

The source mechanism and numerical modelling of the 1953 Suva tsunami, Fiji

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Abstract

A study is presented on the cause of the destructive tsunami that struck Suva City in 1953 following a moderate offshore earthquake (M_S 6.75). Alternative earthquake and submarine landslide source mechanisms are modelled using the Geowave tsunami simulation model and compared with observational reports. A simulation using a 60 million cubic metre submarine landslide located at the head of the Suva Canyon, 4 km to the WSW of Suva City reproduces the observed run-up. The simulation shows that high variability in tsunami impact over short coastal distances of Suva are attributable to the complex interplay of wave propagation with the barrier reef system, variable lagoon bathymetry and irregularly shaped coastline. The earthquake tsunami may have been responsible for the observed small “warning” wave, which preceded the destructive tsunami waves initiated by the submarine landslide.

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Keywords: submarine landslides; tsunami; numerical modelling; Suva; Fiji

1. Introduction

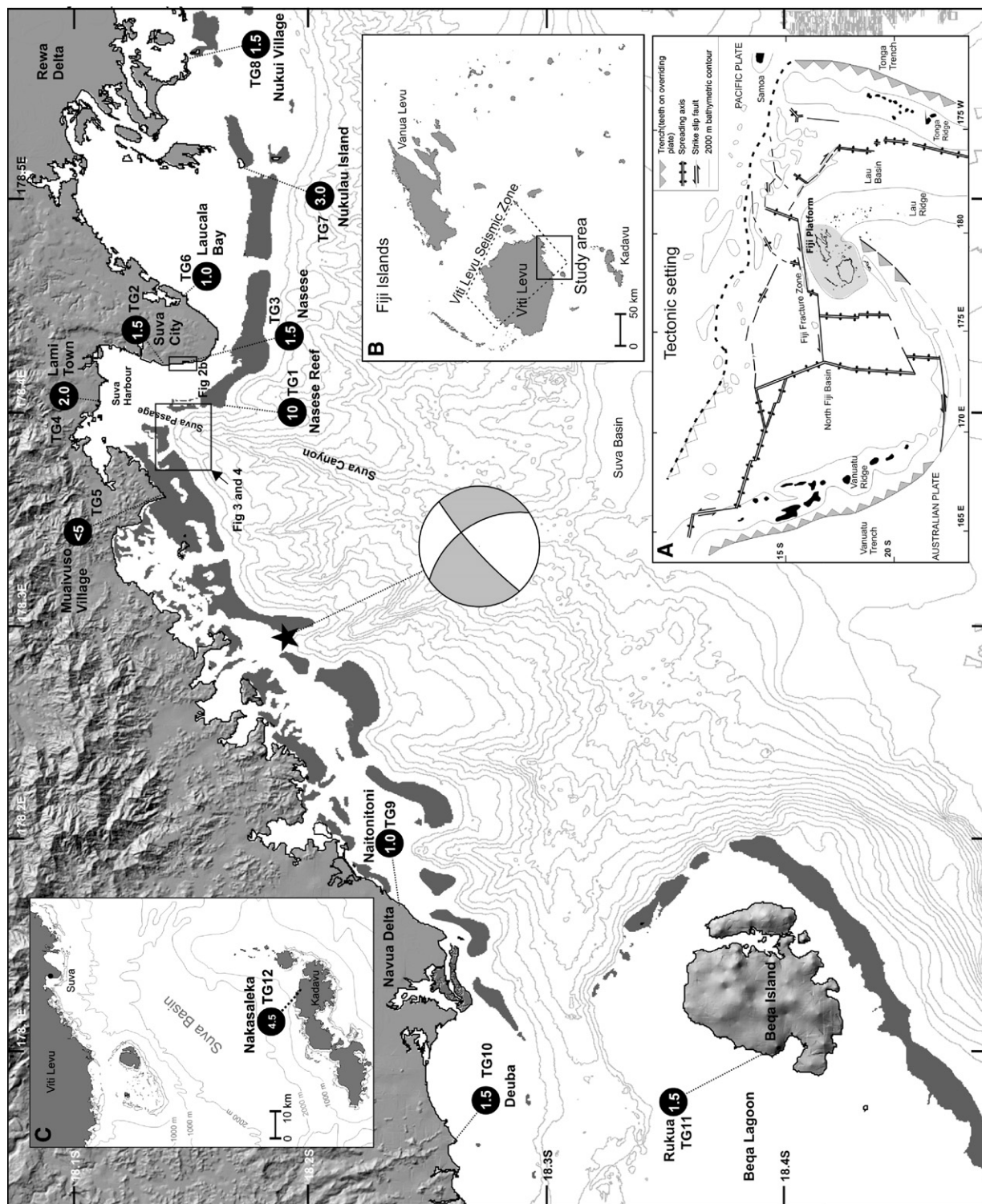
This paper presents the results of a study on the source mechanism and numerical modelling of the local tsunami that struck Suva City in 1953. The threat of submarine landslides as sources of destructive local tsunamis have recently been highlighted by the catastrophic events in Flores Island, Indonesia in 1992 (Imamura et al., 1995), Skagway, Alaska in 1994 (Kulikov et al., 1996; Synolakis et al., 2002a; Watts et al., 2003), Sissano, Papua New Guinea in 1998 (Tappin et al., 2001; Synolakis et al., 2002b) and Izmit, Turkey in 1999 (Yalciner et al., 1999). Large, highly focussed and devastating tsunamis triggered by moderate magnitude earthquakes, are recognized as

due to local submarine landslides. These tsunamis, generated nearshore, provide very little warning and are characterised by large localised peak run-ups (Synolakis et al., 2002b).

An important contribution to tsunami hazard assessment and mitigation is the production of predictive simulations of tsunami generation, propagation and run-up (Watts, 2000). These simulations require accurate bathymetry data and tsunami source parameters. Predictive models used for simulations need to be tested and calibrated by the running of case studies. Some recently presented case studies of local tsunamis have suffered by lacking unequivocal historical accounts (e.g. California, Greene and Ward, 2003), Kaikoura (Walters et al., 2006). They may also be complicated by a combination of earthquake and submarine landslide sources (Borrero et al., 2001; Yalciner et al., 2002).

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The spectacular waves of the 1953 Suva tsunami, observed widely around the Suva coast, followed after a moderate magnitude offshore earthquake (M_S 6.75) at 12:26 pm on the 14th of September. Several historical documents provide informative accounts from witnesses of tsunami formation and the ensuing inundation along the coast of SE Viti Levu, near Suva, as well as Kadavu and other nearshore islands. Reports on coastal wave heights and arrival times provide the necessary data to underpin simulations. Multibeam bathymetry recently acquired for the area off the Suva coast shows in unprecedented detail the location and geometry of the source of the 1953 Suva tsunami and provides the basis for a high resolution simulation computational grid. In this paper, we accurately map the submarine landslide that generated the 1953 event. Using this information we simulate the 1953 event using the Geowave model (Watts et al., 2003).

2. Regional setting

The Fiji Islands lie in a complex tectonic region at the boundary between the Australian and Pacific plates in the SW Pacific. They lie in the active back-arc region, behind the west dipping Tonga arc trench system and the east dipping Vanuatu arc trench system. The main islands lie on the Fiji Platform, a broad, shallow submarine shelf surrounded by water less than 2 km deep (Smith and Raicebe, 1984; Brocher and Holmes, 1985) (Fig. 1A). The area offshore of SE Viti Levu, is fringed by a broad marginal shelf no more than 100 m deep and up to 5 km wide. The shelf supports an outer barrier coral reef and an inner system of interconnected lagoons. On the marginal slope, beyond the shelf break, the water depth increases from 100 m to 2000 m within a distance of 30 km. The Suva Basin occurs at the 2000 m isobath at the base of the slope (Fig. 1).

