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Author	松原, 彰子(Matsubara, Akiko)
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Influence of Tsunamis on Coastal Lowlands:
Case of the 2011 Tohoku Earthquake

Akiko Matsubara

I. Introduction

The Japanese Islands are composed of arcs and trench systems and were tectonically active during the Quaternary. In the islands, coastal lowlands are distributed mainly in the subsiding regions. Rivers supply large amounts of sediment to the coastal lowlands; this material is derived from volcanoes or the upper reaches of uplifting mountains. This deposition has been ongoing since the last glacial stage in the Late Pleistocene, resulting in the accumulation of thick unconsolidated deposits.

The coastal lowlands of the Japanese Islands can be classified into three types: (1) alluvial fans that develop at river mouths with a large supply of coarse sediments, which face the steep sea bottom; (2) alluvial deltas, which dominantly occur in the inner parts of bays and are supplied with large amounts of fine sediment; and (3) sand and gravel ridge-backmarsh complexes, in which the ridges are usually parallel to the shore and represent former coastal barriers and beach ridges. Of the three types of coastal lowlands, the ridge-backmarsh complexes are most extensive.

Coastal ridges such as coastal barriers and beach ridges are widely distributed along stable trailing-edge coasts across the globe. The primary requisites for the formation of coastal ridges are sufficient sediment supply, processes allowing the development and maintenance of the ridges and an appropriate geomorphological setting. Although the Japanese Islands are in a tectonically active area that includes island arcs and trench systems, coastal ridge landforms are generally found in the coastal lowlands of this area (Fig. 1).

