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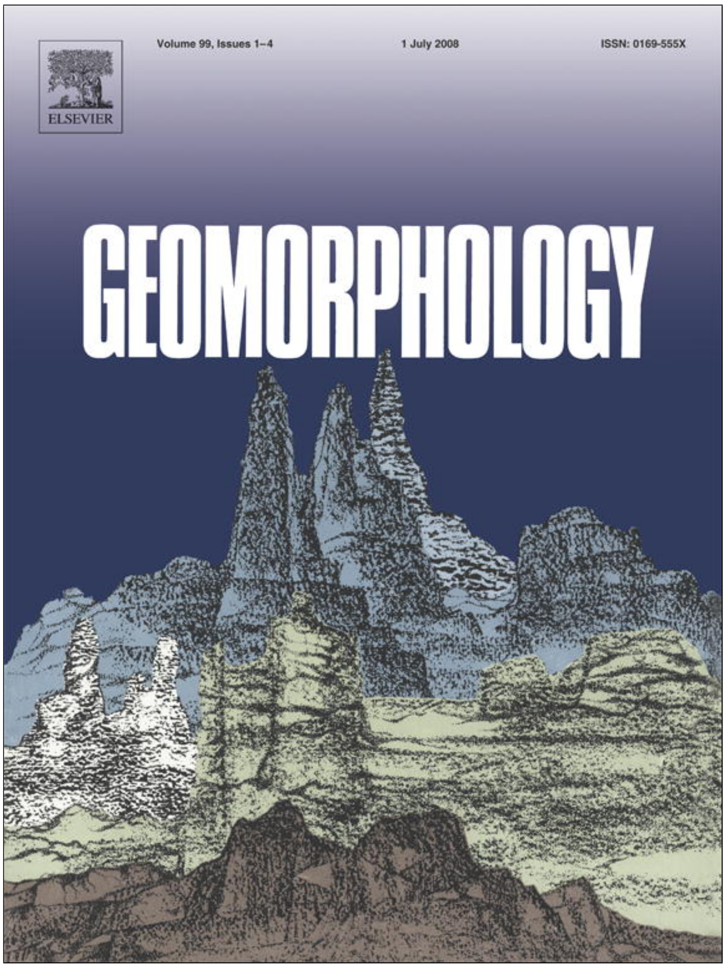

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Tsunamigenic incisions produced by the December 2004 earthquake along the coasts of Thailand, Indonesia and Sri Lanka

Sergio Fagherazzi [a,*], Xizhen Du [b]

[a] *Department of Earth Sciences and Center for Computational Science, Boston University, Boston MA, USA*
[b] *Department of Earth Sciences, Boston University, Boston, MA, USA*

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Abstract

Field observations and satellite images indicate that tsunami waves exhibit specific patterns during flooding and recession forming characteristic incisions in the coastal landscape. To study these incisions we analyze high resolution remote sensing images of the coastline of Indonesia, Thailand and Sri Lanka impacted by the tsunami of December 26th, 2004. The analysis sheds light on the different mechanisms by which currents scour incisions during the flooding and receding phases of a tsunami. During flooding the high velocity flow indents the levees of existing tidal channels and bays, leaving short flood scours. The receding water then dissects the coastline with equally spaced return channels widening toward the coast.

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Keywords: Tsunami; Flood scours; Return channels

1. Introduction

Tsunami waves are generated by large-scale underwater disturbances, such as seabed displacements triggered by seismic activity, volcanic eruptions, underwater landslides, underwater explosions, or meteorite impacts with the ocean (Bourgeois et al., 1988; Hills and Goda, 1998; Bryant, 2001; Gedik et al., 2005; Ramachandran et al., 2005; Rasheed et al., 2006). In the Pacific Ocean, tsunamis are a relatively common phenomenon, given the high frequency of earthquakes in this area. Catastrophic tsunamis have also impacted large areas in the Indian and Atlantic oceans (Murty and Bapat, 1999; Altinok and Ersoy, 2000; Besana et al., 2004). The December 2004 tsunami was probably one of the most devastating in the Asian continent. The tsunami was initiated by an earthquake of magnitude 9.0 Mw, the epicenter of which was located at 3.4°N, 95.7°E off the coast of Sumatra, Indonesia (Ioualalen et al., 2007). The resulting wave traveled for thousands of kilometers, wreaking havoc along the coasts of Indonesia, Thailand and Sri Lanka, killing hundreds of thousands of people and causing billions of dollars worth of damage.

Since then, several investigations have been conducted to determine the ecological, economic and societal impact of the tsunami in the Indian Ocean region. However, within all the available studies, few have focused on the geomorphologic and sedimentologic changes and features produced by the December 2004 tsunami waves along the coasts of Indonesia, Thailand and Sri Lanka. Mascarenhas (2006) reports the formation of new inlets and the breaching of barrier islands along the Nagore–Velankanni coast, India. Szczucinski et al. (2006) indicate extensive erosion in river mouths and tidal channels along the Andaman Sea coast, Thailand. Dawson (1994) was the first to recognize the importance of geomorphological processes associated with tsunami waves. In his paper he showed that the coastal landscape can be modified by both tsunami run-up orthogonal to the shoreline and episodes of vigorous backwash.

As we know, the primary cause of the tsunami damage lies in the destructive nature of its long waves. Tsunami waves propagate in almost a straight line near the coastline causing large run-ups that vary at a scale of tens of kilometers as a function of coastal bathymetry (Ioualalen et al., 2007). Even though the wave height is relatively uniform at the local scale (less than

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* Corresponding author. Tel.: +1 617 353 2092.
E-mail address: Sergio@bu.edu (S. Fagherazzi).