Suva (pop. 77000) is located on the SE coast of Viti Levu, within the Viti Levu Seismic Zone, a broad zone of intraplate seismicity in the Fiji Platform (Fig. 1B) (Hamburger et al., 1990). A number of damaging historical earthquakes have occurred in this area in 1869, 1906, 1953, 1961 and 1975 (Everingham, 1983a, 1988). The 1953 and 1975 events were associated with local tsunamis (Houtz, 1962; Everingham, 1983b).

3. Data and methods

3.1. Bathymetry data

High resolution multibeam bathymetry data outside the barrier reef of Suva was used to accurately define the source of the 1953 Suva tsunami. The bathymetry data was acquired using the Reson SeaBat 8160 Multibeam Echo Sounder system (Gouldby et al., 2003). This system operates with 126 beams, at 50 kHz and has a depth range of 2500 m. The motion sensor data was collected by a TSS Dynamic Sensor and sound velocity measurements were made using the SBE SeaCat 19+ CTD probe (Gouldby et al., 2003). The raw multi-beam data was extensively post-processed using Navisoft Sweep software for removing erroneous beams, filtering of noise, and correcting for tides and sound velocity. The post-processed data was gridded at 20 m using the Surfer© ver. 8 software and subsequently shaded relief images and bathymetry maps were generated.

3.2. Historical data

The study of past tsunami events is important as it provides a comparison for numerical results with the actual observed event. In order to compile observational evidence on various aspects of the 1953 Suva tsunami, a number of historical documents were examined. An invaluable source of data was the Fiji Geological Survey 1953 Suva earthquake questionnaires kept in the Fiji Mineral Resources Department archives. Examination of printed material such as old newspapers, magazines, and Fiji Geological Survey administrative correspondence, articles, reports and publications proved valuable for this purpose. Interviews were conducted during the present study with eyewitnesses in several households and villages along the SE coast of Viti Levu.

3.3. Tsunami model

In this study, the Geowave tsunami generation, propagation, and inundation model was used (Watts et al., 2003). The initial tsunami parameters (surface water profile and velocity) in Geowave are computed with the Tsunami Open and Progressive Initial Conditions System

Fig. 1. Onland hillshade model and offshore bathymetry of SE Viti Levu (main figure). Bathymetric contour interval is 100 m. Also shown are the epicentre (star) and focal mechanism the 1953 Suva earthquake, the source area of the tsunami (area of Figs. 3 and 4) and observed wave heights along the coast (in black circles). The numbers prefixed by TG refer to the numerical tide gauges used in the simulation model. Dark shaded areas represent the coral barrier reef. Inset A: Tectonic setting of Fiji. Inset B: shows the general location of the study area. Inset C: Map of Suva–Kadavu area showing the 1953 run-up and numerical tide gauge at Nakasaleka, Kadavu.

(TOPICS) (Watts et al., 2003). TOPICS is able to produce tsunami sources for both earthquakes and submarine landslides. In the case of earthquakes, TOPICS defines vertical coseismic displacements from the half-plane solution of an elastic dislocation problem (Okada, 1985). The initial free surface elevation estimate above a submarine landslide source is based on semi-empirical curve fits of 2D (Grilli and Watts, 1999) and later 3D (Grilli and Watts, 2001; Grilli et al., 2002; Grilli and Watts, 2005; Watts et al., 2005) numerical experiments on laboratory fluid dynamics simulations of wave generation. Tsunami propagation and inundation in Geowave is simulated with the FUNWAVE code, a Boussinesq water wave model developed at the University of Delaware (Wei and Kirby, 1995; Wei et al., 1995; Chen et al., 2000; Kennedy et al., 2000). In order to demonstrate various aspects of a tsunami attack, Geowave has been designed to output numerical tide gauges, free surface snapshots, inundation limits, wave timing and water velocities. Geowave has been previously validated based on case studies of several earthquake and submarine landslide generated tsunamis (Watts et al., 2003; Day et al., 2005; Ioualalen et al., 2006).

3.4. Simulation grid

The bathymetry data used in the tsunami computational grid are from a number of data sources. Outside the barrier reef, the bathymetry from the upper slope of SE Viti Levu is from the recently conducted Reson multibeam survey (20 m resolution). Data beyond the outer depth limit of this survey, from the Suva Basin and Kadavu slope, is from 1:250 000 Lomaiviti Bathymetric Map Sheet 5 (Smith, 1992). Bathymetry of the lagoon is from swath mapping surveys carried out by the South Pacific Applied Geoscience Commission and the Fiji Hydrographic Office, and from British Admiralty Charts: Suva Harbour 1660, Western Approaches to Suva Harbour 1673 and Beqa Passage and Lagoon 1682. The near-shore topography of Viti Levu, Beqa and Kadavu islands are from 20 m topographic contours derived from the Department of Lands and Surveys, Fiji 1:50 000 map sheets O29, N29, N30, N32 and O32. Higher resolution (2 m) height data for the Suva City area is from the Suva Pacific Cities data set (Biukoto et al., 2001). Coastal elevations from the Muaivuso Peninsula were derived from differential GPS field surveying. The barrier reefs were mapped from 1:50 000 topographic maps sheets with average height at mean sea level taken as 0.35 m (Solomon and Kruger, 1996). The final grid was re-compiled from these separate data sets with a grid cell size set at 100 m and with sea level

set at mean sea level (MSL), 0.96 m above the Fiji chart datum (Anon, 2004). For the 1953 simulation, the grid was adjusted to remove reclaimed areas and the sea level was set to mean low tide level, 0.7 m below MSL. The spring tidal range in this area is about 1.3 m (Anon, 2004).

4. The 1953 Suva earthquake and tsunami

The Suva earthquake of 1953 is the most destructive earthquake in Fiji's history (Houtz, 1962). The earthquake killed three people and there were 20 cases of serious injuries. The Suva Wharf, bridges, buildings and water reticulation facilities in SE Viti Levu suffered severe damage. The earthquake was a magnitude M_S 6.75 event, with the epicentre located offshore, about 15 km to the WSW of Suva City at a focal depth of 21 km (Houtz, 1962; Sykes et al., 1969). The maximum felt intensities were MM VIII along the coast of SE Viti Levu (Everingham, 1988). The duration of the main shock was 25 to 30 s long (The Fiji Times and Herald, 1953a,b). The focal-mechanism solution of the earthquake indicates strike-slip faulting with a significant but poorly constrained dip-slip component, an east–west tension axis and NW dextral and NE sinistral nodal planes (Hamburger et al., 1990). The focal mechanism and isoseismals of the earthquake indicate rupturing along a 30 km segment of a prominent NW trending onshore–offshore structural lineament.

The 1953 Suva tsunami was witnessed by several hundred people in Suva, Kadavu and in the outer

Table 1
Observed and simulated tsunami wave heights and arrival times of the 1953 Suva tsunami

Location	Numerical tide gauge	Observed in 1953		Submarine landslide simulation of 1953	
		Wave height (m)	Arrival time ^a (min)	Wave height (m)	Arrival time ^b (min)
Suva Barrier Reef	TG1	3 to 15	–	8 to 10	2
Suva City	TG2	1 to 1.5	4–5	1.3 to 1.5	6
Nasese	TG3	1.5	4–5	1.3 to 1.5	6
Lami	TG4	1.5 to 2	–	2.4	7
Muaivuso Village	TG5	<5	–	3.8	6
Laucala Bay	TG6	1	15	0.5	13
Nukulau Island	TG7	2 to 3.5	–	2.7	8
Nukui Village	TG8	1.5	–	1.2	17
Naitonitoni	TG9	0.5 to 1	10–15	0.5	10
Deuba	TG10	1.5	–	0.5	13
Rukua	TG11	1.5	15	0.5	15
Nakasaleka	TG12	4.5	12	0.3	12

^a Time after earthquake.