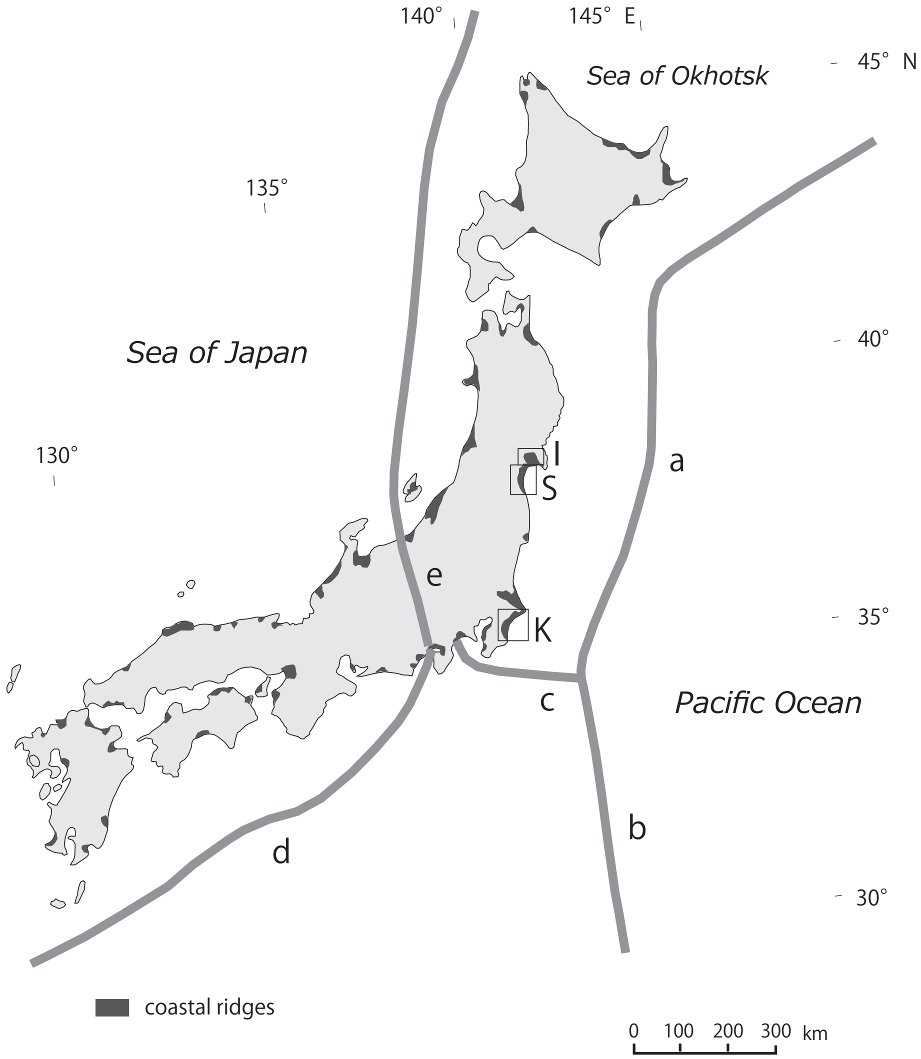

Fig. 1 Distribution of coastal ridges and plate boundaries in Japan
I: Ishinomaki Lowland S: Sendai Lowland K: Kujukurihama Lowland
a. Japan Trench b. Izu-Ogasawara Trench c. Sagami Trough
d. Suruga-Nankai Trough e. Fossa Magna

Matsubara (1988; 2000) reconstructed the palaeoenvironmental changes that had occurred within the embayments along Suruga Bay, on the basis of analysis of fossil foraminiferal assemblages from bore-hole cores; Matsubara (1988; 2000) used these to describe the geomorphological development of the coastal ridges in this area during the Holocene. These case studies served to indicate the processes involved in the development of coastal barriers while the sea level rose during the early to mid-Holocene, in addition to those involved in the development of beach ridges when the sea level stabilized or was slightly lowered during the late Holocene.

From the perspective of human activities in coastal lowlands, archaeological sites dating from the later Jomon period, around 3,000 BP, are widely distributed on the coastal ridges. This suggests that the coastal ridges in the lowlands were important landforms for human settlement during the Holocene. Furthermore, natural disasters such as tsunamis or typhoons may have affected the coastal lowlands. The Tohoku Earthquake was a massive earthquake (epicentre: 38°06.2’ N, 142°51.6’ E, Mw 9.0), which occurred on 11 March 2011. The source region of the earthquake was 450 km in length from north to south and 200 km in width from east to west along the Japan Trench. Tsunamis inundated wide areas along the coasts of the Tohoku and Kanto districts facing the Pacific Ocean.

In this study, the influence of tsunamis caused by the Tohoku Earthquake on landforms such as coastal ridges in three coastal lowlands; the Sendai, Ishinomaki and Kujukurihama, will be discussed.

II. Sendai Lowland

1. Geomorphological development of coastal ridges

The Sendai lowland faces the Pacific Ocean; it is around 50 km in length from north to south and 10–20 km wide from east to west. The Nanakita, Natori and Abukuma Rivers flow through the lowland into Sendai Bay. Most parts of the lowland have an altitude of less than 5 m, and the landforms in this area consist of natural levees along rivers and three coastal ridges, which are numbered I to III from landward to seaward (Fig. 2).

