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Geomorphological Development of Coastal Ridges during the Holocene and Recent Beach Erosion:
Case Studies of the Coastal Lowlands along Suruga Bay and Amanohashidate along Miyazu Bay

Akiko Matsubara

I. Introduction

Considering the geomorphological development of coastal ridges, studies on barrier complexes worldwide have shown that the rise in sea level during the Holocene was a major factor affecting the development of coastal barriers. Generally, barriers developed and transgressed landward when the sea level was rapidly rising. In contrast, the barriers began to grow seaward when sedimentation rate exceeded the rate of sea level rise. Following this, beach ridges also began to develop in a seaward direction.

A common trend in the relative sea level change around Japan during the Holocene is that the sea rose above the present level as a result of hydroisostatic movements. During the Holocene transgression, the relative sea level generally reached its maximum (3 to 5 m higher than at present) around 7,000 cal BP. As such, the geomorphological evolution of the coastal lowlands was deeply influenced by these Holocene sea level changes.

Matsubara (1988, 2000, 2002, 2005, 2015) reconstructed the palaeoenvironmental changes in the coastal ridges developed in the coastal lowlands, on the basis of an analysis of fossil foraminiferal assemblages in bore-hole cores, and used these to describe the geomorphological development of the coastal ridges during the Holocene. These case studies served to indicate the processes involved in the development of coastal barriers while the sea level was rising during the early to mid-Holocene, in addition to those involved in the development of beach ridges when the sea level stabilized or slightly lowered during the late Holocene.

On the modern coast of the lowlands, coastal erosion caused by a decrease in sediment supply from rivers, has become a serious problem since the period of economic growth after WWII in Japan.

In this paper, the geomorphological development of coastal ridges during the Holocene in three areas: Inner part of Suruga Bay (Coast of the Ukishimagahara lowland), Western part of Suruga Bay (Miho Spit in the Shimizu Lowland), and Inner part of MIyazu Bay (Amanohashidate), is summarized. Furthermore, beach erosion in those coastal ridges will be discussed (Fig. 1).

II. Inner part of Suruga Bay: Coast of the Ukishimagahara lowland

The coast along the inner part of Suruga Bay is situated between the mouths of the Kano River to the east and the Fuji River to the west (Fig. 2). The Ukishimagahara lowland along the coast is recognized as a barrier-backmarsh system. The present-day coastal ridges consist of sand and gravel, supplied mainly from the Fuji River flowing along Fossa Magna, the plate boundary between the North American and Eurasian Plates in the central part of the Japanese Islands (Fig.1). Furthermore, sand and gravel are sourced from the volcanic rocks distributed in the Kano River basin. Suruga Bay is situated at the plate boundary at which the Philippine Sea Plate subducts beneath the Eurasian Plate along the Suruga Trough (Fig. 1). The Suruga Trough is considered to be one of the hypocentral regions of massive earthquakes. Therefore, tsunamis are predicted to significantly influence the coast. Additionally, the coast of the inner part of Suruga Bay often suffers from the damaging influences of high waves and high tides in typhoons, because high waves can reach the inner bay through the bay's wide mouth, which is open to the Pacific Ocean.

The Ukishimagahara lowland, representing sand and gravel ridge-backmarsh complexes, is located in the west of the Kano River delta, and adjoins the alluvial fans of