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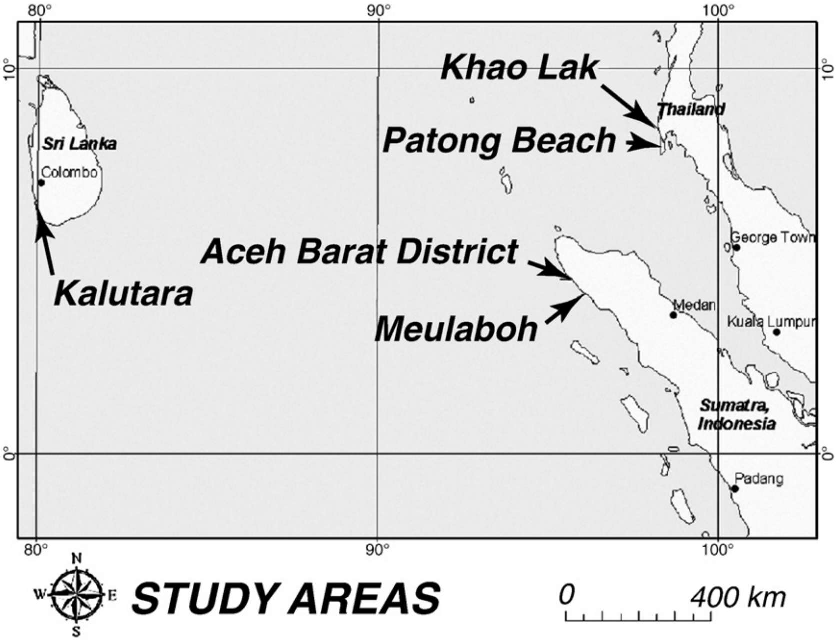

Fig. 1. Study areas in the Indian Ocean impacted by the December 26th, 2004 tsunami.

1 km) the corresponding currents are most likely concentrated in few selected areas causing locally enhanced erosion.

A similar discharge concentration has been noticed in tidal fluxes in shallow areas, leading to scour and channel formation (Fagherazzi and Furbish, 2001). Recent studies show that the flow concentration ultimately determines the development of channels in tidal environments (Rinaldo et al., 1999a,b; Fagherazzi et al., 1999; Fagherazzi and Furbish, 2001; Fagherazzi, 2002; Fagherazzi et al., 2003; Fagherazzi and Sun, 2004). Therefore a similar behavior can reasonably be expected when tsunami waves hit the coast.

In this study, we will examine the characteristics of the December 2004 tsunami incisions. The analysis will be carried out across three different time periods: pre-tsunami, a few days after the tsunami, and 6 months after the tsunami. We also address the relation between tsunami incisions and tidal channels, the role of tsunami currents in producing different landforms, and the interaction between tsunami waves and already existing tidal features.

2. Field sites and methodology

The research was carried out by comparing two sets of IKONOS satellite images in three different coastal locations impacted by the tsunami of December 2004: Khao Lak and Patong Beach, Thailand; Aceh Barat and Meulaboh, Indonesia; and Kalutara Beach, Sri Lanka (Fig. 1). The three sites were selected based on the presence of tsunami return channels and on the differences in tsunami wave height. The satellite images were taken on 01/03/2003 and just after the tsunami on 12/29/2004 (CRISP, 2004, http://www.crisp.nus.edu.sg). The planimetric dimensions of the incisions (e.g. length, width and spacing) were directly measured from the satellite images. A field survey conducted on 16/08/2005 in Khao Lak provided the vertical dimension of selected incisions and allowed comparison of the satellite images with ground-based photographs at the same locations.

The tsunami impacted the Khao Lak area along the Andaman coast of Thailand with waves between 6 and 10 m high (Chaimanee and Tathong, 2005; Tsuji et al., 2006). Given the gentle slope of the coast at this location, with lowlands 2–3 km wide and only 4–5 m above sea level, the wave run-up reached a distance of 1.5 km inland before encountering a steep scarp (Hori et al., 2007). The entire area was characterized by tsunami deposition with a basal layer of coarse sand (median grain size 0.3–0.7 mm and molluscan shell fragments) covered by fine-

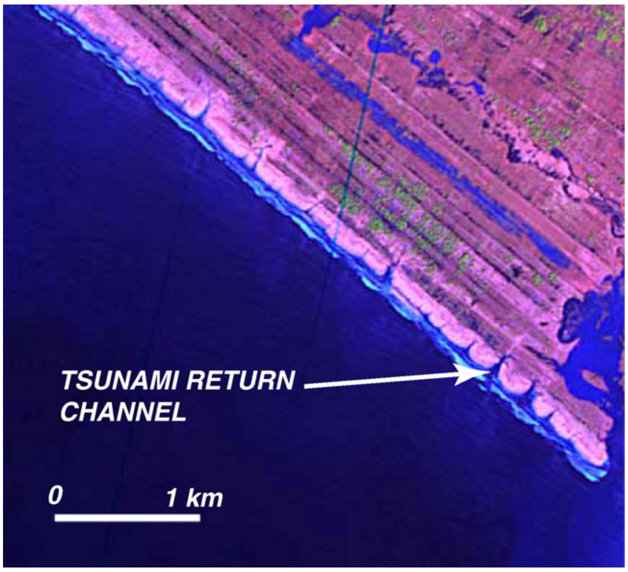

Fig. 2. Tsunami return channels in the Aceh Barat district, near Banda Aceh, Indonesia (29/12/2004 Images acquired and processed by CRISP, National University of Singapore IKONOS image, CRISP, 2004).

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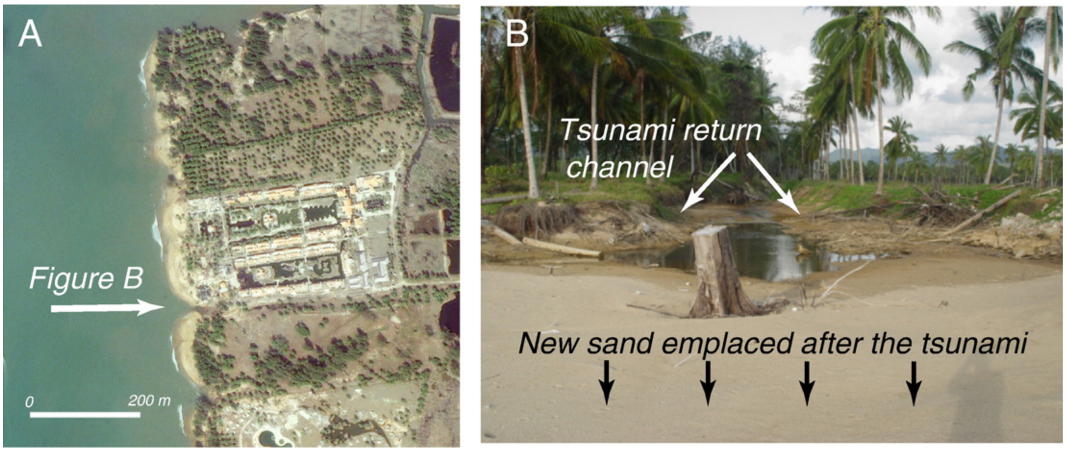

Fig. 3. Tsunami return channels in Khao Lak, Thailand. The satellite image was taken on 29/12/2004 (Images acquired and processed by CRISP, National University of Singapore IKONOS image, CRISP, 2004), the ground-based photograph on 17/08/2005.

grained deposits (median grain size 0.06–0.012 mm) (Hori et al., 2007).

