# Coastal Recovery following the destructive tsunami of 2004: Aceh, Sumatra, Indonesia

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## ABSTRACT

We describe the recovery of coastal landforms in Aceh, Sumatra after the hugely destructive Indian Ocean tsunami of December 26, 2004, using three sets of IKONOS images at a resolution of 1 m. The image sets were taken about two years before the tsunami, immediately following the tsunami, and about one year after the tsunami. We found a remarkably efficient recovery in progress, building new depositional forms seaward of the eroded coastline that effectively obliterate the morphological signals of the tsunami. Such detailed observations covering a long stretch of coast are now possible due to the availability of high-resolution satellite images. To the best of our knowledge this is the first time-based study of the recovery of a long stretch of coast (175 km) after catastrophic destruction by a tsunami. We suggest that tectonic coasts, like the one discussed here, may undergo similar changes periodically on a geological time-scale. Thus, it is possible that morphological evidences of catastrophic tsunamis are not necessarily preserved in the geological record.

## INTRODUCTION

The role of tsunamis in large-scale coastal evolution has been previously investigated (Scheffers and Kelletat, 2003; Gehrels and Long, 2007), and unusual erosional and depositional landforms have been explained by invoking past tsunami events (Bryant and Nott, 2001; Nott, 2004; Scheffers, 2004). Often, however, sedimentary deposits are better indicators of past tsunamis and has thus received more attention. For example, the earthquake-generated submarine slump that gave rise to the Lituya Bay (Newfoundland) tsunami of 1929 left five cm of sand on top of coastal peats (Bornhard et al., 2003). Bigger tsunamis related to asteroid impacts (e.g., Eltanin, Chixulub) or submarine slumps (e.g., Storegga, Canary Islands) are expected to leave characteristic deposits over a very large area, examples of which have been identified in the field (Brookfield, M., http://atlas-conferences.com/cgi-bin/abstract/camau-08). Many of these studies of past tsunamis focus on sedimentary deposits, but here we focus on morphological changes documented by remote sensing images (Fig. 1).

The huge Indian Ocean tsunami of December 26, 2004 devastated the coast of the Aceh region in northwestern Sumatra, affecting >175 km of coast from Banda Aceh to Meulaboh (Fig. 2). The tsunami almost completely removed the suite of coastal depositional landforms that included various types of beaches, low sand dunes and swamps. However, a new coast that closely resembled the pre-tsunami version started to appear within weeks. In little more than a year the erosional effect of the tsunami was successfully masked by a new suite of depositional forms, except where the natural landscape had earlier been altered anthropogenically by sinking large-scale fish tanks (locally called *tambaks*) into the wetlands. We traced this remarkable rebuilding process using three sets of high-resolution satellite images (IKONOS) and field visits. Although the destructive effect of this tsunami on the coast and its sedimentary deposits have been described several times (Borrero, 2005; Moore et al, 2006; Paris et al., 2007), to our knowledge this is the first detailed account of post-tsunami changes towards a coastal recovery.

## METHODOLOGY

This longitudinal study is based primarily on three sets of IKONOS images, each of which covers the 175 km of Aceh coast at 1 m resolution. The images are dated (a) January 10 and 13, 2003 (prior to the tsunami), (b) December 29, 2004 and January 15, 2005 (3 and 20 days after the tsunami), (c) February 1, 2006 (13 months after the tsunami). After the tsunami, we searched through the archives of the Centre for Remote Imaging, Sensing and Processing (CRISP) and found that we could compile sets of pre-tsunami and tsunami satellite scenes for the entire length of the study coast by combining images taken on two different but very close dates. It was unlikely that the coast had changed morphologically between these dates. The third set was imaged under request and so completed on the same day. Registration of the images allowed every point on a pre-tsunami image to be automatically and correctly located on the corresponding image of the other two sets. We could determine how much erosion had occurred on the coast (e.g., the corresponding point on the post-tsunami images would be in the water), and also how far the building of a new coast has advanced (Fig. 1). One of the authors of this paper (PPW) carried out extensive fieldwork on the

