The December 26th 2004 Indian Ocean tsunami in Northwest Sumatra and Offshore Islands

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Abstract

An International Tsunami Survey Team (ITST) conducted field surveys of tsunami effects on the west coast of northern and central Sumatra and offshore islands 3-4 months after the December 26th 2004 tsunami. Study sites spanned 800 km of coast from Breuh Island north of Banda Aceh to the Batu Islands, and included 22 sites in Aceh Province in Sumatra and on Simuelue Island, Nias Island, the Banyak Islands, and the Batu Islands. Tsunami runup, elevation, flow depth, inundation distance, sedimentary characteristics of deposits, nearshore bathymetry, and vertical land movement (subsidence, uplift) were studied.

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Maximum tsunami elevations were greater than 16 m and maximum tsunami flow depths were greater than 13 m along a 135 km stretch of coast in northwestern Sumatra. Tsunami flow depths were 10 m at 1500 m inland. Extensive tsunami deposits, primarily composed of sand and typically 5 to 20 cm thick, were observed in northwestern Sumatra.

INTRODUCTION

The Indian Ocean tsunami of December 26, 2004 caused widespread devastation and loss of life throughout the Indian Ocean basin and beyond. The tsunami was triggered by a large (M_w 9.0-9.3) earthquake that ruptured a 1200-1300 km segment of interplate thrust fault extending from offshore northern Sumatra to the Andaman Islands (Lay et al., 2005; USGS, 2005; Stein and Okal, 2005). The earthquake occurred at 07:58:53 local time in Indonesia (00:58:53 UTC). The tsunami arrived in northern Sumatra, the hardest hit region, within 15 to 20 minutes after the earthquake. Fatalities in Indonesia totaled 128,645 with more than 37,063 missing and 532,898 displaced (USAID Fact Sheet, July 7, 2005).

The first post-tsunami survey was of northwest and northeast Sumatra, including the hard-hit Banda Aceh area, and was conducted during the first week of January 2005 (Borrero, 2005; Borrero this volume). Tsunami scientists from Indonesia, Japan, Turkey, Russia, and the United States conducted three additional surveys in January in northern Sumatra and the offshore islands (Tsuji et al, 2005a; Yalciner et al., 2005, Gusiakov, 2005). The largest measured tsunami heights, which were at Lhoknga in northwest Sumatra about 15 km southwest of Banda Aceh, were greater than 30 m (Tsuji et al., 2005a; Borrero, 2005). Tsunami height decreased to about 15 m at Meulaboh (Yalciner et al., 2005), which is located in northwestern Sumatra about 175 km southeast of Banda Aceh. Tsunami heights of about 2 m were measured in Sibolga, a fishing port in a natural embayment about 500 km southwest of Banda Aceh. During the January surveys, most, if not all, of the roads were impassible, resulting in large gaps in the field data collected.

To fill these data gaps, an International Tsunami Survey Team (ITST) consisting of 12 US and 5 Indonesian scientists, the authors of this paper, formed to collect additional data on the December 26, 2004 tsunami. The ITST included experts in tsunami geology, tsunami hydrodynamics (tsunami propagation and inundation), tsunami hazard assessment, tsunami education, coastal geology and processes, bathymetry collection, and palynology. This ITST was different than others in that it had seven geologists, the greatest number of geologists on a post-tsunami survey ever. The make-up of the ITST allowed collection of both tsunami water level and deposit data, including documentation of the deposits from the December 26, 2004 tsunami and reconnaissance for paleotsunami deposits. Coastal change data, including estimates of subsidence and uplift, and adjustment of the coast to the new land levels were also collected.

The pre-survey goals of the data collection effort were; (1) to fill the gaps in the measurements of tsunami elevation, flow depth, run-up, and inundation distances between Lhoknga (northern Sumatra) and Padang (southern Sumatra), (2) to conduct detailed sedimentological investigations, including paleotsunami studies, (3) to survey onland topography and nearshore bathymetry, filling a critical data void for tsunami propagation and inundation modeling, (4) to investigate the effectiveness of previous tsunami education and hazard mitigation strategies, and (5) to make additional estimates of co-seismic subsidence and uplift from the 26 December 2004 earthquake.

To accomplish these goals, the ITST was divided into two groups that conducted surveys from March 31 to April 22, 2005 using a charter boat that served both as transportation and lodging. While the first group was in Jakarta, Indonesia on March 28, 2005 enroute to the survey area, a magnitude 8.7 earthquake occurred on the adjacent fault segment to the south of the one that ruptured on December 26, 2004. A new, high priority goal of documenting the tsunami created by this earthquake was added to the previous goals. This paper only presents the results of investigations of the December 24, 2004 tsunami. Initial observations of both the December 26, 2004 and March 28, 2005 tsunamis are posted at http://walrus.wr.usgs.gov/news/reports.html.

FIELD METHOD

The ITST collected measurements in a manner similar to other post-tsunami field investigations (Dengler et al., 2003; Gelfenbaum and Jaffe, 2003). Measurements were taken primarily on shore-normal transects, although a considerable number of off-transect measurements were also taken. Sites were chosen using satellite imagery, information from surveys made in January 2005, and logistical considerations.

Tsunami water levels and topography were measured relative to sea level at the shore using a laser range finder shooting to either a prism on top of a rod or a water level indicator (e.g.; debris in a tree). Water levels measured (Figure 1) included; (1) runup, the elevation at maximum inundation, (2) tsunami elevation, the sum of water depth during the tsunami and elevation relative to the shoreline, and (3) flow depth during the tsunami. Minimum flow depth during the tsunami was indicated by broken branches (Figure 2a) or stripped bark in trees, debris in trees, snapped trees, gouge marks in trees, impact marks on rock outcrops, and water marks on buildings (rare along the sites on the west coast of Sumatra visited by this ITST because nearly all the buildings were destroyed). Runup was indicated either by a wrack line of debris or a trimline, which is the elevation on a hill or cliff below which all vegetation was stripped by the tsunami (Figure 2b).

Water elevations at all but the southernmost sites were corrected to the tidal level at 09:00 on December 26, 2004, which is approximately 1 hour after the earthquake, using tides calculated by Tsuji et al. (2005). This choice was made because eyewitnesses near Banda Aceh reported that a later wave, not the first wave, was the largest and eyewitness reports of the arrival time of the first wave varied from approximately 15 minutes near Banda Aceh to 30 minutes at Simuelue Island. The water level data we collected represents a combination of effects from all the waves in the wavetrain. The largest wave caused the maximum tsunami water level or greatly influenced it if multiple waves were additive. Hence, we corrected to our best estimate of sea level at arrival time for the largest wave. In practice, the choice of tsunami arrival time in tidal correction scheme, except for the southern sites, does not introduce error > 0.2 m because the tidal range is low (< 1 m). For subsided regions, inland distances were referenced to the shoreline at the time of the survey. These distances have not been corrected to the shoreline location before the tsunami, the most pertinent distance for planning purposes, which typically was farther seaward because of erosion during and after the tsunami. Distances in uplifted regions were referenced to the pre-tsunami shoreline.

Flow directions were estimated in the field from orientation of trees ripped up by the tsunami, aligned debris on the ground, preferential scour around buildings, toppled palm trees and building materials, wrapped debris, and bent vegetation. Bent vegetation within or at the base of tsunami deposits was also used to indicate flow direction.

Tsunami deposits were examined in pits and trenches dug at intervals along a shore-normal transect and at selected locations off transect (Figure 3a). The deposits were measured, photographed, and described in the field and samples were taken for laboratory analyses. In the field, bulk samples of layers within the deposits were taken, and, at about a dozen locations, samples were taken at ½ cm or 1 cm intervals to document the fine-scale vertical variation of grain size in the deposit (Figure 3b).

At several sites, the ITST searched for paleotsunami deposits by taking push cores in environments with good preservation potential and by examining eroded channel banks and scarps near the shoreline (Figure 4a). Potential paleotsunami deposits were measured, photographed, and described in the field and samples were taken for laboratory analyses.

Nearshore bathymetry was collected at selected sites using a simplified version of the Coastal Profiling System as described by Ruggiero et al. (2005). A shallow water echo sounder and GPS antenna were mounted to a stainless steel mast attached to 25' skiff, the RV Scarab. HYPACK (Coastal Oceanographics Inc.) hydrographic surveying software was used as the data synchronization software and navigation system allowing for the use of pre-set survey tracklines. Individual bathymetric soundings, several per meter along each trackline, have a horizontal positioning accuracy of a few meters and a vertical accuracy (after smoothing through waves and performing a tidal correction using values from Tsuji et al, 2005) of approximately 0.25 m. At each site, multiple cross-shore (typical spacing of 200 m) and alongshore (typical spacing of 500 m) track lines have been combined to develop gridded bathymetric surfaces typically ranging from approximately two to three kilometers in the alongshore and 1 kilometer in the cross-shore out to a depth of about 30 m.

