Nat. Hazards Earth Syst. Sci., 11, 1371–1379, 2011
www.nat-hazards-earth-syst-sci.net/11/1371/2011/
doi:10.5194/nhess-11-1371-2011

Natural Hazards and Earth System Sciences

Evidence of a previously unrecorded local tsunami, 13 April 2010, Cook Islands: implications for Pacific Island countries

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Received: 16 March 2011 – Accepted: 27 April 2011 – Published: 13 May 2011

Abstract. Tsunami hazard assessments for Pacific Islands Countries (PICs) tend to focus on subduction zone sources. It is generally recognised that while volcanic-related tsunamigenic sources exist, they are probably only of minor relevance to the overall hazardscape of the Pacific. This paper outlines the evidence for a previously unrecorded local tsunami that struck the uninhabited south coast of Mangaia, Cook Islands, on 13 April 2010. The tsunami had a maximum inundation of 100 m inland and a runup of 12 m a.s.l. This event was most probably caused by a small submarine slope failure, the most recent of an unknown number of previous inundations. Since most PICs have a volcanic origin, it is suggested that current perceptions about the local and regional significance of such events is inaccurate. A review of volcanic-related tsunamigenic sources throughout the Pacific reveals a wealth of data concerning submarine slope failures in particular and a more general background of active volcanism. These sources are as relevant to PICs close to or far away from subduction zones. As populations grow and the coastlines of many PICs and those on the edge of the Pacific Ocean become increasing occupied, the likelihood for loss of life from these events increases.

1 Introduction

Pacific Island Countries (PICs) such as the Cook Islands are geographically remote (Fig. 1), have relatively low population numbers and are perceived to have a limited infrastructure exposure to tsunami inundation. In many cases, however, critical infrastructure is in coastal or low-lying areas and is vulnerable not only to tsunamis, but also storms and cyclones (Goff et al., 2011a).

In general terms, there is currently a well-developed local awareness of the cyclone hazard. Five cyclones passed through the Cook Islands in a five week period during February and March 2005 (WMO/CAS Tropical Meteorology Research Programme Steering Committee, 2006). Similarly, regional awareness has been raised by repeat events affecting neighbouring islands, such as Niue, where deposition of boulders by waves on cliff tops up to 30 m above sea-level occurred in 1991 and 2004 during severe Tropical Cyclones Ofa and Heta, respectively (Nott, 2004). The tsunami hazard, however, is less well defined.

It has long been recognised that the Cook Islands, like all PICs, are susceptible to tsunamis generated by regional and distant seismicity associated with Pacific Ring of Fire (PRF) sources (Australian Government Bureau of Meteorology, 2009). There is, however, a significant limitation in all of the tsunami hazard assessments, probabilistic or otherwise, carried out for PICs in recent years. While recognising that other sources exist, the focus has always been on simplified subduction zone events. As a result, we are aware from model output that the Tonga-Kermadec trench (TKT) is the most significant source of tsunamigenic earthquakes for the Cook Islands with 2000 yr maximum amplitudes around 1.7 m for the northern group and up to 2.8 m in parts of the southern group (Thomas and Burbidge, 2009). Complementary modelling work has concurred, adding that there is also a limited regional threat from the South Solomon and New Hebrides trenches to the west. Large earthquakes on the Kuril and Peru-Chile trenches may also represent a distant tsunami threat (Australian Government Bureau of Meteorology, 2009).

These types of tsunami hazard assessments are largely based upon numerical modelling of simple subduction zone scenarios. This is entirely understandable, but to recommend that the Cook Island authorities "use the tsunami hazard studies that have been completed for the Southwest Pacific Nations to date, any historical tsunami records and GIS data

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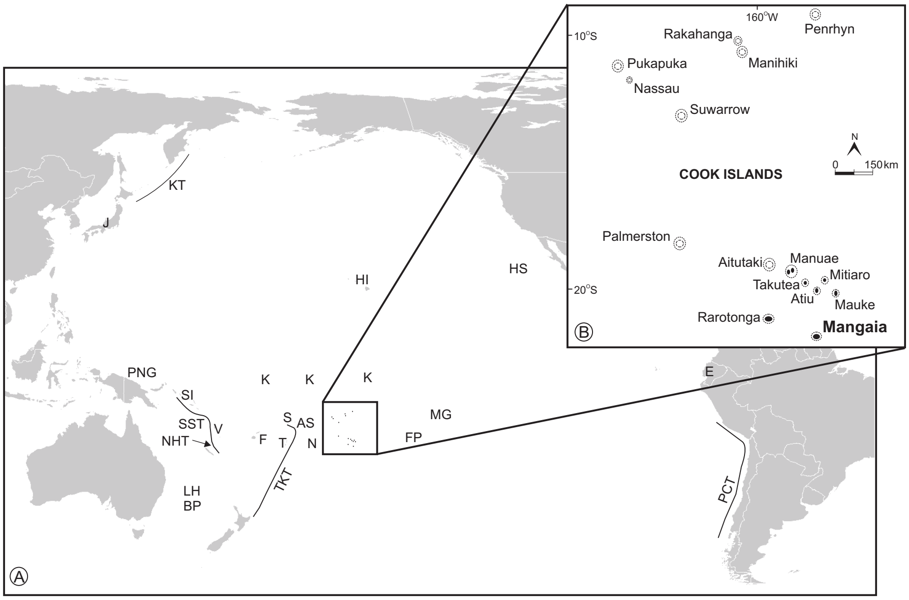