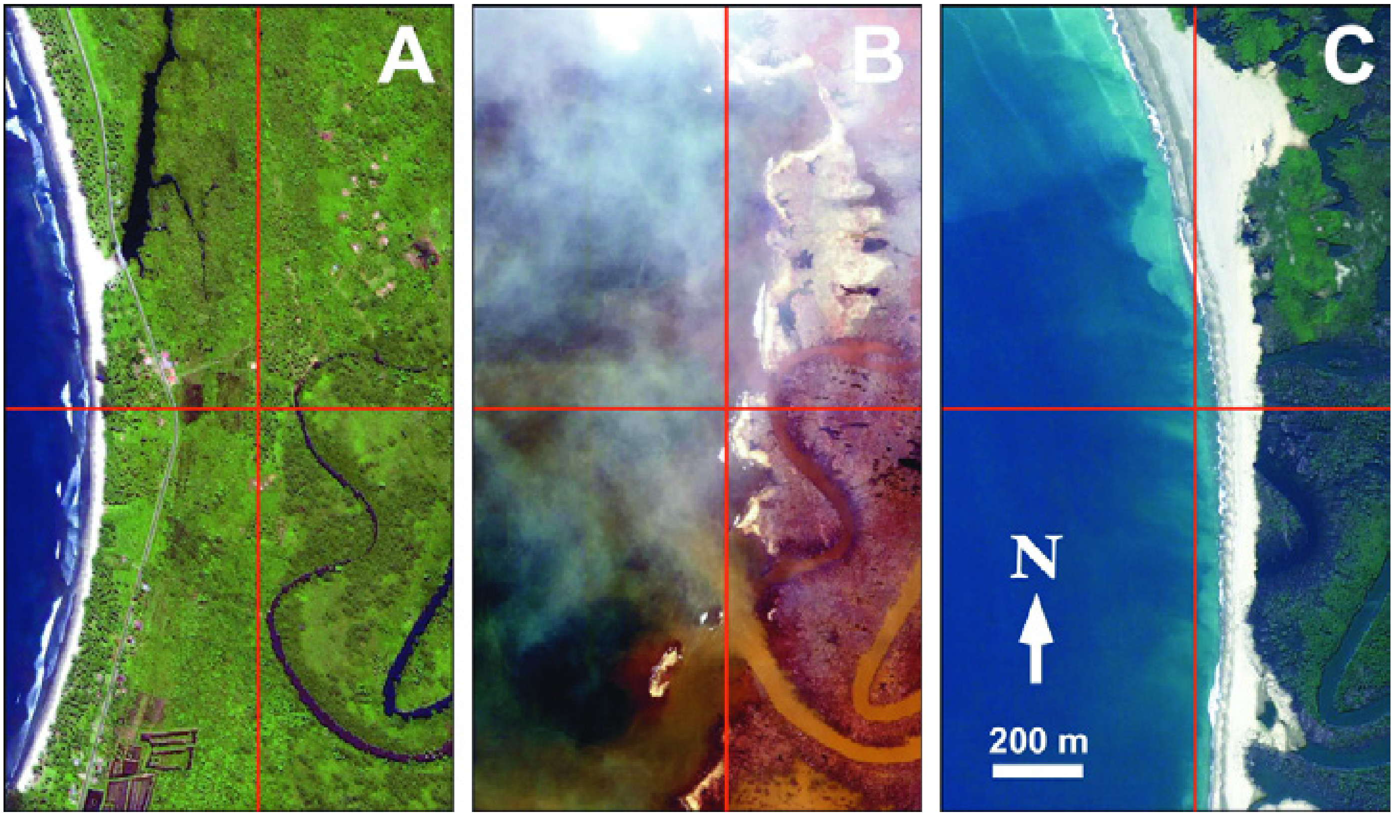


*Figure 1. Erosion and rebuilding of a west-facing beach in a bay, Aceh, Sumatra. Image width is 1 km. Cross-hairs indicate the same location on all three images. A: image of the pre-tsunami coast, date January 10, 2003; B: erosion caused by the December 26, 2004 tsunami, date December 29, 2004; C: the new beach rebuilt in 13 months, date February 1, 2006. Note (a) although the rebuilt beach has not yet reached its previous location, it is already bigger in size; and (b) removal of morphological evidence of the tsunami within a time-span of about a year.*

northern half of the coast repeatedly to serve as ground-truthing for the satellite images. He first conducted fieldwork in May 2005, five months after the tsunami, and subsequently in August 2006 and March 2007. His observations on ground verified the image-based conclusions reached in this study.

## THE ACEH COAST

Rocky headlands partition the Aceh coast into several km long units of sandy beaches, spits and barriers that receive material from rivers, longshore drift, and offshore sources. The 175 km coastal stretch studied displays six morphologic units: headlands, bay beaches, barrier beaches backed by lagoons and swamps, swamps with *tambaks*, J-shaped (zetaform) beaches (Schwartz, 2005), and straight beaches. Fringing corals occur in the northern part of the coast where they reduce the power of wind waves striking the shoreface. Beaches here are cusped, and commonly backed by low, vegetated sand dunes. Isolated rocky outcrops and small hills emerge from below beach sand in places. Small rivers often flow sub-parallel to the coast before reaching an outlet to the sea. Prior to the tsunami the majority of small rivers were blocked by river-mouth bars, creating vegetated back-barrier swamps. In brief, bay beaches occur in the north, whereas straight beaches