Sedimentary Geology 282 (2012) 40–56

Contents lists available at SciVerse ScienceDirect

Sedimentary Geology

journal homepage: www.elsevier.com/locate/sedgeo

Sediment sources and sedimentation processes of 2011 Tohoku-oki tsunami deposits on the Sendai Plain, Japan — Insights from diatoms, nannoliths and grain size distribution

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ARTICLE INFO

Article history:
Received 2 April 2012
Received in revised form 1 July 2012
Accepted 25 July 2012
Available online 2 August 2012

Keywords:
Tsunami deposit
Tohoku-oki tsunami
Grain size analysis
Diatoms
Nannoliths

ABSTRACT

The 11th March 2011 Tohoku-oki tsunami inundated the low-lying Sendai Plain (Japan) more than 5 km inland leaving sand and mud deposits over most of the area. In order to establish the sources of the tsunami deposits and interpret processes of their sedimentation, samples were collected from the deposits, underlying soils and the beach along a shore-perpendicular transect and analysed for grain size, diatom assemblages and nannoliths. The fining-inland tsunami deposits consisted of poorly to moderately sorted medium to coarse sand within 2 km of the coastline and very poorly to poorly sorted mud farther inland. More specifically, there was a slight fining of the coarse to medium sand mode within the sandy deposits and an increased contribution of the coarse and very coarse silt fraction in the mud deposits. The tsunami deposits also exhibited vertical changes including fining upward and coupled coarsening-fining upward trends. Few diatoms were present in beach sediments, soils and tsunami deposits within 1 km of the coastline, while diatoms were more abundant farther inland. Diatom assemblages in the soil and tsunami deposits were similar and dominated by species typical of freshwater-brackish habitats, while no typically marine species were encountered. Nannoliths were generally absent in the studied sediments, except for few specimens. Our data indicate that there was probably no or only a very minor component of marine sediments transported onland by the tsunami. The sandy tsunami deposits within ~1 km of the coastline were mostly derived from beach and dune erosion. From 1 to 2 km landward the contribution of these sources decreased, while sources comprising local soil erosion and the entrainment of sediments from the Teizan-bori canal increased. Farther inland, local soil erosion was the major sediment source for the mud deposits. The tsunami deposits were most likely deposited during at least two inundations, mostly out from suspension resulting in an upward grain size fining trend. However, bed load deposition was also important in the sandy deposits as suggested by a common grain size upward coarsening, position on C–M diagrams and frequent horizontal lamination. The present study reveals that even very large tsunamis may not transport marine sediments onland and thus many commonly applied indicators of tsunami deposits based on the assumption of their offshore origin (marine diatoms, foraminifera, nannoliths, marine sediments) may be of limited use.

1. Introduction

The recent large disasters caused by the 2004 Indian Ocean and the 2011 Tohoku-oki tsunamis were unexpected and resulted in over 180,000 and nearly 16,000 confirmed fatalities, respectively. However, as recent studies have revealed, such events should have

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0037-0738/$ – see front matter
http://dx.doi.org/10.1016/j.sedgeo.2012.07.019

been expected because geological records suggest that similarly large events have occurred in these regions in the past (e.g. Monecke et al., 2008; Satake et al., 2008; Namegaya et al., 2010). In the Indian Ocean tsunamis were not known to have occurred along the region's coastlines before the 2004 event, with the exception of the 1883 Krakatau tsunami, but geological data have since shown that similar events probably took place every *c.* 500–700 years (Jankaew et al., 2008; Monecke et al., 2008; Fujino et al., 2009; Prendergast et al., 2012). In Japan however, predecessors of the 2011 Tohoku-oki tsunami were already known prior to the 2011 event (Abe et al., 1990; Minoura et al., 2001; Namegaya et al., 2010; Sugawara et al., 2011, in press), but recent observations indicate that the magnitude of these older events was probably underestimated (Goto et al., 2011a). These examples point to the importance of the correct identification and interpretation of tsunami and palaeotsunami deposits to provide a better understanding of event magnitudes for tsunami hazard assessment purposes.

Tsunami deposits are source-dependent and exhibit large variability. They can however, be identified using multiple proxies (diagnostic criteria) interpreted in the local context of sedimentary facies assemblage. Some diagnostic criteria have been developed by studying recent tsunamis (e.g. Gelfenbaum and Jaffe, 2003; Moore et al., 2006; Paris et al., 2007; Sawai et al., 2009), but more recent reviews have also included significant new data incorporating studies of palaeotsunamis (e.g. Morton et al., 2007; Shiki et al., 2008; Bourgeois, 2009; Chagué-Goff, 2010; Peters and Jaffe, 2010; Chagué-Goff et al., 2011; Goff et al., 2012). Criteria now include sediment geometry and sedimentological (sediment structure and texture), physical (anisotropy of magnetic susceptibility), palaeontological (shells, diatoms, foraminifera, pollen, nannofossils), geochemical, mineralogical, archaeological, anthropological and contextual (associated environmental responses) evidence. Many of these criteria are based on the assumption that onshore tsunami deposits contain a significant contribution of offshore material. When considering palaeotsunami deposits it is also important to consider post-depositional changes or the taphonomy of these indicators (Nichol and Kench, 2008; Goff et al., 2012; Szczuciński, 2012; Goto et al., in press-c).