Fig. 1. **(A)** Map of the Pacific Ocean showing names of islands and features discussed in the text (AS: American Samoa inc Ta'u, Ofu, Olosega; E: Ecuador; F: Fiji; FP: French Polynesia inc. Tahiti, Moorea, Bora Bora; HI: Hawaiian Islands; HS: Henderson Seamount; J: Japan; K: Kiribati; KT: Kuril trench; LHBP: Lord Howe, Balls Pyramid; MG: Marquesas Group; N: Niue; NHT: New Hebrides trench; PCT: Peru-Chile trench; PNG: Papua New Guinea; S: Samoa inc. Savai'i, Upolu; SI: Solomon Islands; SST: South Solomon trench; T: Tonga; TKT: Tonga-Kermadec trench; V: Vanuatu). **(B)** Cook Islands – divided into the northern and southern groups. Names of the main islands are given but not all are discussed is the text.

to identify low-lying communities which may be potentially prone to tsunami impacts" (Australian Government Bureau of Meteorology, 2009), seems somewhat blinkered. Subduction zones are only one of a suite of potential tsunamigenic sources, albeit the most common in historic time. Landslide (10 %), volcanic (4 %), meteorological (3 %), submarine strike-slip faulting (12 %), and unknown causes (8 %) together add up to 37 % of the total number of historic tsunamigenic sources (Gusiakov, 2009; Whitmore et al., 2009).

It is becoming increasingly apparent to earth scientists that researchers do not currently have a sufficient understanding of all the geophysical processes associated with subduction zone events (Satake and Atwater, 2007). The implication here is that subduction zone events can and often do generate larger tsunamis that current modelling suggests. Indeed, recent numerical modelling work on the 1771 Meiwa Tsunami in Japan makes this case (Goto et al., 2010). In that study, modelling of a tsunami generated solely by a large subduction zone earthquake could not replicate the historically documented outcomes. Modelling of a subduction zone event that included a synchronous submarine landslide on the scarp face, however, was capable of replicating the outcomes (Goto et al., 2010). A similar process has also recently been proposed to explain a unique suite of high elevation tsunami deposits associated with an event on the TKT to the north of New Zealand (Goff et al., 2011b).

The association of a fault rupture and a submarine landslide is not unreasonable given the extreme groundshaking that occurs during any large submarine earthquake. Indeed, such associations have been used to explain larger-than-normal tsunami waves experienced following even moderately small earthquakes such as the 1998 Papua New Guinea event (Harbitz et al., 2006). The recent 2009 South Pacific tsunami (2009 SPT) is also indicative of the complexity of apparent subduction zone events. The tsunami was originally thought to have been generated by a single earthquake, but subsequently it was shown to be associated with an earthquake doublet, a $M_{\mathrm{w}} = 8.1$ normal fault rupture on the outer trench-slope was followed within minutes by a $M_{\mathrm{w}} = 8.0$ subduction interface thrust event. Both ruptures contributed to tsunami generation (Beavan et al., 2010). This recent event indicates that while simple generic subduction modelling gives a general idea of what could happen, they can reasonably be assumed to provide limited estimates of the maximum size of tsunamis from such sources since they are only approximations of the generating mechanism (e.g., Govers and Wortel, 2005; Fritz et al., 2011). It would appear that tsunami hazard planning based solely upon existing simple subduction zone models is unwise. It is important, however, to attempt to approximate the nature and extent of tsunamis generated from subduction zone events because they are the most significant *distant* tsunami sources for PICs. At a *regional* and *local* scale the relevance of subduction zone events to individual PICs becomes less well defined. For some PICs close to subduction zones, such as Samoa, Fiji and Tonga, they are still extremely important tsunamigenic sources, but for others such as Kiribati, French Polynesia and the Cook Islands, volcanic-related activity becomes increasingly relevant. In general terms, since most PICs are volcanic in origin, the balance of the most significant local and regional tsunami sources tips more towards a higher percentage of volcanic-related events.

Volcanoes are inherently unstable and eruptions, caldera collapse, flank collapse, pyroclastic flows and even small slope failures are all potentially tsunamigenic (Goff et al., 2011a, 2006; Acocella and Puglisi, 2010; McMurtry et al., 2004; Self, 1992). Many PICs are still volcanically active and form part of the PRF, while those not directly associated with it are generally either linked to hot spot volcanism, mid-ocean ridges or past tectonic activity. Perhaps most importantly, these various types of PICs are all linked to geologically much larger structures that lie below the surface of the sea (Nunn, 1998).

It would seem that modelling of simple subduction zone scenarios helps to provide a partial picture of tsunami sources for PICs such as the Cook Islands. Significant gaps, however, remain in our understanding of the complete picture and there is currently almost no grasp of local and regional volcanic-related tsunamigenic sources. On balance, it seems reasonable to suggest that simple subduction zone events may represent as little as 50 % of the potential tsunamigenic sources for some PICs.

What is known about the tsunami hazard for the Cook Islands is that there have been at least 22 tsunamis since 1837 AD with three appearing to have had waves of up to three metres high (1896 AD – Japan: Anon, 1896; 1903 AD – Papua New Guinea: Anon, 1903; 1909 AD – Ecuador: Anon, 1909). Ironically, the largest historic tsunami from the TKT, which is considered to be the most significant (subduction zone) tsunamigenic source for the Cook Islands, is two metres (Okal et al., 2004). The TKT does, however, happen to be the most common historic tsunami source (9 events: Goff, 2010).

This paper briefly outlines the evidence for a probable local tsunami that inundated Mangaia on the 13 April 2010 and discusses the implications of these findings for the Cook Islands in particular, and PICs in general.

2 Physical setting

Mangaia (21°55′ S, 157°55′ E) is one of the volcanic southern Cook Islands and rises some 4500–5000 m from the sea floor (Summerhayes, 1967). It lies along the Cook-Austral quasi-linear volcanic chain, a hot spot lineament that extends 2500 km from Macdonald Seamount to Palmerston Island (Wood and Hay, 1970). Mangaia is the second largest of the Cook Islands (51.8 km^2) and has a concentric geomorphological structure with a deeply weathered volcanic cone rising to 169 m a.s.l., a raised coral reef called the makatea and swampy lowlands between them (Fig. 2) (Yonekura et al., 1998). The makatea varies between 0.7–2 km in width with a maximum elevation of around 70 m. Its landward margin is steeply cliffed, dropping down 50+ m to the swamps below. The seaward cliffs of the makatea vary from around 2–12 m high and are fronted by a narrow modern fringing reef 150–250 m wide that encircles the entire island (Kirch, 1996).

