Learning from the Aitape tsunami

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Abstract. The Aitape, Papua New Guinea, tsunami of 17 July 1998 was focused on a 14-km sector of coastline centered on the villages of Arop, Warapu, and Nimas. Here the wave height was 10 m or more and all structures within 400–500 m of the shoreline were destroyed. More than 1600 people were killed and 10,000 survivors were forced to relocate inland.

PNG-based researchers collected eyewitness accounts, mapped the pattern of destruction and the distribution and character of tsunami sediments, participated in marine investigations, and mapped and sampled underwater rock exposures that reveal a history of periodic, co-seismic(?) subsidence. They also provided information to the survivors and later convened a conference of scientists, survivors, and managers from which a comprehensive account of the disaster, the response, and the recovery has been developed.

Currently, for near-source tsunamis in PNG the only effective safety measure is to ensure that all people are aware of the warning signs of a tsunami and so know what to do, and that coastal settlements are planned with tsunamis in mind. The authors are participating in a nationwide campaign to promote tsunami awareness and preparedness.

1. Introduction

On the evening of Friday 17 July 1998, about 20 min after a strongly felt local earthquake, a succession of three large waves struck the Aitape coast of Papua New Guinea (Fig. 1). Waves 10–15 m high destroyed three villages, almost without a trace. Confirmed deaths numbered 1650, a further 1000 suffered serious injury, and 10,000 were displaced from their homes.

From the outset, experts were puzzled that such large waves could be generated by a moderate (M7) earthquake, and that the wave was so focused, with most energy directed at a narrow sector of coastline.

Subsequent investigations by international and locally based scientists included two onshore investigations by international teams (the First and Second International Tsunami Survey Teams; Kawata *et al.*, 1999), four major marine surveys by research ships from the Japan Marine Science and Technology Center (JAMSTEC; Matsumoto *et al.*, 1999; Tappin *et al.*, 1999; Matsumoto *et al.*, this volume); one marine survey by a United States team (Sweet and Silver, 1999), and other onshore investigations by teams from Australia, New Zealand, and the United Kingdom (e.g., McCue, 1999; Goldsmith *et al.*, 1999).

The Port Moresby Geophysical Observatory, which operates a national seismic network and maintains a data file of tsunamis, participated in an aftershock survey, and investigated the felt effects of the earthquakes (Ripper *et al.*, 1999). Other PNG-based investigations (e.g., Davies, 1988a, b; Davies *et al.*, 1999; Davies *et al.*, 2000a; Davies *et al.*, 2000b) included interviews with survivors, mapping the damage, mapping and characterizing the tsu-

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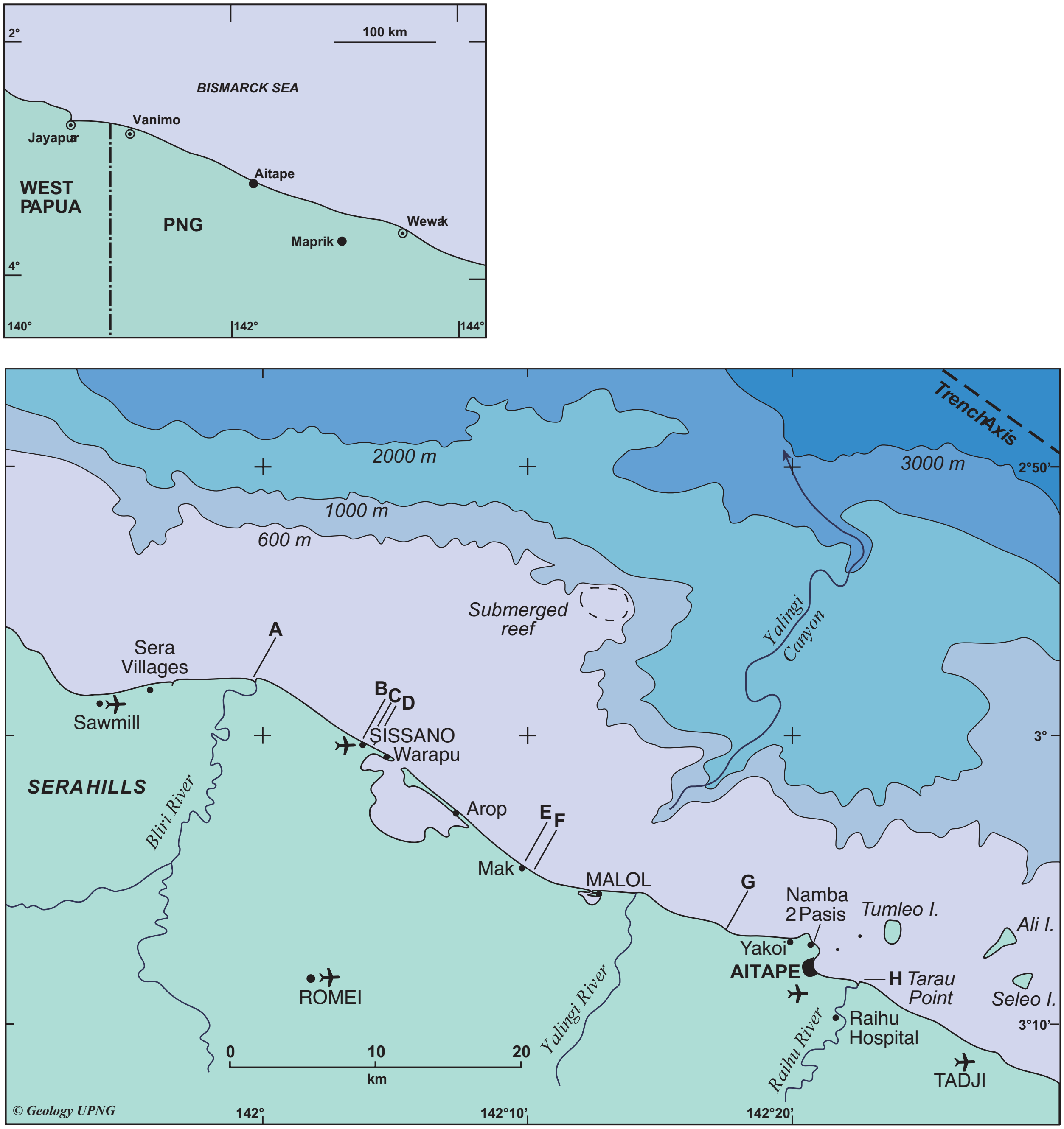

