Tsunami deposits in Holocene estuary sediments, based on lithologic study of cores from two drilling sites in Odaka district, Minamisoma City, Fukushima Prefecture, Northeast Japan

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The purpose of this study is to reconstruct the paleo-environmental changes in the last 10,000 years and to identify the event deposits in sediments of an estuary in the southern part of Minamisoma City, Fukushima Prefecture, northeast Japan. The area was used for growing rice until it was inundated by the tsunami of March 11, 2011. A 15-m-long core of the Holocene sediments and underlying Pleistocene sandy siltstone was taken and sedimentary facies were identified based on the core description. Soft X-ray photograph, grain size analysis, and radiometric 14C dating were conducted to assess the paleo environment and sources of each event deposit. The environment changed as follows: (1) 10,000–8,500 cal. yr BP: the area changed from backshore to sandy and muddy tidal flat following the Last Glacial Maximum, (2) 8,500–6,000 cal. yr BP: tidal flat environment changed to central basin of the estuary during the Holocene maximum transgression, and (3) 6,000 cal. yr BP–present: salt marsh environment formed after the sea level rise. A few event sand beds intercalated in the deposits. The event sand beds contain muddy rip-up clasts and marine shell fragments, and represent lamination, grading structures, and periodic sedimentation. These characteristics suggest that they are possible tsunami deposits.

Key words: environmental changes, estuary, Holocene, tsunami deposits

Introduction

The Idagawa estuarine lowland (formerly Idagawaura) is situated on the coast of the Pacific Ocean in the northern part of Odaka District, Minamisoma City, Fukushima Prefecture, northeast Japan (Fig. 1). The lowland (referred to as Idagawa Lowland) was reclaimed in 1929 and has since been used as a rice growing area. The lowland has poor drainage and has been flooded several times by the Miyata-gawa River (Fukushima Prefecture, 2004). On March 11, 2011, this area was attacked by a tsunami triggered by the 2011 off the Pacific coast of Tohoku Earthquake (Sawai, 2012; Kusumoto et al., 2018; Oota et al., 2018). Kakubari et al. (2017) reported the possibility of tsunami deposits in Holocene sediments of this area based on the lithological study of boring cores (ODMS core) taken 900 m seaward from the study area (Fig. 1). Hence, tsunami and flood deposits were possibly preserved in the estuary present at this site.

The sediments that deposit over shorter periods, such as during tsunami, floods, and storms are collectively called “event deposits.” Tsunami deposits are defined as “sediments deposited by tsunami or tsunami-originated streams that erode seabeds and/or coastal deposits, and transported and reworked elsewhere” (Sawai, 2012). Studying tsunami deposits is important from the viewpoint of disaster mitigation (Seo and Ohkushi, 2014) as it helps in assessing the scale of paleo-tsunamis and predict future tsunamis. The unequivocal identification criteria of tsunami deposits have
not been established yet and is still a matter of debate. However, the deposits can be identified through multiproxy evidence such as historical documents, specific sedimentary structures, grain size composition, chemical analysis, and micro-fossil analysis (Morton et al., 2007; Komatsubara, 2012).

The aim of this study is to reconstruct environmental changes during the Holocene and identify tsunami deposits and their occurrence intervals based on sedimentary facies analysis, grain size analysis, and radiometric $^{14}$C ages.

Study area

The drilling site (N 37°31’25”, E 141°0’35”) is on the western side of the Idagawa Lowland, between the Miyagawa River and an irrigation channel on the south (Fig. 1). The area is an alluvial lowland located in the Pliocene–Pleistocene hills. It is composed of a marsh, a lagoon, and beach ridges along the coast line (Kubo et al., 1990). The sea level was 3–5 m higher during the Holocene maximum transgressive period. Due to the inundation of seawater into the valley ~6,500 years ago, a small estuary was formed at the study area (Ministry of the Environment, Biodiversity Center of Japan, 2013). Subsequently, the estuary increased and decreased in size in response to changes in the sea levels and formed a small lagoon 100 years ago.

Idagawa Lowland is located behind beach ridges and is suitable as a study area due to the sand and gravel that play a significant role as tsunami deposits.

