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Review

Assessing the magnitude of the 869 Jogan tsunami using sedimentary deposits: Prediction and consequence of the 2011 Tohoku-oki tsunami

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ABSTRACT

In this paper, the spatial distribution and sedimentological features of the 869 Jogan tsunami deposit along the Pacific coast of Japan are reviewed to evaluate deposit-based estimates of the magnitude of the Jogan tsunami and the use of tsunami deposits in the prediction of the 2011 Tohoku-oki earthquake and tsunami. Inundation of the Sendai Plain and the offshore wave sources of both tsunamis are compared. The Jogan tsunami deposit is ubiquitous on the coastal plains of Sendai Bay, whereas, to date, it is only identified in a few locations along the Sanriku and Joban Coasts. This resulted in an underprediction of the size of the wave source of the Tohoku-oki tsunami. The inland boundary of the inundation area of the Tohoku-oki tsunami on the Sendai Plain is approximately equivalent to that of the Jogan tsunami, although many sedimentological and geomorphologic factors make a direct comparison of the tsunamis complicated and difficult. The magnitude of the Jogan earthquake (Mw = 8.4), which was derived from the tsunami deposit inland extent and numerical inundation modeling, was too small to predict the magnitude of the Tohoku-oki earthquake (Mw = 9.0–9.1) and tsunami. Additional research is needed to improve deposit-based estimates of the magnitudes of past tsunamis and to increase the ability to use tsunami deposits, in conjunction with inundation modeling, to assess future tsunami hazards.

1. Introduction

Scientific and public interest in for paleotsunami deposit research has dramatically increased after the extensive inundation and heavy damage by the 2011 Tohoku-oki tsunami (e.g. Normile, 2011). This is because the occurrence and widespread inundation by such a large-scale tsunami was already known from sedimentological research. Sedimentological and numerical modeling research on the 869 Jogan tsunami, which is now regarded as one of the possible predecessors of the Tohoku-oki tsunami, was conducted well in advance of the Tohoku-oki event. One of the outcomes of this research was an estimate of the magnitudes of the Jogan earthquake and tsunami. The Japanese government decided to utilize the paleotsunami deposit research more positively, in order to increase accuracy of long-term prediction of and to implement countermeasures for infrequent large-scale tsunamigenic earthquakes (The Headquarters for Earthquake Research Promotion, MEXT, Japan, 2011a).

However, an important question still remained. Were sedimentological and numerical studies on the Jogan tsunami definitive enough to accurately predict the magnitude of a 'forthcoming' (namely, the 2011 Tohoku-oki) earthquake and tsunami? A positive answer to this question implies that the inundation area and source of past large-scale tsunamis can be adequately estimated, and the magnitude of future earthquakes and tsunamis can also be evaluated through paleotsunami deposit studies. A negative answer means the science needs to progress before tsunami deposits and modeling can be used to predict the potential size of future large earthquakes and tsunamis. In fact, doubts on the applicability of the deposit-based estimation and prediction are surfacing after the Tohoku-oki event. For example, a significant gap between the inland extent of tsunami deposits and the limit of inundation for the Tohoku-oki event was observed in this region (Goto et al., 2011). The magnitude of the Jogan and the Tohoku-oki events are seemingly comparable in terms of the extent of tsunami inundation on the Sendai Plain (Sugawara et al., in press). As discussed in Section 3.1, the estimated inundation area of the Jogan tsunami is based on the inland extent of the tsunami deposit. If tsunami deposits did not reach the limit of inundation for the Jogan tsunami, then an inundation distance based on deposits, and the

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magnitude of the earthquake that is based on inundation distance, could have both been underestimated.

Previous studies of the Jogan tsunami deposit are valuable for guiding future directions for paleotsunami research, because this is the first opportunity to evaluate hydrodynamic model estimates of tsunami size based on deposits where a modern tsunami (2011 Tohoku-oki) also created deposits. Unfortunately, most of the literature is written in Japanese and difficult to access for non-Japanese researchers. The purpose of the present paper is to introduce the results of sedimentological research on the Jogan tsunami through a review of the published literature and new data. Estimates of the inundation area and earthquake magnitude based on comparisons of the wave sources of the Jogan and the Tohoku-oki tsunamis are discussed. Implications for future research directions for sedimentological studies of tsunamis are mentioned in the concluding remarks.

2. Previous studies of the Jogan tsunami

2.1. Written records and oral legends

The 13th July, 869, Jogan earthquake is the oldest historical event on the Pacific coast of northeast Japan (Fig. 1), and is thought to have triggered a large-scale tsunami (Yoshida, 1906). Table 1 shows a brief chronological overview of studies of the Jogan tsunami. These studies use historical accounts, sedimentological data, and hydrodynamic modeling to constrain the size of the Jogan earthquake and extent of inundation from the tsunami it generated. A written record (historiography compiled by ancient Japanese government) known as the ‘Nihon Sandai Jitsuroku’ (translation: Chronicles of the three emperors of Japan), describes the number of buildings that collapsed during the earthquake, and gives accounts of the extensive tsunami flooding of the coastal plain that drowned thousands of people. Until the late 1980s, the written record was the exclusive information source for the Jogan event (e.g. Imamura, 1934). The magnitude of the earthquake was estimated at M = 8.5–8.6 based on the written record and analogy to modern tsunamigenic earthquakes in this region (Kawasumi, 1951; Usami and Kayano, 1970). Beginning in the 2000s, dozens of oral legends from the Pacific coast of northeast Japan with possible connection to the tsunami were investigated (Watanabe, 2001); however, no information was found that could be used to quantify the heights and inundation areas of the tsunami, or the earthquake magnitude. The dates of origin of the oral legends and their correlation to the Jogan event were also equivocal.

The Sanriku Coast (Fig. 1) has frequent, extremely damaging tsunamis. In contrast, Sendai Bay and the Joban Coast do not have a historical record of large-scale tsunamis, although they are seismically active regions. The Miyagi-oki earthquake is one of the most dangerous quasi-periodic earthquakes in northeast Japan (99% probability of occurrence during the next 30 years, until the 2011 Tohoku-oki earthquake occurred), which may damage much of Miyagi and neighboring prefectures (ID 1–6 in Table 2). The recurrence interval of Miyagi-oki earthquakes is estimated at around 37 years, with magnitude of M = 7.0–8.2 (Table 2; The Headquarters for Earthquake Research Promotion, MEXT, Japan, 2000, 2011b). However, typical heights for tsunamis generated by Miyagi-oki earthquakes are small. For example, the 1978 Miyagi-oki earthquake (M = 7.4) generated tsunami waves only about 0.5 m high on the Sendai Plain (Watanabe, 1998).

2.2. Studies of the Jogan tsunami deposits

The sand layer deposited by the Jogan tsunami has been used to estimate it's alongshore extent and inundation since the late 1980s. Table 3 summarizes research published during the past 24 years including the locations and results of field surveys of the Jogan tsunami deposit. The references in this table include not only research papers, but also abstracts from Proceedings of scientific meetings and reports from research programs managed by governmental organizations, frequently in Japanese but complete with English abstracts and figure captions.

2.2.1. Study locations

The geological record of the Jogan tsunami was a focus of the early paleotsunamis investigations in Japan (Abe et al., 1990; Minoura and Nakaya, 1991). A number of field surveys to detect traces of the Jogan and other past tsunamis have been conducted in coastal areas from Iwate, Miyagi and Fukushima prefectures (Fig. 1). To date, research teams have surveyed 30 different sites, with more than one group studying some sites. Before 2000, field surveys of the Jogan tsunami deposit were limited to sites on the Sendai Plain and in Soma, which is in northern Fukushima prefecture (Fig. 1 and Table 3). The number of field surveys increased in the early 2000s, with a large increase after 2006 (Tables 1 and 3). This is mainly caused by the start of the “High-priority Observation and Survey on Miyagi-oki Earthquakes” research program in 2005. The Headquarters for Earthquake Research Promotion manage this program (The Headquarters for Earthquake Research Promotion, MEXT, Japan, 2006, 2007, 2008, 2009, 2010, 2011c). The research program and a number of other studies (Table 3) advanced understanding of the Miyagi-oki, Jogan and earlier earthquakes.

