

Three thousand year paleo-tsunami history of the southern part of the Japan Trench

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Abstract

This study conducted a field survey and multiproxy analyses on sediment cores retrieved from the Kobatake-ike pond in Choshi City, Chiba prefecture, Japan. Kobatake-ike pond is located at a high elevation (i.e., 11 m above present-day sea level) and faces the southern part of the Japan Trench. Three sedimentological events were detected within the continuous mud and peat sequences of three thousand years. Based on the multi-proxy analyses, including mineralogical composition, diatom assemblages, and geochemical markers, these sedimentological events were associated with past tsunamis. The most recent event was a sandy layer from the AD 1677 Enpo tsunami, reported by an earlier study conducted in the pond. The estimated recurrence interval for tsunamis was approximately 700 years, comparable to that of the central part of the Japan Trench. The timing of at least two of three sedimentological events seems to have been close (i.e., intervals of few tens of years) before or after the occurrence of large earthquakes and tsunamis along the central part of the Japan Trench. This implies a possible spatiotemporal relation of earthquake generations between the central and southern parts of the Japan Trench, which can be associated with drastic changes in stress fields in the neighborhood of the rupture area. The risk of future large earthquakes and tsunamis along the southern part of the Japan Trench seems exceptionally high, considering the stress change caused by Tohoku-oki earthquake with 9.0 Mw in 2011. This study necessitates the need to investigate the spatiotemporal relationship of large earthquakes from the perspectives of geology, seismology, and history.

Introduction

The Tohoku-oki earthquake and tsunami on March 11, 2011 caused severe damage to the Pacific coast from Tohoku to the Kanto region (Toda 2012). Seismological studies by Simons et al. (2011) and Toda et al. (2011) reported that the strain balance has changed in the southern part of the Japan Trench due to the earthquake. The studies also indicated the possibility of an increase in the risk of future occurrence of large earthquakes in this region. Therefore, historical records and tsunami deposits need to be investigated to understand the recurrence interval and magnitudes of large earthquakes in this region and risk assessment.

Tsunami deposits are useful for identifying tsunami events with more extended time scales, i.e., more than hundreds of years. Therefore, they are effective for detecting huge tsunami events with prolonged recurrence intervals (Goto et al. 2020; Sawai 2012, 2020; Sugawara et al. 2012). Due to the Tohoku earthquake and tsunami in 2011, considerable effort (by scientific communities) has been dedicated to elucidating paleo-tsunami events using tsunami deposits. Moreover, the findings from the analyses of the deposits have been critical for the long-term risk assessment of huge tsunami events. Since the occurrence of Tohoku-oki event in 2011, many studies have been conducted along the coasts facing the central to northern parts of the Japan Trench to reevaluate paleo-tsunami histories (e.g., Goto et al. 2015, 2019; Inoue et al. 2017; Ishimura and Miyauchi 2015; Ishizawa et al. 2018, 2019; Kusumoto et al. 2018; Minoura et al. 2013; Sawai et al. 2012; Sawai et al. 2015; Takada et al. 2016; Takeda et al. 2018; Tanigawa et al. 2014a, 2014b; Watanabe et al. 2014; see also Sawai 2017, 2020). For instance, Tanigawa

et al. (2014b) reported two event layers of the past 6000 years in a meadow of Misawa city, Shimokita Peninsula, Aomori prefecture (Fig. 1). The recurrence interval of the massive tsunamis in the Sanriku region was estimated to be 290–390 years (Ishimura and Miyauchi 2015), 500–750 years (Takada et al. 2016), or 400–600 years (Inoue et al. 2017). Around the Sendai and Ishinomaki plains, near the central part of the Japan Trench, the paleo-tsunami history for the past 3000 years was obtained, including historically well-known tsunamis, i.e., the 869 Jogan, the 1611 Keicho, and the 1454 Kyotoku tsunamis (Sawai et al. 2012). Others (Matsumoto et al. 2013) have reported a prehistoric tsunami occurrence approximately 2,000 years ago in the Sendai and Ishinomaki plains.

In contrast, known historical and prehistoric tsunami deposits in the coasts facing the southern part of the Japan Trench (i.e., Ibaraki to Chiba prefectures) are limited because of the modern urbanization in the coastal regions. Sawai et al. (2012) report three-event layers from approximately 1,000 years ago at northern Ibaraki in Juo Town (Fig. 1a, Sawai et al. 2012). Yanagisawa et al. (2016) identified the deposits formed by the 1677 Enpo Boso-oki earthquake-tsunami (Mw 8.34–8.63) from historical and geological studies at the Kobatake-ike pond in Choshi city (Fig. 1a). To date, there is no unified explanation of paleo-tsunami history in the southern part of the Japan Trench.

Historical records show that large tsunamigenic earthquakes occurred previously in the southern part of the Japan Trench. One such event is the Enpo Boso-oki earthquake and tsunami in 1677, which affected an area extending over 600 km in Choshi city, with a maximum run-up height of approximately 13 m (Hatori 2003; Takeuchi et al. 2007; Tsuji et al. 2012). Although no predecessor of this event is known, a local tradition at the Tokai Shrine in the city (Fig. 1b) indicates that the shrine was affected by a tsunami occurring around AD 976, after which the shrine was relocated from Hiyoriyama in Tokawamachi (Fig. 1) to the Takagami area (Choshi Geopark Promotion Council 2016). The tsunami-related relocation time is based on oral tradition rather than written records; therefore, its reliability is likely lower than other historical tsunamis (e.g., 1677 Enpo Boso-oki tsunami).

The Kobatake-ike pond is a good site for paleo-tsunami research in this region, considering the discovery of the deposits from the 1677 Enpo Boso-oki tsunami. Coastal lakes and marshes are regarded as suitable locations for paleo-tsunami research because the sediments are not disturbed by human activities, even in urbanized areas (Sawai 2012). The Kobatake-ike pond is one such coastal lake located at high elevation (Fig. 1b), thus offering prospects for estimating massive tsunamis' histories and magnitudes. Furthermore, the local traditional knowledge regarding the possible AD 976 event also exists. In this study, a geological survey and sedimentological and geochemical analyses of sediments retrieved from the Kobatake-ike pond were conducted to elucidate the paleo-tsunami history in the southern part of the Japan Trench.

Study area

Choshi Peninsula, which includes the Kobatake-ike pond, is located at the Kanto Plain's eastern edge (Fig. 1a). The late Pleistocene marine terraces consisting of upper and lower Shimousa surfaces are

distributed in the southern part of the peninsula and surround Mt. Atago, where a Mesozoic formation is exposed (Kashima 1985). The Kobatake-ike pond is located at the valley plain, called the Takagami lowland, which developed along these terraces (Fig. 1b). The Takagami lowland is approximately 500 m wide and 3 km long, with a sharply bent shape (Kashima 1985). The eastern margin of the lowland is closed by beach ridges. Ota et al. (1985) report that the Takagami lowland had emerged above sea level by approximately 5,000 yr BP and marine terraces were formed. Subsequently, the Takagami lowland continued to rise to its present elevation. The average uplift rate is estimated to be approximately 0.4 m/kyr (Ota et al. 1985). Based on the diatom analysis results, Kashima et al. (1990) showed that the marine transgression started at 10,000 yr BP. They also reported that the sea level in the Takagami lowland likely reached almost present-day levels at about 7,000 yr BP and temporary desalination may have occurred at 7,000–6,000 yr BP. At approximately 3,000 yr BP, the desalination across the Takagami lowland, was complete. Since then, no evidence of transgression has been confirmed (Kashima 1985).

The Kobatake-ike pond in Choshi city is located 500 m inland from the shoreline at a high elevation (T.P. 11 m, Fig. 1b). Furthermore, 13–20 m high beach ridges comprise the eastern side of the coast. No historical or instrumental records indicate that the pond was inundated by storm surges and waves over the last 400 years, except for the 1677 event. Hence, neither storm waves nor small- and medium-scale tsunamis might have inundated the pond (Yanagisawa et al. 2016). Therefore, evidence of seawater invasion in the pond directly indicates the occurrence of a past large tsunami similar to the AD 1677 event.

The pond water is supplied by a spring of Mt. Atago-yama, located southwest of the pond. This pond is a freshwater environment used as an agricultural reservoir with an area of 0.03 m² and average water depth of 0.5 m. Yanagisawa et al. (2016) identified two sand layers from cores collected from a pond. The upper sand layer was identified as the AD 1677 Enpo tsunami deposit, while the lower sand layer's origin and age are uncertain. Moreover, the authors demonstrated that the magnitude of the AD 1677 earthquake was Mw 8.34–8.63 through numerical simulations. This event is similar to the AD 1896 Sanriku earthquake (Mw 8.3–8.6) that occurred along the northern Japan Trench (Fig. 1a).

Samples And Methods

Field survey

In August 2016, 11 cores were drilled from the pond floor (Fig. 1). To retrieve the cores, a 100-cm-long Russian peat sampler (Jowsey 1966) was used. After measuring the water depth, we obtained the first core at a depth of 100 cm from the pond surface. Cores were obtained side-by-side with at least 20 cm overlap to guarantee lithostratigraphic correlation. Then, we obtained samples reaching up to 400 cm depth at each point to produce a composite lithostratigraphic section. We used the core P-14, which was the longest core among all cores obtained from the Kobatake-ike pond and taken by Yanagisawa et al. (2016), for radiocarbon dating, diatom analysis, and geochemical measurements.

Laboratory analyses

The upper and lower boundaries of the tsunami deposits are sometimes unclear to visual observations (e.g., Bondevik et al. 1997). To ascertain appropriate boundaries, we adopted X-ray computed tomography (CT) scanning, the brightness of which reflects the density or changes in the chemical composition of the sample (Boespflug et al. 1995). The application of CT scanning to tsunami deposits helps to understand characteristics such as grain size distribution and sedimentary structures in a non-destructive way (e.g., Cuven et al. 2013; Falvard et al. 2018; Falvard and Paris 2017). We used CT scanning for all core samples that we obtained and the P-14 core. Then, we defined the sand layer thickness. Analyses were performed using a CT scanner (LightSpeed Ultra 16; GE Healthcare Japan Company, and Aquilion NEW PRIME; Toshiba Medical Systems Corp.) from the Center for Advanced Marine Core Research at Kochi University.

To identify the sand source, we examined the mineralogical composition of the sands in the event deposits. Samples from the event deposits in the Kobatake-ike pond and the beach sand at Kimiga-hama (Fig. 1b), obtained by Yanagisawa et al. (2016), were used for examination. Before this analysis, 10% hydrogen peroxide was added to remove organic material, and the mud component was removed using a 63- μm sieve. Then, the samples were dried and observed using a stereo microscope.

Diatom assemblages were investigated to estimate the origins of the event deposits. The presumed 1677 Enpo tsunami deposit had already been studied by Yanagisawa et al. (2016), who reported the presence of marine diatoms. Therefore, we focused on the analysis of older event deposits. Samples were basically collected at equal intervals above and below the event deposits. However, since the boundary of the lower sand layer was not clear enough, one more sample was retrieved from the bottom of the lower sand layer. Then, diatom analysis was commissioned to Paleo Labo Co.,Ltd., Japan. Each sample was observed under a microscope at a magnification of 600 to 1,000. More than 200 diatom fossils were identified and counted. Diatom shells were categorized into four taxa, i.e., marine, marine-brackish, brackish, and freshwater based on descriptions reported by Kosugi (1988) and Ando (1990).

Among all cores obtained from the Kobatake-ike pond, the P-14 core was the longest, and there were preliminary radiocarbon data. Therefore, we used it for additional high-resolution radiocarbon (^{14}C) dating to construct an age–depth model. Due to a lack of organic matter, we retrieved seven samples of seeds and plant fragments from the mud layer in the P-14 core. Further, in the peat layer, bulk samples were collected at 12 horizons of the P-14 core and 1 horizon of the KBT4 core based on the methods described by Ishizawa et al. (2017). The samples from the KBT4 core were used for correlation of the cores. Then, ^{14}C dating was conducted using accelerator mass spectrometry (AMS, Beta Analytic Inc. in Miami, USA) measurements. The ^{14}C ages were calibrated to the calendar ages using the OxCal 4.3.2 program (Bronk Ramsey 2009a) and the IntCal13 dataset (Reimer et al. 2013). For the P-14 core, we constrained dating results based on stratigraphic order using a sequence model (Bronk Ramsey 2008) and a general outlier model in the OxCal program (Bronk Ramsey 2009b). Then, we constructed an age–

depth model. Furthermore, $\delta^{13}\text{C}$ values of organic materials (Table 2) were measured by the elemental analyzer/isotope ratio mass spectrometer (EA/IRMS).

Geochemical signatures are useful as evidence of inland seawater invasion for paleo-tsunami research (Chagué-Goff et al. 2017). High-resolution (1 mm interval) non-destructive X-ray fluorescence (XRF) analysis was conducted using an ITRAX core scanner (e.g., Croudace et al. 2006) (ITRAX; COX Analytical Systems) at the Center for Advanced Marine Core Research at Kochi University to examine the chemical characteristics of event deposits. The Mo tube was used to measure the scattering ratio (Mo inc/Coh), i.e., a proxy for organic matter (Guyard et al. 2007). The voltage and current were set to 30 kV and 55 mA, respectively, and the exposure time was 10 s. The ITRAX elemental data are semi-quantitative and affected by core properties such as minerals, grain size, and moisture (Croudace et al. 2006). Therefore, we normalized the measurement values by over total counts (kcps) following the procedures described by Bouchard et al. (2011) and Judd et al. (2017).

Results

Sedimentary facies and stratigraphy

The lower half of the core was predominantly composed of black humic peat, which contained several plant fragments (Fig. 2a). Then, a 100–200-cm-thick black mud layer covered the peat layer up to the pond floor. Hereafter, we call the boundary at the mud and peat layers the “mud–peat boundary” because it is expected to indicate significant environmental change at the pond. At the other coring sites, one to three anomalous sand layers consisting of fine to medium sand and locally showing normal grading and inverse grading were interbedded within the humic peat and mud layers (Table 1). Contacts between the sand and the mud or peat were visually unclear. The CT images showed either sharp or blur boundary (Table 1). It was not possible to identify whether or not the contacts were erosive, because the matrix of the sand layer was mud and no rip-up-clast was confirmed in CT images. The thickness of all sand layers was measured carefully by visual observation and CT images (see Appendix). The sand layer thickness varied among the cores (3–22 cm, Table 1, Fig. 2b, c). Furthermore, KBT3, KBT7, and KBT9 had no sand layer (see Table 1, Fig. 2b, c). The KBT4 core exhibited slightly different lithology because there seemed to be three sand layers (Fig. 2a). Therefore, the analyses of grain size, sand content, and ITRAX was performed separately for this core. The CT image further showed that the whitish layer with a high CT-number is observed at the mud-peat boundary (see Appendix). This result suggests that a sandy deposit exists at the mud-peat boundary, although they are invisible as a layer.

Microscopic observation showed that sand particles were present in the mud-peat boundary (Fig. 3b). Furthermore, Fig. 3 suggests that the upper and lower sand layers' mineral compositions and the sands from the mud-peat boundary are similar to the compositions of the beach sand (Fig. 3). The sand layers and mud–peat boundary consisted of predominantly quartz, feldspar, and magnetite, although the particles seem to have experienced severe abrasions (Fig. 3a, b, c).

