Formation processes of tsunami deposits following the 2011 Tohoku-oki earthquake in the estuary of Odaka District, Minamisoma City, Fukushima Prefecture, northeast Japan

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The 2011 Tohoku-oki tsunami inundated the Idagawa estuarine lowland in Odaka District, Minamisoma City, to a distance of up to 3.2 km inland from the shoreline. In this study, the formation processes of the tsunami deposits is reconstructed based on the pathways of the tsunami, facies of the tsunami deposits. The tsunami deposits are divided into three main units (Units 1–3, in ascending order), and Unit 1 is subdivided into Subunits 1A–1C. Subunit 1A consists of fine sand and was deposited by the encroached flow through the drainage channel in the earliest stage of the tsunami. Subunit 1B comprises an assortment of gravels and was formed from the overflow of a sea dike and river bank. Subunit 1C consists of medium to fine sand and was formed from the flooded flow. Most of these sub-units formed from the run-up flow of the first tsunami wave with a remarkably high water level. However, clear erosional contacts are occasionally recognized in the subunits, which were formed from minor run-up flows after the secondary wave. Unit 2 consists of poorly sorted muddy fine sand and was formed from the return flow due to a drop in water level in the latter half of the tsunami. Unit 3 consists of massive mud settled down from the ponding water after the tsunami.

Key words: 2011 Tohoku-oki tsunami, tsunami deposit, formation process, estuary, tsunami water level

Introduction

The 2011 Tohoku-oki earthquake of Mw 9.0 (referred to as the 3.11 Earthquake in this study) occurred at the boundary of the plates off the Pacific coast of Tohoku-oki at 14:26 (JST) on March 11, 2011 (Fig. 1A). The tsunami that was triggered by the earthquake (referred to as 3.11 Tsunami in this study) struck the coastal area between the Kanto region and Hokkaido, Japan, and caused severe damage. Since then, studies of tsunami deposits have developed our knowledge of the transportation and depositional mechanisms of tsunamis (e.g., Naruse et al., 2012; Sugawara, 2014). However, changes in the thickness and facies of tsunami deposits over short distances in inundated land areas are complex, and few reports on the formation processes of tsunami deposits are consequently available (Nanayama and Shigeno, 2004; Fujiwara and Kamataki, 2007; Takashimizu et al., 2012). It has been postulated that significant changes in the thickness and facies of tsunami deposits reflect the sources of the deposits, local topography, surface sediments along the pathways of the tsunami, and changes in the flow velocity over short distances (Naruse et al., 2010).

Most previous investigations of tsunami sediments in land areas have been carried out in large strand plains, coastal wetlands, and lakes (Sawai, 2012). And many studies on the 3.11 Tsunami deposits were reported on the Sendai Plain and delta plains in Sanriku coastal bays (e.g., Naruse et al., 2012; Abe et al., 2012). However, few reports on the 3.11 Tsunami deposits in Fukushima Prefecture have been published due to the accident at the Fukushima 1 Nuclear Power Plant caused by the earthquake and tsunami (Fig. 1B). Fur-
thermore, few studies report on the response of facies and formation processes to topographic features and artificial structures (Takashimizu et al., 2012). And studies examining the formation processes of tsunami deposits corresponding to recorded tsunami waveforms are rare (Fujiwara and Kamataki, 2007; Oota et al., 2017).

In this study, the formation processes of the tsunami deposits were reconstructed for the 3.11 Tsunami in Odaka District, Minamisoma City, in a small estuarine lowland located in a 20 km zone from the Fukushima 1 Nuclear Power Plant. In this regard, the relationship between the local topography in the pathway of the tsunami, sources of...
the tsunami sediments, and record of the tsunami water level was considered.