Figure 1: Map of the Aitape coast. Bathymetric contours are from multibeam survey (Matsumoto *et al.*, 1999). Sunken reefs have been identified at approximately 500 m depth and at 82 m depth. (The shallower reef is not shown; it is 8 km from shore.) Sissano Lagoon is the body of water inland from Warapu and Arop. The Sissano Government Station was at D and Nimas village (the easternmost Sissano village, mentioned in the text) at C. Sissano Mission was at B. Teles and Lambu villages of the Malol community, which were extensively damaged, extend from the mouth of the Yalingi River eastward to the mid-point between Malol and Yakoi. The main focus of the wave was on the 14-km sector of coast from Mak to just beyond Warapu, D–E. Here the wave heights were 10 m or more, and destruction extended as far as 500 m inland. From the mouth of the Bliri River to Sissano (A–B), and from Mak to Tarau Point (F–H), wave heights were not more than 4 m above sea level.

nami sediments, and first enquiries into the tsunami history and subsidence history of this coast.

Other overseas research has focused on the mathematical modeling of the wave and re-interpretations of the earthquake data, aimed at determining the location and nature of the source. Results include the identification of a seismic signal that could have been generated by a submarine slump or landslide at Aitape, in T-wave records from stations around the Pacific (Synolakis *et al.*, 2001).

All in all, the Aitape 1998 tsunami has been investigated more thoroughly than any previous tsunami. The outcome of the investigations is that most scientists believe that the tsunami was caused by a submarine slump or landslide, that presumably was triggered by the shaking of the initial earthquake. The finding has alerted communities around the world to the possibility that catastrophic tsunamis can arise from submarine gravity-driven mass movement, and do not necessarily require fault rupture. However, there remains a strong body of opinion that the tsunami was caused by co-seismic fault movement (e.g., Hurukawa *et al.*, 1999).

Other activities by PNG-based scientists have included a program of public awareness, firstly amongst the survivors, and latterly nationwide, and the organizing of an international conference at which the disaster, the response, and the recovery phase were reconstructed and discussed by scientists, disaster managers, non-government organization representatives, and survivors (Davies, 1999; 2001, in preparation).

This paper outlines the results of PNG-based onshore investigations into the tsunami.