Diatom analysis

First, we measured the diatom assemblage at the mud-peat boundary in the P-14 core because it may indicate a critical local environmental change. Generally, freshwater species were predominant at a core depth of 155 cm, whereas few (<5%) marine species and approximately 18% of marine-brackish species were also observed (Fig. 4). The proportion of marine-brackish and brackish species was drastically higher immediately above the mud-peat boundary, while the marine species proportion decreased (Fig. 4). The total percentage of marine and brackish species exceeded 30% (Fig. 4). At the mud-peat boundary (i.e., 165 cm), the percentages of marine, marine-brackish, and brackish species were approximately 0.5%, 1%, and 4%, respectively. Below the mud-peat boundary, the percentage of marine, marine-brackish, and brackish species decreased.

At 272–292 cm, the freshwater species were generally dominant, shown by the vertical changes in diatom assemblages (Fig. 4). At a core depth of 272 cm, marine, marine-brackish and brackish species percentages were approximately 1%, 0.5%, and 6%, respectively. At the lower sand layer in P-14 (i.e., 284 cm, Table 1), the percentages of marine, marine-brackish, and brackish species were approximately 0.5%, 0.5%, and 3%, respectively. The percentages of marine and brackish species were approximately 0.5% and 2%, respectively, below the lower sand layer (Fig. 4).

Radiocarbon dating

The results of radiocarbon dating revealed that the P-14 core presents the geological record from BC 1129 (Table 2, Fig. 5). The age of plant fragments retrieved from the mud layer, i.e., between the upper sand layer and mud-peat boundary at 86 and 165 cm below the surface, ranged approximately AD 750–1000 (1060–1200 yr BP). Old ages (1520 and 1750 yr BP) were obtained from seeds and organic sediments in the mud layer. The depositional ages of the sand layer at depths of 80–86 cm, the mud-peat boundary, and the sandy layer at depths of 278–287 cm could be constrained to AD 947–1909, AD 896–966, and AD 234–330, respectively (2σ , Table 2).

Geochemical signatures

The elemental profiles of the P-14 core obtained with the ITRAX core scanner are shown in Figure 6. The Mo inc/Coh ratio of the mud layer was lower than that of the underlying peat, suggesting that sediments in the mud layer had a low organic matter.

Although each elemental profile exhibited subtle variations with the mud and peat layer, the Si, K, Fe, and Ti profiles showed a trend of lower concentration in peaty sediment than in muddy sediment. Ca and Sr's elemental profiles exhibited a distinct and sharp increase in counts/kcps around the mud-peat boundary at 165 cm below the surface. Unlike the mud and peat layers, the lower Mo inc/Coh ratios of the sand layers at depths of 80–86 cm and 278–287 cm indicate a lack of organic matter. In contrast, the Si and K profiles showed a distinct increase in counts/kcps, and slight Ca and Sr peaks in counts/kcps

occurred in the sand layers. Although Fe and Ti concentrations showed no remarkable change in the upper sand layer, a distinct increase was apparent in the lower sand layer. However, the Mn profile had few apparent changes in both sand layers than the mud and peat deposits. The S profile showed no characteristic peak in counts/kcps at the upper and lower sand layers. However, it exhibited a sharp increase in counts/kcps at 275 cm below the surface, i.e., immediately above the lower sand layer.

Discussion

Major environmental change in the Kobatake-ike pond

The lithostratigraphy, CT images and radiocarbon (^{14}C) results showed that general lithology is consistent among the cores in the Kobatake-ike pond during the last 3,000 years. The cores showed a lithological change from peat to mud and this is a sole possible major environmental change in this site. The radiocarbon dating indicated that the age of this boundary ranged from AD 896 to 966 (2σ). Formation of mud and peat layers is generally regulated by the balance of plant production and decomposition (Sakaguchi 1974). Peat layer is formed mainly by the deposition of the plant residue that is broken down imperfectly when the plant production is superior to decomposition (Sakaguchi 1974). In the current pond environment, no plants grow in the central part; hence, mud is deposited. Meanwhile, the pond's outer rim is covered by reeds, although there is no marked difference in water depth. Hence, there is a chance that peat is developed in some parts of the present pond. Therefore, it is likely that a slight change in water depth might markedly affect mud or peat layer formation.

The $\delta^{13}\text{C}$ values of the dating materials retrieved from the peat and mud layers provide further evidence for the environmental change in the past Kobatake-ike pond. In the case of aquatic plants in the lake, $\delta^{13}\text{C}$ values of approximately zero to -10‰ were reported (Watanabe et al. 2010). These values are higher than the range of $\delta^{13}\text{C}$ values (approximately -20 to -32‰ , Schwarz and Redman 1978; Watanabe et al. 2010) reported for terrestrial C3 plants.

At the Kobatake-ike pond, dating materials obtained from the peat layer and the top of the mud layer had $\delta^{13}\text{C}$ values corresponding to the isotopic compositions of terrestrial plants, i.e., approximately -22 to -28‰ (Table 2). However, the plants obtained at 76–151 cm below the surface showed $\delta^{13}\text{C}$ values of approximately -15 to -19‰ , with slightly heavier isotope compositions than terrestrial plants (Table 2). These heavy isotope compositions suggest that these plant materials might be aquatic plant fossils. This implies that the pond's water depth might have increased at the time of mud-peat boundary, which resulted in a change in the depositional environment from a wetland to a pond and led to the vegetation change from terrestrial plants to aquatic plants. To increase the pond's water depth, either an increase in the influx or decrease in the discharge is required. The following two hypotheses can be deduced to explain environmental changes.

1) Hydrological change in the water supply: A factor to increase the water influx to the pond is a spring at Mt. Atago-yama (Yanagisawa et al. 2016), although neither geological nor historical data exist that imply

a hydrological change in the spring. Note that no significant river flows into the Kobatake-ike pond.

2) Enclosure of the basin: Considering the historical maps and the present topography, the Kobatake River, i.e., flowing out of the pond, might have been dammed in the past by human activities. This is a reasonable assumption, although there is no historical or geological evidence. In Japan, many small storage reservoirs have been developed earlier than the Edo Period in response to an increase in the population and demand for agricultural production (Shirai and Naruse 1983).

In summary, major environmental change from peat to mud in the Kobatake-ike pond can be explained by subtle deepening of water depth either by the natural or artificial processes, although we cannot specify the actual cause(s) and thus further research is required.

Identification of event deposits

Two distinct sandy deposits were interbedded within the mud and peat layers in the Kobatake-ike pond cores (Fig. 2). It is noteworthy that KBT4 core exhibits a different lithology with three sand layers and an isolated black mud between the lower two sand layers (Fig. 2). However, the middle sand layer (i.e., 175–178 cm) and an isolated black mud (i.e., 178–219 cm) were not observed in the other cores. It was deduced that these sediments were probably formed locally after the deposition of lower sand layer (see Appendix for details). Therefore, the lower sand layer in KBT4 core (i.e., 219–241 cm) can be contrasted the lower sand layer in other cores and we confirmed that two sand layers could be observed visually, as Yanagisawa et al. (2016) reported. The sandy layers at core KBT4 showed normal and inverse grading (see Appendix). Considering the depositional environment of this pond, the presence of sand layers is unusual because no source of sand exists in its immediate vicinity. Therefore, we identified them as event deposits. In addition, although no visible sand layer exists near the mud–peat boundary, CT images suggest that minor sand particles were concentrated immediately above the mud-peat boundary, as evidenced by the mineralogical observations (Fig. 3). Geochemical signatures show other evidence that Ca and S profiles exhibit a distinct increase in counts/kcps compared to normal sediment (Fig. 6). Therefore, we infer that an unusual depositional event might have occurred above this boundary.

Based on the lithostratigraphy, CT images and ^{14}C ages, the upper sandy layer, the layer containing unusual sand particles above the mud-peat boundary, and lower sandy layer were consistent among the cores. These horizons were named Events 1–3 in descending order. The results of the correlation of each event among the cores are shown in Figure 2.

Identification of tsunami deposits

The Kobatake-ike pond is located on a hill 11 m above the present sea level, but one must consider its past elevation and sea level when discussing the source of the event deposits. In the Choshi Peninsula, even when considering tectonic uplift and sea-level changes, this pond is regarded as having been located on a hill far from the sea for the last 3,000 years (Kashima et al. 1990; Ota et al. 1985). Yanagisawa et al. (2016) reported that no historical or instrumental records suggest pond

inundation by storm surges or waves over the last 400 years. They also excluded the possibility of storm wave deposition in the pond. Through numerical simulations of the 1677 Enpo tsunami in the Kobatake-ike pond, they revealed that an earthquake with a magnitude (M_w) greater than 8.3 is necessary for tsunami waves to inundate the Kobatake-ike pond. Therefore, we inferred that only large-scale tsunamis could inundate the Kobatake-ike pond. The pond is surrounded by the Late Pleistocene marine terraces, and terrestrial weathering might have produced some amount of sandy sediments, which can be a source of the event deposits. Nevertheless, there is no cliff around the Kobatake-ike pond supplying the sandy deposits into the pond. Furthermore, it is unlikely that relatively frequent processes, such as typhoons or floods, have supplied such weathered sediments to the Kobatake-ike pond, because the deposition of the sand is quite infrequent; it is only three times during the period from BC 1129 to AD 1950. Therefore, even if the source of sands was the Late Pleistocene terraces, they might not have been eroded unless the infrequent and large event such as tsunamis.

Event 1

The upper sandy layer in the Kobatake-ike pond, has been identified as the 1677 Enpo tsunami deposit based on the analysis of tephra, microfossil and historical documents, and radiocarbon ages of AD 1405–1445 (2σ) obtained below the layer (Yanagisawa et al. 2016). Our results are consistent with their interpretation.

Event 2

Although no visible sand layer is observed, a whitish layer with high CT numbers exists at the bottom of the mud layer (see Appendix). Microscopic observation also revealed that relatively coarse grains were concentrated in this part (Fig. 3). In the 2011 Tohoku-oki tsunami, thick sandy deposits were usually reported near the coast, but no sand layer was visible near the inundation limit (e.g., Goto et al. 2011; Takai et al. 2013). In addition, very thin or no sand deposits were sometimes left in the case of small tsunamis (Judd et al. 2017).

Geochemical signatures are effective for identifying such subtle evidence of seawater inundation (Chagué-Goff 2010; Judd et al. 2017; Minoura and Nakaya 1991). Ca and Sr concentrations in seawater are generally higher than those in freshwater (Wedepohl 1971). The higher Ca and Sr concentrations in the ITRAX profiles (Fig. 6) suggest that seawater flowed into the Kobatake-ike pond at the timing of Event 2. Diatom analysis also showed that marine, marine-brackish, and brackish species are all contained in this horizon (Fig. 4), which supports the possible occurrence of seawater inundation. Si and K are mainly found in rock-forming minerals. Similar to other seawater indicators (Fig. 6), their profiles were relatively higher in Event 2 than in underlying peat layer. Si is a primary element of silicate minerals such as quartz and feldspar (Chagué-Goff et al. 2012). Feldspar, pyroxene, and amphibole also contain K or Ca (Chagué-Goff et al. 2012). These minerals are commonly found in beach sand in the area (Sudo 2006). Indeed, quartz and feldspar are main contents of sand particles in both Event 2 and the beach sand at Kimigahama (Fig. 3). Therefore, it can be considered that the tsunami waves eroded and transported the beach sand into the Kobatake-ike pond. In contrast, Fe and Ti are the primary elements of heavy minerals. These

elements are therefore regarded as signature materials of terrestrial sources (Chagué-Goff et al. 2012; Hadler et al. 2015; Ramírez-Herrera et al. 2012; Williams et al. 2011). Therefore, increasing Fe and Ti concentrations in Event 2 than peat layer can also be attributed to erosion and transportation of the beach sand with heavy minerals such as magnetite by tsunami waves. Based on these sedimentological, geochemical, and paleontological results, we interpreted the Kobatake-ike pond was inundated by the seawater at the timing of Event 2 although the seawater inundation did not leave a visible sand layer.

Note that the radiocarbon dating revealed that the age of mud-peat boundary immediately below Event 2 is AD 896–966 (2σ). This age range aligns with that inferred from the local tradition of the tsunami that might have struck the Choshi area around AD 976 (Choshi Geopark Promotion Council 2016).

Event 3

Lithostratigraphic observations and CT images revealed that Event 3 (e.g., KBT4 core) shows normal grading and inverse grading (see Fig. S1). A similar sedimentary structure is typically reported for deposits formed by recent massive tsunamis such as the 2011 Tohoku-oki tsunami (Nakamura et al. 2012; Naruse et al. 2012) and the 2004 Indian Ocean tsunami (Naruse et al. 2010). Naruse et al. (2010) propose that inverse grading occurs during the waxing stage of oscillatory flows, such as tsunami run-up or backwash flows; then, the graded part is formed during the waning stage. Moreover, Sawai (2012) reported that inverse grading can be interpreted as grain coarsening because of suspended sediment passage with flow acceleration. Furthermore, Moreira et al. (2017) report inverse or massive sedimentary sequences in the basal section of AD 1755 tsunami deposits. They attributed these sequences to the dominance of bedload-dominated transport and deposition regarded high flow velocities and high-density sediment loads during the tsunami inundation (e.g., Jaffe et al. 2012). Therefore, these structures can be regarded as characteristic features of tsunami deposits—the results of the diatom analyses provided further direct evidence of seawater inundation. A few marine and brackish species were observed at Event 3 (Fig. 4), which suggests that the inflow of seawater to the Kobatake-ike pond coincided with the deposition of Event 3. It is noteworthy that marine and brackish species were also observed in the normal sediments above and below Event 3 (Fig. 4), although diatoms of marine and brackish species are not originally produced in the normal sediments in the pond (Yanagisawa et al. 2016).

Geochemical signatures indicating seawater, such as salinity, reportedly do not remain in the porous sand layers and flow down to the bottom soil by rainwater (e.g., Chagué-Goff et al. 2015). These indicators tend to be preserved in organic or fine sediments (e.g., Chagué-Goff 2010). Likewise, diatoms may migrate downward in porous sediments. Chiba et al. (2015) demonstrated possible migration of diatoms from a porous sandy deposit to underlying layer, based on constant head permeability test. Yanagisawa et al. (2016) observed marine-brackish species in the muddy sediment immediately below the AD1677 Enpo tsunami deposit, and argued that the downward migration of diatoms might have occurred. Considering such observations, diatoms originally included in Event 3 might have migrated downward through the porous peat layer. The presence of marine-brackish diatoms in the muddy sediment above

Event 3 indicates that the horizon must be included in Event 3, since the grain size distribution and CT images suggested that the horizon indicated significant sandy fractions (see Fig. S1).

ITRAX analysis revealed elevated ratios of seawater-related elements, such as Ca/kcps and S/kcps in the event layer 3 (Fig. 6). The presence of marine diatoms (Fig. 4) also indicated that the Kobatake-ike pond was inundated by the seawater in Event 3. Moreover, a sulfur (S) peak in count/kcps is recognized in Event 3, which is higher in seawater than in freshwater (Casagrande et al. 1977; Chagué-Goff 2010; Goff et al. 2012). The increasing elements concentrations, such as Si/kcps and K/kcps (and Ca/kcps) in event layer 3 can be reflected the silicate minerals such as quartz and feldspar containing in the sand particles in both Event 3 and the beach sand at Kimiga-hama (Fig. 3). Also higher Fe and Ti concentrations in Event 3 can be reflected the heavy minerals such as magnetite observed in Figure 3. Considering the mineralogical observation, the sediment source of Event 3 was the beach. The diatom, geochemical and grain-size data suggest that the sediment was derived by a seawater inundation due to highly likely a tsunami.

