**PREDICTION OF SLUMP GENERATED TSUNAMIS:**

**THE JULY 17TH 1998 PAPUA NEW GUINEA EVENT**

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## ABSTRACT

The local tsunami of July 17th 1998 that struck Papua New Guinea is most probably the result of an offshore sediment slump. This conclusion is based on multibeam bathymetric data, visual observation of the seabed, and sediment piston cores. Offshore data has been utilised to interpret the tectonic framework of the area off northern PNG, the local sedimentary regime and, from this and onshore evidence of sediment dispersal a model of sediment failure has been constructed. Utilising the seabed observations, the distribution of seabed failure has been mapped and the tsunami source location accurately identified. Fluid expulsion from the sediment has been assessed from the presence of authigenic carbonates and chemosynthetic communities. It is proposed that multibeam bathymetry, sediment sampling, and visual seabed observation are critical in the identification of coastlines vulnerable to tsunami attack and, in combination with onshore studies and numerical simulations, tsunami prone areas may be identified. Ultimately, as more case studies are undertaken, underwater landslide prediction may at last become possible.

## INTRODUCTION

With the increasing availability of high-resolution multibeam-mapping systems, there is an expanding knowledge of detailed seabed morphology and the processes through which this morphology has formed. One aspect of this increased database is the recognition of submarine slump-created seabed features and their tsunamigenic potential. Seabed slump scars are now identified off of many coasts. Examples include: Alaska (von Heune et al., 1999), Chile (von Huene et al., 1997), the east coast of the United States of America (Driscoll et al., 2000), California (Orange et al., 1999) and the Ryukyu Islands (Matsumoto et al., 1997). Some of these slumps are located far from shore or in deep water and thus their tsunamigenic potential is limited. Others, however, are near to shore and their formation may well have generated a local tsunami that struck the neighboring coast. The most recent event is the Papua New Guinea tsunami of July 17, 1998 (Kawata et al., 1999; Tappin et al., 1999; Tappin et al., 2001).

The Papua New Guinea (PNG) tsunami brought the threat of locally generated tsunamis sharply into perspective when it was realised that the most likely cause was a sediment slump just offshore (Kawata et al., 1999; Tappin et al., 1999). Over 2,000 people died when the 10 m plus waves focused onto a short stretch of shoreline (Kawata et. al., 1999). Earthquakes are common along the north coast of PNG, but the tsunami was entirely unexpected given the main shock had a magnitude of 7.1. The impact on PNG was obviously considerable, but for many coastal communities worldwide it was a 'wake-up' call to the catastrophic threat of locally generated tsunamis.

The objective of this paper is to present a synthesis of the offshore data acquired after the 1998 PNG event and to consider how data of this type may contribute to the prediction of slump generated tsunamis. One of the challenges of tsunami science is to further understand the mechanisms of offshore sediment failure that may be tsunamigenic. Understanding how and why slumps occur will enable us to predict their occurrence, or at least to identify areas facing the greatest hazards. In the instance of PNG, there has been considerable debate over the source of the tsunami, although in the authors' view the offshore evidence confirms a slump source. Offshore data has proved invaluable in discriminating between alternative tsunami source mechanisms.

## THE PAPUA NEW GUINEA TSUNAMI

The PNG tsunami attained a maximum height of 15 m with extreme focusing along the low-lying sand spit fronting Sissano Lagoon. The waves resulted in the loss of over 2,000 lives and the complete destruction of three villages with four more badly damaged.

A number of lines of evidence suggested that the tsunami was not the direct result of coseismic displacement but rather of a sediment slump. Survivors' accounts indicated that the wave arrived at the sand spit at or about the same time as the first strong aftershock or second earthquake (Davies, 1998). A tsunami wave originating from the main shock would have arrived (from an earthquake located ~20 km offshore) within ten minutes. The tsunami actually arrived twenty minutes after the main shock. Analysis of the earthquake frequency content showed the main shock not to be unusually tsunamigenic (Newman and Okal, 1998b). Mathematical simulation based on a dislocative source (Titov and Gonzalez, 1998; Newman and Okal, 1998b, Kawata et. al., 1999) recreated neither the maximum wave height nor the longshore wave height distribution.

An offshore survey was required to identify the tsunamigenic potential of the area offshore northern PNG and to discriminate between alternative tsunami source mechanisms. Bathymetric data would also be used to identify features that would focus waves onto the coast. The most likely alternative to a sediment slump was a steeply dipping reverse fault upthrust to the south

(Titov and Gonzalez, 1998; Newman and Okal, 1998b, Kawata et. al., 1999). An appeal by Alf Simpson, the Director of the South Pacific Applied Geoscience Commission (SOPAC), led to a response by the Japan Marine Science and Technology Center (JAMSTEC) that offered at least two offshore surveys. Based on the success of the first two surveys, a third survey followed.

Prior to these surveys, the area offshore of northern PNG was unknown in detail. Interpretation of regional gravity and bathymetric data showed a complex of microplates bounded by shallow trenches (Figure 1). The geological evolution of the area is interpreted as a series of collisions along the northern margin of the Australian plate that has resulted in suturing of island arc and oceanic terranes along the northern part of PNG (Cooper and Taylor, 1987; DeMets et al., 1994; Crowhurst et al., 1996; Stevens et al., 1998; Tregoning et al., 1998).

**THE OFFSHORE SURVEYS**

Two surveys were initially planned by JAMSTEC and SOPAC, and took place between January and March, 1999. A third JAMSTEC/SOPAC survey took place in September 1999. The survey objectives were to provide a regional geological context to the tsunami source mechanism, to identify possible tsunami sources, and to acquire detailed bathymetry for numerical simulations. Participating scientists formed a multidisciplinary and multinational group.

