GEOGRAPHICAL REPORTS
OF TOKYO METROPOLITAN UNIVERSITY 47 (2012) 1-10

REPORT ON THE TSUNAMI DEPOSITS CAUSED BY THE 2011 OFF THE PACIFIC COAST OF TOHOKU EARTHQUAKE IN THE SOMA REGION, FUKUSHIMA PREFECTURE, NORTHEAST JAPAN

Ryo HAYASHIZAKI and Masaaki SHIRAI

Abstract The 2011 off the Pacific coast of Tohoku Earthquake is considered to be a recurrence of the Jogan Earthquake (A.D. 869), and generated tsunamis that caused great damage to a wide range of east Japan on the Pacific side. In this paper, we describe tsunami damages and lithofacies of the tsunami deposits caused by the 2011 off the Pacific coast of Tohoku Earthquake in the Soma region, Fukushima Prefecture, northeast Japan. We found evidence in support of numerous previous studies on tsunami deposits in the area and also report characteristics that have not yet been well-documented. Thickness of the silt layer, which is formed during the stagnant phase after the tsunami run-up, may reflect local relief well. Although further verification is required, description of tsunami deposits at Turishihama Beach indicates the existence of one of the very few run-up tsunami deposits around the shoreline.

Key words: tsunami deposits, sedimentary structures, coastal plain, The 2011 off the Pacific coast of Tohoku Earthquake, Soma region in Fukushima Prefecture

1. Introduction

On March 11, 2011, the 2011 off the Pacific coast of Tohoku Earthquake occurred with a magnitude of 9.0 (Simons *et al.* 2011); this is the largest magnitude recorded in the history of seismic observations in Japan. The main shock occurred at 14:46 on March 11, 2011 (JST). The epicenter is located off Sanriku, 130 km ESE of the Oshika Peninsula (Fig. 1a), and the focal depth is 24 km (Okada 2011). The greatest disaster on record was caused by a huge tsunami that left nearly 20,000 persons dead or missing (National Police Agency, 2011). Because the inundation area of the 2011 off the Pacific coast of Tohoku Earthquake tsunami is similar to that simulated for the A.D. 869 Jogan Earthquake's tsunami (Satake *et al.* 2008), this earthquake is considered to be a recurrence of the Jogan type earthquake.

The Japanese islands have been attacked a large number of tsunamis in recorded history (Watanabe 1998), and many prehistoric tsunami deposits were reported from outcrops and core samples (Fujiwara 2007). Tsunami deposits provide evidence that is important in estimating tsunami inundation area and recurrence interval. General features of tsunami deposits include: (1) the deposits

