

A study on the interaction between extreme waves and coastal development processes for identification of tsunami and storm deposits in the tsunami far-field

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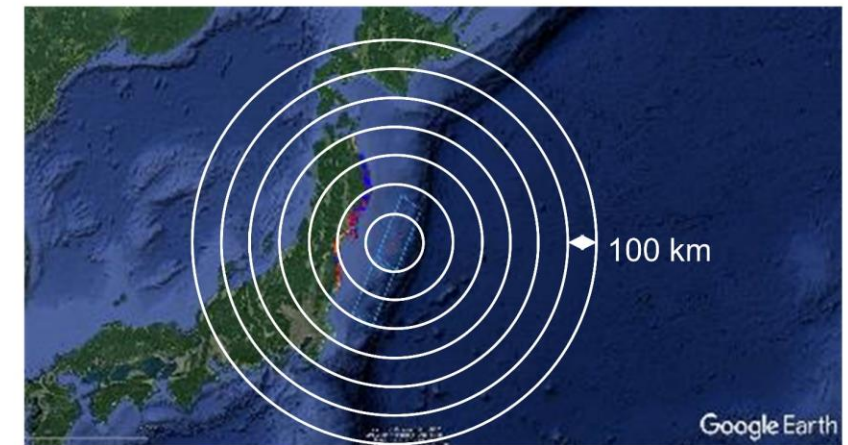
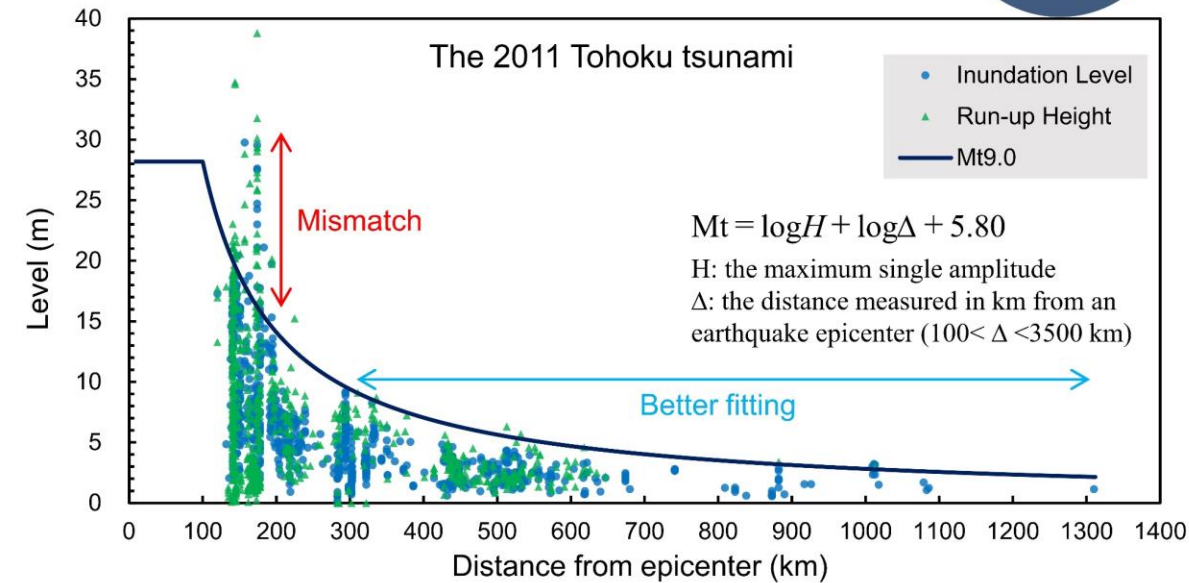
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Advantages of a tsunami far-field study

- It is known that the local tsunami wave height variation is large in the tsunami near-field, which can be attributed to the tsunami source parameters independent of the seismic moment: rupture complexity in the form of heterogeneous slip distribution patterns etc. (Geist, 2002).
- For sites that are more than 100 km away from a tsunami source, the linear relationship between the tsunami height and the distance from the epicenter has been known (Mt: Abe, 1981); the tsunami records in such areas are useful information to constrain the magnitude of tsunamis rather than a local field.
- In the 2011 Tohoku tsunami (Mw 9.0), the maximum tsunami height matched the Mt 9.0 depending on the distance from the epicenter, but anomalous high wave were observed within 200 km from the epicenter.

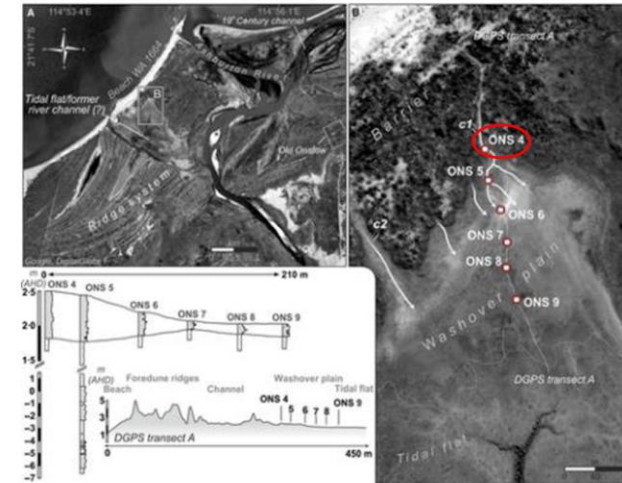


Measured tsunami data in the 2011 Tohoku EQ (Mw 9.0: <https://coastal.jp/tsunami2011/>) and estimated tsunami wave height with a tsunami magnitude (Mt) of Mw 9.0 EQ. The white circles indicate the distance every 100 km from the epicenter.

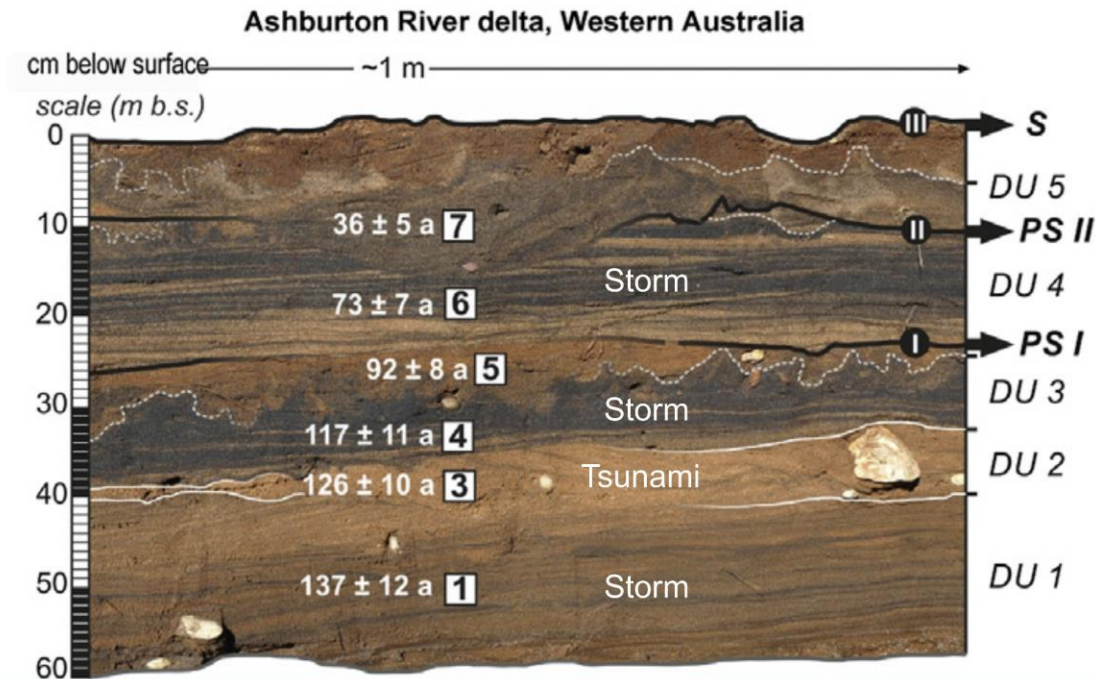
Difficulties of research in a tsunami far-field

- The identification of tsunami deposits is often based on the extreme flow due to the long wavelength (e.g., Morton et al., 2007; Watanabe et al., 2018).
- Therefore, as the tsunami run-up distance becomes shorter, the identification of tsunami deposits becomes more difficult unless the age of the tsunami is known, as they exhibit similar features to storm deposits (Shanmugam, 2012; May et al., 2015).
- In addition, the time window for paleoseismic archives is limited in regions away from former ice sheets because of the shifting accommodation space (Dura et al., 2011; Kelsey et al., 2015; Nakanishi et al., 2020a).

Washover sequence deposited on an estuarine tidal flat located in the back of a dune belt of the Asburton River delta in Western Australia (DU: depositional units, PS: paleosurface; S: surface; black lines I-III). Optically stimulated luminescence dating permitted to link DU 1, 3, and 4 with specific historical tropical cyclones, and DU 2 with the 1883 Krakatoa. Modified after May et al. (2015).

