ELSEVIER
Marine Geology xx (2007) xxx–xxx
MARINE GEOLOGY
INTERNATIONAL JOURNAL OF MARINE GEOLOGY, GEOCHEMISTRY AND GEOPHYSICS
www.elsevier.com/locate/margeo

Effects of landforms on tsunami flow in the plains of Banda Aceh, Indonesia, and Nam Khem, Thailand

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Accepted 7 October 2006

Abstract

Mapping on high-resolution satellite images and in the field shows differences in landforms and characteristics of tsunami flow on two contrasting coastal plains following the giant earthquake on December 26, 2004: the plain of Banda Aceh on the northern tip of the Sumatra island, Indonesia, and the Nam Khem plain in the Andaman Sea coast of Thailand. The landforms of the Banda Aceh coastal plain are characterized as deltaic lowland with tidal plains in the western and central parts, and strand plain with beach ridges in the eastern part. The run-up tsunami flow invaded areas about 3–4 km from the coast. Strong tsunami flow severely damaged the tidal plain and the landforms along the coast except coastal dunes in the east. Most of the landforms except sand dunes along the coast had almost no effect on the protection against the tsunami, but the higher micro-landforms such as beach ridges and natural levees prevented the flow of the tsunami from its invasion into the inland near the end of tsunami inundation.

The tsunami inundation spread out over the entire Nam Khem coastal plain with an average depth of 4–5 m. The direction of run-up flow was almost perpendicular to the coastline, whereas backwash flow directions were controlled by topography. Backwash flow was concentrated in the lower portions of the plain, for example in small stream channels. Wedge-shaped channels in the lower parts of the streams were formed due to the concentration of backwash flow. The existence of the swales between parallel beach ridges corresponds well with the distribution of thick tsunami deposits. Coastal erosion of the plain was caused by the direct attack of tsunami waves, and the lower reaches of small rivers were eroded by strong backwash flow.

Keywords: Sumatra–Andaman earthquake; tsunami flow; tsunami deposits; coastal plain; Banda Aceh; Nam Khem

1. Introduction

Large tsunamis produce significant geomorphological changes when they reach the coast, including extensive erosion and deposition of distinct sedimentary layers. Studies have been undertaken on the characteristics of deposits of former tsunamis (Atwater, 1992; Minoura et al., 1994; Dawson, 1994; Nishimura and Miyaji, 1995; Sato et al., 1995; Imamura and Takahashi, 1995; Dawson et al., 1995, 1996; Clague et al., 1999, etc.), and several reviews on paleo-tsunami deposits have been published by Dawson and Shi (2000), Goff et al. (2001), Scheffers and Kelletat (2003), Scheffers et al. (2005), but less research has focused on the change of coastal landforms by tsunami flow and on the spatial distribution of tsunami deposits in relation to coastal landforms.

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0025-3227/$ - see front matter © 2007 Published by Elsevier B.V.
doi:10.1016/j.margeo.2006.10.030

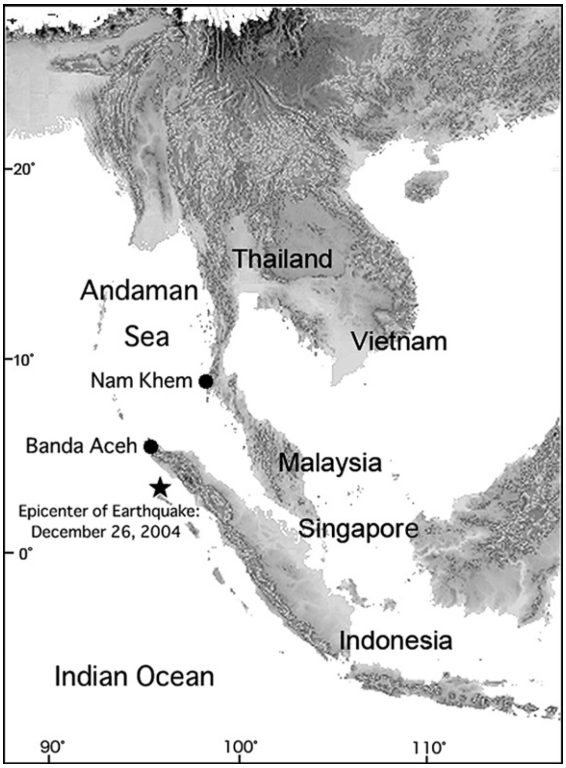

Fig. 1. Map showing the location of the Banda Aceh and the Nam Khem plains in Indonesia and Thailand.

