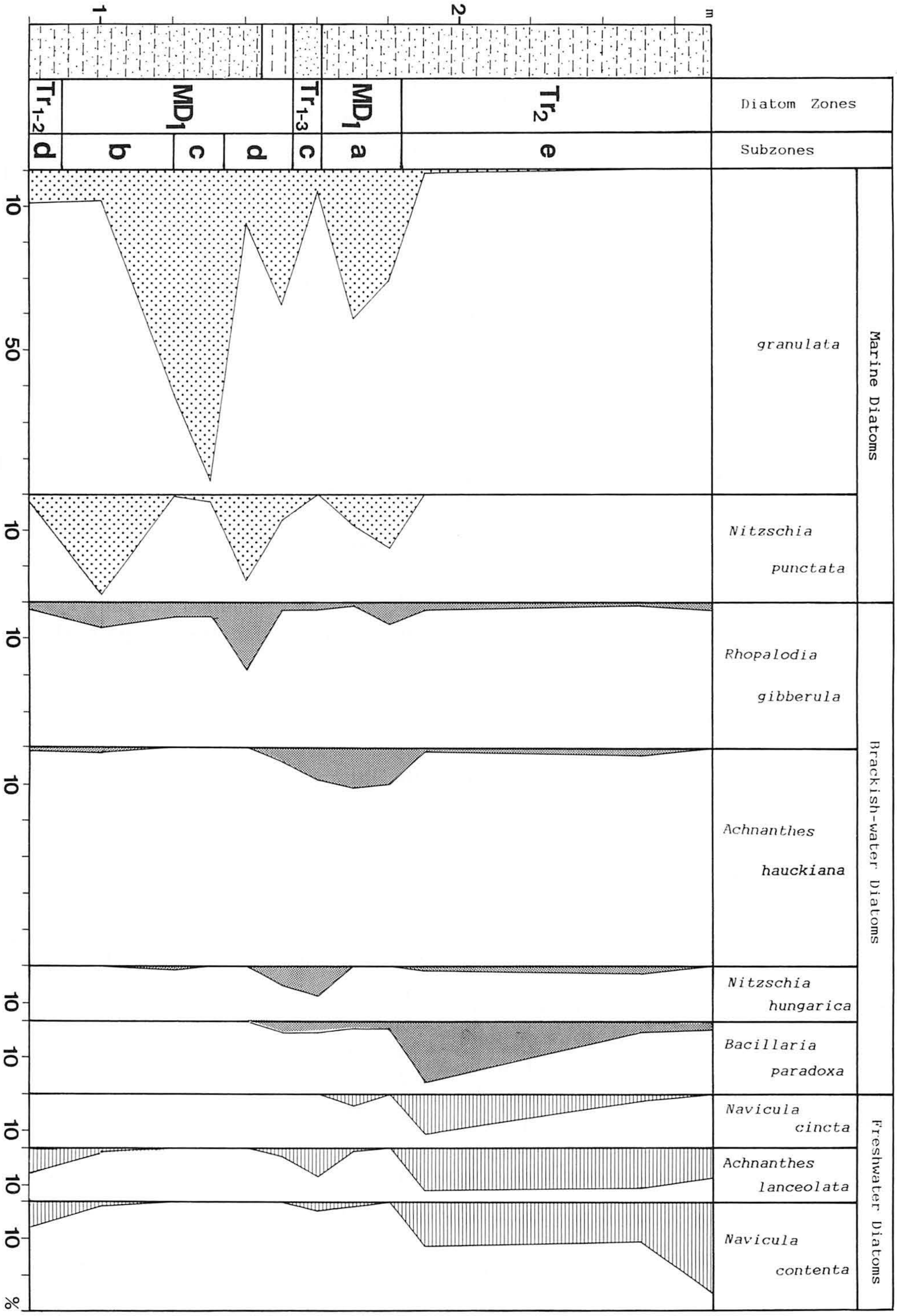

Fig. 7. Diatom diagrams of Site B showing the occurrence of the prominent taxa. Facies of the sediments are shown in the first column, diatom zones in the second column, subzones in the third column, marine diatoms in the fourth column, brackish-water ones in the fifth column, and freshwater ones in the sixth column.

gibberula, while at the upper horizon it changed to the littoral *Nitzschia granulata* (Fig. 7).