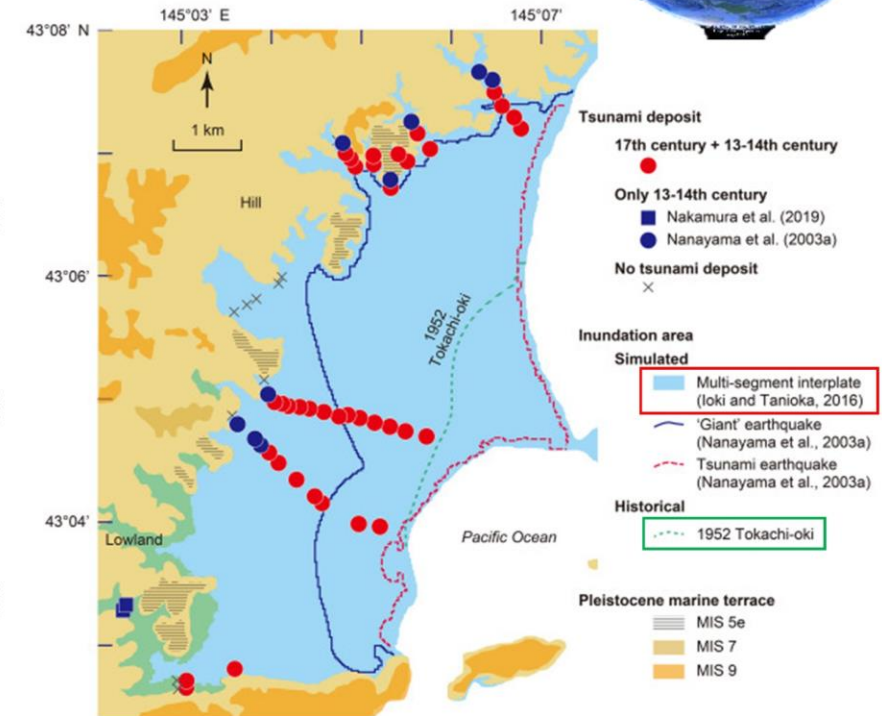
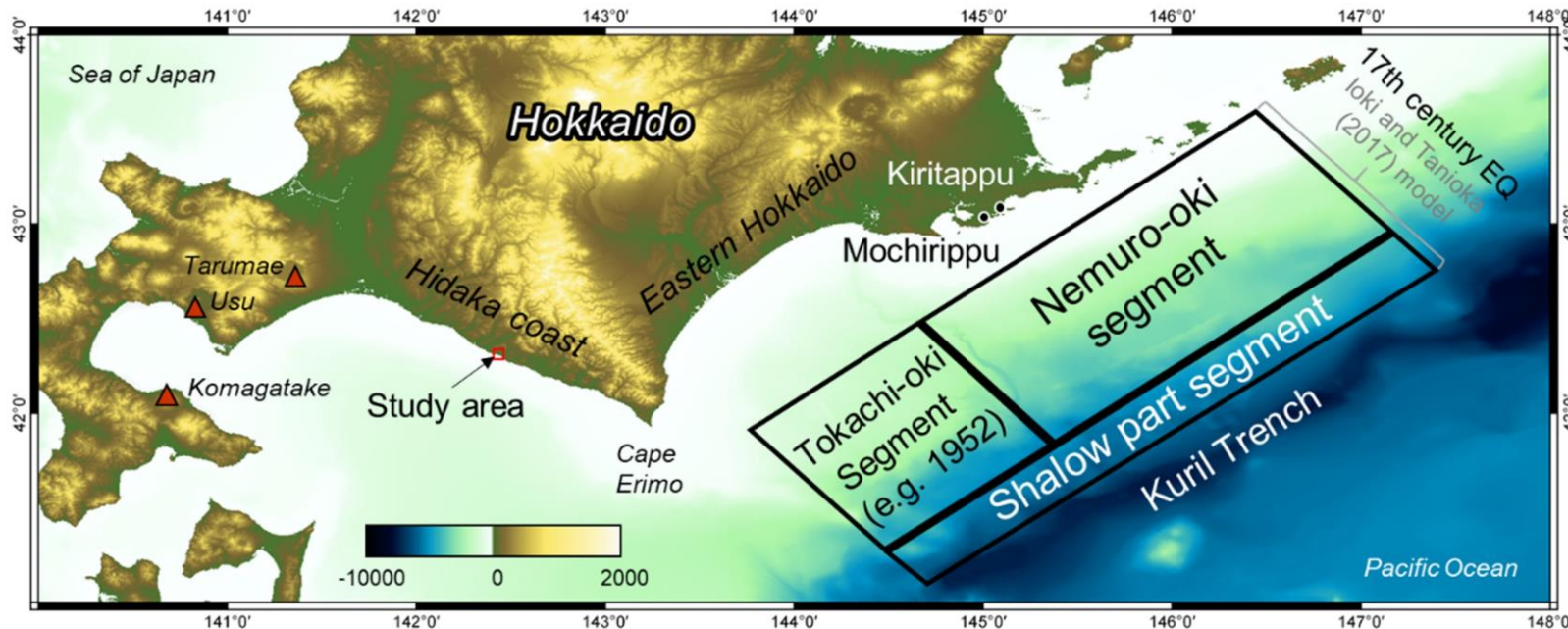


Onslow washover fan and sampling sites (May et al., 2015).



Giant paleo-earthquakes in the southern Kuril Trench

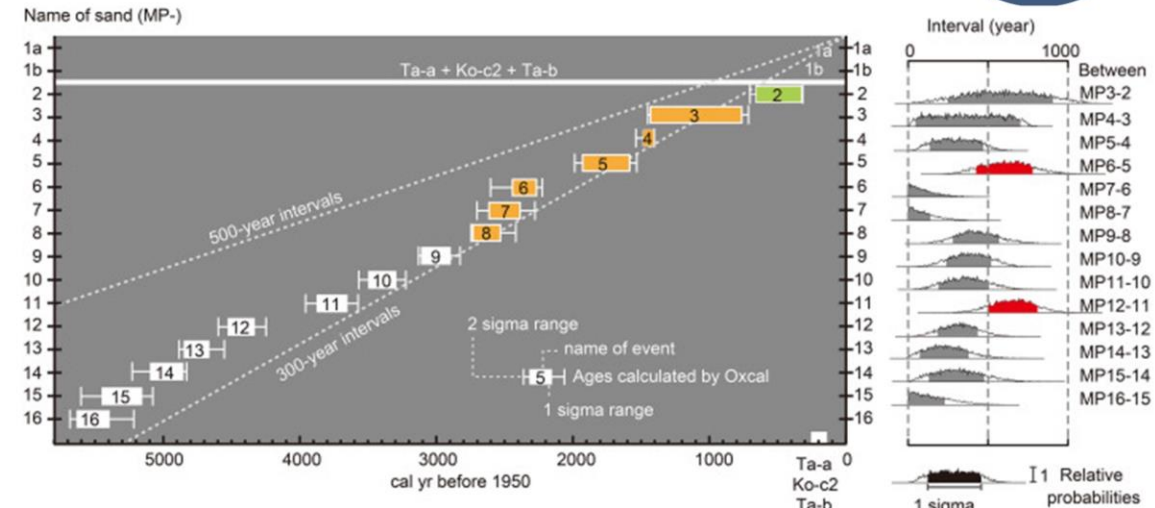
- The great earthquakes historically observed in the Tokachi-oki and Nemuro-oki segments comprise recurrence intervals of approximately 50–100 years (e.g., the 1952 Tokachi-oki EQ: Mw 8.1).
- The geological record of eastern Hokkaido over the past 6,000 years suggests the existence of giant earthquakes associated with the Kuril Trench (e.g., the 17th-century EQ: Mw8.8)



Simulated inundation areas and distributions of Pleistocene marine terraces and tsunami deposits of the 17th-century and the 13th- or 14th-century earthquakes in Kiritappu marsh (Sawai, 2020).

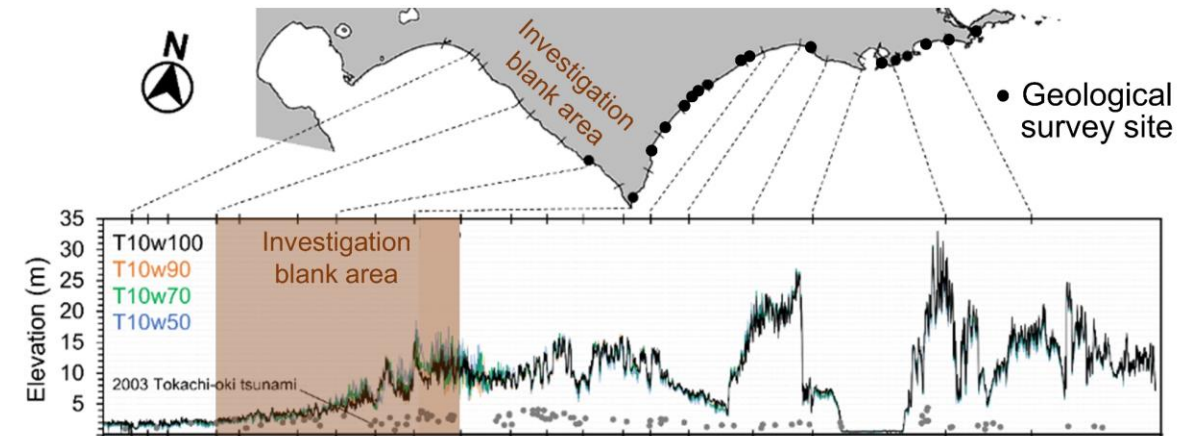
Giant paleo-earthquakes in the southern Kuril Trench

- The outside seismic history of the Kuril Trench is considered to have a recurrence interval of several hundred years (ca. 500 years) based on tsunami deposit studies (Sawai, 2020).
- However, it is unclear how far tsunamis occurred by these earthquakes extended, making it difficult to estimate the magnitude of these giant earthquakes.