2.2.2. Setting and survey method

The Jogan tsunami deposit was first identified as a sand layer within peat and humic mud in the back marshes of the Sendai Plain (No. 13 in Fig. 1 and detailed map and profile in Fig. 2a and b, detail of the deposits in Fig. 3a and b) (Abe et al., 1990; Minoura and Nakaya, 1991). Subsequent research has followed basically the same strategies and methods as the pioneering work. Most of the surveys are in marshes (now utilized for rice paddies), coastal lakes, and drained lands, all of which are common in the coastal plains and lowlands in this region (Table 3). In northeast Japan, direct observation of past tsunami deposits at natural outcrops is unusual. Instead, Shishikura et al. (2007) observed the Jogan and other tsunami deposits at a 100-m-long outcrop, which was excavated at an existing agricultural drainage. Opening of deep trenches to search for the Jogan deposit was only done in earlier studies (Abe et al., 1990; Minoura and Nakaya, 1991). Coring equipment, such as man-powered and power-driven corers and geoslicers, are commonly used for many of the investigations. In general, the maximum inland extent of tsunami deposits can be considered as a proxy for inundation. In order to better determine the shore-normal maximum inland extent of the tsunami deposit, 18 surveys along shore-normal transects (sub-heading Trs in Table 3) were made taking evenly spaced cores (typically tens of to one hundred meters between cores).

2.2.3. Identification criteria

Potential event layers that can be associated with the Jogan and other tsunamis have been found in 28 areas. These event layers are composed mainly of gravel layers at the Sanriku Coast, and of sand layers in the coastal lowlands of Sendai Bay and the Joban Coast (Table. 3). Correlation of these event layers to the Jogan tsunami was attempted in 25 surveys using radiocarbon dating. A regional tephra (To-a), which was deposited at AD 915 by the eruption of Towada volcano, 46 years after the Jogan tsunami (Machida and Arai, 2003), is frequently used as a key bed for stratigraphic correlation in coastal areas of Sendai Bay and the northern Joban Coast (Fig. 3b). Earlier regional tephras (~5000 years BP) are also found on the Sanriku and Joban Coasts (e.g. Haraguchi and Goya, 2007; Imaizumi et al, 2008). They can be used to estimate the recurrence interval for large-scale earthquakes, but not for direct correlation of the Jogan event.

Radiocarbon dating of event layers is the primary criteria to identify the Jogan tsunami deposit. Other criteria are the sedimentological features (e.g. Morton et al., 2007) of the event deposit. Most of the studies identified the Jogan tsunami deposit based mainly on

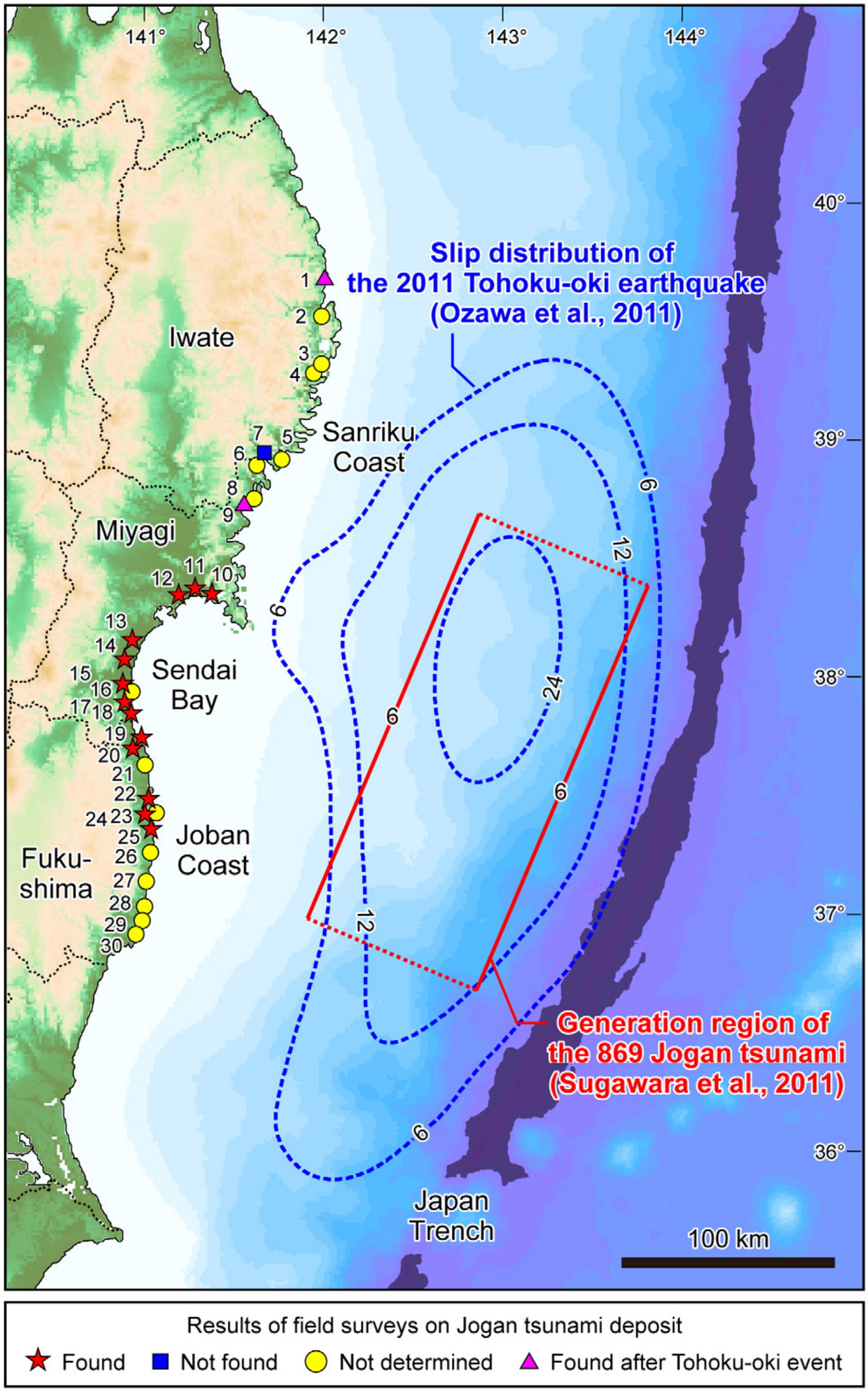

Fig. 1. Location map for the Pacific coast of northeast Japan. Symbols indicate the surveyed areas and whether or not the Jogan deposit was found. Numbers (1–30) correspond to areas in Table 3. The hypothesized generation region for the Jogan tsunami is indicated by the red rectangle. Broken blue lines are contours of slip (in meters) of the 2011 Tohoku-oki earthquake estimated from GPS observations (Ozawa et al., 2011).

its sedimentology and analogue to common characteristics of modern tsunami sand layer. Geochemical and paleontological criteria (e.g. Chagué-Goff, 2010; Goff et al., 2012) are applied to 8 survey areas. Not using these criteria may potentially lead to less accurate identification of the Jogan deposit.

Discriminating tsunami deposits from other high-energy event deposits is recognized as major problem. For example, both tsunamis and storms are capable of inundating coastal areas with seawater and depositing sediments on land. Modern observations have clarified the nature of these event deposits, and the criteria for discriminating between event deposits is the focus of many papers (e.g. Nanayama et al., 2000; Richmond et al., 2011; Shanmugam, 2011). Studies have found that the shore-normal distribution and sedimentological characteristics differ for tsunami and storm deposits (e.g. Morton et

Table 1
Chronology of the Jogan earthquake and tsunami. See Fig. 1 and Table 3 for further information on locations.

