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Structure and depositional processes of a gravelly tsunami deposit in a shallow marine setting: Lower Cretaceous Miyako Group, Japan

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Abstract

This study reports a newly discovered gravelly tsunami deposit from the Lower Cretaceous Miyako Group, Japan. The deposit was formed in an open shallow marine setting. The event deposit erosionally overlies shoreface deposits and shows marked lateral facies change. At the basin margin, the deposit is composed mainly of amalgamated HCS sandstones with liquefaction structures, overlain by finer sediments that contain many plant fragments or micas. Conglomerates accompanying the HCS sandstones contain molluscan fossils and many coral clasts. In the basin center, the event deposit is made up mainly of conglomerates and lenticular sandstone beds, and passes upwards into alternating sandstones and siltstones. A condensed organic debris layer is intercalated within the alternating section. Conglomerates contain abundant beach gravel, and also contain beachrock, coral blocks, and boulders. Bivalve fossils are well preserved despite their occurrence in grain-supported conglomerates. The event deposit is divided into sub-layers bounded by internal scours that are wavy and intersect. Each sub-layer consists of a conglomerate grading into a sandstone layer. Imbrications just above the scours in sub-layers show seawards paleocurrents; however, imbrications just beneath the sandstone horizons in the same sub-layers feature landward paleocurrents. Respective sub-layers in the tsunami deposit were formed by substrate erosion due to backwash flow, gravel deposition, reworking by flood flow, and sand deposition during the stagnant water period. The overall upward-fining trend reflects decline of the tsunami event. Development of the gravelly deposit in the central part of the basin and lateral facies change may be attributed to hydrodynamic response of the tsunami pulse to local bathymetry and geography.

Keywords: Tsunami deposit; Sedimentary structures; Depositional processes; Lower Cretaceous; Miyako Group

1. Introduction

Tsunamis are large sea waves caused by earthquakes, submarine slides, volcanic eruptions and asteroids (Bondevik et al., 1997). They have a long wavelength (up to 200 km) and travel across the oceans at great velocity (Dawson and Smith, 2000). From a geological viewpoint, tsunamis are notable as short lived but extremely powerful agents with a very complex pattern of erosion and deposition, leaving large volumes of sediment on the seafloor and coastal areas (Bondevik et al., 1997).

Depositional processes of tsunamis have been investigated mainly by coring and trenching of recent and historical tsunami deposits (e.g. Minoura and Nakaya, 1991; Clague and Bobrowsky, 1994; Shi et al., 1995; Minoura et al., 1996; Hindson and Andrade, 1999). Outcrop-scale observations are also necessary to learn about features of tsunami deposits, such as their internal structure and lateral facies changes, and to detect them

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in the geological record. However, the characteristics of tsunami deposits are still largely unknown, especially in submarine environments. Reports of submarine tsunami deposits are much less frequent than would be expected from the recurrence intervals of such events, although some studies have reported marine tsunami deposits from outcrops on land (e.g. Shiki and Yamazaki, 1996; Fujiwara et al., 2000; Massari and D'Alessandro, 2000; and Takashimizu and Masuda, 2000).

In this study, we identify an event deposit newly discovered in the Lower Cretaceous Miyako Group in Japan as a tsunami deposit. This is a rare case in which inversely directed imbrications resulting from flood- and backwash-flow are preserved. Favourable outcrop conditions enabled us to observe metre-scale sedimentary structures and trace lateral facies changes, and hence reconstruct tsunami sedimentary processes in a shallow marine environment.

2. Geological setting

The Lower Cretaceous (Aptian-Albian) Miyako Group crops out sporadically along a 35 km stretch of the Rikuchu coast in Iwate Prefecture, NE Japan (Fig. 1A). The Miyako Group is subdivided (Fig. 1B) into the Raga, Tanohata, Hiraiga and Aketo Formations in ascending order (Hanai et al., 1968). Its total thickness, about 200 m, changes in response to basement topography (Fig. 2). Crest directions of wave ripples in the Miyako Group indicate that the palaeocoastline trended north–south (Fig. 1B). Although Japan has been tectonically rotated by the opening of the Japan Sea and

