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Beach Ridge Ranges and the Holocene Sea-level Fluctuations on Alluvial Coastal Plains, Northeast Japan

Hide-aki Matsumoto*

1 Introduction

On the alluvial coastal plains, facing the open sea, beach ridge ranges are recognized in general along the present coastline. Beach ridge ranges seem to be formed according to the Holocene shoreline progradation. Then, beach ridge ranges are useful to indicate the locations of past shoreline. To elucidate the formative factors and periods of beach ridge ranges are important to reconstruct the proceeding process of beach ridge type coastal plains.

The previous studies in Japan, such as Nakano (1956), Mii (1966), Moriwaki (1982) and others, deduced the formative factors and periods of beach ridge ranges and proposed some correlations between beach ridge ranges and Holocene sea-level fluctuations. However, the exact sea-levels and shoreline locations in relation to beach ridge ranges were not confirmed enough. The relationship between beach ridge ranges and Holocene sea-level change was not clarified in detail.

In this paper, the formative factors of beach ridge ranges were clarified by continuous tracing of shoreline change during the last 6,000 years, applying the grain size analysis. The formative periods of beach ridge ranges were estimated on the basis of radiocarbon age determination on various materials.

In general, beach ridge ranges are recognized as sandy ridges on alluvial plains. They have various curvatures and different dissective sculptures. In many cases beach ridges are divided into three ranges depending on the morphological characteristics. Sand body which constructs beach ridge ranges is marine and aeolian in origin. Aeolian sand overlies marine sand and the thickness of aeolian sand is about 2 to 5 m and occasionally exceeds 10 m. Longitudinal swales are recognized between and along beach ridge ranges. Peat and peaty clay materials are accumulated on the swales about 1 to 4 m in thickness.

In Northeast Japan, alluvial plains in large and small scales are distributed at each embayment. Several beach ridge ranges are recognized clearly on Sendai coastal plain, Ishinomaki coastal plain, Akita (south of Hachiro-gata) coastal plain, Tanabu

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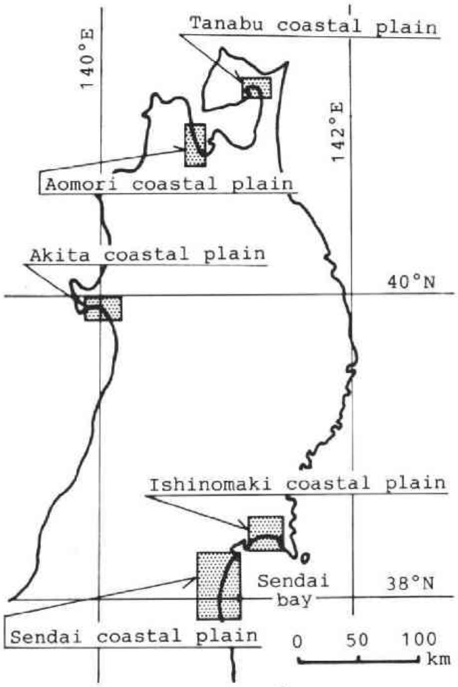


Fig. 1 Index map of study area.

coastal plain and Aomori coastal plain (Fig. 1). These plains are relatively larger ones in scale in Japan.

2 Beach ridge ranges in Sendai coastal plain

2.1. Physiography

Sendai coastal plain faces the Sendai Bay and is about 50 km long from north to south, 10 to 15 km wide from east to west. The plain is surrounded by Hilly areas, 100 to 200 m in altitude. Most of the plain is below 5 m in altitude and inland part stands 10 to 15 m. The Nanakita, Natori and Abukuma rivers flow on the plain. The channel lengths of these rivers are 45 km, 100 km[1] and 239 km and their drainage areas are 208 km^2, 939 km^2 and 5,400 km^2.

Beneath this plain, about 60 m thick alluvium lies and it is divided into eight facies (see Fig. 2) by Matsumoto (1981a).

Basal gravel (BG) : BG consists of fluvial sand and gravel. Gravels in BG are 5 to 10 cm in diameter and occasionally above 20 cm. Depositional age of this layer is estimated before 15,800 yr B.P.

1) This includes a channel length of the largest branch of this river that is the Hirose River.

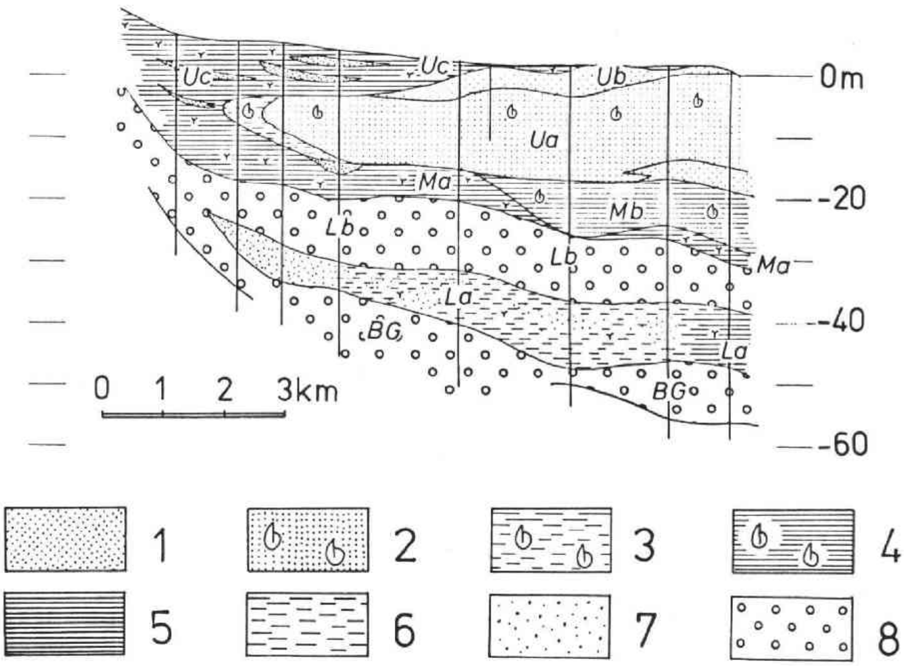


Fig. 2 An alluvial sequence in Sendai coastal plain.
This figure is the cross section along the Nanakita River which flows northern part of this plain (after Matsumoto 1981b).
1: aeolian sand 2: marine sand 3: marine silt 4: marine clay 5: fluvial clay 6: fluvial silt 7: fluvial sand 8: sand and gravel.

Lower terrestrial silt and clay (La): La was deposited under the fluvial environment around 15,800 yr B.P. in accordance with the postgracial sea-level rise.

Lower sand and gravel (Lb): Lb is a fan deposit during 15,800 yr B.P.~9,280 yr B.P. Gravels in Lb are 1 to 3 cm in diameter.

Middle terrestrial silt and clay (Ma): Ma was deposited about 9,280 yr B.P. as swampy deposit including a lot of plant debris.

Middle marine silt and clay (Mb): Mb is a back barrier deposit and includes shallow marine and brackish shells.

Upper marine sand (Ua): Ua includes shells and abraded shell-fragments and is a shoreface to shallow marine deposit. The lower part of Ua was deposited in the transgressional stage and the upper part was deposited in the regressional stage. Ma, Mb and the lower part of Ua formed a barrier complex in the transgressional stage.

Upper terrestrial sand (Ub): Ub is well sorted and includes no shell. It is aeolian in origin.

Uppermost terrestrial silt and clay (Uc): Uc is a back marsh deposit and

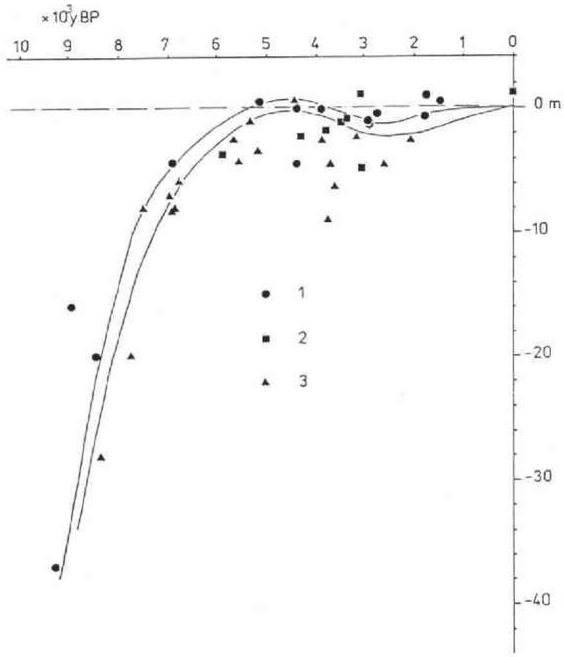


Fig. 3 Sea-level change during the Holocene around Sendai coastal plain.
1 : peat sample 2 : wood sample 3 : shell sample.
Sea-level change was estimated between these two lines.

occasionally includes fluvial sands. This layer overlies directly on Ma at the inner part.

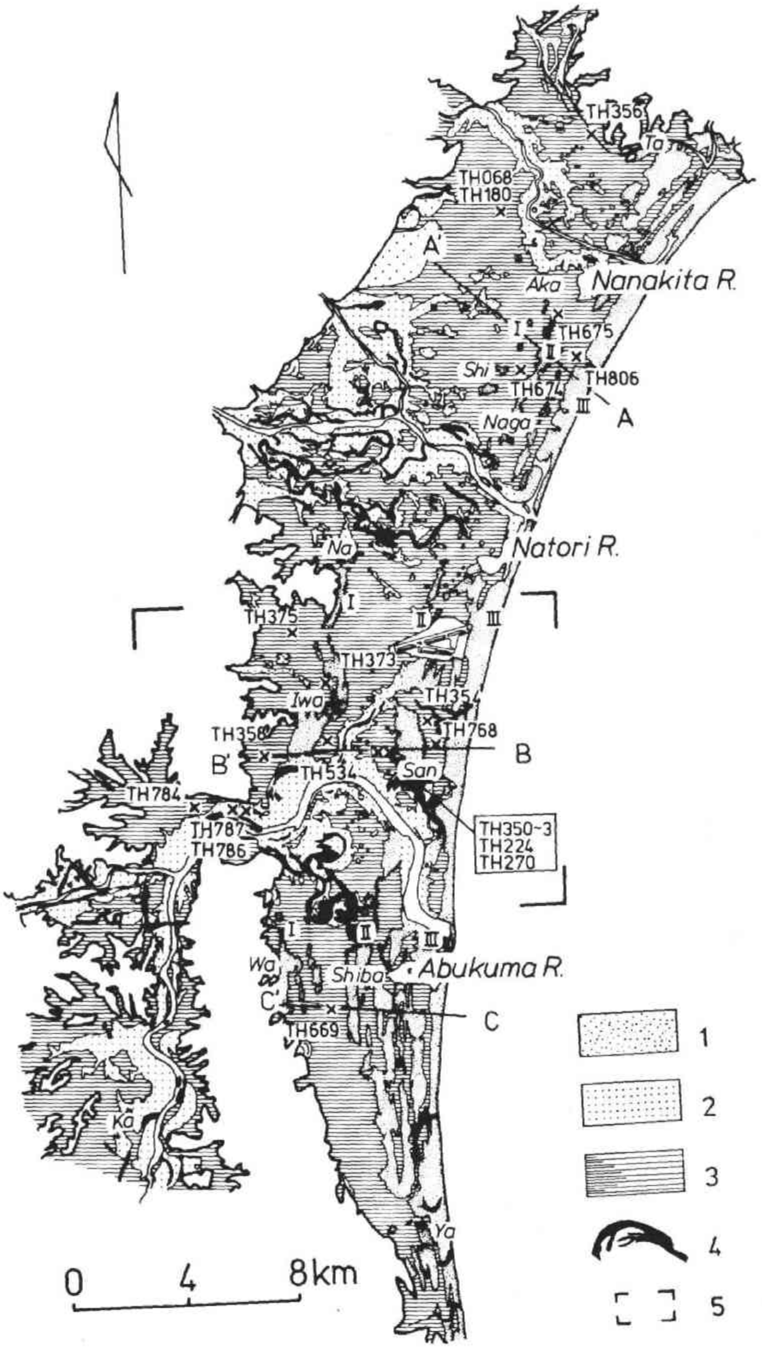
The Holocene sea-level change on this plain is clarified as follows (see Fig. 3, after Matsumoto 1981a).

