Three Thousand Year Paleotsunami History of Southern Part of Japan Trench

Hokuto Higaki (✉ hokuto.higaki.p2@dc.tohoku.ac.jp)

Tohoku Daigaku <https://orcid.org/0000-0002-1877-7075>

Kazuhisa Goto

Tokyo Daigaku Daigakuin

Hideaki Yanagisawa

Tohoku Gakuin Daigaku

Daisuke Sugawara

Tohoku Daigaku

Takashi Ishizawa

Tohoku Daigaku

Research article

Keywords: Tsunami deposit, Radiocarbon dating, ITRAX, Southern part of Japan Trench

Posted Date: August 6th, 2020

DOI: <https://doi.org/10.21203/rs.3.rs-50008/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Version of Record: A version of this preprint was published at Progress in Earth and Planetary Science on April 25th, 2021. See the published version at <https://doi.org/10.1186/s40645-021-00415-w>.

Abstract

Paleotsunami studies along the southern part of Japan Trench are scarce. Additional geological evidence must be collected. This study conducted field survey and multi-proxy analysis for drilling cores taken from a pond of Choshi City, Chiba prefecture, Japan, where the 1677 Enpo tsunami deposit was reported earlier. The pond is suitable for detection of sedimentary evidence of low-frequency but large tsunamis only because it is located at a high elevation (11 m). Three event deposits are intercalated in the three thousand year long continuous mud and peat sequences. Based on multi-proxy analyses conducted of grain size distributions, diatom assemblages, and geochemical markers, these event deposits were identified as tsunami deposits; the most recent was the AD 1677 Enpo tsunami. The estimated recurrence interval of the tsunami is approximately 700 years, which is comparable to those of the central part of the Japan Trench. It is noteworthy that the timing of these tsunami events along the southern part of the Japan Trench seems to have been close (few tens of years intervals) before or after the occurrence of large earthquakes and tsunamis along the central part of the Japan Trench. Therefore, a spatial-temporal relation of earthquake and tsunami generations might exist between central and southern parts of the Japan Trench, which might be explained by drastic changes of stress fields surrounding the rupture area of a huge earthquake. Considering the current situation, by which the Mw=9.0 2011 Tohoku-oki earthquake had occurred at central part of the Japan Trench, this possibility should be investigated carefully from perspectives of seismology and history because risks of future occurrence of large earthquake and tsunami events along the southern part of Japan Trench might be extremely high.

Introduction

The 2011 Tohoku-oki earthquake and tsunami, which occurred on March 11, 2011, caused severe damage to the Pacific coast, extending from Tohoku to Kanto region (Toda 2012). As a result of this earthquake and tsunami, efforts to elucidate the paleotsunami events using tsunami deposits and to make use of that knowledge for the long-term risk assessment of huge tsunami events, became attractive to society (Sugawara et al. 2012). The tsunami deposits are useful to identify tsunami events having time scales of more than the past hundreds of thousand years. Therefore, they are effective for detecting huge tsunami events with a long recurrence interval (Sawai 2012). However, areas where sufficient investigations are conducted are limited along the Japanese coast (Goto et al. 2012). Further comprehensive paleotsunami research is necessary.

Since the 2011 Tohoku-oki event, many researchers have studied paleotsunami deposits along the Pacific coasts facing the Japan Trench to reevaluate paleotsunami histories along the central to northern parts of the Japan Trench (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; Tanigawa et al. 2014b; Watanabe et al. 2014, see also Sawai 2017, accepted). For instance, two event layers for the past 6000 years were reported in a meadow of Misawa city, Shimokita Peninsula, Aomori prefecture (Fig. 1, Tanigawa et al. 2014b). In the Sanriku region, the recurrence interval of the huge tsunamis was estimated as 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 Japan Trench, the paleotsunami history for the past 3000 years was obtained, including historically well-known tsunamis such as the 869 Jogan, the 1611 Keicho and the 1454 Kyotoku tsunamis (Sawai et al. 2012). Others also reported a prehistoric tsunami occurring approximately 2,000 years ago in the Sendai and Ishinomaki plains (Matsumoto et al. 2013).

In contrast to the many paleotsunami studies at the coast facing the northern and central part of Japan Trench, very few reports describe historical and prehistoric tsunami deposits in the area facing to the southern part of the Japan Trench (i.e., Ibaraki to Chiba prefectures) because it was believed that few locations there are suitable for research as a result of urbanization of the coastal regions. Sawai et al. (2012) reported three event layers for the past approx. 1,000 years at northern Ibaraki at Juo Town (Fig. 1a, Sawai et al. 2012). Yanagisawa et al. (2016) conducted historical and geological studies of the 1677 Enpo Boso-oki tsunami at Kobatake-ike pond in Choshi city. Moreover, they identified the deposits formed by the 1677 Enpo earthquake tsunami. Nevertheless, no unified explanation of paleotsunami history in the southern part of Japan Trench has been reported to date.

Simons et al. (2011) and Toda et al. (2011) reported from seismological studies that the strain balance has changed at the southern part of Japan Trench as a result of the 2011 Tohoku-oki earthquake and also indicated the possibility that future occurrence of large earthquakes in this region has increased. In fact, historical records show that large tsunamigenic earthquakes in the southern part of Japan Trench occurred in the past; the 1677 Enpo Boso-oki earthquake and tsunami is one such event (Hatori 2003). The area affected by this tsunami extended over 600 km, with maximum run up height of approximately 13 m in Choshi city (Hatori 2003; Takeuchi et al. 2007; Tsuji et al. 2012). Although no predecessor of this event is known, local tradition at the Tokai shrine (located in Takagaminishimachi) in the city indicates that the shrine was affected by a tsunami occurring in AD 976, after which the shrine was relocated from Hiyoriyama in Tokawamachi (Fig. 1) to the Takagami area (Choshi Geopark Promotion Council office 2016).