Methods

A 15-m-long core was taken from June 25 to 28, 2018. The drilling site is named ODMS II, and the core of diameter 7.0 cm is referred to as the ODMS II core. The core is composed of Pliocene–Pleistocene basement rock (Dainenji Formation), Holocene estuarine sediments with intercalated event sand beds, and the tsunami deposits that formed by the 2011 off the Pacific coast of Tohoku Earthquake (referred to as 3.11 tsunami deposits in this study) at the top. The penetration depth was 15 m and the Holocene base was found at the depth of 14.27 m. The unconsolidated Holocene sediments of the core were cut in half vertically, its lithology identified, and samples were obtained for soft X-ray photography, grain size analysis, and radiometric $^{14}$C dating.

1. Core description

The surface sections were described in terms of lithology, sedimentary structures, color tones, grain size, constituent particles, and bioturbation intensity. The results were summarized in description sheets with a scale of 1/5 and explained as columnar sections with a scale of 1/25. The sedimentary facies were identified based on the columnar sections and the paleo environments were constructed sub-
sequently.

2. Soft X-ray photographs

Each 1.0-m-long sample was divided into four transparent acrylic cases (length 25.0 cm, width 5.0 cm, and thickness 1.0 cm). Soft X-ray images were captured for the samples from above an 11.00-m depth using an X-ray imaging inspection apparatus (SOFTEX Co. Ltd., M-60, irradiation time 40 s, voltage 40 kVp, current 3.0 mA). Photographs were not captured for samples from below the depth of 11.00 m due to large gravels that originated from the Dainenji Formation (core depth 14.27–14.40 m).

3. Grain size analysis

Samples for grain size analysis were collected at ~2.0–3.0 cm intervals for the sandy part, and 10.0 cm intervals for the muddy part. They were added to a 10% H2O2 solution to eliminate organic matters. The grain size was measured by a Coulter LS13 320 (Beckman Coulter Co. Ltd.) laser diffraction grain size analyzer, which is based on laser diffraction and Fraunhofer diffraction theory. Mean grain size data were used in this study.

4. Radiometric ¹⁴C ages

Five well-preserved wood fragments (core depth 0.78, 0.8, 4.0, 6.85, and 10.285 m) and three shells (core depth 1.99, 2.46, and 12.95 m), which were possibly in situ, were collected and washed with deionized water. The sample ages were determined by the Institute of Accelerator Analysis Ltd. using the AMS (Accelerator Mass Spectrometry) method. The ages were calibrated by OxCal v4.3 (Bronk Ramsey, 2009) using the Marine 13 database (Reimer et al., 2013) for shells, and IntCal 13 database (Reimer et al., 2013) for wood (Table 1).

| Lab. code | Depth (m) | Material | \( \delta^{13}C(\%) \) (AMS) | Conventional \( ^{14}C \) age (yrBP) | 2σ calibrated age (cal. yrBP) |
|-----------|----------|----------|---------------------|------------------------|-------------------------------|
| IAAA-181265 | 0.78     | Wood     | -32.42±0.28         | 1,294 ± 20              | 1,230–1,290                   |
| IAAA-180388 | 0.80     | Wood     | -26.50 ± 0.49       | 1,741 ± 22              | 1,590–1,710                   |
| IAAA-180389 | 1.99     | Shell    | -10.01 ± 0.29       | 1,594 ± 23              | 1,070–1,240                   |
| IAAA-180390 | 2.46     | Shell    | -0.38 ± 0.45        | 2,139 ± 24              | 1,630–1,810                   |
| IAAA-180391 | 4.00     | Wood     | -24.20 ± 0.32       | 3,433 ± 25              | 3,610–3,730                   |
| IAAA-180392 | 6.85     | Wood     | -28.53 ± 0.36       | 3,737 ± 25              | 4,060–4,160                   |
| IAAA-180393 | 10.285   | Wood     | -27.88 ± 0.33       | 7,470 ± 30              | 8,200–8,370                   |
| IAAA-180394 | 12.95    | Shell    | 4.24 ± 0.49         | 8,259 ± 30              | 8,650–8,950                   |

Ages are calibrated by OxCal v4.3 (Bronk Ramsey, 2009) using Marine 13 database (Reimer et al., 2013) for shells, IntCal 13 database (Reimer et al., 2013) for woods.

