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SEDIMENT PROVENANCE OF TSUNAMI DEPOSITS: IMPLICATIONS FOR ASSESSING THE RELATIVE INTENSITY OF PALEOTSUNAMIS FROM THE SENDAI COASTLINE OF JAPAN

by

Tiffany Hitomi Otai

A Thesis
Submitted to the Graduate School,
the College of Arts and Sciences
and the School of Ocean Science and Engineering
at The University of Southern Mississippi
in Partial Fulfillment of the Requirements
for the Degree of Master of Science

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ABSTRACT

The 2011 Tohoku tsunami impacted the northeastern coast of Japan and caused unexpected damages due to the underestimation of this type of hazard. Of particular importance is the fact that geologic evidence for a predecessor event, the Jogan tsunami (CE 869), could have forecasted the severity of the 2011 Tohoku event. While the timing of tsunamis is important for effective hazard mitigation, outside of the 2011 Tohoku event, the intensity of past tsunamis remains unclear. To understand paleotsunami intensity, it is important to document characteristics of modern analogues like the 2011 event. This study utilizes surface distributions of foraminifera from coastal and offshore locations within Sendai Bay to determine the provenance for 2011 Tohoku tsunami sediments preserved within rice fields on the Sendai Plain near the towns of Yamamoto, Shinchi, and Suijin-numa. We use foraminiferal taxonomy and taphonomy to characterize surface sediments from various locations in and around Sendai Bay as well as the 2011 Tohoku tsunami sediments. The taxonomic and taphonomic assemblages of the 2011 tsunami sediments are similar to that of the intertidal zone, indicating that the dominant sediment source was from locations within 300 m of the coastline. PAM (partitioning around medoids) cluster analysis further provided evidence of a coastal to nearshore sediment source as it clustered the 2011 Tohoku tsunami sediment within intertidal biofacies. By understanding the provenance of a known modern analogue, this technique may be useful to future studies that aim to investigate the relative intensity of tsunamis preserved in the geological record.

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Additionally, I would like to thank the other members of my committee, Dr. Kemal Cambazoglu and Dr. Davin Wallace, whose incredible insight, enthusiasm, and guidance have improved my project, the scientific process, and my writing.

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DEDICATION

First, I'd like to thank my advisor, Jessica Pilarczyk who inspired me to pursue geological science when I entered Rutgers University as an undergraduate in 2014. I would not have discovered the wonderful field of geology had I not met her. I would also like to thank her for showing me that women can be successful and thrive STEM fields despite the severe lack of representation in it today, for trying cow tongue with me on one of my first days in Japan, and showing me the coolest parts of Japan on our off days.

I'd like to thank my parents and my brother for always supporting me and making sure I always had people to fall back on when I was going through a rough time. Thank you for teaching me to always try new things and to aim for higher goals even if it seemed unreachable. お母さんとお父さん、ありがとう。Obrigada mãe.

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LIST OF ABBREVIATIONS

T.P.	Tokyo Peil
CE	Common era
m	Meters
km	Kilometers
cm	Centimeters
cm^3	Cubic centimeter
M_w	Moment magnitude
T1	Transect 1
YM	Yamamoto
SH	Shinchi
SJ	Suijin-numa

CHAPTER I - INTRODUCTION

Earthquake-generated tsunamis are capable of impacting the northeastern coast of Japan resulting in damage to infrastructure and loss of life (Norio et al, 2011). For example, the 2011 Tohoku earthquake caused $185 billion (USD) in damage and over 13,000 deaths (Norio et al., 2011). On March 11, 2011 at 14:46 (Japan Standard Time), a giant megathrust earthquake (M_w 9.0) generated by the Japan Trench triggered a large tsunami that inundated the Sendai Plain (Goto et al., 2011; Mori et al., 2011). The tsunami resulted in inundation distances of up to 5.4 km inland and a maximum wave height of 15 m above T.P. (Goto et al., 2011; Sugawara and Goto, 2012). As one of the largest earthquakes known to have originated from the Japan Trench, the Tohoku earthquake caused the seafloor along the trench to be laterally displaced by 60-70 m and vertically displaced by 5 m over a length of 500 km (Ito et al., 2011; Sato et al., 2011). Inadequate risk assessment and preparations associated with the subsequent tsunami was responsible for significant loss of infrastructure and lives (Sawai et al., 2012).

Following the 2011 Tohoku tsunami, renewed attention was paid to an anomalous sand layer linked to the CE 869 Jogan event, as well as developing a comprehensive chronology of tsunamis that predate the historical record (Sawai et al., 2012; Sawai et al., 2015; Sawai, 2020). Subsequent field investigations revealed six tsunami deposits within coastal sediments of the Sendai Plain that span the past 3,000 years (Sawai et al., 2012; Sawai et al., 2015). Four of the six tsunami deposits are corroborated by historical records, including events occurring in CE 2011 (Tohoku), 1611, 1454, and 869 (Jogan) (Abe et al., 1990; Minoura and Nakaya, 1991; Minoura et al., 2001; Satake et al., 2007; Sawai et al., 2008; Sugawara et al., 2011; Sawai et al., 2012). Radiocarbon ages of the

two oldest deposits suggest they were deposited between BCE 140 – CE 150 and BCE 670-910 BCE respectively (Minoura, et al., 2001; Sawai et al., 2012; Sawai et al., 2015). Additionally, historical records show the CE 1896 (Sanriku) and CE 1933 (Showa-Sanriku) earthquake and tsunamis affecting the plain. However, sediment deposits are lacking because the tsunami heights from the earthquakes were less than a few meters as opposed to the other events (Jogan) which had large tsunami inundation up to a few kilometers (Fuiji et al., 2011).

The geological investigations along the Sendai Plain that documented six tsunami events over the past three millennia are important for determining the recurrence interval of both great (M_w 7-8) and giant (>M_w 9) earthquakes. Though multiple tsunami deposits are found on the Sendai Plain, the recurrence interval for large earthquakes is approximately every 37 years; while the estimated recurrence interval for great earthquakes and their accompanying tsunamis (i.e., 2011 Tohoku earthquake and tsunami) is between 550 and 1,000 years (585 and 557 years between Jogan (CE 869), Kyotoku (CE 1454), and Tohoku (2011)) (Satake, 2015; Sawai, 2020). While the timing of tsunamis is an important step towards effective risk mitigation (Sawai et al., 2012), outside of the 2011 Tohoku event, the intensity of past tsunamis remains unknown or at best, unclear.

Relative intensity is characterized by physical attributes of the tsunami waves including how far inland they inundate, their wave-height (i.e., flow depth), and the number of waves impacting a coastline (Jaffe and Gelfenbaum, 2007; Uchida et al., 2010). Wave characteristics for a particular coastline, and therefore ‘relative tsunami intensity’, are challenging to assess when investigating paleotsunami deposits for which

there is no associated observational record and represents a key knowledge gap in our understanding of the timing and intensity of past events.

To address this knowledge gap, this study utilizes surface distributions of foraminifera from coastal and offshore locations within Sendai Bay to determine the provenance for 2011 Tohoku tsunami sediments preserved within rice fields on the Sendai Plain. By understanding the provenance of a known modern analogue, this technique may be useful in assessing the relative tsunami intensity of paleotsunami deposits for which there is no information.

CHAPTER II – SITE DESCRIPTION

The study site encompasses areas within Sendai Bay and surrounding coastlines of the Sendai Plain (Fig. 1a and 1b). The Sendai Plain is a gently sloping, low-lying coastal plain that is 50 km long, 10 km wide, and is generally less than 5 m above Tokyo Peil in elevation (m T.P.; regional sea level datum that corresponds to mean sea level in Tokyo Bay) (Matsumoto, 1981; Tamura and Masuda, 2005). The plain is bounded by hills to the north, south, and west. The main sediment sources to Sendai Bay include the Abukuma, Nanakita, and Natori rivers, which have contributed to the growth of the plain and shelf (Tamura and Masuda, 2005; Pilarczyk et al., 2012). The coastline is heavily developed and includes coastal forests planted in ~CE 1600 (Richmond et al., 2012), medium-density housing, anthropogenic canals, and rice fields (Pilarczyk et al., 2012; Szczuciński et al., 2012). The coastal plain formed through seaward progradation since the middle Holocene and is wave dominated with a tidal range of 1 m (Tamura and Masuda, 2005).

The Sendai Bay coastline is composed of a series of sandy beaches, such as Gamou and Watari beaches (Fig. 1c and 1d). Sandy beaches in Sendai consist of four major subenvironments: low-lying dunes that are sparsely vegetated, backshore, foreshore, and a high-energy swash zone (Fig. 1c and 1d). Set back from the coastline by ~400 m is a series of rice fields characterized by organic-rich and muddy sediments (Shishikura et al., 2011; Chagué-Goff et al., 2012), which contain tsunami deposits including the 2011 Tohoku tsunami deposit (Goto et al., 2011). The 2011 Tohoku tsunami cores presented in this study were collected in rice fields in Yamamoto, Shinchi, and Suijin-numa or a lacustine environment in Suijin-numa (SJ2) (Fig. 1e, 1f, 1g). Along

the Sendai coastline, barriers such as artificial dunes, tsunami walls, and tetrapods exist (Pilarczyk et al., 2012; Tappin et al., 2012) to protect against inundation and separate the rice fields from the sea.

Sendai Bay, is a 60 km wide open bay system composed of four major geomorphic subenvironments: the shoreface (0-15 m of water depth), which is predominantly composed of medium to fine sand, the inner shelf platform (15-50 m of water depth), which is dominated by sand-mud alterations, the middle shelf slope (50 to 120 m of water depth), which is composed of very coarse to coarse sand, and the outer shelf platform (120 to 145 m of water depth), which is composed of very coarse to coarse sand (Saito, 1989; Ikehara et al., 2014; Tamura et al., 2015).

On March 11, 2011, 14:46 (Japan Standard Time), a giant megathrust earthquake (M_w 9.0) generated by the Japan Trench, located approximately 150 km east of the city of Sendai, triggered a large tsunami that inundated the Sendai Plain (Goto et al., 2011; Mori et al., 2011). The tsunami generated by the earthquake resulted in a maximum recorded inundation height of 15 m above the T.P. and a maximum inland reach of 3.1 to 5.4 km on the Sendai Plain near the city of Sendai (Goto et al., 2011). At the tsunami core collection sites in Yamamoto and Suijin-numa Lake, the maximum tsunami run-up height was 8.4 m (Mikami et al., 2015) (Fig. 1b, 1e, 1g). Similarly, in nearby Shinchi (Fig. 1b, 1f), the run-up height was 9.0 m (Mikami et al., 2015).

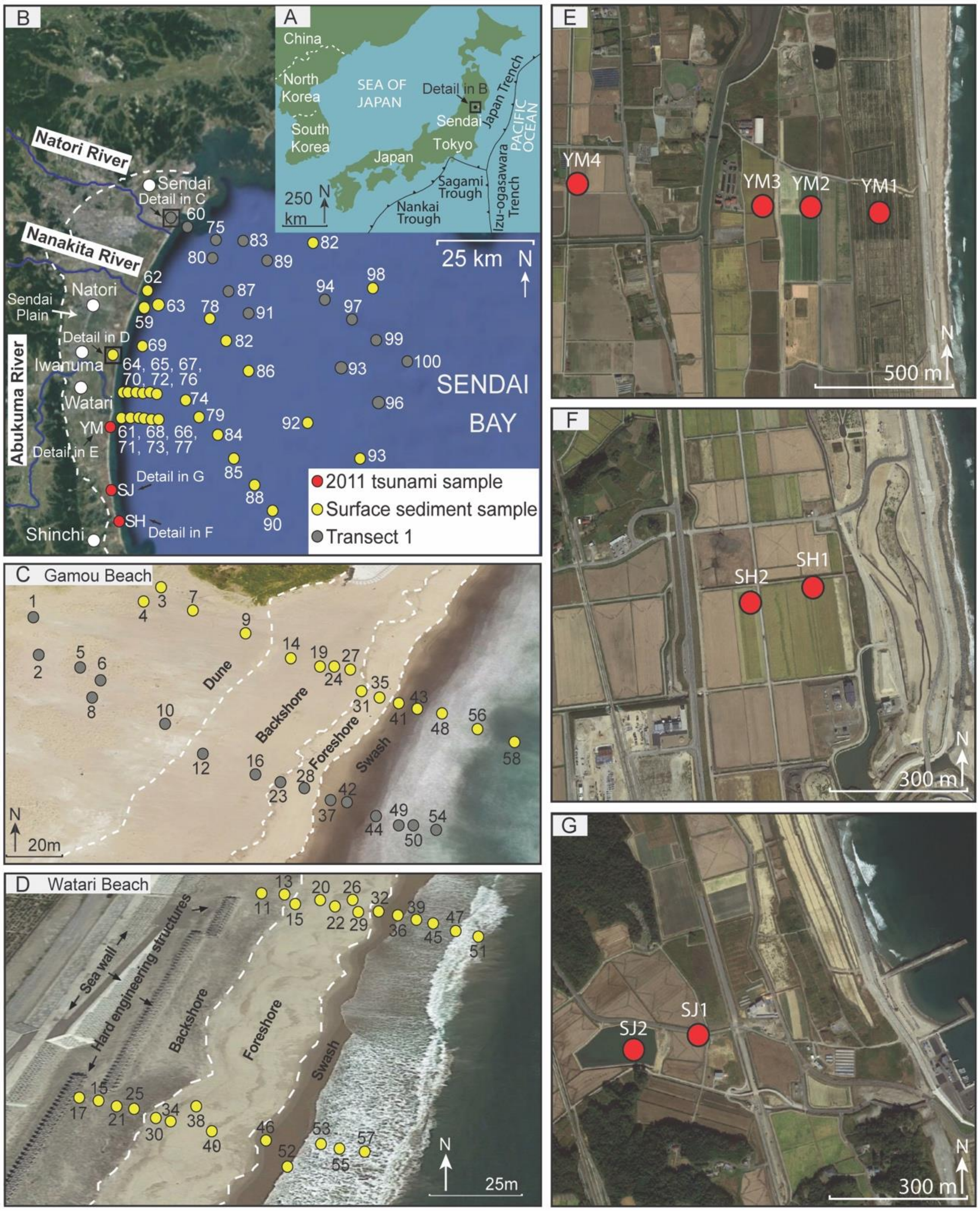

Figure 1 *Site map*

Location map of Sendai Bay on the eastern coast of north-central Japan relative to broad-scale tectonics. The location of surface sediment samples from offshore (**b**) and onshore (**c**, **d**) sampling sites are denoted by yellow and grey circles. Surface samples represented in Transect 1 (T1; Fig. 2-3; Fig. S1) are indicated by grey circles. Red circles denote 2011 tsunami cores excavated at Yamamoto (**e**), Shinchi (**f**), and Suijin-numa (**g**). At the tsunami core collection sites in Yamamoto and Suijin-numa Lake, the

maximum tsunami run-up height was 8.4 m (Mikami et al., 2015) (Fig. 1.1b, 1e, 1g). Similarly, in nearby Shinchi (Fig. 1b, 1f), the run-up height was 9.0 m (Mikami et al., 2015).

CHAPTER III– METHODS

3.1 Field sampling

Field sampling involved two phases: 1) collection of surface sediment samples to understand foraminiferal distributions within coastal, nearshore, and offshore areas of Sendai Bay and 2) collection of 2011 Tohoku tsunami deposits from inland areas of the Sendai Plain.

3.2 Surface sediment sample collection

A total of 100 surface sediment samples were collected from major point sources where sediment is available for tsunami-driven transport within Sendai Bay and along the coastline (Fig. 1b, 2a). Coastal collection sites included Gamou (Fig. 1c) and Watari (Fig. 1d) beaches where dune, backshore, foreshore, and swash samples (57 samples) were collected by means of a walking survey. Sampling locations in this study were specifically targeted because the surface sediments at these locations were representative of each of the sub-environments listed above. In addition to the coastal samples collected from supra- and inter- tidal locations, a total of 42 nearshore and offshore surface sediment samples were collected via grab sampler deployed from a boat. The nearshore sediment samples were collected in June 2018, 7 years after the 2011 Tohoku tsunami event. The offshore sediment samples were collected between August and September 2012, 15 months after the Tohoku tsunami. Approximately 10 cm^3 of surface sediment was collected from the upper 3 cm of the seafloor by the grab sampler. All samples were placed in refrigerated storage at 4 °C until subsampled for foraminiferal analysis.

Transect 1 (T1), a 38 km shore-perpendicular transect, was established in order to assess changes in foraminiferal assemblages with increasing distance from the Sendai

shoreline (Fig. 1b and 2a). Of the 100 surface samples, 27 are included in T1 and span all major subenvironments from the dunes to the furthest offshore collection sites.

A Leica RTK-GPS was used to obtain location and elevation data for all supra- and inter-tidal samples; whereas, a Trimble SPS351 was used to obtain location data and a Senbondenki PDR-1300 depth sounder was used to obtain depth measurements for all nearshore and offshore samples collected via boat.

3.3 Tohoku tsunami deposit collection

The 2011 Tohoku tsunami samples were collected along a series of shore-perpendicular transects from the following locations in the Sendai region two months after the tsunami: Yamamoto (YM; 4 cores), Suijin-numa (SJ; 2 cores), and Shinchi (SH; 2 cores) (Fig. 1e, 1f, 1g). The samples were collected between April and May 2011. Locations such as rice (Fig. 1e, 1f, 1g) and grassy (Fig. 1e, 1f, 1g) fields within 200 m to 1,300 m of the coastline were selected because of the presence of 2011 tsunami deposited sediment and because of the contrasting stratigraphy between the tsunami sediments and the underlying substrate (e.g., soil). A Geoslicer available from the Geological Survey of Japan was used to obtain cores containing tsunami sediments ranging in thickness from 10 cm to 30 cm, where the full extent of the tsunami deposit and at least 3 cm of the underlying substrate were captured. Stratigraphic features such as unit thickness, fining upwards sequences and the presence of rip-up clasts were documented in the field. Elevation and distance from the shoreline for each coring site were obtained using a Leica RTK-GPS. All elevations were tied to Tokyo Peil (T.P.).

All eight cores collected from the three tsunami transects were sampled at 1 cm resolution for foraminiferal analysis (a total of 71 individual samples). For each sample,

~10-20 cm^3 of sediment was subsampled into a centrifuge tube and stored in refrigerated storage.

3.4 Foraminiferal analysis

For all surface and tsunami sediment samples, 10-20 cm^3 of sediment was subsampled for foraminiferal analysis. Foraminiferal analysis followed the methods of Pilarczyk et al. (2011), where subsampled sediment was wet sieved using a 63 µm sieve and subsequently dried at 30°C in a drying oven. Once dry, a microsplitter was used to obtain counts of ~300 specimens (Scott and Hermelin, 1993). A known volume of sediment for each sample was analyzed using an Olympus SZX16 stereomicroscope following the procedures of Pilarczyk et al. (2020) where each individual was assigned a taxonomic identification and placed into one of four taphonomic categories (Pilarczyk et al., 2020). Taxonomic identifications followed that of Uchida et al. (2010), Pilarczyk et al. (2012), Usami et al. (2017) and Loeblich and Tappan (1987). The taphonomic condition for each individual was evaluated based on the following categories: unaltered, corraded, fragmented with rounded edges, and fragmented with angular edges. Unaltered tests are characterized by specimens that are not altered physically or chemically and are in "pristine" condition. Corraded tests are those that have minor physical and chemical alteration and appear rounded, pitted and/or chalky. Fragmented with rounded edged individuals are those that have been fragmented and subsequently abraded. Fragmented with angular edged individuals are those that have been fragmented, but have not been abraded (Fig. 2).

The total concentration of foraminifera, as well as the relative abundances of individual species and taphonomic characters were calculated for each sample

(Supplementary table S1a, S1b) and plotted with increasing distance from the shoreline (Fig. 2, 3).

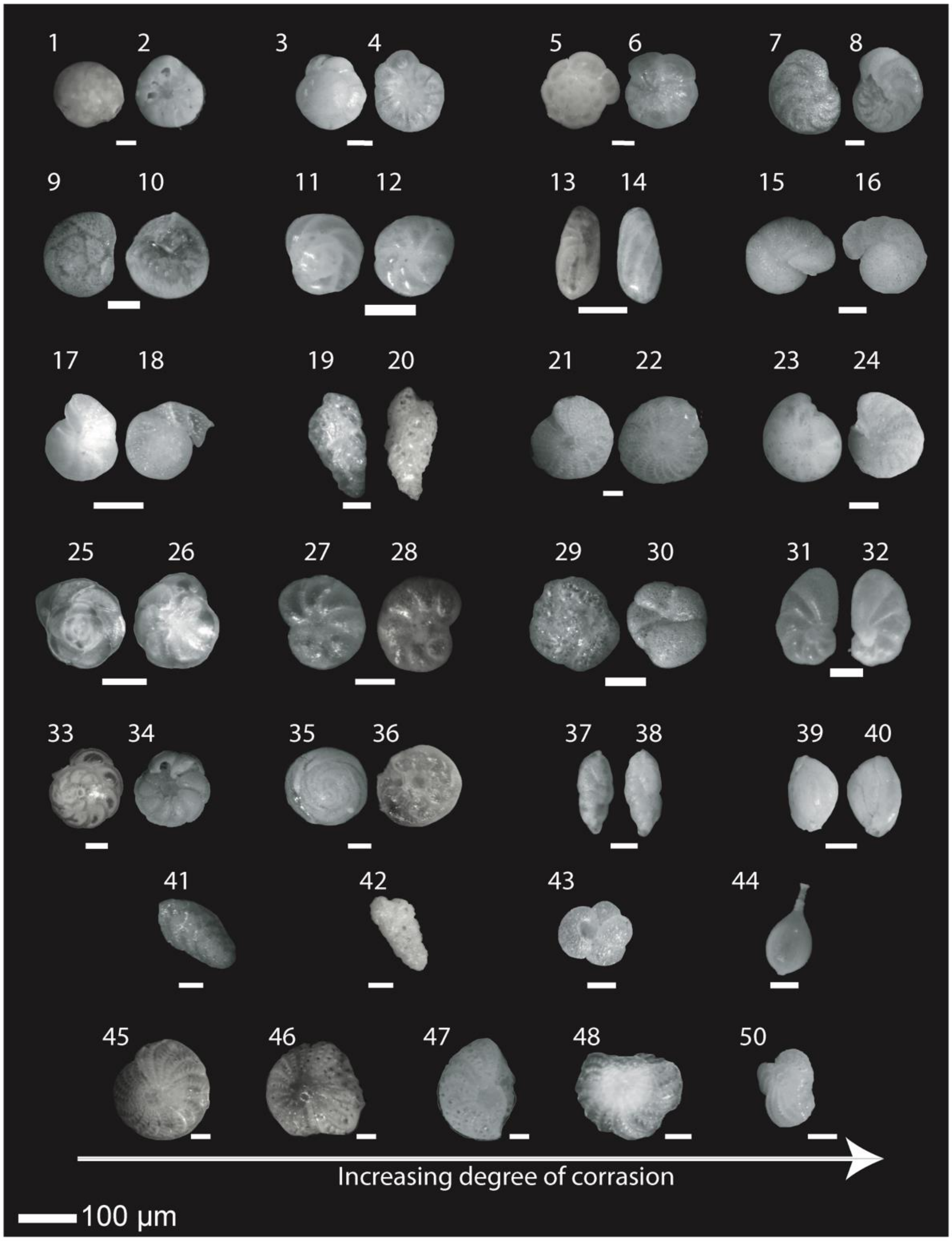

Figure 2 *Foraminiferal plate*

Light microscope images of dominant foraminiferal taxa (1-44) and taphononomic categories (45-50). (1-2) *Ammonia convexa*, (3-4) *Ammonia parkinsoniana*, (5- 6) *Ammonia tepida*, (7-8) *Anomalinidae* sp., (9-10) *Rosalina* sp., (11-12) *Buccella frigida*, (13-14)

Buliminella elegantissima, (15-16) *Cibicides lobatulus*, (17-18) *Cibicides refulgens*, (19-20) *Eggerella* sp., (21-22) *Elphidium crispum*, (23-24) *Elphidium* spp., (25-26) *Epistominella* spp., (27-28) *Haynesnia* sp., (29-30) *Trochammina* sp., (31-32) *Nonionella* spp., (33-34) *Pararotalia nipponica*, (35-36) *Patellina* spp., (37-38) *Uvigerinella glabra*, (39-40) *Quinqueloculina* spp., (41) *Bolivina* spp., (42) *Textularia* spp., (43) Planktic specimen, (44) *Lagena* spp., Taphonomic conditions of *Elphidium crispum* showing increasing degree of corrasion (combined effect of corrosion and abrasion): (45) unaltered, (46) corraded, (47-48) fragmented with angular edges, and (50) fragmented with rounded edges.

3.5 Cluster analysis

Partitioning around medoids (PAM) cluster analysis was used to determine biofacies (zones) based on the distribution of foraminiferal assemblages (taxonomic and taphonomic) in surface sediments from Sendai Bay and the surrounding coastline (Pilarczyk et al., 2011; Kosciuch et al., 2018; Pilarczyk et al., 2020). Biofacies were then clustered with 2011 tsunami sediments to determine their major sediment source (i.e., provenance).

PAM cluster analysis uses an algorithm to fit samples into groups (i.e., clusters) using silhouette widths that range from -1 to 1 (Kaufman and Rousseeuw, 2009). A width of 1 signifies a perfect assignment to a group; whereas a width of -1 indicates an incorrect classification (Pilarczyk et al., 2020). Prior to cluster analysis, relative abundances of species and their taphonomic condition were standardized by calculating z-scores for each data point. Z-scores standardize datasets by determining a value's standard deviation from the mean (Kaufman and Rousseeuw, 2009). The z-scores were clustered using a cluster package in R, this was chosen because using the algorithm removes user bias. To determine the best dataset for defining modern subenvironments, the surface sediment samples were clustered using three cluster scenarios: 1) taxonomic data, 2) taphonomic data, and 3) taxonomic and taphonomic data. 2 to 5 clusters were tested to determine

which test yielded the highest silhouette widths and percent accuracy (Supplementary Table 2 and 3).

Once the modern biofacies were determined, intervals within each of the 2011 tsunami cores were independently clustered with the surface samples to determine the sediment source for the tsunami deposited sediment. Following the methods outlined above, relative abundances of taxonomic and taphonomic data from YM1 (12, 1-cm intervals within the tsunami layer), YM2 (3, 1-cm intervals within the tsunami layer), YM3 (5, 1 cm intervals within the tsunami layer), YM4 (4, 1-cm within the tsunami layer), SH1 (3, 1-cm within the tsunami layer), SH2 (2, 1-cm within the tsunami layer), SJ1 (7, 1-cm within the tsunami layer), and SJ2 (7, 1-cm within the tsunami layer) were first converted to z-scores and then imported into the cluster package in R.

