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Erosion and Sedimentation from the 17 July, 1998 Papua New Guinea Tsunami

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Abstract — This paper describes erosion and sedimentation associated with the 17 July 1998 Papua New Guinea tsunami. Observed within two months of the tsunami, distinct deposits of a layer averaging 8-cm thick of gray sand rested on a brown muddy soil. In most cases the sand is normally graded, with more coarse sand near the base and fine sand at the top. In some cases the deposit contains rip-up clasts of muddy soil and in some locations it has a mud cap. Detailed measurements of coastal topography, tsunami flow height and direction indicators, and deposit thickness were made in the field, and samples of the deposit were collected for grain-size analysis in the laboratory. Four shore-normal transects were examined in detail to assess the shore-normal and along shore distribution of the tsunami deposit. Near the shoreline, the tsunami eroded approximately 10–25 cm of sand from the beach and berm. The sandy layer deposited by the tsunami began 50–150 m inland from the shoreline and extended across the coastal plain to within about 40 m of the limit of inundation; a total distance of up to 750 m from the beach. As much as 2/3 of the sand in the deposit originated from offshore. Across most of the coastal plain the deposit thickness and mean grain size varied little. In the along-shore direction the deposit thickness varied with the tsunami wave height; both largest near the entrance to Sissano Lagoon.

Key words: Tsunami deposit, Papua New Guinea, coastal sedimentation, erosion, flow direction indicators.

Introduction

Tsunami waves approach land with sufficiently high velocities and bed shear stresses to suspend and transport large quantities of sediment. Despite the destructive power of a tsunami, in which trees are uprooted and structures destroyed, a tsunami can leave behind a clearly identifiable deposit. If the sediment deposited by a tsunami is buried and preserved, then a geologic record of that tsunami will be created. Using a sedimentological analysis, geologists may be able to read the geologic record to infer the occurrence of past tsunamis. The recognition of deposits from past tsunamis allows geologists to extend the relatively short or non-existent historical record of

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tsunamis in an area, thus improving assessment of tsunami hazard (ATWATER, 1987; BOURGEOIS and MINOURA, 1997; GOFF *et al.*, 2001; JAFFE and GELFENBAUM, 2002).

The interpretation of palaeotsunamis is improved by studies of sedimentary deposits associated with modern tsunamis. An important goal of these studies is to determine which characteristics of a tsunami, if any, can be interpreted from the sedimentological record that is left behind. For instance, do trends in the grain-size distribution or thickness of a tsunami deposit relate to the height or speed of a tsunami wave? Questions such as these can only be answered from a more complete, detailed analysis of modern tsunami deposits and the tsunami waves that produced them.

Since 1992 there have been 10 major tsunamis worldwide, including Nicaragua and Flores in 1992, Okushiri in 1993, East Java, Shikotan, and Mindoro in 1994, Irian Jaya and Peru in 1996, Papua New Guinea in 1998, and most recently Peru in 2001. Recent studies of these events has led to an improved understanding of tsunami generation, propagation, and inundation. In particular, studies of the sedimentary deposits from the Okushiri, Japan tsunami (SATO *et al.*, 1995; NISHIMURA and MIYAJI, 1995), and the Flores Island, Indonesia tsunami (DAWSON, 1994; SHI *et al.*, 1995) describe the pattern of sedimentation associated with a tsunami. For example, SHI *et al.* (1995) find that the grain-size fines landward in the deposit on Flores Island. The purpose of this manuscript is to describe the erosion and sedimentation associated with the 17 July 1998 Papua New Guinea tsunami, thus adding to the observations of modern tsunami sedimentation that will ultimately improve the identification and interpretation of palaeotsunamis in the geologic record.

Description of 1998 PNG Tsunami

On the evening of July 17, 1998 a magnitude 7.0 earthquake was followed by a series of tsunami waves that devastated villages on the north coast of Papua New Guinea (PNG). As later confirmed by field surveys, eyewitnesses reported waves at least 7–10 m high at the coast. The confirmed death toll was over 2200, and the coastal villages of Warapu and Arop, located on barrier spits around Sissano Lagoon, were totally destroyed (Figs. 1 and 2). Thousands of survivors were forced from their homes and villages and set up temporary camps further inland or on nearby hills.

The tsunami consisted of three large waves, the first making land fall approximately 20 minutes after coastal residents felt the earthquake (DAVIES, 1999). The second came within 5 minutes of the first wave and the third wave came within 5 minutes of the second wave. According to eyewitnesses, the second and third waves flowed over the low-lying coast before the first wave completely receded. Waves ripped large trees out of the ground by the roots and moved both traditional wooden and modern brick and mortar structures off of their pilings or foundations tens to hundreds of meters away into the lagoon. Preliminary analysis of seismographs and other field evidence put the location of the seafloor disturbance that caused the

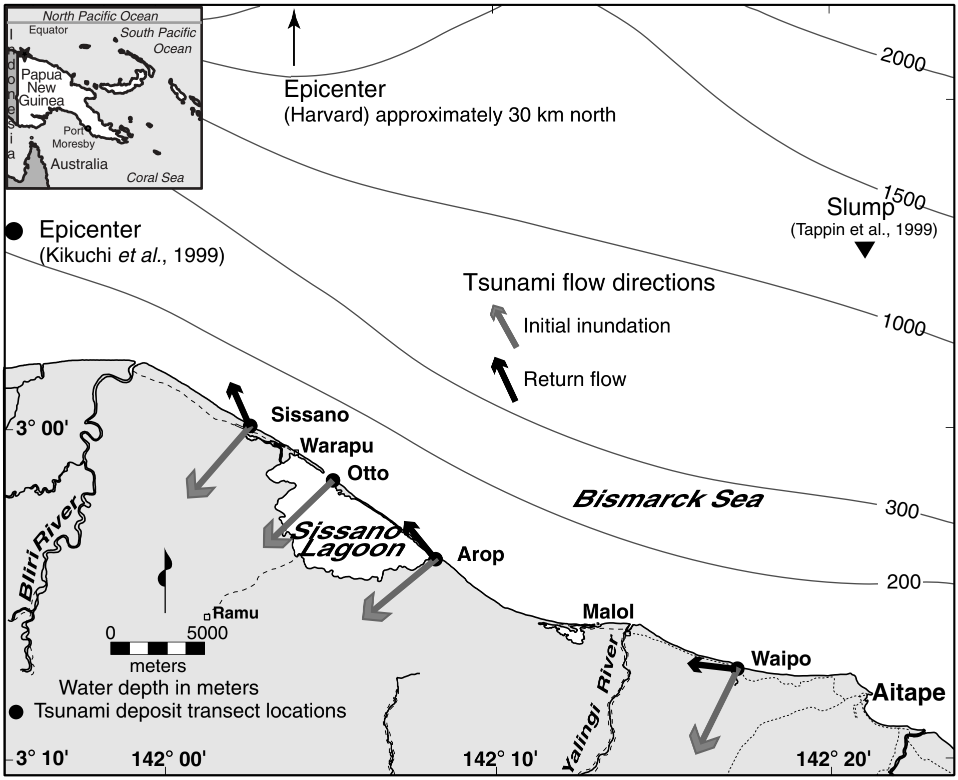

Figure 1
Location map of the north coast of Papua New Guinea struck by the 1998 tsumani. The gray shaded arrow indicates the flow direction of the main tsunami inundation; the black arrow indicates the direction of return flow after inundation.

tsunami approximately 20 km offshore the Sissano Lagoon. Initial tsunami generation and propagation model results suggested that an earthquake of this size alone could not be responsible for the large wave heights observed on the coast (KAWATA *et al.*, 1999), thus motivating a search for an additional seafloor disturbance. A marine geophysical survey later identified a submarine failure which may have contributed to the generation of the tsunami (TAPPIN *et al.*, 1999). A debate persists regarding whether the tsunami that devastated the north coast of PNG was generated by an earthquake, a landslide, or a combination of the two mechanisms (GEIST, 2000; OKAL and SYNOLAKIS, 2001; GEIST, 2001; TAPPIN *et al.*, 2001).

An international team of tsunami researchers, referred to as the 1st International Tsunami Survey Team (ITST), surveyed the area within a few weeks of the tsunami. The team of scientists and engineers from Japan, the United States, Australia, and New Zealand installed seismographs, measured water levels, and interviewed eyewitnesses to learn more about the tsunami and its effects (KAWATA *et al.*, 1999).


b
a

Soon after the 1st ITST completed their survey, a second group of international scientists returned to PNG and retrieved seismographs, collected more water-level and velocity indicator data, assessed damage to buildings and structures, documented societal effects, and examined the sediments left behind by the tsunami. The 2nd ITST arrived in Aitape, Papua New Guinea on September 29, 1998, and included representatives from Japan, the United States, Korea, and Papua New Guinea.

Historical Tsunamis in Northern Papua New Guinea

Northern Papua New Guinea lies near the boundary of the Australian and Pacific plates. The plate boundary is complex and includes subduction, transform faulting, and thrusting (TAPPIN *et al.*, 2001). Overall, convergence is at an oblique angle and at a rate of about 100 mm/yr. This rapid convergence gives rise to numerous large earthquakes. In the past 100 years there have been 16 earthquakes with magnitude over 5.7. The largest, in 1935 and 1971, had a magnitude of 7.9 (RIPPER *et al.*, 1998).

