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Tsunami deposits associated with the 1983 Nihonkai-Chubu earthquake tsunami in coastal forests near Happo Town, Akita Prefecture, Japan

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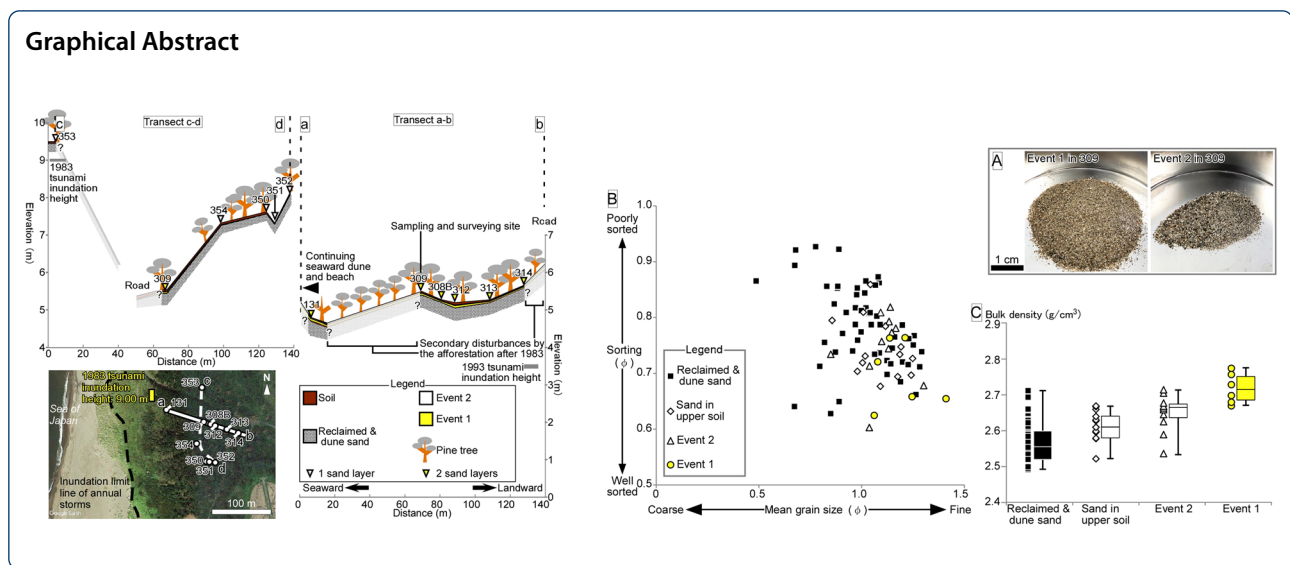
Abstract

On 26 May 1983 the Nihonkai-Chubu earthquake occurred off the western coast of Noshiro City, Akita Prefecture, Japan. The tsunami associated with this earthquake caused widespread damage to the northeastern coastal region of the Sea of Japan, including Akita Prefecture, and left behind sand and mud deposits. These deposits were first described in the 1990s, but have not been studied further. During December 2019 and January 2020, we conducted geological surveys to investigate post-1948 soil thinning in the pine-based coastal protective forests planted near Happo Town. A sand layer that thinned inland was observed in the soil at depths greater than 10 cm. Because the sand layer contained well-preserved fossil brackish–marine diatoms and exhibited a high bulk density, it is likely that the sand was transported inland from the coast. The sand layer was distributed from the coast to 150–270 m inland, but only within the coastal protective forest. By reference to historical records, we concluded that this sand layer was deposited by the 1983 tsunami, because this region could not have been reached by any event other than the tsunami produced by the Nihonkai-Chubu earthquake. We also observed another sand layer above the tsunami deposits, which may have been formed by Typhoon 9119 on 28 September 1991.

Keywords: 1983 Nihonkai-Chubu earthquake, Tsunami deposit, Typhoon 9119, Aeolian sand, Coastal protective forest, Diatom

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Main text

Introduction

The Nihonkai-Chubu earthquake occurred off the western coast of Noshiro City, Akita Prefecture, Japan, on 26 May 1983 (Fig. 1; Aida 1984; Hatori 1984; Satake 1985; Shuto 1984a). The tsunami associated with this earthquake caused widespread damage to the northeastern coast of the Sea of Japan, including the coastal region of Akita Prefecture (Sato et al. 1994, 1995; Tohoku University's School of Engineering and the Japan Nuclear Energy Safety Organization 2020). Sand and mud deposits in the tsunami inundation area were observed and reported during the 1980s and 1990s, but further studies were not conducted in coastal areas along the Sea of Japan (Kamataki et al. 2015, 2016, 2017, 2018; Kawakami et al. 2017; Sato et al. 1994, 1995). Some deposits attributed to historical tsunamis that occurred in the Sea of Japan have been described on Russian Island in the Sea of Japan (Razjigaeva et al. 2018, 2020); however, no historical tsunami deposits with good age constraints have been found along the Japanese coast of the Sea of Japan. Pine trees have been extensively planted in coastal areas of Akita Prefecture, and soil has formed in these forests. Studies of the 2011 Tohoku tsunami deposits revealed that tsunami deposits can be preserved in such coastal pine-forest environments along the Pacific coast of northeastern Japan (Bellanova et al. 2021).