Similar deposits have been found along the coastline of northern Sumatra, Indonesia. Here the tsunami deposited a discontinuous sheet of sand up to 80 cm in thickness and left mud up to 5 km inland (Moore et al., 2006). The deposits are composed of coarse sand with grain size between 0.3 and 0.7 mm fining landward (Moore et al., 2006). In this location the height of the tsunami wave ranged from 15 to 30 m (Gibbons and Gelfenbaum, 2005). The run-up was highly variable and depended on the width of the coastal plain.

The third study area, Kalutara Beach, Sri Lanka, was impacted by tsunami waves with a height of 4–6 m (Papadopoulos et al., 2006). Inundation extent varied from less than 50 m to a maximum of 1 km (USGS Western Coastal & Marine Geology, 2005).

3. Return channels produced by tsunami waves

We first analyze a series of return channels created by tsunami waves in the Aceh Barat district southeast of Banda Aceh, Indonesia (Fig. 2), in Khao Lak, Thailand (Fig. 3), and in Kalutara Beach, Sri Lanka (Fig. 4). The channels are fan-shaped and widen toward the coastline. By comparing the dimensions of the three characteristic return channels indicated in Figs. 2–4 we note that their shape is similar, with a width that decreases linearly inland from the coastline and a typical fan angle around 45° (Fig. 5). The return channel in Banda Aceh is larger, whereas the ones selected in Kalutara and Khao Lak are almost identical. However, in Kalutara beach we selected the largest return channel and, therefore, we expect the average channel dimensions to be smaller. The channels are shallow, with a

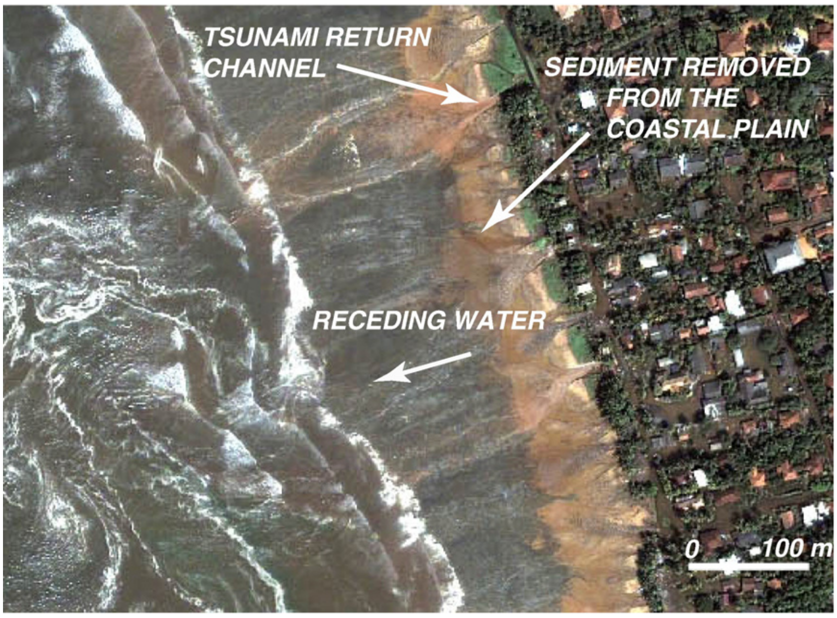

Fig. 4. Receding water and channel incision along Kalutara Beach, Sri Lanka. The water with high concentration of suspended sediments is returned to the ocean through fan-shaped incisions (courtesy of Digital Globe http://www.digitalglobe.com).

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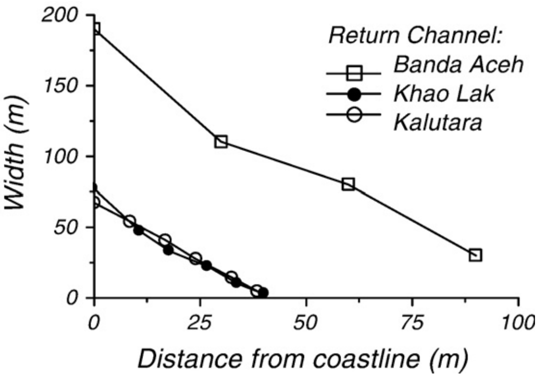

Fig. 5. Width of the tsunami return channels indicated in Figs. 2, 3 and 4 as a function of the co-ordinate along the incision axis.

depth of 1–2 m in the Khao Lak area (Fig. 3), and present a flat bottom.

Local topographic characteristics, human construction works, lithology, and vegetation can influence the location and geometry of these channels. For example, the return channel shown in Fig. 3B formed between two palm rows, where the substrate is less resistant because of absence of tree roots.

To study the characteristic spacing between return channels we plotted the distance between two consecutive channels as a function of distance along the coast (Fig. 6A,B,C). Channel distances show a high variability, with most of the points clustered around a characteristic length and few others having higher values. We interpret such variability as a by-product of local conditions. In fact it is reasonable to assume that channel formation can be prevented by vegetation, construction works, substrate characteristics, and coastal features like headlands and tidal channels. To determine the characteristic channel spacing we plotted in Fig. 6D and f all the data in Aceh Barat and Kalatura in a decreasing order. In both locations we note a sharp change in slope, with few large distances between channels clearly separated from the others. We interpret these locations as areas in which a channel was forced to form at a farther distance because of local conditions, and we therefore remove these outliers before calculating the average spacing and its standard deviation (Fig. 6A and C). In Khao Lak we were unable to compute an average value given the small number of data points and their variability, but we report the general trend of the data with the channel spacing that seems to increase from north to south.