The present-day landforms and deposits in the lowland were analysed by Matsumoto

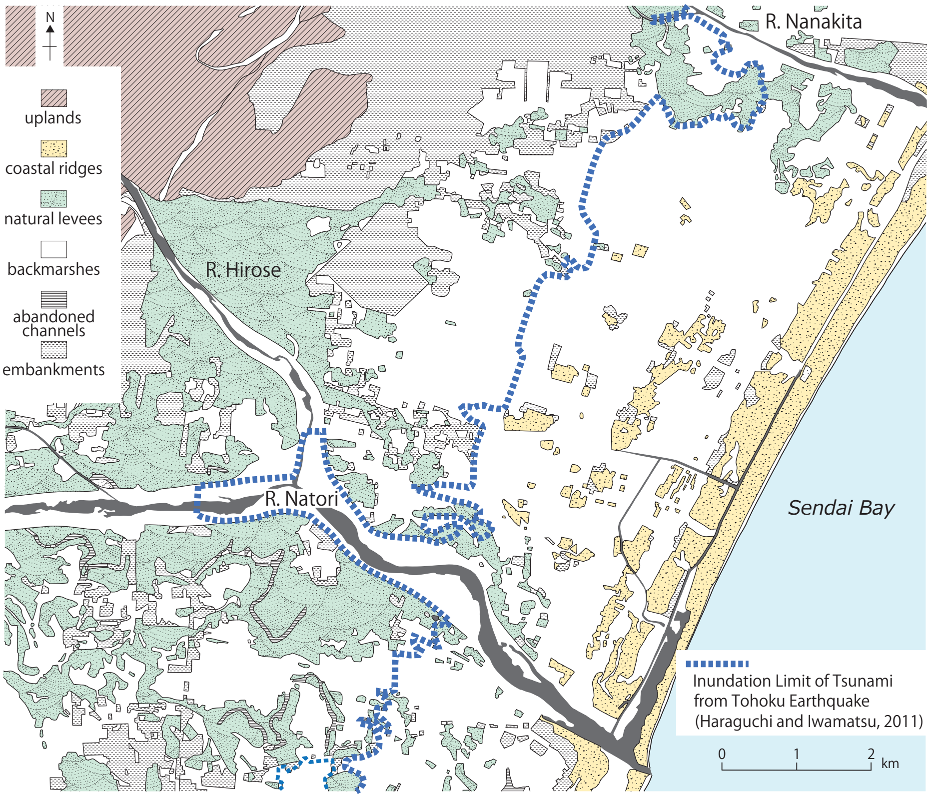

Fig. 2 Inundation area of tsunami from Tohoku Earthquake in the northern part of Sendai Lowland
Landform classification is based on GSI Map (GSI HP)

(1981; 1984), Tamura and Masuda (2005) and Tamura *et al.* (2006). Matsumoto (1981; 1984) determined the geomorphological development of the coastal ridges during the Holocene using ^{14}C dating.

According to the results of those studies, coastal ridges I, II and III in the northern part of the lowland were constructed around 5,000 cal BP, 2,500 cal BP and 700 cal BP, respectively. In the central part of the lowland, coastal ridges I, II and III developed during 4,500 to 4,000 cal BP, 3,300 to 1,000 cal BP and around 1,000 cal BP, respectively. Formation of coastal ridge I was completed at around 2,900 cal BP in the southern part of the lowland.

2. Influence of tsunami on the lowland

At Sendai Bay, the maximum height of tsunami waves was recorded as more than 8.6 m at the Ishinomaki coast, which is located in the northern part of the bay (Japan Meteorological Agency: JMA, 2012). Shishikura *et al.* (2012) examined the distribution of tsunami deposits in the Sendai lowland. According to that study, in the northern part of the lowland, sandy deposits reached between 2.71 and 3.40 km inland, and muddy deposits reached 2.88 to 3.93 km inland. This is in contrast to the limit of inundation, which was 3.80 to 5.14 km inland (Geographical Survey Institute: GSI, 2014). In the central part of the lowland, the inland limits of sandy and muddy deposits were 3.14 km and 4.54 km, respectively. The limit of inundation was 5.05 km in this area. In the southern part of the lowland, sandy and muddy deposits were present up to 2.89 km and 3.05 km inland, respectively, whereas, the limit of inundation was 3.72 km. These findings suggest that the distribution of tsunami deposits was smaller than the inundated area.

Coastal ridges I to III were all influenced by the tsunami (Haraguchi and Iwamatsu, 2011; GSI, 2014). However, the tsunami reached neither the natural levees along the Natori, Hirose and Nanakita Rivers nor the inner embankments in the backmarshes (Fig. 2). Abe *et al.* (1990) and Sawai *et al.* (2007) reconstructed the inundated areas of ancient tsunamis accompanying massive earthquakes in the Sendai lowland, on the basis of analyses of historic documents, archaeological excavations and deposits in the lowland. According to these results, the tsunami from the Jogan Earthquake, which occurred in 869 AD, reached around 4 km inland, causing inundation of the backmarshes behind the coastal ridges.