3 Evidence of inundation – 13 April 2010

Data were gathered during a visit to Mangaia in September 2010. At the time, a story was circulating on the main island of Rarotonga about a large wave(s) that had inundated the south coast of Mangaia (Fig. 2) a few days after the Chilean earthquake and subsequent Pacific-wide tsunami warning on 27 February. There were no other details.

Data were collected in two forms, personal accounts and physical evidence. Where possible personal accounts were collected directly from the individual, but on occasion this was not practical. Field measurements were taken using staff and tape measure surveys with orientation and position recorded by compass and GPS, respectively. The elevations were measured relative to sea level at the time of survey and subsequently adjusted relative to high tide.

3.1 Personal accounts

The disjunct between information circulating on Rarotonga and Mangaia was remarkable. Contrary to the general belief on Rarotonga that inundation was associated with the 2010 Chilean tsunami, Mangaia's Chief of Police, Aerenga Matapo, advised that the wave(s) inundated southern Mangaia one day after a tsunami information bulletin (pacific.2010.04.11.095237) was issued by the Pacific Tsunami Warning Centre on 11 April 2010 (http://www.weather.gov/ptwc). The tsunami information bulletin referred to a 68 km deep, $M_w = 7.0$ Solomon Islands (11° S, 161.1° E) earthquake that occurred at 09:53 UTC (10 April 2010, 11:53 p.m. Cook Islands time). The tsunami travel time from the Solomon Islands is around 6 h. In the absence of any other tsunami information and a lack of storm activity in the area at the time, it was thought that the wave that inundated the southern coast of Mangaia on the 13 April 2010 might have been related to the Solomon Islands earthquake (Aerenga Matapo, personal communication, September 2010).

People in the village of Tamarua (Fig. 2a), close to the south coast, heard a wave(s) strike the southern cliffs early on the morning of the 13 April (Taoi Nooroa, personal communication, September 2010). It is assumed that this was around dawn because two fishermen, who were already out

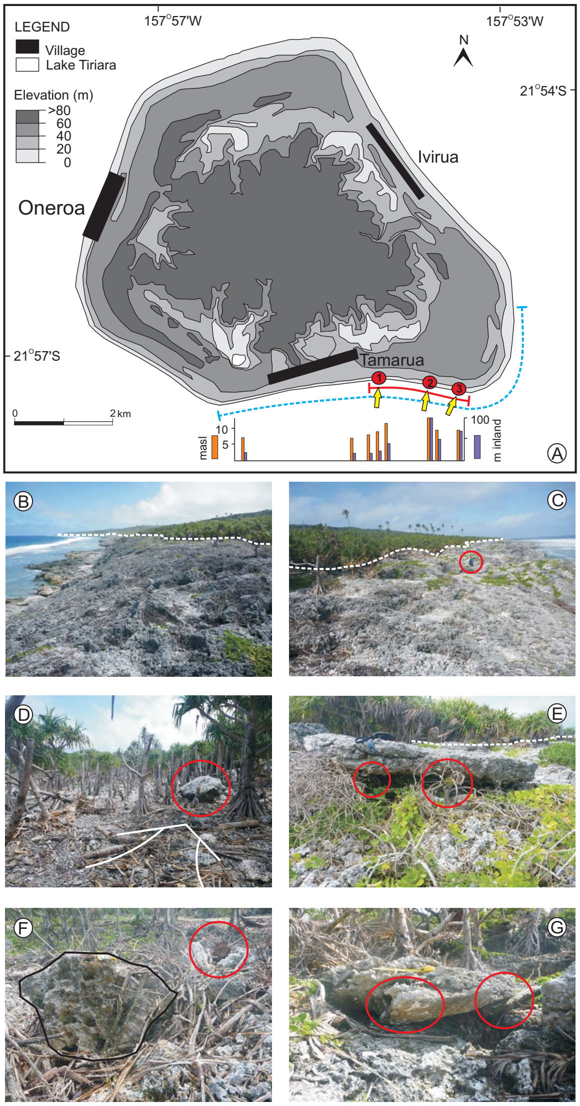

Fig. 2. (A) Map of Mangaia showing the approximate location of the three main villages. Red circles mark the location of Points 1–3 discussed in the text, the red solid line marks the extent of the main study area and the blue dashed line shows the inundation-affected coastline. The orange and purple bars indicate measured points of inundation and runup, respectively. Yellow arrows indicate mean A-axis orientations of boulders at Points 1–3. **(B)** Photo taken from Point 1 looking west. **(C)** Photo taken from Point 1 looking east, red circle shows person for scale. Snapped pandanas tree trunk in centre left of photo. **(D)** Photo taken at Point 2 showing a patch of snapped pandanas trees with coral boulder (ringed in red) overlying crushed vegetation. **(E)** Photo taken at Point 3 showing coral boulder crushing live vegetation (ringed in red) **(F)** Point 1 – photo looking north with large coral boulder tilted on its side overlying and overlain by dead vegetation. Red circle shows intact pandanas tree and root system deposited among debris. **(G)** Impact marks on underside of coral boulder (left circle) which overlies pandanas tree trunk (right circle).

at sea beyond the fringing reef, were able to see the water recede prior to inundation, although they did not observe the subsequent runup (Allan Tuara, personal communication, September 2010).