dominate the southern section. The only significant anthropogenic alterations of the coast include small harbors with single piers and *tambaks* (fish farms). *Tambaks* are rectangular tanks with vertical sides, constructed in the wetlands immediately back of the beach. They tend to be between 0.5 and 1 ha in area and deep enough for growth and storage of live fish on a commercial basis. These *tambaks* are large enough to interfere with the ambient flow of water and sediment. Overall the effects of the tsunami varied among the six coastal morphologic units, as did the post-tsunami building of the new coast, which are described below.

## THE EARTHQUAKE AND TSUNAMI

The tsunami was generated by one of the largest earthquakes ever recorded, with a moment magnitude of 9.3 on the Richter scale. The earthquake occurred at the convergence boundary between the subducting Indo-Australian Plate and the southeastern part of the Eurasian Plate, here divided into the Burma Plate and the Sunda Plate. The highly oblique motion between the Indo-Australian Plate and the Burma and Sunda Plates had resulted in shearing off a plate sliver parallel to the subduction zone from Sumatra to Burma. This plate sliver, the Burma Microplate, had been stressed via subduction. Its rebound from this frictional resistance on December 26, 2004 started the earthquake.

The main-shock rupture began at 00:58:53 UTC or 7:58:53 local time at a depth of about 30 km at 3.3°N, 96.0°E, 50 km off the west coast of Sumatra. Northwards from the epicenter, more than 1200 km of a curved boundary was ruptured between the plates, the largest known earthquake rupture (Lay et al., 2005). Total energy released by the earthquake was 4.3 x $10^{18}$ J. The rupture lasted for about 10 minutes and more than 30 km$^3$ of sea water was displaced due to shifts of sea floor, generating the tsunami (Bilham, 2005).