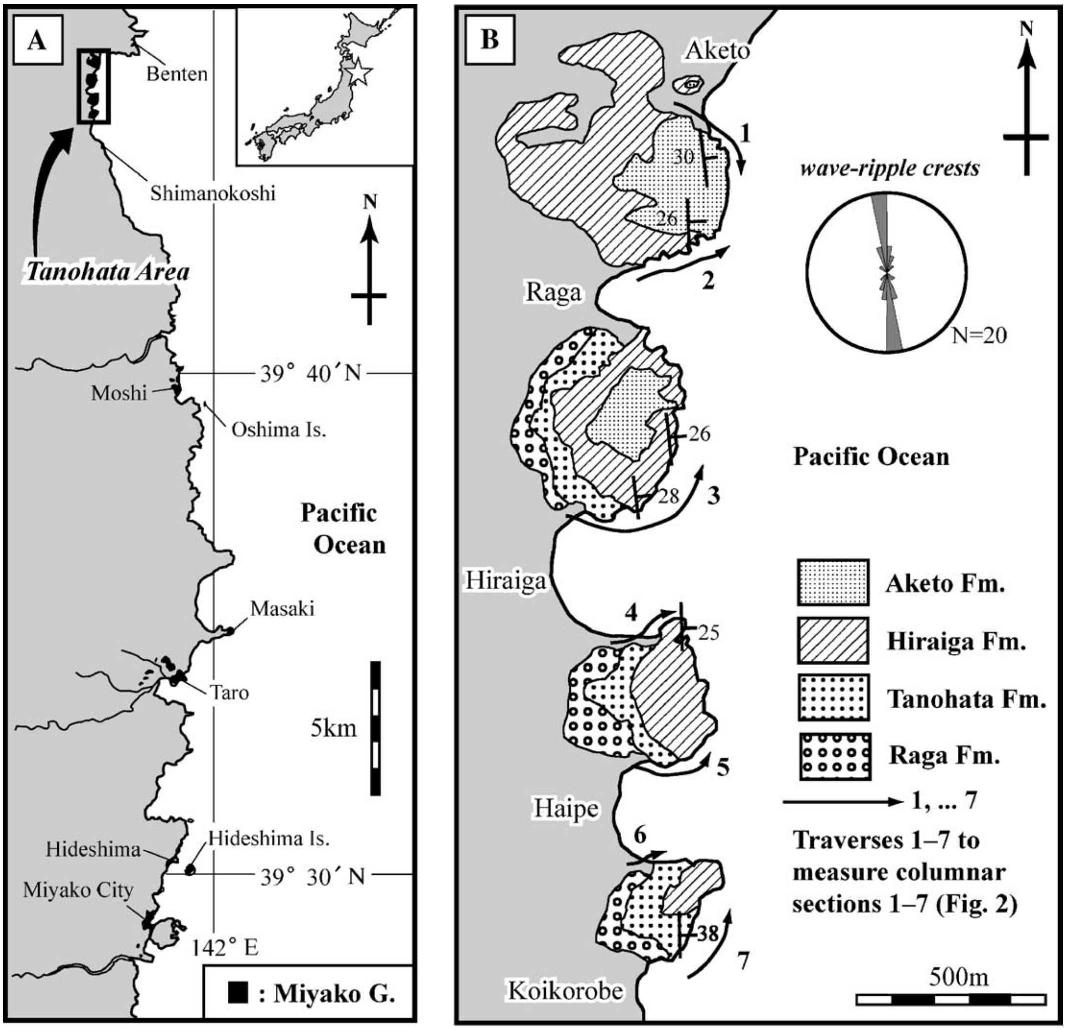

Fig. 1. (A) Distribution of the Miyako Group. (B) Geological map of the Tanohata Area. Numbered arrows indicate the traverses made to measure the columnar sections shown in Figs. 2 and 3.

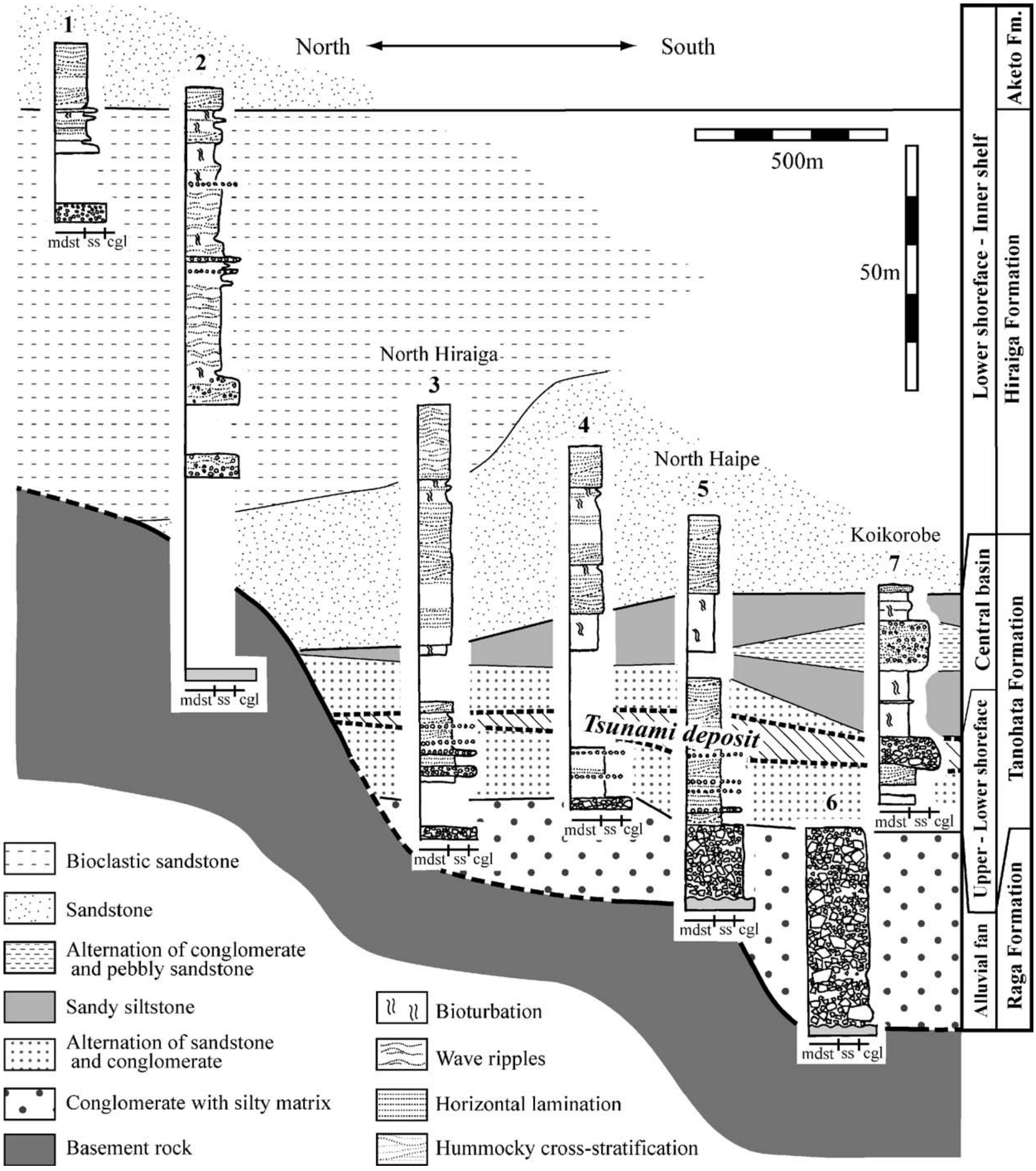

Fig. 2. Stratigraphic context of the tsunami deposit. The deposit is intercalated in the shoreface deposit within the Tanohata Formation. Locations of the columns are given in Fig. 1. Note that basement topography lowers southwards.

accretion in NE Japan, the Miyako Group and its wave ripple orientations would also have rotated as a unit. Fig. 2 thus represents a cross section parallel to the palaeocoastline. Japan was attached to the eastern margin of Eurasia in Early Cretaceous time, and hence the source of the Miyako Group is inferred to have lain to the west. This inference is supported by eastward-directed paleocurrents in the Raga and the Tanohata Formation. The Raga Formation, directly overlying the basement, is an alluvial fan-delta deposit that consists of grain-supported, poorly sorted conglomerates and minor pebbly sandstones interpreted as debris flow or talus deposits.