Konno et al. (1961) studied tsunami deposits on the northeastern coast of Japan, which were deposited by the tsunami resulting from the 1960 Chile Earthquake. They discussed the relations among deposits and breached tsunami flow characteristics. Based on the morphology of a coastal embankment, they identified three types of tsunami flows: sheet flow, linear flow and eddies. Evidence for the three types of flow can also be seen on several coastal lowlands. Sato et al. (1995) clarified distribution of onshore tsunami deposits caused by the 1993 Southwest Hokkaido and 1983 Japan Sea earthquakes and found that the thick and widespread siliclastic tsunami deposits occurred where higher vertical run-up was observed. Gelfenbaum and Jaffe (2003) conducted detailed research on the 1998 Papua New Guinea tsunami deposits and clarified detailed characteristics of the tsunami deposits. They found that the incoming tsunami flowed nearly perpendicular to the shore, but a slower backwash or return flow was directed obliquely to the shore in local topographical lows.

These are limited case studies, and further detailed research on the distribution of tsunami deposits in relation to the flows on land and landforms of coastal lowlands is necessary.

The catastrophic tsunami accompanying the giant earthquake off Sumatra on December 26, 2004, inundated coastal lowlands in northern Sumatra, Indonesia,

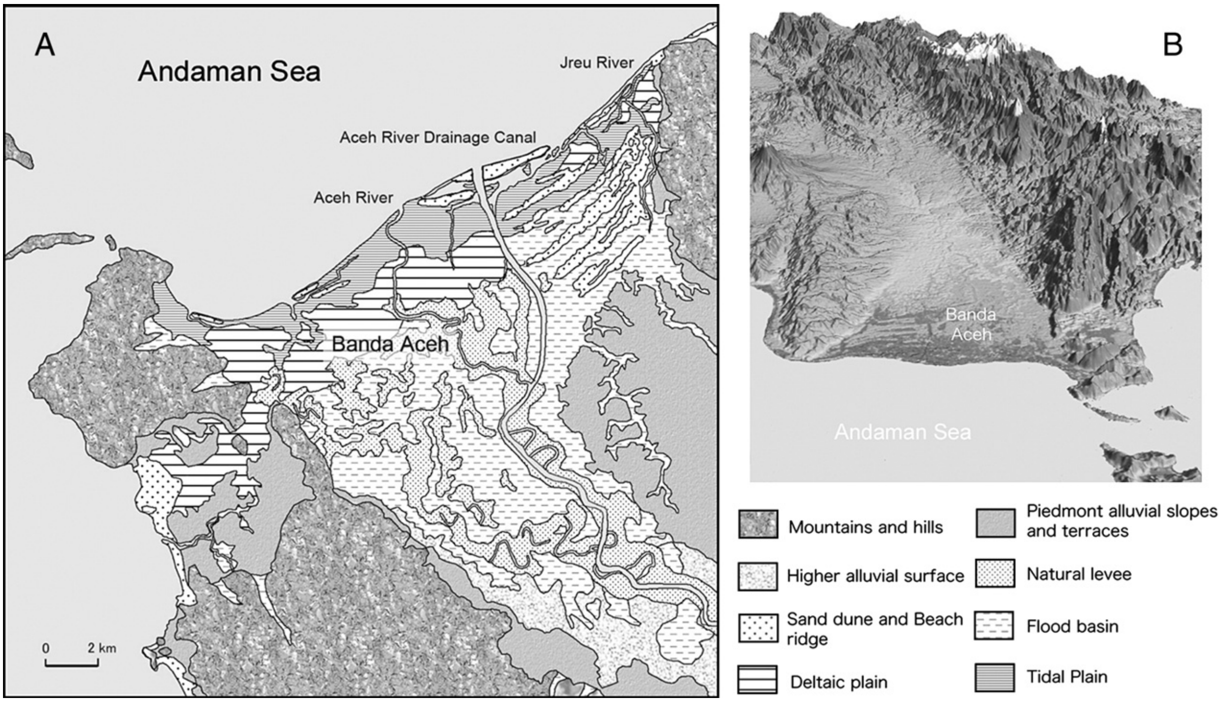

Fig. 2. Landform classification map of the Banda Aceh coastal plain.

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and along the southern Andaman Sea coast of Thailand. In this paper, we compare how coastal plain landforms affected tsunami flow, how the tsunami changed landforms, and how it deposited sediment on the coastal plains of Banda Aceh in Sumatra and Nam Khem, southern Thailand (Fig. 1).

2. Regional setting

The Banda Aceh coastal plain is located along the lower reaches of the Aceh River. It is situated in a graben formed by movement of the Sumatra Fault (Fig. 2). The coastal plain is characterized by deltaic and tidal lowland in the central and western parts, and by distinct rows of beach ridges in the eastern part. Elevation of the plain is 1–3 m high above sea level in the central and western parts, except the higher parts of natural levees along the present and abandoned channels. The eastern coastal area is also low-lying, but there is a small sand dune along the coast and rows of beach ridges, 1–2 m above the swales, exist in the inner area. Shrimp and fish ponds are formed in tidal lowlands of the central and western parts of the plain. Deltaic lowland and beach ridges are occupied by houses, and the Banda Aceh urban area is located on the deltaic plain in the central part of the coastal plain (Fig. 2). Calculated high and low tide levels of the Oleelheue near Banda Aceh on Dec. 26, 2004 are 172 cm and 42 cm, respectively, and the tidal range of the region is less than 1.5 m (based on the data by Tsuji et al., 2005).