2. The Setting

The section of coast that received the brunt of the tsunami (Fig. 1) is low-lying except for isolated hills, and mostly comprises flat land, swamps, and lagoons, separated from the sea by a sand barrier, 1–2 m above sea level and 100–200 m across, widening to 400 m at Nimas (C in Fig. 1) and westward. The sand barrier is highest at the beachfront berm and slopes gently downwards away from the sea. The morphology is similar to that of the barrier islands of the eastern North America coast, where it is attributed to the effect of relative rise in sea level (Komar, 1998: Figs. 2–22 and 2–25). In the Aitape case, the rise of sea level is due to subsidence of the land, as evidenced by sunken reefs offshore (Fig. 1 and see under Subsidence). In both cases, Aitape and North America, the sand barrier is replenished by sand transported along the coast from nearby rivers, by longshore drift. The sand barrier, and hence the shoreline, retreats landward with time.

Sissano Lagoon (Fig. 1) was at the center of the impact of the tsunami. The lagoon, 10 km long, up to 5 km wide, and mostly 2–4 km deep, was formed when the area subsided during and after a major earthquake in 1907 (Neuhauss, 1911: 25–6; A.B. Lewis in Welsch, 1998: 127–31). Oceanward, the lagoon is bounded by the sand barrier, which here is mostly 100–150 m across.

Offshore from the lagoon, a broad gently-inclined shelf extends out to sea for 18 km, where it is at a depth of 600 m. The shelf is interrupted by an embayment and canyon in the east (Fig. 1). Beyond the 600 m contour the sea floor is uneven, and falls away rapidly to reach a depth of 4000 m in the New Guinea Trench, 44 km from the coast. The trench marks a plate boundary where the seaward plate drives obliquely to the west-southwest beneath the Australian plate (Matsumoto *et al.*, this volume).

Before the tsunami, 11,500–12,000 people lived in villages along the coast from Malol to Sissano (Fig. 1). Most were in three major villages or groups of villages, at Malol (4000 people), Arop (2500), Warapu (2500), and Sissano (2500). With a few exceptions, the houses were of traditional materials. Most were within 100–400 m of the ocean and stood on ground that was only 1–2 m above high water mark.

3. The Tsunami

On the evening of Friday 17 July 1998, at 6:49 pm, 12 min after sunset, there was a strong earthquake, sufficient to cause some damage at the old church at Sissano and some liquefaction of sediments. There followed a loud boom, as though of thunder, and some minutes later a roaring sound, variously described as the noise of a low-flying heavy jet plane or as the woop-woop-woop of a heavy helicopter.

People who had gone to the water's edge to look for the source of the noise saw the sea recede to below normal low-water mark, and then saw a wave develop. Most turned and ran for safety but almost all were caught by the wave which broke some hundreds of meters from the beach, approached rapidly, rose to tree-top height as it crossed the berm, then crashed down on their villages.

Thirty-five minutes after the initial earthquake, at around 7:25 pm, the destruction had ceased and calm had returned. It was now pitch dark. There was no moon and, in the Sissano area, the stars were blotted out by a low haze. The silence was broken only by the cries of the injured and of searchers looking for loved ones.

Rescue began that night, the survivors helping each other. The first outside help arrived 16 hours after the event on the Saturday morning, and the major rescue effort began a day later, 40 hours after the event. By Monday evening (72 hours) all surviving injured were in hospitals at Vanimo, Raihu (Aitape) and Wewak (Taylor *et al.*, 1999; Holian and Keith, 1999; Davies, 2001).

4. Public Awareness and Information

Based on experiences at the time of the volcanic eruption and mass evacuation of Rabaul in 1994, the PNG-based scientists were aware that there would be a need to provide information about the tsunami to the victims, to explain to them what had happened, to reassure them that it was a natural phenomenon, and to be available to answer their questions. As part of their briefing for government officers in Port Moresby in early August, the members of the First International Tsunami Survey team (Kawata *et al.*, 1999) confirmed the urgent need to get reliable information to the disaster managers and survivors.

Our public information program began in early August. It involved a series of visits to hospitals, care centers and, later, the survivor villages. Hurriedly prepared pamphlets were printed by the University Printery and distributed in thousands on each visit. Results of investigations by overseas scientists and ourselves, that had been presented in weekly stories in the national press, were reproduced in the pamphlets and, at the end of the year, were gathered together in a booklet (Davies, 1998a), and widely distributed.

Despite these efforts there remained in several of the survivor communities a strong belief that the tsunami had been man-made. This led to further uncertainty and unease in these communities. In an effort to combat the rumors, we organized a visit by a team of overseas tsunami scientists who had been involved in the onshore and offshore investigations, and an engineer expert in coastal protection. The team visited each of the survivor villages in September 1999, explained their findings about the tsunami to the people, and answered questions. Subsequently, in cooperation with the Asian Disaster Reduction Center and Tohoku University, we developed a tsunami information poster and pamphlet and distributed these, firstly to the survivor villages, and then nationwide.