Stage 1 : From ca. 10,000 yr B.P. to ca. 8,000 yr B.P. The sea-level rose rapidly from −40 m to −10 m.

Stage 2 : From ca. 8,000 yr B.P. to ca. 5,000 yr B.P. The sea-level rose slowly and reached nearly the present level about 5,000 yr B.P.

Stage 3 : Since 5,000 yr B.P. up to the present. The sea-level has been rather stable with slight fluctuations during this period.

Fig. 4 Distribution of micro-landforms on Sendai coastal plain.
1 : beach ridge range 2 : natural levee 3 : back marsh 4 : abandoned channel
5 : the area described in Fig. 12-a.
x : sampling site of C-14 sample.
Ta : Tagajo Aka : Akanuma Shi : Shimoiida Naga : Nagayashiki Shiba : Shibamach Ka : Kakuda Ya : Yamashita.
I : BR-I II : BR-II III : BR-III.


TH356
Ta
TH068
TH180
A'
Aka
Nanakita R.
TH675
TH806
Shi
TH674
A
Naga
Natori R.
Na
TH375
TH373
TH354
Iwa
TH356
TH768
B'
B
TH534
San
TH784
TH787
TH786
TH350-3
TH224
TH270
Wa
Shiba
Abukuma R.
C'
C
TH669
Ka
Ya
0 4 8km
1
2
3
4
5

Based on the alluvial sequence and the sea-level change, the change of shoreline was explained. It was located about 20 km inland from the present shoreline at about 7,800 yr B.P., when the sea-level stood at about -10 m. Then, the shoreline began to proceed seaward because the rate of sea-level rise became slower.

2.2. Distribution of beach ridge ranges

There are natural levees and abandoned channels along and near river channels (Fig. 4). Several beach ridge ranges run along the coastline, and they are in three rows above the plain surface. Beach ridge range I (BR-I) is the innermost one located along the foot of hilly land, it is 4 to 6 km far from the present shoreline. Beach ridge range II (BR-II) lies between BR-I and beach ridge range III (BR-III). BR-III runs along the present coastline and it divides into two or three branches to the north of the Nanakita and to the south of the Abukuma.

Each range is not continued near the river channels by fluvial actions. The author divides this plain into three areas conveniently. The northern part is the area north from the Natori river channel. The central part is the area between the Natori and the Abukuma. The southern part is the area south from the Abukuma.

The altitudes of beach ridge ranges are 3.5 m (BR-I), 2.0 m (BR-II) and 3.0 m (BR-III), at the central part, BR-I is at some parts buried by swale deposits. The interval is about 3 km between BR-I and BR-II and about 1 km between BR-II and BR-III.

2.3. Grain size analysis of marine and non-marine sand

The differences of grain size distribution of sandy deposits on river bed, shallow marine, swash zone, sand dune and others are explained by many previous articles (Friedman 1961 and 1967 ; Uesugi 1971 and 1972 ; Matsumoto 1977 *etc*).

The author examined the difference of the grain size frequency distribution between marine and non-marine sand at the present coastal area to decide the boundary between marine and non-marine (aeolian) sand and to reveal the past shoreline change which is recorded in the regressional sand layer.

1) Sampling and analysis

Along the coastline nineteen sampling lines were set at an interval of about 2 km (Fig. 5). Three types of geomorphological situation were selected for sampling on each sampling line. They are sand dune, back shore and swash zone (Fig. 6). Three or four sand samples were collected from each geomorphological situation. Sands were picked up at 10 to 20 cm depth in order to exclude the traction load which was moved on the surface by wave and wind. Then, 62 dune sands, 61 back shore sands and 84 swash zone sands were collected.

Moreover, 48 shallow marine sands were sampled in total from the sea floor at the

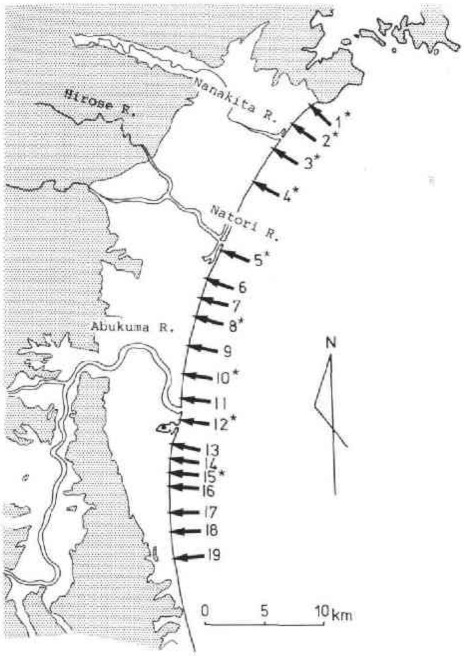


Fig. 5 Sampling lines of sand deposit (Sendai coastal plain).
Dune, back shore and swash zone sands were collected from each sampling lines.
Shallow marine sands were collected from (*) marked lines.

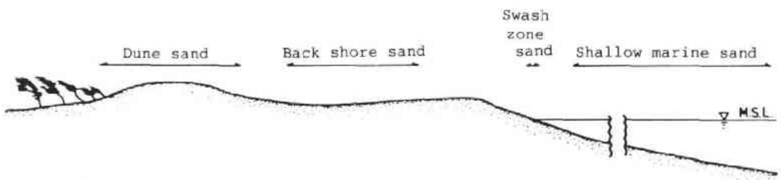


Fig. 6 Thematic profile of coastal area and sampling situations.

depth of 2 m, 4 m, 6 m, 8 m and 10 m along 9 sampling lines in Fig. 5. These samples were tested by the conventional sieving method, using 0.5 phi sieve interval, and grain sizes were determined. Coarser side of sieve was almost −3.5 phi and finer side 4.0 phi. No sample included coarser granules than −3.5 phi. In any sample, silt~clay materials which passed through 4.0 phi sieve were so small in quantity, less than 0.1% in weight, then they were neglected in this analysis.

Mean diameter ($\bar{\chi}$), standard deviation (σ) and skewness (α) were calculated depending on the following equations (after Friedman 1961 and 1967).

$$\bar{\chi}=\frac{1}{100}\sum fi \cdot mi$$

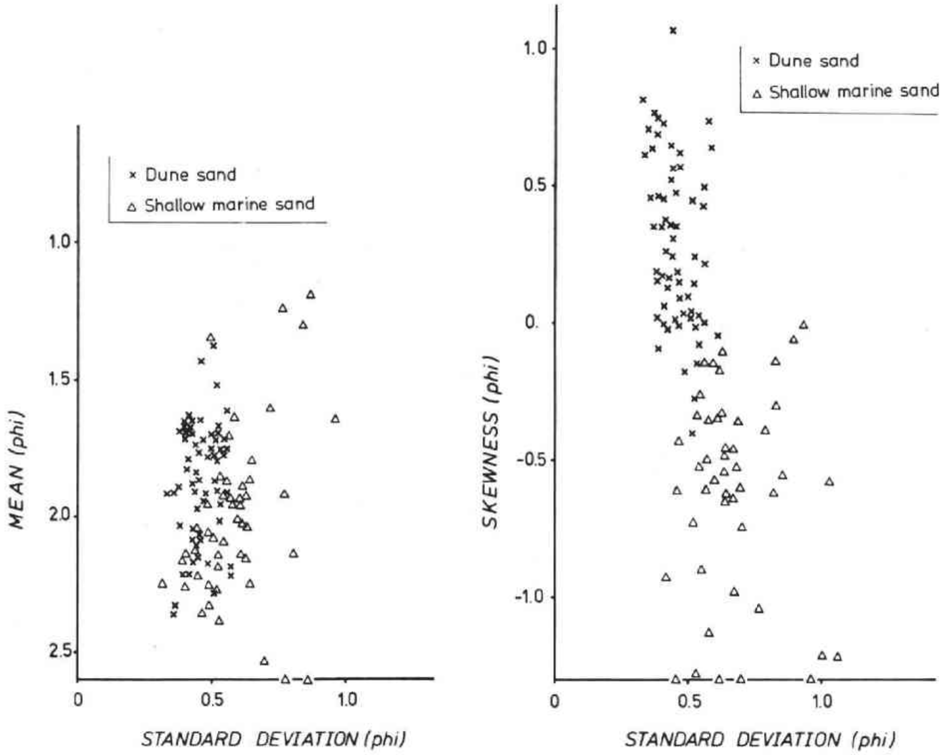


Fig. 7 Grain size characteristics of dune and shallow marine sands.
a : Standard deviation and mean diameter
b : Standard deviation and skewness.

$$\sigma=\left(\frac{1}{100}\sum \mathrm{fi}\cdot(\mathrm{mi}-\bar{\chi})^2\right)^{\frac{1}{2}}$$

$$\alpha=\frac{1}{100}\sum \mathrm{fi}\cdot(\mathrm{mi}-\bar{\chi})^3.$$

fi : frequency of the different grain size grades present in the sediment.
mi : midpoint of each grain size grade in phi values.

