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HOLOCENE SEA-LEVEL CHANGES AND EVOLUTION OF THE LOWER TOKACHI RIVER PLAIN, HOKKAIDO, JAPAN

ABSTRACT: OHIRA A., *Holocene sea-level changes and evolution of the lower Tokachi River plain, Hokkaido, Japan.* (IT ISSN 1724-4757, 2003).

Litho- and biostratigraphic data obtained from analyses of borehole logs, ^{14}C dates by accelerator mass spectrometry, and diatom assemblages record Holocene relative sea-level (RSL) changes and the evolution of the lower Tokachi River plain in Hokkaido, Japan. The Holocene sedimentary fill consists of a lower sandy unit, a middle marine clayey unit, an upper sandy unit, and an uppermost peaty unit. This stratigraphy is typical for deltaic settings in relation to Holocene sea-level changes. RSL rose from about –18 m to about –2 m above present mean sea level between c. 9300 (9753-9008) and c. 6700 (6844-6574) cal. yr BP, at an average long-term rate of c. 6.2 (5.1-7.4) mm/yr. RSL in the mid-Holocene appears to have not risen above 0 m. RSL at c. 5000 (5042-4840) and at c. 4300 (4420-4154) cal. yr BP were both about –1 m. RSL rose slightly to almost 0 m at c. 3800 (3962-3695) cal. yr BP. By c. 8500-8000 cal. yr BP, transgression had occurred because the rising sea flooded the valley. Rapid progradation of the delta occurred from c. 7500 cal. yr BP, when the RSL rise rate probably decreased, to c. 6500 cal. yr BP, and marsh expanded over the delta plain. Sand barriers had already begun to form before c. 4000 cal. yr BP. Vertical aggradation of the floodplain began after c. 4200 cal. yr BP. The main course of the Tokachi River in the delta plain appears to have stabilized during the late Holocene, on the basis of the gravel-sized sediment distribution and lithostratigraphy of the subsurface deposits. Obvious sand sheets recognized in the uppermost peat layer in the coastal zone imply the occurrence of large tsunamis.

KEY WORDS: Holocene, Sea-level change, Coastal evolution, Delta plain, Tokachi River, Hokkaido (Japan).

INTRODUCTION

Many studies on Holocene sea-level changes and coastal evolution in the Japanese islands show that relative sea-level (RSL) curves are influenced by both eustatic and tectonic movements and that the processes of coastal evolution have regional differences and variations (Umitsu, 1991, 1996). Previous studies have presented several Holocene RSL curves from Hokkaido, the northern main island of Japan. Most of these curves are based on index points that were obtained from the Okhotsk coast (Matsushima, 1982a; Maeda, 1984; Hirai, 1987; Sakaguchi & *alii*, 1985; Ohira & Umitsu, 1999). They imply that a rapid sea-level rise occurred during the early to middle Holocene, with the highest stand recorded in the middle Holocene, and that minor sea-level fluctuations occurred during the late Holocene. On the other hand, there are a few RSL curves from the Pacific coast of Hokkaido. An RSL curve from an estuary of Lake Akkeshi in eastern Hokkaido shows that remarkable fluctuations occurred during the last 3000 years (Sawai & Kashima, 1996; Sawai & Mishio, 1998). However, eastern Hokkaido is tectonically very active and has been affected by great earthquakes related to the subduction of the Pacific plate (Shimazaki, 1974; Suzuki & Kasahara, 1996). Sawai (2001) regards that the co-seismic (abrupt uplift) and inter-seismic (continuous subsidence) crustal movements probably affected the sedimentary succession of the Akkeshi estuary. Moreover, few RSL curves from the Pacific coast for the period before c. 3000 yr BP have been published, and there are also few studies on RSL change and coastal evolution in Hokkaido during the Holocene that are based on calibrated ages.

The Tokachi River, one of the major rivers in Hokkaido, is 156 km long (the main river channel) and has a drainage area of 9010 km^2 (fig. 1). It flows from the central mountainous region to the Pacific Ocean and forms a riverine coastal plain in its lower reaches. The plain is located about 110 km west-southwest of Lake Akkeshi and about 200 km northwest of the Kuril Trench. The plain appears to be situated in a relatively stable area with respect to seismic crustal movements, because pre-seismic subsidence is not evident and no obvious co-seismic movements

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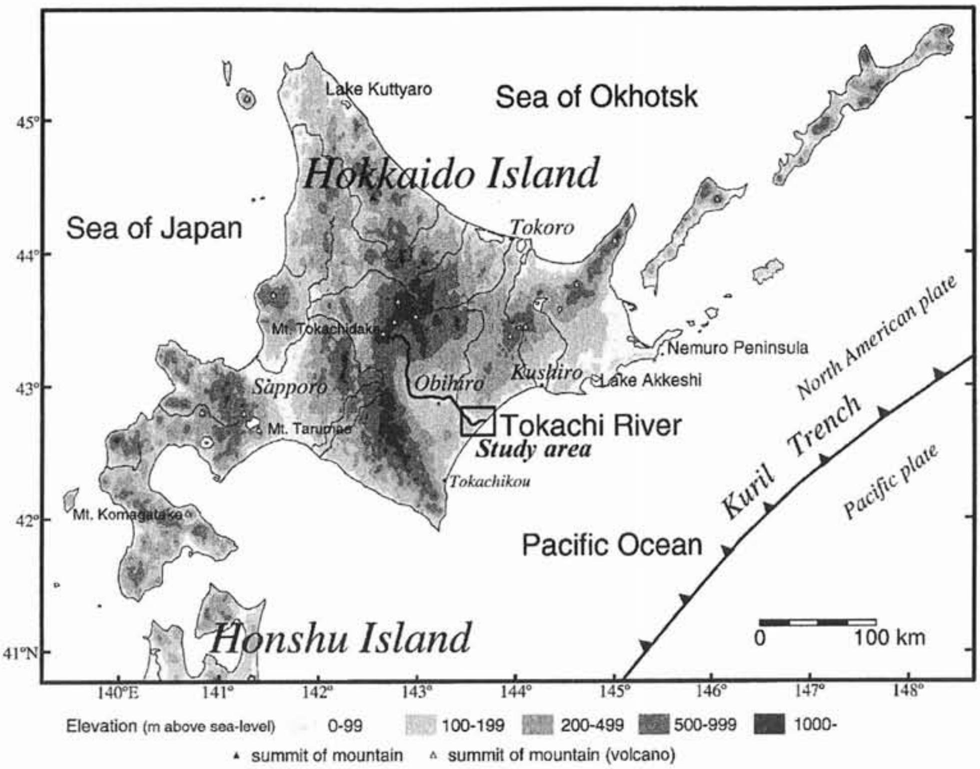


FIG. 1 - Relief map showing the location of the study area.

have been reported. Consequently, a Holocene RSL curve from the plain may be little affected by seismic crustal movements. This paper presents a Holocene RSL curve from the lower Tokachi River plain on the Pacific coast of Hokkaido and describes the evolution of the plain on the basis of analyses of detailed litho- and biostratigraphy and calibrated ages.

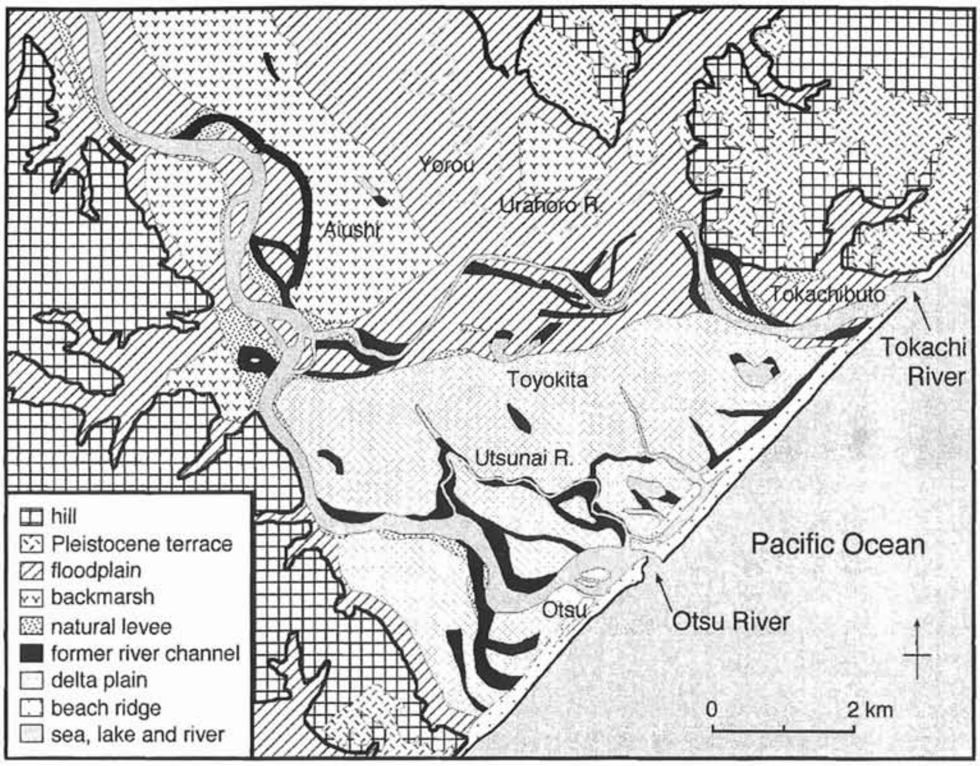
REGIONAL SETTING

The Tokachi River has its source on Mt. Tokachidake, a Quaternary volcano. It first traverses the upper part of the Tokachi plain, which is composed mainly of dissected alluvial fans, then crosses the riverine coastal plain between approximately 200-m-high hills composed of Neogene sedimentary rocks, and finally empties into the Pacific Ocean (fig. 1). The study area was located between lat 42.40°-42.45° N and long 143.38°-143.43° E.