3. The third Transitional Zone (Tr_{1-3} Zone) (+1.54 m to +1.63 m)

a) Tr_{1-3}-c subzone

At the middle horizon of this subzone, marine diatoms decreased to less than 20%, brackish-water ones increased up to about 60% and freshwater ones slightly increased (Fig. 4). Dominant diatoms in this subzone were the brackish-water *Achnanthes hauckiana* and the marine *Nitzschia granulata* accompanied with the brackish-water *Nitzschia hungarica* and the freshwater *Achnanthes lanceolata*.

4. The Marine Diatom Zone (MD_1 Zone) (+1.63 m to +1.84 m)

a) MD_1-a subzone

In the MD_1-a subzone, marine diatoms increased up to about 60% of the total count, whereas brackish one and freshwater ones decreased to less than 40% and 10%, respectively (Fig. 4). The dominant diatom was the littoral *Nitzschia granulata* at the lower horizon of this subzone, while at the upper horizon the littoral *Nitzschia punctata* was dominant and accompanied with the brackish-water *Rhopalodia gibberula* and *Achnanthes hauckiana* (Fig. 7).

5. The Transitional Zone (Tr_2 Zone) (+1.84 m to +2.7 m)

a) Tr_2-e subzone

At the lower horizon of this subzone brackish-water diatoms decreased to less than 40%, a few marine ones were counted, while freshwater ones increased up to 50% (Fig. 4): various diatoms such as the brackish-water *Bacillaria paradoxa*, the freshwater *Achnanthes lanceolata, Navicula contenta* and *Navicula cincta* (Fig. 8) were found.

At the upper horizon of this subzone, brackckish-water diatoms decreased less than 20%, no marine ones were counted, while freshwater one increased more than 80% (Fig. 4). Dominant diatoms in this subzone were the freshwater *Navicula contenta* and *Achnanthes lanceolata* accompanied with a few brackish-water diatoms (Fig. 7).

It is considered that the Tr_2 Zone at the horizon (from +1.84 m to +2.7 m) finished at about 6000 yr B.P., because the plant remains at the −0.1 m horizon of Site C gave a ^{14}C age of 6340±110 yr B.P. and Akahoya tephra at the +1.8 m horizon showed about 6300 yr B.P.

Site C (+1.0 m to +2.2 m):

1. The Marine Diatom Zone (MD_1 Zone) (+1.0 m to +1.53 m)

About 70% of diatoms of the MD_1 Zone was occupied by marine and brackish-water diatoms (Fig. 5). The MD_1 Zone is divided into three subzones according to the dominant diatoms.

a) MD_1-b subzone

In the MD_1-b subzone, marine and brackish diatoms occupied about 30–40% of the total of diatoms, respectively, while freshwater ones occupied about 10–20% (Fig. 5). This subzone was dominated by the littoral *Nitzschia granulata* and the brackish-water *Rhopalodia gibberula* accompanied with the littoral *Amphora acutiuscula* and *Nitzschia punctata* (Fig. 8).

b) MD_1-c subzone

In the MD_1-c subzone, marine diatoms increased up to 80% of the total, while brackish-water and freshwater ones decreased to less than 20% and less than 10%, respectively (Fig. 5). In this subzone, the dominant diatoms were the littoral *Amphora acutiscula, Nitzschia granulata* accompanied with the brackish *Rhopalodia gibberula* (Fig. 7).

c) MD_1-d subzone

In the MD_1-d subzone, marine and brackish diatoms occupied about 20–60% and about 30–40% of the total of diatoms, respectively, while freshwater ones about 10–20% (Fig. 5). At the lower horizon of this subzone various diatoms such as the littoral *Nitzschia granulata, Nitzschia punctata* and the brackish-water *Rhopalodia gibberula* were found. While in the upper horizon of this subzone the