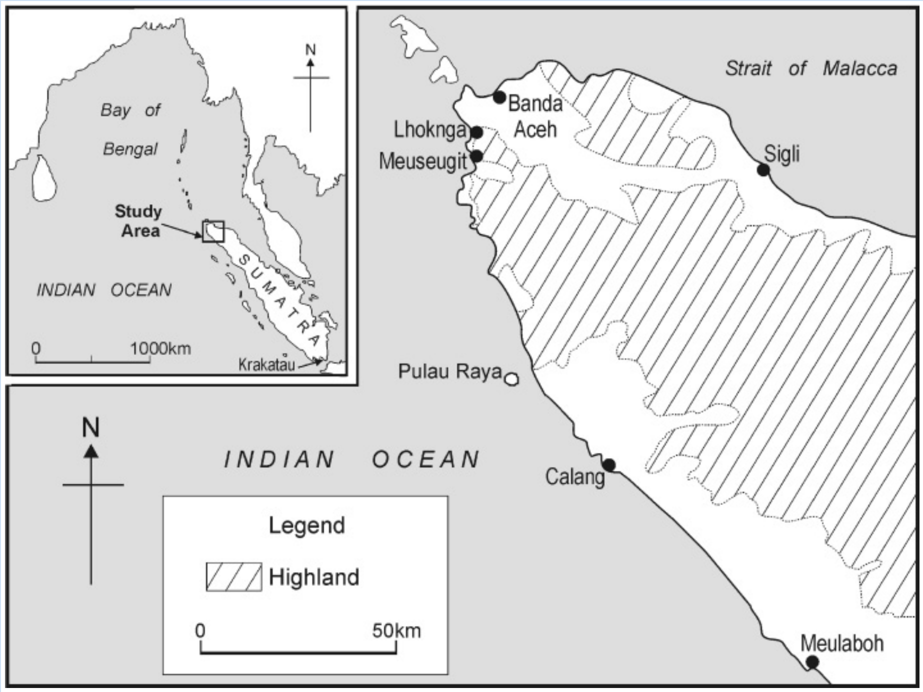


*Figure 2. Location map of the part of the Aceh coast affected by the tsunami.*

This was one of the largest tsunamis on record. Destructive waves reached the coast of Sumatra and southwestern Thailand between two and four hours after the earthquake, and later in other areas along the coasts of the Bay of Bengal and Indian Ocean. Waves 15-34 m high came onshore along the northernmost 100 km of the Aceh coast of Sumatra (http://walrus.wr.usgs.gov/tsunami/sumatra05/ ). On the north-facing coast of Aceh, beyond the promontory, such waves were lower, 10-12 m in height, but the extent of inland penetration and the scale of damage were devastatingly increased by the low elevation of the coast and post-earthquake regional subsidence that complemented the recovery of the western edge of the Burma Microplate. Three consecutive run-ups and a final backwash have been recognized from the sand deposits, with the maximum run-up identified as 60 m a.s.l. and 6 km inland. The recurrence interval of a tsunami of this magnitude has been computed as between 500-1000 years (Thio et al., 2005). It should be noted that tsunamis in the Indian Ocean are not as common as in the Pacific. Even so, destructive tsunamis affected Sumatra in 1797, 1833, 1843, 1861 and the one from Krakatau in 1883 (Waltham, 2005). Smaller unremembered tsunamis may of course have happened in the past.

Impacts of the tsunami differed among the six coastal geomorphic units mentioned above. Images and field observations revealed that the tsunami almost completely stripped the vegetation and unconsolidated sediment from the rocky subsurface, leaving only a thin deposit of brown mud and sand and eroding a number of scourpools. The deposited sand formed a discontinuous sheet up to 80 cm thick and tsunami muds were found up to 5-6 km inland. Along the coast where fringing coral reefs occur, the tsunami eroded the beach to expose beachrock and the underlying coral platform. The tsunami was ineffective in eroding hard rock but it destroyed all beaches and scoured the swamps (Fig. 3). A few tall trees survived the event. The bays were eroded back a significant distance, in places to about 500 m, but the headlands were not eroded. The geometry of the coast did not change although the distance between the headlands and bayheads thus increased after the tsunami (Fig. 4). Some sand was deposited on the coast but most of the eroded material was transported out and deposited offshore (Paris et al., 2007; http://walrus.wr.usgs.gov/tsunami/sumatra05/).