Eastern Hokkaido constitutes a part of the Kuril-Hokkaido arc and is the location of a convergence zone where the Pacific plate subducts under the North American plate. The Pacific coast of eastern Hokkaido is frequently affected by great earthquakes (Suzuki & Kasahara, 1996). Pre-seismic crustal deformation along the Pacific coast of eastern Hokkaido is characterized by chronic oceanward tilting and contraction in the direction perpendicular to the trench axis (Shimazaki, 1974). The tidal record from a tide-gauge station at Kushiro, on the Pacific coast about 60 km northeast of the lower Tokachi River plain, shows that Kushiro subsided at a rate of 9.27 mm/yr between 1958 and 1996 (Ozawa & *alii*, 1997). The rate of subsidence decreases toward the southwest, and at the tide-gauge station at Tokachikou on the Pacific coast (about 50 km southwest of the study area), it is 1.45 mm/yr. Crustal movement in the study area is not completely clear. However, the study area is relatively more stable than the area to the east (from Kushiro to the Nemuro Peninsula), because pre-seismic subsidence is not evident and no obvious co-seismic movements or indications, except for inundation by tsunamis, have yet been recognized on the plain.

The landforms of the lower Tokachi River plain were mapped from 1:40 000 aerial photographs taken in 1947, before the plain was modified by drainage works and agricultural developments (fig. 2). The names of the river courses used in this paper are those that were used before 1964, when the main course of Tokachi River was artificially modified. The landforms of the plain are floodplain, natural levees, former river channels, back marsh, delta plain with distributary channels, and beach ridges. Many abandoned distributary channels and traces on the delta plain remain alongside the Otsu River. Floodplains are developed beside the Tokachi and Urahoro rivers, and backmarsh has formed between them. Former channels of the Tokachi River can also be identified alongside the river. Two rows of beach ridges trend NE-SW along the coast. The lowermost river courses bend eastward, according to the dominant direction (NE) of the longshore

FIG. 2 - Landforms of the Tokachi River plain.



current. The linear shoreline shows obvious effects of coastal erosion.

The climate of Hokkaido is affected by the Asian monsoon. The Siberian air mass brings severe cold and extensive snow to Hokkaido in winter, although the Pacific Ocean side of Hokkaido receives less snow than the Sea of Japan side. In August-September, the moist Northern Pacific air mass migrates to Hokkaido, occasionally bringing much rainfall and fog, and the migration of the Okhotsk air mass prevents a rise in temperature. The study area belongs to the subarctic climatic zone. Mean annual temperature is 4.5 °C, and annual precipitation is 938 mm in Otsu, on the Pacific coast. The climate varies seasonally. The mean winter temperature (December-February) is –7.4 °C, and the mean summer temperature (June-August) is 14.4 °C. Mean precipitation is 94 mm in winter and 353 mm in summer. Seasonal frost is recognized in eastern Hokkaido, which receives several snowfalls in winter.

The annual total and average discharge of the Tokachi River, measured at Moiwa station located about 8 km upstream from Otsu, are about 6.3×10^9 m^3 and 199 m^3/s respectively. The discharge varies seasonally in response to climate, and the maximum discharge is about 3000 m^3/s. Floods frequently occurred in the plain before the drainage works were built.

There is no tide-gauge station in the study area. However, the mean spring tide range is probably microtidal. Mean spring tide range on the Pacific coast of Hokkaido varies from 0.5 to 1.5 m and at the tide-gauge station at Kushiro it is 0.8 m (National Astronomical Observatory, 2000).

METHODS

Lithostratigraphy of the lower Tokachi River plain is based on engineering borehole and hand-drilled borehole data. The engineering borehole data and core samples, obtained as a part of the geological survey prior to the construction of roads and bridges, were collected from official organizations, such as Hokkaido Development Bureau. Subsurface sediments were also collected by hand-drilling from 45 sites using bi-partite gouge augers (Eijkelkamp Agrisearch Equipment, The Netherlands). The elevation of the ground surface at each hand-drilling site was determined from a benchmark in relation to the Japanese standard datum of leveling using an automatic optical level (*B21*, Sokkia, Japan). The elevation standard used in Japan is based on the mean sea level of Tokyo Bay.

Eighteen accelerator mass spectrometry (AMS) radiocarbon (^{14}C) ages on plant material (peat), shell, and wood fragments were determined by Beta Analytic Inc. (Table 1). Conventional ^{14}C ages, the result of fractionation corrections to the measured ^{14}C age, were used for calibration. Calibrated ages were obtained from the calibration program CALIB 4.3 (Stuiver & Reimer, 1993; Stuiver & *alii*, 1998), with a correction for the global reservoir effect on marine shell, namely, about 400 years of surface seawater

TABLE 1 - AMS radiocarbon dating results from the lower Tokachi River plain

Borehole see Figure 3	Elevation*1 (m above sea level)	Dated material	Measured ^{14}C age 1 σ (yr BP)	$\delta\,^{13}C$ (‰)	Conventional ^{14}C age 1 σ (yr BP)	Calibrated age(s) (cal. yr BP)*2 mean (2 σ range*3)	Laboratory code
AU	−7.72 ~ −8.02	wood	6790 ± 60	−30.5	6700 ± 60	7572 (7673-7434)	Beta-124739
AU	−11.72 ~ −12.02	shell	7390 ± 150	0.8	7820 ± 150	8299 (8586-7956)*4	Beta-124740
UB	−5.35 ~ −5.65	plant	2020 ± 40	−26.8	1990 ± 40	1946, 1942, 1929 (2037-1831)	Beta-135461
UB	−9.35 ~ −9.65	shell	7180 ± 40	0.7	7600 ± 40	8028 (8150-7951)*4	Beta-135462
UB	−13.35 ~ −13.65	shell	7540 ± 30	2.0	7990 ± 30	8413 (8536-8368)*4	Beta-135463
UB	−18.35 ~ −18.65	shell	8470 ± 40	−6.2	8770 ± 40	9389, 9227, 9103 (9753-9008)*4	Beta-135464
UB	−22.35 ~ −22.65	wood	8330 ± 30	−27.1	8290 ± 30	9396, 9388, 9367, 9361, 9344 9294, 9288, 9284 (9465-9134)	Beta-135465
UB	−27.35 ~ −27.65	humic soil	39260 ± 580	−27.6	39220 ± 580		Beta-135466
TK	0.72	plant (peat)	5270 ± 30	−26.1	5250 ± 30	5990, 5965, 5952 (6169-5927)	Beta-144515
TK	1.87	plant (peat)	3770 ± 40	−25.6	3760 ± 40	4145, 4116, 4093 (4241-3984)	Beta-144516
YO	1.68	plant (peat)	3610 ± 30	−26.5	3590 ± 30	3887, 3876, 3873 (3978-3778)	Beta-144517
(outcrop)	depth (1.65)	plant (peat)	2300 ± 50	−24.9	2300 ± 50	2339 (2357-2154)	Beta-144518
AU2	0.74	plant (peat)	5220 ± 50	−26.0	5200 ± 50	5931 (6168-5892)	Beta-144519
UT	−1.96	plant	5930 ± 40	−27.5	5890 ± 40	6722, 6698, 6678 (6844-6574)	Beta-155906
UT	−0.83	plant (peat)	4400 ± 40	−27.6	4360 ± 40	4870 (5042-4840)	Beta-155907
UT	−0.28	plant (peat)	3740 ± 40	−26.8	3710 ± 40	4084, 4028, 4005 (4216-3926)	Beta-155908
T02	−0.85	plant	3890 ± 40	−24.8	3890 ± 40	4350, 4327, 4299 (4420-4154)	Beta-155909
T03	0.02	plant	3610 ± 40	−28.7	3550 ± 40	3833 (3962-3695)	Beta-155910

*1 Elevation is based on the mean sea level of Tokyo Bay.

*2 Calibrated ages were obtained using CALIB 4.3 (Stuiver and Reimer, 1993).