2) Result of the analysis

Dune sand is deposited onshore and shallow marine sand is deposited offshore. These two are deposited under contrastic geomorphological environment. At first, the author attempted to make clear the difference of grain size characteristics between these two. Differentiation between dune and shallow marine sand is shown in Fig. 7-a and b. Mean diameter of dune sand ranges from 1.5 to 2.4 phi and standard

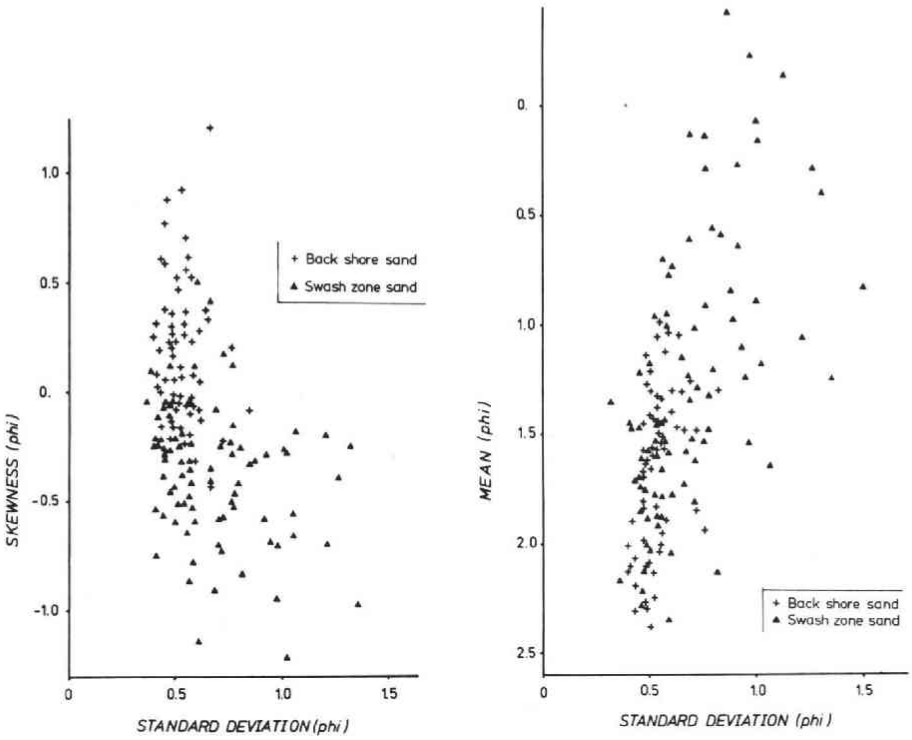


Fig. 8 Grain size characteristics of back shore and swash zone sands.
a : Standard deviation and mean diameter
b : Standard deviation and skewness.

deviation from 0.35 to 0.6. Mean diameter of shallow marine sand ranges from 1.2 to 2.4 phi and the standard deviation from 0.3 to 1.0. Most of dune sand show larger value than −0.1 in skewness, while shallow marine sand shows negative skewness. These two kinds of sand are clearly separated by the value of skewness.

Next, other two geomorphological situations, back shore and swash zone, occupy a considerable proportion of coastal area. It is necessary to confirm the grain size characteristics of these sediments in order to make a complete restoring of the past shoreline level. The grain size characteristics of back shore and swash zone sand are shown in Fig. 8-a and b. Mean diameter of back shore sand ranges from 1.0 to 2.4 phi, standard deviation from 0.35 to 0.7 and skewness from −0.25 to +1.0. Mean diameter of swash zone sand ranges from −0.4 to +2.4 phi, standard deviation from 0.35 to 1.5 and skewness is less than +0.1. These two sands are also clearly separated by skewness. It seems that back shore sand has a quite similar grain size characteristics to that of dune sand and swash zone sand is similar to shallow marine sand. Thus,

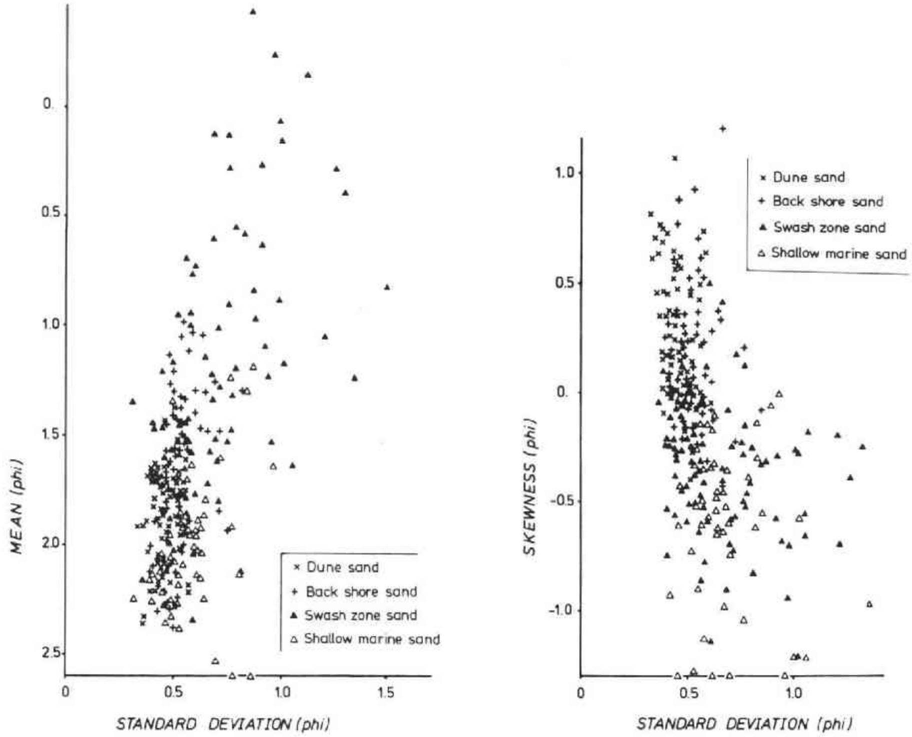


Fig. 9 Grain size characteristics of marine and non-marine (aeolian) sands.
a : Standard deviation and mean diameter
b : Standard deviation and skewness.

dune and back shore sands are considered the same category in grain size characteristics and shallow marine and swash zone sands are considered the same. The author regards the former two kinds of sands as non-marine (aeolian) and the latter two as marine.

Fig. 9-a and b show the difference of grain size distribution between marine and non-marine (aeolian) sands. They are separated mainly by the value of skewness. The distinction of marine and non-marine (aeolian) sands in Sendai coastal plain is based on the following three points.

(1) Sand deposit coarser than 1.0 phi ($\bar{\chi}<1.0$ phi) in mean diameter is marine.

(2) Sand deposit larger than 0.7 in standard deviation is marine.

(3) Sand deposit less than 0.1 in skewness is marine and that larger than -0.25 in skewness is non-marine (aeolian).

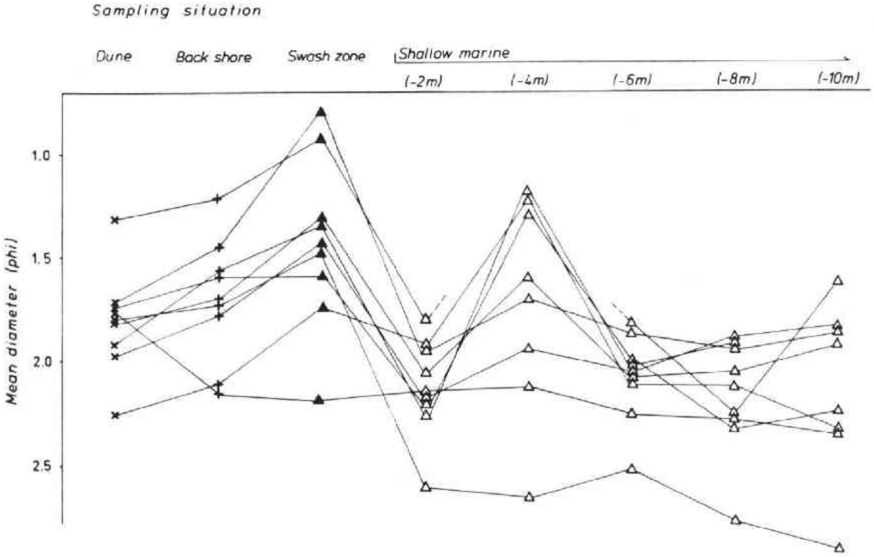


Fig. 10 Change in mean diameter along each sampling line. Sampling lines are indicated as (*) in Fig. 5.

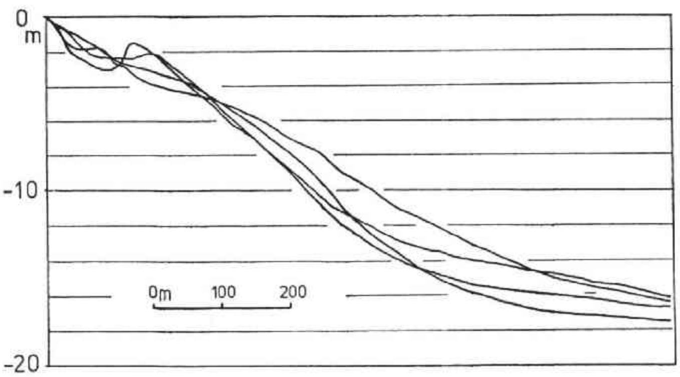


Fig. 11 Some offshore profiles in Sendai coastal area.

The third, the examination of grain size (mean diameter) variation along each sampling line is shown in Fig. 10. It seems to depend largely on geomorphic situations. Mean diameter of sand from the depth of 4 m varies greatly at the landward part compared to that of the offshore part. Two distinct peaks are observed in each sampling line, major peak at swash zone and minor peak at 4 m in depth except a few profiles. On the other hand, typical submarine profiles are described in Fig. 11.

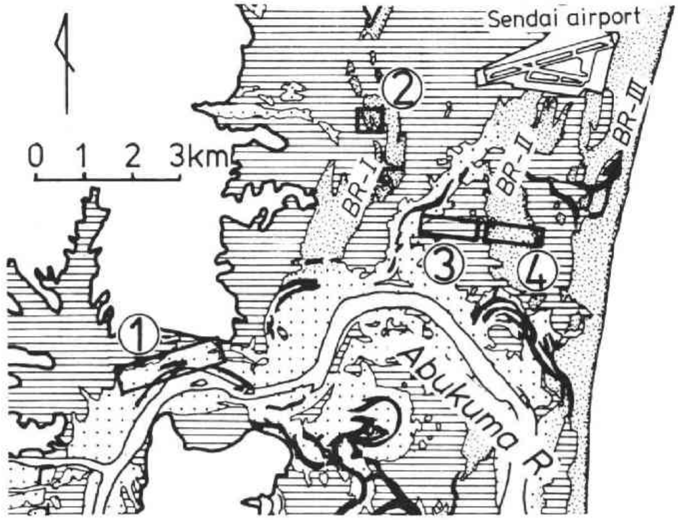


Fig. 12-a Locality of alluvial sequences in Fig. 12-b, c, d and e.

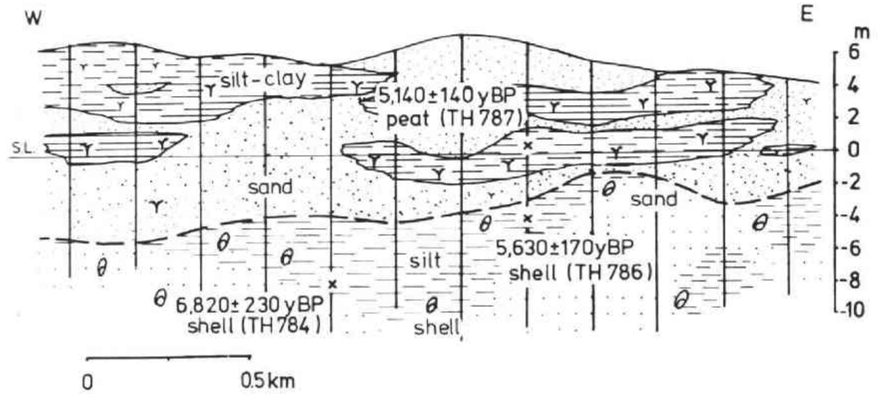


Fig. 12-b Alluvial sequence of site ①
Boundary between marine and terrestrial deposits shown as broken-line.

