Tsunami deposit associated with the 2011 Tohoku-oki tsunami in the Hasunuma site of the Kujukuri coastal plain, Japan

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Abstract

We describe the detailed sedimentary characteristics of a tsunami deposit associated with the 2011 Tohoku-oki tsunami in Hasunuma, a site on the Kujukuri coastal plain, Japan. The thick tsunami deposit was limited to within 350 m from the coastline whereas the inundation area extended about 1 km from the coastline. The tsunami deposit was sampled by excavation at 29 locations along three transects and studied using peels, soft-X imaging and grain-size analysis. The deposit covers the pre-existing soil and reached a maximum measured thickness of 35 cm. It consists mainly of well-sorted medium to fine sand. On the basis of sedimentary structures and changes in grain size, we divided the tsunami deposit into several sedimentary units, which may correspond to multiple inundation flows. The numbers of units and their sedimentary features vary among the three transects, despite the similar topography. This variation implies a considerable influence of local effects such as elevation, vegetation, microtopography, and distance from footpaths, on the tsunami-related sedimentation.

Key words: 2011 Tohoku-oki tsunami, grain-size analysis, Hasunuma, Kujukuri, sedimentary structure, tsunami deposit.

INTRODUCTION

Tsunami deposits are clear evidence of previous tsunami inundations. Identification of tsunami deposits in the geologic record can constrain estimates of the recurrence interval of tsunamis (Nanayama et al. 2003; Cisternas et al. 2005; Kelsey et al. 2005; Jankaew et al. 2008; Sawai et al. 2009) and their inundation area (MacInnes et al. 2010; Sawai et al. 2012, 2015; Sugawara et al. 2013). Given their value in future disaster prevention in coastal areas, tsunami deposits have been studied around the Pacific rim (e.g. Clague et al. 2000; Pinegina et al. 2003; Atwater et al. 2005; Martin et al. 2008), in Europe (e.g. Dawson et al. 1988, 1995; Bondevik et al. 1997; Luque et al. 2002), and in other regions (e.g. Pérez-Torrado et al. 2006; Donato et al. 2008; Jankaew et al. 2008; Monecke et al. 2008; Reinhardt et al. 2012; Fujino et al. 2014). For establishing accurate identification of paleo-tsunami deposits, clear criteria are necessary to distinguish tsunami sediments in a stratigraphic record from sediments deposited by river floods and storm surges (e.g. Tuttle et al. 2004; Morton et al. 2007). Case studies of modern tsunami deposits and observations of related tsunamis are valuable in this effort.

This paper describes lateral and vertical changes (thickness, grain size, and sedimentary structures) in the tsunami deposit associated with the 2011 Tohoku-oki tsunami in Hasunuma, a site
on the Kujukuri coastal plain of eastern Japan. Grain size, in conjunction with thickness and sedimentary structure of the deposit, is one of the most fundamental ways of characterizing tsunami-induced deposits because it is strongly associated with the depth and velocity of the causal flow; thus, previous studies of modern tsunami deposits have reported grain-size data (e.g. Fujino et al. 2010; Jaffe et al. 2012). High-resolution grain-size data for the 2011 tsunami deposits are, however, still too fragmentary to discuss how the deposits relate to flow conditions. Our observations may thus improve our ability to interpret the relationship between modern or paleo-tsunami deposits and their hydraulic conditions.

SETTING

GEOMORPHOLOGY

The Kujukuri coastal plain is a strand plain about 60 km long and up to 10 km wide that faces the Pacific Ocean in Chiba Prefecture, eastern Japan (Fig. 1). Hasunuma is a seaside site in the middle part of the Kujukuri coastal plain. From the coast landward, it consists of a sandy beach (150–200 m wide), a foredune ridge (500–1000 m wide, up to 5 m in elevation), and an inter-ridge swale (Tamura et al. 2010; Figs 1b,2). A coastal forest is composed mainly of densely spaced tall pine trees and bushes grows in a band 200–300 m wide all along the seaward side of the foredune ridge throughout the Hasunuma site (Fig. 1b), and sand dunes occupy the space between the forest and the beach. Several straight footpaths extend from the foredune ridge through the forest to the beach, almost orthogonal to the coastline.