Considering the background presented above, the pursuit of further paleotsunami research at Kobatake-ike pond in Choshi city is undoubtedly important because this pond is located 500 m inland from the shoreline at a high elevation (11 m), so that not only storm waves but also small and medium-scale tsunamis cannot inundate it (Yanagisawa et al. 2016). Therefore, evidence of seawater invasion in the pond can directly indicate the occurrence of a past tsunami as large as the AD 1677 event. For this study a geological survey and sedimentological and geochemical analyses were conducted at Kobatake-ike pond to elucidate the paleotsunami history in the southern part of Japan Trench until a few thousand years ago.

Study area

Coastal lakes and marshes are regarded as suitable locations for paleotsunami research because sediment is not disturbed by human activity, even in urbanized areas (Sawai 2012). Kobatake-ike pond is one such coastal lake that also happens to be located at high elevation (Fig. 1b), which offers great benefits for estimating the histories and sizes of large tsunamis.

Choshi Peninsula, which includes Kobatake-ike pond, is located at the eastern edge of the Kanto Plain. Late Pleistocene marine terraces consisting of upper and lower Shimousa surfaces are distributed in the southern part of the peninsula and surrounding Mt. Atago, where a Mesozoic formation is exposed (Kashima 1985). 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) reported that the Takagami lowland had emerged above sea level by approx. 5000 yrBP and that marine terraces were formed. Thereafter, Takagami lowland continued to rise to its present elevation. The average uplift rate is estimated as approx. 0.4 m/kyr (Ota et al. 1985). Kashima et al. (1990) showed, based on results of diatom analysis, that the marine transgression started at 10000 yrBP; a drowned valley began to form. They also reported that sea level had probably reached almost present-day levels at about 7000 yrBP and that temporary desalination occurred at 7000–6000 yrBP in the Takagami lowland. About 3000 yrBP, desalination had finished across the Takagami lowland. No evidence of transgression since then has been confirmed (Kashima 1985).

According to the summary of study area by Yanagisawa et al. (2016), at the east side of the coast are 13–20 m high beach ridges. No historical or measurement records indicate that the pond was inundated by storm surges and waves over 400 years (Yanagisawa et al. 2016). The water of this pond is provided from a spring of Mt. Atago-yama located southwest of the pond. This pond is a freshwater environment used as an agricultural reservoir with 0.03 m² area and 0.5 m average water depth. Yanagisawa et al. (2016) obtained drilling cores from the pond and identified two sand layers from the cores; the upper sand layer is interpreted as the AD 1677 Enpo tsunami deposit, although the origin and the age of the lower sand layer are uncertain. They also demonstrated that the magnitude of the AD 1677 earthquake is inferred as Mw=8.34–8.63, which is similar to the AD 1896 Sanriku earthquake (Mw 8.3–8.6) which occurred along the northern Japan Trench (Fig. 1a).

Methods/experimental

Field survey

In August 2016, 11 drilling cores were taken from the pond floor (Fig. 1). To retrieve the cores, a 100-cm-long Russian peat sampler was used (Jowsey 1966). After measuring the water depth, we obtained a first core with 100 cm depth from the pond floor. The sediment was soft. The digging aperture of the first hole was buried immediately. Therefore, to take undisturbed sediments deeper than 100 cm, we inserted the corer next to the first hole (within 100 cm). To secure continuity of the sediment, we dug the second core from 20 cm shallower than the bottom of the previous core (i.e., 80–180 cm). We repeated this work until

the corer did not penetrate the ground. Then we obtained up to 400 cm cores from each point to produce a composite columnar section. Additionally, we used a P-14 core that was taken by Yanagisawa et al. (2016) because the core is long. Some preliminary radiocarbon dating, which is useful for our discussion, was performed.

Laboratory analyses

Upper and lower boundaries of the tsunami deposits are well known to be ambiguous to visual observation sometimes (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 of the chemical composition of the sample (Boespflug et al. 1995). We used CT scanning for all core samples that we took plus 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.) of the Center for Advanced Marine Core Research at Kochi University.

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). The presence of marine diatoms was reported in this deposit. Therefore, we emphasized our analysis of older event deposits. Samples were collected from the mud and peat sediments above and below the event deposits. Diatom shells were categorized into marine, marine-brackish, brackish, and freshwater taxa based on descriptions reported by Kosugi (1988) and Ando (1990).

The P-14 core is representative. Therefore, we used it for additional high-resolution radiocarbon (^{14}C) dating to construct an age–depth model. We picked seven organic materials (e.g., seeds and plant fragments) from the P-14 core. Following methods described by Ishizawa et al. (2017), bulk samples were also collected at 12 horizons of P-14 core and 1 horizon of KBT4 core, the latter of which was used for correlation of the cores. Then ^{14}C dating was conducted using accelerator mass spectrometry (AMS) 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 (Bronk Ramsey 2009b) in the OxCal program; then we constructed an age–depth model.

Geochemical signatures are useful as evidence of inland seawater invasion for paleotsunami 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) of the Center for Advanced Marine Core Research at Kochi University to examine the chemical characteristics of event deposits. The Mo tube was used. The voltage and current were set respectively as 30 kV and 55 mA. 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 procedures described by Bouchard et al. (2011) and by Judd et al. (2017).

