Major Contribution of Tsunami Deposit Studies to Quaternary Research

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Large tsunamis are important not only as a serious natural disaster but also a controlling factor in coastal sedimentation processes. Tsunami deposits have been studied in both geological and disaster prevention fields and play an important role in connecting these studies. Large tsunamis cause rapid and large-scale sediment transport in lacustrine, coastal, shallow-marine and deep-marine environments. They play a positive role to form and preserve sand, gravel and shell beds in the geological record. Tsunami deposits probably occupy significant part of coastal geological strata.

Tsunami deposits in the geological records help us to estimate the recurrence interval of subduction-zone earthquakes that cause tsunamis. Histories of such earthquakes inferred from tsunami deposits span 3,000 years for the Nankai and Suruga Troughs, nearly 10,000 years for the Sagami Trough and 6,500 years for the southern Kuril Trench. Tsunami deposits also aid in estimating the relative size of paleo-tsunamis. Studies in eastern Hokkaido, north Japan, revealed the repeated occurrence of unusually large tsunamis with inundation of several kilometers. These mega-tsunamis have occurred at about 500-year-intervals over the last 6,500 years along the southern Kuril Trench.

Although some problems and difficulties remain, tsunami deposits are useful for reconstructing tsunami history and evaluating risk of future tsunami events. With the development of methods for differentiating tsunami deposits from other event deposits, and evaluating the hydraulic force and inundation depths, we will be able to learn much about past tsunamis from the deposits and to make use of such information for disaster prevention. Collaboration of a broad range of scientists and engineers, such as geologists, geomorphologists, seismologists, geophysicists and tsunami engineers, would enable to solve existing problems in paleo-tsunami research.

Keywords : coastal sedimentation, disaster prevention, Quaternary geology, subduction-zone earthquake, tsunami deposits

I. Introduction

Large tsunamis transport a huge volume of sediments and leave behind the deposits both in undersea and onland environments. The deposits transported by tsunamis, tsunami deposits, are sometimes preserved in geological record. Such tsunami deposits have been an important research target over the last two decades in the fields of the Quaternary geology,

paleo-seismology, and disaster prevention.

Large tsunamis are an important controlling factor in sediment transport, deposition and preservation processes not only in coastal but also in deep-marine environments. Large-scale sediment transport and deposition in coastal area have been observed in many historical (*e.g.* Shuto, 1989) and recent tsunamis including the 2004 Indian Ocean tsunami (*e.g.* Shanmugam, 2006). Conversely, large tsunamis are capable

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of triggering outgoing sediment flows, transporting sediment to the deep sea bottom as pointed out by Shiki and Yamazaki (1996) and Shanmugam (2006) on the basis of field observation data.

Large tsunamis cause severe consequences in coastal regions, including human casualty and damage to buildings, coastal topography and ecosystems (*e.g.* Watanabe, 1998 ; Danielsen *et al.*, 2005 ; Matsutomi *et al.*, 2005 ; Tomita *et al.*, 2005 ; Kench *et al.*, 2006). Japanese Islands are at a high risk of tsunami disaster, because of concentrated population and industries in the coastal area facing troughs and trenches along active plate convergent boundaries. Tsunami deposits enable us to reconstruct a long history of subduction-zone earthquakes beyond written records. On the basis of such long and precise tsunami histories, we could forecast future earthquakes and tsunamis and make a plan to mitigate the damage caused by these events.

The purposes of this review paper are summarizing the major contribution of Japanese paleo-tsunami researches in the Quaternary researches and prospecting the direction of fu-

ture studies. Japan has the longest history of paleo-tsunami researches in the world and many reports on tsunami deposits (*e.g.* Fujiwara, 2004). Since the first report by Kon'no (1961), tsunami deposits in the geological record have been reported from various localities throughout the Japanese Islands (Fig. 1). Most of these examples were reported from the Holocene coastal lowland, with rare exceptions from older sedimentary basins.

Tsunamis are mostly caused by subduction-zone earthquakes, although, in rare cases, other geological events such as volcanic eruptions, large-scale submarine landslides and extraterrestrial impacts also trigger tsunamis. Therefore, in this report I focus primarily on tsunami deposits on coasts along subduction zones.