Most of these earthquakes, however, occurred on land and failed to generate tsunamis. Moreover, for northern Papua New Guinea there is only a short historical record of tsunamis impacting the coast. In the 20th century, a magnitude 7 earthquake generated a tsunami that hit the area west of Aitape on December 15, 1907 (RIPPER *et al.*, 1998). Prior to the earthquake, there was a smaller lagoon, called Warupu Lagoon with two small islands inhabited by the Warupu clan. Coseismic subsidence of about 100 km^2 of coast formed a larger lagoon in the location of the present Sissano Lagoon (MCSAVENEY, *et al.*, 2000). A second tsunami generated by a 7.9 magnitude earthquake occurred on September 20, 1935 near the northern shore of PNG in an area close to the 1998 event. However, no tsunami intensity or runup heights are available for that event. A third tsunami in northern Papua New Guinea occurred on October 31, 1970 near Madang to the east of the present event. This tsunami was triggered by a magnitude 7.0 earthquake and created 4-m high waves.

The area of greatest impact from the 1998 tsunami lies between the Bliri River to the west and the Yalingi River to the east (Fig. 1). These rivers, and several smaller ones, drain the Torricelli Mountains that lie 10–15 km from the coast. The rivers supply sand to the coast and both rivers have built large sandy deltas. This sediment supply feeds the beaches and has built sandy barrier spits that separate the low-lying coastal plain and lagoons from the ocean. The coastal plain in this region is heavily wooded, low-lying, and swampy. Although only a few meters in elevation, the high ground along the spits was the site of many of the coastal residences.

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Figure 2

Photographs of debris torn off nearby structures by the tsunami and wrapped around standing trees.

Tsunami Deposit Transects

Measurements of land elevation, flow direction, flow depth, and tsunami deposit thickness and character were made approximately two months after the tsunami. Topography was measured with a rod and level and values are reported relative to mean sea level. The small tide range and steep beach slopes permitted field estimates of mean sea level to within approximately 0.25 m. Flow direction was estimated in the field from bent or broken palms, exposed roots and grass aligned parallel on their sides, and most commonly, debris wrapped around or piled against immobile objects like palm trees left standing. Flow direction was interpreted from the orientation of the feature and measured with a compass. Flow depth was estimated by measuring the height of broken limbs, debris found in trees, debris found piled on the ground, or water marks on buildings (Fig. 2). In general, estimates of flow depth from these indicators represent minimum values.

Small pits were dug to examine the sedimentary deposits left by the 1998 tsunami. Tsunami deposits were common and identified as gray sand above a brown, rooted soil (Fig. 3). The deposits were measured, photographed, and described in the field

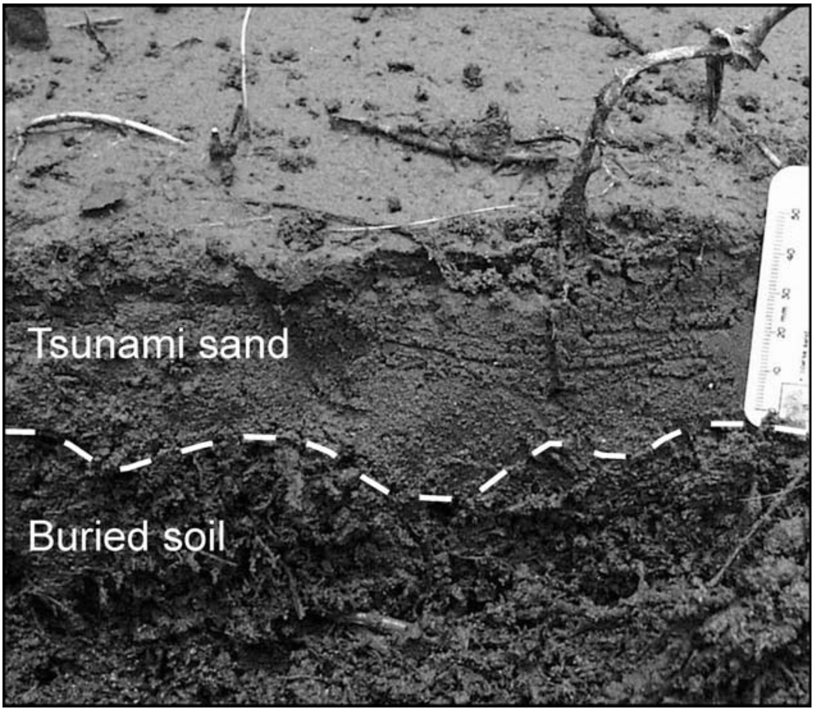

Figure 3
Photograph of sand deposited by the 1998 tsunami overlying a buried soil.

and samples were taken for laboratory analyses. In the field, bulk samples of the deposit were taken, and, in a few locations, samples were taken at 1-cm intervals down through the deposit.

Grain size was analyzed for all of the sediment samples collected. Samples were wet sieved at 4 phi to separate silt and clay from the sand-sized material. The sand was run through a setting tube and the results reported in ¼-phi intervals. The fine sediment was run through a laser-diffraction particle analyzer and also reported in ¼-phi intervals. Grain-size statistics were calculated using methods described in CARVER (1971).

Detailed measurements were made along four cross-shore transects in the vicinity of Sissano Lagoon (Fig. 1). The transects were located, from east to west, at Waipo Village, Arop School, Otto near the west end of East-Sissano spit, and at Sissano Village.

Waipo Transect

Setting and topography

The Waipo transect is adjacent to the inlet of a small lagoon near the village of Waipo, about half way between Aitape and Malol (Fig. 4). An interview with a local farmer who survived the tsunami provided a first-hand account of the event. The eyewitness reported feeling a large earthquake and seeing the trees swaying. He reported that it was difficult to stand, but that the village huts were not extensively damaged by the earthquake. Within approximately 15 minutes after the earthquake the sea first lowered, followed shortly thereafter by an approaching wall of water. The first wave was approximately 1.5-m high at a location about 200 m from shore (Fig. 4). Surveying later showed this site to be 1.5 m above sea level for a water elevation of 3 m above sea level. The first wave swept the eyewitness off his feet and carried him inland. Before the water from the first wave could withdraw, a second wave approached, riding over the water from the first wave. A short time later, a third wave approached, again riding atop the water from the first two waves. The maximum water depth at this site 200 m from the shore, as determined by information from the eyewitness, was 4.5 m above the ground, giving a total water elevation at this site of 6 m above sea level. The tsunami destroyed most of the village huts at Waipo. In addition, a steel and wooden bridge that crossed the river was ripped off its foundation and transported several tens of meters inland (Fig. 4).

The topography along the Waipo transect undulates across sandy ridges and low-lying troughs (Fig. 5a). Adjacent to the shoreline is a steep beach face and a berm at an elevation 2 m above sea level. Beyond the berm is a back beach trough that is sloped down to the west allowing water to flow parallel to shore and drain through the trough. Landward of the trough is a 1–4 m high erosional scarp with exposed roots. An eyewitness reported that the scarp was formed by the tsunami. It is not clear if a smaller scarp existed prior to the tsunami, or if the scarp formed entirely as

Figure 4
Aerial photograph showing the Waipo transect. The bridge was dislodged from its supports by the tsunami and carried landward. The white dot west of the transect is the location of the tree stump shown in Figure 6. Photograph taken August 8, 1998, three weeks after the tsunami, by the PNG National Mapping Bureau.

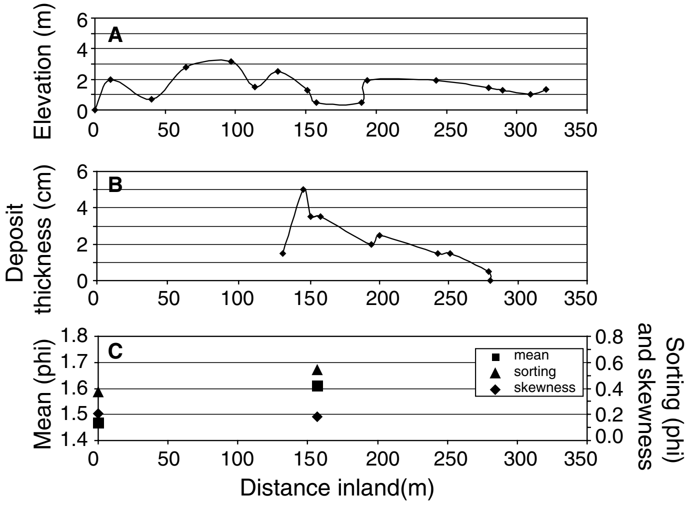

Figure 5
Topography, tsunami deposit thickness, and grain-size statistics of the beach sand and of the tsunami deposit along the Waipo transect.

a result of the return flow of tsunami water. The profile has two more sandy ridges, with elevations of 3.2 m and 2.5 m above sea level. Approximately 150 m from the shoreline is a 40-m wide trough with an elevation less than 0.5 m above sea level. This trough is intermittently wet and dry. Landward of this trough the profile flattens out at an elevation of between 1 and 2 m.

Flow direction and depth indicators

Flow at the Waipo transect traveled in two main directions, 280 degrees (west alongshore) and 210 degrees (southwest onshore) (Fig. 4). At a few locations along the transect flow indicators suggest flow in both of these directions. For example, at about 160 m from the shoreline, the flow at different times was in the cross-shore direction and perpendicular to that direction. The two directions suggest that the initial inundation of the tsunami was in the cross-shore direction, but that the water drained the coastal plain alongshore to the west to the nearby river channel.

The 1st ITST, noting broken branches and debris in trees, estimated wave heights of 4–7 m in the area around Waipo (KAWATA *et al.*, 1999). A few months later, few flow depth indicators remained along the Waipo transect, nevertheless one that did, approximately 160 m from the shoreline, was a tree stump capped nearly 1 m above the ground with a thin layer of sand (Fig. 6). This sand had likely settled out of suspension from within the tsunami and had been deposited on the stump. If so, the tsunami crested at least 1 m high at this location and carried sand-sized material in suspension at least 1 m above the bed.