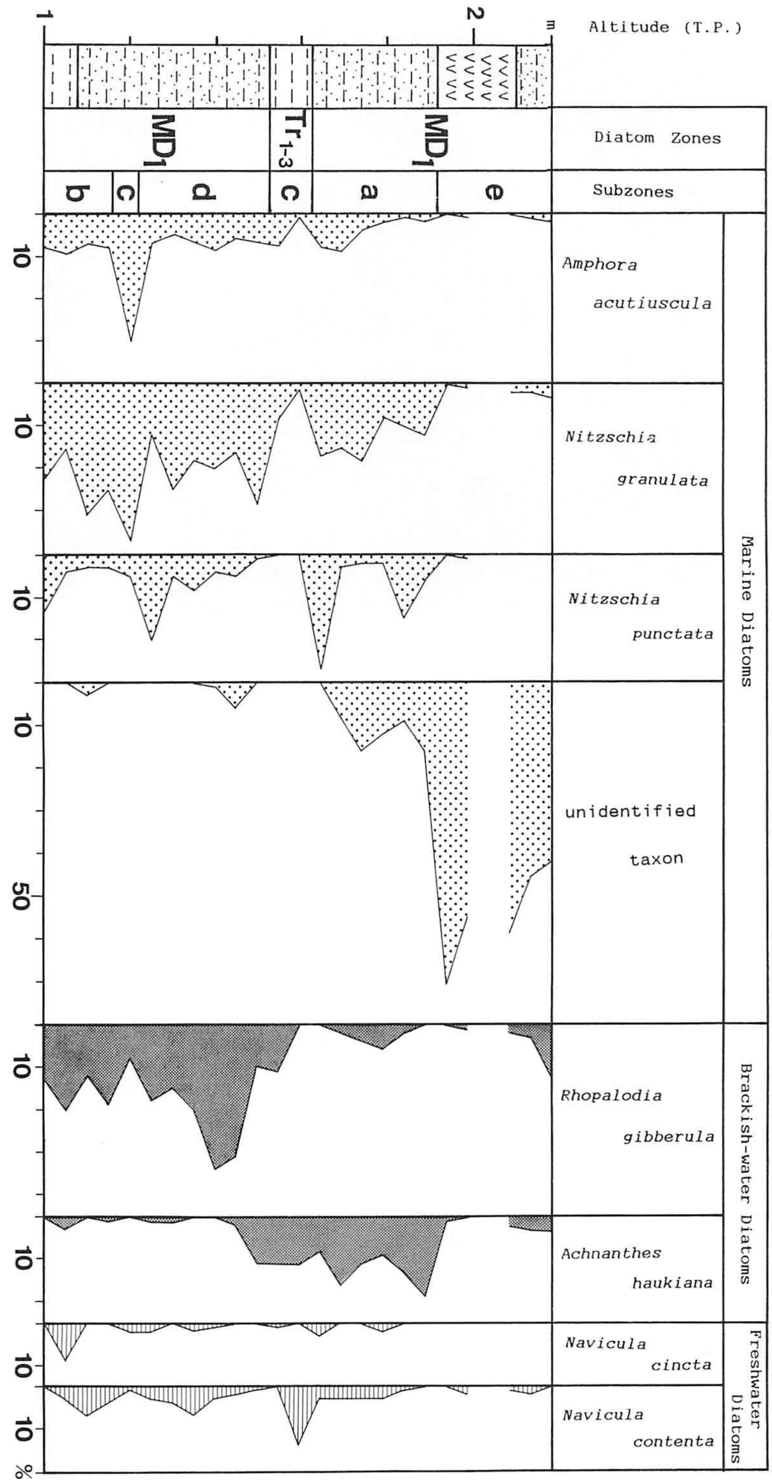

Fig. 8. Diatom diagrams of Site C showing the occurrence of the prominent taxa. Facies of the sediments are shown in the first column, diatom zones in the second column, subzones in the third column, marine diatoms in the fourth column, brackish-water ones in the fifth column, and freshwater ones in the sixth column.