Sedimentation rate of the Kobatake-ike pond

Before interpreting the timing of three tsunami events, it is important to check whether these tsunami events have affected to the age–depth model. It might be readily apparent from the age–depth model (Fig. 5) that the sedimentation rate changes suddenly at the mud–peat boundary. The rate below the boundary is approximately 1 m/kyr, while above the boundary is 2.7 m/kyr. If this sedimentation rate is reflective of actual conditions, the deposition of the mud (approximately 80 cm) between Events 1 and the mud-peat boundary occurred within approximately 100 years (Fig. 5). Furthermore, a large time gap separates the layers below and above that mark the 1677 tsunami deposit (Event 1). As reported for the 2011 Tohoku-oki tsunami, a tsunami can erode the original sediment in the coastal pond. Such significant erosion can result in a large time gap below the tsunami deposit (Shinozaki et al. 2015). However, approximately 4 m thick sediment is expected to have been eroded by the tsunami associated with Event 1 (=1677 Enpo tsunami) if we consider the sedimentation rate between Events 1 and the mud-peat boundary. Such significant erosion is unlikely to have occurred at the high elevation of the Kobatake-ike pond, together with a historical account of the 1677 Enpo tsunami. In addition, the water depth of the pond is small, and it cannot accommodate such a thick sediment. Yanagisawa et al. (2016) reported that radiocarbon dating of plant materials obtained from the muddy sediment below Event 1 (core P-7; Yanagisawa et al. 2016) ranged from AD 1405 to 1445. Therefore, erosion of the pond floor sediment by the 1677 tsunami should have been limited. Alternatively, the following two hypotheses can be regarded as explaining this change in sedimentation rate and time gap beneath Event 1.

Tsunami-induced sediment mixing related to Event 2

The possibility exists that the age–depth model was affected by the tsunami inundation to mix the soft muddy sediment. Shinozaki et al. (2015) reported for Suijin-numa pond in Sendai Plain that the original muddy sediment was eroded and suspended by the 2011 tsunami to form an approximately 50-cm-thick reworked mud layer above sandy tsunami deposits. According to radiocarbon dating of the reworked mud layer, the ages obtained from the mud layer were almost homogenized. They reported that the muddy tsunami deposits contained a mixture of organic materials of various ages during the last 1100 years due to tsunami erosion.

Such homogenized ages in the mud layer of a pond are similar to our dating results obtained between Events 1 and the mud-peat boundary (Fig. 5). In addition, geochemical signatures revealed that the Kobatake-ike pond was inundated by the tsunami at Event 2 immediately above the mud-peat boundary. Thus, erosion and deposition of reworked mud might have occurred due to the tsunami at Event 2. If tsunami-induced reworking of the mud has taken place, the mud layer above the boundary represents an age older than the actual tsunami age. Similar to the Suijin-numa case (Shinozaki et al. 2015), this phenomenon might only occur in the softer mud layer: it might not occur in the peat layer because they possess a higher erosion threshold than mud (Jacobs et al. 2011; Otsubo and Muraoka 1988; Tuukkanen et al. 2014). Homogenized dating results cannot be ascertained above and below Event 3 (Fig. 5), which is intercalated within the harder peat layer. Therefore, it is unlikely that the tsunami-induced reworking affected the radiocarbon ages of Event 3.

If this model is correct, it is difficult to restrict the limiting minimum age of Event 2 using homogenized radiocarbon dating results, although the limiting maximum age of AD 896–954 is unaffected because the age was obtained from the hard peat layer below the mud-peat boundary, which can be regarded as having not been reworked. The homogenized mud should have been terminated below Event 1 (1677 Enpo tsunami deposit) because radiocarbon age of plant materials obtained from the mud below Event 1 was AD 1405-1445 (Yanagisawa et al. 2016), which is much younger than the homogenized age. The radiocarbon dating result can also be used as a reliable limiting minimum age of Event 2 and also as a limiting maximum age of Event 1.

Reservoir effect

The dissolved inorganic carbon in water used for photosynthesis by aquatic plants has a lower ^{14}C concentration than in the atmosphere because of seawater and freshwater reservoir effects. Therefore, the radiocarbon dating values of aquatic plant fossils are known to tend to be older than the actual age (Kilian et al. 1995; Watanabe et al. 2010). For example, Kilian et al. (1995) performed radiocarbon dating using aquatic plants in raised bog deposits. They reported that these results were strongly affected by local reservoir effects and reported dates hundreds of years older than the actual age.

At the Kobatake-ike pond, the $\delta^{13}\text{C}$ values of dating materials obtained from the mud layer between Events 1 and the mud-peat boundary show slightly heavier isotope compositions than those of terrestrial

plants (Table 2). These heavy isotope compositions suggest that these plant materials might be aquatic plant fossils. If this is the case, the radiocarbon ages obtained from the mud layer between Events 1 and the mud-peat boundary might be affected by local reservoir effects and might represent hundreds of years older than the actual age.

In this way, the age of Event 2 cannot be sufficiently constrained. Considering the radiocarbon ages' uncertainty, the tsunami of Event 2 might have occurred during the 10th to 15th centuries (AD 896–1445), although no written record is known for such a tsunami event. The relocation of the shrine at AD 976 can be related to the tsunami; however, the age of the relocation is based only on the local traditional knowledge, for which the reliability has not yet been evaluated. Further investigation is needed to constrain the age of the tsunami event between the 10th and 15th centuries.

Paleotsunami history along the southern and central part of Japan Trench

Our results demonstrated that three massive tsunamis struck the studied area during the past three thousand years: AD 1677, AD 900–1400, and AD 300. Although age restriction of Event 2 is poor, the average recurrence interval of tsunami events inferred from this result is approximately 700 years. Additionally, it is noteworthy that the timing of the paleo-tsunami events is close to the ages of known paleotsunamis in the central part of the Japan Trench (Fig. 7).

Sawai et al. (2012) conducted a comprehensive survey along the Pacific coast from Miyagi Prefecture to northern Ibaraki prefecture. They identified five large tsunami events based on historical and geological evidence and inferred that they were formed by the AD 1611 Keicho, AD 1454 Kyotoku and AD 869 Jogan tsunamis and older tsunamis at AD 400–500 and BC 500–400. Saino (2012) and Matsumoto et al. (2013) reported that a tsunami struck the Sendai Plain around 2050 yr BP, which was not reported by Sawai et al. (2012) (see also discussion by Sawai 2020).

The AD 1677 Enpo tsunami occurred in the southern part of the Japan Trench approximately 60 years after the AD 1611 Keicho tsunami (Fig. 7). The evidence for seawater inundation in Event 2 suggests that a large tsunamigenic earthquake struck the Choshi region during the 10–15 centuries (AD 896–1445) and the possible known tsunami around AD 976 at Choshi City, which is close to the AD 869 Jogan tsunami, is one candidate. However, since the age cannot be constrained well, we cannot fully exclude the possibility that the tsunami might have occurred close to the AD 1454 Kyotoku tsunami (Sawai et al. 2015). Further age constraint for the Event 2 is required. The radiocarbon ages showed that Event 3 was deposited between AD 234 and AD 330. The age seems close to the event in 2050 yr BP (Matsumoto et al. 2013; Saino 2012) or in AD 400–500 (Sawai et al. 2012) along the central part of the Japan Trench, although the error ranges of both tsunami deposits at the southern and central parts of the Japan Trench are large.

No visible event deposit that can be correlated with the BC 500–400 tsunami event reported in the central part of the Japan Trench (Sawai et al. 2012) was identified in the cores obtained from the Kobatake-ike pond (Fig. 7). The ITRAX result showed no geochemical evidence indicating seawater invasion and even suggests that the event without a sandy deposit is less likely to exist (Fig. 6). Therefore, no massive tsunami was generated during this period in the southern part of the Japan Trench. An alternative explanations are that the tsunami could not reach the elevation of the Kobatake-ike pond (11 m) or the tsunami reached but the deposits were eroded by later tsunamis. However, the CT images and ITRAX profiles did not provide useful information to assess whether or not the event deposits had been eroded. Regarding the lack of historical documents and sufficient quantitative estimation of inundation processes and sources (e.g., Sawai 2017, 2020), the question remains whether or not the BC 500–400 tsunami occurred in the central part of the Japan Trench.

The discussion presented above related to the correlation of paleo-tsunami histories between the central and southern parts of the Japan Trench might indicate important spatiotemporal relations of large earthquakes in these areas. A large earthquake may have been triggered by the occurrence of a large earthquake in an adjacent area. The occurrence of large earthquakes in different seismic sources during a short period of a few days to a few tens of years is historically well known from the Nankai Trough (Ando 1975; Sugino et al. 2011). In the case of the Japan Trench, strain accumulation after the 2011 Tohoku earthquake was inferred and reported (Simons et al. 2011; Toda et al. 2011). Our results may provide potential geological evidence to support such concerns.

Conclusions

We identified three tsunami events occurring during the past three thousand years from drilling cores obtained at the Kobatake-ike pond. The uppermost tsunami deposit can be correlated with the AD 1677 Enpo tsunami. Radiocarbon dating results further indicated that the older tsunamis might have occurred at AD 896–1445 and AD 234–330. The average recurrence interval of the tsunami events was 700 years. This interval is comparable to those estimated around the coasts facing the central part of the Japan Trench. Additionally, the results show that the paleo-tsunami histories in the central and southern parts of the Japan Trench may occur in a relatively short-time-interval, although the error ranges of both tsunami deposits at the southern and central parts of the Japan Trench are large. This result implies that a spatiotemporal relation of large earthquake generations (strain accumulation and release) might exist between the central and southern parts of the Japan Trench areas. This possibility should be considered in tsunami hazard assessments.

Abbreviations

yrBP: years before present

Declarations

Availability of data and materials

Please contact author for data requests.

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Competing interests

The authors declare that they have no competing interest.

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Authors' contributions

HH, KG, HY, and DS conducted fieldwork and collected samples. KG proposed the study topic and conceived and designed the study. HH and TI picked out organic materials for radiocarbon dating and constrained event ages by OxCal. HH led the writing of the text and preparation of the figures. All authors participated in discussions during the research, later reading, and approval of the final manuscript.

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Reference

- Ando K (1990) Environmental indicators based on freshwater diatom assemblages and its application to reconstruction of paleo-environments. *Annals of The Tohoku Geographical Association* 42:73-88. [doi:10.5190/tga1948.42.73](https://doi.org/10.5190/tga1948.42.73) (in Japanese, with English abstract)
- Ando M (1975) Source mechanisms and tectonic significance of historical earthquakes along the Nankai Trough, Japan. *Tectonophysics* 27:119-140. [doi:10.1016/0040-1951\(75\)90102-X](https://doi.org/10.1016/0040-1951(75)90102-X)
- Boespflug X, Long BFN, Occhietti S (1995) Cat-scan in marine stratigraphy: a quantitative approach. *Mar Geol* 122:281-301. [doi:10.1016/0025-3227\(94\)00129-9](https://doi.org/10.1016/0025-3227(94)00129-9)
- Bondevik S, Svendsen JI, Johnsen G, Mangerud J, Kaland PE (1997) The Storegga tsunami along the Norwegian coast, its age and run up. *Boreas* 26:29-53. [doi:10.1111/j.1502-3885.1997.tb00649.x](https://doi.org/10.1111/j.1502-3885.1997.tb00649.x)
- Bouchard F, Francus P, Pienitz R, Laurion I (2011) Sedimentology and geochemistry of thermokarst ponds in discontinuous permafrost, subarctic Quebec, Canada. *J Geophys Res* 116. [doi:10.1029/2011JG001675](https://doi.org/10.1029/2011JG001675)
- Bronk Ramsey C (2009a) Bayesian analysis of radiocarbon dates. *Radiocarbon* 51:337-360. [doi:10.1017/S0033822200033865](https://doi.org/10.1017/S0033822200033865)
- Bronk Ramsey C (2009b) Dealing with the outliers and offsets in radiocarbon dating. *Radiocarbon* 51:1023-1045. [doi:10.1017/S0033822200034093](https://doi.org/10.1017/S0033822200034093)
- Casagrande DJ, Siefert K, Berschinski C, Sutton N (1977) Sulfur in peat-forming systems of the Okefenokee Swamp and Florida Everglades: origins of sulfur in coal. *Geochim Cosmochim Acta* 41:161-167. [doi:10.1016/0016-7037\(77\)90196-X](https://doi.org/10.1016/0016-7037(77)90196-X)
- Chagué-Goff C (2010) Chemical signatures of palaeotsunamis: a forgotten proxy? *Mar Geol* 271:67-71. [doi:10.1016/j.margeo.2010.01.010](https://doi.org/10.1016/j.margeo.2010.01.010)
- Chagué-Goff C, Andrew A, Szczuciński W, Goff J, Nishimura Y (2012) Geochemical signatures up to the maximum inundation of the 2011 Tohoku-oki tsunami - implications for the 869 AD Jogan and other palaeotsunamis. *Sedi Geol* 282:65-77. [doi:10.1016/j.sedgeo.2012.05.021](https://doi.org/10.1016/j.sedgeo.2012.05.021)
- Chagué-Goff C, Goff J, Wong HKY, Cisternas M (2015) Insights from geochemistry and diatoms to characterise a tsunami's deposit and maximum inundation limit. *Mar Geol* 359:22-34. [doi:10.1016/j.margeo.2014.11.009](https://doi.org/10.1016/j.margeo.2014.11.009)
- Chagué-Goff C, Szczuciński W, Shinozaki T (2017) Applications of geochemistry in tsunami research: a review. *Earth Sci Rev* 165:203-244. [doi:10.1016/j.earscirev.2016.12.003](https://doi.org/10.1016/j.earscirev.2016.12.003)
- Chiba T, Takemura T, Uemura K (2015) Effect of the diatom fossils infiltration on the lower layer diatom fossil assemblages. Abstract O3 presented at the JSD 36th Meeting, The University of Tokyo, Japan, 9-10

May 2015. *Diatom* 31:56-64. (in Japanese)

http://diatomology.org/eng/diatom/list/diatom_abstracts/diatom31_56-64.pdf

Choshi Geopark Promotion Council (2016) A story of blessings of nature and the disaster.