Figure 6
Photograph of sand atop a tree stump 1m above the ground. The sand was deposited out of suspension from the tsunami.

Deposit

No tsunami deposit was observed over the area from the shoreline inland for 120 m. Exposed roots and debris on the ground indicated the tsunami had eroded this area. The depth of erosion was indeterminable. More than 130 m from the shoreline, a layer of light-colored sand rested on a rooted and compacted dark-colored sandy soil. The deposit thickened from 1.5 cm to a maximum of 5 cm almost 150 m from the shoreline (Fig. 5b), then thinned to the most inland deposit 280 m from the shoreline. Vegetation (trees and underbrush) was densest beyond the landward limit of the tsunami deposit at this transect. The limit of tsunami inundation was found about 40 m further landward than the limit of the tsunami deposit.

Sedimentology

The tsunami deposited a thin sedimentary layer that grades upward from coarse sand at the base of the deposit to fine sand above. This fining upward was observed only in deposits more than a few centimeters thick. The thinner deposits either were not vertically graded or the grading was not detected. The tsunami deposit overlay a compact sandy soil and the contact between the deposit and the soil was typically abrupt. The tsunami deposit was too thin along this transect to collect several vertically-spaced samples for laboratory analysis of the fining-upward sequence. Grain-size analyses were conducted on bulk samples from two sites along the Waipo transect. The mean grain size of the beach sand at the shoreline was 1.5 phi, slightly coarser than the mean size of the tsunami deposit 157 m from the shoreline which was 1.6 phi (Fig. 5c). Sorting and skewness are likewise similar at the two sites. The mode of both samples is 1.25 phi. The size distributions suggest that the sand at the shoreline could be the source of the sandy layer deposited by the tsunami further inland.

Arop Transect

Setting and topography

The Arop transect, located about 500 m east of Sissano Lagoon, traversed the Arop school complex (Fig. 7). The Arop village was one of the areas hit hardest by the tsunami, with over 800 people killed and all of the village huts destroyed. Much of the village had been located on the narrow sandy spit between the ocean and Sissano Lagoon (Fig. 1). Close to shore, the tsunami completely uprooted full-sized palm trees and carried them inland. The Arop school, located east of the Lagoon and approximately 600 m south of the shoreline, suffered damage to some of its buildings.

The Arop transect crosses a steep beach face backed by a broad low-lying plain (Fig. 8a). The beach berm is 2.2 m high and is the highest elevation along the entire 700-m long transect. Landward of the berm the profile drops to less than 0.5 m above mean sea level and gradually rises to 2 m above sea level 700 m inland.

Flow direction and depth indicators

Flow direction indicators along the Arop transect suggest two main directions of flow (Fig. 7). Many of the indicators record onshore flow roughly perpendicular to the shoreline (240 degrees). Other indicators imply return flow parallel to the shoreline (320 degrees) through a broad topographic low (approximately 80 to 350 m from the shoreline). Landward of 350 m from shore, where the elevation gradually rises from 0.5 to 2 m above sea level, all evidence indicates onshore flow only. In general, the return flow was toward the lagoon and not back toward the beach.

The 1st ITST estimated wave heights of 10–15 m along the coast near Arop (KAWATA *et al.*, 1999). These estimates came from broken branches near the tops of trees and debris found in the trees within 100 m of the beach. We estimated water levels further inland along the transect. At 200–450 m inland, water 1.7–4.5 m high piled debris against trees and broke branches in standing trees. Between 500–700 m inland, water levels decreased from 1.3 m to 0.3 m within 50 m of the limit of tsunami inundation. These estimates contain uncertainty because the level at which debris is piled up against an obstacle like a tree can be either higher or lower than the water level at the time of inundation.

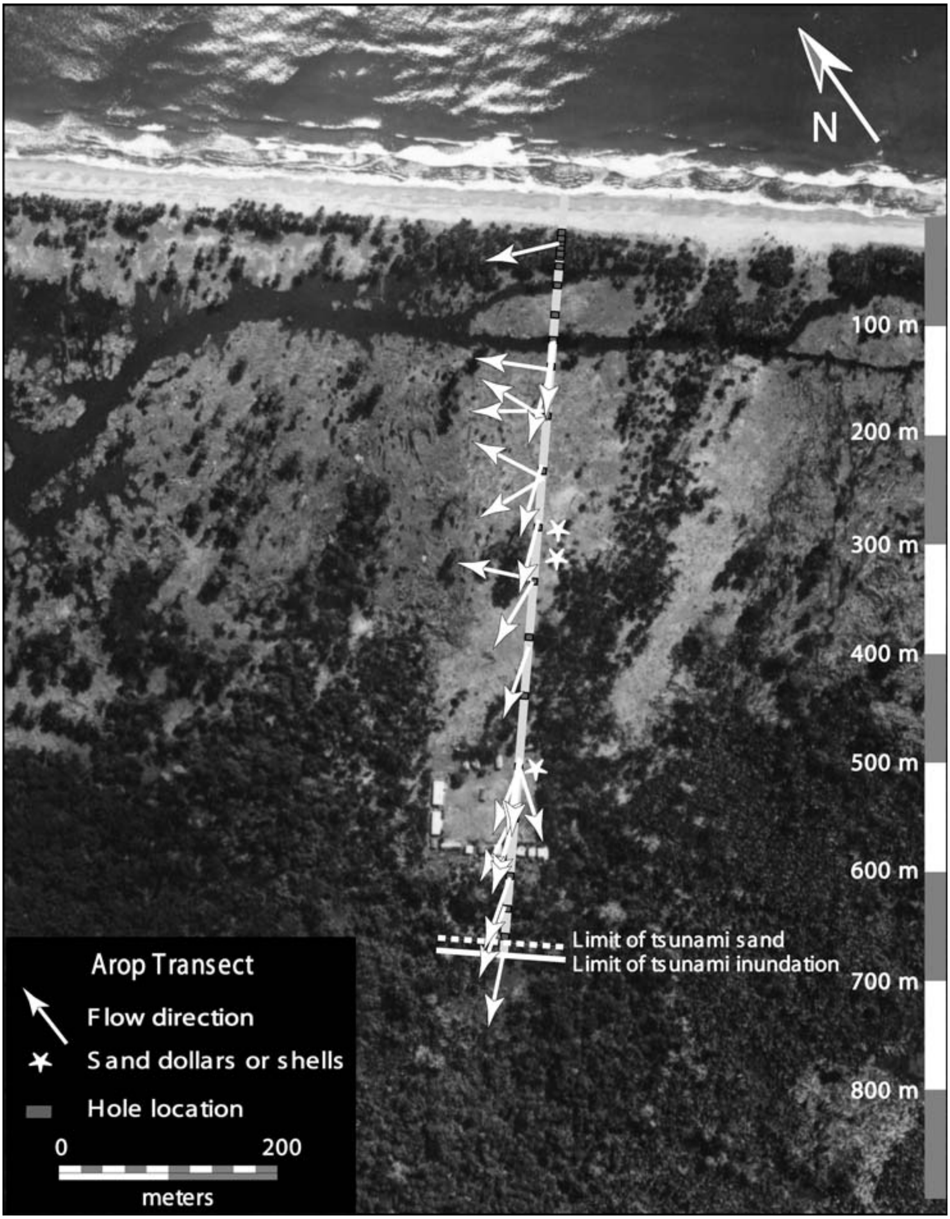

Figure 7
Aerial photograph showing the Arop transect. Photograph taken August 8, 1998 by the PNG National Mapping Bureau.

Deposit

The beachface and berm showed no evidence of deposition from the tsunami. On the berm, exposed roots and scour at the base of some palm trees indicated erosion of

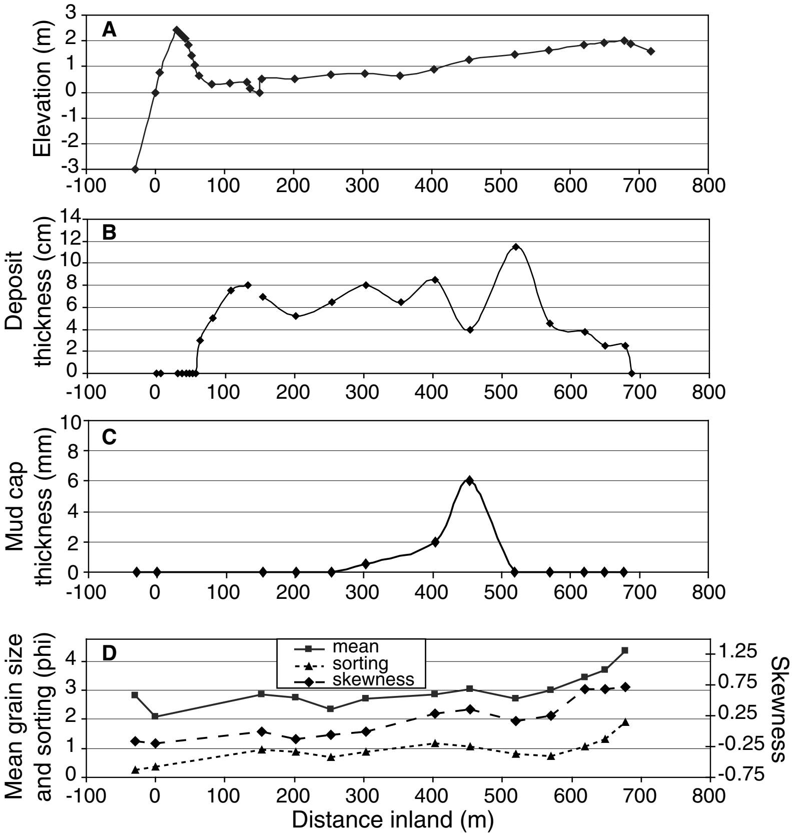

Figure 8
Topography, tsunami deposit thickness, and grain-size statistics of the beach sand and of the tsunami deposit along the Arop transect.

an estimated 20–30 cm of sand. The zone of erosion extended to the landward side of the berm, about 50 m from the shoreline.