Estimates of uplift and subsidence from the December 26 earthquake were made using a variety of field evidence. Estimates of uplift are primarily based on the elevation of uplifted reef platforms above sea level. The amount of uplift was calculated as the difference between the elevation of the reef flat and mean lower low water, which is approximately the level to which the coral will grow. Uplift was also estimated as the difference in pre- and post December 26, 2004 shoreline elevations, although this method was only able to be applied in areas where the tsunami was small and did not destroy evidence of the pre-December 26, 2004 shoreline.

Subsidence in this region is very difficult to quantify. We estimated levels of subsidence in Sumatra by measuring the position of palm trees in the foreshore and assuming that the root balls of living palm trees do not penetrate the salt water table. Trees present in the foreshore owe their location to either erosion or subsidence. Because the roots are in the salt water here and the trees are still in growth position, they must have subsided there rather than having sediment removed from around them. We use the depth of the root ball below mean sea level as the measure of minimum subsidence.

Another way of estimating subsidence uses eyewitness accounts of the former position of the shoreline. Using the offshore distance provided by locals, and slopes calculated from transects beginning at the high tide line moving landward, we calculate a depth of subsidence that would cause the transgression. While eyewitness accounts are not necessarily robust, these data are similar to the root ball depth measurement at sites where both techniques were possible.

When we encountered locals with first-hand knowledge of the December 26, 2004 tsunami, we recorded their accounts. At sites we studied in northern Sumatra, eyewitness accounts were rare because there were so few survivors. At the offshore island sites in the southern part of the study area where there were more survivors the ITST collected more eyewitness reports. The results of the eyewitness interviews and implications for mitigation are discussed in McAdoo and others (this volume).

FIELD OBSERVATIONS

The ITST took field measurements at 22 sites from March 31 to April 22. Of these sites, evidence of the December 26, 2004 tsunami was observed at 16 sites. However, some of the sites lacking evidence might have had this evidence prior to the March 28, 2005 tsunami. For all sites between Brueh Island and Kuala Meurisi, a distance of 135 km, the December 26, 2004 maximum tsunami elevations were greater than 16 m and maximum tsunami flow depths were greater than 13 m (Table 1; Figure 4). The tsunami destroyed all buildings in a zone within 500 m of the shoreline along this section of coast. In places, this zone of total destruction was wider than 1500 m. Typically, only the foundations of the buildings remained. There is a slight trend of decreasing tsunami elevations and flow depths from north to south (Figure 5; Table 1), although because these measurements are limited by physical evidence (e.g. tree left standing with broken branches or snagged debris indicating tsunami flow depth) remaining after the tsunami it is not known whether this trend is real. Tsunami elevations were smaller, but still large (5-14m), in northern Simeulue Island and a small island to the north, Pulau Salaut. Tsunami elevation decreased significantly to the south. Tsunami elevations were about 4 m on the central and southwest coast of Simuelue Island and at northwest Nias Island.

The tsunami flow depth decreased little as it moved inland in northern Sumatra (Table 1, Appendix I). At Jantang, tsunami flow depth was greater than 15 m at 500 m inland. At Kuala Meurisi, tsunami flow depth was greater than 10 m at 1500 m inland.

Evidence was found for both the uprush and return flow (Appendix I). At Jantang, flow was near perpendicular to the shoreline orientation in open areas and veered when it encountered high hills, flowing in the gaps and valleys between the hills (Figure 6). At Kuala Meurisi, bent vegetation buried within a tsunami deposit indicated the tsunami flowed onshore at approximately 15 degrees and 45 degrees relative to the shoreline orientation during formation of the deposit at 470 m and 1426 m, respectively (Appendix I).

Extensive tsunami deposits, composed primarily of sand, were found in northern Sumatra where tsunami inundation distances were great (Table 2). Tsunami deposit penetrated inland to within 20 m of the limit of inundation at most sites (Table 2). A zone of no deposition or erosion was observed near the shoreline at all sites. The width of this zone, which was larger at sites where the tsunami was large, was approximately 80 m wide at Jantang (Figure 7). The maximum shore-normal extent of tsunami deposits measured was 1659 m at Kuala Meurisi (Figure 4b). The deposit extent scaled with the limit of inundation, which is a function of the size of the tsunami wave and slope of the land. At Busung, Simeulue Island, a smaller tsunami and steeper slopes resulted in inundation of 80 to 130 m and a shore-normal extent of the deposit was 55 to 80 m.

Thicknesses of tsunami deposits were variable along transects (Figure 7) and from site to site (Appendix I). At Kuala Meurisi, deposit thickness variation was large in a ridge-swale system with greater thickness in the swales. The maximum deposit thickness observed at any site was 70 cm at , although typical thicknesses were 5 to 20 cm. The thickest deposits did not correlate with the deepest tsunami flow depths (e.g.; Jantang, Figure 7). Deposits were usually composed of multiple layers; thickness may reflect deposition during multiple waves and/or during uprush and return flow.

Grading of deposits was noted in the field and, when time permitted, samples were collected at ½ cm or 1 cm intervals in the vertical and brought back to the US for laboratory grain size analysis. Both field observations and laboratory data documented normal and inverse grading, as well as massive sections in tsunami deposits (Figure 8).

In addition to studying the deposits from the December 26, 2004 tsunami, the ITST conducted paleotsunami deposit reconnaissance. Possible paleotsunami deposits were observed at Lhok Luepung, Busung and Langi.

The modification of tsunami waves as they approach shore is a strong function of the nearshore bathymetry. This data was not available for the sites the ITST studied. To fill this critical data need, bathymetric data were collected at 8 sites: Jantang, Lhok Kruet, Lhok Leupung, north of Kuala Meurisi, Kuala Meurisi, Langi (Simeulue Island), Busung (Simeulue Island), Lagundri Bay (Nias Island), and Tuangku (Banyak Islands). In total, more than 300,000 soundings were collected in water depths ranging from 1.6 to 33.6 m.

Uplift or subsidence from the December 26, 2004 earthquake was estimated at 7 sites (Table 3). The maximum estimated subsidence, 2 m, was at Jantang in northwestern Sumatra. Beaches in subsided regions were eroding at the time of the survey (4 to 5 months after the co-seismic subsidence) as the nearshore profile and beach were still adjusting to the higher sea level caused by the subsidence. This erosion is impacting roads and redevelopment plans for coastal villages. The maximum estimated uplift, 2.4 m, was observed at Pulau Salaut, which is north of Simeulue Island (Table 3).

DISCUSSION

Even though this data set is one of the best ever collected for a modern tsunami, it has limitations that should be noted. At most locations, tsunami flow depth near the shore was not documented because few trees, the primary recorder of flow depths, were left standing after the tsunami. Values reported for tsunami flow depths and tsunami elevations, except at the trimline, are minimum values because the ITST was conservative in interpretation of physical evidence and omitted questionable evidence or the remaining evidence often did not allow a true measurement (e.g.; trees that were broken off at the top below the level of the maximum tsunami elevation). At most locations, the error was small compared to the measured value. Inundation distances reported are also minimums because the longest transects were not feasible given limited time and a large study area. For example, inundation distances at our transects at Jantang and Lhok Kruet, where the tsunami flooding was stopped by high hills (Figure 2b), were 665 m and 415 m (Table 2); inundation distances in valleys at these sites, as determined from post-tsunami satellite images, were 2700 m and 4400 m (Figure 6). Tsunami deposit inland penetration measured along our transects (Table 2), likewise, do not account for deposition far inland in valleys or broad coastal plains and are not maximum values.

The data collected by the ITST will be used to improve the understanding of December 26, 2004 tsunami and tsunamis in general. Measurements of tsunami elevation and flow depth, in conjunction with the topographic, bathymetric, and tsunami deposit data, can be used to constrain and validate hydrodynamic models for tsunami inundation. Estimates of subsidence and uplift can be used to constrain seafloor displacement models to allow better characterization of the source for the December 26, 2004 tsunami. Data collected adds to the catalogue of sedimentary characteristics and geometries for tsunami deposits, which can be used for identification of paleotsunami deposits. The data set will also be used to develop relations between tsunami flow and deposit. Once developed, these relations can be applied to paleotsunami deposits to estimate the magnitude of structure of past tsunamis (Jaffe and Gelfenbaum, 2002).