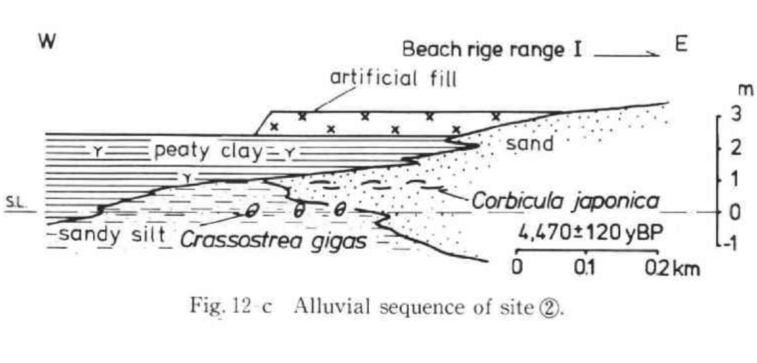


Fig. 12-c Alluvial sequence of site ②.

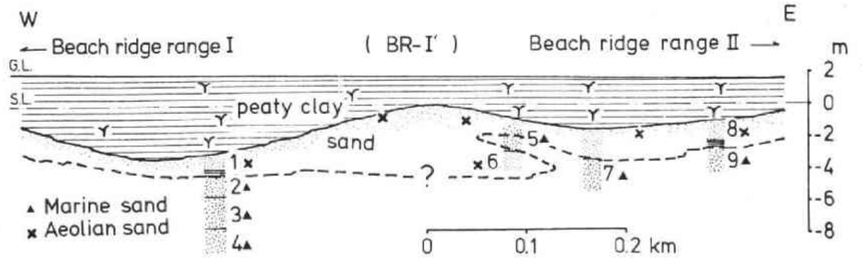


Fig. 12-d Alluvial sequence of site ③.
Broken-line indicates the shoreline change in this sequence.

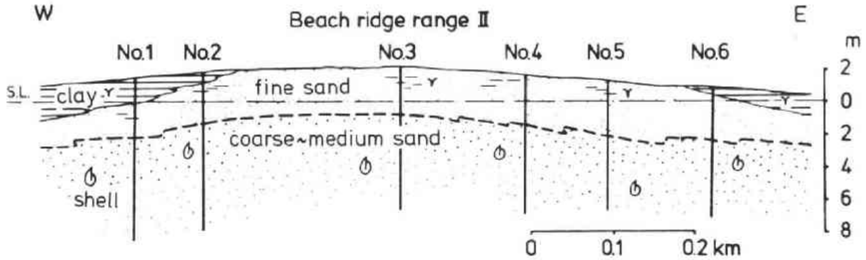


Fig. 12-e Alluvial sequence of site ④.
Broken-line indicates the shoreline change in this sequence.

Submarine slope from 0 to 15 m in depth has the average gradient about 25/1,000. A longitudinal submarine bar is located at 4 to 6 m depth in many cases. From this examination, a very important information is obtained to decide the past shoreline or sea-level, that swash zone sand indicates the largest grain size around a coastal area.

2.4. Shoreline change during the last 6,000 years

In the central part of Sendai coastal plain geological sections were obtained at four sites (Fig. 12-a).

Site ① is about 2.5 km landward from BR-I and is about 8 km distant from the present shoreline. The geological sequence observed by boring logs is shown in Fig. 12-b. Terrestrial sediment which consists of silty~clayly marsh deposit and sandy fluvial deposit is recognized at the upper part of this section about 6 to 10 m in thickness. Sand~sandy silt deposits which include marine shells and shell-fragments underlie the terrestrial sediment. The upper limit of the marine deposit is −5 m in altitude at the landward part of this section and −2 m at the seaward part. The past shoreline changed along the boundary surface (broken line in Fig. 12-b) between marine and terrestrial sediments in this section. Then, it seems that shoreline progressed seaward during the sea-level rose from −5 to −2 m. The age when the

Table 1 The results of grain size analysis on site ③ in Sendai coastal plain

unit No. \ statistical parameter (phi)	mean diameter	standard deviation	skewness
1	1.60	0.63	0.17
2	0.07	1.25	−0.18
3	2.40	0.66	−0.68
4	1.61	1.07	−0.78
5a	1.26	1.20	−0.11
5b	1.20	1.21	−0.47
6a	1.36	0.44	0.06
6b	1.37	0.45	−0.09
7a	1.16	0.92	−0.59
7b	1.93	0.81	−1.57
8a	1.87	0.62	−0.02
8b	1.81	0.58	0.04
9	1.12	0.78	−0.52

sea-level reached −3 m is estimated about 5,600 yr B.P. based on three C-14 data : 6,820±230 yr B.P. (TH-784), 5,630±170 yr B.P. (TH-786) and 5,140±140 yr B.P. (TH-787). The former two ages are obtained from shells in marine deposits and the latter one is from peat in terrestrial deposit. C-14 data are listed in Table 2.

Site ② is located on the landward slope of BR-I. The geological section is shown in Fig. 12-c. Ground surface is 3.1 m in altitude. *Corbicula japonica* was obtained at the altitude of 0.5～1.0 m and *Crassostrea gigas* was obtained at 0.0～0.5 m. The past sea-level at this site is determined at +1.0 m by the upper limit of *Corbicula japonica.* The age is estimated about 4,500 yr B.P. depending on the C-14 age of *Crassostrea gigas* (TH-373).

Site ③ is located between BR-I and BR-II (see Fig. 12-a) and the geological section is shown in Fig. 12-d. At the upper part of this section, peaty clay is found which is swampy deposit on the inter beach ridge ranges depression. At the lower part medium to coarse grained sand body is recognized which sometimes includes shells and round pebble gravels. The boundary surface between swampy deposit and sandy deposit is undulating. The sand body can be divided into 9 units depending on their grain size characteristics. The grain size analysis of sand samples collected from these 9 units is operated to restore the past shoreline level. Results of the analysis are shown in Table 1. Sand samples from unit No. 2, 3, 4, 5 and 7 are marine and those from the unit No. 1, 6, and 8 are non-marine (aeolian) according to the above distinction. The distinction is in accord with the observation *i.e.* the upper part of

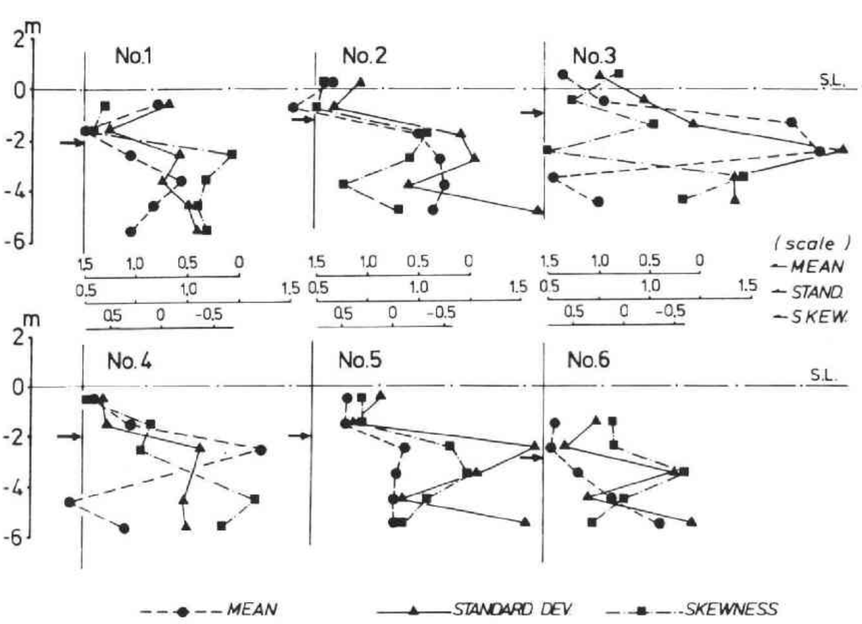


Fig. 13 The results of grain size analysis on 6 boring cores in Fig. 12-e. (→) indicates the past shoreline level which was estimated from grain size characteristics.

sand body is well sorted and includes no shell, and the lower part is poorly sorted and includes marine shells and round pebble gravels. The boundary surface between marine and non-marine (aeolian) sand is restored as a broken line in Fig. 12-d. The past shoreline is considered to have sifted seaward along this surface. Meanwhile, the sea-level dropped from the level +1.0 m shown at the site ② to about −4 m. Afterwards, it rose gradually, and the shoreline proceeded toward BR-II.

Around the center of this cross section a subsurface sand ridge is found. It is traced toward north and south. This subsurface sand ridge was formed by a temporal rise of sea-level. Such a sand ridge correlative to this subsurface sand ridge is recognized on other coastal plains of Akita and Ishinomaki. The author identifies this sand ridge as one of the beach ridge ranges and names beach ridge range I' (BR-I'), because of the location between BR-I and BR-II.

Site ④ is located across the BR-II (Fig. 12-a). Fig. 12-e shows the geological section estimated from 6 boring logs (No. 1~6). The upper part of sand body is fine grained and includes no shell against the lower part which consists of medium to coarse sand and includes shells and shell-fragments. On 6 boring cores grain size analysis was operated in an interval of 1 m to confirm the past shoreline level. The results are shown in Fig. 13. According to the above mentioned distinction, the upper

Table 2 C-14 data

Locality	Code No.	Altitude (m)	Sample	Depositional environment	C-14 age (yr B.P.)	References
Northern part of Sendai coastal plain	TH-068	−6.0	shell (*Macoma incongrua*)	shallow marine	6,775±185	Omoto and Ōuchi (1978)
	TH-080	−2.3	wood	back marsh	4,315±145	
	TH-674	−0.8	peat		2,510±120	
	TH-675	−3.6	shell (*Meretrix lusoria*)	shallow marine	2,970±120	
	TH-806	−0.3	peat	back marsh	730±130	
Central part of Sendai coastal plain	TH-224	−0.7	peat		1,790±100	
	TH-225	−0.7	peat		1,490± 90	
	TH-270	−9.0	shell (*Meretrix lusoria*)	shallow marine ∫ beach	3,750±110	
	TH-350	−5.0	wood		3,070±110	
	TH-351	−4.5	shell fragments		2,630±100	
	TH-352	−6.3	shell frag. (*Spisula sachalinensis*)		3,580±110	Matsumoto (1981)
	TH-353	−1.0	peat	back marsh	2,960±110	
	TH-354	−7.0	shell frag. (*Spisula sachalinensis*)	shallow marine	1,650± 90	
	TH-358	−0.2	peaty clay	back marsh	4,400±120	
	TH-373	+0.9	shell (*Corbicula japonica*)	shallow marine	4,470±120	
	TH-375	−0.2	peat	back marsh	3,900±120	
	TH-534	−4.3	shell frag. (*Crassostrea gigas*)	shallow marine	5,520±170	
	TH-768	−0.8	peat	back marsh	1,060±100	
	TH-784	−8.1	shell (*Crassostrea gigas*)	shallow marine	6,800±230	
	TH-786	−2.7	shell (*Crassostrea gigas*)		5,630±170	
	TH-787	+0.3	peat	back marsh	5,140±140	
Southern part of Sendai coastal plain	TH-699	0.0	peat		2,820±130	

Akita (south of Hachiro-gata) coastal plain	TH-442	—	peat	moor land	1,500±100	Hibino *et al* (1979)
	TH-638	+1.0	peat	back marsh	3,330±150	
	TH-639	+2.0	peat		2,320±120	
	TH-640	+2.0	peat		570±100	
	TH-671	+2.0	peat		780±100	
	TH-767	+5.5	peat	moor land	4,470±130	
Ishinomaki coastal plain	TH-558	−1.5	peat	back marsh	1,440±100	
	TH-559	−0.7	wood		2,960±120	
	TH-561	+0.8	peat		2,140±120	
	TH-562	−0.7	shell (*Crassostrea gigas*)	shallow marine	3,350±130	
	TH-563	−0.4	peat	back marsh	1,950±120	
	TH-684	−1.0	peat		2,190±130	
	TH-769	−0.5	wood	beach	1,520±100	
Tanabu coastal plain	TH-644	+1.0	peat	back marsh	3,050±120	
	TH-645	+0.8	peat		4,470±140	
	TH-687	+3.0	wood		2,180±130	
	TH-770	+2.0	peat		580±120	
Aomori coastal plain	TH-641	+1.7	peat		5,100±160	
	TH-642	+1.0	peat		2,570±120	

C-14 ages were determinated by C-14 measurement system of Tohoku University (Institute of Geography).