Results

Sedimentary facies and stratigraphy

In the lower half of the core, the stratigraphy consists mainly of black humic peat that includes many plant fragments (Fig. 2). Then, a 100–200-cm-thick black mud layer covers the peat layer to the pond floor. Because this boundary at mud and peat layers is expected to indicate major environmental change at this pond, we call this boundary the “mud–peat boundary” hereinafter. At some coring sites, 1–3 sand layers consisting of fine to medium sand and locally showing normal grading and inverse grading, were interbedded within humic peat and the mud layer (Table 1). These sand layers have clear upper and lower boundaries. The thickness of all sand layers was measured carefully using CT images (see Appendix). The sand layer thickness varies among the cores. In fact, KBT3, KBT7, and KBT9 have no sand layer (Table 1). KBT4 core exhibits slightly different lithology because there seem to be three sand layers (Fig. 2). Therefore, we separately performed some more analyses for this core and finally confirmed that the middle sand layer was probably formed simultaneously with the lower sand layer (see Appendix). Therefore, we identify that two sand layers exist in the pond, as reported by Yanagisawa et al. (2016).

CT image further shows that the whitish layer with high CT numbers are 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.

Diatom analysis

We firstly measured the diatom assemblage at the mud–peat boundary in the P-14 core, because this boundary may indicate important local environmental changes. At this boundary, the main species are generally freshwater species, whereas minor marine and marine-brackish species (<5%) are observed just below the mud–peat boundary at 165 cm depth (Fig. 3). The percentage of marine, marine-brackish and brackish species becomes drastically higher immediately above the mud–peat boundary (Fig. 3). At 155 cm depth, although the percentage of brackish species is decreasing, the percentage of the marine species is increasing. The total percentage of the marine and brackish species exceeds 20% (Fig. 3).

At 272–292 cm depth, the vertical distribution of diatom assemblages shows that the freshwater species are generally dominant (Fig. 3). At 284 cm depth in the lower part of the sand layer, however, the percentage of marine, marine-brackish, and brackish species are, respectively, approximately 0.5%, 0.5%, and 3%. Below the sand layer 292 cm depth, marine and brackish species percentages are, respectively, approximately 0.5% and 2%. Above the sand layer at depth of 272 cm, marine, marine-brackish, and brackish species percentages were approximately 1%, 0.5%, and 6%, respectively (Fig. 3).

Radiocarbon dating

Radiocarbon dating revealed that the P-14 core presents the geological record since B.C. 1129 (Table 2, Fig. 4). The depositional ages of the sand layer at depth of 80–86 cm, and the mud–peat boundary and the sand layer at depth of 278–287 cm can be constrained respectively 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 5. Scattering ratio (Mo inc/Coh) is regarded as a proxy for organic matter (Guyard et al. 2007). The Mo inc/Coh ratio of the mud layer is lower than the underlying peat, suggesting that sediments in the mud layer are poor in organic matter.

Although each elemental profile exhibits subtle variations with the mud and peat layer, the Si, K, Fe, and Ti profiles show a trend by which their concentration in peaty sediment is lower than those in muddy sediment. The elemental profiles for Ca and Sr exhibit a distinct and sharp increase in counts/kcps around mud–peat boundary at 165 cm depth.

Unlike the mud and the peat layers, the lower Mo inc/Coh ratios of the sand layers at depth of 80–86 cm and 278–287 cm indicate that these sand layers are poor in organic matter. By contrast, Si and K profiles show a distinct increase in counts/kcps at both sand layers. Furthermore, slight peaks of Ca and Sr in counts/kcps occur at 80–86 cm and 278–287 cm depth. Although the concentrations of Fe and Ti show no remarkable change at 80–86 cm depth, a distinct increase is apparent at 278–287 cm depth. However, the Mn profile has few apparent changes at both sand layers compared with the mud and peat deposits. The S profile shows no characteristic peak in counts/kcps at 80–86 cm or 278–287 cm depth, but it exhibits a sharp increase in counts/kcps at 275 cm depth immediately above the sand layer.

Discussion

Correlation of event deposits

This study revealed that mud and peat layers were deposited continually in the Kobatake-ike pond during last 3000 years. Among them, we identified two distinct sandy deposits interbedded within black mud and peat layers. These sandy deposits have clear upper and lower boundaries. Some sandy deposits show normal grading and inverse grading (see also grain size results presented separately in the Appendix).

Considering the depositional environment of this pond, the presence of sand layers is unusual because there is no source of sand exists. Therefore, we identified them as event layers. In addition, although no visible sand layer exists at the mud–peat boundary, CT images suggest that there are minor sands. Geochemical signatures show other evidence that Ca and S profiles exhibit a distinct increase in

counts/kcps compared to normal sediment (Fig. 5). Therefore, we infer that a depositional event might have occurred at this boundary.

Based on the stratigraphy and ^{14}C ages, these event layers were correlated among cores. These event layers were named event layers 1–3 in descending order. Figure 2 shows the correlation of event layers among cores.

Identification of tsunami deposits

The present 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 event layers. In Choshi peninsula, even if considering uplift and sea level changes, this pond is regarded as having been located on a hill far from the sea for the last 3000 years (Ota et al., 1985; Kashima et al., 1990). Therefore, it is very unlikely that Kobatake-ike pond was changed into marine-brackish environment by the relative sea level change. Furthermore, Yanagisawa et al. (2016) performed numerical simulation of the 1677 Enpo tsunami inundation for Kobatake-ike pond, which revealed that an earthquake with intensity greater than $M_w=8.3$ is necessary for tsunami waves to reach Kobatake-ike pond. They also indicated that no historical or measurement record suggests pond inundation by storm surges or waves over the last 400 years and excluded possibility of storm wave deposition in the pond. Therefore, we inferred that only tsunamis can inundate the Kobatake-ike pond.

Based on analyses of tephra, macrofossil and historical documents as well as ^{14}C dating by Yanagisawa et al. (2016), event layer 1 was already identified as originating from the 1677 Enpo tsunami deposit. We agree with their interpretation.