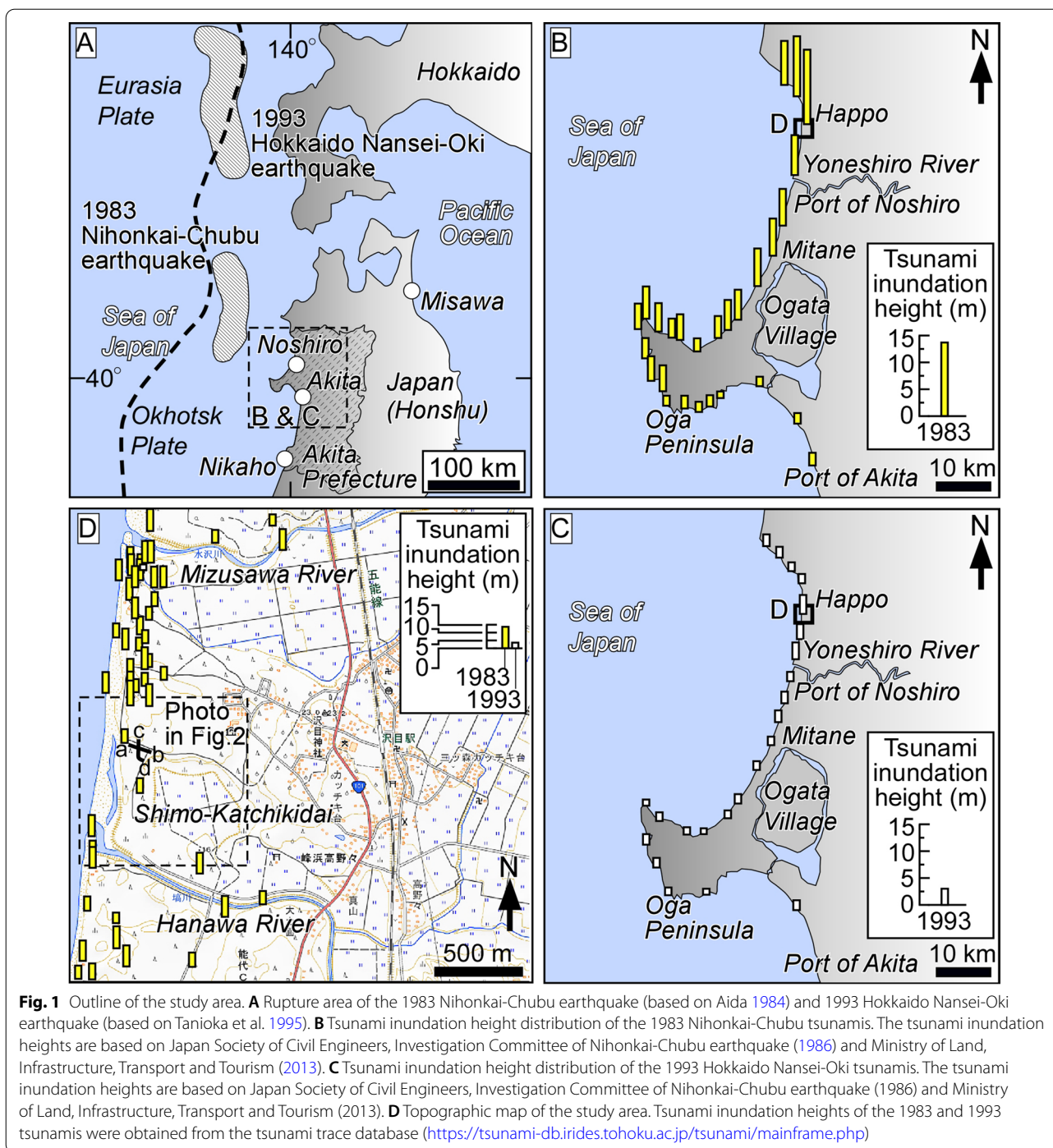
In some cases, tsunami deposits can be difficult to distinguish from other event deposits (Komatsubara et al. 2008; Costa and Andrade 2020; Sawai 2012); for example, sand dunes formed of aeolian sand occur along the coast of the Sea of Japan, and can migrate during events, such as typhoons (Endo 2017; Matsubara 2000; Totman 1985). Therefore, it is important to distinguish between tsunami deposits and aeolian sand

along the coast of the Sea of Japan, where high dunes are developed (Kaizuka et al. 1985) and overwash caused by storm surges is relatively rare.

Tsunami deposits with well-constrained ages are important for recording disasters, as well as for estimating post-depositional changes, such as weathering and early diagenesis (Goto et al. 2021; Nishimura 2009). Herein we document the basic geological characteristics of tsunami deposits and aeolian sand, including their distributions, grain-size parameters, and diatom assemblages, in Happo Town, Akita Prefecture. Our aims in this study were to assess the characteristics of sediments for which the elapsed time after deposition is known from historical records, and to attempt to distinguish between tsunami deposits and sediments formed by other mechanisms, such as aeolian sand.

Coastal dunes on the northern Sea of Japan coast

On the Sea of Japan coast, including the study area, high sand dunes are formed by strong winds (Kim et al. 2009; Kaizuka et al. 1985; Koike 1982; Tamura 2016). Due to the meteorological conditions, storm surges are uncommon in the Sea of Japan (Hiyajo et al. 2011); in addition, the daily tide level difference is small, averaging a few tens of centimeters (e.g., Saitoh et al. 2011; Yamanaka and Shimozono 2022), so wave heights rarely exceed the elevation of the sand dunes even during storm surges. In fact, in Happo Town on the northern Sea of Japan coast, there are no records of great storm surges and overwash inundations having occurred between 1983 and 1993 (Minehama Village 1995). Coastal protective forests have been planted to block wind and trap aeolian sand (Abe et al. 2013).



Coastal protective forests near Happo Town

The coastal protective forests in the study area mainly consist of Japanese black pine (*Pinus thunbergii*) and have been managed by Akita Prefecture since 1952. Before the pines were planted, this area was covered by dunes (Abe et al. 2013) (Fig. 2). Dune sand was still present at the surface in the coastal area immediately after

the Japanese black pines had been planted. The sand subsequently became covered by vegetation (Fig. 2). The region was designated as an erosion control and windbreak protection forest in 1982. During the 1983 Nihonkai-Chubu earthquake, part of the forest died as a result of the tsunami (Abe et al. 2013; Akita Prefectural Earthquake Countermeasure Group 1984; Harada