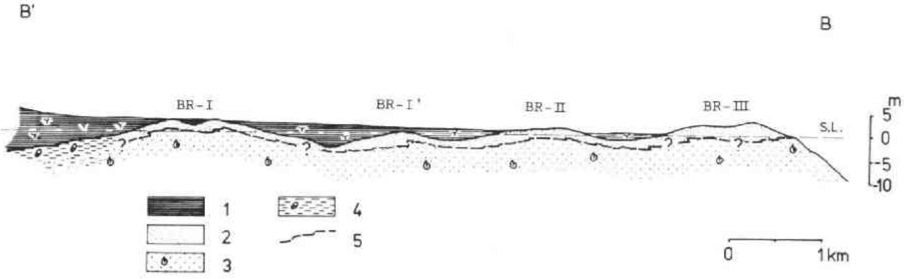


Fig. 14 Profile of beach ridge ranges and the past shoreline change.
1 : swale deposit 2 : non-marine (aeolian) sand 3 : marine sand 4 : marine silt 5 : shoreline change.

part is non-marine (aeolian) and the lower part is marine. Therefore, the past shoreline moved on the broken line in Fig. 12-e. The past sea-level reached the highest level −1.0 m just below BR-II, in this section. Thereafter the sea-level fell to −2 m beneath the swale between BR-II and BR-III.

2.5. Beach ridge ranges and the Holocene shoreline change

The shoreline change during the last 6,000 years is summarized in Fig. 14. About 5,600 yr B.P. the sea-level was recorded −3 m at about 1 km inner position from BR-I (Site ① in Fig. 12-a). It rose and reached +1.0 m which is recorded at the landward side of BR-I (Site ②). This was the first maximum sea-level. Then, the shoreline moved seaward and simultaneously dropped to −4 m beneath the swale between BR-I and BR-I'. Further, the sea-level rose and reached the second maximum level −1.5 m. Afterwards the shoreline proceeded and the sea-level fluctuated slightly to the third maximum level −1.0 m in altitude just below BR-II. Then, the shoreline proceeded to the present location and the sea-level dropped temporarily lower than −2.0 m.

Comparing the shoreline change with the undulational shape of regressional sand surface, the undulation seems to be formed by sea-level fluctuations. Higher sea-levels, *i.e.* higher shoreline levels, took place just below each beach ridge range, and lower sea-levels, *i.e.* lower shoreline levels recorded just below each inter ridge swale. The author concluded that the beach materials deposited under high sea-level circumstances remain as beach ridge ranges on the coastal plain. In Sendai coastal plain, four beach ridge ranges, including the subsurface one, *i.e.* BR-I, BR-I', BR-II and BR-III were formed corresponding to the sea-level fluctuation. Silt ~ clay materials such as flood loam and plant debris deposited on depressions, between beach ridge ranges formed inter ridge swales.

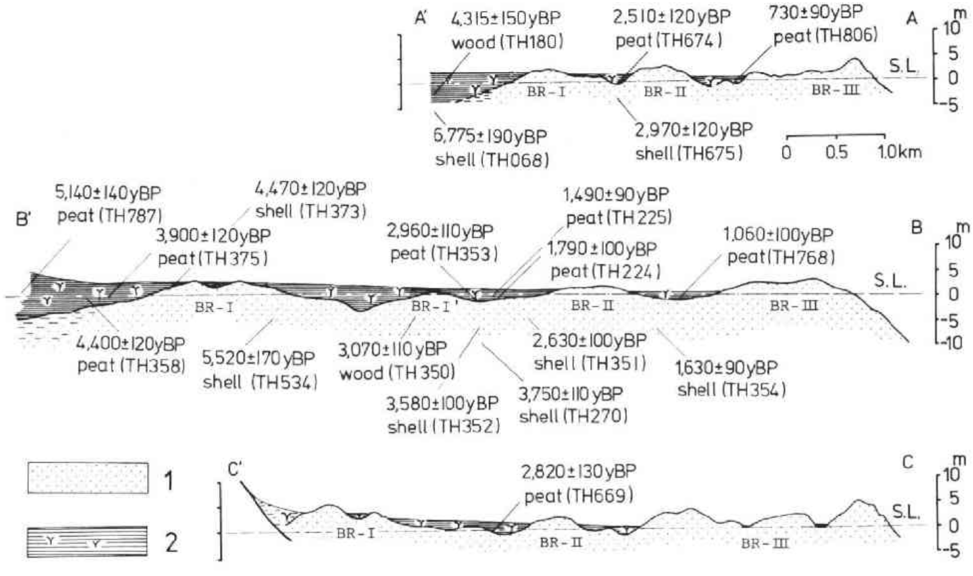


Fig. 15 Profiles of beach ridge ranges and the C-14 data along A-A', B-B' and C-C' in Fig. ④.
1 : sand 2 : silt～clay.

2.6. Formative periods of beach ridge ranges

Based on the formative factors of beach ridge ranges, the depositional age of swale bottom sediments would certainly suggest the formative period of the outer ranges.

Profiles of beach ridge ranges and the C-14 data in Sendai coastal plain are shown in Fig. 15. In the northern part of this plain, the regressional sand deposit indicates undulational surface (A-A' in Figs. 4 and 15). Peat and peaty clay materials accumulated on depressions between beach ridge ranges from inter ridge swales. Swale bottoms are −0.8 m in altitude between BR-I and BR-II, and −0.5 m between BR-II and BR-III. Back marsh extended widely behind BR-I. A wood sample collected from this back marsh deposit was measured 4,315±150 yr B.P. (TH-180)[2]. Therefore it is assumed that BR-I had been formed up to about 4,300 yr B.P. A peat sample collected from the bottom of the swale between BR-I and BR-II was measured 2,510±120 yr B.P. (TH-674) and shell-fragments from marine sand below this swale 2,970±120 yr B.R. (TH-675). Then, it is considered that BR-II began to be formed after about 2,500 yr B.P. A peat sample from the bottom of the swale between BR-II and

2) After Omoto and Ouchi (1978).

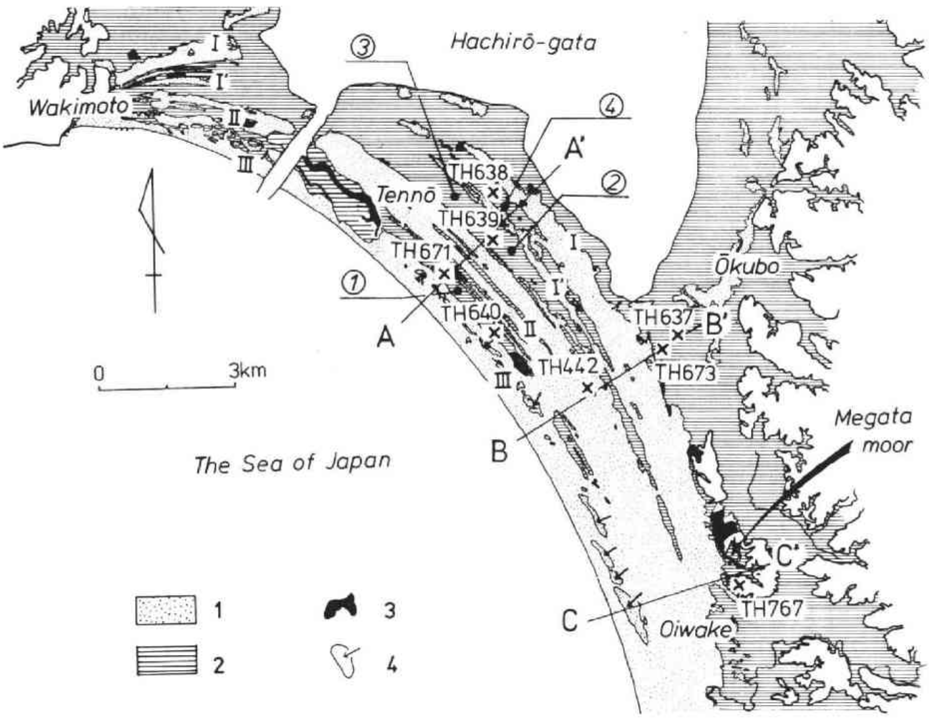


Fig. 16-a Distribution of beach ridge ranges on Akita (south of Hachiro-gata) coastal plain.
1 : beach ridge range 2 : back marsh 3 : moor land 4 : depression in sand dune.
①～④ : sampling sites of sand deposits under inter swale deposits.

BR-III was measured 730±130 yr B.P. (TH-806). Thus it is considered that a part of BR-III had been formed at about 730 yr B.P.

At the central part of this plain (along B-B′ area in Figs. 4 and 15), a swale bottom sediment behind BR-I was measured 4,400±120 yr B.P. (TH-358) and *Crassostrea gigas* sampled from landward slope of BR-I was 4,470±120 yr B.P. (TH-373). It is considered that BR-I had been formed before 4,500 yr B.P. Swale bottom deposits between BR-I and BR-II were measured from 2,960±110 yr B.P. (TH-353) to 1,790±100 yr B.P. (TH-224). And shell collected from shallow marine deposits at the seaward side of BR-II was measured 1,630±90 yr B.P. (TH-354). A peat sample from the swale bottom between BR-II and BR-III was measured 1,060±90 yr B.P. (TH-768). Then, it is considered that BR-II had been developed from 2,800 yr B.P. to 1,700 yr B.P. and BR-I′ began to be built nearly about 3,000 yr B.P. depending on TH-350, TH-351 and TH-353.