^b Time after landslide initiation.

islands. A list of arrival times and wave heights from eyewitness reports is given Table 1 and observational locations shown in Fig. 1. Historical records indicate that the tsunami occurred during low tide, when sea level was about 0.7 m below mean sea level. The sea receded along the entire foreshore of the Suva coast below the lowest tide level soon after the main earthquake shock (Usher, 1987; Mrs Sharon Light pers. comm 2003). The maximum height of the waves outside the Suva Reef was estimated by eyewitnesses to be 3 to 15 m high (Houtz, 1962). The build up of these waves was fortunately broken by the barrier reefs. The waves crashed on the barrier reef front, dislodging reef blocks and throwing them on the reef flat. A reduced set of waves remained on passing over the barrier reef. These waves propagated across the harbour and firstly swept over the seawall and road at Nasese and penetrated at least 100 m inland (Fig. 2A,B). It then

proceeded to invade Suva City from the southern end with wave heights up to 1.5 m (The Fiji Times and Herald, 1953a). Ships berthed at the Suva Wharf were badly damaged. The horizontal inundation distance in the city area was no greater than 50 m (The Fiji Times and Herald, 1953a). A 1.5 to 2 m high wave was observed at the coast of Lami, which entered the harbour through Suva Passage. At Muaivuso Point, the village and school, built on a 5 m high marine terrace, were not affected by the waves. The first wave at Laucala Bay on the east coast of the Suva Peninsula arrived 15 min after the main earthquake shock. The rock breakwater of Laucala Bay airport had holes smashed through it by the waves. At Nakasaleka Village, on the northern coast of Kadavu, 100 km to the south of Suva, the first wave arrival was accurately timed to the nearest minute at 12 min after the earthquake (Fig. 1C). The arrival times of the first waves at Deuba, Rukua in Beqa and at

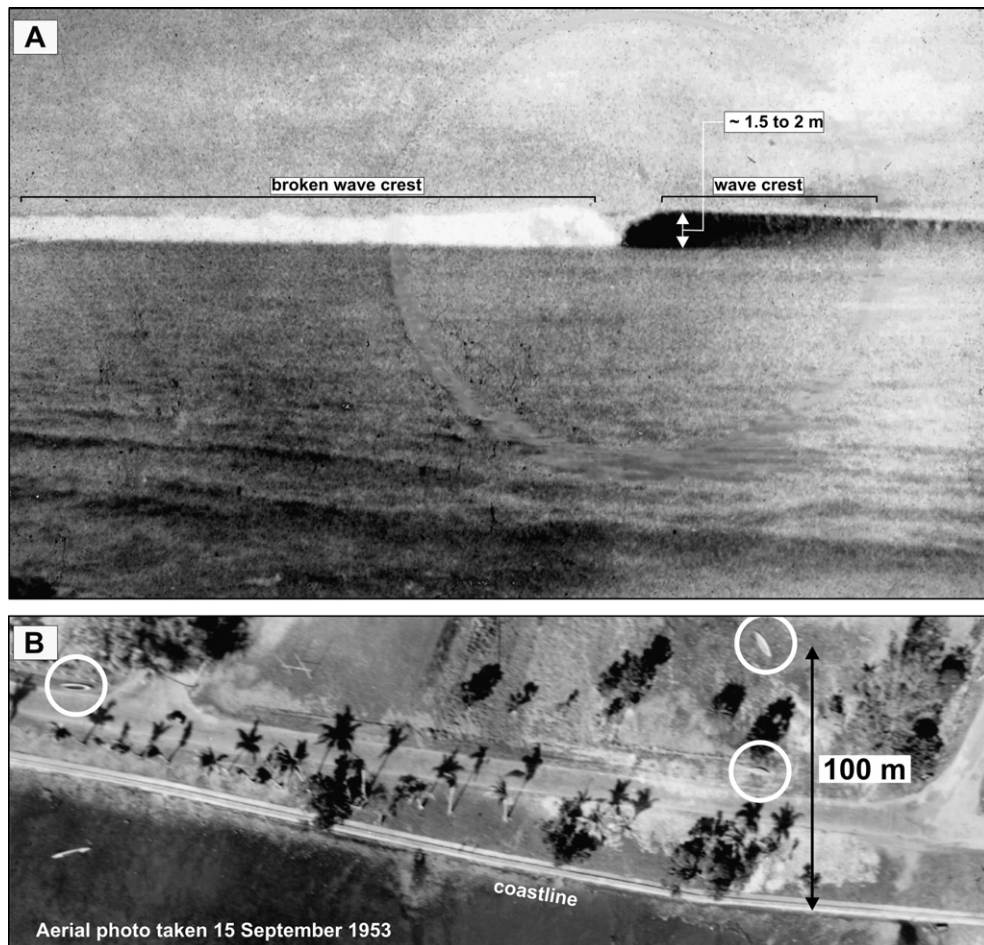


Fig. 2. (A) Photograph taken by an eyewitness of the 1953 tsunami leading wave (bore) approaching the Suva coast. (B) An aerial photograph of the Nasese coast taken by Adastra Airways for the Fiji Geological Survey a day after the 1953 Suva earthquake. The circles show boats that were carried inland by the tsunami waves, indicating inland penetration of at least 100 m at this location.

Naitonitoni in Navua Delta to the west of Suva, were about 10 to 15 min after the earthquake. Areas not protected by barrier reefs such as the islands of Nukulau and Makaluva on the Nukubu Reef and Nukui Village in the Rewa Delta and Nakasaleka village in Kadavu were the most severely affected areas. Nakasaleka and Nukui villages were almost completely destroyed. Wooden structures on the islands of Nukulau and Makaluva were swept away or severely damaged (Usher, 1987). A total of five people died from drowning; three in Suva and two in Nakasaleka.

5. Earthquake tsunami

Following the earthquake there was no reported shoreline subsidence or uplift near the epicentre of the 1953 event. Field checks along the coast of SE Viti Levu show no evidence for recent vertical displacements of shoreline features. These observations are consistent with the focal mechanism solutions for this earthquake, which indicate predominantly strike–slip faulting. Offshore swath bathymetric mapping also revealed no evidence for recent surface deformation along the fault. Statistical data on coseismic surface rupturing show that earthquakes with magnitude in the order of M_w 6 to 7 have a 40 to 80% probability of producing surface rupturing (Lettis et al., 1997). Given the strike–slip nature of the 1953 earthquake source and lack of clear evidence for any coseismic surface deformation along

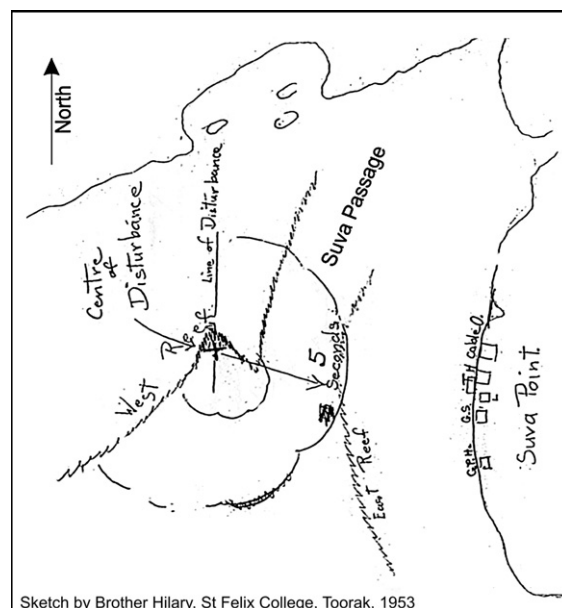


Fig. 3. Eyewitness sketch map showing the exact location of initial sea upheaval west of the Suva Passage entrance during the 1953 Suva tsunami (Fiji Geological Survey 1953 Suva Earthquake questionnaire).

the source fault during this event, it is unlikely that any water waves were generated by the earthquake shock. If they were generated at all, the waves would have been insignificantly small compared to the much larger destructive waves actually observed by eyewitnesses.

