REPORT OF THE NEW ZEALAND RECONNAISSANCE TEAM TO THE AREA OF THE 17 JULY 1998 TSUNAMI AT SISSANO LAGOON, PAPUA NEW GUINEA

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SUMMARY

A M_w 7.1 earthquake off the north coast of New Guinea, generated a locally very destructive tsunami at 08:49 17th July 1998 UTC (6:49 PM local time). More than 2189 people died, and no structures were left standing along 19 km of coast. A reconnaissance team from the N.Z. Society for Earthquake Engineering visited the area a month after the event. Over three days, they examined effects of the tsunami on structures and landforms, measured profiles and sampled deposits. A fast moving wall of sand-laden water left fishing nets and other detritus in trees up to 17.5 m above sea level. Concrete was stripped to the reinforcing, and some trees were ripped out and carried more than a kilometre. The team saw evidence of new subsidence of ~300-400 mm on the landward side of the spit fronting Sissano Lagoon. The site is in an active sedimentary basin, the Aitape Trough with 4,500-m thickness of Neogene sediments, between the Bewani fault zone and the Wewak Trench. The area may have subsided 3 times this century. *In situ* stumps of drowned trees in the lagoon record one of the earlier events. The low-angle Harvard University CMT solution (M_w 7.1, depth ~6.0 km, ~10° landward dip on fault with northward displacement) is consistent with the tectonic setting and pattern of aftershocks. Elastic modelling of the energy release with ~2 m horizontal displacement over 600 km^2, suggests ~400 mm subsidence (landward) and ~600 mm uplift (seaward in >3 km water depth). The team suggests that convergent flow of the displaced water into the area of subsidence focused wave energy on the coast and generated the locally very high wave. The spit fronting Sissano Lagoon is unsafe for habitation. There is potential for coseismic coastal subsidence to focus tsunami in other areas with similar tectonic settings. This potential suggests that both eastern and western New Zealand coasts have a serious hazard from local tsunami that is presently underestimated for the western coastline because of the lack of historical occurrences.

1.0 INTRODUCTION

A tsunami with wave heights locally exceeding 15 m was generated by a M_w 7.1 earthquake on 17th July 1998, near Sissano Lagoon, on the north coast of Papua New Guinea (Figure 1). Striking shortly before 7 pm local time, at dusk, it ranks as one of the great tsunami disasters of the century. The true death toll will never be known, but may greatly exceed the official toll of 2,189. Most of the deaths were in the villages of Warapu and Arop (Figure 1, Table 1), situated on a narrow sand spit fronting Sissano Lagoon. A fast-moving wall of sand-laden water up to 15 metres high hit these villages, within a few minutes of the earthquake. Here, local disaster relief workers told us only about 800 people had survived from a population estimated to be more than 5,000. No structures were left standing in this area. The region of extreme damage (total destruction of all buildings) along the coastline was some 19 kilometres, while the total length of coastline affected by the tsunami was some 40 kilometres. The height of the tsunami was anomalous for the earthquake magnitude.

In late July, the New Zealand Society for Earthquake Engineering decided to send an investigative team into the area.

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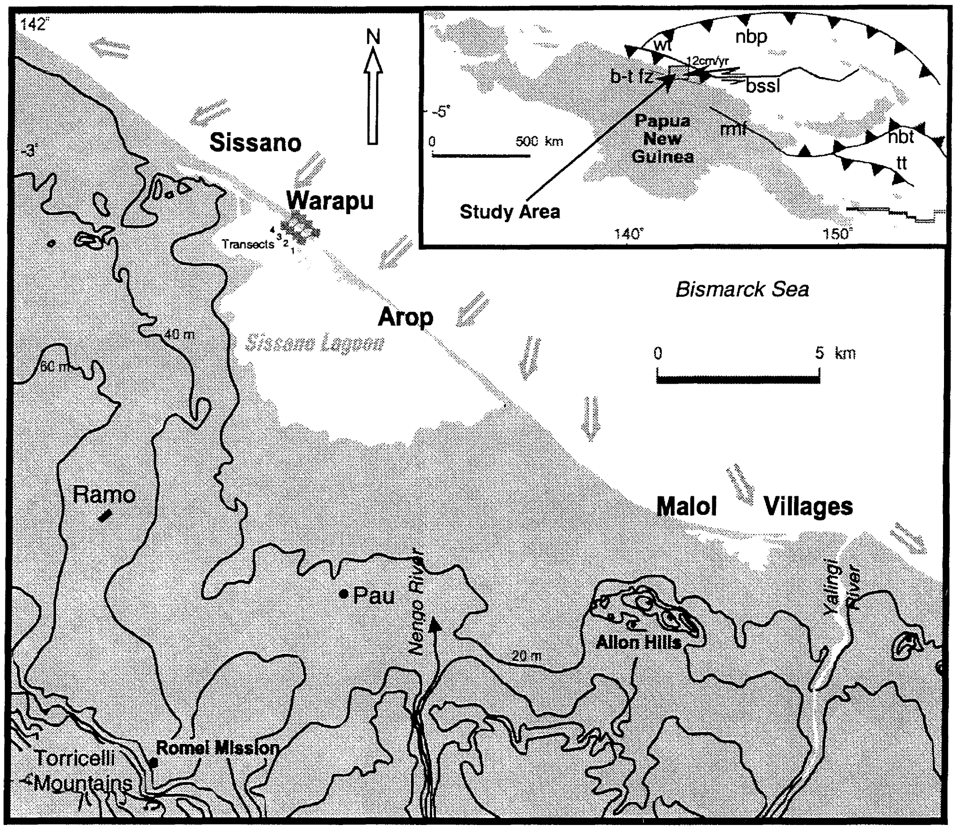

Figure 1: *Location map of Sissano Lagoon. Thick double arrows indicate direction of tsunami approach to coastline (tm – Manus Trench, nbp – North Bismarck Plate, wt – Wewak Trench, bssl – Bismarck Sea Seismic Lineation, b-t fz – Bewani-Torricelli Fault Zone, rmf – Ramu-Markham Fault, nbt – New Britain Trench, tt – Trobriand Trench). Transect profiles shown in Figure 7.*

Table 1: Disaster statistics as of 30/7/98. Figures for Ramo in square brackets were erased 3/8/98 and are inferred (Data source: noticeboard, Aitape Disaster Relief Centre photographed 14/8/98). Note that 1990 populations for Arop, Warapu and Sissano are not listed. These villages were of similar extent to Pou and Malol.

