Extreme runup from the 17 July 2006 Java tsunami

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[1] The 17 July 2006 magnitude M_w 7.8 earthquake off the south coast of western Java, Indonesia, generated a tsunami that effected over 300 km of coastline and killed more than 600 people, with locally focused runup heights exceeding 20 m. This slow earthquake was hardly felt on Java, and wind waves breaking masked any preceding withdrawal of the water from the shoreline, making this tsunami difficult to detect before impact. An International Tsunami Survey Team was deployed within one week and the investigation covered more than 600 km of coastline. Measured tsunami heights and run-up distributions were uniform at 5 to 7 m along 200 km of coast; however there was a pronounced peak on the south coast of Nusa Kambangan, where the tsunami impact carved a sharp trimline in a forest at elevations up to 21 m and 1 km inland. Local flow depth exceeded 8 m along the elevated coastal plain between the beach and the hill slope. We infer that the focused tsunami and runup heights on the island suggest a possible local submarine slump or mass movement. **Citation:** Fritz, H. M., et al. (2007), Extreme runup from the 17 July 2006 Java tsunami, *Geophys. Res. Lett.*, *34*, L12602, doi:10.1029/2007GL029404.

1. Introduction

[2] On Monday July 17, 2006 at 08:19:28 UTC (15:19:28 local time), a magnitude M_w 7.8 earthquake occurred 200 km off the south coast of western Java in Indonesia and ruptured $\sim$200 km along the trench [*Ammon et al.*, 2006]. According to *Reymond and Okal* [2006], this earthquake involved very slow rupture through the energy to moment ratio $\Theta = \log_{10} (E^E/M_0) = -6.1$ compared to the usual $\Theta = -4.9$ [*Newman and Okal*, 1998]. Similarly, its T waves recorded at Diego-Garcia feature a parameter γ [*Okal et al.*, 2003] deficient by two orders of magnitude compared to those of typical events from the Sumatra series [*Reymond and Okal*, 2006]. This slow earthquake generated a tsunami that severely damaged coastal communities along the south-west and south-central Java provinces. The estimated tsunami death toll exceeds 600 along a 200 km stretch of coastline, with 413 fatalities in and around the tourist resort of Pangandaran. Flow depths of up to 5 m caused the destruction of 3000 houses in Pangandaran. A lifeguard reported that, mercifully, the tsunami hit on Monday afternoon, when there were few tourists on the beaches compared to the preceding Sunday. In Pangandaran, the majority of the dead were women (205) and children (78). This tsunami was difficult to escape because the affected area was too close to the epicenter for an early warning system to have been effective, and there was little or no felt ground shaking. Lifeguards sitting on elevated concrete towers had difficulties in recognizing the initial ocean withdrawal, because large wind waves breaking at the coast masked most of the recession of the water at the shoreline that preceded the tsunami.

[3] Transoceanic propagation of the tsunami was computed with the MOST-model [*Titov et al.*, 2005] and resultant maximum tsunami wave heights are shown in Figure 1.

[4] In the far field, 2000 km SSE of the earthquake epicenter, the tsunami struck the Steep Point region of Western Australia close to high tide. At Steep Point, the tsunami runup was on the order of 2 m with inundation distances exceeding 100 m after adjusting for the tide level upon arrival of the 3 tsunami waves between 11:30 and 12:00 UTC. At a sand spit within Shelter Bay a runup of 7 m was reported on a steep limestone cliff within 10 m of the shoreline [*Prendergast and Brown*, 2006]. The runup at Steep Point in Australia is comparable to the 2004 Indian Ocean tsunami runup in northern Oman at 5000 km from the epicenter of the Sumatra-Andaman earthquake [*Okal et al.*, 2006]. The 7 m runup at a cliff is not comparable to similar runup heights several hundred meters from the shoreline in Somalia [*Fritz and Borrero*, 2006].