The lower part of the Tanohata Formation is a shoreface deposit, composed of a sandstone-dominated alternation of fine sandstone and conglomerate. The sandstones, which are massive or hummocky-cross stratified (HCS), amalgamated to form thick beds. Massive sandstones and conglomerates were deposited from sediment gravity flows. The abundance of HCS indicates a wave-dominated environment.

The upper part of the Tanohata Formation represents an enclosed, lagoonal environment, and is composed of thick sandy siltstone that encloses a wedge-shaped gravelly unit (Fig. 2). The wedge-shaped body is interpreted as a tidal inlet deposit. The thickness of the upper part of the Tanohata Formation changes laterally from 6 to 30 m (Fig. 2). The sandy siltstone is massive and intensely bioturbated on traverses 4, 5 and 7, whereas on traverse 3, it is weakly bioturbated and laminated. Thin sandstone and a conglomerate form occasional interbeds in the sandy siltstone. The wedge-shaped deposit consists of alternating pebbly sandstones and well-sorted conglomerates which are horizontally laminated or planar-cross stratified, and occasionally, herringbone-cross stratified.

The Hiraiga Formation is regarded as a lower shoreface to inner shelf deposit. Alternating HCS sandstones and siltstones in the Aketo Formation are also considered to be deposits of the same environments. The Hiraiga Formation consists of the upper bioclastic sandstones and the lower siliceous sandstones (Fig. 2) that alternate in the middle part of the Hiraiga Formation. The siliceous sandstones are amalgamated or alternate with siltstone, and are hummocky-cross stratified. Molluscan fossils are concentrated to form lenticular lags in HCS sandstones. The bioclastic sandstones alternate with siltstones with occasional conglomerate interbeds. Wave ripples and hummocky-cross stratifications are commonly observed in these sandstones. Most of the grains of these sandstones are *Orbitlina*, a larger foraminifer, and fragments of molluscan shells.

In addition to these settings, Sano (1991) reported a small coral-rudist buildup from the Miyako Group. This buildup was deposited on a shallow, rocky sea floor. In summary, the Miyako Group in the Tanohata Area was deposited in small basins with associated reefs, and records an environmental change from alluvial fan-delta to inner shelf, reflecting a rise of relative sea level.

3. Description of the event deposit

The event deposit reported here overlies the shoreface facies in the lower part of the Tanohata Formation (Figs. 2 and 3). It is present at Koikorobe (Traverse 7) and has been identified in the same horizons in Traverses 3 and 5 at North Hiraiga and North Haipe (Figs. 1B and 2). The event deposit is composed mostly of sandstone at North Hiraiga and North Haipe (Traverses 3 and 5), and of conglomerate at Koikorobe in Traverse 7 (Fig. 3). Especially at Koikorobe, relatively near the basin centre, a complex deposit can be observed, characterized by several scour-and-grading structures that are not seen in 'normal' background sediments of the Miyako Group.

Event deposits are distinguished from background sediments by the abundance and good preservation of fossils, lack of bioturbation, presence of organic-rich sediments and liquefaction structures. The background sediments rarely yield well-preserved molluscan fossils, and in the lower part of the Tanohata Formation are sometimes intensely bioturbated.

3.1. Event deposit at Koikorobe (Traverse 7)

The event deposit at Koikorobe (Traverse 7) is mainly composed of grain-supported conglomerate (Figs. 3–7). Its basal scour is irregularly undulating (Fig. 4A) and eroded the underlying HCS sandstone to a depth of at least 1.5 m. The event deposit itself is 5 to 8 m thick, contains lenticular poorly sorted sandstone interbeds tens of centimeters thick (Fig. 5), and fines upwards into alternating pebbly sandstone and siltstone beds (Fig. 7A) that contain pebble-to cobble-sized mud clasts and have wavy erosional bases.

Although most of the gravel is granule to cobble sized, boulders do occur near the erosional base (Fig. 4A), their maximum diameter reaching 1.7 m. Beach gravel clasts, characterized by their platey shape and high rounding, are commonly observed in the conglomerate. Cobble- to boulder-sized clasts of coral and beachrock also occur. Some of the coral clasts are unabraded.

The Koikorobe event deposit displays more than four internal scours that divide it into sub-layers (Fig. 5), each of which consists of a conglomerate bed that grades upwards into a sandstone bed. Thicknesses vary: sub-layer 1 is 0.6–2.2 m; sub-layer 2 is 0–2 m; sub-layer 3 is 0.3–1.4 m; and sub-layer 4 is 1–1.6 m. The sandstone of each sub-layer is truncated by the conglomerate at the base of the overlying sub-layer (Figs. 4B and 5). In each sub-layer the conglomerates form mounds (Figs. 5 and 6) and include discontinuous minor sand beds. Swale-shaped scours truncate the tops of the conglomerates, bringing the conglomerates of adjacent sub-layers into direct contact (Figs. 5 and 7A). Locally, scour has removed an underlying sub-