<http://www.choshi-geopark.jp/file/saigai.pdf>. (in Japanese). Office

Croudace IW, Rindby A, Rothwell RG (2006) ITRAX: description and evaluation of a multi-function new X-ray core scanner. *Geol Soc Lond Spec Publ* 267:51-63. [doi:10.1144/GSL.SP.2006.267.01.04](https://doi.org/10.1144/GSL.SP.2006.267.01.04)

Cuven S, Paris R, Falvard S, Miot-Noirault E, Benbakkar M, Schneider J-L, Billy I (2013) High-resolution analysis of a tsunami deposit: case-study from the 1755 Lisbon tsunami in southwestern Spain. *Marine Geology* 337:98-111. [doi:10.1016/j.margeo.2013.02.002](https://doi.org/10.1016/j.margeo.2013.02.002)

Falvard S, Paris R (2017) X-ray tomography of tsunami deposits: Towards a new depositional model of tsunami deposits. *Sedimentology* 64:453-477. [doi:10.1111/sed.12310](https://doi.org/10.1111/sed.12310)

Falvard S, Paris R, Belousova M, Belousov A, Giachetti T, Cuven S (2018) Scenario of the 1996 volcanic tsunamis in Karymskoye Lake, Kamchatka, inferred from X-ray tomography of heavy minerals in tsunami deposits. *Mar Geol* 396:160-170. [doi:10.1016/j.margeo.2017.04.011](https://doi.org/10.1016/j.margeo.2017.04.011)

Goff J, Chagué-Goff C, Nichol S, Jaffe B, Dominey-Howes D (2012) Progress in palaeotsunami research. *Sedi Geol* 243-244:70-88. [doi:10.1016/j.sedgeo.2011.11.002](https://doi.org/10.1016/j.sedgeo.2011.11.002)

Goto K, Chagué-Goff C, Fujino S, Goff J, Jaffe B, Nishimura Y, Richmond B, Sugawara D, Szczuciński W, Tappin DR, Witter RC, Yulianto E (2011) New insights of tsunami hazard from the 2011 Tohoku-oki event. *Mar Geol* 290:46-50. [doi:10.1016/j.margeo.2011.10.004](https://doi.org/10.1016/j.margeo.2011.10.004)

Goto K, Ishizawa T, Ebina Y, Imamura F, Sato S, Udo K (2020) Ten years after the 2011 Tohoku-oki earthquake and tsunami: geological and environmental effects and implications for disaster policy changes. *Earth Sci Rev* Available online 23. <http://www.ncbi.nlm.nih.gov/pubmed/103417>

Goto K, Nishimura Y, Sugawara D, Fujino S (2012) The Japanese tsunami deposit researches. *Jour Geol Soc Jpn* 118:431-436. [doi:10.5575/geosoc.2012.0042](https://doi.org/10.5575/geosoc.2012.0042) (in Japanese, with English abstract)

Goto T, Satake K, Sugai T, Ishibe T, Harada T, Gusman AR (2019) Tsunami history over the past 2000 years on the Sanriku coast, Japan, determined using gravel deposits to estimate tsunami inundation behavior. *Sedi Geol* 382:85-102. [doi:10.1016/j.sedgeo.2019.01.001](https://doi.org/10.1016/j.sedgeo.2019.01.001)

Goto T, Satake K, Sugai T, Ishibe T, Harada T, Murotani S (2015) Historical tsunami and storm deposits during the last five centuries on the Sanriku coast, Japan. *Mar Geol* 367:105-117. [doi:10.1016/j.margeo.2015.05.009](https://doi.org/10.1016/j.margeo.2015.05.009)

Guyard H, Chapron E, St-Onge G, Anselmetti FS, Arnaud F, Magand O, Francus P, Mélières M-A (2007) High-altitude varve records of abrupt environmental changes and mining activity over the last 4000 years

in the Western French Alps (Lake Bramant, Grandes Rousses Massif). *Quat Sci Rev* 26:2644-2660.
[doi:10.1016/j.quascirev.2007.07.007](https://doi.org/10.1016/j.quascirev.2007.07.007)

Hadler H, Baika K, Pakkanen J, Fischer P, Henning P, Ntageretzis P, Robke B, Willershauser T, Vött A (2015) Palaeotsunami impact on the ancient harbour site Kyllini (western Peloponnese, Greece) based on a multi-proxy approach. *Z Geomorphol Suppl* 59:7-41. [doi:10.1127/zfg_suppl/2014/S-00187](https://doi.org/10.1127/zfg_suppl/2014/S-00187)

Hatori T (2003) Irregular height deviation of the 1677 Enpo Boso-Oki tsunami, eastern Japan. *Hist Earthq* 19:1-7 (in Japanese, with English abstract)

Inoue T, Goto K, Nishimura Y, Watanabe M, Iijima Y, Sugawara D (2017) Paleo-tsunami history along the northern Japan Trench: evidence from Noda Village, northern Sanriku coast, Japan. *Prog Earth Planet Sci* 4:42. [doi:10.1186/s40645-017-0158-1](https://doi.org/10.1186/s40645-017-0158-1)

Ishimura D, Miyauchi T (2015) Historical and paleo-tsunami deposits during the last 4000 years and their correlations with historical tsunami events in Koyadori on the Sanriku Coast, northeastern Japan. *Prog in Earth and Planet Sci* 2:1-18. [doi:10.1186/s40645-015-0047-4](https://doi.org/10.1186/s40645-015-0047-4)

Ishizawa T, Goto K, Yokoyama Y, Miyairi Y (2019) Non-destructive analyses to determine appropriate stratigraphic level for dating of tsunami deposits. *Mar Geol* 412:19-26.
[doi:10.1016/j.margeo.2019.02.009](https://doi.org/10.1016/j.margeo.2019.02.009)

Ishizawa T, Goto K, Yokoyama Y, Miyairi Y, Sawada C, Nishimura Y, Sugawara D (2017) Sequential radiocarbon measurement of bulk peat for high-precision dating of tsunami deposits. *Quat Geochronol* 41:202-210. [doi:10.1016/j.quageo.2017.05.003](https://doi.org/10.1016/j.quageo.2017.05.003)

Ishizawa T, Goto K, Yokoyama Y, Miyairi Y, Sawada C, Takada K (2018) Reducing the age range of tsunami deposits by ¹⁴C dating of rip-up clasts. *Sedi Geol* 364:334-341.
[doi:10.1016/j.sedgeo.2017.09.008](https://doi.org/10.1016/j.sedgeo.2017.09.008)

Jacobs W, Le Hir P, Van Kesteren W, Cann P (2011) Erosion threshold of sand–mud mixtures. *Contin Shelf Res* 31:S14-S25. [doi:10.1016/j.csr.2010.05.012](https://doi.org/10.1016/j.csr.2010.05.012)

Jaffe BE, Goto K, Sugawara D, Richmond BM, Fujino S, Nishimura Y (2012) Flow speed estimated by inverse modeling of sandy tsunami deposits: results from the March 11 2011 tsunami on the coastal plain near the Sendai Airport, Honshu, Japan. *Sedi Geol* 282:90-109. [doi:10.1016/j.sedgeo.2012.09.002](https://doi.org/10.1016/j.sedgeo.2012.09.002)

Jowsey PC (1966) An improved peat sampler. *New Phytol* 65:245-248. [doi:10.1111/j.1469-8137.1966.tb06356.x](https://doi.org/10.1111/j.1469-8137.1966.tb06356.x)

Judd K, Chagué-Goff C, Goff J, Gadd P, Zawadzki A, Fierro D (2017) Multi-proxy evidence for small historical tsunamis leaving little or no sedimentary record. *Mar Geol* 385:204-215.
[doi:10.1016/j.margeo.2017.01.002](https://doi.org/10.1016/j.margeo.2017.01.002)

Kashima K (1985) Holocene diatom assemblages in Takagami Lowland, central part of Choshi Peninsula, and its relation to changes of sea-level. *Daiyonki-kenkyu* 24:125-138. doi:[10.4116/jaqua.24.125](https://doi.org/10.4116/jaqua.24.125) (in Japanese, with English abstract)

Kashima K, Ota Y, Matsushima Y, Liew P, Sawa M (1990) Holocene sea-level change in Takagami Lowland, the Choshi Peninsula, Japan. *Daiyonki-kenkyu* 29:139-149. doi:[10.4116/jaqua.29.139](https://doi.org/10.4116/jaqua.29.139) (in Japanese, with English abstract)

Kilian MR, van der Plicht J, van Geel B (1995) Dating raised bogs: new aspects of AMS ^{14}C wiggle matching, a reservoir effect and climatic change. *Quat Sci Rev* 14:959-966. doi:[10.1016/0277-3791\(95\)00081-X](https://doi.org/10.1016/0277-3791(95)00081-X)

Kosugi M (1988) Classification of living diatom assemblages as the indicator of environments, and its application to reconstruction of paleoenvironments. *Daiyonki-kenkyu* 27:1-20. doi:[10.4116/jaqua.27.1](https://doi.org/10.4116/jaqua.27.1) (in Japanese, with English abstract)

Kusumoto S, Goto T, Sugai T, Omori T, Satake K (2018) Geological evidence of tsunamis in the past 3800 years at a coastal lowland in the Central Fukushima Prefecture, Japan. *Mar Geol* 404:137-146. doi:[10.1016/j.margeo.2018.07.004](https://doi.org/10.1016/j.margeo.2018.07.004)

Matsumoto H, Kumagai M, Yoshida M (2013) Paleotsunami deposit of 2050 years ago and its inundation distance, on the Sendai Coastal Lowland, Northeastern Japan. *J Hum Inform* 18:79-94 (in Japanese, with English abstract)

Minoura K, Hirano S, Yamada T (2013) Identification and possible recurrence of an oversized tsunami on the Pacific coast of northern Japan. *Nat Hazards* 68:631-643. doi:[10.1007/s11069-013-0640-z](https://doi.org/10.1007/s11069-013-0640-z)

Minoura K, Nakaya S (1991) Traces of tsunami preserved in inter-tidal lacustrine and marsh deposits: some examples from northeast Japan. *J Geol* 99:265-287. doi:[10.1086/629488](https://doi.org/10.1086/629488)

Moreira S, Costa PJM, Andrade C, Ponte Lira C, Freitas MC, Oliveira MA, Reichart G-J (2017) High resolution geochemical and grain-size analysis of the AD 1755 tsunami deposit: insights into the inland extent and inundation phases. *Mar Geol* 390:94-105. doi:[10.1016/j.margeo.2017.04.007](https://doi.org/10.1016/j.margeo.2017.04.007)

Nakamura Y, Nishimura Y, Putra PS (2012) Local variation of inundation, sedimentary characteristics, and mineral assemblages of the 2011 Tohoku-oki tsunami on the Misawa coast, Aomori, Japan. *Sedi Geol* 282:216-227. doi:[10.1016/j.sedgeo.2012.06.003](https://doi.org/10.1016/j.sedgeo.2012.06.003)

Naruse H, Arai K, Matsumoto D, Takahashi H, Yamashita S, Tanaka G, Murayama M (2012) Sedimentary features observed in the tsunami deposits at Rikuzentakata City. *Sedi Geol* 282:199-215. doi:[10.1016/j.sedgeo.2012.08.012](https://doi.org/10.1016/j.sedgeo.2012.08.012)

Naruse H, Fujino S, Suphawajraksakul A, Jarupongsakul T (2010) Features and formation processes of multiple deposition layers from the 2004 Indian Ocean tsunami at Ban Nam Kem, southern Thailand. *Isl Arc* 19:399-411. doi:[10.1111/j.1440-1738.2010.00732.x](https://doi.org/10.1111/j.1440-1738.2010.00732.x)

Ota Y, Matsushima Y, Miyoshi M, Kashima K, Maeda Y, Moriwaki H (1985) Holocene environmental changes in the Choshi Peninsula and its surroundings, easternmost Kanto, central Japan. *Daiyonki-kenkyu* 24:13-29. doi:[10.4116/jaqua.24.13](https://doi.org/10.4116/jaqua.24.13) (in Japanese, with English abstract)

Otsubo K, Muraoka K (1988) Critical shear stress of cohesive bottom sediments. *J Hydraul Eng* 114:1241-1256. doi:[10.1061/\(ASCE\)0733-9429\(1988\)114:10\(1241\)](https://doi.org/10.1061/(ASCE)0733-9429(1988)114:10(1241))

Ramírez-Herrera M-T, Lagos M, Hutchinson I, Kostoglodov V, Machain ML, Caballero M, Goguitchaichvili A, Aguilar B, Chagué-Goff C, Goff J, Ruiz-Fernández A-C, Ortiz M, Nava H, Bautista F, Lopez GI, Quintana P (2012) Extreme wave deposits on the Pacific coast of Mexico: tsunamis or storms? – A multi-proxy approach. *Geomorphology* 139-140:360-371. doi:[10.1016/j.geomorph.2011.11.002](https://doi.org/10.1016/j.geomorph.2011.11.002)

Ramsey CB (2008) Deposition models for chronological records. *Quat Sci Rev* 27:42-60. doi:[10.1016/j.quascirev.2007.01.019](https://doi.org/10.1016/j.quascirev.2007.01.019)

Reimer PJ, Bard E, Bayliss A, Beck JW, Blackwell PG, Ramsey CB, Buck CE, Cheng H, Edwards RL, Friedrich M, Grootes PM, Guilderson TP, Hafliðason H, Hajdas I, Hatté C, Heaton TJ, Hoffmann DL, Hogg AG, Hughen KA, Kaiser KF, Kromer B, Manning SW, Niu M, Reimer RW, Richards DA, Scott EM, Southon JR, Staff RA, Turney CSM, van der Plicht J (2013) IntCal13 and Marine13 radiocarbon age calibration curves 0-50,000 years Cal BP. *Radiocarbon* 55:1869-1887. doi:[10.2458/azu_js_rc.55.16947](https://doi.org/10.2458/azu_js_rc.55.16947)

Saino H (2012) Excavated evidence of tsunamis in the Sendai plain. *Q Archaeol Stud* 58:6-11 (in Japanese)

Sakaguchi Y (1974) *Earth Science of Peat Bog—an Investigation of an Environmental Change*. University of Tokyo Press, 329p (in Japanese)

Sawai Y (2012) Study on paleotsunami deposits in geologic stratum. *Jour Geol Soc Japan* 118:535-558. doi:[10.5575/geosoc.2012.0063](https://doi.org/10.5575/geosoc.2012.0063) (in Japanese, with English abstract)

Sawai Y (2017) Paleotsunami research along the Pacific coast of Tohoku region. *Jour Geol Soc Japan* 123:819-830. doi:[10.5575/geosoc.2017.0055](https://doi.org/10.5575/geosoc.2017.0055) (in Japanese, with English abstract)

Sawai Y (2020) Subduction zone paleoseismology along the Pacific coast of northeast Japan – progress and remaining problems. *Earth Sci Rev* 208. doi:[10.1016/j.earscirev.2020.103261](https://doi.org/10.1016/j.earscirev.2020.103261). <http://www.ncbi.nlm.nih.gov/pubmed/103261>

Sawai Y, Namegaya Y, Okamura Y, Satake K, Shishikura M (2012) Challenges of anticipating the 2011 Tohoku earthquake and tsunami using coastal geology. *Geophys Res Lett* 39:n/a-n/a. doi:[10.1029/2012GL053692](https://doi.org/10.1029/2012GL053692)

- Sawai Y, Namegaya Y, Tamura T, Nakashima R, Tanigawa K (2015) Shorter intervals between great earthquakes near Sendai: scour ponds and a sand layer attributable to A.D. 1454 overwash. *Geophys Res Lett* 42:4795-4800. doi:[10.1002/2015GL064167](https://doi.org/10.1002/2015GL064167)
- Schwarz AG, Redmann RE (1988) C4 grasses from the boreal forest region of northwestern Canada. *Can J Bot* 66:2424-2430. doi:[10.1139/b88-329](https://doi.org/10.1139/b88-329)
- Shinozaki T, Goto K, Fujino S, Sugawara D, Chiba T (2015) Erosion of a paleo-tsunami record by the 2011 Tohoku-oki tsunami along the southern Sendai Plain. *Mar Geol* 369:127-136. doi:[10.1016/j.margeo.2015.08.009](https://doi.org/10.1016/j.margeo.2015.08.009)
- Shirai Y, Naruse T (1983) A study of irrigation and conservation of Ponds in Japan—Some Consideration of Pond List in 1981 —. *Geogr Sci* 38:20-35. doi:[10.20630/chirikagaku.38.1_20](https://doi.org/10.20630/chirikagaku.38.1_20) (in Japanese)
- Simons M, Minson SE, Sladen A, Ortega F, Jiang J, Owen SE, Meng L, Am-Puero JP, Wei S, Chu R, Helmberger DV, Kanamori H, Hetland E, Moore AW, Webb FH (2011) The 2011 magnitude 9.0 Tohoku-Oki earthquake: mosaicking the megathrust from seconds to centuries. *Science* 332:1421-1425. doi:[10.1126/science.1206731](https://doi.org/10.1126/science.1206731)
- Sudo S (2006) Sand and Beach of Japan (10) Sand and Beach of Iioka - Choshi district, Chiba Prefecture, Central Japan. *Chishitsu News* 625:57-65 (in Japanese)
- Sugawara D, Goto K, Imamura F, Matsumoto H, Minoura K (2012) Assessing the magnitude of the 869 Jogan tsunami using sedimentary deposits: prediction and consequence of the 2011 Tohoku-oki tsunami. *Sedi Geol* 282:14-26. doi:[10.1016/j.sedgeo.2012.08.001](https://doi.org/10.1016/j.sedgeo.2012.08.001)
- Sugino H, Korenaga M, Sakagami M, Ebisawa K (2011) Probabilistic tsunami hazard assessment considering time lag of seismic event on Nankai Trough. *J Jpn Soc Civ Eng B2* 67:I_306 - I_310. doi:[10.2208/kaigan.67.I_306](https://doi.org/10.2208/kaigan.67.I_306) (in Japanese, with English abstract)
- Takada K, Shishikura M, Imai K, Ebina Y, Goto K, Koshiya S, Yamamoto H, Igarashi A, Ichihara T, Kinoshita H, Ikeda T (2016) Distribution and ages of tsunami deposits along the Pacific coast of the Iwate Prefecture River Division Department of Prefectural Land Development, Iwate Prefecture government. *Annu Rep Act Fault Paleoequake Res* 16:1-52 (in Japanese, with English abstract)
- Takai A, Yasutaka T, Endo K, Katsumi T, JGS Technical Committee on Geoenvironmental Engineering (2013) Distribution and physicochemical properties of tsunami deposits generated by the 2011 Great East Japan earthquake. *Jiban Kogaku Janaru (The Japanese Geotechnical Journal)* 8:391-402. doi:[10.3208/jgs.8.391](https://doi.org/10.3208/jgs.8.391) (in Japanese, with English abstract)
- Takeda H, Goto K, Goff J, Matsumoto H, Sugawara D (2018) Could tsunami risk be underestimated using core-based reconstructions? Lessons from ground-penetrating radar. *Earth Surf Proc Land* 43:4. doi:[10.1002/esp.4282](https://doi.org/10.1002/esp.4282)