III. Ishinomaki Lowland

1. Geomorphological development of coastal ridges

The Ishinomaki lowland, which is a beach ridge plain, is located northeast to the Sendai lowland and in the lower reaches of the Old Kitakami River, facing the northern part of Sendai Bay (Fig. 3). The lowland is around 10–20 km in length from east to west and 50 km wide from north to south. Most parts of the Ishinomaki lowland have an elevation above sea level of less than 3 m. Five coastal ridges are distributed about 9 km inland from the present-day coastline (Matsumoto, 1984; Ito, 1999; 2003). The innermost coastal ridge began to develop during the Holocene transgression (Ito, 2003).

2. Influence of tsunami on the lowland

In the western part of the Ishinomaki lowland, the inland limits of the distribution of sandy and muddy deposits were 1.87 km and 2.20 km, respectively (Shishikura *et al.*, 2012); however, the limit of inundation was 2.55 km inland (GSI, 2014). Although the outer three coastal ridges were influenced by the tsunami from the Tohoku Earthquake, the tsunami did not reach the areas around the inner two coastal ridges (Haraguchi and Iwamatsu, 2011; GSI, 2014) (Fig. 3).

IV. Kujukurihama Lowland

1. Geomorphological development of coastal ridges

The Kujukurihama lowland is a typical beach ridge plain of Japan; it is oriented northeast-southwest, and it is around 60 km in length facing the Pacific Ocean. As the lowland is located on the margin of the Kanto Basin, crustal uplift occurred during the Late Quaternary. All rivers in the lowland flow into the Pacific Ocean and intersect the coastal ridges. The coastal ridges can be classified into three zones, numbered I to III from landward to seaward, and are generally better developed in the southwestern than in the northeastern part of the lowland (Matsubara, 2014) (Fig. 4, 5).

Moriwaki (1979; 1982) examined the geomorphological development in the Kujukurihama lowland after the culmination of the Holocene transgression around 7,000 cal BP. The results of that study showed that the coastal ridges had already developed between 6,500 and 6,000 cal BP. Completion of the formation of coastal ridges I, II and III occurred during the periods 5,500 to 4,500 cal BP, 4,500 to 2,500 cal BP and around 1,500 cal BP, respectively.

Sampling of the Holocene deposits was conducted along the Magame River in the central part of the lowland by Masuda *et al.* (2001a; b). From geological cross-sections, a