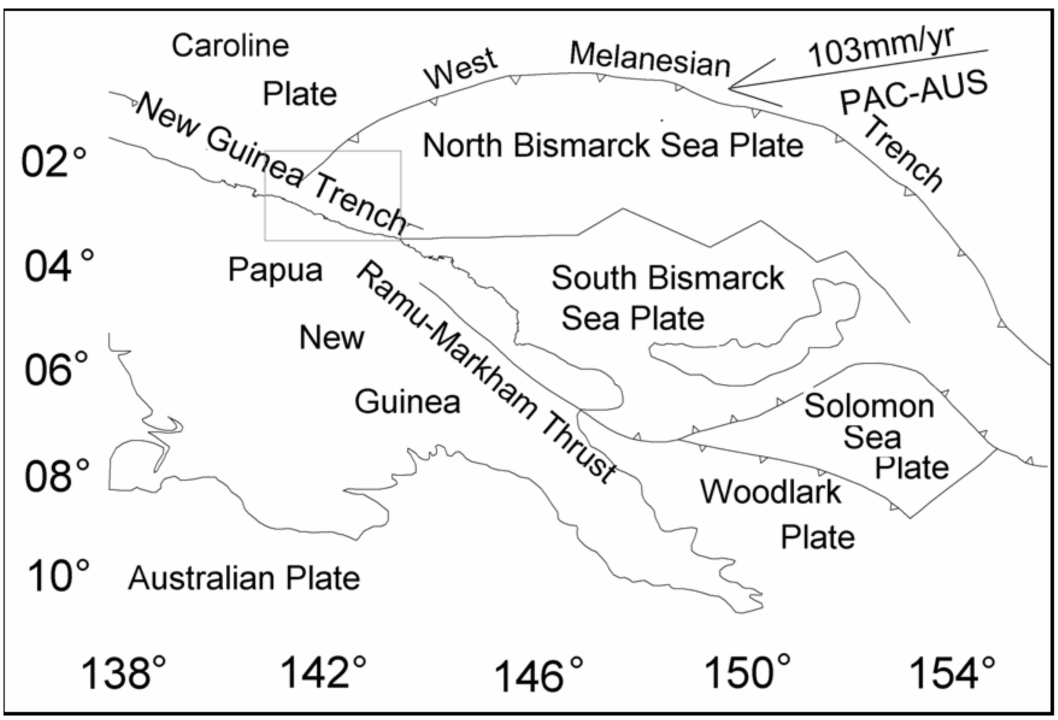
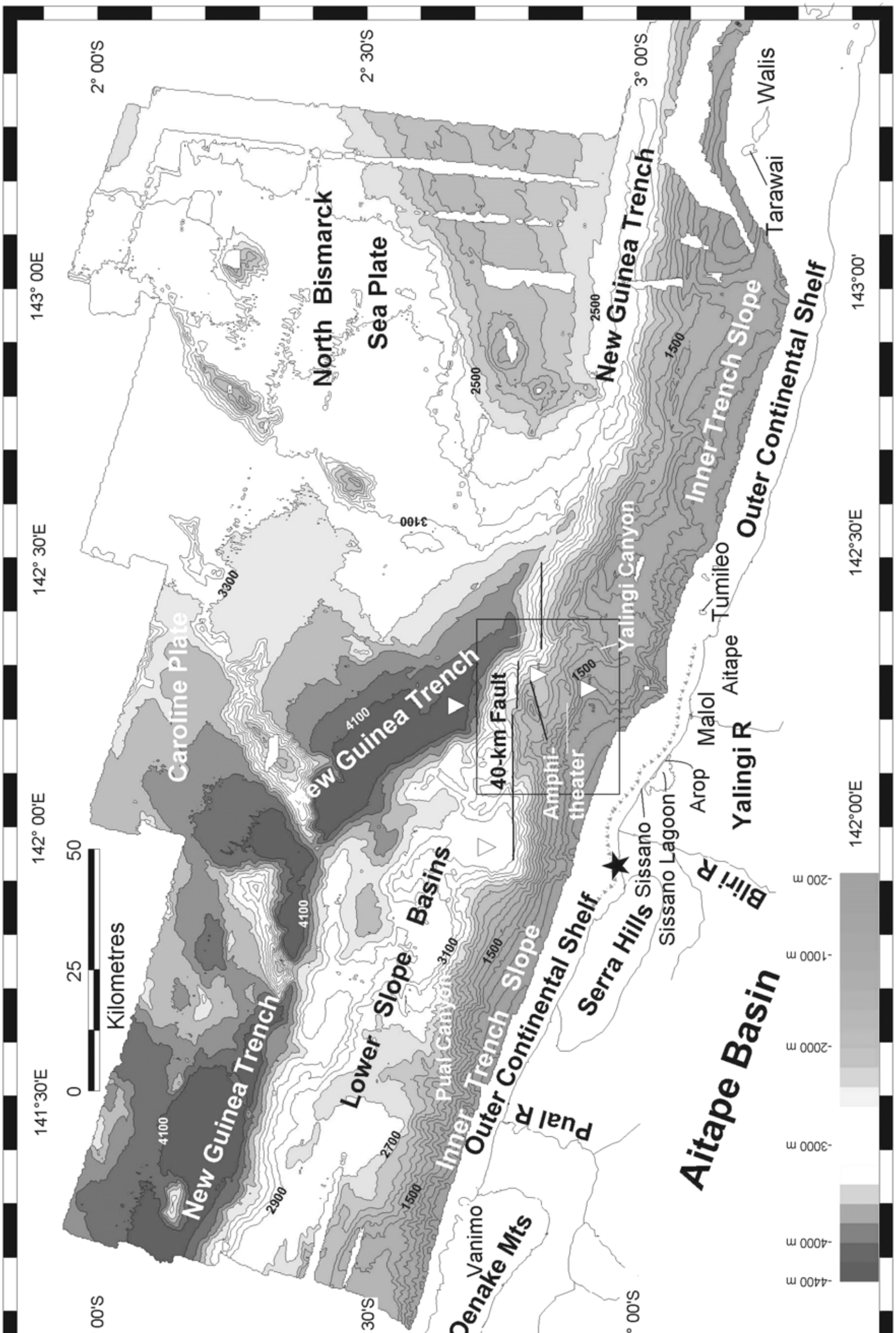



Figure 1: Plate tectonic setting of Papua New Guinea, with main microplates named. Arrow shows convergence azimuth of the Pacific (comprising the Caroline and North Bismarck Sea plates) and Australian plates. Box indicates the area of the bathymetric map shown in Figure 2.



2° 00'S
2° 30'S
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141°30'E
142° 00'E
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0
25
50
Kilometres
North Bismarck
Sea Plate
Caroline Plate
New Guinea Trench
Lower Slope Basins
Pual Canyon
Inner Trench Slope
Outer Continental Shelf
40-km Fault
Amphi-
theater
Yalingi Canyon
Serra Hills
Oenake Mts
Vanimo
Pual R
Bliri R
Sissano
Sissano Lagoon
Arop
Malol
Aitape
Tumileo
Tarawai
Walis
Yalingi R
Aitape Basin
4100
2900
2700
1500
3100
3300
2500
-200 m
-1000 m
-2000 m
-3000 m
-4000 m
-4400 m

Facing page. Figure 2. Bathymetry and main morphologic elements offshore of northern Papua New Guinea together with the main coastal locations and features. Filled triangles identify the area devastated by the 17th July 1998 tsunami. Black star is the most likely epicentral location of the 17th July 1998 earthquake. Open triangles are Sediment Core locations. Box is the area of Figure 3. Contour interval of 200 meters.

The first survey acquired 19,000 km2 of multibeam bathymetry, 4.2 khz high-resolution sub-bottom seismic lines, and four 8 m long sediment piston cores. Gravity and magnetic data were also acquired. The second survey utilized the tethered Remotely Operated Vehicle (ROV), the Dolphin 3-K, to acquire seafloor images using VCR and still photos together with rock samples and short (30 cm) push cores. The third survey utilized the manned submersible (MS), Shinkai 2000 and acquired further VCR images, still photos and rock and sediment samples.

