Submarine earthquake- and tsunami-induced event deposits

— Disturbance of the sea floor by huge earthquakes and their related tsunamis, and the use of disturbance records in marine sediments for the history of past huge earthquakes and tsunamis —

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[Translation from *Synthesiology*, Vol.11, No.1, p.12–22 (2018)]

Huge earthquakes and tsunamis have agitated and disturbed the sea floor. Many marine geological surveys after the 2011 off the Pacific coast of Tohoku Earthquake indicated large disturbances of the sea floor by the earthquake and its related tsunami across a wide area from the coastal to the Japan Trench floor. Resuspension of marine surface sediment by the earthquake and tsunami might generate turbidity currents. Deposition of turbidites, which are deposits from turbidity currents, has been recognized. Therefore, earthquake- and tsunami-induced turbidite is a potential tool for understanding the history of past huge earthquakes and tsunamis. For the estimation of the origin and evolution of earthquake- and tsunami-induced turbidity currents and the selection of suitable locations for turbidite paleoseismology, marine geological information such as samples and characteristics of surface sediments and depositional modes is useful and important.

Keywords **:** Marine sediment, sea floor environments, turbulence, earthquake, turbidite, marine geological map

1 Introduction

The 2011 off the Pacific coast of Tohoku Earthquake (hereinafter, will be called 2011 off Tohoku Earthquake) that occurred on March 11, 2011 and the giant tsunamis that followed caused serious damage to the coastal areas from East Japan to Hokkaido, with the worst damage on the Pacific coast of the Tohoku region. This earthquake and tsunamis were initially labeled “beyond expectation,” but it is now known that the tsunami deposits on land show that there were previous cases observed in stratigraphic records,[1] and it was recognized that analysis of records is important in understanding the history of giant earthquakes and tsunamis. On the other hand, it was revealed that the results of analyzed records had not been utilized sufficiently in disaster prevention plans.[2] Some of the tsunami deposits on land may contain particles originating from deep water regions from which they cannot be transported by ordinary or stormy waves,[3] and it is thought that there are incidences where marine sediment is disturbed by tsunamis and washed ashore. In fact, according to the results of surveys of the Tohoku coast and offshore regions after 2011 that will be mentioned later, the phenomena of resuspension, reworking, and redeposition of the marine sediments have been reported in wide-ranging areas from the Sanriku coast forearc slopes to the Japan Trench floor, including the coasts and the shelf regions from the Sendai Bay, Sanriku, and off Hachinohe.[4]–[9] This indicates that in places where such redeposition phenomena remain, the evidences of past giant earthquakes and tsunamis may remain in the geological record on the sea floor, just like the tsunami deposits on land, and there is a possibility that these can be used for decoding history. In fact, the past earthquake occurrence history is being studied by comparing the tsunami deposit records on land with the sediment records in the Japan Trench floor.[7]

On the other hand, the areas from the shore to the offshore are closely intertwined with human activities, such as being used for constructions, fishing, and leisure. Moreover, fishing activities are conducted in the deepwater area from the shelf to the upper slopes further off the coast, and to know how the submarine environment from the shore to the offshore changes by earthquakes and tsunamis is important in predicting how earthquakes and tsunamis may affect human activities. However, there are very few cases that specifically show how the submarine environment changed due to certain earthquake and tsunami events or how the environment recovered.

Here, based on the current status of research after the 2011 off Tohoku Earthquake and Tsunami, we shall summarize the disturbance of the sea floor due to earthquakes and tsunamis and the process of resuspension and redeposition of marine sediment due to such events. After outlining the current situation of earthquake recurrence history research using the deposits produced during the earthquake (hereinafter, will be called earthquake event deposits), we wish to emphasize the importance of organizing marine sediment information as fundamental information that allows accurate understanding of the process. Also, we discuss what should be done for the future of paleoseimological research using earthquake and tsunami records left in marine sediment.

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Original manuscript received September 14, 2017, Revisions received November 16, 2017, Accepted November 17, 2017

2 Reworking, resuspension, and redeposition of marine sediment by earthquakes and tsunamis and the changes in marine environment

The occurrence of large-scale transport of sediments on the sea floor due to an earthquake became apparent during the Grand Banks Earthquake (M7.2) that occurred on the Atlantic coast of North America in 1929. Concerning this earthquake, several ocean cables that were installed in the submarine slope were severed, and the occurrence of turbidity currents was assumed due to the collapse of submarine slopes.[10] A turbidity current is a gravity current that flows down a slope due to the force of gravity while the particles are maintained in the turbulence of seawater mixed with sediment particles[11] (Fig. 1A). The speed of the turbidity currents of the Grand Banks Earthquake was the fastest in the slope region at 28.4 m/s, calculated from the distance between the ocean cables and the disconnect time, and was estimated to be about 8.3–6.2 m/s at the deep sea basin floor further off the coast.[10] Later, turbidites (deposits of the turbidity currents, Fig. 1B) were found in areas where the turbidity currents flowed, and it was found that a series of events occurred: collapse of submarine slopes due to the earthquake → occurrence and flow of turbidity currents → deposition of turbidites.[12] Similar sequential severance of ocean cables during earthquakes have been reported in several cases,[13][14] and this also occurred during the 2011 off Tohoku Earthquake.[15] There are many reports of turbidite depositions on sea floors around epicenters in submarine surveys immediately after earthquakes,[16]–[18] and it is clear that earthquakes are one of the generative factors of turbidites.

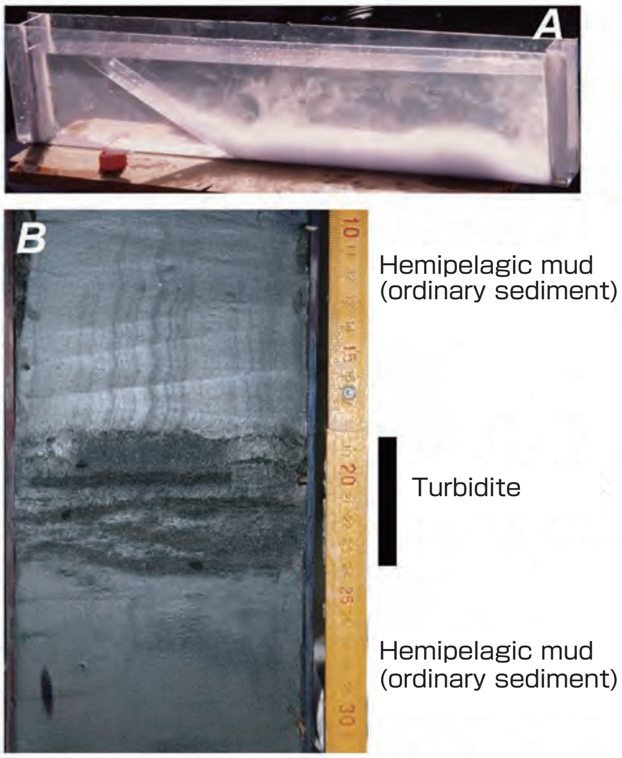

Fig. 1 Turbidity current (A) created in a water tank, and turbidite (B) that is a deposit from turbidity current as seen in a marine sediment core