Results

Based on the lithology, color tone, grain size, constituent particles, bioturbation intensity of the core, and radiometric ¹⁴C ages, the cores of ODMS II and ODMS (Kakubari et al., 2017) were correlated and their depositional environments were assessed (Figs. 2 and 3).

1. Lithology and depositional environments

Core depth 14.27–13.56 m: Poorly sorted greenish–gray sand overlies on the sandy siltstone of the Dainenji Formation with erosional base. The lowest layer consisted of very fine sand and the grain size increased from fine to medium on the upper layers. Sub-angular granite pebble (approximate diameter 7 cm) was found at the depth of 14.1 m. The other constituent pebbles (diameter from a few mm to 1 cm) were mostly greenish–gray sandy siltstones that originated from the surrounding hills of the Dainenji Formation. These characteristics were similar to those of Facies A in the ODMS core (Kakubari et al., 2017, Figs. 4A and B), which may have deposited under backshore environments. Granite pebbles might have been derived from the Abukuma Mountains through a river, such as the Abukuma-gawa River and reworked from the coast by transgression. These pebbles may have been deposited under backshore settings during the transgressive period, similar to Facies A (Kakubari et al., 2017).

Core depth 13.56–10.20 m: Silty fine sand gradually overlies below backshore sediments (Facies A). The lower part was composed of poorly sorted dark green silty fine to coarse sand. It contained fragments of oyster and silty sub-rounded to sub-angular pebbles (diameter 0.5–4.0 cm). The upper part was composed of poorly sorted dark green and dark gray silty fine to medium sand that contained silty sub-rounded to sub-angular pebbles (diameter 0.5–3.5 cm) and
muddy rip-up clasts. Well-preserved oysters and bivalves such as *Callithaca* sp. and *Scapharca* were observed in the 11.00–10.95-m interval. Bioturbation was found to be intense through this interval. These characters matched those of Facies B (Figs. 4D and E), as described by Kakubari et al. (2017). The intertidal molluscan assemblages present in the sediments indicated that they were deposited under a tidal-influenced sandy tidal flat environment (Dalymple, 1992).

**Core depth 10.20–8.63 m:** Sandy tidal flat sediments (Facies B) were overlain by muddy sediments. The lower part demonstrated an upward-fining succession of dark greenish–gray clay to silt yielding burrows with the presence of silty sub-rounded to sub-angular pebbles (diameter 0.8–1.5 cm). Shell fragments and carbonaceous matters are scattered throughout. The middle part is composed of sandy clay and silty clay. The sediments in the 9.83–9.56-m interval showed lamination structures and week bioturbation. A few wood fragments and carbonaceous matters were included as well. A single fine gray sand layer of 1.0 cm thickness was interbedded in the 9.30–9.31-m interval. A gray ash layer, 3.5 cm in thickness, was present in the 9.065–9.03-m interval. The upper part comprised of dark green clay and a few wood fragments. Bioturbation was almost absent in this interval. These successions are similar to those of Facies E (Figs. 4F and G), as described by Kakubari et al. (2017) and have been considered as event deposits (Shiki, 1993; Sawai, 2012; Kamataki et al., 2015).

The muddy sediments comprised of black and dark green silt and silty clay as major components. They contained plants, wood, and shell fragments. The 1.90- to 1.00-m interval was composed of black organic rich sandy clay and clay that contained stems. These characteristics are similar to those of Facies G (Figs. 4H and I), as described by Kakubari et al. (2017). The salt marsh deposits (Ishihara et al., 2004; Dalrymple, 1992) may have deposited due to the mixing of seawater with fresh water.

**Core depth 8.63–0.38 m:** Two sand beds were present at depths of 8.63–8.60 m and 8.53–8.50 m, and represent the grading structures of coarse and medium sand to very fine sand. The other sand beds deposited above this interval comprised of blackish–brown and dark green fine to medium sand. The sand sheets having a sharp or erosional base and a thickness of a few millimeters to 10 cm were intercalated in muddy sediments. A majority of the sand beds that represented normal grading (Fig. 5D) and lamination structures (Fig. 5B) contained muddy rip-up clasts (Fig. 5C) and broken shell fragments. These characteristics matched those of Facies F (Figs. 4H and I), as described by Kakubari et al. (2017) and are inferred as artificial fill and paddy soil.