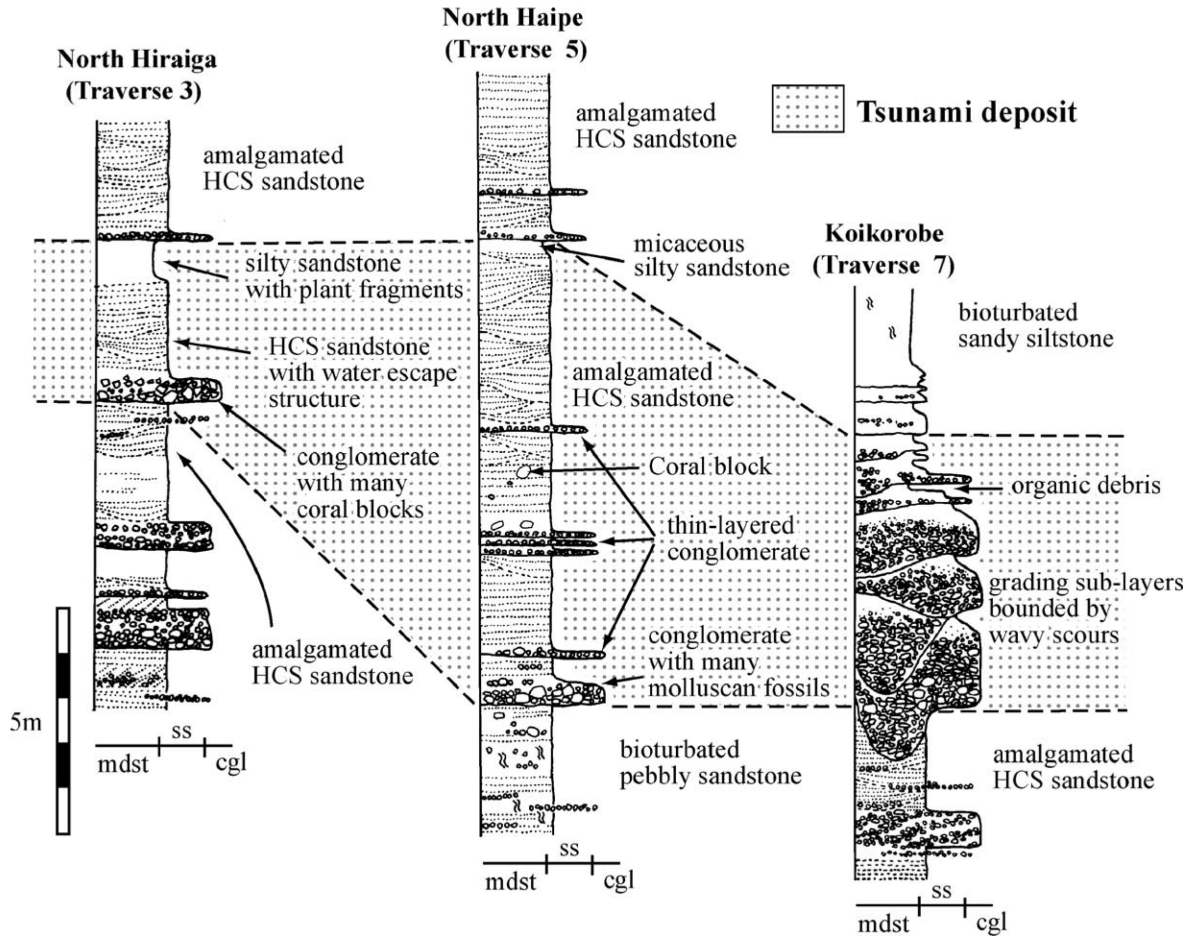

Fig. 3. Lateral facies changes of the tsunami deposit. The deposit at Koikorobe is composed mainly of conglomerates, whereas those at North Hiraiga and North Haipe consist of HCS sandstones with fossiliferous conglomerates. These deposits commonly have organic-rich or micaceous layers in their upper parts.

layer completely (Fig. 5). Contacts between sub-layer 1 and sub-layer 2 are notable for concentrations of molluscan fossils in the conglomerate layers. Viewed at outcrop scale, the conglomerate of sub-layer 4 changes laterally into pebbly sandstone. From 5 to 8 sub-layers have been detected in total. However, in the upper part, counting sub-layers precisely is difficult due to structural complexities such as lateral facies changes and intersection of scours.

The platey clasts in beach gravels are imbricated (Fig. 4E) and establish the paleocurrent direction recorded in the conglomerates of each sub-layer. Thus, the imbrication just above the erosional base of sub-layer 4 shows a southeastwards- (seawards-) directed paleocurrent, whereas the imbrication just below the sandstone in the same sub-layer shows a northwestwards- (landwards-) directed paleocurrent (Fig. 6). The paleocurrents above the erosional bases of other sub-layers also indicate southeastwards-directed flows. However the imbrications just below the sandstone layers are obscure in sub-layers 1 and 2, and indicate a southwestward paleocurrent in sub-layer 3.

The conglomerates contain many coral clasts, oyster shells and other molluscan fossils including *Pterotrigonia yokoyamai*, *Nipponitrigonia kikuchiana* and *Praecaprotina yaegashii*. Although many are broken and fragmented, intact specimens are also common (Fig. 4C), and 36% of bivalves with umbos are unbroken and are not abraded.

A black layer composed of condensed organic debris is intercalated within the upper alternating sandstone and mudstone of the event deposit (Figs. 4F and 7A), although plant fragments are rare in the lower and middle parts (sub-layers 1–4) of the event deposit. The black layer has a maximum thickness of 20 cm,