Outline of the topographic and geological features of Odaka District

The Sousou Hills, located along the coast of the Pacific Ocean in Fukushima Prefecture, northeast Japan, extend north to south, their width being approximately 8–10 km between Abukuma Mountains and the coast line (Fig. 1B). Odaka District in Minamisoma City is located on the coast of the Pacific Ocean in the northern part of Fukushima Prefecture. In this district, the Odaka-gawa and Miyatata-gawa Rivers flow eastward to the Pacific Ocean, eroding the hills to form alluvial lowlands. In this study, these lowlands are referred to as the Odaka and Idagawa lowlands, respectively. The Miyata-gawa River is a small river of approximately 6.9 km in length, with its source in the Sousou Hills. The Idagawa Lowland is approximately 4.5 km in length in an east–west direction, and approximately 0.5–1.5 km in width in the north–south direction. It is composed of beach ridges, a lagoon, and a marsh on the seaside (Kubo et al., 1990; Fig. 2A). The lagoon area is below sea level, where had reclaimed in 100 years ago (Fukushima Prefecture, 2004), and most of the lagoon and marsh are used as paddy fields. Additionally, artificial changes in land forms have developed in recent years at the Idagawa Lowland, and massive embankments have been constructed along the beach ridge, residential area, the bank of the Miyata-gawa River, and Route 6 (Fig. 2). Thus, the lowland is surrounded by hills, the beach ridge, the sea dike, and the bank of the Miyata-gawa River, and only the mouth of Miyata-gawa River opens to the sea.

According to a comparison of the digital elevation model (DEM) of the Geospatial Information Authority of Japan before and after the 3.11 Earthquake, the elevation of the ground surface subsided by approximately 0.5 m in the Idagawa Lowland. The shore perpendicular (a–b) cross-section and the shore parallel (c–d) cross-section, based on the DEM in 2012, are shown in Figs. 2B and 2C. The maximum topographic difference in elevation was 3.2 m within the tsunami inundation area in the a–b cross-section. The beach ridge was approximately +1.5 m, the lagoon is −1.0–−1.5 m, and the marsh is 0.0–+3.0 m in elevation after the earthquake. The sea dike was constructed continuously on the beach ridge and its top is approximately +5.5 m in elevation. The lagoon is almost completely enclosed by the beach ridge; however, only the mouth of the river opens into the Pacific Ocean. The road extending north to south was constructed on the boundary of the lagoon and marsh using embankment and is referred to as Transverse Road in this study. The relative height of the ground surfaces between the lagoon and marsh on both sides of Transverse Road is approximately 1.5 m, indicating a notable difference in topographic features in the tsunami inundation area (Fig. 3C). The Miyata-gawa River in the Idagawa Lowland is divided by an artificial liner bank and is located in the northern part of the lowland, at a height of 4–5 m above the lowland surface (Fig. 3B). The distance between the banks is approximately 40 m, and the elevation of the top of the bank, near the mouth of the river, is approximately +3.5 m (Fig. 2C). The area between the banks consists of a river channel that is 5–10 m in width and flood plains with a relative height of 1–2 m. Additionally, the drainage channel is approximately 2 m in depth and 10 m in width, runs through the center of the lagoon (Fig. 3D), and joins the Miyata-gawa River toward the inside of the beach ridge. The elevation height of the drainage channel bank is approximately −0.5 m. In the Idagawa Lowland, it was reported that many paleotsunami sand layers are intercalated in Holocene sediments (Kakubari et al., 2017).

Methodology

1. Investigation of traces of the tsunami

A survey of the traces of the tsunami in Odaka District was carried out in April 2013. The traces indicating the water depth of the tsunami consist of water marks on the side walls of constructions and houses as well as the driftage and collision marks left by the driftage. The traces indicating the flow direction of the tsunami comprise inclinations of electric poles and road facilities (Fig. 3D) as well as erosion at the upper stream side of highlands, such as the ridges between paddy fields. A level staff and laser rangefinder (Leica Geosystems, DISTO D8) were used to measure the tsunami water depth.

2. Sedimentary investigation of tsunami deposits

(1) Field survey of the pits

Fifty pits, approximately 1.5 m in length and breadth and approximately 0.4 m in depth, were excavated using shovels from April 2013 to October 2015 in the tsunami inundation area (Figs. 2A and 3E). The locations of the pits were set to examine the tsunami inundation area spatially. The sedimentary features are explained using pits P1–P13 along the a–b transect and pits P14–P19 along the c–d transect.