## POST-TSUNAMI REBUILDING

New depositional forms started to build on this coast only a few weeks after the tsunami. As the third set of images show, such beaches reached a substantial dimension (Figs. 1 and 5) and the wetlands were partially filled with sediment and revegetated (e.g., by ipomoea) within thirteen months after the tsunami. An annual cycle of seasonal erosion and deposition was also completed on this coast during this time. Almost all of the new beaches are bigger than they were before the tsunami, especially the bay beaches and the barrier beaches in the northern part of the coast from Banda Aceh to Pulau Raya. Strikingly, the bigger rebuilt beaches still have not prograded to the same seaward position as the pre-tsunami beaches (Figs. 1 and 5). The new beaches started with a handicap, tens of meters inland of the landward limit of the old ones, as the low dunes or cliffs at the back of the old beaches had been eroded by the tsunami. The morphology of the new beach, however, reflects that of the old one in terms of geometry and presence of berms, vegetated dunes and cusps. The six geomorphic settings of the Aceh coast listed above reformed in the same locations even where the tsunami had completely destroyed them. The new curved beaches, J-shaped-bay beaches, and straight beaches reappeared in their old locations, reflecting the morphology of the pre-tsunami beaches (Fig. 4). Straight beaches, found south of Pulau Raya, do not exceed the old ones in size, unlike the bay beaches of the north. The headlands did not show much damage after the tsunami, only the weathered material and low-level vegetation at their bases were removed. Vegetation in such locations has started to return.

Sand for the development of new beaches appears to have come from the sea rather than inland. There is no evidence of any significant amount of material being transferred to the coast by rivers, and all depositional features are strongly developed near the sea while wetlands behind the beaches remain partially unfilled. Field visits also indicate that the post-tsunami movement of sand was onshore from the sea to the coast (Fig. 6). Beaches that started to rebuild only a few weeks after the tsunami have been observed to migrate landward through overwash (http://walrus.wr.usgs.gov/tsunami/sumatra05/).

## THE FUTURE

Given a few more years, the barrier beaches are expected to build up sufficiently to recreate lagoons and divert water courses, vegetation to return more extensively, and the morphological signs of the tsunami to be even more effectively erased. The only evidence that is likely to remain would be the part of the coast with corals, where coarse material has piled up backshore and several boulders have been transported and left stranded on the reef flat. In the future, however, it may be difficult to attribute these definitively to a tsunami and not to large storms. The impermanence of the effect of the 1883 Krakatau tsunami on the nearby coasts of south Sumatra and west Java supports such a conclusion.

## CONCLUSION

The Aceh coast was temporarily destroyed by the tsunami of 26 December 2004. The coast retreated by approximately 500 m in places, eroding almost the entire suite of depositional landforms overlying the consolidated bedrock underneath. The building of a new coast has been remarkably swift, and mimicks the older suite of depositional forms, but the coast has yet to build back to its former location. On the Aceh coast, tsunamis appear to be episodic destructive events that are followed by coastal transport processes that tend to remove or mask the evidence of such destruction. The post-tsunami coast that develops is sufficiently similar to the old coast in form that, it may not be possible after several years, to identify the occurrence of even a huge tsunami like the one discussed, without examining the subsurface.

Given the lack of a long recorded time-series, the recurrence interval of tsunamis in this area are difficult to compute. Thio et al. (2005), however, have estimated the return period of Indian Ocean tsunamis similar to the December 26, 2004 event to be 500-1000 years. We conclude that the Aceh coast may be altered drastically by large tsunamis at intervals that are relatively brief on a geological time-scale. However, a new coast may evolve swiftly afterwards and is likely to resemble the pre-tsunami coast. We cannot at present extend this conclusion to other coasts beyond Aceh but our reconnaissance studies on the Khao Lak area of the Andaman Coast of Thailand, another tsunami-eroded area that remains in a natural state, indicate that a new coast was also rebuilt there subsequent to the tsunami, masking the devastating morphological changes. We intend to pursue this topic.

