Tsunami behavior using spatial analysis of onshore tsunami deposits from the 2011 Tohoku-oki Earthquake, Fukushima prefecture, Japan

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The behavior of the 2011 Tohoku-oki tsunami using spatial analysis of onshore tsunami deposit in the Odaka area, Minamisoma City, was reconstructed based on a field survey, facies descriptions, bed thickness, magnetic susceptibility, anisotropy of magnetic susceptibility (magnetic fabric), grain size distribution, and topographical data. The results are summarized as follows;
1. In the Odaka area, two tsunamis struck from the northeast and east. The water collided with the embankments of the prefectural road 260 and the Odaka River, and joined at the western part of the area. The head part of the tsunami eroded the soil in the rice paddy fields and the eroded mud clasts were taken in by the tsunami waters. As a result of this, the mud content increased in the fluid inland.
2. The integrated tsunami inflow at western part changed direction and started to outflow toward the northeastern mouth of the river. This outflow caused accumulation of the muddy fraction along the embankments, and resulted in lower mud content in the fluid toward the downstream area.
3. In the northern part of the area, tsunami deposits included abundant coarse materials with artificial tsunami debris derived from the residential area located toward the east of the study area.

Keywords: tsunami deposits, magnetic fabric, grain size characteristics, spatial analysis, mud clast

Efficient radiocarbon dating method for precise age estimation of tsunami deposit

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Depositional age of tsunami deposit can provide valuable information for the tsunami hazard assessment. Radiocarbon (^{14}C) dating method is commonly used for estimating a depositional age of tsunami deposit. The advantage of this method is wide applicability in age and its reliability. However, the accuracy of the dating result depends on the gradient of the calibration curve which represents the time series variation of ^{14}C age and calendar age. Therefore, during the period with wiggles in the calibration curve, ^{14}C age has chance to be correlated to multiple calendar age, and consequently the estimated calendar age shows large statistical error.
To solve this problem, some statistical method based on a series of large number of ^{14}C measurement has been used for constraining the dating results. For example, sequentially measured ^{14}C age can be wiggle-matched to the gradient of the calibration curve, and thus calendar age is estimated precisely. Alternatively, adopting a Bayesian approach is another way to constrain the sequentially measured ^{14}C age by their stratigraphic order. However, these methods need large number of ^{14}C measurements, and it is costly. In case of tsunami sedimentology, precise dating should be conducted at wide area to estimate the size and recurrence interval of tsunami, so it is important to discuss minimum required measurement number to securely obtain high precision calendar age.
In this study, we present the efficient measurement method of ^{14}C age for precise age estimation of tsunami deposit. Based on the correlation with the calibration curve, required sampling positions and their priorities for measurement, and measurement number of ^{14}C age are discussed. Using this method, precise dating of tsunami deposit can be conducted with high cost-effectiveness, and thus it can be contribute to hazard assessment of tsunami.

Keywords: tsunami deposit, radiocarbon dating

Depositional evidence for the 14th November, 2016, Kaikoura Tsunami at Little Pigeon Bay, New Zealand

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The recent Mw7.8 Kaikoura earthquake cluster which occurred at 12:02 am on 14th November, 2016 local time, was one of the largest and most complex in New Zealand’s history. The first earthquake epicentre was located inland in the Marlborough fault system at coordinates 173.02°E, 42.69°S, with the rupture then spreading across 13 northeast propagating faults. At least three major faults ruptured offshore and caused complex seafloor displacement that resulted in a tsunami. The only known damaging inundation was recorded at Little Pigeon Bay in Banks Peninsula ~160 km south of the tsunami source area. The first wave arrived at ~1 am local time, with the largest wave arriving close to high tide approximately ~4 hours after the initial rupture. The bay has a distinctly north-facing, funnel-shaped geomorphology which focussed the tsunami and resulted in severe damage to a 100 year old timber-framed cottage located ~10 m from the shore at the site. Fortunately there were no casualties. We report on post-tsunami survey observations made at Little Pigeon Bay during four successive field campaigns on the 16th, 19th and 30th November 2016, and on 15th January 2017. This includes preliminary results and interpretations of electrical conductivity (EC) analysis data obtained from tsunami-related sediment sampled during the campaigns. Two distinct tsunami debris-inundation lines were observed. The upper debris-inundation line was ~140 m inland and ~4.0 m above mean sea level - about 2.9 m above the tide level at the time of the inferred maximum tsunami arrival. Depositional evidence included: 1) fine greyish sand and organic marine and terrestrial debris deposited in the cottage and up to the inferred inland extent of inundation; 2) flood marks on the cottage walls indicating the tsunami depth above land level at the cottage location; 3) upstream imbrication of gravels/cobbles in the dry creek bed; 4) salt crusts at sheltered locations initially observed only on the third field campaign with much reduced levels observed on the fourth campaign. Salinity data, obtained from EC measurements of surface sediment samples collected up to about 230 m inland, corroborate the extent of inundation inferred through the observed debris-inundation lines. Pending ITRAX elemental profiles and sedimentary (grain size) analyses will provide a better understanding of the characteristics of the sediments left by the tsunami. We discuss the implications of using depositional tsunami evidence at this site to identify and potentially hindcast older events associated with a similar source. Further, we highlight the role that localised geomorphology plays in influencing the nature and extent of inundation and damage associated with locally-sourced tsunami events.