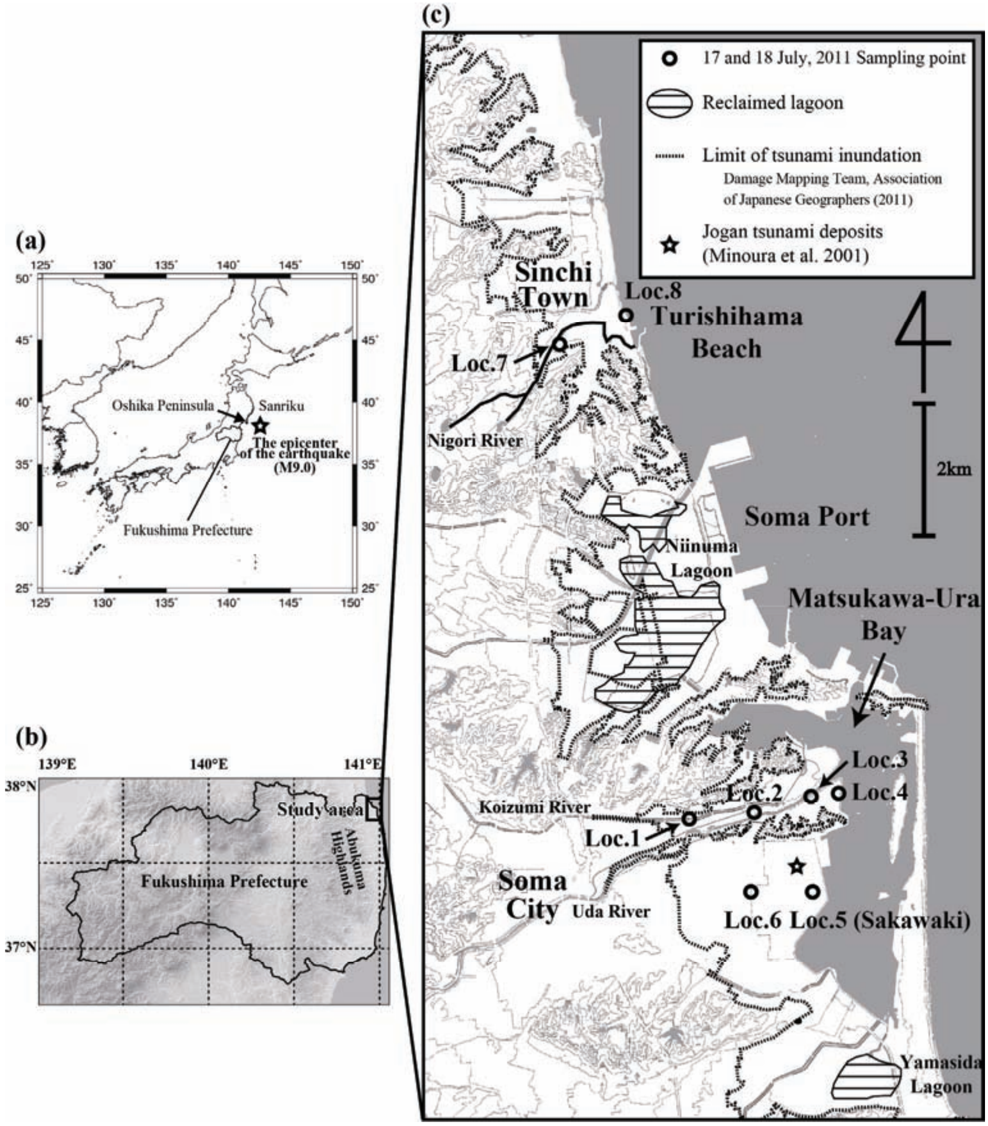

Fig. 1 (a) The epicenter of the 2011 off the Pacific coast of Tohoku Earthquake. (b) Location of study area in Fukushima Prefecture. (c) Locations of tsunami deposits. Modified from the 1:25000 scale map of the Geographical Survey Institute of Japan, "Shinchi" and "Somanakamura".

cover the surface almost continuously on gentle topography, (2) deposit thickness and mean grain size decrease with distance from the shoreline, (3) deposit thickness and depositional characteristics vary greatly across local surface undulations, and (4) graded bedding that reflects tsunami run-up or backwash is present in thick deposits (Nishimura and Miyagi 1995). In this paper, we describe tsunami damages and the lithofacies of the tsunami deposits caused by the 2011 off the Pacific coast of Tohoku

Earthquake around the Soma region, the Pacific side of Fukushima Prefecture, northeastern Japan (Fig. 1b).

2. Geomorphological Setting

The Soma region of Fukushima Prefecture is located in the east of the Abukuma highlands (Fig. 1b). The area consists of coastal plains and hills. In the Matsukawa-Ura Bay, a coastal lagoon covers an area of 5.9 km^2 along the line of the coast. The Niinuma Lagoon and the Yamashida Lagoon existed north and south of the Matsukawa-Ura Bay and were reclaimed in 1935 and 1944, respectively (Nakagawa 1955). The Jōgan Earthquake tsunami deposits were found on the western coast of the Matsukawa-Ura Bay (Minoura *et al.* 2001) (Fig. 1c).

The height of the 2011 off the Pacific coast of Tohoku Earthquake tsunami was greater than 9.3 m in the region of the study area (Japan Meteorological Agency 2011), and maximum run-up height was 11.8 m around Soma Port and 15.9 m around Turishihama Beach (Shimosako *et al.* 2011). Many reports of the tsunami inundation area have been constructed using aerial photographs and satellite images obtained after the tsunami. A tsunami inundation map created by the Tsunami Damage Mapping Team, Association of Japanese Geographers (2011) is used in Fig. 1c.

We conducted field investigation at 8 locations (Loc. 1–8) in the Soma region from July 16 and 17, 2011.