The Geowave model and the parameters of the 1953 earthquake source were used to quantitatively evaluate the tsunami caused by this earthquake. The fault source parameters and the initial earthquake tsunami parameters derived from TOPICS are shown in Table 2. The fault source depth, width and dip are constrained by the earthquake hypocentral depth and focal mechanism data. The slip direction reflects the dominant orientation of slickenline lineations on NW trending fault planes measured in the epicentral area. The slip value was estimated using established relationships between the surface wave magnitude (M_s), seismic moment (M_0) and fault rupture parameters (Ekstrom and Dziewonski, 1988; Wells and Coppersmith, 1994). The maximum amplitudes achieved at the coast by the simulated earthquake tsunami do not exceed 20 cm and would therefore not have contributed significantly to the observed destructive waves. In fact, the first arrivals of the simulated earthquake tsunami at numerical tide gauges in Beqa and Naitonitoni (Fig. 1) fit eyewitness descriptions of a preliminary small wave arriving within a few seconds of the earthquake (Houtz, 1962), followed several minutes later by the arrival of larger destructive

Table 2
Earthquake tsunami source parameters

Fault characteristics	Quantities
X_0 (longitude)	178.3
Y_0 (longitude)	−18.2
d (km)	21
φ (°)	146
λ (°)	121
δ (°)	50
Δ (m)	1
L (km)	30
W (km)	27
μ (Pa)	4.4×10^{10}
Tsunami source characteristics	Quantities
M_0 (J)	2.3×10^{19}
λ_0 (km)	27
η_0 (m)	−0.14

The inputs for TOPICS are, in descending order, the longitude of the earthquake centroid X_0 , the latitude of the earthquake centroid Y_0 , the centroid depth d , the fault strike clockwise from north φ , the fault slip direction clockwise from north λ , the fault dip δ , the maximum slip Δ , the fault length along rupture L , the fault width along rupture W , and the shear modulus μ . The output from TOPICS are the seismic moment M_0 , the characteristic wavelength λ_0 , and the characteristic tsunami amplitude η_0 .

waves. A previous suggestion as to the cause of this preliminary “warning” wave has been the impact of earthquake vibration of the reef on the sea (Houtz, 1962). We infer here that the percussor “warning” wave was the effect of the earthquake tsunami, which was later followed by destructive submarine landslide initiated tsunami waves.

6. Submarine landslide source

6.1. Historical data

The location of the submarine landslide source of the 1953 Suva tsunami can be ascertained from descriptions in well documented eyewitness reports. The centre of

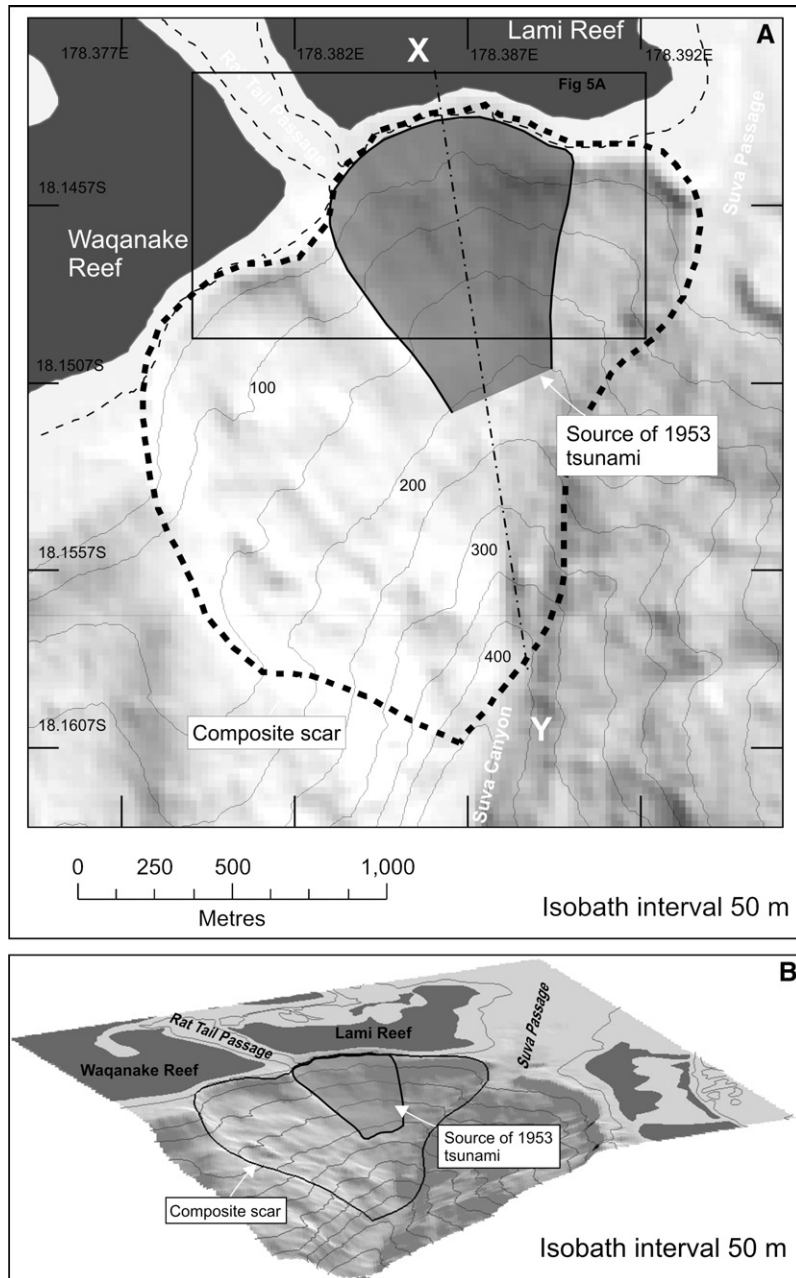


Fig. 4. (A) 20 m gridded multibeam bathymetric shaded relief image showing the location of the 1953 landslide tsunami source within a large composite landslide scar at the Suva Canyon head. X–Y indicates location of cross section presented in Fig. 5. (B) 3D bathymetric image of the source area.

the initial upheaval of the sea is consistently reported by eyewitnesses in Suva to be at the entrance of the Suva Passage about 4 km southwest of Suva. It is also consistently reported that the initial upheaval occurred no more than a minute after the end of the main earthquake shock (*The Fiji Times and Herald*, 1953b,c). A remarkable account in *The Fiji Times and Herald* (1953d) of an inter-island boat captain who was on a southwest approach of the Suva Passage entrance at the time of the earthquake is as follows: "...the cutter *Adi Tirisa* was on its way to Suva... beyond the reef some 4 to 5 miles southwest of Suva... she was badly shaken and a little later three great spouts burst out of the sea, carrying mud, stones, and part of a long-wrecked vessel...". From this description, it can be clearly discerned that the captain had witnessed the formation of the tsunami.

The strongest evidence and most accurate location of the Suva Passage entrance source area is provided by a well located sketch map (Brother Hilary, Fiji Geological Survey 1953 Suva earthquake questionnaire). The sketch map shows the location of the initial area of upheaval of the sea, at the western end of the Suva Passage entrance, as was observed during the 1953 event. A copy of Brother Hilary's sketch map done in 1953 is shown in Fig. 3. The accounts of two other observers in the Suva earthquake questionnaires corroborate the location of the disturbance described by Brother Hilary.