*3 Calibrated age range was obtained from intercepts (Method A).

*4 Global reservoir effect on marine shells was corrected (local reservoir correction was not applied).

(local reservoir correction not applied). ^{14}C ages quoted in the paper are expressed as cal. yr BP (2σ range obtained by the intercept method). The measured ^{14}C ages published by previous studies, expressed as yr BP, were also used as the need arose, with tentative calibrated ages (as converted by the author) shown in parentheses (fractionation correction not applied), because few previous studies discuss the RSL changes in relation to calibrated ages.

Biostratigraphical data are based on the diatom assemblages of the sediments. The samples used were from the cores of two engineering boreholes UB and AU, and one hand-drilled borehole UT (fig. 3). Diatom strew slides were prepared by treating 1- to 2-g sediment samples in 15% hydrogen peroxide for about 30 minutes to remove organic matter, and then rinsing with distilled water in a centrifuge. An aliquot of the sample was dried on a cover glass and mounted on a glass slide with a synthetic resin of high refractive index (*Mount Media*, Wako Pure Chemical Industries, Japan). Diatom valves were identified using a high-magnification light microscope (*OPTIPHOT*, Nikon, Japan) and information and photographic plates in Hendey (1964), Patrick & Reimer (1966), and Krammer & Lange-Bertalot (1991a, b, 1997a, b). The diatom ecological data are mainly based on Kashima (1986), Kosugi (1988), Vos & de Wolf (1993), and the above-mentioned studies. Diatom frequencies are expressed as a percentage of total diatom valves using a minimum sum of 200 valves. Selected taxa with high abundance and ecologically important species are graphed.

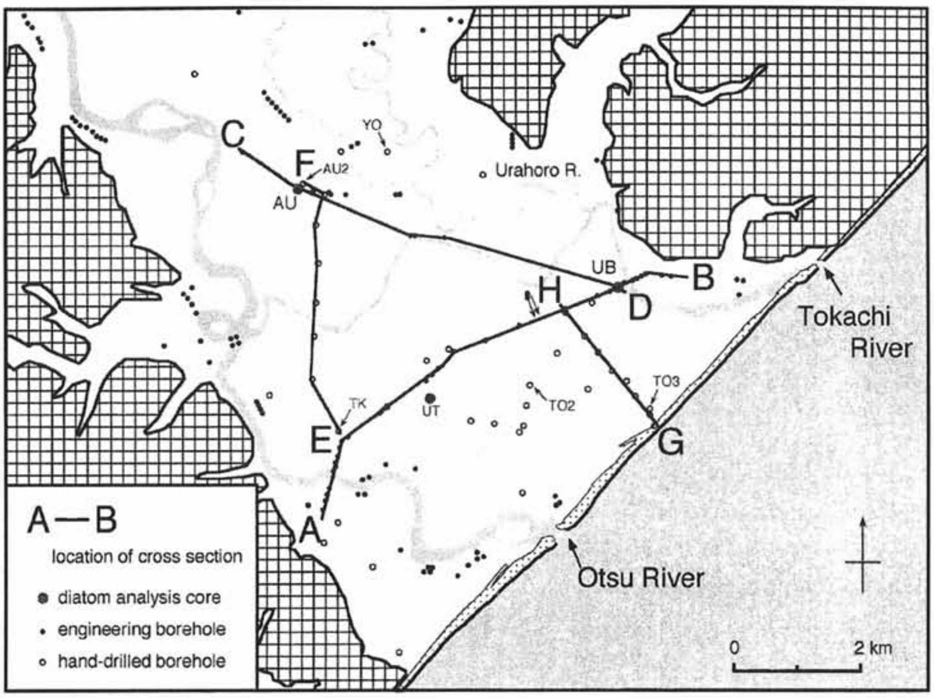
LITHOSTRATIGRAPHY AND RADIOCARBON AGE

Geological cross-sections A-B and C-D (locations shown in fig. 3) illustrate the stratigraphy of the lower Tokachi River plain (figs. 4 and 5). Over 40 m of sediments fill the former valley of the Tokachi River, incised into the Neogene basal rocks during the last glacial period. Section A-B (fig. 4) shows a buried terrace surface recognized at about −27 m in the eastern part of the plain. The humic soil at the top of the terrace in borehole UB (Urahoro Bridge) was dated at 39 220 ± 580 yr BP (conventional ^{14}C age). There is no ^{14}C age from the lowermost sediments, but the sediments above −27 m are certainly Holocene from the facies observed in the core samples of borehole UB. The Holocene sedimentary fill is composed of four main lithostratigraphic units: the lower sandy unit; the middle clayey unit; the upper sandy unit; and the uppermost peaty unit.

The lower unit is generally sandy and includes several horizontally continuous muddy layers. Many shell fossils were found in the uppermost horizon of the unit, as shown in sections A-B and C-D (figs. 4 and 5). A shell fragment from about −18.5 m in Borehole UB was dated at 9753-9008 cal. yr BP. The lithological contact between the lower and the middle units is very sharp and dips gently in a seaward direction. The average gradient of the contact from borehole AU to borehole UB is about 0.7% (0.67/10 000).

The middle unit is dominated by clays and silts and is characterized by frequent shell inclusions. The unit has a

Fig. 3 - Location of boreholes and geological cross-sections. Legend is the same as for figure 2.



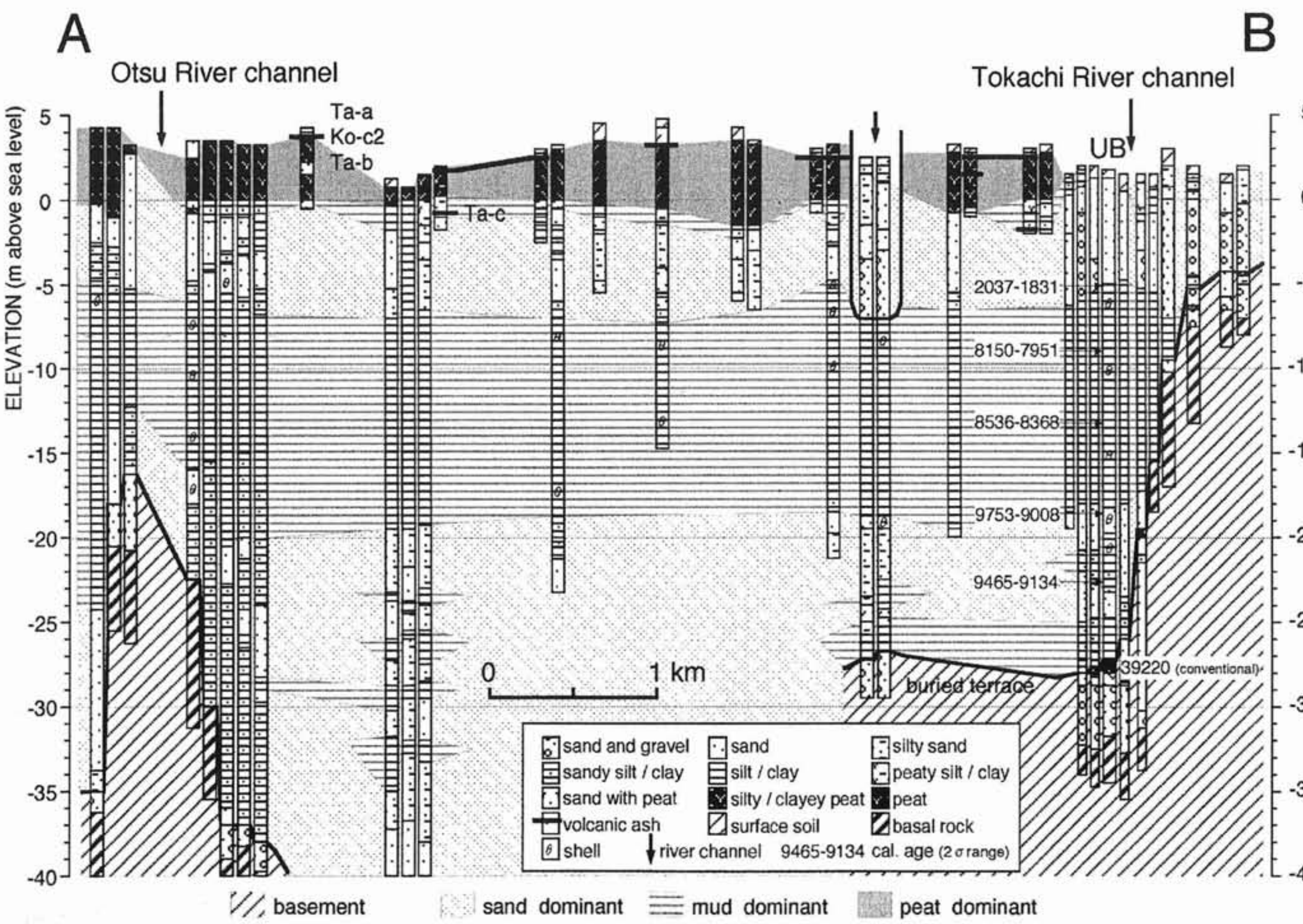


Fig. 4 - Geological cross-section A-B.