Keywords: Tsunami, Deposits, Kaikoura earthquake, Little Pigeon Bay, New Zealand

Sedimentary process of a small sandy event deposit due to the storm surge and storm wave of a typhoon.

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We revealed features and depositional processes of the sandy event deposits (SED), which was caused by a storm surge and high waves during the 1959 Miyakojima typhoon around Hirahama coastal lowland, along the western coast of Oshima Peninsula, southwestern Hokkaido. We excavated new three trenches at the lowland and studied sedimentary features and grain-size. Sedimentary features implies that the 1959 SED was deposited from an unidirectional run-up flow. The deposits can be subdivided into three units: units T, S and F in ascending order. Unit T shows 3D dunes. Unit S shows bedform transition from 2D dunes to ripples. Unit D consists of a mud layer including suspended plant and pieces of wood. Grain-size analysis shows that Units T and S have a peak at around 2.0 Phi (P-2 population) as same as the beach sand from Hirahama Coast and a wide grain-size distribution over 0-4 Phi because fluvial bed of Yumiyama River(P-1 and P-3 populations) mixed. According to Dmax, Unit T shows coarsening upward from -0.25 to 0.25. On the other hand, Unit S shows to be finning upward and 0.75 from 0.25. Therefore, Unit T recorded the amplification process of the storm surge and high waves energy due to typhoons in after 9:00 on September 18. Unit S recorded the decay process of the high waves and storm surge energy associated with the movement of the typhoon of 13:00 to 14:00 or later. After 0:00 to 1:00 on September 19, suspended solids and wood fragments in stagnant water covered the Unit S then deposited Unit D because the typhoon was gone.

Keywords: washover sediments, 1959 Miyakojima typhoon, sedimentary structure, sedimentary process, grain-size analysis

Features of erosion and sedimentation due to the September 2015 flooding of the Kinu River, central Japan

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Fluvial flooding is among the most destructive natural disasters comparable to tsunamis. An accurate identification between flood and tsunami deposits still remains controversial, which complicates appropriate future risk assessments for these disasters. Enhancing descriptive data on modern flood and tsunami deposits is one of the basic approach to the problem. In this study, we describe the patterns of erosional scour and sedimentary deposition generated by the September 2015 flooding of the Kinu River in Joso City, Ibaraki Prefecture, central Japan. During the flooding event, water levels in the Kinu River rose rapidly due to heavy rain that ultimately overtopped, and subsequently breached a levee, causing destructive flooding on the surrounding floodplain. Distinctive erosional features are found near the breached levee, with sandy crevasse-spray deposit distributed adjacent to them. Based on the observation in conjunction with grain-size and diatom analyses, the deposit can be divided into three sedimentary units. The vertical and lateral changes of these sedimentary features might be the result of temporal and spatial changes associated with flow during the single flooding event. These observations and quantitative data provide information that can be used to reveal the palaohydrology of flood deposits in the stratigraphic records, leading to improved mitigation of future flooding disasters.

Keywords: Flood deposit, Erosion, Sedimentation, diatom analysis, September 2015 flooding, Kinu River

Effect of grain size on distribution of tsunami deposits in flume experiments

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We conducted flume experiments to examine the effects of grain size on tsunami deposit distribution. In the present experiments, tsunami-like bore of three different magnitudes passed through a fixed slope of 1/20 and 4-m-long flat terrestrial area, and transported sand from the upper part of the slope onto the terrestrial area. As the sediment source, we prepared well-sorted quartz sands in different grain sizes (median diameter: 0.20 mm, 0.15 mm, 0.10 mm, and 0.06 mm).
The results suggested that distribution pattern of tsunami deposits depends on sediment grain size. In the cases of coarser sands (0.20 mm and 0.15 mm), tsunami deposits tended to decrease landward across the whole terrestrial area as previous laboratory studies have reported. The amount of the deposit at a given site also decreased with the weakening of tsunami magnitude. By contrast, in the cases of finer sands (0.10 mm and 0.06 mm), tsunami deposits tended to be approximately constant or gradually increase to landward on the terrestrial area. The amount of the deposit at a given site did not always depend on tsunami magnitude on the terrestrial area.
Distribution patterns of tsunami deposits were completely different in each grain size although these experiment were conducted with same hydraulic condition of the tsunami flow. It suggests that grain size is a crucial factor to determine the distribution of tsunami deposit, and effect of grain size should be considered when we estimate tsunami magnitude from distribution of paleotsunami deposits.