- Takeuchi H, Fuji R, Mimura N, Imamura F, Satake K, Tsuji Y, Hoshi K, Matsuura K (2007) Survey of run-up height of Empo Boso-oki earthquake tsunami on the coast from Chiba Prefecture to Fukushima Prefecture. *Hist Earthq* 22:53-59 (in Japanese, with English abstract)
- Tanigawa K, Sawai Y, Shishikura M, Fujiwara O, Namegaya Y (2014a) Event deposits on the Pacific coast of Misawa, Aomori Prefecture, northern Japan. *The Quat Res* 53:55-62. doi:[10.4116/jaqua.53.55](https://doi.org/10.4116/jaqua.53.55) (in Japanese)
- Tanigawa K, Sawai Y, Shishikura M, Namegaya Y, Matsumoto D (2014b) Geological evidence for an unusually large tsunami on the Pacific coast of Aomori, Northern Japan. *J Quaternary Sci* 29:200-208. doi:[10.1002/jqs.2690](https://doi.org/10.1002/jqs.2690)
- Toda S (2012) Long-term earthquake forecasting associated with the 2011 off the Pacific coast of Tohoku earthquake. *Jpn J Multiphase Flow* 26:4-10. doi:[10.3811/jjmf.26.4](https://doi.org/10.3811/jjmf.26.4) (in Japanese, with English abstract)
- Toda S, Lin J, Stein RS (2011) Using the 2011 MW 9.0 off the Pacific coast of Tohoku Earthquake to test the Coulomb stress triggering hypothesis and to calculate faults brought closer to failure. *Earth Planets Space* 63:725-730. doi:[10.5047/eps.2011.05.010](https://doi.org/10.5047/eps.2011.05.010)
- Tsuji Y, Yanuma T, Hirahata T, Imamura F (2012) Field survey of inundation height of Empo Boso earthquake tsunami (1677) in Boso Peninsula, Chiba Prefecture. *Rep tsunami. J Eng Res* 29:209-223 (in Japanese)
- Tuukkanen T, Marttila H, Kløve B (2014) Effect of soil properties on peat erosion and suspended sediment delivery in drained peatlands. *Water Resour Res* 50:3523-3535. doi:[10.1002/2013WR015206](https://doi.org/10.1002/2013WR015206)
- Watanabe T, Hosoda N, Tsuchiya N, Nakamura T, Hirano N, Okamoto A, Nara FW, Tohoku University Tsunami Sediment Research Group (2014) Radiocarbon dating historical tsunami deposits from the Sendai plain, Northeastern Japan: preliminary age model of HS Continuous Soil sediment series. *J Geogr* 123:904-922. doi:[10.5026/jgeography.123.904](https://doi.org/10.5026/jgeography.123.904) (in Japanese, with English abstract)
- Watanabe T, Matsunaka T, Nakamura T, Nishimura M, Izutsu Y, Minami M, Nara FW, Kakegawa T, Wang J, Zhu L (2010) Last Glacial–Holocene geochronology of sediment cores from a high-altitude Tibetan lake based on AMS ¹⁴C dating of plant fossils: implications for paleoenvironmental reconstructions. *Chem Geol* 277:21-29. doi:[10.1016/j.chemgeo.2010.07.004](https://doi.org/10.1016/j.chemgeo.2010.07.004)
- Wedepohl KH (1971) Environmental influences on the chemical composition of shales and clays. *Phys Chem Earth* 8:307-333. doi:[10.1016/0079-1946\(71\)90020-6](https://doi.org/10.1016/0079-1946(71)90020-6)
- Williams S, Prasetya G, Chagué-Goff C, Goff J, Cheung KF, Davies T, Wilson T (2011) Characterising diagnostic proxies for identifying paleotsunamis in a tropical climatic regime, Samoan Islands

Yanagisawa H, Goto K, Sugawara D, Kanamaru K, Iwamoto N, Takamori Y (2016) Tsunami earthquake can occur elsewhere along the Japan Trench—historical and geological evidence for the 1677 earthquake and tsunami. *J Geophys Res Solid Earth* 121:3504-3516. doi:10.1002/2015JB012617

Tables

Table 1

Core	Latitude (N)	Longitude (E)	Sand layer depth (cm)	Grain size	Sedimentary structures (visual observation)	Basal contact
P-14	35.70985	140.85854	80—86	m-f ¹⁾	No	Sharp
P-14			278—287	m-f	No	Sharp
KBT1	35.70992	140.85861	77—88	m-f	No	Sharp
KBT1			289—295	m-f	No	Sharp
KBT2	35.70965	140.85862	78—83	m-f	No	Unclear
KBT2			266—271	m-f	No	Sharp
KBT3	35.70941	140.85886	—	—	—	—
KBT4	35.70936	140.85855	53—62	m-f	No	Unclear
KBT4			175—178	m-f	No	Sharp
KBT4			219—241	m-f	normal grading and inverse grading	Sharp
KBT5	35.70983	140.85947	75—82	m-f	No	Sharp
KBT6	35.70949	140.85916	286—292	m-f	No	Unclear
KBT7	35.70930	140.85906	—	—	—	—
KBT8	35.70954	140.85868	64—76	m-f	No	Sharp
KBT8			243—251	m-f	No	Unclear
KBT9	35.70977	140.85818	—	—	—	—
KBT10	35.70956	140.85893	221—233	m-f	No	Sharp
KBT11	35.70935	140.85862	10—28	m-f	No	Sharp

1) m: medium sand, f: fine sand

Table 2

Core	Depth (cm)	Material	Conventional Radiocarbon Age(BP)	Calibrated Age (Cal)	$\delta^{13}\text{C}$ (‰) ¹⁾	Beta ID
P-14	45-47	plant material	105.6 ± 0.4 pMC	NA	-25.5	457714
P-14	55-57	plant material	130 ± 30	AD 1670–1780 AD 1800–post 1950	-24.4	457715
P-14	65-67	plant material	80 ± 30	AD 1685–1730 AD 1810–1925 AD 1950–	-24.1	457716
P-14	76	plant material	1060 ± 30	AD 900–925 AD 945–1020	-14.9	JGR ²⁾
P-14	98-100	plant material	1100 ± 30	AD 885–1015	-18.3	457717
P-14	108-113	plant material	1110 ± 30	AD 885–995	-15.9	452555
P-14	125	organic sediment	1750 ± 30	AD 230–380	-22.6	445711
P-14	139-141	plant material	1200 ± 30	AD 720–740 AD 765–895	-17.8	457718
P-14	149-151	seeds	1520 ± 30	AD 430–490 AD 510–515 AD 530–605	-19.4	457719
P-14	165-167	organic sediment	1140 ± 30	AD 775–790 AD 800–980	-27.9	452556
P-14	171-173	organic sediment	1060 ± 30	AD 900–925 AD 945–1020	-27.1	457720
P-14	181-183	organic sediment	1140 ± 30	AD 775–790 AD 800–980	-27.8	457721
P-14	200	organic sediment	1280 ± 30	AD 665–775	-27.2	445712
P-14	250	organic sediment	1620 ± 30	AD 385–475 AD 485–535	-23.0	445713
P-14	258-261	organic sediment	1770 ± 30	AD 180–190 AD 215–340	-22.2	452557
P-14	271-273	organic sediment	1750 ± 30	AD 230–380	-22.1	457722
P-14	277.5-278.5	plant material	1910 ± 30	AD 30–40 AD 50–135	-27.7	JGR ²⁾
P-14	287-288	plant material	1690 ± 30	AD 255–295 AD 320–415	-26.5	JGR ²⁾
P-14	292-294	organic sediment	2470 ± 30	BC 770–415	-23.0	452558
P-14	310	organic sediment	2390 ± 30	BC 540–395	-26.5	445714
P-14	314-316	organic sediment	2330 ± 30	BC 410–375 BC 1131–973	-25.6	457723
P-14	378-380	organic sediment	2880 ± 30	BC 958–939 BC 1161–1144 BC 1192–1176	-24.7	478070
KBT4-2	132-134	organic sediment	1290 ± 30	AD 664–770	-27.0	487208

1) $\delta^{13}\text{C}$ values of organic materials measured by the elemental analyzer/isotope ratio mass spectrometer (EA/IRMS).

2) Results of JGR is by Yanagisawa et al. (2016).

Figures

Figure 1

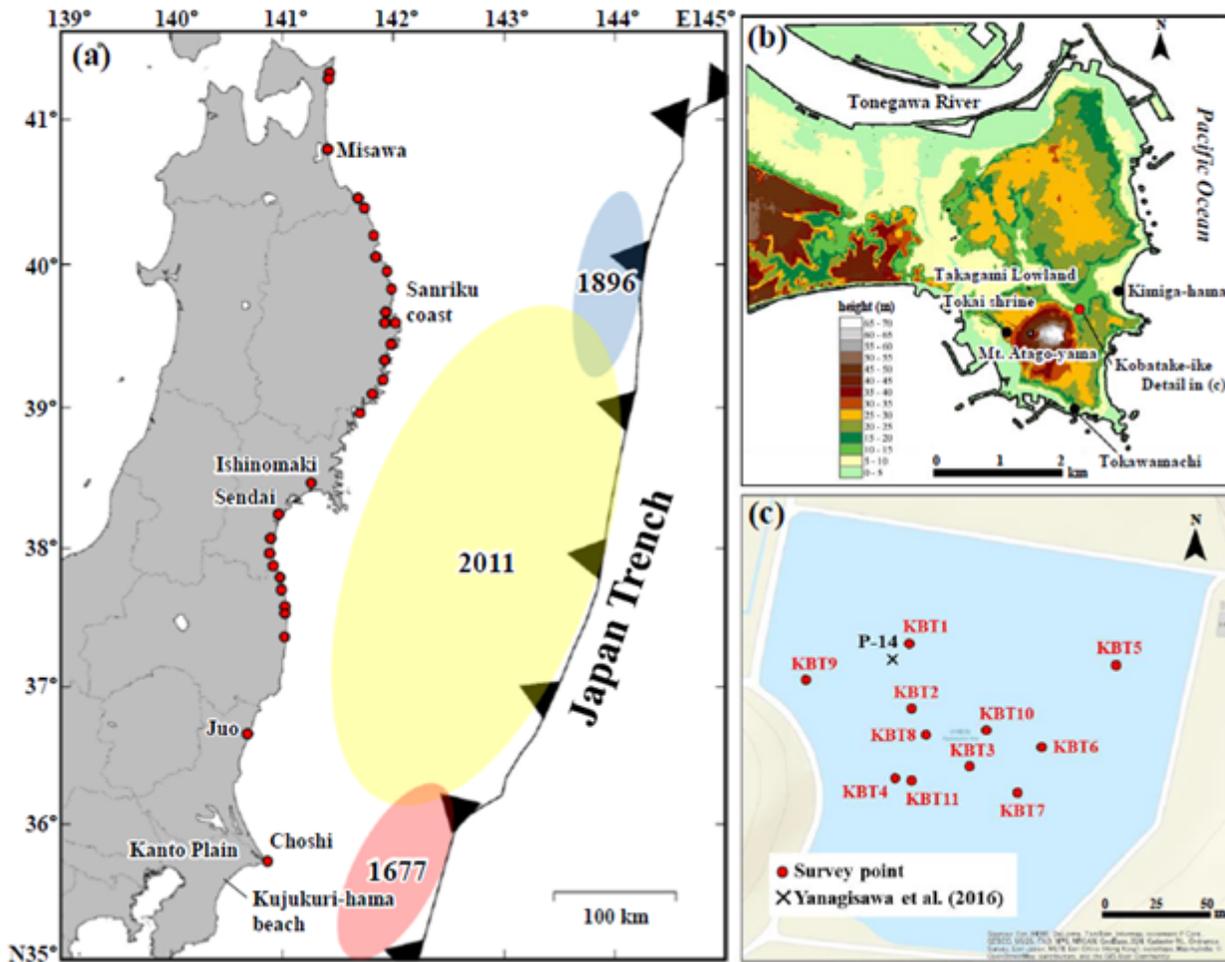


Figure 1

a) Map of Tohoku region showing the location of Choshi City and known paleo-tsunami deposits (red circles) identified by earlier studies. (b) Digital elevation model showing the topography around the Kobatake-ike pond (data from the Geospatial Information Authority of Japan). (c) Survey points (red circles) in the Kobatake-ike pond. KBT1 to KBT11 are core numbers in this study. A black cross mark shows the location of the P-14 core sampled by Yanagisawa et al. (2016).