**Core depth 0.25–0 m:** A single normally graded sand bed (Facies F) eroded and blanketed below the artificial fill and paddy soil (Facies H). This sand bed was deposited by the tsunami triggered by the 2011 off the Pacific coast of Tohoku Earthquake (Oota et al., 2017). The sediments on the sand bed consist of red roughed muddy and sandy sediments. The muddy sediments are considered to have been formed by suspension at the ponding water stage, because the drainage pump was broken and the study area was submerged for over a year after the tsunami (Oota et al., 2017).

### 2. Grain size distribution

The results of grain size analysis are shown in Fig. 2.

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**Table 2** Radio carbon ages obtained from ODMS core.

| Lab. code | Depth (m) | Material | δ¹³C(%) (AMS) | Conventional ¹⁴C age (yrBP) | 2σ calibrated age (cal. yrBP) |
|-----------|-----------|----------|---------------|---------------------------|------------------------------|
| IAAA-160224 | 1.46 | Shell | 0.93±0.33 | 987±22 | 520–630 |
| IAAA-151475 | 2.78 | Shell | -2.71±0.50 | 2,348±25 | 1,880–2,060 * |
| IAAA-160226 | 4.40 | Shell | 1.27 ± 0.66 | 3,336±28 | 3,080–3,310 |
| IAAA-160227 | 7.54 | Shell | 4.53 ± 0.53 | 4,177±28 | 4,150–4,380 |
| IAAA-151476 | 15.40 | Wood | -28.15 ± 0.36 | 5,840±29 | 6,600–6,740 |
| IAAA-151477 | 21.40 | Wood | -27.96 ± 0.53 | 8,275±32 | 9,130–9,330 |

* Ages are calibrated by OxCal v4.3 (Bronk Ramsey, 2009) using Marine 13 database (Reimer et al., 2013) for shells, IntCal 13 database (Reimer et al., 2013) for woods.
* Lab. code IAAA-151475 was calibrated by OxCal v4.2.4 (Bronk Ramsey, 2013).
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Fig. 2  A and B: Sedimentary column, sedimentary facies, and grain size of the ODMS II and ODMS cores. The data in ODMS core are from Kakubari et al. (2017). C: Sedimentary facies and interpreted environment modified from Kakubari et al. (2017). Two-step grayscale and symbols in the lithology refer to the legends of Figs. 2A and B.
Although the mean grain size was smaller than 100 μm, some intervals in the upper part showed a grain size of up to 400 μm.

The central basin sediments (Facies E, core depth 10.20–8.63 m) represent the grading structures in the lower part. A single fine sand sheet was present in Facies E at the depth 9.30–9.31 m.

The mean grain size of the event sand beds (Facies F) in salt marsh deposits (Facies G) indicate that they are mostly composed of fine to medium sand. These sand sheets are normally graded or comprise two or more couples.

3. Radiometric 14C dating

The results of radiocarbon dating are shown in Fig. 3 and Table 1. We excluded the sample at the depth of 0.8 m because it shows older ages than those below the depth of 1.99 m that were likely recycled from an older deposit. Other than that, the samples show older ages in proportion to the depth and suggest that they might have been deposited continuously since 8,650–8,950 cal. yr BP.