5. Survivor Interviews

In the process of giving information to the survivors much was learned about the tsunami—information that has proven to be of value in the scientific investigation. In particular, survivor stories about the timing of the arrival of the wave (Davies, 1998a: 26–30) were a factor in persuading most investigators that the wave was caused by movement of sediments after the earthquake, rather than by co-seismic rupture on a fault (Davies, 1998a: 7–8; Tappin *et al.*, 1999).

Other survivors witnessed the escape of gas from the sea floor before the earthquake, and others told of a kerosene or oily smell in the wave (Davies, 1998a: 16; 1998b). Their stories reinforce the possibility that a sudden release of natural gas was in some way linked to the development of the tsunami. The escape of a large volume of gas could explain the otherwise puzzling observation by most survivors that the water in the wave was unusually warm. Escape of gas in the eastern Mediterranean is known to have raised the temperature of seawater by as much as 6°C (Hasiotis *et al.*, 1996; cited by Soter, 1999).

Many eyewitnesses described how, before the wave arrived, the sea was boiling. This is more readily explained, and is the effect of the reduced pressure at the sea floor, resulting from the extreme lowering of sea level before the wave advanced. The reduced pressure allows the escape of gas that otherwise remains trapped in the sea floor sediments during normal tides (M. Hovland, personal communication, 1999; Hovland and Judd, 1988).

Eyewitnesses also provided useful information about the shape of the wave, how it had come ashore first at a point on the coast at or near Mak (E in Fig. 1), and had progressed westward along the coast. A powered dinghy returning to Sissano from Aitape saw the wave hit the beach behind them, and tried to escape by speeding toward the lagoon mouth. They were caught up in the broken wave and carried ashore at Arop, with the loss of most aboard. Others at Warapu told of seeing the wave strike Arop, 6 km to the east, and how, given this warning, they had time to climb trees or attempt to escape into the lagoon by canoe. The westward progression of the wave, and hence its obliquity to the coast, was confirmed by mapping of the damage which, in this sector, shows trails that extend at an angle southwestward away from the coast, rather than normal to the coast.

Our investigations extended as far west as Jayapura, Indonesia (Fig. 1) where an eyewitness recalled three 2-m waves that washed away canoes and logs as they receded. A seiche wave followed in Jayapura Bay and continued for 24 hours. A modest wave also reached the western end of Manus Island, 470 km east-northeast of Aitape. No tsunami wave was seen on Wuvulu Island, 165 km off the Aitape coast, but dead fish were washed up on the Wuvulu reef.

6. Damage Mapping

The damage to buildings and vegetation was mapped on the ground and on aerial photographs that had been flown three weeks after the event (Aitape Disaster Area photography at 1:10,000 scale, National Mapping Bureau, Waigani NCD). The mapping showed clearly that the greatest energy of the wave was focused on the 14-km sector of coastline from Mak through Arop to Warapu and the Sissano Government Station (D–E in Fig. 1). In this sector all structures were destroyed, leaving only some concrete foundations. Waves swept inland as far as 500 m across the swampy coastal plain, felling 30-m-high trees and stacking them like matchwood (Davies, 1998a: 39–40). The energy of the wave at Nimas (C in Fig. 1) was almost as great, but further west at Sissano Mission (Davies, 1998a: 31–36), and further east in the Malol villages, was significantly less.

In all, 40 km of coastline, from Bliri River to Tarau Point (A–H in Fig. 1) recorded some damage. Eastward from Malol the damage trailed off, so that from Yakoi to Tarau Point (G–H in Fig. 1) only structures that were within tens of meters of the water's edge were damaged.

The results of the damage mapping agree closely with the results of the mapping of wave heights by the First International Tsunami Team (Kawata *et al.*, 1999), with one exception. This is at the western end of Malol village. Here evidence of wave height of 10 m above sea level was reported by Kawata *et al.*, but our enquiries of eyewitnesses indicated that the wave height was not greater than 4 m a.s.l. The moderate level of damage in the western Malol villages, where only the front line of houses was destroyed, and the lack of any damage trail to suggest that the wave penetrated inland, confirms that the wave here had much less energy than in the 14-km sector (D–E in Fig. 1) westward of Mak.