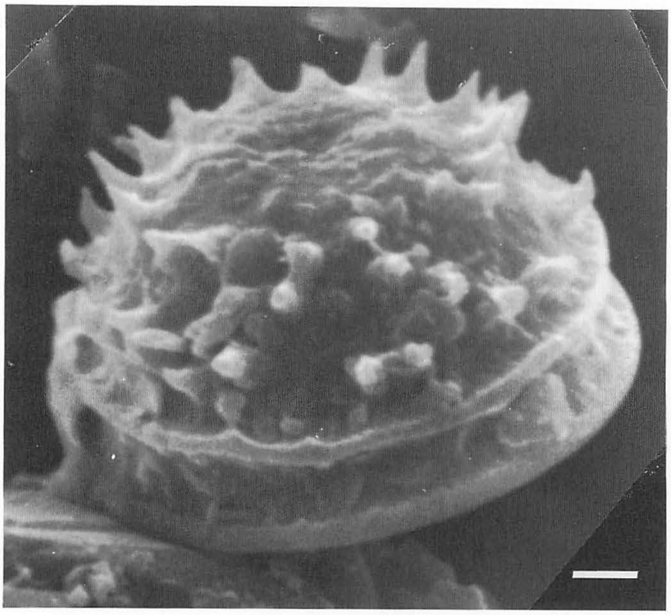

Fig. 9. A photomicrograph of an unidentified taxon assigned to the order Centrales occurred in the MD_1 Zone of Site C. This unidentified taxon assigned to the order Centrales was also abundantly found in the marine diatom zone at the Tamatsu site near Akashi River (Sato, unpublished). Scale bars indicate 1 μm.

dominant diatoms were the brackish-water *Rhopalodia gibberula* accompanied with the littoral *Nitzschia granulata* (Fig. 8).

2. The third Transitional Zone (Tr_{1-3} Zone) (+1.53 m to +1.63 m)

a) Tr_{1-3}-c subzone

Marine diatoms decreased to less than 10% and brackish-water ones occupied about 30% of the total diatoms, while freshwater ones increased up to 40% (Fig. 5). Generally, dominant diatom in this subzone was the freshwater *Navicula contenta* accompanied with the brackish-water *Achnanthes hauckiana* (Fig. 8). Dominant diatom was *Nitzschia granulata* at the lower horizon of this subzone and it was *Nitzschia punctata* at the upper horizon of this subzone.

3. The Marine Diatom Zone (MD_1 Zone) (+1.63 m to +2.2 m)

In the MD_1 Zone, marine diatoms increased and occupied 30-70% of the total of diatoms, while brackish and freshwater diatoms occupied about 10-35% and 10-20%, respectively (Fig. 5). The MD_1 Zone is divided into two subzones according to the dominant diatoms.

a) MD_1-a subzone

As shown in Fig. 8, in this subzone, the dominant diatoms were the brackish-water *Achnanthees hauckiana* and the littoral *Nitzschia granulata* accompanied with *Nitzschia punctata, Amphora acutiuscula* and an unidentified taxon.

The last taxon, which was assigned to the order Centrales (Fig. 9), can not be identified, not only at the species level but also at the genus level. This unidentified taxon is regarded as one of marine diatoms, because this taxon was also found dominated in the marine diatom zone at the Tamatsu site near Akashi River (Sato, unpublished).

b) MD_1-e subzone

The dominant diatom of this subzone was the above-mentioned identified taxon (Fig. 9) accompanied with the littoral *Nitzschia granulata*, the brackish-water *Rhopalodia gibberula* and *Achnanthes hauckiana* (Fig. 8).