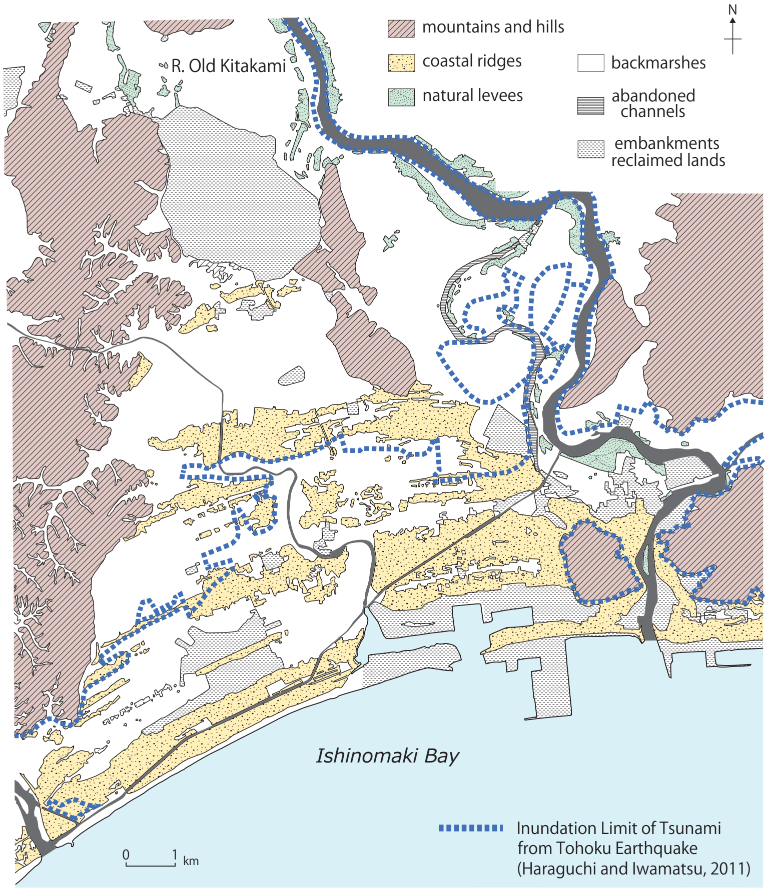

Fig. 3 Inundation area of tsunami from Tohoku Earthquake in Ishinomaki Lowland
Landform classification is based on GSI Map (GSI HP)

buried abrasion platform occurs at around −10 m beneath coastal ridge I around 7 km inland from the present-day coastline. This suggests that at least coastal ridge I developed on top of an abrasion platform during the Holocene.

2. Influence of tsunami on the lowland

The tsunami from the Tohoku Earthquake also influenced the Kujukurihama lowland. The maximum tsunami height in this region was recorded as 2.5 m at the Choshi coast, which is situated at the northeastern end of the Kujukurihama lowland (JMA, 2012). Fujiwara *et al.* (2011; 2012) examined the distribution of the deposits carried by the