CHAPTER IV– RESULTS

4.1 Foraminifera within surface sediments (T1)

T1 spanned a distance of 38 km from the dunes (2.2 m above the T.P.) at Gamou Beach to the offshore in Sendai Bay (82 m below the T.P.) (Fig. 3a). Foraminifera were found in all samples along T1; the concentrations ranged from 1 to 2857 specimens per 10 cm^3. The highest concentrations of foraminifera are found in the offshore zone of T1 (1320 to 2857 specimens per 10 cm^3) and decrease with increasing distance inland in the swash (212 to 215 specimens per 10 cm^3), foreshore (39 to 403 specimens per 10 cm^3), backshore (3 to 30 specimens per 10 cm^3), and dunes (1 to 12 specimens per 10 cm^3) (Fig. 3b). In T1, 24 species of foraminifera were identified (Plate 1). The offshore is dominated by *Buccella frigida* (19 to 43 %) and *Buliminella elegantissima* (0 to 12 %); the swash by *Buccella frigida* (11 to 14 %) and *Pararotalia nipponica* (28 to 32 %); the foreshore by *Ammonia parkinsoniana* (2 to 15 %) and *Buccella frigida* (9 to 20 %); the backshore by *Buccella frigida* (8 to 100 %) and *Pararotalia nipponica* (0 to 33 %); and the dunes by *Elphidium crispum* (16 to 100 %) and *Pararotalia nipponica* (16 to 33 %) (Fig 3c, 3d, 3e, 3f; Supplementary fig. S1a, S1b, S1c, S1d; Supplementary Table 2a). Specific species were indicative of the offshore environment such as *Haynesina* sp. (0 to 3%) and *Nonionella* spp. (0 to 14%) as they are absent from swash, foreshore, backshore, and dune sediment samples. In contrast, *Pararotalia nipponica* is found in high concentrations in swash, foreshore, backshore, and dune sediment samples but in low concentrations in the offshore environment. Additionally, *Ammonia convexa* is found in the swash and foreshore zones.

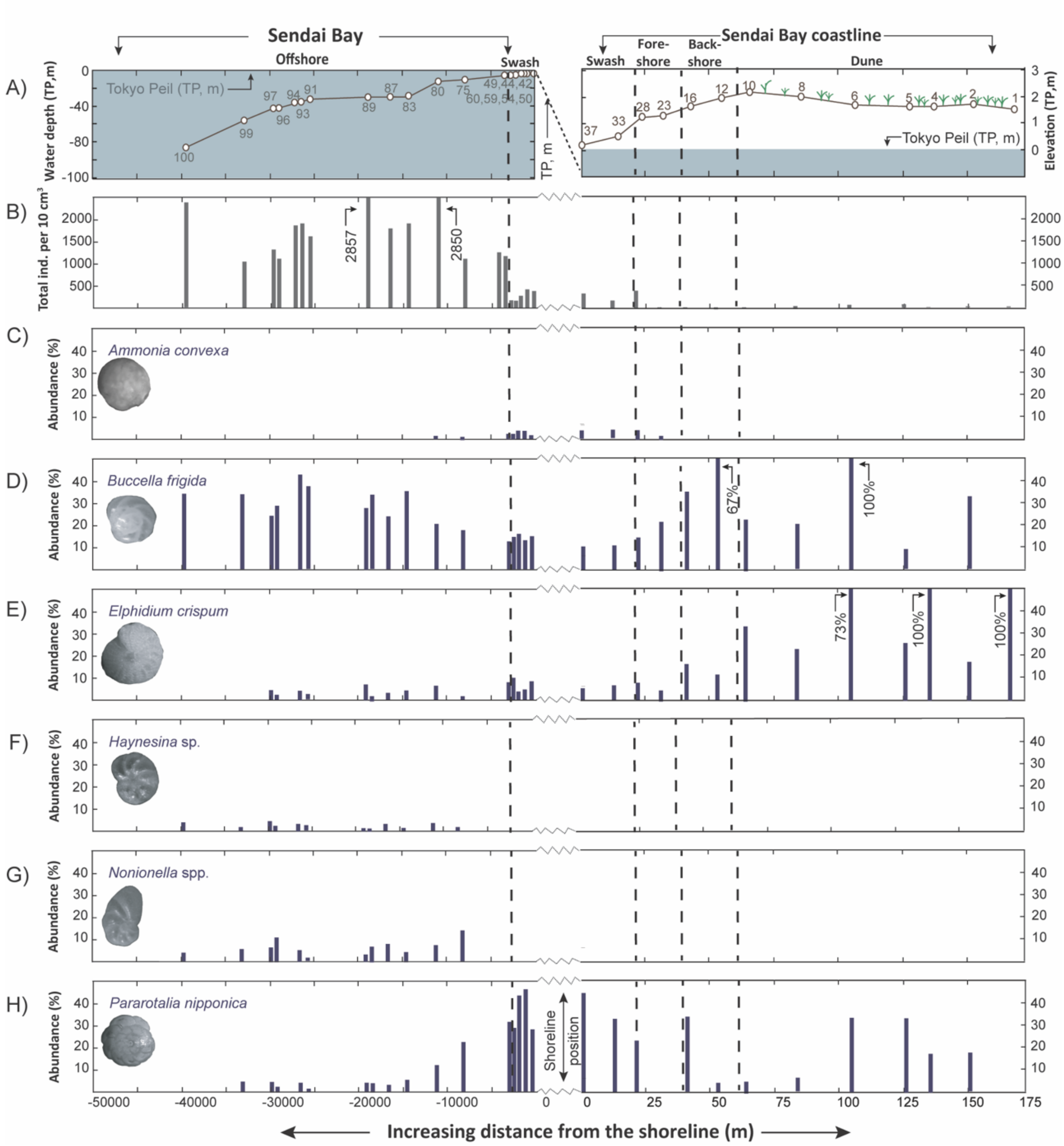

Figure 3 *Foraminiferal distribution along T1*

Foraminiferal taxonomic data for T1. **a)** Elevation/depth profile (using Tokyo Peil, TP; mean sea-level in Tokyo Bay) for T1 extending from the offshore zone of Sendai Bay to the dunes at Gamou Beach. **b)** Total concentration of foraminifera (specimens per 10 cm^3) along T1. **c-h)** Relative abundances of key foraminiferal taxa (% abundance) along T1.

The taphonomic distributions of foraminifera showed similar zonation as the taxonomic distributions. In the offshore, surface samples contained foraminifera that were dominantly unaltered (62 to 95%) (Fig. 4c). This is in contrast to the swash,

foreshore, backshore, and dune environments where the majority of individuals had corraded tests (68 to 71%, 65 to 94%, 52 to 100%, 50 to 100% corraded individuals respectively) (Fig. 4d). Fragmented foraminifera with both rounded and angular edges were the most prevalent in the foreshore (0% to 7%; 0% to 4%) and swash (1% to 5%; 2 to 5%) environments and generally decreased in the offshore (1% to 8%; 1% to 4%), backshore (0%; 0% to 3%), and dune environments (0% to 16%; 0% to 16%).

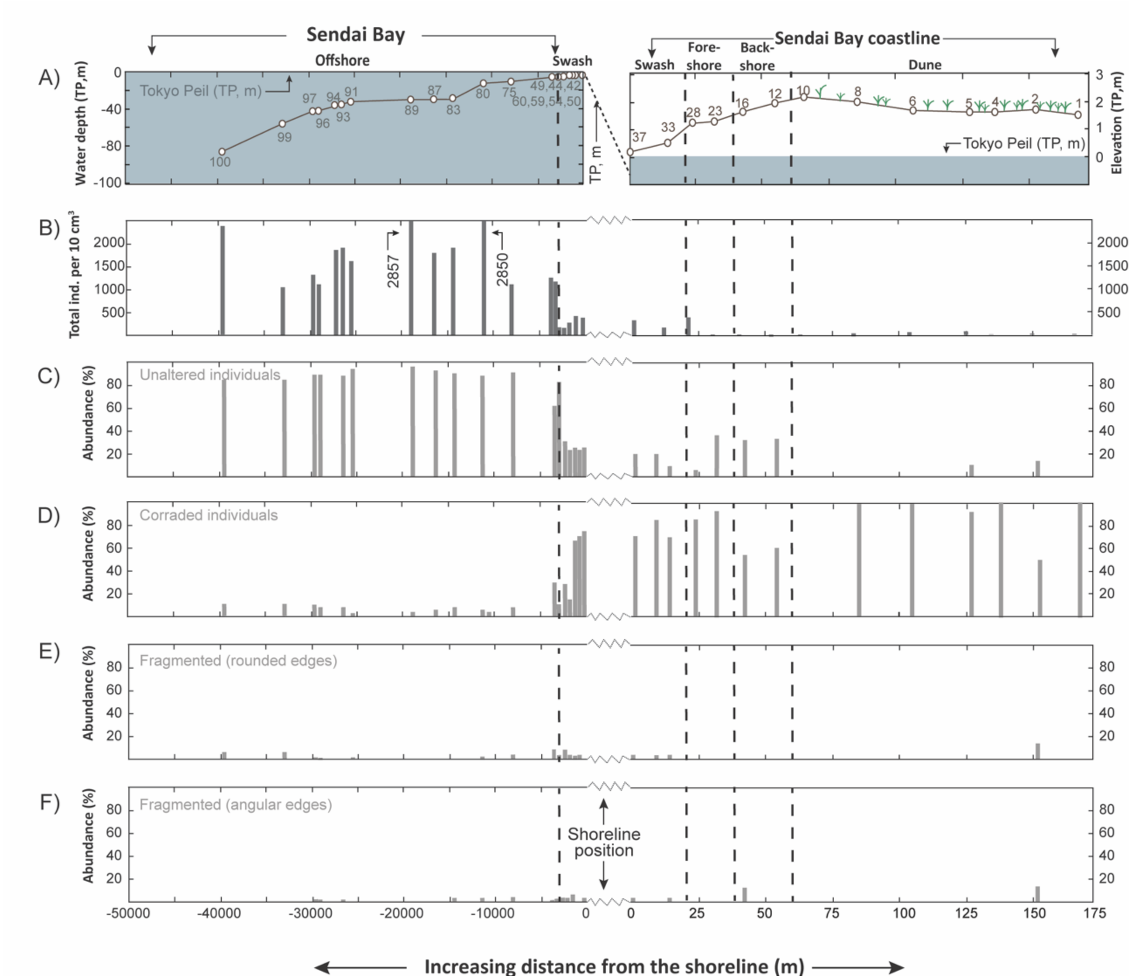

Figure 4 *Taphonomic distribution along T1*

Elevation and foraminiferal taphonomic data for T1. **a)** Elevation/depth profile (using Tokyo Peil, TP; mean sea-level in Tokyo Bay) for T1 extending from the offshore zone of Sendai Bay to the dunes at Gamou Beach. **b)** Total concentration of foraminifera (specimens per 10 cm^3) along T1. **c-h)** Relative abundances of taphonomic categories (% abundance) along T1.

4.2 2011 Tohoku tsunami sediments

The three coring transects established on the Sendai Plain have maximum distances from the shoreline which range in length from 1.2 to 1.5 km from the shoreline (Fig. 1e, 1f, 1g). Core YM1 (244 m from the shoreline and 1.0 m above T.P in elevation) contained a 2011 tsunami layer that was 30 cm thick, Core YM2 (502 m from the shoreline and 2.0 m above T.P. elevation) having a 10 cm thickness, YM3 (664 m from the shoreline and 2.0 m above T.P. in elevation) having a 15 cm thickness, and YM4 (1382 m from the shoreline and 4.0 m above T.P. in elevation) having a 9 cm thickness (Supplementary Table S1b). SH1 (264 m from the shoreline and 1.0 m above T.P. in elevation) had a thickness of 25 cm and SH2 (463 m from the shoreline and 1.0 m above T.P. in elevation) had a thickness of 15 cm. SJ1 (306 m from the shoreline and 2.0 m above T.P. in elevation) had a thickness of 15 cm and SJ2 (760 m from the shoreline and 2.0 m above T.P. in elevation) had a thickness of 15 cm.

Foraminifera were found in tsunami sediments from all eight cores, however of all 71 analyzed intervals within the tsunami layers, only 43 intervals contained foraminifera (Figs 5, 6, 7, 8). The concentrations of foraminifera in the YM transect generally decreased with increasing distance inland with the exception of YM1; At the 0-1 cm intervals in YM, the concentrations range from 77 (YM1) to 460 (YM2) to 280 (YM3) to 123 (YM4) individuals per 10 cm^3. In the SH transect, concentrations range from 10 to 307 individuals per 10 cm^3. The concentrations of foraminifera are highest closer to the coast and lowest further from the coast. The SH cores do not share common intervals however, the average number of foraminifera in SH1 and SH2 is 193 individuals per cm^3 and 17 individuals per cm^3 respectively. In the SJ transect, concentrations range

from 30 to 767 individuals per 10 cm^3. Similar to SH, the concentration of foraminifera within the SJ tsunami sediment is highest in SJ1 which is closer to shore and lower in SJ2 which is further from the coastline. At the 1-2 cm intervals, the concentrations at SJ1 and SJ2 are 223 and 100 individuals per 10 cm^3 respectively.

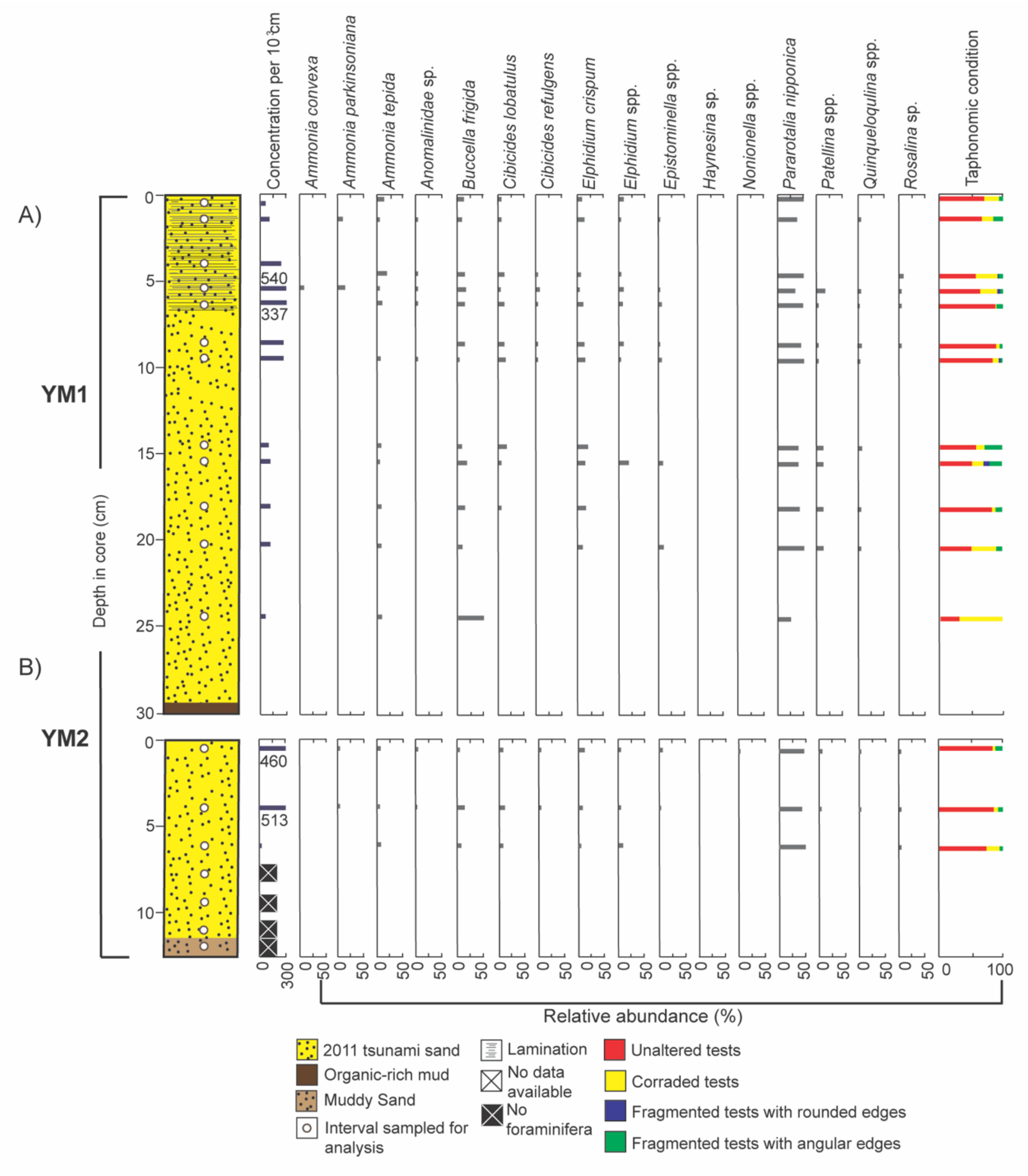

Figure 5 *Yamamoto tsunami core; YM1, YM2*

2011 tsunami cores from Yamamoto. Downcore changes in total foraminiferal concentration (specimens per 10 cm^3) and relative abundances of taxa and taphonomic categories are indicated for cores YM1 (**a**), and YM2 (**b**).

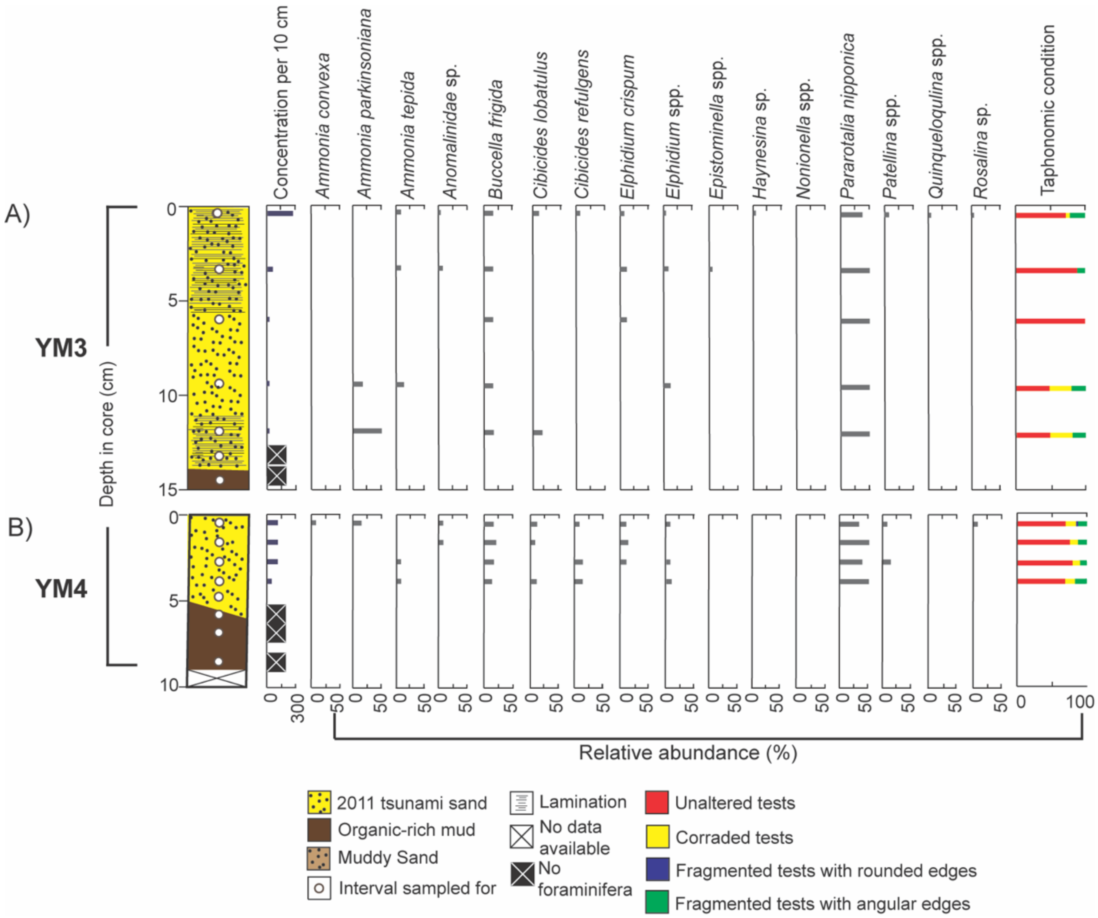

Figure 6 *Yamamoto tsunami core; YM3, YM4*

2011 tsunami cores from Yamamoto. Downcore changes in total foraminiferal concentration (specimens per 10 cm^3) and relative abundances of taxa and taphonomic categories are indicated for cores YM3 (**a**), and YM4 (**b**).

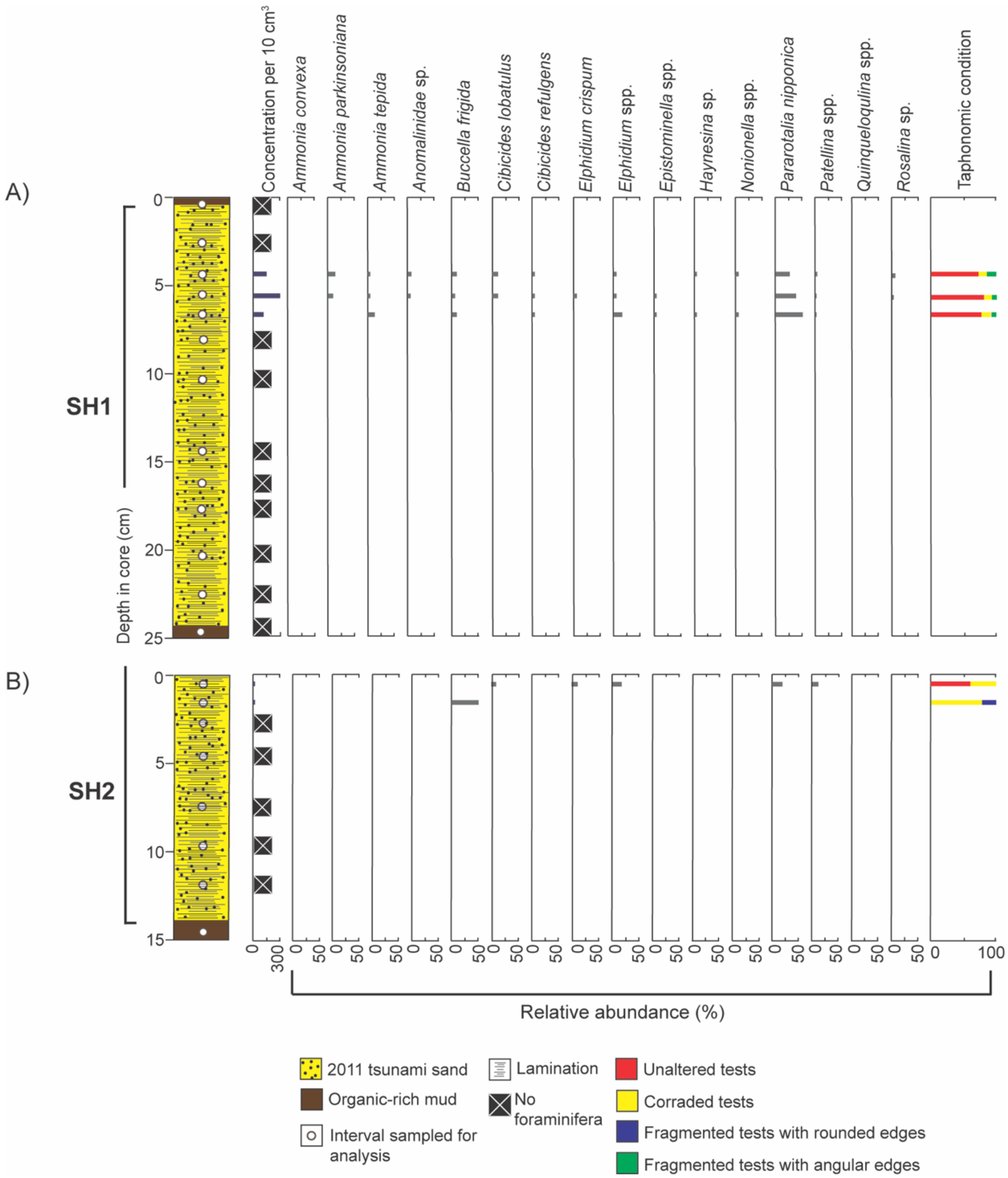

Figure 7 *Shinchi tsunami core*

2011 tsunami cores from Shinchi. Downcore changes in total foraminiferal concentration (specimens per 10 cm^3) and relative abundances of taxa and taphonomic categories are indicated for cores SH1 (**a**) and SH2 (**b**).

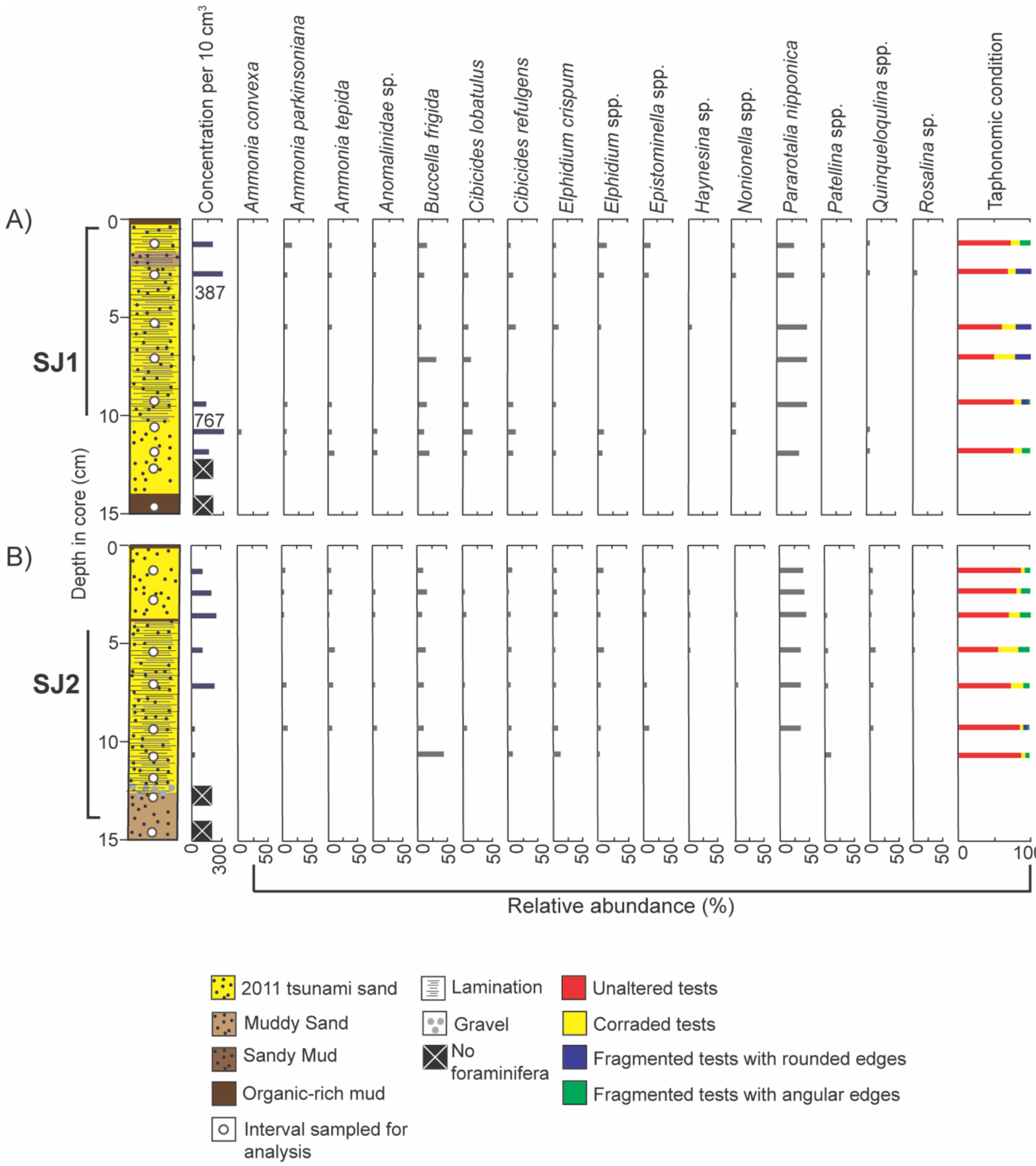

Figure 8 *Suijin-numa tsunami core*

2011 tsunami cores from Suijin-numa. Downcore changes in total foraminiferal concentration (specimens per 10 cm^3) and relative abundances of taxa and taphonomic categories are indicated for cores SJ1 (**a**) and SJ2 (**b**).