2. Post-Tsunami Field Survey

[5] An International Tsunami Survey Team of scientists from Indonesia, the US, New Zealand, Norway and Greece

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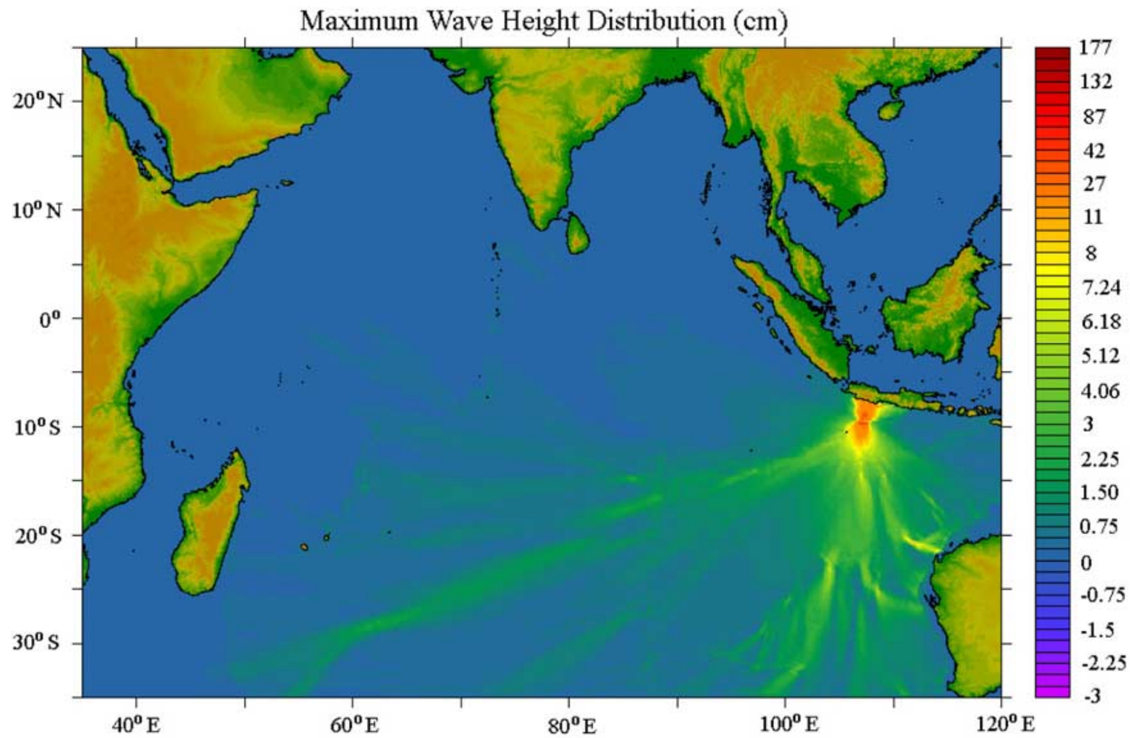

Figure 1. Maximum estimated tsunami heights across the entire Indian Ocean computed using the MOST-model.

surveyed more than 600 km of coastline within 3 weeks of the event. The survey team was granted access to the high security prison island of Nusa Kambangan. The team measured local flow depths, tsunami heights, maximum runup, inundation distances, collected sediment samples and interviewed eyewitnesses in accordance with established methods [*Synolakis and Okal*, 2005]. The survey team measured 168 tsunami flow depths and runup heights.[1] Figure 2 shows the measured maximum tsunami and runup heights. Tsunami heights and runup distributions show a pronounced peak on the south coast of Nusa Kambangan near the prison town Permisan. Measured data were corrected for tide level at the time of tsunami arrival on the basis of tide predictions for the ports of Cilacap, Tjilauteurem, and Segoro. The tsunami arrived as the sea approached low tide rendering the tide level correction less sensitive to the exact arrival time.