The ITST identified sites with potential paleotsunami deposits for future study. Indonesia, because of its short written record of tsunamis, would benefit from studies to quantify the recurrence intervals and magnitudes of paleotsunamis from deposits. The March 28, 2005 event likely increased stress on the fault segment to the south under the Mentawai

Islands that could trigger a tsunamigenic earthquake (Nalbant et al., 2005). Paleotsunami deposit studies in this region are needed to improve assessment of the risk from such a tsunami.

CONCLUSIONS

The ITST found evidence of the December 26, 2004 tsunami at 16 sites spanning 800 km from Brueh Island to Teluk Bandera, Batu Islands. The tsunami devastated cities, towns, and villages along hundreds of kilometers of the northwestern Sumatra coast. Maximum tsunami elevations were greater than 16 m and maximum tsunami flow depths were greater than 13 m at all sites studies between Brueh Island and Kuala Meurisi, a distance of 135 km. The inland tsunami flow depths were large along this section of coast. Tsunami flow depths of 15 m and 10 m were observed at 500 m and 1500 m inland, respectively. In northwestern Sumatra, the tsunami destroyed all buildings in a zone inland of the shoreline that was at least 500 m wide and, in valleys and broad coastal plains, more than 1500 m wide.

Tsunami elevation and damage decreased to the south of devastated coast of northwestern Sumatra. The tsunami elevation was higher than 10 m at northern Simuelue Island, decreased to 4 m at southern Simuelue Island and northern Nias Island, and was about 1 m in the Banyak Islands. Damage decreased correspondingly, with major damage at northern Simuelue Island, moderate damage in southern Simuelue Island and Central Nias Island, and little to no damage farther south.

Extensive tsunami deposits, composed primarily of sand, were formed in northwestern Sumatra during the December 26, 2005 tsunami. The maximum shore-normal extent of tsunami deposits measured was 1659 m, although satellite images indicate that deposition occurred farther inland in locations not studied by the ITST. The thicknesses of tsunami deposits was variable along transects and from site to site. Typical deposit thickness was 5 to

20 cm, while the thickest at any site was 70 cm. The relation between flow and thickness is difficult to interpret because deposits were usually composed of multiple layers that may reflect deposition during multiple waves and/or during uprush and return flow. Field observations and laboratory data documented normal and inverse grading, as well as massive sections in tsunami deposits. A zone of no deposition or erosion was observed near the shoreline at all sites.

Candidate paleotsunami deposits were observed at three sites in northern Sumatra and Simuelue Island. These sites are worthy of further study to determine the recurrence and magnitude of paleotsunamis in this region.

Uplift or subsidence from the December 26, 2004 earthquake was estimated at 7 sites. The maximum estimated subsidence, 2 m, was at Jantang in northwestern Sumatra. The maximum estimated uplift, 2.4 m, was at Pulau Salaut, which is north of Simeulue Island.

In this paper we report initial results. The data collected by the ITST will be used to improve understanding of the December 26, 2004 tsunami and tsunamis in general. Further analysis and modeling of the combination of tsunami deposit, tsunami water level, topographic, and bathymetric data, and as well as future studies of paleotsunami deposits, will play an important role in the mitigation of tsunami hazard in Indonesia.

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Table 1. Selected December 26, 2004 tsunami water levels measured by the team. Maximum measured tsunami flow depth, tsunami elevation, and runup at each site are included in the table. Other measurements that emphasize the landward decay in tsunami flow depth are also included in the table. Locations are shown in Figure 5. See Appendix I for complete data set of tsunami flow measurements, which includes flow direction and details of whether measurements were taken to the side of the transect.

Site Name	Distance from Shore (m)	Tsunami Flow Depth (m)	Tsunami Elevation (m)	Comments
Pulau Brueh	222.0	20.5	22.2	broken tree, maximum flow depth
Pulau Brueh	421.3	14.7	21.1	trimline
Pulau Brueh	534.2	5.9	22.1	tree, maximum tsunami elevation
Pulau Brueh	652.3	5.8	22.1	trimline, run-up, maximum tsunami elevation
Pulut	0.0	32.5	32.5	trimline on rocky outcrop at shoreline, local maximum tsunami flow depth and height
Pulut	495.3	13.8	16.5	trimline, run-up, maximum tsunami elevation along profile
Jantang 3	476.3	16.4	18.1	trimline, maximum flow depth
Jantang 3	627.3	15.0	19.7	broken branches, maximum tsunami height
Jantang 3	664.6	15.0	19.7	trim line; run-up
Lhok Kruet 2	437.2	12.4	17.1	broken branch
Lhok Kruet 2	491.6	13.2	17.9	trimline, run-up
Lhok Kruet 1	275.1	14.9	16.7	trimline, maximum flow depth
Lhok Leupung	632.4	13.7	15.7	broken branches, maximum flow depth
Lhok Leupung	780.3	12.7	16.5	broken branches, maximum tsunami elevation
Lhok Leupung	856.0	9.6	14.0	broken branches
Lhok Leupung	903.3		12.2	debris line, run-up
Kuala Meurisi	644.0	11.0	13.5	broken branches
Kuala Meurisi	1112.3	13.2	17.2	broken branches, maximum tsunami elevation and flow depth
Kuala Meurisi	1591.4	10.9	13.6	broken branches
Kuala Meurisi	1799.2	6.1	11.3	debris in tree
Kuala Meurisi	1820.0		12.9	wrack line on hillside; run-up
Pulau Salaut	124.5	2.0	6.5	debris in palm, maximum tsunami elevation and flow depth
Pulau Salaut	161.9	0.5	4.9	wrack line in jungle, flow into jungle beyond wrack line
Langi island	308.4	5.4	7.0	broken branch and debris, island overwashed
Langi Island	418.8	11.9	13.9	broken branch, maximum tsunami elevation and flow depth, island overwashed

Site Name	Distance from Shore (m)	Tsunami Flow Depth (m)	Tsunami Elevation (m)	Comments
Langi field	234.9	8.3	7.8	broken branch, maximum tsunami elevation and flow depth
Langi field	441.4	0.9	3.0	edge of road; debris in fence, landward of road
Langi village	276.8	6.1	9.9	broken top of palm tree, maximum flow depth
Langi village	294.2		10.9	trimline, maximum tsunami elevation
Langi 102	202.3	6.7	8.1	debris, maximum tsunami elevation and flow depth
Langi 102	334.7		7.3	wrack line on hillside, run-up
Kariya Bakti	158.9	2.0	4.1	wrack line in jungle, flow into jungle beyond wrack line, maximum tsunami elevation and flow depth
Busung 2	82.0		3.1	wrack line, run-up
Busung 1	130.0		4.1	run-up
Alus Alus	100.2		1.1	run-up
Humanga Beach	38.8		0.9	wrack line, run-up
Afulu	84.1	1.8	3.9	debris in tree, maximum tsunami elevation and flow depth
Pulau Asu	40.0		0.9	eye witness, maximum tsunami elevation
Lagundri Bay	40.0		1.2	eye witness, run-up
Hayo	14.0		0.9	eyewitness, elevation on church, maximum tsunami elevation
Teluk Bandera	100.0		1.0	eyewitness, elevation on house, maximum tsunami elevation

Table 2. December 26, 2004 tsunami inundation, deposit inland penetration, and deposit shore-normal extent along transects measured by the ITST.

Site Name	Tsunami Inundation (m)	Deposit Inland Penetration (m)	Deposit Shore-normal Extent (m)
Jantang L1-2	517.5	512.5	417.5
Jantang 3	664.6	627.3	546.8
Lhok Kruet 1	376.4	275.1	243.0
Lhok Kruet L1-4	414.8	>334.1	>112.3
Lhok Leupung	903.3	856.0	768.2
Kuala Meurisi	1820.0	1803.3	1714.3
Langi island	524.4*	492.6	395.2
Langi field	441.4	234.9	110.7
Langi village	294.2	276.8	234.4
Langi 102	334.7	330.8	252.8
Busung 2	82.0	67.9	56.3
Busung 1	130.0	109.3	79.4

* Island overwashed

Table 3. Land level change from the December 26, 2004 earthquake.

Site Name	Latitude (º)	Longitude (º)	Uplift (+) Subsidence (-)	Comments
Jantang	5.27680	95.24410	-0.6	Stump in surf - minimum subsidence because berm crest not fully aggraded
Jantang	5.26197	95.24990	-2.0	Calculated from eye-witness reports of shoreline loss and slope from profile, broken and submerged palm trees in the surf
Lhok Kruet	4.90102	95.39671	subsidence	Palms in surf zone, stump and soil in water
Pulau Salaut	2.98480	95.39258	2.4	Old high tide to new high tide
Pulau Salaut	2.98473	95.39311	1.7	Uplifted berm and beach platform
Langi	2.82924	95.76349	0.9	Uplifted coral reef platform
Kariya Bakti	2.64042	95.80503	1.2	Uplifted coral reef platform

Appendix I. Tsunami water levels and selected deposit thicknesses. Except where noted, coordinates are for shot points and directly apply to measurements when offline distance is zero. Corrections to coordinates and "Distance from Shore" for cases where offline distances are non-zero have not been made. Water depths for offline shots assume online and offline elevations are the same.