THE 2011 TSUNAMI IN THE HASUNUMA SITE

Large tsunami waves were generated by the 11 March 2011 Tohoku-oki earthquake (Mw = 9.0) offshore of northeastern Japan (Fig. 1; Ozawa et al. 2011; Simons et al. 2011). The tsunami reached the Kujukuri coastal plain approximately 1 hour after the earthquake (Okazaki & Ohki 2012). There, three or four major waves were witnessed, and the third or fourth of these waves reached a maximum inundation height of 6.8 m (Okazaki & Ohki 2012; The 2011 Tohoku Earthquake Tsunami Joint Survey (TTJS) Group 2015).

In the Hasunuma site, inundation by the tsunami waves reached about 1 km inland (Fujiwara et al. 2011), and the waves advanced in a direction almost orthogonal to the coastline, as judged from the orientations of fallen power poles and trees. The inundation depth was 1.2 m on the foredune (Okazaki & Ohki 2012) and 3.8 m at the seaward boundary of the forest, as estimated from damage to the trees. A video that documented the waxing stage of the first inundation flow was taken by a visitor at a hotel which was located just behind the coastal forest, 0.8 km northeast of the location A15 in Figure 1c. This video shows a sheet-like inundation flow with a surface velocity of about 1 m/s, which is replaced by a 1 m thick turbulent flow with a velocity of up to 5 m/s in just several tens of seconds. Okazaki and Ohki (2012) report that several scours with a depth of 1 m and a width of 2 m were excavated by the inundation flow along the coast between the coastal forest and the sand dunes in the Hasunuma site.

PREVIOUS STUDIES

Tsunami deposits associated with the 2011 Tohoku-oki tsunami, especially on the Sendai Plain, have been analyzed by sedimentological (e.g. Goto et al. 2011; Abe et al. 2012; Jaffe et al. 2012), paleontological (Pilarczyk et al. 2012; Szczuciński et al. 2012; Takashimizu et al. 2012), and geochemical studies (e.g. Chagué-Goff et al. 2012a,b; Shinozaki et al. 2015). Okazaki and Ohki (2012), who conducted an extensive survey along the Kujukuri coastal plain, including the Hasunuma site, reported various coastal geomorphological changes and preliminary observations of the tsunami deposits. Fujiwara et al. (2011), who surveyed the Hasunuma site a day after the tsunami, observed bedforms on the sand sheet behind the coastal forest, from which they inferred lateral changes in hydraulic conditions.

METHODOLOGY

We visited the Hasunuma site on 12 March, 27 March, 20 June, 21 June, and 16 August in 2011. Because the first day of our fieldwork was part of an urgent survey documenting tsunami inundation and damage, we took only photographs and recorded simple descriptions of the deposit. During subsequent visits, we collected samples for detailed observations and analyses.

We surveyed three transects perpendicular to the shoreline on or near the footpaths; we observed the tsunami deposit at 15 locations along transect A, 4 locations along transect B, and 10 locations along transect C (Fig. 1c–e, Table 1). The transects...
excluded the inter-ridge swale behind the coastal forest because the tsunami deposit on the paved roads there had been removed by local residents soon after the tsunami. We surveyed the topography along each transect on 20 June 2011 using laser survey instruments (Viva TS15, Leica Geosystems, St. Gallen, Switzerland), and we calibrated those measurements by using VRS-GPS survey instruments (Viva GS10, Leica Geosystems) on 9 October 2014 and 9 November 2015 (Fig. 2).