(2) Sampling

Oriented samples from each pit were collected using the Lunch Box method (Nanayama and Shigeno, 1998), and peeled samples were collected using a quick-drying bond spray.
(3) Observation of the sedimentary facies

The oriented and peeled samples were described with regard to color tones, grain size, sorting ratio, constituent particles, and sedimentary structures of the deposits. The results of the observations were explained as stratigraphic columnar sections. Soft X-ray images of the samples were taken for reference in cases where the sedimentary structures were not obvious.
Fig. 3  Photographs of the tsunami inundation area in the Idagawa Lowland. (A) Aerial photograph of the Idagawa Lowland taken on February 28, 2012 [URL2]. (B) Miyata-gawa River at the marsh. (C) Land surface elevation was lower in the lagoon than in the marsh on both sides of the Transverse Road. (D) Flow direction of the tsunami along the drainage channel. (E) Photograph showing a side wall of pit P3. (F) Bank of the Miyata-gawa River was eroded and partially broken by the tsunami. (G) Limit of the tsunami inundation area. (H) and (I) Ponding water left by the tsunami remained over the long term in the lagoon. (J) Destroyed concrete building behind the beach ridge. (K) Trench dug by the tsunami overflowed from the sea dike.
Inundation of the 3.11 Tsunami in the Idagawa Lowland

The 3.11 Tsunami encroached the Idagawa Lowland from the coast and the river and reached a distance of up to 3.2 km inland from the shoreline (Fig. 2A). The tsunami moved over the beach ridge and sea dike and overflowed the bank of the Miyata-gawa River in the lagoon, breaking a part of the sea dike and river bank (Fig. 3F). The tsunami inundation area was constrained by the embankment of Route 6 and the bank of the upper reach of the Miyata-gawa River in the lowland. The water depths at impeded points of the tsunami flow ranged from 1.5 to 2.0 m (Fig. 3G). Traces of the tsunami were recognized approximately 5 km upstream of the mouth of the Miyata-gawa River.

The water depth of the 3.11 Tsunami surveyed in this study and obtained from the Japan Tsunami Trace Database (International Research Institute of Disaster Science, Tohoku University [URL2]) is shown in Figs. 2B and 2C. The maximum range of the tsunami water depth was 12.55 m at the beach ridge, but it suddenly decreased to approximately 7 m between pits P3 and P4 along the a–b transect (Fig. 2B). The change in the tsunami water level further inland was gradual, but, because of the difference in the land surface elevation between the sides of the Transverse Road, the tsunami water depth at the lagoon ranged from 4 to 6 m, and that at the marsh ranged from 2 to 3 m. Along the c–d transect, the water depth of the tsunami above the land surface of the lowland was approximately 6.0 m near the banks of the Miyata-gawa River and decreased to 3–4 m toward both sides (Fig. 2C).

Most tsunami traces indicate a landward current direction in the lagoon, and traces of seaward directions are rarely recognized in the marsh and at the river mouth (Fig. 2A). Furthermore, the traces along the drainage channel and Miyata-gawa River indicated that the tsunami overflowed their banks in the lagoon (Fig. 3D).

Because of damage to the drainage pump and ground subsidence by the earthquake, the lagoon was submerged for about eighteen months after the tsunami (Figs. 3H and 3I). Aerial images taken after the tsunami indicate that the water level of ponding was mostly the same as the height of the bank crown of the Miyata-gawa River in the lagoon (Fig. 3A) [URL3]. Houses destroyed by the tsunami were distributed up to an area of approximately 0.6 km along the beach ridge and the residential area located along the Miyata-gawa River (Figs. 2A and 3J). The overflows eroded the ground surface and created a trench with a width of 5–10 m and a depth of 2–4 m on the inland side of the sea dike (Fig. 3K).

Distribution and sedimentary facies of the tsunami deposits

The 3.11 Tsunami deposits are distributed with a thickness ranging from 1 to 26 cm. Geological cross-sections exaggerating the subsurface depth (1:30) were made to illustrate the tsunami deposit facies (Figs. 4B and 4C). The tsunami deposits show lenticular profiles in the a–b and c–d cross-sections. The a–b cross-section indicates that the beach ridge was located in the erosion area caused by the tsunami. The tsunami deposits thicken toward the inland side, with a maximum layer thickness of 26 cm on the seaward side of Transverse Road (Fig. 4B). The tsunami deposits thin to 15 cm on the inland side of Transverse Road, and at the landward end of the tsunami inundation area, the thickness of the tsunami deposits is 1 cm. The c–d cross-section tsunami deposits are relatively thick around the Miyata-gawa River and thinner toward both sides (Fig. 4C).