Site Name	Latitude (ºN)	Longitude (ºE)	Distance from Shore (m)	Tsunami Flow Depth (m)	Tsunami Elevation Corrected (m)	Tide Correction (m)	Distance Off Line (m)	Direction Off Line (º)	Flow Direction (º)	Sediment Thickness (cm)	Comments
Pulau Brueh	5.68073	95.05970	47.2	17.9	18.5	-0.2	152.6				
Pulau Brueh	5.68077	95.05985	67.0	16.5	16.9	-0.2	142.7				
Pulau Brueh	5.68080	95.06001	83.6	16.8	17.2	-0.2	145.0				
Pulau Brueh	5.68083	95.06011	94.9	15.8	16.3	-0.2	140.3				
Pulau Brueh	5.68086	95.06044	130.7	17.2	17.8	-0.2	130.5				
Pulau Brueh	5.68099	95.06124	222.0	20.5	22.2	-0.2	113.4				broken tree
Pulau Brueh	5.68102	95.06142	240.2	19.8	21.6	-0.2	133.2				
Pulau Brueh	5.68112	95.06206	313.2	16.5	19.6	-0.2	92.3				
Pulau Brueh	5.68123	95.06264	376.6	13.4	18.2	-0.2	76.2				
Pulau Brueh	5.68131	95.06303	421.3	14.7	21.1	-0.2	81.3				
Pulau Brueh	5.68139	95.06414	534.2	5.9	22.1	-0.2	13.1				
Pulau Brueh			652.3	5.8	22.1	-0.2					trim line, maximum inundation along profile
Pulut	5.36600	95.24950	0.0	32.5	32.5	-0.6					trim line on large rock at shoreline
Pulut	5.36451	95.25105			13.4	-0.6					
Pulut	5.36333	95.25212	495.3	13.8	16.5	-0.6					trimline, maximum inundation along profile
Jantang L1	5.28561	95.25011		3.0							flow mark on tree near mosque
Jantang L1	5.28556	95.25050		3.8							watermark inside mosque on wall
Jantang 2	5.28093	95.24474	273.9	12.0	12.4	-0.1	51.0	N			broken branches
Jantang 2	5.28158	95.24612	441.7	9.4	10.1	-0.1	132.0	N			trimline on rocks
Jantang 2	5.28158	95.24612	441.7	11.1	11.8	-0.1	97.3	N			trimline on rocks
Jantang 2	5.28158	95.24612	441.7	17.0	17.7	-0.1	51.0	N			trimline on rocks

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Jantang 2	5.28181	95.24674	538.2	14.4	15.2	-0.1	0.0				trimline, maximum inundation along line.
Jantang L1-2	5.27920	95.24677	390.0	11.5						1	flow mark on a tree
Jantang L1-2	5.28048	95.24718	517.0		14.9	0.2				1	rag up the steep cliff
Jantang 3	5.2746	95.24693	139.0						105		flow direction from bent wooden post
Jantang 3	5.27558	95.24987	460.0						85		flow direction from aligned palm tree
Jantang 3	5.27564	95.24966	466.0						240		flow direction bent tree; return flow
Jantang 3	5.27583	95.24987	467.0						80		flow direction aligned palm tree
Jantang 3	5.27586	95.24967	467.0						75		flow direction from large (10 m) tree
Jantang 3	5.27592	95.24972	472.0						64		flow direction from bent tree
Jantang 3	5.27572	95.24976	476.3	16.4	18.1	0.1	50.0	N		17	trimline
Jantang 3	5.27572	95.24976	476.3	13.7	15.4	0.1	93.0	NE			trimline
Jantang 3	5.27574	95.24995	495.0						254		flow direction from bent grass; return flow
Jantang 3	5.27586	95.25041	552.6	14.4	17.5	0.1	159.6			18	trimline
Jantang 3	5.27621	95.25104	627.3	15.0	19.7	0.1	17.7			6	broken branches
Jantang 3	5.27622	95.25139	664.6	15.0	19.7	0.1	0.0			0	trimline; maximum inundation along line
Jantang L1-1	5.27351	95.25089	491.0		18.9	0.2					trim line - location, distance measured from base of steep slope.
Jantang 1	5.26641	95.24956							250		flow direction from debris wrap; return flow

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Jantang 1	5.26668	95.24984							125		flow direction from corners of brick house; main flow
Jantang 1	5.26668	95.24984							235		flow direction from corners of brick house (return flow)
Jantang 1	5.26948	95.25316	634.7	8.8	15.1	-0.4	26.6	N			broken branches, dead leaves
Jantang 1	5.26980	95.25470	808.1	7.6	14.5	-0.4	29.8	SE			broken branch
Jantang 1	5.26980	95.25470	808.1	9.4	16.3	-0.4	65.0	NE			debris line
Jantang 1	5.26980	95.25470	808.1	9.2	16.1	-0.4	58.9	E			run-up from outcrop
Jantang 1	5.27006	95.25511	852.1	6.7	13.7	-0.4	0.0				trimline; maximum inundation along line
Jantang L1	5.26268	95.24989			11.5	0.2					trimline on hill
Jantang L1	5.26197	95.24990	475.0		17.2	0.2					refrigerator
Lhok Kruet L2	4.90148	95.39927	283.0	10.5	12.5	0.1	104.9				trim line; from road
Lhok Kruet L2	4.90079	95.39822	140.0	9.6	11.3	0.1	13.8				broken branch; from road
Lhok Kruet L2	4.90070	95.39740	64.0	8.8	10.3	0.1	12.2				debris; from road
Lhok Kruet 2	4.90008	95.40207	430.4	9.3	13.3	0.1					
Lhok Kruet 2	4.90010	95.40208	437.2	12.4	17.1	0.1					broken branch
Lhok Kruet 2	4.90034	95.40256	491.6	13.2	17.9	0.1	0.0				trim line, maximum inundation along profile
Lhok Kruet L2	4.89964	95.40094	267.0	9.9	12.2	0.1	11.1				rafted palm fronds; from road
Lhok Kruet L1-4	4.89915	95.40203	414.8		17.4	0.1				14.0	location from nearest sediment pit; tsunami elevation and flow depth from base of steep slope
Lhok Kruet L2	4.89767	95.40212	250.0	11.0	13.3	0.1	30.2				scar on palm; from road
Lhok Kruet L2	4.89725	95.40252	140.0	10.2	11.9	0.1	40.1				palm frond in tree; from road
Lhok Kruet 1	4.89620	95.40281	40.0	9.9	10.4	0.1	0.0			0.1	base of dead tree
Lhok Kruet 1	4.89680	95.40351	140.9	10.4	10.8	0.1	34.2			32	
Lhok Kruet 1	4.89729	95.40415	231.5	11.1	12.4	0.1	95.6			15	
Lhok Kruet 1	4.89754	95.40444	275.1	11.1	12.8	0.1	60.0			12	

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Lhok Kruet 1	4.89754	95.40444	275.1	14.9	16.7	0.1	120.2				trimline
Lhok Kruet 1	4.89754	95.40444	275.1	11.7	13.4	0.1	80.6				trimline
Lhok Kruet 1	4.89779	95.40491	376.4	12.6	15.2	0.1	0.0				trimline, maximum inundation along profile
Lhok Kruet L2	4.89762	95.39920							250		
Lhok Kruet L1	4.89548	95.40460	300.0	14.0							palm frond in tree. Dead leaves and branches below palm frond
Lhok Kruet L1-2	4.88007	95.40235	257.8	7.7	9.8	0.1					trim line on cliff. Location and distance from base of cliff.
Lhok Kruet L1	4.87890	95.40041			9.1	0.1					blanket in trees
Lhok Kruet L1-3	4.87859	95.39782	198.4	6.7	8.0	0.0					location is for shoreline point.
Lhok Kruet L1-3	4.87859	95.39782	225.3		11.4	0.0					location is for shoreline point.
Lhok Kruet L1-1	4.87849	95.39979	197.2	13.0	15.3	0.1					trimline; location and distance from base of cliff
Lhok Leupung	4.69042	95.53537	592.0	11.0	13.6	0.1	6.1				broken branches
Lhok Leupung	4.69064	95.53565	632.4	13.2	15.3	0.1	37.7			9	broken branches
Lhok Leupung	4.69072	95.53573	632.4	9.8	11.9	0.1	29.1	NW			broken branches
Lhok Leupung	4.69072	95.53573	632.4	11.2	13.2	0.1	8.3	NW			broken branches
Lhok Leupung	4.69072	95.53573	632.4	13.7	15.7	0.1	40.4	N			broken branches
Lhok Leupung	4.69072	95.53573	646.8	9.1	11.4	0.1	15.5	N			broken branches
Lhok Leupung	4.69118	95.53649	739.3	11.8	15.1	0.1	105.0	N		8	broken branches
Lhok Leupung	4.69137	95.53677	780.3	12.7	16.5	0.1	104.8	N		6	broken branches
Lhok Leupung	4.69189	95.53720	856.0	9.6	14.0	0.1	56.9	N		8	broken branches
Lhok Leupung	4.69205	95.53774	903.3		12.2	0.1	0.0			0	inundation line; debris line
Kuala Meurisi	4.61072	95.62206	185.1						54, 44		flow direction from bent brush, wrap around
Kuala Meurisi	4.61259	95.62383	469.9	5.6	6.7	0.0	34.2		75	22	broken branches at top of tree; flow direction from in-place stems at 19 cm depth