The channels have an average spacing of 140 m in Aceh Barat, Indonesia (Fig. 6A), 100 m in Khao Lak, Thailand (Fig. 6B), and

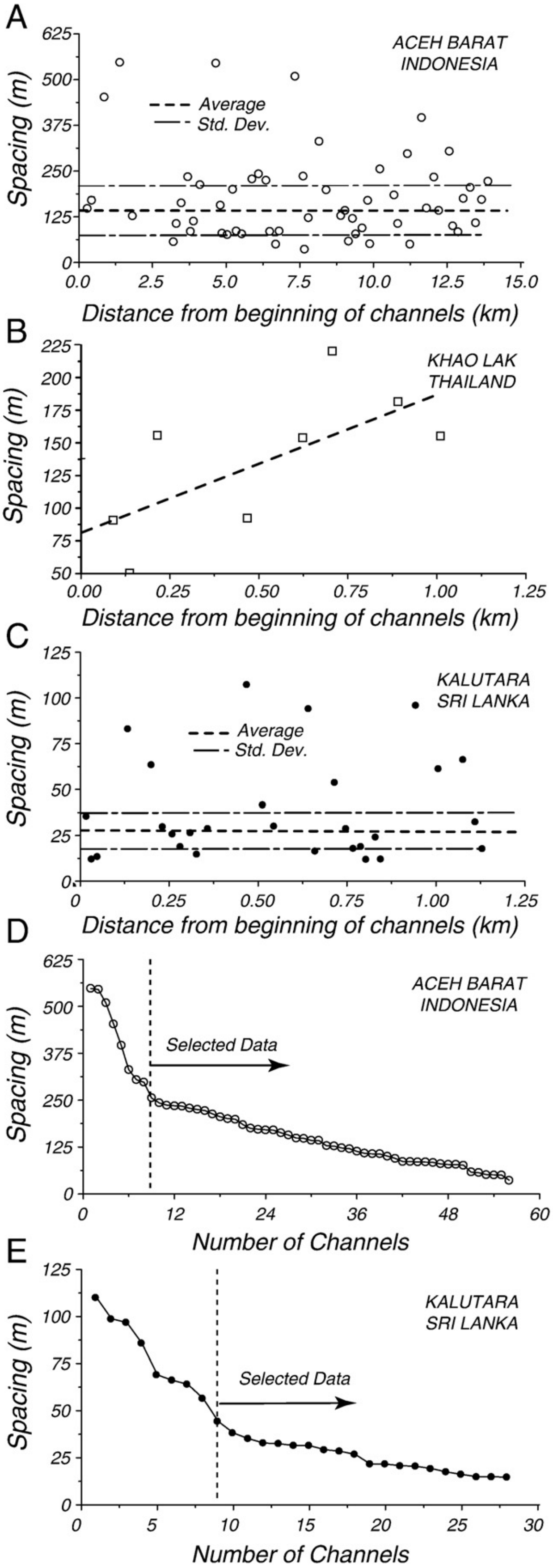

Fig. 6. Spacing between two consecutive tsunami return channels along the coasts of A) Aceh Barat, Indonesia, B) Khao Lak, Thailand C) Kalutara, Sri Lanka. The distance between channels is measured from north to south in Khao Lak and Kalutara, and from west to east in Aceh Barat. D) Spacing of the channels in Aceh Barat ordered in decreasing order of value, the data on the right of the vertical line were chosen to calculate the average and standard deviation in A). E) Spacing of the channels in Kalutara ordered in decreasing order of value, the data on the right of the vertical line were chosen to calculate the average and standard deviation in B).

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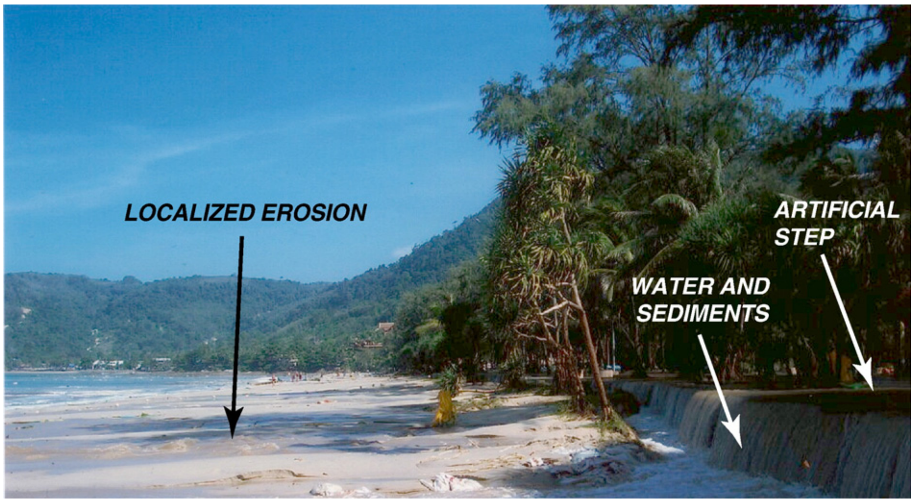

Fig. 7. Receding water with high sediment concentration in Patong Beach, Thailand. The flow produces localized erosion.

around 30 m in Kalatura, Sri Lanka. In Khao Lak we notice a trend from north to south, with the spacing increasing from 50 m to 200 m, whereas in Aceh Barat the average spacing slightly decreases from west to east and in Kalatura slightly increases from north to south.

The data suggest a possible influence of the tsunami wave height on the average spacing, with several small channels in areas where the tsunami height was around 5 m and few large return channels in areas where the tsunami height was around 30 m. In reality, since the scouring mechanism is ultimately linked to the water velocity and related shear stress, other factors are likely to determine the number and spacing of return channels, including the width and slope of the beach, the substrate characteristics, and the total volume of water returning to the ocean, which is a function of wave height and run-up.