## SURVEY RESULTS

### *Bathymetry*

The multibeam bathymetry reveals a complex morphology offshore northern Papua New Guinea (Figure 2). There is the New Guinea Trench, along which the Pacific Plate is being subducted southward beneath PNG. Along strike (east to west) there are morphological changes of the New Guinea Trench that may be traced from the inner trench wall to the Pacific Plate.

To the east of Sissano Lagoon, the inner trench slope is narrow at 15 km with steep gradients. The lower part of the slope is deformed mainly by strike faults. To the west, the inner trench slope increases in width to 25 km, and at the foot of the slope lie a series of lower slope basins with steep upper scarps and backtilted basin floors. The inner slope is dissected by two deeply incised submarine canyons together with numerous smaller canyons that are especially concentrated along the subsided delta front off Sissano (see below). The two larger canyons are offshore continuations of the Pual River in the west and the Yalingi River in the center.

Offshore of Sissano Lagoon, there is an area that is transitional in morphology between the areas to the east and to the west (Figure 3). Here, there is a subsided delta, on the northeast margin of which is located a reef at 500 m water depth. Below the reef lies an arcuate depression, termed the amphitheater. The amphitheater is bounded to the north by an upraised block. The Upraised Block is bounded to the south by an ESE-WSW trending fault (termed here the 14-Kilometer Fault) and the northern margin by an east-west trending normal fault (termed herethe 40-Kilometer Fault). The 40-Kilometer Fault extends westward from the New Guinea Trench to the most easterly of the lower slope basins. It downthrows to the north. In a westerly direction, it is progressively offset northward by a series of north to south trending minor faults. More arcuate structures are present at greater water depths towards the New Guinea Trench.

The east-west variations observed along the inner slope of the New Guinea Trench are reflected in the structure of the Trench and the Pacific Plate to the north. In the east, the Trench trends East to West, is shallow at 3,000 m and V-shaped. Below Sissano, to the west, there is an offset to the north, the trend changes direction to NW-SE, and the Trench becomes planar floored. The depth increases to 4,000 m. Further west, the trench trend becomes ESE-WNW although the trench floor morphology remains planar and at a depth of 4,000 m.

The Pacific Plate comprises two distinct plates along this margin: in the east, the North Bismarck Sea Plate, and in the west, the Caroline Plate. The former is at a shallower depth than the latter, cresting at 1,400 m and appearing to 'carve' into the eastern part of the inner trench wall. There is an arcuate boundary with the Caroline Plate segment along which water depths increase. On the Caroline Plate there are NE-SW trending arcuate chains of seamounts.

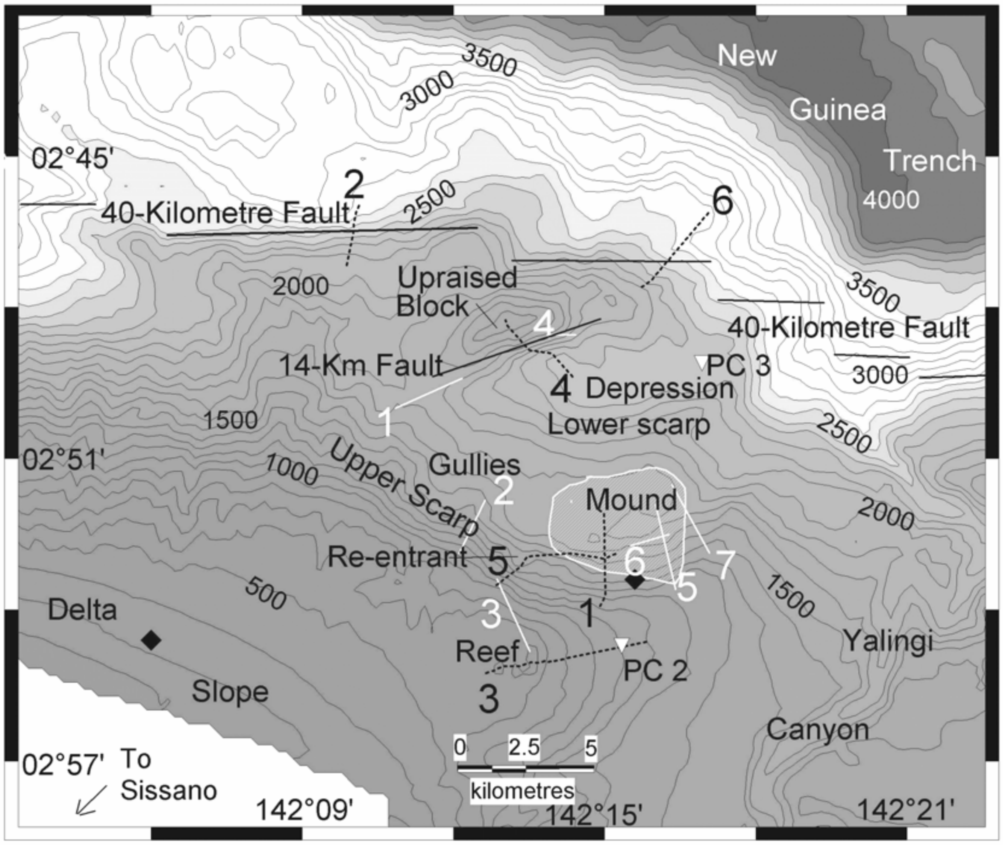


Figure 3. Amphitheater area off of Sissano Lagoon (located in Figure 2) with main morphologic features. Solid black lines are faults; hachured area defines the slump area of July 1998; dashed white lines are ROV traverses; solid white lines are Manned Submersible traverses; white filled triangles are sediment core locations; black diamonds are the two main aftershock locations. Contours at 100 meters.

*Sediment Piston Cores*

Four piston cores, each approximately 8 m long, were acquired. Three (PC-1, 3 and 4) are located in bathymetric lows and one (PC-2) below the subsided reef. Of the former three, one core was located in the New Guinea Trench to the north of Sissano, one in the depression at the foot of the amphitheater, and one in the easternmost lower slope basin. All cores in the depressions sampled olive-green, soft hemipelagic clays with interbedded silt-grade turbidites. The core at the foot of the subsided reef sampled 8 m of olive green, stiff, cohesive clay.

## INTERPRETATION OF THE DATA FROM THE FIRST SURVEY

A number of significant results from the first survey informed us of both the overall structural framework as well as the sedimentary regime in the area. Interpretation of the bathymetry and core data disproved many of our previously held ideas. Undoubtedly, the area is an active convergent margin system, but contrary to our original ideas it is relatively sediment starved compared to nearby margins (e.g., the Sepik River delta). Both these conclusions are of importance in the assessment of tsunami hazards.