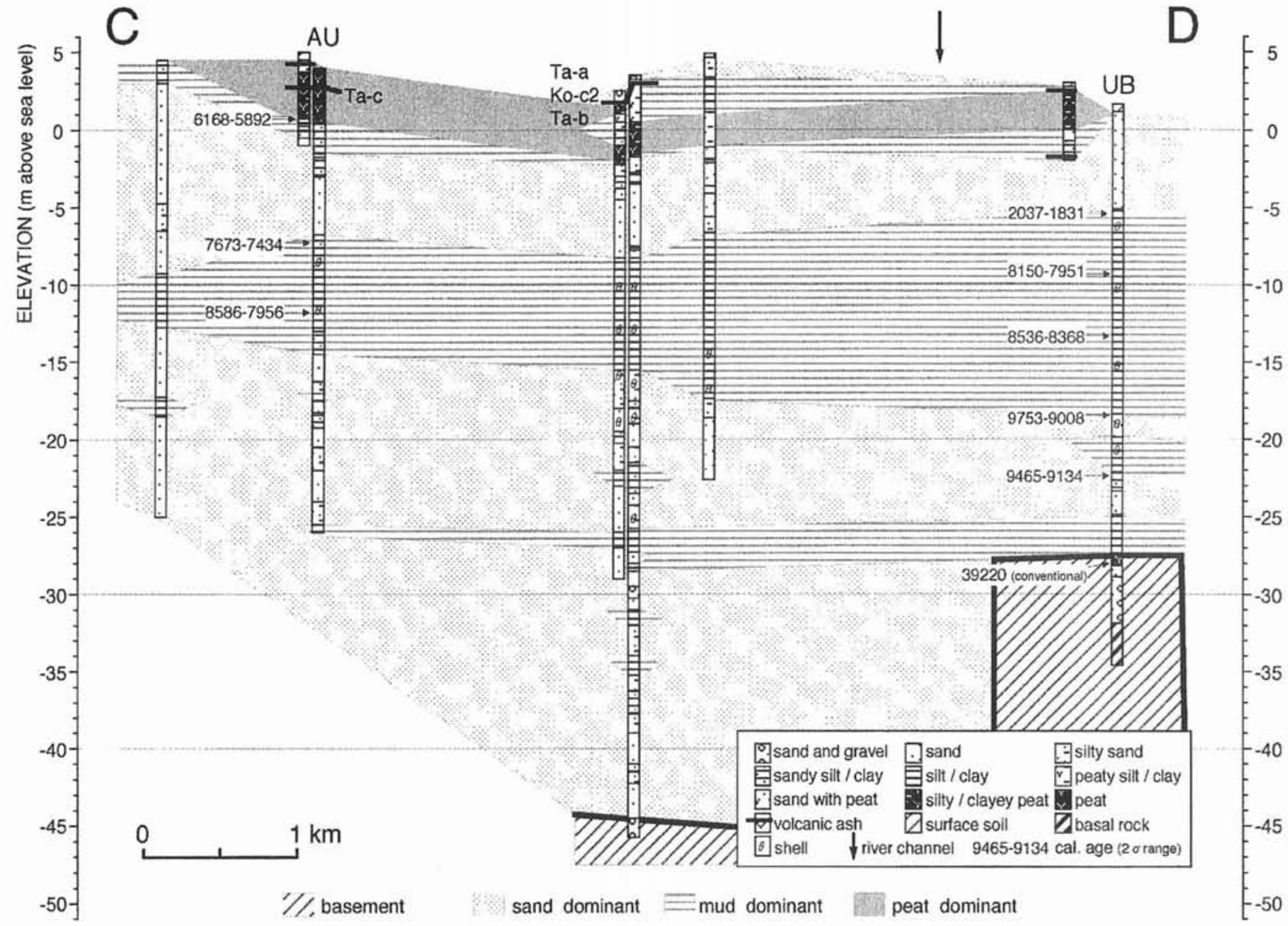


FIG. 5 - Geological cross-section C-D.

maximum thickness of about 14 m and thins landward as shown in section C-D (fig. 5). The unit is distributed about 10 km from the current coastline. The clays and silts are generally dark gray and very soft, and occasionally include very thin beds of fine sand and organic matter. Two shells at about –13.5 m and about –9.5 m in borehole UB were dated at 8536-8368 and 8150-7951 cal. yr BP, respectively. The age of a shell fragment at –11.9 m in borehole AU was also determined to be 8586-7956 cal. yr BP. The lithological contact with the upper unit is generally gradual, and the uppermost part of the unit tends to consist of sandy silts or sandy clays. A wood fragment from this part, about –7.9 m in borehole AU, was dated at 7673-7434 cal. yr BP.

The upper unit is composed mainly of silty sands and sandy silts and is about 5 m thick. A coarsening-upward sequence was recognized in the unit. The sand is generally poorly sorted, and granule- to pebble (diameter 2-10 mm)-sized gravels are distributed near the Tokachi River channel. Gravel was generally found only near the Tokachi River, judging from the engineering borehole descriptions. The lithological contact with the middle unit in borehole UB is very sharp, and the calibrated age of plant material from the lowest part of the upper unit (2037-1831 cal. yr BP) is younger than the age estimated from the accumulation rate of the middle clayey unit. Therefore, the upper sandy unit in borehole UB is likely to be erosional overlap on the middle unit.

The uppermost unit is mainly composed of peat. Clays and silts in the unit are underlain by peat deposits. The peat deposits reach a maximum thickness of about 5 m and are absent near the channels of the Tokachi Rivers, as shown on the right side of section A-B (fig. 4). Several tephra (volcanic ash) layers were recognized in the peat deposits. Plant materials from the base of the peat deposits in boreholes AU2 and TK (locations shown in fig. 3) were dated at 6168-5892 and 6169-5927 cal. yr BP, respectively.

TEPHROCHRONOLOGY AND SUBSURFACE DEPOSITS

Six or seven tephra layers found in the uppermost unit were correlated to the late Holocene tephrochronology in Hokkaido, which has been established by many previous studies (Machida and Arai, 1992). Three tephra layers in the uppermost horizon were identified as the Ta-a (*Tarumae-a*) tephra, the Ko-c2 (*Komagatake-c2*) tephra, and the Ta-b (*Tarumae-b*) tephra in descending order, which fell in AD 1739, AD 1694, and AD 1667, respectively. A thin, very fine-grained white ash at 0.7-0.8 m depth in the peat deposits probably correlates with either the B-Tm (*Bekutosan-Tomakomai*) tephra or the Ma-a (*Mashu-a*) tephra. A 1.5-cm-thick fine-grained pale brown ash at 1.5-1.8 min depth was identified as the Ta-c (*Tarumae-c*) tephra, erupted from Mt. Tarumae in southern Hokkaido, according to the results of tephra analysis. The Ta-c tephra fell about 2357-2154 cal. yr BP, according to ^{14}C dating of plant material from ash obtained from an outcrop near Aiushi. A thin, fine-grained white ash below the base of peat deposits probably correlates with the Ko-g (*Komagatake-g*) tephra, according to the results of tephra analysis.

Geological cross sections E-F and G-H illustrate the detailed stratigraphy of the subsurface deposits (figs. 6 and 7). Section E-F shows the lithostratigraphy of a transect across the Tokachi River channel. This section implies that channel changes have been limited to a zone about 1.5 km wide. The flood deposits from the Otsu River appear to have increased after 4241-3984 cal. yr BP. The peat, dated at c.3978-3778 cal. yr BP, is also covered by flood deposits from the Urahoro River. Section G-H shows the lithostratigraphy of a transect from the beach ridge landward. The sediments behind the beach ridge consist of peat and mud-covered sands. Plant material (a reed root) from the sand, which is regarded as the uppermost horizon of the upper sandy unit, was dated at 3962-3695 cal. yr BP. Another reed root from the sand in borehole TO2 (location shown in fig. 3), about 2 km east of borehole TO3, was dated at 4420-4154 cal. yr BP. Conspicuous sand layers in the peat deposits were recognized in the coastal area. The sands are poorly sorted and include round, flat pebbles (diameter 2-3 cm) near the beach ridge and become well-sorted landward. The most horizontally continuous sand layer was found about 2 cm below the Ta-b ash. This layer is regarded as having been deposited by a huge tsunami occurred in the 17[th] century (Hirakawa & *alii*, 2000). Hirakawa & *alii* (2000) also regarded the other sand layers as tsunami deposits on the basis of their investigations along the Pacific coast of central Hokkaido.