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Kuala Meurisi	4.61240	95.62386	469.9						60	22	flow direction from aligned stems at 13-16 cm depth
Kuala Meurisi	4.61338	95.62463	591.2	6.1	8.7	0.0	54.0			5	snapped tree
Kuala Meurisi	4.61370	95.62491	644.0	11.0	13.5	0.0	109.3			11	broken branches
Kuala Meurisi	4.61390	95.62524	685.2	8.4	10.8	0.0	13.9		65-75	20	broken branches, flow direction from fallen pillar
Kuala Meurisi	4.61448	95.62582	775.5	14.1	17.2	0.0	17.4	E			broken branches - same tree
Kuala Meurisi	4.61562	95.62727	984.9	9.4	12.1	0.0	27.7	S	205	7	broken branches; flow direction indicates return flow
Kuala Meurisi	4.61644	95.62812	1112.3	7.2	11.2	0.0	69.8	N			broken branches
Kuala Meurisi	4.61644	95.62812	1112.3	10.4	14.4	0.0	31.4	S			broken branches
Kuala Meurisi	4.61644	95.62812	1112.3	13.2	17.2	0.0	23.5	N		2.5	broken branches
Kuala Meurisi	4.61672	95.62840	1152.6	10.3	14.0	0.0	28.4	E		2	broken branch; eyewitness
Kuala Meurisi	4.61692	95.62859	1186.2	11.0	14.3	0.0	12.1	N			broken branches
Kuala Meurisi	4.61692	95.62859	1186.2	9.5	12.8	0.0	8.2	NE			broken branches
Kuala Meurisi	4.61692	95.62859	1186.2	12.5	15.7	0.0	16.5	N		1	broken branches
Kuala Meurisi	4.61783	95.62934	1314.6	7.6	10.7	0.0	48.4	NW		12.5	broken branches
Kuala Meurisi	4.61858	95.62985	1426.4						0	18.5	flow direction from grass within sediment
Kuala Meurisi	4.61942	95.63039	1531.9	8.7	11.4	0.0	28.1	E		9	broken branches
Kuala Meurisi	4.61974	95.63080	1591.4	10.9	13.6	0.0	46.5	S			broken branches
Kuala Meurisi	4.62009	95.63115	1650.2	9.2	12.6	0.0	88.8	S		13	broken branches
Kuala Meurisi	4.62021	95.63131	1673.5	10.1	13.8	0.0	115.0	N			broken branches
Kuala Meurisi	4.62073	95.63235	1799.2	6.1	11.3	0.0	53.8	S			debris in tree
Kuala Meurisi	4.62082	95.63249	1820.0		12.9	0.0					wrack line, limit of inundation
Kuala Meurisi	4.61454	95.62617							230-270		
Pulau Saluat L1-3	2.98513	95.39341			6.5	0.1					debris on beach
Pulau Salaut L1-2	2.98481	95.39239	176.1		5.7	0.1					debris in jungle

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Pulau Salaut L1-1	2.98483	95.39325	124.5	2.0	6.5	0.1					debris in palm
Pulau Salaut L1-1	2.98473	95.39311	161.9	0.5	4.9	0.1					wrack line in jungle, flow into jungle beyond wrack line
Langi island	2.83004	95.76647	308.4	5.4	7.0	0.2	27.0			2	broken branch and debris
Langi island	2.83027	95.76701	363.4	7.3	9.1	0.2	53.5			11	debris stripped bark and broken branch
Langi island	2.83027	95.76701	363.4	6.3	8.1	0.2	53.5				
Langi island	2.83054	95.76745	418.8	11.9	13.9	0.2	27.0			15	broken branch
Langi island	2.83061	95.76788	459.5	11.8	13.8	0.2	21.0			20	broken branch
Langi field	2.82858	95.74737	134.0	7.7	7.6	0.1	11.0			7	broken branch
Langi field	2.82858	95.74737	134.0	8.1	6.8	0.1	9.9				broken branch
Langi field	2.82765	95.74719	234.9	8.3	7.8	0.1	27.2			0.5	broken branch; patchy deposit
Langi field	2.82580	95.74737	441.4	0.9	3.0	0.1	0.0				edge of road; debris in fence landward of road - not maximum inundation
Langi	2.82478	95.75727			9.1	0.1					
Langi village	2.82389	95.75733							60		flow direction from palms ripped and toppled
Langi village	2.82414	95.75717	120.9	4.8	6.2	0.1	29.3	N		14	broken branches
Langi village	2.82411	95.75711	192.9	4.3	6.2	0.1	36.7	S	65-245	11	gouge marks and debris
Langi village	2.82361	95.75631	261.4						60	6.5	flow direction from imbedded grass in sand
Langi village	2.82358	95.75631	276.8	6.1	9.9	0.1	27.1	NE		1.5	broken top of palm tree
Langi village	2.82344	95.75611	294.2		10.9	0.1					limit of inundation
Langi	2.82256	95.76089							350		flow direction from damaged building pillar
Langi 102	2.82253	95.75928	117.2	5.1	6.6	0.1	5.8	E		1.5	debris and snapped top
Langi 102	2.82206	95.75931	162.3	4.3	5.6	0.1	4.2	E		8	debris and broken branches
Langi 102	2.82175	95.75933	202.3	6.7	8.1	0.1	19.3	NW		5	debris

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Langi 102	2.82139	95.75947	202.3	5.0	6.5	0.1	47.3	NW			debris
Langi 102	2.82139	95.75947	202.3	5.2	6.6	0.1	68.3	SE			debris in tree
Langi 102	2.82056	95.75992	334.7		7.3	0.1					wrack line on hillside
Kariya Bakti	2.64042	95.80503			4.3	0.3					
Kariya Bakti	2.63827	95.80293	158.9	2.0	4.1	0.3					debris in palms
Busung 2	2.38757	96.33693	82.0		3.1	-0.1	0.0			0	wrack line, inundation limit; corrected for 1.7 m uplift from 3/28/05 earthquake
Busung 1	2.38467	96.33572	130.0		4.1	-0.1					limit of inundation, boats; corrected for 1.7 m uplift from 3/28/05 earthquake
Alus Alus	2.34927	96.37575	100.2		1.1	-0.1	0.0			0	limit of inundation; corrected for 1.7 m uplift from 3/28/05 earthquake
Humanga Beach	1.48436	97.34708	38.8		1.0	0.0					wrack line, limit of inundation; corrected for 0.9 m uplift from 3/28/05 earthquake
Afulu	1.26169	97.23066	84.1	1.8	3.9	0.1					debris in tree; corrected for 1.7 m uplift from 3/28/05 earthquake
Pulau Asu	0.90433	97.28002	40.0		0.9	0.0					eye witness; measured from pre 3/28/05 tide line
Lagundri Bay	0.57842	97.73203	40.0		1.2	0.3					eye witness; corrected for 0.2 m uplift from 3/28/05 earthquake
Hayo	-0.09493	98.26431	14.0		0.9	0.2					eye-witness; water level on church
Teluk Bendara	-0.51108	98.32702	100.0		1.0	-0.3					eye-witness; water level on house; possible subsidence from 3/28/05 earthquake, not corrected