The tsunami deposits are divided into three main units (Units 1–3, in ascending order) based on the materials, grain size, and sedimentary structures (Figs. 3 and 4). (1) Unit 1

Unit 1 is 3–20 cm thick and is subdivided into Subunits 1A, 1B, and 1C. Subunit 1A is 1–5 cm thick, and shows a narrow and long distribution along the drainage channel running longitudinally through the lagoon (Fig. 4A). The base of Subunit 1A eroded the original ground surface; however, the paddy soil remained in the rice fields because the base of the paddy soil could not be eroded (Fig. 5A, P6). This unit mainly consists of gray, well-sorted, and fine sand, and the parallel laminae of mafic minerals show remarkable development, similar to the foreshore deposits. The medium sand layer bearing granules and pebbles and broken pieces of bivalves are found at the base of Subunit 1A (Fig. 5B, P16). The repetition of indistinct graded bedding from upper-fine sand to lower-fine sand can be recognized, because the parallel laminae of the mafic minerals are intercalated. Subunit 1A shows almost uniform facies and grain size distribution in the sea- and landward sides.

Subunit 1B is mainly 3–20 cm thick, distributed along the lagoon of the beach ridge, and it becomes thinner and finer toward the west (inland) as well as towards to north and south from the Miyata-gawa River. This subunit is distributed along the beach ridge and located along the seaward side from pits P3 to P4, at a tsunami water depth of more than 7 m (Fig. 4B). At the base of Subunit 1B, the paddy soil in the rice field is abraded because of severe erosion, which reached the reclaimed soil (Fig. 5A, P1; Fig. 5B, P18). Subunits 1A and 1B could not be recognized in the same localities. Subunit 1B includes 60–80% gravel and...
Fig. 4  (A) Map of the Idagawa Lowland showing the landform classification, tsunami inundation area, locations of tsunami deposit survey sites, damage caused to residential areas by the tsunami, and distributions of Subunits 1A and 1B.  (B) and (C) The shore perpendicular (a–b) and the shore parallel (c–d) geological cross-sections of the tsunami deposits. Units 1A–1C, 2, 3, and the paleocurrent directions are seen in both cross-sections. In Subunit 1B and 1C, clear erosional contacts with gravels are partially recognized.
Fig. 5 Photographs of the sides of the pits and the geological columnar sections. (A) and (B) show the variation of the sedimentary features of the tsunami deposits in the a-b and c-d transects, respectively. Subunit 1A consists of well-sorted fine sand with parallel laminae. Subunit 1B includes considerable amounts of gravels and rock lumps, and Subunit 1C consists of medium to fine sand. In Subunits 1B and 1C, clear erosional contacts with gravels are partially recognized. Unit 2 consisted of muddy fine sand with cross laminae, indicating paleocurrent directions to the sea side. Unit 3 consisted of massive mud.
rock lumps with a diameter of 0.5–20 cm from the artificial embankment origin. They also contain a few mud rip-up clasts. The matrix consists of very fine to medium sand with low mud content along the beach ridge. However, the mud content is high along the Miyata-gawa River. It shows a graded bedding, with the bedding becoming partially reversed in the lowermost part (Fig. 5A, P3). The imbrication of the gravels is recognized in some localities, indicating inland flows. The thickness of Subunit 1B at the broken part of the bank of the Miyata-gawa River exceeds 20 cm on the bank side, but the thickness and grain size suddenly decrease thereafter towards the hills (Fig. 4C).

Subunit 1C is 3–12 cm thick and thinned toward the seaward side in the lagoon. The base of this subunit erodes the original ground surface, but the paddy soil remains in the rice fields because erosion did not reach the base of the paddy soil (Fig. 5, P4, P11). Subunit 1C covers Subunits 1A and 1B, does not contain an erosion surface, and comprised mainly well-sorted, gray, medium to fine sand, accompanied by coarse sand-bearing granules at the base. This subunit includes mud rip-up clasts of 0.5–2 cm in diameter and shows indistinct parallel laminae, recognizable by concentrations of the rip-up clasts and mafic minerals. The landward flow directions are indicated in some places by imbrication of gravels and rip-up clasts (Fig. 5A, P9). The 12 cm thick Subunit 1C includes 70% rip-up clasts with blurred outlines due to partial dissolving on the seaward side of the Transverse Road (Fig. 5A, P8).