6.2. Bathymetry and aerial photo

Previously the sea disturbance at the Suva Passage entrance has been attributed to the collision of two

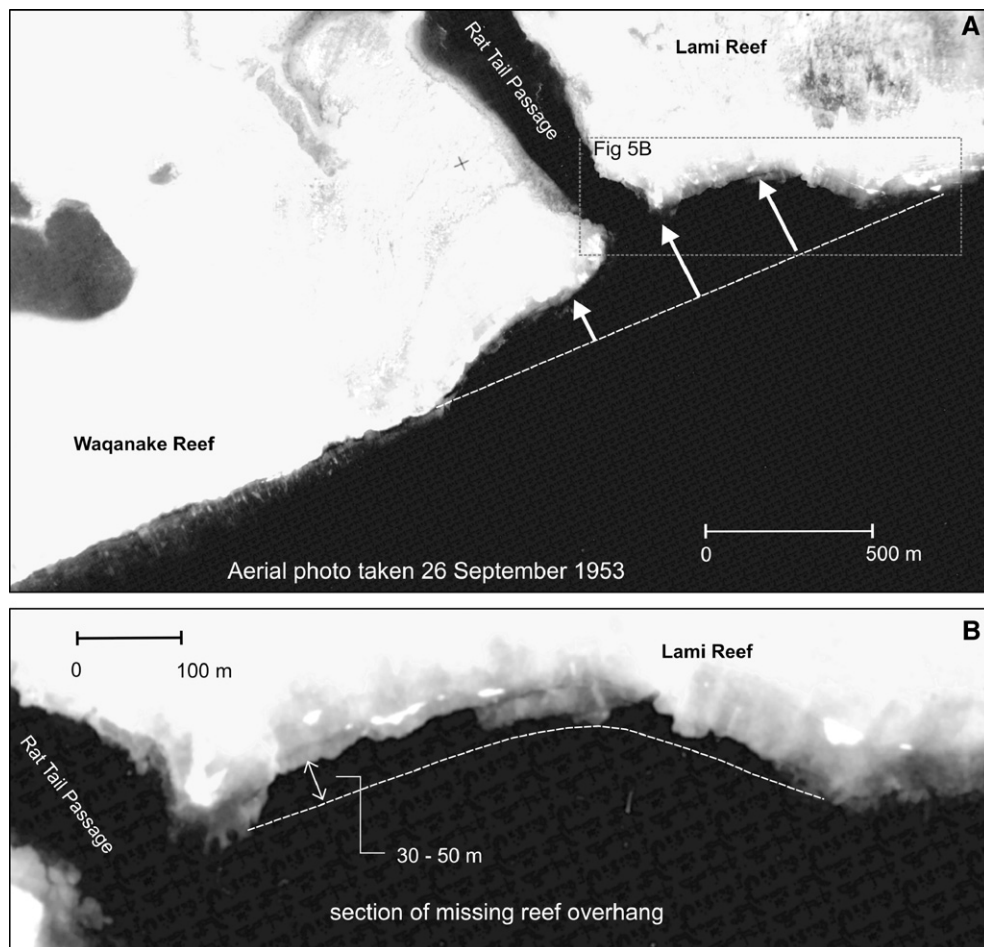


Fig. 5. (A) Composite indentation (shown by arrows) on the barrier reef fronts of Lami and Waqanake Reefs to the west of the Suva Passage. (B) Aerial photo showing reef front loss caused by the 1953 Suva tsunami east of Rat Tail Passage. (Aerial photograph was taken by Adastral Airways for the Fiji Geological Survey 12 days after the 1953 Suva Earthquake).

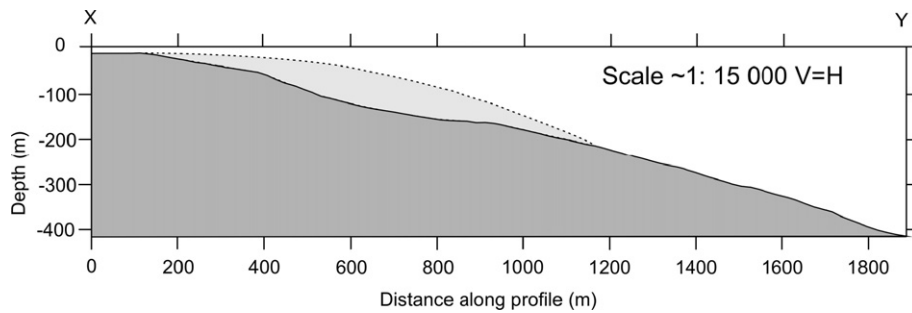


Fig. 6. Cross section of the 1953 landslide showing thickness of up to 80 m determined from the level of preslide surface inferred from undisturbed contours adjacent to slide. Volume of slide mass is approximately 60 million cubic metres (Location of profile shown in Fig. 4).

submarine slides from opposite sides of the passage (Houtz, 1962). However, recently acquired high resolution multibeam bathymetric data reveals a large submarine landslide scar to the west of the Suva Passage entrance (Fig. 4A,B). The entire scar is 1.8 km wide at the headwall scarp. The toe of the scar is at the Suva Canyon floor, where it is 500 m wide and 1.5 km from the headwall scarp. Subaerially, the headscarp is represented by a broad curved indentation in the fronts of the Lami and Waqanake reefs (Fig. 5A). Aerial photos of the barrier reef edge taken in 1951 reveal that this headscarp predates the 1953 tsunami event. The large scar is interpreted as a composite feature that has resulted from several succes-

sive failures. The internal geometry of this scar shows a number of smaller scars that occur adjacent to each other. Furthermore, numerical modelling using the outer dimensions of the entire composite feature failed to produce the run-up observed in 1953.

An aerial photo of the reef front taken soon after the 1953 event shows the development of a new scarp within the central portion of the larger indentation, just east of the Rat Tail Passage entrance (Fig. 5B). A 30 to 50 m wide section of the reef overhang is clearly missing at the new scarp. The multibeam bathymetry data clearly shows a well defined smaller scar within the composite scar between the Suva Passage entrance and

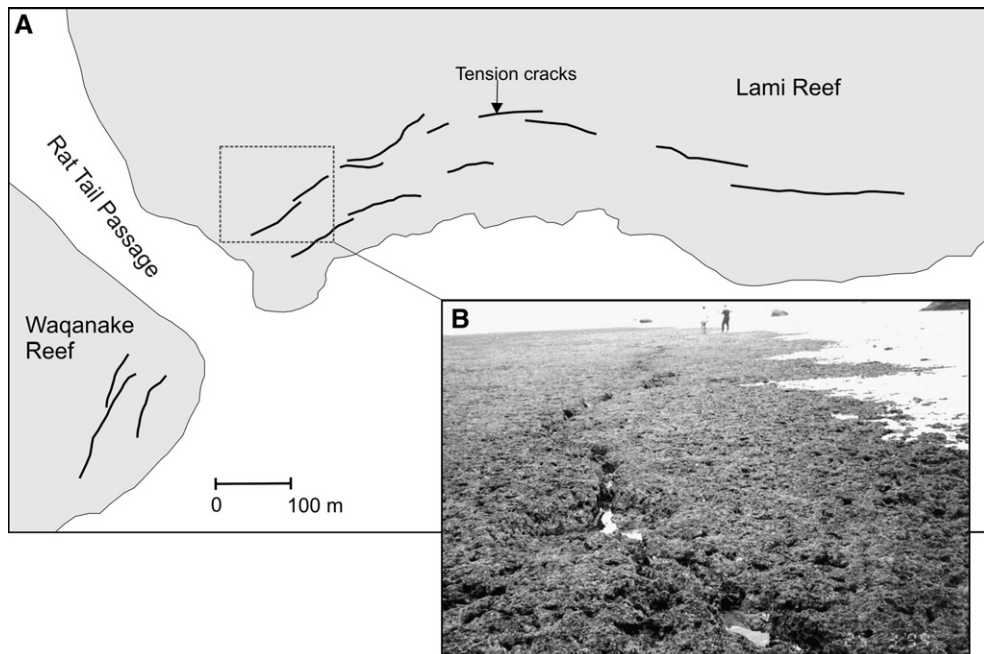


Fig. 7. (A) Tension fractures on the Lami and Waqanake reef flats behind the head scarp of the 1953 failure event (B) An individual fracture on the Lami Reef flat.

the Rat Tail Passage to the west. This scar occurs directly below the position of the sea disturbance shown by Brother Hillary's sketch and is implicated here to be the source of the 1953 Suva tsunami.