Given that event layer 3 is a far more distinct sand layer than event layer 2, we first discuss the origin of event layer 3. Lithostratigraphical observations and CT image revealed that the KBT4 core shows normal grading and inverse grading. A similar sedimentary structure is typically reported for deposits formed by the recent large 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) proposed 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. Sawai (2012) also reported that inverse grading can be interpreted as grain coarsening because of the passage of suspended sediment with acceleration of flow. Therefore, these structures can be regarded as the characteristic features of the tsunami deposits.

Results of diatom analyses further provided direct evidence of seawater inundation. A few marine and brackish species were observed in event layer 3 (Fig. 3), which suggests that an inflow of seawater to Kobatake-ike pond coincided with event layer 3 deposition. It is noteworthy that marine and brackish species were also observed in normal sediments above and below event layer 3 (Fig. 3). 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 are also

known as tending to be preserved in organic or fine sediments (e.g., Chagué-Goff 2010). Yanagisawa et al. (2016) showed that a similar infiltration process might occur for diatoms because they are sufficiently small to behave like mud to silt particles. Therefore, our result can also be considered that diatoms might flow down through the pores below the sand layer. Presence of marine-brackish diatoms in the muddy sediment above event layer 3 indicates that the part of the mud layer above the sand layer is an extension of event layer 3, as the grain size distribution and CT images indicated (see also Fig. S1).

Geochemical signatures also show some characteristics of event layer 3 (Fig. 5). Ca and Sr profiles exhibit a distinct increase in event layer 3. Because Ca and Sr concentrations in seawater are generally known to be higher than in freshwater (Wedepohl 1971), Ca and Sr profiles and the presence of marine diatoms indicate that seawater flowed into the Kobatake-ike pond. In addition, a sulfur (S) peak in count/kcps is recognized in event layer 3, which is higher in seawater than in freshwater (Casagrande et al. 1977; Chagué-Goff 2010; Goff et al. 2012). Si and K are mainly contained in rock-forming minerals. Their profiles show a distinct increase in event layer 3, similarly to other seawater indicators (Fig. 5); Si is a main element of silicate minerals such as quartz and feldspar (Chagué-Goff 2012). Feldspar, pyroxene, and amphibole also contain K or Ca (Chagué-Goff 2012). Furthermore, these minerals are commonly found in beach sand in the area (Sudo 2006). Therefore, it can be considered that tsunami waves eroded and transported beach sand into Kobatake-ike pond. By contrast, Fe and Ti are main elements of heavy minerals. These elements are therefore regarded as signature materials of terrestrial sources (Chagué-Goff 2012; Hadler et al. 2015; Ramírez-Herrera et al. 2012; Williams et al. 2011). Therefore, increasing Fe and Ti in event layer 3 can also be interpreted as a result of erosion and transportation of the beach sand with heavy minerals by tsunami waves. Based on these sedimentological, geochemical, and paleontological results, we identified event layer 3 as a tsunami deposit.

Although no visible sand deposit is observed, the bottom of event layer 2 is defined at the mud–peat boundary. Indeed, a whitish layer with high CT numbers exists at the bottom of mud layer (see Appendix), suggesting that relatively coarse grains were contaminated in this part. In case of the 2011 Tohoku-oki tsunami, thick sandy deposits were usually reported near the coast but no sand layer is 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 case of small tsunamis (Judd et al. 2017). It is pointed out that geochemical signatures are effective to identify such subtle evidence of minor tsunami events (Chagué-Goff 2010; Judd et al. 2017; Minoura and Nakaya 1991).

ITRAX analysis revealed higher counts of Ca/kcps, S/kcps, and Sr/kcps around the mud–peat boundary at 165 cm depth (Fig. 5). Diatom analysis also shows that marine, marine-blackish and brackish species are all contained (Fig. 3). These results suggest that the seawater inundation probably occurred at this timing. Therefore, although the tsunami left no sand layer, event layer 2 can be regarded as having been formed by tsunami waves, probably because the tsunami supplied less sediment than event 1 or 3.

Radiocarbon dating revealed the depositional age of event layer 2 is AD 896–966 (2 σ). Actually, this age range is close to the tradition of the tsunami that might have struck the Choshi area in AD 976 (Choshi

Geopark Promotion Council Office 2016). Therefore, it is reasonable to conclude that AD 976 tsunami is the one which formed event layer 2.

The change of lithology from peat to mud also occurs simultaneously to the formation of event layer 2. The formation of mud and peat layer is generally regulated by the balance of plant production and decomposition (Sakaguchi 1974). The peat layer is formed mainly by deposition of the plant residue that is broken down imperfectly when the plant production is superior to decomposition (Sakaguchi 1974). In the present environment of the pond, no plants grow in the central part and hence, mud is deposited, while the outer rim of the pond is covered by reeds, although there is no marked difference in water depth. Hence, a chance exists that peat is developed in some parts of the present pond. Therefore, it is likely that a slight change of water depth might markedly affect the mud or peat layer formation. If this is the case, then the water depth might have been increased simultaneously to the deposition of event layer 2 to change the depositional environment from peat to mud. Although slight co-seismic subsidence is one possibility, one cannot exclude other possibilities that must be examined carefully.