Local resident Maki Tangimatiti keeps pigs along the south coast (Site 1: Fig. 2a) and uses an old quarry road about 100–150 m inland to access the area. When he fed the animals on the 12 April the surrounding coastal vegetation was undisturbed, but on the following afternoon he found coral boulders, uprooted pandanas trees (*Pandanus tectorius)* and other vegetation washed inland as far as the road and adjacent to his pig enclosure. No large storms or waves had struck the coast between 13 April and the time of the survey in late-September (Maki Tangimatiti, personal communication, September 2010). A reconnaissance survey along the same quarry road, but from the southern end of Ivirua, found that damage to coastal vegetation and deposition of coral debris extended over 4 km east of Site 1 (Fig. 2a: eastern end of blue dashed line) (Taoi Nooroa, personal communication, September 2010).

3.2 Physical evidence

A detailed site survey of the entire affected area was not possible in the time available because of access difficulties, but the maximum extent of longshore inundation was estimated based upon photographic evidence (Fig. 2b) and the personal account of Taoi Nooroa noted in Sect. 3.1. Inundation affected approximately 8 km of coastline (Fig. 2a: dashed blue line), with detailed observations mainly carried out along a 2 km central portion at Points 1–3 (Fig. 2a).

Inundation and runup were recorded at eight sites, six within the 2 km study area and two further West (Fig. 2a). A combined maximum inundation and runup of 100 m inland and 12 m a.s.l., respectively, was recorded at Point 2. Inundation and runup decreased to both the west and east of this point. Flow depths were difficult to measure especially close to the coast where all vegetation had been stripped off the land (Fig. 2b and c). The first indications of a probable minimum flow depth were remnant pandanas tree trunks snapped off at about 1.8–2.0 m above ground level some 15–20 m inland (Fig. 2c – left hand side of photo; Fig. 2d). Snapped branches and vegetation hooked up in trees provided approximations of flow depth (Fig. 3 – Point 3). Flow depths decreased markedly at about 30 m inland from around 2.0–2.8 m to 1.5 m, and then showed a steady decline landward (e.g., Fig. 3).

The A-axis orientation was recorded for 26 boulders. Of these, 24 boulders fall within the N005-030 range, with a 10° modal class at N005-015. The mean A-axis orientation at Points 1–3 are noted on Fig. 2a (yellow arrows), with a more detailed breakdown of individual boulders at Point 3 given in Fig. 3. The largest clast had a volume of over 3.8 m^3 (2.3 m × 1.4 m × 1.2 m) which, assuming a coral clast density of between 1.1–1.4 $t\,m^{-3}$ (Paris et al., 2009) yields a

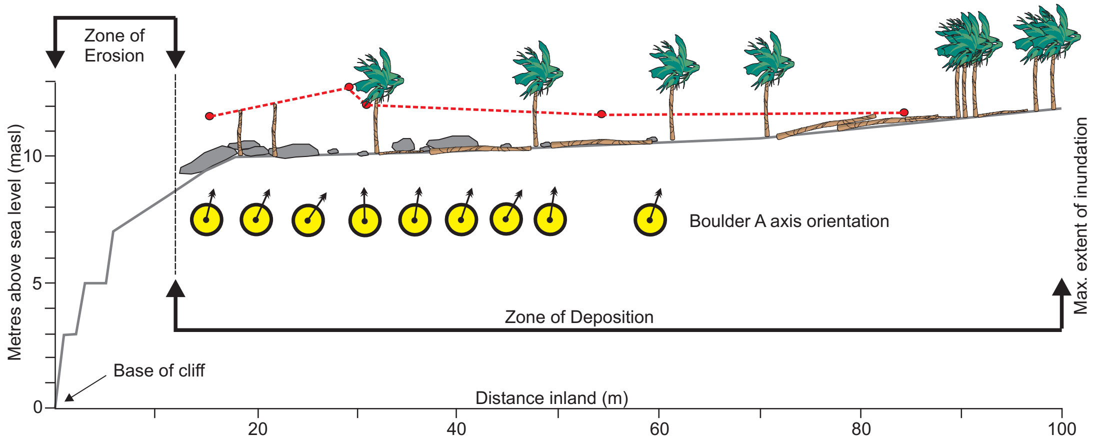

Fig. 3. Point 3: transect perpendicular to coast marking the zones of erosion and deposition. Most boulders cluster near the main break of slope, but can be traced inland about 60 m. The red dashed line joins up points where (minimum?) flow depths were noted. Variations in the A-axis orientation of individual boulders are shown.

weight of close to 5.5 t. The estimates of wave heights required to transport the largest boulder indicate that it would require relatively small storm (1.32 m) and tsunami (0.21 m) waves (Nott, 2003).

The results of survey transects at Points 1–3 indicate that there is a greater clustering of boulder clasts around the break in slope which marks the beginning of the zone of deposition (Fig. 3). Marked changes in flow depth occurred a few metres inland from this break of slope. Boulder clasts could be traced up to 60 m inland and were often found overlying live vegetation (Fig. 2e) or dead organic debris deposited by the wave(s) (Fig. 2f). Many of the boulders and the makatea bedrock exposed along the denuded coastline showed signs of impact scars and the removal of angular protuberances (Fig. 2g). This presumably occurred as boulders were transported as bed load across the makatea bedrock.

There were no visible fine sediment deposits, although freshly deposited, 1–3 cm diameter pebble clasts of coal were identified at Point 2, site of the 1904 wreck of the coal barque *Saragossa*. Freshly deposited coal clasts lying on top of vegetation were traced up to 80 m inland. The remainder of the deposit consisted of uprooted pandanas trees, coconuts and dead canopy vegetation (Fig. 2d and f).

4 Discussion

Estimates of the wave heights required to move the boulders measured on the south coast of Mangaia provide equivocal data. It is entirely plausible that either storm or tsunami waves could have transported these boulders. Storm wave heights of 1–1.5 m are common as Mangaia is directly exposed to the local and distant effects of weather systems crossing the southern Pacific Ocean. While waves of this size are common, transporting boulders across the fringing reef and up a cliffed coastline is normally associated with cyclonic events such as those that affected Niue in 1991 and 2004 (Nott, 2004). The possibility of rogue waves, however, cannot be entirely dismissed, although the absence of storm conditions within the area and region at the time tends to make this scenario less likely (Péquignet et al., 2009).