At about 70 m from the shoreline and within the span of a few tens of meters, the deposit thickness increased to about 8 cm (Fig. 8b). The tsunami deposit was easily identified as a gray sand overlying a brownish muddy soil. The deposit thickness remained relatively constant from 100 to 500 m from shore, varying by only a few centimeters. The deposit thickness peaked at 11 cm approximately 520 m from the shoreline. From there, the deposit thickness decreased in the landward direction over the next 150 m. The deposit further tapered to near zero thickness at a distance of 680 m from the shoreline. The limit of tsunami inundation, as defined by a small debris line, was 720 m from the shoreline.

At some locations along the transect, a thin layer of mud capped the tsunami sand (Fig. 8c). This mud cap, up to 0.6-cm thick, was found mainly in local depressions. The mud cap was the last material to settle out of suspension. Whole sand dollars (a few cm in diameter) and small shells were found on the surface of the deposit as far as 500-m inland (Fig. 7).

Sedimentology

Trends perpendicular to shore The tsunami deposit along the Arop transect was easily identified in the field as a gray sand overlying a brown muddy soil. In a few places, the deposit contained small rip-up clasts from the underlying soil (Fig. 9). At most sites along this transect the tsunami deposit was normally graded, with medium to coarse sand at the base fining upward to fine sand or mud at the top.

Bulk samples of the tsunami deposit were collected at each site along the Arop transect for laboratory analysis. Figure 8d shows the cross-shore trends in mean

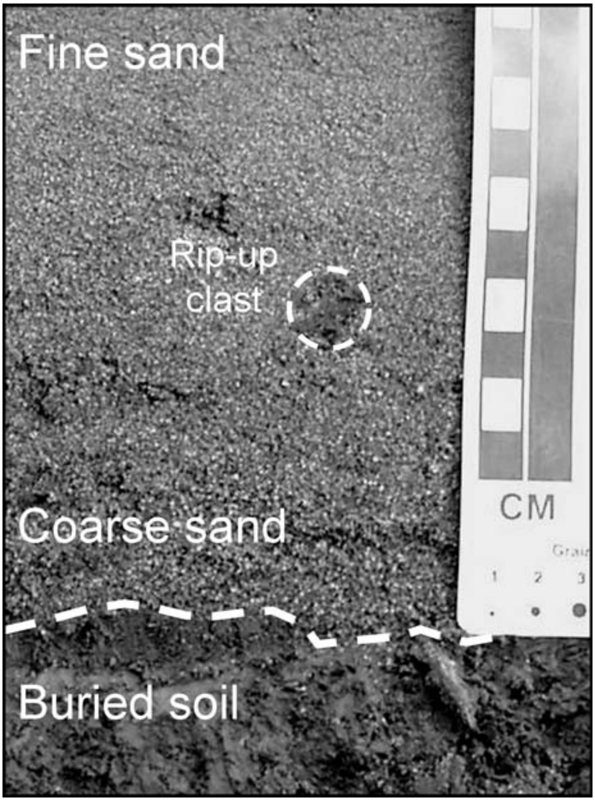

Figure 9
Photograph of the tsunami deposit layer overlying a buried soil. The deposit is normally graded with medium sand near the base and fine sand toward the top. Within the deposit is a rip-up clast of muddy soil.

grain size, sorting, and skewness across the Arop transect. Sand samples taken from the shoreline and from -3 m depth only 30 m offshore show local variability in grain size of the beach material. The beach sand is well sorted and the mean size varies from 2 to 3 phi. Combining both the offshore (-3m depth) and shoreline sites, sand is found in all size classes from 1 to nearly 4 phi.

Along the transect from approximately 150–520 m from the shoreline the mean grain size and the sorting of the sand in the tsunami deposit remain relatively constant. From about 520 m from the shoreline to the limit of the tsunami deposit at 680 m the deposit gets finer. The mean grain size decreases to about 3.25 phi. The decrease in mean size is due almost entirely to an increase in the amount of silt and clay-sized material. The grain-size trend at the Arop transect does not follow the simple model of landward fining. While it is true that the grain size at the beach is coarser than the grain size at the limit of deposit inundation, for the majority of the transect at Arop, the grain size of the tsunami deposit does not vary with distance inland.

Vertical trends At a site approximately 400 m from the shoreline, several sub-samples were taken to quantify the vertical variations in grain size within the deposit. At this site the tsunami deposit was 8-cm thick. Eight samples were taken at 1-cm intervals. The vertical distribution in mean grain size confirms the fining upward sequence that was observed in the field (Fig. 10). The mean grain size smoothly

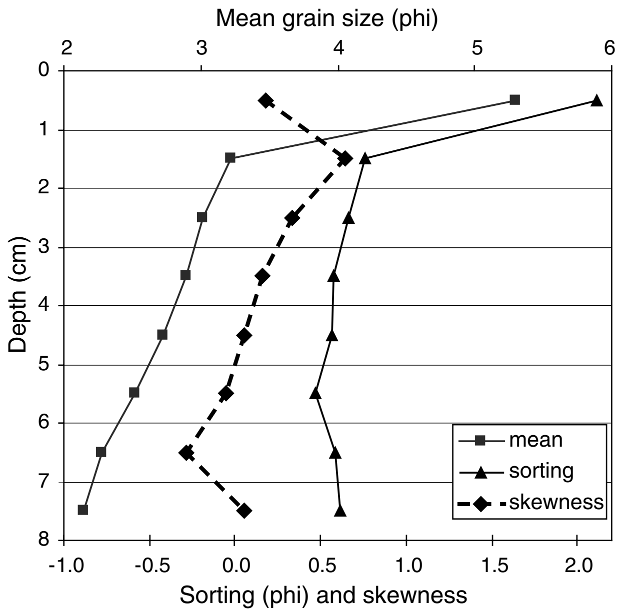

Figure 10
Mean grain size, sorting and skewness at 1-cm intervals of the tsunami deposit in Figure 9.

decreases from 2.25 phi at the base of the deposit to 3.25 phi just below the surface. The surface layer contained mud that decreased the mean size of the top 1 cm to 5.3 phi. The origin of the mud, either from erosion of the underlying soil or from an offshore source, could not be determined.

Otto Transect

Setting and topography

The Otto transect was located near the west end of the sandy barrier spit that extends to the west from Arop and fronts Sissano Lagoon. The width of the spit along this transect, as well as along much of the over 5 km length of the spit, is narrow, extending less than 200 m across from the ocean to the lagoon (Fig. 11). The spit was sparsely to densely populated with vegetation, primarily with a few different varieties of palm trees and low grasses. The highest elevation along the Otto transect is merely 0.73 m above sea level at the primary beach berm located 15 m from the shoreline (Fig. 12a). The elevation drops steadily from a maximum at the berm down to zero at the edge of the lagoon a distance of 160 m from the shoreline.

Flow direction and depth indicators

The entire barrier spit fronting Sissano Lagoon, including the area at the Otto transect, was inundated by the tsunami. All flow direction indicators point landward, roughly perpendicular to the shoreline (Fig. 11). Indicators included fallen palm trees, laid-over grasses, and debris wrapped around obstacles such as standing trees. No flow indicators representing return flow were found along the spit near this transect.

Few flow depth indicators were found along the west end of the eastern barrier spit fronting Sissano Lagoon. Those observed by the 1st ITST suggested maximum tsunami heights of between 10 and 15 m (KAWATA *et al.*, 1999).

Deposit

As at Waipo and Arop, the beach face and berm at Otto showed no evidence of a recent tsunami deposit. Along the first 40–50 m across the top of the berm, exposed roots of grasses and scour around trees indicate erosion. The amount of this erosion is estimated at 10–20 cm.

Starting at a distance of about 60–70 m from the shoreline, about 10 cm of well-sorted gray medium-coarse sand overlay a brown organic-rich soil of muddy sand. Just below the base of the tsunami deposit were root clumps. Fresh grasses still connected to their root clumps were laid over pointing inland within the lower part of the gray sand. The sandy tsunami deposit increased in thickness to a maximum of about 26 cm at a distance of 90 m from the shoreline, then remained nearly constant for at least several tens of meters (Fig. 12b).