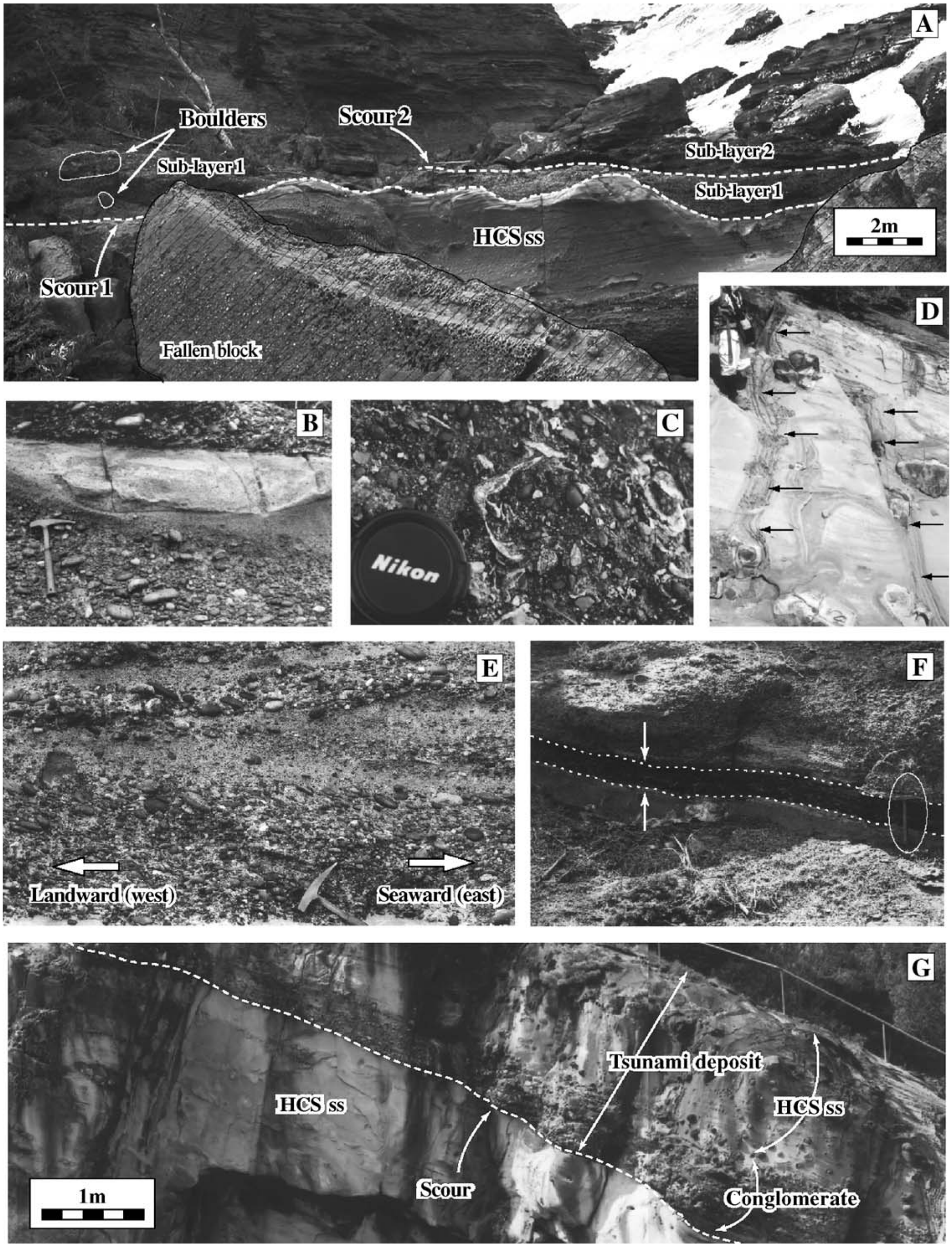

Fig. 4. Photographs of the tsunami deposit. (A) Erosional base (Scour 1) of the tsunami deposit at Koikorobe (Traverse 7). (B) Grading structure observed in sub-layer 3. The sandstone is bounded sharply by the upper scour. (C) *Nipponitrigonia kikuchiana* in the tsunami deposit. It is not broken or abraded despite its occurrence in grain-supported conglomerate. (D) Liquefaction structure (arrowed) in HCS sandstone at North Hiraiga (Traverse 3) (oblique section). (E) Imbrication indicating landward-directed paleocurrent. (F) Organic debris layer (between the dotted lines) intercalated within the upper part of the tsunami deposit. (G) The tsunami deposit at North Hiraiga (Traverse 3).

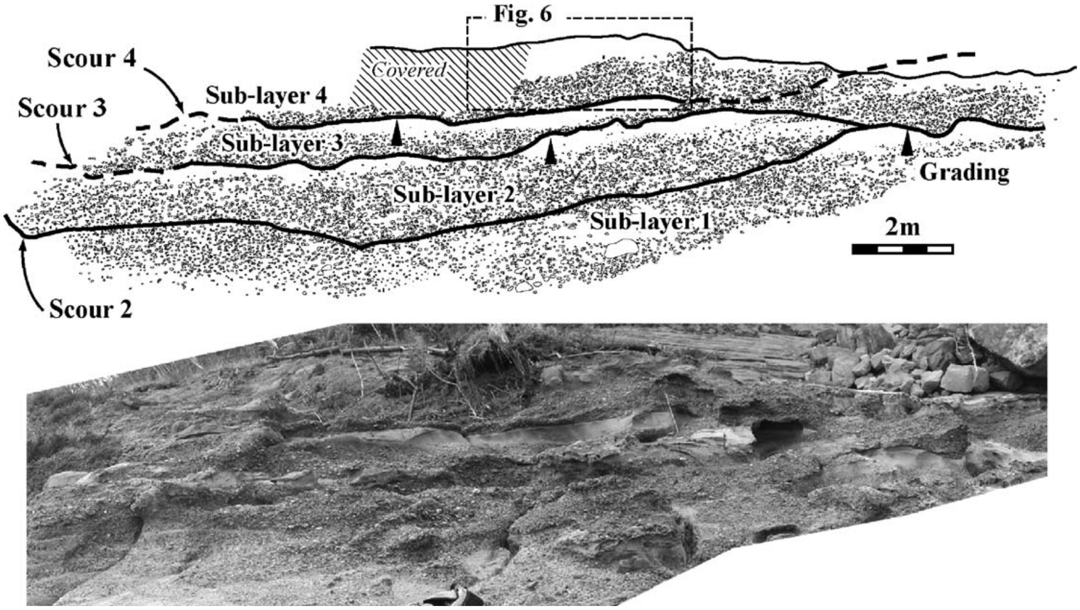

Fig. 5. Internal structure of the tsunami deposit at Koikorobe (Traverse 7) (the upper sequence of Fig. 4A). The deposit is divided into sub-layers bounded by erosional scours, and conglomerates grade into sandstones in each sub-layer. Note that most of the sandstone part of sub-layer 1 is eroded, and that Scour 3 has excised Sub-layer 2 near the right side of the diagram, where it merges with Scour 2.