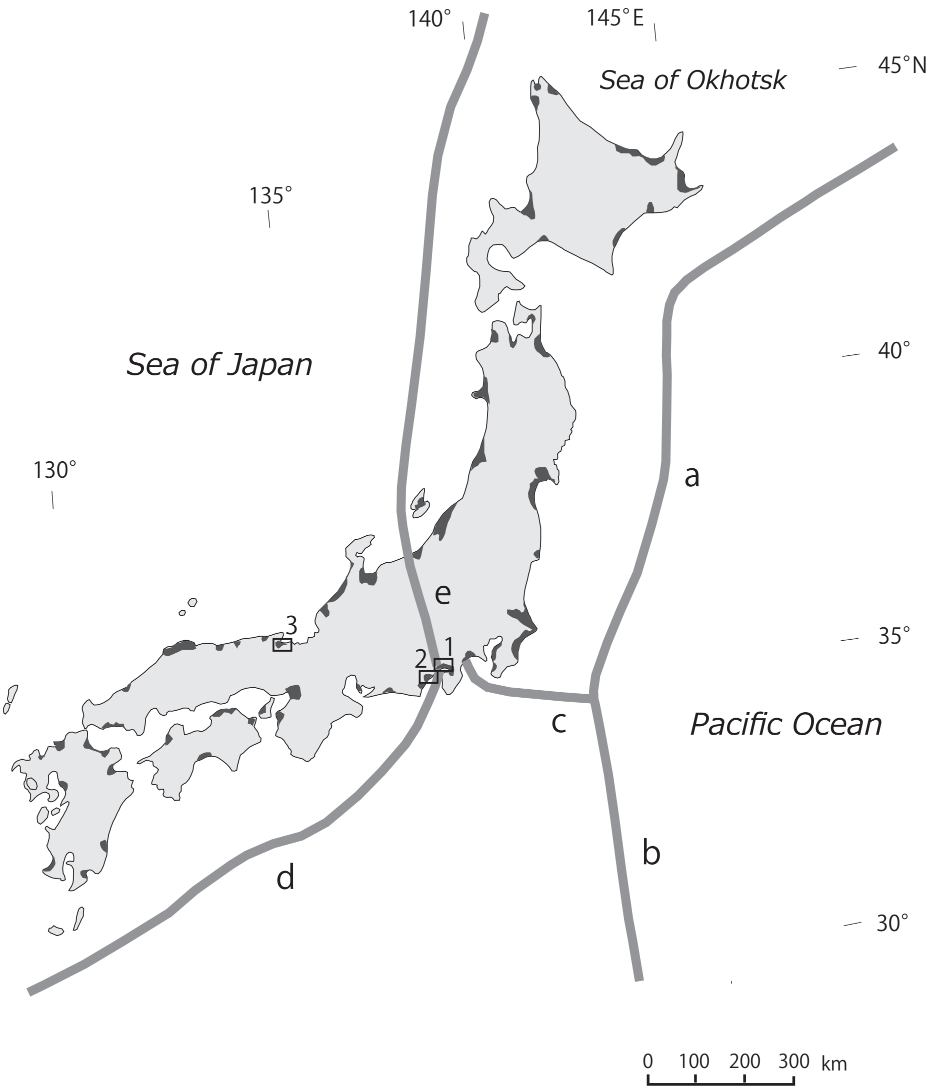
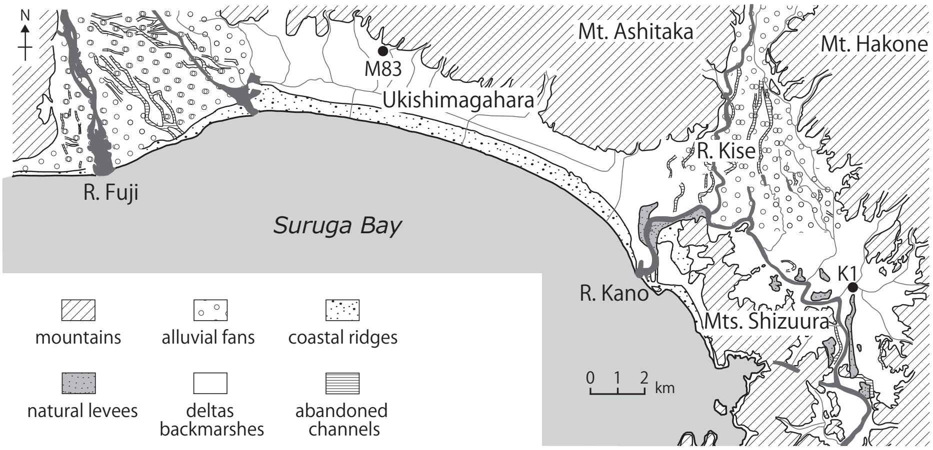