Care Centre	1990 census	Care Centre population	Injured hospitalised	Missing	Dead
Ramo	[395]	[1584]	[345]	[0]†	1082
Pou	1644	1404			863
Rowoi/Amsor	826	1153	49	35	61
Olbrum	468	1032	24		25
Rainbrum	293	89	5		
Malol	2268	3816			95
Aitape (town)	627	415			1
Paup			6		7
Totals	7521*	9483*	429*	35	2134

* Only these totals likely to be verifiable.

† This number appears to be anomalous. We expect the number missing to vary in proportion to the number of known deaths.

The team which left New Zealand on 12th August 1998, consisted of:

Dr Peter Goldsmith, geotechnical and civil engineer;
Dr Alastair Barnett, coastal hydraulics engineer;
Dr Mauri McSaveney, geomorphologist;
Dr James Goff, sedimentologist.

To benefit the people of Papua New Guinea and to use local knowledge, we sought cooperation with organizations within Papua New Guinea and were joined by Dr Scott Elliott, an engineering geologist, and Mr Michael Nongkas, a post-graduate sedimentology student: both from the University of Papua New Guinea.

"The Joint New Zealand Papua New Guinea Research Team", led by Dr Goldsmith, spent three days in and around Sissano Lagoon.

2.0 LOGISTICS

Dr Peter Goldsmith organized field logistics using his business connections and associations in Papua New Guinea and role as Chairman of the New Zealand Papua New Guinea Business Council.

At the time the team was preparing to leave New Zealand, Sissano Lagoon was a prohibited area (and remains so at April 1999) because of the public health risk from contaminated water and to allow time for natural decay to dispose of unrecoverable bodies. Through efforts by the New Zealand High Commissioner and Mr Rimbink Pato of Pato Lawyers, access to the area was granted by the Commissioner of Police only hours before the team departed Port Moresby.

Invaluable assistance in providing and assisting with local transportation and in arranging accommodation at Vanimo and Aitape was given by the Hon. Vincent Auali, Minister for Transport (responsible for the Papua New Guinea Harbours Board), Mr Gregory Emilio, General Manager of the Harbours Board, and Mr Jack Kawagi, Port Manager at Vanimo. Mr Kawagi also accompanied the reconnaissance team into the Sissano area.

The Papua New Guinea National Disaster Committee arranged local sea and helicopter transport from Aitape to Sissano.

So as not to impede ongoing relief efforts, the team chose a field base at Vanimo, northwest of Sissano, and well outside the affected area. The team commuted daily by light plane to Aitape, then traveled from Aitape either by road, sea or helicopter.

The team planned field activities on arrival in Vanimo on 14th August. Prior to the team's departure from New Zealand, a vessel had been hired out of Vanimo. At the last moment, the owners accepted a more profitable charter, so a five-metre longboat was hired at Aitape.

3.0 FIELD RECONNAISSANCE

The field schedule was:

- 15th August – travel to Aitape, attend Disaster Relief coordinating meeting, hire longboat, travel by sea (35 km) to inspect damage to the coastline and at Sissano Lagoon and Warapu Village areas, and return;

- 16th August – travel to Aitape, hire vehicle, drive to Malol Village inspecting damage and interviewing various local people (light rain was encountered during the middle of the day);

- 17th August – travel to Aitape, helicopter to Sissano Lagoon, meet longboat which had traveled from Aitape separately, inspect lagoon shoreline between Arop and Warapu Villages. Obtained evidence of wave height, and measured the depth of deposition and scour along four transects across the spit at Warapu. Locations were determined by GPS. Sediment samples were taken along each transect. Additional longshore sites were linked into the GPS grid. A 1.5 m sediment core was taken at the landward end (lagoon edge) of transect 2.

The flights between Vanimo and Aitape passed over the damaged area and provided excellent opportunities to review the scene (Figure 2).

4.0 PHYSICAL BACKGROUND

The disaster area lies on the leading edge of the Australian tectonic plate, which is in a geologically rapid oblique collision with a number of micro-plates in the Bismarck Sea [1] (Figure 1 inset). Convergence at the North Bismarck plate and the Australian plate is *ca.* 70 mm/yr and lateral shear between them is *ca.* 100 mm/yr. Understandably, large earthquakes occur frequently in the zone of deformation between the plates.

The coastal area is a 10-15 km wide, forested lowland flanking the Torricelli Mountains which rise to 1,600 metres elevation 30 kilometres inland from the coast. Hills reach the coast near Aitape, and Leitre (Figure 3). Sissano Lagoon is a surface expression of subsidence of the Aitape Trough, a sedimentary basin fronting the Torricelli Mountains, inland of the coastal hills.

Rivers carry huge amounts of sediment to the sea from the mountains and the coastline is rapidly accreting. Much of the coastline consists of up-to-4 m-high sandy beaches forming a barrier bar along the prograding coastline. There is a moderate net long-shore drift from east to west driven by the onshore wind (Trade Winds). For about a third of the length of coastline between Aitape and Vanimo (Figure 3), the barrier bar fronts lagoons or low-lying swamps. The well drained sandy bar is exposed to the sea breeze and is a favoured residential site. The sea, beach and lagoons are traditional transportation routes and the bar is the most suitable road route.