At the southern part of this plain (C-C′ in Figs. 4 and 15), a peat sample collected

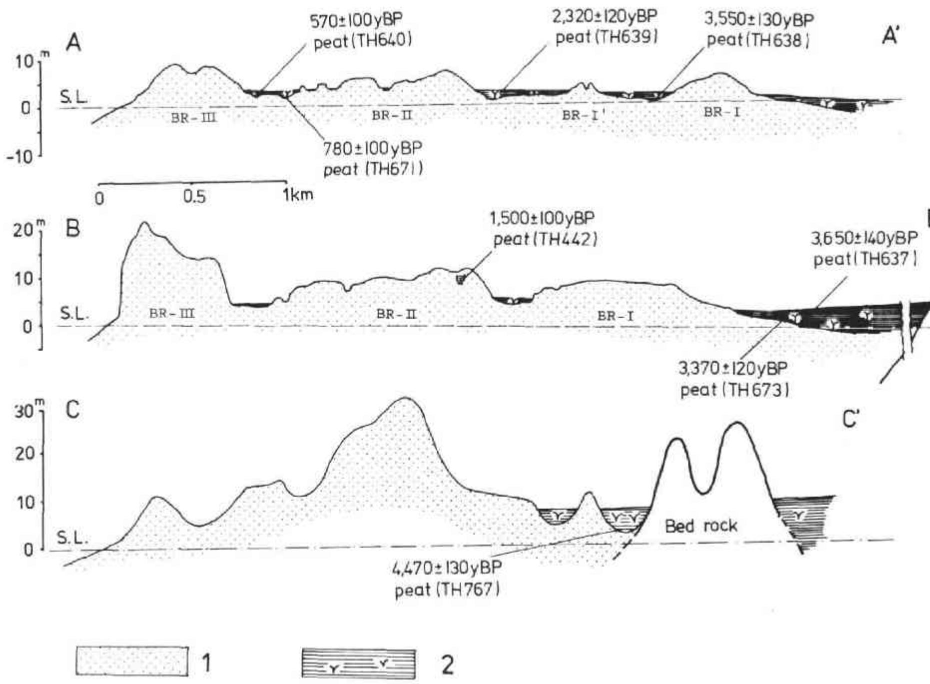


Fig. 16-b Profiles of beach ridge ranges and the C-14 data along A-A′, B-B′ and C-C′ in Fig. 16-a.
1 : sand 2 : silt-clay.

from the bottom of swale between BR-I and BR-II, was measured 2,820±130 yr B.P. (TH-669). BR-II is deduced to be formed before 2,800 yr B.P.

Formative periods which are estimated at three areas in Sendai coastal plain are summarized as follows. The formative period of BR-I is from 5,000 yr B.P. to 4,500 yr B.P. That of BR-II is from 2,800 yr B.P. to 1,700 yr B.P. That of BR-III is from 700 yr B.P. to the present. BR-I′ is considered to be formed from 3,000 yr B.P. to 3,100 yr B.P. depending on TH-350 *etc.*

3 Beach ridge ranges in other coastal plains

3.1. Akita (south of Hachiro-gata) coastal plain

Akita coastal plain was developed as a bay mouth barrier and isolated Hachiro-gata lagoon from the Sea of Japan (Fig. 16-a). Only a narrow inlet connects the lagoon to sea. This plain is about 20 km in length from northwest to southeast and about 4 km in width. The Hachiro-gata lagoon with the original depth of 3 to 4 m had been almost reclaimed artificially till 1966. About 50 m thick alluvium is recognized beneath this lagoonal area and a part of this plain is considered to have been a bay mouth barrier when the sea-level reached −5 m (Mii 1966).

Three major beach ridge ranges are distinguished, and the innermost range is subdivided into two. This morphological setting is similar to that of Sendai coastal plain mentioned above and Ishinomaki coastal plain mentioned later. The four beach ridge ranges recognized on this plain are denominated as BR-I, BR-I′, BR-II and BR-III as in Sendai coastal plain. These ranges are converged to the northwestern and southeastern ends of this plain. Along A-A′ in Fig. 16-a and b, these ranges are 6.5 m in altitude (BR-I), 4.5 m (BR-I′), 7.1 m (BR-II), and 10.0 m (BR-III) and along B-B′, 10.5 m (BR-I), 12.5 m (BR-II) and 22.0 m (BR-III). Inter ridge swales are 2.0 m in altitude (between BR-I and BR-I′), 3.0 m (between BR-I′ and BR-II), 3.5 m (between BR-II and BR-III). Aeolian sand is deposited in large amount on beach ridge ranges. They tend to be higher in elevation toward the Sea of Japan.

Profiles of beach ridge ranges and the C-14 data concerned are shown in Fig. 16-b. In the south of this plain, there are many swamps behind the converged ranges. Peaty materials are accumulated about 4.5 m thick, 10 m in altitude at Megata moor. A peat sample collected from the bottom of this moor was measured 4,470±130 yr B.P. (TH-767), and it indicates that the innermost range (BR-I) had been built till about 4,500 yr B.P. As swale bottom materials between BR-I and BR-I′ along A-A′ and B-B′ areas was 3,550±130 yr B.P. (TH-638), BR-I′ is considered to be developed since about 3,500 yr B.P. Swale deposits between BR-I′ and BR-II was aged 2,320±120 yr B.P. (TH-639) and peaty materials collected from a small moor on BR-II was 1,500±100 yr B.P. (TH-442)[3]. Then, BR-II is considered to be formed from 2,300 yr B.P. to 1,500 yr B.P. Depending on the ages of swale bottom deposits between BR-II and BR-III, 780±100 yr B.P. (TH-671) and 570±100 yr B.P. (TH-640), BR-III is considered to have been developed from about 800 yr B.P. and up to the present.

3.2. Ishinomaki coastal plain

Ishinomaki coastal plain faces the Sendai Bay and is 50 km long from north to south and 10 to 20 km wide from east to west. The Kitakami, Hazama, Eai, Jo and Naruse rivers flow on this plain. This plain is bounded to the west by hilly land about 200 to 300 m in height, and to the east by Kitakami Mountains. There are natural levees, abandoned channels and back marshes. Several beach ridge ranges are recognized along the coastal area (Fig. 17-a).

Depending on the interpretation of alluvium about 40 m thick beneath this plain, postglacial transgression continued till about 7,000 yr B.P., when the sea-level reached −3 m. Later, shoreline had proceeded seaward (Matsumoto 1981b).

Beach ridge ranges are divided into four ranges, BR-I, BR-I′, BR-II and BR-III.

3) After Hibino *et al.* (1979).

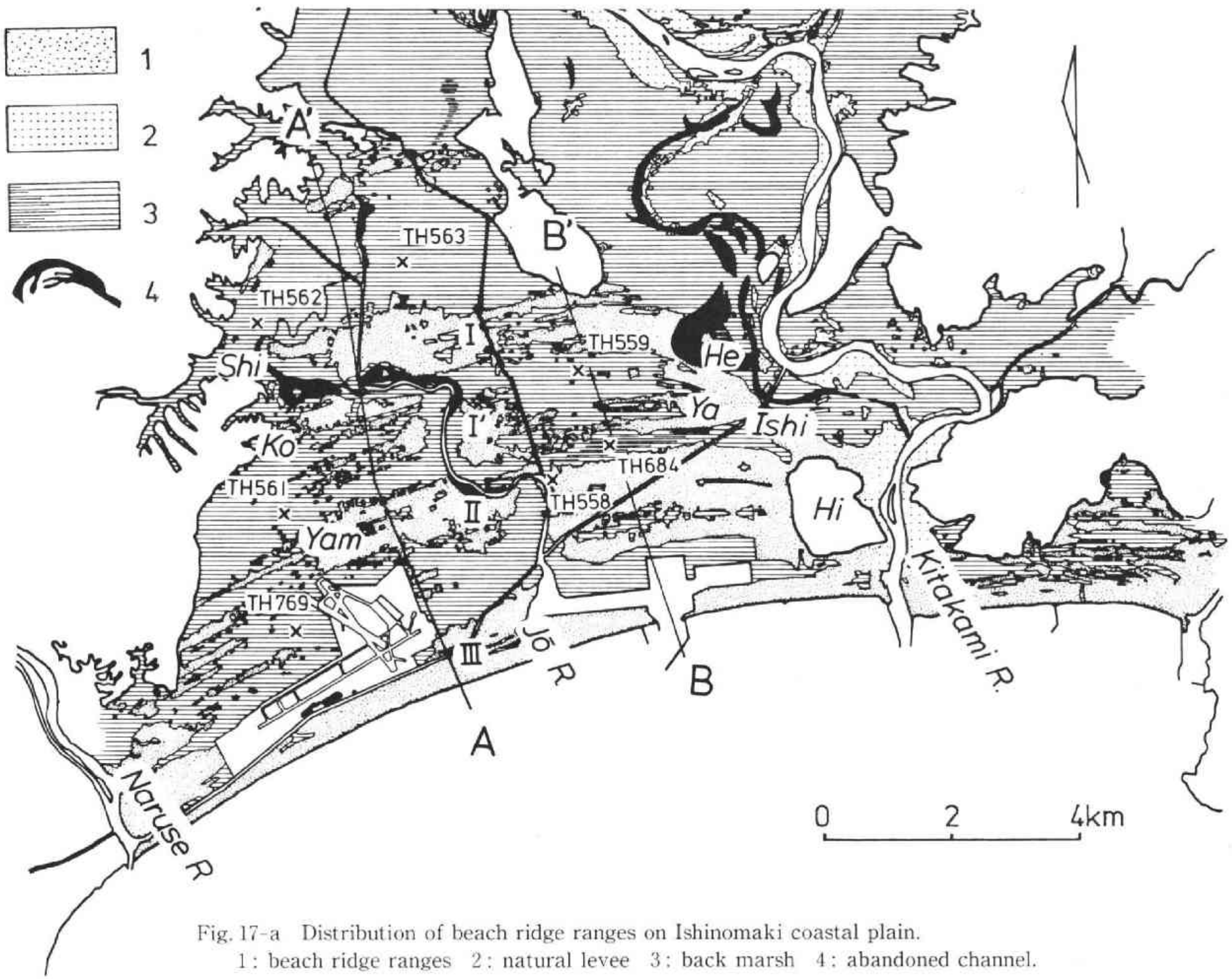


Fig. 17-a Distribution of beach ridge ranges on Ishinomaki coastal plain.
1 : beach ridge ranges 2 : natural levee 3 : back marsh 4 : abandoned channel.