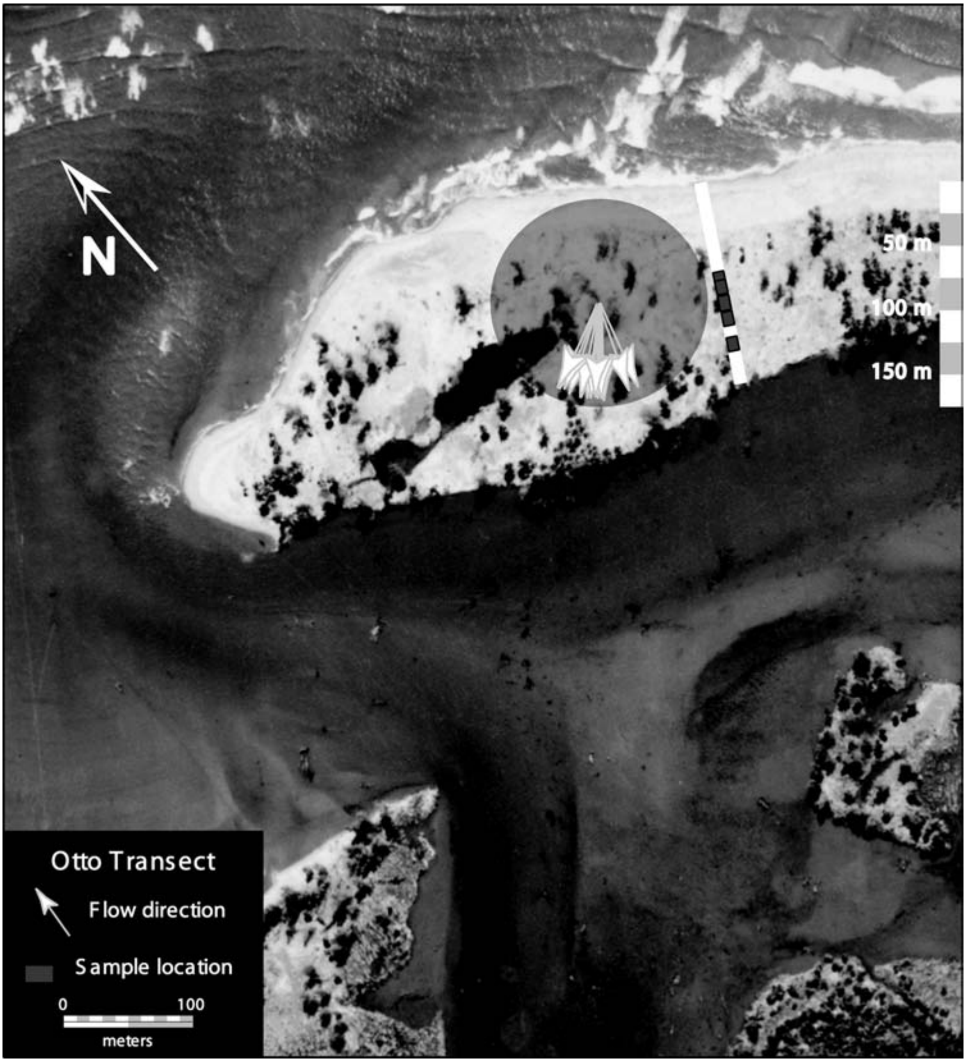

Figure 11
Aerial photograph showing the Otto transect. Photograph taken August 8, 1998 by the PNG National Mapping Bureau.

Sedimentology

Sediment samples of the tsunami deposit were taken from five sites along the Otto transect for laboratory analysis. These sites span only a distance of about 50 m along the center of the spit. In this distance the mean grain size, sorting, and skewness all remain nearly constant across the transect (Fig. 12c). This distance is probably too short to demonstrate horizontal trends in grain size.

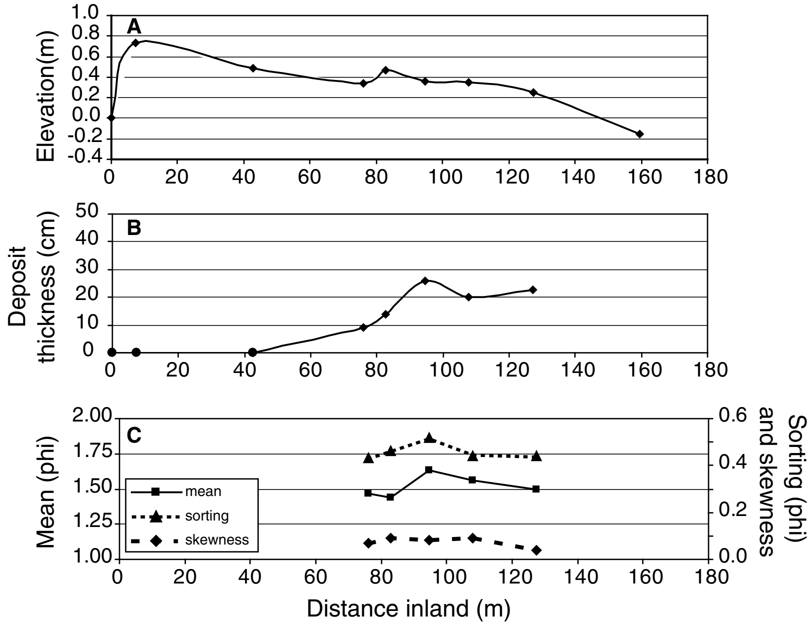

Figure 12
Topography, tsunami deposit thickness, and grain-size statistics of the tsunami deposit along the Otto transect.

Field observations along the Otto transect revealed a tsunami deposit with a massive lower layer from 10–15 cm thick below a thinly laminated upper layer 5–10 cm thick. The laminae showed no signs of ripple cross bedding.

Sissano Transect

Setting and topography

The villages of Sissano and Warapu had been located on the west side of Sissano Lagoon. Warapu, located on the narrow spit between the ocean and the lagoon, was totally destroyed by the tsunami. Sissano was further to the west and set back from the ocean (Fig. 1). Over 1000 people from these two villages lost their lives as a result of the tsunami, and many more were displaced.

The Sissano transect crossed the Sissano village about 3 km west of Sissano Lagoon (Fig. 13). The transect was approximately 600-m long and ended at a small river that flows parallel to the shoreline and is connected to the lagoon.

We interviewed two eyewitnesses who had been in their homes in the Sissano village about 450 m from the shoreline when the earthquake and tsunami occurred. They reported seeing a highly turbulent wave approach that inundated the area all the way to the river. At their house, the wave height was about 1.4 m. The first

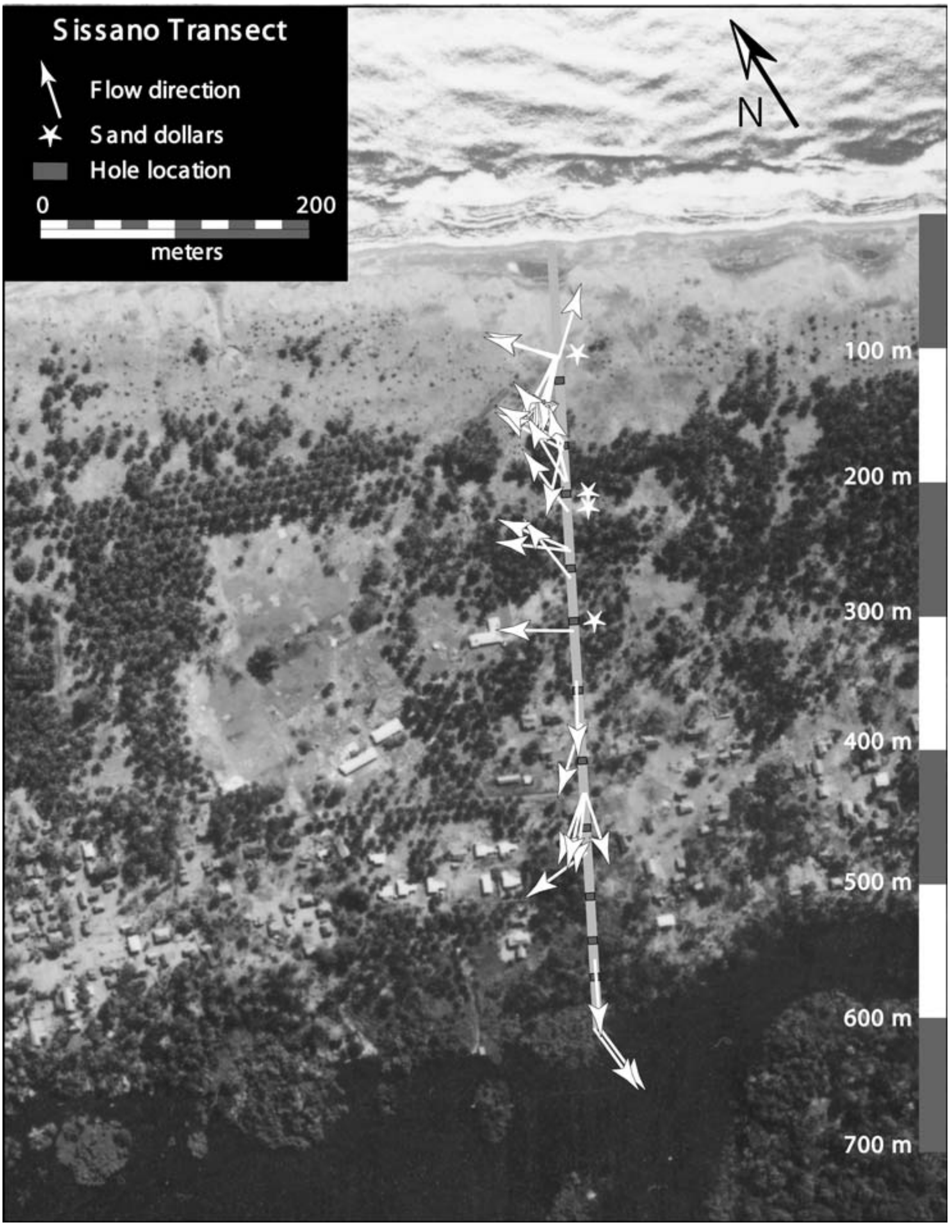

Figure 13
Aerial photograph showing the Sissano transect. Photograph taken August 8, 1998 by the PNG National Mapping Bureau.

wave had little or no return flow associated with it. Soon after the first wave, the second wave rode in over the already flooded village. Likewise, the third wave came in soon after, riding on top of the second wave. After the third wave, the eyewitnesses noticed a return flow as the waters in the flooded village started to recede (Fig. 14).