Discussion

1. Changes in depositional environments

The Holocene sediments were composed of backshore, sandy to muddy tidal flat, estuary, and salt marsh with interbedded event sand beds and artificial fill and paddy soil in the ascending order. Both ODMS II and ODMS (Kakubari et al., 2017) cores were found to be similar in lithology and age. Radio carbon dating indicated that the sedimentation may have started earlier than approximately 9,000 cal. yr BP.
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Fig. 4  A: Facies A at depth 13.56–13.76 m in ODMS II, B: Lower part of Facies A at depth 24.00–24.25 m in ODMS; Bioturbated olive-gray to greenish-gray sand and conglomerate including pebbles. C: Upper part of Facies A at depth 23.20–23.45 m in ODMS; Dark greenish-gray medium to upper fine sand. D: Facies B at depth 10.25–10.50 m in ODMS II, E: Facies B at depth 19.75–20.00 m in ODMS; Olive-gray silty sand and sand including oyster and shell fragments. F: Facies E at depth 9.50–9.75 m in ODMS II, G: Facies E at depth 15.75–16.00 m in ODMS; olive-black silt and silty sand, and gray silt and silty sand with laminae. H: Facies F and G at depth 5.60–5.85 m in ODMS II, I: Facies F and G at depth 5.10–5.35 m in ODMS; gray sand including shell fragments (Facies F) intercalated in olive-black silty sand with shell and wood fragments (Facies G).
The mud layers in the ODMS core are mostly thinner and finer than those in the ODMS core: depth 24.96–23.0 m; ODMS core: depth 19.50–13.36 m) in the ODMS core can be correlated with the upper part of Facies A (depth 24.96–23.0 m) in the ODMS core.

**9,000–8,500 cal. yr BP:** Two samples, one from sandy tidal flat (Facies B, 12.95 m) in the ODMS core and the other from muddy tidal flat (Facies C, 21.40 m) in the ODMS core were aged approximately 9,000 cal. yr BP, indicating that they were likely deposited simultaneously. This implies that the area changed to muddy tidal flat settings at the seaward site (site ODMS) and sandy tidal flat settings at the landward site (site ODMS II) as the sea level rose (Fig. 6B). The presence of muddy sediments in the seaward site suggested that the bay settings were established ~9,000 years ago by the formation of barrier islands or beach ridges along the shoreline.

(2) Expansion period of estuary

**8,500–6,000 cal. yr BP:** Muddy sediments of the central basin of the estuary (Facies E, ODMS core: depth 10.20–8.63 m; ODMS core: depth 19.50–13.36 m) overlay below the sandy sediments. A few bioturbation implies the deposition of muddy sediments under the closed central basin floor. The presence of these sediments at each site indicates that the estuary expanded 1.8 km toward the west of the study area from the present shoreline (Fig. 6C) during the Holocene maximum transgression (approximately 6,500 years ago). This is supported by data from the Ministry of the Environment, Biodiversity Center of Japan (2013), in which an estuary of ~3.0 km wide and a water level of ~5.0 m higher than the present are reported.

Washover deposits (Facies D, depth 20.00 to 19.50 m) were present below the estuarine deposits at the ODMS site (Kakubari et al., 2017), but were flushed out during a landward advance of the ODMS II site. The lack of washover deposits suggest that they have not been transported toward the landward site (site ODMS II).

(3) Reduction period of the estuary

**6,000 cal. yr BP-present:** Salt marsh (Facies G) deposits with intercalated event sand (Facies F) beds (ODMS II site: core depth 8.63–0.38 m; ODMS site: core depth 13.00–1.02 m). As the estuary has reduced its area in response to sea level fall after the transgression, the study area was changed to shallower salt marsh settings (Fig. 6D).

Event sand beds were found at a few centimeters to 1.0-m intervals at the ODMS II site and several dozen centimeters to 1.0-m intervals at the ODMS site (Kakubari et al., 2017). The sand layers in the ODMS II core are mostly thinner and finer than those in the ODMS core (Fig. 2). The age of the deepest position of the sand beds in both cores (ODMS II site: core depth 8.53–8.50 m; ODMS site: core depth 13.36–13.00 m) was approximately 6,000 cal. yr BP (Fig. 3), which
implies that they were deposited by the same event. Artificial fill and paddy soil (Facies H) were deposited at the top of each core.

2. Origin of event sand deposits

(1) Event sand beds at the ODMS II site

The sand layers occurred after 6,000 cal. yr BP. We clarified their stratigraphically unique features, mentioned as follows: (1) the base of the sand layers was mostly sharp or erosional; (2) the sediments comprised shell fragments and muddy rip-up clasts; (3) the sand beds represented laminations and normal or multiple grading structures. These characteristics account for general tsunami deposits (Dawson and Stewart, 2007; Morton et al., 2007; Komatsubara, 2012) but not for other processes, such as washover and flood deposits. Washover sediments do not represent these internal structures, such as normal and inverse grading (Reinson, 1992). Flood deposits typically show inverse grading structures (Iseya, 1989). Furthermore, the distance of approximately 1.8 km between the drilling site and shoreline (Fig. 1) indicates against the role of storm surges as the agent of deposition for the event sand beds. Consequently, these event sand beds preserved in the ODMS II site can be best explained as tsunami deposits.