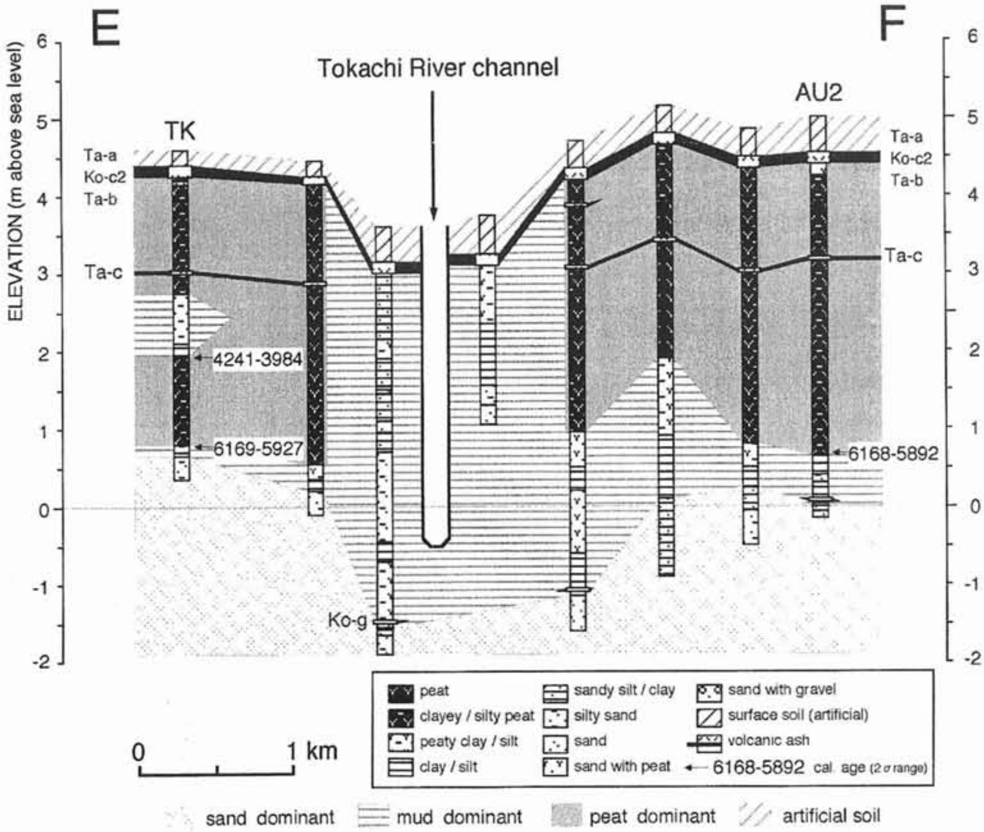


FIG. 6 - Geological cross-section E-F.

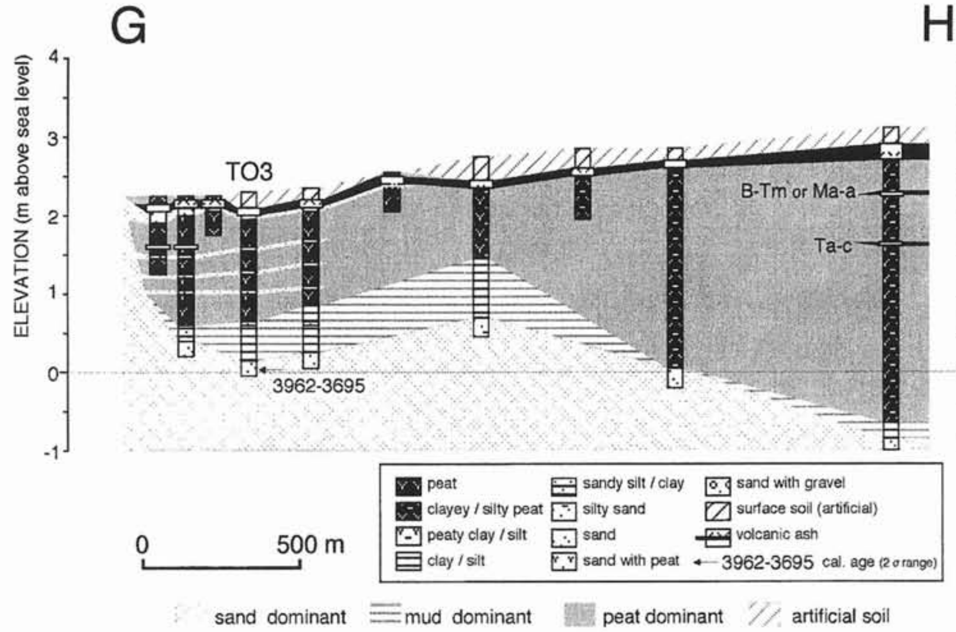


FIG. 7 - Geological cross section G-H.

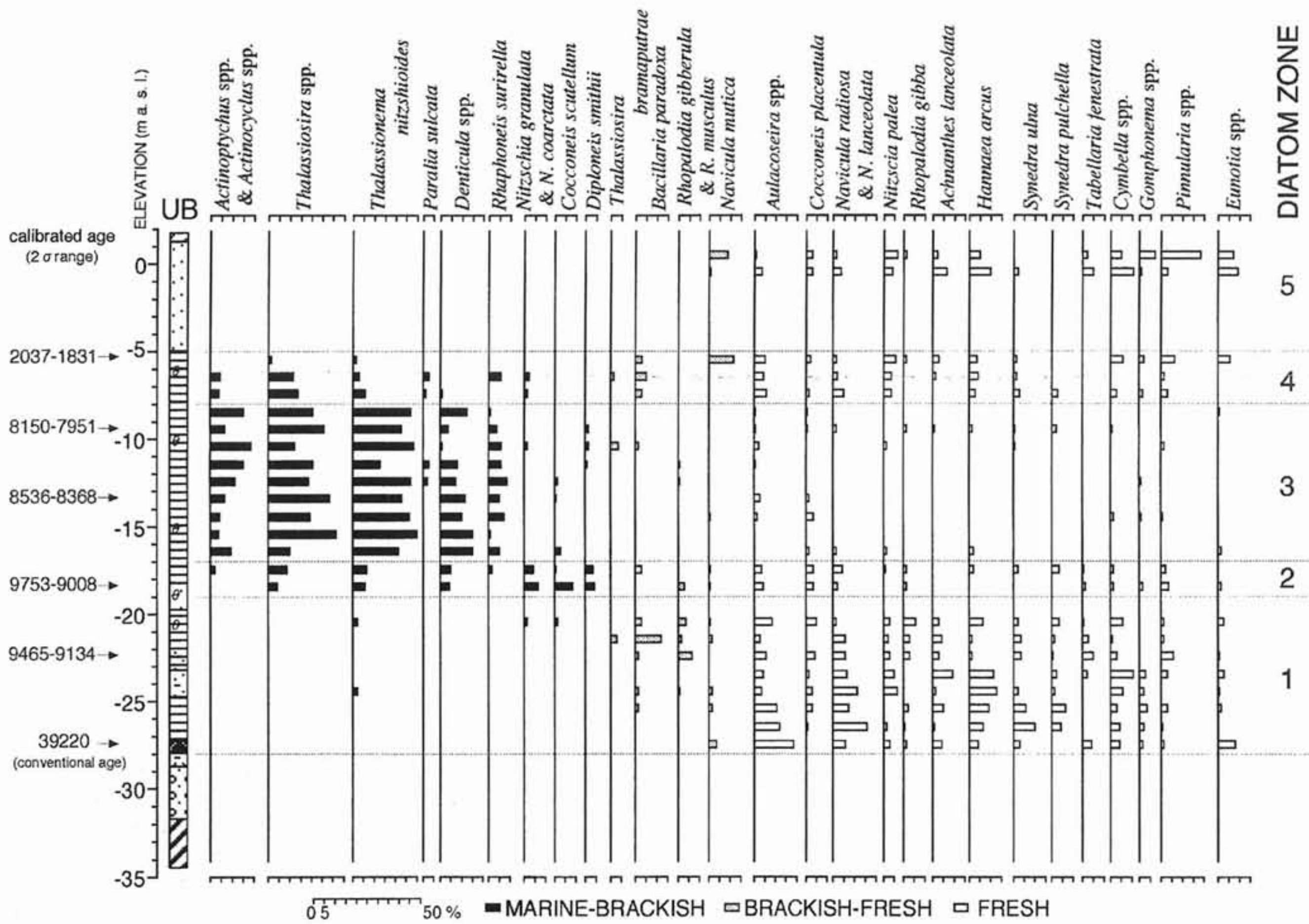


FIG. 8 - Distribution of diatom species and genera in borehole UB. Location of borehole UB is shown in figure 3. Legend of columnar section is the same as for figure 4.