A higher number of foraminifera that are corraded and have tests that are fragmented with angular edges are in higher abundance in the tsunami samples. In the YM cores the average percentage of tests that were corraded are 20% (YM1), 8%, (YM2)

14% (YM3), and 11% (YM4) and the percentage of tests that were fragmented with angular edges, are 12% (YM1), 6% (YM2), 9% (YM3), and 14% (YM4). In the SH cores, the average percent of corraded tests for SH1 and SH2 are 9% and 54% respectively and the average percent of fragmented tests with angular edges are 9% and 16% respectively. In the SJ cores, the average percentage of tests that are corraded are 12% (SH1) and 10% (SH2) respectively and the percentage of tests that are fragmented with angular edges are 11% (SJ1) and 9% (SJ2) respectively.

In the YM, SH, and SJ cores, the concentrations of foraminifera are generally highest at the top and middle of the core with the exception of SJ1. In YM1, the concentrations between 1-2cm, 5-6 cm, and 24-25 cm are 120, 540, and 27 specimens per 10 cm^3 respectively. In YM2, the concentrations of specimens between 0-1 cm and 6-7 cm are 460 and 63 specimens per 10 cm^3 respectively. In YM3, the concentrations of specimens between 0-1 cm and 12-13 cm are 280 and 20 specimens per 10 cm^3 respectively. In YM4, the concentrations of specimens between 4-5 cm and 6-7 cm are 123 and 60 specimens per 10 cm^3 respectively. In SH1, the concentrations of specimens between 4-5 cm, 5-6 cm, and 6-7 cm are 150, 307, and 123 specimens per 10 cm^3 respectively. In SH2, the concentrations of specimens between 1-2 cm and 2-3 cm are 23 and 10 specimens per 10 cm^3 respectively. SJ1 tends to have the highest concentrations at the top and bottom of the core. In SJ1, the concentrations of specimens between 1-2 cm, 5-6 cm, 11-12 cm, and 12-13 are 223, 83, 767, and 150 specimens per 10 cm^3 respectively. In SJ2, the concentrations of specimens between 1-2 cm and 11-12 cm are 100 and 30 specimens per 10 cm^3 respectively (Supplementary Table S1b).

In the YM cores, the dominant species are *Elphidium crispum* (4 to 21 %) and *Pararotalia nipponica* (16 to 68 %). In the SH cores, the dominant species are *Buccella frigida* (0 to 100 %) and *Pararotalia nipponica* (0 to 43 %). In the SJ cores, the dominant species are *Buccella frigida* (7 to 44 %) and *Pararotalia nipponica* (0 to 36 %) (Supplementary Table S1b).

4.3 PAM cluster analysis

PAM cluster analysis was first employed to identify modern environments within and around Sendai Bay. Three tests were employed: 1) taxonomic data (Test 1), 2) taphonomic data (Test 2), and 3) taxonomic and taphonomic data (Test 3) (Fig. 9). The taxonomic dataset yielded an average silhouette width of 0.246 with an 86% accuracy; whereas the taphonomic dataset yielded a higher average silhouette width (0.519), but a lower percent accuracy (73%) (Fig. 9; Supplementary Table S2a, S2b, S2c S3a, S3b, S3c). The taphonomic and taxonomic dataset combined yielded an average silhouette width higher than the taxonomic dataset (0.254) and the highest percent accuracy of all three datasets (93% accuracy). In this scenario, percent accuracy was emphasized because a higher value indicates the proper placement of samples into the appropriate clusters. Each cluster within a test was ascribed a label corresponding to a particular biofacies; Test 1 was ascribed T1.1, T1.2, and T1.3; T2 was ascribed T2.1, T2.2, and T2.3; and Test 3 was ascribed T3.1, T3.2, and T3.3. For Test 1, clusters had similar average silhouette widths (T1.1 = 0.368, T1.2 = 0.212, and T1.3 = 0.219). For Test 2, the clusters varied significantly in their silhouette width values (T2.1 = 0.498, T2.2 = 0.158, T2.3 = 0.795). For Test 3, the clusters had varied average silhouette width values however, had less varied values than Test 2 (T3.1 = 0.392, T3.2 = 0.159, T3.3 = 0.272).

Test 2 which only included taphonomic data produced the highest average silhouette widths while the test which included both taxonomic and taphonomic data produced the highest percent accuracy.

The clusters are discriminated from one another by defining characteristics within the surface sediment. Some species are found exclusively in the offshore (*Bolivina* spp, *Buliminella elegantissima*, *Eggerella* sp., *Haynesina* sp., *Lagena* spp., *Nonionella* spp. Planktics, *Textularia* sp., and *Uvigerinella glabra*). In contrast, the intertidal is represented by *Ammonia parkinsoniana* and *Buccella frigida* and the supratidal is represented by *Elphidium crispum* and *Pararotalia nipponica*. The offshore biofacies are characterized by predominantly unaltered tests (62% to 94%) while the intertidal and supratidal biofacies are characterized by mostly corraded tests (50% to 100%). Because distinct biofacies were established, it is possible to examine a tsunami sediment interval and trace it back to where the sediment was sourced, or its provenance. The biofacies that were established were the offshore, intertidal, and supratidal biofacies.

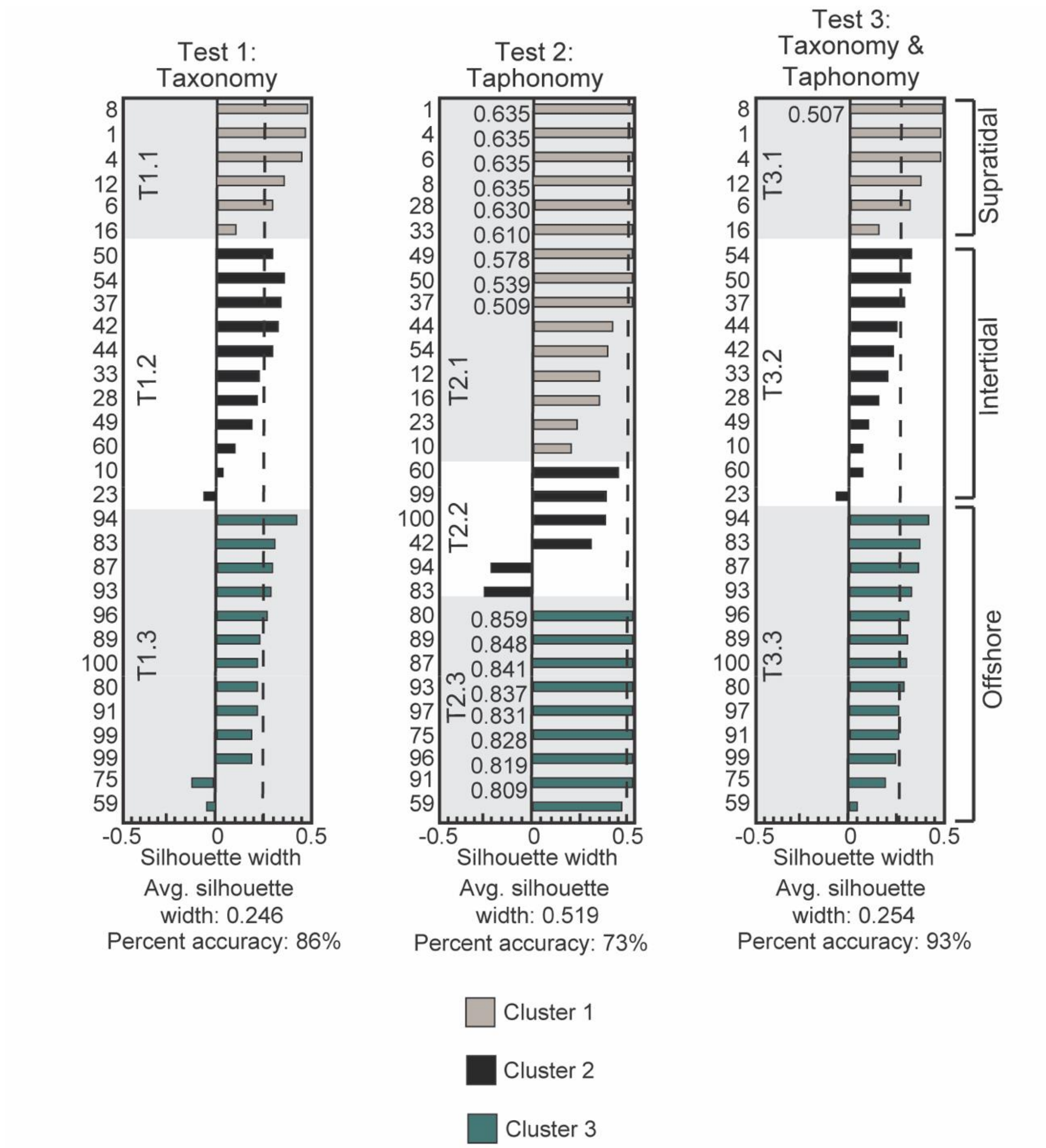

Figure 9 *PAM cluster analysis*

PAM cluster analysis using 3 tests. Displayed are results for the cluster analysis of T1, average silhouette widths and percent accuracy for each test.

The second application of PAM cluster analysis identified the provenance of the tsunami sediment by clustering individual layers within the 2011 tsunami deposit with the modern biofacies (Fig. 10, 11, 12; Supplementary Table S4, S5, S6). Using T3, 1 cm

intervals from the tsunami layers contained within cores from YM, SH, and SJ were isolated and added to the clustered surface samples (Fig. 9). Test 3 was chosen to determine provenance because it produced the most reliable clusters (93% accuracy) as opposed to Test 1 (86%) and Test 2 (73%). The majority of tsunami intervals clustered within the intertidal biofacies (YM = 92% of sampled intervals, SH = 80%, SJ = 100%) which is dominated by swash and foreshore samples. The remainder of the tsunami intervals clustered within the supratidal biofacies (YM = 8% of sampled intervals, SH = 20%, and SJ = 0%) which is dominated by samples from collected from the dune and backshore (Table 1, 2, 3).

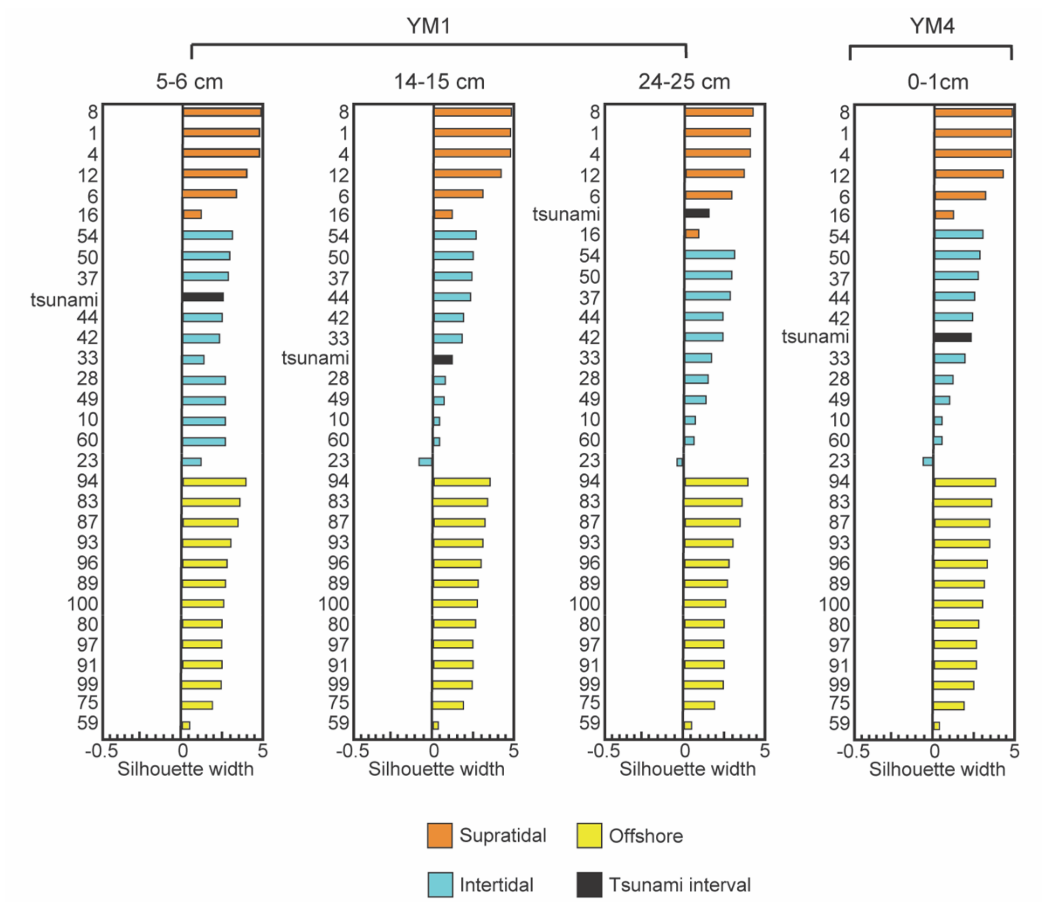

Figure 10 *PAM cluster analysis; Yamamoto*

Results from PAM cluster analysis for YM1 and YM4 indicating silhouette widths of clustered data (Test 3) from T1 and tsunami intervals. The plots describe where each tsunami interval clustered within T1.

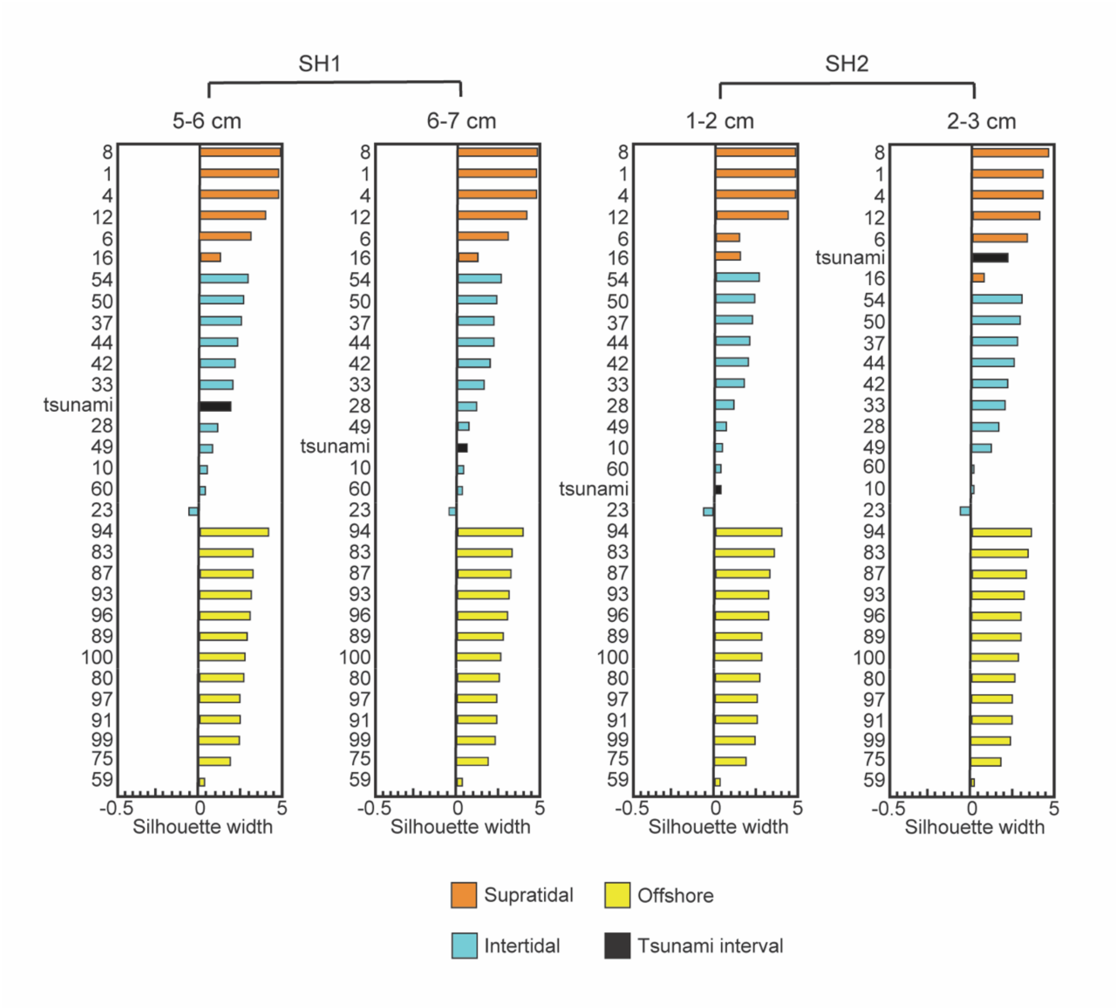

Figure 11 *PAM cluster analysis; Shinchi*

Results from PAM cluster analysis for SH1 and SH2 indicating silhouette widths of clustered data (Test 3) from T1 and tsunami intervals. The plots describe where each tsunami interval clustered within T1.

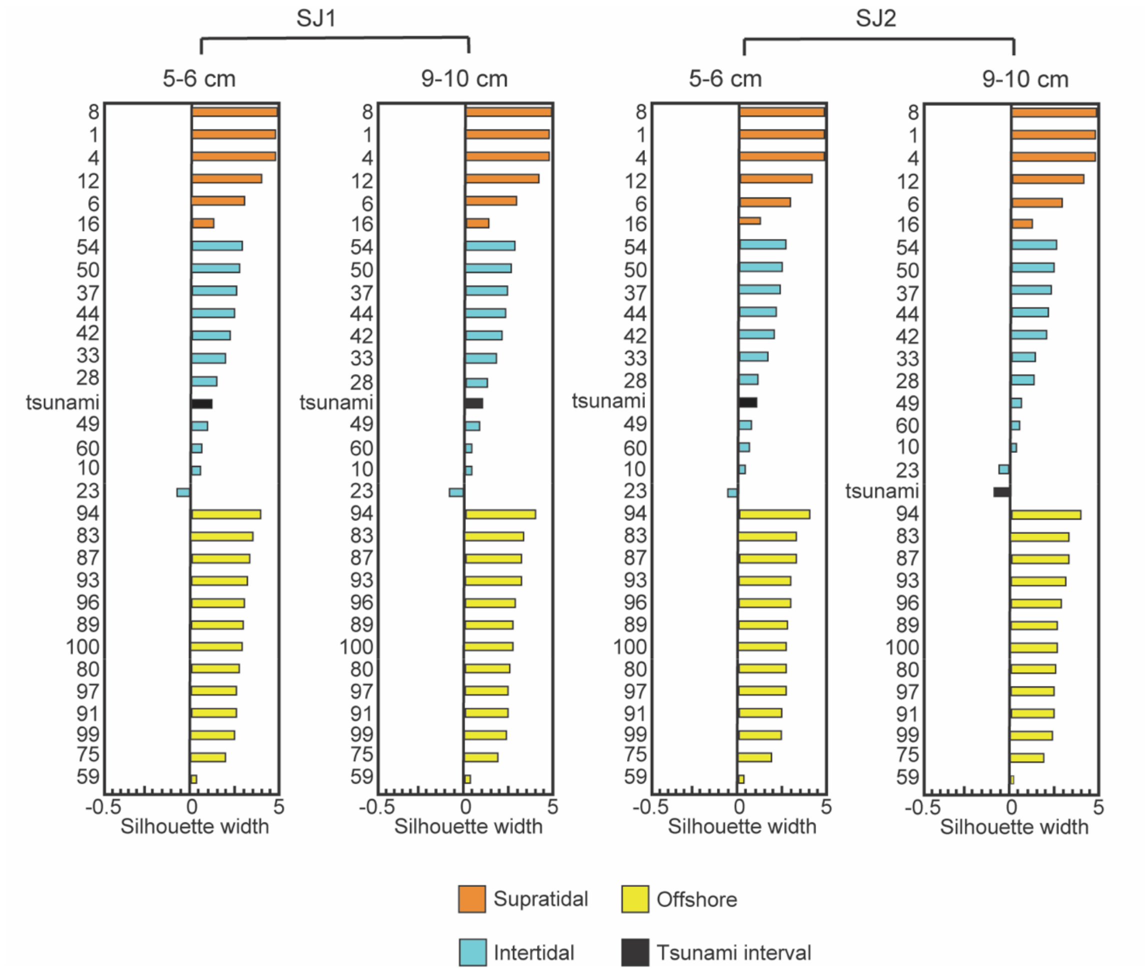

Figure 12 *PAM cluster analysis; Suijin-numa*

Results from PAM cluster analysis for SJ1 and SJ2 indicating silhouette widths of clustered data (Test 3)from T1 and tsunami intervals. The plots describe where each tsunami interval clustered within T1.

Table 1 *Clustered tsunami samples for Yamamoto*

Sample Interval	Clustered Group	Average silhouette width before interval	Average silhouette width after interval
YM1			
0-1 cm	Intertidal	0.158	0.139
1-2 cm	Intertidal	0.158	0.159
4-5 cm	Intertidal	0.158	0.147
5-6 cm	Intertidal	0.158	0.172
6-7 cm	Intertidal	0.158	0.150
8-9 cm	Intertidal	0.158	0.156
9-10 cm	Intertidal	0.158	0.145
14-15 cm	Intertidal	0.158	0.138
15-16 cm	Intertidal	0.158	0.148
17-18 cm	Intertidal	0.158	0.150
20-21 cm	Intertidal	0.158	0.147
24-25 cm	Supratidal	0.392	0.313
YM2			
0-1 cm	Intertidal	0.158	0.159
3-4 cm	Intertidal	0.158	0.158
6-7 cm	Intertidal	0.158	0.144
YM3			
0-1 cm	Intertidal	0.158	0.150
3-4 cm	Intertidal	0.158	0.137
6-7 cm	Supratidal	0.392	0.371
9-10 cm	Intertidal	0.158	0.137
12-13 cm	Intertidal	0.158	0.124
YM4			
0-1 cm	Intertidal	0.158	0.163
1-2 cm	Intertidal	0.158	0.137
2-3 cm	Intertidal	0.158	0.145
3-4 cm	Intertidal	0.158	0.146

Tsunami sediment intervals indicating which group the sediment clustered in, the average silhouette width of the clustered group before the addition of the tsunami sediment interval, and the average silhouette width of the clustered group after the addition of the tsunami sediment interval for YM.

Table 2 *Clustered tsunami samples for Shinchi*

Sample Interval	Clustered Group	Average silhouette width before interval	Average silhouette width after interval
SH1			
4-5 cm	Intertidal	0.158	0.146
5-6 cm	Intertidal	0.158	0.153
6-7 cm	Intertidal	0.158	0.139
SH2			
1-2 cm	Supratidal	0.392	0.346
2-3 cm	Intertidal	0.158	0.173

Tsunami sediment intervals indicating which group the sediment clustered in, the average silhouette width of the clustered group before the addition of the tsunami sediment interval, and the average silhouette width of the clustered group after the addition of the tsunami sediment interval for SH.

Table 3 *Clustered tsunami samples for Suijin-numa*

Sample Interval	Clustered Group	Average silhouette width before interval	Average silhouette width after interval
SJ1			
1-2 cm	Intertidal	0.158	0.157
3-4 cm	Intertidal	0.158	0.150
5-6 cm	Intertidal	0.158	0.152
7-8 cm	Intertidal	0.158	0.136
9-10 cm	Intertidal	0.158	0.149
11-12 cm	Intertidal	0.158	0.120
12-13 cm	Intertidal	0.158	0.158
SJ2			
1-2 cm	Intertidal	0.158	0.157
2-3 cm	Intertidal	0.158	0.153
3-4 cm	Intertidal	0.158	0.158
5-6 cm	Intertidal	0.158	0.142
7-8 cm	Intertidal	0.158	0.166
9-10 cm	Intertidal	0.158	0.158
11-12 cm	Intertidal	0.158	0.118

Tsunami sediment intervals indicating which group the sediment clustered in, the average silhouette width of the clustered group before the addition of the tsunami sediment interval, and the average silhouette width of the clustered group after the addition of the tsunami sediment interval for SJ.

CHAPTER V – DISCUSSION

5.1 Modern distributions of foraminifera in Sendai Bay

Foraminiferal assemblages along T1 changed relative to the distance from the shoreline. This is corroborated by cluster analysis, where three biofacies based on distance from the shoreline were revealed: supratidal (average distance from the shoreline = 114 m ± 44m; average elevation 1.9 m ± 0.25 m above T.P. in elevation; average silhouette width = 0.39), intertidal (-19 m ± 127m; average elevation -0.8 m ± 3.7 m above T.P. in elevation; average silhouette width = 0.15), and offshore (-20,439 m ± 11643 m above T.P. in elevation; average elevation -40.5 m ± 18 m above T.P. in elevation; average silhouette width = 0.27). Specific species were indicative of the offshore environment such as *Haynesina* sp. (0 to 3%) and *Nonionella* spp. (0 to 14%) as they are absent from swash, foreshore, backshore, and dune sediment samples. In contrast, *Pararotalia nipponica* is found in high concentrations in swash, foreshore, backshore, and dune sediment samples but in low concentrations in the offshore environment. Additionally, *Ammonia convexa* is found in the swash and foreshore zones.