Fig. 1 Distribution of coastal ridges and plate boundaries in Japan
1. Inner part of Suruga Bay (Ukishimagahara Lowland)
2. Western part of Suruga Bay (Miho Spit in Shimizu Lowland)
3. Inner part of Miyazu Bay (Amanohashidate)
a. Japan Trench b. Izu-Ogasawara Trench c. Sagami Trough
d. Suruga-Nankai Trough e. Fossa Magna



K1：boring site after Matsubara (1984)　　M83：boring site after Yonekura *et al.* (1985)

Fig. 2 Geomorphological map of Ukishimagahara Lowland along inner part of Suruga Bay

the Fuji River to the west (Figs. 2; 3). The lowland extends approximately 20 km in length from east to west. The coastal ridges in this region comprise sand and gravel. In the backmarsh area, peaty clay with scoria (ObS) is underlain by marine sand and gravel. The surface height of the marine sand and gravel deposits, including the buried barrier (coastal ridge I) deposits, becomes deeper towards the northwest (both towards the Suruga Trough and landward). Coastal ridge II, which is buried behind the present-day coastal ridge III, had prograded seaward from coastal ridge I in the eastern and central parts of the Ukishimagahara lowland, whereas in the western portion of the lowland, the ridge developed upward. This is likely caused by local differences in the subsidence rate.

The geomorphological development of the Ukishimagahara lowland during the Holocene, on the basis of an analysis of fossil foraminiferal assemblages in bore-hole cores may be summarized as follows (Fig. 4).

Sea water that invaded the region began to form a bay around 10,000 cal BP. Although the influence of sea water from outside the bay increased between 9,000 and 8,000 cal BP, open sea water had not yet directly influenced the environment of the bay at this time. Around 8,000 to 7,400 cal BP, the bay began to be enclosed by a coastal barrier and was transformed into a lagoon. This lagoon then turned into a marsh since after ca. 6,800 cal

Fig. 3 Ukishimagahara Lowland at the southern foot of Mt. Fuji

BP. As marine sand and gravel had been already deposited between 9,000 and 8,000 cal BP, coastal ridge I must have begun to form before ca. 8,000 cal BP, emerging between 8,000 and 7,400 cal BP and completely enclosing the lagoon by ca. 6,800 cal BP. This is supported by the results after Fujiwara *et al.* (2008), based on the analyses of sedimentary facies, fossil ostracodes and molluscan assemblages of the Holocene deposits behind coastal ridge I. The peat behind coastal ridge II, which developed seaward from coastal ridge I, began to accumulate around 5,000 cal BP; consequently, coastal ridge II is considered to have enclosed the backmarsh around this time. Furthermore, the present-day coastal ridge III is considered to have been constructed before 2,000 cal BP, because historic relics found both on the ridge and in the backmarsh date from the Yayoi period, around 2,000 cal BP.

Coastal erosion, caused by a decrease in sediment supply from rivers, has become a serious problem since the 1960's. As a result, breakwaters have been constructed against coastal high waves and tsunamis. Additionally, the construction of offshore breakwaters and concrete armours has taken place, and beach nourishment has been implemented as