To measure the thickness of the tsunami deposit, we excavated small pits with a spade at each survey location. Additionally, we used a geoslicer, lunch-box and plastic cases to take samples for observation of internal structures and grain-size analysis where the tsunami deposit was sufficiently thick (Table 1). The geoslicer was used at 21 locations to make peels for detailed observations of sedimentary structures. The lunch-box, a plastic box about 20 cm long, 13 cm wide, and 7 cm deep (Nanayama & Shigeno 1998) was used at 12 locations along transects A and C to take samples for the grain-size analysis. The plate-shaped plastic case, which is 20–25 cm long, 5–10 cm wide, and 1 cm deep, was used at...
22 locations to take samples for the soft-X imaging (Table 1), which was done with a soft X-ray apparatus (SRO-i503-2, Sofron, Softex, Tokyo, Japan) and a digital X-ray sensor (NAOMI NX-04SN, RF Co., Nagano, Japan).

The grain-size analysis was performed by using an image analyzer with an effective measuring range from 30 μm to 30 mm (Retsch Technology GmbH, Haan, Germany). The lunch-box samples were subsampled vertically at 1 cm intervals, and the subsamples were analyzed after drying. Visible organic matter in the subsamples was removed by hand before the analysis, but other organic matter and shells and shell fragments were not removed. A measuring range was set from \( C_0 \) to \( C_2 \) at intervals of 0.25 phi. Then, the mean grain-size, sorting and skewness of the grain-size distribution were calculated from the measurements of each subsample by using the logarithmic graphical method of Folk and Ward (1957).

**RESULTS**

The 2011 Tohoku-oki tsunami deposit extended from behind the beach, where the sand dunes had been breached in some places by the tsunami (Fig. 3a), to the area of the foredune and inter-ridge swale. A thick, continuous sandy layer was deposited in the coastal forest zone (Fig. 3b), whereas further landward, a thin, intermittent sheet of rippled sand was widespread on paved areas of the foredune (Fig. 3c,d). The thick sandy layer within the coastal forest might have formed from rapid sedimentation due to a sudden decrease in current velocity there.
In the coastal forest, the tsunami deposit ranges in thickness from 2 to 35 cm (mean 17.4 cm). The sediments, which typically overlie an organic-rich soil with an erosive boundary, are light grayish and composed mainly of moderately well sorted fine sand (0.6 mean sorting; 2.2 phi mean grain-size). The underlying soil is brownish or light brownish and consists mainly of sticky silty sand mixed with abundant pine needles. It is easy to distinguish the underlying soil from the tsunami deposit, even though the grain sizes in both materials are almost the same. The tsunami deposit contains sparse large shells (1–10 cm) and abundant small (several millimeters) shell fragments, plant fragments.
derived from underlying soil or other areas, and mud clasts and gravel in some locations. At least some of the large shells originated from nearby wastes, as judged from their species composition and size. The smaller shell fragments appear to be similar to those in the beach sand. Here, we briefly describe the lateral and vertical changes in the grain size, thickness, and sedimentary structures of the tsunami deposit. More detailed descriptions, as well as data on sediment sorting and skewness at each location, are given in Appendix I.

LATERAL CHANGES IN THICKNESS AND GRAIN SIZE

The tsunami deposit generally decreases in thickness landward with distance from the coastline, although its thickness varies greatly along our transects (Fig. 4a). Thickness decreases in the landward direction from 30 to 6 cm along transect A, from 17 to 8 cm along transect B, and from 12 to 7 cm along transect C, except at location C10, the terminus of the deposit, where it is 13 cm thick.

The mean grain size of the tsunami deposit which is calculated at each location as the averaged value of all 1 cm intervals, ranges from 1.4 to 2.5 phi. Along transect A, grain size was measured at five locations. The mean grain size shows a fining trend from location A1, right behind a breached dune, where it is medium sand (1.4 phi), through locations A5, A8, A10, and A13, where it is 2.3 phi (Fig. 4b). Along transect C, mean grain size is close to 2.5 phi at all locations except for C7, where it is 2.0 phi (Fig. 4b).

Along transect A and C, sorting and skewness of the tsunami deposit show trends similar to the mean grain-size trend. Along transect A landward, the sorting value gradually decreases from 1.6 at location A1 to 0.5 at location A13, and skewness increases from $-0.6$ to $-0.1$ (Fig. 4c,d). Along transect C, sorting and skewness do not have distinct variation landward except at location C7. They are around 0.4 and 0.0, respectively, at all locations except C7, where they are 0.8 and $-0.3$, respectively (Fig. 4c,d).