It was fortunate that no lives were lost as a result of this event, largely because no one lives on the southern coast of the island. There appear to be two possible explanations for this lack of coastal settlement. First, the landscape is rugged and mainly consists of closely spaced ridges of sharp, heavily weathered and incised makatea that impedes land access. Similar makatea, however, is found elsewhere on the island and this has not prohibited coastal settlement. Second, in the archaeological record there is a recognised breakdown in large nucleated coastal sites in the 15th century, with a change to a more scattered inland settlement pattern (Walter, 1998). Archaeologically, this contemporaneous movement from low-lying coastal to higher elevation inland sites is explained as being the result of a breakdown in long-distance voyaging networks and a decrease in mobility (Walter, 1998). Geologically, however, this contemporaneous shift in settlement patterns has been associated with a period of enhanced tectonic activity, earthquakes and tsunamis in the SW Pacific (e.g., Goff et al., 2010, 2011b; McFadgen, 2007). Perhaps there has been long-term avoidance of this exposed coastline?

The south coast has a cliffed and arcuate shape (Fig. 2a) that may well indicate long-term slope instability on the steep volcanic sides of the island, possibly through a combination of sub-aerial slumping and submarine slope failure exposing the coast to inundation from local tsunamis. Previous researchers have identified the area as a probable site of large submarine slope failures that have been responsible for removing a significant part of the south coast of Mangaia (Summerhayes, 1967; Wood and Hay, 1970).

Personal accounts from fishermen along the south coast indicate that at least two similarly large inundation events have occurred in the recent past. In 1997/1998, at the western end of the area affected by the 13 April event, a fisherman and his son were preparing their nets on the coast road before putting out to sea. They saw a huge wave estimated at about 10 m high forming just off the reef. Before they could run too far uphill they were caught by the oncoming water. Fortunately they were washed further inland by the then waist high water and they were able to escape. A similar, undated event occurred earlier on the south side of Tamarua near Point 2 (Fig. 2a). They again saw a huge wave forming but managed to reach high ground before the wave struck (Pare'ina Nga-tupuna told to Allan Tuara, personal communication, November 2010).

In the absence of detailed bathymetric and geological studies it is difficult to determine the nature and history of volcanic-related hazards such as flank collapse and submarine slope failure on Mangaia. The occurrence of flank collapse and submarine slope failures (and locally generated tsunamis) on Mangaia should not be considered surprising, however, since many of the other southern Cook Islands have experienced similar activity in the past. For example, both Rarotonga and Aitutaki (Fig. 1) are recognised as having experienced catastrophic submarine slope failures (Summerhayes, 1967; Wood and Hay, 1970). Similarly, researchers have shown that Takutea (Fig. 1) is the remains of a large submarine ridge that was probably destroyed by a giant submarine slope failure along the Takutea Saddle between Takutea and Atiu (Wood and Hay, 1970; Summerhayes and Kibblewhite, 1968). Other members of the southern Cook Islands including Mauke, Mitiaro and Atiu bear evidence of boulders deposited by large waves. On Mauke, massive cliff-top boulders up to 15 m^3 can be found over 10 m a.s.l. and 200 m from the cliff edge. Similar features are also found on both Mitiaro and Atiu (Stoddart et al., 1990). While it is always reasonable to invoke cyclone emplacement using recent historic examples (Niue: Nott, 2004), a tsunami origin cannot be discounted especially with geological evidence for catastrophic submarine slope failure associated with several of the neighbouring southern Cook Islands.

It is surprising that so little attention has been given to the hazard and risk associated with volcanic-related tsunamis for the Cook Islands. Are the Cook Islands unique in their apparent abundance of potential volcanic-related tsunamigenic sources? While generally recognising that these tsunamigenic sources exist, little has been done to incorporate them into comprehensive tsunami hazards assessments, to the point that the Cook Islands are considered to have a low risk from anything other than subduction zone sources (e.g., Pearce, 2008). There appears, however, to be a growing awareness of the significance of volcanic-related tsunami hazards in the Pacific region. Considerable attention has been given to the geological evidence for massive tsunamis from giant submarine slope failures in the Hawaiian Islands (McMurtry et al., 2004). Recent work has also focussed on the region-wide effects of caldera collapse in Vanuatu (Goff et al., 2010; 2011a), and the study of megaclasts in coastal Tonga led Frohlich et al. (2009) to conclude that "small (<1 km^3) submarine slope failures sometimes generate locally large tsunamis". This is encouraging, but it seems that these research findings represent only a small fraction of the work to be done. Active volcanoes aside, there is already ample evidence throughout the Pacific region of catastrophic volcanic-related submarine slope failures.

To the north, several Hawaiian Islands are estimated to have lost more than 30 % of their volumes as a result of submarine slope failures once they stopped growing. Equally, many are also believed to have lost at least the same amount from giant submarine slope failures while they were still growing (Holcomb and Searle, 1991). In essence, oceanic volcanoes repeatedly lose large volumes to submarine slope failures as they grow and as they decay. Holcomb and Searle (1991) consider that numerous ongoing submarine slope failures may explain the large volumetric difference between oceanic volcanoes and their archipelagic aprons.

In the West Pacific, Silver et al. (2009) mapped 12 debris avalanches from volcanoes in the Bismarck volcanic arc of Papua New Guinea alone and recognised that tsunamis from even small submarine slope failures may have produced significant run-up on nearby coastlines. They concluded that if any of the submarine slope failures they identified occurred in modern times they would have moderate to significant tsunami impacts on populated coastlines in the region. Continuing to the SE through the Solomon Islands and Vanuatu, ubiquitous, large-scale submarine slope failures attest to the high degree of instability in the region including numerous recent events. Bathymetric data also confirm the presence of a serious explosive volcanic hazard in northern Vanuatu. Both sets of evidence indicate the repeated occurrence of potentially disastrous tsunamis in the region (Kroenke, 1995). At the southern end of Vanuatu it is probable that small volume submarine slope failures occur at one volcano or another every few days to years, but the frequency of giant ocean-island landslides is unknown (Keating and McGuire, 2000).

