



Review

The future of tsunami research following the 2011 Tohoku-oki event

Kazuhiya Goto ^{a,b,*}, Catherine Chagué-Goff ^{c,d}, James Goff ^c, Bruce Jaffe ^e^a Planetary Exploration Research Center, Chiba Institute of Technology, Tsudanuma, Chiba 275-0016, Japan^b International Research Institute of Disaster Science, Tohoku University, 980-8579, Japan^c Australia-Pacific Tsunami Research Centre, School of Biological, Earth and Environmental Sciences, University of New South Wales, Sydney, NSW 2052, Australia^d Australian Nuclear Science and Technology Organisation, Kirrawee DC, NSW 2232, Australia^e US Geological Survey, Santa Cruz, CA, 95060, USA

ARTICLE INFO

Article history:

Received 4 June 2012

Received in revised form 17 August 2012

Accepted 19 August 2012

Available online 29 August 2012

Keywords:

The 2011 Tohoku-oki tsunami

Tsunami deposits

The AD869 Jōgan tsunami

Tsunami geology

ABSTRACT

In this paper we summarize the regional setting, our previous understanding of historical and pre-historical tsunamis on the Pacific coast of Tohoku, Japan, prior to the 2011 Tohoku-oki tsunami, and our current understanding of the sedimentological, geochemical and paleontological features of the onshore and offshore deposits of the event. Post-tsunami surveys revealed many new insights, such as; (1) the maximum extent of the sand deposit is sometimes only 60% of the inundation distance, (2) the inundation limit can be estimated by geochemical analysis even a few months after the event, (3) a minor amount of marine sediment was transported inland by the tsunami on the Sendai and adjacent plains with the major sediment sources being from beach and dune erosion or vented sediments from liquefaction, although nearshore and offshore surveys revealed that there was a significant amount of sediment transport on the seafloor, (4) coarse gravel deposits (~1 m in thickness) were usually thicker than the sand ones (~30 cm in thickness), and (5) beach erosion was minimal in some places while severe in others. Another important aspect of this event is that it was a large, infrequent, tsunami that took place where possible predecessors (e.g., AD869 Jōgan) were already known to have occurred based on historical and geological evidence. The AD869 Jōgan tsunami deposits are noticeably similar to the 2011 Tohoku-oki sands, therefore suggesting that the Jōgan and its source mechanism may have been larger than previously thought. While we have learned many lessons from the 2011 Tohoku-oki event, more research is needed to provide reliable tsunami risk assessments around the world.

© 2012 Elsevier B.V. All rights reserved.

1. Introduction

A great earthquake of Mw 9.0 occurred off the Pacific coast of Tohoku district, Japan (Fig. 1), on March 11, 2011 generating a major tsunami that not only caused widespread damage along the east coast of Japan but also affected coastal areas around the entire Pacific basin. The Japan Meteorological Agency formally named this event “the 2011 off the Pacific coast of Tohoku Earthquake and Tsunami” but “the Tohoku-oki (oki means offshore in Japanese) earthquake and tsunami” is a more popular name. Not only was a remarkably large tsunami generated (~40 m run-up height, Mori et al., 2012), but it resulted in 15,868 dead and 2848 missing (as of 8 August 2012; National Police Agency of Japan, 2012) and substantial damage, including the Fukushima Daiichi nuclear power plant, even though the Pacific coast of Tohoku was one of the best tsunami-prepared areas in the country.

The 2011 Tohoku-oki tsunami was the first example of a large, low-frequency event occurring where historical and pre-historical tsunamis were already known to have occurred through historical (Watanabe, 2001) and geological (e.g., Abe et al., 1990; Minoura, 1990; Minoura et al., 2001; Sugawara et al., in press) evidence. Magnitudes of some of the historical earthquakes and their associated tsunamis had also been estimated based on the known geological record and numerical modeling (Satake et al., 2008; Namegaya et al., 2010; Sugawara et al., 2010, 2011). This point was highlighted by media soon after the 2011 event because such information had not been taken into account in the tsunami disaster prevention plan for the Pacific coast of Tohoku (e.g., Normile, 2011).

From April 2011, Japanese and international researchers conducted rapid response geological surveys to help understand the characteristics of the tsunami and to re-evaluate the magnitude of possible predecessors. This special issue, entitled “the 2011 Tohoku-oki tsunami”, includes 15 papers based on surveys and numerical modeling in Japan and one paper on the effects of the tsunami in the USA. In this introductory paper we summarize the regional setting, the previous knowledge of historical and pre-historical tsunamis on the Pacific coast of Tohoku prior to the 2011 Tohoku-oki tsunami, and our current understanding

* Corresponding author at: Planetary Exploration Research Center, Chiba Institute of Technology, Tsudanuma, Chiba 275-0016, Japan.

E-mail address: kgoto@perc.it-chiba.ac.jp (K. Goto).

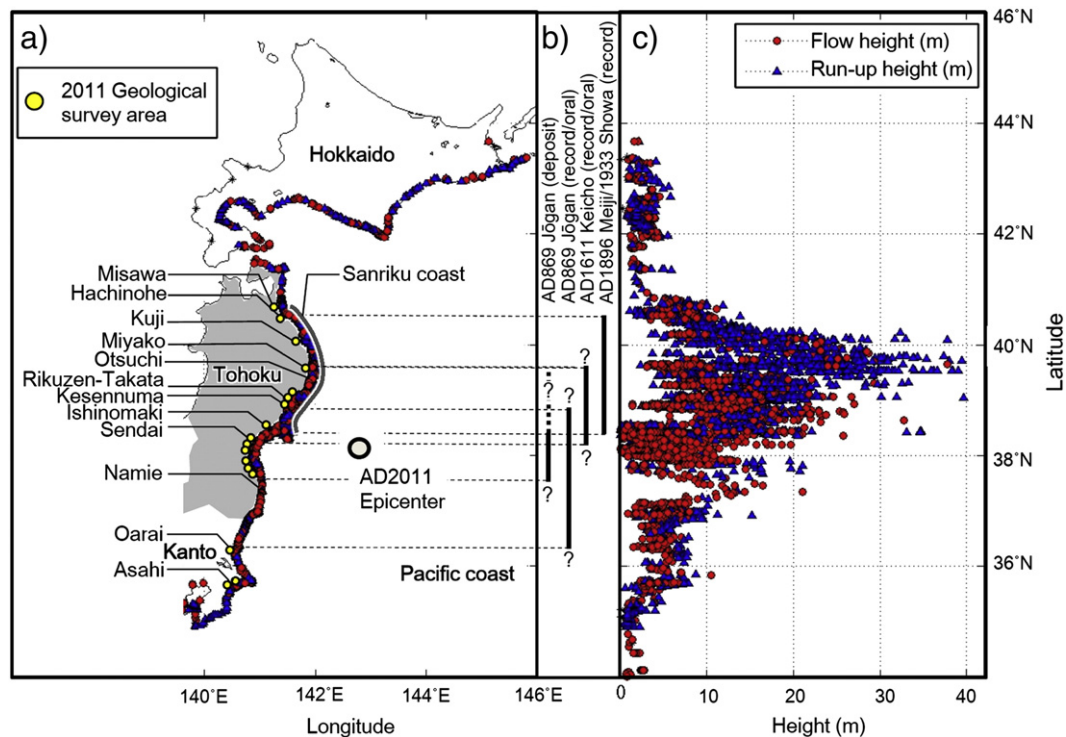


Fig. 1. (a) Map showing the Tohoku district area, Japan (modified after Mori et al., 2012). Geological survey areas for the 2011 Tohoku-oki tsunami by Japanese and international researchers are also shown. (b) Extent of areas affected by the AD869 Jōgan, AD1611 Keicho, AD1896 Meiji, and AD 1933 Showa tsunamis. (c) Flow height (m) (red dots) and run-up height (m) (blue triangles) along the Pacific coast of Japan (data provided by the 2011 Tohoku Earthquake Tsunami Joint Survey Group (30 March 2012 version) (<http://www.coastal.jp/tsunami2011/>), modified after Mori et al., 2012).

of the sedimentological, geochemical and micropaleontological features of the onshore and offshore deposits of the 2011 Tohoku-oki tsunami, as well as post-depositional changes. We also discuss the future direction of geological research and its social relevance in the aftermath of the 2011 Tohoku-oki tsunami.

2. Regional setting and impact of the 2011 Tohoku-oki tsunami

The Pacific coast of Tohoku is generally divided into the Sanriku ria coast in the north and coastal plain areas such as Ishinomaki and Sendai in the south (Fig. 1). Further south from Sendai to the Kanto district, the coast varies between sandy beaches and rocky platforms. The Sanriku coast is characterized by narrow drowned valleys (Fig. 2a) and has frequently been affected by damaging tsunamis every few 10s to 100s years (see Section 3.1). In contrast, the plain area near Sendai (Fig. 2b) is an alluvial lowland with several paleo-beach ridges (e.g., Matsumoto, 1985; Ito, 2006). The area includes a beach, coastal dune ridges up to a few meters high covered with a planted pine forest, and low-lying former wetlands and rice paddies that are at sea level. There is no historical record of large tsunamis over the last thousand years on the Sendai and adjacent plains except for one possible event (1611 Keicho tsunami), although these are seismically active regions and some small tsunamis have been recorded (see Section 3.1).

An important feature of the 2011 Tohoku-oki tsunami was that a remarkably large coastal area was affected with more than 800 km of coast from Hokkaido to Kanto inundated by waves >5 m high (Fig. 1). The maximum fault slip offshore of the Sendai coast was approx. 50 m (Lay et al., 2011; Yagi and Fukahata, 2011). A wave trough arrived first at the coast causing the sea to recede while the first crest struck the Sanriku coast near Miyako about 20 min after the earthquake (Fig. 3). Wave propagation was slow in Sendai Bay because of the shallow bathymetry and the first crest did not reach the coast until about 1 h after the earthquake (Fig. 3).

The effects of local variations in coastal geometries on tsunami inundation can be readily noted. On the Sanriku coast, steep terrain and narrow bay bathymetry caused wave focusing and generated the largest run-ups, with a maximum of 40.4 msl (The 2011 Tohoku Earthquake Tsunami Joint Survey Group (TJSG), 2011; Mori et al., 2012). However, the inundation distance was relatively short (generally up to 2 km) because of relatively steep onshore slopes, except along some rivers where it was much longer (Mori et al., 2012).

In contrast, on the Sendai Plain and adjacent area, the tsunami inundated up to 5.4 km inland (Goto et al., accepted for publication). Along the Sendai Plain, the maximum measured tsunami flow height (also referred to in some papers as inundation height, which is the flow height above mean sea level) was about 19 m (Mori et al., 2012). Video footage taken from a helicopter by NHK TV station (NHK, undated) showed that the first wave was remarkably large and reached the maximum inundation limit on the Sendai Plain, while subsequent waves were smaller.

The flow speed of the wave front can be estimated based on the video records. In the offshore area approximately 1 km seaward of the Sendai Coast, the flow speed of the wave front was estimated at 14 m/s (Kamiya et al., 2011). Flow speeds on land vary from place to place according to the travel distance from the coast, the local topography and the conditions of the ground surface. For example, the tsunami advanced faster on the runway of Sendai Airport than in surrounding areas because of the lower friction of the paved surface (Sugawara and Goto, 2012-this issue). Goto et al. (2011) estimated the flow speed in the area between 1.1 to 2.1 km from the coastline at Sendai to be approximately 4 m/s based on the video record provided by the Japan Coast Guard. Based upon the movement of floating cars in live aerial footage taken by an NHK helicopter over the Sendai Plain, Hayashi and Koshimura (in press) estimated a flow speed of approximately 8 m/s on farmland approx. 1 km from the shoreline decreasing to ~3 m/s about 3 km inland.