Research Purpose

- Field survey to verify the tsunami magnitude in a far-field from the Kuril Trench
- Elucidating the coastal development process to enable precise numerical simulations and event layers discovery

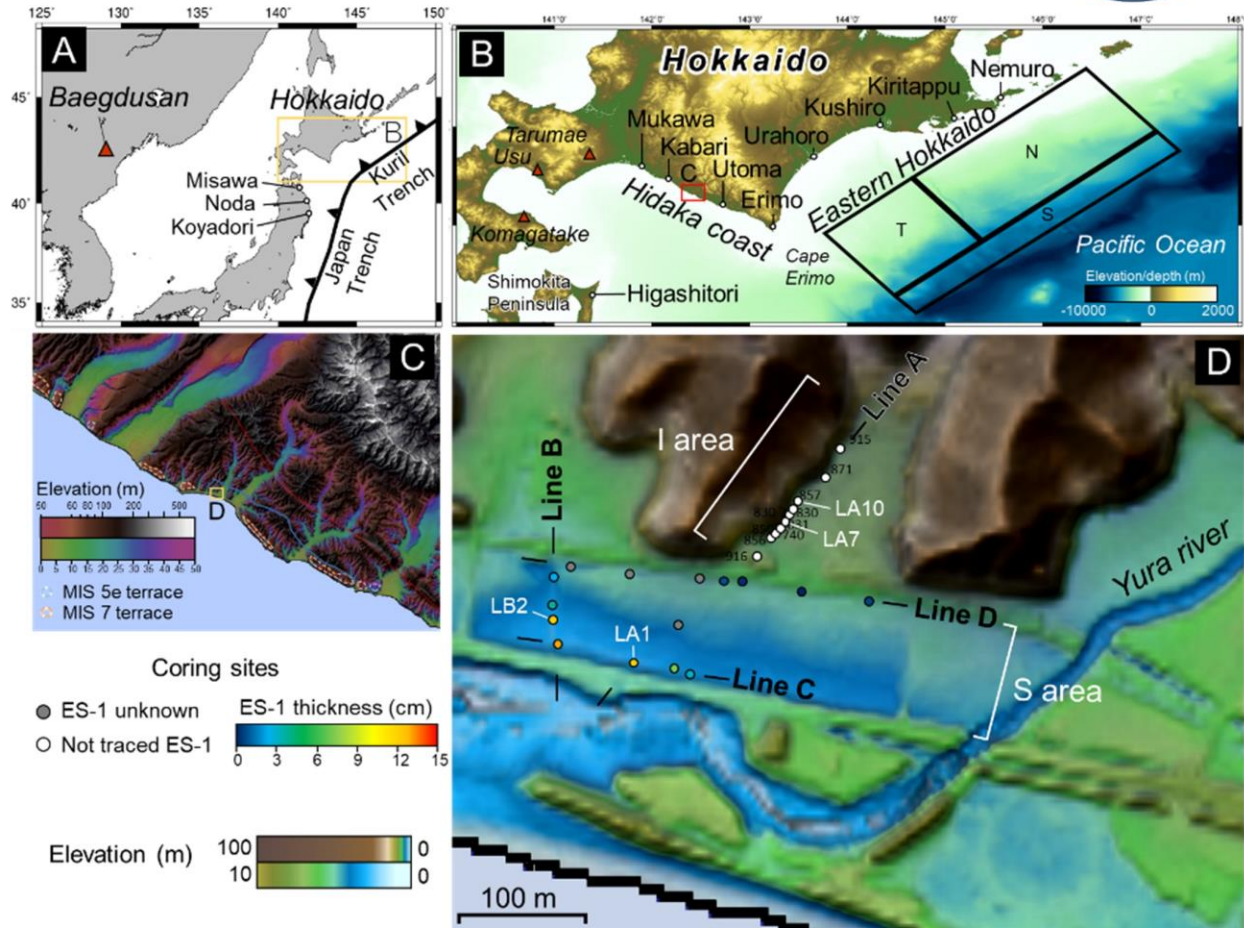


Study area outline

- Study area: Shizunai, Hokkaido, Japan
- Marine terrace: MIS 7 (85–90 m above sea level)
- Holocene highstand: 0–2 m (ca. 4000–3000 BP)
(Okuno et al., 2014, Yokoyama et al., 2012)
- Tide data: MHHW 0.4 m, HAT 0.6 m
- Historical tsunami: Maximum wave height 2 m
(e.g., the 2003 Tokachi-oki EQ and the 2011 Tohoku EQ)
- Inland area (I area): Mainly peatlands
- Seaward area (S area): Mainly floodplains, beach ridge system



Aerial photograph in 1953 at Shizunai. In the photo, the beach ridges (BR) are shown by reading topography.



A: Location map of Hokkaido and Baegdusan. B: Bathymetric and topographic map of Hokkaido. Paleotsunami investigation sites and tephra sources are marked. Black boxes indicate the 17th century earthquake fault (Ioki & Tanioka, 2016). C: Topographic map based on 5 m-grid Digital elevation model data from the central Hidaka coast. Blue and red dashed lines indicate the distribution of the MIS 5e and 7 surfaces, respectively (Koike & Machida, 2001). D: Close-up map of the boring site on the A–D survey lines. Color circles indicate the distribution and layer thickness of ES-1. White circles show the distribution of EI-1–4.

Methods

- Field survey

We collected a total of 25 core samples using hand boring (a $\Phi 7$ cm corer and a Handy Geoslicer; Takada et al., 2002). The elevation of the core sites was measured via real-time kinematic positioning using Global Navigation Satellite System multi-band receivers (GNSS: ZED-F9P U-blox).

- Diatom analysis

The number of individuals was 300 per sample. We identified species using Japanese (for example, Sawai and Nagumo, 2003; Watanabe et al., 2005; Kihara et al., 2015; Chiba et al., 2018) and global references (Krammer & Lange-Bertalot, 1986, 1988, 1991a, b, 1998; Witkowski et al., 2000). Diatoms were classified by salinity (marine: M, marine–brackish: M–B, brackish: B, brackish–freshwater: B–F, and freshwater: F) and life-form, followed by ecological preferences (Denys, 1991; Vos & Wolf, 1993; Dam, 1994; Chiba & Sawai, 2014; Zong & Sawai, 2015). Cluster analysis (CA) was conducted to determine the similarity of diatom assemblages in each layer using PAST (Hammer et al., 2001).

- Grain size analysis

Grain size analysis was performed on the bulk composition of the sand layer and on samples subsampled every 2 cm in the vertical direction. The analysis method was the same as that used by Nakanishi et al. (2020a) using a 1/2 phi dry sieve.

- CNS analysis

We subsampled bulk samples (units of 1 cm) into 7 mL glasses, which were further pretreated with 1 M HCl for 1 h to remove calcium carbonate. Total organic carbon (TOC), total nitrogen (TN), and total sulfur (TS) were measured using a CNS Analyzer (Elementar vario EL cube). The TOC/TS ratio is commonly used as an index of paleosalinity because of the high content of sulfur compounds in reductive and marine environments.

- Radiocarbon dating

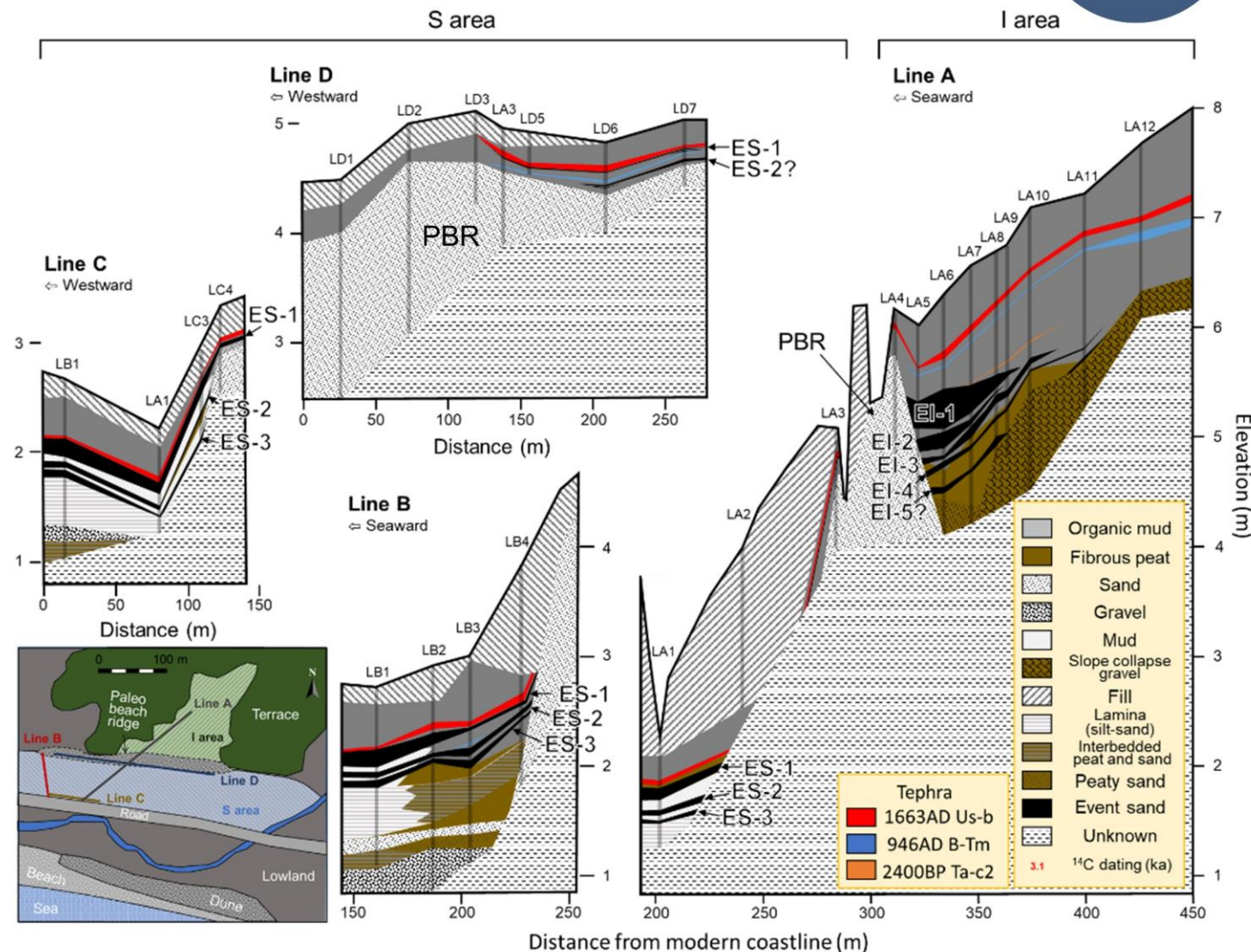
^{14}C dating was performed according to the protocol of Nakanishi et al. (2020a) at the Atmosphere and Ocean Research Institute, Japan, using single stage AMS (Yokoyama et al., 2019). The bulk peat samples were collected above and below the sand layers. The ^{14}C ages were calibrated to calendar ages using the calibration software OxCal 4.4 (Bronk Ramsey, 2017) with the IntCal20 dataset (Reimer et al., 2020). The depositional ages of the sand layers were constrained by a P_Sequence and Sequence model (Bronk Ramsey, 2008, 2009a). Each model was structured separately for peat layers among the tsunami deposits (Ishizawa et al., 2017, 2020).