DIATOM ASSEMBLAGES AND SEDIMENTARY ENVIRONMENTS

Diatom analyses of the cores from boreholes UB and AU were carried out in order to determine the sedimentary environments of the Holocene fill (figs. 8 and 9). The cores UB and AU were sampled for these analyses at 1 m intervals. The core below 0.3 m from borehole UT was analyzed at intervals of 10 cm in order to determine the sedimentary environments associated with the clastic and organic horizons (fig. 10). This study uses diatom assemblages to distinguish among three groups of environments: marine-brackish group (species live in marine and brackish water, and can not live in freshwater); brackish-fresh group (species live in brackish and freshwater, and can not live in marine water); and fresh group (species live in freshwater and can not live in marine and brackish water). Fossil diatom assemblages are generally composed of the autochthonous and allochthonous components. Because it is difficult to distinguish two components, the sedimentary environments of the cores are judged from the dominant group that is corresponded as a autochthonous component.

Borehole UB

Diatom valves were well preserved throughout the core, except in the lower part of the upper sandy unit. Five diatom zones were established on the basis of the diatom assemblages. The characteristics of each zone are as follows: Zone 1 is characterized by a high percentage of freshwater diatoms, such as *Aulacoseira* spp., *Navicula radiosa* and *N. lanceolata*, and *Hannaea arcus*, but accompanied by a small number of marine-brackish-water and brackish-freshwater diatoms, such as *Thalassionema nitzschioides*, *Nitzschia granulata* and *N. coarctata*, and *Bacillaria paradoxa*. Zone 2 is characterized by a high percentage of marine-brackish-water epipelic or epiphytic diatoms, such as *Nitzschia granulata* and *N. coarctata*, and *Cocconeis scutellum*, which are frequently found in intertidal habitats. Zone 3 is characterized by the dominance of marine planktonic diatoms, such as *Thalassiosira* spp. and *Thalassionema nitzschioides*. Zone 4 is characterized by a decrease in marine planktonic diatoms and an increase in the brackish-freshwater diatoms *Bacillaria paradoxa* and *Navicula mutica*. Zone 5 is characterized by the dominance of freshwater diatoms and by the absence of marine-brackish-water diatoms.

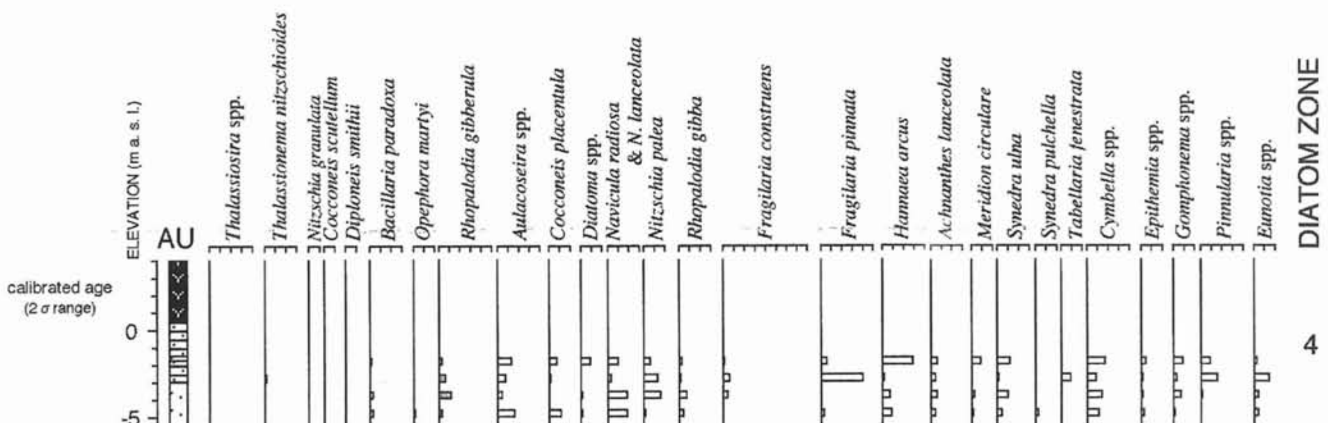


FIG. 9 - Distribution of diatom species and genera in borehole AU. Location of borehole AU is shown in figure 3. Legend of columnar section is the same as for figure 4.

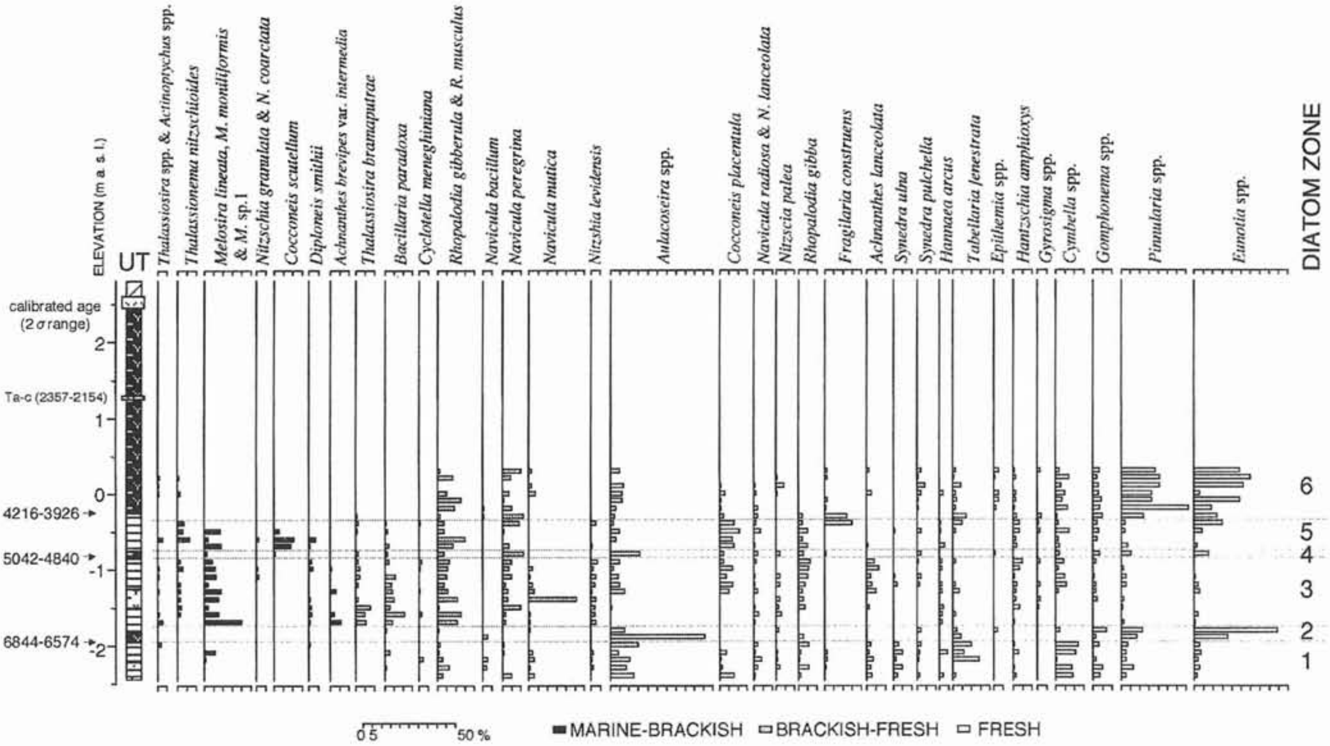


FIG. 10 - Distribution of diatom species and genera in borehole UT. Location of borehole UT is shown in figure 3. Legend of columnar section is the same as for figure 4.

The transitions from each diatom zone to the next suggest the following sedimentary environmental changes: a delta plain subject to occasional marine influences was replaced by a tidal environment. Subsequently, transgression clearly occurred and marine-brackish-water conditions resulted. Finally, a fluvio-deltaic environment appeared. The ^{14}C age and elevation of a shell fragment from zone 2 is regarded as a sea-level index point because the sedimentary environment of zone 2 indicates intertidal conditions.

BOREHOLE AU

Sufficient numbers of diatom valves for analysis were found in this core below about –2 m. The diatom assemblages of core AU were classified into four zones, and their vertical changes resembled those in core UB. Zone 1 is characterized by a high percentage of freshwater diatoms, such as *Cymbella* spp. and *Aulacoseira* spp., but they are accompanied by a high percentage of brackish-freshwater diatoms in the upper part of the zone. Zone 2 is characterized by the noticeable appearance of marine-brackish-water diatoms, such as *Nitzschia granulata* and *Cocconeis scutellum*. Zone 3 is characterized by the dominance of marine planktonic diatoms *Thalassiosira* spp. and *Thalassionema nitzschioides*. Zone 4 is characterized by the dominance of freshwater diatoms, but they are accompanied by a small number of brackish-freshwater diatoms, such as *Rhopalodia gibberula* and *Bacillaria paradoxa*.

The sedimentary environmental changes indicated by the diatom zones are similar to those proposed for core UB. A delta plain with occasional marine-brackish-water influences was replaced by an intertidal environment. Afterward, it is clear that transgression and, subsequently, regression also occurred at this site.