Year	Estimated magnitude of the Jogan earthquake	Study or significant event
869	Jogan earthquake	Documentation of damage and aftermath of the disaster in a historiography (Nihon Sandai Jitsuroku)
1906		First study of the Nihon Sandai Jitsuroku historiography
1934		Listed in the earthquake catalogue of Japan
1951	M 8.6	First estimate of the earthquake magnitude
1970	M 8.5	Re-examination of the earthquake magnitude
1987-		First discovery of Jogan and earlier tsunami deposits on the Sendai Plain First estimate of recurrence interval (~800 years) for large tsunamis on the Sendai Plain
1999-	M 8.3-8.5	Detection of the Jogan tsunami deposit on the northern Joban Coast (Soma) First numerical modeling of the tsunami and estimate of earthquake magnitude
2000-		First study of oral legends of the Jogan and other tsunamis on the Pacific coast of northeast Japan
2005		Start of “High-priority Observation and Survey on Miyagi-oki Earthquakes” program
2006		Detection of the Jogan and earlier tsunami deposits at Sendai Bay (from Ishinomaki to Yamamoto) Discovery of 22 event deposits in Otsuchi Bay
2007	Mw 8.4	Field surveys of Sanriku Coast (from Miyako to Kesen-numa; not detected) Numerical modeling and re-examination of scenarios of the Jogan earthquake
2008		Detection of the Jogan tsunami deposit at Namie (central Joban Coast) Re-examination of the recurrence interval (600–1300 years) for large tsunamis
2009		Detection of the Jogan tsunami deposit at Minami-soma (northern Joban Coast) Field surveys of the southern Joban Coast (Iwaki; not detected)
2010-		Further examination of earthquake scenarios
2011	Tohoku-oki earthquake (Mw9.0)	Detection of candidates of the Jogan tsunami deposit from Sanriku Coast (Miyako and Kesen-numa)

Table 2
List of Miyagi-oki and other tsunamigenic earthquakes in the Pacific coast of northeast Japan (The Headquarters for Earthquake Research Promotion, MEXT, Japan, 2000). Six earthquakes since 1793 were identified as Miyagi-oki earthquakes (ID: 1–6). Latitude and longitude indicate the estimated coordinates of the epicenter.

ID	Year	Month	Day	Latitude	Longitude	M[a]	Type[b]
	869	7	13	37.5–39.5	143–145	8.6	Tsu
	1611	12	2	39	144.4	8.1	Tsu
	1616	9	9	38.1	142	7	?
	1717	5	13	38.5	142.5	7.4–7.5	Tsu
1	1793	2	17	38.5	144.5	8.2	Tsu
2	1835	7	20	38.5	142.5	7.0–7.3	?
3	1861	10	21	38.55	141.15	7.4	Tsu
	1896	6	15	39.5	144	8.2	Tsu
4	1897	2	20	38.1	141.9	7.4	Tsu
	1897	8	5	38.3	143.3	7.7	Tsu
	1898	4	23	38.6	142	7.2	Tsu
	1915	11	1	38.3	142.9	7.5	Tsu
	1933	3	3	39.14	144.31	8.1	Tsu
	1933	6	19	38.05	142.3	7.1	Tsu
5	1936	11	3	36.26	142.065	7.4	Tsu
6	1978	6	12	38.15	142.167	7.4	Tsu

[a] Magnitude of the earthquake.
[b] Type of earthquake (Tsu: tsunamigenic; ?: potential tsunamigenic or ambiguous).

al., 2007). Compared to storm surges, tsunamis have greater hydraulic force and can inundate coastal lowlands several hundreds to kilometers from the beach; therefore, it is reasonable include the inland extent of the event deposit as one of the criteria for discriminating event type.

In Sendai Bay, river floods are more frequent than storm surges (Water, Disaster Management Bureau, MLIT, Japan, 2011). The coastal plains from Ishinomaki to Yamamoto are quite flat, low and broad (maximum width of ~6 km). In this geomorphic setting, both tsunamis and river floods can inundate and deposit sandy sediments on the plain. Discrimination between flood and tsunami deposits is facilitated by restricting investigations to areas not affected by river floods, such as the vicinity of natural levees. Formation by tsunami, rather than floods, is favored for laterally continuous event layers that are far from the coastline and from rivers. In contrast to the coastal plains, discrimination between tsunami and flood deposition is more difficult along the Sanriku and Joban Coasts because low-lying areas are limited to bay heads, and rivers are more common. However, a limited number of potential sandy event layers, which were dated around the Jogan ages, are found in these areas. As a result, the problem of discriminating Jogan deposits from other event deposits has not been addressed in the literature. Note that Sawai et al. (2007a) discussed the discrimination of possible tsunami deposits from deposits of storm surges based on historical documents during the last 400 years. However, it is difficult to use historical records to discriminate Jogan deposits from the other event deposits because of the lack of historical records.

2.2.4. Survey result

Before the Tohoku-oki event, the Jogan tsunami deposit had been identified in all 13 areas where it was looked for from Ishinomaki in northern Sendai Bay (No. 10–12 in Fig. 1 and Table 3) to Namie, in the central Joban Coast (No. 25). The tsunami deposit was not found only in the lowland of Rikuzen-takata (No. 7). The Jogan tsunami is considered to have not inundated the onshore excavation site (The Headquarters for Earthquake Research Promotion, MEXT, Japan, 2009, 2010, 2011c) at No. 7. The Jogan tsunami deposit has not been detected in 14 other areas; evidence of inundation by the Jogan tsunami remains unclear in these areas.

The following list gives the main reasons why researchers did not report finding of the Jogan tsunami deposit:

1. No event horizon in sediment column during the Jogan period (5 areas)
2. Reworking or disturbance of surficial sediments (reversal of age; 4 areas)
3. Absence of sediments during the Jogan period (2 areas)
4. Low traceability of possible event layer (2 areas)

Other reasons are for not attributing an event deposit to the Jogan tsunami includes errors inherent in radiocarbon dating that resulted in ambiguous correlation with the Jogan event. Even where the Jogan tsunami deposit was not detected, most studies do not conclude, “it does not exist in the study area”. Therefore, in Fig. 1, the absence of identification of the Jogan tsunami deposit is noted as “not determined”.

2.3. Sedimentological features

Significant progress has been made in the past 20 years in determining the variety of sedimentary environments, facies and global, regional and local distributions of tsunami deposits (Dawson and Shi, 2000; Dawson and Stewart, 2007; Shanmugam, 2011). Characteristic geometries and sedimentological structures of tsunami deposits, such as the general trend of landward thinning and fining, as well as upward fining of sand layer, are typically reported for modern (e.g. Nishimura and Miyaji, 1995; Gelfenbaum and Jaffe, 2003; Paris et al., 2007) and paleo (e.g. Atwater, 1987; Dawson et al., 1991; Benson et al., 1997) deposits on coastal lowlands. Recent research identified Jogan tsunami

Table 3
List of surveyed areas of the Jogan and other tsunami deposits in northeast Japan. Location of each area (no.) is indicated in Fig. 1.

Region	Location						Setting		Survey method		Deposit type	
	Pref.	City (Town)	Area	Lat. (°N)	Long. (°E)	No.	Land condition	Geomorphology	Obs	Trs	Normal	Event
Sanriku Coast	Iwate	Miyako	Masaki Taro[a]	39.749943	141.993437	1	Unknown	Valley	OC		Bog deposit	Sand gravel
			Hakono-hama	39.598087	141.967753	2	Marsh	Lowland	VC, GS		Peat	Sand gravel
		Otsuchi	Kirikiri	39.351814	141.917011	3	Paddy	Lowland	VC, GS	Y	Peat	Sand gravel
			Otsuchi Bay	39.369723	141.945046	4	Sea	Bay bottom	PC		Bottom clay	Sand gravel
		Oofunato	Goishi-hama	38.989751	141.737830	5	Marsh	Beach	VC, GS		Peat silt	Gravel
		Rikuzen-takata	Furukawa-numa	39.007960	141.632699	6	Lagoon	Lagoon	GS		Peat	Sand
			Nakazeki	39.007960	141.632699	7	Marsh	Lowland	GS		Flood deposit	Sand
	Miyagi	Kesen-numa	Sakino Hajikami	38.824890	141.586101	8	Marsh	Lowland	VC, GS		Peat	Sand gravel
			Oya coast[a]	38.813956	141.573732	9	Unknown	Coastal cliff	OC		Peat black soil	Sand gravel
Sendai Bay		Ishinomaki	Watanoha	38.426910	141.355018	10	Paddy	Coastal plain	PC, GS	Y	Peat	Sand
			Rikuzenakai	38.450440	141.252381	11	Paddy	Coastal plain	PC, GS, OC	Y	Peat	Sand
		Higashi-matsushima	Yamoto	38.422338	141.192306	12	Paddy	Coastal plain	PC, GS	Y	Peat	Sand
		Sendai	Wakabayashi	38.231737	140.930076	13	Paddy	Coastal plain	PC, GS, TC	Y	Peat	Sand
		Natori	Uematsu	38.150224	140.888516	14	Paddy	Coastal plain	PC, GS	Y	Peat	Sand
		Watari	Nagashizu	38.016095	140.863508	15	Paddy	Coastal plain	PC, GS	Y	Peat	Sand
			Torino-umi	38.034092	140.900756	16	Lagoon	Lagoon	GS	Y	Sandy mud	Sand
		Yamamoto	Yamadera	37.980274	140.874381	17	Paddy	Coastal plain	PC, GS	Y	Peat	Sand
			Suijin-numa	37.902238	140.909089	18	Pond	Pond	GS		Peat	Sand
Joban Coast	Fukushima	Soma	Iwanoko Douzuki	37.800824	140.963609	19	Drained land	Coastal plain	PC	Y	Clay	Sand
			Yamashida Isobe	37.775102	140.958884	20	Drained land	Lowland	PC, GS	Y	Silt, clay humic mud	Sand
		Minamisoma	Ouchi Kashima	37.682105	140.996284	21	Paddy	Lowland	PC, GS	Y	Humic mud	Sand
			Fukuoka Odaka	37.549762	141.008686	22	Paddy	Lowland	PC, GS	Y	Peat	Sand
			Idagawa Odaka	37.523507	141.015820	23	Drained land	Lowland	GS		Humic clay	Sand
			Urajiri Odaka[b]	37.519528	141.028889	24	Paddy	Lowland	VC	Y	Peat	Sand
		Namie	Ukedo	37.476566	141.026200	25	Paddy	Terrace	PC, GS	Y	Peat silt	Sand
		Tomioka	Hotoke-hama	37.333600	141.023885	26	Paddy	Terrace	PC, VC, GS	Y	Humic mud humic clay	Sand
		Hirono	Shimoasamigawa	37.211484	141.000655	27	Paddy	Terrace	VC	Y	Humic clay river sediment	
		Iwaki	Yotsukura	37.086411	140.977353	28	Paddy	Lowland	GS		Humic mud peat	Sand
			Tairafujima	37.046281	140.967145	29	Paddy	Lowland	GS		Humic mud peat	Sand
			Simotakaku	37.031003	140.959192	30	Paddy	Lowland	VC	Y	Humic clay	