Geological outline

- Nakanishi et al. (2020b) identified the volcanic ash layers in the Shizunai area as the AD 1663 Usu b tephra (**Us-b**), the AD 946 Baegdusan tephra (**B-Tm**) and the 2400 BP Tarumae c2 tephra (**Ta-c2**).
- In the I area, three volcanic ash layers and four to five sand layers (**EI-1~4**) were found in peat layers.
- In Line B and C, the lower part is consisted of alternating layers of sand and mud. In the upper mud layer, three anomalous sand layers (**ES-1~3**) of were identified.
- Line D profile shows the distribution of a paleo beach ridge (PBR).

The widely distributed sand layers deposited in the mud layer accumulated under low energy is considered as the event layer carried by extreme waves.



Geologic cross sections along the A–D survey lines. The inserted map shows the location of the measuring lines.

Reconstruction of paleo sea level (I area)

- Unit I1: High marsh

Sediment components: fine sand to sandy fibrous peat

Diagnostic species: small *Fragilaria* spp., *Navicula peregrina*

CNS results: Low C/S ratio (less than 10), C/N ratio was 10–19 (intertidal value (10–13) observed (Wilson et al., 2005))

- Unit I2: Supratidal

Sediment components: organic mud containing plant fragments

Diagnostic species: small *Fragilaria* spp., *Epithemia adonata*, *Cocconeis lineata*, *Cosmioneis pusilla*

CNS results: C/N ratio was 14–17, which close to that of the supra-tidal (16–25)

- Unit I3: Freshwater swamp (including event layers)

Sediment components: organic mud containing plant fragments

Diagnostic species: *Eunotia* spp., *Pinnularia* spp., *Gomphonema* spp.

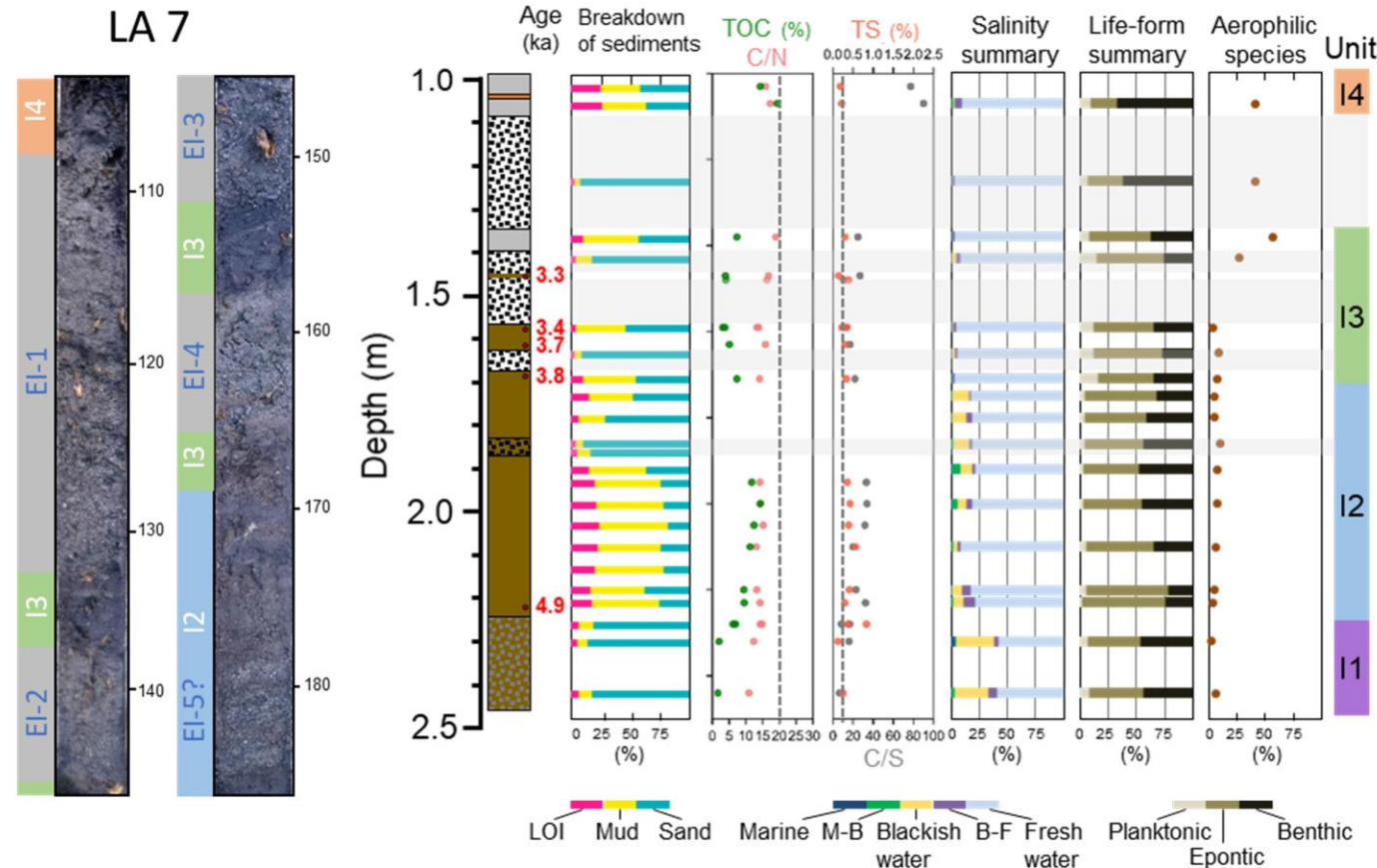
CNS results: high C/S ratio and C/N ratio of 15–22

- Unit I4: Upland

Sediment components: organic mud layer

Diagnostic species: *Hantzschia amphioxys*, *Pinnularia* spp., *Caloneis* spp.

CNS results: high C/S and C/N ratio



Photographs of core samples with event layers and interpretation of sedimentary units.

Vertical change in breakdown of sediments (LOI, mud contents, and sand contents), chemical (TOC/TS, TS, and TOC/TN) and diatom assemblage summary (salinity, life-form, and the percent of valves of dry tolerant species as aerophilic diatom ratio) are shown for the LA7 cores. The color-bars indicate each sedimentary units.

Reconstruction of paleo sea level (S area)

- Unit S1: Lagoon

Sediment components: a silty to clayey lamina layer

Diagnostic species: *Navicula marginalithii*, *N. cincta*, *Diploneis pseudovalis*

- Unit S2: Deep freshwater (temporary)

Sediment components: a dark brown organic mud layer

Diagnostic species: *Aulacoseira spp*, *Tabellaria fenestrata*

- Unit S3: High marsh to supratidal (including event layers)

Sediment components: a grayish-white mud layer

Diagnostic species: *Planothidium lanceolatum*, *Nitzschia sigma*, *Navicula sleviensis*, *Fragilaria rumpens*, *T. fenestrata*

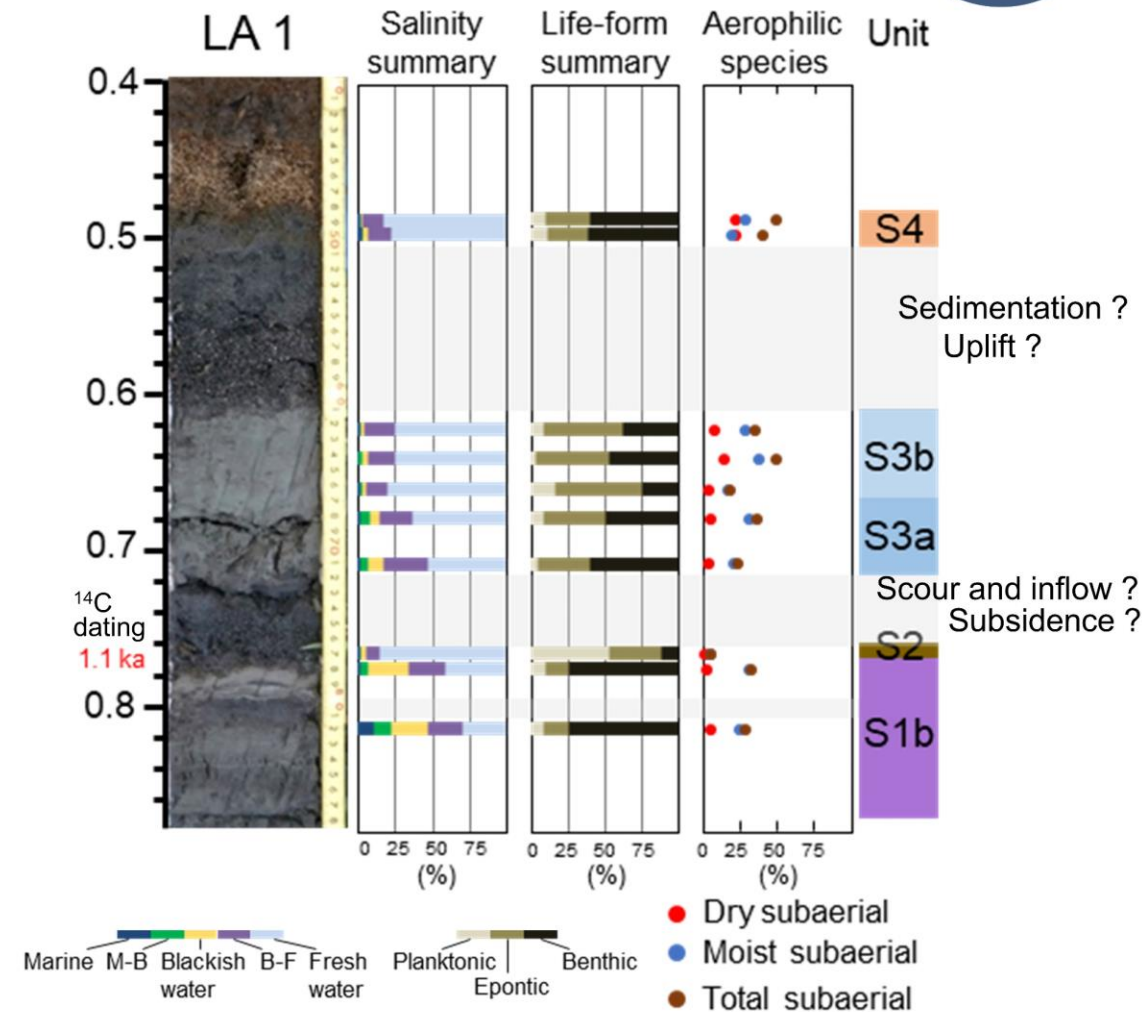
- Unit S4: Upland

Sediment components: a brown sandy mud layer

Diagnostic species: *Humidophila contenta*, *Luticola mutica*

The environmental changes between units S2 and S3 and between units S3 and S4 are abrupt with the event layer.