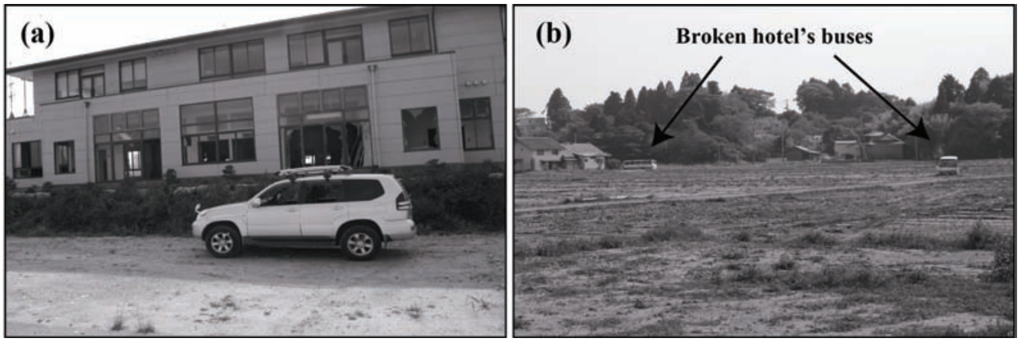

Fig. 2 Photographs of tsunami impact (July 17, 2011). (a): A hotel damaged by tsunami at Loc. 4. (b): Broken hotel's buses near the Loc.3. These buses were transported from the hotel around Loc.4.

Uda River (Loc. 1 to Loc .4)

The Uda River and Koizumi River stream eastward and flow into the northern part of the Matsukawa-Ura Bay (Fig. 1c). At Loc. 4, near the Matsukawa-Ura Bay coastline, the tsunami deposits were about 5 cm thick in the parking area. Ground floor of buildings was broken at Loc. 4 and lots of debris were deposited by the tsunami (Fig. 2a). The hotel's buses were transported 800 m inland by the tsunami (Fig. 2b). Along the Uda River, thinning and fining of the tsunami deposits upstream were observed on the rice paddy field from Loc. 3 to Loc. 1. In the Koizumi River, the riverbed was covered by muddy deposits about 2.5 km upstream from the river mouth (Loc. 1). On the surface of the muddy sediments, many burrows were formed by benthic organisms that had been brought from the bay and survived after the tsunami (Fig. 3a). Local inhabitants said that the riverbed was not covered by muddy deposits before the tsunami. Location 3 was on the rice paddy field beside the Uda River, at 2 m elevation, and tsunami deposits were about 11.5 cm thick.

Sakawaki (Loc. 5 and Loc. 6)

Low-lying rice paddy fields with 2–5 m height are spread along the western coast of the Matsukawa-Ura Bay. The tsunami ran up westward toward the rice paddy field, which is about 2.5 km from the coast (Fig. 3b). Location 5 is located at a height of 2 m in a rice paddy field 200 m west of the coast. Tsunami deposits were only about 5 cm thick on the rice paddy field, but about 27 cm thick in a drainage channel. At Loc. 6, about 800 m west of Loc. 5, the tsunami deposits were 23 cm thick at the corner of the rice paddy field.

Fig. 3 Photographs showing tsunami impact (July 17, 2011). (a): Koizumi riverbed around Loc. 1. (b): The rice paddy field around Loc. 5.

Shinchi

The Shinchi Town is the northern neighbor of the Soma City (Fig. 1c). At Loc. 7 along the Nigori River, about 1 km from the coast, tsunami deposits were 12 cm thick in the rice paddy field. The Nigori River drains south of Turishihama Beach. Within ~750 m upstream from the coastline, buildings were destroyed. Location 8 is on the backshore at Tsurishihama Beach, at about 2 m height. The tsunami destroyed the breakwater and produced depression contours caused by erosion at the backside of breakwater (Fig. 4a). Buildings near the coastline around Turishihama Beach were completely destroyed by the tsunami (Fig. 4b). As shown in Fig. 5, the sand beach was thicker and the gradient of the foreshore was steeper compared to before the tsunami (October 17, 2010).

3. Descriptions and Interpretation of Tsunami Deposits

We describe tsunami deposits preserved well at 3 locations (Locs. 3, 5, and 8).