Sedimentation rate of Kobatake-ike pond

It might be readily apparent from the age–depth model (Fig. 4) that the sedimentation rate changes suddenly near the mud–peat boundary. The rate is about 1 m/kyr below the boundary, but it is higher above the boundary. If this sedimentation rate is reflective of actual conditions, then the mud sediment deposited between event layers 1 and 2 about 100 years (Fig. 4). Furthermore, a large time gap separates layers below and above that marking 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 the large time gap that occurred below and above the tsunami deposit (Shinozaki et al. 2015). However, approx. 4 m thick sediment is expected to have been eroded by the tsunami associated with event 1 (=1677 Enpo tsunami) if one considers the sedimentation rate between events 1 and 2. Such significant erosion is unlikely to have occurred at the high elevation of Kobatake-ike pond together with a historical account of the 1677 Enpo tsunami. Indeed, Yanagisawa et al. (2016) reported that radiocarbon dating of plant materials obtained from the muddy sediment below event layer 1 in the other core (P-7) was cal year AD 1405–1445. 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 layer 1.

Tsunami mixing model: 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. They also applied radiocarbon dating to this reworked mud layer and demonstrated that the age is almost homogenized. Shinozaki et al. (2015) reported that the muddy tsunami deposits contained a mixture of organic materials of various ages during the last 1100 years by tsunami erosion.

These homogenized dating results are similar to our dating results obtained between event layers 1 and 2 (Fig. 4), so that erosion and deposition of reworked mud might have occurred by the tsunami related to event 2 (Fig. 6). If tsunami reworking of mud took place in association with event 2, then the mud layer above event layer 2 might represent an older age than the actual tsunami age. Similarly to the Suijin-numa case (Shinozaki et al. 2015), this phenomenon might only occur in a soft mud layer: it might not occur in a hard peat layer because mud is more erodible than peat. Actually, homogenized dating results cannot be ascertained above and below event layer 3 (Fig. 4), which is intercalated within the hard peat layer. Therefore, it is unlikely that this phenomenon occurred in association with event 3. It does not affect the sedimentation age of event layer 3.

If this model is correct, then it is difficult to restrict the limiting minimum age of event 2 using homogenized radiocarbon dating results, although the limiting maximum age of event 2 as AD 896–954 is unaffected because the dating result obtained from the hard peat layer below event layer 2 is regarded as having not been reworked. This homogenized mud deposit should have been terminated well below event layer 1 (1677 Enpo tsunami deposit) because radiocarbon dating of plant materials obtained from muddy sediment below event layer 1 in the other core (P-7) was cal year AD 1405–1445 (Yanagisawa et al. 2016), which is well younger than the homogenized age. This 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 model: The dissolved inorganic carbon in water used for photosynthesis by aquatic plants has 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 (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 affected strongly by local reservoir effects and reported dates hundreds of years older than the actual age. In addition, the $\delta^{13}\text{C}$ values of approximately zero to -10‰ were reported in the case of aquatic plants in the lake (Watanabe et al. 2010). These values are heavier than the range of $\delta^{13}\text{C}$ values (approximately -20 to -32‰ , Schwarz and Redman 1978; Watanabe et al. 2010) reported for terrestrial C_3 plants.

At Kobatake-ike pond, dating materials obtained from the peat layer and the top of the mud layer have the $\delta^{13}\text{C}$ values of approximately -22 to -28‰ (Table 2), corresponding to the isotopic compositions of terrestrial plants. However, the plants obtained at 76–151 cm depth show $\delta^{13}\text{C}$ values of approximately -15 to -19‰ , with 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. Considering the historical maps and the current landscape in the study area, the Kobatake River flowing from Kobatake-ike pond to Na'arai might have been dammed for some reason such as human activities. If so, then the sedimentary environment might have changed from wetland to pond and led to the vegetation change from terrestrial plants to aquatic plants which have heavier isotope compositions. If this is the case, then radiocarbon ages obtained from mud layer between event layers 1 and 2 might be

affected by local reservoir effects and might represent hundreds of years older age than the actual tsunami age.

However, even considering the older radiocarbon ages affected by the local reservoir effects, the sedimentation rate in the mud layer is markedly faster than that of the underlying peat, which indicates that the reservoir effect model failed to satisfactorily explain the homogenized dating results obtained between event layers 1 and 2. Therefore, although the possibility of the reservoir effect model cannot be fully excluded, the tsunami mixing model is necessary to explain the homogenized ages. In this way, although the age of event 2 cannot be constrained well, it is still plausible that the event corresponds to the historically known AD 976 tsunami event because no other historical large tsunami was recorded during the 10–15 Centuries.

Paleotsunami history along the southern and central part of Japan Trench

Our results demonstrated that three large tsunamis struck the studied area: in AD 1677, around AD 976 and around AD 300. The approximate recurrence interval of tsunami events inferred from this result is constant: about 700 years.

In the central part of the Japan Trench, Sawai et al. (2012) conducted a comprehensive survey along the Pacific coast from Miyagi prefecture to northern Ibaraki prefecture. They mainly identified five large tsunami events from the historical and geological evidence in Tohoku region and inferred them as formed by the AD 1611 Keicho tsunami, AD 1454 Kyotoku tsunami, AD 869 Jogan tsunami and tsunami events at AD 400–500 and BC 500–400. Saino (2012) and Matsumoto et al. (2013) reported that a tsunami struck to the Sendai Plain around 2050 yrBP, which was not reported by Sawai et al. (2012) (see also discussion by Sawai accepted). Among them, AD 869 Jogan tsunami (Sawai et al. 2012) and a tsunami occurred at about 2050 yrBP (Matsumoto et al. 2013; Saino 2012) were likely generated at the central part of Japan Trench because tsunami deposits extended far inland, as they did during the 2011 Tohoku-oki tsunami. However, it remains controversial whether the AD 1611 Keicho tsunami was generated by the earthquake along the Japan Trench (Hatori 1975) or Kuril Trench (Hirakawa et al. 2000; Okamura and Namegaya 2011) (Tetsuka et al. in press). Moreover, although Sawai et al. (2015) assumed the source of the AD 1454 Kyotoku tsunami as the Japan Trench, evaluating its source is difficult because historical description and identification of tsunami deposits of the tsunami are both scarce (Goto et al. submitted). Nevertheless, it is noteworthy that the paleotsunami history along the southern part of Japan Trench inferred from our study is well consistent with that of the central part of the Japan Trench (Fig. 7).