Furthermore, at some localities in the lagoon, Subunits 1B and 1C are divided into two graded layers with clear erosional contact, which is recognized in middle to upper part of the subunit (Fig. 5, P1, P5, P17, P18). The upper layer is relatively thinner and finer than the lower layer. However, it is difficult to chase the continuities of the upper layers, because there are few clear erosional contact in these subunits.

(2) Unit 2

The thickness and depositional facies of Unit 2 differ from those of the marsh and lagoon (Figs. 4B and 5A). In the marsh, Unit 2 is 1–4 cm thick and mainly consists of light yellowish gray fine sand (Fig. 5B, P11). A thin layer of coarse to medium sand can be recognized at the basal part. The basal surface erodes Unit 1. Rip-up clasts of mud and parallel laminae with plant debris appears frequently, and cross laminae with a ripple bedform indicating paleo-current directions toward the seaward side are recognized in the P11 site. Muddy and very fine sand graded as sandy mud is found in the uppermost part of Unit 2. In the lagoon, Unit 2 is 4–9 cm thick, overlaying hardly eroded substrates. It shows poorly sorted muddy fine sand (graded as muddy very fine sand), and sorting of sediments is relatively poorer in comparison with that of the marsh (Fig. 5A, P3).

(3) Unit 3

Unit 3 is 2–6 cm thick, the thickness being thicker toward the Transverse Road in the lagoon (Fig. 5A, P8). Unit 3 consists of massive amounts of humus mud and covers Unit 2 without the presence of an erosion surface.

**Tsunami water level record of the river**

It is difficult to obtain continuous tide records of the 3.11 Tsunami in Tohoku region, because most tide gauge stations were damaged by the massive tsunami. Thus, in this paper the relationship between the formation processes and wave-form is examined using the water level record at Odaka-gawa Water Gauge Station, which is located 5.1 km from the river mouth (Fig. 1C).

At Odaka-gawa Water Gauge Station, the water level record shows three stages, Stages 1–3, based on the amplitude of waves (Fig. 6). Stage 1 comprises only the first wave, and the water level rose by 0.26 m in comparison with that before the tsunami from 14:40 to 15:40 on March 11, 2011. At Stage 2, the water level was higher around 0.1 m from 15:40 to approximately 20:30, and at Stage 3 the subsequent water level gently fell to approximately 0.05 m, in comparison before the tsunami respectively.

**Discussion**

1. **Origin of the tsunami deposits**

Unit 1 is considered the deposit from the run-up flow, because it mainly consists of well-sorted fine sand with imbrication of gravels, indicating inland flow (Fig. 5A). Subunit 1A is interpreted as having been formed from the run-up flow that encroached through the drainage channel after the erosion of the foreshore. The facies of Subunit 1A represented small variations between the sea- and landward sides in the lagoon, as small amounts of fluvial deposits overlaid the drainage channel covered by concrete blocks. Subunit 1B is distributed along the beach ridge and in the area covered by the overbank flows of the Miyata-gawa River, including a large amount of gravels and rock lumps originating from the embankment and mud rip-up clasts. Subunit 1B is considered to have been deposited from the run-up flow beyond the sea dike and the river bank. Photographs taken by a local resident show that the massive tsunami struck across the sea dike after having encroached the small run-up flow through the drainage channel at the first stage of the 3.11 Tsunami in the Odaka Lowland [URL4]. Furthermore, the substratum under Subunit 1A
waspaddy soil, but that under Subunit 1B was reclaimed soil subject to more intense erosion. Therefore, the delayed tsunami flowed over the sea dike and might have eroded Subunit 1A and the paddy soil, resulting in the formation of Subunit 1B. Subunit 1B is distributed along the beach ridge and located in the range where the tsunami water depth exceeded 7m, and it thins and fans out inland. It can be concluded that the run-up flow had a high velocity and could therefore carry a large amount of the coarse gravels from the seaward side, and that sudden reduction in the water depth and flow velocity of the tsunami caused a rapid decrease in the thickness and grain size inland. Deposition of Subunit 1C, which consists of sand including mud rip-up clasts, occurred where the tsunami depth was below 7m, because gravels might not have been carried by the flow.