Some recently-published text books and special issues of journals offer the history and state of paleo-tsunami research in the world. Bryant (2001) and Satake (2005) provide a general description of tsunamis and their associated sediments. Geological disciplines, including sedimentology and paleontology of tsunami deposits, were published in Shiki *et al.* (2000)

Fig. 1 Regional distribution of tsunami deposits reported from Japanese Islands. Some volcanogenic tsunami deposits are included in examples from western Hokkaido and Kyushu. Modified from Fujiwara (2004), Komatsubara and Fujiwara (2007) with additional data.

and Fujiwara *et al.* (2004). Contribution of paleo-tsunami studies in mitigating disasters is discussed in Atwater *et al.* (2005).

II. Advantages of Japanese researches on tsunami deposits

Because Japanese Islands face the active plate boundaries, they are fatally apt to be hit by large tsunamis. In addition to tsunamis generated around the Japanese Islands, those generated in distant place, such as the 1960 Chilean tsunami, have hit the islands. Japanese historical documents, back to 1,300 years ago at the longest, have recorded these tsunami events. We can estimate the date and source areas of tsunamis that have occurred in the last 400 years with considerable accuracy, because of abundant documents covering this period.

We can estimate the source of tsunami deposits from comparison with historical records (see the review by Komatsubara and Fujiwara, 2007). Inversely, tsunami deposits can be used to confirm the inundation area (*e.g.* Minoura *et al.*, 2001) or wave heights (*e.g.* Takada *et al.*, 2002) of tsunamis that were reported in old documents.

Sedimentation and erosion by tsunamis have also been described in Japanese historical documents in the last few hundred years. Meters-long blocks of coral reef and rock washed ashore by the 1771 Meiwa Tsunami, in Ryukyu Islands, are well known as “*tsunami ishi*” in Japan (*e.g.* Kato, 1987). Opening of the mouth of Lake Hamana, central Japan, to connect the Pacific Ocean, by the 1498 Meio Tsunami centered in the Nankai Trough (*e.g.* Shuto, 1989) is another example of sediment transport by historical tsunami events.

Under these historical and geological backgrounds, scientific researches on tsunami deposits were started in Japan by Kon’no (1961), taking the lead among the world. They reported many traces of the 1960 Chilean tsunami, both of deposition and erosion, widely distributed along the Pacific coast of northeast Japan. Kon’no (1961) found that the tsunami deposit was composed of alternation of several sand sheets and muddy films, in some locations, and they interpreted that the alternate structure resulted from repeated deposition by succeed-

ing waves in a tsunami wave train.

Outcrop-scale observations helped geologists to understand the tsunami sedimentation processes. Exposure of the Quaternary shallow marine sequences in Japanese Islands produced by accumulated tectonic uplifts has provided a good condition to observe the sedimentary features of tsunami deposits (*e.g.* Takashimizu and Masuda, 2000 ; Fujiwara *et al.*, 2003a). Trenching surveys also promoted the precise observation of inner structures of tsunami deposits (*e.g.* Nanayama *et al.*, 2000). Bedforms and sedimentary structures formed by tractive currents, including dunes and traction carpet (Lowe, 1982, 1988), characterize the tsunami deposits (*e.g.* Nanayama and Shigeno, 2004 ; Fujiwara and Kamataki, 2007). Hummocky cross stratifications (HCS : Harms *et al.*, 1975 ; Cheel and Leckie, 1993), indicating the deposition from combined flows, characterize the underwater tsunami deposits (Fujiwara *et al.*, 2003a ; Fujiwara and Kamataki, 2007).

Current direction and velocity and settling condition reconstructed from the sedimentary features help us to confirm that the deposits were formed by tsunami.

III. Contribution to Quaternary geology

In this section, I summarize major breakthrough in the Quaternary geology produced by researches on tsunami deposits. These researches promoted better understanding of sedimentary processes in coastal region. A new type of sediment transport process generated by tsunami waves was found through these studies.

1. Coastal sedimentary sequences as storage of tsunami deposits

Paleo-tsunami researches revealed that tsunami deposits are closely related to the development of coastal sequences. Coastal marshes, lakes and lagoons provide a favorable condition for the preservation of tsunami deposits, because of their separation from high-energy waves (*e.g.* Minoura *et al.*, 1987, 1994 ; Tsuji *et al.*, 1998 ; Nanayama *et al.*, 2003). High fluxes of lithic and organic materials protect tsunami deposits from subsequent erosion and bioturbation.

Closed small bays are also excellent places

for preservation of tsunami deposits. Fujiwara *et al.* (1997, 1999, 2000, 2003a) found at least seven tsunami deposits from the middle Holocene muddy bay sequence distributed around the Sagami Trough. Some of these tsunami deposits were correlated with the co-seismic emergence of Holocene marine terraces around the Sagami Trough (*e.g.* Nakata *et al.*, 1980) by detailed ^{14}C age data, and interpreted as originated in the plate boundary earthquakes along the trough.