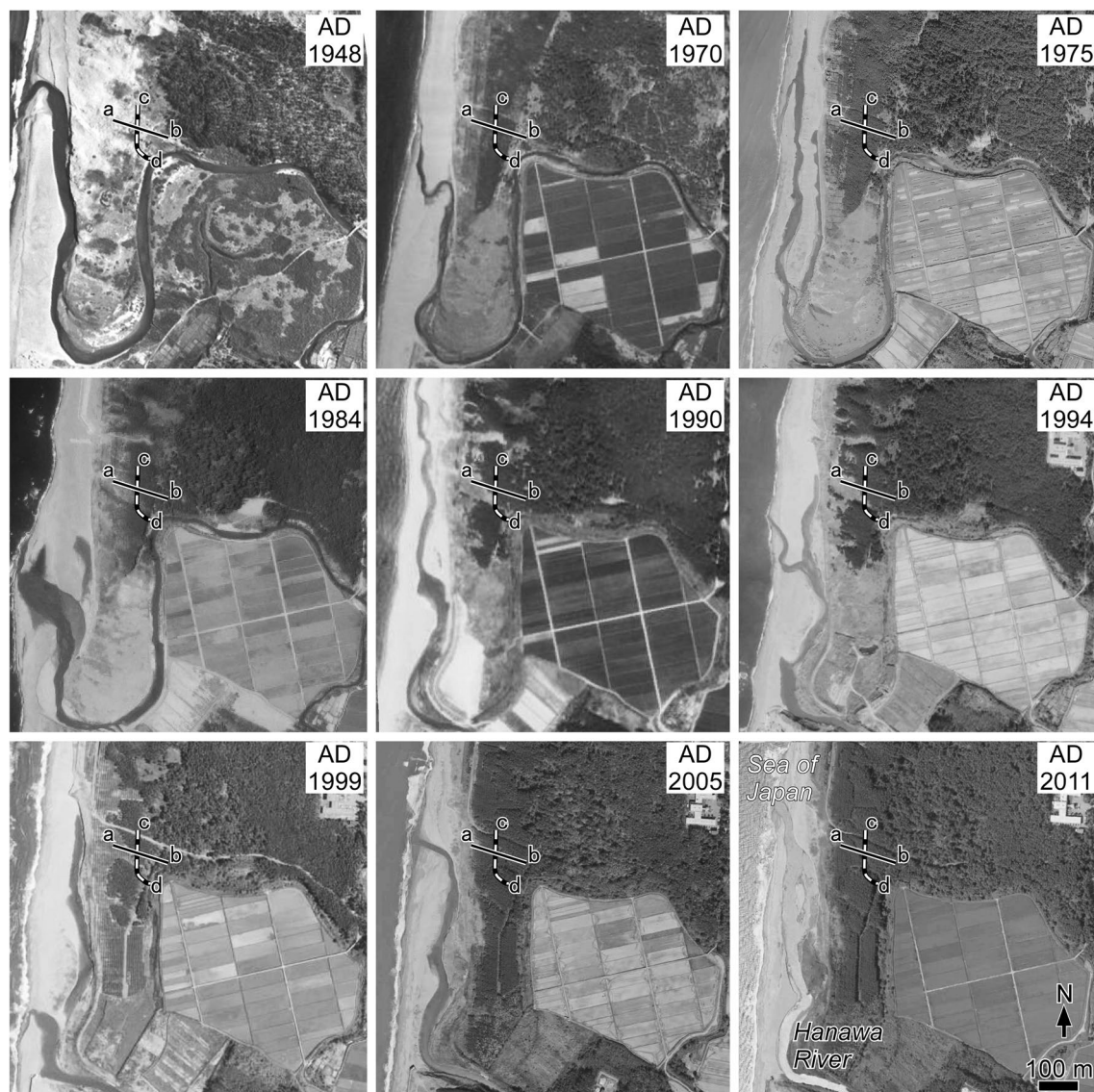
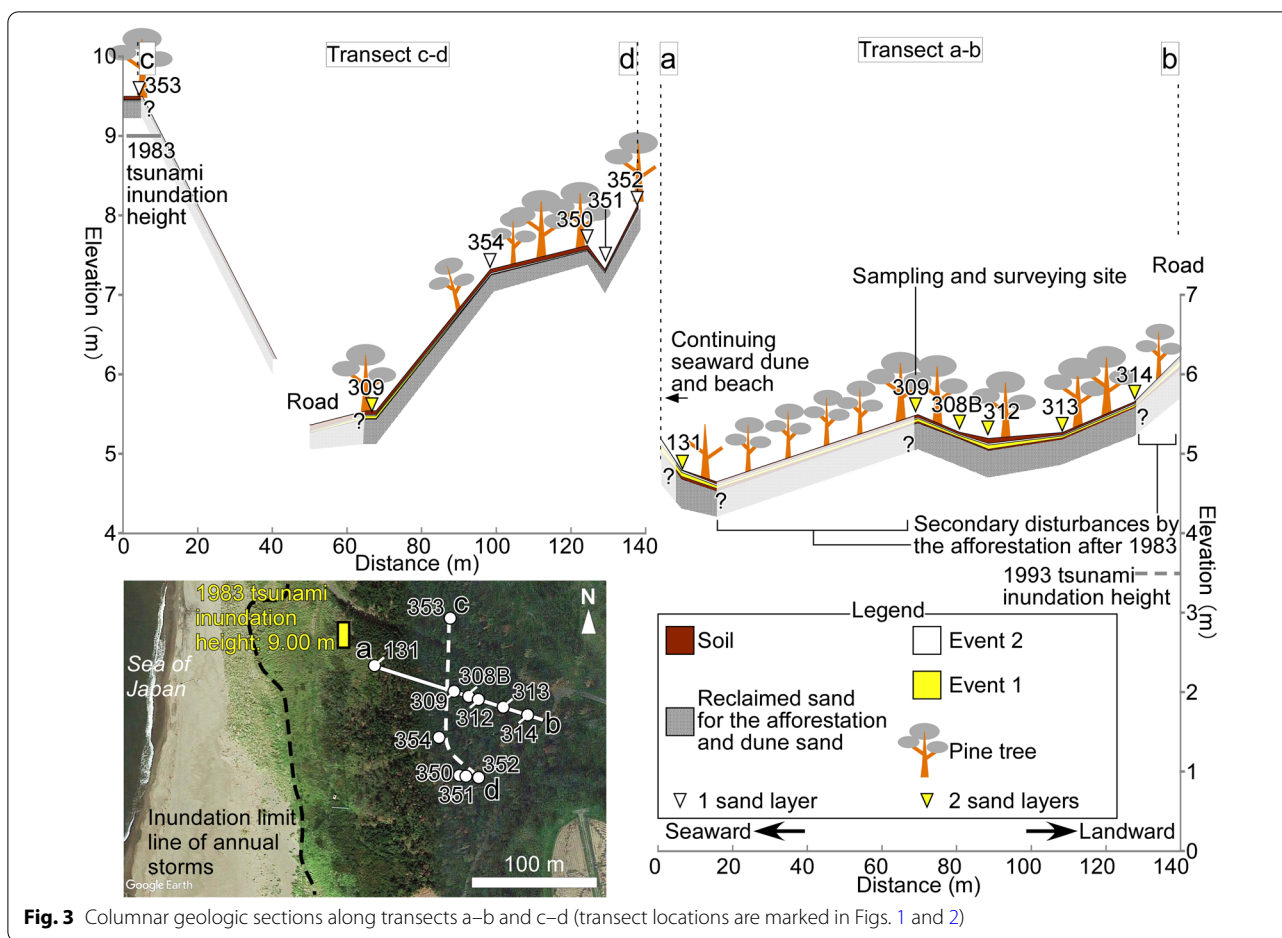