The Nam Khem strand plain is located on the Andaman Sea coast of the Malay Peninsula (Figs. 1 and 3). Landforms of the Nam Khem coastal lowland include distinct rows of beach ridges in its central part, and artificial tin mining mounds and ponds in the northern and southern parts of the plain. The lowland is generally about 3–4 m in elevation, although the tin mining mounds in the northern

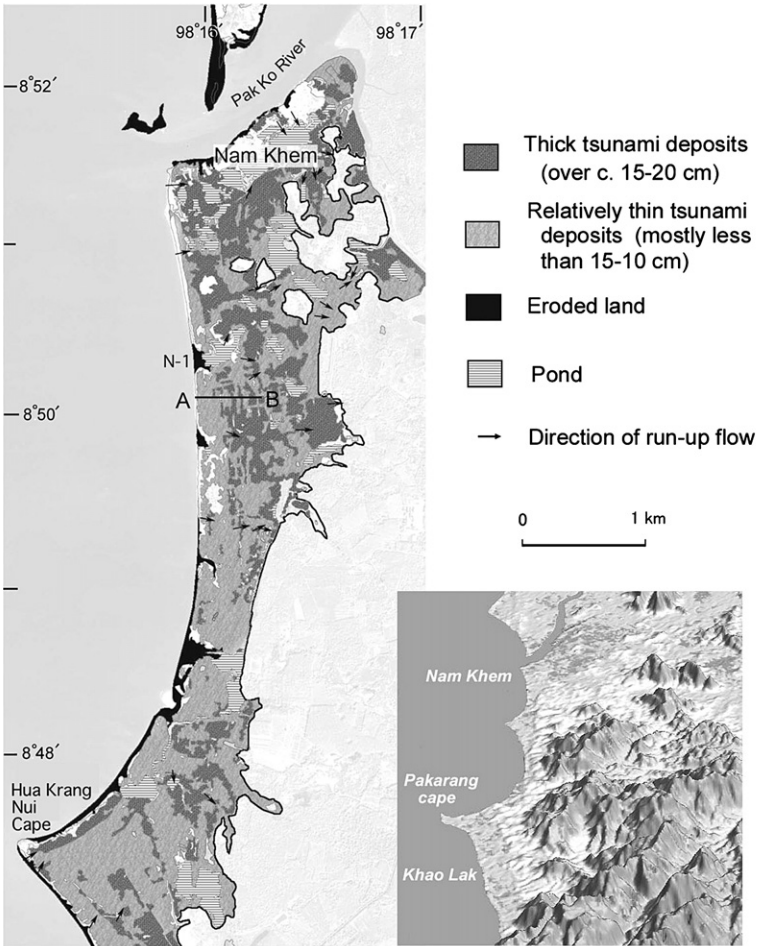

Fig. 3. Distribution of the tsunami deposits in the Nam Khem plain. (A–B shows the location of the transection shown in Fig. 12. Black solid lines indicate the limit of tsunami inundation.).

Fig. 4. Snapped off posts in the Nam Khem plain indicating run-up tsunami direction.

part of the plain rise to over 10 m. Nam Khem village is located in the northern end of the lowland, and grassland and plantations cover the other areas. Elevation of the upland located east of the coastal lowland is mostly above 10 m. Calculated high and low tide levels of the Ao Kaulak near Nam Khem on Dec. 26, 2004, are 237 cm and 62 cm, respectively, and the maximum tidal range of the region is about 2 m (based on the data by Tsuji et al., 2005).

3. Methods

Landforms were classified through interpretation of aerial photographs and satellite images of the plains, and field surveys in both regions. The 1:50,000 scale topo-sheets of Banda Aceh and Nam Khem coastal plains, the 1:25,000 scale aerial photographs of the Nam Khem plain taken on February 16, 2002, the SPOT 2 image of

Fig. 5. Fallen columns in the Banda Aceh coastal plain indicating run-up tsunami direction.

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Fig. 6. Scratches on a floor near the coast of the Banda Aceh coastal plain.

the Banda Aceh plain taken 4 h after the tsunami intrusion on December 26, and the IKONOS satellite image taken on December 29 were used for the interpretation. SRTM-dem data were also used for the interpretation and classification of landforms.

During the field surveys, heights and directions were measured of flow indicators related to tsunami flow on the plains. The orientation of snapped-off fence posts (Fig. 4), fallen trees, and other indicators were measured to determine directions of flow. Fallen columns of destroyed buildings and the scratches on the floors of buildings (Figs. 5 and 6) are also good markers of run-up flow directions in the Banda Aceh coastal plain. The directions of flattened grasses by water flow (Fig. 7)

Fig. 7. Flattened grasses in the Nam Khem plain indicating the direction of backwash flow.

were measured to determine flow tsunami backwash in the Nam Khem plain.