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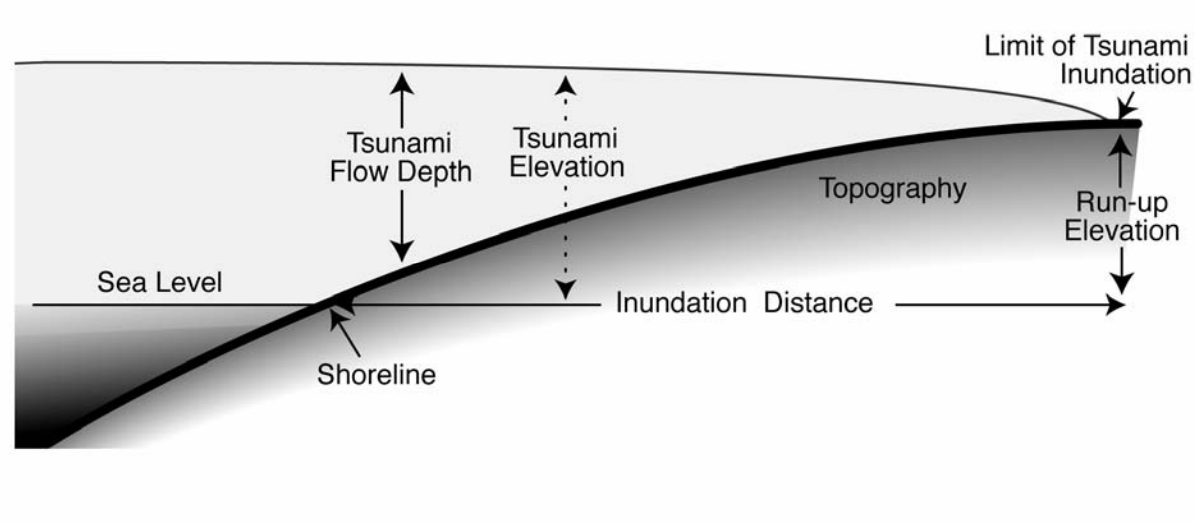

Figure 1. Schematic of tsunami inundating land with terminology used in this paper. Tsunami flow depth is the height of the tsunami above the ground. Tsunami elevation is the height above sea level, which is the addition of the tsunami flow depth and topographic elevation. Inundation distance and run-up elevation are the distance from the shoreline and elevation above sea level at the limit of tsunami inundation.

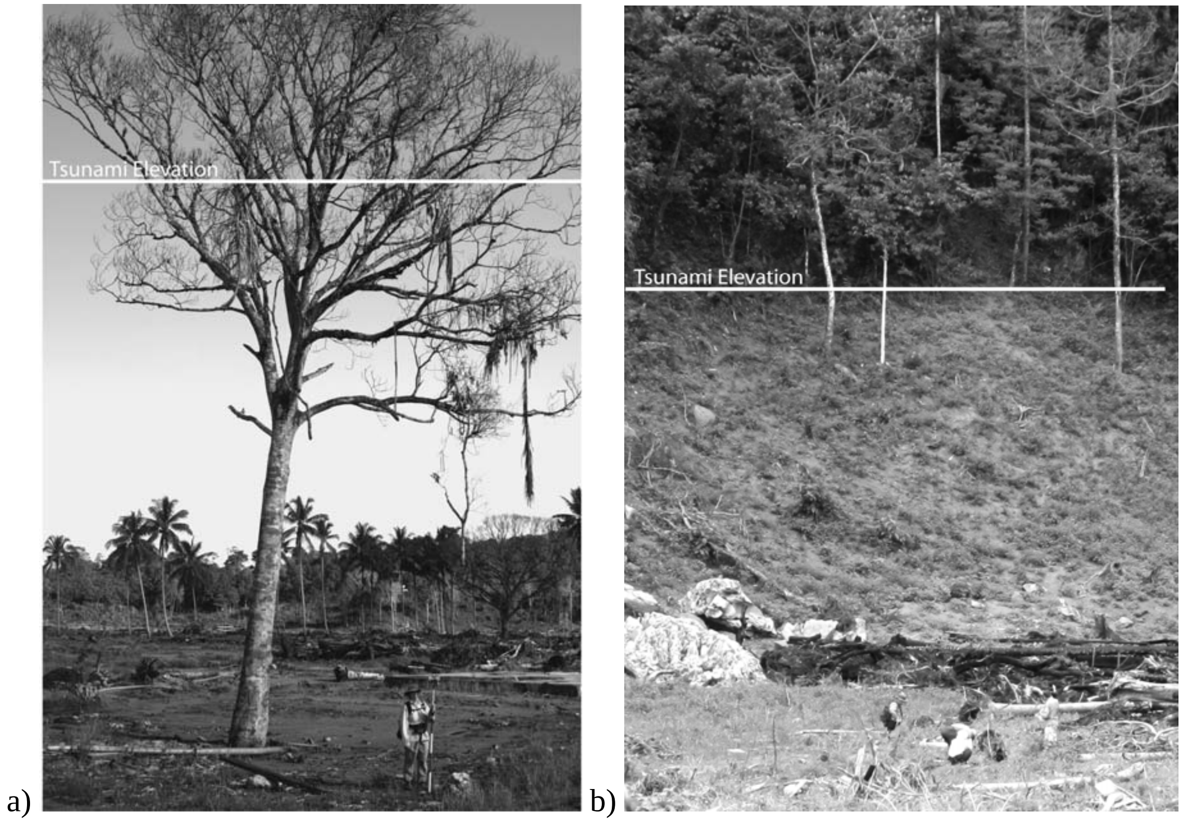

Figure 2. a) Surveying topographic profile in front of a large tree that survived the December 26, 2004 tsunami at Lhok Kruet, Sumatra. Note the branches high in the tree that were broken by the 26 December tsunami. The combination of broken branches and debris high in the tree, primarily palm fronds, indicate that the tsunami flow depth was 9.9 m at this location, which is approximately 275 m inland, b) Trimline at Jantang at 19.7 m above the sea level when the December 26, 2004 hit. Vegetation below the line was stripped by the tsunami and had begun to grow back. Note the team members examining a tsunami deposit in the foreground. Photographs taken by Bruce Jaffe.

a)  b) 

Figure 3. a) Trenching at Jantang, Sumatra. This trench is in a berm that formed several months after the tsunami as the shoreline and nearshore adjusted to coseismic subsidence and erosion from the tsunami. The area landward of the trench was flooded because it subsided during the December 26, 2004 earthquake. Photograph taken by Andy Moore b) Collection of tsunami deposit samples. Samples were transported to the United State for laboratory analyses of grain size. Samples were collected at multiple levels in the deposit to document changes in grain size above the base of the deposit. The goal of collecting these samples is to use them, in conjunction with field observations, photographs, and peels, to develop relations between the tsunami flow and the deposit it leaves (e.g.; flow speed deposit relations). Photograph taken by Bretwood Higman.

a)  b)

Figure 4. a) Push coring in search of paleotsunami deposits at Jantang. Photograph taken by Lori Dengler. b) ITST members examining trench in tsunami deposit approximately 1 km inland at Kuala Meurisi, Sumatra. Note the laterally continuous nature of the deposit, water ponded in local topographic lows, and mudcracks at the surface of the deposit. The trees in the photograph were ripped up from seaward and transported to this location by the December 26, 2004 tsunami. The trunks are oriented parallel to the tsunami flow direction. Photograph taken by Bruce Jaffe.