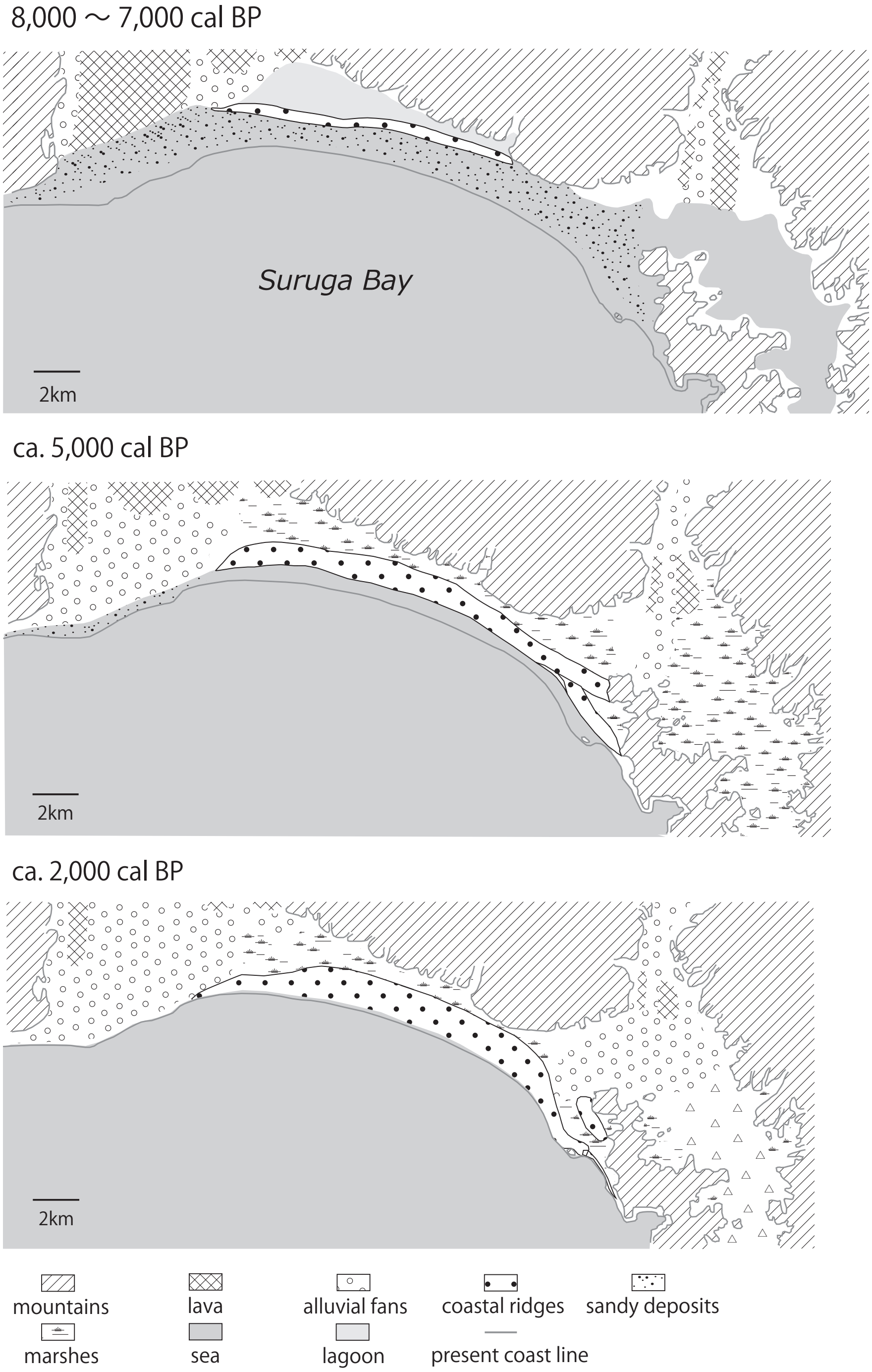


Fig. 4 Palaeogeographical changes in Ukishimagahara Lowland

Fig. 5 Shingle beach along the coast of inner part of Suruga Bay

a form of damage control against coastal erosion (Shibayama and Kayane, eds., 2013) (Fig. 5).

III. Western part of Suruga Bay: Miho Spit in the Shimizu lowland

The Miho spit is located in the eastern part of the Shimizu lowland, and developed from the southeastern part of Udo hill towards the northeast (Figs. 6; 7). The sediments of the coastal ridges in the Shimizu lowland, including the Miho spit, are considered to have been supplied from both the Abe River, which flows in the west of the lowland, and the sea cliffs in the south and southeastern part of Udo hill during the Holocene transgression. The Abe River had also supplied much sediment to develop the alluvial fan at the mouth of the river. The Abe River has been the main source of recent sediments.