Keywords: tsunami deposit, flume experiment, grain size

Basic hydraulic experiment on tsunami sand deposits related with sand grain size and bore wave

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A massive tsunami occurred with the earthquake in Tohoku district on March 11th, 2011. This tsunami attacked coastal areas and caused serious damage. Tsunami measures must be reconsidered to prepare for the Nankai Trough tsunami. Many of the tsunami measures are based on historical records of earthquake and tsunami. Amount of the records are limited, because these disasters are low frequency. Tsunami sand deposits are left many of tsunami records and are expected to analyze paleotsunamis. However, tsunami sand deposits are only used to show the fact of tsunamis and to determine the relative magnitudes. The thickness of sand layer and grain size are considered to relate with tsunami force. These relations could clarify the tsunami source. This study focused on the relationship between the grain size and tsunami force. The objective of this study is investigation on the formation mechanism of tsunami sand deposit by hydraulic experiment.
A two dimensional water channel consisted of a wave maker, a flat section and a slope section. A movable bed section with various grain sizes of sand was set at the end of flat section. The condition of sand used three uniforms and three mixed grain sizes in this experiment. Bore waves of several heights transported the sand to the slope section by run-up. Sand deposit distribution were measured when run-up reached at the highest or after the return flow. The former condition assumed that water permeated in the ground. Water surface elevation and velocity were also measured at several points.
The grain size of sand deposits and the magnitude of incident waves were related distance of run-up. The distances from the shoreline of run-up (DW) and sand deposits (DS) were different. In the case of the smaller grain size, DS/DW became higher and the amount of sand deposits increased. Further, in the case of the plural incident waves inputted, DS/DW became higher in all cases. The sand deposit increased clearly on the halfway of slope area. The distance from shoreline of this position became longer, when the magnitude of incident waves was large. However, the position did not move by the difference of grain size. In the case of mixed sand with three grain sizes, the mixed ratio in sand bed section corresponded with the composition ratio of the sand deposit near the shoreline. However, they were different near the front of run-up. By the condition of the any mixed sand, the total amount of sand deposits was similar. The relation with the number and magnitude of incident waves showed two patterns. In the case of same magnitude waves inputted, the sand deposit increased by each wave near the front of run-up. On the other hand, the sand deposit did not increase by each wave near the shoreline. In the case of decreasing magnitude waves inputted, the sand deposits increased clearly by the lower incident wave near the front of run-up. As in the case of same magnitude waves inputted, the sand deposit did not increase by each wave near the shoreline. The amount of sand deposit related with or without return flow. The type of flow without return preserved the much of sand deposit. On the other hand, return flow took away the most of sand deposits on the slope area. However, when the wall was installed to reflect the wave in the slop section, the sand deposits remained there. Because the wall increased water depth and reduced velocity rapidly, tractive force near the wall became small. The distribution of sand deposits repeatedly increased and decreased on the slope because of limited return flow. On the other hand, when the wall was installed near the front of run-up, the most of sand deposits took away on the slope area by the large return flow.

Keywords: mixed sand, run-up, tractive force

Using experimental tsunamis to evaluate sediment deposit characteristics and inverse model predictions