The color of the ground surface on the IKONOS color image of the Nam Khem coastal plain is a good indication of the thickness of tsunami deposits. In the image, bright white, dark-brownish grey and (greenish) grey areas can be distinguished, except areas covered with trees or buildings. These differences in color were interpreted as differences in the thickness of tsunami deposits, and these interpretations were confirmed in more than fifty pits dug in the field.

4. Tsunami flow and landform change in the Banda Aceh plain

Flow indicators on the Banda Aceh plain generally show inundation from the northwest. However, some areas show different directions of the flow (Fig. 8). On the northeastern coast, flows spread out in a radial pattern from a gap in the sand dune along the coast. In the southwestern part of the plain, northeastward tsunami flow from the west coast penetrated the plain and the flow met in a gap of hills with the southward run-up tsunami flow of the Banda Aceh coastal plain. We also mapped indicators in the western part of the coastal plain that show eastward flows deflected due to the existence of hills.

Tsunami flow extended inland in the central and western parts of the plain for about 4 km, and for about 3 km in the eastern part. Remarkable invasion of the run-up tsunami flow along the Aceh, the Aceh drainage and the Jreu rivers was recorded on the SPOT 2 image. The distances of the invasion of the flow from the coast into the rivers were 8 km, 8.5 km, and 6 km, respectively.

Inundation heights at similar distances from the coast were variable, with greater heights in the central and

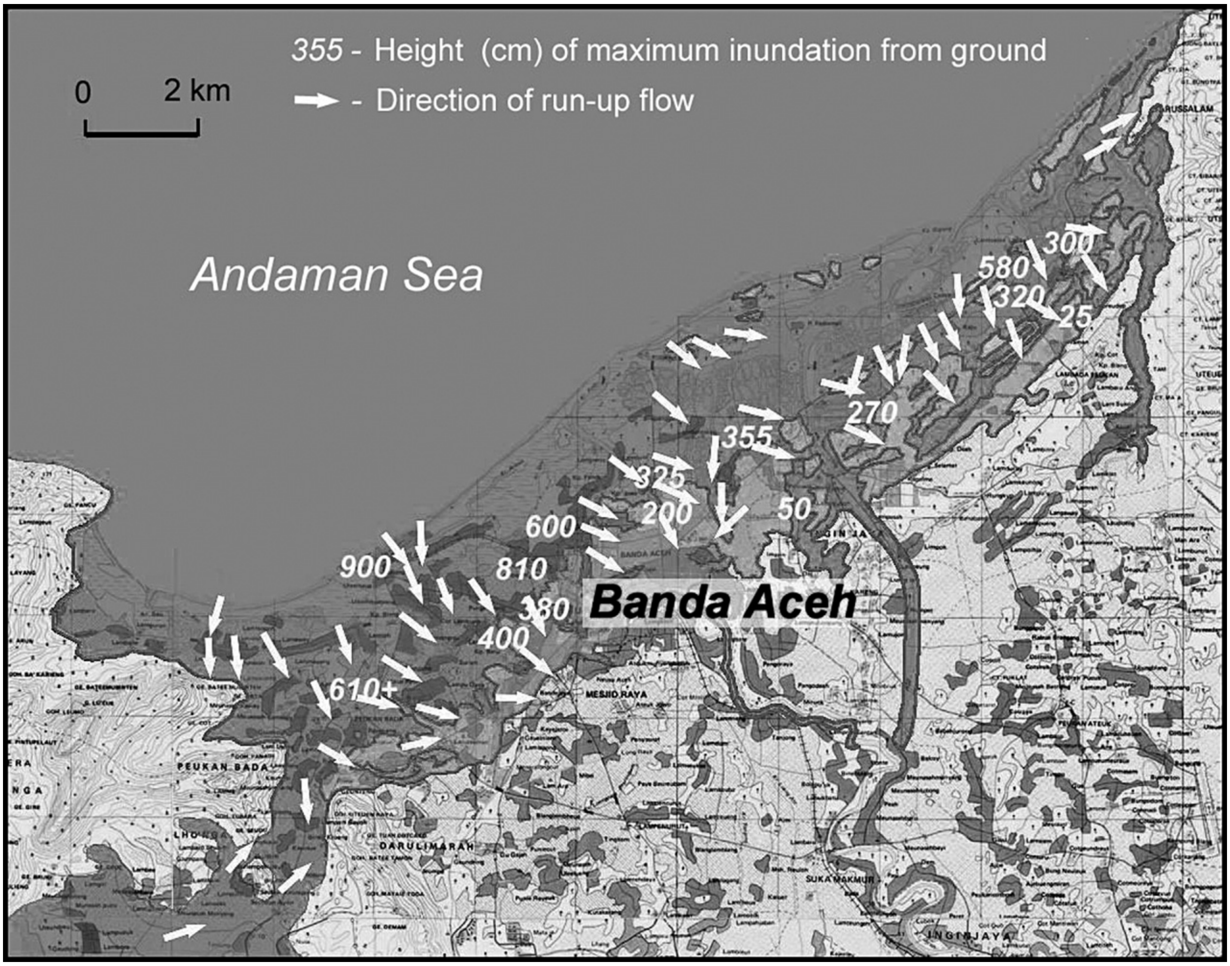

Fig. 8. Directions and heights of the tsunami flow in the Banda Aceh coastal plain.