The channels are most likely carved during the flood and then enlarged during the return flow, when the water flowing out of the mainland scours the substrate in a fan-like structure. This hypothesis is corroborated by satellite images taken during the tsunami in Kalutara (Fig. 4), showing the flow of water and sediments to the ocean in fan-shaped channels. Further evidence is reported in Fig. 7, depicting the final stages of the tsunami recession phase in Patong Beach, Thailand. The receding water contains sand and easily scours the bottom of the beach. In this location the tsunami wave was only 5 m high (Chaimanee and Tathong, 2005) and the hills just landward of the beach reduced the inundation area. On a flat coastline the volume of water returned to the ocean and the corresponding incision is several orders of magnitude larger.

The influence of bidirectional flow on channel incision is evident from the presence of both flood and return flow deposits in newly formed channels (Fig. 8). In this area near Banda Aceh the tsunami wave breached a road in several locations. A flood crevasse splay and a recession crevasse splay were deposited on each side of the road. The flood splay has a rugged surface, due to sediment remobilization during wave recession, whereas the recession splay is uniform and cone shaped, since it was formed when flow velocities were lower.

The mechanism of channel incision can be similar to the one proposed by Fagherazzi and Furbish (2001) in the context of tidal channel formation. Sheet flow moving at high speed over an erodible bottom removes sediment in selected locations where the substrate is relatively weak (i.e. loose sediments, absence of vegetation). The flow then concentrates in the initial incisions leading to widening and deepening. In fact, as indicated by Fagherazzi and Furbish (2001), in flows whose depth is controlled by external forcing like tides or tsunamis, bottom incisions along the flow direction produce a redistribution of momentum from shallow to deep areas, leading to an increase in velocity in the deeper location and channel formation. A strong feedback thus becomes established, with an enlarging channel that attracts more water and the flow concentration that enlarges the channel even further. In the developing phase, nearby incisions compete for the total amount of momentum available so that few become large enough to convoy most of the flow whereas the remaining cease to grow. As a result, a specific spacing between channels is

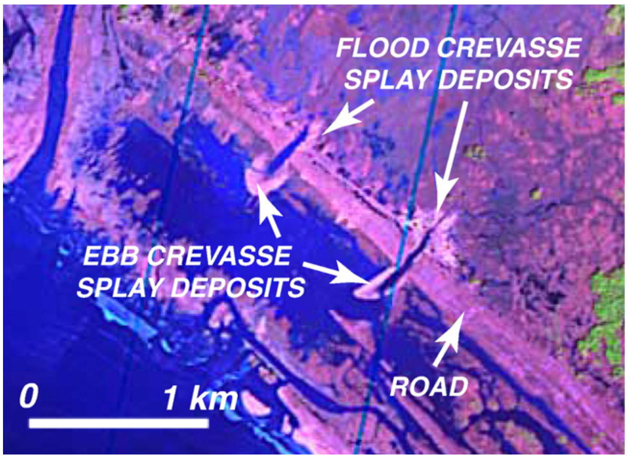

Fig. 8. Crevasse splay deposits in the Aceh Barat district, near Banda Aceh, Indonesia (29/12/2004 Images acquired and processed by CRISP, National University of Singapore IKONOS image, CRISP, 2004).

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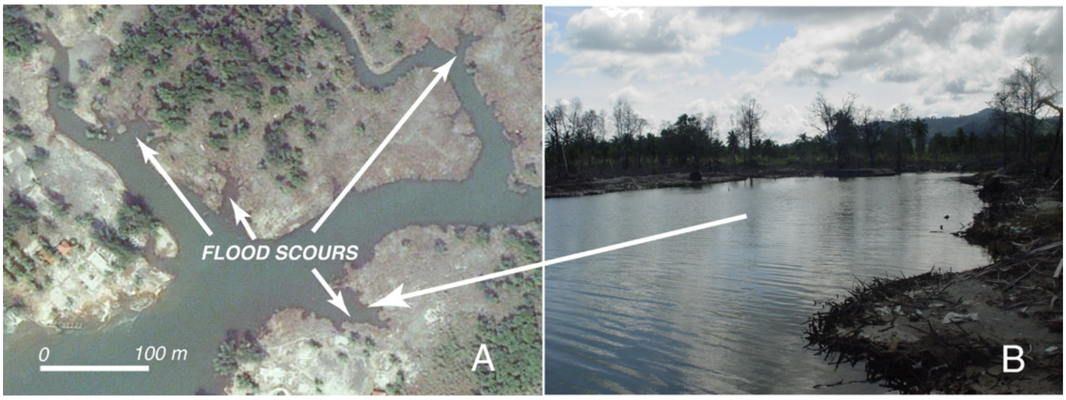

Fig. 9. Flood scours in a tidal channel near Khao Lak, Thailand. A) planimetric view, B) ground photograph.

selected, because for closer distances channel capture would automatically decrease their number.

4. Flood scours along existing tidal channels

Some of the incisions produced by tsunami waves in Khao Lak, Thailand, display a geometry that suggests their formation during the flooding phase of the wave (Fig. 9) and are therefore defined herein as flood scours. Flood scours are erosional features with sharp boundaries and irregular shape but without the elongated planimetric geometry typical of tidal channels. The length of flood scours (10–400 m) is generally higher than their width (10–100 m) but we do not detect a significant trend relating the two geometric dimensions (Fig. 10). In the location described in Fig. 9 the flood scours have a flat bottom with an average depth between 1 and 2 m.

Localized erosion is enhanced by debris (trees, branches, coral boulders, construction materials) transported by the wave; this material is then left at the flood scour boundaries when the wave loses energy and erosive power (Fig. 9B). We also noticed the formation of levees along the channel banks, where debris accumulates and favors local sediment deposition.

Flood scours are common in already existing tidal channels, and are produced by the spilling of the tsunami wave outside of the channel banks. Existing tidal channels concentrate the energy of the tsunami wave, with a larger volume of water entering the channel mouth with respect to nearby coastal locations given the greater water depths. The high speed of the water and the short duration of the wave prevent the flow from following the sinuous channel pattern, which was developed over the centuries by slow tidal fluxes and meander formation. On the contrary, the tsunami wave spills out of the channel banks, producing flood scours of limited length (Fig. 9).