[6] The tsunami deposited sand sheets ~5–15 cm thick at several locations along the coast, primarily in rice paddy fields that dominate behind the beach ridge. The sand sheet thinned inland although deposition continued to within meters of the inundation limit. The sands are commonly plane laminated, and often have a layer of magnetite at the base. In places, some of the underlying soil was ripped-up and incorporated into the overlying deposit. At Pasir Putih, Pangandaran Peninsula National Park, a layer of fresh coral rubble was deposited on what had been a white sand beach.

[7] Numerous video interviews of eyewitnesses were carried out to record estimates of the number of waves, their height, period and tsunami arrival time. Eyewitnesses described two to three main waves with an initial recession of 100 m corresponding to a leading depression N-wave [*Tadepalli and Synolakis*, 1994]. The second wave was reported as the highest with a white upper part suggestive of bore formation and a black sediment-rich lower section. The wave was described as preceded by a rumbling noise. The tsunami arrived between 16:00 and 16:30 pm local time depending on location, with sea conditions returning to normal after about 30 min.

[8] Even with little ground shaking as warning, in some locales many people noticed the incoming tsunami and correctly identified it as such about tens of seconds prior to impact. A common problem seems to have been a lack of understanding where the nearest tsunami safe location was, how high of an elevation would provide safety, and how long to stay there. Evacuation drills are thus seen particularly important when the tsunami is recognized only shortly before impact, when self-evacuation occurs spontaneously.

3. Nusa Kambangan Trimline in Coastal Forest

[9] Nusa Kambangan, literally "floating island", is off the southern coast of Central Java province. It is separated from Java's mainland by a narrow strait, Segara Anakan. The island is approximately 30 km long and 4 km wide with a central ridge up to 202 m high (Figure 3). The island, often referred to as the "Alcatraz" of Indonesia, is off-limits to most casual visitors because of the three high-security prisons located on the island; however, the team was granted limited, "escorted" access.

[10] Nusa Kambangan has a vast nature reserve with large stretches of virgin forest. The tsunami impact carved

[1]Auxiliary materials are available at ftp://ftp.agu.org/apend/gl/2007gl029404.

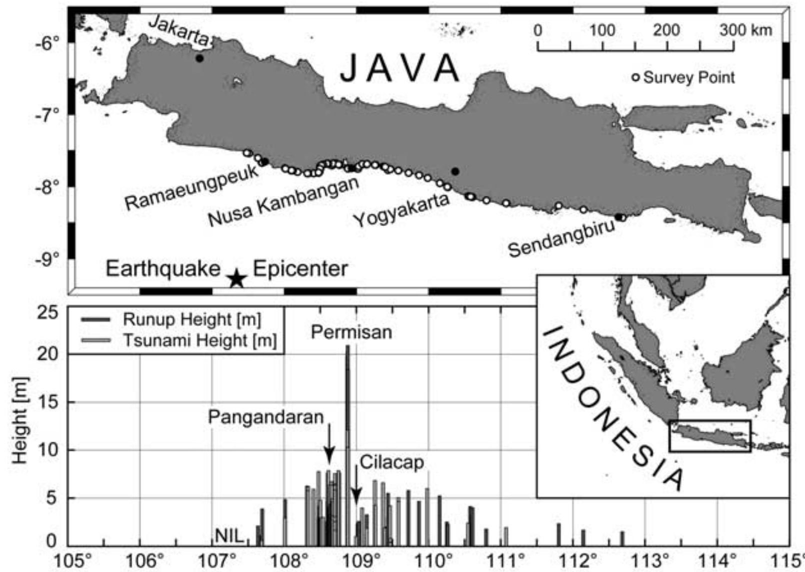

Figure 2. Measured tsunami runup (dark grey) and tsunami heights (light grey) along Java's south coast.