The varied morphology of the area is attributed to the subduction of the two (different) segments of the Pacific Plate. The Pacific Plate is moving west and the Australian/PNG Plate is moving north, resulting in a reported azimuth of convergence of ~070° (DeMets et al., 1994; Stevens et al., 1998; Tregoning et al., 1998). The convergence results in transpression along the margin with the westward moving and shallower North Bismarck Sea Plate acting as a 'snow-plough' that is tearing out the base of the inner trench wall through a process termed 'subduction erosion' (von Huene and Scholl, 1991). In the east, this results in subsidence of the inner trench wall along with the steep gradients and the dominant strike-slip faulting observed in this area. West of Sissano Lagoon, the subduction of the deeper Caroline Plate appears to result in a lesser amount of subduction erosion and a wider inner trench wall, although the gradients along the upper part of the inner trench wall are still steep. Faulting is dominantly normal, dip-slip, and results in the formation of the observed back-tilted lower slope basins. The difference in deformation between the east and west is attributed by Tappin et al. (2001) to the different crustal structure of the North Bismarck Sea and Caroline plates. The former is suggested to be less dense (and hence shallower than the latter) because of its formation by a combination of 'younger' backarc basin and island arc processes whereas the latter is older (~30-40 my), denser, and truly oceanic. The subduction of different crust with different densities results in the features observed.

The transitional area lies between Sissano Lagoon and the junction between the North Bismarck Sea Plate and the Caroline Plate (Figure 3). The result is a more complex morphology of normal faults and 'amphitheater' shaped depressions. The amphitheaters are considered to have formed by sediment slumping. Faults and arcuate amphitheater features appear to become older with depth. Convincing support for the interpretation of a subsiding inner trench wall, and proof that subsidence extends to shallow water depth, is provided by the subsided reef at 500 m (Figure 3). Samples obtained from the reef prove that it formed within the intertidal zone (Tappin et al., 2001). Onshore, the Sissano Lagoon formed by subsidence in 1907 (Neuhauss, 1911; Welsch, 1998), with subsidence continuing to the present day (Goldsmith et. al., 1999).

The amphitheater below the subsided reef is considered to be the most likely location for a recent sediment slump. A number of shallow gradient benches on the amphitheater evidence rotational faulting and the morphology suggests that the amphitheater may be the result of more than one slump event. A multichannel seismic line across the eastern part of the amphitheater provides evidence of a slump (Sweet and Silver, 2002). The 40-Kilometer Fault that marks the amphitheater's northern boundary displays normal (dip-slip) throw to the north.

The large, incised submarine canyons, together with the complex of small canyons on the submerged delta front off Sissano, suggest that there is little sediment being discharged into the amphitheater from land. Correlation with onshore drainage patterns show that the two major canyons are offshore extensions of two (Pual and Yalingi) of the three major rivers draining the adjacent land area. The third river, the Bliri, ends in the swamps and lowlands surrounding Sissano Lagoon and very little sediment or water is issuing seaward at the river mouth. The subsiding Sissano area is thus a sediment trap. The sediment deposited offshore is dependent upon the seabed gradient; thus, soft hemipelagic mud and turbidites accumulate in depressions whereas stiff cohesive sediments are exposed on the steep slopes. We await dating of the cores to estimate sedimentation rates in the area.

The main conclusion drawn from the multibeam and sampling survey is that the most likely source of the 1998 tsunami was in the vicinity of the amphitheater below the subsided reef. If the tsunami were due to a slump in this area, then the slumping mechanism would most likely be by rotational faulting in the stiff, cohesive clays similar to those sampled at the foot of the subsided reef. The fault on the northern margin of the amphitheater is considered an unlikely source of the tsunami because it is a normal fault with downthrow to the north. A reverse throw (to the south) is required if the observations of a leading depression wave reaching the shore are correct (Kawata et al., 1999).

The results of the multibeam survey identified the 40-Kilometer Fault and the amphitheater as the prime targets for visual operations by the ROV and MS surveys to follow (Figure 3).

## VISUAL OBSERVATIONS

The aim of the ROV and MS operations were to identify and observe seabed features that may indicate recent seabed movement resulting either from earthquake shaking (and associated faulting) or seabed sediment slumping. There were six dives using the Dolphin 3-K and seven using the Shinkai 2000.

Potential evidence of recent seabed movement includes fresh rockslides or talus slope deposits, sediment fissuring, fault scarps, and evidence of venting. Although there is no method by which these features, if present, can be dated, it was anticipated that temporal relativity could be gauged by their state of preservation.

### *The Amphitheater*

Two ROV dives (1 and 5, Figure 3) located on the upper scarp face of the amphitheater identified extensive fissuring in the cohesive clays (Figure 4 a, b and c). Individual fissures are over 50 m long, two to three meters wide and similarly deep. The fissures largely follow the depth contours of the amphitheater. Soft sediment overlying the cohesive clays is centimeters deep, confirming the conclusions drawn from the multibeam survey about low sedimentation rates on the steep slopes. The fresh appearance of the fissures (sharp, vertical sides, minimal sediment infill, and no evidence of sidewall collapse) all suggest a recent origin. ROV dive 1 encountered a 10-15 m high vertical headwall that is interpreted as an upper detachment of a sediment slump (Figure 4 d and e). Vertical color variation in the soft sediment at the surface from yellow-brown to lime green at depth suggests that the exposure time at seabed had not been long (yellow-brown sediment has been oxidised). At the foot of the amphitheater, there are bacterial mats and tubeworms (Figure 4 f) the presence of which is indicative of fluid venting. At the western end of the amphitheater (observed on ROV dive 5) there is a 30-40 m cliff comprised of exposed limestone (Figure 4 g), at the foot of which is a thick talus slope deposit of angular limestone blocks (Figure 4 h).

MS Dive 2 (Figure 3) to the west of the limestone cliff also located fissures in the cohesive sediment (Figure 5 a and b) as well as slumped decimeter sized cohesive sediment blocks. The sediment surfaces are degraded however and the features considered not of recent formation. The surface of steeply dipping cohesive sediment observed in a gully is also degraded. Three MS Dives (5, 6 and 7, Figure 3) on the eastern side of the amphitheater located numerous fissures with sharp defined margins. The fissures are associated with slumped limestone blocks (Figure 5 c, d, e and f), sulfide rich sediment (Figure 5 g), common chemosynthetic fauna such as tubeworms, mussels (*bathyiomodiolus* sp?) and bacterial mats (Figure 5 g and h and Figure 6 a) as well as signs of active fluid expulsion (shimmering in the water column). Many of the mussels are displaced downslope and may lie either within or on the sediment