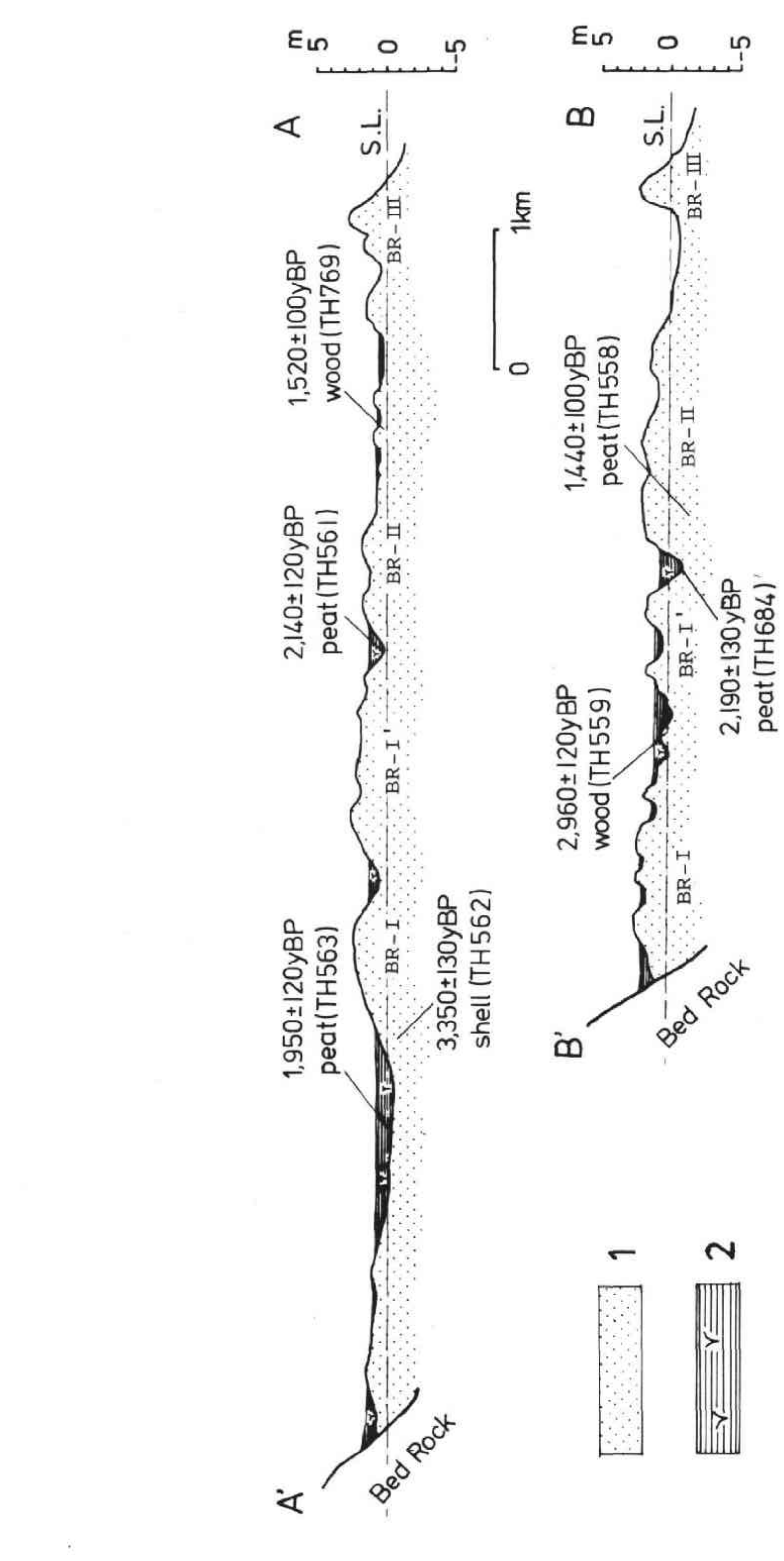


Fig. 17-b Profiles of beach ridge ranges and the C-14 data along A-A' and B-B' in Fig. 17-a.
1 : sand 2 : silt～clay

Innermost range (BR-I) is situated at about 5 km distant from the present shoreline (Fig. 17-a). BR-I′ elongated from Yamashita to Komatsu, looks like a branch of BR-I. This morphological setting is similar to that of Akita and Sendai coastal plain. At the western area of this pain BR-II is partially overlaid by swale deposits. Each beach ridge range is 2.5 m in altitude (BR-I), 2.8 m (BR-I′), 2.0 m (BR-II) and 3.0 m (BR-III) along A-A′ area in Fig. 17-a and b.

Profiles of beach ridge ranges and the C-14 data are shown in Fig. 17-b. Along A-A′, back marsh behind BR-I consists of peat and peaty clay deposits about 1 m thick. Bottom peat of this marsh was dated 1,950±120 yr B.P. (TH-563) and *Crassostrea gigas* collected from −0.7 m was dated 3,350±130 yr B.P. (TH-562). These indicate that the environment was already lagoonal landward of BR-I and a tidal inlet was located near Shioiri before 3,500 yr B.P. A part of BR-I had been formed before that time. Bottom sediments of inter-ridge swales are dated 2,960±120 yr B.P. (TH-559), 2,140±120 yr B.P. (TH-561) and 2,190±130 yr B.P. (TH-684). A wood sample collected from shore face deposit under the swale deposit located seaward side of BR-II was measured 1,520±100 yr B.P. (TH-769). Depending on these facts, it is considered that BR-I′ was formed nearly 3,000 yr B.P. and BR-II was developed from 2,200 yr B.P. to 1,500 yr B.P. The chronological datum which suggests the formative age of BR-III is not found yet from this plain.

3.3. Tanabu coastal plain

Tanabu coastal plain located to the north of Mutsu Bay is about 15 km from east to west, 7 km from north to south. There are three beach ridge ranges, BR-I, BR-II and BR-III, along the coastal zone with about 2 km width and Kanamagari moor is at the landward area about 4 km inland from the present shoreline (Fig. 18). Beach ridge ranges are 4 to 5 m in altitude and Kanamagari moor is about 3 m. BR-I, BR-II, BR-III are separated by narrow swales. However, in profile these three ranges are so closely located with each other that they seem like a single sand ridge. Peat deposit collected from the Kanamagari moor bottom was dated 4,470±140 yr B.P. (TH-645). Peat layer of this moor is underlaid by medium to fine marine sand which includes marine shells. In this area marine limit is recognized at +0.7 m. Sakamoto (1976) collected *Crassostrea gigas* and other shallow marine shells from the marine deposits. The environment changed from shallow marine to moor land till 4,500 yr B.P. in this area, when BR-I is considered to have been already existed. Swale bottom sediment sampled between BR-I and BR-II was dated 2,180±180 yr B.P. (TH-687) and that from the swale between BR-II and BR-III, was dated 580±120 yr B.P. (TH-770). BR-II was formed nearly 2,200 yr B.P. and BR-III has been developed from about 600 yr B.P. BR-I′ is not identified on this plain.

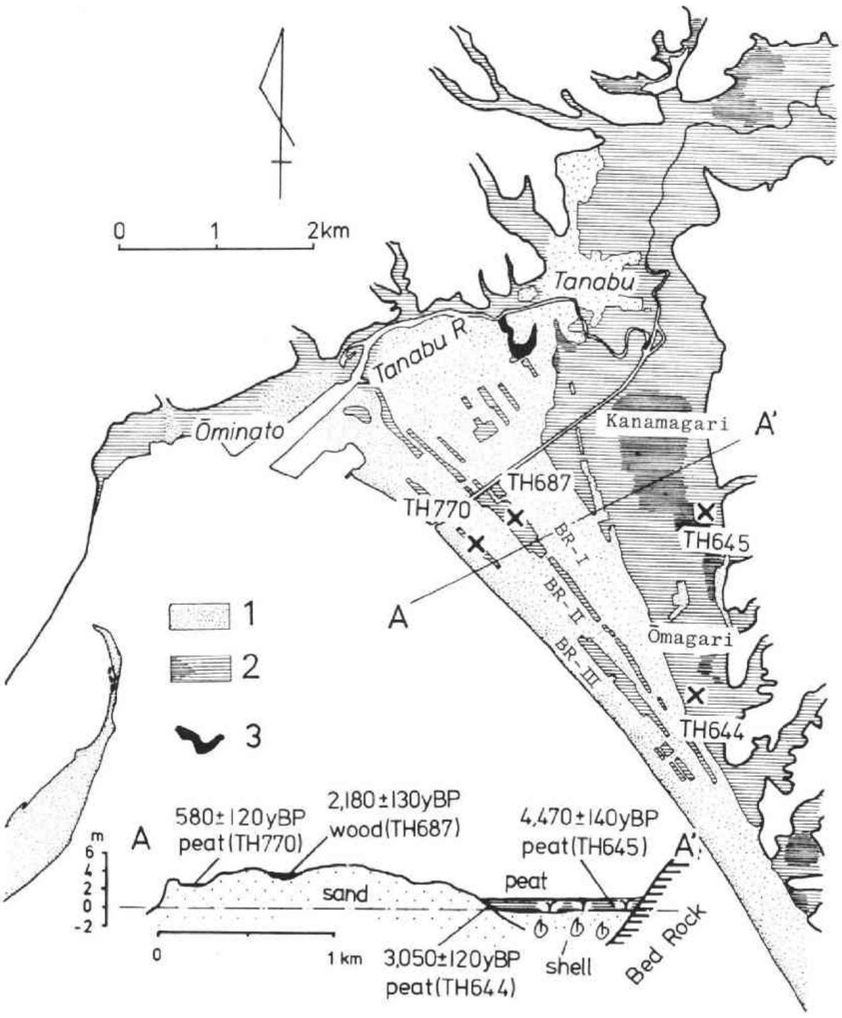


Fig. 18 Distribution and profiles of beach ridge ranges on Tanabu coastal plain. 1: beach ridge range and natural levee 2: back marsh (moor land) 3: abandoned channel.

3.4. Aomori coastal plain

Aomori coastal plain faces the Mutsu Bay and it is 2 to 3 km in average width and about 7 km in maximum width at the plain center. This coastal plain had the gradient $3\sim4/1{,}000$ along the Niida River area. Two beach ridge ranges are distinct at the western and eastern part but they are not clear at the center. The inner beach ridge range is about 1 km inside from the coastline and the outer narrow beach ridge range

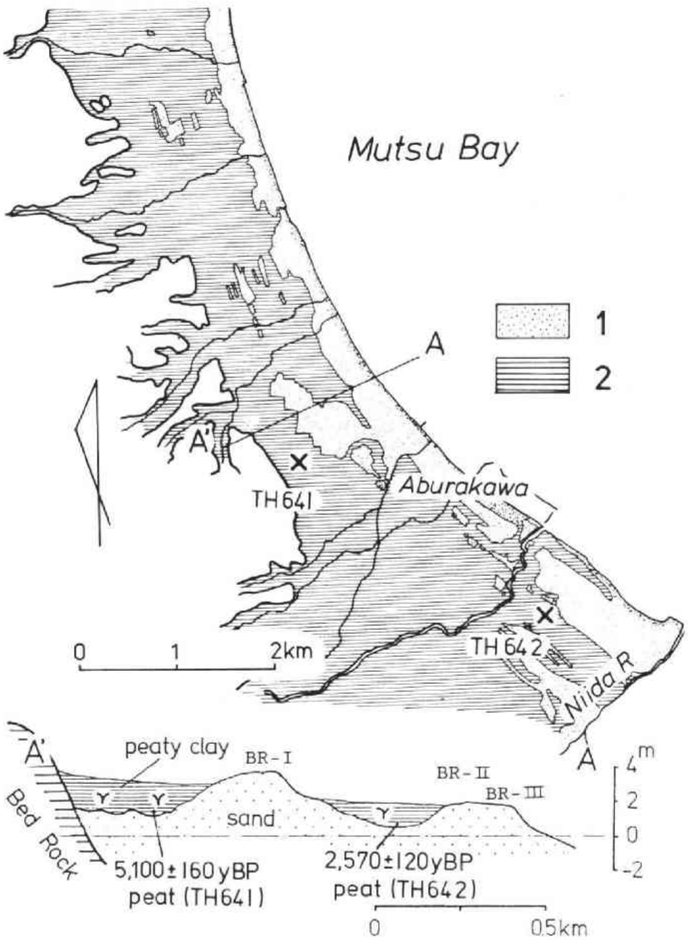


Fig. 19 Distribution and profiles of beach ridge ranges on western part of Aomori coastal plain.
1: beach ridge range 2: back marsh.