Site D (+2.4 m to +3.7 m):

Diatom frustules in the sediments obtained

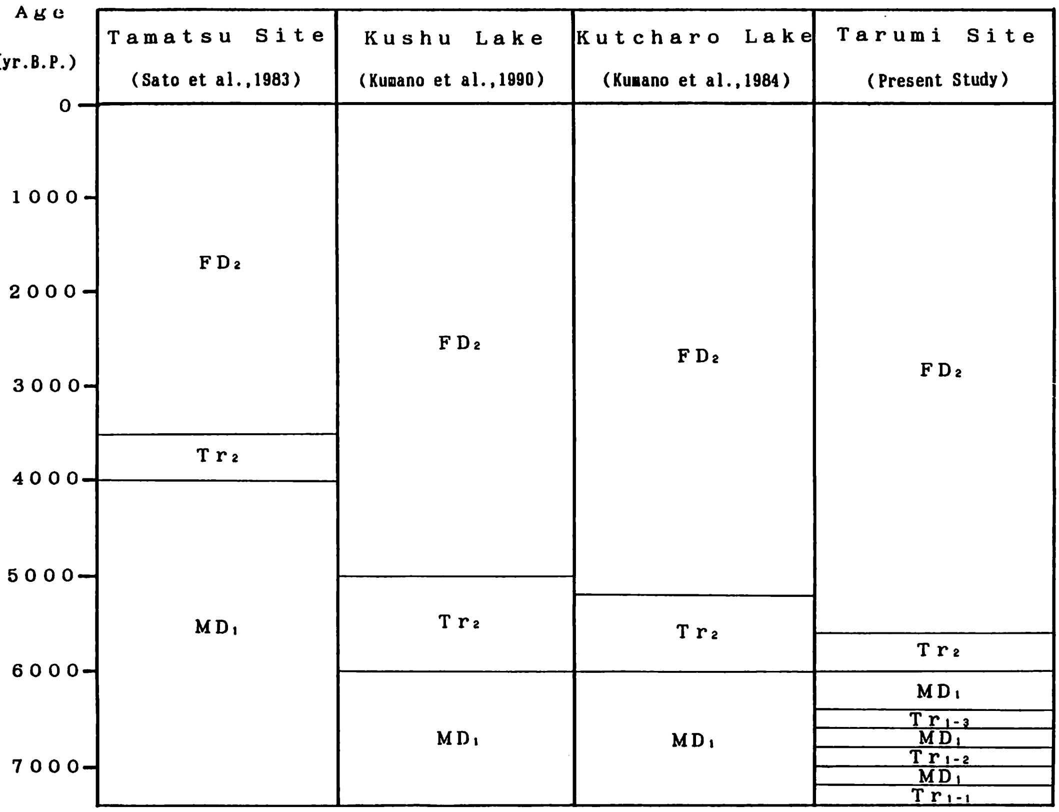

Fig. 10. Comparison of the Tamatsu site (Sato et al. 1983), the Kushu Lake core (Kumano et al. 1990a), the Kutcharo Lake site (Kumano et al. 1984) and the estuary (Tarumi site) of Fukuda River, with reference to diatom zone and subzones.

from this site were too few to count them. Freshwater and brackish diatoms were occurred, however, no marine diatom was found. For example, the lowest horizon of this site was occupied by 26 freshwater taxa and 9 brackish-water taxa, but no marine taxon was occurred. The freshwater taxa of the genus *Pinnularia* were dominated, so that these horizons might be regarded as the freshwater diatom zone (FD Zone).

Discussion

Our previous studies at several sites along the coast of Osaka Bay (Kumano and Miyahara, 1981; Kumano and Fujimoto, 1982; Sato et al., 1983), at Kamo Lake site in Sado Island (Sato and Kumano, 1985, 1986) and at Tokoro site in Hokkaido (Hamano et al., 1985) revealed that the peak of the deposition of the MD_1 Zone occurred at about 6000 yr B.P. and coincided with the peak of the first Holocene transgression at about 6000 yr B.P., and that the deposition of the MD_1 Zone and the Tr_2 Zone finished at about 5000 yr B.P. at Toya River site, Hokkaido (Ihira et al. 1985) and at 4000 yr B.P. at the Takkobu site in Kushiro Moor, Hokkaido (Kumano et al. 1990b) when the first Holocene regression occurred.