Loc. 3 (Fig. 6a)

The tsunami deposits have a wavy base. The deposits are subdivided into 6 layers, which are described in ascending order as follows:

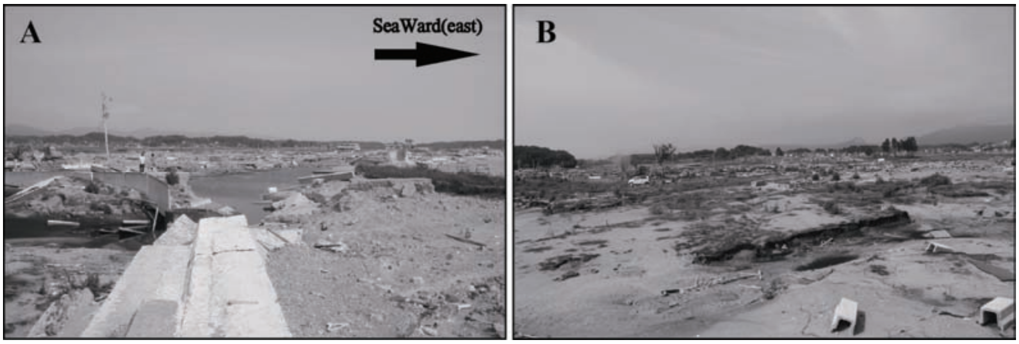

Fig. 4 Photographs of tsunami impact (July 18, 2011). (a): Destroyed breakwater around Loc. 8. (b): Thoroughly destroyed buildings near the coastline around Turishihama Beach.

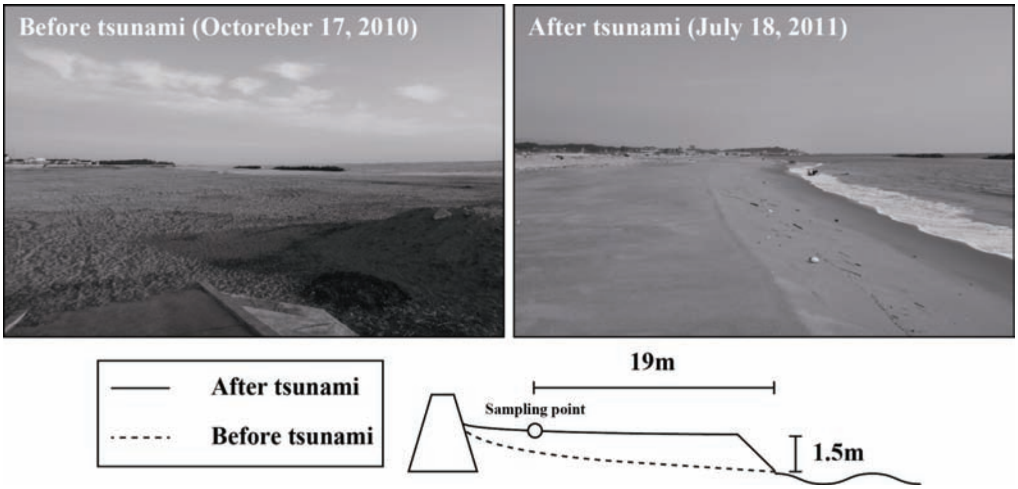

Fig. 5 Turishihama Beach (around Loc.8) landforms before and after the tsunami. Both pictures were taken at the low tide levels.

0–3.5 cm: normally graded, very coarse to coarse sand;
3.5–4.0 cm: lenticular organic-rich black silt;
4.0–5.0 cm: normally graded medium sand;
5.0–5.3 cm: thin organic-rich black silt;
5.3–11.0 cm: normally graded medium to fine sand; and
11.0–11.5 cm: thin silt layer, dried and cracked.