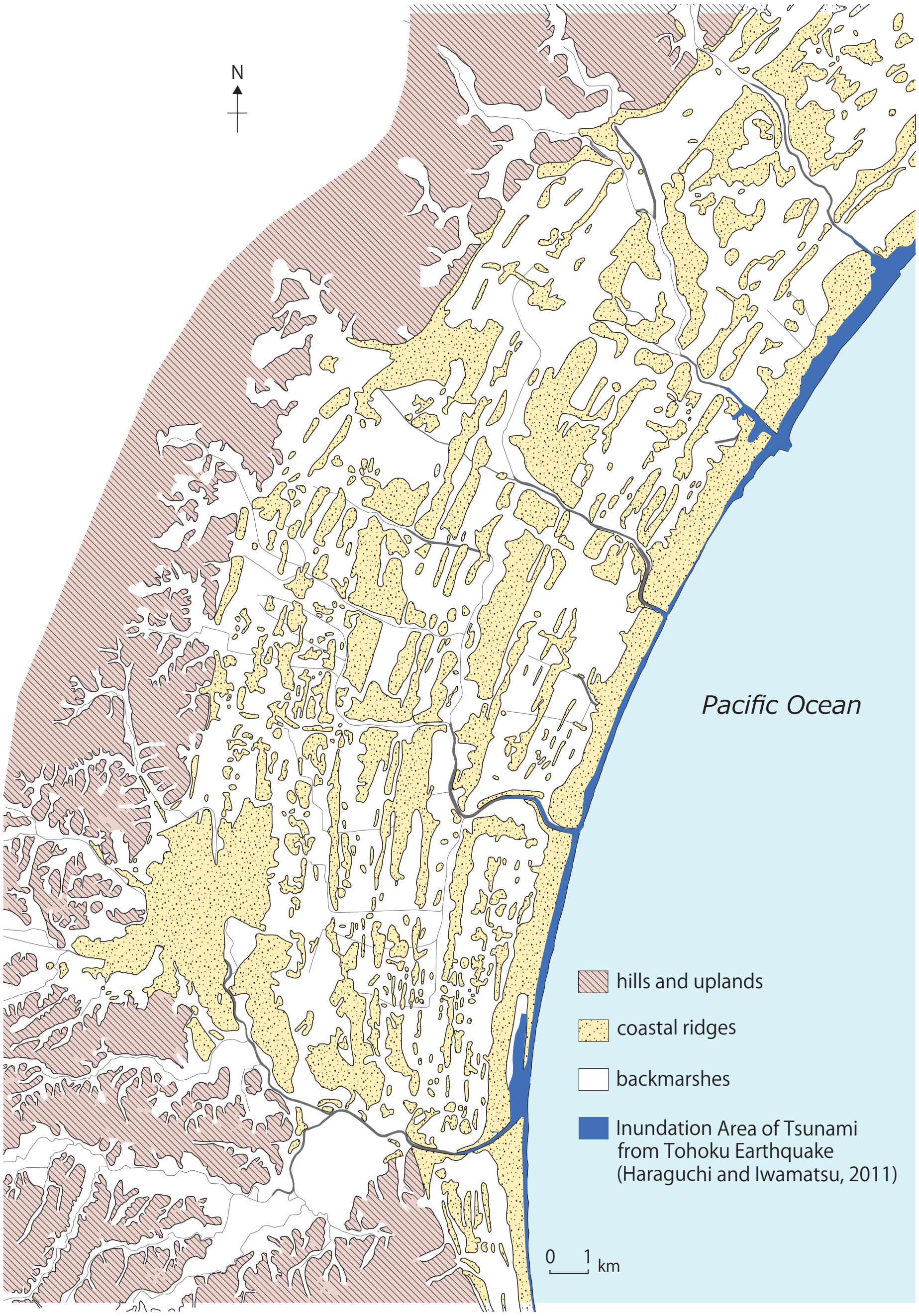

Fig. 4 Inundation area of tsunami from Tohoku Earthquake in southwestern part of Kujukurihama Lowland