It has become clear from several reports that the 2011 off Tohoku Earthquake and Tsunami had major effect on the sea floor. First, the changes in the coastline due to crustal movements following the earthquake and tsunamis could be seen easily by the naked eye, aerial photos, and satellite images. Many reports were provided by the mass media and others immediately after the earthquake. The topographical change of the coastal region adjoining the seashore was estimated from the bathymetric survey in the Sendai Bay, and the geographical distribution of the deposition and erosion of deposits, along with the data for seashore areas, were estimated.[19] The sampling of marine sediments showed that the deposits thought to originate from the 2011 off Tohoku Earthquake and Tsunami were thick in places estimated to be deposition areas and thin in places estimated to be erosion areas, and it was found that the results of the bathymetric survey and sediment sampling basically matched well.[20] In the southern part of the Sendai Bay, the presence of tsunami deposits on the sea floor was reported through high-resolution seismic surveys and sediment cores.[21] On the other hand, in the inland bay that comprises the Sanriku ria coast, the formation of landform due to tsunami deposits is reported at the sea floor of the mouth of the Kesennuma Bay.[22] It is also known that the formation of tsunami deposits occurred in the Hirota Bay, the Okirai Bay, the Touni Bay, and others.[23] In places such as the Onagawa Bay that is comprised of muddy sediments, tsunami deposits exist as clear sand layers, and their disruption by the activities of benthic organisms after deposition have been observed.[24] Sand layers that are intercalated in similar mud layers had been reported before the 2011 earthquake in the northern part of the Sendai Bay, and had been thought to be storm sand layers.[25] However, considering the survey results after 2011, it is highly possible that part of the sand layers might originate from tsunamis. In the shelf beyond the Sendai Bay, a deposit layer formed by repeated turbidity currents has been reported.[6] The series of fine-grained turbidites observed here are composed of a two-story structure of fine-grained turbidites that do not contain cesium 134 in the lower unit, but fine-grained turbidites containing cesium 134 in the upper unit (Fig. 2A, B). It is thought that the lower unit was deposited immediately after the earthquake and tsunamis, while the upper unit was deposited at least a few days after the earthquake and tsunamis, after the Fukushima Daiichi Nuclear Power Plant accident. These indicate that the interior of the Sendai Bay was under a condition in which sediment was suspended for several days or several dozens of days after the earthquake and tsunamis, although details remain unclear, and turbidity currents occurred during the aftershocks following the main quake. The phenomena of transport and redeposition of sediment in the shallow sea were not limited to the Sendai Bay or off Sanriku that are close to the epicenter. Toyofuku *et al.*[8] reported that the reworking of sediments occurred down to about a depth of 200 m off Hachinohe. Since the tsunami affects a wide area, it can be assumed that the affected area of the sea floor is also wide. In off Sanriku, it was shown that the shelf sediments were transported to the deep sea area of a depth of about 900 m, from the analysis of benthic foraminifera.[26] Interestingly, the turbidites here also had a two-story structure, and the lower turbidites originated from almost the same depth zone in the proximal area while only the topmost upper turbidites contained the shallow water benthic foraminifera. This was interpreted as meaning that the lower turbidites were formed through earthquake disturbance while the upper turbidites were formed by the disturbance in the shallow sea region by the following tsunamis. That is, although the deposit layer seems contiguous, they may have been formed from several different depositional processes by the earthquake and the following tsunamis. The turbidity currents washed away the observation devices set on the sea floor, and caused trouble by clogging the devices with mud.[5][27] As it can be seen, the characteristic of a giant tsunami is that it causes wide-ranging disturbance in the shallow sea offshore of the land where the tsunami strikes.

The effect of 2011 off Tohoku Earthquake and Tsunami is not limited to the shallow sea. Noguchi *et al.*[28] reported the occurrence of highly turbid bottom water in the forearc slope region. Arai *et al.*[5] reported the flow of turbidity currents originating from the tsunamis at about a depth of 1000 m in the forearc slope region, and Ikehara *et al.*[29] showed that an event deposit was present in wide-ranging submarine surfaces down to a depth of 5500 m from the outer shelf to the mid slope. McHugh *et al.*[9] reported that there was wide distribution of an event layer originating from the 2011 earthquake and tsunamis on the flat area at a depth of 5000–6000 m called the mid-slope terrace off Sanriku. Moreover, Oguri *et al.*[4] reported suspension at the bottom water in the Japan Trench, and reported the deposition of event deposits containing cesium 137 and excess lead 210. Ikehara *et al.*[7] confirmed similar deposits from several points nearby, and concluded from its deposition structure that it was a deposit of fine-grained turbidites.

The suspension phenomena of the bottom water during an earthquake reported for the 2011 earthquake by Noguchi *et al.*[28] and Oguri *et al.*[4] have been observed in other earthquakes. Ashi *et al.*[30] reported the suspension of the bottom water in the sea basin on the landside of the Nankai Trough slope after the 2004 off the Kii Peninsula earthquake (M7.4), and the presence of muddy water with extremely high concentration of suspended material immediately above the sea floor, and the thickness of this material was estimated to be about 2 m. This result raises speculation of a process in which a pond of mud water (mud pond) with a thickness of about 2 m might have been formed in the depression of the sea floor, and mud might have accumulated to form the earthquake event deposit. Moreover, Ashi *et al.*[31] postulated that such a mud pond can be formed by resuspension of a few cm of unconsolidated deposits that cover a slope, estimated from the surface area of the depression, the thickness of the mud pond, and the surface area of the slope that could supply the mud to the depression. The presence of such a

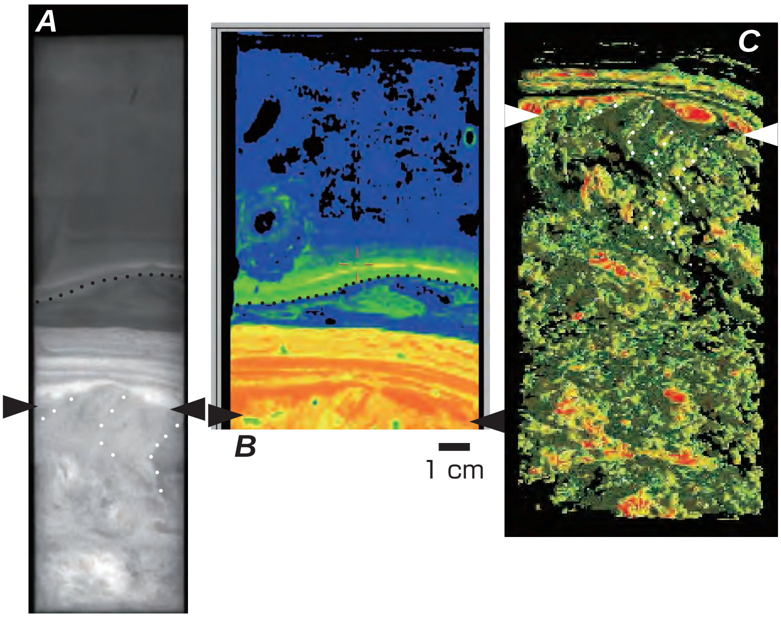

Fig. 2 Sediment formed by the tsunamis in the 2011 off Tohoku Earthquake; collected off Sendai (A: soft X-ray radiograph, B: X-ray CT image of upper layer, C: X-ray CT image of lower layer)

The sediment is composed of two units. The upper unit (upper portion above the arrows) is composed of fine-grained turbidites that become finer in the upper part. This is composed of two turbidite layers that are separated by an internal erosion surface (a surface formed in a series of sediment that cuts the lower sediment; shown in black dotted line). The upper and lower turbidites also become finer on upward (corresponding to the grain-size change from sand to mud, the change is from white to black in Fig. 2A, and from orange-yellow to blue in Fig. 2B). The lower unit is composed of hemipelagic mud that shows abundant disturbance by benthic organisms, but the deformation structure (white dotted line) caused by seismic movement can be seen at the upper part of the lower unit. Although the X-ray CT device allows obtaining 3D data nondestructively and the deformation structure due to seismic movement can be observed easily, the resolution is rather low for observing details of the deposition structure.