VERTICAL TRENDS OF GRAIN SIZE AND SEDIMENTARY STRUCTURE

The tsunami deposit at any given location is not vertically uniform. Indeed, mean grain size often varies more widely in the vertical direction than laterally. For example, it ranges from $-1.6$ to 2.5 phi at location A1 (Fig. 5). A gradual upward-fining trend is common, but it is often interrupted by intermittent rapid coarsening associated with internal erosive boundaries. Although sorting and skewness values tend to fluctuate greatly within each tsunami deposit, in general their variations become smaller upward. On the whole, sorting and skewness exhibit slight upward-decreasing and upward-increasing trends, respectively (Figs A1, A2). Well-developed parallel laminations are observed both by eye and in soft-X images in part of the tsunami deposit.

Sedimentary features also vary among the transects. A thick tsunami deposit with abundant...
gravel and shell fragments showing parallel laminations and multiple upward-fining sequences is characteristic of transects A and C, whereas along transect B, the tsunami deposit is a relatively thin and homogeneous sand layer (Figs. 5–7). Plant fragments, such as pine needles derived from the

Fig. 5  Schematic diagrams of (a) the column, (b) peel photos, (c) soft-X images, and (d) mean grain size plots at locations along transect A. Scale bar represents 5 cm.
underlying soil, are more common along transects B and C than along transect A (Figs 5–7).

We divided the tsunami deposit into several sedimentary units on the basis of sedimentary structures and vertical changes in grain size. Occasionally, these units are bounded by internal erosional surfaces characterized by abrupt changes of grain size and sedimentary structures. The units along each transect are described below.

TRANSECT A

Along transect A, the tsunami deposit is characterizedly thick up to 35 cm with abundant gravel, mud clasts, and shell fragments. Parallel lamina- tions and upward-fining sequences are also distinct at certain stratigraphic levels. We identified four sedimentary units, numbered UA-1 to UA-4 in ascending order, by examining peel samples from seven locations (Table 1). These units are laterally traceable along transect A (Fig. 8).

Unit UA-1 directly overlies organic soil with an erosive boundary and contains abundant plant fragments derived from the underlying soil. It is composed mainly of medium sand with a small amount of gravel (0.7–2.5 phi, 2.0 phi on average). Few upward-fining or upward-coarsening patterns or sedimentary structures such as parallel laminations are recognized. Its thickness decreases landward from 8 to 2 cm.

Unit UA-2 overlies unit UA-1 with an erosive boundary and contains abundant gravel and mud clasts. It is composed mainly of medium to fine sand (0.1–2.5 phi, 2.0 phi on average), and it has fewer shell fragments than the underlying unit. It displays parallel laminations and a gradual upward-fining pattern (e.g. from 2.2 to 2.4 phi at location A10). Its thickness ranges from 3 to 8 cm, and it is absent or amalgamated with the underlying unit UA-3 at locations A6 and A8.

TRANSECT B

Along transect B, the tsunami deposit is characterized by abundant plant fragments and lesser amounts of gravel, mud clasts, and shell fragments. Its sedimentary structures are indistinct. We identified two sedimentary units by examining peel samples from four locations (Table 1). The lower unit UB-1 is
lateral traceability, whereas the upper unit U_B-2 pinches out between locations B2 and B3 (Fig. 8).

Unit U_B-1, which directly overlies organic soil with an erosive boundary, is characterized by abundant plant fragments derived from the underlying soil. It is composed mainly of medium to fine sand with small amounts of shell fragments, gravel, and mud clasts. There is little vertical

Fig. 7  Schematic diagrams of (a) the column, (b) peel photos, (c) soft-X images, and (d) mean grain size plots at locations along transect C. Scale bar represents 5 cm.

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change in mean grain size. The unit thickness is consistently 7–8 cm along the transect.