Is it due to erosion and sedimentation by extreme waves?
Seismic uplift or subsidence?



Vertical change in diatom assemblage summary (salinity, life-form, and the percent of valves of dry tolerant species as aerophilic diatom ratio) are shown for the LA1 cores. The color-bars indicate each sedimentary units.

Coastal development process

Each Stage Period [Relative Sea-level Change]

- 6000–4000 BP [Highstand]

In I area, there were salt marshes, suggesting that seawater flowed in this area.

- 4000–3000 BP [Slow regression]

I area was closed off from the sea due to the formation of the paleo beach ridge as the sea regression and changed into a swamp.

- 3000–1300 BP [Rapid regression]

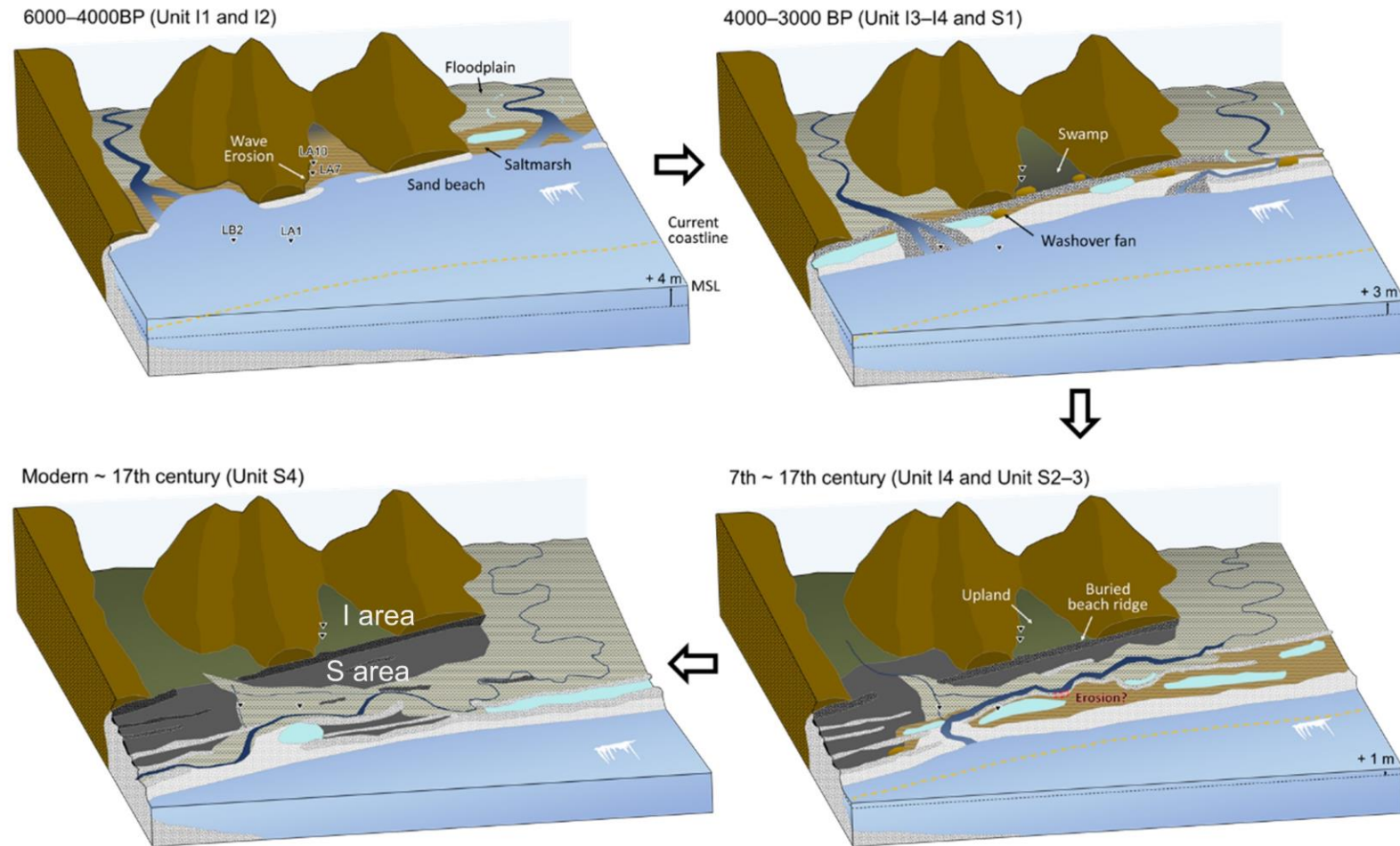
The rapid sea level fall resulted in no formation of wetlands.

- 1300–400 BP [Slow regression]

River floodplains are widely developed. Beach ridges were formed by sea regression, and saltmarshes and lagoons were formed between the ridges.

- 400 BP–Present [Stable]

The relative sea level closed to the present, and the depositional environment changed from floodplain to upland after 17th century event.

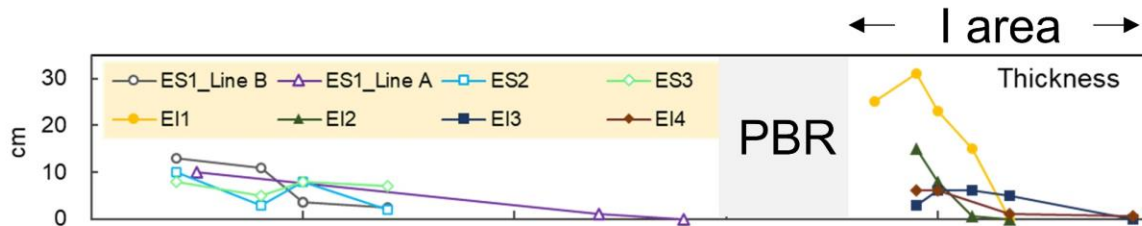


Schematic illustration of coastal development in the Shizunai area during the Holocene.

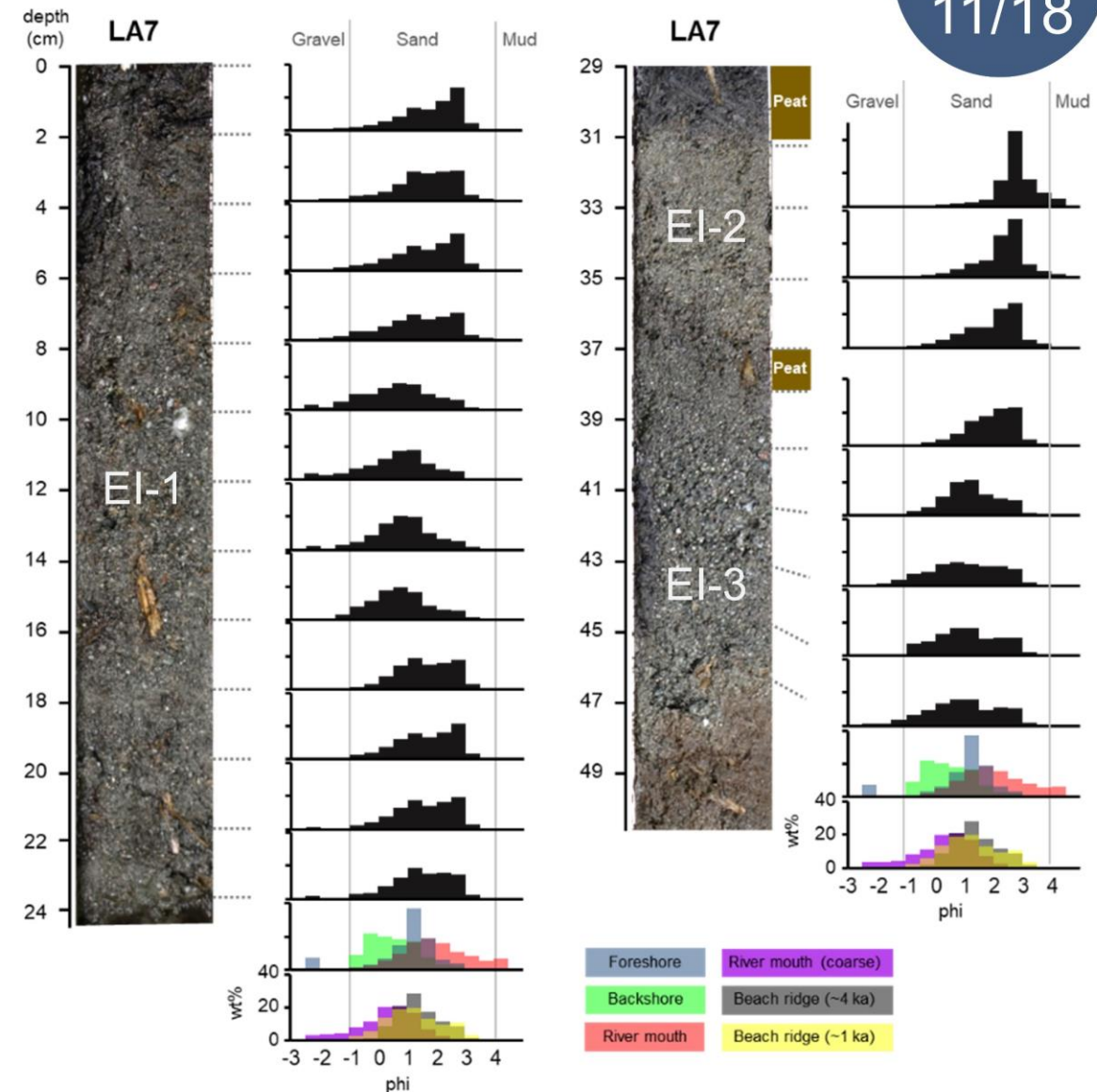
Features of the event layers (I area)

- The distribution of EI-1 (3140–2840 BP) and EI-2 (3440–3270 BP) is limited to a few tens of meters from the PBR, and they are thick near PBR but rapidly become thinner inland.
- EI-3 (3460–3370 BP) and EI-4 (3900–3670 BP) tend to be thin in sheet form inland, with a distribution of at least 100 m from PBR.
- In the vertical direction, EI-2~EI-4 show a remarkable single normal grading, while EI-1 shows sequential normal-reverse grading.