BOREHOLE UT

In this core, the diatom assemblages were obviously different between the clastic and peaty horizons. They were classified into six zones. Zone 1, the lowermost sandy mud, is characterized by a high percentage of freshwater diatoms, such as *Aulacoseira* spp. and *Cymbella* spp., but they are accompanied by a small number of marine-brackish-water diatoms in the upper part. Zone 2, in the peaty horizon at about –1.8 to –2.0 m, is characterized by the dominance of freshwater diatoms such as *Aulacoseira* spp. and *Pinnularia* spp. Zone 3, in the muddy horizons with plant materials, is characterized by a rapid increase in marine-brackish-water diatoms, such as *Melosira lineata* and *M. moniliformis* and *M.* sp.1 and *Thalassionema nitzschioides*, and a high percentage of brackish-freshwater diatoms, such as *Rhopalodia gibberula* and *R. musculus*. Zone

4, in the peaty horizon at about –0.8 m, is characterized by a high percentage of freshwater diatoms such as *Aulacoseira* spp. Zone 5 is characterized by a high percentage of marine-brackish-water diatoms, especially by the noticeable appearance of *Cocconeis scutellum*. Zone 6 is characterized by the dominance of freshwater diatoms, such as *Pinnularia* spp. and *Eunotia* spp.

The diatom zones show that the sedimentary environments of the clastic horizons were intertidal (estuarine) and those of the peaty horizons reflect marshy conditions. These characteristics probably indicate transgressive sedimentation in response to sea-level rise. ^{14}C ages were obtained from the peat immediately above or below the intertidal (estuarine) sediments. Therefore, these ages can be used as index points of former sea level.

DISCUSSION

HOLOCENE RELATIVE SEA-LEVEL CHANGES

A calibrated age/elevation graph of selected radiocarbon dates from the lower Tokachi River plain is presented in fig. 11. Six sea-level index points and several ^{14}C dates close to the RSL curve are plotted in this graph. The relative trend of the graph represents the curve of mean high water of spring tides, because the sea-level index points for the plain are the age and elevation of intertidal sediments or those of terrestrial sediments close to intertidal sediments. Only the ^{14}C dating material for sea-level index point 1 is a shell fragment from the intertidal sediments in core UB. The species couldn't be identified from the shell fragment. Therefore, there is a possibility that the material is an allochthonous fossil and its ^{14}C date may have not corresponded to the age of the intertidal sediment. However, this paper temporarily uses the ^{14}C date of the material because another ^{14}C date on the intertidal sediments couldn't be obtained.

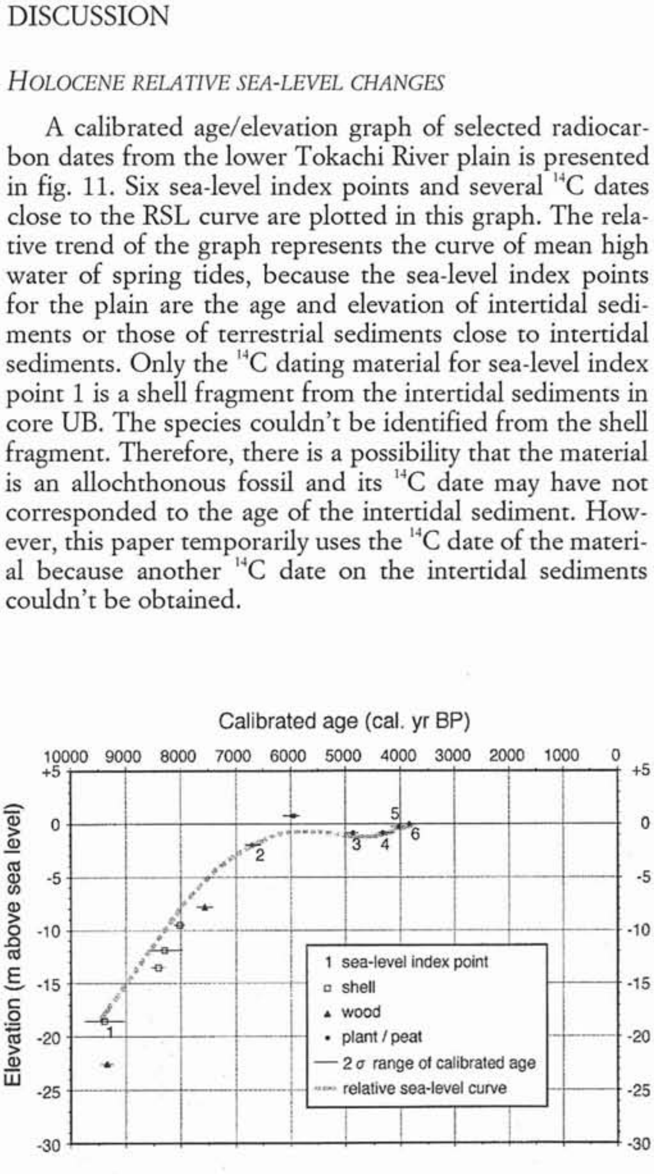


FIG. 11 - Calibrated age/elevation graph of selected radiocarbon dates from the lower Tokachi River plain.

In general, the graph illustrates a period of rapid RSL rise during the early to mid-Holocene from about –18 m to –2 m between c. 9300 (9753-9008) and c. 6700 (6844-6574) cal. yr BP, with an average long-term rate of c. 6.2 (maximum-minimum: 7.4-5.1) mm/cal. yr. It is estimated that the RSL rise rate probably decreased after c. 7500 (7673-7434) cal. yr BP because delta progradation had begun by that time. It is possible that RSL between c. 6700 and c. 5000 cal. yr BP did not rise above 0 m, because the base of the freshwater peat, dated at c. 6000 cal. yr BP, is about 1 (0.7) m, and the sedimentary environment of the deposits about 1 m below the base is also a freshwater environment. The RSL at both c. 5000 (5042-4840) and c. 4300 (4420-4154) cal. yr BP was about –1 m. After that, RSL rose slightly and reached almost 0 m at c. 3800 (3962-3695) cal. yr BP.

Previously published RSL curves from the Okhotsk coast of Hokkaido (Matsushima, 1982a; Maeda, 1984; Hirai, 1987; Sakaguchi & *alii*, 1985; Ohira & Umitsu, 1999) show that the highest RSL stand, at about 3-4 m, occurred at c. 6000-5500 yr BP (measured ^{14}C age, with no correction for the global and local reservoir effect). These curves were based on index points obtained from areas of uplift such as the Tokoro Plain. If this date is converted to a tentative calibrated date using a calibration curve applicable to marine samples (Stuiver & *alii*, 1998), the highest stand appears to have occurred at c. 6400-5900 cal. yr BP. The RSL at that period in the lower Tokachi River plain is not precisely determined but appears to have not risen above 0 m. Thus, the vertical displacement of RSL in the middle Holocene between the Okhotsk coast and the lower Tokachi River plain is probably due to regional differences in Holocene crustal movements between the two regions.

Maeda & *alii* (1992) investigated the elevations of late Holocene RSLs along the Pacific coast of eastern Hokkaido and noted a gradual decrease in RSL toward the tip of Nemuro Peninsula. They explained the vertical displacement by a glacio-hydroisostatic adjustment caused by the last deglaciation, and considered no vertical displacement associated with the subduction of the Pacific plate to have accumulated on a timescale of 10^3-10^4 years. However, this argument is not valid because they compared RSL elevations of different dates, ranging from 2820 to 5780 yr BP, and did not consider the fluctuations in sea level. On the other hand, Okumura (1996) investigated the regional variation in crustal movement in eastern Hokkaido on the basis of the altitudes of late Pleistocene marine terraces. According to this study, a gentle eastward tilting and a rather steep westward bending occurred along the Pacific Ocean coast because the elevation of the former shoreline gradually increases from Nemuro Peninsula to the eastern margin of the Tokachi plain (Tokachibuto) and then decreases less gradually westward. However, Holocene crustal movements corresponding to those determined from the late Pleistocene marine terraces have not been confirmed. The lower Tokachi River plain has likely been a relatively stable region of the Pacific coast of Hokkaido during the Holocene, because the trend of RSL curve from the plain is similar to that from a relatively stable area on the Pacific coast of northeastern Honshu. Fujimoto (1990) presented the RSL curve from the valley-bottom plains around Matsushima Bay. It is notable that the highest sea level (1.0-1.5 m) during the Holocene occurred c. 3500 yr BP (c. 3700-3800 cal. yr BP). The same is true of the RSL curve from the lower Tokachi River plain, although the elevation of RSL at that date is lower than that for Matsushima Bay.

The RSL curves from the Okhotsk coast (Maeda, 1984; Hirai, 1987; Sakaguchi & *alii*, 1985) also show that minor fluctuations occurred during the mid- to late Holocene. They indicate that the RSL stood below 0 (−0.5) m at c. 5000-4000 yr BP (c. 5700-4500 cal. yr BP) and rose to about 2 m at c. 3800-2800 yr BP (c. 4200-2900 cal. yr BP). The low stand at c. 5000-4000 yr BP is called the «Middle Jomon minor regression» (Ota & *alii*, 1990; Umitsu, 1991). The RSL curve from the Tokachi River plain shows a slight rise between c. 4300 and c. 3800 cal. yr BP. This minor rise likely corresponds to the rise that took place after the Middle Jomon minor regression.