Figure 2: ***The former site of Warapu Village. Houses once lined the main street (centre). Profiles and heights of tsunami (Figure 9) were measured here.***

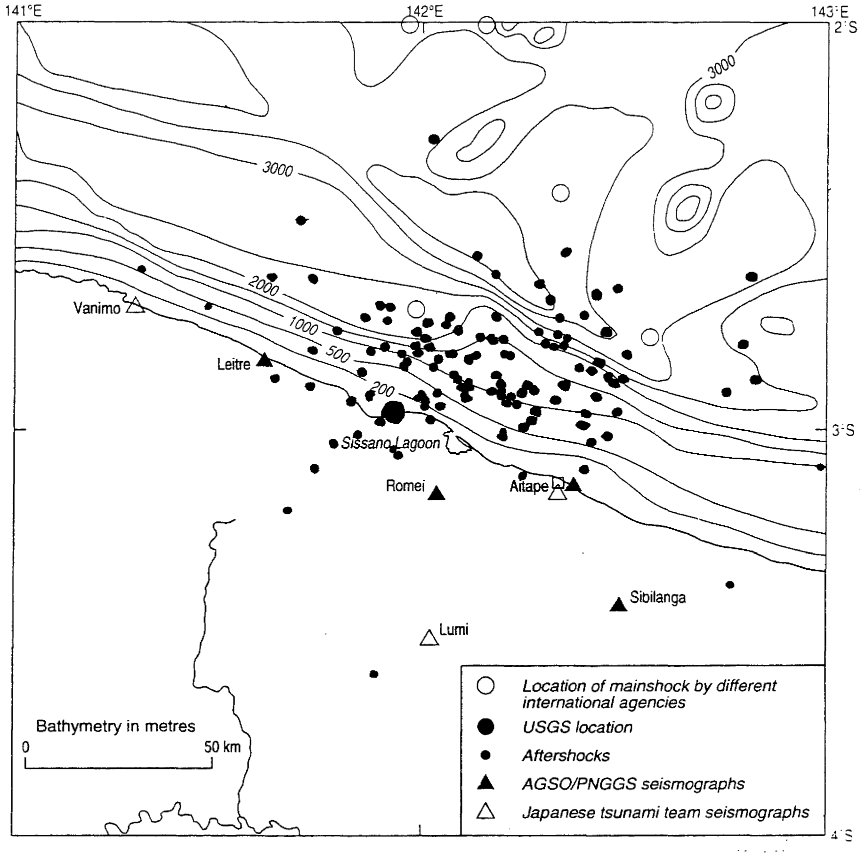

Figure 3: ***Location of earthquake epicentre and 115 aftershocks within 120-kilometre radius, July-December 1998 (modified from [5] with additions and corrections from [4]).***

The rest of the coastline is rocky cliffs of 30 million-year old volcanic rocks near Aitape and raised reef limestone immediately Southeast of Leitre [2]. The rocky coastlines are along local areas of rapid tectonic uplift.

Sissano Lagoon lies between the deltas of the Yalingi and Bliri (Arnold) Rivers. It is reported to have formed in an earthquake in 1907 when the spit subsided 1.8-3.6 metres [3], opening a former coastal lake to the sea (Willem de Lange, pers comm. October 1998). Much of the lagoon is little more than a metre deep. It receives a diffuse drainage through swampland from the interior, and receives sediment principally from the sea. There were two gaps in the barrier bar in 1968 (as mapped 1:100 000 Aitape sheet 7391 Series T683, Royal Australian Survey Corps), but only one by 1998. During the tsunami of 1998 a substantial amount of marine sand was deposited in the lagoon. If reported tsunami of 1934 and 1907 brought similar influxes, it is likely that tsunami are the principal suppliers of sediment to the lagoon.

The lagoon complex along this section of coast extends 22.5 km from the Sissano Mission in the Northwest to the eastern end of Malol (Figure 1). There are openings to the sea at Malol and between the former villages of Warapu and Arop.

5.0 EARTHQUAKE

A shallow (6 km deep) earthquake of magnitude (Mw) 7.1 with calculated epicentre at 2° 57.7' S, 141° 55.6' E [4], triggered the tsunami. Ground shaking was strong at Sissano and caused minor damage to some structures. The main shock was followed about 20 minutes later by a major aftershock of M_b 5.6 [4]. The aftershock pattern (Figure 3) suggests that the earthquake was associated with fault rupture of a gently dipping fault immediately offshore from Sissano Lagoon [5], although the calculated USGS epicentre is just onshore west of the lagoon.

6.0 FIELD OBSERVATIONS

General observations were made of damage to structures and lifelines. Dwellings, mature trees and people were plucked from the site and transported several kilometres into the lagoon (Figure 4).

***Figure 4:** Mature tree ripped from Warapu village and deposited more than a kilometre away in Sissano Lagoon. Note the shallowness of the water indicated by the grounded tree.*

The team also examined landform morphology, evidence of wave height, and depths of deposition and scour. Evidence for wave height included broken branches (unreliable because of the accompanying gale of displaced air in front of the fast-moving wave), debris snagged in trees (Figure 5, reliable), stripped bark and impact damage (Figure 6, reliable), material pushed against tree trunks (Figure 7, moderately reliable), and away from the central disaster area, interviews with witnesses (Figure 8, of variable reliablity). Debris and damage heights were measured across four transects on the area of the spit that was the former site of Warapu village (Figures 1, 2 and 9). Sediment samples were taken along each transect and a 1.5 metre core (Figure 10) was taken at the lagoon edge. Results indicate a maximum wave height of up to 17.5 metres above sea level (Figure 9). The heights, however, are uncorrected for bending of the trees by the rushing water. Maximum heights varied locally by as much as 4 metres, possibly reflecting local reinforcement of the tsunami by incoming ocean swells.

Figure 5: ***Tree drowned at the lagoon edge due to coseismic subsidence of the seaward shore of Sissano Lagoon at Arop village. Note bucket (boxed) caught in branches indicating height reached by tsunami. Scour during backflow out of the lagoon has undercut several coconut palms at the lagoon edge in the background.***

6.1 Earth Deformation

An earlier survey party [6,7] reported seeing no evidence of earth deformation. We, however, were alerted to a small amount of coseismic land subsidence because one of our site visits ended near high tide. A number of standing trees, with their bases in the lagoon water, were seen to have been recently drowned (Figure 5 for example). At one site on the inner edge of the spit at Arop, the upper level of the new high tide was indicated by drowned and flattened grass (Figure 11). The exact amount of subsidence was difficult to determine accurately in the absence of an obvious datum. The Warapu and Arop spits were estimated to have subsided by no more than ca. 0.3-0.4 metres. Subsidence of such a small amount is not easily detected. We know that, rather than seeing no evidence of deformation, the earlier party merely failed to recognise it, because Kawata et al.[7, Figure 3] illustrate the same dead tree as in Figure 5. Evidence of deformation also was missed by a party that came after us although the latter party had been alerted to look for it, but had not been told what to look for, or where (B. Jaffe, USGS, personal communication, December 1998).