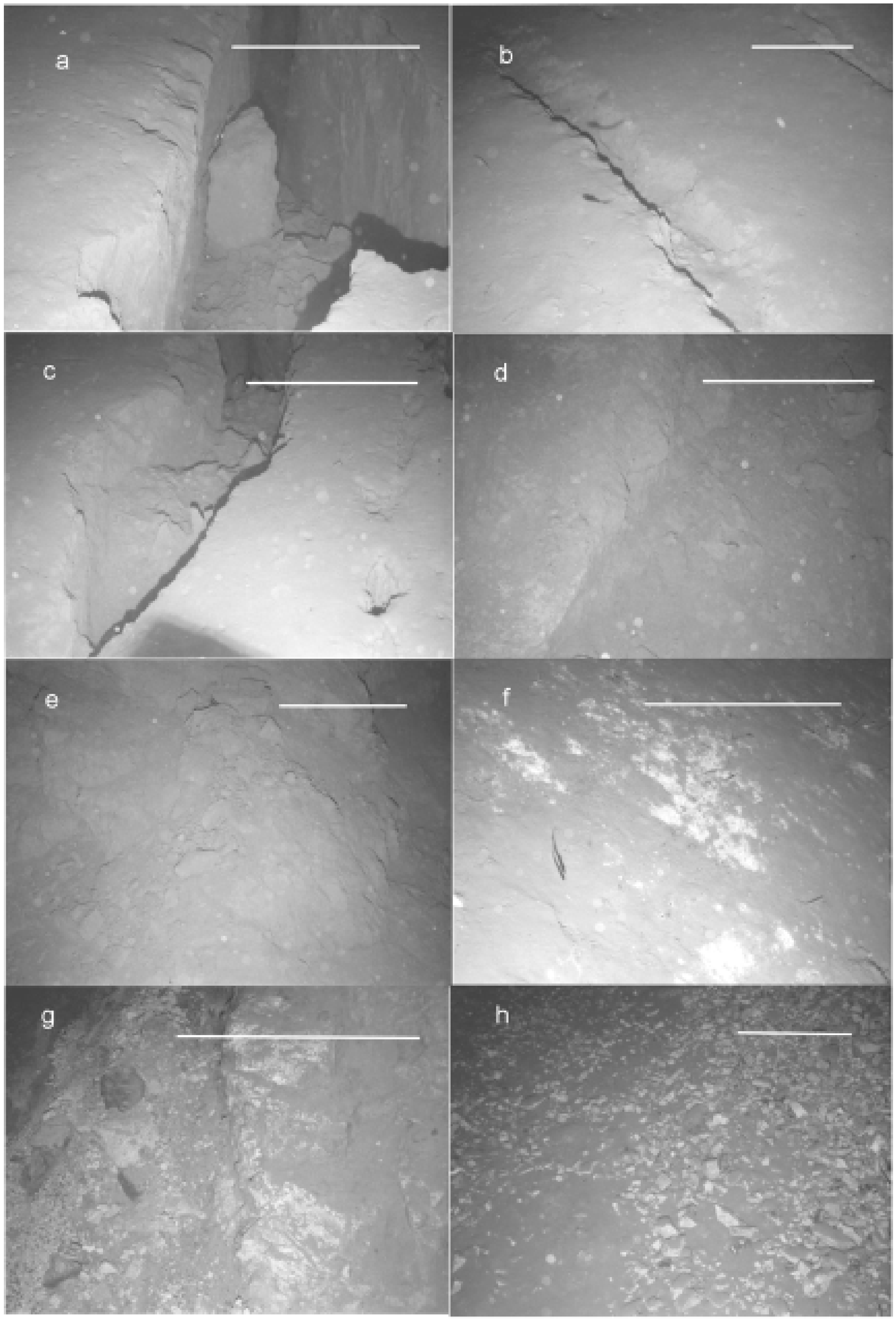


Figure 4. Photographs of upper scarp of amphitheater: a, b, and c; fissures in cohesive sediment: d and e; upper detachment on ROV 1 traverse: f; bacterial mats: g; limestone cliff on ROV 5 traverse: h; talus blocks below limestone cliff. Scale bar is one meter long.

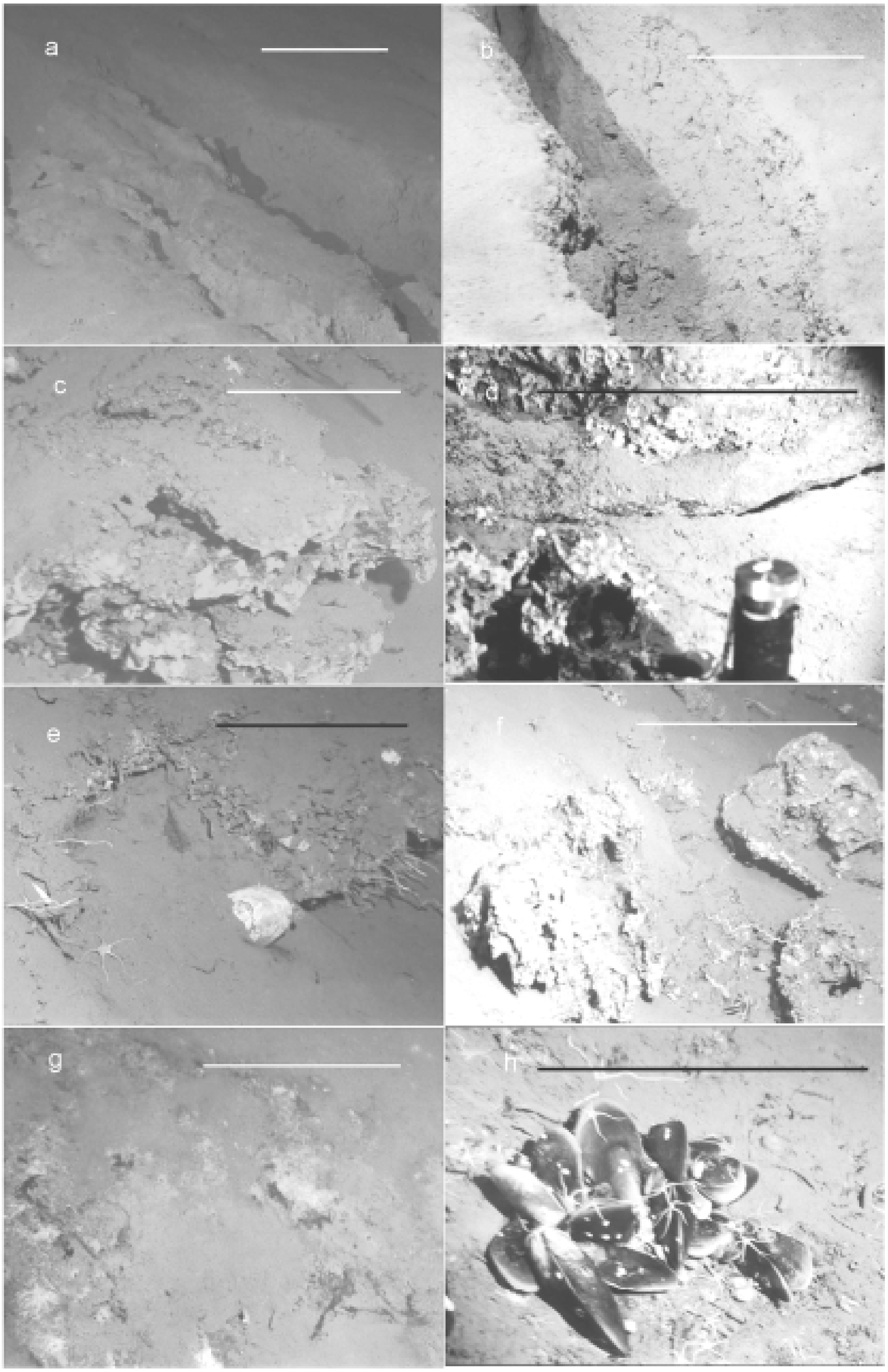


Figure 5. Photographs of upper scarp of amphitheater: a and b; fissures in the west: c, d, e and f; slumped vuggy limestone blocks with in 'e' slumped mussel shell and tube worms: g; sulfide rich sediment (black) and bacterial mats (white): h; mussels and starfish on sulfide rich sediment. White line is one meter. Black line is 0.5 meters.