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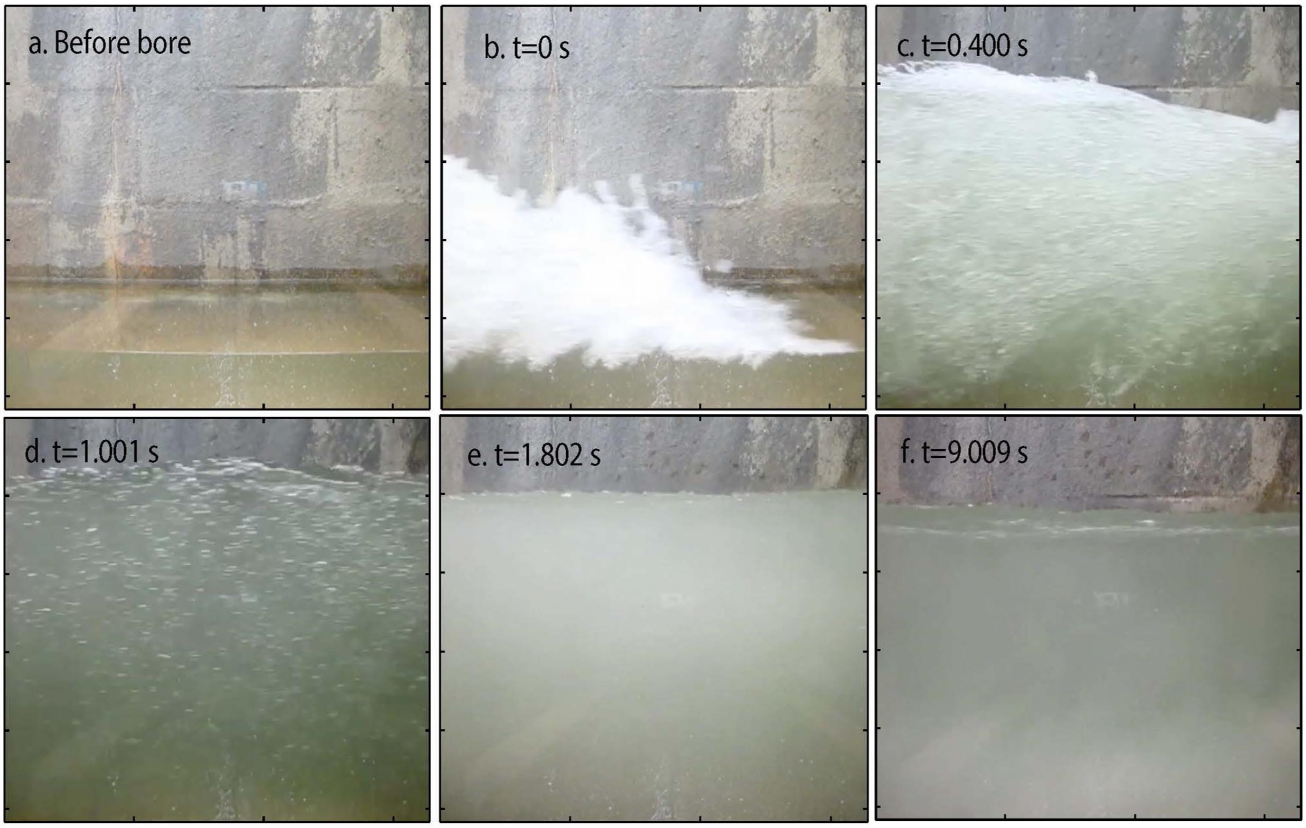
Tsunami deposits can imperfectly record the hydraulic conditions of devastating extreme events. Quantitative models relating sediment characteristics to flow hydraulics hold the potential to improve coastal hazard assessments. However, data from recent natural tsunamis have rarely been accurate enough, over a range of parameter space, to quantitatively test proposed inverse models for predicting flow characteristics. To better understand how to "read" flow depth and velocity from deposits, we conducted controlled and repeatable laboratory flume experiments in which different grain size distributions (GSDs) of sand were entrained, transported and deposited by hydraulic bores. The bores were created by impounding and instantaneously releasing ~6 m^3 of water with a computer-controlled lift gate. The experiments represent 1/10 to 1/100 scale physical models of large events. Both flow characteristics (including Froude numbers) and suspended sediment transport characteristics (including Rouse numbers and grain size trends) scale consistently with documented natural tsunamis.

We use the experimental data to interpret how entrainment, transport and mixing influence deposit GSDs along the flume, and to evaluate an advection-settling model for predicting flow depth and velocity. Suspension-dominated deposits get finer and thinner in the direction of transport. The data show that two key controls on GSDs along the flume are (a) the size distribution of the sediment source, and (b) turbulent dispersion of grains. First, we find that the influence of source GSDs on deposit GSDs is strongest near the sediment source. Size-dependent suspension and settling become increasingly important farther down the flume. Transport distances of 1-2 advection length scales are required for deposit GSDs to be sensitive to flow hydraulics. Second, by looking at the spatial distribution of grains of a given size class along the flume, we show that turbulent dispersion strongly influences local deposit GSDs. By comparing different grain size classes, we interpret that dispersion is more important than resuspension for transporting some grains farther distances than expected based on mean advection and settling rates. Importantly, intermediate deposit grain size percentiles (e.g. D50) are less sensitive to dispersive transport than either the fine or coarse tails of local deposit GSDs. Using deposit GSDs along the flume, an advection-settling model best predicts flow depths and velocities when calculated for intermediate percentiles (e.g. D50), rather than for coarse size fractions (e.g. D95) as has been assumed in previous works. Overall, well-controlled experimental data should be used to improve inverse models for predicting tsunami characteristics from deposits, and to rigorously evaluate the accuracy and uncertainty of model-based hazard assessments.

Keywords: tsunami deposit, inverse model, flume experiment


a. Before bore
b. t=0 s
c. t=0.400 s
d. t=1.001 s
e. t=1.802 s
f. t=9.009 s

Magnetic fabric evidence for rapid, characteristic changes in the dynamics of the 2011 Tohoku-oki tsunami

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Magnetic fabric (MF) and rock magnetic measurements were applied to sediments deposited by the 2011 Tohoku-oki tsunami to reveal the dynamics of the tsunami run-up and the character of the sedimentation along the Misawa coast, Aomori Prefecture, northern Japan. Two main types of sedimentary environment are described: a higher energy, tangential stress-dominated environment with imbrication and traction/rolling transportation and a calmer, post-peak wave environment ruled by gravitational stress. Rapid characteristic changes in the tsunami dynamics are also described. The tsunami began with erosion of the pre-tsunami surface caused by rapidly increasing energy. Bedload features such as ripple stratification were developed by the repeated accelerations and decelerations of the tsunami wave during run-up. The arrival of the peak wave was indicated by high-density flow, “slurry-like” sediments. Following the peak wave, the decreasing energy was marked by a change in MF.