Unit $U_{B-2}$ displays distinct parallel laminations. Its lower boundary is indistinct, and it displays almost no vertical change in mean grain size. Its thickness decreases from 10 cm at location $B1$ to 5 cm at location $B2$, and it is absent or amalgamated with the underlying unit $U_{B-1}$ at locations $B3$ and $B4$.

TRANSECT C

Along transect C, the tsunami deposit is characterized by well-sorted fine sand, a gradual upward-fining trend, parallel laminations, and abundant gravel. We identified three sedimentary units by examining peel samples from 10 locations (Table 1). These units can be traced laterally along transect C (Fig. 8).

The lowest unit $U_{C-1}$, which directly overlies organic soil with an erosive boundary, contains abundant plant fragments derived from the underlying soil. The unit is composed mainly of fine sand (1.7–2.5 phi, 2.2 phi on average) with a small amount of gravel. Few upward-fining or upward-coarsening patterns and sedimentary structures such as parallel laminations are recognized. The unit ranges from 2 to 7 cm in thickness.

Unit $U_{C-2}$ contains abundant gravel on its erosive base, and it displays parallel laminations and gradual upward fining (e.g. from 2.3 to 2.6 phi at location $C1$). Parallel laminations are sometimes visible only in the soft-X images. The deposit consists mainly of fine sand (0.8–2.6 phi, 2.3 phi on average) with plant fragments, and it contains few shell fragments. Its thickness ranges widely from 2 to 11 cm.

Unit $U_{C-3}$ exhibits distinct parallel laminations and an upward-fining trend (e.g. from 2.3 to 2.6 phi at location $C5$). It is composed mainly of well-sorted fine sand (1.9–2.6 phi, 2.4 phi on average) with abundant shell fragments and a smaller amount of plant fragments. Its lower boundary is indistinct, and its thickness ranges from 2 to 11 cm, but it is absent or amalgamated with the underlying unit $U_{C-2}$ at locations $C1$, $C2$, and $C9$.

Some of these units appear to be nearly identical across the transects, despite the mismatch in the number of units among the transects. For example, $U_{C-2}$ resembles $U_{A-2}$ and $U_{C-3}$ resembles $U_{A-3}$; however, $U_{C-1}$ is similar to $U_{B-1}$ but not to $U_{A-1}$ with respect to sedimentary facies. It is difficult to treat units of different transects as an equivalent unit, because it is uncertain whether they were deposited contemporaneously by the same inundation flow.

DISCUSSION

LATERAL CHANGES OF THE TSUNAMI DEPOSIT IN THE HASUNUMA SITE

The 2011 Tohoku-oki tsunami deposit in the Hasunuma site shows a general landward-thinning trend (Fig. 4a). A landward-thinning pattern is reported in other tsunami deposits. For example, tsunami deposits in Thailand associated with the 2004 Sumatra earthquake show landward thinning along a 2 km long transect on Phra Thong Island and along a 200 m long transect at Bang Sak Beach (Fujino et al. 2008; Goto et al. 2008). The 2011 tsunami deposits on the Sendai Plain also tend to thin landward (e.g. Goto et al. 2011; Abe et al. 2012; Szczuciński et al. 2012). Thinning at a horizontal scale of a few hundred to a few thousand meters is attributed to a landward decrease in sediment supply and current velocity (Hiscott 1994; Choowong et al. 2008; Goto et al. 2008, 2011). Landward thinning is therefore considered to be a general feature of tsunami deposits and can be used as a criterion to identify paleo-tsunami events (e.g. Clague & Bobrowsky 1994; Namayama et al. 2007; Fujino et al. 2010).