EI-1, 2 and EI-3, 4 have slightly different sedimentary structures.



The lateral variation of each sand layer thickness.

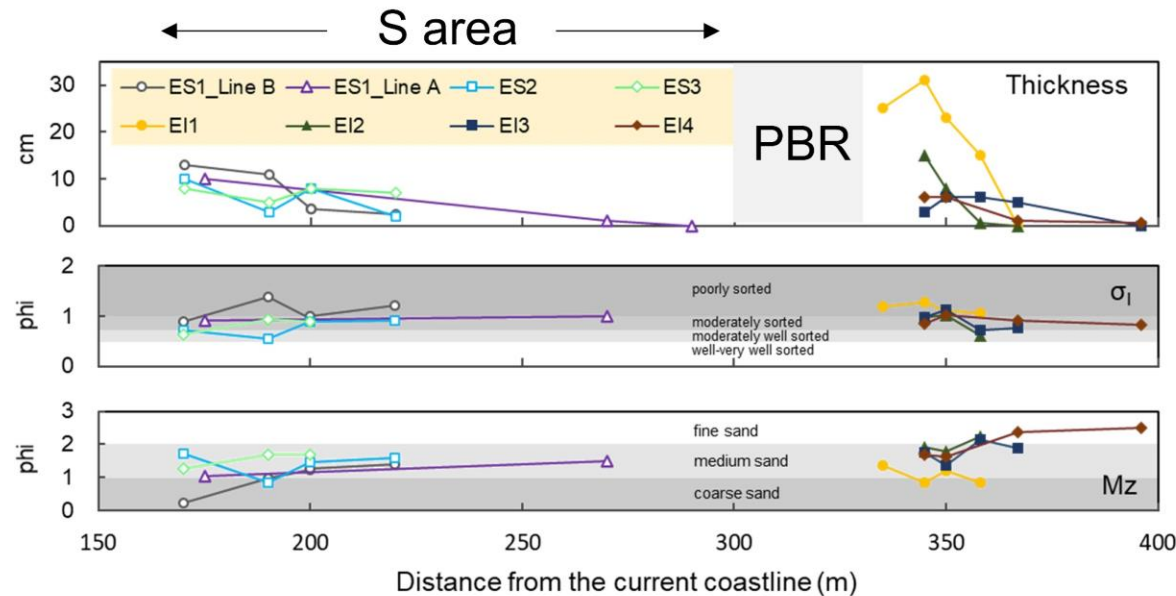


Vertical variations of EI-1–3 at the LA7 and in grain size histogram per 2 cm depth.

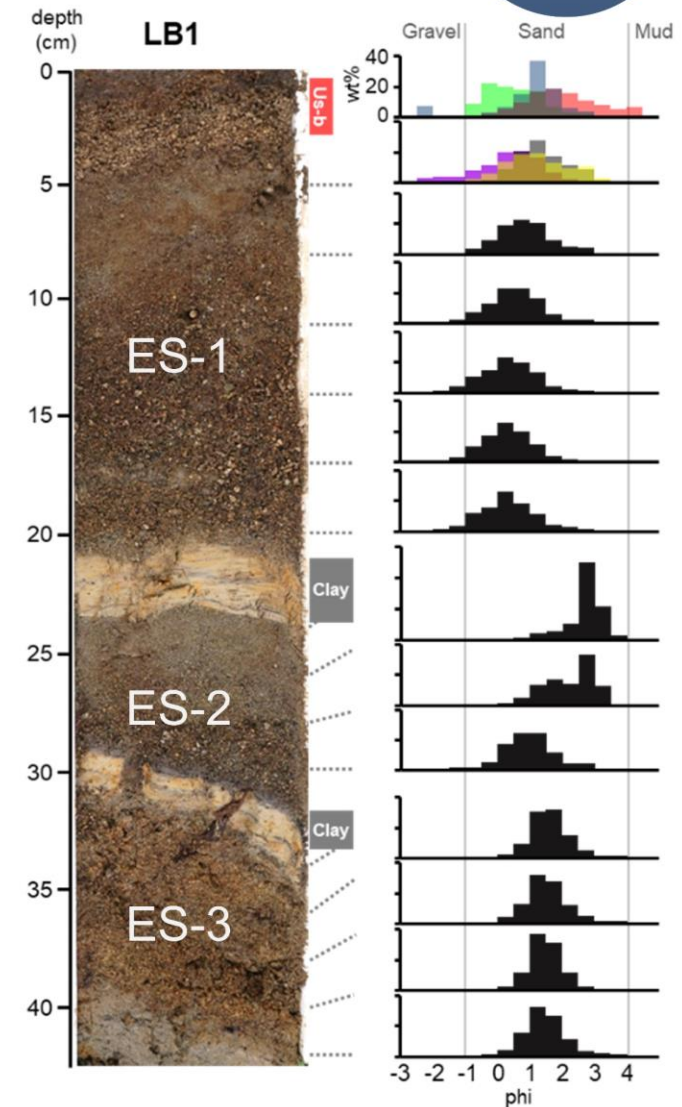
Features of the event layers (S area)

- ES-1~3 show a sheet-like distribution more than 100m from the present shoreline, and all sand layers have a significant normal grading.
- EI-1(17th century) and EI-2 (9th century) are accompanied by changes in the depositional environment before and after their deposition.

In tsunami far-field, event layers may be missed due to the limited distribution of them behind beach ridges.



The lateral variation of each sand layer thickness, inclusive graphic standard deviation (σ_1), and inclusive graphic mean diameter (Mz).



Vertical variations of ES-1~3 at the LB1 in grain size histogram per 2 cm depth.

Comparison with modern event layers

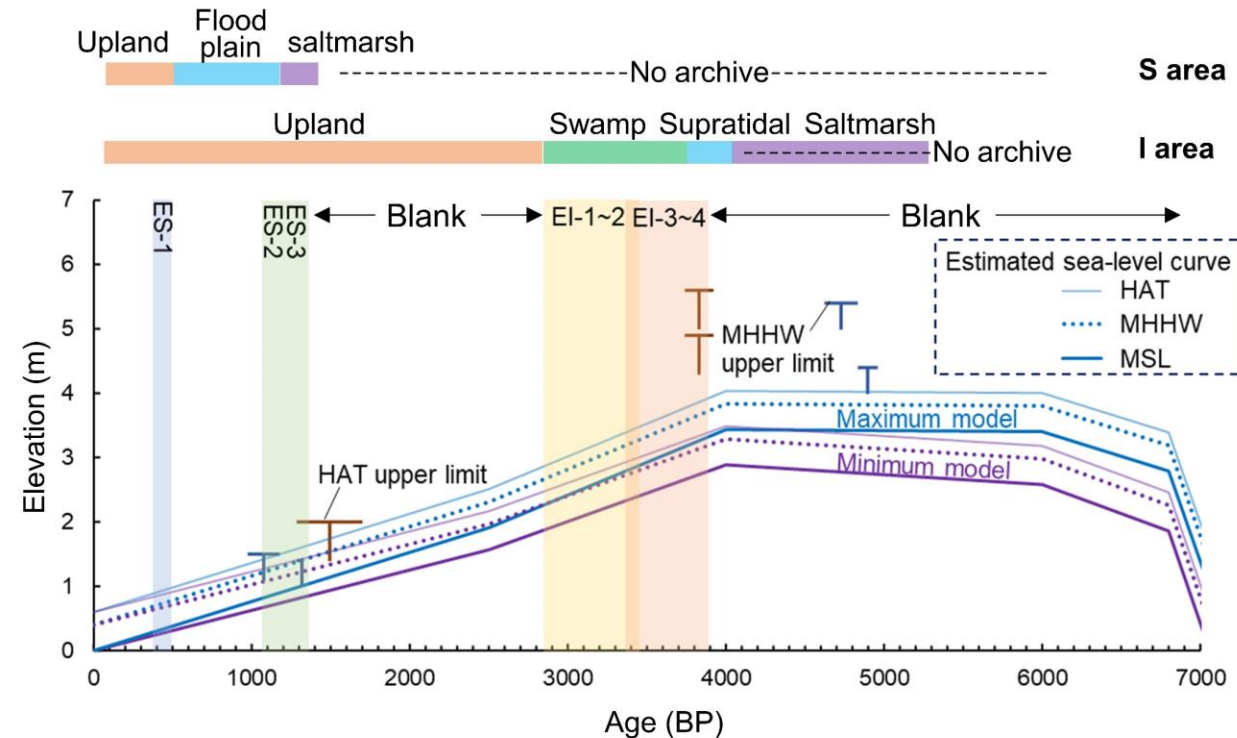
- In order to verify the origin of the event layers, we compared them with the tsunami deposits reported in the area with similar geomorphological conditions to this study area and the characteristics of the modern storm deposits in Hokkaido.
- The most significant difference between the modern tsunami and storm deposits is the **lateral extent and grading units**.
- ES-1~3, EI-3, 4 are distributed more than 100 m from the coastline and show similar features to **modern tsunami deposits**.
- EI-1 (and EI-2 ?) shows similar features to the **storm surge deposits** in terms of distribution over tens of meters and sedimentary structure.