Keywords: magnetic fabric , tsunami dynamics, 2011 Tohoku-oki tsunami

Spatial distribution of tsunami deposits of the 1993 Hokkaido Nansei-oki Earthquake at a lowland along the Valentine Bay, Primorye coast, Russia

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he coast of eastern Primorye Russian coastal provinces had been affected repeatedly by tsunamis caused by earthquakes that occurred along the eastern margin of the Sea of Japan. The most recent one is the 1993 Hokkaido Nansei-oki earthquake and tsunami. Recently, cooperative study by Russian and Japanese researchers carried out along the eastern Primorye coast and found modern and paleotsunami deposits at several places (Ganzey et al., 2015). In July 2016, we visited the Valentine Bay where the 1993 deposits are found to be preserved well in a lowland. The Valentine Bay is located about 200 km east of Vladivostok and about 440 km west northwest of Okushiri Island, Hokkaido. The 1993 tsunami height was measured to be about 4m and caused damage to fishing boats and harbor facilities. Our survey area was about 500 m square, and it had been used as a meadow by cultivating low dunes. The survey was done by excavation with handy geo-slicer or small scoop. We observed at 35 points, and 27 of which were sampled. The 1993 tsunami deposit are sandy and covered with an average 3-5 cm soil. The distribution is sheet-like and be traced up to ca. 300 m inland from the beech. The maximum thickness of the layer is 10.5 cm, and the mean grain size of the sand is 1.4 - 2.8 ϕ. Both sediment thickness and mean grain size tend to be thinner and finer from the coast to the inland, but thick and coarse especially at along the old river channel between the dunes. Near the distribution limit, the sand layer became patchy. Also, behind the factory damaged by the tsunami on the sand dune, coal pieces were mixed in the sand layer, suggesting that the tsunami crossed the dunes and carried artificial materials along with beach sand. Today, there are very few places where we can track tsunami deposit from the coast to the migration limit. The modern tsunami deposit at the Valentine Bay is important to examine the processes of formation, succession and preservation that occurred while it is related to the microtopography and the environment.

Ganzey, L. A., Razjigaeva, N. G., Nishimura, Y., Grebennikova, T. A., Kaistrenko, V. M., Gorbunov., A. O., Arslanov, K. A., Chernov, S. B. and Naumov, Y. A., 2015, Deposits of Historical and Paleotsunamis on the Coast of Eastern Primorye. Russian Journal of Pacific Geology, 9, 64-79.

Keywords: tsunami deposit, Hokkaido Nansei-oki earthquake, Primorye coast, spatial distribution, preservation

Tsunami characteristics and sediment deposition in the Primorye coast, Russia, due to the Japan Sea earthquakes: a numerical study

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In this presentation, tsunami heights and periods in the coastal areas of Primorye, Russia, due to the Japan Sea earthquakes, are investigated based on tsunami numerical modeling. In addition, possibility of formation of sandy onshore tsunami deposits is discussed using sediment transport modeling.
The Japan Sea coasts from Hokkaido to Niigata, Japan, have repeatedly been affected by large-scale earthquakes and tsunamis from the eastern margin of Japan Sea, such as the 1993 southwest-off Hokkaido earthquake. Assessment of risks from earthquakes and tsunamis has been carried out over years based on historical materials and geological records. However, geological evidence is still too sparse to reconstruct the recurrence and magnitude of earthquakes and tsunamis in the Japan Sea coasts. Because of the geomorphological setting in the coast, including development of huge sand dunes and extensive anthropogenic land modification, suitable sites for tsunami deposit survey are quite limited in this region. On the opposite coast of Japan Sea, the tectonic and geomorphological settings of Primorye may offer a higher preservation potential of geological records. Recently, Japanese and Russian scientists carried out joint geological surveys in the coastal marshlands of Primorye and discovered sandy event layers from several locations (Ganzey et al., 2015). Tsunamis from the eastern margin of Japan Sea often reach the coasts of Primorye, Russia. For example, tsunami height of 5 m was recorded at the time of the 1993 southwest-off Hokkaido earthquake. The sand layers from Primorye are likely interpreted as the deposits of tsunami origin.
This study investigates the relationship between tsunami generation region in the eastern margin of Japan Sea and the tsunami characteristics in Primorye by means of numerical modeling. Nearshore tsunami heights and periods, as well as onshore sediment erosion and deposition, are examined based on numerical simulations of the tsunami hydrodynamics and sediment transport, to discuss possibility of formation of the sand layers by tsunamis from the Japan Sea earthquakes.