process, in which turbidites are formed by the generation of turbidity currents as unconsolidated sediment in the uppermost surface layer of the sea floor is resuspended by seismic movement (Fig. 3B), has been suggested from the sediment color measurement results and organic matter contents of the turbidites of the lakes in Chile,[32] and the radioactivity measurement on the landside slope of the Japan Trench.[9] Concerning actual occurrence of resuspension of marine sediment by seismic movement, Oguri *et al.*[33] conducted continuous submarine observations off Sanriku, and observed the resuspension and the deposition of surface sediments during an aftershock (M7.3) of the 2011 off Tohoku Earthquake. Perhaps the deposition of turbidites at the tip of submarine landslides and submarine debris avalanches, as shown in Fig. 3A, along with the presence of horseshoe landforms that seemed to be submarine landslides as seen on the bathymetric maps, might have provided an assumption to the researchers that the collapse of submarine slopes during an earthquake is essential in the formation of seismo-turbidites. However, in the resuspension process of surface sediments, the occurrence of large submarine landslides is not necessary for the formation of seismo-turbidites. Moreover, if the sedimentation rate is sufficiently large against the frequency of earthquake occurrence, sediment that comprises the turbidites that is resuspended during earthquakes is stored on the slopes during intervals of earthquakes, and it will be possible for turbidites to be formed at each earthquake. For example, in a place where the sedimentation rate at the landside slope is 50 cm/1000 year, and the average earthquake occurrence interval is 200 years, 10 cm of sediment is formed on the slopes between earthquakes, and surface sediment of several cm can be supplied sufficiently enough to form turbidites in the next earthquake. On the other hand, in a place where the sedimentation rate is 10 cm/1000 years, there will be 2 cm of sediment deposited between earthquakes, and when the deposits are resuspended during an earthquake, slopes are eroded and old sediment with low water content is exposed. Therefore, it is estimated that turbidites are not formed at each earthquake at such locations.

Deformation structures by seismic motion is another seismic record in marine sediments. There are several structures that are reported as deformation structures by seismic movement.[34] Sakaguchi *et al.*[35] reported a structure where surface sediment breaks in a breccia pattern due to seismic movements at the topmost part of a drill core from the landside slopes of the Nankai Trough, and stated it was formed in the 1944 Tonankai Earthquake, from the measurement of excess lead 210. Ikehara *et al.*[6] reported a linear structure arranged vertically (Fig. 2C) at the outer shelf off Sendai, and showed that it had a different size and interval compared to the vein structure observed in the mudstone of Kazusa Group that was formed by seismic movement,[36][37] but had the same form and length/interval ratio. Moreover, since this deformation structure was covered by event deposits formed by the 2011 tsunami, it was thought to be formed by the seismic movement of 2011. Such estimation of earthquake recurrence history using sediment with deformation structures caused by seismic movements has been used to study the lake sediments in Switzerland.[34]

3 Status of investigation of earthquake recurrence history using seismo-turbidites

Investigation of earthquake recurrence history using turbidites that are intercalated in the sediment of sea and lake floors are being conducted around the world.[7][18][34][38]–[40] Many papers have been published in the last few years. Other than the aforementioned disturbance and resuspension by seismic movements and tsunamis, turbidity currents can be caused by surge currents during storms, hyperpycnal flows that flow out of rivers during flooding, liquefaction of sediment due to repeated load of strong waves during

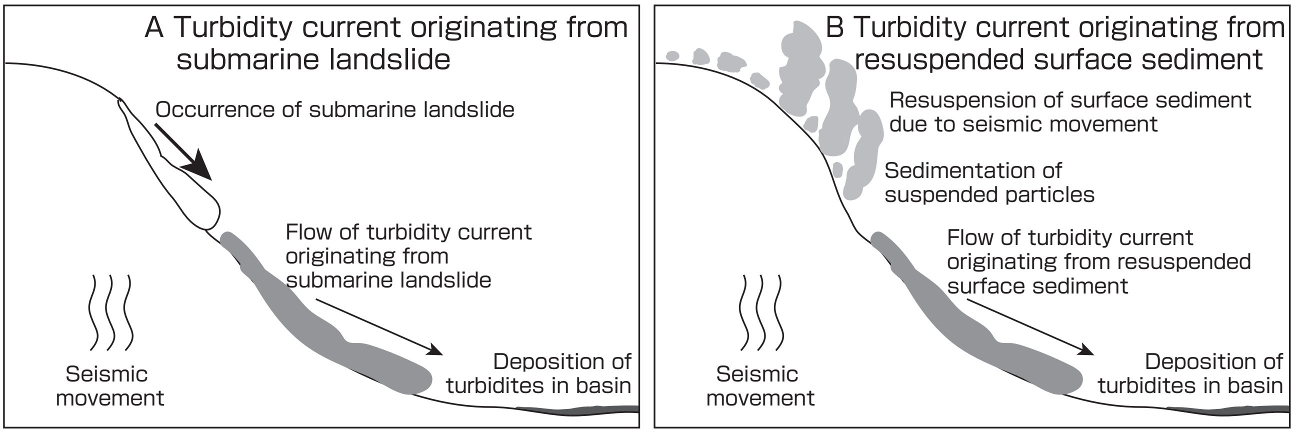

Fig. 3 Two deposition models of seismo-turbidites
(A) Origin from submarine landslide in which a submarine slope failure occurs due to seismic movement, and (B) origin from resuspended surface sediments where the unconsolidated surface sediments are agitated due to seismic movement.

storms, increased pore pressure due to rapid deposition of deposits, groundwater outflow on the sea floor, volcanic eruptions, fall of extraterrestrial objects, and others.[39][41][42] Therefore, it is important to identify the cause of formation of the turbidites found in sediments, but it is not easy to discern the cause of formation from the characteristics of the turbidites themselves. In the turbidity currents originating from rivers and shallow sea regions, particles originating from land or shallow sea can be expected, and these can be used to identify the cause of formation.[43] For example, if an underwater delta front at a river mouth collapses during an earthquake, the particles that flow out have almost the same composition as the river sediments, and it will be difficult to identify the cause of formation from grain composition only. Therefore, in current practice, obtained turbidites are often considered seismic, based on the geographical and sedimentological settings that receive little effect of the shallow sea, such as if the sampling point of sediment is distant from a submarine canyon that continues from a river, or is within an independent depression without any submarine canyons. Therefore, depression formed along a fault movement on a landward slope of a trench (slope basin) is considered as one of the optimal places for studying earthquake occurrence history using turbidites.[44] Also, the formation of turbidites during an earthquake of a certain magnitude or larger and their accumulation as a deposit record are important factors. It is hardly known what kind of earthquake event deposit was formed by an earthquake of what magnitude in a particular place. However, as mentioned earlier, in places where turbidites are formed by resuspension and redeposition of surface sediments, it is necessary for sufficiently larger amount of sediment to deposit on the slopes between earthquakes, compared to the amount of sediment that become resuspended. Also, for an earthquake event deposit to escape from the disturbance by benthic organism activities and the physical erosion of the sea floor so it could be used accurately as deposit records, it should have plenty of volume that accumulates between earthquakes, and should be away from sea floor surfaces that are easily subject to erosion and benthic organism disturbance. In practice, it is extremely important to select such locations from submarine topography and sedimentation to gather high quality samples for analysis.[39][44][45] Not all samples collected can be used to investigate earthquake recurrence history.