The Shimizu lowland faces the western part of the Suruga Bay, and is surrounded by Neogene mountains to the north and the Pleistocene Udo hills to the south. Within the

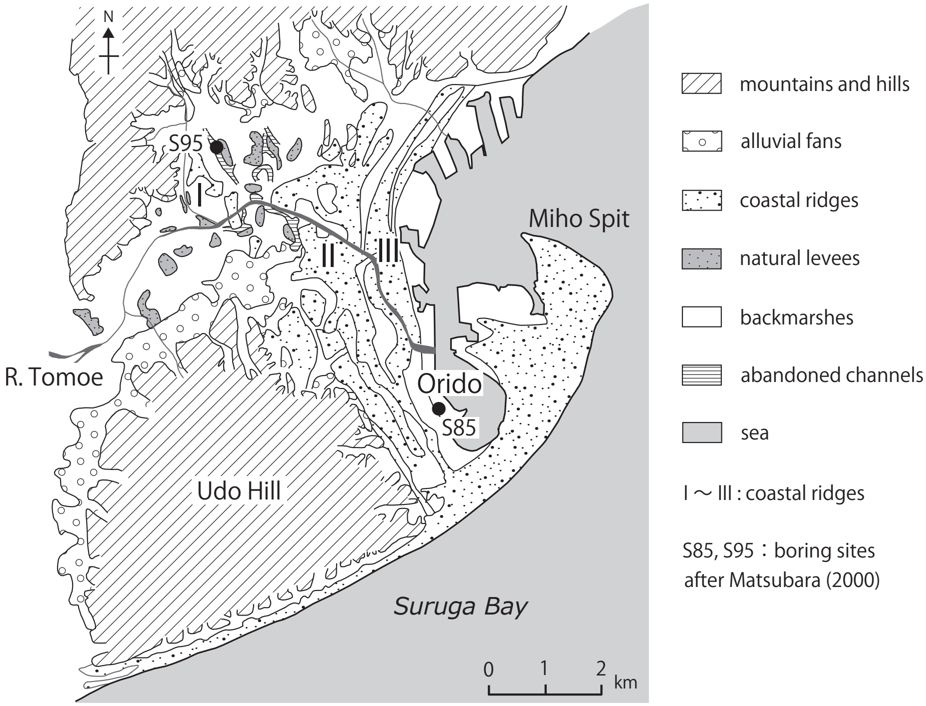


Fig. 6 Geomorphological map of Shimizu Lowland along the coast of western part of Suruga Bay

lowland, the Tomoe River runs eastward and flows into Suruga Bay. Three coastal ridges, numbered I to III in a seaward direction, are remarkably developed in a north to south direction. Coastal ridges I and II may be recognized as Holocene marine terraces in front of the former sea cliffs to the east of Udo hill, which developed on the abrasion platforms. Furthermore, the Miho spit comprising sand and gravel, is developed from the southeastern part of Udo hill towards the northeast.

The ^{14}C date of a shell in the uppermost marine deposits of coastal ridge I at the eastern foot of Udo hill is around 6,600 cal BP (Matsushima, 1984). This suggests that the innermost coastal ridge at the eastern foot of the Udo hill had already developed around the time of the culmination of the Holocene transgression. The Orido inlet exists between the coastal ridges and the Miho spit (Fig. 6), and a valley was formed on the surface of the Udo hill sediments beneath the Orido inlet, extending southward to a submarine