a sharp trimline in the forest at elevations between 10 and 21 m along the hill slope behind a 1.5 km long and 50 m wide beach, significantly exceeding runup measurements elsewhere along the coast. *Pandanus*, *Hibiscus* and large *Cocos* trees up to 500 m inland were damaged and/or uprooted by the tsunami and their debris piled several meters high along the coastal plain separating the beach and the hill slope (Figure 4). The severely damaged forest – several hundred meters inland – along with the several meters high piles of debris from uprooted trees suggests that protective coastal vegetation can be overwhelmed by large enough tsunamis [*Latief and Hadi*, 2006], whereas in some cases during 2004 the Indian Ocean tsunami a protective role was attributed to coastal vegetation [e.g., *Danielsen et al.*, 2005; *Synolakis and Kong*, 2006]. Beach erosion with removal of more than 1 vertical meter of sand was observed, with substantial sediment deposits found in the floodplain behind the beach ridge. Local flow depths exceeded 8 m above terrain along the elevated coastal plain 200 m inland from the beach – for reference, flow depths during the 2004 Indian Ocean tsunami reached 5 m in Sri Lanka [*Liu et al.*, 2005], 16 m in Banda Aceh [*Borrero*, 2005] and 20 m on Pulau Breuh off the north tip of Sumatra [*Jaffe et al.*, 2006]. We infer that the focused tsunami and runup heights on the island suggest a possible local submarine slump or mass movement given the favorable bathymetry in the area with an offshore canyon. The discriminant $I_2 = 5.9 \times 10^{-2}$, which relates the maximum runup to the characteristic width is significantly larger than the limit $I_2 = 10^{-4}$ between tectonic and landslide sources indicating a landslide source [*Okal and Synolakis*, 2004]. However, this inference remains to be investigated by bathymetric surveys.

[11] Fortunately the coastal zone on Kambangan was largely uninhabited limiting the death toll to 19 "farmers" although at least one of the prisons was inside the flood plain near the maximum inundation distance. The island

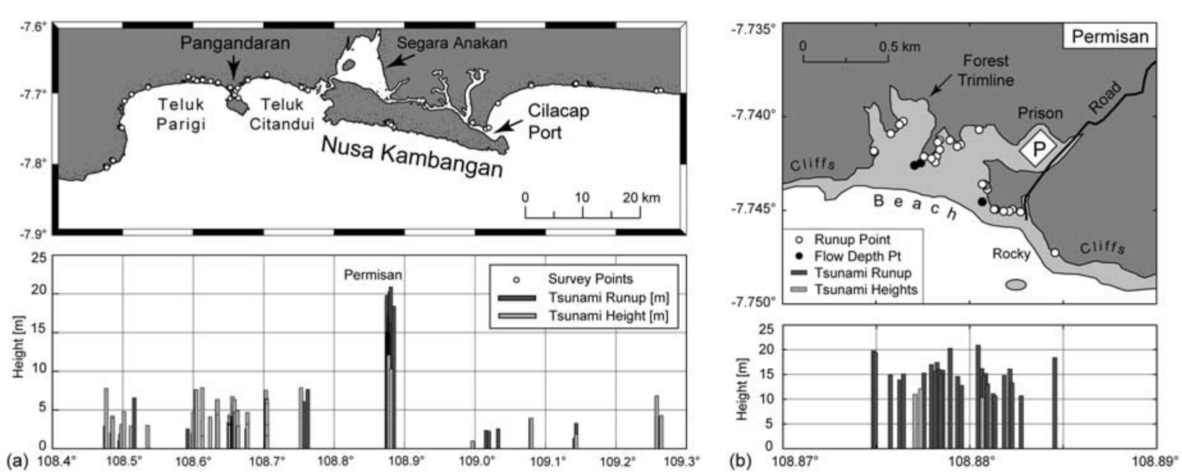

Figure 3. Nusa Kambangan overview and detail with measured runup heights (dark grey) and tsunami heights (light grey).