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Keywords: Tsunami, Primorye, Japan Sea, Deposits, Numerical modeling

Crustal movements inferred from fossil diatom assemblages during the last 1000 years, in the lower reaches of Toberi river area, Taiki, iHokkaido, Japan

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The details of paleo-sea level changes and paleo tsunami deposits have been studied, and also discussed about the paleo seismology along the Kuril Trench in the pacific coast at eastern Hokkaido, Japan (e.g. Nanayama et al. 2003, Sawai et al. 2004). As a result of these studies, the history of multi-segment earthquakes (M 9 class) have been revealed. The average recurrence interval of multi-segment earthquakes is estimated to be 400–500 years and the latest earthquake occurred in 17th century. However, the extent of the tsunami and the crustal movements due to the 17th century multi-segment earthquake are still unclear in westward of the eastern Hokkaido.
Nature-looking view and vast marsh are keeping relatively in lower reaches of Toberi river, at eastern Hokkaido, Japan, so volcanic tephras due to the series of volcanic eruptions (e.g. Mt. Komagatake, Tarumae and Usu) during 17th century and some tsunami deposits are well preserved in the marsh deposits (Nanayama et al. 2003, Furukawa and Nanayama 2006). However, few studies have been done to investigate the paleo-environmental change including the tectonic movements in this area. In order to reveille the tectonic movement due to the great earthquake occurred along the Kuril trench, we conducted GPS and geoslicer survey in lower reaches of Toberi river. Moreover, we analyzed fossil diatoms in the 83 cm long core sample obtained from 1.2 km landward from the coast.
As a result of field survey, the range of elevation was 1.3–7.5 m in study area, and we recognized a sand deposit show landward-thinning and extend to 1.4 km inland area in peaty deposits. In addition, the environmental change during the last 1000 years was inferred from changes of diatom assemblages and ages of tephras. We recognized the two major changes of diatom assemblages by the cluster analysis. The first is freshwater species change recognized in upper peaty and muddy deposits (0-30 cm depth). It is possible that the change caused by the land-use changes in upstream side of Toberi river and the river channel change in 19-20th century. Second is the change of relative abundance in freshwater, freshwater-brackish and brackish-marine species in lower peaty, muddy and sandy deposits (40-83 cm depth). The diatom assemblage showed a gradual increase of brackish-marine species prior to the deposition of sandy deposits and gradual decrease of these species posterior to the deposition before deposition of AD 1663 Us-b tephra. It is presumed that the changes of diatoms in lower peaty deposits were refraction of the relative sea level changes due to the inter-seismic, co-seismic or post-seismic crustal movements by great earthquakes along the Kuril Trench in 17th century. It suggests the possibility that the pattern of crustal movement recognized in this study is similar to the movement pattern in the area from Akkeshi to Nemuro (Sawai et al. 2004).

Keywords: Toberi river, Tsunami deposit, Fossil diatom assemblage

Investigation of tsunami disasters using lake kitagata sediments

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After tsunami disaster caused by the 2011 Tohoku-Pacific Ocean Earthquake vigilance awareness of tsunami has increased in Japan. Many large-scale tsunami disaster in Japan occurred in the Pacific Ocean side originated from earthquakes along the Japan trench or Nankai trough. According to the past history written in documents and existing geological records, large-scale tsunami occurred in the Sea of Japan side. Therefore, we reconstructed past tsunami records focusing on the coastal areas, especially in the Hokuriku region. Generally tsunami deposits have sedimentary structures such as lamina, coarse grain size, and rip up clast (Sawai 2012). However, because of the beach ridge and expected small scale of Tsunami in the Sea of japan side, clear tsunami sedimentary structures can be found only at limited locations in Hokuriku. Therefore we tried to detect tsunami deposit by measurement of physical quantities and observation of diatom. This study analyzed the lake sediments from Lake Kitagata, Fukui Prefecture. The advantage of analyzing lake sediments is good age resolution due to higher sediment accumulation rate than ocean sediment.

We discovered two doubtful layers of tsunami deposit . The layer of depth 170 to 203 cm shows a decrease of water content, coarse mineral grain size($\Phi<7$), and increase in calcium carbonate. A lot of seawater species diatom is found in this layer. This layer was deposited around 1450AD, when no historical tsunami record in Hokuriku was reported in historical documents.

The layer of depth 344 to 352cm also shows increase in calcium carbonate, decrease in water content and coarsening of mineral particle size. Diatoms observation confirms seawater species of *Actinocyclus gallicus* in spite that the kitagata was freshwater lake at that time. Dating results indicates this layer corresponds to around 700AD, so that we considered this layer deposited by Taiho tsunami that have occurred 701 AD from historical document record.

Keywords: lake sediment, tsunami, diatom

Recurrence intervals of large earthquake inferred from tsunami deposit at Idagawa lowland, Minami-Soma city in Fukushima Prefecture.