This slide is 800 m wide at the head scarp and approximately 950 m in length downslope. The long axis of the slide is oriented at 175° . A cross section through the slide (Fig. 6) shows that the head scarp is inclined at 25° to 30° . The top of the failure has a concave upward slide plane. This is followed downslope by a more planar failure surface. The slide has incised about 80 m relative to the projected profile of the undisturbed seabed surface. The slide thickness was determined by the separation between the pre-failure and post-failure seafloor surface. The pre-failure seafloor surface is estimated by extrapolating undisturbed isobaths outside the periphery of the failure across the disturbed area. The slide has an overall thickness to length ratio of 8.4% and can be classified as translational (Mulder and Cochonat, 1996). The runout path of this landslide is directly into the Suva Canyon. There is an absence of displaced debris mass in the runout path of the slide and it is likely that the displaced material transformed into a debris flow and eventually a turbidity current, which travelled several tens of kilometres downslope along the Suva Canyon. Turbidity currents in the Suva Canyon soon after the earthquake were responsible for submarine cable breakages and abrasion marks on retrieved cable pieces (Houtz and Wellman, 1962).

6.3. Subaerial headscarp fractures and tsunami boulders

Two sets of tensions cracks have been mapped on the Lami and Waqanake reef flat behind the head scarp of the

1953 failure (Fig. 7A). The inner crack occurs within 50 to 60 m of the present head scarp and the outer crack occurs a further 60 to 80 m behind the inner crack. Both the fracture sets are curved and subparallel to the present head scarp. The outer crack is 1.2 km long and spans almost the entire crest of the Lami Reef. The tension cracks form an en echelon system of fractures. The individual fractures are up to 150 m in length, are highly irregular over a few metres and can be up to 10 cm wide (Fig. 7B). The fractures are filled with carbonate cement and with reef organisms and show no evidence of recent or ongoing movement.

As described in Section 4.0, the waves from the 1953 tsunami dislodged sections of the barrier reef edge and deposited them on the reef flat. Eyewitnesses reported the presence of previously unseen boulders on the reef flats near the Suva Passage soon after the 1953 tsunami (The Fiji Times and Herald, 1953e). The dislodged reef limestone blocks are still present as boulder zones on the Lami and Waqanake reef flats behind the headscarp of the 1953 failure. Field measurements show that the largest of the coral limestone blocks deposited by the 1953 tsunami have volumes between 20 to 30 m^3 and would weigh about 50 to 80 t, if a specific gravity of 2600 kg/m^3 is assumed (Fig. 8).

The substantial size and congregated deposition of these boulders indicate that they were uniquely a feature of highly focussed and intense energy waves from the near source area of the 1953 tsunami. Weather driven waves, such as storm surges and cyclonic swells have considerably smaller amplitudes in Fiji (Krishna, 1983), and therefore insufficient energy. Weather driven waves are also expected to have a much more widespread impact on the reef and a broader distribution of debris, unlike the congregated deposits that presently occur on the reef flats.



Fig. 8. Coral limestone boulders on the Waqanake Reef, 4 km southwest of Suva. Larger and more blocky boulders in background were deposited by the 1953 Suva tsunami. Adult person is sitting on largest boulder for scale.

The Suva Passage boulders are comparable in size to tsunami boulders mapped elsewhere, for example in southern Italy (Mastronuzzi and Sanso, 2000). The presence of tension fractures and tsunami boulders on the Lami and Waqanake reefs further confirm the landslide source mechanism for the 1953 tsunami.

7. Numerical modelling of the submarine landslide source

The initial sea surface conditions calculated using TOPICS and the parameters of the submarine landslide source of the 1953 Suva tsunami identified in Section 6.2, are shown in Table 3. The model calculates a surface wave above the slide, with trough amplitude of 41 m and peak amplitude of 11 m, 65 s after the failure initiation. The shaded contour map of this initial sea surface and subsequent snapshots of the sea surface elevation at time steps 2, 5 and 11 min are shown in Fig. 9A, B, C and D respectively.

The simulation shows that within a couple of minutes after slide generation, breaking of the leading elevation waves on the barrier reef fronts causes maximum positive amplitudes to be achieved (Fig. 9B). Edge waves are observed along the reef fronts, which collide

into each other to produce larger amplitudes on the reef flats. On passing over the reef flats the wave heights are considerably reduced and waves that enter the Suva Harbour are 4 to 5 times smaller. A positive leading wave passes over the Nasese Reef and initially strikes the Suva Peninsula at Nasese with a solitary 1.5 m high elevation wave (Fig. 9C). After striking Nasese this wave then migrates northwards and invades the Suva CBD area. From Nasese, the leading wave also travels southward along the coast and refracts around the Suva Peninsula before travelling north along the eastern coast of the peninsula in Laucala Bay (Fig. 9D). A set of simulated leading elevation waves migrate eastward from the source area along the barrier reef front as edge waves (Fig. 9C). This wave subsequently invades Nukulau and Makaluva islands (Fig. 9D) with amplitudes 2.5 m high. They then proceed further through the reef passages and eventually strikes Nukui Village.

A sensitivity analysis was carried out by varying the location of the source 200 m to the S, E and W of its defined position and varying the slide parameters by $\pm 20\%$ of the measured values. For all the re-runs of the simulation, the location of the peak run-up positions occurs persistently at Lami and Nasese. The arrival times of the first elevation wave at all tide gauges vary by only 1 to 8%. The wave amplitudes generally vary by 15 to 20%. As expected, larger dimensions of the slide geometry, higher slope angle and shallower water depths of the slide, produce larger amplitudes. The most sensitive parameters are the slide depth and the slide density. These parameters produce up to 35% variation in the initial tsunami amplitudes and up to 40 to 70% variation in wave amplitudes in some coastal tide gauges.

8. Comparison of the submarine landslide simulation to observational data

Twelve numerical tide gauges were placed in the simulation model to coincide with locations where eyewitness data were reported in 1953 (Fig. 1). The wave profiles from selected tide gauges are shown in Fig. 10. The amplitudes and arrival times of the largest elevation waves recorded by tide gauges are listed in Table 1 alongside observed values from 1953. Comparison of the two sets of data shows a correspondence between the simulated and observed wave heights and arrival times. Several specific aspects of the submarine landslide simulation are in close agreement with the description of the tsunami in historical reports. Some key correlations are highlighted below.

The simulation correctly shows an initial drawdown in the Suva Harbour within 5 min of tsunami generation

Table 3
Submarine landslide tsunami source parameters

Landslide characteristics	Quantities
X_0 (longitude)	178.39 E
Y_0 (longitude)	18.15 S
ψ (orientation)	195°
γ (kg/m ³)	1900
b (m)	950
T (m)	80
w (m)	800
d (m)	125
θ (°)	20

Tsunami source characteristics	Quantities
a_0 (m/s ²)	1.003
$u_{\max}$ (m/s)	65.38
s_0 (m)	4258
t_0 (s)	65.14
λ_0 (m)	2280.92
η_0 (m)	−40.85

The inputs for TOPICS are, in descending order, the longitude of the initial slide centre X_0 , the latitude of the initial slide centre Y_0 , the counter clockwise orientation from north ψ , the specific density γ , the initial landslide length b , the maximum initial landslide thickness T , the maximum landslide width w , the mean initial landslide depth d , and the mean initial incline angle θ . The outputs from TOPICS are the slide initial acceleration a_0 , the theoretical maximum (terminal) slide velocity $u_{\max}$, the characteristic time of slide motion t_0 , the characteristic wavelength λ_0 , and the characteristic tsunami amplitude η_0 from the depression at time $t=t_0$.