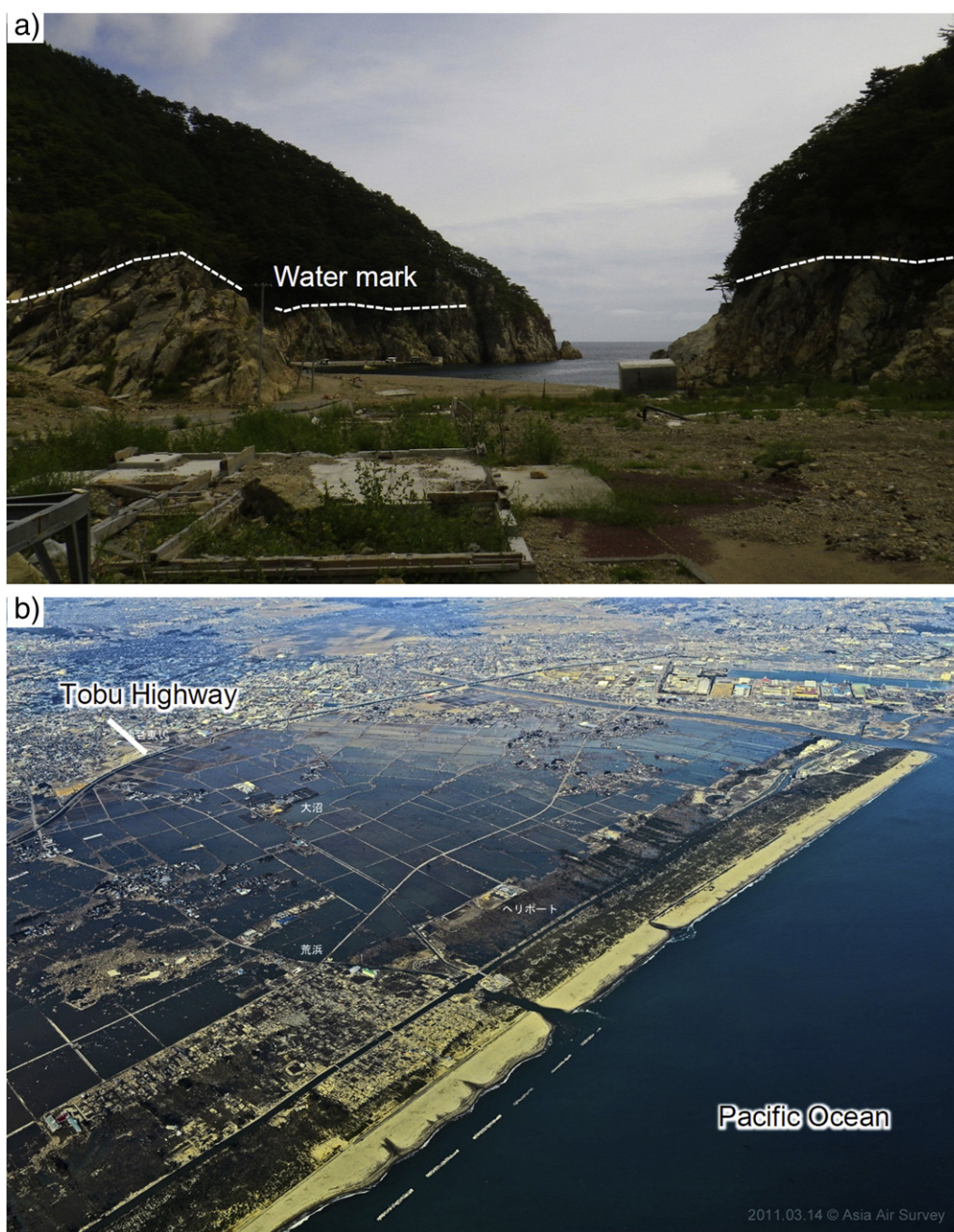


Fig. 2. (a) Photograph showing a typical site for the Sanriku coast (Aneyoshi area in Miyako City). The run-up height here reached ~40 m (the 2011 Tohoku Earthquake Tsunami Joint Survey Group, 2011). The flow height around the shore was approx. 20 m (Mori et al., 2012). (b) Aerial photograph taken of the Sendai Plain (provided by Asia Air Survey Co. Ltd.), taken March 14, 2011. The tsunami generally inundated up to the Tobu Highway (~5.4 km from the shoreline, Goto et al., accepted for publication).

On the Sanriku coast, Fritz et al. (2012) estimated the velocity of backwash flow at Kesennuma Bay to be around 11 m/s based upon analysis of a survivor's video. Near Miyako, the incoming wave front velocity may have reached as much as 32 m/s based on sequential photographs taken from high ground (Ohishi, 2011).

3. Historical and pre-historic tsunamis on the Pacific coast of Tohoku

3.1. Historical records

Japan has continuous and detailed historical records since the 7th Century and its history is divided into several Eras (Fig. 4). Each era between Heian and Edo is subdivided into hundreds of imperial Eras (e.g., the Jōgan Era) and Japanese historical tsunamis are usually

named using imperial Era names (sometimes this also includes the location name such as the 1896 Meiji-Sanriku tsunami). Natural disasters caused by earthquakes, tsunamis, typhoons and volcanic eruptions strongly affected the political regimes at the time and there are therefore good historical records of such events. On the Pacific coast of Tohoku, at least 22 tsunamis (excluding the Tohoku-oki) have been recorded since the 9th Century (Fig. 4; Shuto, 2012 pers. comm.). However, as seen in Fig. 4, 20 events were recorded after the Edo period from the 17th Century while only two events were recorded between the 8th and 16th Centuries. This is probably because historical records are scarce before the Edo period as a result of political instability and a relatively small population size in the Tohoku region over that period. Therefore, it is likely that more local tsunamis may have occurred between the 8th and 16th Centuries but that records were not kept.

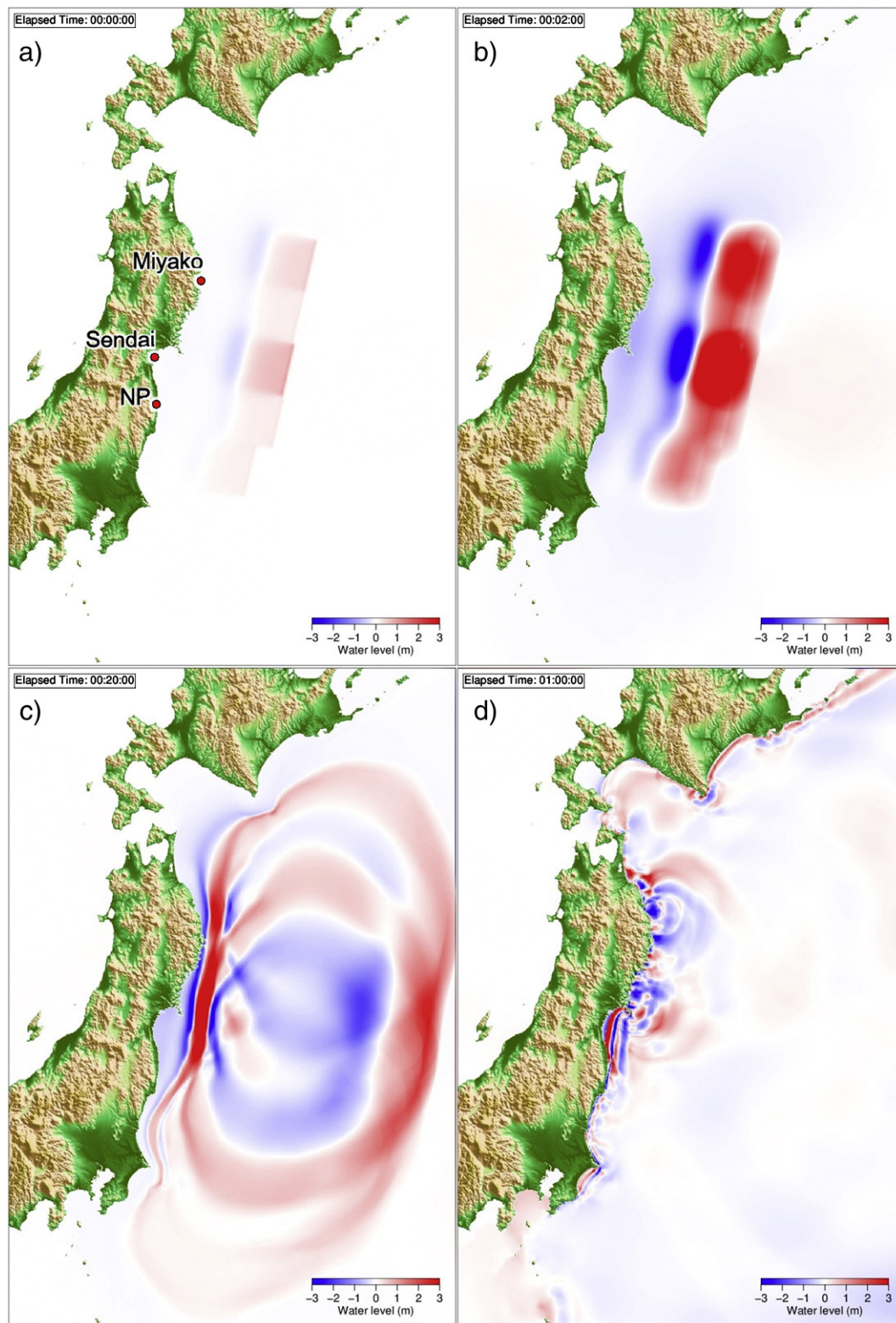


Fig. 3. Snapshots of computed water levels at (a) 0 (min), (b) 2 (min), (c) 20 (min), and (d) 60 (min) after tsunami wave generation (after Sugawara and Goto, 2012-this issue) (Courtesy: D. Sugawara). NP: Fukushima Daiichi Nuclear Plant.

Out of the 22 known historical tsunamis, fatalities were reported in nine events. Fatalities exceeded 1000 in four of these events; the AD869 Jōgan (>1000 dead), AD1611 Keicho (>5000 dead), AD1896 Meiji (21,953 dead) and the AD1933 Showa (1529 dead) tsunamis (Shuto et al., 2007). While these tsunamis devastated large areas along the Pacific

coast of Tohoku, it should be noted that the number of fatalities depended largely on the distribution of the affected population. Hence we cannot exclude the possibility that other known historical tsunamis were locally large, perhaps large enough to leave a sedimentary record, but that there were no affected populations in the areas of inundation.