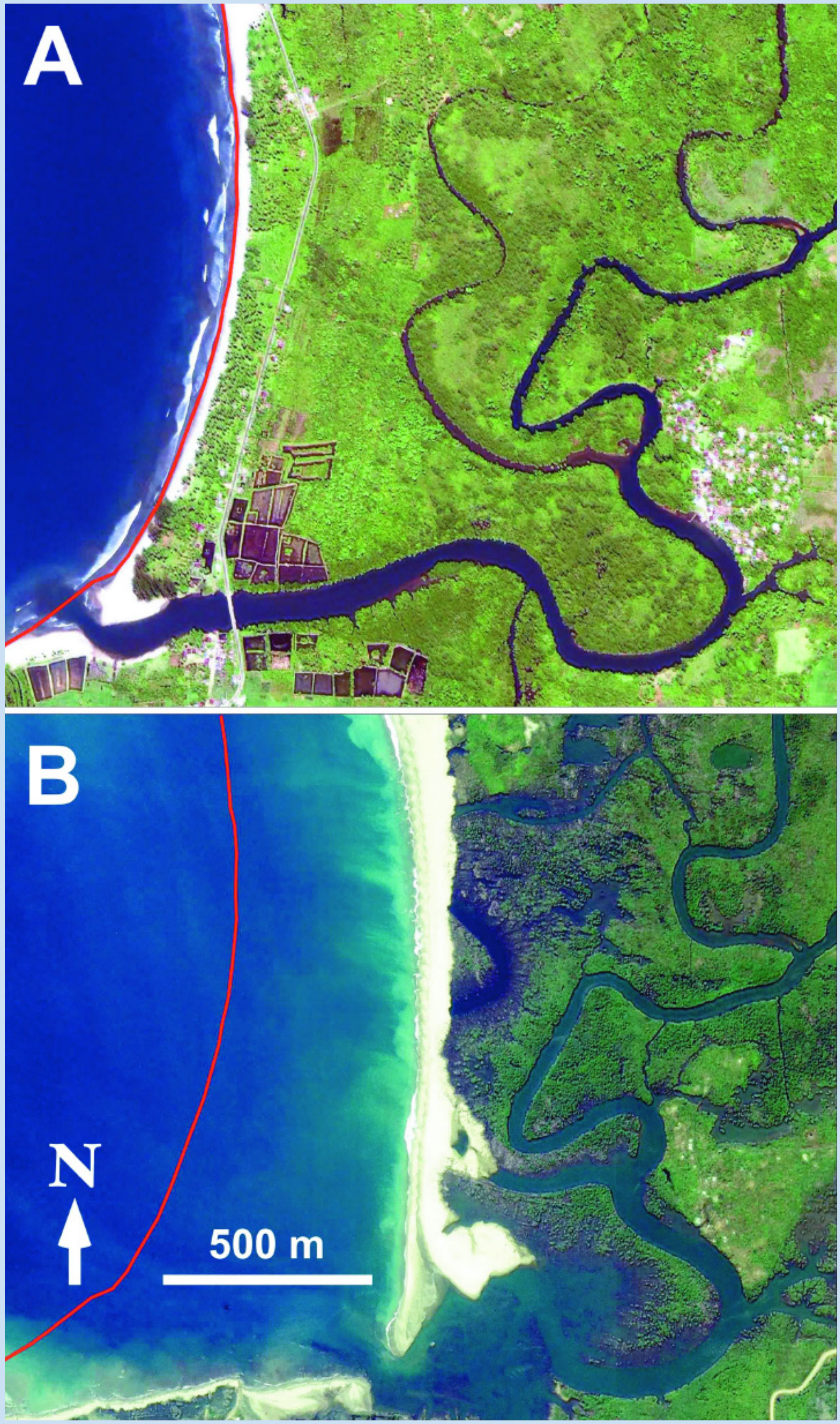


***Figure 3. High-resolution comparison of a west-facing beach. A: pre-tsunami beach; B: the new west-facing beach in the same location 13 months after the tsunami. Line in red indicates location of the pre-tsunami coastline. River systems behind the old barrier beach have been disrupted by the tsunami and have still not fully adjusted to new conditions.***