In the estimation of earthquake recurrence history using earthquake event deposits such as turbidites, the samples collected from appropriate places are used to identify the horizon of earthquake event layers intercalated in the samples, and the age of past earthquake occurrences are determined by studying the depositional ages of earthquake event deposits (Fig. 4).[39] Also, the epicenter and the size of rupture areas are estimated from the spatial distribution of earthquake event deposits formed at the same time. For the identification

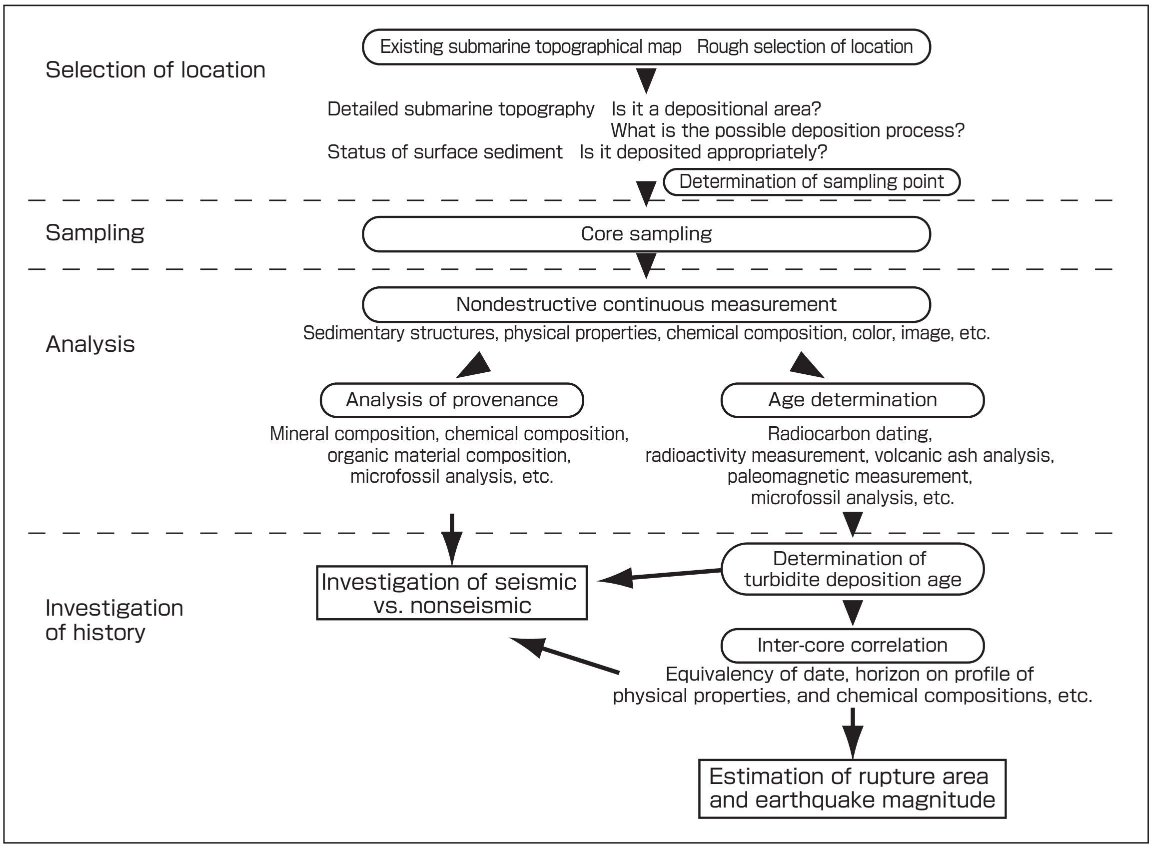

Fig. 4 Method for estimating earthquake recurrence history using seismo-turbidites

of the horizon of the event layer, sedimentary structures that could be observed by the naked eye, X-ray images, or X-ray CT images, and change in sediment color, grain-size, bulk density, susceptibility, mineral and chemical compositions, and others are used (Fig. 4).[39] In some cases, microfossils and organic compositions in the deposits may be used as indices. The identification of the earthquake event deposit by combining these techniques is essential.

The most common method for determining the depositional age of marine sediments is the radiocarbon dating method using planktonic foraminifera tests. Other methods include identification and correlation of obtained volcanic ash with age-known volcanic ash, correlation with geomagnetic paleosecular variation and paleomagnetic intensity variation curves, microfossil biostratigraphy, oxygen isotope stratigraphy of planktonic and benthic foraminifera, and radiocarbon dating using organic matters in the sediments. Of these, the method with the highest dating accuracy is the volcanic ash of historic eruption for which the eruption date has been determined. The radiocarbon dating of planktonic foraminifera that is most regularly used has errors of several dozen years (up to several thousand years ago) to several hundred years (several 10,000 years ago). Recently, there are attempts to calculate the event dates by considering the error using the Bayesian statistics for the probability distribution of individual date values, but needless to say, it is better to have as many datings as possible to obtain the reliable event date.

For the more reliable correlation of event layers between samples, it is desirable to compare from a position on the continuous data (profile) such as the geomagnetic paleosecular variation curve, color value, physical property value, or element concentration, while referencing radiocarbon dating and using the absolute isochronous surface such as mutually correlative volcanic ash as the standard. It is also preferable to obtain numerical data with high resolution as much as possible. To achieve this, nondestructive measurement is advantageous. Since there are many types of nondestructive analyzing devices, events can be compared by combining the profiles of multiple items with high resolution, and by adding many dates, it is expected to increase the accuracy of dating and earthquake event correlation.

If it becomes possible to compare earthquake events among the samples, it becomes possible to estimate the spatial distribution of turbidite deposition of a particular earthquake. From the results of submarine surveys conducted immediately after an earthquake, as the spatial distribution of seismo-turbidites is often limited to the earthquake rupture area and its proximity,[17][18] it is expected that estimation of earthquake magnitude and location of the rupture area will become possible from the distribution of seismo-turbidites. Some seismic movement deformation structures are thought to be related to the magnitude of seismic movement.[46] There are attempts to estimate the earthquake magnitude from the spatial distribution of seismic movement deformation structures and seismo-turbidites.[34] If this becomes possible, the estimations of earthquake occurrence location and magnitude become possible as well as the time of earthquake occurrence. But in the current situation, the establishment of an accurate comparison method for seismic deposits is the major issue.

4 Importance of background data to better understand the phenomena that occur on the sea floor during earthquakes

We have already shown that in the survey after the 2011 off Tohoku Earthquake, resuspension, reworking, and redeposition of the sediments occur on the sea floor due to earthquakes or tsunamis. However, it is rather difficult to clearly show that such sediment was formed by the earthquake or tsunamis of 2011. It is also difficult to quantitatively measure the amount of transported sediment on the sea floor. One of the reasons is because most of the surveys of marine sediments are done after geological or climatic events such as giant earthquakes and tsunamis or floods, while very few surveys are conducted to observe the sea floor during normal times. Data before an event that can be compared with survey results after an event is important for quantitative understanding of the phenomena that occur on the sea floor during an event.