The supratidal (dune and backshore) biofacies is characterized by *Elphidium crispum* and *Pararotalia nipponica*. The concentrations of foraminifera have an average of 10 specimens per 10 cm^3. The tests of foraminifera in this biofacies are predominantly corraded (66% to 100%). Compared with Kosciuch et al. (2018) who investigated Tropical Cyclone Pam, a category 5 storm, which affected Undine Bay, Vanuatu, the beach, which is analogous the supratidal biofacies, had a foraminiferal concentration of 81 to 28 specimens per 5 cm^3. The dominant taphonomic condition observed was corroded tests. In comparison with Kosciuch et al. (2018), our concentrations are not

similar however, we record similar taphonomic conditions of tests. In comparison to Pilarczyk et al. (2020), who conducted their study in Kujukuri Bay, approximately 360 km south of Sendai, documented that the backshore was dominated by *Pararotalia nipponica*, *Ammonia parkinsoniana*, and *Cibicides refulgens* and the dune by *Pararotalia nipponica* and *Ammonia parkinsoniana*, we document similar species. Additionally, the study also reports a majority of corraded foraminifera in the backshore and dunes which are similar to our results.

The intertidal (foreshore and swash) biofacies is characterized by *Ammonia parkinsoniana* and *Buccella frigida*. The concentrations of foraminifera have an average of 327 specimens per 10 cm^3. The tests of foraminifera in this biofacies are predominantly unaltered (52% to 94%). Similar to our study, Pilarczyk et al. (2020) found that the swash, analogous to the intertidal biofacies, on the Kujukuri coastline was dominated by *Pararotalia nipponica*, *Ammonia parkinsoniana*, and *Elphidium crispum* and the foreshore was dominated by *Pararotalia nipponica* and *Ammonia parkinsoniana*. The taphonomic condition of foraminifera in the swash zone were predominantly unaltered while foraminifera in the foreshore were corraded. While we documented a large number of corraded foraminifera in the foreshore, we also found corraded foraminifera in the swash zone.

The offshore biofacies is characterized by *Haynesina* sp. and *Nonionella* spp. The concentrations of foraminifera have an average of 1770 specimens per 10 cm^3. The tests of foraminifera in this biofacies are predominantly unaltered (62% to 94%). Compared with Kosciuch et al. (2018), the open bay environment, which is analogous to the offshore biofacies, had a foraminiferal concentration of 2248 to 3730 specimens per 5

cm^3 and the beach, which is analogous the supratidal biofacies, had a foraminiferal concentration of 81 to 28 specimens per 5 cm^3. The dominant taphonomic condition recorded were unaltered tests. In comparison with this study, the recorded concentrations are not similar however, similar taphonomic conditions of tests are documented.

As seen in the results, the dominant condition of foraminifera in the offshore zone is unaltered tests while the dominant condition of the foraminiferal tests on the coast is predominantly corraded. We hypothesize a higher number of corraded tests on the coast due to the tests being subaerially exposed and weathering processes. Conversely, the tests in the offshore environment are protected in the water column under less dynamic processes than on the coast. This observation agrees with Kosciuch et al. (2018) and Pilarczyk et al. (2020) who found that foraminifera in deeper waters tend to be unaltered because they are sheltered from subaerial exposure while increased residence time on the coast could cause foraminiferal tests to corraded.

The use of cluster analysis has been previously employed and used successfully in other studies and regional settings to resolve surface distributions, or 'biofacies' (Kemp et al., 2012; Kosciuch et al., 2018; Pilarczyk et al., 2020). Kemp et al. (2012) employed PAM cluster analysis taking taxonomic data and elevation into consideration and discriminated 6 biofacies within a salt marsh environment in New Jersey, USA. In more recent studies, Kosciuch et al. (2018) and Pilarczyk et al., (2020) found that using taphonomic characteristics in addition to taxonomy can discriminate modern environments. Kosciuch et al. (2018) found 6 modern environments (open bay, forereef, reef crest, reef flat, mangrove, and beach) in a reef system within Undine Bay, Vanuatu. Pilarczyk et al. (2020) discriminated 3 modern environments (offshore, supratidal, and

intertidal) in Kujukuri Bay, Japan. In contrast to Pilarczyk et al (2020) whose tests revealed that taphonomic data was ideal for discriminating the same biofacies that were discriminated in this study (supratidal, intertidal, and offshore), the results of this study and Kosciuch et al. (2018) found that using the combination of taxonomy and taphonomic data are the best at discriminating biofacies.

The clusters are discriminated from one another by defining characteristics within the surface sediment. Some species are found exclusively in the offshore (*Bolivina* spp, *Buliminella elegantissima*, *Eggerella* sp., *Haynesina* sp., *Lagena* spp., *Nonionella* spp. Planktics, *Textularia* sp., and *Uvigerinella glabra*). In contrast, the intertidal is represented by *Ammonia parkinsoniana* and *Buccella frigida* and the supratidal is represented by *Elphidium crispum* and *Pararotalia nipponica*. The offshore biofacies are characterized by predominantly unaltered tests (62% to 94%) while the intertidal and supratidal biofacies are characterized by mostly corraded tests (50% to 100%). Because we have established distinct biofacies, it is possible to examine a tsunami sediment interval and trace it back to where the sediment was sourced, or its provenance.

5.2 Foraminiferal trends in the 2011 Tohoku tsunami sediment

Tsunami sediments revealed by geoslicer cores at the study site show that the 2011 Tohoku tsunami deposit ranged in thickness from 5 to 30 cm. Major stratigraphic and grain size characteristics of the same cores were previously described by the Geological Survey of Japan and report that the tsunami deposit is characterized by graded bedding, parallel lamination, fining upwards sequences, and sharp lower contacts. Additionally, the sediments in the tsunami deposit have been found to be between coarse and medium sand. These characteristics are similar to studies that investigated the

sedimentological, micropaleontological, and geochemical characteristics of 2011 tsunami sediments elsewhere in Sendai (Chagué-Goff et al., 2012; Goto et al., 2012; Pilarczyk et al., 2012; Szczuciński et al., 2012), and in general are similar to paleotsunami deposits found in the Tohoku region of Japan (Sawai et al., 2012; Sawai et al., 2015).

The distribution of foraminiferal species in the tsunami sediments remain consistent throughout the cores. In the YM and SH transects, the concentrations of specimens decreased with increasing distance inland. The SJ transect does not have decreasing concentrations with further distance inland. SJ2 was sampled from Suijin-numa lake suggesting that SJ2 was able to preserve the 2011 tsunami sediment better than SJ1 which is located in a paddy field. The underlying soil was barren of foraminifera; a similar observation was made by a study on the Sendai Plain with the exception of 2 sites which can be attributed to bioturbation (Pilarczyk et al., 2012).

In comparison with the T1 surface sediments, the concentrations of foraminifera in the 2011 Tohoku tsunami sediments are generally the same (Fig. 4, 5, 6, 7). In the YM transect, the concentrations of foraminifera range from 20 to 540 specimens per 10 cm^3. In the SH transect, the concentrations range from 10 to 307 specimens per 10 cm^3. In the SJ transect, the concentrations range from 30 to 767 cm^3. Pilarczyk et al. (2012) which conducted their study in the same area, the Sendai Plain, found concentrations of foraminifera in the 2011 Tohoku tsunami sediment to be between 18 and 101 specimens per 1 cm^3. Hawkes et al. (2007) reported between 250 to 6480 specimens per 5cm^3 in tsunami sediments from the 2004 Indian Ocean Tsunami on the Malaysia-Thailand Peninsula. We report lower concentrations of foraminifera in the 2011 tsunami sediments from our study site.

In comparison with Hawkes et al., (2007) who discriminated foraminiferal zones within the 2004 Indian Ocean tsunami sediments which indicated backwash, the backwards flow of the tsunami, foraminiferal zones regrading species distributions throughout the cores were not documented; the species distributions along the cores were consistent meaning backwash was not identified in our tsunami sediment. However, Pilarczyk et al. (2011) found a homogenous distribution of species in the tsunami sediment from the 1945 Makran tsunami deposit. Within the 2011 Tohoku tsunami cores, the concentrations of foraminifera are higher at the top and center of the cores. Hawkes et al. (2007) found similar patterns where the concentration of foraminifera was highest at the upper parts of core while Pilarczyk et al. (2012), found that abundance did not vary with depth within the 2011 Tohoku tsunami sediments. Within the tsunami sediment, a higher number of tests were found to be fragmented with angular edges suggesting rapid transport and deposition. In both studies conducted by Pilarczyk et al. (2011) and Pilarczyk et al., (2012), fragmentation and rounding of the tests was found in the tsunami deposits of the 1945 Makran Trench and 2011 Tohoku tsunami similar to our findings. The varying characteristics of the tsunami deposits at each site suggest that when conducting provenance studies, it is important to go on a site by site basis because the geomorphology and dynamics of inundation for that area can affect how the tsunami deposit settles and deposits sediment.

The most common species in the 2011 Tohoku tsunami cores are *Pararotalia nipponica* and *Buccella frigida.* Uchida et al. (2010) documented foraminifera found by Onuki et al. (1969) in tsunami deposits from both nearshore and offshore origin. In Kamaishi and Miyako Bays, 140 and 100 km north of Sendai Bay, tsunami sediments

from the 1960 Chile earthquake and tsunami reported *Buccella frigida, Buliminella elegantissima, Elphidium crispum, Trochammina inflata*, which are located in the nearshore environments. In Toba, Japan 540 km South of Sendai, Okahashi et al. (2002) documented *Pararotalia nipponica* and *Elphidium crispum*, from the sublittoral zone, as the dominant species. Our study documents the aforementioned species in T1, however only the latter were documented in the 2011 Tohoku tsunami sediments. Though planktic foraminifera are often documented in tsunami deposits (Pilarczyk et al., 2011), high numbers of planktic species in the tsunami sediment were not documented. In comparison with T1, there are a greater number of fragmented tests with angular edges as seen in Pilarczyk et al. (2012) (2011 Tohoku Tsunami sediments) and Kosciuch et al., (2018) (Tropical Cyclone Pam sediments). With increasing distance inland, tsunami sediment deposits become increasingly less thick which consistent with the findings of Pilarczyk et al. (2012) and Szczuciński et al. (2012). Despite landward thinning, the species assemblages remain consistent (Fig. 5, 6, 7, 8). Between YM, SH, and SJ, the species assemblages are similar. The most dominant species in all three transects are *Pararotalia nipponica* and *Buccella frigida*. However, SH and SJ both contain the foraminifera *Haynesina* sp. and *Nonionella* spp. foraminifera that YM1 is lacking.

5.3 Sediment provenance of the 2011 Tohoku tsunami

Previous studies (Pilarczyk et al., 2012; Szczuciński et al., 2012) conducted along the Sendai Plain sought to determine the provenance of the 2011 Tohoku tsunami deposit using different sedimentological and microfossil proxies. Pilarczyk et al. (2012) concluded based on foraminiferal and grain size data that the source material for 2011 Tohoku tsunami sediments was the intertidal and dune environments, with a minor

component of offshore marine material. In slight contrast, Szczuciński et al. (2012) used sediment grain size, diatoms, and nannoliths on the same tsunami trenches described in Pilarczyk et al. (2012) to resolve that 2011 tsunami deposits within 1 km of the coastline were made up of beach and dune sediments. In Sendai Bay, marine sediments are reported to be composed of mud, very fine sand, and fine sand (Hattori, 1976; Saito 1989). However, Szczuciński et al. (2012) found that those size fractions belonged to the least common fractions within their tsunami sediment deposits while medium to coarse sand which is found in beach sands and coastal soils dominated the deposits. The lack of agreement over the source of sediments comprising the 2011 Tohoku tsunami deposits makes provenance analysis on paleodeposits a challenging task. The use of PAM cluster analysis, a user non-biased method of clustering, assists in this regard because it discriminates between three modern biofacies (supratidal, intertidal, and offshore), making it possible to statistically compare 2011 tsunami sediments with actual surface sediment distributions. Studies by Pilarczyk et al. (2012) and Szczuciński et al. (2012) relied on previously published ecological distributions to interpret the microfossils in 2011 tsunami sediments; whereas the present study uses regionally specific mapped distributions.

Our results show that 40 times out of 43, 2011, 1 cm thick intervals from within the 2011 tsunami deposit clustered in the intertidal group (Table 1, 2, 3). The 3 samples that did not cluster in the intertidal group, clustered in the supratidal group instead. The 40 samples that clustered in the intertidal group were found in cores YM1 (at a depth of 24-25 cm downcore), YM3 (at a depth of 6-7 cm downcore), and SH2 (at a depth of 1-2 cm downcore). These intervals were not located close to the contact between tsunami

sediment and the underlying soil which suggests that exposure processes impacting the pre-2011 surface did not affect the placement of these intervals into the supratidal group. The intervals which are not clustered with the intertidal typically consisted of a majority of corraded individuals which is consistent with that of the dune samples which are in the supratidal group. On the basis of foraminiferal data, no tsunami interval clustered in the offshore biofacies. In this respect, our results agree with those of Szczuciński et al. (2012) who identified that the source of tsunami sediments was from the beach and dune. Our results did not find an offshore signal, possibly because offshore species were not dominant enough in the tsunami sediment to define the clusters determined through PAM analysis. However, a possible signal from the offshore biofacies should not be discounted; Pilarczyk et al. (2012) found planktic foraminifera which are also common in the offshore biofacies at Sendai Bay and in the 2011 Tohoku tsunami sediments. It is possible that there is a small offshore signal in our tsunami sediments, but the signals from the intertidal and supratidal could be much stronger.

5.4 Sediment provenance and the relative intensity of paleotsunamis impacting the Sendai coastline

Current instrumentation and historical records fall short in capturing the complete range of tsunamis (i.e., frequency and intensity) that can occur over centuries to millennia (Satake and Atwater, 2007). Though historical records provide information on the intensity of tsunamis, this information is difficult to obtain for tsunamis that predate the observational record. To understand tsunamis over longer time scales, ranging from centuries to millennia, the geological record may be employed to better infer patterns of

frequency and intensity of past events (Dawson and Shi, 2000), which aids in developing more effective risk mitigation strategies for the future.

Historical records and geological evidence from the Sendai region suggest the recurrence interval for great earthquakes and their accompanying tsunamis is potentially less than previously thought (between 550 and 1,100 years) (Sawai, 2020). In Tohoku, tsunami deposits associated with historical and paleo-events are often found in low-lying, low-energy environments such as rice fields and marshes, (Sawai et al., 2012; Szczuciński et al., 2012). Studies that have investigated these deposits have provided important information regarding the timing, and therefore, recurrence of past events. This information is valuable to estimating the risk of earthquakes and tsunamis for a particular region and leads to more informed hazard mitigation strategies. However, many of these earthquake reconstructions and associated tsunami studies do not report on the intensity of the tsunamis that run inland. Given that not all tsunamis have the same flow depth, inundation distance, etc., it is important for hazard mitigation to understand the full variability in intensity and not only recurrence.

Assessing relative intensity for past tsunamis impacting the Sendai region is problematic. Inundation models based on hypothetical earthquake rupture models (Mori et al., 2017) and sediment transport modeling (Namegaya and Satake, 2014) can assist in reconstructing the flow depth and inundation distance for events for which there is no observational record. However, neither of these methods considers sediment provenance, which can strengthen inundation models through ground-truthing, and if misunderstood, may confound sediment transport models. Rather, an understanding of surface sediment distributions is key to understanding the provenance of tsunami deposits and can

potentially lead to improved insight into the distance of sediment transport and depth of scour by tsunami wave for future studies regarding modeling paleotsunami intensity and sediment transport.

The proxy tool-kit, developed for understanding tsunami deposits preserved in the geologic record can assist in identifying tsunami deposits from underlying and overlying layers as well as provide insight into sediment provenance (Mamo et al., 2009, Chagué-Goff et al., (2011); Goff et al., (2012); Naruse and Abe, 2017; Pilarczyk et al., 2014, Sawai et al., 2012); two important aspects for understanding the risk posed to a coastline by future tsunamis. In particular, foraminifera, provide an opportunity to assess modern and paleotsunami studies as they can provide insight into flow direction because foraminifera found in tsunami deposits come from diverse habitats (Dawson and Shi, 2000; Hawkes et al., 2007; Pilarczyk et al., 2014). This is because tsunamis entrain and deposit such species and corresponding sediments as they inundate coastal and inland areas (Dawson et al., 1996; Hawkes et al., 2007; Sugawara et al., 2009; Pre et al., 2012; Briggs et al. 2014; Pilarczyk et al. 2014). In using the multi-proxy approach, inundation models of paleotsunamis may be physically verified.

The 2011 tsunami deposit is ideal for studying paleotsunamis because of the wealth of physical data collected from this event in addition to our study (e.g., Mori et al., 2011; Morio et al., 2011; Sawai et al., 2012; Pilarczyk et al., 2012). With the known distribution of foraminifera in Sendai Bay and the provenance of the 2011 Tohoku tsunami, future studies may compare foraminiferal distributions in paleodeposits to the 2011 tsunami deposit to infer the intensities of the paleodeposits such as those reported by Sawai et al. (2012) and Sawai et al. (2015).

CHAPTER VI – CONCLUSION

The Sendai Plain of eastern Japan has a documented paleotsunami history which includes the 2011 Tohoku tsunami. This study used surface distributions of foraminifera from major point sources of sediment along the coastal and offshore Sendai Bay to resolve a dominantly intertidal sediment source for the 2011 tsunami sediments, with a minor contribution of supratidal sediments. Surface distributions of foraminifera were separated into three biofacies using PAM cluster analysis (supratidal, intertidal, and offshore) that were generally linked to increasing distance from the shoreline.

Foraminifera within the 2011 Tohoku tsunami deposit indicate an intertidal origin, which is dominated by foraminifera from the swash and foreshore subenvironments (*Pararotalia nipponica* and *Ammonia parkinsoniana)* and have predominantly unaltered tests. This characterization of the foraminiferal assemblages within 2011 tsunami sediments is similar to equivalent deposits found elsewhere in Sendai and provide an opportunity to interrogate the provenance of a modern analogue of known intensity. Using the 2011 Tohoku tsunami deposit as a basis of comparison, future studies are positioned to compare it to a series of five paleotsunami deposits described in the literature, but for which relative tsunami intensity is either speculative or unknown. The long-term record of tsunamis in the Sendai region provides a unique possibility to understand patterns of tsunami frequency and intensity over millennial timescales, which may be instrumental in understanding and mitigating the impacts of future tsunamis.

APPENDIX A – Foraminiferal trends along T1

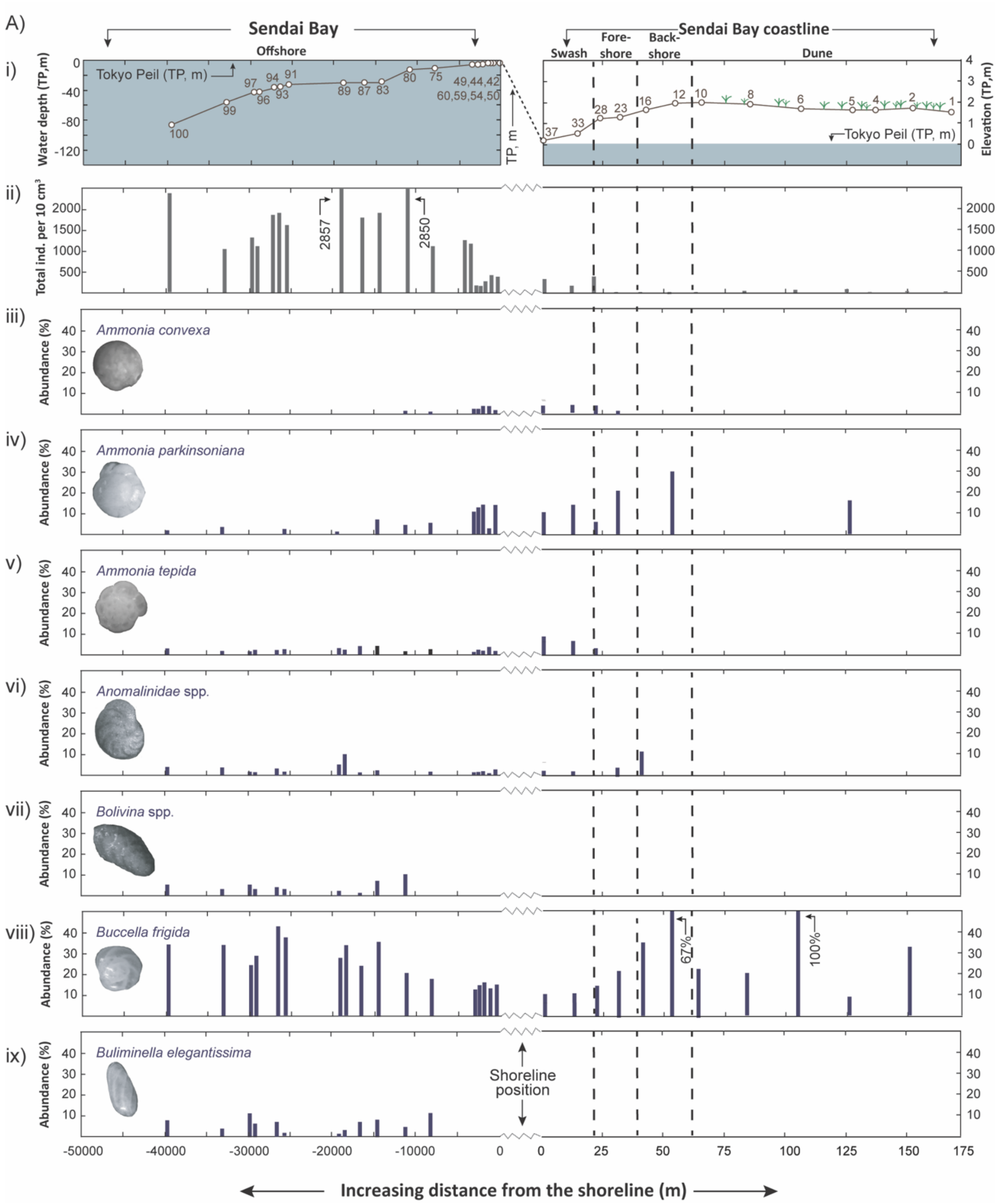

Figure S1a *Taxonomic data*

Elevation and foraminiferal taxonomic data for T1. **i)** Elevation/depth profile (using Tokyo Peil, TP; mean sea-level in Tokyo Bay) for T1 extending from the offshore zone of Sendai Bay to the dunes at Gamou Beach. **ii)** Total concentration of foraminifera (specimens per 10 cm^3) along T1. **iii-ix)** Relative abundances of key foraminiferal taxa (% abundance) along T1.

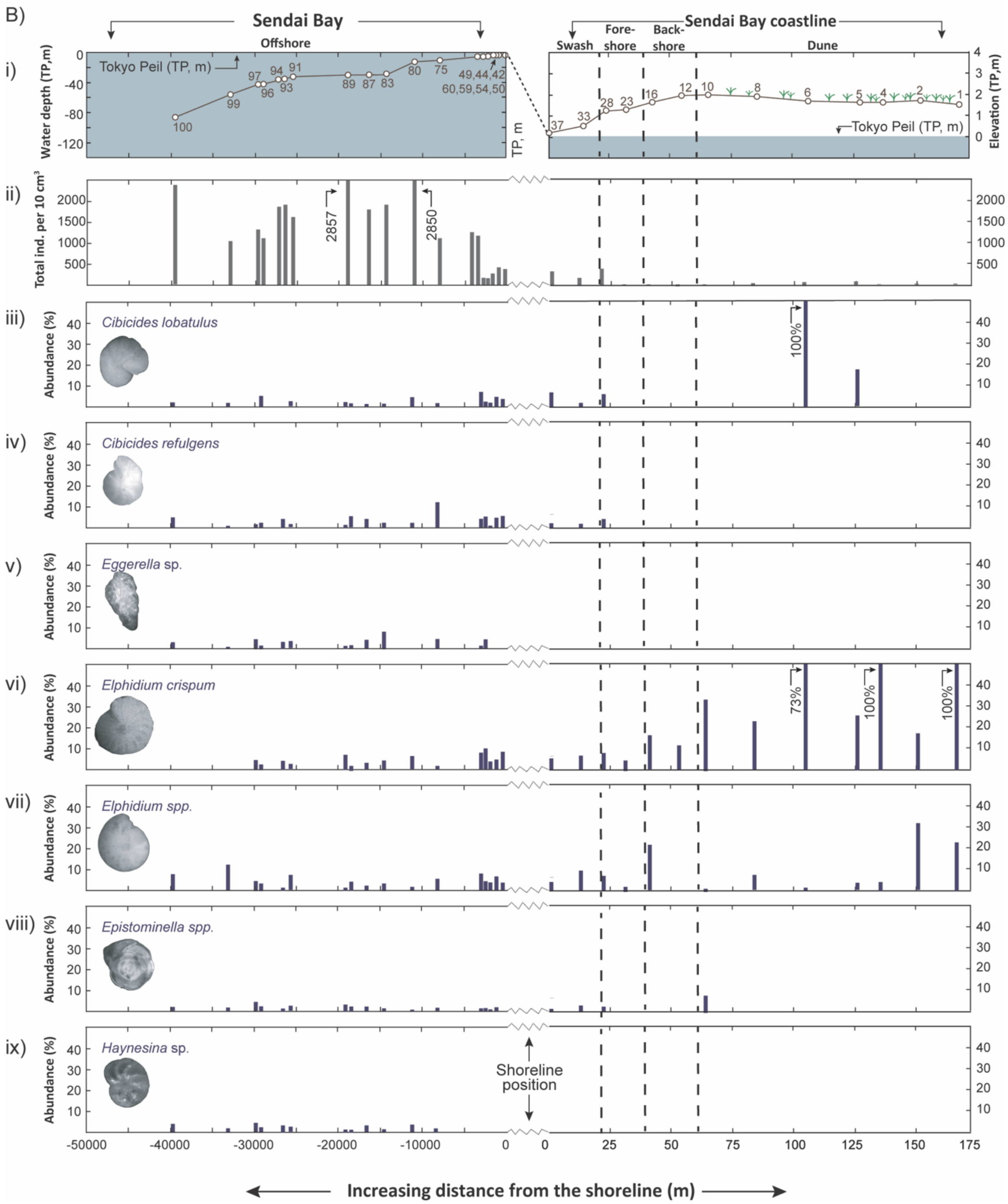

Figure S1b *Taxonomic data*

Elevation and foraminiferal taxonomic data for T1. **i)** Elevation/depth profile (using Tokyo Peil, TP; mean sea-level in Tokyo Bay) for T1 extending from the offshore zone of Sendai Bay to the dunes at Gamou Beach. **ii)** Total concentration of foraminifera (specimens per 10 cm^3) along T1. **iii-ix)** Relative abundances of key foraminiferal taxa (% abundance) along T1.