Although others have yet to confirm that the spit has subsided, other evidence supports our observations and photographs. Dislocation modelling of crustal displacement [8] using the low-angle option of the Harvard Rapid Moment Tensor Solution (M_w 7.1, depth: 0-6 km, and ~10° Southsoutheast dip of the seaward thrust fault) suggests that about 600 km^2 of sea floor was displaced 2.2 metres towards the Wewak Trench along a gently dipping fault. The model suggests ~0.4 m subsidence at the landward edge of fault displacement and ~0.5 m uplift about 30 km offshore in 3,500 m water depth. The modelled subsidence is consistent with that observed by our team if the spit of Sissano Lagoon approximately overlies the base of a formerly locked zone of the fault (as suggested by the aftershock pattern – Figure 3). This suggests that the 17th July tsunami was a classic subduction-zone event [9], and hence we infer the subsidence to have been coseismic. Sissano Lagoon subsided by 1.8-3.6 m (6-12 ft) in 1907 in association with an earthquake [3], but some of this may not have been coseismic. We infer that the lagoon formed and is maintained by tectonic subsidence.

Figure 6: Coconut palm trunk abraded by sand during the tsunami impact at Warapu village.

We saw a number of ancient, worm-bored *in situ* stumps of drowned trees in Sissano Lagoon adjacent to Warapu Village (Figure 12). They and their associated submerged former shoreline step indicate an earlier episode of minor subsidence. It did not appear to be submerged enough to be from 1907: we suggest that it may have occurred during the earthquake of 1934, although no ground deformation is reported for that event. The average return period for subsidence may be as short as 30-40 years.

There is a long geological history of subsidence along this coast, which is where the sedimentary basin of the Aitape Trough reaches the coast [2]. This trough contains 4,500 metres thickness of Neogene sediment. Adjacent lengths of coastline to east and west, however, show evidence of rapid emergence from the sea.

6.2 Deposition and Erosion

Sand deposition exceeded 1 metre on the seaward beach ridge of Transect 2. Scour holes up to 2 metres deep occurred in the vicinity of Warapu. The sediment core taken from the edge of Sissano Lagoon at the southern end of Transect 3 shows at least two erosional contacts (Figure 10), the upper one overlain by a fining-upwards sequence of sand that was 870 mm thick. Its content of fresh plant material identified it as the deposit of the July tsunami. Similar depths of scour and deposition were seen elsewhere along the spit (Figure 18).

Tsunami-generated currents along the outer coast rapidly eroded the beach front (Figure 13) and in many places scour caused trees to fall into the sea.

6.3 Engineering Observations

Prior to the tsunami, the villages of Malol, Arop and Warapu were typical of villages along the northern coast of Papua New Guinea (Figure 14). Buildings were largely of simple traditional design: thatched roof, wooden structures with unsophisticated connections, and little or no bracing (Figure 8, 15, 16). A number of buildings were however, analogous to light timber-frame constructions in New Zealand, built on concrete piles or reinforced-concrete slabs on ground (Figure 14, 15, 17).

Structures closest to the coast bore the brunt of the wave energy. When they lost the battle, the structures next in line were subject to not only the wave force, but also the projectile impact of the accumulating debris from the structures in front of them, and so on – all happening at a speed of 70 kph or faster in highly turbulent water!

The most compelling observation was that in the central disaster area along the spit fronting the lagoon, all structures, irrespective of degree of sophistication, suffered the same fate: none withstood the tsunami. The more traditional structures simply washed away (Figure 2, 17), sometimes largely intact. Timber piles 100 mm x 100 mm were snapped off just above ground level. Concrete piles 150 mm x 150 mm were similarly snapped (Figure 15), or uprooted. Concrete piles reinforced with metal rods had the concrete stripped off them. At least one concrete slab had the concrete stripped back to the central reinforcement. A steel pontoon of 1.5 m diameter was simply bent in half around a tree (Figure 19) and a child's bicycle was totally wrecked, with no major part left unbent (Figure 20).

Others [6,7] have discussed how Casuarina trees appeared to offer structures and people some protection from tsunami damage, but we noted little preferential survival of tree types for mature trees. Immature Casuarina certainly survived inundation better than did immature coconut palms, because their thin trunks and small leaves offered less drag in the water. Coconut palms, however, survived well where they were tall enough that their fronds were above water (Figure 18). No species appeared to survive major root scour, and many trees of a variety of genera were simply ripped out of the ground, most being shallow rooted and growing in loose sandy soil.

Within the area of greatest impact, the force of the water was awesome. A wave with an average height of about 11m struck Warapu and Arop at about 70 kph. The sand-laden fluid had a density greater than seawater (say 1.1 tonnes per cubic metre). The resultant force to be instantaneously absorbed by any static object in its path was about 4.4 kN per square metre of cross section exposed to the wave – a lateral load of about 90 kN for a building cross section of 20 square metres - five to ten times the weight of many of the buildings.