Within the Southwest and Central Pacific, numerous giant submarine slope failures have been identified such as those on the flanks of the Lord Howe and Balls Pyramid volcanoes. Their morphologies are broadly similar to those reported from the Hawaiian Islands (Kennedy et al., 2011). Similarly, further East giant submarine slope failures are considered responsible for removing large parts of the Samoan archipelago, including Ta'u, Ofu, and Olosega in American Samoa (Holcomb and Searle, 1991; Daly, 1924) and Savai'i and Upolu in Samoa (Kear and Wood, 1959). For example, the giant landslide on Ta'u is represented sub-aerially as a series of down-faulted benches on its southern flank that are believed to be the remnant of catastrophic collapse involving ~ 30 km^3 (Williams, 2009). Recent modelling of the resultant tsunami has ~ 2 m waves inundating the low-lying northern Cook Islands 500 km to the Northeast and a >5 m inundation affecting Upolu 100 km to the West (Williams, 2009), a truly region-wide event.

In French Polynesia, giant submarine slope failures have been inferred from geological structures in Tahiti, Moorea, Bora Bora and from all of the islands of the Marquesas group (Holcomb and Searle, 1991). Similarly, the broad embayed coastline of Niue to the west of the Cook Islands has been proposed as evidence for a series of large submarine slope failures (Summerhayes, 1967). The nature and extent of potential tsunamis from these sources are yet to be evaluated.

It is worth noting that while researchers are well aware of many of the Pacific's active submarine volcanoes, new ones are still being discovered. For example, in 1975, Vailulu'u the youngest volcano in the Samoan volcanic chain was discovered 45 km east of Ta'u. Like many other submarine volcanoes, it is not only that this could be a tsunamigenic source as a result of a volcanic eruption (it is only 590 m deep), but also from submarine landslides off the volcano's slopes that rise 4800 m above the sea floor (Hart et al., 2000). Equally, the Pacific Ocean has over 10^4 seamounts taller than 1 km (Holcomb and Searle, 1991). Giant submarine slope failures have been reported from large seamounts such as Henderson Seamount, 700 km west of the Gulf of California, (Taylor et al., 1980). Other smaller seamounts, however, with submarine slope failure volumes of between 20–50 km^3 are more common. The smallest of these are similar to sub-aerial volcanoes such as Mount St. Helens, and may well be capable of generating submarine slope failures of several cubic kilometres (Holcomb and Searle, 1991). To put this into context, it is worth reiterating the findings of Frohlich et al. (2009) who recognised that even small $<1\ \mathrm{km}^3$ submarine slope failures sometimes generate locally large tsunamis. Previous studies have also shown that moderate to large (10–10 km^3) submarine slope failures may well be responsible for some of the largest identified tsunamis (Tappin et al., 2001).

The lack of recognition within the tsunami research community of the potential significance of volcanic-related tsunamigenic sources for PICs such as the Cook Islands is a concern. It can be argued that since landslides and volcanoes represent only 14 % of historic tsunamigenic sources (Gusiakov, 2009), there is a far greater need for researchers to focus their attention on subduction zone events. There are, however, two significant points against this argument. First, most PICs are of volcanic origin and since there are a suite of recognised volcanic-related tsunamigenic sources we would do well to determine how important they are in the Pacific region. Second, it seems most probable that many local and regional tsunamis from volcanic-related sources have not been recorded in historical databases. The source origins of many tsunamis recorded in the early written history of the Pacific can be equivocal especially when no significant local earthquake was noted (e.g., Cook Islands: 7 March 1909; http://www.ngdc.noaa.gov/hazard/tsu.shtml). Furthermore, many significant local (and regional?) events go unnoticed simply because they are not associated with a major earthquake, and also may affect currently unpopulated areas (e.g., Cook Islands: 13 April 2010).

5 Conclusions

A study of a previously unrecorded local tsunami on Mangaia in the Cook Islands has raised concern about the lack of understanding of volcanic-related tsunamigenic sources in the Pacific region. While recognising that these sources exist, most of the tsunami hazard and risk assessment work carried out in the Pacific to date does not appear to consider them of major significance. This approach is surprising for three reasons. First, there is a wealth of literature relating to volcanic-related tsunamigenic sources in the Pacific. Second, the majority of PICs are of volcanic origin and would, therefore, seem likely to suffer relatively more from these sources than other areas of the World. Third, tsunamis from these sources are most likely to be of local and regional significance and, hence, will have little to no warning associated with them. While early warning systems work well for more distantly sourced tsunamis, it is precisely this type of near-sourced event that requires comprehensive and effective community based awareness and education programmes to reduce loss of life – one of the most important goals of tsunami hazard and risk assessment work in the Pacific.

It seems likely that tsunamis from volcanic-related sources are under-represented in the historic record because the inundation events were not associated with obvious large earthquakes. Similarly, many of the probably high frequency, low magnitude (local) tsunamis have gone mostly unnoticed because they affected coastlines that were either sparsely or unpopulated at the time of inundation. As populations grow and the coastlines of many PICs become increasing occupied, the likelihood for loss of life from these events increases.

Acknowledgements. This work was carried out under Research permit #12/10 provided by the Office of the Prime Minister with funding from the University of the South Pacific. I gratefully acknowledge the assistance provided by the community of Mangaia, in particular that of the Island Secretary, Helen Henry. Rod Dixon, Director of the University of the South Pacific in the Cook Islands, is thanked for his tireless support. Jonathan Nott kindly processed the wave height data for boulder transport.