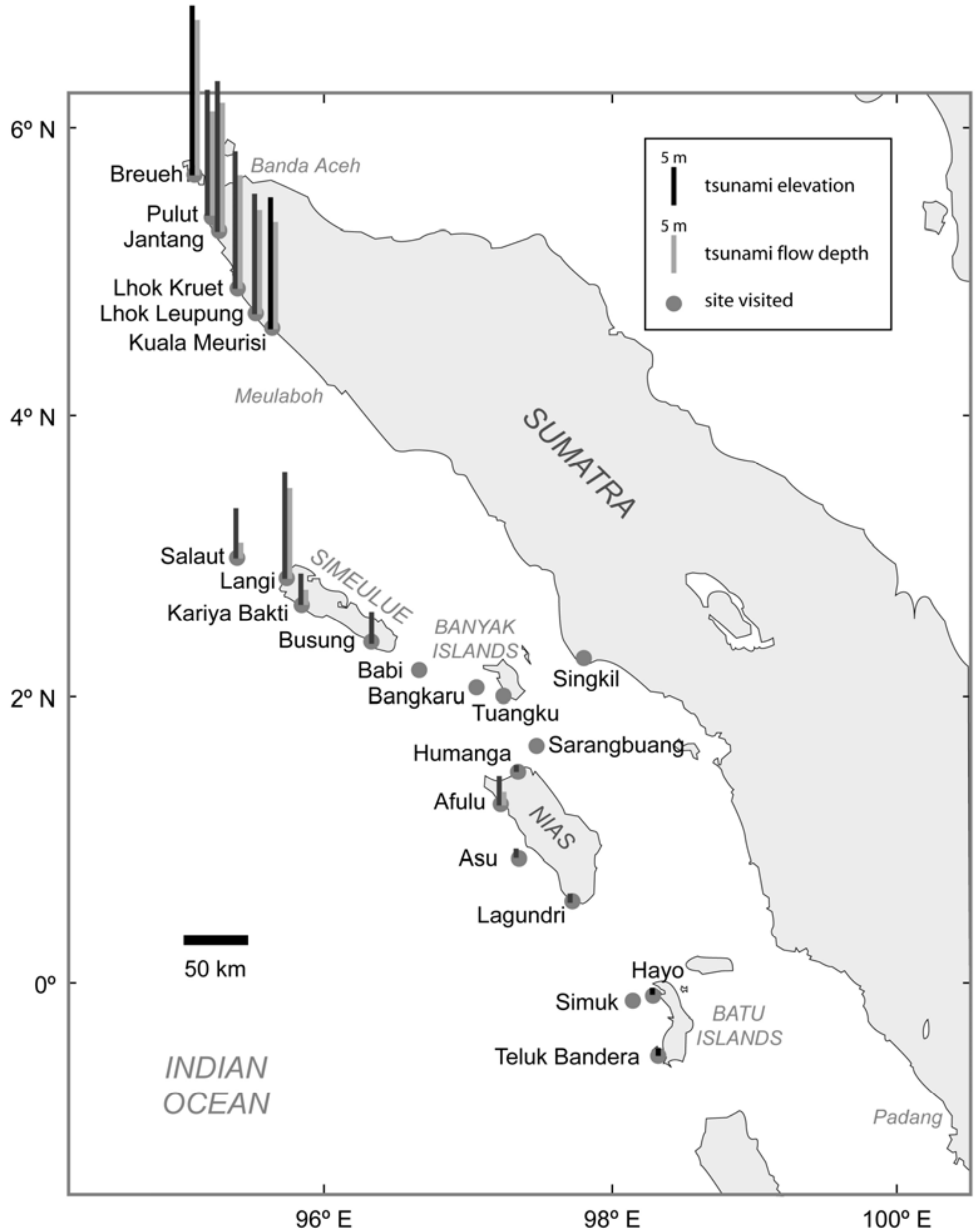

Figure 5. Maximum elevations and flow depths measured by the ITST for the December 26, 2004 tsunami.

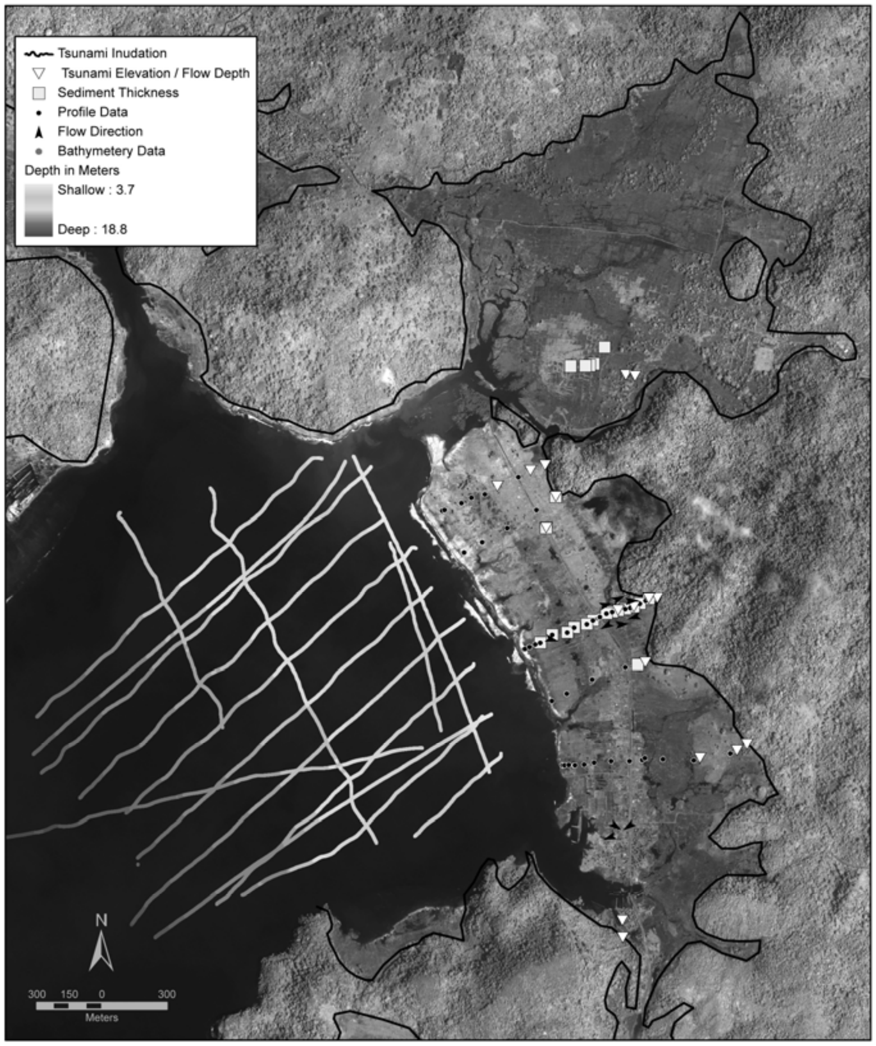

Figure 6. QuickBird satellite image of Jantang, Sumatra taken on January 22, 2005 showing measurement locations for tsunami deposits, water levels, flow directions, profiles, and bathymetry. Arrows point in the direction of tsunami flow. Tsunami limit of inundation detected in image was verified in the field at locations near the measurements. Tsunami deposits covered most of the area inundated by the tsunami.

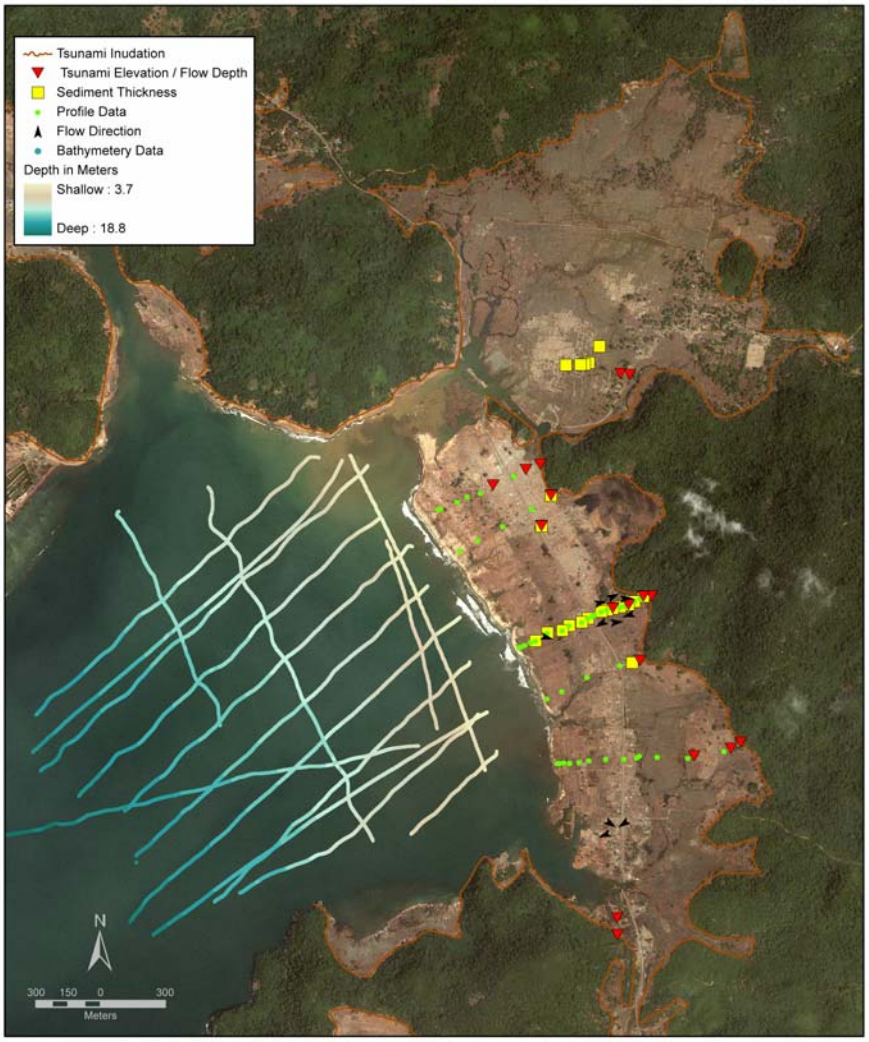

Figure 6 (color). QuickBird satellite image of Jantang, Sumatra taken on January 2, 2005 showing measurement locations for tsunami deposits, water levels, flow directions, profiles, and bathymetry. Arrows point in the direction of tsunami flow. Tsunami limit of inundation detected in image was verified in the field at locations near the measurements. Tsunami deposits, which appear as a reddish tan or light brown color in the image, covered most of the area inundated by the tsunami.