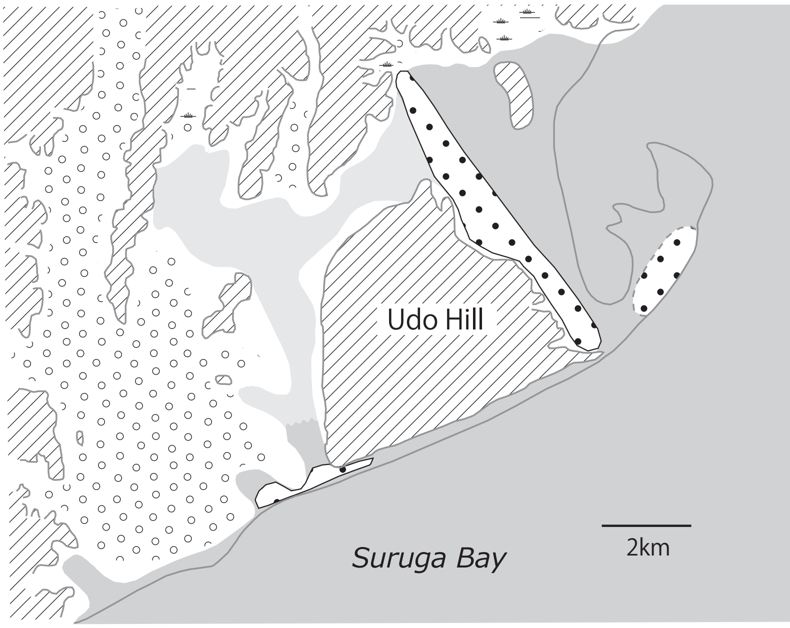
Fig. 7 Miho Spit

canyon in Suruga Bay. Simultaneously, the Miho spit developed on a ridge on the surface of the Udo hill sediments.

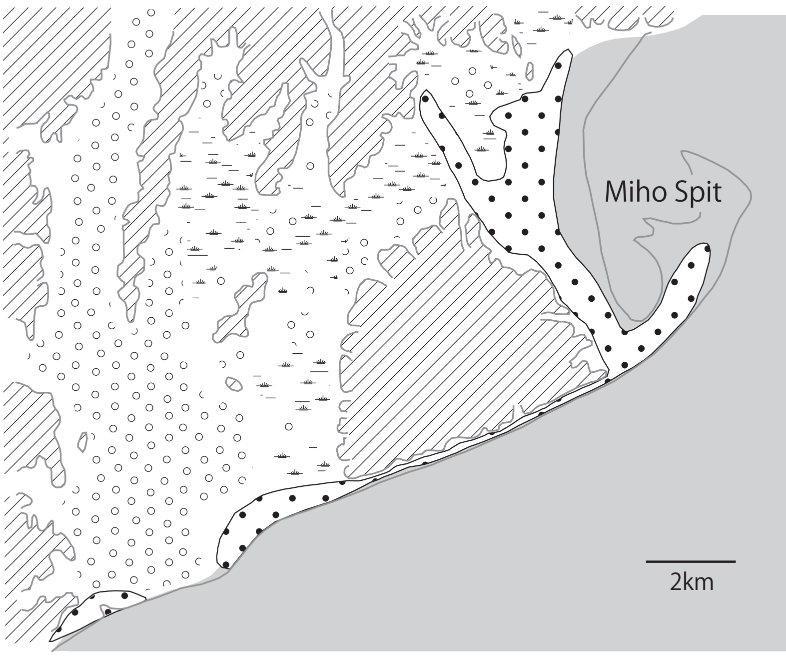
The development of the coastal ridges in the Shimizu lowland, on the basis of an analysis of fossil foraminiferal assemblages in bore-hole cores can be summarized as follows (Fig. 8).

Sea water had already invaded the region by around 8,500 cal BP, and had also flowed through the narrow pass between Udo hill and the Miho spit. The innermost coastal ridge I had been constructed before at least ca. 6,600 cal BP, and the coastal ridge II began to develop seaward from ridge I and emerged to completely enclose the bay around 4,200 cal BP. Furthermore, the Miho spit developed and began to connect with Udo hill around 6,400 cal BP. Finally, the outermost coastal ridge III began to develop after 1,800 cal BP.