***Figure 7:** A sheet of ridging iron wrapped around a coconut palm indicates the minimum height of the tsunami on the spit at Arop village. The concrete foundation below is all that survives of an iron-clad, timber-frame building.*

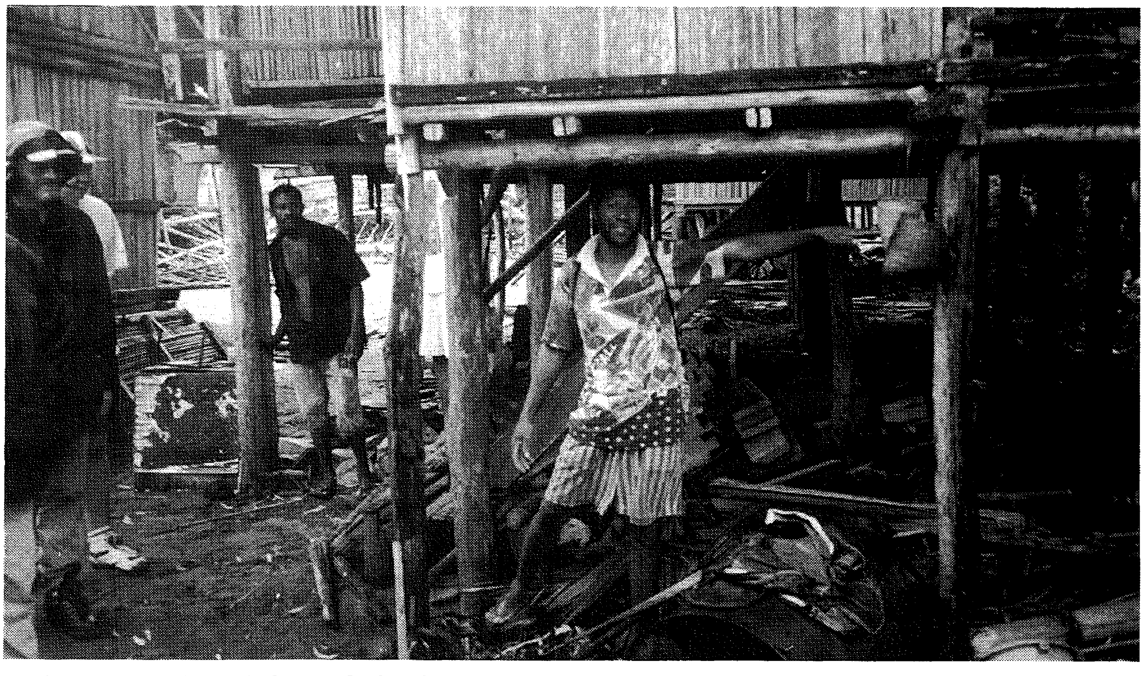

***Figure 8:** A Malol villager indicates the height he saw water reaching to when the tsunami swept by beneath his home.*

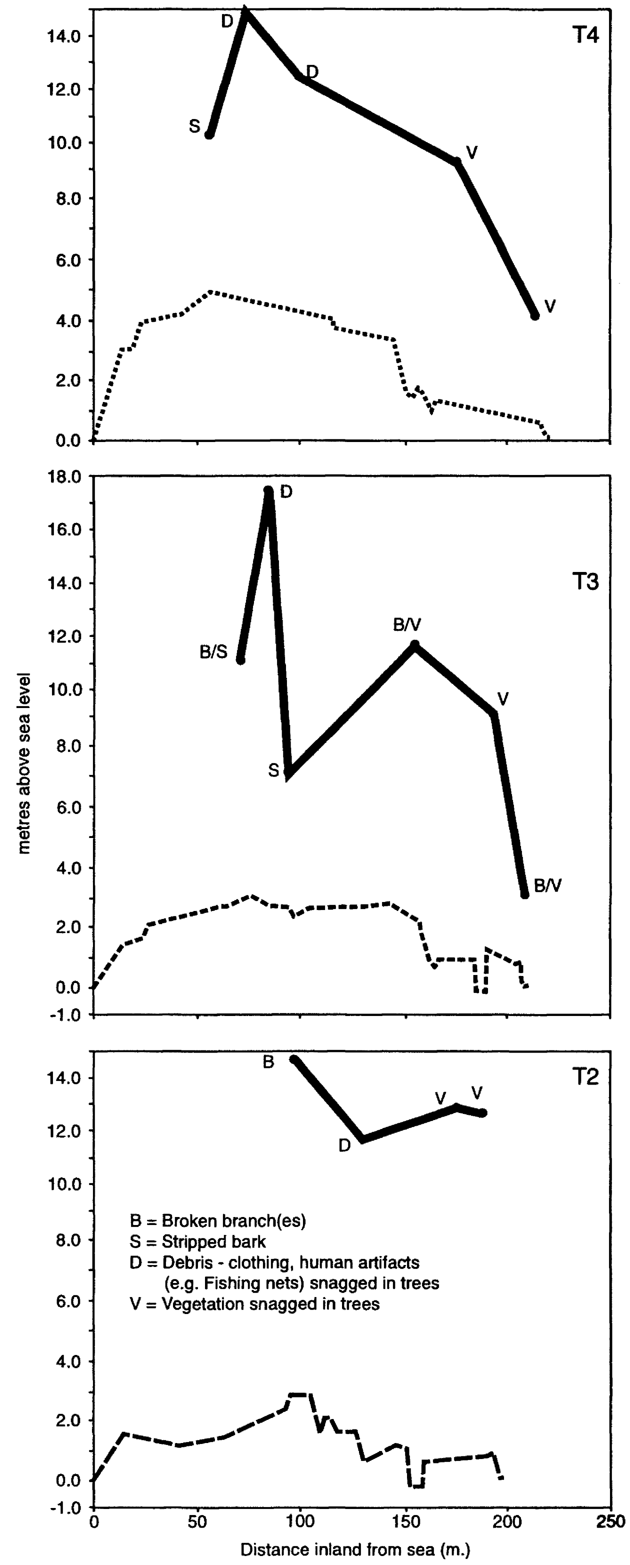

Figure 9: Plots of three profiles (dashed lines) measured across the spit at Warapu Village showing maximum heights (solid lines) reached by the tsunami waves. Heights uncorrected for possible flexing of the trees under the tsunami load. Profile T1 at end of spit not shown.