AIST has been engaging in surveys for marine geological maps of the seas around Japan since the 1970s, and it has been working on sedimentological maps (Fig. 5). A sedimentological map is a geoscience map that presents the transport and deposition processes of sediments over the past tens of thousands of years, rather than a bottom sediment map that merely shows the distribution of sediments. It adds the analysis results of submarine photographs and sub-bottom profiling records to the analysis of grain size and composition of marine sediments collected from sampling points/ arranged in lattice at intervals of 4–7 nautical miles (7.4–13 km), although the intervals may change according to the sea area of the map segment, depth, and duration of survey cruise. For one sheet of sedimentological map that is compiled at the scale of 1:200,000, about 100 mud sampling points are set. While sediment sampling in an ordinary marine geological survey is conducted for a specific objective, the sediment sampling for sedimentological maps is done by arranging the sampling points at even intervals of the map area, to obtain even and uniform information of marine sediment. If necessary, samples are collected to clarify a specific objective, and supplementary sampling is conducted. AIST is the only organization in Japan that systematically collects marine sediment information.

The data for sedimentological maps can be used to evaluate effects on the sea floor in events such as earthquakes and tsunamis or floods. In the case of the 2011 off Tohoku Earthquake and Tsunami, the sea floor photos obtained by AIST for the sedimentological map from Sanriku to off Sendai Bay were used to analyze the changes in benthic organisms before and after the earthquake and tsunamis, and it was shown that there were changes in the distribution of brittle star (Ophiurida), the major benthic organism of this area.[47] Also, the comparison of sediments in the Sendai Bay before and after the 2011 off Tohoku Earthquake and Tsunami showed that the disturbance and redeposition of sediment occurred throughout the Sendai Bay due to tsunamis.[48] Considering the later analysis results, maximum of about 10 cm of surface sediment was resuspended, and the state of sediment suspension continued for several days or more. Comparison of the surface sediment before and after an earthquake and tsunami clearly indicates what happened or did not happen during the events. The accumulation of these facts is expected to be useful for estimating what may happen and where on the sea floor it may happen during future giant earthquakes and tsunamis.

Comprehensively gathered sea floor sediment samples and information can be used for estimating the origin of turbidity currents arising from earthquakes and tsunamis. To know where a turbidity current occurred due to the disturbance on the sea floor by an earthquake and tsunami, how it flowed, and where it formed turbidites is important in accurately investigating earthquake recurrence history using turbidites. But at this point, there are few cases where the origins and flow routes are accurately estimated. In the process of flowing, a turbidity current deposits part of sedimentary particles contained in the turbidity current, while on the other hand, particles of surface sediments are entrained in the current at the head of the flow.[11] Therefore, not all particles that comprise turbidites indicate the origin of the current. On the other hand, it has not lost all of the particles of the place of origin. For example, this is shown in the fact that the turbidites at the bottom of the Nankai Trough off Shikoku contain particles of the Fuji River that is over 600 km away that is thought to be their origin.[49] Therefore, information on the sediment samples and their compositions at the origin or along the flow route is important in estimating the origin and flow route of a turbidity current. For the surface sediment samples collected comprehensively to create the sedimentological maps, the grain size distribution, particle composition, and chemical composition are analyzed and published.[50] For the recent estimation of particle sources,

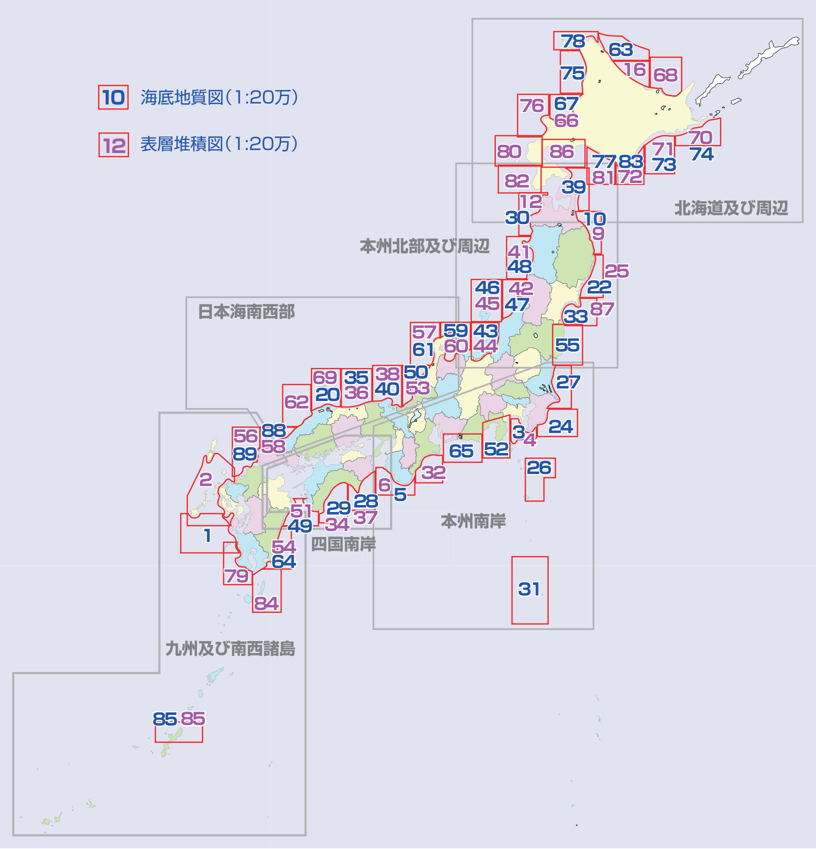

Fig. 5 Publication of marine geological maps by AIST

Frames containing red numerals are areas where 1:200,000 sedimentological maps have been published. Frames containing blue numerals are areas with published 1:200,000 marine geological maps, and grey frames are places with published 1:1,000,000 marine geological maps. From the homepage of Geological Survey of Japan, AIST.

other than the major element composition, various minor and trace elements and isotope ratio are used.[51] The information of the geographical distribution of such chemical composition before earthquakes or tsunamis is expected to be useful in estimating the origin and flow route of turbidity currents.

5 Summary and future prospects

Deep sea sediments are less likely to be affected by sea level fluctuations, compared to the tsunami deposits on land that are affected by the changes in coastal landforms, including the changes of position of coastlines due to supply of sediment from the land as well as the rising sea level after the last glacial period. Marine sediments are expected to serve as recording media of the history of recurrence of earthquakes and tsunamis over long periods of time.[50] Therefore, attempts are made around the world to decode earthquake recurrence history using submarine earthquake event deposits. However, it is not easy to understand the situation of the deep sea floor where one must collect samples from depth of several thousand meters or more, and to obtain high quality samples from appropriate locations. As mentioned earlier, it is necessary to select the appropriate place from the geological cross-section and submarine topographic data with high accuracy and high resolution. AIST's marine geological map and the data and samples on which they are based are the basic data for selecting such locations. Therefore, it is necessary to further conduct the surveys for compiling marine geological maps and to quickly publish the results. Also, surveys of the main four islands of Japan have been completed for the marine geological maps, but the survey regions (Fig. 5) tend to be on the landside compared to the sites of earthquake occurrence around Japan. Preparation of basic marine geological information for the offshore area in which giant earthquakes are expected to occur is necessary in the future.