(2) Consideration of the event sand beds in the ODMS II and ODMS cores (Kakubari et al., 2017)

The thinning and finning of the sand layers toward the landside sites (Figs. 2Ac and Bc) imply the landward transport of sand from the sea. Although each of the sand sheets
in both cores can be correlated as the lowest sand beds, more analysis is still required. Moreover, some of the sand beds at the ODMS site (Kakubari et al., 2017) represent basal reverse grading structures, suggesting possible flood deposits. Therefore, it was assumed that all sand beds in both cores could not be correlated.

The occurrence interval of event sand beds at the ODMS II site was calculated to be 600–650 years. Kakubari et al. (2017) calculated the occurrence interval of sand sheets in the ODMS cores as approximately 600 years. These estimated intervals account for the occurrence interval of tsunami in northeast Japan, as investigated by Sawai et al. (2015) in the Sendai Plain.

A single sand layer, 1.0 cm in thickness (depth 9.30–9.31 m), was found in the estuary deposits (Facies E, depth 10.20–8.63 m). Kakubari et al. (2017) did not discover any event sand bed in the interval of the estuary deposits (Facies E, depth 19.50–13.36 m), but mentioned the possible presence of event sand sheets based on grain size analysis (Fig. 2). The lack of event sand deposits in the seaward site indicates a tidal influence. However, the sand layers were more likely to be preserved in the landward site due to a lesser tidal influence. It can be concluded that several events, such as tsunamis, might have occurred periodically earlier than 6,000 years. However, these sediments would not have been preserved in the deeper central basin of the estuary.

Conclusions

Based on a sedimentological interpretation and comparison of the cores at two sites, the following Holocene environmental changes could have taken place. The study area might have changed from a backshore environment to muddy and sandy tidal flats corresponding to sea level rise following the Last Glacial. During the period of Holocene maximum transgression (6,500 years ago), the site changed to the central basin of the estuary. After 6,000 cal. yr BP, the estuary was filled and a salt marsh environment was formed. The study area was reclaimed 100 years ago and has since been used as a rice-growing area.

The event sand beds in the ODMS II core were best explained as tsunami deposits. Moreover, the estimated occurrence interval of the sand beds (600–650 years) was consistent with the invasion period of tsunamis reported for the Sendai Plain.

Tsunami deposits were found in shallower salt marsh settings, but not in the central basin environment of the estuary. It was assumed that the preservation of event sands was constrained by its setting.

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福島県南相馬市小高区における過去１万年間の環境変遷とエスチュアリー埋積堆積物中には含まれるイベント堆積物の識別をおこなうことを目的として、完新統を掘り抜き鮮新-更新統の大年寺層に達する長さ14.45 mのボーリングコアを掘削した。採取した試料のコア記載に基づき堆積相を設定し、軟X線写真撮影、粒度分析、¹⁴C年代測定の結果を総合し古環境の変遷およびイベント堆積物の供給源について考察した。

（1）10,000–8,500 cal. yr BP: 最終氷期後の海進に伴い、研究地域は後浜から泥質および砂質潮汐平底の環境へと変化した。（2）8,500–6,000 cal. yr BP: 糸文海進の最盛期にはエスチュアリー中央盆地の環境が成立した。（3）6,000 cal. yr BP–現在: その後の海退によりエスチュアリーは縮小し、しばしば離水する塩水湿地となった。2011年3月11日に津波が襲来するまでの100年間は水田として利用されてきた。塩水湿地中にはイベント砂層が挟在しており、それらは海成の貝化石やリップアップクラストを含む。また、葉理構造や粒化構造をなすことからそれらの砂層は津波堆積物である可能性が高い。イベント砂層の形成周期はおよそ600年から650年間隔と見積もられ、仙台平野で推定されている津波の襲来周期と一致する。