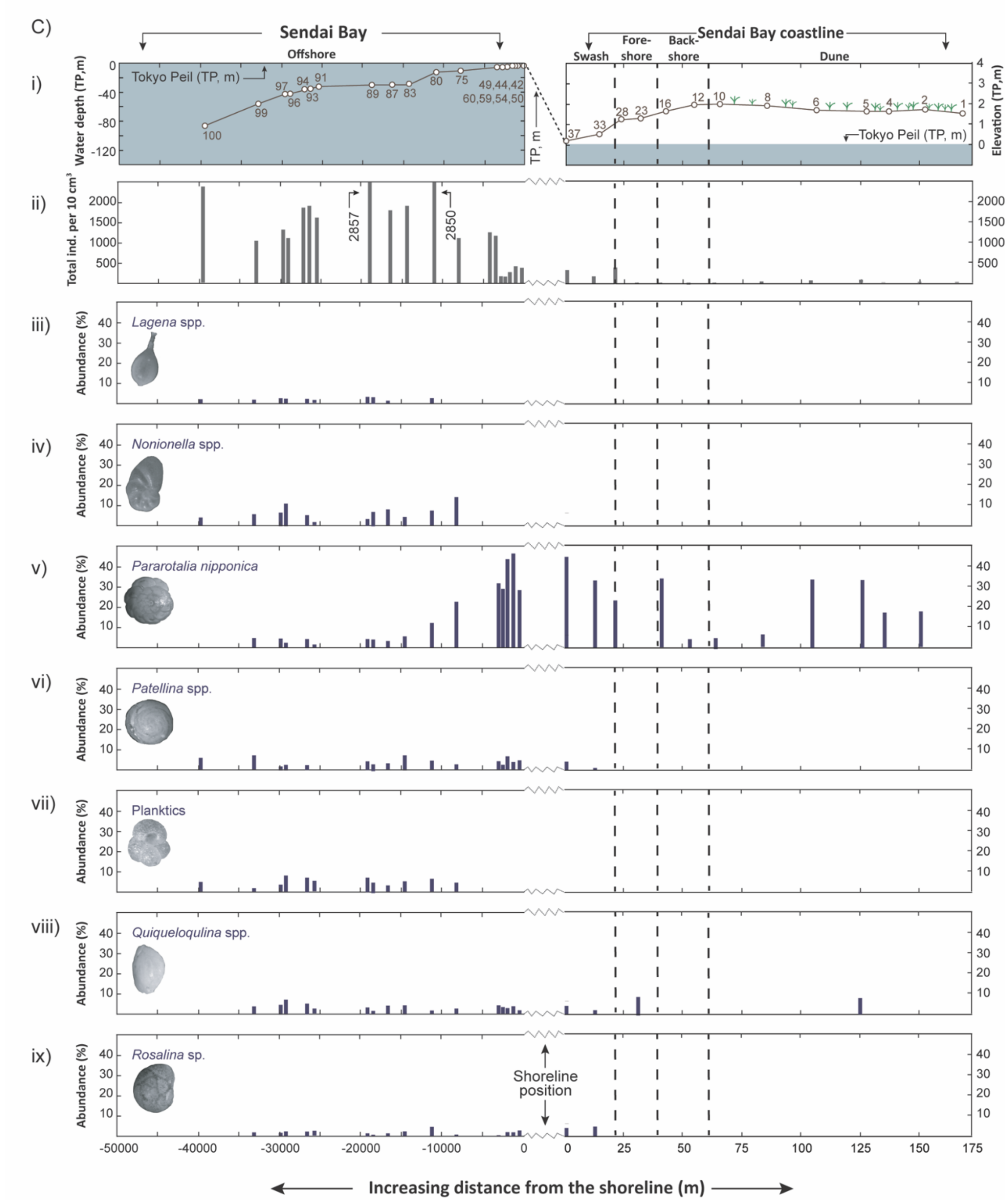

Figure S1c *Taxonomic data*

Elevation and foraminiferal taxonomic data for T1. **i)** Elevation/depth profile (using Tokyo Peil, TP; mean sea-level in Tokyo Bay) for T1 extending from the offshore zone of Sendai Bay to the dunes at Gamou Beach. **ii)** Total concentration of foraminifera (specimens per 10 cm^3) along T1. **iii-ix)** Relative abundances of key foraminiferal taxa (% abundance) along T1.

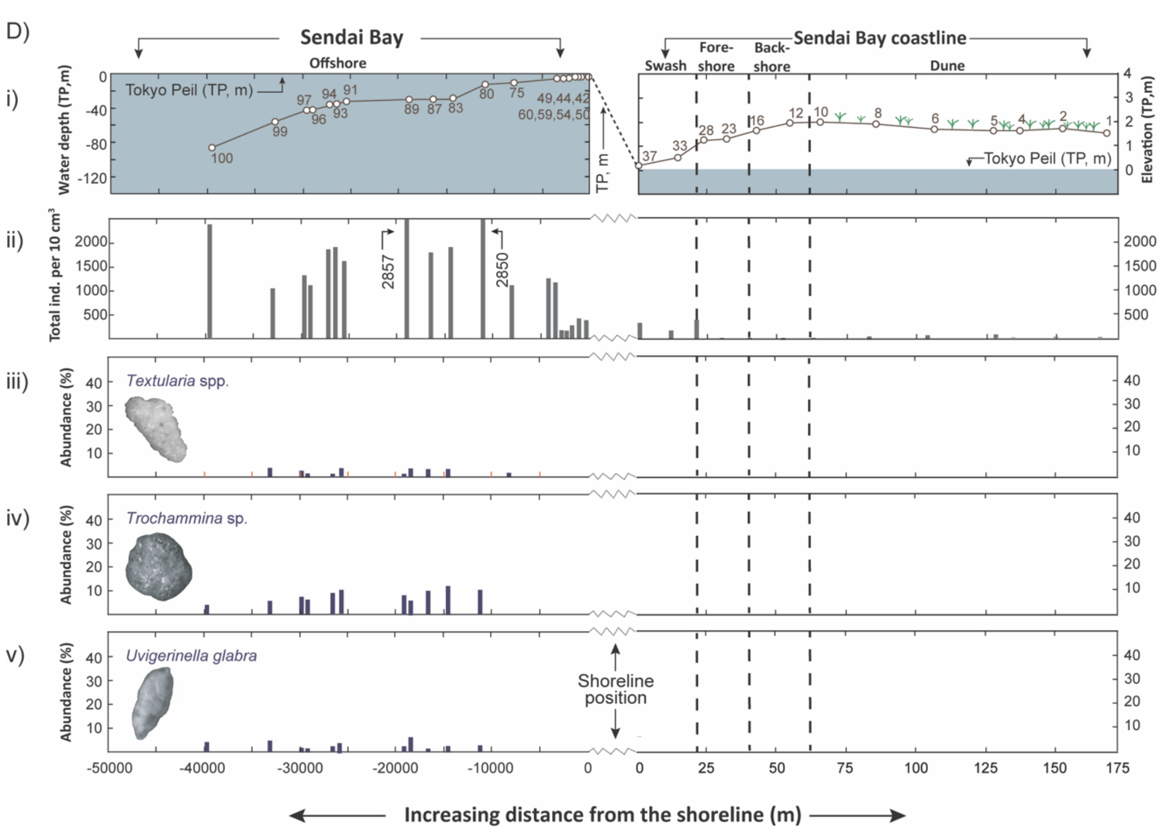

Figure S1d *Taxonomic data*

Elevation and foraminiferal taxonomic data for T1. **i)** Elevation/depth profile (using Tokyo Peil, TP; mean sea-level in Tokyo Bay) for T1 extending from the offshore zone of Sendai Bay to the dunes at Gamou Beach. **ii)** Total concentration of foraminifera (specimens per 10 cm^3) along T1. **iii-ix)** Relative abundances of key foraminiferal taxa (% abundance) along T1.

APPENDIX B – Relative abundance of foraminifera

Table S1a Taxonomic and taphonomic data for T1

Sample Number	1	2	4	5	6	8	10	12	16
Sample Location	38° 15' 35.59652" N, 141° 1' 2.08517" E	38° 15' 34.81738" N, 141° 1' 2.58845" E	38° 15' 35.92148" N, 141° 1' 1.78331" E	38° 15' 34.33513" N, 141° 1' 3.02714" E	38° 15' 34.07385" N, 141° 1' 3.20972" E	38° 15' 33.47833" N, 141° 1' 3.83381" E	38° 15' 33.09405" N, 141° 1' 4.37924" E	38° 15' 32.69923" N, 141° 1' 4.76064" E	38° 15' 32.49716" N, 141° 1' 5.08928" E
Geomorphic Zone	Dune	Dune	Dune	Dune	Backshore	Backshore	Backshore	Backshore	Backshore
Elevation (m above T.P.)	1.6	2.0	1.5	1.8	1.9	2.1	2.2	2.2	2.0
Distance from Shoreline (m)	170	158	141	139	128	111	81	68	57
Specimens per 10 cm^3	1	6	1	12	30	13	12	3	9
Taxonomy									
Ammonia convexa	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ammonia parkinsoniana	0.000	0.167	0.000	0.000	0.000	0.000	0.308	0.000	0.000
Ammonia tepida	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Anomalinidae sp.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.111
Bolivina spp.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Buccella frigida	0.000	0.333	0.000	0.083	1.000	0.200	0.231	0.667	0.222
Buliminella elagantissima	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Cibicides lobatulus	0.000	0.000	0.000	0.167	0.000	0.000	0.000	0.000	0.000
Cibicides refulgens	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Eggerella sp.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Elphidium crispum	1.000	0.167	1.000	0.250	0.000	0.733	0.231	0.333	0.111
Elphidium spp.	0.000	0.167	0.000	0.083	0.000	0.000	0.000	0.000	0.222
Epistominella spp.	0.000	0.000	0.000	0.000	0.000	0.000	0.077	0.000	0.000
Haynesina sp.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Lagena spp.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Nonionella spp.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Pararotalia nipponica	0.000	0.167	0.000	0.333	0.000	0.067	0.000	0.000	0.333
Patellina spp.	0.000	0.000	0.000	0.000	0.000	0.000	0.154	0.000	0.000
Planktics	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Quinqueloculina spp.	0.000	0.000	0.000	0.083	0.000	0.000	0.000	0.000	0.000
Rosalina sp.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Textularia spp.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Trochammina sp.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Uvigerinella glabra	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Taphonomy	**1**	**2**	**4**	**5**	**6**	**8**	**10**	**12**	**16**
Unaltered	0.000	0.167	0.000	0.083	0.000	0.000	0.000	0.333	0.333
Corraded	1.000	0.500	1.000	0.917	1.000	1.000	0.692	0.667	0.667
Fragmented (rounded edges)	0.000	0.167	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fragmented (angular edges)	0.000	0.167	0.000	0.000	0.000	0.000	0.308	0.000	0.000
Total	1	1	1	1	1	1	1	1	1

Table S1a (continued).

23	28	33	37	42	44	49	50	54	59
38° 15' 32.25371" N, 141° 1' 5.60912" E	38° 15' 32.14806" N, 141° 1' 5.92321" E	38° 15' 31.9824" N, 141° 1' 6.3901" E	38° 15' 31.86065" N, 141° 1' 6.68327" E	38° 15' 31.76271" N, 141° 1' 7.04929" E	38° 15' 31.64636" N, 141° 1' 7.34472" E	38° 15' 31.5015" N, 141° 1' 7.72221" E	38° 15' 31.4498" N, 141° 1' 7.93941" E	38° 15' 31.44565" N, 141° 1' 8.23025" E	38° 08' 48.69" N, 140° 57' 09.63" E
Backshore	Foreshore	Foreshore	Foreshore	Foreshore	Foreshore	Foreshore	Swash	Swash	Offshore
1.6	1.3	0.5	0.0	-0.4	-0.6	-0.8	-1.0	-1.2	-10.0
42	33	25	16	8	0	-10	-17	-23	-349
25	39	144	355	403	416	290	215	212	1320
0.000	0.026	0.042	0.040	0.048	0.013	0.015	0.037	0.038	0.009
0.200	0.051	0.139	0.107	0.154	0.025	0.153	0.144	0.108	0.049
0.000	0.026	0.069	0.009	0.010	0.033	0.010	0.023	0.019	0.000
0.040	0.000	0.021	0.018	0.024	0.008	0.025	0.005	0.005	0.010
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.360	0.205	0.146	0.098	0.149	0.113	0.167	0.135	0.113	0.195
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.117
0.000	0.051	0.014	0.071	0.038	0.046	0.025	0.037	0.075	0.000
0.000	0.051	0.028	0.022	0.058	0.046	0.005	0.056	0.047	0.126
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.049
0.160	0.051	0.083	0.067	0.091	0.063	0.049	0.102	0.085	0.019
0.160	0.128	0.042	0.004	0.038	0.067	0.030	0.047	0.090	0.068
0.000	0.026	0.021	0.013	0.000	0.021	0.020	0.009	0.005	0.010
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.231	0.326	0.436	0.284	0.460	0.423	0.288	0.321	0.223
0.000	0.154	0.007	0.040	0.058	0.042	0.049	0.070	0.038	0.018
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.030
0.080	0.000	0.021	0.040	0.024	0.042	0.030	0.042	0.052	0.010
0.000	0.000	0.042	0.036	0.024	0.021	0.000	0.005	0.005	0.049
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.019
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
23	28	33	37	42	44	49	50	54	59
0.360	0.051	0.104	0.262	0.269	0.201	0.212	0.251	0.241	0.820
0.520	0.949	0.854	0.716	0.659	0.724	0.773	0.716	0.684	0.150
0.000	0.000	0.000	0.009	0.072	0.021	0.000	0.005	0.019	0.020
0.120	0.000	0.042	0.013	0.000	0.054	0.015	0.028	0.057	0.010
1	1	1	1	1	1	1	1	1	1

Table S1a (continued).

60	75	80	83	87	89	91	93	94	96
38° 14' 56.16" N, 141° 00' 58.70" E	38° 12' 31.91" N, 141° 05' 05.83" E	38° 10' 13.19" N, 141° 05' 50.99" E	38° 12' 49.20" N, 141° 09' 01.79" E	38° 08' 47.40" N, 141° 07' 33.60" E	38° 11' 23.39" N, 141° 11' 13.80" E	38° 07' 13.79" N, 141° 09' 26.39" E	38° 03' 49.79" N, 141° 13' 01.20" E	38° 08' 06.60"N, 141° 15' 11.40" E	38° 02' 35.99" N, 141° 15' 07.20" E
Offshore	Offshore	Offshore	Offshore	Offshore	Offshore	Offshore	Offshore	Offshore	Offshore
-11.0	-30.4	-30.9	-32.1	-33.1	-32.1	-35.7	-41.2	-41.1	-45.1
-373	-7879	-11298	-12651	-14785	-16923	-18713	-25598	-26360	-28972
1490	1330	2850	1803	1780	2857	1590	1890	1780	1080
0.010	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.059	0.088	0.000	0.000	0.020	0.000	0.000	0.020	0.000	0.000
0.056	0.028	0.009	0.031	0.049	0.024	0.017	0.041	0.021	0.010
0.000	0.010	0.028	0.000	0.010	0.100	0.051	0.009	0.032	0.010
0.000	0.000	0.103	0.075	0.010	0.000	0.003	0.028	0.031	0.029
0.205	0.365	0.248	0.342	0.272	0.337	0.432	0.377	0.366	0.255
0.000	0.118	0.000	0.084	0.079	0.050	0.007	0.009	0.073	0.050
0.030	0.011	0.008	0.009	0.017	0.013	0.023	0.028	0.000	0.039
0.157	0.020	0.032	0.020	0.030	0.050	0.010	0.009	0.031	0.020
0.010	0.049	0.004	0.000	0.098	0.024	0.017	0.037	0.031	0.010
0.000	0.000	0.030	0.000	0.000	0.000	0.000	0.009	0.000	0.010
0.010	0.020	0.107	0.031	0.020	0.030	0.013	0.074	0.010	0.039
0.000	0.010	0.004	0.011	0.020	0.020	0.030	0.028	0.010	0.025
0.010	0.000	0.030	0.019	0.030	0.003	0.013	0.028	0.031	0.029
0.010	0.000	0.020	0.030	0.010	0.000	0.000	0.009	0.010	0.020
0.039	0.143	0.070	0.050	0.084	0.069	0.030	0.010	0.046	0.113
0.120	0.000	0.040	0.013	0.020	0.030	0.017	0.009	0.030	0.029
0.195	0.049	0.075	0.030	0.020	0.033	0.125	0.000	0.021	0.012
0.060	0.050	0.060	0.053	0.039	0.040	0.060	0.056	0.073	0.095
0.030	0.020	0.040	0.032	0.020	0.030	0.010	0.019	0.010	0.087
0.000	0.000	0.032	0.021	0.018	0.009	0.007	0.013	0.021	0.011
0.000	0.020	0.009	0.031	0.020	0.030	0.034	0.019	0.031	0.023
0.000	0.000	0.030	0.108	0.107	0.059	0.081	0.138	0.093	0.066
0.000	0.000	0.021	0.010	0.009	0.050	0.020	0.030	0.028	0.019
1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
60	75	80	83	87	89	91	93	94	96
0.620	0.930	0.949	0.883	0.930	0.941	0.962	0.950	0.880	0.900
0.290	0.050	0.040	0.061	0.070	0.053	0.024	0.040	0.070	0.080
0.080	0.010	0.004	0.029	0.000	0.006	0.010	0.000	0.030	0.010
0.010	0.010	0.007	0.026	0.010	0.000	0.003	0.010	0.010	0.010
1	1	1	1	1.01	1	1	1	0.99	1

Table S1a (continued).

97	99	100
38° 06' 31.20" N, 141° 17' 08.99" E	38° 05' 12.59" N, 141° 19' 29.99" E	38° 03' 11.99" N, 141° 22' 45.00" E
Offshore	Offshore	Offshore
-55.7	-57.0	-82.3
-29219	-33707	-39253
1400	1046	2471
0.000	0.000	0.000
0.000	0.020	0.013
0.009	0.016	0.031
0.327	0.033	0.062
0.052	0.036	0.059
0.336	0.360	0.343
0.129	0.036	0.083
0.000	0.009	0.003
0.010	0.006	0.048
0.040	0.012	0.036
0.010	0.000	0.000
0.040	0.139	0.072
0.040	0.018	0.017
0.040	0.009	0.030
0.010	0.009	0.009
0.069	0.058	0.040
0.040	0.030	0.000
0.010	0.084	0.059
0.020	0.006	0.050
0.030	0.020	0.000
0.009	0.010	0.000
0.021	0.030	0.000
0.078	0.030	0.020
0.010	0.030	0.023
1.326	1.000	0.999
97	99	100
0.900	0.852	0.852
0.090	0.099	0.099
0.000	0.046	0.046
0.010	0.004	0.004
1	1	1

Table S1b Taxonomic and taphonomic data for 2011 Tohoku sediments

Trench	YM1											
Label and Depth (cm)	0-1	1-2	4-5	5-6	6-7	8-9	9-10	14-15	15-16	17-18	20-21	24-25
Sample Location	37° 58' 47.39" N, 140° 54' 44.10" E											
Geomorphic Zone	Tsunami Sediment											
Distance from the Shoreline (m)	244											
Specimens per 10 cm^3	**77**	**120**	**263**	**540**	**337**	**277**	**237**	**63**	**87**	**80**	**80**	**27**
Taxonomy												
Ammonia convexa	0.000	0.000	0.000	0.062	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ammonia parkinsoniana	0.000	0.056	0.000	0.025	0.030	0.012	0.000	0.000	0.038	0.042	0.083	0.000
Ammonia tepida	0.130	0.028	0.089	0.000	0.059	0.060	0.028	0.053	0.038	0.083	0.042	0.125
Anomalinidae sp.	0.000	0.028	0.013	0.025	0.030	0.000	0.014	0.000	0.000	0.000	0.000	0.000
Bolivina spp.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Buccella frigida	0.130	0.250	0.127	0.136	0.089	0.120	0.014	0.105	0.154	0.125	0.083	0.625
Buliminella elegantissima	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Cibicides lobatulus	0.087	0.083	0.101	0.037	0.099	0.084	0.127	0.158	0.038	0.083	0.000	0.000
Cibicides refulgens	0.000	0.000	0.013	0.049	0.010	0.012	0.014	0.000	0.000	0.000	0.000	0.000
Eggerella sp.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Elphidium crispum	0.043	0.111	0.076	0.049	0.089	0.133	0.155	0.211	0.115	0.167	0.083	0.000
Elphidium sp.	0.043	0.028	0.025	0.049	0.030	0.060	0.028	0.000	0.154	0.000	0.000	0.000
Epistominella spp.	0.000	0.028	0.000	0.012	0.050	0.012	0.028	0.000	0.038	0.000	0.083	0.000
Haynesina sp.	0.000	0.000	0.000	0.006	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Lagena spp.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Nonionella spp.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Pararotalia nipponica	0.565	0.361	0.519	0.346	0.485	0.446	0.563	0.421	0.423	0.458	0.583	0.250
Patellina spp.	0.000	0.000	0.000	0.130	0.010	0.012	0.014	0.000	0.000	0.000	0.000	0.000
Planktics	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Quinqueloculina spp.	0.000	0.028	0.000	0.056	0.010	0.036	0.014	0.053	0.000	0.042	0.042	0.000
Rosalina sp.	0.000	0.000	0.038	0.019	0.010	0.012	0.000	0.000	0.000	0.000	0.000	0.000
Textularia spp.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Trochammina sp.	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Uvigerinella glabra	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Taphonomy												
Unaltered	0.652	0.667	0.570	0.753	0.842	0.904	0.803	0.579	0.538	0.750	0.500	0.375
Corraded	0.261	0.194	0.329	0.142	0.010	0.048	0.085	0.158	0.154	0.083	0.375	0.625
Fragmented (rounded edges)	0.000	0.000	0.013	0.043	0.000	0.000	0.014	0.000	0.077	0.000	0.000	0.000
Fragmented (angular edges)	0.087	0.139	0.089	0.062	0.149	0.048	0.099	0.263	0.231	0.167	0.125	0.000
Total	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Table S1b (continued).

YM2			YM3					YM4			
0-1	3-4	6-7	0-1	3-4	6-7	9-10	12-13	0-1	1-2	2-3	3-4
37° 58' 47.89" N, 140° 54' 33.59" E			37° 58' 47.89" N, 140° 54' 25.88" E					37° 58' 51.20" N, 140° 53' 57.69" E			
Tsunami Sediment			Tsunami Sediment					Tsunami Sediment			
502			664					1382			
460	**513**	**63**	**280**	**63**	**27**	**27**	**20**	**123**	**103**	**127**	**60**
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.054	0.000	0.000	0.000
0.036	0.026	0.000	0.000	0.000	0.000	0.125	0.500	0.081	0.000	0.000	0.000
0.080	0.045	0.053	0.071	0.053	0.000	0.125	0.000	0.000	0.000	0.053	0.056
0.014	0.006	0.000	0.024	0.053	0.000	0.000	0.000	0.027	0.032	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.036	0.182	0.053	0.131	0.105	0.250	0.000	0.167	0.135	0.226	0.289	0.167
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.065	0.084	0.053	0.107	0.000	0.000	0.000	0.167	0.108	0.065	0.000	0.111
0.036	0.032	0.000	0.048	0.000	0.000	0.000	0.000	0.054	0.000	0.026	0.056
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.101	0.084	0.053	0.060	0.105	0.125	0.000	0.000	0.054	0.129	0.079	0.000
0.022	0.026	0.053	0.036	0.053	0.000	0.125	0.000	0.054	0.000	0.079	0.056
0.043	0.013	0.000	0.000	0.053	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.012	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.007	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.471	0.455	0.684	0.417	0.579	0.625	0.625	0.167	0.378	0.548	0.342	0.556
0.043	0.006	0.000	0.071	0.000	0.000	0.000	0.000	0.027	0.000	0.132	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.029	0.026	0.000	0.012	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.014	0.013	0.053	0.012	0.000	0.000	0.000	0.000	0.027	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.877	0.916	0.789	0.929	0.895	1.000	0.500	0.500	0.703	0.806	0.711	0.722
0.036	0.045	0.158	0.012	0.000	0.000	0.375	0.333	0.162	0.097	0.079	0.111
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.027	0.000	0.000	0.000
0.087	0.039	0.053	0.060	0.105	0.000	0.125	0.167	0.108	0.097	0.211	0.167
1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Table S1b (continued)

SH1			SH2	
4-5	5-6	6-7	1-2	2-3
37° 53' 01.22" N, 140° 55' 46.32" E			37° 53' 00.18" N, 140° 55' 41.05" E	
Tsunami Sediment			Tsunami Sediment	
264			463	
150	**307**	**123**	**23**	**10**
0.000	0.000	0.000	0.000	0.000
0.111	0.098	0.000	0.000	0.000
0.044	0.065	0.081	0.000	0.000
0.044	0.033	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.133	0.076	0.135	0.000	1.000
0.000	0.000	0.000	0.000	0.000
0.111	0.120	0.000	0.143	0.000
0.067	0.011	0.027	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.054	0.000	0.143	0.000
0.044	0.076	0.162	0.286	0.000
0.000	0.033	0.027	0.000	0.000
0.022	0.000	0.027	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.022	0.000	0.054	0.000	0.000
0.200	0.326	0.432	0.286	0.000
0.044	0.022	0.027	0.143	0.000
0.000	0.000	0.000	0.000	0.000
0.044	0.033	0.027	0.000	0.000
0.111	0.054	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000
1.000	1.000	1.000	1.000	1.000
0.733	0.891	0.811	0.571	0.000
0.067	0.076	0.135	0.429	0.667
0.000	0.000	0.000	0.000	0.000
0.200	0.033	0.054	0.000	0.333
1.000	1.000	1.000	1.000	1.000

SJ1						
1-2	3-4	5-6	7-8	9-10	11-12	12-13
37° 54' 06.19" N, 140° 55' 15.80" E						
Tsunami Sediment						
306						
223	**387**	**83**	**33**	**110**	**767**	**150**
0.000	0.000	0.000	0.000	0.000	0.026	0.000
0.134	0.034	0.040	0.000	0.030	0.030	0.022
0.030	0.043	0.040	0.000	0.030	0.004	0.067
0.015	0.034	0.000	0.000	0.000	0.052	0.044
0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.134	0.078	0.080	0.300	0.121	0.096	0.200
0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.045	0.052	0.040	0.100	0.061	0.143	0.044
0.030	0.086	0.120	0.000	0.061	0.104	0.067
0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.030	0.026	0.080	0.000	0.030	0.000	0.044
0.090	0.069	0.040	0.000	0.000	0.104	0.067
0.090	0.069	0.000	0.000	0.000	0.030	0.000
0.000	0.017	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.030	0.060	0.000	0.000	0.030	0.365	0.000
0.313	0.319	0.560	0.600	0.636	0.000	0.400
0.015	0.043	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.045	0.034	0.000	0.000	0.000	0.044	0.044
0.000	0.034	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.866	0.828	0.640	0.500	0.727	0.861	0.867
0.045	0.060	0.200	0.300	0.152	0.052	0.067
0.000	0.000	0.000	0.000	0.000	0.078	0.000
0.090	0.112	0.160	0.200	0.121	0.009	0.067
1.000	1.000	1.000	1.000	1.000	1.000	1.000

Table S1b (continued).