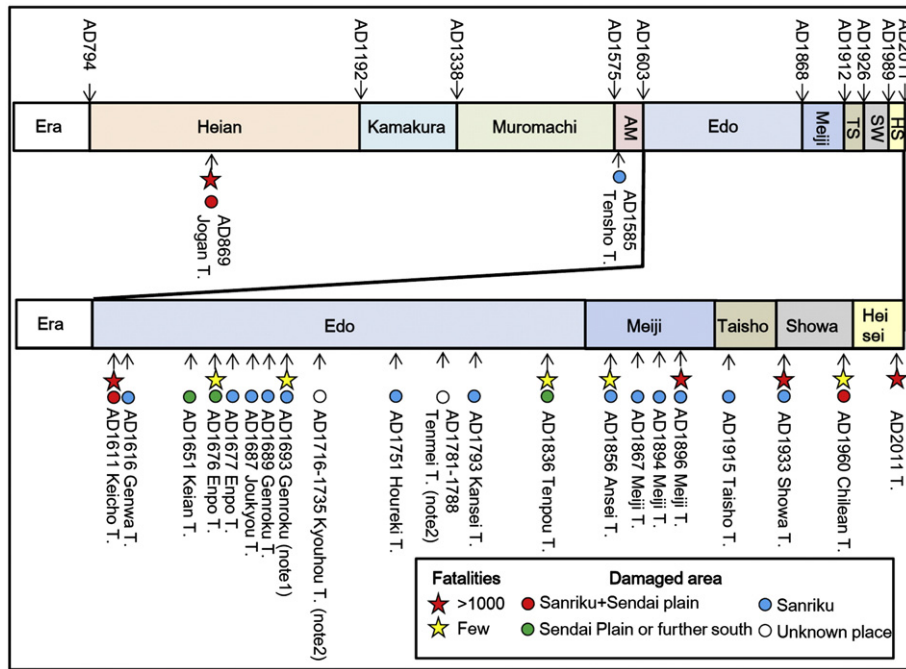


Fig. 4. Historical tsunami records for the Pacific coast of Tohoku (Shuto, 2012 pers. comm.). AM: Azuchi-Momoyama. Note 1: There is a possibility that this was an extreme typhoon event. Note 2: The exact timing of this tsunami is uncertain.

Among these four possibly larger tsunamis, there are written records for the AD869 Jōgan tsunami near Sendai city with oral traditions noted in the region between Oarai and Kesennuma on the Sanriku coast (Fig. 1, Watanabe, 2001). The three other tsunamis (AD1611, AD1896 and AD1933) only affected the Sanriku coast, although the AD1611 event may also have partly inundated the Sendai Plain (e.g., Hatori, 2009).

In terms of affected areas the AD1611, AD1896 and AD1933 events probably cannot be regarded as predecessors of the 2011 Tohoku-oki tsunami because of their limited area of devastation (Fig. 1), although the run-up heights of the 2011 Tohoku-oki tsunami and AD1896 event are comparable along the Sanriku coast (both had ~40 m run-up heights: Mori et al., 2011, 2012). The AD1933 tsunami was considered to have been generated by an outer rise, normal fault event (Kanamori, 1971) and as such the earthquake-generating mechanism was different to that of the 2011 Tohoku-oki event. The nature of the earthquake-generating mechanism of the AD1611 tsunami on the other hand is poorly understood, as is the impact of the event. It is possible that the AD1611 tsunami was actually larger than the AD1896 event with several km of inundation on the Sendai plain (Hatori, 2009). The AD869 Jōgan tsunami still remains the best candidate as a predecessor of the 2011 Tohoku-oki tsunami. However, there are no known historical descriptions or oral traditions of this event to the north of Kesennuma and south of Oarai in areas that were affected by the 2011 Tohoku-oki tsunami.

3.2. Geological evidence

The AD1611, AD1896 and AD1933 events were relatively well recorded in historical documents whereas their onshore deposits are rarely preserved because of intensive land use practices (i.e., agriculture) along the Pacific coast of Tohoku (e.g., Sawai et al., 2006). A major focus of geological surveys prior to the 2011 Tohoku-oki event was to study the AD869 Jōgan deposits because the extent of the inundation area was uncertain. Sugawara and Imamura (2010) and Sugawara et al. (2012-this issue-b) reviewed studies of the AD869 Jōgan tsunami deposits and here we briefly summarize the main geological records that were known prior to the 2011 Tohoku-oki event.

Minoura (1990), Abe et al. (1990), and Minoura and Nakaya (1991) were the first to identify the Jōgan tsunami deposit after which the National Institute of Advanced Industrial Science and Technology (AIST) (Sawai et al., 2006, 2007a,b, 2008a,b; Shishikura et al., 2007; Sawai, 2010) and Tohoku University (Minoura et al., 2001; Sugawara et al., 2002, 2010, 2011) played central roles in undertaking broader studies. By the time of the 2011 Tohoku-oki tsunami, geologists from AIST and Tohoku University had taken more than 600 cores and concluded that the tsunami had run up at least 3 to 4 km inland from the paleo-coastline on the Sendai and Ishinomaki plains (Sawai et al., 2008a; Sugawara et al., 2011). Studies of the Jōgan tsunami on the Sendai Plain have been aided not only by the subsurface preservation of the deposit at less than 1 m depth but also that it is generally overlain by a volcanic ash layer (AD915: Towada-tephra). These two factors make it relatively easy to identify (Goto et al., 2012). Multiple research groups all reached similar conclusions that included numerical modeling estimates for a magnitude 8.4 generating earthquake (Minoura et al., 2001; Satake et al., 2008; Namegaya et al., 2010; Sugawara et al., 2011). This estimate is based on the assumption that the extent of the recognizable sand deposits is the minimum inundation distance of the tsunami.

Before the Tohoku-oki event, the AD869 Jōgan tsunami deposit had been identified from Ishinomaki to Namie (Fig. 1, see summary by Sugawara et al., 2012-this issue-b). However, the AD869 Jōgan deposit has not been found in the lowlands of Rikuzen-Takata on the Sanriku coast and as such the Jōgan tsunami is considered not to have inundated this area (The Headquarters for Earthquake Research Promotion, 2011). Although possible AD869 Jōgan deposits were reported in the inner bay of the Otsuchi Bay (Torii et al., 2007), no onshore AD869 Jōgan sediments were found on the Sanriku coast prior to the 2011 Tohoku-oki tsunami despite an extensive survey by the Headquarters for Earthquake Research Promotion (2011). This is probably due to the difficulty of identifying AD869 Jōgan tsunami deposits on the Sanriku coast since ^{14}C dating is the only method that has been used to determine the age of sediments in the region.

A recurrence interval for large-scale tsunamis with inundation distances of several km on the Sendai and Ishinomaki plains has

been estimated at around 600–1300 years (e.g., Minoura and Nakaya, 1991; Sawai et al., 2007a). In contrast, the recurrence interval for the Sanriku coast is poorly defined (The Headquarters for Earthquake Research Promotion, 2011).

4. Ongoing research of the 2011 Tohoku-oki tsunami deposits

Case studies of recent tsunami impacts have proven to be extremely useful in understanding geologic processes and refining criteria used to identify paleotsunami deposits in the geological record (Goff et al., 2012). Many researchers conducted rapid geological surveys of the on-shore and offshore 2011 Tohoku-oki tsunami deposits. Here we review the current understanding of the features of these deposits and the implication for a better understanding of the AD869 Jōgan tsunami.

4.1. Onshore deposits

Onshore tsunami deposits including mud to boulder sized sediments were studied from April 2011 onwards by various Japanese groups in northern Tohoku including the Sanriku coast (Baker et al., 2011; Kamada, 2011; Yamada et al., 2011; Sasaki et al., 2012a,b; Seo, 2012; Tanaka et al., 2012a; Nakamura et al., 2012-this issue; Naruse et al., 2012-this issue), Sendai and adjacent plains (Iijima et al., 2011; Shirai et al., 2012; Abe et al., 2012-this issue; Goto et al., 2012-this issue-a; Takashimizu et al., 2012-this issue) and southern Tohoku to Kanto area (Okazaki and Ohki, 2011; Fujiwara et al., 2012; Hayashizaki et al., 2012; Kodama and Hisada, 2012; Putra et al., 2012; Shigeno et al., 2012) (Fig. 1).

In addition to these Japanese groups an international survey team, in cooperation with UNESCO-IOC (United Nations Educational, Scientific and Cultural Organization -Intergovernmental Oceanographic Commission) and IITC (International Tsunami Information Center), conducted geological investigations during May 2011 along a shore-perpendicular transect on the Sendai plain (so-called T3 transect) adjacent to Sendai Airport. The T3 transect was in an area where no heavy shoreline protection structure existed and for which additional data on the tsunami, such as video records, were available (Goto et al., 2011).

During post-tsunami field surveys in the last few decades, international survey teams have usually worked along different transects and with different sampling strategies to try and understand the overall features of tsunami deposits and to avoid duplication. In contrast, the UNESCO-IOC survey team of the 2011 Tohoku-oki tsunami worked along the same transect with sampling regimes structured for the study of multiple proxies and methodologies in order to better understand the sedimentation and erosion processes of the tsunami. The outputs from this international survey team includes sedimentological (Goto et al., 2011; Szczuciński et al., 2012-this issue; Richmond et al., 2012-this issue), geochemical (Chagué-Goff et al., 2012-this issue-a,b), mineralogical (Jagodziński et al., 2012-this issue), and micropaleontological (Pilarczyk et al., 2012-this issue; Szczuciński et al., 2012-this issue) analyses as well as forward and inverse modeling (Sugawara and Goto, 2012-this issue; Jaffe et al., 2012-this issue). Analyses of satellite and video footages (Tappin et al., 2012-this issue) were also applied along the same transect. In addition, follow-up surveys were carried out in August and October 2011 along the transect to assess geochemical changes (Chagué-Goff et al., 2012-this issue-a). This is the first time that such an intensive field survey and analysis have been carried out and this represents a good model for future post-tsunami geological surveys.

4.1.1. Distribution and sedimentary features of mud to sand deposits

Extensive research of onshore mud to sand deposits led to the following conclusions regarding the distribution and sedimentary features of the 2011 Tohoku-oki tsunami.

1. On the Sendai and Ishinomaki plains, the tsunami inundated up to 5.4 km inland (e.g., Mori et al., 2012; Goto et al., accepted for publication) but a recognizable sand layer (Fig. 5a, i.e., >0.5 cm thick) only extended up to ~3 km inland and the deposit continued as a mud-rich unit (Fig. 5b) almost to the inundation limit (Goto et al., 2011; Shishikura et al., 2011; Abe et al., 2012-this issue; Chagué-Goff et al., 2012-this issue-a,b; Szczuciński et al., 2012-this issue; Takashimizu et al., 2012-this issue; Richmond et al., 2012-this issue).
2. On the Sendai Plain and adjacent lowlands the maximum extent of the sand layer (≥ 0.5 cm thick) was over 90 % of the inundation distance when this was less than 2.5 km (Abe et al., 2012-this issue). On the other hand, the maximum extent of the sand layer (≥ 0.5 cm thick) was 3 km (57–76% of the inundation distance) irrespective of the inundation distance when this was more than 2.5 km (Abe et al., 2012-this issue).
3. In many areas mud to sand deposits reached a maximum thickness of ~30 cm and generally thinned inland (Goto et al., 2011; Abe et al., 2012-this issue; Nakamura et al., 2012-this issue; Naruse et al., 2012-this issue; Szczuciński et al., 2012-this issue; Takashimizu et al., 2012-this issue; Richmond et al., 2012-this issue), although Richmond et al. (2012-this issue) reported a 60 cm thick sand deposit that filled a scour hole on the landward side of a sand dune. However, significant local variability and complexity in thickness, grain size and sedimentary structures were recorded and attributed to man-made and natural topographic variations, as well as the complex behavior of the tsunami wave (Goto et al., 2011; Takashimizu et al., 2012-this issue; Richmond et al., 2012-this issue).
4. Sandy tsunami deposits on the Sendai Plain and the Sanriku coast were characterized by parallel laminated or massive sands and silt with fragments of woods and glass, rip-up mud clasts and an erosional base (Goto et al., 2011; Abe et al., 2012-this issue; Naruse et al., 2012-this issue; Szczuciński et al., 2012-this issue; Takashimizu et al., 2012-this issue; Richmond et al., 2012-this issue). The tsunami deposits generally consist of one- to a few units, with multiple layers mainly observed close to the shoreline (Naruse et al., 2012-this issue; Szczuciński et al., 2012-this issue; Jaffe et al., this issue).
5. The limit of tsunami inundation was identified using geochemical marine markers (e.g., S, Na and Cl), in the absence of any sedimentological evidence within 2 months following the tsunami (Chagué-Goff et al., 2012-this issue-a,b). Marked decreases in S and Cl over time indicated that rainfall resulted in the leaching of salts from sandy sediments. However, both S and Cl markers as well as Sr were still well preserved in the muddy sediments and soil beyond the limit of the recognisable sand deposit seven months after the tsunami (Chagué-Goff et al., 2012-this issue-a). Furthermore, a marine chemical signature was also preserved in the soil underlying the sand, in particular where seawater had ponded after the tsunami (Chagué-Goff et al., 2012-this issue-a).