The tendency of the tsunami wave to follow the pattern of the tidal channels can be determined by comparing the angle between the axis of the flood scour and the channel axis to the

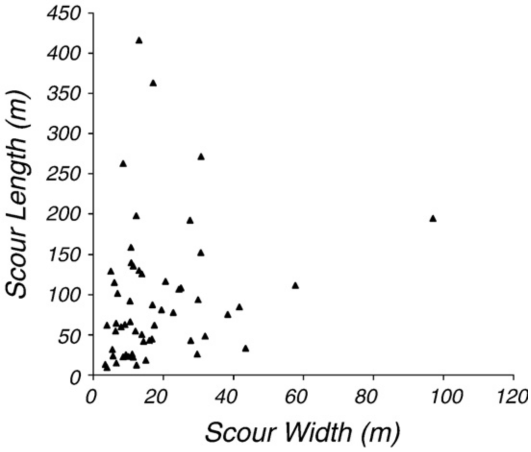

Fig. 10. Incision length as a function of width for the flood marks indicated in Fig. 8.

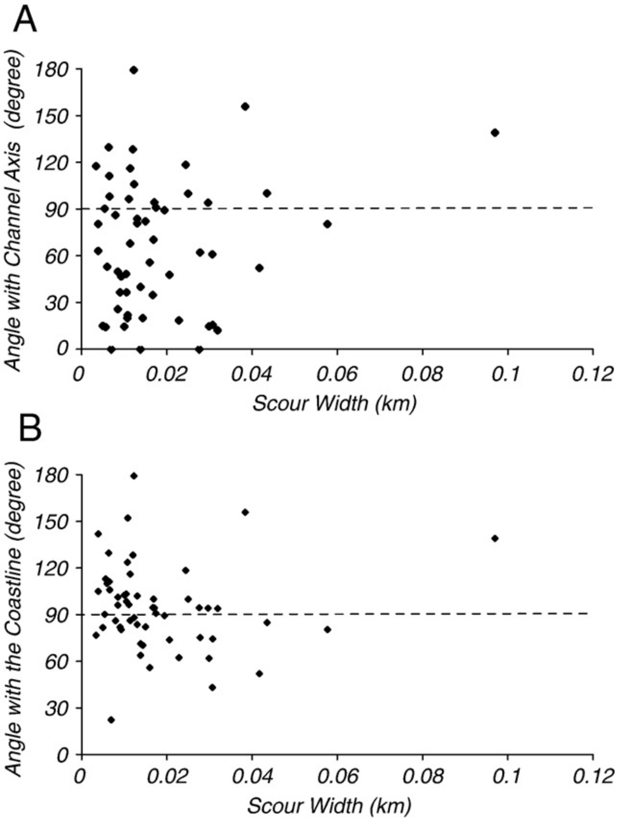

Fig. 11. Orientation of the flood marks in Khao Lak (see Fig. 8). A) Angle between the incision and the channel axis as a function of scour width; B) angle between the incision and the coastline as a function of scour width.

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angle between the flood scour axis and the coastline (Fig. 11). If the tsunami wave follows the tidal channel and then spills out of the channel producing a flood scour, then the orientation of the scour should be perpendicular to the channel axis. Available data show instead a wide distribution of angles between the scours and the channel axis, whereas the angles between the scours and the coastline are clustered around 90°. This clearly indicates that the influence of existing tidal channels on tsunami wave direction is mild, and that the wave travels mainly perpendicular to the coastline. On the other hand, the relatively deep water depths in the tidal channel reduce the energy dissipation so that erosion concentrates in the channels. Flood scours are then produced by a spatially uniform frontal wave impacting the banks of the channels at different angles.

We propose that flood scours are erosion marks produced by tsunami waves during flooding when the substrate is sloping against the direction of the water flow. Under these conditions gravity acts against the bottom shear stresses and the erosive potential of the wave rapidly decreases during propagation. When the bottom shear stress becomes lower than the critical value for erosion, the erosion suddenly shuts down producing a marked erosion scarp. Often return flow incisions are superimposed on flood scours, and are produced by the receding water (Fig. 9A). Return flow incisions are more elongated and form when the water is returning to the ocean. Since the recession lasts longer than the flood and gravity favors erosion, the time available to scour the substrate increases.

The fact that small elongated channels discharge in large scours (Fig. 9A) confirms our hypothesis that the two landforms were produced separately during flood and recession, otherwise the width would constantly decrease along the incision.

Flood scours formed in developed areas as well (Fig. 12), with shapes similar to the ones observed along tidal channels. Herein elongated branches are superimposed on a short scour. The branches are not sinuous like common tidal and coastal channels, since the flow does not have time to develop bends and meanders. We propose that the short scour was formed during flooding, whereas the elongated channels formed during the receding phase of the wave when the water concentrated in the already existing incision increasing velocity and erosion potential.

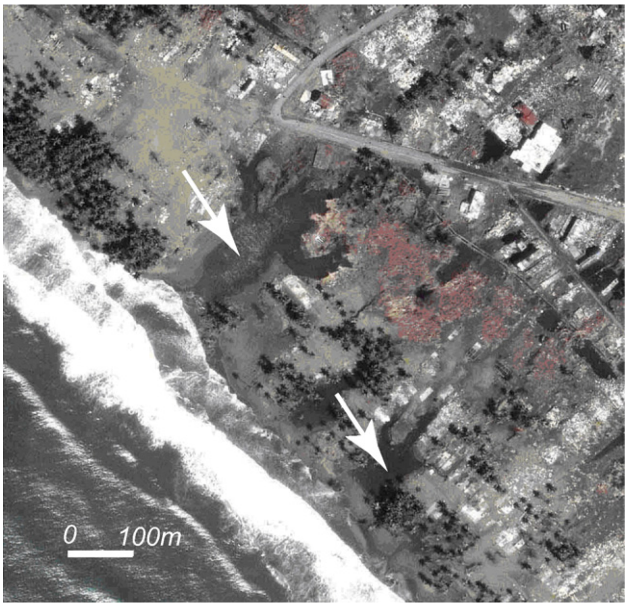

Fig. 12. Tsunami incision in Meluaboh, Indonesia, short incisions branch out in linear channels (29/12/2004 Images acquired and processed by CRISP, National University of Singapore IKONOS image, CRISP, 2004).