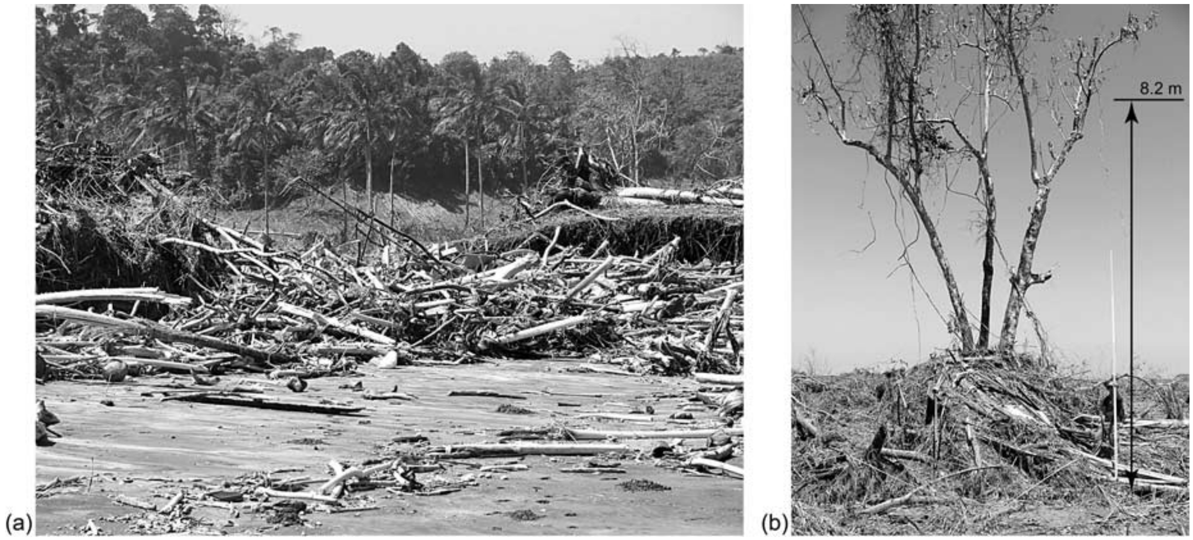

Figure 4. Nusa Kambangan: (a) zoom image of beach erosion in the foreground and a sharp trimline in the background carved into the forest by the tsunami, and (b) scars on the bark of a tree indicating more than 8 m flow depth 200 m from the beach.

took the brunt of the impact and protected the town of Cilacap located on the mainland behind a submerged shoal and the island, just to the east of Permisan. Cilacap has the only natural harbor with deep-water berthing facilities on Java's south coast as well as an oil terminal and is therefore visited by large vessels. The harbor is located in the strait naturally shielded by Nusa Kambangan. At the pilot station, the moored pilot boat Maiden III (GRT 332t) touched the ground corresponding to an initial 1.5 m draw down of the water level, which was followed by a 1 m rise.

[12] Given that this is the second tsunami in 12 years to strike South Java – the 1994 event was also produced by a slow earthquake and killed about 200 people [*Synolakis et al.*, 1995; *Tsuji et al.*, 1995] – community-based education and awareness programs are particularly essential to help save lives in locales at risk from near-source tsunamis, when neither the shoreline recession nor the ground shaking can be expected to be easily recognized as precursors [*Sieh*, 2006; *Synolakis*, 2006]. One encouraging sign is the conduct of evacuation drills in south Java, undertaken in the immediate aftermath of this tsunami [*Kerr*, 2006].

4. Conclusions

[13] The rapid response of the survey team in visiting Java after the 17 July 2006 event led to the recovery of important data on the characteristics of tsunami impact in the near field. This tsunami was difficult to escape as the earthquake was hardly felt, no warnings were given to the affected population prior to the impact, and the initial drawdown was masked by the receding tide and wind waves. The prison island of Nusa Kambangan in Central Java was by far the area hardest hit with runup heights up to 21 m and local flow depths exceeding 8 m. We infer that the focused tsunami and runup heights on the island suggest a possible local submarine slump or mass movement. The destruction of an entire forest several hundred meters inland with debris piling several meters high demonstrates the limits of forests as protective measures against tsunamis.

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