4.1.2. Environmental impact assessment

The impact of tsunami inundation on the soil and surrounding environment was assessed in May, August and October 2011 along transect T3 (Chagué-Goff et al., 2012-this issue-b). While evaporation had resulted in elevated electrical conductivity (a measure of salinity) in a number of ponds (inundated paddy fields and/or depressions) in May, rainfall over the next five months led to dilution, although brackish water was still recorded in a number of ponds. Bioavailable trace metals and exchangeable arsenic measured in May 2011 in tsunami sediments and the underlying soil were found to occur in levels similar to background levels in Japanese soils. However, contamination of the sediments and underlying soil down to ~15 cm by saltwater was recorded in May 2011 (Chagué-Goff et al., 2012-this issue-b). Salt concentrations were still over background both in tsunami



Fig. 5. (a) Sand and mud deposit on Sendai Plain. (b) Mud-dominated deposit on the Sendai Plain. Note the mm-thick sand layer beneath the mud deposit (courtesy: S. Fujino). (c) Gravel deposit (more than 60 cm) at Aneyoshi, Miyako. The lower contact was much deeper than on the figure shown. (d) Boulder deposit (about 140 tons) at Settai, Miyako. TS: tsunami deposit.

deposits and the underlying soil five months after the tsunami, reflecting the long lasting effect of tsunami inundation (Chagué-Goff et al., 2012-this issue-b).

4.1.3. Sources of mud to sand deposits

Sediment sources of the 2011 Tohoku-oki mud to sand deposits on the Sendai and adjacent plains are unusual. Based on heavy mineral assemblages (Putra et al., 2012; Jagodziński et al., 2012-this issue), microfossil analysis (diatoms and nannoliths: Szczuciński et al., 2012-this issue; diatoms: Takashimizu et al., 2012-this issue; foraminifera: Putra et al., 2012; Pilarczyk et al., 2012-this issue) tsunami deposits on the Sendai Plain were found to be mostly derived from beach, sand dune, lagoon and inland soils rather than offshore sediments. Stable carbon and nitrogen isotope analysis of mud however suggests at least a minor contribution of marine organic matter (Chagué-Goff et al., 2012-this issue-a), while Pilarczyk et al. (2012-this issue) propose a intertidal or beach origin for the sand, based on stable carbon isotope data.

In addition, Goto et al. (in press) reported that large amounts of the sediments deposited along a transect in the Arahama area on

the Sendai Plain probably originated from liquefaction because sands had been vented from beneath the soil in the rice paddies. This suggests that such vented sediments might be an important local source of tsunami deposits if liquefaction is generated by strong ground motion from a near-field earthquake (Goto et al., in press).

These results led to the conclusion that a minor amount of marine sediments had been transported inland by the tsunami onto the Sendai and adjacent plains, while the major sediment sources for the sandy deposits were beach and dune erosion or vented sediments from liquefaction. The muddy deposits were most probably derived from erosion of rice paddy soils. Similar results were reported to the north of Honshu (Misawa City) by Nakamura et al. (2012-this issue) who report that the particle size and mineral assemblage of the sand are similar to those of the coastal dune sand, suggesting it was the main source material of the tsunami sediment.

At Rikuzen-Takata on the Sanriku coast on the other hand, Naruse et al. (2012-this issue) and Tanaka et al. (2012a) found that the sediments were derived not only from eroded beach sands but also from the seafloor of the inner bay or more pelagic regions.

The reason for a variable contribution of marine sediments in on-shore deposits is probably related to tsunami propagation characteristics, its interaction with bathymetry and availability of sediments for erosion and transport (Sugawara and Goto, 2012-this issue; Szczuciński et al., 2012-this issue) but further careful research is required to clarify sediment transport processes and sources.

4.1.4. Post depositional changes

Follow-up surveys were carried out in August and October 2011 to assess post-depositional changes and their implications for paleotsunami research (Chagué-Goff et al., 2012-this issue-a). Chagué-Goff et al. (2012-this issue-a) concluded that the organic matter content both in the sandy and muddy deposit had varied little over time and that a geochemical marine signature was still recognizable seven months after the tsunami despite more than 900 mm of precipitation. The signature was particularly evident in mud and underlying soil, and its preservation was independent of sediment thickness.

4.1.5. Coarse clasts

Coarse clasts ranging from granule to boulder size were also observed in some places, particularly along the Sanriku coast where gravels were scattered landward of several beaches (Fig. 5c, Baker et al., 2011; Yamada et al., 2011; Goto et al., 2012-this issue). Some gravel deposits were up to 1 m thick and thinned landward (Yamada et al., 2011; Goto et al., 2012-this issue). This is a striking contrast to the sand deposit thickness that generally did not exceed ~30 cm.

Boulder deposits including large concrete fragments of seawall were observed in many areas affected by the 2011 Tohoku-oki tsunami (Fig. 5d). Many local slope failures were generated by the strong ground motion of the Mw 9.0 earthquake and some boulders from these sources were reworked inland by the tsunami (Goto et al., 2012-this issue). The largest boulder (excluding artificial objects) weighing about 140 tons (6.5 m × 2.5 m × 2.4 m) was found in a rice paddy at Settai, Miyako City (Yamada et al., 2011).

Boulders transported by the 2011 Tohoku-oki tsunami were usually deposited on top of less than a few tens of cm-thick sand to gravel deposits indicating that the latter, possibly deposited from bed load, covered the ground surface first (Goto et al., 2012-this issue). Some clasts at the inland extent of inundation were covered by an upward fining sand layer. This feature indicates that some boulders were deposited prior to the suspended sands, with the sands subsequently laid down before the water level dropped below the top of the clasts (Goto et al., 2012-this issue).

4.1.6. Hydrodynamics

Both forward (Sugawara and Goto, 2012-this issue) and inverse (Jaffe et al., 2012-this issue) models were applied to transect T3 on Sendai Plain.

Sugawara and Goto (2012-this issue) investigated offshore propagation and inundation of the 2011 Tohoku-oki tsunami along transect T3 on the Sendai Plain. The modeled profile showing flow depths of 2.4–6 m and speeds of 3.4–6.2 m/s in the paddy fields is generally consistent with measured depths and estimated speeds from video footage. The waveform on the beach showed that the wave train was composed of an initial high wave followed by several smaller ones and that the erosion of the beach and sedimentation in the paddy fields were mainly caused by the first wave.

Jaffe et al. (2012-this issue) applied inverse modeling at seven locations near the coast of transect T3 and calculated flow speeds in a range from 2.2 to 9.0 m/s, which is generally consistent with those estimated by Sugawara and Goto (2012-this issue) although the values were strongly dependent on the choice of Manning's roughness parameterization.

Future analysis of video footage taken at Sendai Airport may allow the validation of the results of these forward and inverse models.

4.2. Beach morphology

The geomorphological effects of the tsunami at the beach were investigated along the Sendai coast (Tanaka et al., 2012b; Udo et al., 2012; Goto et al., in press; Tappin et al., 2012-this issue). This area was chosen because it had high-resolution Digital Elevation Model (DEM) data available both before and after the tsunami, numerous aerial photographs as well as helicopter-borne video footage. The complete loss of the ~150 m wide beach was not observed on the Sendai coast except in specific places such as at some of the river mouths (e.g., Tanaka et al., 2012b). Tappin et al. (2012-this issue) reported that the impact along a 'natural' coast with minimal coastal defences was manifested by erosion of the back beach causing 10–20 m of coastal recession. Minor erosion on the beach face took the form of V-shaped channels that were further developed during backwash (Tanaka et al., 2012b; Udo et al., 2012; Goto et al., in press; Tappin et al., 2012-this issue). Evidence of erosion included remnant dune pedestals and a shore-parallel elongated scour depression immediately landward of the former dune ridge (Richmond et al., 2012-this issue). Tanaka et al. (2012b) reported locally severe beach erosion in some areas along the Sendai coast. Discontinuous coastal protection was severely damaged, resulting in significant erosion of the adjacent sandy coast. Furthermore, severe breaching caused by a strong return flow from the inland catchment area was observed on sandy coasts where old river mouths were located (Tanaka et al., 2012b). Goto et al. (in press) reported that the beach berm along the Sendai coast had rebuilt within three months of the tsunami and an erosional channel that had cut through the beach had been quickly infilled by sand accumulation within 13 days.

At Rikuzen-Takata, beach and sand dunes that were covered by a coastal pine forest were completely washed away (Naruse et al., 2012-this issue) and the beach has not fully recovered partly because of extensive subsidence (~84 cm).

Beach erosion appears to have been minor in some places while severe in others and the major controlling factors for beach erosion are still uncertain. As stated in Section 4.1.3, there are multiple sources for the tsunami deposits and the ratio of the volume of sediments supplied from these sources may differ from place to place depending on tsunami inundation processes, wave forces and local topography. Hence, an analysis of the total balance of erosion and sedimentation volumes is important in order to assess the main sources for onshore deposits along each survey transect (e.g., Goto et al., in press).

4.3. Offshore erosion and deposits

Nearshore and offshore surveys revealed that a significant amount of sediment was transported on the seafloor. Up to 10 m of erosion was reported in the narrow part of Kesennuma Bay, an area that prior to the tsunami was approximately 8 m deep (Haraguchi et al., 2012). A similar magnitude of erosion was also noted in a narrow section of Hachinohe harbor (c. 13 m; Tomita, 2011).

Akimoto et al. (2012) and Haraguchi et al. (2012) studied the impact of the tsunami on the seafloor of Kesennuma inner bay (~20 m water depth) using a side-scan sonar and depth sounder. As a result of this work, Haraguchi et al. (2012) reported the reworking of several meters of seafloor sediments at 10–15 m water depth, and that large dunes were formed on the seafloor by the tsunami. They suggested that it was highly likely that up to meter-thick sandy or silty paleotsunami deposits could be preserved in such shallow, sheltered bays where large bedforms would be protected from high energy, open coast waves.

Deeper, offshore deposits were also studied soon after the tsunami. Arai et al. (2011) studied offshore sediments between 300 and 5940 m water depth including those that covered a seafloor seismometer. They reported that in water depths between 2900 and 5900 m offshore from the Sanriku coast the seafloor was covered by muddy deposits in some areas that prior to the earthquake and tsunami had a sand and

gravel substrate (Arai et al., 2011). The muddy sediment was part of a large deposit composed mainly of clay to coarse sand that showed an offshore grain-size fining (Arai et al., 2011). They noted that the sediment was probably the turbidite deposit associated with tsunami backwash and possibly originated from the margin of the continental shelf where water depths are shallower than 300 m.

Turbidite deposits 1–25 cm thick were observed in 13 core samples taken between July and August 2011 in a broad region between the Sendai and Sanriku coasts (120 km N–S × 150 km W–E) at variable depths from 122 to 5500 m (Ikehara et al., 2011). Cesium-134 and Cesium-137 released from the damaged nuclear plant (Fukushima–Daichi nuclear plant) was detected on top of the turbidites and as such the deposits are considered to have been formed by a submarine slope failure related to the 2011 earthquake and tsunami (Ikehara et al., 2011).