Evolution of the Lower Tokachi River Plain

The detailed litho- and biostratigraphy and the chronological data demonstrate the following evolutionary processes on the lower Tokachi River plain (fig. 12). The Holocene sedimentary-fill sequence is typical for deltaic settings and is regarded to have formed in relation to Holocene sea-level changes. This implies that the evolution of the plain basically depended on the relationship between RSL change and sedimentation from the Tokachi River.

The diatom assemblages suggest that the lower sandy unit was deposited on a delta plain with occasional marine-brackish-water influences. The lithostratigraphy of the lower unit, which includes horizontally continuous muddy layers, also suggests that short-term transgressions

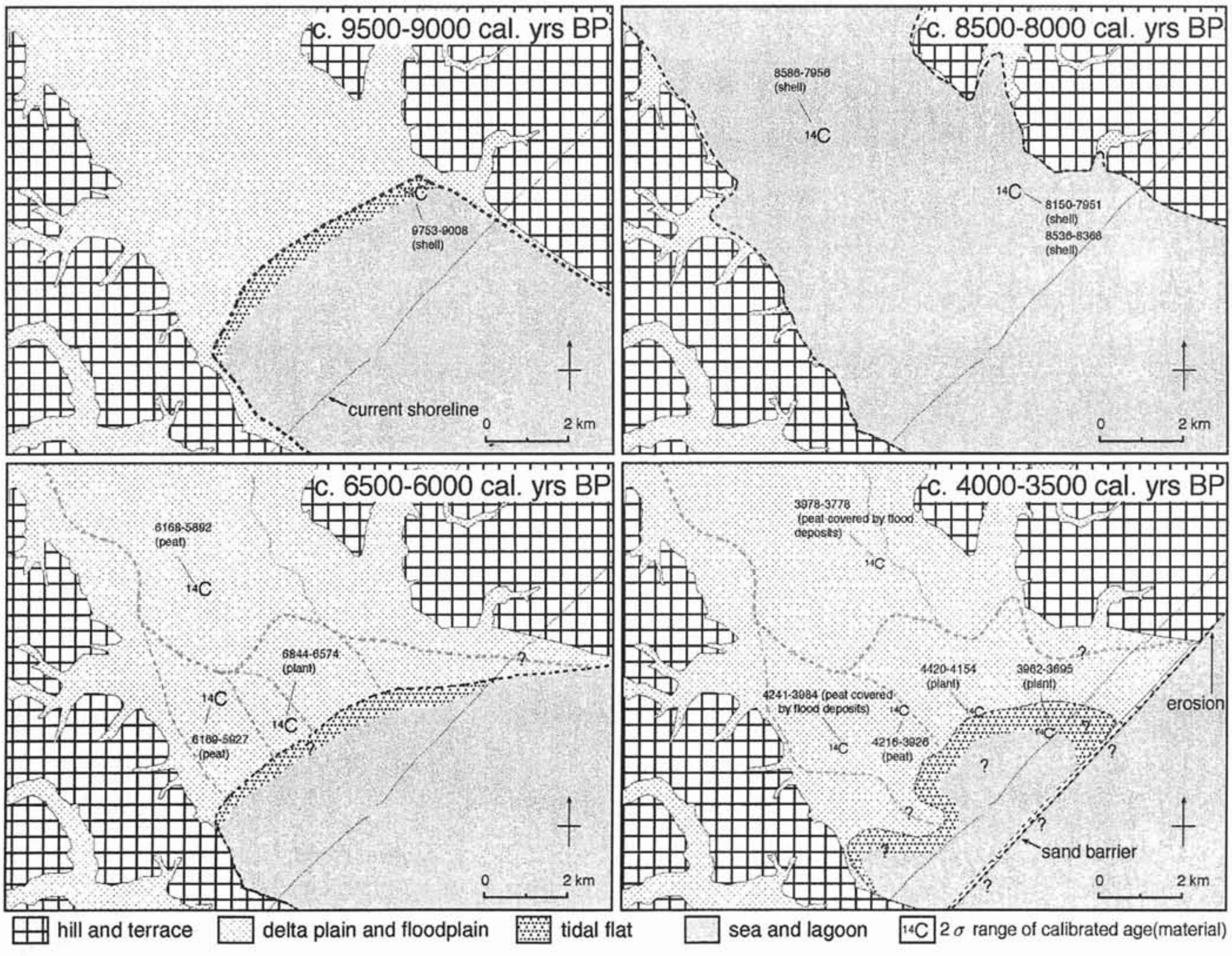


FIG. 12 - Schematic diagram of the paleogeography of the Lower Tokachi River plain during the Holocene.

occurred several times. There are few ^{14}C ages from the unit, but it was deposited in the early Holocene. The RSL elevation at c. 9300 cal. yr BP was about –18 m. The sedimentary environment at that time as inferred from the diatom assemblage of borehole UB indicates that tidal flats had extended to the vicinity of borehole UB, and a delta plain had probably formed behind the tidal flats. RSL rose from –18 m to –2 m between c. 9300 and c. 6700 cal. yr BP. This rapid sea-level rise was associated with evident transgression because the rising sea flooded the Tokachi River valley as well as another valley formed by an earlier distributary. By c. 8500-8000 cal. yr BP, the maximum transgression extended about 10 km inland from the current coastline, and the embayment had expanded across the lower plain. The delta prograded rapidly from c. 7500 cal. yr BP, when the RSL rise rate probably decreased, until c. 6500 cal. yr BP, and sediments from the river gradually filled the embayment. A freshwater marsh also covered the expanded delta plain at this time. The southwestern part of the embayment appears to have been filled more recently, perhaps by sedimentation from the Otsu River, because the main course of the lowermost Tokachi River bends to the east in the direction of the longshore current. By c. 4000 cal. yr BP, sand-barrier formation had already begun, because a reed root found in the marsh behind the current beach ridges was dated at 3962-3695 cal. yr BP. However, the sand barriers of this period cannot be accurately located because the rate of coastal erosion is unknown. Shoreline retreat continued because RSL reached almost to the present level as shown by cliff erosion around the lower Tokachi River plain. The distribution of gravel-sized sediments and the lithostratigraphy of the subsurface deposits indicate that the main channel of the Tokachi River in the delta plain appears to have stabilized during the late Holocene. The floodplain near the Otsu and Urahoro rivers likely began to aggrade after c. 4200 cal. yr BP, perhaps because of a slight rise in RSL at that time. The lower Tokachi River plain has been frequently inundated by tsunamis from the Pacific Ocean during the late Holocene.

CONCLUSIONS

The Holocene RSL curve from the lower Tokachi River plain is relatively unaffected by seismic crustal movements. A RSL curve from c. 9300 to c. 3800 cal. yr BP was reconstructed by using six sea-level index points and several radiocarbon dates located stratigraphically near to former sea levels. This curve shows a different trend compared with previously published RSL curves from the Okhotsk coast. The RSL middle Holocene (c. 6400-5900 cal. yr BP) highstand at 3-4 m, recognized by the previous studies, was not detected from the lower Tokachi River plain. The RSL of that period in the vicinity of the plain appears to have not risen above 0 m. The vertical displacement between the Okhotsk coast and the lower Tokachi River plain on the Pacific eoast is probably due to differences in Holocene crustal movements between the two regions. The RSL curve also shows that a slight (1 m) rise in sea level took place c. 5000 to c. 3800 cal. yr BP, and the RSL at c. 3800 cal. yr BP reached almost 0 m. However, the remarkable fluctuations during the last 3000 years, reconstructed from an estuary in eastern Hokkaido that was probably influenced by seismic crustal movements, were not found in the mid-Holocene RSL curve from the lower Tokachi River plain. The general trend of the RSL curve from the plain is similar to that of the RSL curve from a tectonically stable area of northeastern Honshu. These findings suggest that not only are seismic crustal movements not apparent in the lower Tokachi River plain, but also that the Holocene was a relatively stable period with respect to long-term crustal movements.

In general, the evolution of the plain depended on the relationship between RSL change and the sedimentation of the Tokachi River. Between c. 9300 and c. 7500 cal. yr BP, transgression occurred because the rate of sea-level rise exceeded the sedimentation rate of the river. On the other hand, between c. 7500 and c. 6500 cal. yr BP the delta advanced rapidly, probably because the rate of RSL rise had decreased. Moreover, during the late Holocene, the formation of sand barriers, the retreat of the shoreline, and the aggradation of the floodplain were caused by the regional coastal and fluvial processes in addition to RSL changes. Sand sheets found in peat deposits in the coastal zone also suggest the occurrence of large tsunamis.

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