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Large interplate earthquakes and tsunamis repeatedly occur along the Japan Trench as inferred from historical documents and geological surveys (e.g. Usami, 1996; Utsu, 1999; Tsuji, 2000; Watanabe, 2000). The central Fukushima Prefecture is the southern limit of the distributions of tsunami deposits of the AD 869 Jogan earthquake. Previous studies in Idagawa lowland, Minami-Soma city reported that there were at least three tsunami deposits with normal grading structures and erosional contacts during the recent 2,800 years (Goto and Aoyama, 2005, JpGU; Oikawa et al., 2011, JpGU; Oota and Hoyanagi, 2014, GSJ). Our study site is a polder located about 12 km north of the Fukushima Daiichi Nuclear Power Station.

In this study, we estimate the depositional ages and average recurrence intervals of tsunamis using radiocarbon dating and Bayesian analysis. We analyzed two cores (IDG-02 and IDG-06) of the 13 core samples obtained using the 3 m handy geo-slicer. We found seven tsunami deposits (EV1-EV7) with multiple normal and reverse grading structures, laminas and rip-up clasts (Kusumoto et al., 2016, JpGU; Kusumoto et al., 2016, AGU). The top sand unit (EV1) is distributed on the ground surface and is considered as the 2011 Tohoku tsunami deposit. For the second sand unit (EV2), we distinguished EV2n in IDG-02 core sampled on the north side of Miyata River and EV2s in IDG-06 core sampled on the south side. For AMS ^{14}C dating, we selected terrestrial plant fragments, seeds, woods and charcoals from ordinary deposit and measured 11 samples for IDG-02 core and 14 samples for IDG-06 core. The measured ^{14}C age were calibrated to calendar year using terrestrial calibrated curves IntCal13 of the OxCal version 4.2 program (Bronk Ramsey, 2009; Reimer et al., 2013). The age-depth model was constructed using individual radiocarbon dates, the Poisson-process deposition model and Event Free Depth scale (Fig. 1; Bronk Ramsey, 2008; Ramsey et al., 2012).

For IDG-06 core, the depositional age of EV2s is constrained as 790-1120 calAD based on the 2011 Tohoku tsunami deposit (EV1) and a total of 4 samples between EV2s-EV3. For IDG-02 core, the age of EV2n also ranges from 1100 calAD to 1665 calAD based on the age of EV1 and a plant fragment between EV2n-EV3. The time interval between EV1-EV2s is about 820-1220 years while the interval between EV1-EV2n is about 350-910 years.

The depositional ages of EV3 and EV4 are constrained as 380-530 calAD and 320-470 calAD based on a total of 6 samples between EV2-EV3, a charcoal between EV3-EV4 and 5 samples between EV4-EV5. The time interval between EV2-EV3 is about 350-760 years.

The depositional ages of EV5 and EV6 are constrained as 400-240 calBC and 560-370 calBC based on 2 samples between EV4-EV5, 3 samples between EV5-EV6, respectively. The age of EV7 is estimated as 1210-820 calBC from a total of 5 samples above and below EV7. The time interval between EV5-EV6 is about 330-810 years.

The above results show that the time intervals of tsunami deposits are variable. Time intervals for EV3-EV4 and EV5-EV6 are relatively short, suggesting frequent occurrence, while the intervals for EV1-EV2, EV2-EV3, EV4-EV5 and EV6-EV7 are about 350-820 years, suggesting infrequent occurrence of large earthquakes. The deposit EV2s may correspond to the 869 Jogan earthquake. If that is the case, the time intervals between EV1 and EV2s (1142 years) is much longer than the other intervals.

Keywords: tsunami deposit, AD 869 Jogan tsunami, radiocarbon dating, average recurrence intervals