Edited by: T. Glade
Reviewed by: W. Dudley and another anonymous referee

References

Acocella, V. and Puglisi, G.: Hazard Mitigation of Unstable Volcanic Edifices, Eos Transactions, AGU, 91(40), 357–358, doi:10.1029/2010EO400002, 2010.

Anon.: Tidal wave at Rarotonga, The Mercury (Hobart, Tasmania), p. 4, 16 July 1896.

Anon.: The recent tidal wave, The Advertiser (Adelaide, SA), p. 7, 21 March 1903.

Anon.: Tidal wave at Rarotonga, The Sydney Morning Herald (NSW), p. 13, 7 April 1909.

Australian Government Bureau of Meteorology.: SOPAC Member Countries National Capacity Assessment: Tsunami Warning and Mitigation Systems, Cook Islands, Rarotonga, Australian Government Bureau of Meteorology, Melbourne, 67 pp., 2009.

Beavan, J., Wang, X., Holden, C., Wilson, K., Power, W., Prasetya, G., Bevis, M., and Kautoke, R.: Near-simultaneous great earthquakes at Tongan megathrust and outer rise in September 2009, Nature, 466, 959–963, 2010.

Daly, R. A.: The geology of American Samoa, Carnegie Inst. of Washington Pub., 340, 95–143, 1924.

Fritz, H. M., Borrero, J. C., Synolakis, C. E., Okal, E. A., Weiss, R., Titov, V. V., Jaffe, B. E., Foteinis, S., Lynett, P. J., Chan, I.-C., and Liu, P. L.-F.: Insights on the 2009 South Pacific tsunami in Samoa and Tonga from field surveys and numerical simulations, Earth-Sci. Rev., doi:10.1016/j.earscirev.2011.03.004, in press, 2011.

Frohlich, C., Hornbach, M. J., Taylor, F. W., Shen, C.-C., Moala, A., Morton, A. E., and Kruger, J.: Huge erratic boulders in Tonga deposited by a prehistoric tsunami, Geology, 37, 131–134, 2009.

Goff, J.: Cook Islands: End of visit report, Australian Tsunami Research Centre Miscellaneous Report No. 4, Cook Island Government, Rarotonga, 5 pp., available at: www.nhrl.unsw.edu.au, 2010.

Goff, J., Dudley, W. C., deMaintenon, M., Cain, G., and Coney, J. P.: The largest local tsunami in 20th century Hawaii, Mar. Geol., 226, 65–79, 2006.

Goff, J., Nichol, S. L., and Kennedy, D.: Development of a palaeotsunami database for New Zealand, Nat. Hazards, 54, 193–208, doi:10.1007/s11069-009-9461-5, 2010.

Goff, J., Chagué-Goff, C., Dominey-Howes, D., McAdoo, B., Cronin, S., Bonté-Grapetin, M., Nichol, S., Horrocks, M., Cisternas, M., Lamarche, G., Pelletier, B., Jaffe, B., and Dudley, W.: Palaeotsunamis in the Pacific, Earth-Sci. Rev., doi:10.1016/j.earscirev.2010.10.005, in press, 2011a.

Goff, J., Lamarche, G., Pelletier, B., Chagué-Goff C., and Strotz L.: Palaeotsunami precursors to the 2009 South Pacific tsunami in the Wallis and Futuna archipelago, Earth-Sci. Rev., doi:10.1016/j.earscirev.2010.11.003, in press, 2011b.

Goto, K., Kawana, T., and Imamura, F.: Historical and geological evidence of boulders deposited by tsunamis, southern Ryukyu Islands, Japan, Earth-Sci. Rev., 102, 77–99, doi:10.1016/j.earscirev.2010.06.005, 2010.

Govers, R. and Wortel, M. J. R.: Lithosphere tearing at STEP faults: Response to edges of subduction zones, Earth Planet. Sci. Lett., 236, 505–523, 2005.

Gusiakov, V. K.: Chapter 2: Tsunami history: recorded, in: The Sea, Vol. 15, Tsunamis, edited by: Bernard, E. N., and A. R. Robinson, Harvard University Press, Cambridge, Massachusetts, 23–53, 2009.

Harbitz, C. B., Løvholt, F., Pedersen, G., and Masson, D. G.: Mechanisms of tsunami generation by submarine landslides: a short review, Norsk. Geogr. Tidsskr., 86, 255–264, 2006.

Hart, S. R., Staudigel, H., Koppers, A. A. P., Blusztajn, J., Baker, E. T., Workman, R., Jackson, M., Hauri, E., Kurz, M., Sims, K., Fornari, D. J., Saal, A., and Lyons, S.: Vailuluu undersea volcano: The new Samoa, Geochem. Geophy. Geosy., 1, 1–13, doi:2000GC000108, 2000.

Holcomb, R. T. and Searle, R. C.: Large landslides from oceanic volcanoes, Mar. Georesour. Geotec., 10, 19–32, 1991.

National Geophysical Data Center: available at: http://www.ngdc.noaa.gov/hazard/tsu.shtml, Tsunami data and information, last access: 14 March 2010.

Pacific Tsunami Warning Centre: available at: http://www.weather.gov/ptwc, last access: 8 March 2010.

Kear, D. and Wood, B. L.: The geology and hydrology of Western Samoa, New Zealand Geological Survey Bulletin, 63, 90 pp., 1959.

Keating, B. H. and McGuire, W. J.: Island edifice failure and associated tsunami hazards, Pure Appl. Geophys., 157, 899–955, 2000.

Kennedy, D. M., Brooke, B. P., Woodroffe, C. D., Jones, B. G., Waikari, C., and Nichol, S.: The geomorphology of the flanks of the Lord Howe Island volcano, Tasman Sea, Australia, Deep-Sea Res. II, 58, 899–908, 2011.

Kirch, P. V.: Late Holocene human-induced n Polynesian island ecosystem, Proceedings of the National Academy of Sciences, 93, 5296–5300, 1996.