Further analyses may clarify whether these offshore deposits originated from earthquake-induced turbidites or tsunami-induced sediment gravity (or suspended) flows or both. Indeed, tsunami waves may have been able to induce sediment movement on the continental shelf. According to numerical modeling by Sugawara and Goto (2012-this issue), current velocities of the 2011 Tohoku-oki tsunami reached 1 m/s about 80 km offshore from the Sendai Plain, which corresponds to a water depth of 270 m. A current velocity of 1 m/s is sufficient to erode and entrain a wide range of clastic materials (e.g., Sugawara and Goto, 2012-this issue).

The linkage between sediment movement in the sea and on land is still uncertain. As stated in Section 4.1.3, minor volumes of marine sediment may have been deposited on the Sendai Plain, nevertheless large volumes of sediment may possibly have been moved in the nearshore and offshore zones. Numerical modeling by Sugawara and Goto (2012-this issue) implies that the flow speed of the first incoming tsunami wave dropped to ~1 m/s on the beach face, approximately 0.5 km offshore of the coastline because the energy of the front part of the first wave was reflected in the nearshore zone and propagated offshore as a reflected wave. The flow speed of the reflected wave slowed the incoming one. Consequently, the flow speeds almost cancelled each other out, with the net flow speed therefore suddenly dropping to nearly ~1 m/s (Sugawara and Goto, 2012-this issue). Sugawara and Goto (2012-this issue) infer that the reflection of the wave energy and abrupt decrease of speed may have resulted in the accretion of a considerable amount of sediment on the beach face and hence, the tsunami transported only a small quantity of marine sediment on land.

Further analysis based on sediment transport models may clarify this linkage between sediment movement from the sea to the land.

4.4. The impact of the 2011 Tohoku-oki tsunami outside of Japan

Wilson et al. (2012-this issue) reported the tsunami impact on the California coast, USA. While the tsunami along the California coast was not catastrophic, there was nonetheless one fatality as well as considerable damage to Crescent City and Santa Cruz harbors. According to Wilson et al. (2012-this issue) the tsunami generated strong currents (up to 7 m/s) within Crescent City and Santa Cruz harbors that redistributed considerable volumes of sediment. This led to significant regulatory issues regarding sediment disposal, causing months of delays in the harbor reconstruction process. In Crescent City harbor, at least 289,400 m³ of sediment were scoured in an area of 0.67 km². A minimum infill volume of 154,600 m³ was calculated with the sediment covering 55% of that portion of the harbor included in the bathymetric surveys (Wilson et al., 2012-this issue).

4.5. The AD869 Jōgan tsunami revisited

Re-evaluation of the magnitude of the AD869 Jōgan earthquake and tsunami is critically important for the future understanding of

tsunami risk along the Pacific coast of Tohoku. This can only be achieved through a better understanding of the tsunami deposit it left behind. This exercise has significant implications for correctly estimating the magnitude of both historical and pre-historic earthquakes and tsunamis around the world. Therefore, researchers are also re-assessing the AD869 Jōgan tsunami deposits concurrently with studies of the 2011 Tohoku-oki event.

Tentative conclusions by researchers who studied the sediments of the Sendai and Ishinomaki plains suggest that the AD869 Jōgan and 2011 Tohoku-oki tsunami sands are similar (Goto et al., 2011; Shishikura et al., 2011; Sugawara et al., in press; Abe et al., 2012-this issue; Chagué-Goff et al., 2012-this issue-a; Pilarczyk et al., 2012-this issue). Both are massive, laminated or graded, often with mud and soil rip-up clasts, and both have a similar inland extent of approximately 3 km from their respective coastlines (Goto et al., 2011). Goto et al. (2011) and Abe et al. (2012-this issue) also reported that the AD869 Jōgan event may have had a greater inundation distance than previously thought. Chagué-Goff et al. (2012-this issue-a) report a chemical composition of the AD869 Jōgan tsunami sands characterized by high Sr and Rb concentrations that are comparable to those of the Tohoku-oki sand deposit, suggesting that the sediment sources may be similar.

These similarities imply that the sands that comprise these two deposits are from comparable sources. The earthquake magnitude of the AD869 Jōgan event was assumed to be around Mw = 8.4 (Satake et al., 2008; Namegaya et al., 2010; Sugawara et al., 2011) based on the assumption that the maximum extent of sand deposits represented the minimum inundation distance. However, we might have significantly underestimated the inundation distance of the AD869 Jōgan tsunami. Goto et al. (2011), Abe et al. (2012-this issue) and Chagué-Goff et al. (2012-this issue-a) suggest that the maximum extent of the 2011 sand deposits are not a good indicator of the minimum inundation distance on the Sendai Plain. Thus, the AD869 Jōgan tsunami and its generating mechanism may have been larger than previously thought (Goto et al., 2011).

Is it possible therefore, to more accurately estimate the inundation distance of paleotsunamis in general and the AD869 Jōgan in particular? Chagué-Goff et al. (2012-this issue-a) suggest that geochemical indicators may well prove vital in identifying the inland extent of historical and paleotsunamis beyond the limit of recognizable sand deposition, in particular when fine grained sediments (e.g., mud) are preserved. Moreover, the use of geochemistry is particularly relevant in areas where marine microfossils are sparse or lacking as is the case with the Sendai Plain.

Another important aspect in the re-evaluation of the magnitude of AD869 Jōgan earthquake and tsunami is whether deposits can be identified further north from Ishinomaki (or south from Namie). If AD869 Jōgan tsunami deposits are indeed present along the Sanriku coast, then the length of the generating fault rupture will need to be extended further north and consequently the magnitude of the earthquake would be increased, perhaps to as much as a Mw = 9.0. After the 2011 Tohoku-oki tsunami, Hirakawa (2012) reported possible AD869 Jōgan (and AD1611) tsunami deposits on sea cliffs at Kesennuma and Miyako, where outcrops were exposed by erosion caused by the 2011 Tohoku-oki tsunami. However, more specific evidence of the tsunami origin of these deposits is yet to be provided. Therefore, it is still uncertain whether AD869 Jōgan tsunami deposits extend northward along the Sanriku coast.

Unlike the Sendai and adjacent plains, a greater number of large tsunamis have inundated the Sanriku coast since AD869. The absence of an historical record of large tsunamis such as the AD1611 and AD869 on the Sanriku coast does not necessarily indicate the absence of these events. With a larger number of tsunamis in this region it might be difficult to precisely identify the AD869 Jōgan tsunami deposits from (perhaps many) sand deposits of possible paleotsunami origin since dating technology (i.e., ¹⁴C dating) has a margin of error of several decades. This probably accounts for

the failure to find onshore AD869 Jōgan tsunami deposits during extensive research carried out prior to the 2011 Tohoku-oki tsunami ([The Headquarters for Earthquake Research Promotion, 2011](#)).

Alternatively, it is also possible that the AD869 Jōgan tsunami did not reach the Sanriku coast ([The Headquarters for Earthquake Research Promotion, 2011](#)). The 2011 Tohoku-oki earthquake was an unusual multi-segment event with many faults displaced continuously (or intermittently) over a few minutes (e.g., [Ide et al., 2011](#)). [Satake et al. \(2011\)](#) inferred that the 2011 Tohoku-oki tsunami could be explained by the rupture of two major faults; one is a AD1896 Meiji-Sanriku type event off the Sanriku coast and the other is off the Sendai coast, with the latter being previously considered as the source of the AD869 Jōgan earthquake. Even though the magnitudes of the AD869 Jōgan earthquake and tsunami might have been underestimated ([Goto et al., 2011](#)), the geological record of the AD869 Jōgan tsunami on the Sendai Plain might be explained if we assume an extremely large fault slip (~50 m) similar to the 2011 event off the Sendai coast without the displacement of the AD1896 Meiji-Sanriku type fault off the Sanriku coast. Therefore, the absence of AD869 Jōgan tsunami deposits on the Sanriku coast may not directly contradict the recent findings on the Sendai Plain that suggested that the magnitudes of the AD869 Jōgan earthquake and tsunami were underestimated (e.g., [Goto et al., 2011](#)).

Further careful study is therefore required to determine whether AD869 Jōgan tsunami deposits can be identified or not along the Sanriku coast—this is vital for the future evaluation of tsunami risk along the Pacific coast of Tohoku.

5. Future research directions following the 2011 Tohoku-oki tsunami

Over the past 25 years research has been carried out to try and understand the nature of tsunami deposits with a significant increase in this work since the 2004 Indian Ocean tsunami (e.g., [Goff et al., 2012](#)). The 2011 Tohoku-oki event indicates that the understanding of tsunami deposits is still poorly developed and we need more comprehensive studies to provide better tsunami risk assessments. We have however, learned many lessons from this event and many questions have also been raised, questions that are critically important for future tsunami risk assessments around the world:

- 1) Why did the recognizable sand deposit extend up to only about 3 km inland? Previous studies of recent tsunamis between 1992 and 2006 show that when inundation distances are less than 2.0 km, the maximum extent of the recognizable sand deposit (≥ 0.5 cm-thick) is over 90% of the inundation distance (e.g., [MacInnes et al., 2009](#)). The 2011 Tohoku-oki tsunami deposits also fit this trend when the inundation distances were up to 2.5 km, but this rule does not apply when they are more than this ([Abe et al., 2012-this issue](#)). It is still uncertain which factors are critically important in determining the relationship between the maximum extent of the sand deposit and the inundation distance.
- 2) What are the key controls over whether or not marine sediments are deposited onshore? Marine sediments appear to be a minor component of the 2011 Tohoku-oki tsunami deposits, at least on the Sendai Plain. In contrast, other tsunami deposits such as those formed by the 1998 Papua New Guinea ([Gelfenbaum and Jaffe, 2003](#)) and 2004 Indian Ocean (e.g., [Kokociński et al., 2009](#); [Sawai et al., 2009](#)) tsunamis contained a considerable percentage of marine sediments. What are the key controls over whether or not marine sediments are deposited onshore?
- 3) Why is the thickness of the sand deposit limited to ~30 cm? With the exception of some local examples, sand deposits were generally limited to a maximum of ~30 cm in thickness even though the tsunami was over 10 m high and travelling at more than 10 m/s on the Sendai Plain ([Sugawara and Goto, 2012-this issue](#)), passing

through the coastal zone and with no strong backwash observed. Why were thicker deposits not formed? Is the maximum thickness of the sandy tsunami deposit not correlated with the general features of the tsunami or tsunami deposits, such as tsunami height and current velocity, or total weight, volume and area of deposition? The volume of sediment available for transport, sediment flux, equilibrium suspended sediment concentration, duration of sediment transport, and the local topography may all be key factors in determining the maximum thickness of the sand deposits (and also the maximum volume of sediments transported onshore). However, further field observations, experimental studies and numerical modeling are required to understand the relationship between tsunami hydrodynamics and the maximum thickness of sand deposits (and the maximum volume of sediments transported on land).