Fig. 2 History of topographic and land-use changes around Shimo-Katchikidai on the northern Akita coast, based on aerial photographs taken by the Geospatial Information Authority of Japan from 1948 to 2011 (Geospatial Information Authority of Japan 2022). The positions of the transects (a–b and c–d) shown in Fig. 3 are marked

and Imamura 2006; Tanaka 2009). The 1983 tsunami deposits have been recognized in rice paddies along the Hanawa River and reported by Sato et al. (1994). Except for the 1993 Hokkaido Nansei-Oki earthquake tsunami, no major floods or tsunamis have occurred in this region since the 1983 Nihonkai-Chubu earthquake (Abe et al. 2013). However, the tsunami inundation heights of the 1993 Hokkaido Nansei-Oki earthquake were less than 2 m in most coastal areas of Akita Prefecture (Hatori 1994). In Akita Prefecture, the Mizusawa River mouth had the highest inundation height, reaching 3.47 m in Happo Town (Fig. 1). However, the

inundation height was lower than those in our study area (Fig. 3) (Shuto 1994; Shuto and Matsutomi 1995); therefore, it is unlikely that the 1993 tsunami reached the level of the coastal protective forests. Moreover, no human damage was incurred by the 1993 tsunami in Akita Prefecture (Noshiro City 2017). Although pine trees were also planted in the river mouth area of the Hanawa River from April 16 to May 14, 1992, there was no damage to the trees in this study area due to the 1993 Hokkaido Nansei-Oki Earthquake Tsunami (Akita Prefecture 1993; Minehama Village 1995).



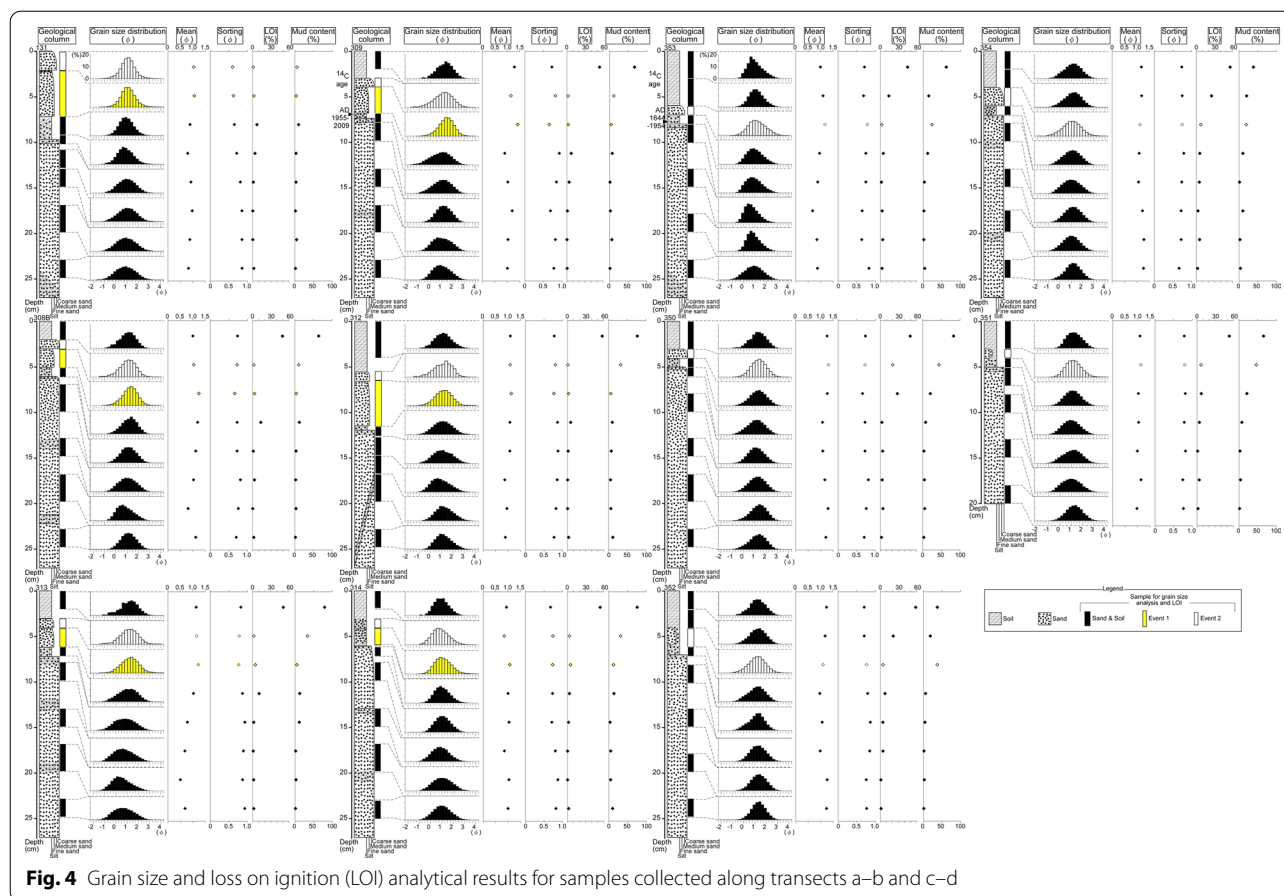
Materials and methods

Many traces of the 1983 tsunami have been observed and recorded near the Hanawa River (Fig. 1). At the closest site to transect a–b, the tsunami inundation height was 9.00 m (Shuto 1984b). This tsunami inundation height was judged to be highly reliable (Tohoku University’s School of Engineering and the Japan Nuclear Energy Safety Organization 2020), because it was obtained in a survey using a hand level and tape measure. The inundation height of the 1993 Hokkaido Nansei-Oki tsunami in the Mizusawa River mouth (3.47 m, Fig. 1) was also judged to be highly reliable (Tohoku University’s School of Engineering and the Japan Nuclear Energy Safety Organization 2020). We investigated topographical and land-use changes in the study area using aerial photographs (Geospatial Information Authority of Japan 2022) to select survey sites and estimate topographical changes in the area (Fig. 2). We conducted a topographical survey in the coastal protective forest at Shimo-Kat-chikidai using a GPS (Promark3, Magellan, USA) and a laser range finder (Impulse 200LR, Laser Technology Inc., USA) (Fig. 3), in which we established transects a–b

and c–d. Elevations above sea level along transect a–b (sites 131, 309, 308, 312, 313, and 314) were 4.4 to 6.2 m; those along transect c–d (sites 353, 309, 354, 350, 351, and 352) were 5.3 to 9.5 m. We also obtained 25-cm-long core samples from each of the survey sites using a Handy Geoslicer. Sub-samples were obtained from the cores for grain-size analyses, loss on ignition (LOI) measurements, radiocarbon dating, and microfossil analyses. We referred to Engel and Brückner (2011), Jagodziński et al. (2012), Costa et al. (2015), and Goto et al. (2017) for identifying tsunami deposits.