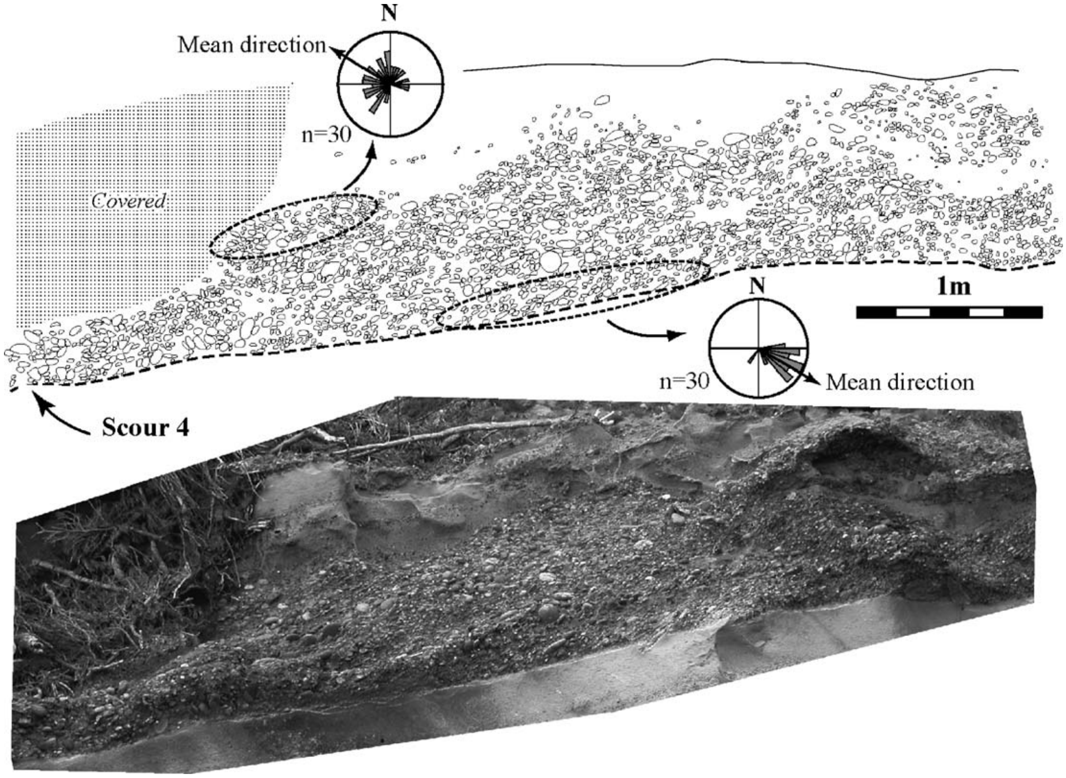

Fig. 6. Enlarged sketch and picture of sub-layer 4 showing gravel imbrications in tsunami deposits (position indicated in Fig. 5). The paleocurrents inferred from the imbrications are directed southeastward at the base of the conglomerate, and northwestward directly beneath the overlying sandstone.

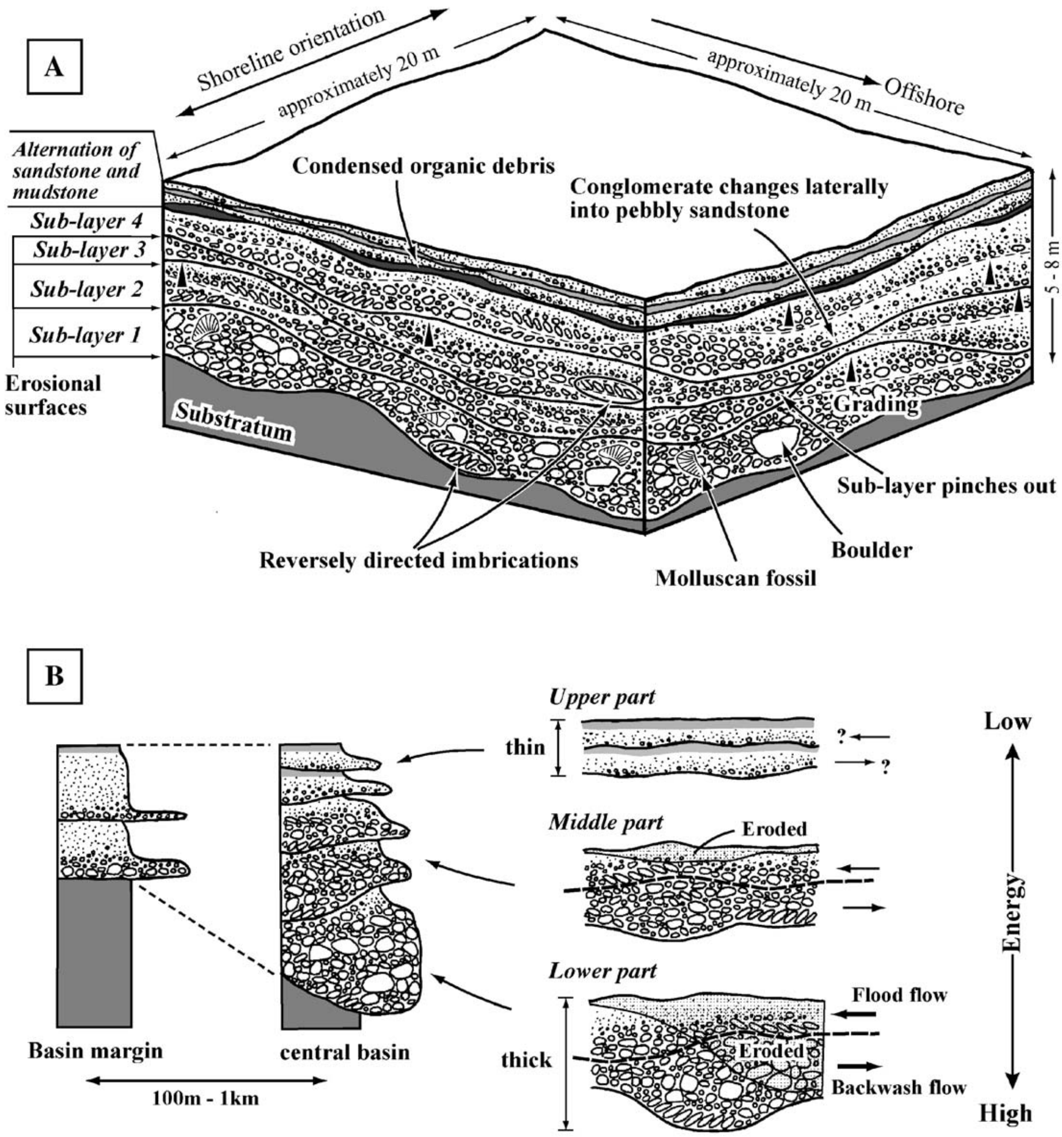

Fig. 7. (A) Block diagram illustrating major features of the gravelly tsunami deposit. Dotted lines indicate reactivation surfaces formed by flood flows. Scours form hummocky and swaley topography and intersect each other. Sandstone layers are discontinuous because they are truncated by overlying scour surfaces. In the middle part, conglomerates grade laterally into pebbly sandstones. (B) Depositional processes recorded in the gravelly tsunami deposits. Backwash flow eroded the substrate and deposited gravel. The gravel was re-worked during the following flood flow and was buried by sand deposited from suspension during the ensuing stagnant water period. Decline in energy of the tsunami over time is reflected in decreasing erosion and overall fining upwards of the deposited sediments. At the margin of the basin, sandy deposits are dominant over gravels, and sub-layers are not developed.

and pinches out because of erosion by the overlying pebbly sandstone (Fig. 7A).