(Figure 5 e, Figure 6 a). Along the upper margin of the amphitheater, a detachment surface or headwall provides evidence of the lateral extent of the slump (Figures 6 b and c). At the foot of the amphitheater, located on a ~4 $km^2$ mound (Figure 3) that appears to be the primary slump mass, there are numerous fissures (Figure 6 d). The disposition of these fissures suggests thrusting from the south (Tappin et al., 2001).

*The subsided reef*

ROV dive 3 on the subsided reef confirmed the origin of this structure. Samples proved the reef to be of intertidal origin (Figure 6 f); thus 500 m of subsidence had taken place since reef formation. A prolific chemosynthetic community of *bathymodiolus* sp? and tubeworms (Figure 6 e) confirmed that active fluid venting is taking place along the top of the continental slope.

*The Upraised Block*

Observation by both ROV (Dive 4) and MS (Dive 4) of the southern wall of the upraised block identified slump and fault scars (Figure 6 g) and loose blocks that formed talus slope deposits (Figure 6 h). The blocks are decimeter size with many are rounded although some are angular. There is not the overall appearance of freshness seen in the blocks at the foot of the limestone cliff at the amphitheater (compare Figures 4 h and 6 h). Seabed gradients are steep, in many places vertical to overhanging (Figure 7 a). An apparent fault (the 14-Kilometer Fault, Figure 3) running along the base of the upraised block showed evidence of recent vertical displacement of at most a decimeter.

*The 40-Kilometer Fault*

Two ROV dives on the fault to the north of the upraised block (Figure 3) illustrated significant variation along this feature. In the west (MS Dive 2), there is an exposed rock face (Figure 7 b) with talus slope deposits at its foot (Figure 7 c). Some rock debris was angular and therefore recently formed, but many rounded boulders (Figure 7 c) gave the appearance of age. There is no evidence of reverse fault movement; the movement is dip-slip or normal with downthrow to the north. MS Dive 6 located on the east of this feature discovered exposed rock only at shallow depth (Figure 7 d) and the seabed was found to be mainly sediment covered with little disturbance.

Overall, the amphitheater area showed the most evidence of seabed movement in both rock and cohesive sediment. The most common and active disturbance was located in the east. Fresh, sharp fissure boundaries, and angular slipped sediment and rock blocks suggest recent movement. Movement on the 40-Kilometer Fault and on the southern margin of the upraised block is minimal.

## DISCUSSION OF THE OFFSHORE SURVEY RESULTS

Seabed investigation using multibeam bathymetry, sediment coring, and rock sampling together with visual observation using ROV and MS demonstrate that the most likely source of the July 17, 1998 PNG tsunami was a slump within the amphitheater sediments (Tappin et al., 2001). Slump width is widest at ~5 km and ~5 km long. Applying a typical 15% maximum thickness to length ratio, the 5 km length dimension indicates a slump thickness of ~750 m (Schwab et al., 1993; Turner and Schuster, 1996). This thickness is supported by the seismic data of Sweet and Silver (2002). The alternative fault source mechanism is not supported because the 40-Kilometer Fault is normal with downthrow to the north and is only active along its western segment. To be the tsunami source, the fault would have to be a reverse fault, with an overthrust