Figure 2 shows a representative tsunami deposit which formed *ca.* 7,500–7,400 cal BP in a small bay in the southern Kanto region. It overlies the bay mud with a scoured surface, consists of a stack of several conglomerate sheets and yields abundant exotic shells.

2. Sediment transport process by tsunami waves

Identification of tsunami deposits is important, because large paleo-tsunami events have been recognized from their deposits. Reliability of paleo-tsunami study strongly depends on the reliable discrimination of tsunami deposits from other events such as storms. The identification has been a hot topic for geologists since the beginning of paleo-tsunami research. Model-

ing sediment transport processes by tsunami waves provides a clue to solve the problem. Although some sedimentological features of tsunami deposits were proposed by previous works (*e.g.* Dawson *et al.*, 1991; Foster *et al.*, 1991; Nishimura and Miyaji, 1995; Nanayama *et al.*, 2000), definitive criteria to identify the tsunami deposits have not been clarified over the past 15 years. Typical proposed criteria are; 1) sand sheets showing a tapered cross section with landward thinning, and 2) dislocated huge blocks and wash over sediments indicating much larger run-up height than expected from normal storm waves. These problems were reviewed in Dawson and Shi (2000), Felton and Crook (2003), and Shanmugam (2006).

Tsunamis have 100 times or longer wavelengths and wave periods than those of storms. Because of these wave characteristics, tsunamis form a unique sedimentary features in their deposits as found in the 1703 Kanto tsunami deposit (Fujiwara *et al.*, 2005, 2006) and middle Holocene tsunami deposits (Fujiwara *et al.*, 2003a; Fujiwara and Kamataki, 2007) in the southern Kanto region (Fig. 3). Here I summarize them into the following four features.

Firstly, alternate stack of sand sheets and

Fig. 2 Tsunami deposit in the middle Holocene bay sequence in the southern Kanto region. The tsunami deposit composed of shelly conglomerate formed in a drowned valley with a water depth of 10–20 m. Detailed analyses of sedimentary structure and depositional process of this tsunami deposit is described in Fujiwara and Kamataki (2007). Location of the outcrop is shown in Fig. 1.

Fig. 3 Prototype geological section showing the tsunami sedimentation process

Four sedimentary features represent long-period run-ups and backwashes of tsunamis. 1) Alternate stack of sand sheets and mud drapes shows that the deposit is a result of repeated occurrence of high-energy waves. 2) Each sand sheet shows the deposition from a waning sediment flow. 3) Cyclic turnover of flow-directions at tsunami events is shown by the alternate stack of sand sheets deposited from up- and return-flows. 4) A progressive fining-upward trend of the whole deposit represents the waning process of the tsunami.

mud drapes characterize the tsunami deposits. Tsunami wave train with ten-minute-order period is congruent with the alternate stacking pattern in the deposits. Incremental deposition of sand sheets indicates that the deposit resulted from repeated occurrence of high-energy waves. Mud drapes separating each sand sheet was formed during the stagnant stages by suspension fallout.

Secondly, each sand sheet represents the deposition from the individual wave in a tsunami wave train. General fining-upward trend and stacking pattern of the bedforms and sedimentary structures reflect a waning process of the sediment flow. Because of their long wavelengths, up to 100 km, each wave generates a long lasting current, ebb and flood, in coastal regions. Through the waning process of the

current, each sand sheet is deposited. In general, lower part is characterized by dunes or large-scale current ripples and includes various size gravels. HCS is sometimes observed. Upper part includes wave ripples and is covered by a mud drape.

Thirdly, cyclic turnover of flow directions reflects the repeated occurrence of up- and return-flows at tsunami events. In Figure 3, flow direction of each sand sheet is shown by inclination of oblique lines.

Finally, a progressive fining-upward trend of the whole deposit represents the waning process of the tsunami. Vertical stack of finer and thinner sand sheets in the upper horizon reflects the progressive decrease in power of successive waves.

These four sedimentary features represent long-period run-ups and backwashes of tsunamis; storm waves with short wavelengths and wave periods of 10 to 20 seconds at the longest cannot explain the features.

Tsunami deposits with all the above four characters are rare in natural condition. For example, mud drapes and sand sheets may be partly or totally eroded by overlying sand sheets. Figure 3 shows a prototype of depositional model for explaining the tsunami sedimentation process, and further improvement is needed for a wide application.