Figure 1

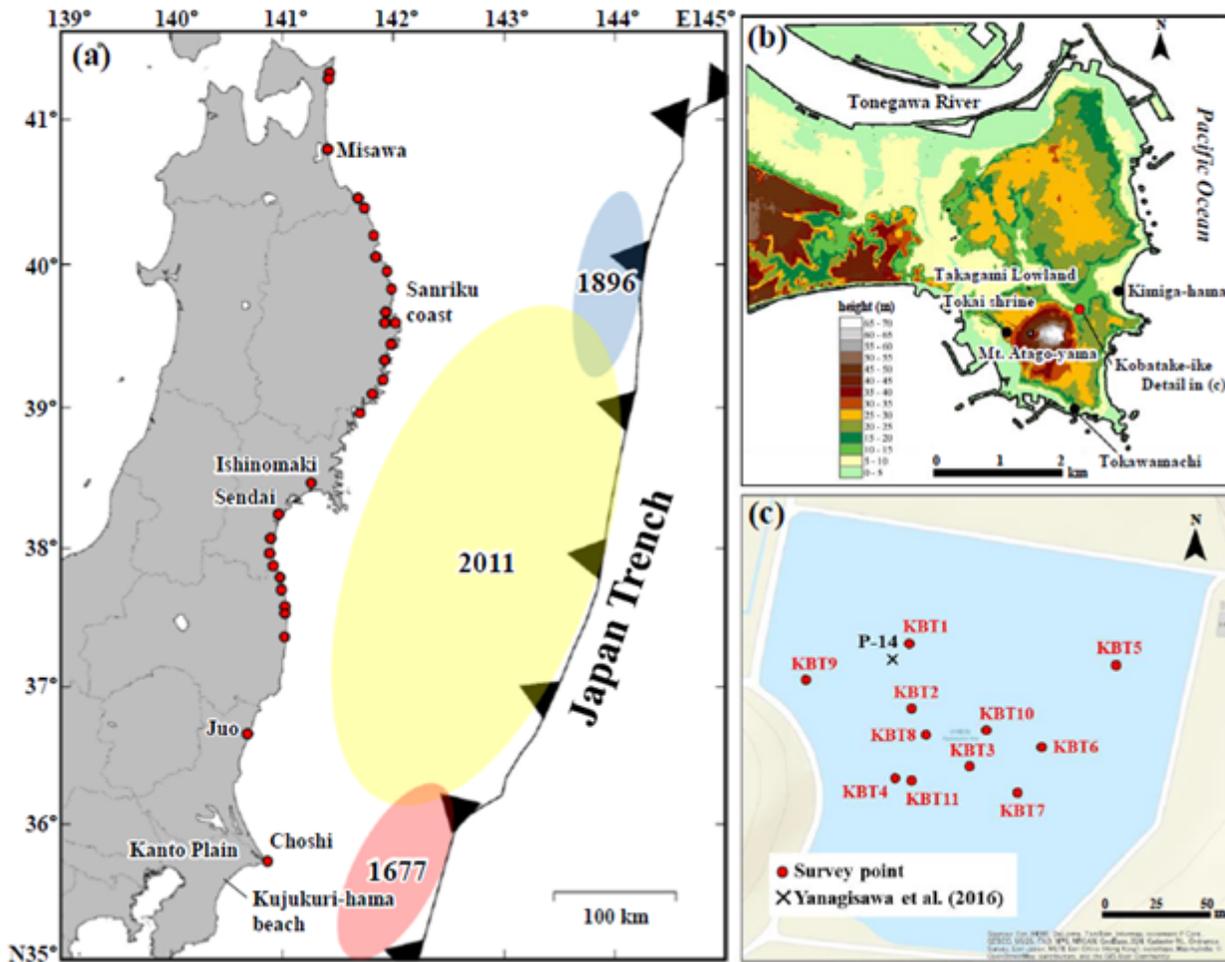


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Figure 2

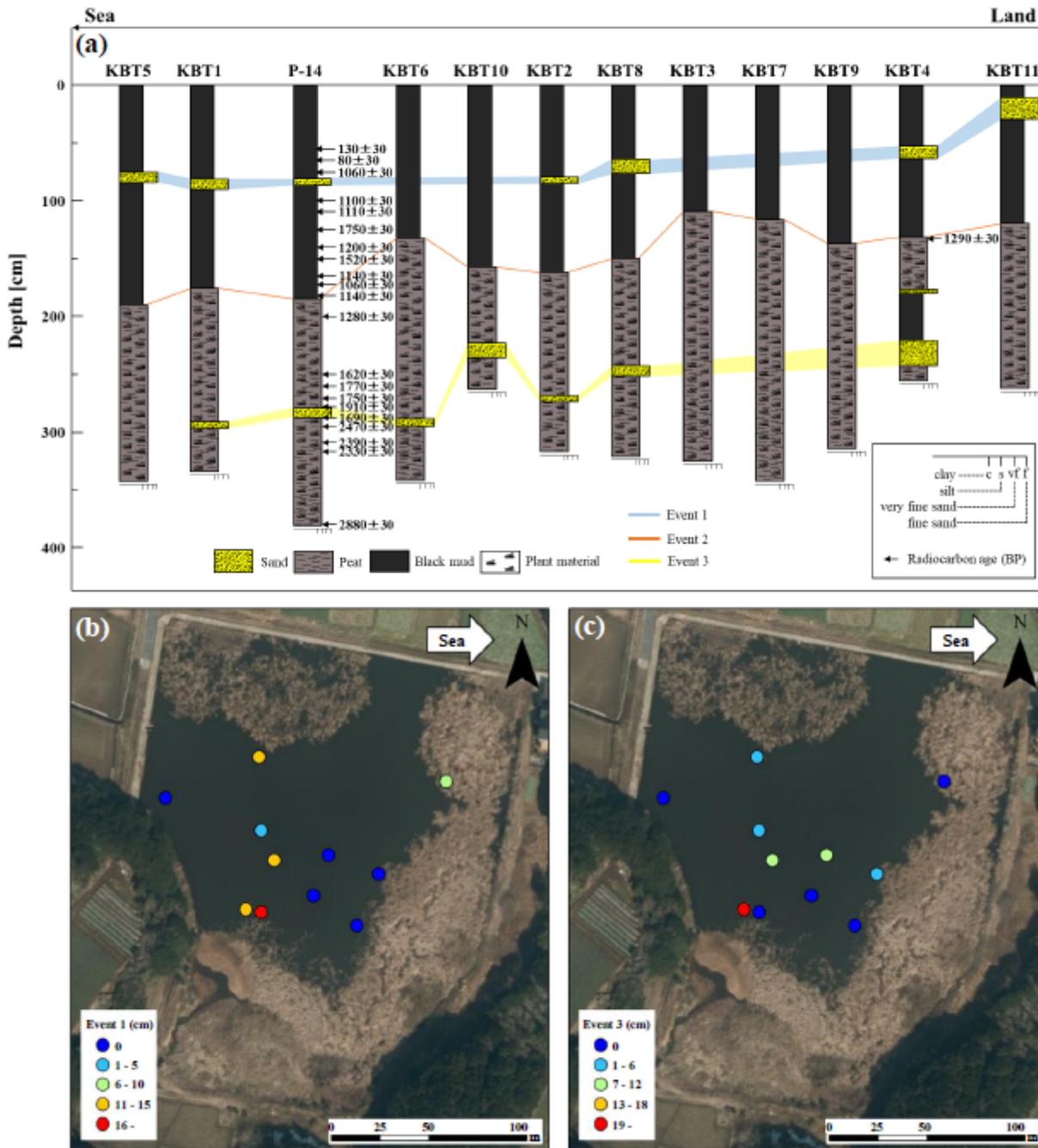


Figure 2

(a) Stratigraphic correlation of the geological column of the cores in a sea-land direction. Note that the KBT4 core's sedimentary facies seem to be different from others, and a detailed explanation is presented in the Appendix. Aerial photographs shows the thickness distribution of the (b) upper sand layer 1 and (c) lower sand layer 3.

Figure 2

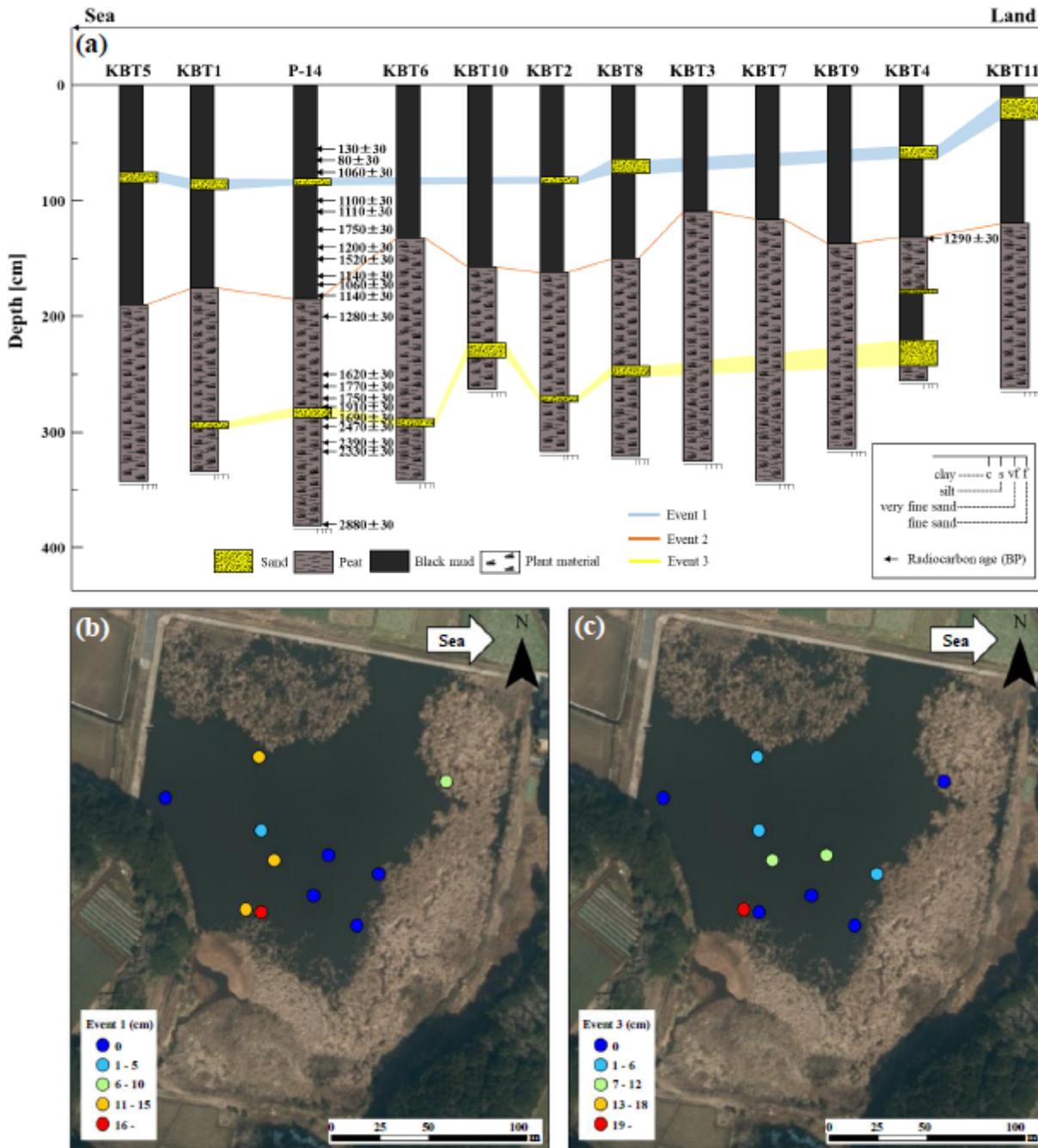


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Figure 3

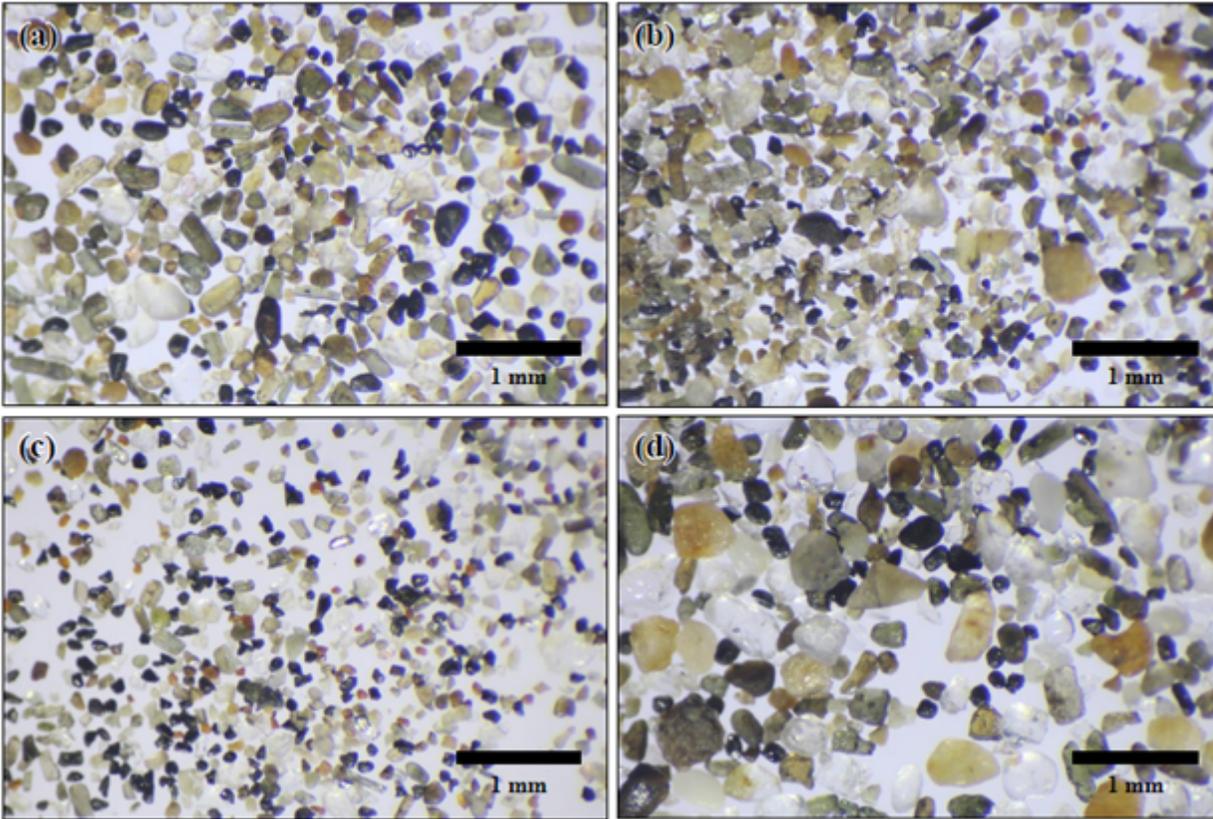


Figure 3

Microscopic photo of sands contained in the (a) upper sandy layer, (b) mud-peat boundary, (c) lower sandy layer, and (d) the beach.

Figure 3

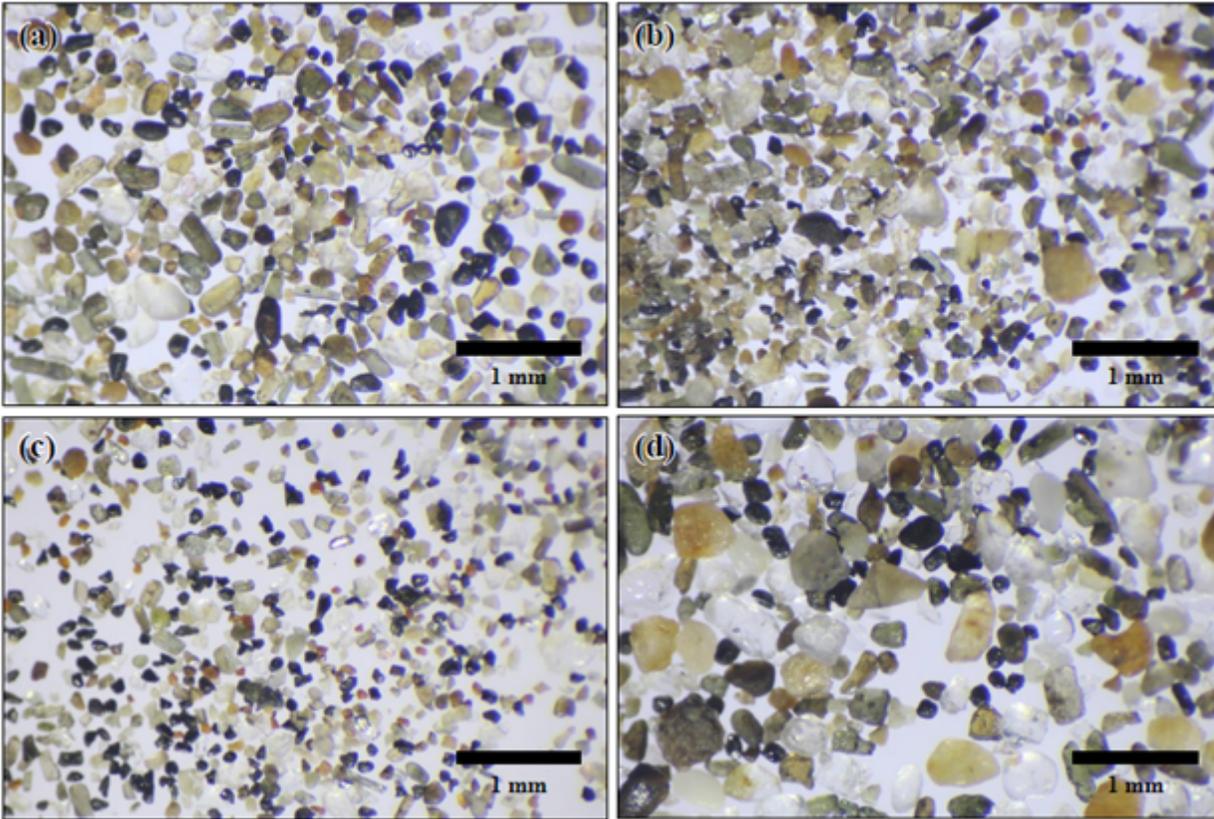


Figure 3

Microscopic photo of sands contained in the (a) upper sandy layer, (b) mud-peat boundary, (c) lower sandy layer, and (d) the beach.