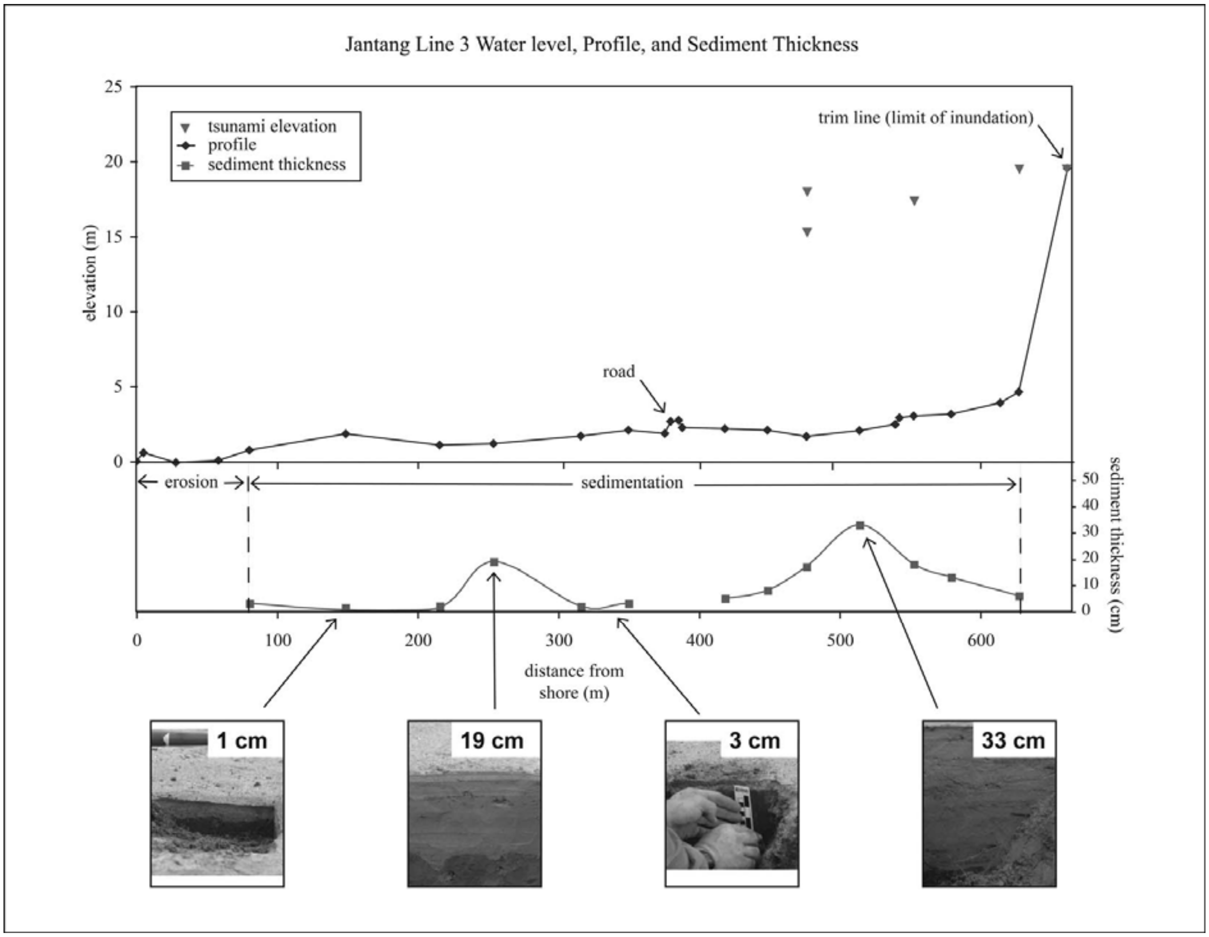

Figure 7. Topographic profile, tsunami deposit thickness, and tsunami flow depths and elevations at Jantang, Sumatra, on transect 3 (center transect in Figure 6). Maximum tsunami flow depth was 16.4 m at 476 m inland and decreased to 15.0 at 628 m inland, which is 37 m seaward of the trimline. Tsunami elevations increased from 18.1 m to 19.7 m over this section of the transect. Note that there was an erosion zone seaward of the tsunami deposit and that deposit thickness varied along transect, appearing to respond to subtle changes in topographic slope.

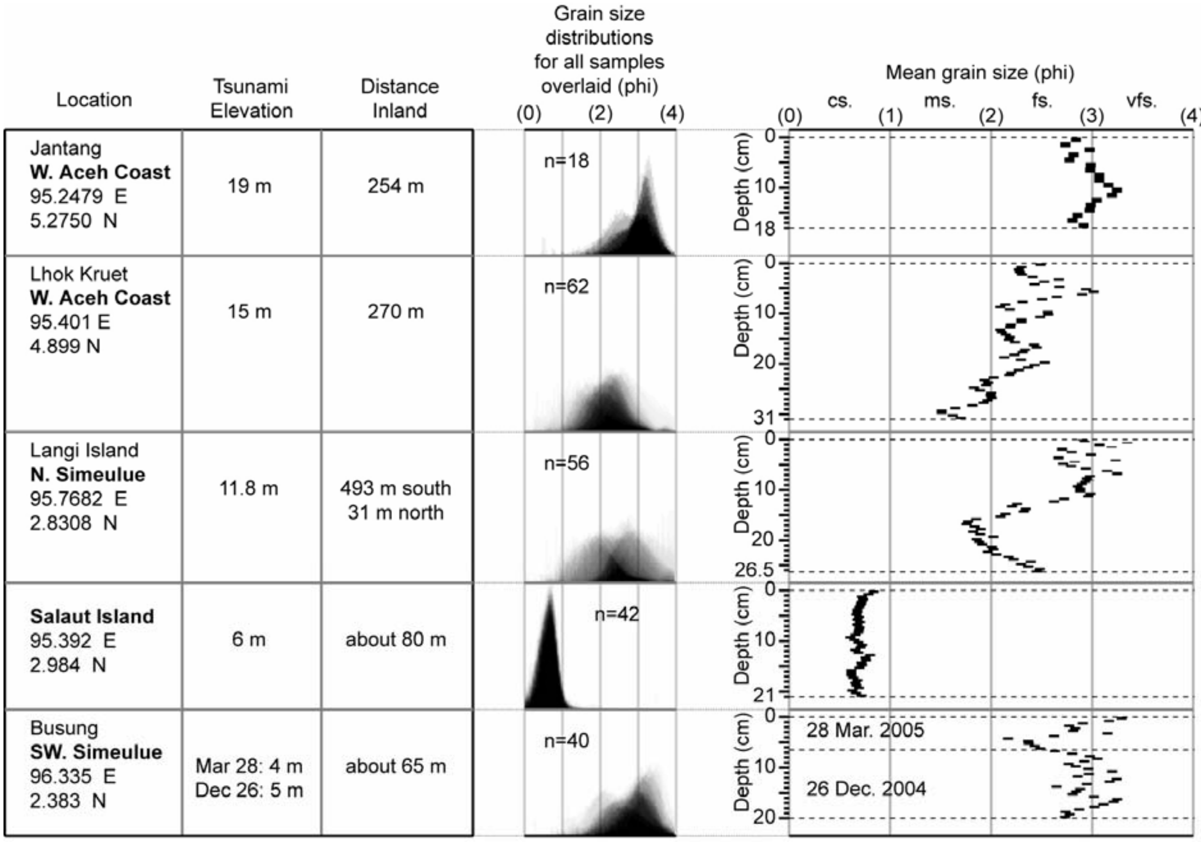

Figure 8. Vertical variation in the mean grain size of thick tsunami deposits created during the December 26, 2004 tsunami. At selected locations, we collected vertically contiguous sand samples from tsunami deposits for lab analysis. Grain sizes of each sample were determined using settling velocity data from a 189-cm long settling column. A composite distribution was plotted by binning grain size at 0.05 phi intervals and overlaying transparent histograms. Mean grain size is plotted against depth in the deposit where the vertical thickness of each rectangular mark is equal to sample thickness (scale at left) and the width of the mark is greater than the standard error of the estimate for mean grain size.