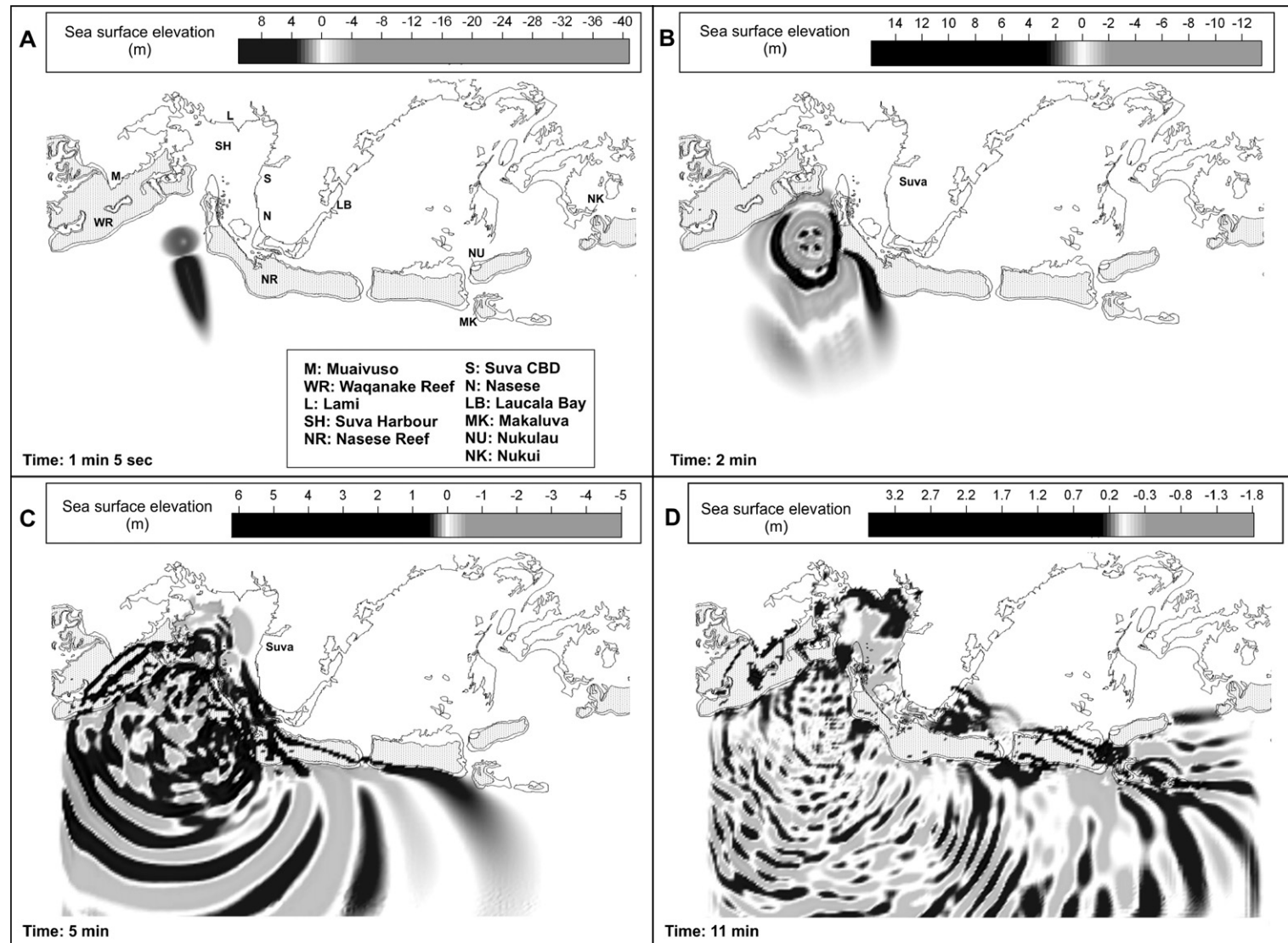


Fig. 9. Simulated sea surface elevation of the 1953 Suva tsunami at times steps 1 min 5 s, 2, 5 and 11 min of tsunami propagation from a submarine landslide source at the head of the Suva Canyon shown in Fig. 4.

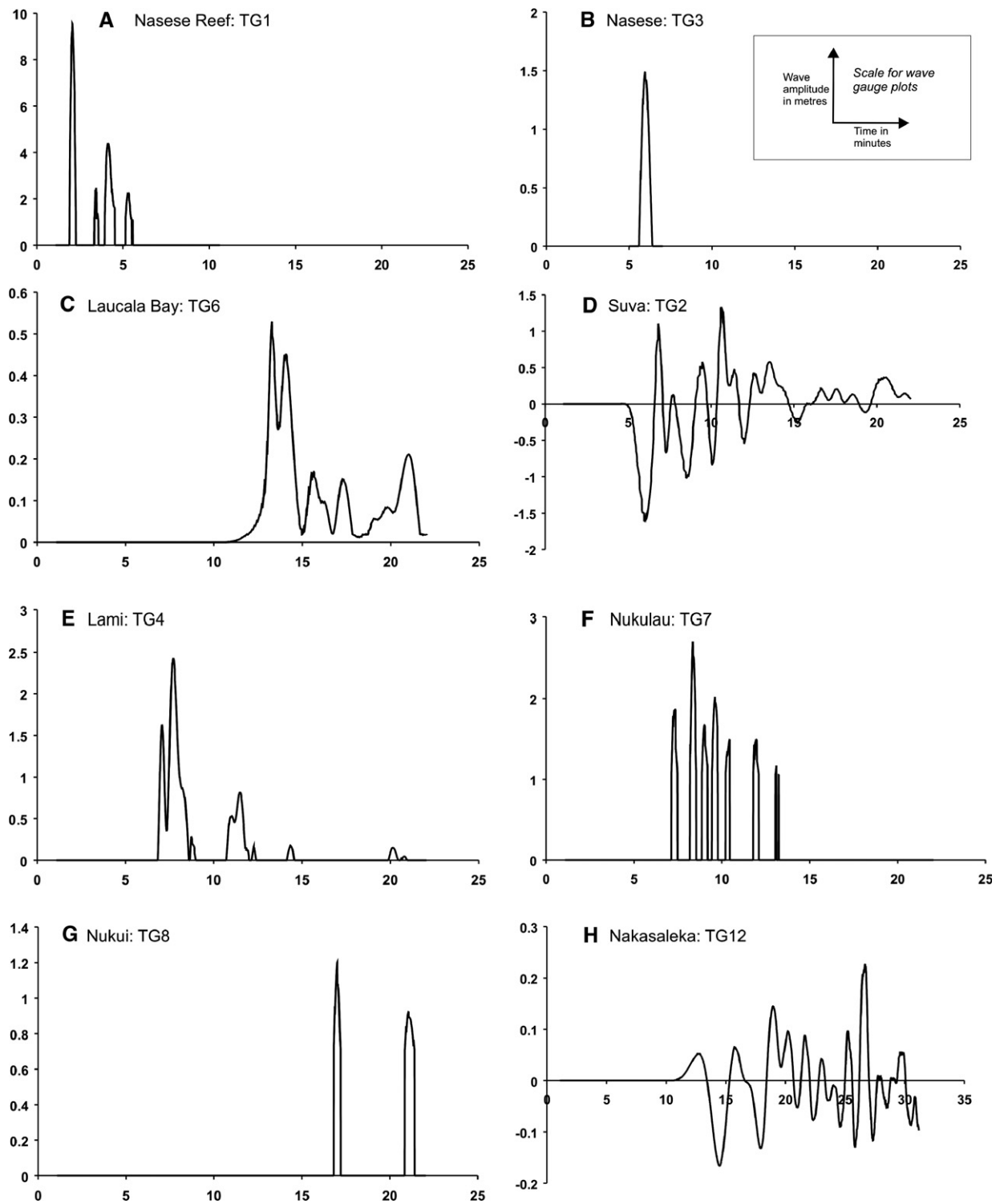


Fig. 10. Simulated coastal wave profiles of the 1953 Suva tsunami. Location of numerical tide gauges are shown in Fig. 1. Note vertical scales are different.