Kroenke, L. W.: A morphotectonic interpretation of SOPACMAPS 1:500 000 Charts, Central Solomon Islands – southern Tuvalu, SOPAC Technical Report 220, 42 pp., 1995.

McFadgen, B. G.: Hostile shores: catastrophic events in pre-historic New Zealand and their impact on Maori coastal communities, Auckland University Press, New Zealand, 298 pp., 2007.

McMurtry, G. M., Tappin, D. R., Fryer, G. J., Wilkinson, I. P., Williams, M., Fietzke, J., Garbe-Schoenberg, D., and Watts, P.: Megatsunami deposits on Kohala Volcano, Hawaii, from flank collapse of Mauna Loa, Geology, 32, 741–744, 2004.

Nott, J.: Waves, coastal boulder deposits and the importance of the pre-transport setting, Earth Planet. Sc. Lett., 210, 269–276, 2003.

Nott, J.: The tsunami hypothesis – Comparisons of the field evidence against the effects, on the western Australian coast, of some of the most powerful storms on Earth, Mar. Geol., 208, 1–12, 2004.

Nunn, P. D.: Pacific Island Landscapes: landscape and geological development of southwest Pacific Islands, especially Fiji, Samoa and Tonga, Institute of Pacific Studies, University of the South Pacific, Suva, Fiji, 318 pp., 1998.

Okal, E. A., Borrero, J. C., and Synolakis, C. E.: The earthquake and tsunami of 17 November 1865: evidence for far-field tsunami hazard from Tonga, Geophys. J. Int., 157, 164–174, 2004.

Paris, R., Wassmer, P., Sartohadi, J., Lavigne, F., Barthomeuf, B., Desgages, E., Grancher, D., Baumert, P., Vautier, F., Brunstein, D., and Gomez, C.: Tsunamis as geomorphic crises: Lessons from the December 26, 2004 tsunami in Lhok Nga, West Banda Aceh (Sumatra, Indonesia), Geomorphology, 104, 59–72, 2009.

Pearce, H.: SOPAC/GA Tsunami hazard and risk assessment Project. Inventory of Geospatial data and options for tsunami inundation and risk modeling, Phase 1 PIC summary, SOPAC Miscellaneous Report 657, 32 pp., 2008.

Péquignet, A. C. N., Becker, J. M., Merrifield, M. A., and Aucan, J.: Forcing of resonant modes on a fringing reef during tropical storm Man-Yi, Geophys. Res. Lett., 36, L03607, doi:10.1029/2008GL036259, 2009.

Satake, K. and Atwater, B. F.: Long-term perspectives on giant earthquakes and tsunamis at subduction zones, Ann. Rev. Earth Pl. Sc., 35, 349–374, 2007.

Self, S.: Krakatau revisited: The course of events and interpretation of the 1883 eruption, GeoJournal, 28, 109–121, 1992.

Silver, E., Day, S., Ward, S., Hoffmann, G., Llanes, P., Driscoll, N., Appelgate, B., and Saunders, S.: Volcano collapse and tsunami generation in the Bismarck Volcanic Arc, Papua New Guinea, J. Volcanol. Geoth. Res., 186, 210–222, 2009.

Stoddart, D. R., Woodroffe, C. D., and Spencer, T.: Mauke, Mitiaro and Atiu: Geomorphology of makatea islands in the southern Cooks, Atoll Research Bulletin No. 341, National Museum of Natural History, Smithsonian Institution, Washington, DC, 65 pp., 1990.

Summerhayes, C. P.: Bathymetry and topographic lineation in the Cook Islands, New Zealand Journal of Geology and Geophysics, 10, 1382–1399, 1967.

Summerhayes, C. P. and Kibblewhite, A. C.: Atiu Provision bathymetry NZ Oceangraphic Institute Chart Island Series, 1: 200 000, 1968.

Tappin, D. R., Watts, P., McMurtry, G. M., Lafoy, Y., and Matsumoto, T.: The Sissano Papua New Guinea tsunami of July 1998 – Offshore evidence on the source mechanism, Mar. Geol., 175, 1–23, doi:10.1016/S0025-3227(01)00131-1, 2001.

Taylor, P. T., Wood, C. A., and O'Hearn, T. J.: Morphological investigations of submarinevolcanism: Henderson Seamount, Geology, 8, 390–395, 1980.

Thomas, C. and Burbidge, D.: A Probabilistic Tsunami Hazard Assessment of the Southwest Pacific Nations, Geoscience Australia Professional Opinion No. 2009/02, available at: http://www.pacificdisaster.net/pdnadmin/data/original/GeoScience_Aus_2009_TS_assesmnt.pdf, 2009.

Walter, R. K.: Anai'o: The archaeology of a fourteenth century Polynesian community in the southern Cook Islands, New Zealand Archaeological Association Monograph, 22, 115 pp., 1998.

Whitmore, P., Brink, U. T., Caropolo, M., Huerfano-Moreno, V., Knight, W., Sammler, W., and Sandrik, A.: NOAA/West Coast and Alaska Tsunami Warning Center Atlantic Ocean response criteria, Science of Tsunami Hazards, 28, 86–107, 2009.

Williams, S.: Ocean-flank collapse on the south of Ta?u, Manu?a Group, Samoa Islands: implications for risk management, Unpublished MSc thesis, University of Canterbury, 2009.

WMO/CAS Tropical Meteorology Research Program Steering Committee: Statement on tropical cyclones and climate change, Project TC-2, Scientific assessment of climate change effects on tropical cyclones, 4 pp., 2006.

Wood, D. L. and Hay, R. F.: Geology of the Cook Islands, Bulletin of the New Zealand Geological Survey, Wellington, 82, 1–103, 1970.

Yonekura, N., Ishii, T., Saito, Y., Maeda, Y., and Matsushima, Y.: Holocene fringing reefs and sea-level change in Mangaia Island, southern Cook Islands, Palaeogeogr. Palaeoecl. 68, 177–188, 1988.