The Sissano transect crosses a low beach berm and narrow trough close to the shoreline, and it continues across a broad flat plain almost 600 m to a small river connected to the lagoon (Fig. 15a). The beach berm and trough are close to the shoreline and the berm reaches only 1 m above sea level. Landward of the trough the elevation rises gradually to 2.5 m above sea level at a distance 100 m from the shoreline. From there the profile remains nearly flat, undulating slightly, and gradually rising to 3 m above sea level 500 m from the shoreline. From the maximum elevation of 3 m the profile descends toward sea level at the river.

Flow direction and depth indicators

Flow direction indicators were measured at several locations along the Sissano transect and are plotted on the aerial photograph in Figure 13. Indicators suggest

Figure 14
Photograph near the Sissano transect showing two flow directions. The fallen palm trees indicate the direction of the main tsunami inundation (1) and the bent grasses indicate the direction of subsequent return flow (2).

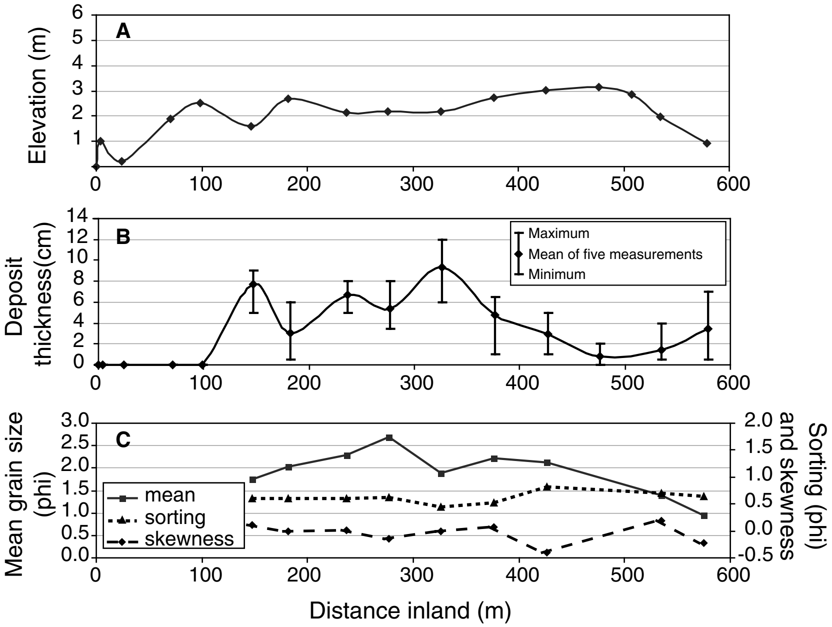

Figure 15
Topography, tsunami deposit thickness, and grain-size statistics of the tsunami deposit along the Sissano transect.

flow in several directions along the Sissano transect. Numerous fallen trees within 200 m of the shoreline represent the primary flow and are all aligned in approximately the southwest direction at 230°. Bent-over grass and piles of debris wrapped around standing trees suggest a secondary flow in the northwest direction at 340°. Other secondary flow indicators were aligned toward the northeast at 40° or toward the north at 350°. We ascribe the primary flow to initial high-energy inundation of the tsunami, and the secondary flow to backwash or return flow. Secondary flow indicators like grasses are easily aligned by even small flows, so they probably indicate the direction of the last flow to which they were subjected. A site 185 m from the shoreline contains both primary (220°) and secondary (350°) flow indicators suggesting two phases of flow at different times (Fig. 14). The return flow indicators all along the transect are aligned toward local topographic lows.

The 1st ITST estimated wave heights along the coast near Sissano of 5–10 m (KAWATA *et al.,* 1999). These estimates came from broken branches near the tops of trees and debris found in the trees. Inland along the transect we estimated the flow depth by measuring the height of debris found in trees and the height of debris piled up against trees or pilings. At a distance of 350 m from the shoreline we observed flow depth indicators at 1.8 m above the ground. Around 475 m from the shoreline we measured depth indicators at 0.8 m, 0.9 m, 1.2 m, and 1.5 m above the ground.

Deposit (small-scale lateral variability)

Within the first 100 m of the shoreline along the Sissano transect we found no evidence of tsunami deposition. By 150 m from the shoreline the tsunami deposit was almost 8 cm thick on a rooted and compact sandy soil. Variability in the tsunami deposit thickness was determined by measuring the thickness along the transect and by measuring the thickness 5 and 10 m away along a line perpendicular to the main transect (Fig. 15b). From 150 to 425 m inland along the Sissano transect the variability in the shore-parallel direction is similar to the variability in the shore-normal direction. In this zone, the average thickness is about 6 cm, the minimum is 0.5 cm, and the maximum is 12 cm. The tsunami deposit thins from a maximum of 12 cm thick at about 350 m to a minimum of 0–2 cm thick at a distance of 474 m from the shoreline. Approaching the river, the tsunami deposit thickens again slightly.

Sedimentology

Field observations revealed more variability and complexity in the sedimentology of the tsunami deposit along the Sissano transect than along the Otto, Arop, or Waipo transects. At Arop in particular, the tsunami deposit is a single fining upward layer. Along the Sissano transect the deposit in some places is a single fining upward layer, but in other places the deposit is composed of multiple layers. At 150–275 m from the shoreline we noted only one layer. Along that stretch, the mean grain size of the deposit decreases landward (Fig. 15c). At 320 m and beyond, the deposit contains two recognizable layers, both of which commonly fine upwards. Mean grain size increases landward along this part of the transect. Except at the location 320 m from the shoreline, only one depth-integrated sample was collected for grain-size analysis at each location. If there were multiple layers deposited from different waves, then a simple trend in grain size of the composite would not be expected.

At the site 320 m from the shoreline, where the deposit was 6-cm thick, samples were collected at 1-cm intervals from the top of the deposit to the base. The mean, sorting, and skewness of the sediment at each depth in the deposit is shown in Figure 16. While the sorting and skewness remain nearly constant with depth in the deposit, the mean grain size clearly shows two fining-upward sequences. Because the mean grain size is reported at the depth of the center of the sample, Figure 16 does not properly show the actual transition between the two layers. In fact, the transition between the two layers is abrupt. The abrupt transition in grain size may or may not represent an erosional surface. We do not know whether or not a part of the lower layer was eroded before deposition of the upper layer.

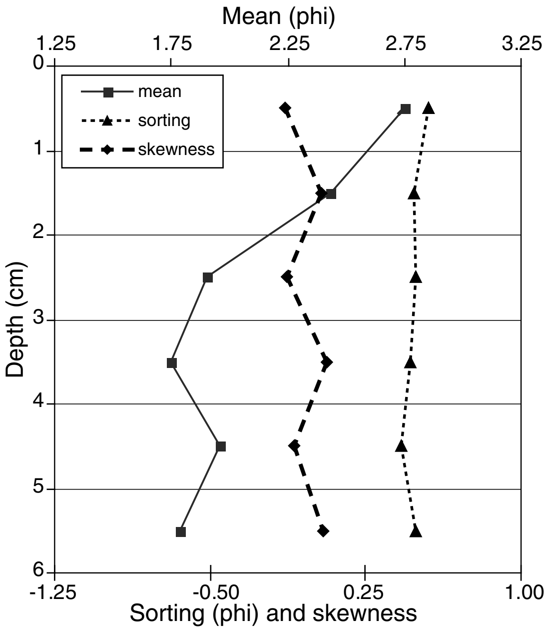

Figure 16
Mean grain size, sorting and skewness at 1-cm intervals of the tsunami deposit on the Sissano transect 320 m from the shoreline. The deposit here contains two fining-upward sequences suggesting deposition out of suspension from two waves.

Discussion/Summary

Shore-normal Trends in Deposit

The tsunami waves that struck PNG approached land with sufficiently high velocities to suspend and transport large quantities of sand. Despite their destructive power, in which trees were uprooted and structures destroyed, the waves left behind a sandy deposit. This sandy layer was deposited as a continuous sheet that varied in thickness depending, in part, on local topography, the presence of obstructions, and the density of vegetation.

A tsunami deposit was found at every site we visited along the northern PNG coast in the vicinity of Sissano Lagoon extending from approximately 100 m from the shoreline across the coastal plain to very near the limit of inundation, a distance of up to 750 m. At Waipo the deposit tapers inland from a maximum thickness near the shoreline. At Arop and Sissano, however, the deposit is more nearly tabular, with a rapid increase in thickness near the coast, a long nearly flat middle section, and then a gradual decrease on the landward side. The maximum thickness is not near the coast, but farther inland. Along the Otto transect the spit is so narrow that it was completely inundated by the tsunami, which flowed a long ways into the lagoon. Therefore, a deposit shape was not determined.

Along each of the transects in which both the landward limit of sand deposition and the landward limit of the tsunami could be identified, the landward limit of the deposit fell short of the limit of tsunami inundation. The sand stopped 40–50 m short of the landward limit of the tsunami at the Arop and Waipo transects. At Otto, the landward limit of the deposit was not found, and at Sissano, neither limit was found. DAWSON (1994) measured similar distances between the deposit and the maximum inundation for the Java tsunami.