The tsunami deposit in the Hasunuma site also shows variation in thickness between locations less than 50 m apart (Fig. 4a). Abrupt changes in thickness similar to the present example are also recognized in other recent tsunami deposits (Kon’no 1961; Nishimura & Miyaji 1995; Gelfenbaum & Jaffe 2003; Hori et al. 2007; Paris et al. 2007; Fujino et al. 2008) and in paleo-tsunami deposits (Namayama et al. 2007; Sawai et al. 2009). Such changes have been ascribed to local topographic variations. For example, Hori et al. (2007) conclude that local topography and microtopography influenced spatial variation in thickness of the 2004 Indian Ocean tsunami deposits along the western coast of Thailand; Sawai et al. (2009) attribute localized thickening of a 17th-century tsunami deposit to the filling of local depressions; and Fujiwara and Tanigawa (2014) ascribe local thickening of a tsunami deposit to changes in sedimentation occurring where current velocities were decreased by a topographic barrier. In the case of the Hasunuma site, topographic irregularities and obstacles such as bushes and trees locally affected the deposit thickness by causing decreased current velocities and flow depths...
During the run-up flow. For example, the thickest deposit (35 cm), found at location A2, is less than 10 m from location A3, where the thinnest deposit (2 cm) is found (Fig. 4A), and, in fact, these two locations are separated by a topographic step of 50 cm high (Fig. 2a). The occurrence of multiple inundation flows can also explain the irregularity in the trend of thickness, which then would affect the capacity of the flows to cause erosion and sedimentation.

In contrast to the landward thinning, landward fining of the tsunami deposit in the Hasunuma site is less distinct (Fig. 4b), even though landward fining is widely cited as evidence for tsunami deposits (e.g. Atwater & Moore 1992; Dawson & Shi 2000; Fujino et al. 2010). Landward fining is
generally explained by the decreasing capacity (Hiscott 1994) of the inundation flow as it moves inland (e.g. Moore et al. 2007; Fujino et al. 2010). There are several explanations for the absence of clear landward fining in the Hasunuma site. First, the inundation flow passed the entire lengths of the transects with almost no decrease in capacity, because the flow was possibly concentrated along the footpaths that passed through the forest zone. Second, grain-size segregation was negligible over the short distances covered by these transects. Third, subsequent inundation flows disturbed any grain-size pattern in deposits of earlier flows, as we argued in the case of landward thinning. Last, sediment taken up by the tsunami was originally very well sorted in keeping with the sediment source, that is, the breached sand dunes.

The sorting and skewness of the tsunami deposit show faint trends similar to the mean grain-size trend; sorting slightly decreases landward and skewness slightly increases landward (Fig. 4c,d). The landward decrease in sorting suggests spatial segregation of grain size caused by a decreased inundation flow, and the landward increase in skewness indicates selective sedimentation of coarser particles seaward. Thus, the indistinct trends of sorting and skewness trends appear to reflect the same causes as the poorly defined landward fining.

The 2011 Tohoku-oki tsunami deposits on the Sendai Plain show thinning and fining trends extending several kilometers inland (e.g. Goto et al. 2011; Abe et al. 2012; Szczuciński et al. 2012) that probably reflect the spatial waning of the inundation flow. These features are similar to those in the Hasunuma site, although the distances on the Sendai Plain area were greater than in the Hasunuma site owing to the different scale of the tsunami inundation there. However, the tsunami deposits on the Sendai Plain show a landward increase in sorting (Szczuciński et al. 2012), opposite to the landward trend in the Hasunuma site, which can be attributable to more efficient erosion and entrainment of smaller soil particles during the long-distance inundation on the Sendai Plain.

VERTICAL CHANGES IN THE TSUNAMI DEPOSIT IN THE HASUNUMA SITE

Vertical changes in grain size and sedimentary structures at each location probably result from variations of the inundation flow over time. The basal erosional surfaces and well-developed parallel laminations suggest an influence of strong flows. The upward-fining structure reflects waning of the inundation flow over time, and the internal erosional surfaces indicate waxing phases of the inundation flow (Naruse et al. 2010). The slight upward-decreasing trend in sorting, as well as the slight upward increase in skewness to values close to zero, reflect the selective segregation of coarser particles caused by temporal waning of the inundation flow during the tsunami event. Wavy laminations imply an oscillatory component of the inundation flow. Thus, the vertical sequence of the tsunami deposit possibly records temporal changes in hydraulic conditions of the inundation flow.