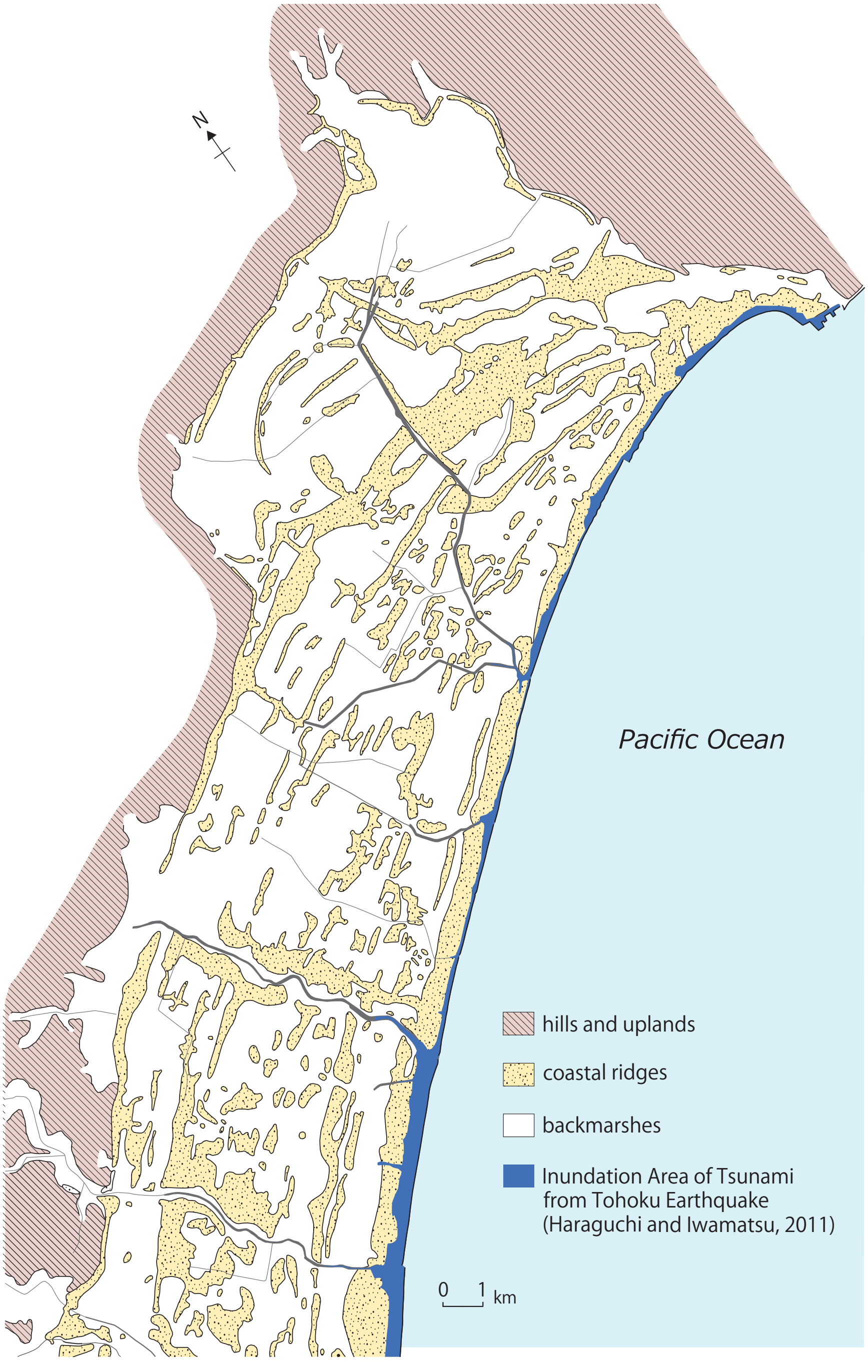

Fig. 5 Inundation area of tsunami from Tohoku Earthquake in northeastern part of Kujukurihama Lowland

tsunami from the Tohoku Earthquake, while Haraguchi and Iwamatsu (2011) and GSI (2014) showed the inundation areas (Fig. 4, 5). Based on these studies, it is suggested that the tsunami reached the outermost ridge III in the Kujukurihama lowland. Tsunami deposits were observed at locations behind the outermost coastal ridge, around 1 km inland from the present-day coastline in the central part of the lowland.

V. Influence of Tsunamis on Coastal Ridges

As the Sendai and Ishinomaki lowlands are located along Sendai Bay, it is considered that the scale of the tsunami was large in both areas. However, the tsunami influenced the coastal ridges differently in these areas. Although all of coastal ridges I to III were influenced by the tsunami in the Sendai lowland, the tsunami did not reach the areas around the inner two coastal ridges in the Ishinomaki lowland. The difference was because the Sendai and Ishinomaki lowlands belong to different types of coastal lowlands. The landforms of the Sendai lowland are coastal ridge-backmarsh systems. However, in the Ishinomaki lowland, which is a beach ridge plain, coastal ridges are more strongly developed than in the Sendai lowland. Thus, it is inferred that the difference in the landforms of the coastal lowlands caused the differences in the inundation areas.

According to Matsubara (2000; 2003; 2015), the coastal ridges in the lowlands may have been important landforms for human settlement during the Holocene. Human activity has been influenced by the development of coastal ridges and devastating volcanic events. Time-lags are recognized between the final stages of coastal ridge formation and when humans began to advance and settle on the ridges. The time-lags represent the fact that it took thousands of years for the coastal ridges to become stabilized and free from the influence of sea water, such as high waves, high tides and tsunamis. This is supported by the fact that coastal ridges, particularly the outermost ridges, were influenced by the tsunami following the Tohoku Earthquake.

VI. Conclusions

The influence of the tsunami from the Tohoku Earthquake on the landforms in three coastal lowlands; the Sendai, Ishinomaki and Kujukurihama, was examined. The results can be summarized as follows.

The coastal ridges in each area, particularly the most seaward ridges, were influenced by the tsunami following the Tohoku Earthquake. All the coastal ridges in the Sendai lowland, which contains coastal ridge-backmarsh systems, were influenced by the tsunami. However, the tsunami did not reach the areas around the inner two coastal ridges in the Ishinomaki lowland, which is a beach ridge plain environment. In addition, the tsunami did not reach natural levees along the rivers and inner embankments in the backmarshes of the Sendai lowland.

These results suggest that the inundation area of tsunamis is influenced by small-scale landforms in coastal lowlands.

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