A large amount of gravel was dug from the riverbed for construction materials in the period of economic growth after WWII in Japan; therefore, the sediments supplied to the Miho spit decreased rapidly, and severe coastal erosion began to occur along the spit. After gravel digging was prohibited in the late 1960's, sediment supply again increased in ca.7,000 cal BP



5,000～4,000 cal BP



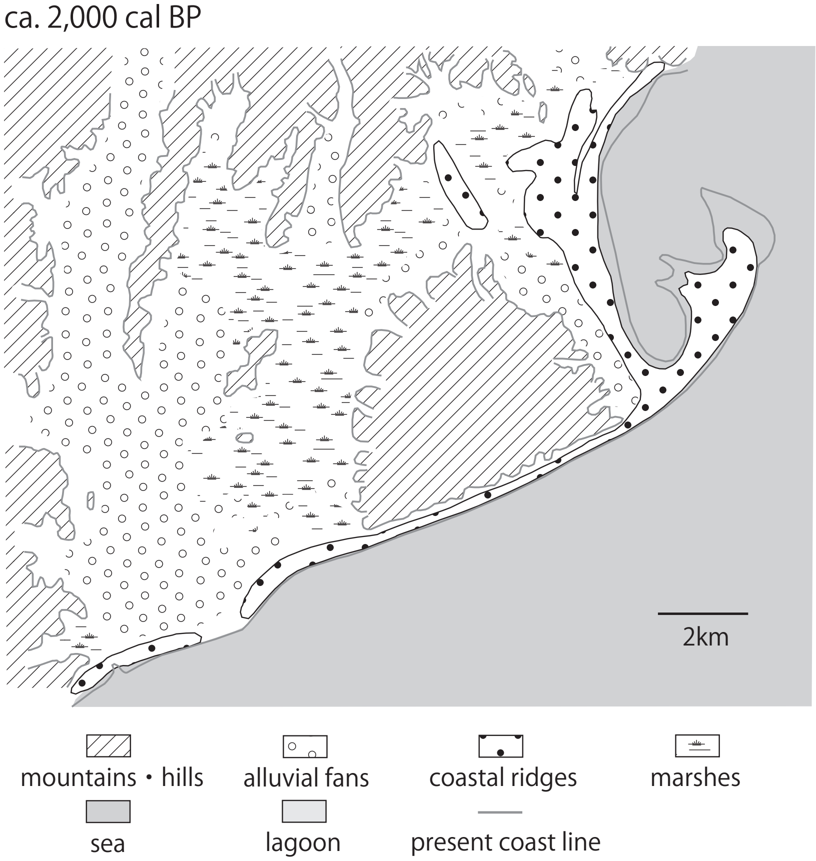


Fig. 8 Palaeogeographical changes in Shimizu Lowland

some parts of the coast. Later, offshore breakwaters were constructed and beach nourishment has been implemented to guard against coastal erosion (Uda, 2010) (Fig. 9).

IV. Inner part of Miyazu Bay: Amanohashidate

Amanohashidate is one of the most famous coastal barriers in Japan; it is situated in the southeastern part of the Tango Peninsula in Kyoto Prefecture, facing the Sea of Japan (Fig. 1). Amanohahsidate developed north to south, approximately 3 km in length (Figs. 10; 11). It encloses Miyazu Bay, which is one of the inlets along Wakasa Bay. The lagoon

Fig. 9 Offshore breakwaters of Miho Coast

behind the coastal barrier is called Aso-Kai (Lake Aso). According to the bathymetric map of Lake Aso, the deepest area around −13 m is situated just behind the barrier (Fig. 10). The lake deposits are mainly composed of muddy sediment (Hirai, 1995). The Noda River flows into Lake Aso at the western (innermost) part of the lake. Coastal ridges develop on the delta around the mouth of the Noda River.

According to Uemura (2010), the Holocene marine deposits along the Noda River are recognized in the area about 1.5 km inland from the river mouth. This suggests that a former bay expanded around Lake Aso during the Holocene transgression. Matsubara and Shiomi (2010) analyzed the fossil molluscan assembalges in the Holocene marine deposits obtained in the Noda River delta. The fossil molluscan assembalges mainly consist of *Ringicula doliaris* and *Papiha undulate* belonging to a typical assemblage found in the middle part of the bay with muddy bottoms. Consequently, it is inferred that the palaeoenvironment of the inner part of Lake Aso had not been influenced by the open sea water.