SJ2						
1-2	2-3	3-4	5-6	7-8	9-10	11-12
37° 54' 04.29" N, 140° 55' 07.79" E						
Tsunami Sediment						
760						
100	**220**	**253**	**130**	**217**	**77**	**30**
0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.067	0.015	0.026	0.000	0.077	0.087	0.000
0.067	0.091	0.013	0.128	0.062	0.043	0.000
0.000	0.045	0.039	0.000	0.015	0.043	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.133	0.182	0.105	0.154	0.138	0.130	0.444
0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.015	0.039	0.000	0.015	0.043	0.000
0.100	0.030	0.053	0.077	0.046	0.087	0.111
0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.067	0.061	0.079	0.051	0.046	0.087	0.111
0.100	0.045	0.053	0.128	0.062	0.043	0.222
0.033	0.030	0.053	0.000	0.031	0.087	0.000
0.000	0.015	0.013	0.026	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.026	0.000	0.046	0.000	0.000
0.400	0.424	0.434	0.308	0.323	0.304	0.000
0.000	0.000	0.039	0.077	0.077	0.000	0.111
0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.033	0.030	0.013	0.051	0.046	0.043	0.000
0.000	0.015	0.013	0.000	0.015	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.000	0.000	0.000	0.000	0.000	0.000	0.000
1.000	1.000	1.000	1.000	1.000	1.000	1.000
0.733	0.742	0.750	0.821	0.815	0.783	0.889
0.100	0.167	0.092	0.051	0.092	0.130	0.111
0.033	0.000	0.000	0.051	0.000	0.000	0.000
0.133	0.091	0.158	0.077	0.092	0.087	0.000
1.000	1.000	1.000	1.000	1.000	1.000	1.000

APPENDIX C – PAM cluster analysis

Table S2a PAM cluster analysis results using 2-5 clusters. Taxonomy was used.

2 Clusters				
Sample ID	Geomorphic zone	Sample	Silhouette width	Avg. cluster widths
50	Swash	17	0.367	
54	Swash	18	0.357	
42	Foreshore	14	0.349	
49	Foreshore	16	0.348	
37	Foreshore	13	0.321	
44	Foreshore	15	0.310	
2	Dune	2	0.291	
8	Backshore	6	0.290	
28	Foreshore	11	0.274	
1	Dune	1	0.270	
4	Dune	3	0.270	
33	Foreshore	12	0.230	
16	Backshore	9	0.226	
23	Backshore	10	0.224	
12	Backshore	8	0.221	
5	Dune	4	0.220	
10	Backshore	7	0.145	
6	Backshore	5	0.140	
60	Offshore	20	0.032	
59	Offshore	19	0.017	0.245
94	Offshore	28	0.407	
83	Offshore	23	0.329	
96	Offshore	29	0.317	
93	Offshore	27	0.317	
87	Offshore	24	0.307	
100	Offshore	32	0.271	
89	Offshore	25	0.261	
97	Offshore	30	0.258	
80	Offshore	22	0.241	
91	Offshore	26	0.219	
99	Offshore	31	0.213	
75	Offshore	21	0.133	0.273
Avg silhouette width				0.255

3 Clusters				
Sample ID	Geomorphic zone	Sample	Silhouette width	Avg. cluster widths
8	Backshore	6	0.445	
1	Dune	1	0.422	
4	Dune	3	0.422	
12	Backshore	8	0.394	
6	Backshore	5	0.274	
2	Dune	2	0.188	
16	Backshore	9	0.153	0.328
50	Swash	17	0.278	
54	Swash	18	0.268	
37	Foreshore	13	0.266	
42	Foreshore	14	0.244	
44	Foreshore	15	0.226	
33	Foreshore	12	0.202	
28	Foreshore	11	0.145	
49	Foreshore	16	0.103	
60	Offshore	20	0.085	
5	Dune	4	0.043	
59	Offshore	19	0.038	
10	Backshore	7	0.000	
23	Backshore	10	-0.141	0.135
94	Offshore	28	0.389	
83	Offshore	23	0.323	
96	Offshore	29	0.308	
93	Offshore	27	0.305	
87	Offshore	24	0.302	
89	Offshore	25	0.253	
100	Offshore	32	0.246	
97	Offshore	30	0.242	
80	Offshore	22	0.241	
91	Offshore	26	0.202	
99	Offshore	31	0.181	
75	Offshore	21	0.115	0.259
Avg silhouette width				0.224

Table S2a (continued).

4 Clusters				
Sample ID	Geomorphic zone	Sample	Silhouette width	Avg. cluster widths
1	Dune	1	0.866	
4	Dune	3	0.866	
8	Backshore	6	0.671	0.801
2	Dune	2	0.180	
6	Backshore	5	0.176	
23	Backshore	10	0.174	
16	Backshore	9	0.127	
12	Backshore	8	-0.101	0.111
37	Foreshore	13	0.281	
50	Swash	17	0.273	
42	Foreshore	14	0.252	
54	Swash	18	0.244	
44	Foreshore	15	0.236	
33	Foreshore	12	0.214	
28	Foreshore	11	0.142	
60	Offshore	20	0.099	
49	Foreshore	16	0.075	
59	Offshore	19	0.046	
5	Dune	4	0.017	
10	Backshore	7	-0.016	0.155
94	Offshore	28	0.392	
83	Offshore	23	0.320	
96	Offshore	29	0.312	
87	Offshore	24	0.300	
93	Offshore	27	0.293	
89	Offshore	25	0.244	
100	Offshore	32	0.238	
97	Offshore	30	0.228	
80	Offshore	22	0.226	
91	Offshore	26	0.201	
99	Offshore	31	0.134	
75	Offshore	21	0.104	0.249
Avg silhouette width				0.244

5 Clusters				
Sample ID	Geomorphic zone	Sample	Silhouette width	Avg. cluster widths
1	Dune	1	0.859	
4	Dune	3	0.859	
8	Backshore	6	0.619	0.779
2	Dune	2	0.286	
16	Backshore	9	0.282	
23	Backshore	10	0.259	0.275
37	Foreshore	13	0.261	
50	Swash	17	0.216	
42	Foreshore	14	0.210	
33	Foreshore	12	0.183	
44	Foreshore	15	0.178	
54	Swash	18	0.159	
60	Offshore	20	0.099	
28	Foreshore	11	0.086	
59	Offshore	19	0.043	
49	Foreshore	16	-0.010	
10	Backshore	7	-0.016	
5	Dune	4	-0.034	0.115
6	Backshore	5	0.633	
12	Backshore	8	0.439	0.536
94	Offshore	28	0.356	
96	Offshore	29	0.312	
83	Offshore	23	0.300	
87	Offshore	24	0.300	
93	Offshore	27	0.280	
89	Offshore	25	0.227	
100	Offshore	32	0.224	
97	Offshore	30	0.221	
80	Offshore	22	0.210	
91	Offshore	26	0.132	
99	Offshore	31	0.105	
75	Offshore	21	0.070	0.228
Avg silhouette width				0.261

Table S2b PAM cluster analysis results using 2-5 clusters. Taphonomy was used.

2 Clusters				
Sample ID	Geomorphic zone	Sample	Silhouette width	Avg. cluster widths
50	Swash	17	0.362	
54	Swash	18	0.357	
49	Foreshore	16	0.352	
8	Backshore	6	0.321	
44	Foreshore	15	0.313	
37	Foreshore	13	0.310	
42	Foreshore	14	0.308	
1	Dune	1	0.301	
4	Dune	3	0.301	
28	Foreshore	11	0.295	
5	Dune	4	0.246	
33	Foreshore	12	0.242	
12	Backshore	8	0.221	
16	Backshore	9	0.217	
23	Backshore	10	0.216	
2	Dune	2	0.198	
6	Backshore	5	0.186	
10	Backshore	7	0.153	
60	Offshore	20	-0.016	0.257
94	Offshore	28	0.432	
83	Offshore	23	0.348	
87	Offshore	24	0.345	
93	Offshore	27	0.344	
96	Offshore	29	0.335	
89	Offshore	25	0.311	
100	Offshore	32	0.308	
97	Offshore	30	0.283	
80	Offshore	22	0.279	
91	Offshore	26	0.275	
99	Offshore	31	0.260	
75	Offshore	21	0.209	
59	Offshore	19	0.055	0.291
Avg silhouette width				0.271

3 Clusters				
Sample ID	Geomorphic zone	Sample	Silhouette width	Avg. cluster widths
1	Dune	1	0.951	
4	Dune	3	0.951	
6	Backshore	5	0.951	
8	Backshore	6	0.951	
28	Foreshore	11	0.909	
5	Dune	4	0.854	0.928
23	Backshore	10	0.087	
10	Backshore	7	0.078	
2	Dune	2	0.060	
42	Foreshore	14	-0.080	
54	Swash	18	-0.085	
44	Foreshore	15	-0.148	
50	Swash	17	-0.327	
12	Backshore	8	-0.337	
16	Backshore	9	-0.337	
37	Foreshore	13	-0.367	
49	Foreshore	16	-0.530	
33	Foreshore	12	-0.552	-0.212
75	Offshore	21	0.811	
91	Offshore	26	0.805	
96	Offshore	29	0.805	
89	Offshore	25	0.799	
80	Offshore	22	0.795	
93	Offshore	27	0.775	
87	Offshore	24	0.774	
97	Offshore	30	0.765	
94	Offshore	28	0.764	
59	Offshore	19	0.751	
83	Offshore	23	0.746	
99	Offshore	31	0.677	
100	Offshore	32	0.677	
60	Offshore	20	0.287	0.731
Avg silhouette width				0.414

Table S2b (continued).

4 Clusters				
Sample ID	Geomorphic zone	Sample	Silhouette width	Avg. cluster widths
8	Backshore	6	0.471	
1	Dune	1	0.461	
4	Dune	3	0.461	
12	Backshore	8	0.378	
6	Backshore	5	0.268	
16	Backshore	9	0.053	0.349
54	Swash	18	0.324	
50	Swash	17	0.302	
37	Foreshore	13	0.274	
42	Foreshore	14	0.265	
44	Foreshore	15	0.260	
33	Foreshore	12	0.207	
28	Foreshore	11	0.141	
49	Foreshore	16	0.132	
5	Dune	4	0.065	
60	Offshore	20	0.057	
2	Dune	2	-0.014	
23	Backshore	10	-0.030	0.165
10	Backshore	7	0.000	0.000
94	Offshore	28	0.411	
83	Offshore	23	0.338	
87	Offshore	24	0.334	
93	Offshore	27	0.333	
96	Offshore	29	0.316	
89	Offshore	25	0.296	
100	Offshore	32	0.291	
80	Offshore	22	0.261	
97	Offshore	30	0.261	
91	Offshore	26	0.257	
99	Offshore	31	0.246	
75	Offshore	21	0.191	
59	Offshore	19	0.009	0.273
Avg silhouette width				0.238

5 Clusters				
Sample ID	Geomorphic zone	Sample	Silhouette width	Avg. cluster widths
8	Backshore	6	0.464	
1	Dune	1	0.455	
4	Dune	3	0.455	
12	Backshore	8	0.373	
6	Backshore	5	0.264	
16	Backshore	9	0.049	0.343
2	Dune	2	0.000	0.000
54	Swash	18	0.364	
50	Swash	17	0.351	
37	Foreshore	13	0.320	
44	Foreshore	15	0.300	
42	Foreshore	14	0.270	
33	Foreshore	12	0.241	
28	Foreshore	11	0.177	
49	Foreshore	16	0.172	
5	Dune	4	0.094	
60	Offshore	20	0.073	
23	Backshore	10	-0.054	0.210
10	Backshore	7	0.000	0.000
94	Offshore	28	0.411	
83	Offshore	23	0.332	
93	Offshore	27	0.327	
87	Offshore	24	0.324	
96	Offshore	29	0.305	
89	Offshore	25	0.291	
100	Offshore	32	0.291	
97	Offshore	30	0.261	
91	Offshore	26	0.257	
80	Offshore	22	0.252	
99	Offshore	31	0.244	
75	Offshore	21	0.191	
59	Offshore	19	-0.007	0.268
Avg silhouette width				0.245

Table S2c PAM cluster analysis results using 2-5 clusters. Taxonomy and taphonomy were used.

2 Clusters				
Sample ID	Geomorphic zone	Sample	Silhouette width	Avg. cluster widths
50	Swash	17	0.362	
54	Swash	18	0.357	
49	Foreshore	16	0.352	
8	Backshore	6	0.321	
44	Foreshore	15	0.313	
37	Foreshore	13	0.310	
42	Foreshore	14	0.308	
1	Dune	1	0.301	
4	Dune	3	0.301	
28	Foreshore	11	0.295	
5	Dune	4	0.246	
33	Foreshore	12	0.242	
12	Backshore	8	0.221	
16	Backshore	9	0.217	
23	Backshore	10	0.216	
2	Dune	2	0.198	
6	Backshore	5	0.186	
10	Backshore	7	0.153	
60	Offshore	20	-0.016	0.257
94	Offshore	28	0.432	
83	Offshore	23	0.348	
87	Offshore	24	0.345	
93	Offshore	27	0.344	
96	Offshore	29	0.335	
89	Offshore	25	0.311	
100	Offshore	32	0.308	
97	Offshore	30	0.283	
80	Offshore	22	0.279	
91	Offshore	26	0.275	
99	Offshore	31	0.260	
75	Offshore	21	0.209	
59	Offshore	19	0.055	0.291
Avg silhouette width				0.271

3 Clusters				
Sample ID	Geomorphic zone	Sample	Silhouette width	Avg. cluster widths
8	Backshore	6	0.487	
1	Dune	1	0.474	
4	Dune	3	0.474	
12	Backshore	8	0.395	
6	Backshore	5	0.284	
16	Backshore	9	0.093	0.368
54	Swash	18	0.266	
50	Swash	17	0.248	
37	Foreshore	13	0.223	
42	Foreshore	14	0.211	
44	Foreshore	15	0.206	
33	Foreshore	12	0.170	
28	Foreshore	11	0.105	
49	Foreshore	16	0.089	
10	Backshore	7	0.046	
60	Offshore	20	0.028	
5	Dune	4	0.018	
2	Dune	2	-0.027	
23	Backshore	10	-0.049	0.118
94	Offshore	28	0.411	
87	Offshore	24	0.344	
83	Offshore	23	0.343	
93	Offshore	27	0.333	
96	Offshore	29	0.330	
89	Offshore	25	0.296	
100	Offshore	32	0.291	
80	Offshore	22	0.278	
97	Offshore	30	0.261	
91	Offshore	26	0.257	
99	Offshore	31	0.249	
75	Offshore	21	0.191	
59	Offshore	19	0.040	0.279
Avg silhouette width				0.230

Table S2c (continued).

4 Clusters				
Sample ID	Geomorphic zone	Sample	Silhouette width	Avg. cluster widths
8	Backshore	6	0.471	
1	Dune	1	0.461	
4	Dune	3	0.461	
12	Backshore	8	0.378	
6	Backshore	5	0.268	
16	Backshore	9	0.053	0.349
54	Swash	18	0.324	
50	Swash	17	0.302	
37	Foreshore	13	0.274	
42	Foreshore	14	0.265	
44	Foreshore	15	0.260	
33	Foreshore	12	0.207	
28	Foreshore	11	0.141	
49	Foreshore	16	0.132	
5	Dune	4	0.065	
60	Offshore	20	0.057	
2	Dune	2	-0.014	
23	Backshore	10	-0.030	0.165
10	Backshore	7	0.000	0.000
94	Offshore	28	0.411	
83	Offshore	23	0.338	
87	Offshore	24	0.334	
93	Offshore	27	0.333	
96	Offshore	29	0.316	
89	Offshore	25	0.296	
100	Offshore	32	0.291	
80	Offshore	22	0.261	
97	Offshore	30	0.261	
91	Offshore	26	0.257	
99	Offshore	31	0.246	
75	Offshore	21	0.191	
59	Offshore	19	0.009	0.273
Avg silhouette width				0.238

5 Clusters				
Sample ID	Geomorphic zone	Sample	Silhouette width	Avg. cluster widths
8	Backshore	6	0.464	
1	Dune	1	0.455	
4	Dune	3	0.455	
12	Backshore	8	0.373	
6	Backshore	5	0.264	
16	Backshore	9	0.049	0.343
2	Dune	2	0.000	0.000
54	Swash	18	0.364	
50	Swash	17	0.351	
37	Foreshore	13	0.320	
44	Foreshore	15	0.300	
42	Foreshore	14	0.270	
33	Foreshore	12	0.241	
28	Foreshore	11	0.177	
49	Foreshore	16	0.172	
5	Dune	4	0.094	
60	Offshore	20	0.073	
23	Backshore	10	-0.054	0.210
10	Backshore	7	0.000	0.000
94	Offshore	28	0.411	
83	Offshore	23	0.332	
93	Offshore	27	0.327	
87	Offshore	24	0.324	
96	Offshore	29	0.305	
89	Offshore	25	0.291	
100	Offshore	32	0.291	
97	Offshore	30	0.261	
91	Offshore	26	0.257	
80	Offshore	22	0.252	
99	Offshore	31	0.244	
75	Offshore	21	0.191	
59	Offshore	19	-0.007	0.268
Avg silhouette width				0.245

APPENDIX D – PAM cluster analysis using 3 clusters. Outliers removed (2 and 5).

Table S3a PAM cluster analysis results using 3 clusters. Taxonomy was used.

Taxonomy									
Sample ID	Geomorphic zone	Sample	Silhouette width	Avg. cluster widths	Sd cluster widths	Avg elevation	Sd elevation	Avg distance from shoreline	Sd distance from shoreline
8	Backshore	4	0.482						
1	Dune	1	0.468						
4	Dune	2	0.468						
12	Backshore	6	0.413						
6	Backshore	3	0.280						
16	Backshore	7	0.095	0.368	0.153	1.900	0.260	114.300	44.609
50	Swash	15	0.361						
54	Swash	16	0.338						
37	Foreshore	11	0.318						
42	Foreshore	12	0.312						
44	Foreshore	13	0.287						
33	Foreshore	10	0.239						
28	Foreshore	9	0.228						
49	Foreshore	14	0.187						
60	Offshore	18	0.101						
10	Backshore	5	0.036						
23	Backshore	8	-0.077	0.212	0.139	-0.900	3.392	-27.000	115.386
94	Offshore	26	0.357						
83	Offshore	21	0.300						
87	Offshore	22	0.297						
93	Offshore	25	0.281						
96	Offshore	27	0.265						
89	Offshore	23	0.238						
97	Offshore	28	0.224						
100	Offshore	30	0.224						
80	Offshore	20	0.223						
91	Offshore	24	0.179						
99	Offshore	29	0.173						
75	Offshore	19	0.119						
59	Offshore	17	-0.034	0.219	0.098	-40.500	17.858	-20439.000	10969.223
Avg. silhouette width				0.246	0.136				
% accuracy				0.867					

Table S3b PAM cluster analysis using 3 clusters. Taphonomy was used.

Taphonomy									
Sample ID	Geomorphic zone	Sample	Silhouette width	Avg. cluster widths	Sd cluster widths	Avg elevation	Sd elevation	Avg distance from shoreline	Sd distance from shoreline
1	Dune	1	0.635						
4	Dune	2	0.635						
6	Backshore	3	0.635						
8	Backshore	4	0.635						
28	Foreshore	9	0.631						
33	Foreshore	10	0.611						
49	Foreshore	14	0.579						
50	Swash	15	0.539						
37	Foreshore	11	0.509						
44	Foreshore	13	0.455						
54	Swash	16	0.433						
12	Backshore	6	0.407						
16	Backshore	7	0.407						
23	Backshore	8	0.194						
10	Backshore	5	0.167	0.498	0.155	25.000	1.260	0.883	61.744
60	Offshore	18	0.436						
99	Offshore	29	0.362						
100	Offshore	30	0.362						
42	Foreshore	12	0.299						
94	Offshore	26	-0.237						
83	Offshore	21	-0.271	0.158	0.323	-37.300	30.053	-18722.635	16904.284
80	Offshore	20	0.859						
89	Offshore	23	0.847						
87	Offshore	22	0.841						
93	Offshore	25	0.837						
97	Offshore	28	0.831						
75	Offshore	19	0.828						
96	Offshore	27	0.819						
91	Offshore	24	0.810						
59	Offshore	17	0.490	0.796	0.116	-34.300	13.305	-17081.778	10429.158
Avg. silhouette width				0.520	0.290				
% accuracy				0.733					

Table S3c PAM cluster analysis results using 3 clusters. Taxonomy and taphonomy were used.

Taxonomy & Taphonomy									
Sample ID	Geomorphic zone	Sample	Silhouette width	Avg. cluster widths	Sd cluster widths	Avg elevation	Sd elevation	Avg distance from shoreline	Sd distance from shoreline
8	Backshore	4	0.508						
1	Dune	1	0.493						
4	Dune	2	0.493						
12	Backshore	6	0.419						
6	Backshore	3	0.309						
16	Backshore	7	0.131	0.392	0.148	1.900	0.260	114.272	44.609
54	Swash	16	0.298						
50	Swash	15	0.284						
37	Foreshore	11	0.264						
44	Foreshore	13	0.246						
42	Foreshore	12	0.226						
33	Foreshore	10	0.186						
28	Foreshore	9	0.137						
49	Foreshore	14	0.097						
10	Backshore	5	0.041						
60	Offshore	18	0.040						
23	Backshore	8	-0.074	0.159	0.121	-0.800	3.740	-19.852	127.401
94	Offshore	26	0.400						
83	Offshore	21	0.341						
87	Offshore	22	0.336						
93	Offshore	25	0.323						
96	Offshore	27	0.308						
89	Offshore	23	0.291						
100	Offshore	30	0.282						
80	Offshore	20	0.272						
97	Offshore	28	0.254						
91	Offshore	24	0.253						
99	Offshore	29	0.246						
75	Offshore	19	0.189						
59	Offshore	17	0.039	0.272	0.088	-40.500	18.074	-20439.000	11643.315
Avg. silhouette width				0.254	0.140				
% accuracy				0.933					

APPENDIX E – Provenance analysis for Yamamoto

Table S4a *Provenance analysis for YM1.*

0-1cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.499	
1	Dune	1	0.485	
4	Dune	2	0.485	
12	Backshore	6	0.406	
6	Backshore	3	0.298	
16	Backshore	7	0.119	0.382
54	Swash	16	0.278	
50	Swash	15	0.255	
37	Foreshore	11	0.249	
44	Foreshore	13	0.222	
42	Foreshore	12	0.206	
33	Foreshore	10	0.174	
28	Foreshore	9	0.107	
49	Foreshore	14	0.083	
0-1cm	tsunami	31	0.083	
10	Backshore	5	0.043	
60	Offshore	18	0.037	
23	Backshore	8	-0.063	0.139
94	Offshore	26	0.403	
83	Offshore	21	0.339	
87	Offshore	22	0.335	
93	Offshore	25	0.320	
96	Offshore	27	0.317	
89	Offshore	23	0.289	
100	Offshore	30	0.280	
80	Offshore	20	0.277	
97	Offshore	28	0.259	
91	Offshore	24	0.254	
99	Offshore	29	0.248	
75	Offshore	19	0.184	
59	Offshore	17	0.048	0.273
Avg. silhouette width				0.242

1-2cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.497	
1	Dune	1	0.484	
4	Dune	2	0.484	
12	Backshore	6	0.404	
6	Backshore	3	0.296	
16	Backshore	7	0.116	0.380
54	Swash	16	0.300	
50	Swash	15	0.280	
37	Foreshore	11	0.263	
44	Foreshore	13	0.254	
42	Foreshore	12	0.214	
33	Foreshore	10	0.190	
1-2cm	tsunami	31	0.132	
28	Foreshore	9	0.130	
49	Foreshore	14	0.114	
10	Backshore	5	0.055	
60	Offshore	18	0.038	
23	Backshore	8	-0.052	0.160
94	Offshore	26	0.402	
83	Offshore	21	0.340	
87	Offshore	22	0.328	
93	Offshore	25	0.324	
96	Offshore	27	0.303	
89	Offshore	23	0.291	
100	Offshore	30	0.284	
80	Offshore	20	0.269	
97	Offshore	28	0.254	
91	Offshore	24	0.252	
99	Offshore	29	0.247	
75	Offshore	19	0.189	
59	Offshore	17	0.036	0.271
Avg. silhouette width				0.249

Table S4a (continued).

4-5cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.500	
1	Dune	1	0.486	
4	Dune	2	0.486	
12	Backshore	6	0.408	
6	Backshore	3	0.300	
16	Backshore	7	0.122	0.384
54	Swash	16	0.279	
50	Swash	15	0.258	
37	Foreshore	11	0.257	
44	Foreshore	13	0.235	
42	Foreshore	12	0.212	
33	Foreshore	10	0.194	
4-5cm	tsunami	31	0.134	
28	Foreshore	9	0.107	
49	Foreshore	14	0.080	
10	Backshore	5	0.040	
60	Offshore	18	0.038	
23	Backshore	8	-0.068	0.147
94	Offshore	26	0.404	
83	Offshore	21	0.340	
87	Offshore	22	0.335	
93	Offshore	25	0.322	
96	Offshore	27	0.317	
89	Offshore	23	0.291	
100	Offshore	30	0.285	
80	Offshore	20	0.274	
97	Offshore	28	0.258	
91	Offshore	24	0.254	
99	Offshore	29	0.249	
75	Offshore	19	0.188	
59	Offshore	17	0.035	0.273
Avg. silhouette width				0.246

5-6cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.503	
1	Dune	1	0.489	
4	Dune	2	0.489	
12	Backshore	6	0.411	
6	Backshore	3	0.303	
16	Backshore	7	0.119	0.385
54	Swash	16	0.303	
50	Swash	15	0.286	
37	Foreshore	11	0.271	
5-6cm	tsunami	31	0.260	
44	Foreshore	13	0.257	
42	Foreshore	12	0.225	
33	Foreshore	10	0.180	
28	Foreshore	9	0.138	
49	Foreshore	14	0.102	
10	Backshore	5	0.049	
60	Offshore	18	0.048	
23	Backshore	8	-0.061	0.172
94	Offshore	26	0.401	
83	Offshore	21	0.340	
87	Offshore	22	0.330	
93	Offshore	25	0.325	
96	Offshore	27	0.302	
89	Offshore	23	0.291	
100	Offshore	30	0.284	
80	Offshore	20	0.264	
97	Offshore	28	0.254	
91	Offshore	24	0.253	
99	Offshore	29	0.246	
75	Offshore	19	0.188	
59	Offshore	17	0.027	0.270
Avg. silhouette width				0.254

Table S4a (continued).