3. Toward better understanding of sedimentary processes in coastal regions

Tsunami deposits provide an opportunity for geologists to understand the dynamic sedimentary processes during the Late Quaternary. Large-scale rapid depositional events, such as tsunamis and storms, play an important role in the formation and preservation of sediments in coastal regions. Thickly deposited sediment from these catastrophic events occasionally has been preserved in geologic section, surviving from severe physical and biological disturbances.

Sand and gravel beds with exotic shells have been often reported from the Holocene muddy bay sequences in various localities in Japan. In many cases, forming processes of such "unusual" beds have been ambiguously regarded as deposits of storm or flood origin. Tsunami deposits occupy an important part of these

“unusual” coarse-grained deposits and shell beds as shown by Fujiwara *et al.* (1997, 1999, 2003b) from the studies in the southern Kanto region.

The shell beds generated by tsunamis have a lenticular shape and alternate with muddy sand layers. This occurrence shows that these beds were formed through the alternation of winnowing stages by strong waves and stagnant stages dominated by suspension fallout. The high diversity in original habitats of molluscan shells, from muddy bay floors to rocky shores, is attributed to erosion and the mixture of sediments around the bays by strong currents. The well preserved condition of the shells indicates rapid deposition and burial during the tsunami events.

With highly dense AMS ^{14}C age data, we can date these geological events with accuracy within 100 years (*e.g.* Masuda, 1998 ; Fujiwara *et al.*, 2004). Recognition of event deposits, represented by tsunami deposits, and accurate age determination enable us to understand the dynamical development of sedimentary sequences through time.

IV. Contribution to earthquake and tsunami disaster prevention

We have limited experiences of mega-natural events such as large tsunamis because of their low frequency. Lack of understanding on these mega-events often leads to unprecedented damages by these natural disasters. The 2004 Indian Ocean tsunami and Hurricane Katrina in 2005 are recent examples of such events. Detailed knowledge of the future risks based on the past events would be useful in disaster prevention.

Instrumental and historical records of tsunamis are limited and unable to account for the long recurrence history, 100 years or longer, of great tsunamis. In addition, we cannot directly observe the tsunami source area located deep under the sea. We can, however, use the tsunami deposits in geological records in the same way as we analyze seismograph, tide gauge and old document records.

1. Reconstruction of tsunami history from deposits in Japan

A long history of tsunamis covering the later half of the Holocene has been reconstructed

from the study of tsunami deposits in Japanese Islands. Discovery of unusually large prehistoric tsunamis from the Pacific coasts of eastern Hokkaido had an impact not only to the Earth scientists but also to general public. Historically, plate boundary earthquakes ranging Mw 7.8–8.2 were the largest in the southern Kuril Trench (Fig. 1) during the last 200 years (see the review by Nanayama *et al.*, 2003 ; Satake *et al.*, 2003). In the eastern Hokkaido, the maximum tsunami height and inundation distance of the 1952 Tokachi-oki earthquake (Mw 8.2) were about 6.5 m high (Watanabe, 1998) and 1.5 km (Satake *et al.*, 2003). However, tsunamis that inundated three or more kilometers inland were confirmed by tsunami deposits in the Holocene marsh sequence in this region (*e.g.* Hirakawa *et al.*, 2000 ; Nanayama *et al.*, 2003). Estimated recurrence interval of these outside tsunamis from the ^{14}C dating and tephrochronology is about 500 years. The last occurrence of such mega-tsunami event was in the mid 17 th Century.

Along the Nankai, Suruga and Sagami Troughs, historical and prehistoric tsunami deposits have been reported from at least 15 sites (*e.g.* Okamura *et al.*, 1997 ; Tsuji *et al.*, 1998). Histories of great ($M \sim 8$) subduction-zone earthquakes inferred from tsunami deposits span 3,000 years for the Nankai and Suruga Troughs and nearly 10,000 years for the Sagami Trough. The inferred histories contain variable recurrence intervals. The shortest intervals, 100–200 years for the Nankai Trough and 150–300 years for the Sagami Trough, are similar to those referenced in historical records. Longer intervals inferred from the tsunami deposits probably reflect variability in rupture mode, incompleteness of geologic records, and insufficient research. Details of these results were reviewed in Komatsubara *et al.* (2006) and Komatsubara and Fujiwara (2007).