(Figs. 9C and 10D). This is due to the northward spreading of the initial depression wave through the Suva Passage. After about 7 min, the simulation shows an anomalous build up of positive amplitudes in the Lami foreshore area (Fig. 10D), an effect validated by descriptions in 1953 of focussed wave activity in the Lami area. This activity led to seawall damage and deposition of reef boulders on the Lami foreshore (Usher, 1987).

The simulation of a wave initially striking the Suva coast at Nasese is consistent with the sequence of events observed in 1953. The steep profile of this wave has the characteristics of a bore (Fig. 10B), and resembles the approaching wave observed in the Suva Harbour (Fig. 2A). Focussed wave effects in the Nasese area resulted in a relatively large area of inundation, inland sediment deposition, seawall damage and a person drowning. As replicated by the simulation, inundation of the Suva CBD area was reported to have commenced from the southern end (The Fiji Times and Herald, 1953a; Usher, 1987).

A close correlation is seen between the simulation and recorded observations of waves travelling east from the source area. Eyewitnesses on Nukulau island to the east of Suva described the approach of the waves from the west as a “great wave running along the reef” (The Fiji Times and Herald, 1953f). This is resembled by the simulated leading wave travelling east along the reef front in Fig. 9C. A set of steep amplitude waves recorded by the tide gauge on Nukulau (Fig. 10F) is consistent with the report of three waves sweeping away recreational facilities on the island (Usher, 1987).

The maximum simulated heights of the positive leading waves that pass over the Waqanake Reef and strike the coast of Muaivuso are 3.5 to 4 m high (Fig. 9C) and as reported are well below the level of marine terrace at this location (Table 1). In Laucala Bay, on the east coast of the Suva Peninsula, the simulated arrival time shows a close match to the observed arrival time (Fig. 10C).

Tide gauges located more than 30 km to the west of the tsunami source area, at Naitonitoni (TG9), Deuba (TG10), Rukua (TG11) and about 100 km to the south at Nakasaleka (TG12), show a good resemblance to observed tsunami arrival times. The wave heights at these distal gauges, however, are generally lower than what was observed (Table 1).

9. Discussion

9.1. Single source for the 1953 Suva tsunami

Irreconcilable arrival times led (Houtz, 1962) to suggest multiple submarine landslide sources for the 1953 Suva tsunami. Using the arrival times Houtz defined the source

area as a locus of points along the barrier reef fronts between Suva and Beqa (see Fig. 1). However, the results of the numerical simulation of the 1953 Suva tsunami in the present study indicate that multiple submarine landslide sources are not required to reconcile near-field arrival times that were observed in 1953, but a single source area at the Suva Canyon head is sufficient. Accurate simulation of arrival times of waves from the Suva Canyon head source area at distal locations to the west of Suva and at Kadavu counteracts further the possibility of multiple submarine landslide sources along the barrier reef front of SE Viti Levu. We do not rule out the possibility, however, of the earthquake tsunami as the source of the preliminary “warning” wave observed at a number of locations.

Additional evidence contradicting multiple submarine landslide tsunami sources of the 1953 tsunami is provided by the distribution of tsunami boulders on the barrier reef flats. An aerial survey of the barrier reefs of southern Viti Levu conducted by the Geological Survey of Fiji in 1983 (Holmes et al., 1987) shows that the largest concentration of boulders occur on the Waqanake, Lami and Nasese Reefs surrounding the Suva Passage entrance. In this survey, considerably smaller boulders found randomly scattered on other parts of the barrier reef in southern Viti Levu are likely have been deposited by storm surges or cyclonic driven wind waves. None were found to be so densely distributed as that at the entrance of Suva Passage. The exclusiveness of dense boulder distribution at the Suva Passage entrance is yet another assertion that this site alone was the source area of the 1953 tsunami and that no other tsunamigenic reef edge failures of similar or larger size have occurred elsewhere along the southern coast of Viti Levu in the recent past.

9.2. Tsunami wave propagation

The simulation of wave propagation from the source area to the coastline shows how tremendously variable wave dynamics and resulting coastal wave heights can be over very short longshore distances in the Suva area. To a large extent, this is due to the presence of a system of intervening barrier reefs and deep water passages, and a highly irregular coastline. Highly variable bathymetry of the shallow lagoon, due to underlying bedrock structure and reef growth, also contributes to a diverse range of wave effects. The important role of the barrier reef system as a natural breakwater to approaching tsunami waves is highlighted by the simulation. Most of the wave energy is dissipated while breaking on the barrier reef front. Wave amplitude and velocity reduced by up to 80% on passing over the barrier reefs.

Wave focusing in the Lami and Nasese areas are shown in the simulation and its effects can be clearly discerned from observations during the 1953 tsunami. The wave heights at the Lami coast are 3 times greater than waves 800 m offshore. We attribute build up of waves in the Lami area to shoaling and wave convergence on the shallow protruding reef platform that fronts the Lami foreshore. The seabed rises gradually at a gradient of 2° to the shallow reef platform. Gradual shoaling and convergence cause an increase in tsunami amplitude. Peak amplitudes occur at Nasese, as it is the closest area on the Suva Peninsula in the azimuthal direction of the slide failure and lies close to the direct path of wave radiation. Possibly another contributing factor of focussing effects at Nasese is the wave converging around the Nasese Reef, which is convex-shaped seaward.

Lower wave heights at distal tide gauges are attributed to poor quality nearshore bathymetry data. As a result the model is unable to precisely simulate shoaling and wave focussing effects expected at these locations. The bathymetry at distal tide gauges to the west of Suva are from spot depth recordings only and at Nakasaleka (Kadavu Island) from 100 m isobaths. The effect of poor quality bathymetry is clearly highlighted at Nakasaleka. The tsunami arrival time at Nakasaleka tide gauge is remarkably consistent with the recording in 1953, however, the simulated wave height is only 0.25 m compared to the observed value of 4.5 m (Fig. 10H). Nakasaleka Village is located at the head of a small bay, which is 800 m long and narrows from 600 m near the mouth to 200 m at the head. Waves that enter a narrowing bay are confined, forcing waves to build in amplitude. It is likely that elevated waves experienced here in 1953 would have been subjected to this process. The 100 isobaths used in the simulation grid is too coarse to resolve the bathymetry of this bay. Wave focussing at Nakasaleka is consistent with the fact that other villages on more straight sections of the northern coast of Kadavu received only very small waves and were not damaged at all.

10. Conclusions

Using high resolution bathymetry data and historical records we define the source of the 1953 Suva tsunami as a submarine landslide at the head of the Suva Canyon within 4 km of Suva City. Using the source parameters of this landslide we have successfully simulated observed wave heights and arrival times at eight near-field localities using Geowave tsunami generation, propagation, and inundation model. The simulation

shows that highly variable observations of coastal wave heights and arrival times in 1953 are the result of complex wave dynamics effects influenced by the barrier reef system, uneven nearshore bathymetry and the irregular coastline, and not multiple submarine landslide tsunami sources as previously thought. The earthquake tsunami, however, may have been responsible for the observed preliminary “warning” wave.

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