6-7cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.505	
1	Dune	1	0.490	
4	Dune	2	0.490	
12	Backshore	6	0.414	
6	Backshore	3	0.306	
16	Backshore	7	0.126	0.388
54	Swash	16	0.280	
50	Swash	15	0.261	
37	Foreshore	11	0.248	
44	Foreshore	13	0.236	
42	Foreshore	12	0.204	
33	Foreshore	10	0.187	
6-7cm	tsunami	31	0.167	
28	Foreshore	9	0.113	
49	Foreshore	14	0.085	
10	Backshore	5	0.050	
60	Offshore	18	0.036	
23	Backshore	8	-0.067	0.150
94	Offshore	26	0.402	
83	Offshore	21	0.340	
87	Offshore	22	0.330	
93	Offshore	25	0.320	
96	Offshore	27	0.309	
89	Offshore	23	0.288	
100	Offshore	30	0.281	
80	Offshore	20	0.272	
97	Offshore	28	0.253	
91	Offshore	24	0.248	
99	Offshore	29	0.244	
75	Offshore	19	0.186	
59	Offshore	17	0.038	0.270
Avg. silhouette width				0.247

8-9cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.503	
1	Dune	1	0.489	
4	Dune	2	0.489	
12	Backshore	6	0.412	
6	Backshore	3	0.304	
16	Backshore	7	0.120	0.386
54	Swash	16	0.295	
50	Swash	15	0.272	
37	Foreshore	11	0.260	
44	Foreshore	13	0.252	
42	Foreshore	12	0.211	
33	Foreshore	10	0.191	
8-9cm	tsunami	31	0.160	
28	Foreshore	9	0.122	
49	Foreshore	14	0.094	
60	Offshore	18	0.043	
10	Backshore	5	0.041	
23	Backshore	8	-0.059	0.157
94	Offshore	26	0.401	
83	Offshore	21	0.339	
87	Offshore	22	0.328	
93	Offshore	25	0.321	
96	Offshore	27	0.304	
89	Offshore	23	0.289	
100	Offshore	30	0.281	
80	Offshore	20	0.266	
97	Offshore	28	0.255	
91	Offshore	24	0.250	
99	Offshore	29	0.245	
75	Offshore	19	0.185	
59	Offshore	17	0.033	0.269
Avg. silhouette width				0.248

Table S4a (continued).

9-10cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.505	
1	Dune	1	0.490	
4	Dune	2	0.490	
12	Backshore	6	0.414	
6	Backshore	3	0.306	
16	Backshore	7	0.125	0.388
54	Swash	16	0.280	
50	Swash	15	0.260	
37	Foreshore	11	0.241	
44	Foreshore	13	0.234	
42	Foreshore	12	0.202	
33	Foreshore	10	0.180	
9-10cm	tsunami	31	0.132	
28	Foreshore	9	0.109	
49	Foreshore	14	0.083	
10	Backshore	5	0.049	
60	Offshore	18	0.038	
23	Backshore	8	-0.063	0.145
94	Offshore	26	0.402	
83	Offshore	21	0.340	
87	Offshore	22	0.329	
93	Offshore	25	0.322	
96	Offshore	27	0.309	
89	Offshore	23	0.289	
100	Offshore	30	0.283	
80	Offshore	20	0.269	
97	Offshore	28	0.254	
91	Offshore	24	0.249	
99	Offshore	29	0.245	
75	Offshore	19	0.187	
59	Offshore	17	0.035	0.270
Avg. silhouette width				0.245

14-15cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.497	
1	Dune	1	0.483	
4	Dune	2	0.483	
12	Backshore	6	0.406	
6	Backshore	3	0.299	
16	Backshore	7	0.120	0.381
54	Swash	16	0.273	
50	Swash	15	0.257	
37	Foreshore	11	0.235	
44	Foreshore	13	0.220	
42	Foreshore	12	0.198	
33	Foreshore	10	0.184	
14-15cm	tsunami	31	0.112	
28	Foreshore	9	0.094	
49	Foreshore	14	0.084	
10	Backshore	5	0.040	
60	Offshore	18	0.034	
23	Backshore	8	-0.064	0.139
94	Offshore	26	0.406	
83	Offshore	21	0.342	
87	Offshore	22	0.334	
93	Offshore	25	0.324	
96	Offshore	27	0.316	
89	Offshore	23	0.291	
100	Offshore	30	0.286	
80	Offshore	20	0.272	
97	Offshore	28	0.257	
91	Offshore	24	0.252	
99	Offshore	29	0.248	
75	Offshore	19	0.188	
59	Offshore	17	0.039	0.273
Avg. silhouette width				0.242

Table S4a (continued).

15-16cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.507	
1	Dune	1	0.491	
4	Dune	2	0.491	
12	Backshore	6	0.415	
6	Backshore	3	0.305	
16	Backshore	7	0.124	0.389
54	Swash	16	0.288	
50	Swash	15	0.268	
37	Foreshore	11	0.251	
44	Foreshore	13	0.245	
42	Foreshore	12	0.210	
33	Foreshore	10	0.183	
28	Foreshore	9	0.140	
49	Foreshore	14	0.096	
15-16cm	tsunami	31	0.088	
10	Backshore	5	0.048	
60	Offshore	18	0.034	
23	Backshore	8	-0.074	0.148
94	Offshore	26	0.401	
83	Offshore	21	0.341	
87	Offshore	22	0.331	
93	Offshore	25	0.323	
96	Offshore	27	0.307	
89	Offshore	23	0.290	
100	Offshore	30	0.282	
80	Offshore	20	0.272	
97	Offshore	28	0.253	
91	Offshore	24	0.252	
99	Offshore	29	0.247	
75	Offshore	19	0.188	
59	Offshore	17	0.040	0.271
	Avg. silhouette width			0.246

17-18cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.502	
1	Dune	1	0.487	
4	Dune	2	0.487	
12	Backshore	6	0.411	
6	Backshore	3	0.303	
16	Backshore	7	0.128	0.386
54	Swash	16	0.289	
50	Swash	15	0.267	
37	Foreshore	11	0.255	
44	Foreshore	13	0.236	
42	Foreshore	12	0.209	
33	Foreshore	10	0.183	
17-18cm	tsunami	31	0.137	
28	Foreshore	9	0.109	
49	Foreshore	14	0.092	
10	Backshore	5	0.042	
60	Offshore	18	0.041	
23	Backshore	8	-0.061	0.150
94	Offshore	26	0.402	
83	Offshore	21	0.340	
87	Offshore	22	0.334	
93	Offshore	25	0.321	
96	Offshore	27	0.309	
89	Offshore	23	0.289	
100	Offshore	30	0.281	
80	Offshore	20	0.273	
97	Offshore	28	0.256	
91	Offshore	24	0.252	
99	Offshore	29	0.247	
75	Offshore	19	0.185	
59	Offshore	17	0.044	0.272
	Avg. silhouette width			0.247

Table S4a (continued).

20-21cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.505	
1	Dune	1	0.490	
4	Dune	2	0.490	
12	Backshore	6	0.413	
6	Backshore	3	0.304	
16	Backshore	7	0.135	0.389
54	Swash	16	0.281	
50	Swash	15	0.269	
37	Foreshore	11	0.247	
44	Foreshore	13	0.238	
42	Foreshore	12	0.209	
33	Foreshore	10	0.183	
28	Foreshore	9	0.116	
20-21cm	tsunami	31	0.110	
49	Foreshore	14	0.091	
10	Backshore	5	0.050	
60	Offshore	18	0.032	
23	Backshore	8	-0.059	0.147
94	Offshore	26	0.403	
83	Offshore	21	0.342	
87	Offshore	22	0.331	
93	Offshore	25	0.321	
96	Offshore	27	0.305	
89	Offshore	23	0.289	
100	Offshore	30	0.282	
80	Offshore	20	0.276	
97	Offshore	28	0.251	
91	Offshore	24	0.248	
99	Offshore	29	0.245	
75	Offshore	19	0.190	
59	Offshore	17	0.047	0.271
Avg. silhouette width				0.246

24-25cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.434	
1	Dune	1	0.413	
4	Dune	2	0.413	
12	Backshore	6	0.386	
6	Backshore	3	0.300	
24-25cm	tsunami	31	0.147	
16	Backshore	7	0.098	0.313
54	Swash	16	0.310	
50	Swash	15	0.294	
37	Foreshore	11	0.284	
42	Foreshore	12	0.248	
44	Foreshore	13	0.242	
33	Foreshore	10	0.165	
28	Foreshore	9	0.145	
49	Foreshore	14	0.126	
10	Backshore	5	0.063	
60	Offshore	18	0.045	
23	Backshore	8	-0.033	0.172
94	Offshore	26	0.401	
83	Offshore	21	0.336	
87	Offshore	22	0.328	
93	Offshore	25	0.315	
96	Offshore	27	0.310	
89	Offshore	23	0.288	
100	Offshore	30	0.277	
80	Offshore	20	0.275	
97	Offshore	28	0.262	
91	Offshore	24	0.254	
99	Offshore	29	0.252	
75	Offshore	19	0.181	
59	Offshore	17	0.037	0.271
Avg. silhouette width				0.245

Table S4b *Provenance analysis for YM2*

0-1cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.510	
1	Dune	1	0.495	
4	Dune	2	0.495	
12	Backshore	6	0.420	
6	Backshore	3	0.312	
16	Backshore	7	0.133	0.394
54	Swash	16	0.287	
50	Swash	15	0.269	
37	Foreshore	11	0.259	
44	Foreshore	13	0.248	
42	Foreshore	12	0.212	
0-1cm	tsunami	31	0.210	
33	Foreshore	10	0.188	
28	Foreshore	9	0.122	
49	Foreshore	14	0.089	
10	Backshore	5	0.048	
60	Offshore	18	0.047	
23	Backshore	8	-0.068	0.159
94	Offshore	26	0.400	
83	Offshore	21	0.339	
87	Offshore	22	0.330	
93	Offshore	25	0.318	
96	Offshore	27	0.304	
89	Offshore	23	0.287	
100	Offshore	30	0.278	
80	Offshore	20	0.271	
97	Offshore	28	0.253	
91	Offshore	24	0.248	
99	Offshore	29	0.244	
75	Offshore	19	0.184	
59	Offshore	17	0.036	0.269
Avg. silhouette width				0.251

3-4cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.502	
1	Dune	1	0.488	
4	Dune	2	0.488	
12	Backshore	6	0.409	
6	Backshore	3	0.301	
16	Backshore	7	0.123	0.385
54	Swash	16	0.296	
50	Swash	15	0.277	
37	Foreshore	11	0.263	
44	Foreshore	13	0.255	
42	Foreshore	12	0.215	
33	Foreshore	10	0.193	
3-4cm	tsunami	31	0.157	
28	Foreshore	9	0.124	
49	Foreshore	14	0.098	
60	Offshore	18	0.045	
10	Backshore	5	0.042	
23	Backshore	8	-0.061	0.159
94	Offshore	26	0.400	
83	Offshore	21	0.338	
87	Offshore	22	0.326	
93	Offshore	25	0.322	
96	Offshore	27	0.302	
89	Offshore	23	0.289	
100	Offshore	30	0.282	
80	Offshore	20	0.265	
97	Offshore	28	0.254	
91	Offshore	24	0.250	
99	Offshore	29	0.245	
75	Offshore	19	0.186	
59	Offshore	17	0.028	0.268
Avg. silhouette width				0.248

Table S4b (continued).

6-7cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.507	
1	Dune	1	0.492	
4	Dune	2	0.492	
12	Backshore	6	0.415	
6	Backshore	3	0.307	
16	Backshore	7	0.132	0.391
54	Swash	16	0.282	
50	Swash	15	0.261	
37	Foreshore	11	0.259	
44	Foreshore	13	0.241	
42	Foreshore	12	0.208	
33	Foreshore	10	0.189	
28	Foreshore	9	0.121	
6-7cm	tsunami	31	0.102	
49	Foreshore	14	0.075	
10	Backshore	5	0.035	
60	Offshore	18	0.033	
23	Backshore	8	-0.073	0.145
94	Offshore	26	0.400	
83	Offshore	21	0.340	
87	Offshore	22	0.330	
93	Offshore	25	0.323	
96	Offshore	27	0.310	
89	Offshore	23	0.291	
100	Offshore	30	0.287	
80	Offshore	20	0.270	
97	Offshore	28	0.255	
91	Offshore	24	0.254	
99	Offshore	29	0.247	
75	Offshore	19	0.191	
59	Offshore	17	0.034	0.272
Avg. silhouette width				0.246

0-1cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.503	
1	Dune	1	0.489	
4	Dune	2	0.489	
12	Backshore	6	0.411	
6	Backshore	3	0.303	
16	Backshore	7	0.121	0.386
54	Swash	16	0.283	
50	Swash	15	0.265	
37	Foreshore	11	0.249	
44	Foreshore	13	0.236	
42	Foreshore	12	0.209	
33	Foreshore	10	0.186	
0-1cm	tsunami	31	0.158	
28	Foreshore	9	0.116	
49	Foreshore	14	0.083	
60	Offshore	18	0.052	
10	Backshore	5	0.040	
23	Backshore	8	-0.066	0.151
94	Offshore	26	0.402	
83	Offshore	21	0.339	
87	Offshore	22	0.329	
93	Offshore	25	0.320	
96	Offshore	27	0.310	
89	Offshore	23	0.288	
100	Offshore	30	0.281	
80	Offshore	20	0.266	
97	Offshore	28	0.255	
91	Offshore	24	0.249	
99	Offshore	29	0.245	
75	Offshore	19	0.184	
59	Offshore	17	0.031	0.269
Avg. silhouette width				0.246

Table S4b (continued).

3-4cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.504	
1	Dune	1	0.489	
4	Dune	2	0.489	
12	Backshore	6	0.412	
6	Backshore	3	0.304	
16	Backshore	7	0.123	0.387
54	Swash	16	0.272	
50	Swash	15	0.258	
37	Foreshore	11	0.240	
44	Foreshore	13	0.235	
42	Foreshore	12	0.203	
33	Foreshore	10	0.181	
28	Foreshore	9	0.122	
49	Foreshore	14	0.084	
10	Backshore	5	0.048	
60	Offshore	18	0.035	
3-4cm	tsunami	31	0.031	
23	Backshore	8	-0.070	0.137
94	Offshore	26	0.400	
83	Offshore	21	0.340	
87	Offshore	22	0.328	
93	Offshore	25	0.320	
96	Offshore	27	0.306	
89	Offshore	23	0.288	
100	Offshore	30	0.280	
80	Offshore	20	0.271	
97	Offshore	28	0.252	
91	Offshore	24	0.248	
99	Offshore	29	0.244	
75	Offshore	19	0.186	
59	Offshore	17	0.041	0.269
Avg. silhouette width				0.241

6-7cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.453	
1	Dune	1	0.431	
4	Dune	2	0.431	
12	Backshore	6	0.393	
6	Backshore	3	0.278	
6-7cm	tsunami	31	0.170	
16	Backshore	7	0.152	0.371
54	Swash	16	0.293	
50	Swash	15	0.279	
37	Foreshore	11	0.249	
44	Foreshore	13	0.228	
42	Foreshore	12	0.222	
33	Foreshore	10	0.184	
28	Foreshore	9	0.148	
49	Foreshore	14	0.069	
10	Backshore	5	0.055	
60	Offshore	18	0.044	
23	Backshore	8	-0.053	0.124
94	Offshore	26	0.392	
83	Offshore	21	0.333	
87	Offshore	22	0.328	
93	Offshore	25	0.314	
96	Offshore	27	0.305	
89	Offshore	23	0.280	
100	Offshore	30	0.275	
80	Offshore	20	0.263	
97	Offshore	28	0.248	
91	Offshore	24	0.239	
99	Offshore	29	0.238	
75	Offshore	19	0.176	
59	Offshore	17	0.039	0.274
Avg. silhouette width				0.235

Table S4b (continued).

9-10cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.509	
1	Dune	1	0.494	
4	Dune	2	0.494	
12	Backshore	6	0.418	
6	Backshore	3	0.309	
16	Backshore	7	0.127	0.392
54	Swash	16	0.272	
50	Swash	15	0.255	
37	Foreshore	11	0.242	
44	Foreshore	13	0.219	
42	Foreshore	12	0.207	
33	Foreshore	10	0.174	
28	Foreshore	9	0.112	
49	Foreshore	14	0.080	
9-10cm	tsunami	31	0.064	
10	Backshore	5	0.045	
60	Offshore	18	0.035	
23	Backshore	8	-0.061	0.137
94	Offshore	26	0.401	
83	Offshore	21	0.338	
87	Offshore	22	0.334	
93	Offshore	25	0.319	
96	Offshore	27	0.316	
89	Offshore	23	0.288	
100	Offshore	30	0.278	
80	Offshore	20	0.276	
97	Offshore	28	0.257	
91	Offshore	24	0.253	
99	Offshore	29	0.247	
75	Offshore	19	0.183	
59	Offshore	17	0.050	0.272
Avg. silhouette width				0.243

12-12cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.488	
1	Dune	1	0.477	
4	Dune	2	0.477	
12	Backshore	6	0.396	
6	Backshore	3	0.288	
16	Backshore	7	0.104	0.371
54	Swash	16	0.258	
50	Swash	15	0.239	
37	Foreshore	11	0.223	
44	Foreshore	13	0.221	
42	Foreshore	12	0.186	
33	Foreshore	10	0.166	
28	Foreshore	9	0.096	
12-13cm	tsunami	31	0.075	
49	Foreshore	14	0.060	
10	Backshore	5	0.028	
60	Offshore	18	0.025	
23	Backshore	8	-0.092	0.124
94	Offshore	26	0.407	
83	Offshore	21	0.343	
87	Offshore	22	0.335	
93	Offshore	25	0.325	
96	Offshore	27	0.317	
89	Offshore	23	0.293	
100	Offshore	30	0.288	
80	Offshore	20	0.270	
97	Offshore	28	0.258	
91	Offshore	24	0.254	
99	Offshore	29	0.249	
75	Offshore	19	0.191	
59	Offshore	17	0.035	0.274
Avg. silhouette width				0.235

Table S4c *Provenance analysis for YM3.*

0-1cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.499	
1	Dune	1	0.486	
4	Dune	2	0.486	
12	Backshore	6	0.408	
6	Backshore	3	0.300	
16	Backshore	7	0.113	0.382
54	Swash	16	0.297	
50	Swash	15	0.273	
37	Foreshore	11	0.266	
44	Foreshore	13	0.240	
42	Foreshore	12	0.232	
0-1cm	tsunami	31	0.229	
33	Foreshore	10	0.185	
28	Foreshore	9	0.117	
49	Foreshore	14	0.092	
10	Backshore	5	0.047	
60	Offshore	18	0.043	
23	Backshore	8	-0.060	0.163
94	Offshore	26	0.403	
83	Offshore	21	0.341	
87	Offshore	22	0.333	
93	Offshore	25	0.323	
96	Offshore	27	0.312	
89	Offshore	23	0.291	
100	Offshore	30	0.285	
80	Offshore	20	0.267	
97	Offshore	28	0.255	
91	Offshore	24	0.252	
99	Offshore	29	0.247	
75	Offshore	19	0.189	
59	Offshore	17	0.020	0.271
Avg. silhouette width				0.251

3-4cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.504	
1	Dune	1	0.489	
4	Dune	2	0.489	
12	Backshore	6	0.412	
6	Backshore	3	0.304	
16	Backshore	7	0.123	0.387
54	Swash	16	0.272	
50	Swash	15	0.258	
37	Foreshore	11	0.240	
44	Foreshore	13	0.235	
42	Foreshore	12	0.203	
33	Foreshore	10	0.181	
28	Foreshore	9	0.122	
49	Foreshore	14	0.084	
10	Backshore	5	0.048	
60	Offshore	18	0.035	
3-4cm	tsunami	31	0.031	
23	Backshore	8	-0.070	0.137
94	Offshore	26	0.400	
83	Offshore	21	0.340	
87	Offshore	22	0.328	
93	Offshore	25	0.320	
96	Offshore	27	0.306	
89	Offshore	23	0.288	
100	Offshore	30	0.280	
80	Offshore	20	0.271	
97	Offshore	28	0.252	
91	Offshore	24	0.248	
99	Offshore	29	0.244	
75	Offshore	19	0.186	
59	Offshore	17	0.041	0.269
Avg. silhouette width				0.241

Table S4c (continued).

6-7cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.453	
1	Dune	1	0.431	
4	Dune	2	0.431	
12	Backshore	6	0.393	
6	Backshore	3	0.278	
6-7cm	tsunami	31	0.170	
16	Backshore	7	0.152	0.371
54	Swash	16	0.293	
50	Swash	15	0.279	
37	Foreshore	11	0.249	
44	Foreshore	13	0.228	
42	Foreshore	12	0.222	
33	Foreshore	10	0.184	
28	Foreshore	9	0.148	
49	Foreshore	14	0.069	
10	Backshore	5	0.055	
60	Offshore	18	0.044	
23	Backshore	8	-0.053	0.124
94	Offshore	26	0.392	
83	Offshore	21	0.333	
87	Offshore	22	0.328	
93	Offshore	25	0.314	
96	Offshore	27	0.305	
89	Offshore	23	0.280	
100	Offshore	30	0.275	
80	Offshore	20	0.263	
97	Offshore	28	0.248	
91	Offshore	24	0.239	
99	Offshore	29	0.238	
75	Offshore	19	0.176	
59	Offshore	17	0.039	0.274
Avg. silhouette width				0.235

9-10cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.509	
1	Dune	1	0.494	
4	Dune	2	0.494	
12	Backshore	6	0.418	
6	Backshore	3	0.309	
16	Backshore	7	0.127	0.392
54	Swash	16	0.272	
50	Swash	15	0.255	
37	Foreshore	11	0.242	
44	Foreshore	13	0.219	
42	Foreshore	12	0.207	
33	Foreshore	10	0.174	
28	Foreshore	9	0.112	
49	Foreshore	14	0.080	
9-10cm	tsunami	31	0.064	
10	Backshore	5	0.045	
60	Offshore	18	0.035	
23	Backshore	8	-0.061	0.137
94	Offshore	26	0.401	
83	Offshore	21	0.338	
87	Offshore	22	0.334	
93	Offshore	25	0.319	
96	Offshore	27	0.316	
89	Offshore	23	0.288	
100	Offshore	30	0.278	
80	Offshore	20	0.276	
97	Offshore	28	0.257	
91	Offshore	24	0.253	
99	Offshore	29	0.247	
75	Offshore	19	0.183	
59	Offshore	17	0.050	0.272
Avg. silhouette width				0.243

Table S4c (continued).

12-12cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.488	
1	Dune	1	0.477	
4	Dune	2	0.477	
12	Backshore	6	0.396	
6	Backshore	3	0.288	
16	Backshore	7	0.104	0.371
54	Swash	16	0.258	
50	Swash	15	0.239	
37	Foreshore	11	0.223	
44	Foreshore	13	0.221	
42	Foreshore	12	0.186	
33	Foreshore	10	0.166	
28	Foreshore	9	0.096	
12-13cm	tsunami	31	0.075	
49	Foreshore	14	0.060	
10	Backshore	5	0.028	
60	Offshore	18	0.025	
23	Backshore	8	-0.092	0.124
94	Offshore	26	0.407	
83	Offshore	21	0.343	
87	Offshore	22	0.335	
93	Offshore	25	0.325	
96	Offshore	27	0.317	
89	Offshore	23	0.293	
100	Offshore	30	0.288	
80	Offshore	20	0.270	
97	Offshore	28	0.258	
91	Offshore	24	0.254	
99	Offshore	29	0.249	
75	Offshore	19	0.191	
59	Offshore	17	0.035	0.274
Avg. silhouette width				0.235

Table S4d *Provenance analysis for YM4.*

0-1cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.499	
1	Dune	1	0.486	
4	Dune	2	0.486	
12	Backshore	6	0.408	
6	Backshore	3	0.300	
16	Backshore	7	0.113	0.382
54	Swash	16	0.297	
50	Swash	15	0.273	
37	Foreshore	11	0.266	
44	Foreshore	13	0.240	
42	Foreshore	12	0.232	
0-1cm	tsunami	31	0.229	
33	Foreshore	10	0.185	
28	Foreshore	9	0.117	
49	Foreshore	14	0.092	
10	Backshore	5	0.047	
60	Offshore	18	0.043	
23	Backshore	8	-0.060	0.163
94	Offshore	26	0.403	
83	Offshore	21	0.341	
87	Offshore	22	0.333	
93	Offshore	25	0.323	
96	Offshore	27	0.312	
89	Offshore	23	0.291	
100	Offshore	30	0.285	
80	Offshore	20	0.267	
97	Offshore	28	0.255	
91	Offshore	24	0.252	
99	Offshore	29	0.247	
75	Offshore	19	0.189	
59	Offshore	17	0.020	0.271
Avg. silhouette width				0.251

1-2cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.496	
1	Dune	1	0.483	
4	Dune	2	0.483	
12	Backshore	6	0.402	
6	Backshore	3	0.294	
16	Backshore	7	0.120	0.380
54	Swash	16	0.289	
50	Swash	15	0.268	
37	Foreshore	11	0.258	
44	Foreshore	13	0.240	
42	Foreshore	12	0.213	
33	Foreshore	10	0.173	
28	Foreshore	9	0.125	
49	Foreshore	14	0.098	
10	Backshore	5	0.044	
60	Offshore	18	0.035	
1-2cm	tsunami	31	-0.037	
23	Backshore	8	-0.065	0.137
94	Offshore	26	0.401	
83	Offshore	21	0.340	
87	Offshore	22	0.330	
93	Offshore	25	0.323	
96	Offshore	27	0.305	
89	Offshore	23	0.290	
100	Offshore	30	0.283	
80	Offshore	20	0.268	
97	Offshore	28	0.253	
91	Offshore	24	0.251	
99	Offshore	29	0.246	
75	Offshore	19	0.188	
59	Offshore	17	0.035	0.270
Avg. silhouette width				0.240

Table S4d (continued).

2-3cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.499	
1	Dune	1	0.486	
4	Dune	2	0.486	
12	Backshore	6	0.405	
6	Backshore	3	0.296	
16	Backshore	7	0.112	0.381
54	Swash	16	0.281	
50	Swash	15	0.271	
37	Foreshore	11	0.246	
44	Foreshore	13	0.242	
42	Foreshore	12	0.213	
33	Foreshore	10	0.184	
28	Foreshore	9	0.141	
49	Foreshore	14	0.095	
60	Offshore	18	0.052	
10	Backshore	5	0.045	
2-3cm	tsunami	31	0.038	
23	Backshore	8	-0.070	0.145
94	Offshore	26	0.401	
83	Offshore	21	0.340	
87	Offshore	22	0.329	
93	Offshore	25	0.324	
96	Offshore	27	0.309	
89	Offshore	23	0.291	
100	Offshore	30	0.283	
80	Offshore	20	0.267	
97	Offshore	28	0.255	
91	Offshore	24	0.252	
99	Offshore	29	0.246	
75	Offshore	19	0.188	
59	Offshore	17	0.034	0.271
Avg. silhouette width				0.243

3-4cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.500	
1	Dune	1	0.486	
4	Dune	2	0.486	
12	Backshore	6	0.407	
6	Backshore	3	0.299	
16	Backshore	7	0.119	0.383
54	Swash	16	0.283	
50	Swash	15	0.262	
37	Foreshore	11	0.241	
44	Foreshore	13	0.232	
42	Foreshore	12	0.204	
33	Foreshore	10	0.183	
3-4cm	tsunami	31	0.129	
28	Foreshore	9	0.115	
49	Foreshore	14	0.079	
60	Offshore	18	0.044	
10	Backshore	5	0.041	
23	Backshore	8	-0.066	0.145
94	Offshore	26	0.403	
83	Offshore	21	0.341	
87	Offshore	22	0.331	
93	Offshore	25	0.322	
96	Offshore	27	0.314	
89	Offshore	23	0.290	
100	Offshore	30	0.284	
80	Offshore	20	0.271	
97	Offshore	28	0.256	
91	Offshore	24	0.251	
99	Offshore	29	0.246	
75	Offshore	19	0.187	
59	Offshore	17	0.034	0.272
Avg. silhouette width				0.244

Table S4d (continued).