2. Collaborative Work in Geology and Geophysics

Collaboration of scientists and engineers is needed to better understand the paleo-tsunamis. Individual study fields, *e.g.* tsunami geology and tsunami simulations, have both advantages and limitations. On one hand, geological records are incomplete both in space and time.

On the other hand, geological field survey data are indispensable for evaluating the validity of tsunami numerical simulations.

An excellent example of collaborative work between geology and geophysics regarding tsunami deposits was achieved in the Pacific coast of eastern Hokkaido. In this case, spatial distribution of inundation area and run-up heights of the 17th century gigantic tsunami was estimated from the tsunami deposit (*e.g.* Nanayama *et al.*, 2003 ; Hirakawa *et al.*, 2005). Then, the earthquake fault parameters such as the location, geometry and distribution of slip on the fault were reconstructed using tsunami numerical simulation (Satake *et al.*, 2004). The results indicate that a multi-segment earthquake (Mw 8.5) off Tokachi and Nemuro (Fig. 1) was most suitable. The study resulted in the publication of map showing the tsunami inundation area in eastern Hokkaido (Satake and Nanayama, 2004). This outcome of paleo-tsunami studies was used for planning a disaster prevention policy by the Japanese government.

V. Conclusive Remarks

In this paper, I briefly described the progress of paleo-tsunami research based mainly on my own studies. Though the geological record provides us with much information on past events, we are circumspect in choosing and interpreting the data on paleo-tsunamis. Our knowledge and techniques concerning paleo-tsunami research are not yet complete.

Key problems and prospective goals of paleo-tsunami research can be summarized as the following three subjects, as already pointed out by Bourgeois and Minoura (1997) and Fujiwara *et al.* (2004). When these key problems are solved, we will certainly be able to learn much regarding tsunami history from the geological records, and make use of this information for the better understanding of the natural processes and to prevent future disasters.

1. Reliable identification of tsunami deposits

Identification of tsunami deposits is a basic problem in paleo-tsunami studies. The criteria and models reviewed in this paper explain the field observation and theoretical tsunami wave-forms, but improvement is still needed for con-

sideration of wide variety of tsunami deposits and reconstruction of more precise tsunami history. For this purpose, collaborative works among field geology, flume experiments and numerical simulations are needed.

2. Accurate dating and correlation of events

Understanding when, where and what regarding the past tsunamis would help us to estimate the features and scale of future tsunami events. Development of database of tsunami deposits, including their temporal and spatial distributions based on detailed age determination, is needed.

3. Quantitative evaluation of ancient tsunami events

Evaluation of inundation areas and depths and current velocities of past tsunamis from deposits would be useful for evaluating risk of future tsunami disasters. Eastern Hokkaido is the best field to evaluate the inundation limits of past tsunamis from deposits, because wide uncultivated peaty marshes in this region provide a favorable condition for paleo-tsunami study. In other regions of Japanese Islands, it is difficult to evaluate the inundation limits from deposits, because of poor preservation of tsunami deposits due to small size of coastal marsh and artificial disturbances. Development of alternative indexes and techniques for evaluating the scale of past tsunamis from geological records is particularly important

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津波堆積物の研究は第四紀学にどう貢献したか

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〔要 旨〕

大規模な津波は、重大な自然災害の原因としてだけでなく、沿岸での堆積作用の要因としても重要である。津波堆積物は、自然科学と防災工学などの分野で研究され、これらの分野を橋渡しする役割も担っている。大規模な津波はさまざまな場所で、急速かつ大規模な堆積物の移動を起こし、地層の形成や保存に少なからず関わっている。

地層中の津波堆積物は、海溝型地震と津波の履歴復元に役立っている。この履歴復元は、南海トラフや駿河トラフでは過去約 3,000 年間、相模トラフでは約 10,000 年間、千島海溝では約 6,500 年間に及んでいる。また、北海道東部では、遡上範囲が内陸数 km にも達する歴

史・観測記録とは桁違いに大きな津波が、過去に 500 年程度の再来間隔で発生していたことも津波堆積物の研究から判明した。

いくつかの課題はあるが、津波堆積物は海溝型地震と津波の履歴を復元し、地震と津波による将来のリスクを評価するのに役立つ。ストームなど他の堆積物との識別や、堆積物から津波の流体力の定量的な復元が可能になれば、津波堆積物の有用性はさらに向上するだろう。地質学、地形学、地震学、地球物理学、津波工学など多分野の連携によって、こうした問題は解決されると期待される。

キーワード：沿岸堆積作用、海溝型地震、第四紀学、津波堆積物、地震・津波防災

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