The AD 1677 Enpo tsunami occurred in the southern part of Japan Trench approximately 60 years after the AD 1611 Keicho tsunami (Fig. 7). In addition, if event 2 can be correlated to the AD 976 tsunami, our results suggest that a large tsunamigenic earthquake struck the Choshi region about one hundred years after the AD 869 Jogan earthquake (Fig. 7). Furthermore, radiocarbon dating results show that event layer 3 was deposited between AD 234 and 330. This age seems close either to the event in 2050 yrBP (Matsumoto et al. 2013; Saino 2012) or in AD 400–500 (Sawai et al. 2012) along the central part of

Japan Trench, although the error ranges of both tsunami deposits at southern and central parts of Japan Trench are large. Additional careful research must be conducted.

No visible event deposit that can be correlated with the AD 1454 Kyotoku tsunami or the BC 400–500 tsunami event reported in the central part of Japan Trench (Sawai et al. 2012) was identified in the cores obtained from Kobatake-ike pond (Fig. 7). The ITRAX result also shows no geochemical evidence indicating seawater invasion and even suggests that the event layer without a sandy deposit is less likely to exist (Fig. 5). Therefore, possibly, no large tsunami was generated during this period in the southern part of Japan Trench. Or, if it had occurred, then the tsunami was unable to reach the elevation of Kobatake-ike pond (11 m). Regarding this result, however, because of the lack of historical documents and the lack of sufficient quantitative estimation of inundation processes and sources (Sawai 2017, accepted), it is still disputable whether the AD 1454 Kyotoku tsunami and the BC 400–500 tsunami occurred in the central part of the Japan Trench.

The discussion presented above related to correlation of paleotsunami histories between the central and southern parts of Japan Trench might indicate important temporal–spatial relations of the causative large earthquakes between these areas. A large earthquake may have been triggered by the occurrence of a large earthquake at an adjacent area. Occurrence of large earthquakes in different seismic sources during a short term 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 constitute important direct geological evidence to support such concerns.

Conclusions

We identified three tsunami events occurring during the past three thousand years from drilling cores obtained at 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 respectively at AD 976 and AD 234–330. The approximate recurrence interval of the tsunami events is 700 years. This interval is comparable to those estimated around the coasts facing the central part of the Japan Trench. Additionally, results show that the paleotsunami histories, at least the recent two events, in the central and southern parts of the Japan Trench closely occur in a short time interval of a few tens of years. This result implies that a spatial–temporal relation of large earthquake generations (strain accumulation and release) might exist between central and southern part of Japan Trench areas. This possibility should be considered in tsunami hazard assessment.

Abbreviations

yrBP: years before present

Declarations

Availability of data and materials

Please contact author for data requests.

Acknowledgements

We appreciate a landowner for giving us permission to perform surveys. CT imaging and non-destructive XRF analyses were conducted at the Center for Advanced Marine Core Research in Kochi University (accept no. 16A008, 16B008, 17A005 and 17B005). Diatom analysis was commissioned to Paleo Labo Co.,Ltd., Japan. Radiocarbon dating was conducted using AMS at Beta Analytic Inc. in Miami, USA.

Competing interests

The authors declare that they have no competing interest.

Funding

This research was supported by research funding from JSPS KAKENHI Grant Number JP17H02971 and was supported as a commissioned project of the Nuclear Regulation Authority.

Authors' contributions

HH, KG, HY, and DS conducted fieldwork and collected samples. KG proposed the study topic, and also 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 approving the final manuscript.

Author details

¹ Department of Earth Sciences, Graduate School of Science, Tohoku University, Sendai 980-8578, Japan; ² International Research Institute of Disaster Science, Tohoku University, 468-1 Aza-Aoba, Aramaki, Aoba-ku, Sendai 980-0845, Japan; ³(present address) Department of Earth and Planetary Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan; ⁴ Department of Regional Management, Tohoku Gakuin University, 1-3-1 Tsuchitai, Aoba-ku, Sendai 980-8511, Japan; ⁵ Museum of Natural and Environmental History, 5762 Oya, Suruga-ku, Shizuoka, Shizuoka Prefecture 422-8017, Japan

Reference

- Ando K (1990) Environmental indicators based on freshwater diatom assemblages and its application to reconstruction of paleo-environments. *Ann Tohoku Geogr Assoc* 42:73-88 (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
- Boespflug X, Long BFN, Occhietti S (1995) Cat-scan in marine stratigraphy—a quantitative approach. *Mar Geol* 122:281-301
- Bondevik S, Svendsen JI, Johnsen G, Mangerud J, Kaland PE (1997) The Storegga tsunami along the Norwegian coast, its age and runup. *Boreas* 26:29-53
- 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
- Bronk Ramsey C (2008) Deposition models for chronological records. *Quaternary Science Reviews* 27(1-2):42-60
- Bronk Ramsey C (2009a) Bayesian analysis of radiocarbon dates. *Radiocarbon* 51(1):337-360
- Bronk Ramsey C (2009b) Dealing with the outliers and offsets in radiocarbon dating. *Radiocarbon* 51(3):1023-1045
- Casagrande DJ, Siefert K, Berschinski C, Sutton N (1977) Sulfur in peat-forming systems of the Okefenoke Swamp and Florida Everglades: origins of sulfur in coal. *Geochim Cosmochim Acta* 41:161-167
- Chagué-Goff C (2010) Chemical signatures of palaeotsunamis: a forgotten proxy? *Mar Geol* 271:67-71
- 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 869AD Jogan and other palaeotsunamis. *Sedi Geol* 282:65-77
- 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
- Chagué-Goff C, Szczuciński W, Shinozaki T (2017) Applications of geochemistry in tsunami research: A review. *Earth-Science Reviews* 165:203-244
- Choshi Geopark Promotion Council office (2016) A story of blessings of nature and the disaster. The Choshi Geopark (in Japanese)