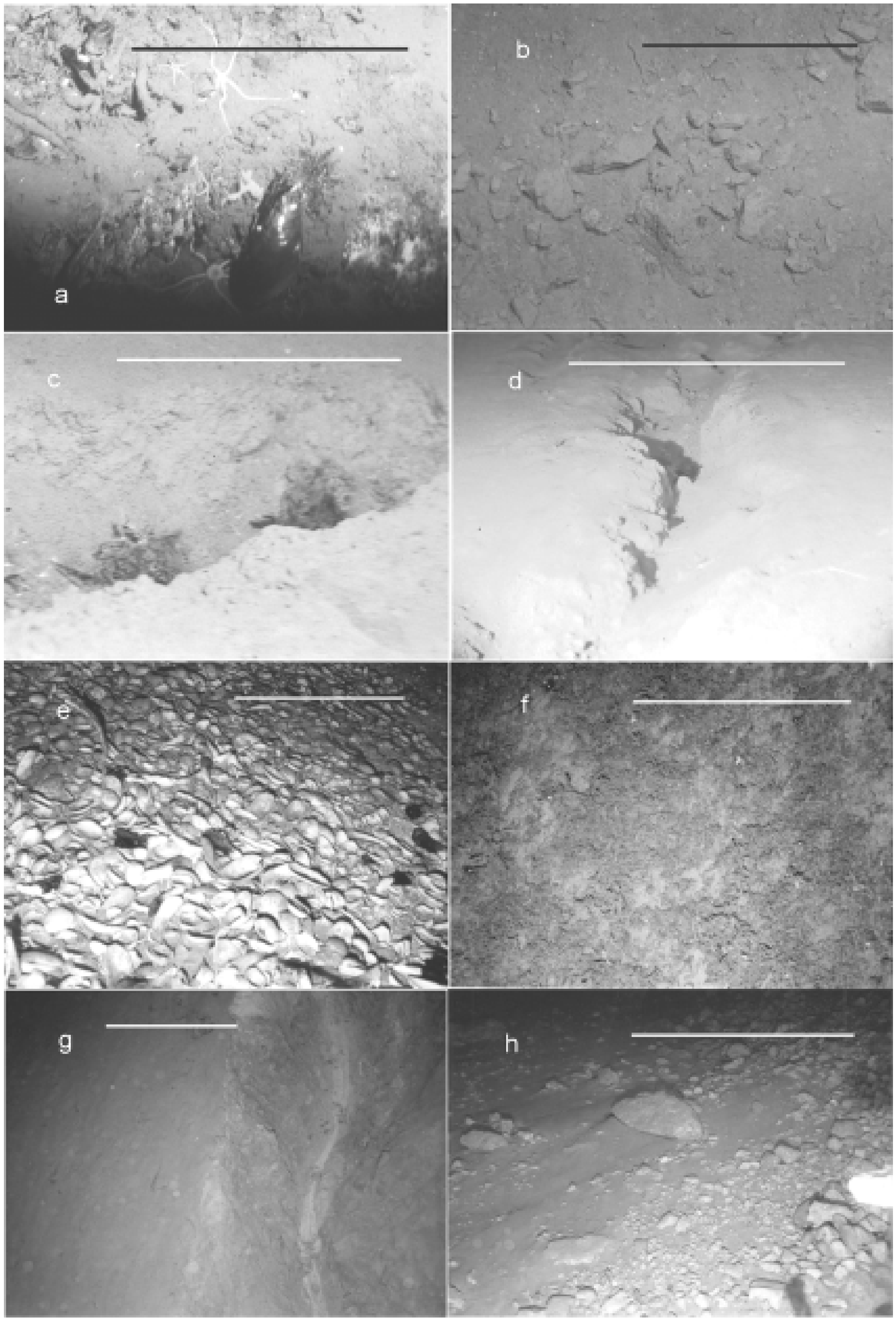


Figure 6. Photographs of -- Amphitheater eastern upper scarp: a; slumped mussel shells: b; loose sediment blocks on upper detachment: c; fissure at the top of upper detachment: d; fissure on mound at base of upper scarp – Subsided Reef: e; tube worm and mussel bed: f; acropora field – Upraised Block: g; fissure in sediment and rock: h; talus blocks. White line is one meter. Black line is 0.5 meters.

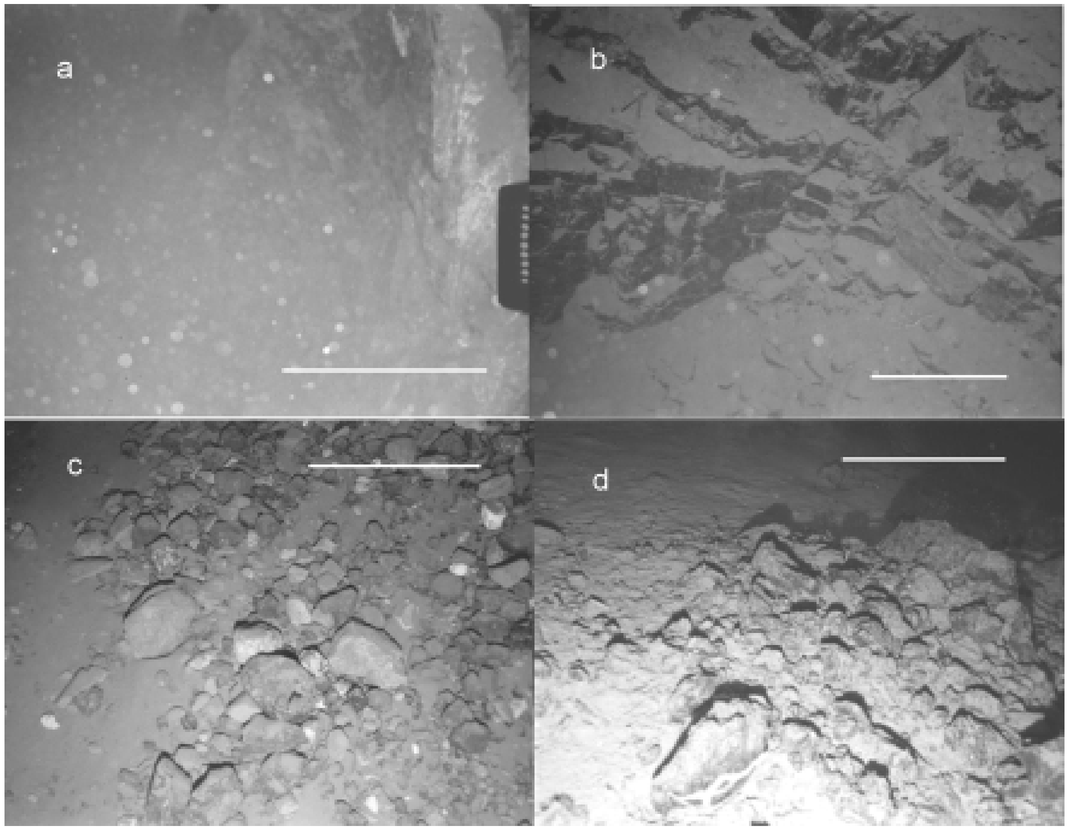


Figure 7. Photographs of -- Upraised Block: a; vertical ?fault face -- 40-Kilometer Fault on western segment: b; exposed fault face: c; rounded cobble boulders: d; weathered cobbles on the eastern fault segment. Scale bar is one meter long.

to the south, and be active along its entire length. A blind thrust (a thrust that does not cut the seabed) is also unlikely as there is no seabed manifestation of a thrust at depth.

Recent slumping within the amphitheater is strongly supported by the fissuring, the upper detachments or headwall, and the fluid venting. The upper detachment of a slump was observed on two dives. The slump is interpreted to lie in the east of the amphitheater in the area where the fissures are most numerous and where there is active fluid venting with associated chemosynthetic faunas. The slump was activated by rotational faulting (or crack propagation) in cohesive sediment rather than translational sliding in softer sediment. The fissures along the amphitheater are interpreted as formed by extension as the slump moved downslope. Fissures on the Mound proper are compressional features formed by upthrusting in the lower part of the slump. The multichannel seismic line acquired over the eastern part of the amphitheater supports this interpretation and suggests a slump volume of around ~6 km$^3$ (Sweet and Silver, 2002).

Dating of the sediment slump at present can only be attempted by comparing the morphologies of the observed features. The sharpest fissure edges are in the eastern half of the amphitheater. Those in the west are degraded and therefore considered ‘older’ by comparison. The increase in chemosynthetic faunas together with active venting towards the east also suggests this area to be presently (and most recently) active. To actually pinpoint the time of failure, we are now attempting to date the mussel shells sampled from the eastern part of the headwall. Tappin et al. (2001) suggest that the slumping led to increased fluid expulsion resulting in the post-slump population explosion in the biotas observed. The size of sampled mussel shells and published growth rates support our conclusion that a slump mainly located in the eastern amphitheater was the source of the July 17$^{th}$ tsunami.

The presence of a slump in the eastern part of the amphitheater is also supported by the increase in sediment thickness in an eastward direction. Observations from the diving surveys suggest that sediment thickness is greater in the east because bedrock is exposed along the western part of the amphitheater but not in the east. The slump is located in an area of thick sediment accumulation (as also shown by the multichannel seismic lines acquired by Sweet and Silver, 2002).

The lithology (or strength and composition) of the sediment is important in tsunami generation because it controls the failure mechanism that in turn controls the magnitude of the tsunami wave generated. For example, failure of stiff clay is more likely to be tsunamigenic than failure in soft sediment (Turner and Schuster, 1996; Watts and Borrero, 2001). Thus, it is necessary to explain the sedimentary regime operating in an area and to describe the overall depositional environment from land to sea. In northern PNG, there are three main river systems that flow northward to the sea. Two, the Pual and Yalingi, flow directly into the incised submarine canyons observed on the inner trench slope. The third, the Bliri, terminates in a complex of swamps surrounding Sissano Lagoon. There is little egress to the sea. A range of mountains (the Toricelli-Bewani) that lie close to the coast limits the catchment area of the three named rivers. The main drainage of northern PNG is by the eastward flowing Sepik River that lies south of the Toricelli-Bewani Mountains. The Sepik discharges into the sea much farther east. The limited fluvial system around Sissano Lagoon explains the low sediment input offshore into the area of the survey. The fine clays, subsidiary silts, and sand turbidites sampled in the cores are the product of tropical weathering onshore.