The samples used for grain-size analyses were weighed after drying at 110 °C, then washed ultrasonically several times to remove mud. Bulk density measurements were conducted using the helium pycnometric technique with an AccuPyc 1330 (Micromeritics, USA) (Viana et al. 2002).

For the grain-size analyses, the grain size was determined using a CAMSIZER X2 (Retsch Technology GmbH, Germany). Grain-size statistics were analyzed using the GRADISTAT software package (Blott and Pye 2001) following the methods described by Folk and



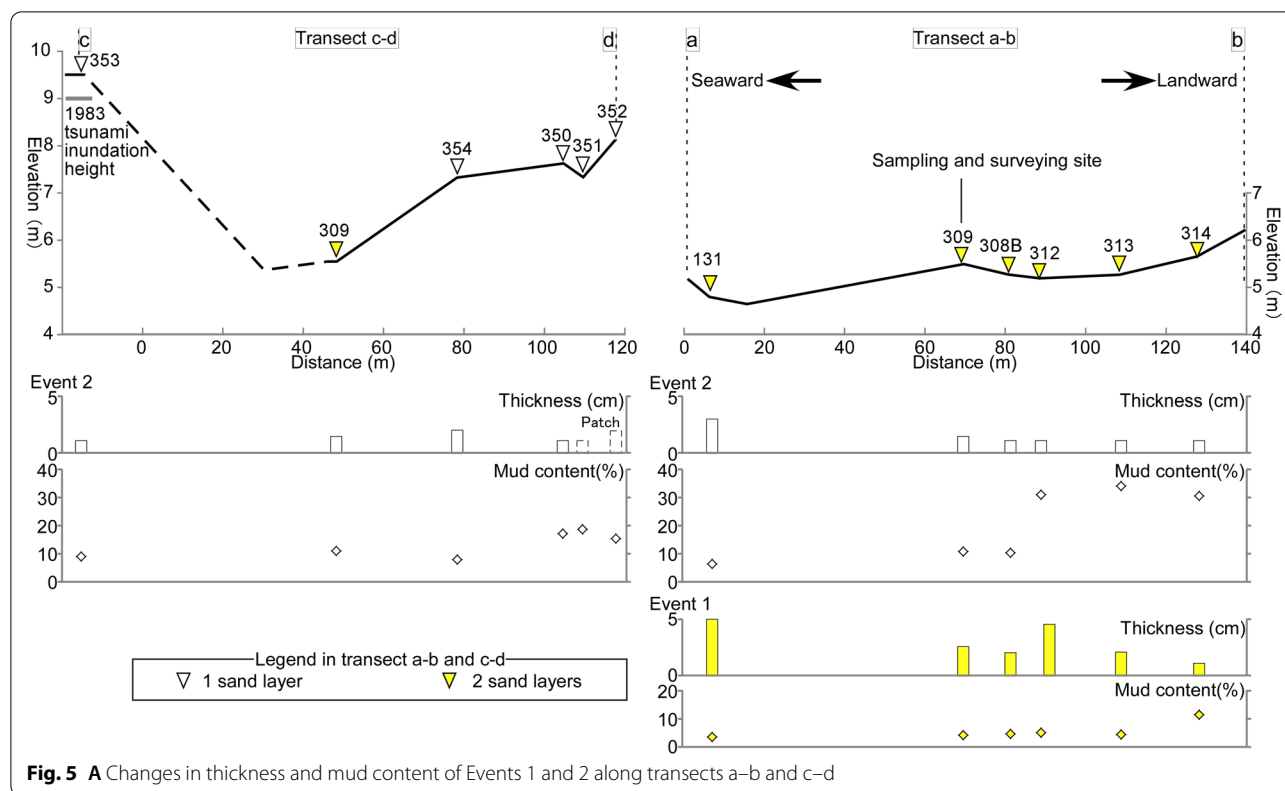
Ward (1957). The LOI was measured at 750 °C for 1 h (Japanese Standards Association 2000).

For the diatom analyses, the sub-samples were treated with hydrogen peroxide. Slides were prepared using Pleurax medium (Mount Media, Fuji Film-Wako) and observed using a 1000× optical microscope with oil immersion. At least 300 valves were identified and counted for each sample, a diagram was created, and the ratio of broken to unbroken valves was calculated. Species identifications were conducted and ecological preferences were inferred using information from previous studies (Chiba and Sawai 2014; Chiba et al. 2018, 2020; Krammer 2000; Krammer and Lange-Bertalot 1986, 1988, 1991a, 1991b; Levkov et al. 2013; Naya 2012). For the pollen analysis, we referred to Matsushita (1993) and calculated the number of individual grains, particularly for *P. thunbergii* pollen. The soil development and the timing of rapid increase of *P. thunbergii* pollen reflect the period of the pine planting. In addition, we conducted ¹⁴C dating to determine the ages of plant materials in the soil samples, and used these ages to date the event deposits.

Results

Lithostratigraphy

At each survey site, sandy deposits were observed at depths of ~10 cm or deeper, and soil was present above the sand. In addition, some sand layers were detected within the soil (Fig. 4). Two sand layers, the deeper containing slightly brownish sand and the shallower composed of slightly whitish sand, were observed along transect a–b, and one slightly whitish sand layer was detected along transect c–d (except at site 309, which contained both sand layers) (Fig. 3). The slightly brownish sand layer, which we called Event 1, became thinner and exhibited an increasing mud content inland (Fig. 5). The slightly brownish sand occurred continuously from the coast to 150–270 m inland, within the coastal protective forest. In addition, this layer contained some sedimentary structures; for example, at site 131 the layer became finer-grained upward and contained mud clasts (Fig. 4, Additional files 1 and 2). This normal grading was recognized by visual observation of the core rather than quantified by means of physical grain-size measurement or X-ray computed tomography (CT) images. In contrast,



the slightly whitish sand layer (which we called Event 2) did not exhibit a consistent trend of change in thickness. These two event deposits were clearly observed in the CT images (Additional file 2).

Radiocarbon ages

Radiocarbon dating of the boundary between the sand underlying the soil and the soil layer is expressed as the age in soil formational years. Two samples of plant material were obtained, one each from survey sites 309 and 353, and analyzed. The 95.4% probability ages were 1955–2009 cal. AD for site 309 (7 cm depth) and 1644–1954 cal. AD for site 353 (8 cm depth) (Additional file 3).