Sediment grain size characteristics are one of the most commonly reported features of tsunami deposits (e.g., Dawson et al., 1991; Minoura and Nakaya, 1991; Gelfenbaum and Jaffe, 2003; Goff et al., 2004; Moore et al., 2006, 2011; Paris et al., 2007; Higman and Bourgeois, 2008; Morton et al., 2008; Fujino et al., 2010). Tsunami deposits are mainly supplied from local sedimentary environments (soils, dunes, beach, shallow marine), and if data on their sediment grain sizes are available then it is possible to interpret the likely sediment source. The sediment grain size distribution of tsunami deposits also reflects the hydrodynamic conditions at the time of deposition (e.g., Gelfenbaum and Jaffe, 2003; Moore et al., 2011). The most common parameter mentioned is a landward and upward fining of the deposits that is related to a decrease in water flow velocity and ability to transport sediments, and a shift to sedimentation through deposition out of suspension (Dawson and Shi, 2000). There are often several upward fining layers in a tsunami deposit and these are generally assigned to deposition associated with individual waves in a tsunami wave train (e.g. Higman and Bourgeois, 2008; Chagué-Goff et al., 2012). However, there are several examples where such grain size trends do not occur or where coarsening upward layers or units are reported (e.g. Higman and Bourgeois, 2008; Moore et al., 2011). Such upward coarsening units are considered to be due to bed load shear or traction carpet deposition (Le Roux and Vargas, 2005; Moore et al., 2011). Variations in grain size characteristics are also a key parameter in attempts to model palaeotsunami and tsunami depositional processes (Jaffe and Gelfenbaum, 2007; Jaffe et al., 2011) and consequently these data are one of the most significant variables for helping to determine not only event frequency but also palaeotsunami magnitude.

Diatoms are almost ubiquitous algae present in many environments (marine, brackish, freshwater) producing siliceous frustules, which are often well preserved in sediments (Battarbee, 1986). They have great value as indicators of saline conditions thus making them the most commonly studied microfossil in historical tsunami and palaeotsunami deposits (e.g. Hemphill-Haley, 1995, 1996; Dawson et al., 1996; Dawson and Smith, 2000; Sawai, 2002; Witon and Witkowski, 2003; Sawai et al., 2004b, 2008a, 2009; Razzhigaeva et al., 2006; Dawson, 2007; Kokociński et al., 2009; Goff et al., 2010; Chagué-Goff et al., 2011, 2012; Winsborough et al., 2012). According to Goff et al. (2012) the most important features of diatom assemblages for tsunami studies are the presence of species typical of a mix of multiple environmental sources, and the low concentration of diatoms within sandy as opposed to muddy tsunami deposits. These characteristics help with the identification of tsunami deposits, determining their sediment source and providing insights into the hydrodynamic processes operating during inundation (broken frustules). Importantly, diatom data have also been reported as useful in identifying the maximum inundation limit of palaeotsunamis, with exotic species found well beyond the preserved tsunami sand layer (Hemphill-Haley, 1996). Goto et al. (2011a) suggest that diatoms, together with geochemical data, could well prove to be invaluable in helping to better understand palaeotsunami magnitude.

To date, calcareous nannoplankton and other nannoliths have only been used in a few studies of tsunami deposits (e.g. Andrade et al., 2003; Paris et al., 2010). Nannoliths are a heterogeneous morphological suite of biogenic carbonate particles with an equivalent size to the silt-clay fraction (<63 μm). They are mainly composed of coccoliths, a suite of calcite complex structures produced by marine coccolithophores belonging to the *Haptophyta* microalgae division (Winter and Siesser, 1994; Billard and Inouye, 2004). Coccoliths are one of the main components of deep ocean carbonate oozes (Baumann et al., 2004; Ziveri et al., 2004). However, this group can also be found in coastal facies, where smaller-sized aragonite spicules of certain colonial ascidians are often present. Nannoliths have been used as palaeoenvironmental proxies and a marine tracer in coastal sediments (Ferreira and Cachão, 2005; Guerreiro et al., 2005; Alday et al., 2006; Drago et al., 2006) and as such may be a useful sediment source indicator in tsunami deposits.

The present study applies analyses of sediment grain size, diatoms and nannoliths in deposits laid down by the 11th March 2011 tsunami generated by the M_W 9.0 megathrust earthquake (Ozawa et al., 2011) on the Sendai Plain (Fig. 1a), where inundation reached more than 5 km inland (The, 2011 Tohoku Earthquake Tsunami Joint Survey Group, 2011; Goto et al., in press-a). The main objectives of this study are to a) establish the sediment sources of the Tohoku-oki onshore tsunami deposits on the Sendai Plain, b) provide new insights into the sedimentation processes that occur during large tsunamis and c) test the application of grain size, diatoms and nannoliths as useful indicators of deposits laid down by large tsunamis in temperate climatic zones.

2. Study area

The low lying Sendai Plain is composed mostly of Holocene fluvial and coastal sediments forming sandy beach ridges parallel to the coast and natural levees, with back marshes dominated by organic-rich and muddy sediments (Sugawara et al., in press). The plain was formed by rapid shoreline progradation marked by three complex beach ridges, which developed around 5000–4500 years BP, 2800–1600 years BP and 700 years BP to present (Matsumoto, 1985). Two major (Natori and Abukuma) and several minor rivers have supplied most sediments forming the plain and the coastal zone (Sawamoto, 2002). Modern sediments discharged at the river mouths are transported northward by longshore currents, and thus beach sediments in the study area are mainly supplied from the Abukuma River about 10 km south (Hattori,