Notes for table headings.
Survey method: Obs = observation method (OC = outcrop, VC = vibro-corer, GS = geoslicer, PC = piston corer, TC = deep trench), Trs = excavation along transect(s).
Identification criteria: 14C = radiocarbon dating, Sdm = sedimentological observation, Chm = geochemical analysis, Fssl = paleontological analysis.
Survey result: Dis. = shore-normal distribution distance of the Jogan tsunami deposit measured from paleo-coastline (Elev. = highest elevation of the deposit).
Ref. No and Authors1: Abe et al. (1990), 2: Goto and Aoyama (2005a), 3: Goto and Aoyama (2005b), 4: Haraguchi et al. (2006a), 5: Haraguchi and Goya (2007), 6: Haraguchi and Ishibe (2009), 7: Haraguchi et al. (2006b), 8: Haraguchi et al. (2007), 9: Hirakawa et al. (2011), 10: Imaizumi et al. (2008), 11: Imaizumi et al. (2007a), 12: Imaizumi et al. (2007b), 13: Imaizumi et al. (2010), 14: Minoura et al. (2001), 15: Minoura (1990), 16: Minoura and Nakaya (1991), 17: Oikawa et al. (2011), 18: Sawai (2010), 19: Sawai et al. (2007b), 20: Sawai et al. (2008b), 21: Sawai et al. (2008a), 22: Sawai et al. (2006), 23: Sawai et al. (2007b), 24: Sawai et al. (2007c), 25: Shishikura et al. (2006), 26: Shishikura et al. (2007), 27: Sugawara et al. (2002), 28: Sugawara et al. (2009), 29: Sugawara et al. (2010), 30: The Headquaters for Earthquake Research Promotion, MEXT, Japan (2011c), 31: Torii et al. (2007).
[a] Candidate of the Jogan tsunami deposit found and reported after the 2011 Tohoku-oki event.
[b] Found before and reported after the 2011 Tohoku-oki event.

Region		Identification criteria					Survey result				Inundated by 2011 tsunami	Ref. No.	Remarks
	No.	To-a	14C	Sdm	Chm	Fssl	Detection	First report	Dis.	Elev.			
Sanriku Coast	1						?	2011			Y	9	
	2		Y					2007			Y	7, 8, 30, 31	Latest event layer is dated at 1,960BP
	3		Y					2007			Y	7, 8, 30, 31	Hiatus of sedimentation during the last 2,000 years
	4		Y	Y				2006			Y	4, 5, 7, 8, 10, 30, 31	22 event layers during the last 6,000 years
	5		Y					2007			Y	6, 7, 8, 30, 31	No event layer during 1,910BPAD1,920
	6		Y					2007			Y	7, 8, 11, 30, 31	Reversal of 14C age (reworked)
	7		Y				N	2007			Y	7, 8, 11, 30, 31	Reversal of 14C age (reworked)
	8		Y					2007			Y	7, 8, 30, 31	Hiatus of sedimentation during the last 2,000-3,000 years
	9			Y			?	2011		5 m	Y	9	Six event layers during the last 5,400 years
Sendai Bay	10	Y	Y	Y			Y	2006	1 km		Y	24, 25, 26, 30	
	11	Y	Y	Y			Y	2006	3 km		Y	24, 25, 26, 30	
	12	Y	Y	Y			Y	2006	3 km		Y	24, 25, 26, 30	
	13	Y	Y	Y	Y	Y	Y	1990	2-3 km	2.5 m	Y	1, 14, 15, 16, 18, 19, 21, 26, 28, 29, 30	
	14	Y	Y	Y			Y	2006	4 km		Y	18, 19, 21, 26, 30	
	15	Y	Y	Y		Y	Y	2006	2 km		Y	18, 19, 21, 26, 30	
	16					Y		2007			Y	19, 30	Discontinuous distribution of the event layer
	17	Y	Y	Y		Y	Y	2006	2 km		Y	18, 19, 21, 26, 30	
	18	Y	Y	Y		Y	Y	2007					
Joban Coast	19	Y				Y	Y	2001			Y	27, 30	Discontinuous distribution of the event layer
	20	Y	Y	Y		Y	Y	2005			Y	2, 3, 13, 17, 30	Small number of dating
	21							2009			Y	30	Discontinuous distribution of the event layer
	22		Y				Y	2009	1.5 km		Y	30	
	23			Y				2005			Y	2, 3	Small number of dating
	24		Y	Y		Y	Y	2011		3 m	Y	17	
	25		Y				Y	2008	1.4 km	< 4 m	Y	12, 13, 30	
	26		Y					2009			Y	17, 23, 30	Two event layers during the last 5000 years No event layer during BC1000–AD900
	27		Y					2011			Y	17	No event layer during BC1400–AD1,600
	28		Y					2009			Y	30	Reversal of 14C age (reworked)
	29		Y					2009			Y	30	Reversal of 14C age (reworked)
	30		Y					2011			N	17	No event layer during BC1500–AD1300 No event layer during AD0–AD1000 No event layer after AD1400

deposits by comparing the sedimentological features of candidate event layers with those of tsunami deposits. In general, the presence of these features implies deposition of sand by landward-oriented strong current, likely caused by inundation of a tsunami.

On the Sendai Plain, observations from over 100 excavation sites have established the maximum and average thickness of the Jogan tsunami deposit as 30 cm and 8 cm, respectively (Figs. 2a and 4; Sugawara et al., 2010). Thinner layers (<5 mm) and even concentrations of sand are recognizable during field observations. Fig. 3a and b show the Jogan tsunami deposit found at 1.5 and 2.5 km from the paleo-coastline (P1 and P2 in Fig. 2a, respectively). At P1, an 8-cm-thick medium sand layer is found within marsh deposits (Fig. 3a). Inclusion of rip-up clasts and a sharp basal contact with the underlying peat imply erosion of a paleo-soil prior to the deposition of the sand. In contrast, at P2, the Jogan tsunami deposit is recognizable as a concentration of 1-cm-thick fine sand (Fig. 3b). The underlying and overlying deposits consist of muddy sediments with abundant humic matter, and do not show any sedimentological evidence of erosion of a paleo-soil before, and of environmental change after, deposition of the sand.