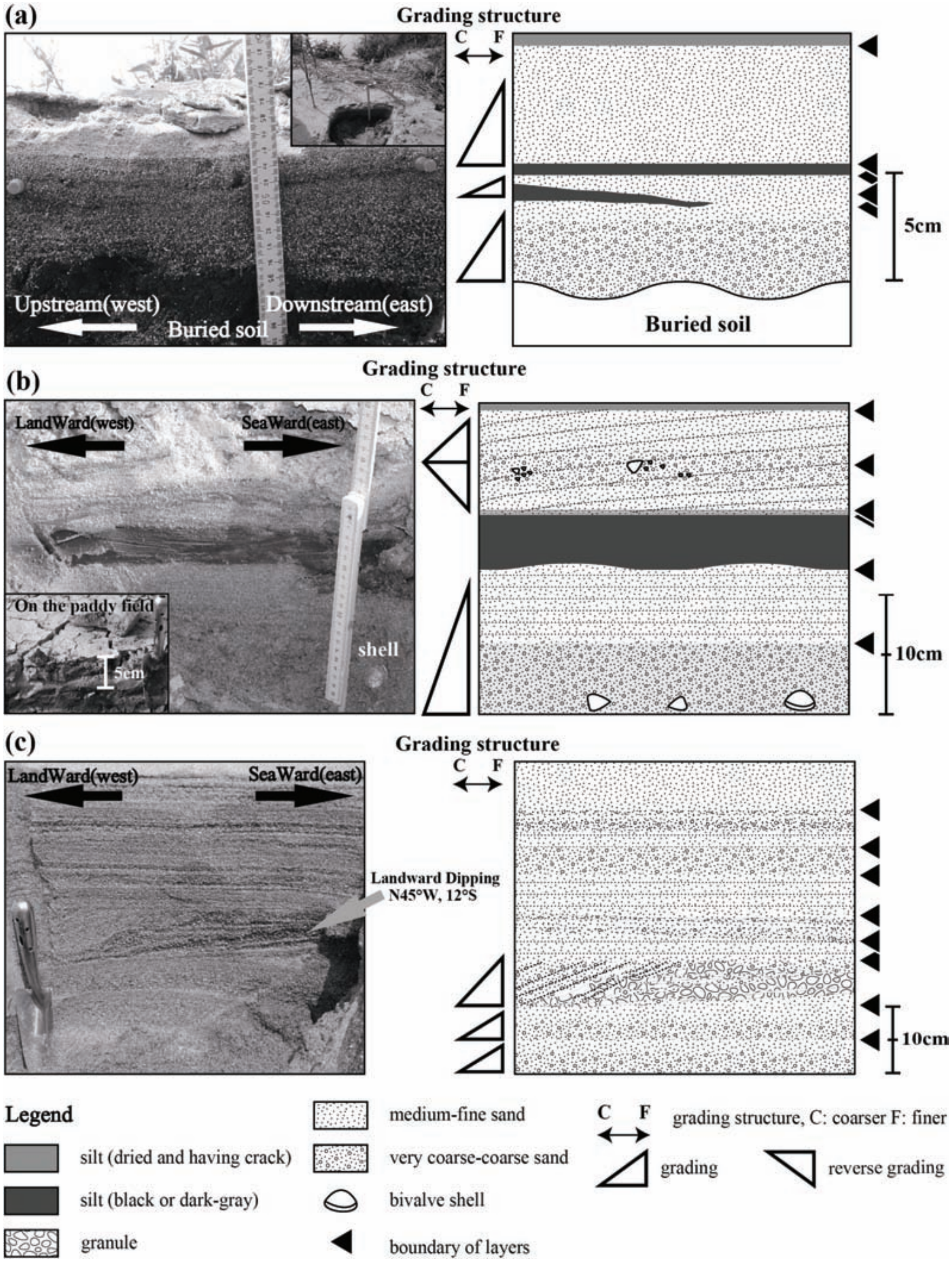

Fig. 6 Photographs and descriptions of the tsunami deposits at (a) Loc. 3, (b) Loc. 5, (c) Loc. 8.