Properties of sand in core samples

The sand from the different layers (Figs. 4 and 5) exhibited consistently different properties (Fig. 6). The sediment in Event 1 had the smallest mean grain size and the best sorting, whereas the samples from Event 2 had a wider range of both grain size and sorting than those from Event 1. The sand below the soil had the widest range of grain size. The mean bulk density of the sediment was lowest in the sand below the soil, and that of

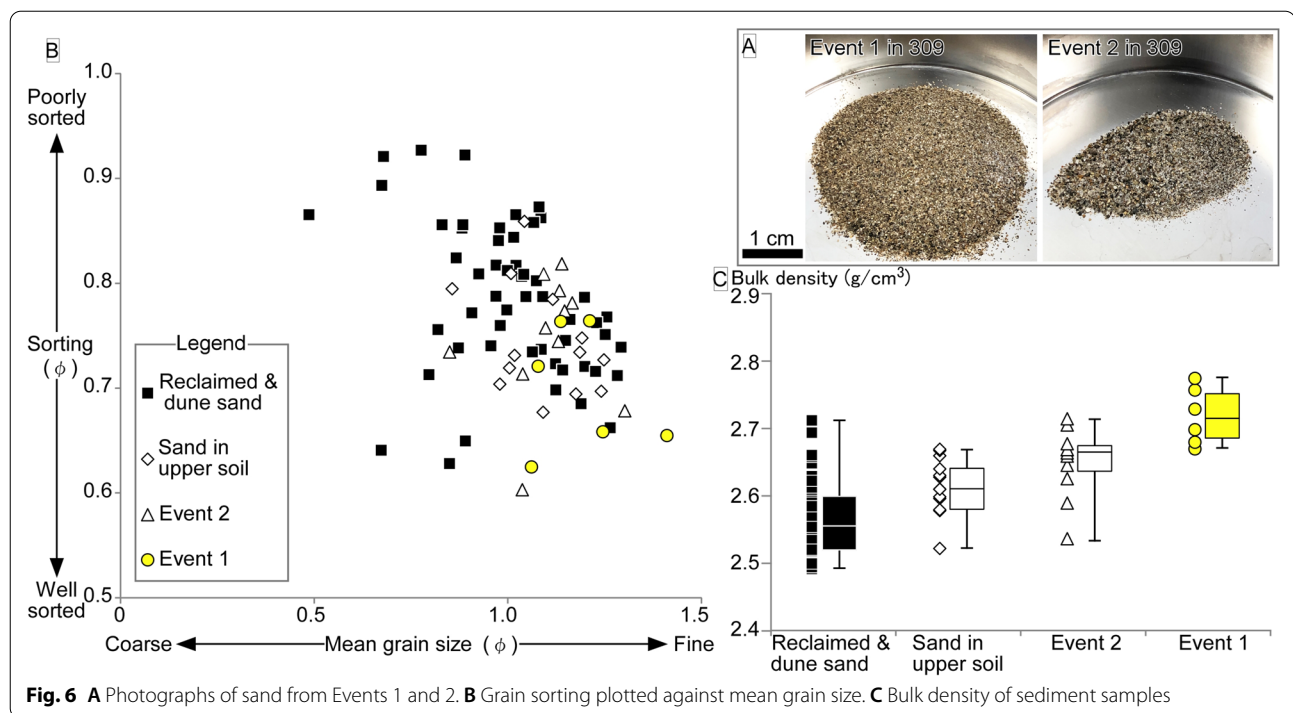
the soil was slightly higher. The density of Event 1 was the highest, followed by that of Event 2 (Fig. 6).

Diatom assemblage

Diatom analyses were conducted on the cores from site 309 and site 353. Freshwater diatoms, including *Pinnularia borealis*, *Luticola incana*, *Humidophila* sp. 1, and *Hantzschia amphioxys*, were dominant in all samples (Fig. 7). *Humidophila* sp. 1 was more abundant in the upper soil than in the bottom sand. In Event 1, well-preserved freshwater diatom species (including *Encyonema silesiacum*) and brackish–marine diatoms (including *Thalassiosira nanolineata*) were observed. In contrast, poorly preserved diatoms were observed (such as *E. silesiacum*) in Event 2; however, the diatom assemblage was otherwise similar to that of the soil. Fragments of brackish–marine species, including *Thalassionema nitzschioides*, were observed in all samples.

Pinus thunbergii pollen

Few types of fossil pollen were obtained in the analyses. The abundance of *P. thunbergii* pollen increased near the boundary between the underlying sand layer and the soil layer (Fig. 7, Additional file 4).



Discussion

Identification of reclaimed and dune sand, Event 1, and Event 2

We identified the sand layers in the studied succession—the basal sand, Event 1, and Event 2—as representing dune or reclaimed sand, a tsunami deposit, and a typhoon deposit, respectively, on the basis of the sediment characteristics and local historical records.

Reclaimed and dune sands

We identified the sand at the bases of all core samples as dune sand or reclaimed sand, based on the history of the study area (Fig. 2; Abe et al. 2013). When the pine trees were planted, the sand used was the surrounding dune sand (Abe et al. 2013), so the grain-size distribution and density of the basal sand are similar to those of dune sand. The soil above the sand is inferred to have formed after the pine trees were planted in the 1950s because of the rapid increase in the abundance of *Pinus thunbergii* pollen. LOI values also increased as a result of soil formation (Fig. 4). The evidence from ^{14}C ages is consistent with soil formation having occurred during or after pine-tree planting in the 1950s (Abe et al. 2013; Akita City 2020; Akita Prefectural Earthquake Countermeasure Group 1984).

The 1983 tsunami deposit

Event 1 showed moderate thinning and an increasing mud content inland, but did not become markedly finer-grained inland (Fig. 5). Goto et al. (2017) applied inland thinning and fining as standard criteria for recognition of tsunami deposits; however, these criteria are not applicable in this case. Our results suggest that Event 1 was formed by strong currents, because this coarse-grained event deposit exhibits a sharp basal contact. However, the unit's inland-fining tendency of sand particles is uncertain, because only a short transect near the coast was sampled (Fig. 5). In addition, the density of Event 1 was greater than that of dune sand and reclaimed sand. This difference indicates that denser particles were selectively transported and deposited by a strong current. Event 1 also contained well-preserved brackish–marine diatoms (Fig. 7). Diatoms have been reported as being well-preserved (Sawai et al. 2012; Tanigawa et al. 2018) in previously identified tsunami deposits in Japan.