Surveys along shore-normal transects have determined the inland extent of the Jogan tsunami deposit in 9 areas (Table 3). In the coastal plains from Ishinomaki to Yamamoto, the maximum inland extent reached approximately 3–4 km from the paleo-coastline (Sawai et al., 2007a, 2008a; Shishikura et al., 2007). The elevation of the Jogan deposit at its maximum inland extent is 2.5 m on the Sendai Plain (Abe et al., 1990) and around 3 m in Soma (Oikawa et al., 2011). Fig. 4 shows the thickness of the Jogan tsunami deposit along 6 transects on the Sendai Plain (transects A–F in Fig. 2a). The maximum thickness of the sand layer is more than 25 cm near the coast. The general trend is landward thinning, with thickness decreasing to less than 5 cm inland of 2.5 km from the Jogan paleo-shoreline. Data from several transects are required to recognize the landward-thinning trend because of local variability in the thickness and the discontinuous distribution of the sand layer. The maximum inland extent of the Jogan tsunami deposit on the Sendai Plain is about 3–4 km from the present coastline (Fig 2a). The paleo-coastline during the Jogan age is estimated to be about 1 km landward of the present coastline (Ito, 2006; Sawai et al., 2008a). Therefore, relative to the paleo-coastline, the maximum inland extent of the deposit on the Sendai Plain is 2–3 km.

Upward and landward fining of the Jogan tsunami deposit was not quantitatively investigated by previous studies. Fig. 5 shows the vertical variation of grain-size of the Jogan tsunami deposit from 4 different locations on the Sendai Plain (S3, S4, S5 and S7 in Fig. 2a). The thickness of the deposit ranges from 4 to 28 cm. Grain size of 2 cm vertical intervals was measured using a laser-diffraction particle-size analyzer (SALD-3100 J; Shimadzu CO., LTD.). Mean grain size of the sand is plotted against relative depth of the sampled interval (defined as the ratio between the depth below the top of the sand layer and its thickness). Vertical variation of the mean grain size is quite moderate; it ranges from 300 μm at S 7 to 350 μm at S 3, S4 and S5. No significant vertical trend in mean grain size, which can be associated with hydraulic character or sediment transport, is apparent. Mean grain size does decreases inland for two of the sites where vertical grading was measured (S7 is 700 m inland of S3). However, the decrease is quite moderate, and is still within the range of medium sand. Fig. 6 shows the horizontal variation of mean grain size of the Jogan tsunami deposit along transect F (Fig. 2a). This figure shows all data without regard to elevation in the deposit because the vertical variation of mean grain size at single survey site does not show any significant trend. Over a distance of 1 km, the maximum and minimum grain size decrease from 400 to 300 μm, and from 350 to 300 μm, respectively, and the skewness and kurtosis vary little. The horizontal variation in mean grain size and sorting are limited by the characteristics of the sediment source. The Jogan tsunami deposit is commonly reported as a massive layer of medium- to fine-grained sand (e.g. Abe et al., 1990; Minoura et al., 2001; Sawai et al., 2008b); had the source sediment contained gravels, coarse sand, or silt, it would have contained particles of those sizes. Minoura and Nakaya (1991) suggested the source as well-sorted beach and dune sands; this implies that hydraulic sorting by tsunami run-up could not modify the inherent grain-size composition of the source. Potential inland sources of sandy sediment are older beach ridges (Fig. 2b); so the grain size of the Jogan tsunami deposit reflects the grain size near the coastline.

Interpretation of multiple layers in a tsunami deposit may provide useful information that constrains the type of depositional event, as well as the character of wave source. For example, a deposit in a coastal lake on the southern Sendai Plain was identified as forming from the Jogan tsunami because it contained multiple sand layers (Sawai et al., 2008b). However, most of the onshore Jogan tsunami deposit has been documented as a structureless sand layer (e.g. Sawai et al., 2007a; Sugawara et al., 2010). Observations in the months and years after the 2004 Indian Ocean tsunami established that deposits can be altered by erosion and redeposition, mixing and formation of soil, as well as human activities (Szczuciński, 2012). In case of the Jogan tsunami deposit, internal structures such as stacks of sedimentary units or upward finings might have been disturbed during hundreds of years of preservation. However, it is more likely that the deposit did not originally have any complex structure, because of a simple inundation pattern caused by the waveform and local geomorphology. In general, the initial waveform in the focal region and the bathymetry between the focal region and the shore determine the tsunami waveform in the coastal zone. Numerical models show that the wave train of the Jogan tsunami in the nearshore of Sendai Bay is characterized by a remarkably high first wave and following smaller waves (Sugawara et al., 2011). The geomorphic setting of the paleo- (and even present) Sendai Plain is characterized by an elevated sand dune parallel to the coastline and extensive back mashes behind it (Figs. 2a and b) resulting in most of the Jogan tsunami flooding by the first wave. After overtopping the sand dune, water ponded within the marshes and remained there for a long time. In this geomorphic setting, backwash doesn't occur across the entire coastal plain. It is limited to channels and drainages, and creates erosional features. The patterns of tsunami erosion and deposition on coastal plains are important to understand because they can be used to learn the sediment transport and run-up/backwash processes of the tsunami that created them. However, largely because of the geomorphic setting, the Jogan tsunami deposit does not provide useful information on the waveform in nearshore area, and on the corresponding characteristics of the wave source.

Geochemical analysis of deposits is a robust method for identification of marine inundation at a number of sites over a broader area. On the Sendai Plain, evidence of tsunami inundation was first found by detection of chemical elements that originated in seawater within the event layers (Abe et al., 1990). Paleontological analysis of microfosssils is another tool for identifying tsunami deposits. The Jogan and other event layers were identified in 8 areas using the vertical variation in diatom assemblages (Table 3; Minoura et al., 2001; Sawai et al., 2007c, 2008a,b; Oikawa et al., 2011). Marine species do not necessarily dominate the tsunami deposit. For example, brackish species dominated the assemblage on the Sendai Plain; whereas marine species were predominate in the tsunami deposit from Soma (Minoura et al., 2001). Sawai et al. (2008a) reported that the diatom assemblage of the tsunami deposit from the southern Sendai Plain consists of mixture of marine, brackish and freshwater species. The path of tsunami run-up and environmental factors, such as the type of surficial sediment, distance from the sea, and the distribution of water bodies on land, may affect the composition of diatom assemblages. An increase of mud content is commonly observed in the upper part of the Jogan tsunami deposit (Shishikura et al., 2007; Sugawara et al., 2010). This implies that water was ponded after the tsunami and may be evidence for a change in sedimentary environment due to coseismic subsidence, such as was observed after the 2011 event (Ozawa et al., 2011). Crustal deformation after the Jogan event has been investigated