	ES-1	ES-2	ES-3	EI-1	EI-2	EI-3	EI-4	Modern tsunami deposits	Modern storm surge deposits
Deposited age									
from		8th	7th	3140 BP	3440 BP	3460 BP	3900 BP	AD 2011	AD 1959-2015
to	17 th century	10th century	8th century	2840 BP	3270 BP	3370 BP	3670 BP	in Misawa	in Hokkaido
Distribution of sand layers									
Distance from beach ridge [m]	230	180 <	180 <	60	50	100	100	150-250 Sheet	Several tens meters Lobe
Elevation [m asl]	4.5	4.7 <	2.5 <	5.5	5.5	5.8	6.0	4-6	4-6
Thickness [cm]	0.5-13	2-10	5-8	15-31	0.5-15	3-6	0.5-6	0.5-30	0-50
Variation toward inland									
Thickness	Thinning like sheet	Thinning like sheet	-	Rapid Thinning	Rapid Thinning	Thinning like sheet	Thinning like sheet	Thinning like sheet	Rapid Thinning
Grain size	Fine	Fine	Fine	No trend	Fine	Fine	Fine	Fine	Coarse
Sorting	No trend	No trend	No trend	Well sorting	Well sorting	Well sorting	Well sorting	No trend	Poor sorting
Other features									
sedimentary structure	Normal grading	Normal grading	Normal grading	sequential Inverse-normal grading	Normal grading, homogeneous	Inverse-normal grading	Inverse-normal grading, homogeneous	Inverse-normal grading, Subunits layers, Pallarell laminae	Pallarell laminae, Subunits layers
Candidate supply source	Beach ridge Beach	Beach ridge	Beach ridge Tidal sand	River mouth Beach	Tidal sand	River mouth Beach ridge	River mouth Beach ridge	Beach	Beach
Basal contact	Clear	Clear	Slightly clear	Slightly clear Containg gravel	Slightly clear	Clear	Clear	Clear	Clear
Rip-up clast						○		○	
Characteristical diatoms	Marine and Tertiary species	Similar to below layer	Similar to below layer	Similar to below layer	Tertiary species	Brackish and Tertiary species	Brackish and Tertiary species	intertidal supratidal marine	Sandbar Soil
Enviroments of lower contact	Floodplain	Floodplain	Floodplain	Upland	Wet meadow	Wet meadow	Wet meadow	Beach, Coastal forest, Lowland	Beach, Sandbar, Grassland
Reference								Nakamura et al. (2012) Koiwa et al. (2014) Tanigawa et al. (2018)	Nishimura and Miyaji, (1996) Ganzei et al. (2010) Shigeno and Nanayama, (2016) Chiba and Nishimura, (2018)

Potential of Holocene coastal wetlands as geologic archives

- If the EI-1~3 and ES-1~4 are tsunami deposits, megathrust earthquakes with a recurrence interval of several hundred years are the most likely candidates for the wave sources.
- However, The time period preserved for the event layer is limited to after 1500 BP and 4000–3000 BP.
- Before 4000 BP, seawater inflow was recognized by diatom and CNS analysis, and it is possible that the thin sand layer was disturbed in this environment.
- From 3000 to 1500 BP, the sea level continued to fall, and the wetland environment where an event layer is preserved was not formed in the seaward area of the paleo beach ridge.

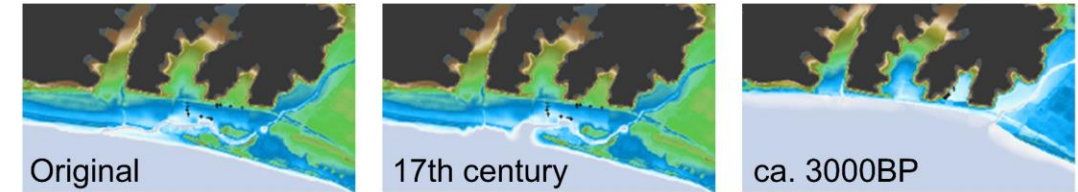
Extreme wave archives depend on the history of sea-level change including wetlands development.



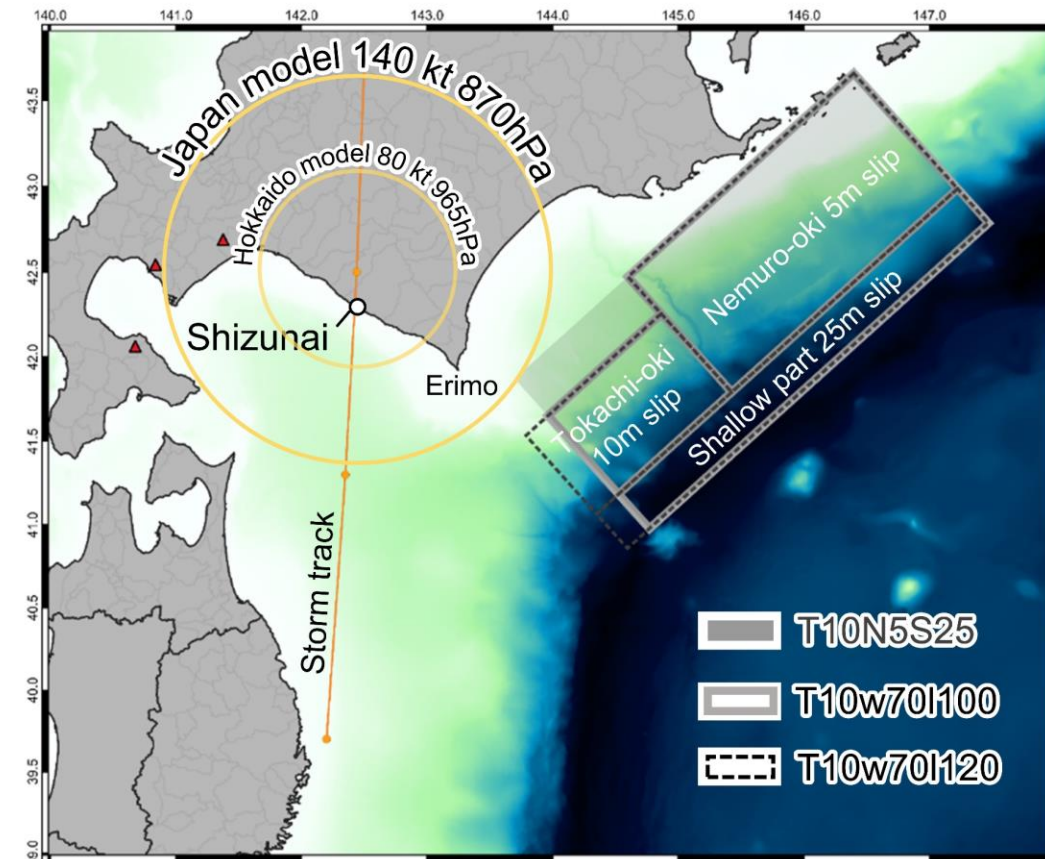
Sea-level index points as HAT and MHHW obtained in this study in the Shizunai area. Estimated sea-level curve based on the GIA model (Shimokita Peninsula: Yokoyama et al., 2012) and the uplift obtained from the elevation of marine terraces. The color shades indicate the depositional age of the event layers and the depositional environmental unit.

Are these events tsunamis or storms ?

- We ran numerical simulations to verify whether the distribution of the event layers could be reproduced by tsunamis or storm surges.
- **Source code:** Delft-3D Flow with SWAN (Deltares, 2011)
- **Grid data:** Nesting #3645, #1215, #405, #135, #45, #15, #5m. #5m grid reconstructed the topography of the 17th century and ca. 3000 BP, considering artifacts, sea-level and coastal development.
- **Physical Conditions:** The mean grain size was set 0.37 mm, which is dominant in the beach sand, which are considered to be the main source of erosion. Manning's roughness coefficient was set for both land and sea is $0.03 \text{ m}^{-1/3\text{s}}$.
- **Tsunami simulation conditions:** The rupture region of the T10N5S25 model (Ioki and Tanioka, 2016) with a modified fault width was used as a tsunami caused by a giant earthquake in the Kuril Trench. The model reproduced the 17th-century tsunami deposits in the Erimo area (T10w70: Nakanishi et al., submitted). As a variable condition, the fault length of the Tokachi-oki segment (T10) was prepared in two conditions of 100 and 120 km (T10w70I100 and T10w70I120).
- **Storm surge simulation conditions:** The path of the typhoon Chanthu, which caused significant damage to Hokkaido in 2016, was used as a reference to adjust the path of the typhoon to have the highest wave height in the Shizunai area. Wind speed and minimum pressure are set the two conditions as the best records observed in the Hokkaido and all Japan; the Hokkaido model referenced 80 kt and 965 hPa for Mireille in 1991 and Shirley in 1965, the Japan model referenced 140 kt and 870 hPa for Tip in 1979. The radius to maximum winds was calculated from the conversion formula of Gross (2004).