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western part of the plain. The tsunami reached a height about 9 m on the ground near the port of the Banda Aceh and about 6–8 m in the western part of the plain about 2 km inland. In the eastern part of the plain about 2 km from the coast, however, tsunami heights were mostly lower than 3 m (Fig. 8).

Severe coastal erosion occurred in the parts of the tidal plain used for shrimp or fish ponds. The small narrow banks separating the ponds were easily eroded by the tsunami returning these areas to former tidal flat conditions (Fig. 9). The conversion of these areas to tidal flats was due to erosion by the tsunami rather than tectonic subsidence. Interviews with local people confirmed that tidal areas are now exposed at low tide to the same extent as they were before the tsunami, and tide levels marked on several bridges are almost similar to levels before the tsunami. It was difficult to reconstruct the flows of the tsunami backwash flow in the Banda Ache plain because there are few indicators of backwash flow on the ground.

5. Tsunami flow directions and deposits in the Nam Khem plain

Based on our measurements on the ground, most of the tsunami run-up on the Nam Khem plain was eastward from the Andaman Sea and perpendicular to the coast. Some run-up flows entered through the Pak Ko River mouth (Laem Pom Sea) and inundated the northern part of the plain from the northwest. These two flows met in the Nam Khem village in the northwest part of the plain. Tsunami inundation height on most of the plain was 5–8 m above mean sea level (Tables 1 and 2). Maximum inundation height in the Khao Lak plain, about 10 km south of the Nam Khem plain, was recorded about 11 m (2005 Thailand Group, 2005).

Fig. 9. Aerial view of the western part of the Banda Aceh coastal plain. Photo was taken at high tide on Aug. 28, 2005.

Table 1
Tsunami inundation heights measured in the Banda Aceh coastal plain

Banda Aceh					
No.	Latitude	Longitude	Height (cm)	Base level	Remarks
1	N5°33′55.1″	E95°19′46.5″	200	Ground	Water mark on a wall
2	N5°34′11.6″	E95°19′46.7″	325	Ground*	Water mark on a wall
3	N5°34′32.5″	E95°20′42.2″	355	Ground	Water mark on a wall
4	N5°33′48.4″	E95°19′01.1″	520	Ground	Water mark on a wall
5	N5°34′04.9″	E95°19′00.5″	600	Ground	Water mark on a wall
6	N5°33′41.4″	E95°19′00.6″	600	Ground	Water mark on a wall
7	N5°32′48.7″	E95°18′24.1″	400+	Ground	Water mark on a wall
8	N5°28′42.2″	E95°14′43.6″	580+	Ground	Water mark on a wall
9	N5°32′02.1″	E95°16′52.9″	610	Ground	Stuck grass on a column
10	N5°34′54.3″	E95°21′50.5″	270	Ground	Water mark on a wall
12	N5°35′59.0″	E95°23′27.6″	320	Ground	Water mark on a wall
13	N5°36′10.3″	E95°23′46.7″	300	Ground	Water mark on a wall
14	N5°36′16.9″	E95°23′15.9″	610	Ground	Water mark on a wall
15	N5°35′50.0″	E95°23′48.0″	25	Ground	Water mark on a wall
16	N5°33′38″	E95°18′27″	800	Ground	Water mark on a wall
17	N5°33′26.5″	E95°17′08″	900	Ground	Destruction of a roof
18	N5°33′43″	E95°18′20″	810	Ground	Destruction of a roof

(*80 cm higher than the neighbouring paddy field).

The directions of backwash tsunami flows were variable. General trend of tsunami backwash flows from the eastern end of the lowland or slopes of tin mining dumps was east to west or southeast to northwest towards the sea. Detailed examination, however, indicates that backwash flow directions were controlled by topography (Figs. 10 and 11). This indicates that backwash flow concentrated in low areas of the plain such as small stream channels. This was also pointed out by Gelfenbaum and Jaffe (2003) in Papua New Guinea.

We used differences in color and texture of the ground surface on the IKONOS image as a base for mapping of the tsunami deposits (Fig. 3). In general, thick tsunami deposits are distributed widely in the northern part of the Nam Khem plain, where tsunami flows from the west and northwest converged. In the central part of the Nam Khem plain, parallel beach ridges capped by thin tsunami deposits are oriented north to south. Deposits >20 cm thick are found in depressions; on ridges deposits are <10 cm thick (Fig. 12). The variable