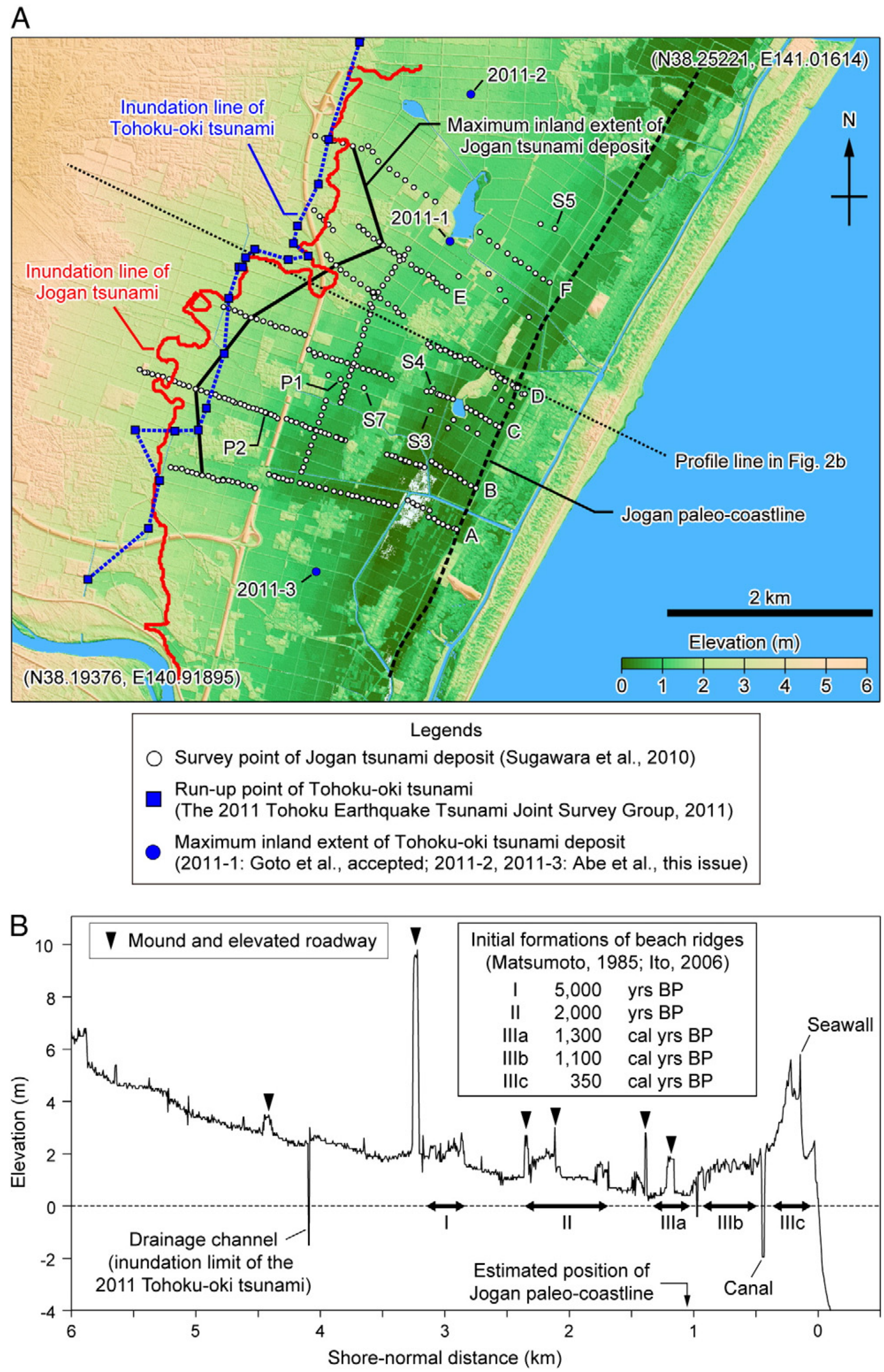

Fig. 2. A. Location map of surveys on the Sendai Plain (area no. 13 in Fig. 1 and Table 3). Solid black line indicates the inland limit of the Jogan tsunami deposit (Sugawara et al., 2010). Survey points P1 and P2, S3 to S7 correspond to the locations of photographs and grain-size data in Figs. 3 and 5, respectively. The dotted blue line with blue squares indicates the limit of inundation of the 2011 Tohoku tsunami (The 2011 Tohoku Earthquake Tsunami Joint Survey Group, 2011). The blue circle indicates the maximum inland extent of sandy deposit by the Tohoku-oki tsunami (2011–1: Goto et al., accepted for publication; 2011–2 and 2011–3: Abe et al., in press this issue). The solid red line indicates the limit of inundation of the Jogan tsunami derived from the numerical modeling (Sugawara et al., 2011). This figure is based on Digital map 5 m Grid (Elevation), Sendai, published by Geospatial Information Authority of Japan. The location of the Jogan paleo-coastline was estimated according to the formation ages of the shore-parallel beach ridges during the late Holocene (Fig. 2B; Matsumoto, 1985; Ito, 2006), and their shapes were reconstructed based on landform classification using the aerial photographs (Sugawara et al., 2010). B. Topographic profile of the Sendai Plain. The times of formation of the beach ridges were determined based on the radiocarbon dating of sediments from inter-beach ridge marshes (Matsumoto, 1985; Ito, 2006). The location of the Jogan paleo-coastline is estimated to be between the beach ridges IIIa and IIIb (Sugawara et al., 2010). Note that the beach ridge IIIa is not clear in this profile.

based on diatom assemblages as well as sedimentary facies of the under- and over-lying sediments of the Jogan tsunami deposit. The signatures of coseismic subsidence in sediments directly above the tsunami deposit were detected in Minami-soma City (The Headquarters for Earthquake Research Promotion, MEXT, Japan, 2009, 2010, 2011c).

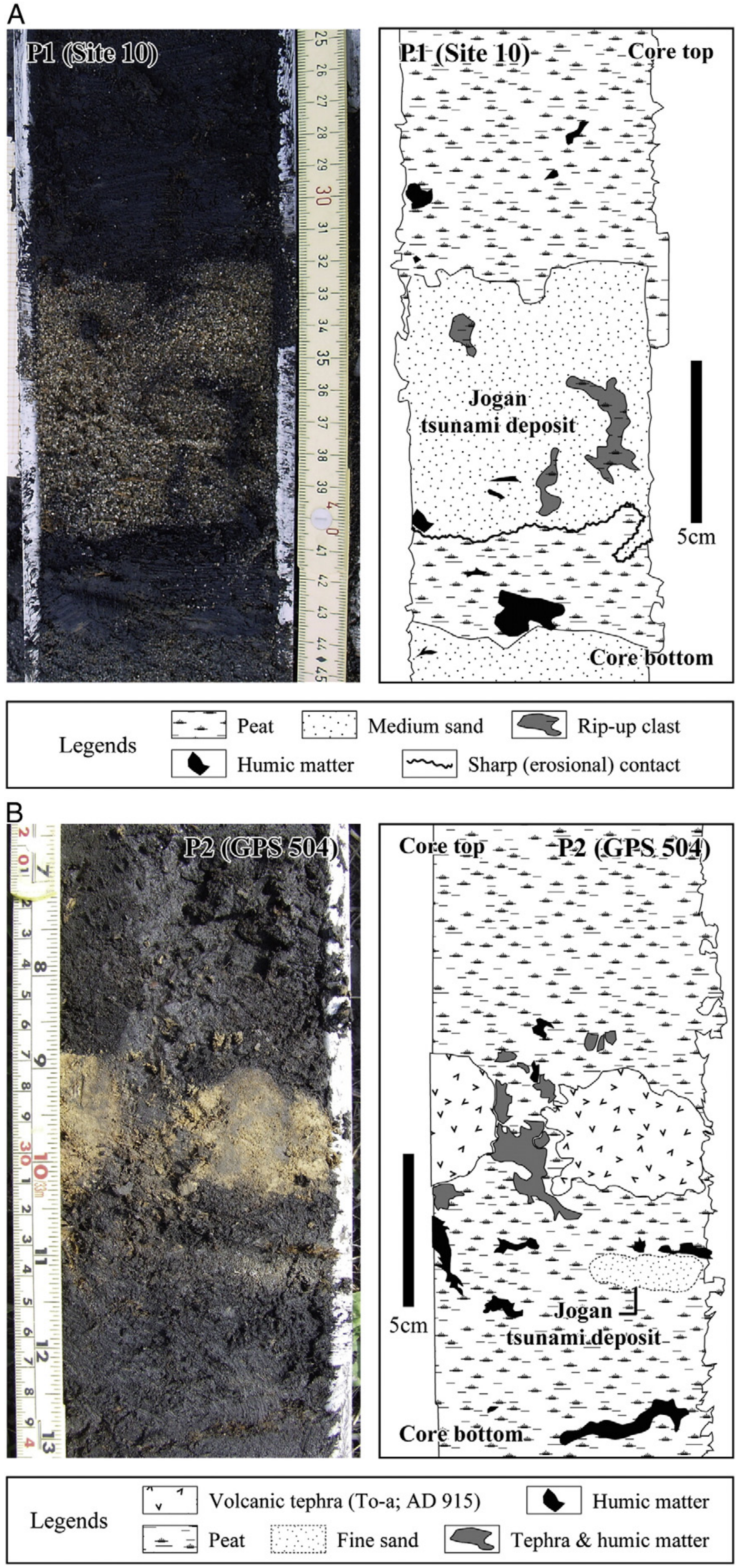

Fig. 3. A. The Jogan tsunami deposit at P1 (Site 10). The location of P1 is indicated in Fig. 2A. Modified after Sugawara et al. (2010). B. The Jogan tsunami deposit at P2 (GPS 504). The location of P2 is indicated in Fig. 2A. Modified after Sugawara et al. (2010).