Fig. 13. Return flow incision and flood mark in a tidal channel near Khao Lak, Thailand. A) The return flow incision is formed on a substrate sloping in the same direction of wave propagation, whereas the flood mark is formed at the channel bank where the bank slope is against the wave direction (photograph taken on 17/08/2005).

The difference between return flow incisions and flood scours is shown in Fig. 13 (same location than Fig. 9). Here the tsunami wave crossed a tidal channel scouring the bottom before the channel in an elongated and dendritic incision and then impacted the opposite bank perpendicularly, scouring a semicircular mark with steep boundaries.

5. Tsunami waves and the sediment budget in tidal channels and inlets

Aerial photographs taken just after the tsunami show coastline erosion, removal of sediment within the channels, and a plume of sediment discharged from the channels in the ocean. This clearly indicates a surplus of sediments moved from the beach to the inner shelf after tsunami events (Fig. 14A). A ground survey after 6 months shows the presence of extensive deposits in front of existing channels (Fig. 14B). This sand was temporally stored in the inner shelf by the tsunami and it has then been transported back to the coastline by storms and wave action. Since the return of the sand occurred in few months, the system was unable to recover the initial condition and redistribute the material deep inside the tidal channels. Most of the sand was then dumped at the channel entrance choking the tidal inlet. In time the combined action of waves and tidal currents will redistribute this material inside the channel and along the coastline.

Based on these observations we can include the role of tidal channels and tsunami return channels in already existing conceptual models of sediment fluxes during and after tsunami waves (Gelfenbaum and Jaffe, 2003; Szczucinski et al., 2006).

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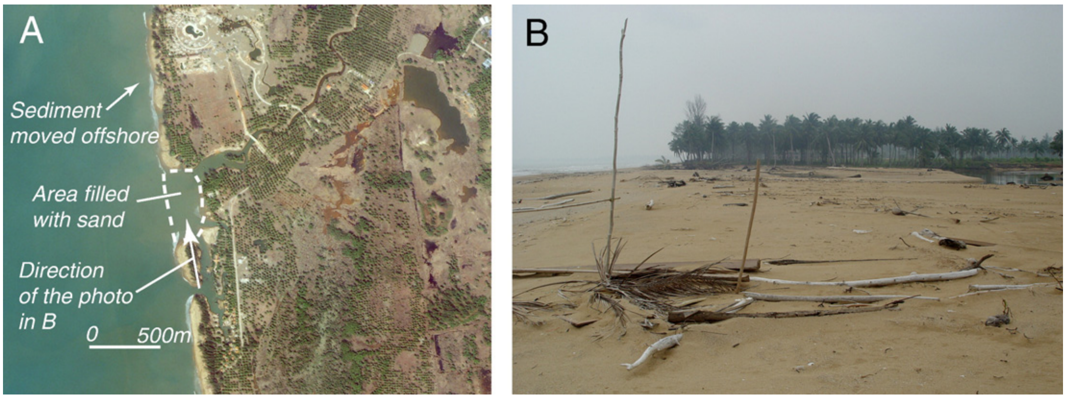

Fig. 14. Comparison between an aerial photograph taken on 29/12/2004 (Images acquired and processed by CRISP, National University of Singapore IKONOS image, CRISP, 2004), and a ground-based photograph taken on 16/08/2005. A) During the tsunami the beach was eroded with sediments transported offshore in plumes; B) in the following 8 months a series of storms deposited a thick layer of sand at the coastline engulfing the tidal inlet.

We identify eight distinct phases of scour and sediment redistribution during and after a tsunami wave:

a) The sediment is mobilized in large quantities in the nearshore area by the incoming tsunami wave;
b) The tsunami hits the coast, eroding the beach until the vegetation boundary is reached. The waves remove the substrate and the vegetation in selected areas producing flood scours;
c) More sediment is entrained during the flooding from the forest/land surface;
d) The flooding water decreases in speed and starts depositing debris and sediment. Sorting occurs and in some areas tsunami deposits are formed;
e) The water starts receding from the flooded area and sediment is picked up by the return flow currents. Some of the previous deposits are remobilized;
f) Most of the fine sediment (fine sand and silt) is flushed out to the ocean through tsunami return channels and already existing tidal channels. The channels are scoured, increasing in depth. Often the receding wave selects topographic lows or areas eroded during flood (flood scours) to concentrate the flow and the transport of sediment;
g) At the end of the tsunami, the beach is eroded and out of equilibrium with respect to the local wave climate. Several return channels are still present on the beach surface and the eroded sediment is stored in the inner shelf;
h) In the following months the sand is brought inshore by storms. A large volume of sediments is mobilized in a short time, so that it accumulates in the inlets forming a dune that gently slopes toward the channel interior. Most of the return channels on the beach are infilled by the returning sand. The enlargement of already existing tidal channels and flood scours far from the coastline are preserved since it will take several decades for tidal fluxes and storm surges to remobilize the sediment at the channel inlet and redistribute it deep into the coastal plain.