After high quality samples are collected, it is necessary to conduct analysis at high resolution as much as possible. As mentioned earlier, the identification of event layers is possible from quick and high-resolution data, by combining several nondestructive measurement devices that are being developed recently. Such quick analysis enables analysis of several samples, and contributes to the construction of more reliable data. It is desirable to build such an analysis system at AIST. On the other hand, an event deposit that is comprised from different deposition processes than ordinary sediment is thought to have different grain size, grain composition, and structure compared to ordinary sediments. Such a difference probably makes the appearance of the sediment different. It is important to nurture "eyes to read sediment" to understand the difference in appearance, without relying solely on analysis data. The "eyes to read sediment" is nurtured by looking consciously at various and numerous sediment samples. Also, the experience increases by repeatedly observing samples and comparing them with abnormal values and change patterns in nondestructive measurement. It is important to constantly be aware of what creates the differences and changes in the sediment, not just to observe the event deposit through nondestructive measurement data. Moreover, in the interpretation of the nondestructive measurement results, there were many instances in which knowledge gained in places that may be irrelevant to earthquake history research such as the paleo-environmental change was useful. To nurture the "eyes to read sediment," the effort to widen the horizon, not just gain experience in one thing, is important. We think it is particularly important for young researchers to gain as much experience as possible.

In Japan, which is an earthquake-prone nation located in the plate boundaries of the West Pacific, the knowledge of recurrence history of past earthquakes and tsunamis is basic information for safe and secure living. We hope to collect and analyze marine geological information to contribute to the safety and security of society.

References

[1] H. Abe, Y. Sugeno and A. Chigama: Estimation of the height of the Sanriku Jogan 11 Tsunami (A.D. 869) in the Sendai Plain, *Zishin*, 43, 513–525 (1990) (in Japanese).

[2] Y. Okamura: Reconstruction of the 869 Jogan tsunami and lessons of the 2011 Tohoku earthquake: Significance of ancient earthquake studies and problems in announcing study results to society, *Synthesiology*, 5 (4), 234−242 (2012) (in Japanese) [*Synthesiology English edition*, 5 (4), 241–250 (2012)].

[3] J. Uchida, K. Abe, S. Hasegawa and O. Fujiwara: Studies on the source of run-up Tsunami deposits based on foraminiferal tests and their hydrodynamic verification, *The Quaternary Research*, 46 (6), 533–540 (2007) (in Japanese).

[4] K. Oguri, K. Kawamura, A. Sakaguchi, T. Toyofuku, T. Kasaya, M. Murayama, K. Fujikura, R. N. Glud and H. Kitazato: Hadal disturbance in the Japan Trench induced by the 2011 Tohoku-Oki Earthquake, *Scientific Reports*, 3, 1915, doi: 10.1038/srep01915 (2013).

[5] K. Arai, H. Naruse, R. Miura, K. Kawamura, R. Hino, Y. Ito, D. Inazu, M. Yokokawa, N. Izumi, M. Murayama and T. Kasaya: Tsunami-generated turbidity current of the 2011 Tohoku-Oki earthquake, *Geology*, 41 (11), 1195–1198 (2013).

[6] K. Ikehara, T. Irino, K. Usami, R. Jenkins, A. Omura and J. Ashi: Possible submarine tsunami deposits on the outer shelf of Sendai Bay, Japan resulting from the 2011 earthquake and tsunami off the Pacific coast of Tohoku, *Marine Geology*, 358, 120–127 (2014).

[7] K. Ikehara, T. Kanamatsu, Y. Nagahashi, M. Strasser, H. Fink, K. Usami, T. Irino and G. Wefer: Documenting large earthquakes similar to the 2011 Tohoku-oki earthquake from sediments deposited in the Japan Trench over the past 1500 years, *Earth and Planetary Science Letters*, 445, 48–56 (2016).

[8] T. Toyofuku, P. Duros, C. Fontainer, B. Mamo, S. Bichon, R. Buscail, G. Chabaud, B. De andre, S. Gouber, A. Grémare, C. Menniti, M. Fujii, K. Kawamura, K. A. Koho, A. Noda,

Y. Namegaya, K. Oguri, O. Radakovitch, M. Murayama, L. Jan de Nooijer, A. Kurasawa, N. Ohkawara, T. Okutani, A. Sakaguchi, F. Jorissen, G.-J. Reichart and H. Kitazato: Unexpected biotic resilience on the Japanese seafloor caused by the 2011 Tohoku-Oki tsunami, *Scientific Reports*, 4, 7517, doi:10.1038/srep07517 (2014).

[9] C. M. McHugh, T. Kanamatsu, L. Seeber, R. Bopp, M.-H. Cormier and K. Usami: Remobilization of surficial slope sediment triggered by the A.D. 2011 Mw9 Tohoku-Oki earthquake and tsunami along the Japan Trench, *Geology*, 44, 391–394 (2016).

[10] B. C. Heezen and M. Ewing: Turbidity currents and submarine slumps, and the 1929 Grand Banks earthquake, *American Journal of Science*, 250, 849–873 (1952).

[11] E. Meiburg and B. Kneller: Turbidity currents and their deposits, *Annual Reviews of Fluid Mechanics*, 42, 135–156 (2010).

[12] D. J. W. Piper, P. Cochonat and M. L. Morrison: The sequence of events around the epicentre of the 1929 Grand Banks earthquake: initiation of debris flows and turbidity current inferred from sidescan sonar, *Sedimentology*, 46 (1), 79–97 (1999).

[13] B. C. Heezen and M. Ewing: Orleansville earthquake and turbidity currents, *Bulletin of the American Association of Petroleum Geologists*, 39 (12), 2505–2514 (1955).

[14] S-K. Hsu, J. Kuo, C-L. Lo, W-B. Doo, C-Y. Ku and J.-C. Sibuet: Turbidity currents, submarine landslides and the 2006 Pingtung earthquake off SW Taiwan, *Terrestrial, Atmospheric, and Oceanic Sciences*, 19 (6), 767–772 (2008).

[15] Y. Shirasaki, K. Ito, M. Kuwazuru and K. Shimizu: Submarine landslides as cause of submarine cable fault, *Journal of Japan Society for Marine Surveys and Technology*, 24 (1), 17–20 (2012) (in Japanese).

[16] T. Nakajima and Y. Kanai: Sedimentary features of seismoturbidites triggered by the 1983 and older historical earthquakes in the eastern margin of the Japan Sea, *Sedimentary Geology*, 135 (1-4), 1–19 (2000).

[17] K. Ikehara and K. Usami: Sedimentary processes of deep-sea turbidites caused by the 1993 Hokkaido-Nansei-oki Earthquake, *The Quaternary Research*, 46 (6), 477–490 (2007) (in Japanese).

[18] J. R. Patton, C. Goldfinger, A. E. Morey, K. Ikehara, C. Romsos, J. Stoner, Y. Djadjadihardja, Udrekh, S. Ardhyastuti, E. Z. Gaffer and A. Viscaino: A 6600 year earthquake history in the region of the 2004 Sumatra-Andaman subduction zone earthquake, *Geosphere*, 11 (6), 2067–2129, doi: 10.1130/GES01066.1 (2015).

[19] K. Udo, H. Tanaka, A. Mono and Y. Takeda: Beach morphology change of southern Sendai coast due to 2011 Tohoku Earthquake Tsunami, *Journal of Japan Society of Civil Engineers Division B2 (Coastal Engineering)*, 69 (2), I_1391-I_1395 (2013) (in Japanese).

[20] T. Tamura, Y. Sawai, K. Ikehara, R. Nakashima, J. Hara and Y. Kanai: Shallow-marine deposits associated with the 2011 Tohoku-oki tsunami in Sendai Bay, Japan, *Journal of Quaternary Science*, 30 (4), 293–297 (2015).