The minor upper layers of Subunits 1B and 1C indicate that they formed from run-up flows after the secondary wave. It is considered that the energy of the tsunami flows after the secondary wave was attenuated, because deep water was left by the first wave in the lagoon. Therefore, most of the sandy fractions might not have moved on the bottom of deep water; Subunits 1B and 1C were consequently partially formed.

Unit 2 in the marsh mainly consists of muddy fine sand, including plant fragments, with cross laminae, indicating paleocurrent directions toward the sea; therefore, Unit 2 is interpreted to have been formed by the return flow (Fig. 4A). Traction deposits with parallel and cross laminae were formed because the water depth of the return flow was small, and the flow velocity was high. In contrast, Unit 2 consists of a poorly sorted and graded bedding layer and shows few traces of the tsunami in the lagoon, indicating a seaward flow direction. It can be concluded that the return flow velocity decreased, and most of the grains settled from suspension. Unit 3 consists of massive mud and is considered to have been formed by settling down by suspension at the ponding water stage after the tsunami.

Takashimizu et al. (2017) also divided the 3.11 Tsunami deposits in the Odaka Lowland into three units (Units 1–3, in ascending order). These authors classified Unit 1 as run-up flow deposits, Unit 2 as return flow deposits, and Unit 3 as deposits from ponding water based on an analysis of the paleocurrent directions using magnetic fabric. These results are consistent with the interpretation for the 3.11 Tsunami deposits in the Idagawa Lowland in this study.

2. Formation processes of the tsunami deposits

The formation processes of the 3.11 Tsunami deposits in the Idagawa Lowland are reconstructed as Fig. 7 on the individual stage of the tsunami water level, based on the inundation, distribution, and sedimentary facies of the tsunami deposits.

(1) Before the tsunami struck

The Idagawa Lowland was a small estuary behind the beach ridge and was surrounded by the hills, the sea dike, and the bank of the Miyata-gawa River.

(2) Stage 1

1–1: Run-up flow encroached through the Miyata-gawa River, and the drainage channel was directly exposed to the open sea. The run-up flow spilled from the bank of the drainage channel, which had a low elevation height, and formed Subunit 1A.

1–2: The run-up flow overflooded the bank of the Miyata-gawa River, and the drainage channel was directly exposed to the open sea. The run-up flow spilled from the bank of the drainage channel, which had a low elevation height, and formed Subunit 1A.

1–3: The run-up flow overflooded the sea dike due to the increased water depth. Severe erosion and the large hydrodynamic force of the flow destroyed the residential area along the bank, and Subunit 1B was deposited.

1–4: The run-up flow, decreasing the water depth, inundated an area 3.2 km inland from the shoreline and deposited Subunit 1C, which included many mud rip-up clasts. Severe erosion occurred on the seaward side of the Transverse Road as a result of damming by the embankment and the confluence with the diagonal overflow from the river bank. Thick muddy deposits were also formed.

1–5: The flooded water left by the tsunami hardly drained, because the return flow was impeded by the beach ridge and sea dike.
Formation processes of tsunami deposits following the 2011 Tohoku-oki earthquake in the estuary

**Fig. 7** Schematic model of the formation of the tsunami deposits in the small estuary system in the Idagawa Lowland behind the beach ridge before the tsunami, during Stages 1–3, and after the tsunami. Stages 1–3 are shown in Fig. 6.
(3) Stage 2
The tsunami water had been remained with large water depth on the lowland. And subsequent minor run-up flows overflooded the sea dike and the bank of the Miyata-gawa River and partially formed Subunits 1B and 1C.

(4) Stage 3
The return flow was mainly drained through the Miyata-gawa River and could be attributed to a drop in the water level; Unit 2 was subsequently formed on the lowland. It shows a comparably well-sorted traction, and sand was deposited in the marsh where the water was shallow. Poorly sorted muddy sand settled down from the suspension because of the low flow velocity in the lagoon when the water was deep.

(5) Ponding after the tsunami
As the water depth of the tsunami became lower than the height of the bank of the Miyata-gawa River, the tsunami water could not be drained, and Unit 3 consisting of massive silt settled down from the ponding water for the long term.