Along all four transects, the areas with net erosion as a result of the tsunami were limited to portions of the beach and berm close to the ocean. The width of that zone varied from 50–150 m and was located adjacent to the shoreline. The thickness of sand eroded by the tsunami was difficult to determine accurately, but we estimated it at 10–25 cm using the depth of exposed roots. Only at Warapu did erosion extend far from the beach. There, on a narrow western spit between the ocean and Sissano Lagoon (Fig. 1) erosion occurred not only along the beach and the top of the berm, but also on the central portion of the spit (Figs. 17, 18). Eyewitness accounts and scour exposing tree roots show that this area eroded up to 1.3 m for many tens of meters in the shore-normal direction. Perhaps the wave broke over the top of the spit

Figure 17
Photograph of a tree with exposed roots near Warapu. The depth of the exposed roots and eyewitness accounts suggest 1–1.5 m of erosion of sand from the barrier spit.

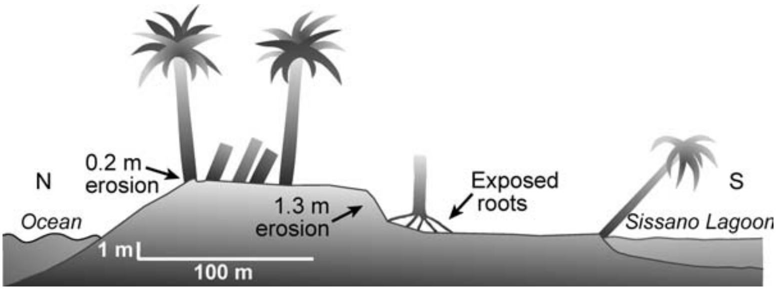

Figure 18
Sketch of profile near Warapu showing erosion on the back side of the barrier spit.

and plunged to the ground resulting in the added scour, or an alongshore flow originated from the lagoon that scoured into the spit, or maybe a hydraulic jump formed over the berm.

The source of the sand transported by a tsunami can be difficult to identify. Several clues help identify the source for the sediment deposited in PNG. First, along both the Sissano and the Arop transects the deposit contains many marine shells, including small sand dollars. The sand dollars must have been transported from at least several tens of meters offshore since sand dollars typically live outside the normal wave breaking zone. Second, too little sand was eroded from the sub-aerial beach to account for the total volume deposited. The volume of sand deposited per unit distance in the alongshore is calculated along the Arop transect to be 36 m^3/m. If the average scour depth was 25 cm, the amount of sand eroded landward of the shoreline was only 14 m^3/m. This is likely a high estimate because the maximum scour across the berm was probably 25 cm, the average would be less. This analysis suggests that sand must have been supplied from offshore. In fact, more than twice as much sand came from offshore as came from the subaerial beach and berm. This result for PNG differs from the observations by SATO *et al.* (1995), who found that deposits of the 1993 and 1983 Japan Sea tsunamis came mainly from the sub-aerial beach and berm.

Alongshore Trends in Deposit

The zone of inundation from the 1998 tsunami covered only about 40 km in the alongshore direction. Within this 40-km long stretch of coast the maximum wave levels varied from 2–3 m near Aitape in the east to nearly 15 m along the spit fronting Sissano Lagoon and back down to 2–3 m near the Bliri River to the west. A section of coast spanning about 20-km long sustained water levels over 10-m high. This focusing of wave energy may reflect several factors, including the proximity of the source disturbance and the focusing nature of the bathymetry on the shelf and slope (MATSUYAMA *et al.*, 1999).

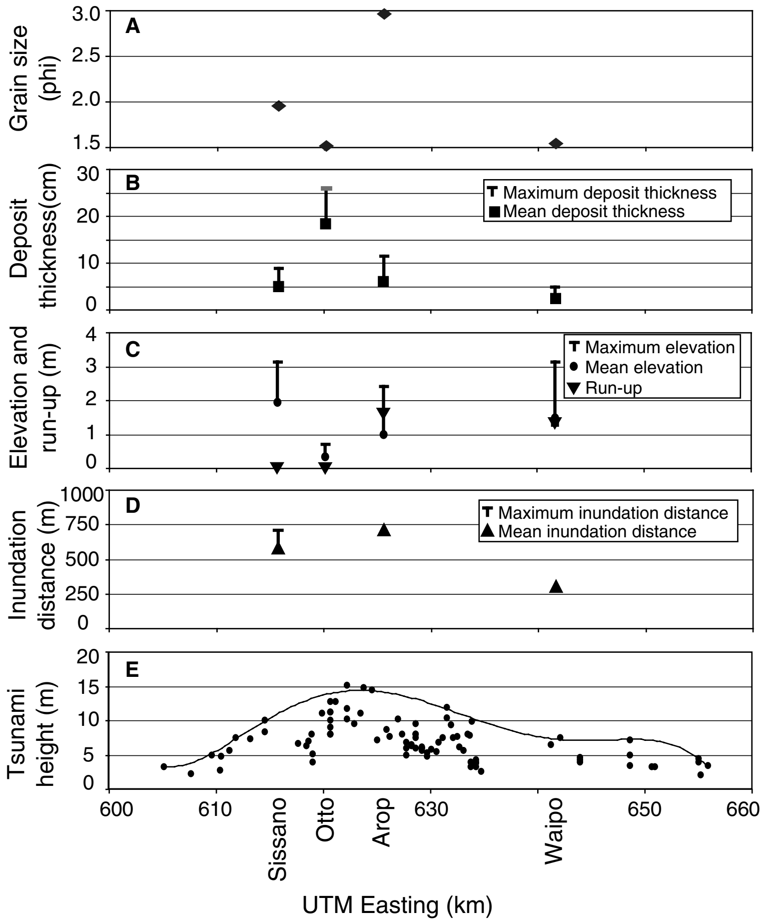

Figure 19

Alongshore variation in A) mean grain size of the tsunami deposit from each transect; B) mean and maximum tsunami deposit thickness; C) average and maximum elevation, and runup; D) inundation distance; and E) tsunami height as reported by KAWATA *et al.* (1999). The smooth curve is a spline through the maximum wave heights.

Tsunami inundation distance, or the distance measured from the shoreline to the landward limit of inundation, varied in a similar manner to the wave height, with the maximum inundation near the lagoon (Fig. 19). The maximum inundation distance that we observed over land, at the Arop transect, measured about 750 m. The tsunami penetrated even farther where the waves traveled over the lagoon. Eyewitnesses reported that debris carried by the tsunami washed up against the southern shores of the lagoon up to 4–5 km from the spit, or nearly five times farther over water than over land.

Tsunami runup, or the elevation relative to sea level at the landward limit of inundation, does not appear related to tsunami wave height (Fig. 19). By contrast, for short-period wind waves on beaches, runup is found to depend on beach slope, wave height, and wave period (BATTJES, 1974; HOLMAN and SALLENGER, 1985). Moreover, based on laboratory and numerical studies, SYNOLAKIS (1991) found that the runup from unbroken long-period tsunami waves on a plane beach depends on beach slope and wave height. In Papua New Guinea, runup of the tsunami was complicated by, among other things, irregular topography; none of the sites have a simple topographic profile of a monotonically increasing elevation from the shoreline to the limit of inundation. In other words, none of the sites consist entirely of a plane beach. Along much of the coast the maximum elevation is at the beach berm or along a beach ridge, then the elevation decreases again in the landward direction. In fact, even though the wave height was over 10 m at the Otto and Sissano transects, the runup is close to 0 m because the tsunami inundation extended to the far side of a lagoon and a river leading to the lagoon, respectively. The complicated topography, varying roughness across sand, mud, and vegetation, and varying degree of infiltration into the soil below result in no clear relationship between wave height and runup (Fig. 19).

On a regional scale, tsunami deposit thickness does appear related to wave height (Fig. 19). Deposit thickness (both the maximum across the transect and the mean) is smallest at Waipo where the wave height was smallest and greatest at Otto and Arop, where the wave height was greatest. The thickness of the sand layer deposited by the tsunami varies locally as well as regionally in the alongshore direction. Locally, the tsunami deposit thickness varies about twofold in response to variations in local topography. In general, deposit thickness increases slightly in local depressions and decreases over local highs in the topography.

Mean grain size of the tsunami deposit seems unrelated to deposit thickness or wave height (Fig. 19). The grain size of the deposit more likely depends on the grain size of the sediment available to be transported. Based on estimates of the water velocity in the tsunami from the 1st ITST (1998), all of the sediment grain sizes on the PNG coast within the study area are easily transported.

Vertical Trends in Deposit

Sediment transport and depositional processes can be inferred from the detailed vertical trends in the tsunami deposit. Most of the deposits examined are vertically graded, meaning the grain size varies with depth in the deposit. Most sites had one continuously graded bed with the coarsest material at the base and fining upward. A few sites had multiple normally graded beds one atop another. Each graded bed implies deposition from suspension as flow velocity decreases. Normal grading is a common sedimentary structure associated with deposition from a turbulent suspension. For example, normal grading is a common feature of turbidites, the deposits formed by deposition from a turbidity current (SANDERS, 1977). In a turbulent flow there is a sediment grain-size gradient, with coarse material proportionally concentrated near the bed and finer material more evenly distributed throughout (SMITH, 1977; GELFENBAUM and SMITH, 1986). As the flow wanes and the sediment settles out of suspension, the coarse material will settle first and the finer material will follow. At Arop, the normally graded deposit suggests deposition from a single event or wave. At Sissano, the two layers of normally graded sediment imply deposition from two tsunami waves.