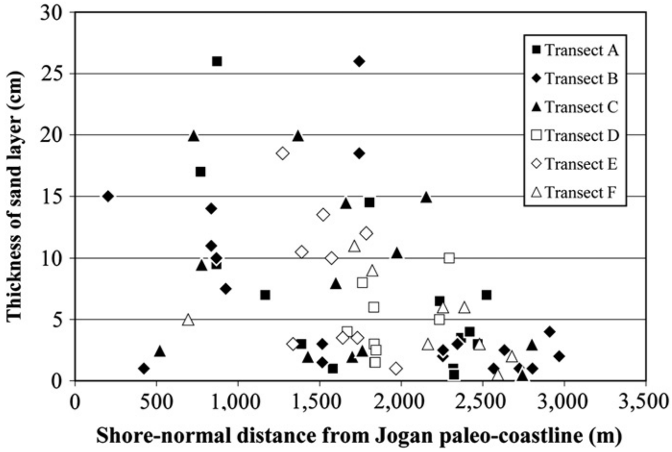

Fig. 4. Thickness of the Jogan tsunami deposit versus shore-normal distance from the Jogan paleo-coastline. Locations of transects A–F are indicated in Fig. 2A. Modified after Sugawara et al. (2010).

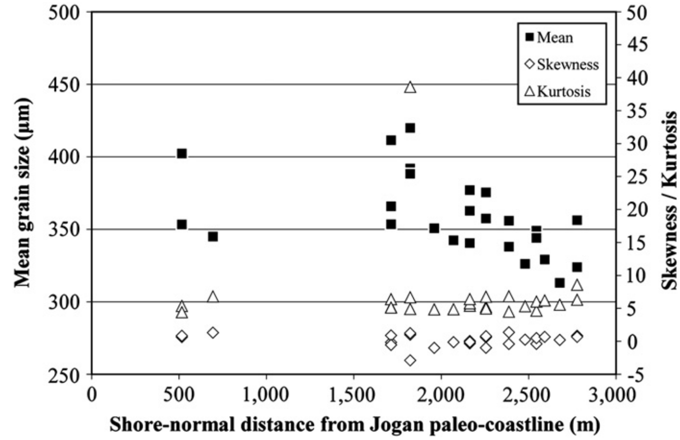

Fig. 6. Lateral change in grain size of the Jogan tsunami deposit along transect F (Fig. 2A). Core samples were measured in 2-cm vertical intervals. Each data point is plotted without distinction in depth.

3. Key findings and unresolved issues

3.1. Estimation of inundation area

The characteristics of the wave source and waveform of the Jogan tsunami were investigated qualitatively after 2000 in numerical studies using the spatial distribution of the Jogan deposit (e.g. Minoura et al., 2001). Detailed numerical modeling studies conducted after 2007 relate the inundation area, which is based on the Jogan deposit spatial distribution, to fault parameters. Several earthquake scenarios were tested to determine whether the tsunami inundation matched the distribution of the tsunami deposit on the Sendai Plain. Currently, an "at least" Mw = 8.4 earthquake off Miyagi prefecture, with a fault length of 200 km, width of 85–100 km, and displacement of more than 6–7 m, is favored as the most probable scenario for the Jogan earthquake (Satake et al., 2008; Namegaya et al., 2010; Sugawara et al., 2011). Modeling indicates that the inundation line (maximum run-up distance) was approximately 3.5 km from the paleo-coastline of the Sendai Plain (Fig. 2a; Sugawara et al., 2011).

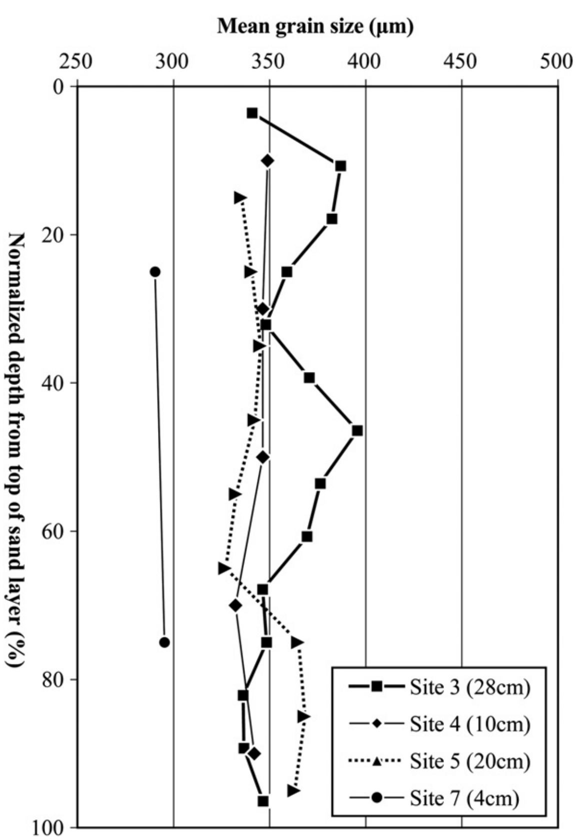

Fig. 5. Vertical change in grain size of the Jogan tsunami deposit. Thickness of each layer is denoted in parenthesis in the key. The horizontal axis is the ratio between the depth below the top of the sand layer and its thickness. Locations of S3 to S7 are indicated in Fig. 2A.

A possible weakness in this comparison is that the mapped maximum inland extent of the Jogan deposit is an underestimate of the inundation. Observations from modern tsunamis show that the sandy deposit maximum inland extent does not necessarily reach the limit of inundation. The sandy tsunami deposit is from about 50% (e.g. Shi et al., 1995) to nearly a 100% (e.g. MacInnes, et al., 2009) of the inundation. As long as the comparison is based on the maximum inland extent of the deposit, there is no constraint to limit the upper value of the run-up distance. Sugawara et al. (2011) addressed the gap between the maximum inland extent of the sandy tsunami deposit and inundation by calculating threshold shear stresses, which were derived from the observations of erosional features of the basal contact of the Jogan tsunami deposit and the physical properties of the soil. The yield stress of cohesive sediments is correlated with the critical shear stress of the sediment (e.g. Otsubo and Muraoka, 1988). The thresholds of shear stress for soil erosion constrain the maximum or minimum flow speeds and inundation. Although the analysis is preliminary, the resulting ratio between the maximum inland extent of deposition and inundation is as high as 85% (Sugawara et al., in press). This corresponds to an intermediate value found for modern tsunamis suggesting that the modeling results are not a gross underestimate. Practical application of this approach for determining the extent of deposition relative to inundation requires further investigation into topics such as preservation and identification of erosional features, compaction and change in physical characteristics of the soil, and measurement of yield stresses.

The inundation line of the Tohoku-oki tsunami on the Sendai Plain is approximately 4–5 km from the present coastline. This is approximately the same location as the inundation line of the Jogan tsunami (Fig. 2a). The coincidence in location does not mean the tsunamis were the same size. When the Tohoku-oki tsunami inundated the Sendai Plain, geomorphic changes such as migration of coastline during the last 1,142 years, vegetation cover, and engineering structures would have affected the processes of the tsunami run-up and sediment transport.

Precision of the modeling result makes the arguments more complicated. Tsunami modeling could reproduce different inundation area from same wave source, depending on the accuracy of reconstructed paleotopography as well as the spatial resolution of the topography data and tide level at the time of the paleotsunami event. Direct comparison of both tsunamis is difficult, but possible if the difference between present and paleo-coastlines are accounted for and a shear-stress analysis is used to correct the underestimate of inundation by the maximum inland extent of the sandy Jogan deposit. With these two corrections, the Jogan tsunami inundation on the Sendai Plain is 70–88% of the Tohoku-oki tsunami inundation. Sedimentological and modeling studies on the Jogan tsunami deposit have succeeded in documenting that much of the Sendai Plain was inundated by the Jogan tsunami and that the possibility of other tsunamis, such as the Tohoku-oki tsunami, could also inundate as far, or farther, inland.

3.2. Estimation of wave source

On the other hand, the estimated magnitude of the Jogan earthquake (Mw = 8.4) is much smaller than observed magnitude of the Tohoku-oki earthquake (Mw = 9.0–9.1). In terms of energy released, the magnitude of the Jogan earthquake accounts 10–13% of the Tohoku-oki earthquake. In case of the Tohoku-oki event, the length of focal region along the Japan Trench, where more than 6 m of fault slip is estimated, is two times longer than that of the Jogan event (Fig. 1; Ozawa et al., 2011). The Tohoku-oki tsunami inundated most of surveyed areas of the Jogan tsunami deposit, although the tsunami deposit was found from only the half of them (Fig. 1 and Table 3). If the height and run-up distances of the Jogan tsunami was truly equivalent to that of the Tohoku-oki tsunami, area of wave source (focal region) and offshore initial wave height (fault slip) might have been equivalent as well. In this case, the Jogan tsunami could have flooded almost all the surveyed areas and likely deposited sediments.