- 4) What was the role of liquefaction? Liquefaction was extreme at many places in the tsunami affected area because of the strong ground shaking during the Mw 9.0 earthquake. This liquefaction may have destabilized both onshore and offshore surface sediments. On land, vented sediments were an important local source for onshore tsunami deposits. It is highly likely that extensive liquefaction occurred offshore, which may have contributed significantly to the movement of large amounts of sediment on the seafloor by the tsunami, although there is currently no literature reporting sea-bottom liquefaction due to ground shaking by the earthquake. Underwater vented sediments may well have significantly altered the original seafloor substrate before the tsunami passed over it. What was the role therefore, if any, of underwater-vented sediments in the tsunami sediment supply and transport process and is it possible to identify the effects of such activity on the seafloor?
- 5) Are we correctly estimating the recurrence interval and magnitude of past tsunamis from only the sand deposits? The thickness of the 2011 Tohoku-oki sand deposits is highly variable and discontinuous in places, although it generally thins landward ([Goto et al., 2011](#); [Szczeniński et al., 2012-this issue](#); [Richmond et al., 2012-this issue](#)). A similar feature is also observed in the 2004 Indian Ocean tsunami deposits (e.g., [Szczeniński, 2012](#)). This suggests that paleotsunami deposits may also be discontinuous sand sheets. Therefore, looking for paleotsunami sand deposits in one or even a few cores (or outcrops) may be insufficient for developing a comprehensive understanding of the paleotsunami record (and recurrence interval). Moreover, the height of a tsunami changes depending upon whether it arrives at high or low tide (e.g., the tidal range at Sendai is about 1.8 m) and so if two tsunamis of the same magnitude inundated a particular area (e.g., Sendai) in the past (and present), the resulting volume of sediment and size of sand particles transported inland would likely differ. The tsunami deposits may work well to assess the onshore impact of tsunamis, even if tide levels affect tsunami height and inundation. However, the problem of tide levels may be serious when researchers think about the magnitude of the tsunami source. The thickness and grain size of the tsunami deposits as well as the absence of sand in a particular core site may not necessarily indicate the scale (or absence) of tsunami impact. Can we overcome this problem?
- 6) Can we use coarse clast deposits as paleotsunami indicators? Deposits formed by granule to cobble size clasts have only recently become the focus of tsunami researchers. Such deposits formed by the 2011 Tohoku-oki tsunami appear to be thick (~1 m) behind gravel beaches and thin landward with the deposit extending inland as a sand- or mud-rich unit to almost to the maximum inundation limit ([Yamada et al., 2011](#); [Goto et al., 2012-this issue](#)). Can we identify granule to cobble paleotsunami deposits in cores or outcrops? Boulder deposits have recently been used as historical and paleotsunami indicators (e.g., [Goto et al., 2010](#)). However, some of the 2011 Tohoku-oki tsunami boulders originated

from slope failures caused by the strong earthquake and thus no remains of marine life are attached. If paleotsunami boulders originated from a similar process, then how can we determine whether they were transported by a tsunami, and when?

- 7) Can we accurately estimate the inundation area of a paleotsunami? Chagué-Goff et al. (2012-this issue-a) show that geochemical indicators may well be vital in identifying the inland extent of historical and paleotsunamis by determining the marine origin of fine-grained sediments beyond the limit of recognizable sand deposition. This is particularly relevant when alternative or complementary methods such as the study of marine microfossils cannot be used because they are sparse or lacking as is the case for the Sendai Plain. Geochemical data would allow researchers to redraw paleotsunami inundation maps and re-assess the magnitude of events such as the Jōgan tsunami and earlier paleotsunamis, not only on the Sendai Plain but elsewhere around the world. This has important implications for tsunami risk assessment, hazard mitigation and preparedness. It may also be possible to estimate the inundation area of a paleotsunami using forward or inverse models. For example, Sugawara et al. (2011) extended the Jōgan tsunami inundation area from the limit of sand deposits based on numerical analysis that assumed that the bottom shear stress of the tsunami around the maximum extent of the sand deposits was strong enough to erode the bottom soil. Sugawara et al. (2012) further applied the sediment transport model proposed by Takahashi et al. (2000) to estimate the inundation distance to explain the sand distribution. Alternatively, inverse models (e.g., Jaffe and Gelfenbaum, 2007; Jaffe et al., 2012-this issue) may be applied to the sand deposits at the maximum extent of sand deposition to estimate the flow speed at that point, which may be an important constraint on the forward modeling of the paleotsunami.
- 8) Can we estimate the slip amount of the fault from tsunami deposits? If we successfully estimate the inundation area from the deposits, can we correctly estimate the fault model? It is probably not easy. The maximum slip amount of the fault for the 2011 earthquake was ~50 m offshore of Sendai (e.g., Yagi and Fukahata, 2011). This is well beyond the empirical formula (e.g., Wells and Coppersmith, 2001) for the relationship between the slip amount and earthquake magnitude. This extremely large fault slip was observed near the trench axis of shallow crust (e.g., Yagi and Fukahata, 2011) and is considered to be the reason for the generation of such a large tsunami. In the case of numerical estimations of paleo-earthquake magnitude from tsunami deposits, the slip amount of the fault is usually estimated using the empirical relationship (e.g., Satake et al., 2008; Sugawara et al., 2010), but this assumption does not work in the case of the 2011 Tohoku-oki tsunami. The effect of an extremely large fault slip was probably recorded from the offshore or nearshore wave height rather than being based on the inundation distance in case of the 2011 Tohoku-oki tsunami on the Sendai Plain (Yanagisawa, pers. comm.), because the Sendai Plain is remarkably flat and the tsunami inundation distance is largely controlled by topography. Is it possible then to estimate the local offshore and nearshore wave height from tsunami deposits?

We understand that some of these questions can probably be solved in the near future, but some may be well beyond our current state of knowledge. Whatever the case, we need to carry out considerably more research to better understand tsunami deposits in order to improve future disaster prevention plans around the world.

6. Conclusions

Following the 2011 Tohoku-oki event, tsunamis and their geological fingerprints have become the subject of interest to many, not only in Japan but around the world. Considerable attention is also being paid to this work by national and local governments in Japan. In December

2011, the Japanese government made a new law for tsunami disaster prevention plans and recommended that local governments prepare for the “maximum possible earthquakes and tsunamis in each region” and that geological research for tsunami risk assessment is strongly recommended before preparing future local disaster prevention plans (Ministry of Land, Infrastructure, Transport and Tourism, 2011).

It is indeed true that geology is vital to gaining a better understanding of past tsunamis along any coastline and to interpreting the hydrodynamic features of paleotsunamis. However, the 2011 Tohoku-oki tsunami event tells us that there is still much to be learnt from tsunami deposits if we are to produce reliable tsunami risk assessments. Following the 2011 Tohoku-oki tsunami, we must return to the key question – why were the results of geological studies of the AD869 Jōgan event not incorporated into disaster prevention plans in Japan? Although most geological studies of the AD869 Jōgan tsunami had not been published in mainstream, peer-reviewed international journals, the results were nonetheless high quality and well disseminated. The AD869 Jōgan tsunami was indeed one of the best studied events in the world. However, Goto et al. (2012) candidly admit that tsunami geology is not a mature discipline and that prior to the 2011 earthquake it had not reached a sufficient level of recognition in Japan where researchers and disaster prevention experts from various fields were interacting effectively. Furthermore, in general terms, people continue to be unable to comprehend the significance and relevance of extreme events that occur on timescales spanning several 100s–1,000s of years that far exceed the human (or building) lifespan (Goto et al., 2012). This is where much of the challenge lies for tsunami scientists in education outreach to the general public.

One possible future direction for tsunami researchers is to enhance the social relevance of their work by focusing on the prediction of tsunamis as opposed to insisting on predicting earthquakes (Goto et al., 2012). This is particularly important when seismological consensus on how we should set an upper limit for earthquake magnitude has not been achieved—we should therefore explore estimating tsunami magnitude and frequency based on the physical evidence these events have left behind. The magnitude of the AD869 Jōgan Earthquake might have been significantly underestimated at ~8.4, yet we knew that the ensuing tsunami reached 3 to 4 km inland. We could have considered disaster prevention measures that predicted a tsunami of this magnitude even without knowing the precise earthquake magnitude (Goto et al., 2012). For example, Satake and Nanayama (2004) produced a map of the tsunami inundation history for a “500-year-span earthquake and tsunami” for eastern Hokkaido. This was based on sedimentary records. Such maps may be extremely useful for local tsunami risk assessment even if earthquake magnitudes are uncertain (or underestimated).

Acknowledgment

This study is dedicated to all who have been affected by the 11 March 2011 earthquake and tsunami in Japan. We thank D. Sugawara for his cooperation in preparing figures and two anonymous reviewers for their valuable comments.

References

- Abe, H., Sugeno, Y., Chigama, A., 1990. Estimation of the height of the Sanriku Jōgan 11 Earthquake–Tsunami (A.D. 869) in the Sendai Plain, Zisin. *Journal of the Seismological Society of Japan* 43 (4), 513–525 (Second Series (in Japanese with English abstract)).
- Abe, T., Goto, K., Sugawara, D., 2012. Relationship between the maximum extent of tsunami sand and the inundation limit of the 2011 Tohoku-oki tsunami at Sendai Plain, Japan. *Sedimentary Geology* 282, 142–150 (this issue).
- Akimoto, K., Takikawa, K., Yakita, K., Hokamura, T., Takino, Y., 2012. Impact of the 20110311 tsunami on the geography and sediment distribution in Kesennuma Bay, Miyagi, Japan. *Japan. Abstract of Japan Geoscience Union meeting*, no. MIS25-04 (in Japanese with English abstract).
- Arai, K., Naruse, H., Izumi, N., Yokokawa, M., Miura, R., Kawamura, K., Tsuji, T., Kanamatsu, T., Fujikawa, K., Murayama, M., YK11-E04 leg1 and YK11-E06 leg2 Shipboard Scientists, 2011. Muddy sediments associated with the 2011 off the