Table 2
Tsunami inundation heights measured in the Nam Khem plain

Nam Khem							
No.	Latitude	Longitude	Height (cm)	Base level	Remarks	Converted height (cm)	Base level 2
1	N8°51′48.8″	E98°16′23.6″	460	Ground	Water mark on a wall	420	Mean tide level
2	N8°50′52.2″	E98°16′31.3″	80	Ground	Stuck grass on a tree		
3	N8°50′31.3″	E98°16′33.7″	155	Ground	Stuck grass on a tree		
4	N8°51′20.3″	E98°16′04.1″	380	Ground	Stuck grass on a tree		
5	N8°51′04″	E98°16′03″	380	Ground	Stuck grass on a tree	750	Mean tide level
6	N8°51′02.5″	E98°16′12.8″	0	Ground	Swept grass stack	840	Mean tide level
7	N8°50′05″	E98°16′21″	0	Ground	Swept grass	742	Mean tide level
8	N8°50′12.4″	E98°15′29.6″	270	Ground	Stuck grass on a tree	512	Mean tide level
9	N8°47′45.9″	E98°15′41.5″	205	Road	Broken signboard	699	Mean tide level
10	N8°48′47.9″	E98°15′58.4″	280	Road	Stuck grass on a tree	512	Mean tide level
11	N8°50′56.4″	E98°16′15.5″	400	Ground	Stuck grass on a tree		
12	N8°51′00.5″	E98°16′17.5″	0	Ground	Swept grass stack	c 850	Mean tide level

Base level is the mean tide level from December 2004 to March 2005, calculated from tidal data of Ao Kaulak by Yoshinobu Tsuji, Yuichi Namegaya and Junichi Ito (Earthquake Research Institute, the University of Tokyo) (http://www.eri.u-tokyo.ac.jp/namegaya/sumatera/tide/index.htm). The original height data were measured from the sea level at the time, and the data were converted to the heights based on the above mentioned mean tide level.

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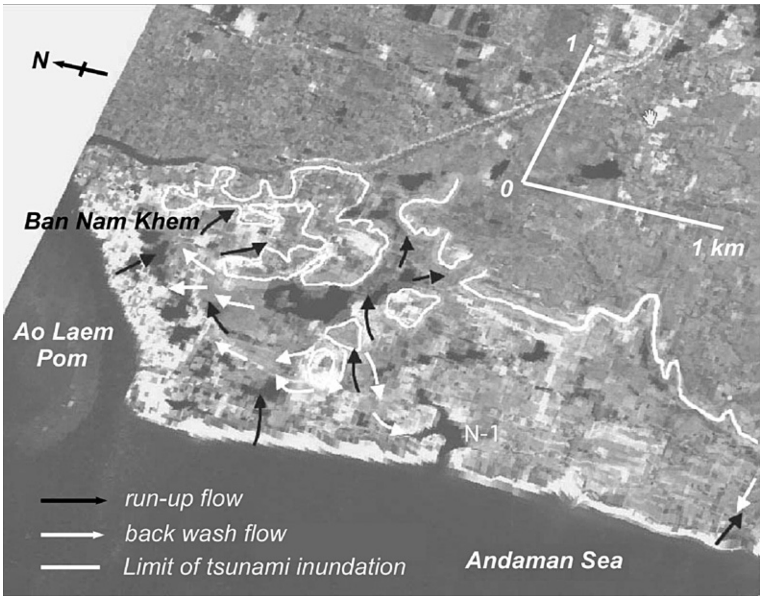

Fig. 10. Tsunami flow in northern part of the Nam Khem plain. 3D diagrams were drawn based on the SRTM-dem data.

thickness of deposits is the result of tsunami deposition on older parallel beach ridges, with thicker tsunami deposits in the swales between higher beach ridges.

6. Landform changes on the Nam Khem plain

The most remarkable landform changes occurred in the lower parts of the small streams connecting with the Andaman Sea. Prior to the tsunami, small river channels flowing to the Andaman Sea coast on the Nam Khem plain and Khao Lak plain, 10 km south of the Nam Khem plain, were narrow and their mouths were usually blocked by deposition of beach sand. Near the mouth of small channels, ponds had formed in several abandoned tin mining pits. The channels changed their planar shape to a wedge shape type and their river mouths opened with the width of 50–200 m after the tsunami event.

Distinct tsunami deposits are not found either beside the channels or near the ends of eroded channels. Measured flows directions were mainly concentrated in or towards the channels, indicating backwash flow. Thus, the main widening of the channels was caused not by tsunami run-up, but by concentrated strong backwash flows from inland.