The wavy base of the tsunami deposits indicates erosion of buried soil by the tsunami, as has been described by Gulfenbaum and Jaffe (2003) and others. Many papers have reported normally graded tsunami deposits, which reflect waning tsunami flow (Shiki *et al*. 2008). The lowest and coarsest layer of the tsunami deposits (0–3.5 cm) may reflect the most powerful tsunami flow (Fujiwara and Kamataki 2007). A thin silt layer containing many plant fragments settled during the stagnant phase after the tsunami run-up (Nanayama and Shigeno 2006). Two organic-rich black silt layers (3.5–4.0 cm and 5.0–5.3 cm) indicate settling of the fragments during the stagnant phases. Therefore, the underlying 0–3.5 cm and 4.0–5.0 cm normally graded sand layers were formed by the tsunami run-up immediately before the stagnant phase. The uppermost silt layer (11.0–11.5 cm) may also have formed during the stagnant phase. However, silt layers can also be formed in puddles during the backwash phase, and so the uppermost silt layer may have formed at the end of tsunami inundation. As a result, it was not possible to identify whether the 5.3–11.0 cm normally graded sand layer was formed by run-up or by backwash.

Loc. 5 (Fig. 6b)

The tsunami deposits were directly overlying the base of the drainage channel, where pebbles and bivalve shells were scattered. The deposits are subdivided into 7 layers. In ascending order, these layers are described as follows:

0–6.0 cm: normally graded dark gray coarse sand, rich in pebbles and opaque minerals;
6.0–12.0 cm: normally graded coarse to medium laminated sand, with wavy upper boundary;
12.0–16.5 cm: organic-rich dark gray silt;
16.5–17.0 cm: laminated sand, including thin organic-rich dark-gray silt layer;
17.0–21.5 cm: reverse graded medium sand to granule with landward-dipping laminae and shell fragments;
21.5–26.0 cm: normally graded coarse to medium sand with landward-dipping laminae; and
26.0–27.0 cm: silt layer, dried and cracked.

The tsunami deposits are thin on the rice paddy field and thick in the drainage channel at Loc. 5. These facts reflect typical tsunami feature of deposit thickness varies greatly according to local surface relief (Nishimura and Miyagi 1995). Bivalve shells and opaque minerals, being high specific gravity, are scattered at the base of the tsunami deposits. Bivalve shells may have been transported from the Matsukawa-Ura Bay by the tsunami run-up. Heavier particles might require more support from the tractive force (Shiki *et al.* 2008), and the presence of large amounts of opaque minerals indicates that the current energy of the tsunami is relatively high. Organic-rich, dark gray silt layer (12.0–16.5 cm) indicates settlement of fragments during the stagnant phase. Consequently, the sand layers from 0–12.0 cm have been formed during the tsunami run-up. The sand layer with silt laminae at 16.5–17.0 cm was formed by ripping up the lower layers. The landward-dipping laminae and abundant shell fragments in the section from 17.0–21.5 cm suggest that the sand layers in the section from 17.0–26.0 cm may also have been formed by the tsunami run-up. The inversely graded sand layer (17.0–21.5 cm) indicates deposition under high-density currents, and the normally graded sand layer (21.5–26.0 cm) indicates deposition from waning currents (Fujiwara *et al.* 2003). The uppermost silt layer (26.0–27.0 cm) was formed after the tsunami reached the run-up limit or after the end of tsunami inundation.

Loc. 8 (Fig. 6c)

Although we investigated up to ca. 50 cm depth from the beach surface, the basement of the tsunami deposits was not encountered. The deposits are subdivided into 9 layers. In ascending order, these layers are described as follows:

0–5 cm: normally graded coarse to medium sand;

5–10 cm: normally graded very coarse to medium sand;

10–17 cm: coarse sand with landward-dipping granule layer (N45°W, S12°), and overlying landward-dipping laminae;

17–20 cm: medium sand with parallel laminae;

20–24 cm: coarse sand with gently seaward-dipping laminae;

24–30 cm: medium sand with parallel laminae;

30–34 cm: coarse sand with parallel laminae;

34–40 cm: coarse to medium sand with parallel laminae; and

40–47 cm: medium to fine sand.