The final system configuration depends on the budget between erosion and deposition on the flooded surface (Fig. 15). It is suggested that if deposition on the flooded surface exceeds erosion, the system does not have enough sediment to recover the initial configuration. The sand is then accumulated at the beach following the equilibrium profile postulated by Dean (1991) but a gap is left between the newly emplaced sand and the vegetation boundary (see Fig. 3B). On the other hand, if

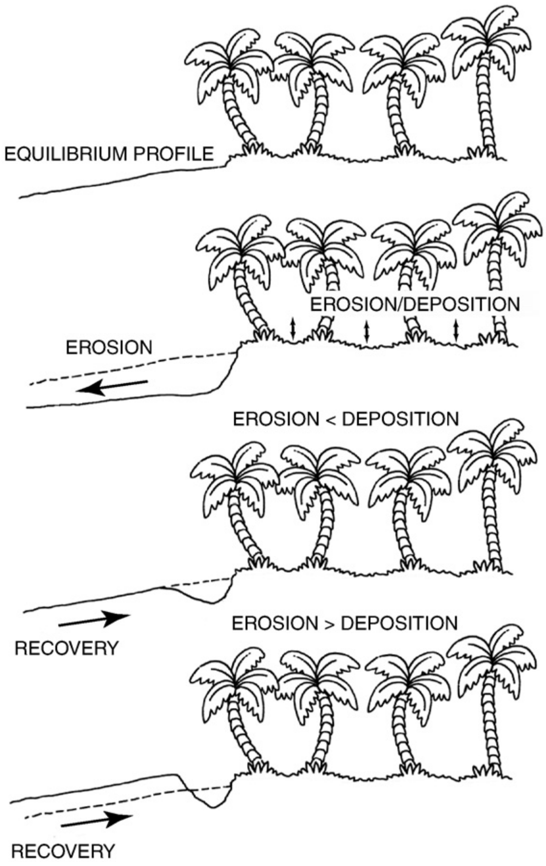

Fig. 15. Effects of tsunami waves on the longitudinal beach profile. A) Coastline in equilibrium before the tsunami; B) the tsunami wave produces erosion at the beach and deposition or erosion on the flooded surface. C) Final configuration for deposition on the flooded surface exceeding erosion. D) Final configuration for erosion on the flooded surface exceeding deposition.

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erosion on the flooded surface exceeds deposition, the excess sand is deposited at the beach, but a gap between the vegetation and the new deposits is still present, caused by the short duration of the recovery phase. In fact the equilibrium profile can reform only after a full distribution of storms occurring over a timescale of years. Only infrequent storms with high run-up can rework the beach sand up to the vegetation boundary, and produce a smooth beach profile. Since there is more sand available, the beach progrades conserving the initial profile.

6. Discussion

Our conceptual model is based on the results reported by Gelfenbaum and Jaffe (2003) for the Papua New Guinea tsunami of the 17th July 1998. At this location tsunami waves 7–10 m high hit a flat sandy coastline only 4–5 m above mean sea level, in conditions similar to the three locations of our study. Gelfenbaum and Jaffe (2003) examined four transects indicating erosion of 10–25 cm of sand from the beach and berm and the deposition of a continuous layer in the flooded area with average thickness of 8 cm. The upward fining of the sediments suggested that the deposition occurred before the water retreat, as indicated in our conceptual model. Gelfenbaum and Jaffe (2003) also determined a flow direction almost perpendicular to the coastline during inundation and a return flow directed obliquely to the shore toward local lows in topography, thus confirming our hypothesis of a concentration of flow in selected areas during the recession phase.

Several studies conducted after the December 2004 tsunami report results that are in accordance with our model. Szczucinski et al. (2006) indicate that tsunami waves caused intensive erosion and subsequent deposition of sediment along the Adaman Sea coast of Thailand. Hori et al. (2007) and Szczucinski et al. (2006) measured a deposition layer with up to 0.5 m of sediments covering the entire inundation area. In the Banda Aceh area. Moore et al. (2006) identify the presence of sediment scour in the first 50 m from the shore and tsunami deposits between 10 and 20 cm in the coastal plain up to 400 m inland. They also indicate three possible sand sources for the tsunami deposits: subtidal, shoreface and inland, thus suggesting a possible erosion of the coastal plain surface during the flooding phase.

Both surveys suggest a total deposition in the flooded area greater than erosion, so that the sediment deficit in the inner shelf should prevent the full recovery of the shoreline profile after the event. However, both studies did not account for the scouring of existing tidal channels or the formation of new incisions, which can return significant sediment volumes to the ocean.

Meilianda et al. (2007) are the first to present a quantitative budget of shoreline sediment fluxes before and after the tsunami in Banda Aceh, Indonesia. Through the study of remote sensing images they determined a chaotic shoreline retreat just after the tsunami. In the following 6 months 60% of the sediment loss had been compensated by shoreline accretion on the west coast of Banda Aceh City whereas further erosion (15% of the sediment loss during the tsunami) occurred on the northwest coast. The fact that not all locations show a beach recovery after the tsunami stresses the importance of inner shelf processes and longshore currents in redistributing the sediment eroded at the coastline.

The observations reported herein bear important consequences for interpreting the stratigraphic record of tsunami waves. Common stratigraphic studies have focused on the formation and preservation of tsunami deposits in the geological record (Gelfenbaum and Jaffe, 2003; Hori et al., 2007; Szczucinski et al., 2006). Herein we show that most of the morphological change occurs in the shore-normal direction, with large volumes of sand removed by the tsunami at the coastline and then returned to the beach in a short time interval. Given the short duration of the deposition phase, these sediments are well mixed and are characterized by the presence of debris of different size. These shoreline deposits are probably the most distinctive features of tsunami events. We also show that incisions are also typical of tsunami events. A series of parallel, tapered incisions widening toward the coastline are characteristics of large flooding events. If filled with sediment of different composition, these incisions can be preserved in the geological record. Similarly, flood scours are a suitable indication of tsunami events, given their unique morphology with width and depth of the same order of magnitude and their sharp boundaries. The inventory of incision geometries reported in Figs. 4 and 10 can be then used to identify similar features in the geological record.

7. Conclusions

Field observations and satellite images indicate that tsunami waves exhibit specific patterns during flooding and recession. During flooding the high flow velocities indent the banks of existing tidal channels and bays, producing short flood scours.

Flood scours are erosional features with sharp boundaries and irregular shapes that are oriented perpendicularly to the coastline. Flood scours are common in already existing tidal channels, and are produced by the spilling of the tsunami wave outside of the channel banks.

During the return flow the receding water dissects the coastline with return channels that widen toward the ocean with a typical fan angle of 45°. The dimension and the spacing of return channels seem controlled by the wave height at that specific location.

The high speed currents produced by the tsunami waves scour already existing tidal channels and inlets, relocating large volumes of sediments from the beach to the inner shelf. In the subsequent months, depending on local wave climate and longshore sediment transport, part of this sand is redeposited back on the shoreline, choking tidal channels and inlets and erasing the tsunami return channels.

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