- Croudace IW, Rindby A, Rothwell RG (2006) ITRAX: description and evaluation of a new X-ray core scanner. In new techniques in sediment core analysis. Geol Soc Lond Spec Publ 267:51-63
- Goff J, Chagué-Goff C, Nichol S, Jaffe B, Dominey-Howes D (2012) Progress in palaeotsunami research. Sedi Geol 243:70-88
- Goto K, Chagué-Goff C, Fujino S, Goff J, Jaffe B, Nishimura Y, Richmond B, Sugawara D, Szczucinski W, Tappin DR, Witter R, Yulianto E (2011) New insights of tsunami hazard from the 2011 Tohoku-oki event. Mar Geol 290:46-50
- Goto K, Nishimura Y, Sugawara D, Fujino S (2012) The Japanese tsunami deposit studies. Jour Geol Soc Japan 118:431-436 (in Japanese, with English abstract)
- Goto K, Ishizawa T, Ebina Y, Imamura F, Sato S, Udo K (submitted) Ten years after the 2011 Tohoku-oki earthquake and tsunami: Geological and environmental effects and implications for disaster policy changes. Earth-Sci Rev
- 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
- 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
- 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 of Kyllini (western Peloponnese, Greece) based on a multi-proxy approach. Z Geomorphol Suppl 59:7-41
- Hatori T (1975) Tsunami Magnitude and Wave Source Regions of Historical Sanriku Tsunamis in Northeast Japan. Earthq Res Inst 50:397-414 (in Japanese, with English abstract)
- 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)
- Hirakawa K, Nakamura Y, Echogo T (2000) Large paleo-tsunamis along the Pacific coast of Tokachi region, Hokkaido. Chikyu Monthly, Special Issue 31:92-98 (in Japanese)
- 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
- 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 Earth Planet Sci 2:1-18

- 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
- Ishizawa T, Goto K, Yokoyama Y, Miyairi Y, Sawada C, Takada K (2018) Reducing the age range of tsunami deposits by ^{14}C dating of rip-up clasts. *Sedi Geol* 364: 334-341
- Ishizawa T, Goto K, Yokoyama Y, Miyairi Y (2019) Non-destructive analyses to determine appropriate stratigraphic level for ^{14}C dating of tsunami deposits. *Mar Geol* 412:19-26
- Jowsey PC (1966) An improved peat sampler. *New Phytol* 65:245-248
- 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
- Kashima K (1985) Holocene diatom assemblages in Takagami Lowland, central part of Choshi Peninsula, and its relation to changes of sea-level. *Quatern Res* 24:125-138 (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. *Quatern Res* 29:139-149 (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. *Quaternary Science Reviews* 14(10):959-966
- Kosugi M (1988) Classification of living diatom assemblages as the indicator of environments, and its application to reconstruction of paleoenvironments. *Quatern Res* 27:1-20 (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
- Matsumoto H, Kumagai M, Yoshida M (2013) Paleo-tsunami deposit of 2050 years ago and its inundation distance, on the Sendai Coastal Lowland, Northeastern Japan. *Journal of Human Informatics* 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. *Natural Hazards* 68:631-643
- 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
- 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*

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

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

Okamura Y, Namegaya Y (2011) Reconsideration of the 17th century Kuril multi-segment earthquake. *Ann Rep Act Fault and Paleoequake Res* 11:15-20 (in Japanese, with English abstract)

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. *Quatern Res* 24:13-30 (in Japanese, with English abstract)

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

Reimer PJ, Bard E, Bayliss A, Beck JW, Blackwell PG, Ramsey BC, Grootes PM, Guilderson TP, Hafliðason H, Hajdas I, Hatte 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

Saino H (2012) Excavated evidence of tsunamis in Sendai plain. *Quarterly of Archaeological Studies* 232:6-11 (in Japanese)

Sakaguti Y (1974) Earth science of peat bog—an investigation of an environmental change. University of Tokyo Press, 329p (in Japanese)

Sawai Y (2012) Study of paleotsunami deposits in geologic stratum. *Jour Geol Soc Japan* 118:535-558 (in Japanese, with English abstract)

Sawai Y (accepted) Subduction zone paleoseismology along the Pacific coast of northeast Japan — progress and remaining problems. *Earth-Sci Rev*

Sawai Y (2017) Paleotsunami research along the Pacific coast of Tohoku region. *Jour Geol Soc Japan* 123:819-830 (in Japanese, with English abstract)

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:L21309

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

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

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

Sudo S (2006) Sand and Beach of Japan (10) Sand and Beach of Ilioka - 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

Sugino H, Korenaga M, Sakagami M, Ebisawa K (2011) Probabilistic Tsunami hazard assessment considering time-lag of seismic event on Nankai Trough. *J Japan Soc Civ Eng Ser B2 (Coastal Engineering)* 67(2):L306 - L310 (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, River Division Department of Prefectural Land Development, Iwate Prefecture Government (2016) Distribution and ages of tsunami deposits along the Pacific coast of the Iwate Prefecture. *Annu Rep Active Fault Paleoeearthquake 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. *The Japanese Geotechnical Society* 8:391-402 (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 Surface Processes and Landforms. Earth Surf Proc Land* 43:4