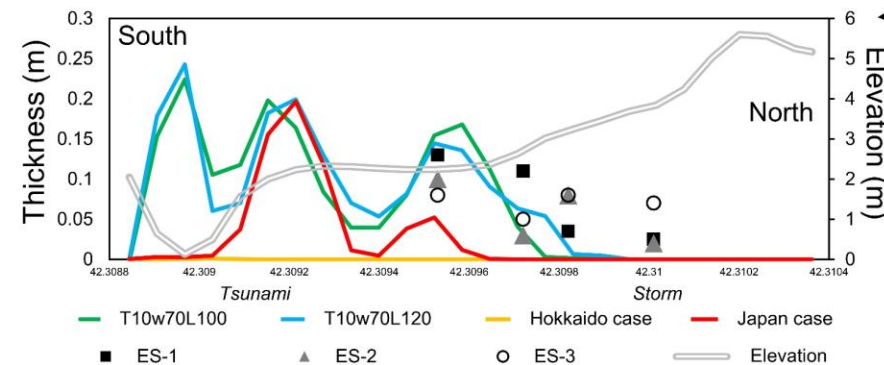


5m mesh grid reconstructed the topography (+: the event layers distribution)

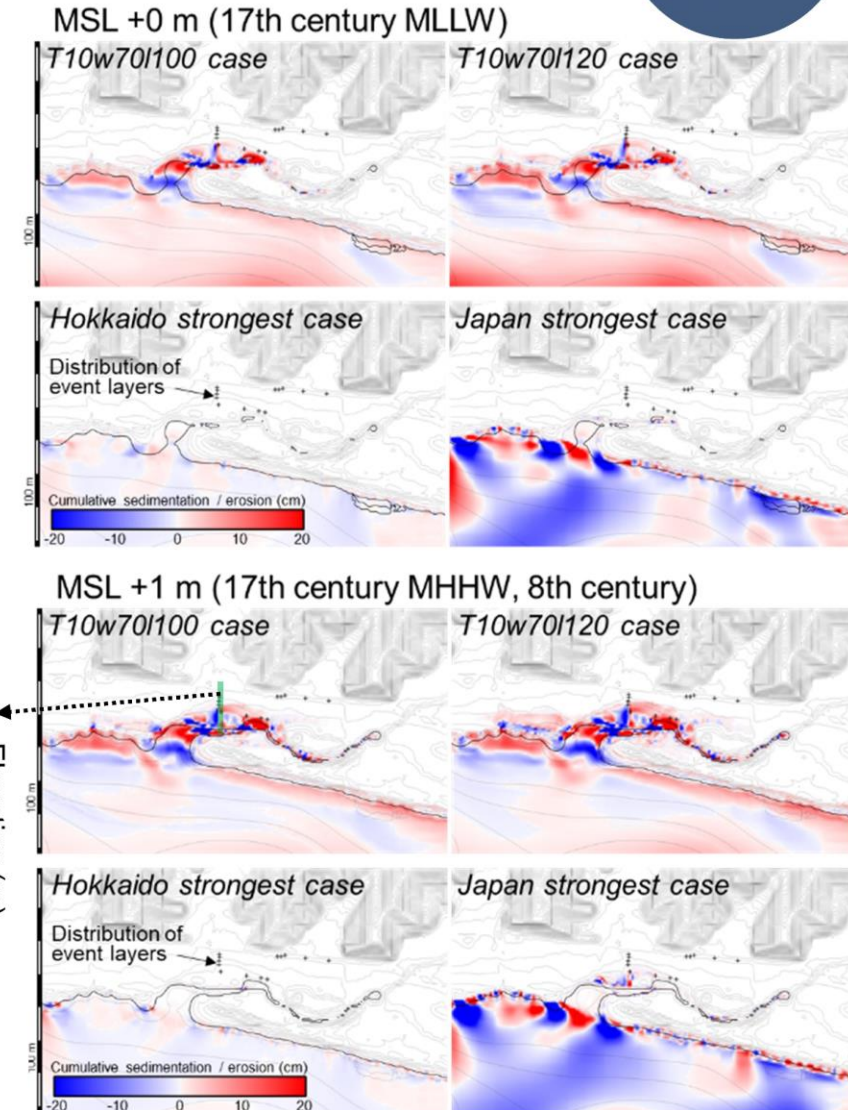


Numerical simulations

- All models could not perfectly cover the ES-1's distribution
⇒ Need to consider different source models and increase the accuracy of topographic conditions
- For storm surge, the strongest model (even the unrealistic typhoon in Hokkaido) showed little deposition in the distribution area of the event layers.
- The sand thickness of was strongly influenced by the topography.
- The storm deposits were rapidly thinned, while the tsunami deposits showed a sheet-like pattern than the storm surge deposits.



The thickness of the sand layer deposited by each source model (MSL +1 m) is shown on the green line, and the thickness distribution of ES-1~3 is also shown.

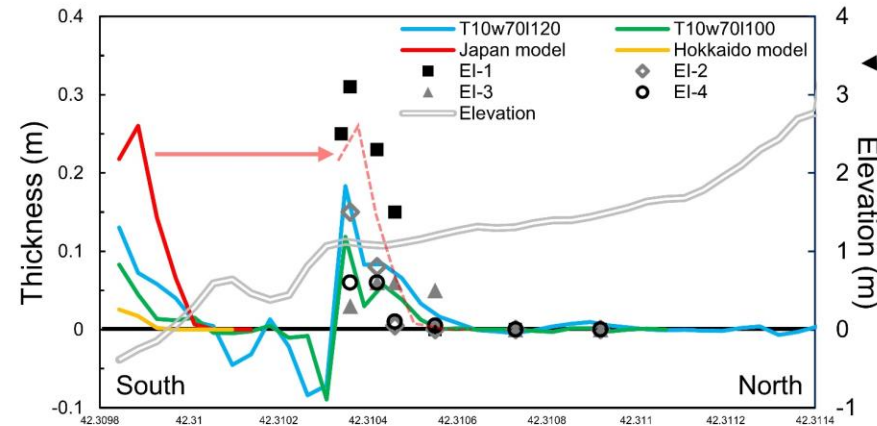


Accumulated deposition and erosion calculated by each source model. Black crosses show the distribution of ES-1~3.

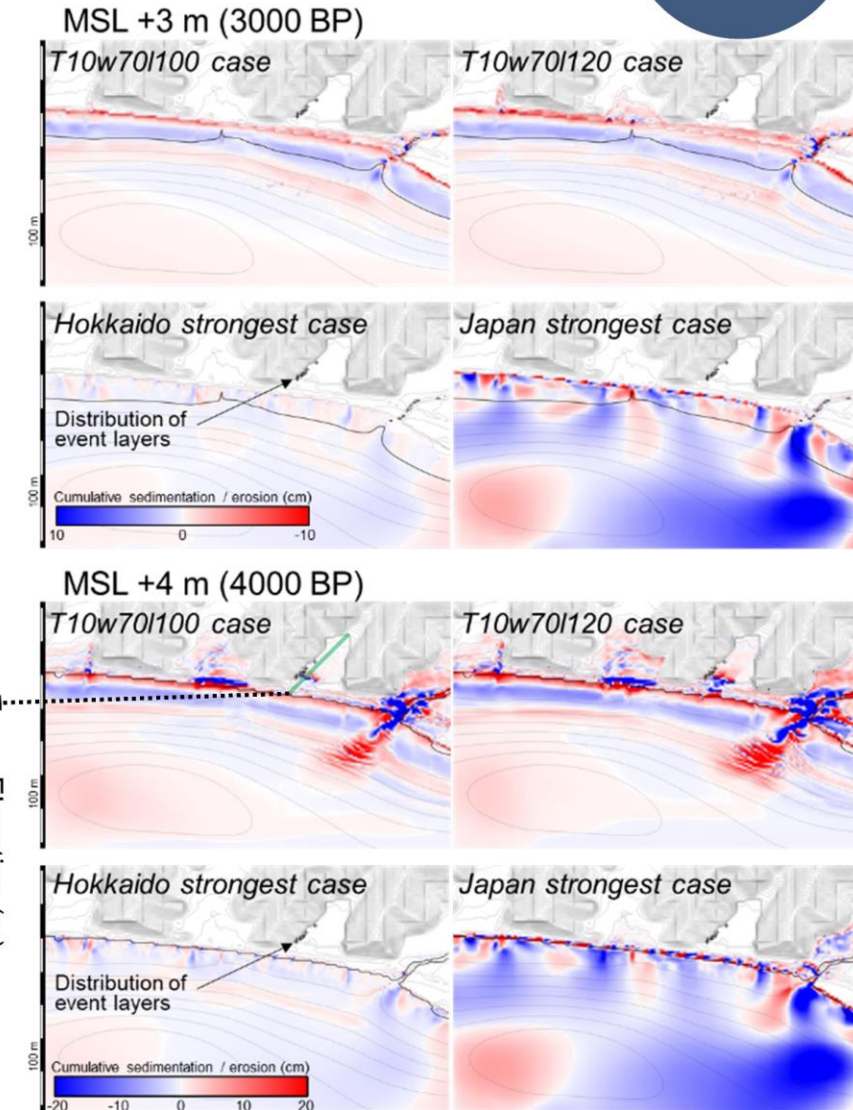
Numerical simulations

- In all conditions, there is no inundation over the PBR when the MSL is +3 m.
- In the MSL +4 m cases, both tsunami conditions showed similar sediment distributions to EI-2~4.
- The rapid decrease in thickness of EI-1 is similar to that of storm deposits, but the distribution areas do not overlap.

Based on the reconstructed paleo topography, most of the event layers can be reproduced by tsunamis induced possible megathrust earthquakes.



The thickness of the sand layer deposited by each source model (MSL +4 m) is shown on the green line, and the thickness distribution of EI-1~4 is also shown.



Accumulated deposition and erosion calculated by each source model. Black crosses show the distribution of EI-1~4.

Conclusion

- Field surveys revealed seven new event layers and coastal development processes in the central part of the Hidaka coast (Shizunai) were away from wave sources.
- The coastal development in this area was driven by the sea-level rise during the mid-Holocene, indicating a change from saltmarsh to uplands. However, the rapid regression suggests that there are times when the event layers are potentially not preserved due to insufficient accommodation space required for wetland formation.
- Reconstruction of the depositional environment using multi-proxies enables the discovery of event layers with limited distribution and also provides important insights for numerical simulations and discovering event layers.
- Most of these event layers have similarities with modern tsunami deposits in the sedimentary structures, but it is difficult to identify only the sedimentological information because of their limited distribution.
- We performed the numerical simulations based on the reconstructed paleo coastal topography and found that the distribution of many event layers can be reproduced by tsunamis caused by megathrust earthquakes in the Kuril Trench. However, to explain the anomalous distribution of ES-1 and the thickness distribution of EI-1, it is necessary to consider different wave sources and more detailed paleo topography.

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