7. Mapping the Tsunami Sediments

Following on from the initial reconnaissance studies by Jaffe *et al.* (1998), several transects were surveyed and tsunami sands sampled and studied. The samples included several from the floor of the lagoon. Generally the sands are around 10 cm thick, but are much thinner in the coastal strip, within 100 m of the shore, and much thicker at locations where the wave traveled down slope, such as at the seaward edge of Warapu and Arop villages, and at the seaward edge of the road near the coast east of Malol (Fig. 1), where deep scour-holes were filled with sand. Near the rocky headland at Tarau Point, east of Aitape (H in Fig. 1), the waves scoured a pot hole and filled it with sand to a depth of at least 1.7 m (Davies, 1998a: 22–23). Size fractions were determined for all samples but results are not yet published.

8. Subsidence

The First International Tsunami Survey team searched for but found no evidence of co-seismic subsidence, and on repeated visits to the scene we too saw no clear evidence of subsidence. In contrast, the New Zealand team observed and photographed one location where the base of a tree was below lagoon water level, and concluded that there had been subsidence at the time of the earthquake (Goldsmith *et al.*, 1999).

Subsequently it has become clear that the coastal lands have subsided, perhaps by as much as 70–80 cm, with some estimates suggesting subsidence of 1–1.5 m. Whether the subsidence was all co-seismic, or whether it was progressive, through the months since the first earthquake, remains open to question.

Evidence that the lagoon area has a long history of subsidence was discovered in September 1999 when we investigated reports that cracks were developing in the lagoon floor. Just inside the lagoon mouth, a steep face that had been eroded by tidal currents exposed a 2-m section through the sediments that underlie the lagoon.

The sediments between 2 and 3 m below sea surface comprised a homogeneous sticky mud, weakly bedded, that showed the traces of former plant roots. This is lagoonal mud, perhaps deposited since the 1907 subsidence event.

The sediments at 3 to 4 m below sea surface were a spectacular alternating sequence of pale gray, sticky muds and black peat beds. The peat beds comprised leafy material and sticks and twigs. Some of the peat beds were only a few centimeters apart and others were as much as 15–20 cm apart. We took this to be evidence of repeated subsidence, presumably co-seismic.

Material from the lowermost exposed peat bed was dated by carbon-14 method at 990 years plus or minus 70 years BP (present is standardized at the year 1950; A. Hogg, Report on sample Wk-7864, 8 November 1999, Radiocarbon Dating Laboratory, University of Waikato). The result indicates a total subsidence of at least 4 m in the last 970–1100 years. (The 4 m depth remains to be confirmed. It was measured by dive computer but may have been greater than 4 m, given that the water was a mix of salt and fresh. Later investigations suggest a depth of 5 m.)

9. Frequency of Tsunamis

Because the written historical record for this coast is short: only 150 years (e.g., see Everingham, 1977), we do not know the recurrence interval of major tsunamis. Based on written records of mission workers, there has been no catastrophic tsunami on the Aitape coast for at least 102 years. This is contrary to some reports, including that of Carey (1935), who wrote of a tsunami at the time of the 1907 earthquake and subsidence event. Other more-nearly-contemporary accounts of the 1907 event (Neuhaus, 1911; and A.B. Lewis in his 1909 diary, as recorded by Welsch, 1998) do not mention a tsunami, Lewis noted that houses at Arop village, on the sandbar, were still standing in 1909 (Welsch, 1998).

However, there certainly have been damaging tsunamis in prehistoric time. At least one of the village groups has an oral history story of a major tsunami that approached from the west (Davies, 1998a: 37–38 and unpublished interviews), and during the peat-sampling dive in 1999 we noted at least one of the submerged peat beds contained a significant concentration of sand, probably indicating a major tsunami. Subsequent attempts to sample the peat bed by free diving, and by using a simple coring device, were unsuccessful. A further attempt to obtain a complete section, using a man-portable drill rig, will be made later this year.

For all of PNG, in the 150 years of historical records, the longest interval free of damaging tsunamis was the 65 years from 1931–1996 and the shortest was 2 years, 1996–1998. Regrettably, the 1996 tsunami, which caused loss of life at Biak in West Papua, was not well publicized in PNG, so what should have been a timely reminder of the ever-present tsunami hazard was not heeded.

10. Advice to Government

Another role for the PNG-based scientists has been to advise the government about the safety of this sector of coastline. Factors against returning to this part of the coast are:

- The modelers have demonstrated conclusively that the maximum energy of any tsunami generated in this region will be focused on the same sector of coast. This is because of the focusing effect of the broad shelf and the adjacent submarine canyon and embayment.

- Villages on the frontal sand barrier, from Mak to Sissano, have poor escape routes.

- There is at present no cost-effective warning system for tsunamis that originate within 40 km of the coast, on the inner wall of the New Guinea Trench, which is the most likely source region.

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