Okal (1999) showed that the slump failed about 12 minutes after the main shock, ruling out ground acceleration as the cause of failure. Thus a mechanism is required to account for the delay in failure. The sediments we sampled were stiff and normally to slightly overconsolidated (Tappin et al., 2001). We therefore discounted a disentegrative (turbidity current) mechanism of tsunami generation. The retention of internal sediment structure (shown in the seismic profile of Sweet and Silver, 2002) also discounts this mechanism. Pore water migration in the impermeable, stiff clay would be slow and unlikely to induce failure after such a short period of time. Fluid pathways would be more likely to be within more porous/permeable layers (such as the vuggy limestones we sampled) in the slumped mass, along the basal sediment/bedrock interface (the zone of decollement identified on the seismic data), or along faults. The average shear strength estimated along the slump failure plane is an order of magnitude smaller than would be expected for stiff clay at the known failure depth (Watts and Grilli, 2002). Some other mechanism must account for the delay in failure.

Watts et al. (2002) calculate vertical coseismic displacement from the main shock using the shallow-dipping focal mechanism solution and an epicentre near the shoreline. They reproduce the subsidence of Sisanno Lagoon (as measured by McSaveny et al., 1999) and uplift of the Upraised Block. We suggest that the stress gradient within the overlying plate pumped water through the fault system from compressive towards extensional regions. The amphitheatre lies above the strongest stress gradients resulting from the earthquake main shock (and therefore the strongest water advection). We suggest that the stress difference following the main shock resulted in high-pressure water being pumped into and along the control fault (proposed by Tappin et al., 2001) that lies along the amphitheatre headwall. The water flow may have abutted against and then destabilised the sediment mass in the eastern part of the amphitheatre. High pressure water facilitates hydrofracture and crack propagation that may lead to mass failure, especially when initiated at depth beneath a sediment mass (Martel, pers. com.). The water located at depth also lubricates slump motion and may explain the low inferred shear strength of the stiff clay along the failure plane. Based on this failure scenario, the twelve minute delay between the main shock and sediment failure represents the advection time of the water from depth to the slump failure plane. Slumping of the cohesive clays resulted in the internal faulting observed which facilitated fluid escape from both within and beneath the slump. The manifestation of the fluid escape is the chemosynthetic faunas and fluid expulsion features such as the shimmering in the water column. The venting is ongoing as pore water pressures around and within the mobilized sediment slowly return to equilibrium.

There is an interesting symmetry at play in the 12 minute delay between the main shock and the slump, versus the 8 minute delay between the slump and two strong aftershocks that occurred almost simultaneously 20 minutes after the main shock. One may readily calculate that slump displacement released as much potential energy as the main shock released in elastic energy. The slump lies directly above the epicenter of the eastern aftershock. We hypothesize that the slump triggered both aftershock events, a readjustment of elastic energy that is know to happen following rapid mass displacement. Roughly 1% of the slump potential energy change was released during the two strong aftershocks. We further speculate that the 8 minute delay may also be explained by the advection of water through fault systems leading down to the subduction zone. The aftershocks may have occurred along secondary thrust faults or at the subduction boundary.

## CONCLUSIONS

With our experience of the PNG offshore surveys, we have no doubt of the importance of offshore data in the elucidation and validation of possible tsunami source mechanisms, whether these may be coseimic displacement or sediment slump. In the context of prediction, multibeam bathymetry provides data critical to the identification of offshore seabed features such as slumps and faults that in their formation may have been (and could potentially be) tsunamigenic. With the availability of high-resolution bathymetry, detailed knowledge of possible source locations improves the accuracy of numerical simulations. In the instance of PNG, an unusually large local tsunami has been demonstrated to be the probable result of sediment slumping together with bathymetric focussing. The location of the tsunami source determines both the magnitude and the focussing of the tsunami wave(s). A full fluid dynamic simulation of tsunami generation, knowledge of the exact location of the source, and detailed bathymetric data provide the most realistic numerical simulation of the event to date (Tappin et al., 2001).

In the wider context, consideration of both onshore and offshore morphology allows sedimentation patterns to be elucidated, enabling an evaluation of the tsunamigenic potential of extant sediments. Offshore Sissano Lagoon, moderate rates of sedimentation were interpreted from the multibeam data (further demonstrating the value of this data set). Piston coring proved the sediments on the steeper slopes to be stiff and cohesive. Sediment stiffness was a critical factor in the mode of failure (rotational slumping rather than translational sliding or turbidity flow in fluidized sediment) and therefore controlled the transfer of energy into the water column during tsunami generation. Mass movement center of mass motion has a significant effect on tsunami amplitude and wavelength (Watts and Grilli, 2002). Certain sediment characteristics, such as sediment cohesion, can be important predictors of mass failure and tsunami generation (Watts and Borrero, 2001).

Fluid content of the sediment also directly affects sediment stability. For example, off the East Coast of the USA, rapidly deposited and undercompacted sediments are considered likely to fail because of fluid overpressure (Dugan and Flemings, 2000). Large scale fissuring may provide visual evidence of pending slope instability (Driscoll et al., 2000). In contrast, mass failure in the instance of the PNG slump was entirely different, as the sediments are impermeable stiff clays, and failure is attributed to the injection of pressurized fluid. Offshore PNG, diffuse and low levels of fluid expulsion are evidenced by the presence of authigenic carbonate. Increasing levels of expulsion result in bacterial mats, clams and mussels and tubeworms, and ultimately the observed shimmering in the water column. The catalyst to failure may be stress variations as

opposed to earthquake ground shaking. In either case, chemosynthetic communities may be indicators of failure prone sediments (Tappin et al., 2001). Slumping may be caused by a transient water pulse and hydrofracture, whereas slumped sediment becomes a longer-term source of low level venting. Chemosynthetic faunal associations together with population densities may be used to establish levels of fluid activity that directly affect slope stability (Tappin et al., 2001).
We conclude therefore that offshore surveying is an essential aspect of any assessment of areas considered under threat from tsunami attack. There are few case histories at present and PNG is probably one of the best studied to date. There is however often a great deal of offshore data that was acquired for other purposes and that can be utilized in assessing tsunami hazard. Use of these databases enables scientists to focus their future efforts on areas that are most tsunami prone. More focussed studies are then required to identify specific tsunami generation scenarios. Under such circumstances, mass failure and tsunami prediction are only one step away. Simultaneously, we also need to develop cost-effective tsunami mitigation strategies.

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