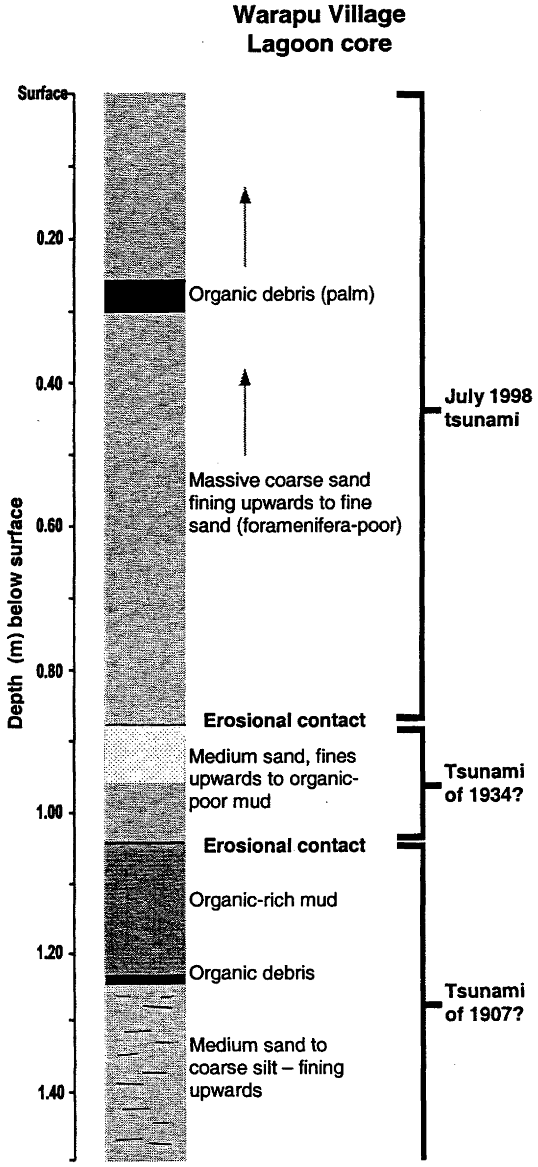

Figure 10: Log of sediment core taken from the edge of Sissano Lagoon at Transect 3, Warapu Village. Dates of earlier tsunami are unverified field estimates.

The resultant effects were countless deaths, horrific injuries and total destruction of all structures (Figures 2, 18). People were sandblasted and dismembered by fast-moving, sand-laden water. Clothing was ripped from bodies. The death toll on the spit fronting Sissano Lagoon may have been ~70% of the local population.

The forces exerted by the tsunami grossly exceeded most design-code requirements, and only the most sophisticated of engineered structures could be expected to have survived unscathed. Such structures are quite inappropriate for the economy and present village life along the northern coast of Papua New Guinea.

Figure 11: Grass (arrowed) flattened at the new high-tide level on the inner margin of the spit at Sissano Lagoon where Arop Village once stood.

Figure 12: Stumps rooted in place at low-tide level in Sissano Lagoon beside Warapu Village record an earlier episode of subsidence of the lagoon. They appeared to be too well preserved and not submerged enough to be from the 1.8-3.4 metres of subsidence in 1907, so we reasoned that they might date from unreported subsidence associated with the earthquake of 1934. We were unable to test this hypothesis.

Figure 13: In places, the beach front was heavily scoured by passage of the tsunami along the coast.

Figure 14: A typical village along the northern coast of Papua New Guinea outside the region of significant tsunami damage. The destroyed villages of Arop and Warapu probably had similar proportions of traditional and iron clad dwellings.

Figure 15: Three members of the reconnaissance team inspect damage at Malol Village. Here tsunami damage was only intermittent along the coast, where ocean swells boosted the tsunami over the beach berm.

Figure 16: On the lateral edge of a local damaged zone in Malol Village, this traditional style dwelling might have survived intact on more adequate piling. Clusters of tilted piles (left centre and background) indicate sites of destroyed dwellings.

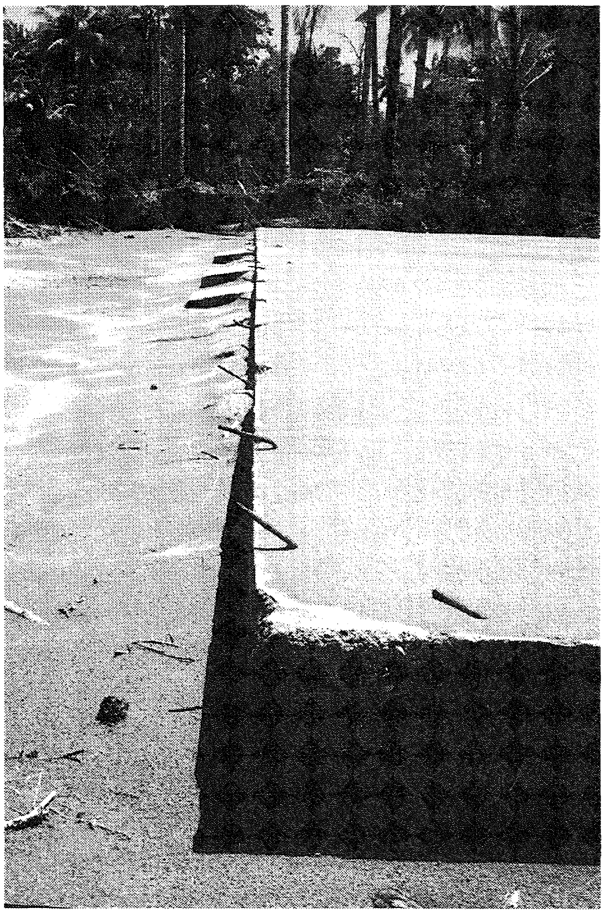

Figure 17: A concrete slab is all that remains of this wood-frame building at Warapu Village.

Built-up, well-formed roads and streets that are normal to an advancing wave tend to focus and channel waves, and hence the danger to life may be greater in a more technological economy. If a similar magnitude tsunami were to hit a New Zealand coastal settlement, we would expect to see great loss of life and similar total destruction of all buildings. We do not, however, have the same population densities in coastal settlements as were present at Sissano Lagoon.

The design of infrastructure, lifeline facilities, coastal planning etc, in New Zealand do not adequately take into account the enormous forces associated with tsunami. Such risks should be considered in the future. Hazard assessment maps are needed to identify the areas of likely tsunami flooding in at-risk communities, so as to guide local tsunami hazard planning. Unique mitigation measures may need to be developed for the communities most at risk. Existing earthquake detection networks may need to be upgraded to develop a warning system suitable for local tsunami.

6.4 Tsunami timing and damage distribution

Survivors from the coastal spit of Sissano Lagoon report that within a few minutes of the earthquake they were hit by three mounting waves with only a matter of seconds between wave fronts. Every building was destroyed as the huge, fast-moving wall of sand-laden water up to 15 metres high washed over the spit.