## ACKNOWLEDGEMENTS

Albert Ang (CRISP) assisted in processing the IKONOS images. S.C. Liew and L.K. Kwoh acknowledge the support received from the Agency for Science, Technology and Research (A*STAR), Singapore. Avijit Gupta would like to thank CRISP for making it possible for him to visit the Centre and work with the satellite images. Poh Poh Wong's fieldwork was carried out with support from the Faculty Staff Support Scheme, National University of Singapore. Figures 2 and 5 were prepared by Lee Li Kheng. The IKONOS images used for this paper were received and processed at CRISP, National University of Singapore. The

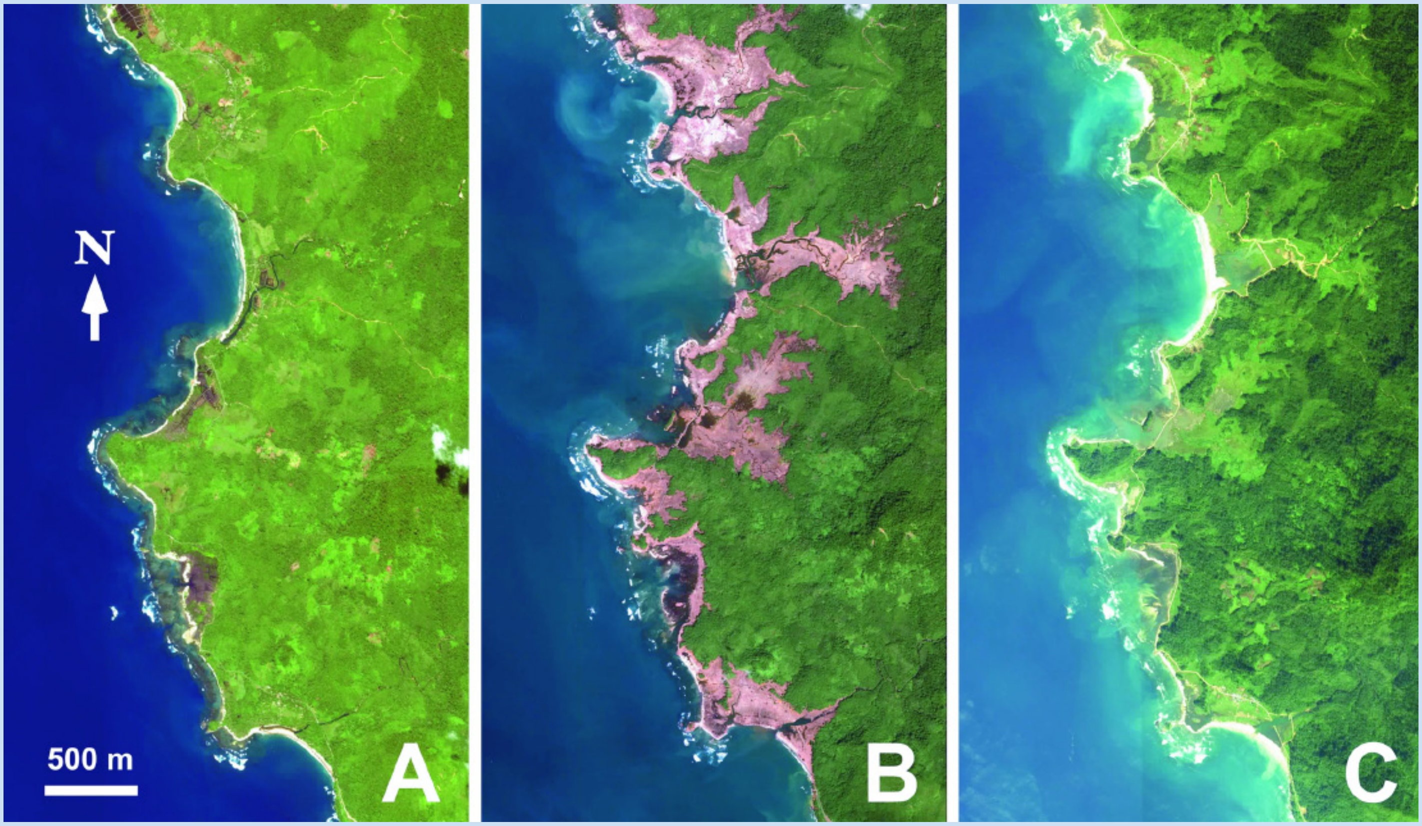


*Figure 4. A: Pre-tsunami headland and bay coast, B: the same coast after destruction by the tsunami; C: new coast rebuilt after 13 