Evidence of erosion by the tsunami can be seen on the northwestern tip of the Nam Khem plain, on the coast beside of the small channel mouth and on both sides of the Hua Krang Nui Cape in the central part of the Nam Khem plain (Fig. 3). Beaches in the most exposed part of the area, near the Hua Krang Nui Cape, retreated or vanished after tsunami inundation. There is not distinct deposition of tsunami boulders in Nam

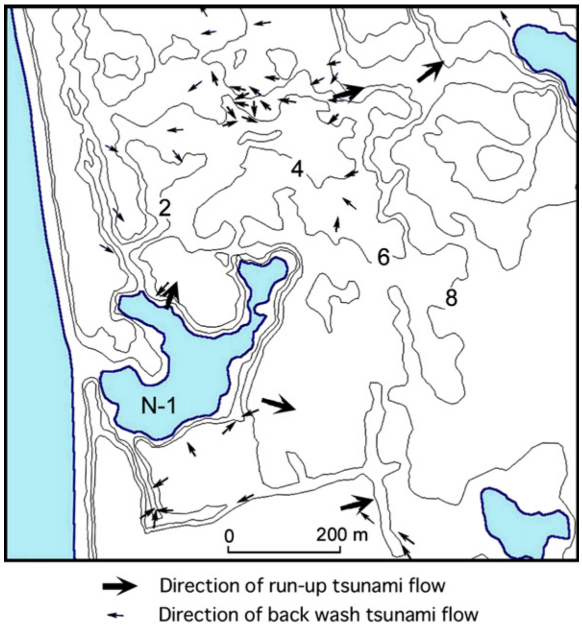

Fig. 11. Detail tsunami flows measured in the coastal site around N-1 in the Nam Khem coastal plain. Location of N-1 is shown in Figs. 3 and 10. Contour lines were drawn using a digital photogrammetric system (KLT Win ATLAS). Ground elevation is shown as relative height from a temporal benchmark.

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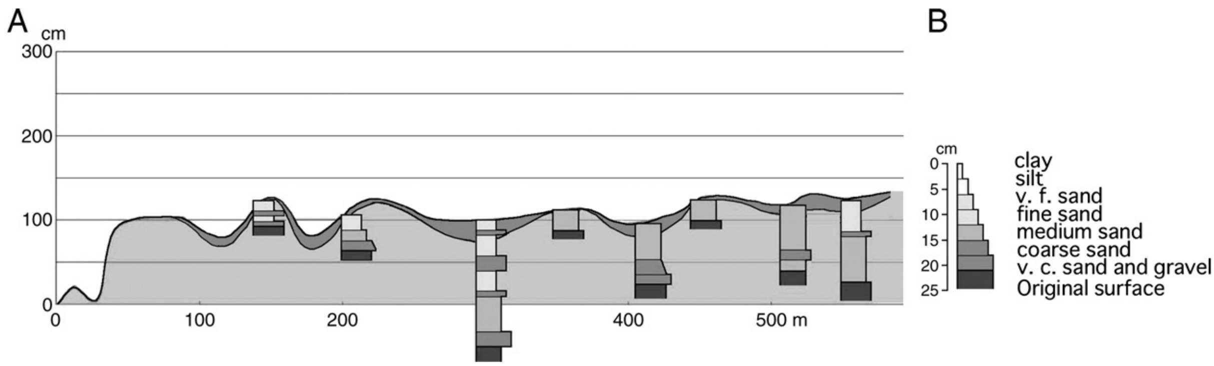

Fig. 12. Tsunami deposits in the central Nam Khem plain shown in the E–W cross section of the plain. Elevation in the diagram is shown from a temporal benchmark, and location of the transection is shown in Fig. 3.

Khem plain as seen in the Pakarang Cape of Khao Lak coastal plain.

7. Effect of landforms on tsunami flow in the plains

Regional differences in tsunami flow patterns and tsunami height can be seen on the Banda Aceh and the Nam Khem plains. The differences are related to the characteristics of the landforms of the plains. In the case of the Banda Aceh Plain, mouths of small rivers in the coastal area were not eroded like the river mouths in the Nam Khem plain. Erosion of channels was not violent and the linear erosion is not observed on the plain. In some areas of the plain, however, coastal landforms were greatly modified. Shrimp and fish ponds on the tidal plain were extremely damaged and some of them disappeared after the tsunami (Figs. 13 and 14). This indicates that the backwash flow was not concentrated in the Banda Aceh plain, and sheet erosion of backwash flow dominated in the plain. This condition is shown on the SPOT image taken 4 h after the tsunami intrusion (Fig. 15).

In the Nam Khem plain, most parts of the surface of the plain were not eroded and are covered by tsunami deposits. Thickness of the deposits is related to the topography of the plain, with the thickest tsunami deposits in the central part of the plain between beach ridges. Erosion of the channels occurred and the lower reaches of the rivers changed their planar shape to a wedge shape. It is clear that the backwash flows eroded

Fig. 13. Severely damaged shrimp ponds in the western part of the Banda Aceh coastal lowland. (Dec.1, 2005).

Fig. 14. Severely damaged coastal area and tidal flat in Banda Aceh. Photo was taken at low tide on Dec.1, 2005.

and dissected the channels in the plain, similar to the linear-flow condition pointed out by Konno et al. (1961).