6-7cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.513	
1	Dune	1	0.497	
4	Dune	2	0.497	
12	Backshore	6	0.421	
6	Backshore	3	0.311	
16	Backshore	7	0.132	0.395
54	Swash	16	0.274	
50	Swash	15	0.258	
37	Foreshore	11	0.240	
44	Foreshore	13	0.233	
42	Foreshore	12	0.201	
33	Foreshore	10	0.176	
28	Foreshore	9	0.122	
49	Foreshore	14	0.080	
6-7cm	tsunami	31	0.068	
60	Offshore	18	0.043	
10	Backshore	5	0.039	
23	Backshore	8	-0.068	0.139
94	Offshore	26	0.399	
83	Offshore	21	0.339	
87	Offshore	22	0.328	
93	Offshore	25	0.319	
96	Offshore	27	0.301	
89	Offshore	23	0.290	
100	Offshore	30	0.278	
80	Offshore	20	0.266	
97	Offshore	28	0.254	
91	Offshore	24	0.251	
99	Offshore	29	0.247	
75	Offshore	19	0.186	
59	Offshore	17	0.043	0.269
Avg. silhouette width				0.243

9-10cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.509	
1	Dune	1	0.494	
4	Dune	2	0.494	
12	Backshore	6	0.418	
6	Backshore	3	0.309	
16	Backshore	7	0.127	0.392
54	Swash	16	0.272	
50	Swash	15	0.255	
37	Foreshore	11	0.242	
44	Foreshore	13	0.219	
42	Foreshore	12	0.207	
33	Foreshore	10	0.174	
28	Foreshore	9	0.112	
49	Foreshore	14	0.080	
9-10cm	tsunami	31	0.064	
10	Backshore	5	0.045	
60	Offshore	18	0.035	
23	Backshore	8	-0.061	0.137
94	Offshore	26	0.401	
83	Offshore	21	0.338	
87	Offshore	22	0.334	
93	Offshore	25	0.319	
96	Offshore	27	0.316	
89	Offshore	23	0.288	
100	Offshore	30	0.278	
80	Offshore	20	0.276	
97	Offshore	28	0.257	
91	Offshore	24	0.253	
99	Offshore	29	0.247	
75	Offshore	19	0.183	
59	Offshore	17	0.050	0.272
Avg. silhouette width				0.243

Table S4d (continued).

1-2cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.519	
1	Dune	1	0.501	
4	Dune	2	0.501	
12	Backshore	6	0.428	
6	Backshore	3	0.316	
16	Backshore	7	0.148	0.402
54	Swash	16	0.265	
50	Swash	15	0.244	
37	Foreshore	11	0.226	
44	Foreshore	13	0.205	
42	Foreshore	12	0.191	
33	Foreshore	10	0.164	
28	Foreshore	9	0.107	
49	Foreshore	14	0.067	
10	Backshore	5	0.034	
60	Offshore	18	0.029	
1-2cm	tsunami	31	0.027	
23	Backshore	8	-0.077	0.123
94	Offshore	26	0.407	
83	Offshore	21	0.342	
87	Offshore	22	0.336	
93	Offshore	25	0.323	
96	Offshore	27	0.322	
89	Offshore	23	0.290	
100	Offshore	30	0.283	
80	Offshore	20	0.272	
97	Offshore	28	0.254	
91	Offshore	24	0.251	
99	Offshore	29	0.248	
75	Offshore	19	0.186	
59	Offshore	17	0.039	0.273
Avg. silhouette width				0.240

2-3cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.456	
1	Dune	1	0.435	
4	Dune	2	0.435	
12	Backshore	6	0.418	
6	Backshore	3	0.345	
2-3cm	tsunami	31	0.232	
16	Backshore	7	0.099	0.346
54	Swash	16	0.313	
50	Swash	15	0.308	
37	Foreshore	11	0.286	
44	Foreshore	13	0.263	
42	Foreshore	12	0.252	
33	Foreshore	10	0.202	
28	Foreshore	9	0.172	
49	Foreshore	14	0.135	
60	Offshore	18	0.049	
10	Backshore	5	0.010	
23	Backshore	8	-0.080	0.173
94	Offshore	26	0.402	
83	Offshore	21	0.341	
87	Offshore	22	0.331	
93	Offshore	25	0.326	
96	Offshore	27	0.304	
89	Offshore	23	0.294	
100	Offshore	30	0.287	
80	Offshore	20	0.268	
97	Offshore	28	0.257	
91	Offshore	24	0.254	
99	Offshore	29	0.249	
75	Offshore	19	0.190	
59	Offshore	17	0.031	0.272
Avg. silhouette width				0.254

APPENDIX F – Provenance analysis for Shinchi

Table S5a *Provenance analysis for SH1.*

4-5cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.505	
1	Dune	1	0.491	
4	Dune	2	0.491	
12	Backshore	6	0.415	
6	Backshore	3	0.307	
16	Backshore	7	0.123	0.389
54	Swash	16	0.283	
50	Swash	15	0.268	
37	Foreshore	11	0.248	
44	Foreshore	13	0.220	
42	Foreshore	12	0.200	
33	Foreshore	10	0.182	
4-5cm	tsunami	31	0.140	
28	Foreshore	9	0.112	
49	Foreshore	14	0.091	
10	Backshore	5	0.040	
60	Offshore	18	0.035	
23	Backshore	8	-0.067	0.146
94	Offshore	26	0.404	
83	Offshore	21	0.341	
87	Offshore	22	0.336	
93	Offshore	25	0.325	
96	Offshore	27	0.316	
100	Offshore	30	0.300	
89	Offshore	23	0.297	
80	Offshore	20	0.271	
91	Offshore	24	0.259	
97	Offshore	28	0.258	
99	Offshore	29	0.253	
75	Offshore	19	0.203	
59	Offshore	17	0.032	0.277
Avg. silhouette width				0.248

5-6cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.506	
1	Dune	1	0.492	
4	Dune	2	0.492	
12	Backshore	6	0.416	
6	Backshore	3	0.309	
16	Backshore	7	0.121	0.389
54	Swash	16	0.280	
50	Swash	15	0.263	
37	Foreshore	11	0.255	
44	Foreshore	13	0.234	
42	Foreshore	12	0.205	
33	Foreshore	10	0.198	
5-6cm	tsunami	31	0.187	
28	Foreshore	9	0.107	
49	Foreshore	14	0.089	
10	Backshore	5	0.045	
60	Offshore	18	0.032	
23	Backshore	8	-0.060	0.153
94	Offshore	26	0.403	
83	Offshore	21	0.340	
87	Offshore	22	0.333	
93	Offshore	25	0.322	
96	Offshore	27	0.313	
89	Offshore	23	0.291	
100	Offshore	30	0.288	
80	Offshore	20	0.271	
97	Offshore	28	0.256	
91	Offshore	24	0.253	
99	Offshore	29	0.248	
75	Offshore	19	0.191	
59	Offshore	17	0.029	0.272
Avg. silhouette width				0.249

Table S5a (continued).

6-7cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.513	
1	Dune	1	0.497	
4	Dune	2	0.497	
12	Backshore	6	0.421	
6	Backshore	3	0.311	
16	Backshore	7	0.132	0.395
54	Swash	16	0.274	
50	Swash	15	0.258	
37	Foreshore	11	0.240	
44	Foreshore	13	0.233	
42	Foreshore	12	0.201	
33	Foreshore	10	0.176	
28	Foreshore	9	0.122	
49	Foreshore	14	0.080	
6-7cm	tsunami	31	0.068	
60	Offshore	18	0.043	
10	Backshore	5	0.039	
23	Backshore	8	-0.068	0.139
94	Offshore	26	0.399	
83	Offshore	21	0.339	
87	Offshore	22	0.328	
93	Offshore	25	0.319	
96	Offshore	27	0.301	
89	Offshore	23	0.290	
100	Offshore	30	0.278	
80	Offshore	20	0.266	
97	Offshore	28	0.254	
91	Offshore	24	0.251	
99	Offshore	29	0.247	
75	Offshore	19	0.186	
59	Offshore	17	0.043	0.269
Avg. silhouette width				0.243

Table S5b Provenance analysis for SH2.

1-2cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.519	
1	Dune	1	0.501	
4	Dune	2	0.501	
12	Backshore	6	0.428	
6	Backshore	3	0.316	
16	Backshore	7	0.148	0.402
54	Swash	16	0.265	
50	Swash	15	0.244	
37	Foreshore	11	0.226	
44	Foreshore	13	0.205	
42	Foreshore	12	0.191	
33	Foreshore	10	0.164	
28	Foreshore	9	0.107	
49	Foreshore	14	0.067	
10	Backshore	5	0.034	
60	Offshore	18	0.029	
1-2cm	tsunami	31	0.027	
23	Backshore	8	-0.077	0.123
94	Offshore	26	0.407	
83	Offshore	21	0.342	
87	Offshore	22	0.336	
93	Offshore	25	0.323	
96	Offshore	27	0.322	
89	Offshore	23	0.290	
100	Offshore	30	0.283	
80	Offshore	20	0.272	
97	Offshore	28	0.254	
91	Offshore	24	0.251	
99	Offshore	29	0.248	
75	Offshore	19	0.186	
59	Offshore	17	0.039	0.273
Avg. silhouette width				0.240

2-3cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.456	
1	Dune	1	0.435	
4	Dune	2	0.435	
12	Backshore	6	0.418	
6	Backshore	3	0.345	
2-3cm	tsunami	31	0.232	
16	Backshore	7	0.099	0.346
54	Swash	16	0.313	
50	Swash	15	0.308	
37	Foreshore	11	0.286	
44	Foreshore	13	0.263	
42	Foreshore	12	0.252	
33	Foreshore	10	0.202	
28	Foreshore	9	0.172	
49	Foreshore	14	0.135	
60	Offshore	18	0.049	
10	Backshore	5	0.010	
23	Backshore	8	-0.080	0.173
94	Offshore	26	0.402	
83	Offshore	21	0.341	
87	Offshore	22	0.331	
93	Offshore	25	0.326	
96	Offshore	27	0.304	
89	Offshore	23	0.294	
100	Offshore	30	0.287	
80	Offshore	20	0.268	
97	Offshore	28	0.257	
91	Offshore	24	0.254	
99	Offshore	29	0.249	
75	Offshore	19	0.190	
59	Offshore	17	0.031	0.272
Avg. silhouette width				0.254

APPENDIX G – Provenance analysis for Suijin-numa

Table S6a Provenance analysis for SJ1.

1-2cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.507	
1	Dune	1	0.492	
4	Dune	2	0.492	
12	Backshore	6	0.416	
6	Backshore	3	0.307	
16	Backshore	7	0.123	0.390
54	Swash	16	0.295	
50	Swash	15	0.276	
37	Foreshore	11	0.253	
44	Foreshore	13	0.244	
42	Foreshore	12	0.214	
1-2cm	tsunami	31	0.184	
33	Foreshore	10	0.179	
28	Foreshore	9	0.127	
49	Foreshore	14	0.093	
10	Backshore	5	0.042	
60	Offshore	18	0.038	
23	Backshore	8	-0.058	0.157
94	Offshore	26	0.402	
83	Offshore	21	0.341	
87	Offshore	22	0.329	
93	Offshore	25	0.319	
96	Offshore	27	0.301	
89	Offshore	23	0.288	
100	Offshore	30	0.281	
80	Offshore	20	0.272	
97	Offshore	28	0.249	
91	Offshore	24	0.245	
99	Offshore	29	0.243	
75	Offshore	19	0.189	
59	Offshore	17	0.038	0.269
Avg. silhouette width				0.249

3-4cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.512	
1	Dune	1	0.497	
4	Dune	2	0.497	
12	Backshore	6	0.422	
6	Backshore	3	0.314	
16	Backshore	7	0.130	0.395
54	Swash	16	0.287	
50	Swash	15	0.268	
37	Foreshore	11	0.257	
44	Foreshore	13	0.247	
42	Foreshore	12	0.212	
33	Foreshore	10	0.186	
3-4cm	tsunami	31	0.126	
28	Foreshore	9	0.124	
49	Foreshore	14	0.082	
60	Offshore	18	0.046	
10	Backshore	5	0.040	
23	Backshore	8	-0.071	0.150
94	Offshore	26	0.401	
83	Offshore	21	0.341	
87	Offshore	22	0.326	
93	Offshore	25	0.321	
96	Offshore	27	0.299	
89	Offshore	23	0.288	
100	Offshore	30	0.283	
80	Offshore	20	0.267	
97	Offshore	28	0.251	
91	Offshore	24	0.249	
99	Offshore	29	0.245	
75	Offshore	19	0.189	
59	Offshore	17	0.030	0.268
Avg. silhouette width				0.247

Table S6a (continued).

5-6cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.504	
1	Dune	1	0.489	
4	Dune	2	0.489	
12	Backshore	6	0.412	
6	Backshore	3	0.304	
16	Backshore	7	0.126	0.387
54	Swash	16	0.291	
50	Swash	15	0.275	
37	Foreshore	11	0.253	
44	Foreshore	13	0.246	
42	Foreshore	12	0.215	
33	Foreshore	10	0.183	
28	Foreshore	9	0.132	
5-6cm	tsunami	31	0.117	
49	Foreshore	14	0.091	
60	Offshore	18	0.052	
10	Backshore	5	0.042	
23	Backshore	8	-0.070	0.152
94	Offshore	26	0.401	
83	Offshore	21	0.341	
87	Offshore	22	0.330	
93	Offshore	25	0.325	
96	Offshore	27	0.308	
89	Offshore	23	0.290	
100	Offshore	30	0.283	
80	Offshore	20	0.271	
97	Offshore	28	0.255	
91	Offshore	24	0.254	
99	Offshore	29	0.248	
75	Offshore	19	0.189	
59	Offshore	17	0.034	0.271
Avg. silhouette width				0.248

7-8cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.496	
1	Dune	1	0.482	
4	Dune	2	0.482	
12	Backshore	6	0.400	
6	Backshore	3	0.290	
16	Backshore	7	0.123	0.379
54	Swash	16	0.282	
50	Swash	15	0.262	
37	Foreshore	11	0.249	
44	Foreshore	13	0.229	
42	Foreshore	12	0.207	
33	Foreshore	10	0.173	
28	Foreshore	9	0.115	
49	Foreshore	14	0.089	
10	Backshore	5	0.046	
60	Offshore	18	0.031	
7-8cm	tsunami	31	0.024	
23	Backshore	8	-0.066	0.137
94	Offshore	26	0.403	
83	Offshore	21	0.342	
87	Offshore	22	0.333	
93	Offshore	25	0.324	
96	Offshore	27	0.311	
89	Offshore	23	0.291	
100	Offshore	30	0.285	
80	Offshore	20	0.271	
97	Offshore	28	0.255	
91	Offshore	24	0.253	
99	Offshore	29	0.247	
75	Offshore	19	0.189	
59	Offshore	17	0.038	0.272
Avg. silhouette width				0.241

Table S6a (continued).

9-10cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.504	
1	Dune	1	0.489	
4	Dune	2	0.489	
12	Backshore	6	0.410	
6	Backshore	3	0.302	
16	Backshore	7	0.134	0.388
54	Swash	16	0.291	
50	Swash	15	0.273	
37	Foreshore	11	0.254	
44	Foreshore	13	0.244	
42	Foreshore	12	0.213	
33	Foreshore	10	0.180	
28	Foreshore	9	0.127	
9-10cm	tsunami	31	0.102	
49	Foreshore	14	0.088	
60	Offshore	18	0.047	
10	Backshore	5	0.043	
23	Backshore	8	-0.070	0.149
94	Offshore	26	0.400	
83	Offshore	21	0.340	
87	Offshore	22	0.327	
93	Offshore	25	0.322	
96	Offshore	27	0.305	
89	Offshore	23	0.290	
100	Offshore	30	0.283	
80	Offshore	20	0.269	
97	Offshore	28	0.253	
91	Offshore	24	0.251	
99	Offshore	29	0.245	
75	Offshore	19	0.188	
59	Offshore	17	0.034	0.270
Avg. silhouette width				0.246

11-12cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.513	
1	Dune	1	0.498	
4	Dune	2	0.498	
12	Backshore	6	0.424	
6	Backshore	3	0.315	
16	Backshore	7	0.134	0.397
54	Swash	16	0.252	
50	Swash	15	0.234	
37	Foreshore	11	0.212	
42	Foreshore	12	0.197	
44	Foreshore	13	0.191	
33	Foreshore	10	0.158	
28	Foreshore	9	0.078	
11-12cm	tsunami	31	0.069	
49	Foreshore	14	0.051	
60	Offshore	18	0.036	
10	Backshore	5	0.030	
23	Backshore	8	-0.075	0.120
94	Offshore	26	0.410	
93	Offshore	25	0.349	
83	Offshore	21	0.344	
87	Offshore	22	0.335	
96	Offshore	27	0.311	
100	Offshore	30	0.291	
89	Offshore	23	0.288	
80	Offshore	20	0.270	
91	Offshore	24	0.264	
97	Offshore	28	0.254	
99	Offshore	29	0.245	
75	Offshore	19	0.165	
59	Offshore	17	0.068	0.276
Avg. silhouette width				0.239

Table S6a (continued).

12-13cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.503	
1	Dune	1	0.489	
4	Dune	2	0.489	
12	Backshore	6	0.410	
6	Backshore	3	0.302	
16	Backshore	7	0.117	0.385
54	Swash	16	0.300	
50	Swash	15	0.281	
37	Foreshore	11	0.259	
44	Foreshore	13	0.255	
42	Foreshore	12	0.217	
33	Foreshore	10	0.187	
12-13cm	tsunami	31	0.143	
28	Foreshore	9	0.130	
49	Foreshore	14	0.098	
60	Offshore	18	0.053	
10	Backshore	5	0.036	
23	Backshore	8	-0.057	0.158
94	Offshore	26	0.400	
83	Offshore	21	0.339	
87	Offshore	22	0.329	
93	Offshore	25	0.321	
96	Offshore	27	0.303	
89	Offshore	23	0.289	
100	Offshore	30	0.281	
80	Offshore	20	0.268	
97	Offshore	28	0.254	
91	Offshore	24	0.252	
99	Offshore	29	0.246	
75	Offshore	19	0.186	
59	Offshore	17	0.033	0.269
Avg. silhouette width				0.249

Table S6b Provenance analysis for SJ2.

1-2cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.507	
1	Dune	1	0.492	
4	Dune	2	0.492	
12	Backshore	6	0.416	
6	Backshore	3	0.307	
16	Backshore	7	0.124	0.390
54	Swash	16	0.286	
50	Swash	15	0.272	
44	Foreshore	13	0.248	
37	Foreshore	11	0.247	
42	Foreshore	12	0.219	
33	Foreshore	10	0.187	
1-2cm	tsunami	31	0.164	
28	Foreshore	9	0.125	
49	Foreshore	14	0.094	
60	Offshore	18	0.057	
10	Backshore	5	0.048	
23	Backshore	8	-0.058	0.157
94	Offshore	26	0.400	
83	Offshore	21	0.340	
87	Offshore	22	0.332	
93	Offshore	25	0.323	
96	Offshore	27	0.305	
89	Offshore	23	0.290	
100	Offshore	30	0.281	
80	Offshore	20	0.272	
97	Offshore	28	0.255	
91	Offshore	24	0.253	
99	Offshore	29	0.247	
75	Offshore	19	0.187	
59	Offshore	17	0.033	0.271
Avg. silhouette width				0.250

2-3cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.503	
1	Dune	1	0.489	
4	Dune	2	0.489	
12	Backshore	6	0.411	
6	Backshore	3	0.302	
16	Backshore	7	0.121	0.386
54	Swash	16	0.285	
50	Swash	15	0.270	
37	Foreshore	11	0.259	
44	Foreshore	13	0.251	
42	Foreshore	12	0.214	
33	Foreshore	10	0.194	
28	Foreshore	9	0.124	
2-3cm	tsunami	31	0.118	
49	Foreshore	14	0.097	
10	Backshore	5	0.046	
60	Offshore	18	0.045	
23	Backshore	8	-0.061	0.153
94	Offshore	26	0.400	
83	Offshore	21	0.339	
87	Offshore	22	0.329	
93	Offshore	25	0.320	
96	Offshore	27	0.302	
89	Offshore	23	0.289	
100	Offshore	30	0.279	
80	Offshore	20	0.268	
97	Offshore	28	0.255	
91	Offshore	24	0.252	
99	Offshore	29	0.246	
75	Offshore	19	0.185	
59	Offshore	17	0.035	0.269
Avg. silhouette width				0.247

Table S6b (continued).

3-4cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.505	
1	Dune	1	0.491	
4	Dune	2	0.491	
12	Backshore	6	0.414	
6	Backshore	3	0.306	
16	Backshore	7	0.123	0.388
54	Swash	16	0.291	
50	Swash	15	0.275	
37	Foreshore	11	0.260	
44	Foreshore	13	0.254	
42	Foreshore	12	0.217	
33	Foreshore	10	0.182	
3-4cm	tsunami	31	0.150	
28	Foreshore	9	0.138	
49	Foreshore	14	0.098	
10	Backshore	5	0.053	
60	Offshore	18	0.044	
23	Backshore	8	-0.067	0.158
94	Offshore	26	0.400	
83	Offshore	21	0.339	
87	Offshore	22	0.325	
93	Offshore	25	0.321	
96	Offshore	27	0.298	
89	Offshore	23	0.289	
100	Offshore	30	0.281	
80	Offshore	20	0.265	
97	Offshore	28	0.251	
91	Offshore	24	0.249	
99	Offshore	29	0.244	
75	Offshore	19	0.188	
59	Offshore	17	0.027	0.267
Avg. silhouette width				0.248

5-6cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.509	
1	Dune	1	0.494	
4	Dune	2	0.494	
12	Backshore	6	0.418	
6	Backshore	3	0.308	
16	Backshore	7	0.126	0.391
54	Swash	16	0.276	
50	Swash	15	0.257	
37	Foreshore	11	0.242	
44	Foreshore	13	0.226	
42	Foreshore	12	0.218	
33	Foreshore	10	0.164	
28	Foreshore	9	0.114	
5-6cm	tsunami	31	0.102	
49	Foreshore	14	0.078	
60	Offshore	18	0.065	
10	Backshore	5	0.035	
23	Backshore	8	-0.067	0.142
94	Offshore	26	0.401	
83	Offshore	21	0.338	
87	Offshore	22	0.335	
93	Offshore	25	0.320	
96	Offshore	27	0.311	
89	Offshore	23	0.290	
100	Offshore	30	0.278	
80	Offshore	20	0.272	
97	Offshore	28	0.257	
91	Offshore	24	0.254	
99	Offshore	29	0.248	
75	Offshore	19	0.185	
59	Offshore	17	0.043	0.272
Avg. silhouette width				0.245

Table S6b (continued).

7-8cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.506	
1	Dune	1	0.492	
4	Dune	2	0.492	
12	Backshore	6	0.415	
6	Backshore	3	0.307	
16	Backshore	7	0.123	0.389
54	Swash	16	0.292	
50	Swash	15	0.282	
37	Foreshore	11	0.260	
44	Foreshore	13	0.258	
42	Foreshore	12	0.218	
33	Foreshore	10	0.196	
7-8cm	tsunami	31	0.196	
28	Foreshore	9	0.138	
49	Foreshore	14	0.103	
60	Offshore	18	0.055	
10	Backshore	5	0.052	
23	Backshore	8	-0.060	0.166
94	Offshore	26	0.399	
83	Offshore	21	0.338	
87	Offshore	22	0.326	
93	Offshore	25	0.321	
96	Offshore	27	0.299	
89	Offshore	23	0.289	
100	Offshore	30	0.281	
80	Offshore	20	0.264	
97	Offshore	28	0.253	
91	Offshore	24	0.251	
99	Offshore	29	0.245	
75	Offshore	19	0.186	
59	Offshore	17	0.030	0.268
Avg. silhouette width				0.252

9-10cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.505	
1	Dune	1	0.491	
4	Dune	2	0.491	
12	Backshore	6	0.414	
6	Backshore	3	0.306	
16	Backshore	7	0.123	0.388
54	Swash	16	0.294	
50	Swash	15	0.277	
37	Foreshore	11	0.254	
44	Foreshore	13	0.247	
42	Foreshore	12	0.216	
33	Foreshore	10	0.183	
9-10cm	tsunami	31	0.182	
28	Foreshore	9	0.125	
49	Foreshore	14	0.093	
60	Offshore	18	0.044	
10	Backshore	5	0.041	
23	Backshore	8	-0.060	0.158
94	Offshore	26	0.403	
83	Offshore	21	0.342	
87	Offshore	22	0.331	
93	Offshore	25	0.321	
96	Offshore	27	0.304	
89	Offshore	23	0.288	
100	Offshore	30	0.282	
80	Offshore	20	0.275	
97	Offshore	28	0.251	
91	Offshore	24	0.248	
99	Offshore	29	0.245	
75	Offshore	19	0.190	
59	Offshore	17	0.037	0.270
Avg. silhouette width				0.250

Table S6b (continued).

11-12cm				
Sample ID	Geomorphic zone	Sample	Silhouette width	Average cluster widths
8	Backshore	4	0.513	
1	Dune	1	0.498	
4	Dune	2	0.498	
12	Backshore	6	0.416	
6	Backshore	3	0.303	
16	Backshore	7	0.137	0.394
54	Swash	16	0.268	
50	Swash	15	0.254	
37	Foreshore	11	0.231	
44	Foreshore	13	0.215	
42	Foreshore	12	0.202	
33	Foreshore	10	0.158	
28	Foreshore	9	0.131	
49	Foreshore	14	0.070	
60	Offshore	18	0.048	
10	Backshore	5	0.033	
23	Backshore	8	-0.073	
11-12cm	tsunami	31	-0.117	0.118
94	Offshore	26	0.401	
83	Offshore	21	0.340	
87	Offshore	22	0.334	
93	Offshore	25	0.323	
96	Offshore	27	0.310	
89	Offshore	23	0.289	
100	Offshore	30	0.280	
80	Offshore	20	0.267	
97	Offshore	28	0.253	
91	Offshore	24	0.252	
99	Offshore	29	0.248	
75	Offshore	19	0.187	
59	Offshore	17	0.029	0.270
Avg. silhouette width				0.235

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