Witnesses reported four inundation events in Iioka, about 20 km northeast of the Hasunuma site (Fig. 1a; Okazaki & Ohki 2012). In this study, we recognized two to four sedimentary units within the tsunami deposit. The multiple units perhaps reflect multiple inundation flows. Multiple units corresponding to multiple inundations, have been reported in other tsunami deposits associated with recent large tsunamis (Nanayama & Shigeno 2006; Matsumoto et al. 2008; Naruse et al. 2010, 2012). The structural features of these modern analogues that can be applied to the interpretation of paleo-tsunami deposits to estimate the hydraulic properties of the inundation flows (Naruse et al. 2010).

CONCLUSIONS

The 2011 Tohoku-oki tsunami left a thick sandy deposit in the Hasunuma site, Japan, mainly in the coastal forest zone on the foredune ridge. The tsunami deposit, which overlies the 2011 surface soil with an erosional boundary, consists mainly of well-sorted medium to fine sand, and is often accompanied by shell and plant fragments, gravel, and mud clasts. Field observations and analytical measurements revealed lateral changes in the thickness and grain size, vertical changes in the grain size and sedimentary structures of the tsunami deposit. We identified 2–4 sedimentary units within the deposit along three transects, suggesting that these sedimentary units formed under the influence of multiple run-up flows.

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APPENDIX I

DETAILED DESCRIPTION AND CHARACTERISTICS OF THE DEPOSIT AT EACH LOCATION

TRANSECT A

Along transect A, peel samples were taken at seven locations (A1, A2, A5, A6, A8, A10, A13; Figs 1C, 5). The tsunami deposit at A1 is 30 cm thick and consists mainly of medium to fine sand, but includes coarser sand and gravel. Gravel is stratified at 7–10 and 23–27 cm from the bottom and scattered around 2 and 18 cm. Mud clasts are found around 14 cm. Parallel laminations are apparent at 14–15 and 20–22 cm along with abundant shell fragments. Plant fragments are concentrated within 0–7 cm.

At A2, the tsunami deposit is 35 cm thick. Gravel is stratified along with large shell fragments at 5–6 and 27–28 cm from the bottom and scattered on the basal surface. Mud clasts are scattered around 6 and 9 cm. Parallel laminations are well developed at 15–27 and 28–34 cm along with abundant small shell fragments. Plant fragments are concentrated within 0–5 cm.

At A5, the tsunami deposit is 31 cm thick and consists mainly of moderately well sorted medium to fine sand. Gravel is absent, but mud clasts are scattered around 2, 14, and 24 cm from the bottom. Parallel laminations are well developed at 10–26 cm along with abundant small shell fragments. Plant fragments are scattered near the basal surface.

At A6, the tsunami deposit is 35 cm thick. Mud clasts are arranged in layers 4 and 6 cm from the bottom. Parallel laminations are well developed at 0–3 and 13–35 cm along with abundant small shell fragments. Almost no plant fragments are found.

At A8, the tsunami deposit is 31 cm thick and consists mainly of moderately well sorted fine sand. Mud clasts are scattered around 8 cm from the bottom along with a small amount of plant fragments. Weak parallel laminations are present at 16–20 cm along with small shell fragments.

At A10, the tsunami deposit is 20 cm thick and consists mainly of well sorted fine sand. Parallel laminations are well developed nearly throughout the deposit. Small shell fragments are scattered throughout the deposit, whereas plant fragments are found only near the basal surface.

At A13, the tsunami deposit is 13 cm thick and consists mainly of well sorted fine sand. Parallel laminations appear to be weakly developed at 8–10 cm from the bottom, but the soft-X image shows that it extends throughout the deposit. Mud clasts are found around 5 cm, and small shell fragments are scattered throughout the deposit.

TRANSECT B

Along transect B, peel samples were taken at four locations (B1–B4; Table 1, Figs 1d and 6). At B1, the tsunami deposit is 17 cm thick. Parallel laminations are apparent between 7 and 14 cm from the bottom. Plant fragments are concentrated between 0 and 5 cm and are scattered at the top. Gravel and mud clasts are absent, and small shell fragments are few.

