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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