Before the Tohoku-oki event, the necessity of further field surveys to determine the alongshore distribution of the Jogan tsunami deposit on Sanriku and the southern Joban Coasts was repeatedly pointed out (Shishikura et al., 2007; Satake et al., 2008; Namegaya et al., 2010). The surveyed areas in Fig. 1 and Table 3 cover most of coast affected by the Tohoku-oki tsunami; however, the Jogan tsunami deposit was not often detected (although the deposit was found from two areas on the Sanriku Coast after the Tohoku-oki event). Assuming that earthquake magnitude and tsunami sedimentation of the Jogan to the Tohoku-oki events are similar, not finding the Jogan tsunami deposit on these coasts can be accounted by following reasons: (1) the tsunami did not leave a detectable (common) sandy deposit, and (2) the tsunami deposit was not preserved because of erosion or land utilization after deposition.

For example, the Sanriku Coast is characterized by the steep geomorphology of a drowned (ria) rocky coast, with limited coastal lowlands. The Joban Coast is characterized by sea cliffs. In general, erosion is dominant in these areas and tsunami deposits may not be preserved for a long time. Lowlands on these coasts are found near rivers where the influence of flood event can be significant. In addition, surficial sediments on such narrower lowlands are more likely to be reworked by human activities during modern and historical ages than sediments on the broader coastal plains. Reversals of 14C ages, possibly due to man-made land modification, were reported for sediment dated from the Sanriku and Joban Coasts (Table 3; The Headquarters for Earthquake Research Promotion, MEXT, Japan, 2008, 2009, 2010, 2011c). Although it is possible that inadequate surveys are an explanation for not finding the Jogan deposit, most surveys that did not find the Jogan deposit were in lowlands and marshes, environments where the Jogan was found on the Sendai Plain (sub-heading Geomorphology in Table 3). This underscores that the selection of the survey area in potential tsunami-affected regions requires careful consideration taking into account geologic and sedimentologic, as well as geomorphic and historical geographic, information.

3.3. Estimation of fault slip

Estimation of fault slip can be an alternative approach to evaluate the earthquake magnitude; however, sedimentological and numerical studies of the Jogan event could not predict the magnitude of slip by the Tohoku-oki earthquake (Fig. 1). The estimated slip distribution of the Jogan earthquake is uniform (6–7 m or larger; Satake et al., 2008; Namegaya et al., 2010; Sugawara et al., 2011) over a 200-km-length and 85-to-100-km-width area. This area corresponds to the part of focal region of the Tohoku-oki earthquake where more than 12 m of slip is estimated from GPS observation data (Ozawa et al., 2011). In addition, the fault slip by the Tohoku-oki earthquake exceeded 24 m in the northern half of the wave source of the Jogan earthquake (Fig. 1). In this regard, the relationship between the inland extent of the tsunami deposit and the run-up distance are important for adequate estimation. Observation of the deposits by the Tohoku-oki tsunami on the Sendai Plain reported a considerable gap between the maximum inland extent (2.7–2.8 km) of a thicker (>0.5 cm) sand layer and actual run-up distance (4.5 km) (Goto et al., 2011). If we assume a threshold thickness of 0.5 cm for being preserved as a geologic record, the maximum inland extent of the sandy deposit of the Tohoku-oki tsunami is 62% of the inundation distance. If the relationship between the fault slip and sand deposition for the Tohoku-oki event is applicable for the Jogan event, the magnitudes of the Jogan tsunami and earthquake could have been significantly underestimated. Of course, the behavior of tsunami run-up as well as sediment transport might have been affected by the numerous engineering structures, such as seawalls, canals, and elevated roadways (e.g. Fig. 2b; Sugawara et al., in press). In addition, the onshore sediment source for a tsunami deposit is often limited due to concrete-covered ground surfaces. Sediment transport and deposition also would have been affected by how people used the land at the time of the event. Studies of the existing human- and historical geography at the time of the event may help interpret the distribution and sedimentary characteristics of paleotsunami deposits.

Another simpler explanation for the underprediction is that the Tohoku-oki event is larger than the Jogan event. There is no reason for quasi-periodic, infrequent and large-scale earthquakes to always have identical magnitudes and focal regions. In any case, estimates of the size of the focal region and magnitude of the earthquake from sedimentological and numerical inundation modeling studies of the Jogan tsunami deposit did not portend an earthquake as large as the Tohoku-oki earthquake.

4. Concluding remarks

Studies of the Jogan tsunami deposit have concentrated on sites on the coastal plain of Sendai Bay, in part because it is easier to identify the deposit there (Fig. 1). Even in this setting, sedimentological research on the Jogan tsunami deposit was not able to predict the size of the focal region of the Tohoku-oki earthquake. The inland boundary of the inundation area of the Tohoku-oki tsunami on the Sendai Plain was apparently equivalent to that of the Jogan tsunami (Fig. 2a). However, when considering the difference in the position of present and paleo-coastlines, differences in the geomorphic settings, and that a sandy deposit likely did not form as far inland as the limit of inundation, the Jogan tsunami did not portend a tsunami as large as the Tohoku-oki tsunami. The differences between the postulated Jogan and Tohoku-oki events are large; the magnitude of energy released by the Tohoku-oki earthquake is nearly 8–10 times larger than that by the Jogan earthquake. The fault slip, which in part determines earthquake magnitude, of the Jogan event was too small to predict that an earthquake with the magnitude of the Tohoku-oki event would occur (Fig. 1).

There are unresolved issues for the Jogan tsunami deposit. It is still not known whether a deposit was formed along the entire Sanriku and Joban Coasts and has not been identified because of the difficulties of tsunami deposit identification in rocky and cliffed settings with narrow lowlands. Not finding sandy tsunami deposits does not necessarily mean that an area was not affected by past tsunamis, because deposits can be composed of particles of sizes other than sand (mud to boulders and larger). After the Tohoku-oki tsunami, event deposits that may have formed during the Jogan tsunami that are composed primarily of gravels were reported from the valley bottom in Miyako and fronting the coastal cliffs in Kesen-numa (Fig. 1 and Table 3; Hirakawa et al., 2011). The spatial distribution, sedimentological features and preservation of deposits formed by the Tohoku-oki tsunami in these steep coasts may help identify and interpret similar paleotsunami deposits elsewhere. In addition, landform and land utilization should be carefully considered as important factors that can potentially affect the spatial distribution and features of tsunami deposits and consequently, their identification. The combined perspectives of geology and sedimentology, as well as geomorphology and historical geography, will increase the likelihood of identification of paleotsunami deposits. This is especially the case if the survey area was utilized by people during historical and pre-historical times.

If tsunami deposits in rocky and cliffed coasts are confirmed to be rare or not preserved, the significance of the more common sandy tsunami deposits on coastal plains will grow. It is still possible to estimate part of the character of the wave source of a paleotsunami, such as the fault slip, if future developments in tsunami sedimentology clarify the key constraints for the quantification of tsunami hydrodynamics. Numerical modeling that estimate the flow depth and speed from sandy tsunami deposits has been developed by recent research (e.g. Jaffe and Gelfenbaum, 2007). Through validation of the modeling results with field data from modern tsunamis, some research attempts to apply this method to past tsunamis (e.g. Huntington et al., 2007; Spiske et al., 2010; Witter et al., 2012). The Tohoku-oki tsunami is characterized by abundant observational data on tsunami heights, as well as video footage that provides valuable information on flow depths and speeds. These data will be useful for advancing the quantitative reconstruction of flow state based on tsunami deposits. Flow conditions of past tsunamis may then be estimated from analogues from modern examples, and can be the main constraints for quantitative evaluation of the magnitude of paleo-earthquakes and tsunamis.

Further investigations of modern and paleotsunami deposits are required to improve understanding of their formative sedimentological process and features, preservation potential, and also the relationships with tsunami hydrodynamics under varied geomorphic settings. With this increased knowledge, the ability to estimate the magnitude of past and future tsunamis and earthquakes will increase for events in the coastal areas over the world.

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