At B2, the tsunami deposit is 12 cm thick. Weak parallel laminations are visible around 8 cm from
The bottom. Plant fragments are abundant throughout the deposit.

At B3 and B4, the tsunami deposit is 7 cm and 8 cm thick, respectively, and has similar sedimentological characteristics. At both locations, the deposit is structureless and almost massive. Plant fragments are abundant throughout the deposit.

**TRANSECT C**

Along transect C, peel samples were taken at 10 locations (C1–C10; Table 1, Figs 1E, 7). At C1, the tsunami deposit is 12 cm thick and consists mainly of well sorted fine sand. A few mud clasts are found around 6 cm from the bottom. Parallel laminations are not visible, although soft-X image reveals weak parallel laminations at 6–10 cm. Plant fragments are scattered throughout the deposit.

At C2 the tsunami deposit is 13 cm thick and consists mainly of well sorted fine sand. A few mud clasts are found around 6 cm from the bottom. Weak parallel laminations are visible at 6–8 cm, but the soft-X image reveals weak parallel laminations at 6–12 cm. Plant fragments are scattered at 0–6 cm.

At C3, the tsunami deposit is 25 cm thick. A small amount of gravel is found at 6 cm from the bottom, and a layer of mud clasts is found at 14 cm. Parallel laminations are well developed at 8–13 cm and 18–20 cm, along with abundant small shell fragments. Plant fragments are concentrated at 0–6 cm and scattered around 8 and 14 cm.

At C4, the tsunami deposit is 21 cm thick. A layer of gravel is found 4–7 cm from the bottom. Parallel laminations are well developed at 10–17 cm along with abundant small shell fragments. Plant fragments are concentrated at 0–4 cm.

At C5, the tsunami deposit is 11 cm thick and consists mainly of well sorted fine sand. A layer of gravel lay directly on the basal surface. Parallel laminations are weak 1–5 cm from the bottom, and wavy laminations are visible around 10 cm. The soft-X image shows parallel laminations at 1–9 cm, and reveals that wavy laminations represent ripple cross-laminations.

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**Fig. A1**  Sorting (open circles) and skewness (filled circles) along transect A as measured by grain size-analysis. Color scales show the corresponding descriptive terminology for sorting and skewness according to Folk and Ward (1957).

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At C6, the tsunami deposit is 23 cm thick. A layer of gravel and mud clasts is found around 5 cm from the bottom. A small amount of gravel is scattered at 9 cm, and a few mud clasts are found at 16 cm. Parallel laminations are visible at 14–20 cm, and the soft-X image shows parallel laminations at 8–20 cm. Plant fragments are abundant at 0–14 cm.

At C7, the tsunami deposit is 13 cm thick and consists mainly of medium to fine sand. A gravel layer is found 3 cm from the bottom. Parallel laminations are visible at 4–13 cm along with small shell fragments. Wavy laminations are faintly visible around 2 cm. Plant fragments are concentrated at 0–2 cm.

At C8, the tsunami deposit is 7 cm thick and consists mainly of well sorted fine sand. Mud clasts are scattered around 1 cm from the bottom. Parallel laminations are visible at 6–7 cm, and apparent in the soft-X image at 4–7 cm. Plant fragments are abundant throughout the deposit.

At C9, the tsunami deposit is 7 cm thick and consists mainly of well sorted fine sand. Parallel laminations are almost invisible, although the soft-X image shows well-developed parallel laminations at 1–6 cm from the bottom along with a few small shell fragments. Plant fragments are abundant throughout the deposit.

At C10, the tsunami deposit is 13 cm thick and consists mainly of well sorted fine sand. Parallel laminations are visible at 6–10 cm from the bottom, and apparent in the soft-X image at 2–10 cm. Plant fragments are scattered at the basal boundary.

Fig. A2 Sorting (open circles) and skewness (filled circles) along transect C as measured by grain size-analysis. Color scales show the corresponding descriptive terminology for sorting and skewness according to Folk and Ward (1957).