Concerning Amanohashidate, coastal erosion was recognized in this area during the

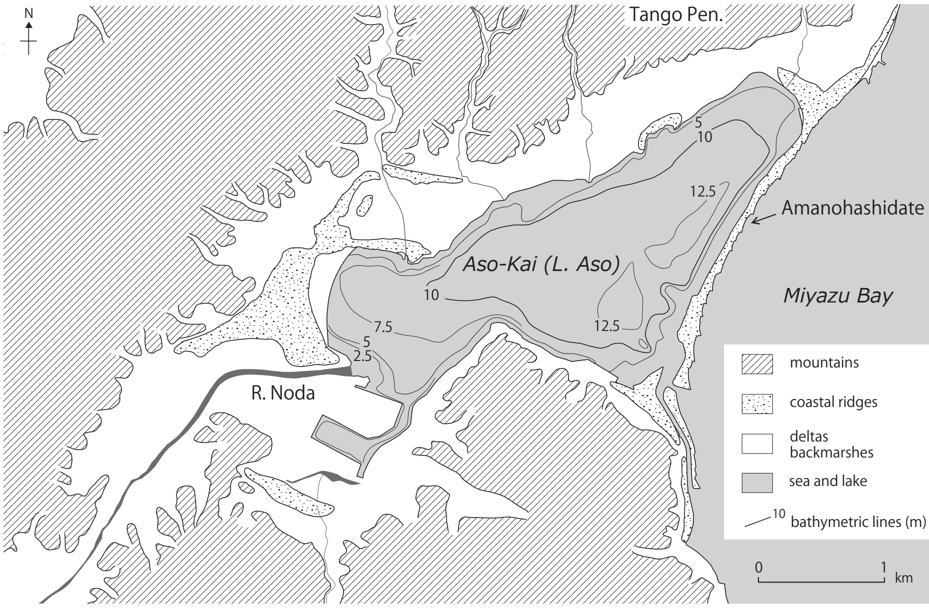


Fig. 10 Geomorphological map of Amanohashidate

Fig. 11 Amanohashidate from the northern mountains
Miyazu Bay (left side), Lake Aso (right side)

Fig. 12 Coastal changes in Amanohashidate from the southern mountains
a. 1987 AD b. 2014 AD
Lake Aso (left side), Miyazu Bay (right side)

Showa period after the sediment supply into Miyazu Bay for this coastal barrier from the rivers decreased because of river improvements such as the construction of sand-trap dams. Furthermore, two ports constructed to the north of the barrier have prevented sand supply from upcoast. Coastal dikes were constructed to protect against beach erosion after WWII. Particularly, since 1971, the larger dikes 30 m long at intervals of 200 m began to be constructed. However, the decrease in sand supply could not be improved, and smooth coastlines along Miyazu Bay changed into serrated ones (Hirai, 1995). In an attempt to rectify this, sand bypass and recycling have been conducted since 1979, which have been effective means of beach nourishment (Shibayama and Kayane, eds., 2013) (Fig. 12).

V. Conclusions

The processes of the geomorphological development of the coastal ridges in three areas are clarified in relation to the relative sea level changes during the Holocene. Furthermore, beach erosion in each area since 20th century is discussed. Coastal erosion has become a serious problem because of a decrease in sediment supply from rivers caused by a large amount of sand and gravel digging, or by a construction of sand-trap dams. As a form of damage control against coastal erosion, the construction of offshore breakwaters has taken place, and beach nourishment also has been implemented.

The formation and evolution of coastal ridges during the Holocene have been mainly influenced by the Postglacial Marine Transgression, whereas the landforms of the coastal ridges at the coastline have been changed by human activities for several decades.

It is predicted that the coastal landforms in the future will be changed not only by the sea level rise caused by global warming, but also by human activities around the coast.

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Note: (J): in Japanese, (J+E): in Japanese with English abstract.