Takashimizu et al. (2012) reported that most of the 3.11 Tsunami deposits in the Sendai Plain were formed from the first run-up tsunami flow, and the return flow deposits were rare due to the return flow having been blocked by the beach ridge. We further propose that minor run-up flows went over the beach ridge and formed a part of Unit 1 in Stage 2. Moreover, we suggest that Unit 2 was widely formed in the tsunami inundation area at Stage 3. The reason for the occurrence of major return flows is that the flooded sea water easily drained back through the river at a small lagoon in comparison with a large strand plain such as the Sendai Plain.

Conclusion
The Idagawa Lowland is situated in a small estuary system and comprises the beach ridge, lagoon, marsh on the seaside, Miyata-gawa River, and drainage channel running through the lowland. The water depth of the 3.11 Tsunami at the beach ridge was approximately 12 m and it reached 3.2 km inland from the shoreline. The deposits of the 3.11 Tsunami ranged from 1 to 26 cm in thickness and are divided into three main units (Units 1–3, in ascending order). The water level of the 3.11 Tsunami recorded in Odaka-gawa shows three stages (Stage 1–3) by the amplitude pattern. Stage 1 comprises the first wave with a remarkably high water level. The water level was slightly lower in Stage 2 and was at its lowest in Stage 3.

Unit 1 is subdivided into Subunits 1A–1C. Subunit 1A consists of well-sorted fine sand, and shows a narrow and long distribution along the drainage channel. Subunit 1A is interpreted to have been formed from the run-up flow that encroached through the drainage channel in the lagoon in the early phase of Stage 1. Subunit 1B consists of fine sand, including gravels and rock lumps, originating from the artificial embankment, and is distributed along the beach ridge and Miyata-gawa River. We propose that severe erosion and the large hydrodynamic force of the spilled run-up flowed over the bank of the Miyata-gawa River and the sea dike, destroying the residential area and depositing most of Subunit 1B in Stage 1. Subunit 1C is distributed across almost the entire inundation area, and mainly consists of medium to fine sand. It is likely that the run-up flow led to a decrease in the water depth inundating the inland area, resulting in the creation of Subunit 1C at the phase of the tsunami extending inland in Stage 1. Furthermore, parts of Subunits 1B and 1C were formed from minor run-up flows in Stage 2.

Unit 2 mainly consists of muddy fine sand and includes plant fragments with cross laminae, indicating paleocurrent directions toward the sea and formation by return flow in Stage 3. It can therefore be premised that the return flow mainly drained along the Miyata-gawa River and formed Unit 2 in the lowland. Unit 3 consists mainly of massive mud and was deposited from suspension during the ponding water stage that occurred after the tsunami.

By reconstructing the formation processes of the tsunami deposits and correlating them with the topography and sediments on the ground surface along the tsunami pathways, we aimed to improve understanding of the relationship among the behavior, sedimentary facies, and water level of the tsunami that inundated the land area. Additionally, understanding the sedimentary features of the deposits created by the 3.11 Tsunami contributes to the identification of paleotsunami deposits.

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福島県南相馬市小高区のエスチュアリーにおける2011年東北沖地震による津波堆積物の形成過程

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南相馬市小高区の井田川低地は小規模なエスチュアリーで, 2011年東北地方太平洋沖地震津波が3.2km内陸まで遡上した. 本論では遡上経路の地形と堆積物の層相のもとづき, 津波堆積物の形成過程を復元した. 津波堆積物は下位よりユニット1～3に区分され, ユニット1はサブユニット1A～1Cに細分化される. サブユニット1Aは細粒砂からなり, 津波の初期に排水路から侵入した津波による堆積物である. サブユニット1Bは雑多な礫が多量に混じる, 浜堤と河川堤防を越流した遡上流による堆積物である. サブユニット1Cは中～細粒砂からなる, 内陸まで到達した遡上流の堆積物である. これらのサブユニットの大部分は, 波高が特に大きかった津波第1波の遡上流により形成された. ただし, サブユニット内には津波第2波以降の小規模な遡上流により形成された明瞭な侵食面が部分的に認められる. ユニット2は淘汰不良な泥質細粒砂からなり, 津波波高が低下した津波後半での戻り流れによる堆積物である. ユニット3は塊状の泥からなり, 津波後の冠水期間に沈積した堆積物である.