- Pacific coast of Tohoku Earthquake: can turbidity currents be caused by great tsunami? Abstract of the Sedimentological Society of Japan meeting, pp. 112–113 (in Japanese).
- Baker, V.R., Goto, K., Komatsu, G., McGuire, L., Oguchi, T., Pelletier, J.D., Matsui, T., 2011. Catastrophic geomorphic effects of the 11 March 2011 Tohoku-Oki Tsunami, Sanriku coastline, northeastern Honshu, Japan. Abstract of 2011 AGU Fall Meeting, NH14A-06.
- Chagué-Goff, C., Andrew, A., Szczuciński, W., Goff, J., Nishimura, Y., 2012. Geochemical signatures up to the maximum inundation of the 2011 Tohoku-oki tsunami—implications for the 869 AD Jōgan and other palaeotsunamis. *Sedimentary Geology* 282, 65–77 (this issue-a).
- Chagué-Goff, C., Niedzielski, P., Wong, H.K.Y., Szczuciński, W., Sugawara, D., Goff, J., 2012. Environmental impact assessment of the 2011 Tohoku-oki tsunami on the Sendai plain. *Sedimentary Geology* 282, 175–187 (this issue-b).
- Fritz, H.M., Phillips, D.A., Okayasu, A., Shimozono, T., Liu, H., Mohammed, F., Skanavis, V., Synolakis, C.E., Takahashi, T., 2012. The 2011 Japan tsunami current velocity measurements from survivor videos at Kesennuma Bay using LIDAR. *Geophysical Research Letters* 39 (L00G23). <http://dx.doi.org/10.1029/2011GL050686>.
- Fujiwara, O., Sawai, Y., Shishikura, M., Namegaya, Y., 2012. Sedimentary features of the Tohoku earthquake tsunami deposits on the central Kujukuri coast, east Japan. *Quaternary Research* 51, 117–126 (in Japanese with English abstract).
- Gelfenbaum, G., Jaffe, B.E., 2003. Erosion and sedimentation from the 17 July 1998 Papua New Guinea tsunami. *Pure and Applied Geophysics* 60, 1969–1999.
- Goff, J., Chagué-Goff, C., Nichol, S.L., Jaffe, B., Dominey-Howes, D., 2012. Progress in palaeotsunami research. *Sedimentary Geology* 243–244, 70–88.
- Goto, K., Kawana, T., Imamura, F., 2010. Historical and geological evidences of boulders deposited by tsunamis, southern Ryukyu Islands, Japan. *Earth-Science Reviews* 102, 77–99.
- Goto, K., Chagué-Goff, C., Fujino, S., Goff, J., Jaffe, B., Nishimura, Y., Richmond, B., Sugawara, D., Szczuciński, W., Tappin, D.R., Witter, R., Yulianto, E., 2011. New insights of tsunami hazard from the 2011 Tohoku-oki event. *Marine Geology* 290, 46–50.
- Goto, K., Shishikura, M., Nishimura, Y., 2012. Putting geological records to use in preventing tsunami-related disasters—current status of and issues in tsunami sedimentology. *Iwanami-Kagaku* 82, 215–219 (In Japanese, English version is available online: <http://www.japanesetechweb.jp/science-technology/jew1113>).
- Goto, K., Fujima, K., Sugawara, D., Fujino, S., Imai, K., Tsudaka, R., Abe, T., Haraguchi, T., accepted for publication. Field measurements and numerical modeling for the run-up heights and inundation distances of the 2011 Tohoku-oki tsunami at Sendai Plain, Japan. *Earth, Planets and Space*. <http://dx.doi.org/10.5047/eps.2012.02.007>.
- Goto, K., Sugawara, D., Ikema, S., Miyagi, T., 2012. Sedimentary processes associated with sand and boulder deposits formed by the 2011 Tohoku-oki tsunami at Sabusawa Island, Japan. *Sedimentary Geology* 282, 188–198 (this issue-a).
- Goto, K., Sugawara, D., Abe, T., Haraguchi, T., Fujino, S., in press. Liquefaction as an important source of the 2011 Tohoku-oki tsunami deposits at Sendai Plain, Japan. *Geology*. <http://dx.doi.org/10.1130/G33123.1>.
- Haraguchi, T., Goto, K., Takahashi, T., 2012. Mega-dunes formed by the 2011 Tohoku-Oki tsunami at the Kesennuma Bay, Japan. Abstract of Japan Geoscience Union meeting, no. MIS25-03. (in Japanese with English abstract).
- Hatori, T., 2009. Regional deviation of inundation heights due to the large Sanriku tsunamis. *Rekishi-Zishin* 24, 41–48 (in Japanese with English abstract).
- Hayashi, S., Koshimura, S., in press. Measurement of the 2011 Tohoku tsunami flow velocity by the aerial video analysis. *Journal of Japan Society of Civil Engineers. Series B2*. (in Japanese).
- Hayashizaki, R., Shirai, M., Muragishi, J., 2012. Backshore deposits inferred as being formed by the 2011 off the Pacific Coast of Tohoku Earthquake Tsunami at the Turishihama Beach. Abstract of Japan Geoscience Union meeting, no. MIS25-P02 (in Japanese with English abstract).
- Hirakawa, K., 2012. Large tsunami history along the Chishima and Japan trenches. *Iwanami-Kagaku* 82, 172–181 (In Japanese).
- Ide, S., Baltay, A., Beroza, G.C., 2011. Shallow dynamic overshoot and energetic deep rupture in the 2011 Mw 9.0 Tohoku-Oki Earthquake. *Science* 332, 1426–1429.
- Iijima, Y., Minoura, K., Hirano, S., Yamada, T., 2011. Great East Japan Earthquake Tsunami. Abstract of the 2011 AGU Fall Meeting, NH11A-1343.
- Ikehara, K., Usami, K., Jenkins, R., Ashi, J., Irino, T., Watanabe, Y., Ujiie, T., 2011. Characteristics of turbidites formed by the 2011 off the Pacific Coast of Tohoku Earthquake. Abstract of the Sedimentological Society of Japan meeting, pp. 58–59 (in Japanese).
- Ito, A., 2006. Marine regression during the historical time in Sendai coastal Plain, Northeastern Japan. *Bulletin of the Faculty of Education, Kagoshima University, Studies in Education* 57, 1–8 (in Japanese with English abstract).
- Jaffe, B.E., Gelfenbaum, G., 2007. A simple model for calculating tsunami flow speed from tsunami deposits. *Sedimentary Geology* 200, 347–361.
- Jaffe, B.E., Goto, K., Sugawara, D., Richmond, B., Fujino, S., Nishimura, Y., 2012. Flow speed estimated by inverse modelling of sandy tsunami deposits: results from the 11 March 2011 tsunami on the coastal plain near the Sendai Airport, Honshu, Japan. *Sedimentary Geology* 282, 90–109 (this issue).
- Jagodziński, R., Sternal, B., Szczuciński, W., Chagué-Goff, C., Sugawara, D., 2012. Heavy minerals in the 2011 Tohoku-oki tsunami deposits—insights into sediment sources and hydrodynamics. *Sedimentary Geology* 282, 57–64 (this issue).
- Kamada, K., 2011. Tsunami deposits on the Osuka Beach, Hachinohe, NE Japan. Abstract of the Sedimentological Society of Japan meeting 119.
- Kamiya, I., Otoi, K., Okatani, T., Koarai, M., 2011. Measurement of the crest on ocean and other geometric characteristics of the tsunami—the 2011 off the Pacific coast of Tohoku Earthquake-. *Proceedings of the Symposium for the Tsunami Joint Survey Group*, pp. 99–103 (in Japanese).
- Kanamori, H., 1971. Seismological evidence for a lithosphere normal faulting—the Sanriku earthquake of 1933. *Physics of the Earth and Planetary Interiors* 4, 289–300.
- Kodama, S., Hisada, K., 2012. Tsunami sandy sediments of the coastal forest reserve in Asahi city, Chiba Prefecture, central Japan. Abstract of Japan Geoscience Union meeting, no. MIS25-P05. (in Japanese with English abstract).
- Kokociński, M., Szczuciński, W., Zgrundo, A., Ibragimow, A., 2009. Diatom assemblages in 26 December 2004 tsunami deposits from coastal zone of Thailand as sediment provenance indicators. *Polish Journal of Environmental Studies* 18, 93–101.
- Lay, T., Ammon, C.J., Kanamori, H., Xue, H., Kim, M.J., 2011. Possible large near-trench slip during the 2011 Mw 9.0 off the Pacific coast of Tohoku Earthquake. *Earth Planets Space* 63, 687–692.
- MacInnes, B.T., Bourgeois, J., Pinegina, T.K., Kravchunovskaya, E.A., 2009. Tsunami geomorphology: erosion and deposition from the 15 November 2006 Kuril island tsunami. *Geology* 37, 995–998.
- Matsumoto, H., 1985. Beach ridge ranges and the Holocene sea-level fluctuations on alluvial coastal plains, northeast Japan. *Science Reports of Tohoku University 7th Series (Geography)* 35, 15–46.
- Ministry of Land, Infrastructure, Transport and Tourism, 2011. A guideline of the law on regional development of tsunami disaster prevention. <http://www.mlit.go.jp/sogoseisaku/point/tsunamibousai>.
- Minoura, K., 1990. Emergence and period of large-scale tsunamis in northeast Japan. *Rekishi-Zishin* 6, 61–76 (in Japanese).
- Minoura, K., Nakaya, S., 1991. Traces of tsunami preserved in inter-tidal lacustrine and marsh deposits: some examples from northeast Japan. *Journal of Geology* 99, 265–287.
- Minoura, K., Imamura, F., Sugawara, D., Kono, Y., Iwashita, T., 2001. The 869 Jōgan tsunami deposit and recurrence interval of large-scale tsunami on the Pacific coast of northeast Japan. *Journal of Natural Disaster Science* 23, 83–88.
- Mori, N., Takahashi, T., Yasuda, T., Yanagisawa, H., 2011. Survey of 2011 Tohoku earthquake tsunami inundation and run-up. *Geophysical Research Letters* 38 (L00G14). <http://dx.doi.org/10.1029/2011GL049210>.
- Mori, N., Takahashi, T., the 2011 Tohoku earthquake tsunami joint survey group, 2012. Nationwide post event survey and analysis of the 2011 Tohoku Earthquake Tsunami. *Coastal Engineering Journal* 54. <http://dx.doi.org/10.1142/S0578563412500015> 27 p.
- Nakamura, Y., Nishimura, Y., Putra, P.S., 2012. Local variation of inundation, sedimentary characteristics, and mineral assemblages of the 2011 Tohoku-oki tsunami on the Misawa coast, Aomori, Japan. *Sedimentary Geology* 282, 216–227 (this issue).
- Namegaya, Y., Satake, K., Yamamoto, S., 2010. Numerical simulation of the AD 869 Jōgan tsunami in Ishinomaki and Sendai plains and Ukedo river-mouth lowland. *Annual Report of Active Fault and Paleoequake Researches* 10, 1–21 (in Japanese, with English abstract).
- Naruse, H., Arai, K., Matsumoto, D., Takahashi, H., Yamashita, S., Tanaka, G., Murayama, M., 2012. Sedimentary features observed in the tsunami deposits at Rikuzentakata City. *Sedimentary Geology* 282, 199–215 (this issue).
- National Police Agency of Japan, 2012. Damage Situation and Police Countermeasures associated with 2011Tohoku district - off the Pacific Ocean Earthquake—8 August 2012. http://www.npa.go.jp/archive/keibi/biki/higaijokyo_e.pdf.
- Normile, D., 2011. Scientific consensus on Great Quake came too late. *Science* 332, 22–23.
- Ohishi, M., 2011. Time-lapse photography of tsunami at Kawashiro, Omoe Peninsula, Miyako City and the maximum run-up height at Aneyoshi. The geological Society of Japan. web site (<http://www.geosociety.jp/hazard/content0054.html>). (in Japanese).
- Okazaki, H., Ohki, J., 2011. Coastal change in Kujukuri Coast at the 2011 Tohoku earthquake. Abstract of the Sedimentological Society of Japan meeting, pp. 51–52 (in Japanese).
- Pilarczyk, J.E., Horton, B.P., Witter, R.C., Vane, C.H., Chagué-Goff, C., Goff, J., 2012. Sedimentary and foraminiferal evidence of the 2011 Tohoku-oki tsunami on the Sendai coastal plain, Japan. *Sedimentary Geology* 282, 78–89 (this issue).
- P.S.Putra, P.S., Y.Nishimura, Y., Y.Nakamura, Y., E.Yulianto, E., 2012. Possible onshore-dominated source of tsunami deposits of the 2011 Tohoku tsunami: a case study from northern Fukushima. Abstract of Japan Geoscience Union meeting, no. MIS25-P03.
- Richmond, B., Szczuciński, W., Chagué-Goff, C., Goto, K., Sugawara, D., Witter, R., Tappin, D.R., Jaffe, B., Fujino, S., Nishimura, Y., Goff, J., 2012. Erosion, deposition, and landscape change on the Sendai coastal plain, Japan resulting from the March 11, 2011 Tohoku-oki tsunami. *Sedimentary Geology* 282, 27–39 (this issue).
- T.Sasaki, T., M.Yanagida, M., K.Ueta, K., 2012a. Microtopography formed by the 2011 Tohoku earthquake tsunami and facies of tsunami deposit at Yoshihama, Iwate. Abstract of Japan Geoscience Union meeting, no. MIS25-P10. (in Japanese with English abstract).
- Sasaki, T., Yoshii, T., Ito, Y., Ueta, K., Aoyagi, Y., Matsuyama, M., Kanaguri, S., Yanagida, M., Okuzawa, K., Watanabe, M., Iida, T., 2012b. Facies and chemical analysis of the 2011 Tohoku earthquake tsunami deposit for identification of paleotsunami deposit. Abstract of Japan Geoscience Union meeting, no. MIS25-P09. (in Japanese with English abstract).
- Satake, K., Nanayama, F., 2004. Hokkaido taiheiyogan no tsunami shinsui rirakizu [Records of tsunami reach on the Hokkaido pacific coast]. *Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology*. (in Japanese).
- Satake, K., Namegaya, Y., Yamaki, S., 2008. Numerical simulation of the AD 869 Jōgan tsunami in Ishinomaki and Sendai plains. *Annual Report of Active Fault and Paleoequake Researches* 8, 71–89 (in Japanese with English abstract).