Figure 4

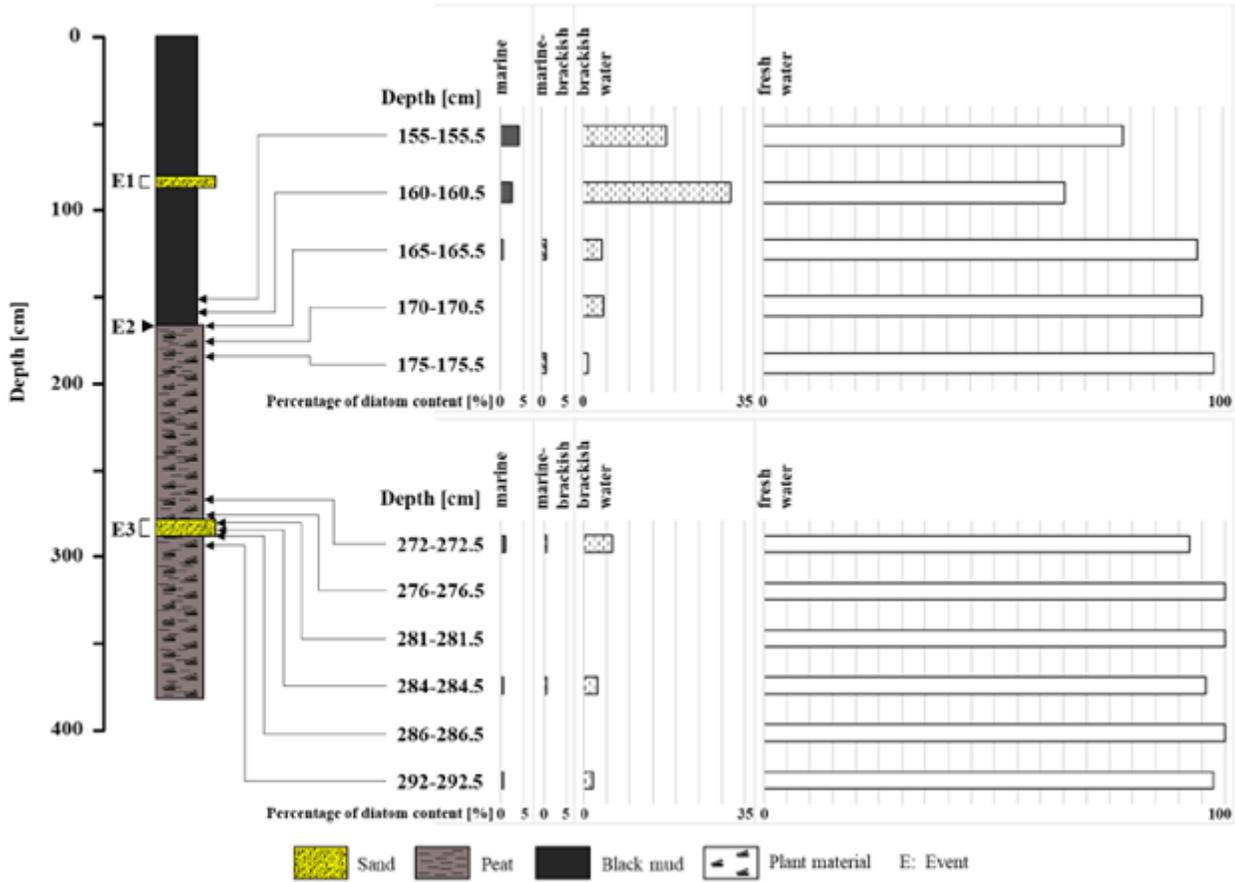


Figure 4

Microscopic photo of sands contained in the (a) upper sandy layer, (b) mud–peat boundary, (c) lower sandy layer, and (d) the beach.

Figure 4

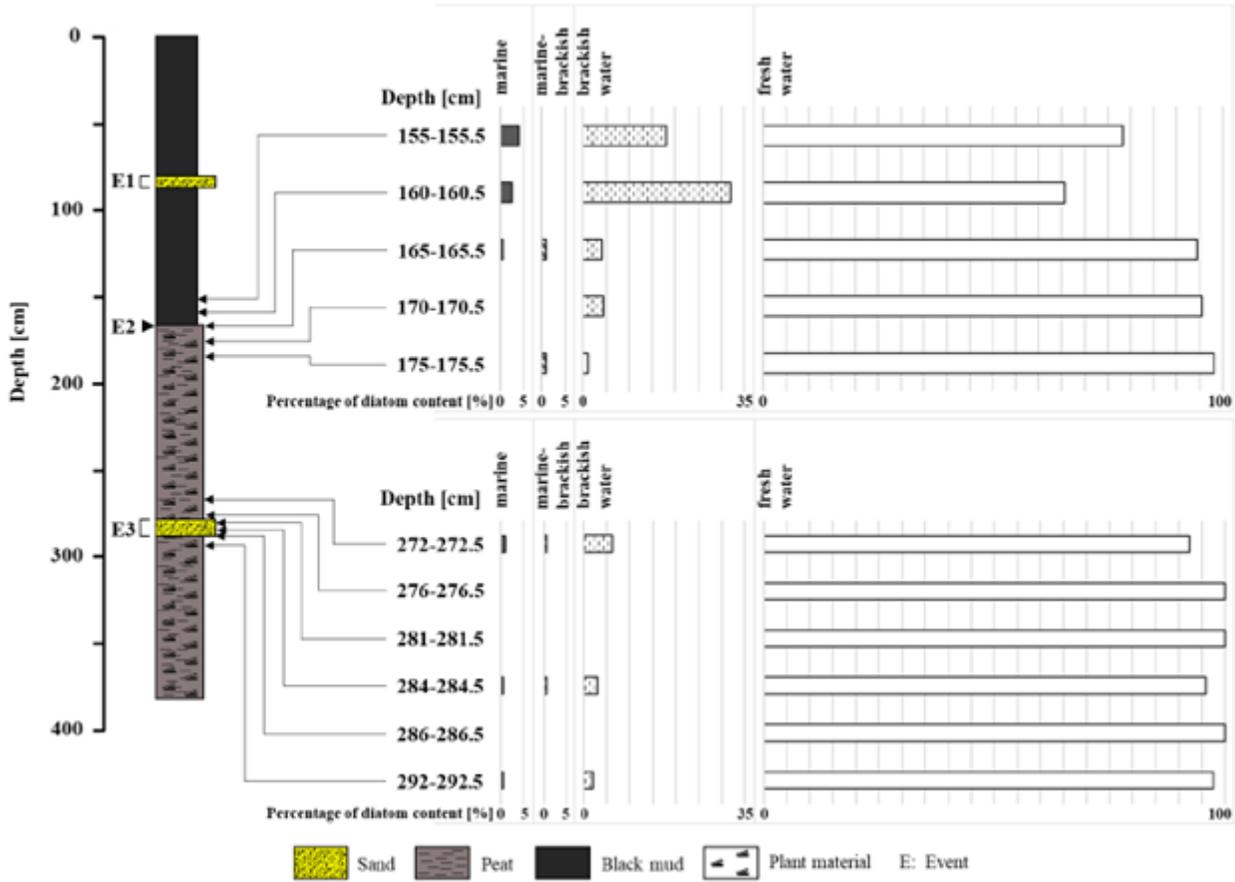


Figure 4

Microscopic photo of sands contained in the (a) upper sandy layer, (b) mud–peat boundary, (c) lower sandy layer, and (d) the beach.

Figure 5

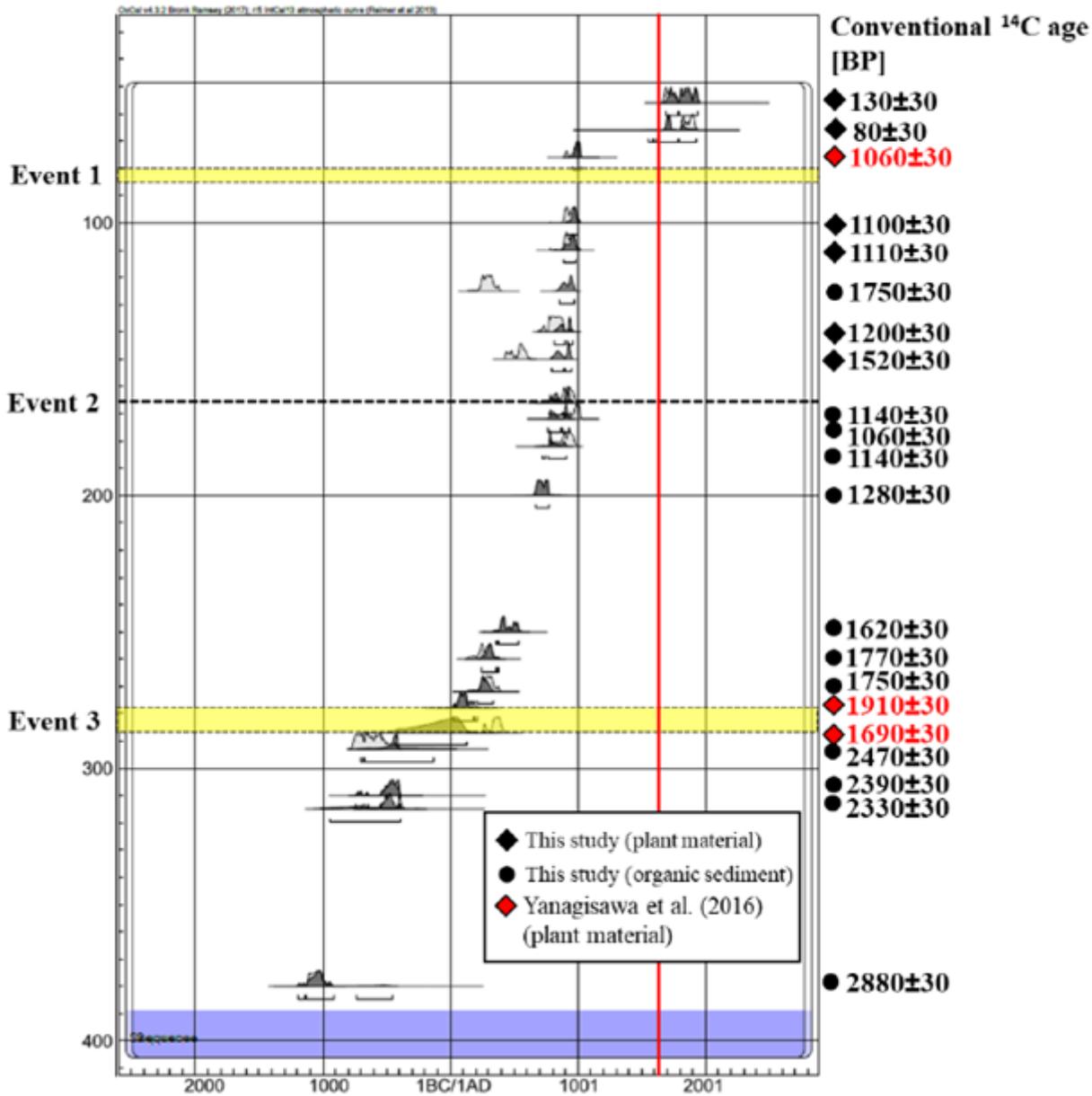


Figure 5

Calibrated ¹⁴C ages for a 2σ probability range. The respective dating results' probability densities are shown in light gray; the black ones show probability density distributions constrained using the sequence model. Marks (red diamond, black diamond, and dot) show sampling points; red, Results reported by Yanagisawa et al. (2016); black, samples measured for this study; diamond, plant materials; circle, organic sediments. The vertical red line represents the AD 1677 tsunami.

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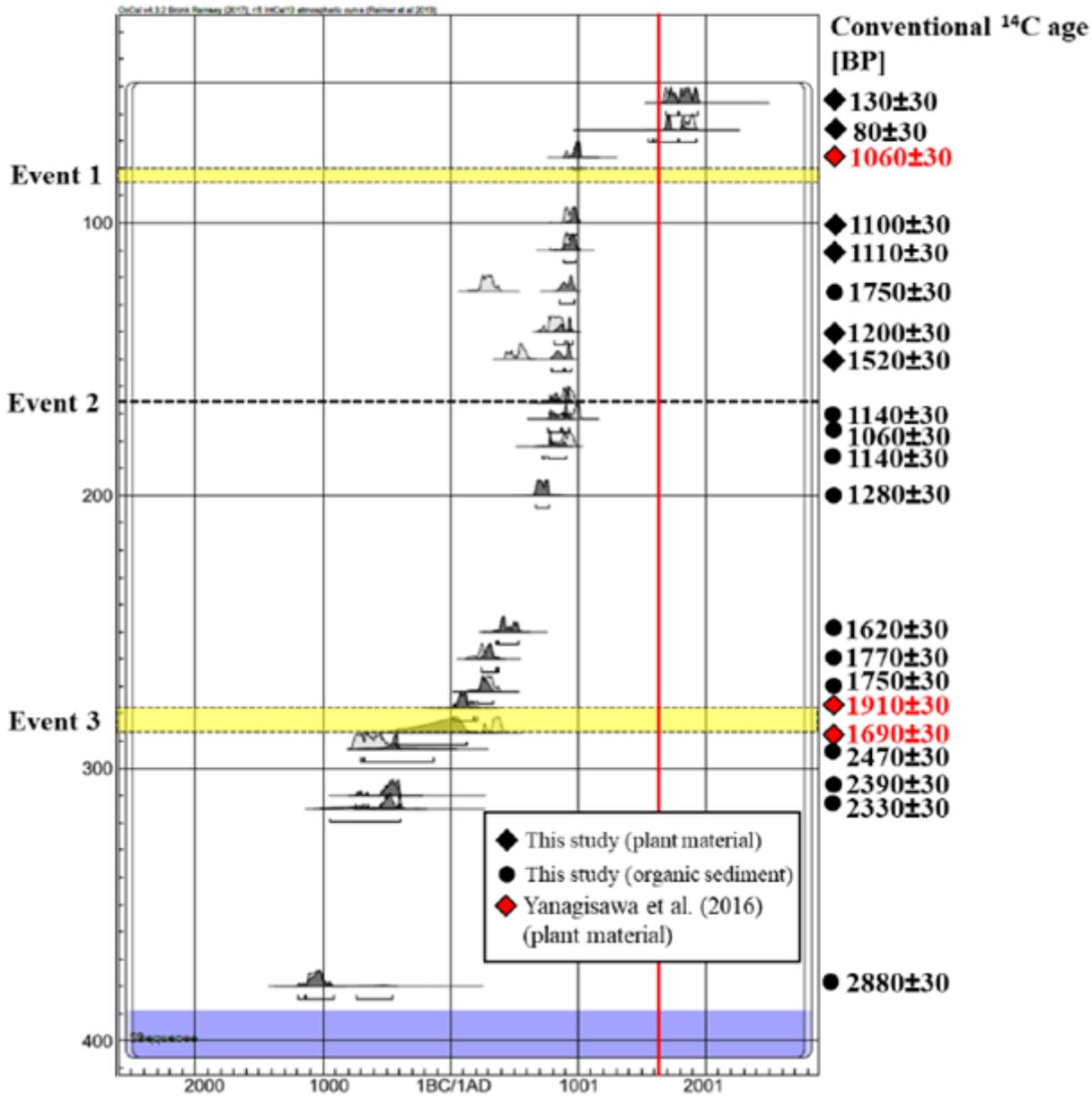