The disaster struck just after sunset, so that the maximum hours of darkness limited the survivors' ability to help one another.

The tsunami diminished rapidly in height and destructive power to the east and west from the lagoon, suggesting that it was generated by a relatively small, localised source close to the coast, or otherwise focussed in on this particular portion of coastline. It appeared to have travelled subparallel to the coast east of Malol and west of Sissano village, again suggesting that the source was close inshore at Sissano Lagoon. Away from the lagoon, the tsunami only intermittently overtopped the beach barrier to sweep inland. These were where it was reinforced by ocean swells and by reflection back from rocky headlands.

At Malol, water up to 2 metres deep swept through the village, but the destruction was very patchy. Buildings appear to have been destroyed quickly where the force of the water pushed on walls, or where sufficient debris snagged around foundation piles (Figure 16), but elsewhere buildings of relatively light construction survived intact where only the foundation poles were inundated (Figure 8).

The tsunami reached the vicinity of Aitape within a few minutes of the first major aftershock, which occurred 20 minutes after the main earthquake [4]. This gave rise to reports that there were two tsunami-generating earthquakes. We inferred from the 20–minute delay that the tsunami travelled slowly along the coast at *ca.* 75 km/hr. This is further support that the tsunami was generated by an inshore disturbance that focused the wave in on the coast before it travelled laterally along the coast as it radiated out from its coastal centre.

7.0 TSUNAMI GENERATION

We infer that the tsunami was generated by displacement of the sea caused by fault motion beneath the sea floor (Figure 21). In addition to the simple vertical motion associated with the uplift and subsidence of the sea floor noted in section 6.1, the horizontal motion of the steeply sloping sea floor also displaced water upward. Much of the sea-floor displacement occurred near the base of the Wewak trench at >3,500 metres water depth. We reason that the resulting tsunami was particularly large at the coast adjacent to Sissano Lagoon in part because it was focussed by the convergent flow of the ocean water into the region that had subsided. Other factors which may have contributed to the unusually large tsunami are focussing by offshore bathymetry, and horizontal movement of submerged cliffs which may be present offshore. Other teams hypothesize a very large submarine landslide [6, 7] as the cause of the tsunami, but for the size of landslide proposed, we would expect it to have created its own substantial earth tremors and to see evidence of this seismic signal perhaps contaminating that of the primary earthquake or its first major aftershock. Such evidence is lacking.

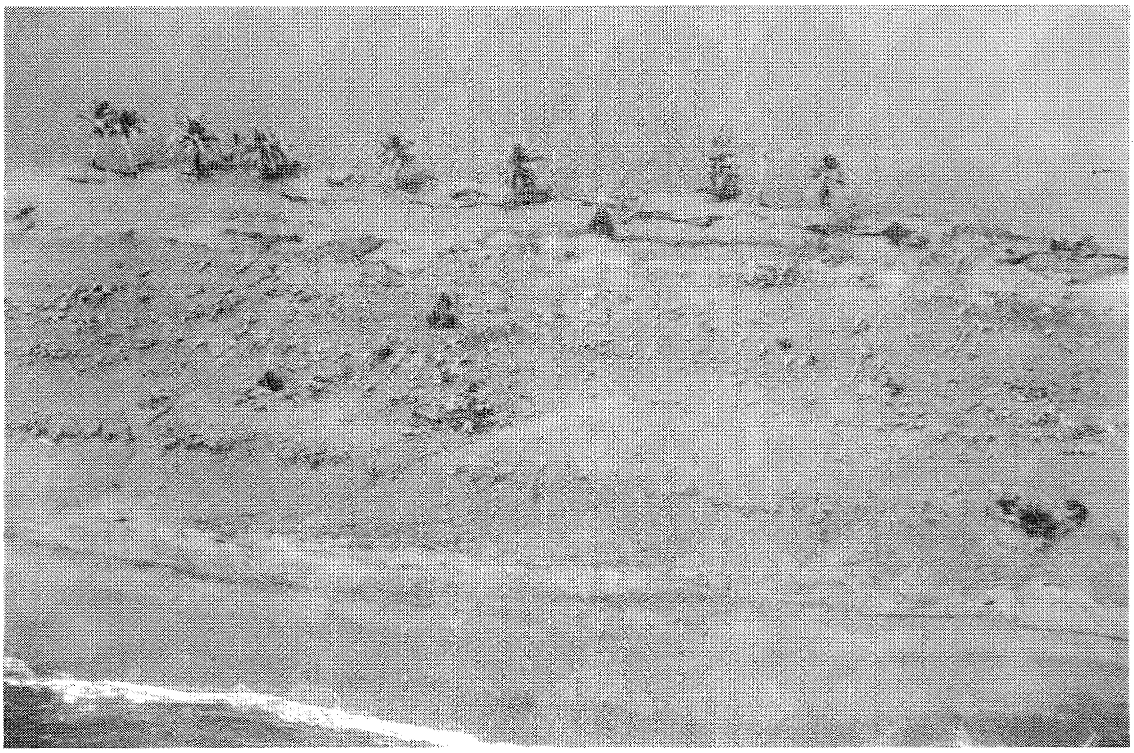

Figure 18: Coconut palms survived well where they were tall enough that their fronds were above the height of the tsunami. Otherwise, the drag on the leaves was sufficient to break the stem, or wrench the palm bodily from the ground. Immature Casuarina trees fared better than immature coconuts because their thin trunks and small leaves offered less drag in the fast-moving water. Scouring of the spit surface, especially adjacent to the Sissano Lagoon was widespread. This possibly is evidence of extreme turbulence from a hydraulic jump as the water slowed in passing across the spit.

Figure 19: A heavy steel pontoon 1.5 metres in diameter was wrapped around a coconut palm.

Figure 20: Every major part of this child's bicycle was deformed as it was tossed around in the tsunami.