runs along the present shoreline. The former is 4.0 m in height and the latter is less than 2 m. Two C-14 data were obtained from the western part of this plain (Fig. 19). A peat sample collected from the bottom of swale behind the inner range was measured 5,100±160 yr B.P. (TH-641). A swale bottom peaty clay between these two ranges was measured 2,570±120 yr B.P. (TH-642). These data instruct that the inner range was developed from about 2,500 yr B.P. Then the inner range is correlated with the BR-I and the outer range with BR-II on other coastal plains as for the formative periods. BR-III is not seen on this plain. The reason is considered that BR-III was eroded out, or that it is included into BR-II. There is, however, no evidence to explain

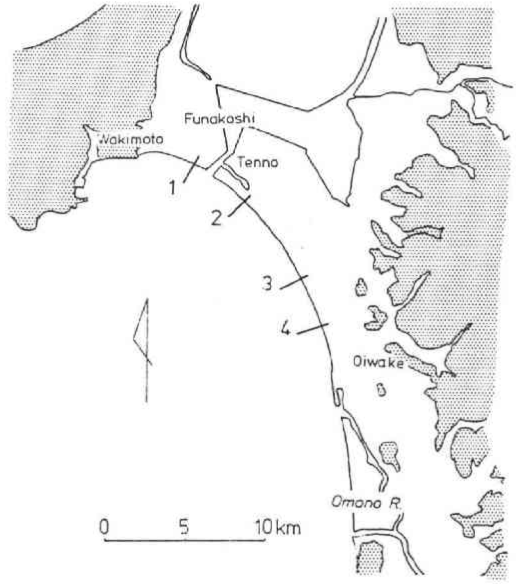


Fig. 20 Sampling lines in Akita (south of Hachiro-gata) coastal plain.

this situation.

4 Discussion

4.1. Beach ridge ranges and the Holocene sea-level fluctuations

The sea-level and shoreline change during the last 6,000 years was traced in Sendai coastal plain. It was concluded that beach ridge ranges were formed by sea-level fluctuations under the continuous shoreline proceeding condition. In other words, the beach materials deposited at a high level corresponding to each sea-level peak were recognized as beach ridge range on the coastal palin.

Mii (1966) investigated Akita (south of Hachiro-gata) coastal plain and suggested that beach ridge ranges were formed by intermittent shoreline progradation according to intermittent sea-level falls. He thought that the origin of beach ridge ranges were intermittent emergence of offshore submarine bars.

The author carried out the grain size analysis on sand materials deposited under the inter ridge swale deposits to resolve the disagreement between this study and Mii's conclusion. That is to say, if beach ridge ranges were originated from submarine bars, sand deposits under each inter ridge swale deposits should be shallow marine sands.

At first, the author attempted to clarify the difference of grain size characteristics between marine and non-marine (aeolian) sands at the present coastal area of this plain. Sampling lines are shown in Fig. 20. Marine sands are collected from swash zone and non-marine sands are collected from sand dune. Sample number of marine

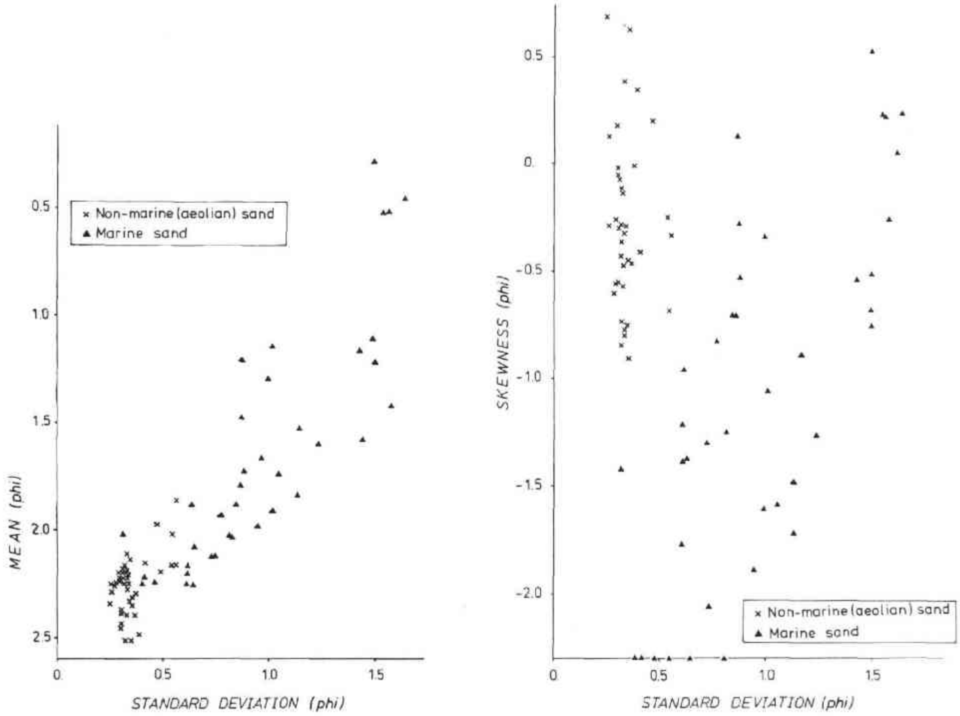


Fig. 21 Grain size characteristics of marine and non-marin (aeolian) sands.
a : Standard deviation and mean diameter
b : Standard deviation and skewness

sand is 38 and non-marine (aeolian) sand is 41. Fig. 21-a and b show the grain size characteristics of two kinds of sand. They are distinguishable by the correlation between skewness and standard deviation. Marine sands indicate larger value in standard deviation and less value in mean diameter than aeolian sands. These two kinds of sand are divided by standard deviation rather than by skewness on this coastal area[4].

Sandy deposit underlaid by swale deposit collected from pits ①, ②, ③ and ④ in Fig. 16-a. The results of analysis are shown in Table 3. Sands collected from four pits are non-marine (aeolian) depending on Fig. 21-a and b. Further, the fact that the beach ridge ranges stand higher toward the Sea of Japan is contradictory to the opinion that beach ridge ranges were formed by intermittent sea-level falls. Hence,

4) This indicates that the distinction of marine and non-marine (aeolian) sand should be based on the unique rule on each coastal area. This theme is discussed in detail (Matsumoto 1983).

Table 3 The results of grain size analysis on sand deposits under inter swale deposits

statistical parameter / sampling site	mean diameter	standard deviation	skewness
①	2.30	0.34	−0.54
②	2.17	0.34	−0.86
③	2.26	0.36	−0.51
④	2.14	0.37	−0.69

Sampling sites are shown in Fig. 16-a.

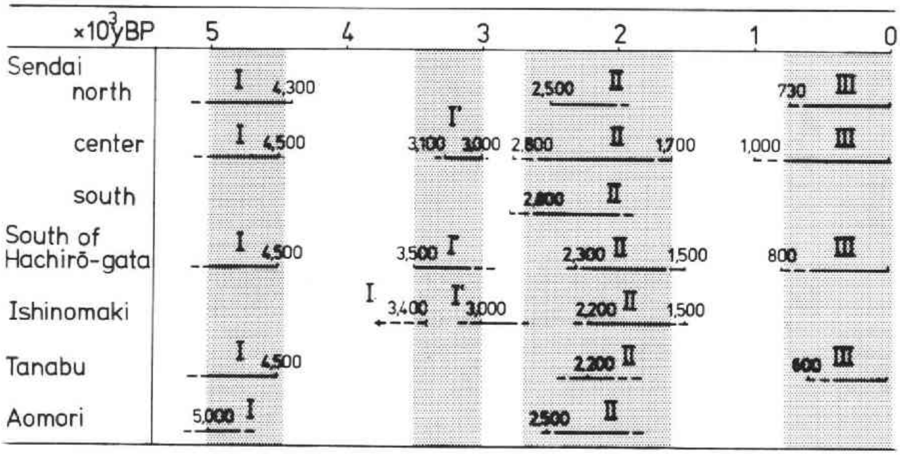


Fig. 22 Formative periods of beach ridge ranges estimated on five coastal plains in this study.

the author can not accept Mii (1966)'s conclusion.

4.2. Formative periods of beach ridge ranges

The simultaneity in formative periods of beach ridge ranges were confirmed on five different coastal plains in Northeast Japan. Each formative period was considered as follows, BR-I was formed between 5,000 yr B.P. and 4,500 yr B.P. BR-I′ was between 3,500 yr B.P. and 3,000 yr B.P. BR-II was between 2,800 yr B.P. and 1,700 yr B.P. and BR-III was formed from about 800 yr B.P. up to the present (Fig. 22). This similarity in age is in accord with the formative factors in this study.

Most of the former studies divided beach ridge ranges into three ranges. In this study, BR-I′ was newly recognized as one of the beach ridge ranges. This range is sometimes occurred as a branch of BR-I and sometimes occurred as a subsurface range. However, its formative period was about 1,500 years later than that of BR-I and former about 1,000 years than that of BR-II. Further, the sea-level rise which formed BR-I′ as the range significant for restoring the seaward proceeding process of beach ridge type coastal plains.

Four maximal stages in sea-level fluctuation estimated by the author are 5,000 yr B.P. (when the sea-level stood at +1.0 m), 3,100 yr B.P. (at −1.5 m), 1,800 yr B.P. (at −1.0 m) and the present time (at ±0 m). On the other hand, minimal stages in sea-level are 3,700 yr B.P. (at around −4.0 m), 2,500 yr B.P. (at −2.0 m) and about 1,000 yr B.P. (at lower than −2.0 m).

5 Summary

1. The vertical and horizontal shoreline change during the last 6,000 years was restored on Sendai coastal plain, utilizing the grain size analysis of sand samples. Sea-level flluctuations, with four maximal and three minimal stages were restored.

2. Beach materials deposited at high level corresponding to the maximal stage of sea-level fluctuation built beach ridge range on the coastal plain. Thus, the beach ridge ranges were built in connection with the sea-level fluctuations under the continuous seaward proceeding condition of shoreline.

3. BR-I′ was confirmed as a beach ridge range in addition to the three ranges commonly recognized in the former studies.

4. Maximal stages of sea-level, which constructed beach ridge ranges, reached +1.0 m (for BR-I), −1.5 m (for BR-I′), −1.0 m(for BR-II) and ±0 m (for BR-III) at the central part of Sendai coastal plain.

5. Formative periods of beach ridge ranges were estimated depending on the C-14 data of five coastal plains: Sendai, Akita (south of Hachiro-gata), Ishinomaki, Tanabu and Aomori coastal plain. Obvious correlation in formative periods were founded as follows (Fig. 22): BR-I between 5,000 yr B.P. and 4,500 yr B.P., BR-I′ between 3,500 yr B.P. and 3,000 yr B.P., BR-II from 2,800 yr B.P. to 1,700 yr B.P. and BR-III from about 800 yr B.P. to the present.

The author will mention another formative factor of beach ridge ranges, adding to the above mentioned factor, *i.e.* the volume change of supplied load to the coastal area. The periodical change of supplied load to the coastal area during the last 6,000 years is not investigated in this paper and remains as a future problem.

Acknowledgement

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