3.2. Event deposit at North Hiraiga (Traverse 3)

At North Hiraiga (Traverse 3), about 1 km from Koikorobe (Traverse 7)(Fig. 1), the event deposit overlies amalgamated HCS sandstone on an erosion surface (Figs. 3 and 4G). However, unlike the case at Koikorobe, the erosion surface is not undulating. The event deposit is composed of a lower conglomerate, middle sandstone and an upper sandy siltstone (Fig. 3). The conglomerate, which is grain-supported and 60 cm thick, consists of pebble- to cobble-sized angular gravel, and contains coral and rudist fragments. No imbrication was observed. The sandstone is fine to medium grained, 1.7 m thick, hummocky cross-stratified, and contains liquefaction structures (Fig. 4D). The sandy siltstone capping it is 1 m thick and is black, due to abundance of organic debris.

3.3. Event deposit at North Haipe (Traverse 5)

The event deposit that crops out at North Haipe (Traverse 5) consists of conglomerate, overlying a flat erosional base, and medium-fine sandstone. This is capped by 25 cm of micaceous silty sandstone (Fig. 3). Both the conglomerate and the sandstone lack bioturbation. The conglomerate is 50 cm thick and yields fossil bivalves, rudists and corals. Clasts are granule- to cobble-sized and form a grain-supported structure. Some of the molluscan fossils are entire, as at Koikorobe (Traverse 7). The sandstone overlying the conglomerate is horizontally laminated or hummocky-cross stratified, and is amalgamated to thick-bedded. Its total thickness is 9.5 m (Fig. 3). It contains cobbles, coral clasts and molluscan fossils. Some thin-bedded conglomerates are interbedded within the sandstone (Fig. 3). These conglomerates rest on erosional surfaces and grade into sandstones. They are also composed of granule- to cobble-sized gravels and are fossiliferous.

4. Discussion

4.1. Identification of the event deposit as the consequence of a tsunami

We concluded that the event deposit observed in the Tanohata Formation was formed by tsunami that inundated a small basin. This conclusion is based on five points, as discussed in turn below. Generally, in wave-dominated shallow marine settings, it is difficult to distinguish tsunami deposits from the ‘normal’ background deposits because tsunami deposit often resemble tempestites, and tend to be removed or modified by subsequent storms (Einsele et al., 1996). However, if features peculiar to tsunami are preserved, tsunami deposits can be recognized. Each of the following five points of evidence may individually be attributed to various other processes. However, tsunami is the only phenomenon that can adequately account for their co-existence in a single deposit.

4.1.1. Inversely directed imbrications

Imbrications observed in the event deposit at Koikorobe (Traverse 7) reflect current reversals from seaward- to landward-directed. The speeds of the currents that entrained the gravel were estimated, from the grain size, to be at least 1–2 m/s. In a tide-dominated environment, such current speeds can occur during tidal action. However, the background sediments in the Tanohata Formation were deposited in a wave-dominated environment, as shown by the presence of abundant wave-generated structures and the lack of any evidence of tidal action. Thus, it is difficult to attribute the opposing imbrications in the event deposits to tidal currents.

Reversals of paleocurrents in tsunami deposits have not often been reported in previous studies due to the scarcity of outcrop-scale observations. However, this criterion has been used as significant evidence for identification of tsunami deposits in some studies, such as those by Takashimizu and Masuda (2000) and Massari and D’Alessandro (2000).

4.1.2. Scour-and-grading structure

The scour-and-grading structure that characterizes the event deposit at Koikorobe (Traverse 7) implies that intervals of stagnant and brisk flow velocities alternated repeatedly and sequentially during a single event. Based on the lack of bioturbation and superimposition of the waves, we infer that these structures were not formed by several discrete events. If there were hiatuses between each sub-layer, the surfaces of each sub-layer would have been disturbed by wave action and by burrowing organisms. It is unlikely that bioturbations were entirely removed from the whole event deposit by erosion from overlying layers, because “normal” deposits in the Tanohata Formation are often deeply burrowed.

Tsunamis are characterized by long wavelength (L) in comparison to height (H) (H/L=<0.04) (Dawson and Shi, 2000). This causes an interval after run-up when water velocity is stagnant before backwash flow develops (Dawson and Shi, 2000). At this point large volumes of sediment may be deposited from the water column (Dawson and Shi, 2000). Consequently, it is likely that tsunami waves typically result in alternation of coarse and fine-grained layers. Thus, Bondevik et al. (1997) reported alternating sand and organic deposits, and attributed them to several pulses of erosion and re-deposition caused by successive tsunami waves. The scour-and-grading structure observed in the event deposit also results from such water action.

4.1.3. Deposition of beachrocks and coral clasts

The abundance of beach gravels in the event deposit indicates intensive beach erosion during the event. It is likely that rocks were washed out from the beach and transported to the lower shoreface environment. Transportation of beach gravels and boulders to the lower shoreface suggests the transport capacity of the event was large. Accumulation of coral clasts also reflects the destructive nature of the event. The coral clasts were torn from patch-reefs or entrained from the sea floor, and mixed with the beach gravels and sand.

4.1.4. Presence of the condensed organic bed

Based on the abundance of organic debris, we also infer that the event washed on to land. To form a condensed organic bed, as in this case, large quantities of organic materials must be provided and sorted from sands and gravels. Although other phenomena may provide organic debris, few can effectively separate it. Surge type gravity currents, for example, may provide organic matter, but would not leave condensed organic layers. Tsunami commonly cause severe erosion on land, and hence presence of organic debris has been used as an important criterion for identification of tsunami deposits in many studies (e.g. Bondevik et al., 1997; Fujiwara et al., 2000; Takashimizu and Masuda, 2000).