The sand layers at 0–5 cm and 5–10 cm exhibit no distinct erosional boundary inside. On the foreshore environment in usual condition, light minerals (quartz, feldspar, and so on) which have lower specific gravity and coarser grain size tend to be carried away by intense swash wave. Subsequently, heavy minerals (magnetite and others) are left on the beach surface and make black-colored laminae (e.g., Komar and Wang 1984). Whereas, these graded layers are not formed by oscillating flow on beach commonly and were estimated as being formed by continuous unidirectional flow such as tsunami. The landward-dipping laminae and granule layer (10–17 cm) is thought to have been formed by landward water currents. Because Loc. 8 is at about 2 m height on the backshore at Turishihama Beach, it is unlikely that swash reached here during high tide. Storms generally cause coastal erosion (Takeda 1997) and rarely result in landward-dipping sand layers. The absence of shallow depressions, interpreted as seawater channels on the beach surface also suggests that swash and storm waves did not reach Loc. 8. Therefore, the landward-dipping lamina and granule layer is thought to have been formed by the tsunami run-up. The 17–20 cm sand layer has parallel laminae and is finer than the 10–17 cm layer, suggesting that the 17–20 cm layer might reflect the waning phase of the run-up, whereas the gently seaward-dipping 20–24 cm coarse sand layer implies backwash tsunami currents. Therefore, the upper medium sand layer with parallel laminae (24–30 cm) might be continuous from lower layers and reflect waning of the backwash tsunami currents. Although of the alternating coarse and medium sand layer (34–40 cm) may have been formed by the tsunami, results of this study were not sufficient to confirm this. It is highly possible that the surface layer (40–47 cm) was remobilized by wind because it was completely dry and showed no remarkable structures. Therefore, this layer is not discussed.

4. Discussion and Summary

We identified characteristics of the tsunami reported by previous studies of the Soma region, Fukushima Prefecture, as follows, (i) the tsunami deposits become generally thinner and finer with distance from the shoreline, have normally or inversely grading, (ii) often have organic-rich silt layers deposited during the stagnant phase, and (iii) display variations in thickness due to local surface relief. In addition, the silt layer in the deposits at Loc. 5 is the thickest in our study area. Tsunami deposits are generally thicker in depressions (Nanayama *et al.* 2000). Moreover, thickness of the silt layer, which is formed during the stagnant phase after the tsunami run-up, may reflect local relief more directly.

Although further verification is required, our description of tsunami deposits at Loc. 8 is one of very few descriptions of run-up tsunami deposits around the shoreline. Very few previous studies of tsunami deposits around the shoreline have been reported, because tsunamis frequently erode coastal areas (Gulfenbaum and Jaffe 2003). Otherwise, it is difficult to distinguish tsunami deposits from coastal deposits (Umitsu *et al.* 2006), because tsunamis transport sandy shallow sea sediments (shallower than 100 m) according to included benthic foraminifera (Nanayama and Shigeno 2006). The characteristics of silt layers at Loc. 3 and Loc. 5 suggest that silt grains were derived from the land surface and from lacustrine deposits. Therefore, the silt layer was not formed during the stagnant phase after the first tsunami run-up at Loc. 8. Even though tsunami water includes silt after the first backwash, a stagnant cannot occur on the beach because water returns directly to the ocean. Consequently, a silt layer is not formed on the beach. Although characteristic silt layers are not intercalated, tsunami deposits are distinguished from beach deposits. A landward-dipping granule–coarse sand layer (10–17 cm) shows that landward flow strong enough to transport gravel continued for more than several seconds. Normally graded sand layers without internal structure (0–5 cm and 5–10 cm) also indicate sustained flow of water. Usual wave and storm wave conditions cannot form these sand (-gravel) layers. As a result, tsunami deposits formed on a beach were recognized in the Soma region. Further work is planned to clarify the new characteristics of the tsunami deposits.

References

Fujiwara, O. 2007. Seismic Tsunami deposits : Major advances over the last 20 years and remaining problems. *The Quaternary Research* **46**: 451-462. **

Fujiwara, O., Kamataki, T. and Tamura T. 2003. Grain-size distribution of tsunami deposits reflecting the tsunami waveform : An example from a Holocene drowned valley on the southern Boso Peninsula, East Japan. *The Quaternary Research* **42**: 67-81. **

Fujiwara, O. and Kamataki, T. 2007. Identification of tsunami deposits considering the tsunami waveform: An example of subaqueous tsunami deposits in Holocene shallow bay on southern Boso Peninsula, Central Japan. *Sedimentary Geology* **200**: 295-313.

Gulfenbaum, G. and Jaffe, B. 2003. Erosion and sedimentation from the 17 July, 1998 Papua New Guinea Tsunami. *Pure and Applied Geophysics* **160**: 1969-1999.