At both locations, the number of graded beds is less than the number of waves reported by eyewitnesses. Throughout the region, eyewitnesses consistently reported three waves inundating the coast. Apparently, each wave that struck the coast did not deposit a sandy layer. Or else, each wave deposited a sandy layer that was subsequently resuspended with the passage of the next wave. Unfortunately, there does not appear to be a one-to-one relationship between the number of waves inundating the coast and the number of sandy layers in a deposit.

Conceptual Model of Tsunami Sedimentation

The detailed observations of erosion and deposition from the PNG tsunami can be used to develop a conceptual model of tsunami sedimentation. In general, the thickness and grain-size distributions found in tsunami deposits are the result of the sediment transport during tsunami inundation. Based on conservation of mass, the rate of change in bed elevation (erosion or deposition) is related to the rate of change of storage of sediment in the water column and to the horizontal gradient of sediment transport, and can be expressed by

$$\frac{\partial \eta}{\partial t} = -\frac{1}{C_b}\left(d\frac{\partial \overline{C}}{\partial t} + \frac{\partial Q}{\partial x}\right) , \qquad (1)$$

where η is the bed elevation, C_b is the sediment concentration in the bed (≈ 0.6), d is the flow depth, $\overline{C}$ is the mean suspended-sediment concentration, and Q is the sediment flux in the shore-normal (x) direction (MIDDLETON and SOUTHARD, 1984). The sediment flux is the product of the velocity and the sediment concentration. The erosion of the beach and berm along the seaward side of each of the transects suggests that the sediment flux within the tsunami was increasing in the landward direction all the way to where deposition began, at a point some 50–150 m inland from the shoreline. This transition from erosion to deposition most likely coincides with the location of the maximum horizontal velocity along each transect.

Deposition of sediment from the tsunami results from a combination of both terms in Equation (1). Both processes, a decrease in sediment storage in the water column as sediment settles out of suspension and convergence of the horizontal sediment flux, take place to varying degrees at different times and locations. Isolating the dominant term for any given situation is not simple. If the horizontal convergence of sediment flux is the dominant process leading to deposition, then the grain size in the deposit should decrease with landward distance. If the decrease in sediment storage in suspension over time controls deposition, then the deposit should be vertically graded with a fining upward sequence. Because the tsunami deposit at both the Arop and the Sissano transects vary little in grain size in the shore-normal direction, and because fining upward sequences are common, settling from suspension was the dominant process leading to deposition at these sites in Papua New Guinea.

Conclusions

Shore-normal transects show signs of flow, erosion, and deposition from the Papua New Guinea tsunami of 17 July, 1998:

1. A distinct deposit was left by the tsunami. The deposit was distributed continuously across the coastal plain and varied in thickness. The average thickness along the transects was 8 cm and the maximum thickness was 26 cm. Rip-up clasts of mud and soil indicate erosion of the underlying soil.
2. Upward fining sediments suggest sediment fell out of suspension before the water retreated. Some deposits show multiple graded beds suggesting multiple waves.
3. The tsunami accelerated across the beach and berm. Erosion of the beach and berm extended 50–150 m inland from the shoreline.
4. As much as 2/3 of the tsunami deposit came from offshore, as shown by clam shells and sand dollars in the deposit and by comparison between volumes of sediment deposited and eroded on the sub-aerial beach and coastal plain.
5. The incoming tsunami flowed nearly perpendicular to shore, but a slower backwash, or return flow, was directed obliquely to the shore, toward local lows in topography.
6. Tsunami deposit thickness and inundation distance varied along the coast. They were greatest where the tsunami wave height was greatest and decreased with decreasing wave height.

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References

ATWATER, B. F. (1987), *Evidence for Great Holocene Earthquakes along the Outer Coast of Washington State,* Science *236*, 942–944.

BATTJES, J. A. (1974), *Surf Similarity*, Proc. 14th Coastal Engineering Conference, Am. Soc. Civil Engrs., 466–479.

BOURGEOIS, J., and MINOURA, K. (1997), *Palaeotsunami studies—Contribution to mitigation and risk assessment*. In *Tsunami Mitigation and Risk Assessment* (ed. V. K. Gusiakov) pp. 1–4.

CARVER, R. E. *Procedures in Sedimentary Petrology* (New York, John Wiley and Sons 1971) 653 pp.

DAVIES, H. (1999), *Tsunami, PNG 1998*, University of Papua New Guinea Press, Port Moresby, 49 pp.

DAWSON, A. G. (1994), *Geomorphological Effects of Tsunami Run-up and Backwash*, Geomorphology *10*, 83–94.

GEIST, E. L. (2000), *Origin of the 17 July 1998 Papua New Guinea Tsunami: Earthquake or Landslide?* Seismol. Res. Lett. *71* (3), 344–351.

GEIST, E. L. (2001), *Reply to Comments by E. A. Okal and C. E. Synolakis on "Origin of the 17 July 1998 Papua New Guinea Tsunami: Earthquake or Landslide?"* Seismol. Res. Lett. *72* (3), 367–372.

GELFENBAUM, G. and SMITH, J. D. (1986), *Experimental Evaluation of a Generalized Suspended-Sediment Transport Theory*. In Shelf Sands and Sandstones (Knight, R. J. and McLean, J. R., eds.), Canadian Society of Petrolium Geologists, Memoir, pp. 133–144.

GOFF, J., CHAGUE-GOFF, C., and NICHOL, S. (2001), *Palaeotsunami Deposits: A New Zealand Perspective*, Sedimentary Geology *143*, 1–6.

HOLMAN, R. A. and SALLENGER, A. H. (1985), *Setup and Swash on a Natural Beach*, J Geophys. Res *90*, 945–953.

JAFFE, B. E. and GELFENBAUM, G. (2002), *Using Tsunami Deposits to Improve Assessment of Tsunami Risk*, Solutions to Coastal Disasters '02 Conference Proceedings, 836–847.

KAWATA, Y., BENSON, B., BORRERO, J. DAVIES, H., DE LANGE, W., IMAMURA, F., LETZ, H., NOTT, J., and SYNOLAKIS, C. E. (1999), *Tsunami in Papua New Guinea was as Intense as First Thought*, EOS, Trans. Am. Geophys. U. *80*, 101–105.

MATSUYAMA, M., WALSH, J. P., and YEH, H. (1999), *The Effect of Bathymetry on Tsunami Characteristics at Sissano Lagoon, Papua New Guinea*, Geophys. Res. Lett. *26* (23), 3513–3516.

MCSAVENEY, M. J., GOFF, J. R., DARBY, D. J., GOLDSMITH, P., BARNETT, A., ELLIOTT, S., and NONGKAS, M. (2000), *The 17 July 1998 Tsunami, Papua New Guinea: Evidence and Initial Interpretation*, Marine Geology *170*, 81–92.

MIDDLETON, G. V. and SOUTHARD, J. B. (1984), *Mechanics of Sediment Movement*, SEPM Short Course Number 3, 2nd Edition, Providence, 401 pp.

NISHIMURA, Y. and MIYAJI, N. (1995), *Tsunami Deposits from the 1993 Southwest Hokkaido Earthquake and the 1640 Hokkaido Komagatake Eruption, Northern Japan*, Pure Appl. Geophys. *144* (3/4), 719–733.

OKAL, E. A., and SYNOLAKIS, C. E. (2001), *Comment on "Origin of the 17 July 1998 Papua New Guinea Tsunami: Earthquake or Landslide?" by E.L. Geist*, Seismol. Res. Lett. *72* (3), 362–366.

RIPPER, I. D., LETZ, H., and MOIHOI, M. (1998), *Pre-tsunami Large Earthquakes of the Aitape Region North Coast Mainland of Papua New Guinea*, Papua New Guinea Geological Survey Report 98/7.

SANDERS, J. E. (1977), *Primary Sedimentary Structures Formed by Turbidity Currents and Related Resedimentation Mechanisms*, SEPM Special Publication *12*, 192–219.

SATO, H., SHIMAMOTO, T., TSUTSUMI, A., and KAWAMOTO, E. (1995), *Onshore Tsunami Deposits Caused by the 1993 Southwest Hokkaido and 1983 Japan Sea Earthquakes*, Pure Appl. Geophys. *144* (3/4), 693–717.

SHI, S., DAWSON, A. G. and SMITH, D. E. (1995), *Coastal Sedimentation Associated with the December 12th, 1992 Tsunami in Flores, Indonesia*, Pure Appl. Geophys. *144* (3/4), 525–536.

SMITH, J. D. (1977) *Modeling of sediment transport on continental shelves*. In *The Sea*, Vol. 6, (E. D. Goldberg, I. N. McCave, J. J. O'Brien, and J. H. Steele, eds.) (Wiley-Interscience, New York) pp. 539–577.

SYNOLAKIS, C. E. (1991), *Tsunami Run-up on Steep Slopes: How Good Linear Theory Really Is*, Natural Hazards *4,* 221–234.

TAPPIN, D. R., MATSUMOTO, T., WATTS, P., SATAKE, K., MCMURTRY, G. M., MATSUYAMA, Y., LAFOY, Y., TSUJI, Y., KANAMATSU, T., LUS, W., IWABUCHI, Y., YEH, H., MATSUMOTU, Y., NAKAMURA, M., MAHOI, M., HILL, P., CROOK, K., ANTON, L., and WALSH, J. P. (1999), *Sediment Slump Likely Caused 1998 Papua New Guinea Tsunami*, EOS, Trans. Am. Geophys. U. *80*, 329–340.

TAPPIN, D. R., WATTS, P., MCMURTRY, G. M., LAFOY, Y., and MATSUMOTO, T. (2001), *The Sissano, Papua New Guinea Tsunami of July 1998—Offshore Evidence on the Source Mechanism*, Marine Geology *175*, 1–23.