On the northern part of the Sea of Japan coast, including the study area, the elevations of the sand dunes are high and the average daily tide level difference is as small as a few tens of centimeters, so waves do not overtop the sand dunes even during storm surges. In fact, in Happo Town there are no records of storm surge inundations

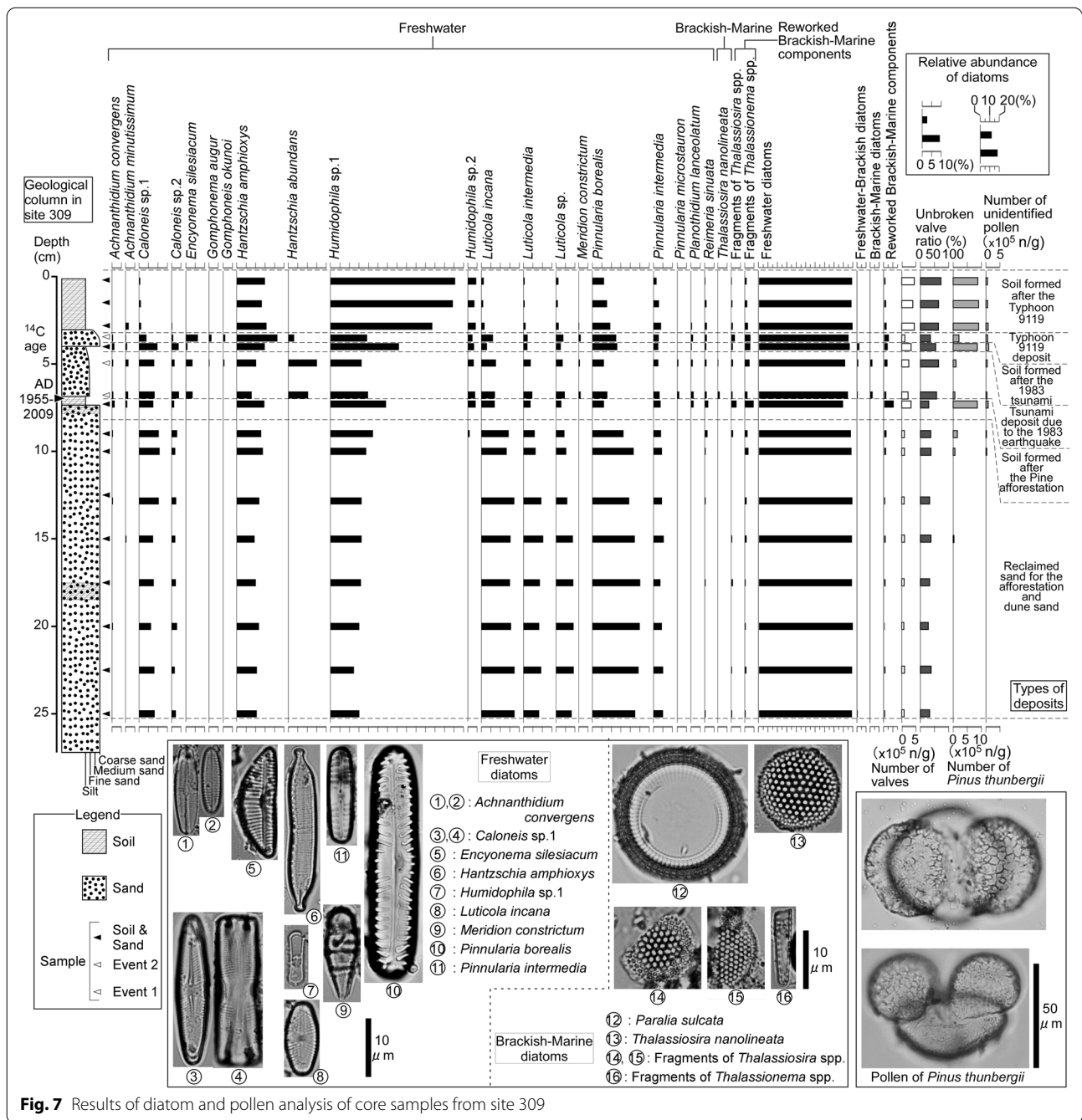


Fig. 7 Results of diatom and pollen analysis of core samples from site 309

between 1983 and 1993. In addition, there is no record of flooding of the Hanawa River, which exceeds the altitude of the survey area. These factors strongly suggest that Event 1 is a deposit formed by the 1983 tsunami.

Typhoon 9119 deposit

Event 2 is found over the thin soil layer lying directly above Event 1, and it is clear from the stratigraphic sequence that Event 2 was deposited after 1983. The

inland-fining tendency of Event 2 is uncertain (Fig. 5). Event 1 contained well-preserved brackish–marine diatoms; in contrast, Event 2 included poorly preserved brackish–marine diatoms (Fig. 7). The species list of the Event 2 diatom assemblage was similar to that of the lower reclaimed sand and dune sand (Additional file 4). The range of mean grain size and sorting in Event 2 was broader than that in Event 1, but was similar to the values of the reclaimed and dune sand below

the soil. Furthermore, the density of Event 2 sand and of the reclaimed and dune sand fell within the same range. These facts strongly suggest that Event 2 and Event 1 were formed by different causes.

The wind events that create high dunes are significant in the study area, and coastal protective forests are planted to block these winds and aeolian sand; therefore, distinguishing tsunami deposits from aeolian dune deposits is crucial (Abe et al. 2013).

Unlike Event 1, an inundation event corresponding to Event 2 is not documented in the local records. Historical records document almost no major flooding or tsunamis in this region after the 1983 Nihonkai-Chubu earthquake. The only event that affected the coast was the 1993 Hokkaido Nansei-Oki earthquake, and the tsunami traces of this event near the survey area were lower than the elevation of the survey area (Shuto 1994; Shuto and Matsutomi 1995).

The sediment mean grain size and sorting, sediment density, diatom assemblage, and unbroken valve ratio in the Event 2 deposit also strongly indicate that Event 2 is not a 1993 Hokkaido Nansei-Oki tsunami deposit. The characteristics of Event 2 are similar to those of dunes and reclaimed sand; therefore, this layer was probably formed by typhoon 9119 (Mireille), which reached the study area on 28 September 1991 (Abe et al. 2013; Akita City 2020; Japan Meteorological Agency 2020; Nagasawa 2020; Noshiro City 2014). Typhoon 9119 caused damage to the coastal areas of Akita Prefecture, including heavy wind damage, and severe damage to fruit trees in the Tohoku region (Japan Meteorological Agency 2020). Salt-wind damage also occurred in Akita Prefecture during the typhoon. One reason why clear traces of typhoon 9119 remain is that seedlings planted after the tsunami inundation did not thrive or function as a coastal protective forest, allowing deposition and preservation of the Event 2 layer. The progress of this pine tree planting can also be judged from aerial photographs (Fig. 2).