4.1.5. Fossil preservation

The good preservation of the molluscan fossils indicates that the conglomerates within which they occur were deposited quickly, and were not repeatedly reworked after sedimentation. If the molluscan shells had later been reworked by storms, longshore currents and other processes, they would soon have been abraded and fragmented, and their original shapes would not have been preserved. Transportation must be brief if allochthonous shells are to be preserved without abrasion. In such a case, some shells that were entire before the event would not suffer fragmentation during transportation.

The presence of coral and molluscan fossils also confirm the marine origin of the gravels. It is unlikely that gravity flows originating on land could entrain so many marine shells. The event conglomerate was clearly derived from a shallow marine or beach environment where a mixture of gravel, coral clasts and shells were deposited.

Although each of these five points of evidence could be attributed to other depositional processes individually, but no phenomenon except tsunami can account for all of them simultaneously. In particular, the opposing imbrications and scour-and-grading structures are not readily explained by any other agents. Deposition of beach gravels and beachrock clasts, accumulation of plant fragments, and the mode of the fossil occurrences also support the tsunami origin of the event deposit.

4.2. Depositional processes during the tsunami event and implications for other examples

The depositional processes during the tsunami event are here reconstructed mainly from observations at the Koikorobe outcrop (Traverse 7). This tsunami deposit is the result of repeated flood- and backwash-flow, and the overall declining energy trend that is superimposed on it. The tsunami inundated a small basin which deepened southward and had a gravelly beach at its bay-head and patch-reefs at its margin. The tsunami deposit described here was deposited in the lower shoreface located off a gravelly beach. Due to local bathymetric and topographic influences, flood- and backwash-flow directions may not be truly perpendicular to the shoreline. Differences in paleocurrent directions between each sub-layer result from these local factors.

Each sub-layer was formed by the combined flood and backwash flow. Imbrication in gravels lying directly on erosional surfaces indicate that the tsunami backwash flow formed an erosional base on each sub-layer (Fig. 6). During the backwash stage, sand and mud were suspended in seawater, and gravel and beachrock, transported from shallower water and the beach, covered the swaley and hummocky erosional surface to form gravel mounds of varying size. During the transitional stage between backwash and flood, water velocity decayed and suspended sands were deposited. The sand beds formed during the transitional stages between backwash and flood may have been relatively thin and poorly preserved due to deposition from a shallower water column. The minor sand beds interbedded within the conglomerates may be remnants of sand beds deposited during the transition. However, the depositional process during the transitional stage between backwash and flood is obscure due to poor preservation, as the following flood flow eroded the sand layer and reworked the gravels. The flood flow provided only suspended sand and gravels entrained from the substrate, because there was no efficient gravel supply area beyond the shoreface. During alternations from flood to backwash the suspended sands were deposited, forming a graded top to each gravel layer (Fig. 7B).

As the tsunami waned, its erosive capacity weakened, and sediment grain size decreased (Fig. 7B). In the initial tsunami stage which formed the lower part of the deposit, backwash flow erosion was sufficiently powerful to remove most of the underlying sand layer deposited by the previous wave. In the following stage which deposited the middle part of the deposit, sand layers developed as the erosional power of the tsunami weakened (Fig. 7B). Mud and organic materials were resuspended with each tsunami wave, and were prevented from settling until the tsunami energy weakened. In the last stage, when current velocity was too low to entrain and transport gravel, deposition terminated in alternating sand and silt layers, including organic debris horizons in the upper part (Fig. 7B). Graded bedding in this part of the deposit may also have resulted from transient stagnation of the current. However, the current direction is difficult to detect (Fig. 7B).

Beach gravels and beachrock were entrained by beach erosion and gathered near the basin center. This results from the concentration of backwash toward local lows in basin topography. At the basin margin, thick sands were deposited from suspension instead of gravel deposits with scour-and-grading structures (Fig. 3). Rapid deposition of sand produced the liquefaction structures observed at North Hiraiga (Traverse 3). Finally, organic debris and fine sediments covered the deposit at both the basin margin and in the center, forming alternating sands and silts and the interbedded organic layer. Other studies have also reported that the coarser parts of tsunami deposits develop in basin centres (e.g. Bondevik et al., 1997; van den Bergh et al., 2003). The latter reported that the 1883 Krakatau tsunami deposit is thickest in the central bay area of Teluk Banten, and rapidly decreases in thickness laterally over hundreds of meters. They also reported that stacked, graded, sub-layers are present where the tsunami deposit is thickest. These lateral facies changes also reflect the hydrodynamic response of tsunami pulses to the local bathymetry and geography.

The tsunami deposit described in this study formed in shallow and open marine settings, is composed of grains varying in size from boulders to silt, and shows characteristic structures. However, these characteristics may not be the same under different conditions elsewhere. Local factors including grain size distribution and topography of the basin vitally influence the structural characteristics of tsunami deposits. Consequently, reference to the local background environment is essential for identification of tsunami deposits.

5. Conclusions

1. We conclude that an event deposit with the following characteristics was formed by a tsunami.
    - (i) The deposit rests on a wavy erosional base and is composed of conglomerates and lenticular sandstone layers in the lower and middle parts, and alternations of sandstone and siltstone in the upper part. A condensed organic debris layer is intercalated within the upper part.
    - (ii) The deposit contains sub-layers bounded by internal erosional surfaces that form a hummocky and swaley topography and intersect each other. In each sub-layer, gravels rest on erosional surfaces and grade upwards into sand layers. Landward- and seaward-directed imbrications are observed within single sub-layers.
    - (iii) The conglomerate is composed of abundant beach gravels and contains beachrock, coral clasts, and boulders.
    - (iv) The deposit contains many molluscan fossils which are well-preserved despite their occurrence in grain-supported conglomerates.
2. Sub-layers in the tsunami deposit were formed by substrate erosion during backwash flow, gravel deposition, reworking during flood flow, and sand deposition during the stagnant water period, respectively. Due to the overall decline in velocity of the tsunami superimposed on the flow reversals, the resultant deposit shows an upward fining trend. The hydrodynamic response of the tsunami pulse to the local bathymetry and the geography causes gravel concentration in the basin center and lateral facies changes toward the basin margins.

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