Takeuchi H, Fuji R, Mimura N, Imamura F, Satake K, Tsuji Y, Hochi 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. *Quatern Res* 53:55-62 (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. *Jour Quatern Sci* 29:200–208
- Tetsuka H, Goto K, Ebina Y, Sugawara D, Ishizawa T (in press) Historical and geological evidence of the 17th-century tsunami(s) along Kuril and Japan trenches: implications to the source of the AD 1611 Keicho earthquake and tsunami. *Geol Soc London Spec Pub*
- 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
- Toda S (2012) Long-term earthquake forecasting associated with the 2011 off the Pacific Coast of Tohoku earthquake. *Japanese Journal of Multiphase Flow* 26:4–10 (in Japanese, with English abstract)
- Tsuji Y, Yanuma T, Hirahata T, Imamura F (2012) Field survey of inundation height of Enpo Boso earthquake tsunami (1677) in Boso Peninsula, Chiba prefecture. *Rep Tsunami Eng Res* 29:209–223 (in Japanese)
- 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. *Journal of Geography* 123(6):904–922 (in Japanese, with English abstract)
- Watanabe T, Matsunaka T, Nakamura T, Nishimura M, Izutsu Y, Minami M, Nara F, Kakegawa T, Zhu L (2010) Last Glacial-Holocene geochronology of sediment cores from a high-altitude Tibetan lake based on AMS ^{14}C dating of plant fossils: implications for paleoenvironmental reconstructions. *Chem Geol* 277:21–29
- Wedepohl KH (1971) Environmental influences on the chemical composition of shales and clays. *Phys Chem Earth* 8:305–333
- Williams S, Prasetya G, Chagué-Goff C, Goff J, Cheung KF, Davies T, Wilson T (2011) Characterising diagnostic proxies for identifying palaeotsunamis in a tropical climatic regime, Samoan Islands. *Proceedings of the MTS/IEEE Oceans 2011 Conference, Kona, Hawaii* 19–22
- 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

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 BP)	$\delta^{13}\text{C}$ (‰)	Beta ID
P-14	45-47	plant material	105.6 $\pm$ 0.4 pMC	NA	-25.5	457714
P-14	55-57	plant material	130 $\pm$ 30	280-170 150-0	-24.4	457715
P-14	65-67	plant material	80 $\pm$ 30	265-220 140-25 0-	-24.1	457716
P-14	76	plant material	1060 $\pm$ 30	1030-1090	-14.9	JGR ¹⁾
P-14	98-100	plant material	1100 $\pm$ 30	1065-935	-18.3	457717
P-14	108-113	plant material	1110 $\pm$ 30	1065-955	-15.9	452555
P-14	125	organic sediment	1750 $\pm$ 30	1720-1570	-22.6	445711
P-14	139-141	plant material	1200 $\pm$ 30	1230-1210 1185-1055	-17.8	457718
P-14	149-151	seeds	1520 $\pm$ 30	1520-1460 1440-1435 1420-1345	-19.4	457719
P-14	165-167	organic sediment	1140 $\pm$ 30	1175-1160 1150-970	-27.9	452556
P-14	171-173	organic sediment	1060 $\pm$ 30	1050-1025 1005-930	-27.1	457720
P-14	181-183	organic sediment	1140 $\pm$ 30	1175-1160 1150-970	-27.8	457721
P-14	200	organic sediment	1280 $\pm$ 30	1285-1175	-27.2	445712
P-14	250	organic sediment	1620 $\pm$ 30	1565-1475	-23.0	445713
P-14	258-261	organic sediment	1770 $\pm$ 30	1770-1760 1735-1610	-22.2	452557
P-14	271-273	organic sediment	1750 $\pm$ 30	1720-1570	-22.1	457722
P-14	277.5-278.5	plant material	1910 $\pm$ 30	1880-1940	-27.7	JGR ¹⁾
P-14	287-288	plant material	1690 $\pm$ 30	1660-1720	-26.5	JGR ¹⁾
P-14	292-294	organic sediment	2470 $\pm$ 30	2720-2365	-23.0	452558
P-14	310	organic sediment	2390 $\pm$ 30	2490-2345	-26.5	445714
P-14	314-316	organic sediment	2330 $\pm$ 30	2360-2325 3080-2922	-25.6	457723
P-14	378-380	organic sediment	2880 $\pm$ 30	2907-2888 3110-3093 3141-3125	-24.7	478070
KBT4-2	132-134	organic sediment	1290 $\pm$ 30	1291-1171	-27.0	487208

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

Figures

Figure 1

(a) Locations of Choshi City and survey points of paleotsunami deposits along the Japan Trench. (b) Surface elevation based on 5 m resolution DEM (Geospatial Information Authority of Japan) showing the Kobatake-ike pond location. (c) Survey points (red dots) in the Kobatake-ike pond. KBT1 to KBT11 are core numbers in this study. A black cross mark shows the location of P-14 core sampled by Yanagisawa et al. (2016).

Figure 2

Stratigraphic comparisons in the sea-land direction based on sedimentary facies and radiocarbon dating. Note that sedimentary facies of the KBT4 core seem different from others, and a detailed explanation is presented in the Appendix.

Figure 3

Relative abundance of diatom assemblages (%) classified into four salinity groups: freshwater, freshwater-brackish, brackish-marine, and marine; upper, mud–peat boundary (event layer 2); lower, sand (event layer 3).

Figure 4

^{14}C dating results for a 2σ probability range. Probability densities of the respective dating results 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.

Figure 5
 Normalized ITRAX XRF data of P-14 core (55-380 cm depth).

Tsunami mixing model

Figure 6

Depositional and erosional processes with depositional curve of tsunami mix model to explain the sedimentation rate change and age gap of the Kobatake-ike pond.

Figure 7

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

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SupplementaryMaterial.pdf](#)
- [SupplementaryManuscript.docx](#)