[21] S. Yoshikawa, T. Kanamatsu, K. Goto, I. Sakamoto, M. Yagi, M. Fujimaki, R. Imura, K. Nemoto and H. Sakaguchi: Evidence for erosion and deposition by the 2011 Tohoku-oki tsunami on the nearshore shelf of Sendai Bay, Japan, *Geo-Marine Letters*, 35 (4), 315–328 (2015).

[22] T. Haraguchi, K. Goto, M. Sato, Y. Yoshinaga, N. Yamaguchi and T. Takahashi: Large bedform generated by the 2011 Tohoku-oki tsunami at Kesennuma Bay, Japan, *Marine Geology*, 335, 200–205 (2013).

[23] I. Sakamoto, Y. Yokoyama, M. Yagi, T. Inoue, S. Iijima, Y. Nkada, M. Fujimaki, K. Tanaka, K. Nemoto, T. Kasaya and Y. Fujiwara: Geo-environment change caused by the 3.11-tsunami disaster around the coastal area revealed by the marine geological investigation, in K. Kogure, M. Hirose, H. Kitazato and A. Kijima (eds.), *Marine Ecosystems after Great East Japan Earthquake in 2011*, 129–130, Tokai University Press (2016).

[24] K. Seike, T. Kitahashi and T. Noguchi: Sedimentary features of Onagawa Bay, northeastern Japan after the 2011 off the Pacific coast of Tohoku Earthquake: Sediment mixing by recolonized benthic animals decreases the preservation potential of tsunami deposits, *Journal of Oceanography*, 72 (1), 141–149 (2016).

[25] Y. Saito: Modern storm deposits in the inner shelf and their recurrence intervals, Sendai Bay, northeast Japan, In A. Taira, and F. Masuda (eds.), *Sedimentary Facies in the Active Plate Margin*, 331–344, Terra Scientific Publishing, Tokyo (1989).

[26] K. Usami, K. Ikehara, R. G. Jenkins and J. Ashi: Benthic foraminiferal evidence of deep-sea sediment transport by the 2011 Tohoku-oki earthquake and tsunami, *Marine Geology*, 384, 214–224 (2017).

[27] R. Miura, R. Hino, K. Kawamura, T. Kanamatsu and Y. Kaiho: Accidental sediments trapped in ocean bottom seismometers during the 2011 Tohoku-Oki earthquake, *Island Arc*, 23, 365–367 (2014).

[28] T. Noguchi, W. Tanikawa, T. Hirose, W. Lin, S. Kawagucci, Y. Yoshida-Takashima, M. C. Honda, K. Takai, H. Kitazato and K. Okamura: Dynamic process of turbidity generation triggered by the 2011 Tohoku-Oki earthquake, *Geochemistry Geophysics Geosystems*, 13 (11), Q11003, doi:10.1029/2012GC004360 (2012).

[29] K. Ikehara, K. Usami, R. Jenkins and J. Ashi: Occurrence and lithology of seismo-turbidites by the 2011 off the Pacific coast of Tohoku earthquake, *Abstracts of IGCP the Fifth International Symposium on Submarine Mass Movements and Their Consequences*, 74 (2011).

[30] J. Ashi, K. Ikehara, M. Kinoshita and KY04-11 and KH- 10-3 shipboard scientists: Settling of earthquake-induced turbidity on the accretionary prism slope of the central Nankai subduction zone, In Y. Yamada *et al.* (eds.), *Submarine Mass Movements and Their Consequences*, 561–571, Springer (2012).

[31] J. Ashi, R. Sawada, A. Omura and K. Ikehara: Accumulation of an earthquake-induced extremely turbid layer in a terminal basin of the Nankai accretional prism, *Earth, Planets and Space*, 66 (51), 1–9, doi:10.1186/1880-5981-66-51 (2014).

[32] J. Moernaut, M. Van Daele, M. Strasser, M. A. Clare, K. Heirman, M. Viel, J. Cardenas, R. Kilian, B. Ladron de Guevara, M. Pino, R. Urrutia and M. De Batist: Lacustrine turbidites produced by surficial slope sediment remobilization: A mechanism for continuous and sensitive turbidite paleoseismic records, *Marine Geology*, 384, 159–176 (2017).

[33] K. Oguri, Y. Furushima, T. Toyofuku, T. Kasaya, M. Wakita, S. Watanabe, K. Fujikura and H. Kitazato: Long-term monitoring of bottom environments of the continental slope off Otsuchi Bay, northeastern Japan, *Journal of Oceanography*, 72 (1), 151–166 (2016).

[34] K. Kremer, S. B. Wirth, A. Reusch, D. Fah, B. Bellwald, F. S. Anselmetti, S. Girardclos and M. Strasser: Lake-sediment based paleoseismology: Limitations and perspectives from the Swiss Alps, *Quaternary Science Reviews*, 168, 1–18

(2017).
[35] A. Sakaguchi, G. Kimura, M. Strasser, E. J. Screaton, D. Curewitz and M. Murayama: Episodic sea floor mud brecciation due to great subduction zone earthquakes, *Geology*, 39 (10), 919–922 (2011).
[36] Y. Hanamura and Y. Ogawa: Layer-parallel faults, duplexes, imbricated thrusts and vein structures of the Miura Group: Keys to understanding the Izu forearc-arc sediment accretion to the Honshu forearc, *Island Arc*, 2 (3), 126–141 (1993).
[37] T. Ohsumi and Y. Ogawa: Vein structures, like ripple marks, are formed by short-wavelength shear waves, *Journal of Structural Geology*, 30 (6), 719–724 (2008).
[38] C. Goldfinger, C. Hans Nelson, J. E. Johnson and the Shipboard Scientific Party: Deep-water turbidites as Holocene earthquake proxies: the Cascadia subduction zone and Northern San Andreas Fault systems, *Annals of Geophysics*, 46 (5), 1169–1194 (2003).
[39] C. Goldfinger, C. Hans Nelson, A. E. Morey, J. E. Johnson, J. R. Patton, E. Karabanov, J. Gutierrez-Pastor, A. T. Eriksson, E. Grâcia, G. Dunhill, R. J. Enkin, A. Dallimore and T. Vallier: Turbidite event history –Methods and implications for Holocene paleoseismicity of the Cascadia subduction zone, *USGS Professional Paper*, 1661-F, US Geological Survey (2012).
[40] H. Pouderoux, J.-N. Proust and G. Lamarche: Submarine paleoseismology of the northern Hikurangi subduction margin of New Zealand as deduced from turbidite record since 16 ka, *Quaternary Science Reviews*, 84, 116–131 (2014).
[41] K. Nakajima: Turbidity current no hassei kiko: Turbitdite o mochiita chiiki jishin hassei kankaku hyoka shuho no kakuritsu ni mukete (Mechanism for occurrence of turbidity current: For the establishment of assessment method for regional earthquake occurrence interval using turbidite, *Bulletin of the Geological Survey of Japan*, 51, 79–87 (2000) (in Japanese).
[42] K. T. Pickering and R. N. Hiscott: *Deep Marine Systems: Processes, Deposits, Environments, Tectonics and Sedimentation*, AGU and Wiley, (2016).
[43] A. Omura, K. Ikehara, K. Arai and Udrekh: Determining sources of deep-sea mud by organic matter signatures in the Sunda trench and Aceh basin off Sumatra, *Geo-Marine Letters*, 37, 549–559, doi:10.1007/s00367-017-0510-x (2017).
[44] K. Ikehara: Terminal basin as a target for turbidite paleoseismology, *The Quaternary Research*, 54 (6), 345–358 (2015) (in Japanese).
[45] C. Goldfinger, S. Galer, J. Beeson, T. Hamilton, B. Black, C. Romsos, J. Patton, C. Hans Nelson, R. Hausmann and A. Morey: The importance of site selection, sediment supply, and hydrodynamics: A case study of submarine paleoseismology on the northern Cascadia margin, Washington USA, *Marine Geology*, 384, 4–46 (2017).
[46] M. A. Rodriguez-Pascua, J. P. Calvo, G. De Vicente and D. Gómez-Gras: Soft-sediment deformation structures interpreted as seismites in lacustrine sediments of the Prebetic Zone, SE Spain, and their potential use as indicators of earthquake magnitudes during the Late Miocene, *Sedimentary Geology*, 135 (1), 117–135 (2000).
[47] T. Yamakita, H. Yamamoto, K. Ikehara, H. Yokooka, Y. Fujiwara, S. Tsuchida, Y. Furushima, K. Oguri, M. Kawato, T. Kasaya, S. Watanabe, K. Fujikura and H. Kitazato: Earthquake and habitat mapping in the deep sea, *Abstract of the International Association for Impact Assessment 2016*, #34 (2016).
[48] K. Ikehara: Influence of the 2011 off the Pacific coast of Tohoku Earthquake and its related tsunami on the shallow sea floor environments: Post-earthquake and tsunami survey results on the Sendai shelf sediments, Reports of research and investigation on multiple geological hazards caused by huge earthquakes, *Geological Survey of Japan Interim Report*, 66, 409−413 (2014) (in Japanese).
[49] A. Taira: *Nihon Retto No Tanjo* (Birth of the Japanese Archipelago), Iwanami Shinsho (1990) (in Japanese).
[50] N. Imai, S. Terashima, A. Ohta, M. Mikoshiba, T. Okai, Y. Tachibana, K. Ikehara, H. Katayama, A. Noda, S. Tomigashi, Y. Matsuhisa, Y. Kanai and A. Kamioka: Geochemical Map of Sea and Land of Japan, *Geological Survey of Japan*, AIST (2010) (in Japanese).
[51] Y. Saitoh, T. Ishikawa, M. Tanimizu, M. Murayama, Y. Ujiie, Y. Yamamoto, K. Ujiie and T. Kanamatsu: Sr, Nd, and Pb isotope compositions of hemipelagic sediment in the Shikoku Basin: Implications for sediment transport by the Kuroshio and Philippine Sea Plate motion in the late Cenozoic, *Earth and Planetary Science Letters*, 421, 47–57 (2015).