The primary reason for the difference of erosion patterns in the two plains is that the ground level and tidal range are different. There is a broad tidal plain in the central and western coastal area of the Banda Aceh plain, and the ground surface is low and flat. This environment did not produce the concentration of backwash and linear-flow erosion was not remarkable. In contrast, the ground level of the Nam Khem plain is generally 2–3 m higher than the stream channels, and

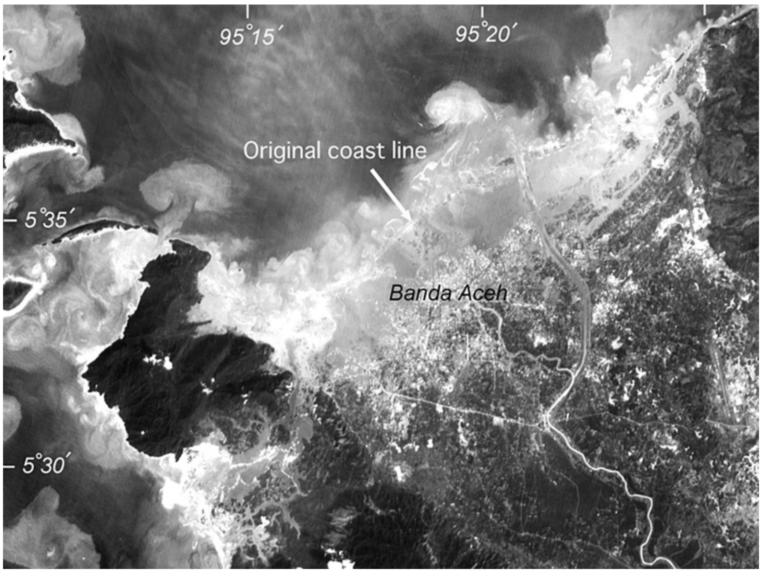

Fig. 15. Inundation and tsunami flow of the Banda Ache Plain shown in the SPOT2 image. The image was taken about 4 h after the earthquake. (Includes material from CNES2005, Distribution Spot Image S.A., France, all rights reserved).

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the backwash flow concentrated in the lower parts of the plain. Because of the concentration of the backwash of the tsunami, strong erosion occurred in lower parts of the plain, especially along channels.

The tsunami heights in the central and western parts of the Banda Aceh coastal plain at similar distances from the coast were higher than in the eastern parts. It is suggested that the existence of low-lying tidal and deltaic plains in the western and central parts of the plain facilitated intrusion of tsunami flow inland. The tsunami inundation height also did not decrease in the regions of the plain. In the eastern coastal region, relatively higher landforms such as dunes and beach ridges prevented the tsunami flow from penetrating inland.

8. Conclusions

Tsunami flow in the Banda Aceh plain, Indonesia, and the Nam Khem plain, Thailand, are related to their landforms. The landforms of the Banda Aceh coastal plain are characterized as deltaic lowlands with tidal plain in the west and central parts and the strand plain and beach ridges in the eastern part of the plain. The landforms of the Nam Khem plain are relatively higher than Banda Aceh coastal plain and characterized by rows of beach ridges and artificial mounds of tin mining dump.

The direction of the run-up tsunami flow is nearly perpendicular to the coastline, and that of the backwash flows in the Nam Khem plain concentrated in the lower parts. Lower reaches of the rivers were eroded and changed their planar shape to wedge shape. Coastal erosion of the plains was caused by direct attack of tsunami wave in both the Nam Khem and Banda Aceh plains, and the broad tidal flat of the Banda Aceh coastal plain was severely damaged by the tsunami flow.

The differences of erosion in the plains are caused by the differences of the landforms and the elevation of the both plains. Linear erosion occurred predominantly in the Nam Khem plain with relatively higher ground level, and sheet erosion dominated in the Banda Aceh tidal plain. Regional differences of low and flat ground condition of the Banda Aceh coastal plain affected the heights and distance of tsunami inundation in the plain. Micro-landforms such as beach ridges and natural levees prevented the flow of the tsunami from penetrating further inland in the area near the margin of tsunami inundation.

The thickness of tsunami deposits of the Nam Khem plain is related to landforms and tsunami flow. The existence of the swales between parallel beach ridges corresponds well with the distribution of the thick tsunami deposits.

Acknowledgements

The authors wish to express gratitude to Prof. Fumiaki Kimata at Nagoya University, Japan and Mr. Didik Sugiyanto at Syiah Kuala University, Indonesia, for their support of our field survey in Banda Aceh. We are grateful to reviewers for their critical reviews and improvements of our manuscript. The research was supported by the Grant-in-Aid for Scientific Research (B1500302) sponsored by Japan Society for the Promotion of Science, the Science and Technology promotion Budget by FY 2004 for the Urgent Indian Ocean Tsunami Research by Ministry of Education, Culture, Sports, Science and Technology, and the Discretion Budget of FY 2005 by the Chancellor of Nagoya University for the Indian Ocean Tsunami Survey. This paper is a contribution to IGCP-Project 495 "Quaternary Land–Ocean Interactions: Driving Mechanisms and Coastal Responses".

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Please cite this article as: Umitsu, M. et al. Effects of landforms on tsunami flow in the plains of Banda Aceh, Indonesia, and Nam Khem, Thailand. Mar. Geol. (2007), doi:10.1016/j.margeo.2006.10.030