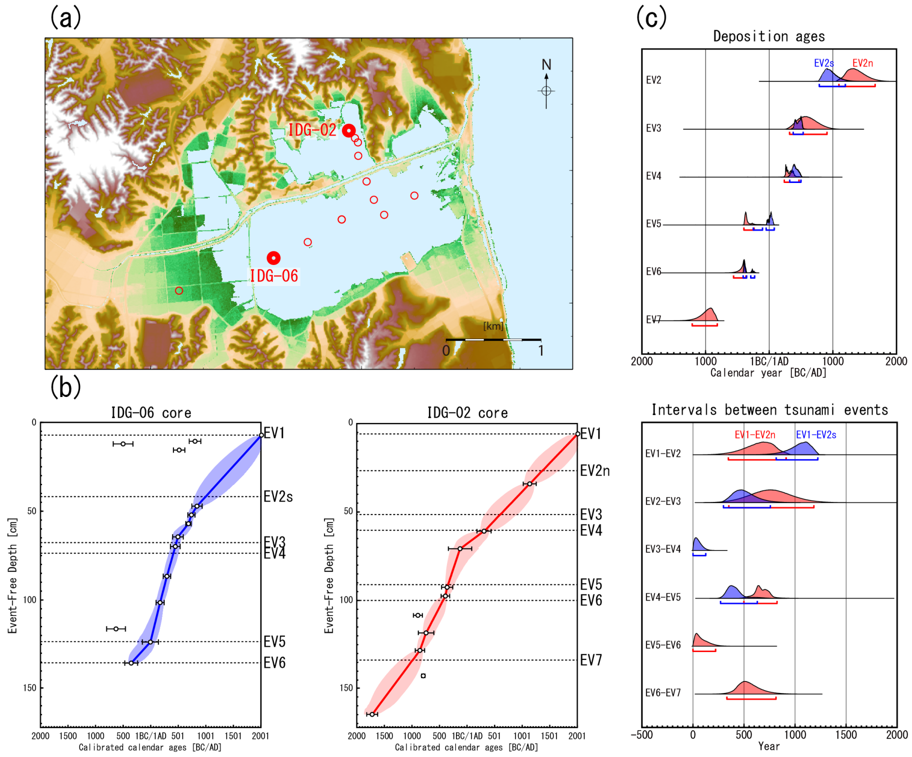

Figure 1. Age-depth relationships for IDG-06 and IDG-02 cores. (a) Topography and sampling sites. (b) The age-depth models for IDG-06 and IDG-02 cores. The circles and bars show the mean values and 2 sigma ranges, respectively. (c) The depositional ages of tsunami deposits and recurrence intervals between tsunami events. Blue color and red color show the results for IDG-06 and for IDG-02 cores, respectively.

Possibility of the interdisciplinary historical tsunami research based on various historical records - Example of 1611 Keicho Oshu Earthquake and Tsunami -

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Various historical documents drawn up 1,000 years or more before exist in Japan. Especially in the 17th century, the Japanese public created a vast quantity of historical data after the Edo period. In this research, I study the technique of interdisciplinary historical tsunami research based on these various historical data in Japan. Therefore, I consider as an example ”Keicho Oshu Earthquake and Tsunami” which occurred in 1611 in the Tohoku district Pacific coast of present day Japan.
In recent years, sedimentary layers on the Pacific coast of the Tohoku district from tsunamis which occurred after the 15th century have been discovered in two or more points. Opinions about the generation of this tsunami event are separated according to dates of 1454 or 1611. About this, I analyze the features based on the use of historical data. As data used as the basis of the tsunami event theory in 1454, "Oudaiki" materialized at the period is mentioned. However, “Oshu" (= the present Tohoku district) which is a stricken area of tsunami is the distant place, and the historical records described hearsay. Furthermore, when the text is interpreted, the disaster range can be interpreted as about 60 km or 400 km, and the actual condition is unclear. Two or more historical records exist that are used as the basis of the tsunami that occurred in 1611. They are various, such as a book copied down and edited by the historical records created by the time near the age that the tsunami occurred, and in later years.
If the descriptive content is analyzed, I can classify the sources of information.
(1) Historical records based on record of the “Omoto family” of Miyako-city, Iwate.
(2) Historical records based on record of the “ Muto family” of Yamada- city, Iwate.
(3) Historical records based on the Otsuchi deputy official place in Otsuchi-city.
(4) Historical records introduced into the Sendai han of Miyagi Prefecture.
(5) Historical records introduced into the Soma Nakamura han of Soma--city, Fukushima.
Since two or more sources of information exist in a stricken area, it is appropriate to having brought about damage from Iwate Prefecture to Fukushima Prefecture after the 15th century to think that it is the tsunami in 1611.
Moreover, it becomes possible by restoring old geographical features from historical data to solve the aspect of a historical disaster in detail. The record and tradition about a "Keicho Oshu Earthquake and Tsunami" in 1611 exist in Miyako, Iwate. The tsunami which carried out river ascension reaches Oyamada, and it is described that the ship drifted ashore in the historical records "Kojitsu-densyoki". The tradition of having tied the ship with the willow which existed in this place once by the tsunami which occurred at the Edo period exists in Miyako Tanokami. This tsunami trace point exists in inland further from the tsunami flood range in 2011. When considered from this, the tsunami in 1611 had a scale larger than the tsunami in 2011. However, this opinion will not be realized if historical geographical features are restored and analyzed. If geographical features are restored based on "50,000-minute one topographical map" which the army ordnance survey created, Heigawa which is flowing through the center in Miyako is flowing near Oyamada's surface of a mountain. Moreover, the Yamaguchi river is flowing through the center of the Miyako city area. That is, the channels of the river differ now and in the past.
The tsunami trace points of Keicho Oshu Earthquake and Tsunami exists on the channel of the old river. Therefore, it becomes possible to explain the contents of historical records by river ascension of tsunami.

If not only the description portion about a disaster but the formation background of historical records and the historical records which are not directly related to a disaster are based on them and analyzed when analyzing a historical disaster, solving in detail will be possible.

Keywords: 1611 Keicho Oshu Earthquake and Tsunami, historical records, interdisciplinary historical tsunami research, Visualization of historical geographical feature