Summary of the stratigraphy

To summarize, the stratigraphy in transect a–b is as follows. The bottom sand is dune or reclaimed sand. The lower soil above the sand formed after the pine trees had been planted after the 1950s. The Event 1 layer within the soil is a tsunami deposit associated with the 1983 Nihonkai-Chubu earthquake, and the Event 2 sand layer is aeolian sand deposited in 1991 by typhoon 9119. Historical records and the lithological successions of the core samples indicate that modern soil is the uppermost unit (Abe et al. 2013; Akita City 2020; Akita Prefectural Earthquake Countermeasure Group 1984; Noshiro City 2014).

The distribution of the tsunami deposit (Event 1) is consistent with the inundation height. For example, at survey site 353, no tsunami deposit was detected, but the typhoon deposit (Event 2) was observed (Additional file 4). The lack of a tsunami deposit at site 353 can be explained by the inundation height having been 9.00 m in that area, but the elevation at site 353 being 9.5 m, meaning that a tsunami deposit is unlikely to have formed (Figs. 3 and 5). In addition, the tsunami deposit was observed along transect a–b (highest elevation 5.5 m at site 309), but not in transect c–d (except at site 309). Therefore, the inundation height of the tsunami was high on the seaward side, and it is likely that the inundation height decreased immediately landward.

The sand in each soil layer was inferred to have been contaminated with a small amount of aeolian sand (Figs. 4 and 6). The characteristics of this sand are very similar to those of the lower reclaimed sand and dune sand (Fig. 6). This sand does not form layers, but its presence indicates that very small amounts of sand from dunes or reclaimed sand are scattered by the annual typhoons.

Identification of reworked diatoms

The ratio of broken to unbroken valves or frustules of diatoms in tsunami deposits has been applied as an index of the diatom preservation in these sediments (Dura and Hemphill-Haley 2020). Such diatoms have previously been reported as poorly preserved (Dawson et al., 1996; Dawson, 2007) or well-preserved (Hemphill-Haley, 1995; Sawai et al., 2012; Tanigawa et al. 2018; Horton et al., 2011). In this study, the diatom frustules in the tsunami deposits were well-preserved, consistent with the findings of later reports.

In this study, fragments of brackish–marine diatoms such as *Thalassionema nitzschioides* and *Thalassiosira* spp. were observed in all samples (Fig. 7, Additional file 4). Dune sands in coastal areas are derived from beach sand (Endo 2017; Matsubara 2000). Diatoms are silt-sized, and thus do not generally accumulate and are scattered by strong winds; however, some fossil brackish–marine diatoms may be deposited with aeolian sand as reworked material, indicating contamination (Chiba et al. 2020). These reworked diatoms tend to remain in the surface environment, where physical and chemical weathering result in poor preservation.

Characteristics of event deposits

The tsunami deposit (Event 1) exhibited the best sorting of the analyzed samples, as well as a high bulk density (Fig. 6). The main sediment sources for tsunami deposits in this region are beach, dune, and reclaimed sands.

The sediment tends to be derived from the near vicinity, and different sediment types can be identified from their grain characteristics. The grain-size characteristics of tsunami deposits are presumed to reflect the hydrodynamics of the tsunami waves, and the bulk density is presumed to reflect the content of heavy minerals, such as magnetite (Fig. 6). Typhoon-derived sand (Event 2) and aeolian sand (in the soil) are poorly sorted compared to tsunami deposits in the study area. This poor sorting may have been caused by variable wind strengths and directions, as well as other factors (Inokuchi 1980; Le Roux and Vargas 2005; Sugawara et al. 2008).

Additional criteria for identification of tsunami deposits

The descriptions of sedimentary units in this study differ in some respects from the general characteristics of tsunami deposits that form behind dunes (e.g., Goto et al. 2017), because those characteristics may be specific to tsunami deposits found in soil developed on dunes, such as coastal area in the Sea of Japan. In the study area, where high dunes are formed, the diatom assemblages are affected by strong winds from the seaward side, so simple detection of marine species may not be a reliable basis for recognition of tsunami deposits. Development of soil and the coastal protective forest may also influence the characteristics of tsunami deposits. Therefore, identification of tsunami deposits should involve consideration of additional distinguishing features; it may be possible to identify such deposits by applying combinations of proxies, such as differences in the density of each deposit and in the quality of diatom preservation.

Conclusions

A sand layer (Event 1) that exhibited inland thinning was observed in the soil at a depth of more than 10 cm in the coastal region near Happo Town. This layer contained well-preserved brackish-marine diatoms that were probably transported inland from the coast. This layer occurred continuously from the coast to 150–270 m inland, but only within the coastal protective forest. Based on historical and geologic records, we postulate that this layer was the result of deposition from the 1983 tsunami, no other cause being plausible. We also observed another sand layer (Event 2) above the tsunami deposit: this second layer was probably formed by Typhoon 9119, which reached the study area on 28 September 1991. By investigating the topographic, sedimentary, and microfossil characteristics of these sandy layers, it is possible to distinguish between aeolian sand and tsunami deposits. These findings are important as a record of tsunami deposits along the coast of the Sea of Japan.

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s40623-022-01687-2>.

Additional file 1. Geologic columns, photographs, and sampling depths of the sites along transects a–b.

Additional file 2. Photographs (a) and computed tomography images (b) of core samples from survey sites 131, 309, and 312.

Additional file 3. Radiocarbon ages of lower sandy soil in core samples from sites 309 and 353.

Additional file 4. Results of diatom and pollen analysis of samples from the core from site 353. One sand layer (Event 1) was found in soil above the reclaimed or dune sand. Freshwater diatoms, such as *Pinnularia borealis*, *Luticola incana*, *Humidophila* sp. 1, and *Hantzschia amphioxys*, were dominant in all samples. *Humidophila* sp. 1 was more abundant in the upper soil than in the bottom sand. In the Event 1 sand layer, the diatom assemblage was similar to that of the soil and lower sand. The percentage of unbroken valves was low in the sand layer. Fragments of brackish-marine species, including *Thalassionema nitzschioides*, were recognized in all samples. Few types of fossil pollen were obtained in the analyses. The abundance of *Pinus thunbergii* pollen increased near the boundary between the lower sand layer (dune or reclaimed sand) and the soil layer.

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Author contributions

TC surveyed the study area and analyzed all samples. YN surveyed the study area and analyzed grain size distributions. Both authors read and approved the final manuscript.

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Availability of data and materials

Not applicable.

Declarations

Competing interests

The authors declare that they have no competing interests.

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