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Figure 6

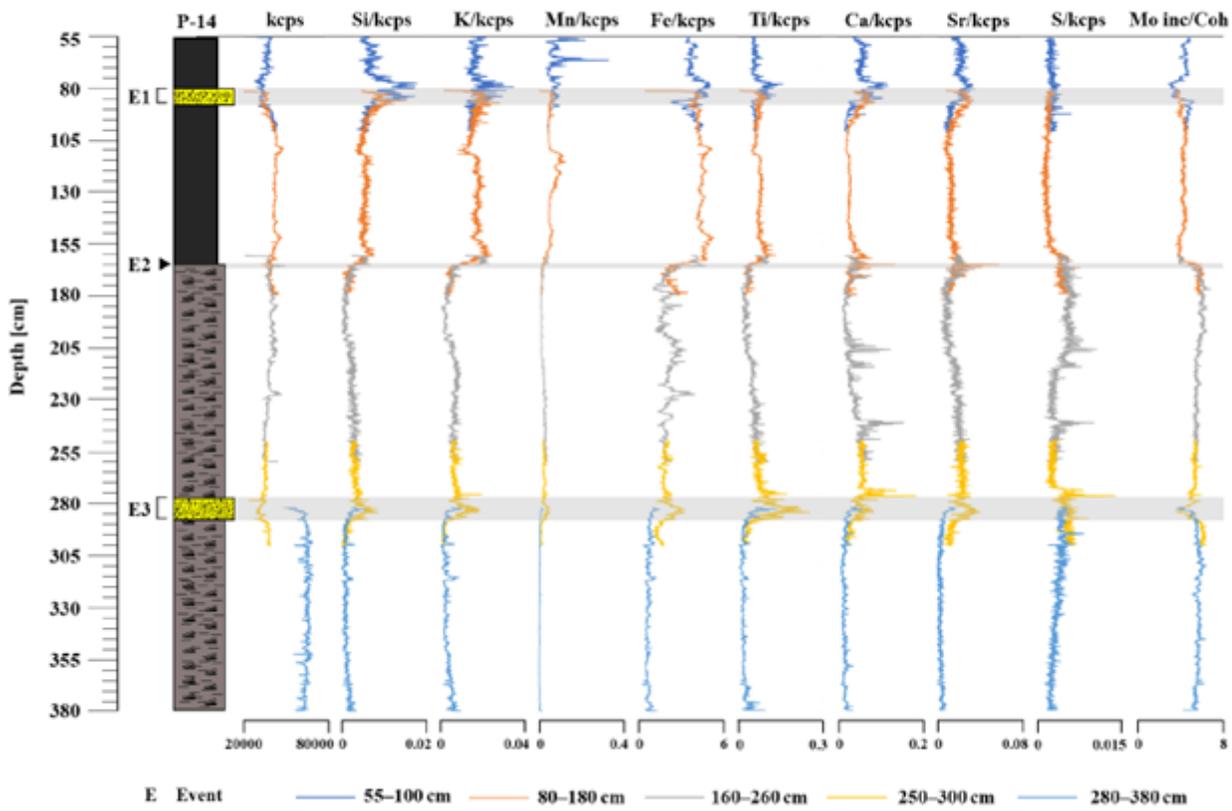


Figure 6

Normalized ITRAX XRF data of P-14 core (55–380 cm depth).

Figure 6

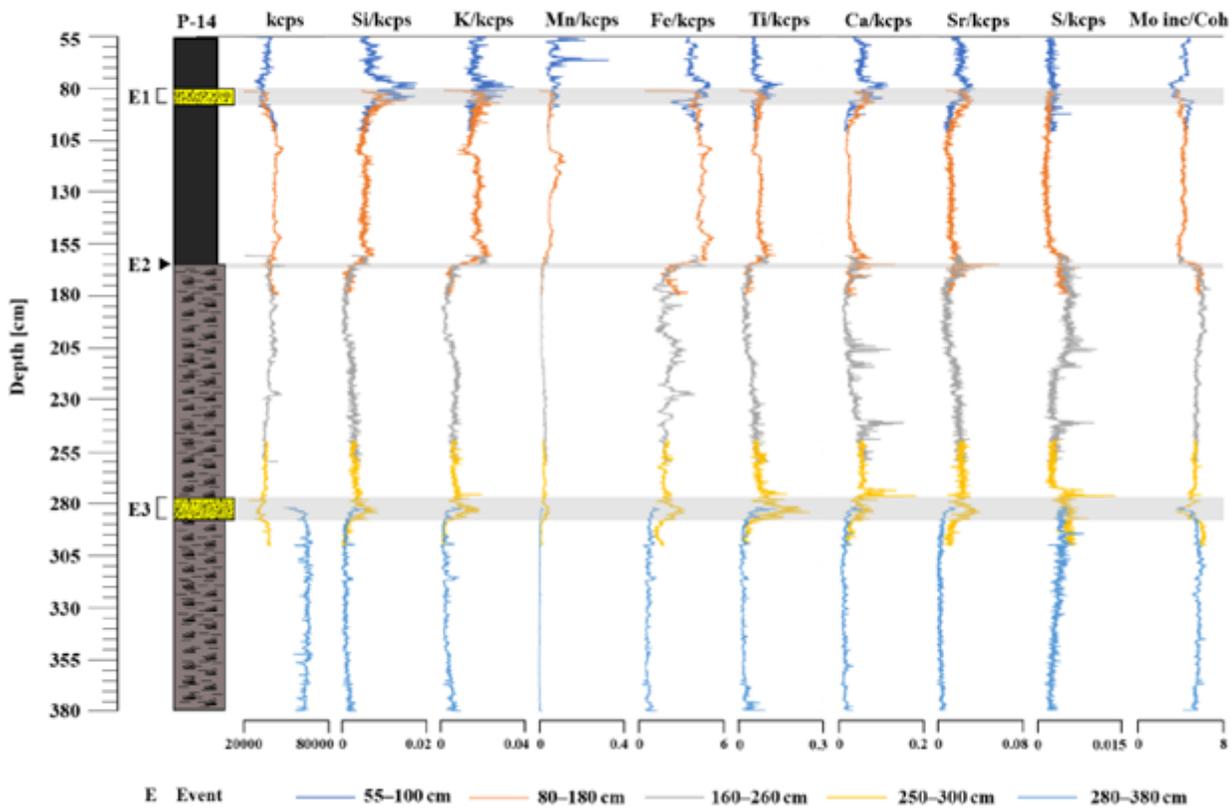


Figure 6

Normalized ITRAX XRF data of P-14 core (55–380 cm depth).

Figure 7

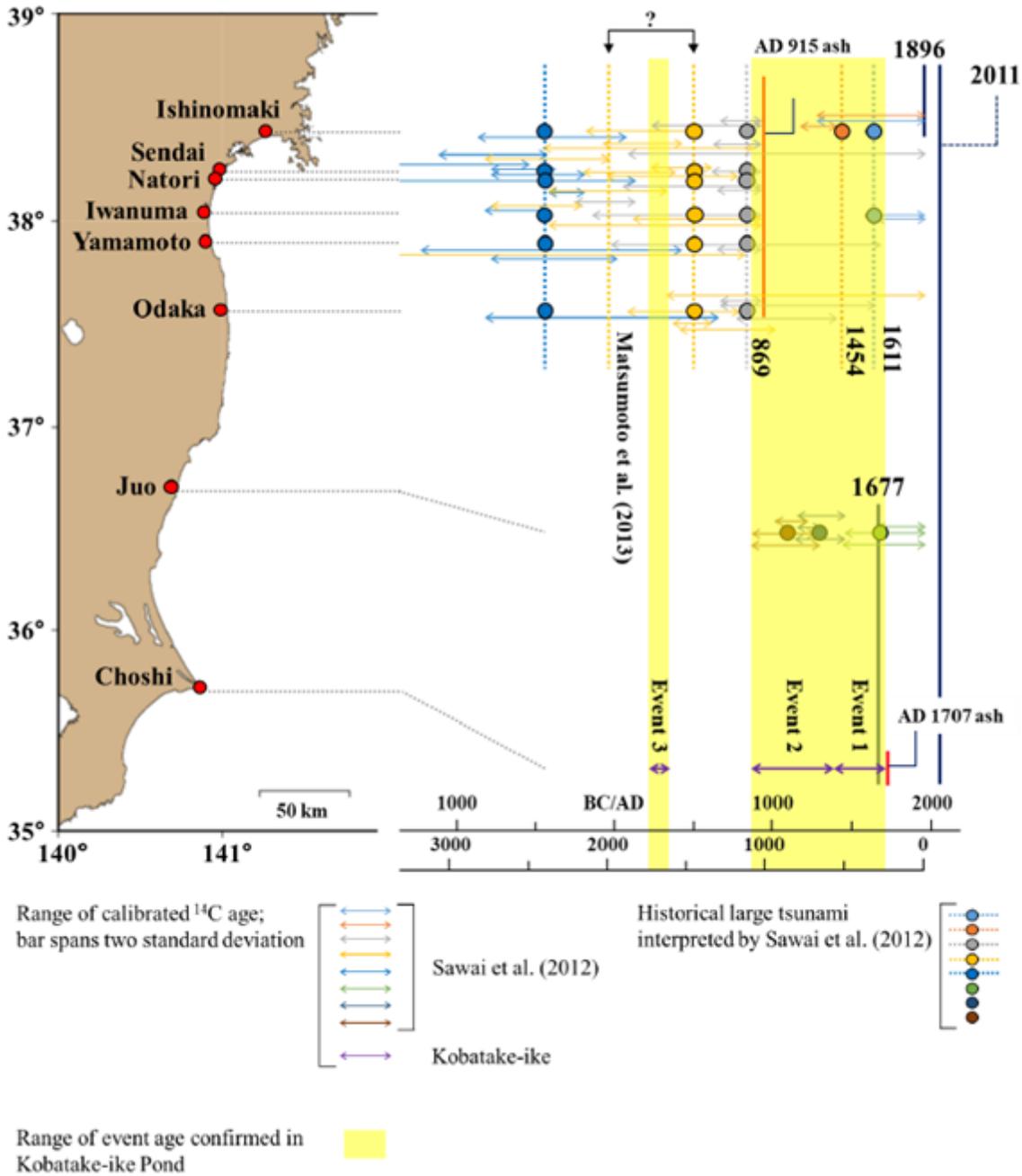


Figure 7

Paleotsunami histories in the Pacific coasts from Miyagi to Chiba prefecture, which faces the central and southern parts of Japan Trench.

Figure 7

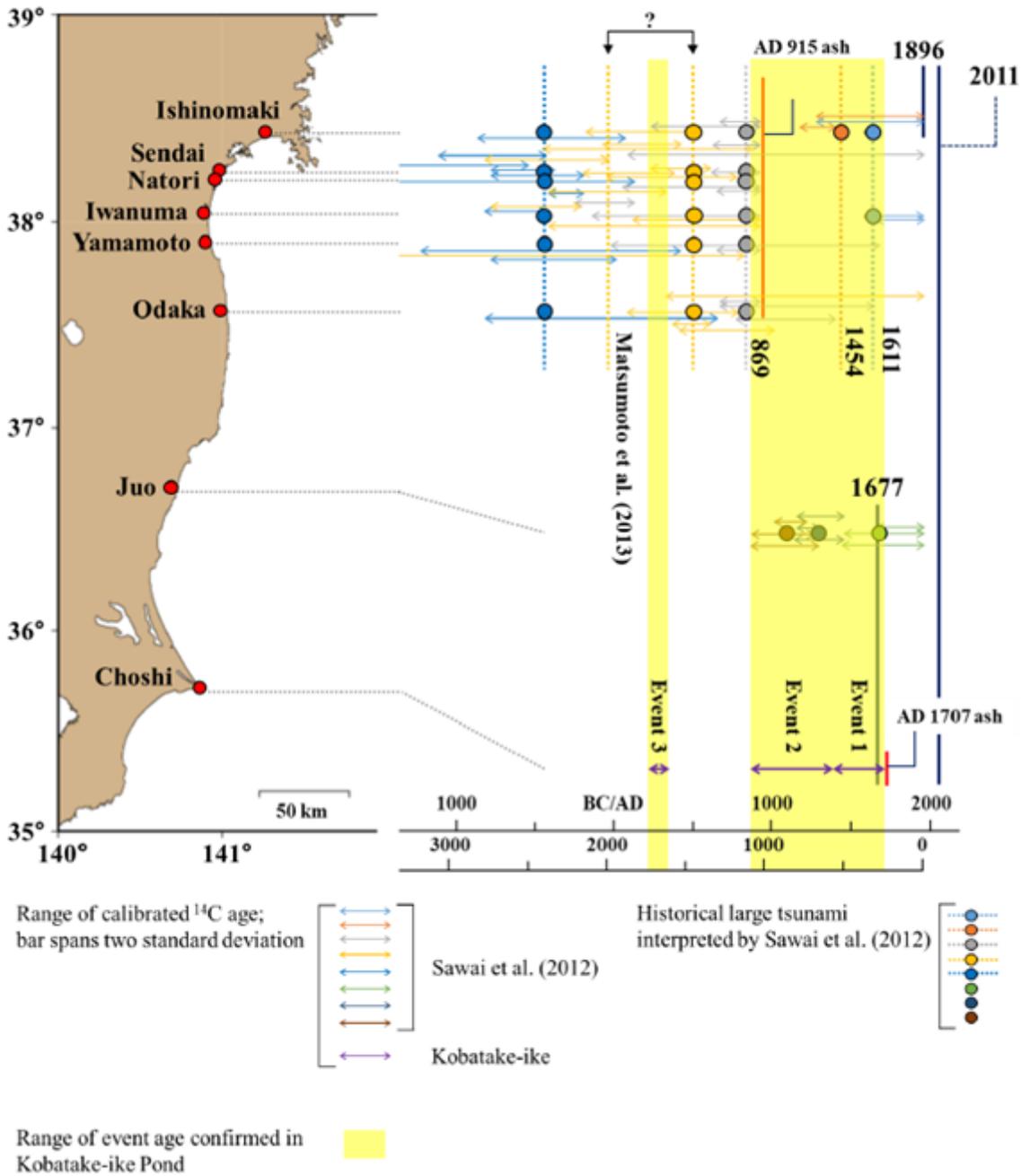


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Paleotsunami histories in the Pacific coasts from Miyagi to Chiba prefecture, which faces the central and southern parts of Japan Trench.

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