Japan Meteorological Agency. 2011. April 13, 2011 Press release information. http://www.jma.go.jp/jma/press/1104/13a/201104131600.pdf (September 26th, 2011) *

Komar, P. D., and Wang, C. 1984. Processes of selective grain transport and the formation of placers on beaches. *Journal of Geology* **92**: 637-655.

Minoura, K., Imamura, F., Sugawara, D., Kono, Y. and Iwashita, T. 2001. The 869 Jogan tsunami deposit and recurrence interval of large-scale tsunami on the Pacific coast of northeast Japan. *Journal of Natural Disaster Science* **23**: 83-88.

Nakagawa, H., Mii, H. and Asano, K. 1955. Studies on the ecology and sedimentation of Matsukawa-Ura, Soma City, Fukushima Prefecture (No.2). *Contributions from the Institute of Geology and Paleontology Tohoku University* **46**: 1-59. **

Nanayama, F., Shigeno, K., Satake, K., Shimokawa, K., Koitabashi, S., Miyasaki, S. and Ishii, M. 2000. Sedimentary differences between the 1993 Hokkaido-nansei-oki tsunami and the 1959 Miyakojima typhoon at Taisei, southwestern Hokkaido, northern Japan. *Sedimentary Geology* **135**: 255-264.

Nanayama, F. and Shigeno, K. 2006. Inflow and outflow facies from the 1993 tsunami in southwest Hokkaido. *Sedimentary Geology* **187**: 139-158.

National Police Agency. 2011. September 26th, 2011 Publicity Matter. http://www.npa.go.jp/archive/keibi/biki/higaijokyo.pdf (September 26th, 2011). *

Nishimura, Y. and Miyaji, N. 1995. Tsunami deposits from the 1993 southwest Hokkaido earthquake and the 1640 Hokkaido Komagatake eruption, northern Japan. *Geophys* **144**: 719-733.

Okada, Y. 2011. Preliminary report of the 2011 off the Pacific coast of Tohoku Earthquake. http://www.bosai.go.jp/e/international/Preliminary_report110328.pdf (September 26th, 2011).

Satatake, K., Namegaya, Y. and Yamaki, S. 2008. Numerical simulation of the AD 869 Jogan tsunami in Ishinomaki and Sendai Plains. *Annual Report on Active Fault and Paleoearthquake Researches* **8**: 71-89. **

Shiki, T., Tsuji, Y., Minoura, K. and Yamazaki, T. 2008. *Tsunamiites-Features and Implications*, Oxford: Elsevier.

Shimosako, K., Tomita, T., Suzuki, T. and Sugano, T. 2011. Soma Port and Onahama Port survey report (Prompt report). http://www.nilim.go.jp/lab/bbg/saigai/h23tohoku/yokosuka/6.pdf (September 26th, 2011). *

Simons, M., Minson, S. E., Sladen, A., Ortega, F., Jiang, J., Owen, S. E., Meng, L., Ampuero, J. -P., Wei, S., Chu, R., Helmberger, D. V., Kanamori, H., Hetland, E., Moore, A. W. and Webb, F. H. 2011. The 2011 magnitude 9.0 Tohoku-Oki earthquake: mosaicking the megathrust from seconds to centuries. *Science* **332**: 1421-1425.

Takeda, I. 1997. Position and height of the landward limit of the backshore on Naka Beach, Ibaraki, Japan. *Geographical Review of Japan* **70**: 512-525. **

Tsunami Damage Mapping Team, Association of Japanese Geographers. 2011. Maps of the Area hit by the Tsunami of 11 March 2011, Northeast Japan. http://danso.env.nagoya-u.ac.jp/20110311/map/index_e.html (September 26th, 2011).

Umitsu, M., Tanavud, C. and Patanakanog, B. 2006. Spatial distribution of tsunami deposits and behavior of the tsunami flow in the Nam Khem coastal plain, southern Thailand. *E-journal GEO* **1**: 2-11. *

Watanabe, H. 1998. *Nihon Higaitsunami Sourann (Comprehensive List of Tsunamis to Hit the Japanese Island 2nd edition)*, Tokyo: University of Tokyo Press. *

(*: in Japanese, **: in Japanese with English abstract)