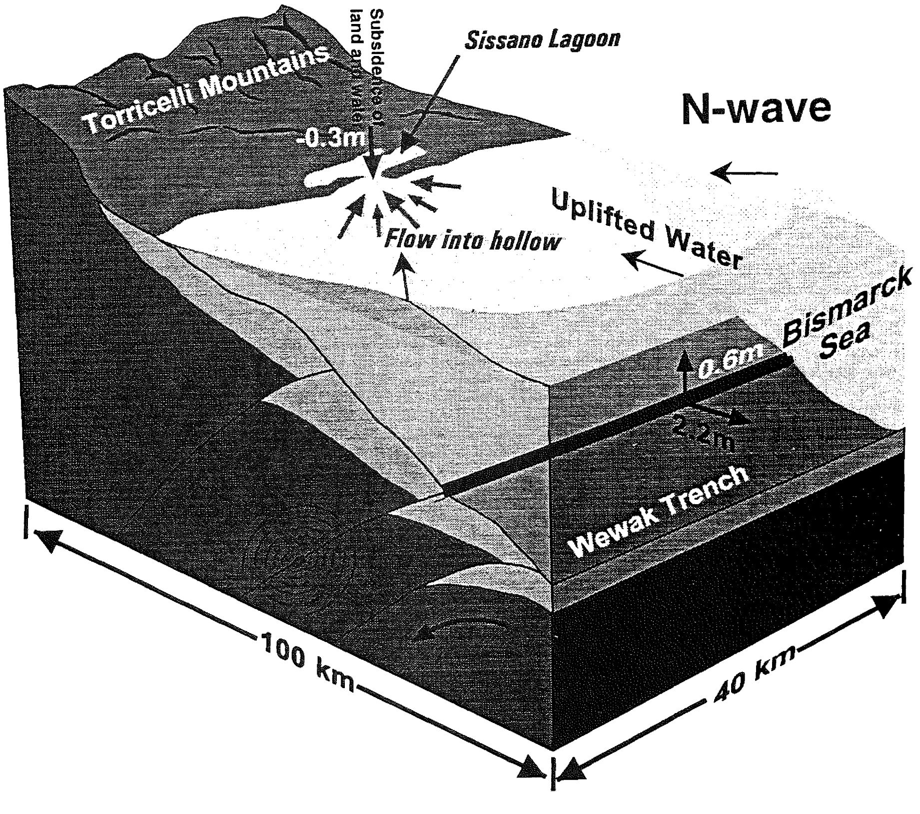

Figure 21: Schematic diagram of the generation of the July tsunami offshore from Sissano Lagoon. Sea surface offshore was raised by both vertical and horizontal motion of the sea floor. Landward wave motion was focused into the inshore depression along the spit at Sissano Lagoon, and hence was more destructive there than expected for an earthquake of M7.1.

8.0 PUBLIC SAFETY AT SISSANO LAGOON

The region appears to have experienced three tsunami this century, but may have an exceptionally long record of human tsunami disasters. In the light of the Sissano Lagoon tragedy of 17th July, a very early (1929) geological discovery [10] made about 16 kilometres inland of the lagoon takes on possible new meaning. A sequence of late Pleistocene sands and silts at an elevation of ca. 100 m, contains a mixed fauna of marine and estuarine shells, plant remains and human bone (the Aitape Skull, thought to be of a *ca* 45-yr old woman with Australian affinities [11]). The fragments of skull, showing no sign of abrasion, were found during a brief 4-hour examination of a stream section in 1929. The sequence is strikingly similar to the expected sedimentary sequence, and state of many of the human remains in Sissano Lagoon.

The sequence of historical geological events centred on the subsiding area of the Sissano Lagoon indicates that the former sites of Warapu and Arop villages are not fit for human habitation. It remains to be seen however if inland sites away from the sea breeze, and exposed to higher incidences of Malaria and Japanese Encephalitis are more sustainable. Away from the immediate area of subsidence, and focussing of tsunami, coastal villages appear to be sustainable with little loss of life, providing that development is set back several hundred metres from the foreshore, and dwellings are firmly attached to well braced and secure piles.

Neither lifestyle nor inadequacies in building design contributed to the enormity of the tragedy at Sissano Lagoon on 17th July 1998. The site is unsuitable for human habitation by any society, no matter what level of sophistication or economy, because of a persistent trend of coseismic coastal subsidence that focuses tsunami on the site. The site characteristic of coastal lowland on the prograding foreshore of a subsiding sedimentary basin that slopes steeply to a deep ocean trench is not unique. There are very similar sites along other sections of the northern Papua New Guinea coast, and elsewhere around the world.

9.0 RECOMMENDATIONS

9.1 Papua New Guinea

- There is need to educate the coastal population of northern and eastern Papua New Guinea about the significant tsunami risk that they are exposed to.
- The coastal area about Sissano Lagoon should not be resettled.
- The area of subsidence is definable, and should be determined by detailed field survey to better determine the area most at risk.
- To aid the maintenance of a long-term memory of the tsunami risk at Sissano Lagoon, memorials to the dead could be built, and the 17th July of each year could be set aside as a special day of remembrance.
- Other areas along the northern coast of Papua New Guinea should be examined to determine if they are also susceptible to coastal subsidence.
- Palaeotsunami studies to locate and date evidence of past tsunami may better define regions of high tsunami hazard.

9.2 New Zealand / Global Issues

- Between 1848 and 1877 four large tsunami hit New Zealand. Each would cause much loss of life were it to happen today. Since 1877, tsunami have been localised or small, except in 1960 when a large one arrived at low tide. The more recent historical record has led NZ coastal communities to seriously underestimate the potential for catastrophe from tsunami.
- We should recognise that all low-lying coastal infrastructure, lifelines and existing communities are at serious risk from tsunami.
- New Zealand has a number of areas where coseismic coastal or offshore subsidence is likely. These should be identified and assessed for tsunami risk.
- The western New Zealand coast may have a low risk from far-field tsunami, but it is significantly at risk from local events.
- Tsunami hazard research in New Zealand should focus on the risk and generation of local tsunami.
- Because of the likelihood of structural damage to buildings from tsunami, it is appropriate under the Building Act to consider events of 0.002 probability in any year (the "500-year event").
- We know very little about the magnitudes of tsunami of 500-year return period around New Zealand.

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