While, as shown in Fig. 10, at Kutcharo Lake site in Hokkaido (Kumano et al., 1984, Sekiya and Kumano, 1983), deposition of the MD_1 Zone and Tr_2 Zone already finished at about 6000 yr B.P., namely, the development of the lagoon or brackish lake took place at 6000 yr B.P. At Kushu Lake site in Rebun Island (Kumano et al., 1990a) deposition of the MD_1 Zone and the Tr_2 Zone already finished at about 5000 yr B.P., namely, the development of the lagoon or brackish lake took place at 5000 yr B.P., although many authors have reported that the peak of the first Holocene transgression occurred at about 6000 yr B.P. as mentioned above. It is suggested that prior to the first Holocene regression, the "Middle Jomon minor regression" at about 4500 yr B.P. named by Ota et al. (1982), the bay-mouth sand bars were completely developed across paleo-Kutcharo Bay from Okhotsk sea at Kutcharo Lake site and paleo-Kushu Bay from Japan Sea at Kushu Lake site, respectively.

In the present study at the estuary (Tarumi site) of Fukuda River along the coast of Osaka Bay, the MD_1 Zone between 7200 and 6300 yr B.P. was alternated three times by three layers of the Tr Zones.

As shown in Fig. 2, Takahashi (1992) recognized the occurrence of three rows of sand bars across the estuary of paleo-Fukuda River developed by the coastal tidal current along the northwestern coast of Osaka bay during the first Holocene transgression. Namely, the innermost row of sand bars firstly developed is located on the tracks of Japanese Railway, the middle row of sand bars secondary developed on the grounds of Wadazumi Shrine, and the outermost sand bar tertiary developed on the national road of Root No. 2. Hence, it is likely that the first Transitional Zone (Tr_{1-1} Zone, 7200 yr B.P.) was caused by the development of the innermost (first) row of sand bar; the second Transitional Zone (Tr_{1-2}), on which many foot-prints of human being were found, was corresponded with the development of the middle row of sand bar; and the third Transitional Zone (Tr_{1-3} Zone, 6340 yr B.P.) was caused by the development of the outermost row of sand bar.

In the present study at the estuary (Tarumi site) of Fukuda River, it is considered that the Tr_2 Zone at the horizon (from $+1.84$ m to $+2.7$ m) finished at about 6000 yr B.P., because the plant remains at the -0.1 m horizon of Site C gave a ^{14}C age of 6340 ± 110 yr B.P. and Akahoya tephra at the $+1.8$ m horizon showed about 6300 yr B.P. So that, at the Kutcharo Lake site, the Kushu Lake site and Tarumi site of Fukuda River the initiations of the Tr_2 Zone are considered to have been caused by the development of sand bar, prior to the first Holocene regression, the "Middle Jomon minor regression" at about 4500 yr B.P. named by Ota et al. (1982).

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熊野　茂*・西海將雄*・奥泉　剛*・佐藤裕司**：大阪湾北西沿岸・福田川河口（神戸市垂水）に於ける珪藻遺骸群集の遷移，特に完新世堆積環境の変遷について

1)第1海産珪藻帯 MD_1 から遷移帯 Tr_2 への移行時期：木片の ${}^{14}C$ 年代値，アカホヤ火山灰の存在から，本調査地に於ける第1海産珪藻帯 MD_1 から遷移帯 Tr_2 への移行時期は，およそ6000年前であると考えられる。

2)3列の砂堆列の形成と珪藻帯との関連：およそ7000年前から6000年前の約1000年間に，第1海産珪藻帯 MD_1 中に3つの遷移帯 (Tr_{1-1}, Tr_{1-2}, Tr_{1-3}) が存在する。この3つの遷移帯の存在は，大阪湾と本調査地とを隔離するように形成された3列の砂堆列の影響を受けた古環境の変遷を反映した結果であると考えられる。（*667 神戸市灘区六甲台1丁目　神戸大学理学部生物学教室，**669-13 三田市弥生ケ岡8丁目　兵庫県立人と自然の博物館）