months. Although local changes in morphology have occurred, it is nearly impossible to recognize the occurrence of the tsunami from the new coast's morphology alone.*

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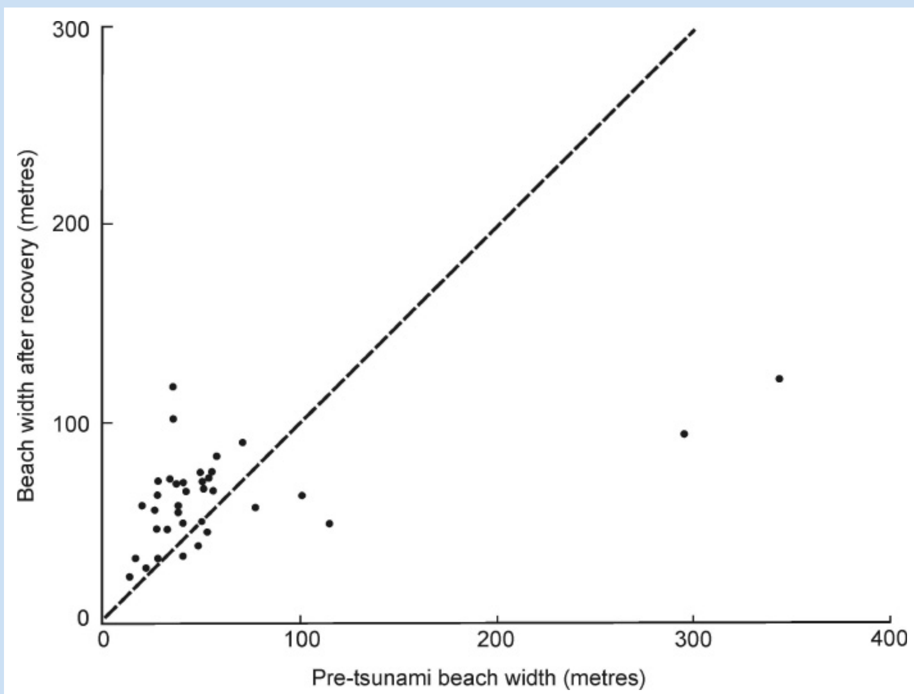


*Figure 5. February 2006 width of the beaches in the northern part of the study coast plotted against width of the pre-tsunami ones. New beaches are wider than the old ones in the same locations, except where the pre-tsunami beaches were very wide. This discrepancy may disappear over time.*

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**Accepted August 2008**

*Figure 6. New post-tsunami beach south of Kr. Ritieng, in May 2005, five months after the tsunami. Photograph: P.P. Wong*

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