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Kazuko USAMI

Completed the doctor’s course at the Graduate School of Science and Technology, Kumamoto University in 2010. Postdoctoral Researcher, Institute of Geology and Geoinformation (IGG), AIST in 2012; and Visiting Researcher, IGG, AIST from 2017. Specialties are micropaleontology and sedimentology. In this paper, was in charge of the discussion for obtaining earthquake recurrence history from seismo-turbidites and disturbance of sea floor sediment during earthquakes.

Discussions with Reviewers

1 Overall

Comment (Masahiko Makino, AIST)

This paper discusses new scientific usefulness that may contribute to earthquake disaster prevention through clarification of the history of occurrence of past earthquakes and tsunamis, by capturing geological evidences in the submarine earthquake and tsunami deposits. The authors have yielded many results through active research by collaborating with other institutions since the 2011 off the Pacific coast of Tohoku Earthquake.

Specifically, the paper discusses the following topics: 1) the process of turbidite formation, 2) the deposits collected in the Sendai Bay that were formed by the tsunamis in the 2011 off Tohoku Earthquake, and 3) the estimation method for earthquake occurrence history using turbidites. It also states that the organization of intellectual infrastructure of marine geological information is important, because high-precision and high-resolution submarine topographic data and geological cross-section records are necessary to advance this study further.

This research is important from the perspective of earthquake disaster prevention, and I think it is appropriate for publication in *Synthesiology*.

Answer (Ken Ikehara)

In the 2011 off the Pacific coast of Tohoku Earthquake, the earthquake and tsunamis caused major damage in wide-ranging areas, as well as in the Tohoku region. The research of earthquake recurrence history using marine sediment presented in this paper had been conducted before the earthquake and tsunamis in 2011, but I think the advancement of research after 2011 is remarkable. Details of what happened on the sea floor during the earthquake and tsunamis were observed and recorded. Although there is much that is still unknown, I hope we can continue our survey and research, to contribute to society through our marine geological research.

Comment (Masanori Goto, AIST)

This paper is about the strategy for clarifying the history of giant earthquakes and tsunamis by analyzing the turbidites in marine sediment, while considering contributing to safe and secure living. It addresses the importance of regular data collection and the role of AIST as well as the state-of-the-art survey and analysis. It is arranged so that it is useful for readers outside the field, and I think it has value to be published in *Synthesiology*.

Answer (Ken Ikehara)

I wrote with contribution of survey and research to society in mind. I also wrote about how the assets of research conducted at AIST can be utilized, and how they should be utilized.

2 Explanation of turbidite

Comment (Masahiko Makino)

Is the water tank experiment for a turbidity current running down a slope in Fig. 1A cited from another paper? The text indicates Reference [11]. If it is a citation, please indicate that in the caption of the figure.

Answer (Ken Ikehara)

The photograph of the turbidity current produced in the water tank was taken by the principal author, and was not cited from another paper. The citation in the text is a part from another paper that explains the turbidity current. To avoid confusion, I moved the indicator of the citation to the appropriate place.

Comment (Masahiko Makino)

For Fig. 2, in this paper, the text explains the “two-story structure” of turbidites, while the figure caption refers to the “interior erosion plane.” I think the formation process will be more easily understood if you explain the “interior erosion plane.”

Answer (Ken Ikehara)

I added and revised the explanatory text based on your comment.

3 Technological issue

Comment (Masahiko Makino)

Were there any technological issues that were solved that allowed the dramatic advancement of the submarine earthquake and tsunami deposit research in recent years?

You mention it in Chapter 3, but can you organize it a bit more and make it more understandable?

Answer (Ken Ikehara)

As a technological factor, I think there is the advancement of nondestructive measurement for the physical and chemical compositions of core samples, as described in Chapter 5. This provides quick, high-resolution data.

In Chapter 3, we explain the research method, so for the point that you indicated, I added in Chapter 5 the fact that nondestructive measurement technology has been advancing recently. However, in practice, there are many researchers who do not look at the actual core, relying completely on measurement data. I believe “eyes to read sediment” are nurtured by looking and comparing data against the actual core, and I added this point to the paper.

Comment (Masahiko Makino)

In Fig. 4, you list the elemental technologies, but the arrows that join the elements are short, and I think it will be more understandable if you work a bit more on the overall layout. Can you enclose the technology clusters in blocks?

Answer (Ken Ikehara)

I revised the figure based on your comment.

Question (Masanori Goto)

In the “Summary and future prospects,” you address the importance of nurturing the “eyes to read sediment.” You write that it is important to look with awareness and to gain experience, but can you be more specific about this? I think this is also applicable to researchers in other fields.

Answer (Ken Ikehara)

This is rather difficult to express in words, but I have experienced several times that things that seem to be irrelevant at a first glance are actually mutually related. It is, of course, important to gain experience, but I think it is more important to gain experience by tackling each topic seriously, and I added descriptions on this point to the text. Also, I think to understand properly how data change at what characteristic parts by comparing the results (data) of nondestructive measurement, which is advancing dramatically in recent years, and the actual material (core) is essential in nurturing the “eyes to read sediment.” I also added this point to the text.