- Satake, K., Sakai, S., Fujii, Y., Shinohara, M., Kanazawa, T., 2011. Tsunami source of the 2011 off the Pacific coast of Tohoku Earthquake. *Iwanami-Kagaku* 81, 407–410 (in Japanese).
- Sawai, Y., 2010. Coring and geoslicing in a lowland near Hotokehama, Tomioka Town, Fukushima, Japan. Annual Report on Active Fault and Paleoeearthquake Researches 10, 23–29 (in Japanese with English abstract).
- Sawai, Y., Shishikura, M., Okamura, Y., Aung, Than Tin, Matsu'ura, T., Takada, K., Fujii, Y., Satake, K., 2006. History of tsunami inundations in Sendai Plain, detected from coastal geology. Abstract of Japan Geoscience Union Meeting 2006. Japan Geoscience Union, Tokyo, p. S208-009 (in Japanese with English abstract).
- Sawai, Y., Shishikura, M., Okamura, Y., Takada, K., Matsu'ura, T., Aung, Than Tin, Komatsubara, J., Fujii, Y., Fujiwara, O., Satake, K., Kamataki, T., Sato, N., 2007a. A study on paleotsunami using handy geoslicer in Sendai Plain (Sendai, Natori, Iwanuma, Watari, and Yamamoto), Miyagi, Japan. Annual Report on Active Fault and Paleoeearthquake Researches 7, 47–80 (in Japanese with English abstract).
- Sawai, Y., Shishikura, M., Okamura, Y., Matsu'ura, T., Aung, Than Tin, Komatsubara, J., Fujii, Y., 2007b. Inundation area by the Jōgan tsunami in the center and south of Miyagi prefecture, reconstructed from deposits. Proceedings of Rekishi-716 Zishin Meeting 22. Society of Historical Earthquake Studies, Tokyo, p. 209 (in Japanese).
- Sawai, Y., Shishikura, M., Komatsubara, J., 2008a. A study on paleotsunami using hand corer in Sendai plain (Sendai City, Natori City, Iwanuma City, Watari Town, Yamamoto Town), Miyagi, Japan. Annual Report on Active Fault and Paleoeearthquake Researches 8, 17–70 (in Japanese with English abstract).
- Sawai, Y., Fujii, Y., Fujiwara, O., Kamataki, T., Komatsubara, J., Okamura, Y., Satake, K., Shishikura, M., 2008b. Marine incursions of the past 1500 years and evidence of tsunamis at Suijin-numa, a coastal lake facing the Japan Trench. The Holocene 18, 517–528.
- Sawai, Y., Jankaew, K., Martin, M.E., Prendergast, A., Choowong, M., Charoentitir, T., 2009. Diatom assemblages in tsunami deposits associated with the 2004 Indian Ocean tsunami at Phra Thong Island, Thailand. Marine Micropaleontology 73, 70–79.
- Seo, N., 2012. Tohoku Earthquake—observation from the estuary of Kuji, Natsui river and Fudai Beach—. Abstract of Japan Geoscience Union meeting, no. MIS25-P08 (in Japanese with English abstract).
- Shigeno, K., Arai, S., Nanayama, F., Ito, T., 2012. Relationship between tsunami inundation and sand distribution due to the 2011 Tohoku Earthquake tsunami. Abstract of Japan Geoscience Union meeting, no. MIS25-P04 (in Japanese with English abstract).
- Shirai, M., Hayashizaki, R., Utsugawa, T., Mukaiyama, Y., Muragishi, J., 2012. Beach deposits inferred as being formed by the 2011 Tohoku Tsunami at the Sendai Coast. Abstract of Japan Geoscience Union meeting, no. MIS25-P01 (in Japanese with English abstract).
- Shishikura, M., Sawai, Y., Okamura, Y., Komatsubara, J., Aung Tin, Than, Ishiyama, T., Fujiwara, O., Fujino, S., 2007. Age and distribution of tsunami deposit in the Ishinomaki Plain, Northeastern Japan. Annual Report on Active Fault and Paleoeearthquake Researches 7, 31–46 (in Japanese, with English abstract).
- Shishikura, M., Sawai, Y., Namegaya, Y., Fujiwara, O., Tanigawa, K., Kagohara, K., Kimura, H., Okamura, Y., Miyashita, Y., Komatsubara, J., Fujii, Y., Okuda, Y., 2011. Pre- and post-tsunami survey along the Japan Trench by Geological Survey of Japan/AIST. Proceedings of the Symposium for the Tsunami Joint Survey Group, pp. 74–76 (in Japanese).
- Shuto, N., Koshimura, S., Satake, K., Imamura, F., Matsutomi, H., 2007. An Encyclopedia of Tsunami. Asakura Publishing Co. Ltd. 368p.
- Geological and historical traces of the 869 Jōgan tsunami field guide of half-day field trip in Sendai. In: Sugawara, D., Imamura, F. (Eds.), 3rd International Tsunami Field Symposium, Sendai, Sanriku, and Okinawa, 10–16 April 2010. 21 pp.
- Sugawara, D., Minoura, K., Imamura, F., 2002. Field survey of the deposits by the AD 869 Jōgan tsunami. *Kaiyo* 28, 110–117 (extra edition, in Japanese).
- Sugawara, D., Imamura, F., Matsumoto, H., Goto, K., Minoura, K., 2010. Quantitative reconstruction of a paleo-tsunami: field survey of Jōgan tsunami and paleotopography. *DCRC Tsunami Engineering* 27, 103–132 (in Japanese).
- Sugawara, D., Imamura, F., Matsumoto, H., Goto, K., Minoura, K., 2011. Reconstruction of the AD869 Jōgan earthquake induced tsunami by using the geological data. *Journal of Natural Disaster Science* 29 (4), 501–516 (in Japanese with English abstract).
- Sugawara, D., Imamura, F., Takahashi, T., 2012. Applicability of sediment transport model to paleotsunami deposit: preliminary examination for the 869 Jōgan tsunami. Abstract of Japan Geoscience Union meeting, no. MIS25-14 (in Japanese with English abstract).
- Sugawara, D., Imamura, F., Goto, K., Matsumoto, H., Minoura, K., in press. The 2011 Tohoku-oki earthquake tsunami: similarities and differences to the 869 Jōgan tsunami on the Sendai Plain. *Pure and Applied Geophysics*. <http://dx.doi.org/10.1007/s00024-012-0460-1>.
- Sugawara, D., Goto, K., 2012. Numerical modeling of the 2011 Tohoku-oki tsunami in the offshore and onshore of Sendai Plain, Japan. *Sedimentary Geology* 282, 110–123 (this issue-a).
- Sugawara, D., Goto, K., Imamura, F., Matsumoto, H., Minoura, K., 2012. Assessing the magnitude of the 869 Jōgan tsunami using sedimentary deposits: prediction and consequence of the 2011 Tohoku-oki tsunami. *Sedimentary Geology* 282, 14–26 (this issue-b).
- Szczuciński, W., 2012. The post-depositional changes of the onshore 2004 tsunami deposits on the Andaman Sea coast of Thailand. *Natural Hazards* 60, 115–133.
- Szczuciński, W., Kokociński, M., Rzeszewski, M., Chagué-Goff, C., Cachão, M., Goto, K., Sugawara, D., 2012. Sediment sources and sedimentation processes of 2011 Tohoku-oki tsunami deposits on the Sendai Plain, Japan—insights from diatoms, nanoliths and grain size distribution. *Sedimentary Geology* 282, 40–56 (this issue).
- Takahashi, T., Shuto, N., Imamura, F., Asai, D., 2000. Modeling sediment transport due to tsunamis with exchange rate between bed load layer and suspended load layer. Proceedings of the International Conference on Coastal Engineering ASCE, pp. 1508–1519.
- Takashimizu, Y., Urabe, A., Suzuki, K., Sato, Y., 2012. Deposition by the 2011 Tohoku-oki tsunami on coastal lowland controlled by beach ridges near Sendai, Japan. *Sedimentary Geology* 282, 124–141 (this issue).
- G.Tanaka, G., H.Naruse, H., S.Yamashita, S., K.Arai, K., 2012a. Ostracodes reveal the seabed origin of tsunami deposits. *Geophysical Research Letters* 39, L05406. <http://dx.doi.org/10.1029/2012GL015320>.
- Tanaka, H., Tinh, N.X., Umeda, M., Hirao, R., Pradjoko, E., Mano, A., Udo, K., 2012b. Coastal and estuarine morphology changes induced by the 2011 Great East Japan Earthquake Tsunami. *Coastal Engineering Journal* 54. <http://dx.doi.org/10.1142/S0578563412500106> (25 pp).
- Tappin, D.R., Evans, H.M., Jordan, C.J., Richmond, B., Sugawara, D., Goto, K., 2012. Coastal changes in the Sendai area from the impact of the 2011 Tōhoku-oki tsunami: interpretations of time series satellite images, helicopter-borne video footage and field observations. *Sedimentary Geology* 282, 151–174 (this issue).
- The 2011 Tohoku Earthquake Tsunami Joint Survey Group, 2011. Nationwide field survey of the 2011 off the Pacific coast of Tohoku Earthquake Tsunami. *Journal of Japan Society of Civil Engineers* B2 (67), 63–66 (Series).
- The Headquarters for Earthquake Research Promotion, MEXT, Japan, 2011. Overall Research Report of High-priority Observation and Survey on Miyagi-oki Earthquakes, 2005–2009 fiscal years. 390p. (in Japanese).
- Tomita, T., 2011. Tsunami damage in ports. Proceedings of the Symposium for the Tsunami Joint Survey Group, pp. 69–73 (in Japanese).
- Torii, K., Haraguchi, T., Imaizumi, T., Miyauchi, T., Shimazaki, K., 2007. Survey of tsunami deposits at Sanriku coast, North East Japan. Abstract of Japan Society of Engineering Geology, 23 (in Japanese).
- Udo, K., Sugawara, D., Tanaka, H., Imai, K., Mano, A., 2012. Impact of the 2011 Tohoku earthquake and tsunami on beach morphology along the Northern Sendai Coast. *Coastal Engineering Journal* 54 (125009), 1–15.
- Watanabe, H., 2001. Is it possible to clarify the real state of past earthquakes and tsunamis on the basis of legends? As an example of the 869 Jōgan earthquake and tsunami. *Rekishi-Zishin* 17, 130–146 (in Japanese).
- Wells, D.L., Coppersmith, K.J., 2001. New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. *Bulletin of the Seismological Society of America* 84, 974–1002.
- Wilson, R., Davenport, C., Jaffe, B., 2012. Sediment scour and deposition within harbors in California (USA), caused by the March 11, 2011 Tohoku-oki tsunami. *Sedimentary Geology* 282, 228–240 (this issue).
- Y.Yagi, Y., Y.Fukahata, Y., 2011. Rupture process of the 2011 Tohoku-oki earthquake and absolute elastic strain release. *Geophysical Research Letters* 38, L19307. <http://dx.doi.org/10.1029/2011GL048701>.
- Yamada, M., Fujino, S., Goto, K., 2011. Relationship between tsunami behaviors estimated from location and size of boulders and onshore gravelly tsunami deposit. The Sedimentological Society of Japan meeting 55–56 (in Japanese).