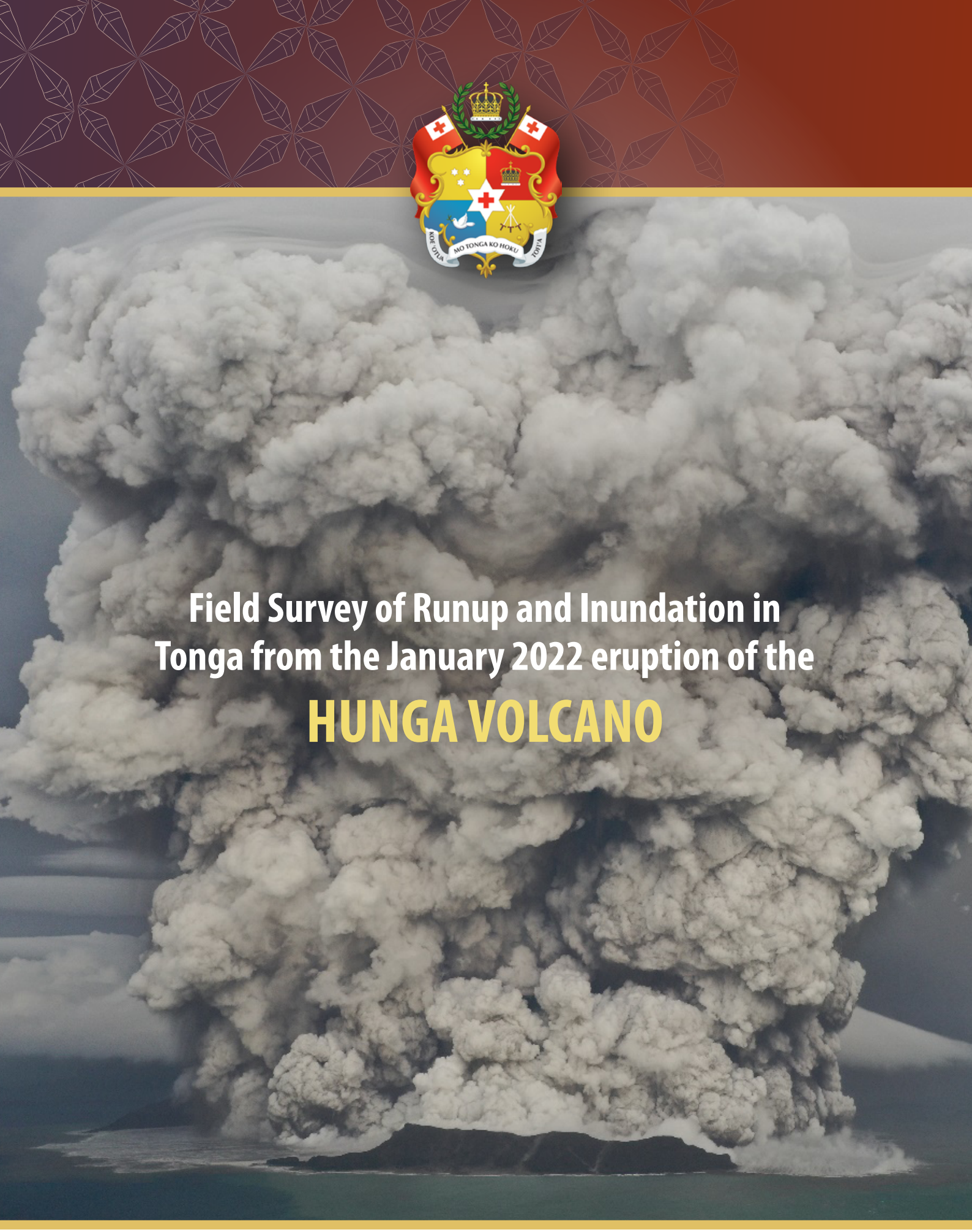

Field Survey of Runup and Inundation in Tonga from the January 2022 eruption of the HUNGA VOLCANO

Pacific Community
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Intergovernmental Oceanographic Commission

eCoast

THE UNIVERSITY OF AUCKLAND
NEW ZEALAND

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UNIVERSITY OF SOUTHERN CALIFORNIA

Field Survey of Runup and Inundation in Tonga from the January 2022 eruption of the Hunga Volcano

Report Status

Version	Date	Status	Approved by
1.0	10 June 2022	Draft	JCB
2.0	5 July 2022	Draft	JCB
3.0	16 September 2022	FINAL	JCB

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Cover Image:

The Hunga volcano erupting on the afternoon of 14 January 2022, approximately 24 hours before the main eruption. (Photo Taaniela Kula, Tonga Geological Services)

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Foreword – Government of the Kingdom of Tonga

The safety of the public from natural disasters is primary to the work of the Government of the Kingdom of Tonga. "*Peaukula*" as locally called and globally known as "tsunami" has demonstrated its power to destroy low lying coastal settlements throughout the Kingdom in September 2009 in the Niuatoputapu Group and recently in January 2022 in Tongatapu, 'Eua and Ha'apai Groups. Two catastrophic *"peaukula"*, a decade apart, generated by two different geological forces, is a reminder and a lesson of the Might of Mother Nature.

The Tonga Strategic Development Framework II 2015-2025 stipulates the need for improved land use planning and resilience to extreme natural events. It requires the Government to place greater focus on services to reduce environmental and natural disaster risks across the Kingdom. The Hunga Volcano "*Peaukula*" has revealed the need for Tonga to refocus and prioritize actions to increase resilience of the public and the country overall to geological generated hazards.

The Hunga Tonga Hunga Ha'apai Recovery and Resilience Building Plan, March 2022-2025 and the Build Back Better Vision for Tonga, August 2022 are additional local policy documents that further prescribes the need for resilient communities and at national level. Inter-governmental agreements such as the Sendai Framework 2015-2030 also states the need for understanding disaster risk, governance and investing in resilience, effective response and building back better in recovery, rehabilitation, and reconstruction.

The information gathered and published in this report is fundamental to the knowledge building, research and scientific based decision-making proceedings, and development designs, planning and building back better initiatives of the Government and improving its services to the public. For this, the Government of the Kingdom of Tonga is grateful to all those involved in producing this report.

The Government recognizes the effort and commitment invested to realize this report. It was indeed without a challenging environment during the COVID19 travel restrictions and with no international communication means. Yet, the good-hearted personnel and close working relationship between Tonga and the International Agencies overcame the odds. The Government of the Kingdom of Tonga therefore thanks the Financiers and Coordinators: Ms. Litea Biukoto of the Secretariat to the Pacific Community (SPC) and Dr. Laura Kong of the International Tsunami Information Centre (ITIC); Dr. Jose Borrero of eCoast Consulting for the tsunami analysis, guidance on field survey and compiling this report; Professor Shane Cronin of Auckland University for the training and leading the Field Investigations; Mr. 'Ofa Fa'anunu, Director of Tonga Meteorological Services and the staff of the Tonga Geological Services facilitating, local coordination and conducting of field survey and investigations. Special thanks to His Majesty's Armed Forces for providing transportation to the outer islands.

It is my hope that this information will serve its purpose and it is in my faith that all things led by the Almighty and our Creator, will be successful at all levels, as we rebuild our nation.

With sincere gratitude,

Minister of Lands, Survey and Natural Resources
Tonga Government

Lord Tu'i'afitu
Minister of Lands and Natural Resources
Government of the Kingdom of Tonga.

Foreword

Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific, and Cultural Organization, (UNESCO IOC)

Tsunamis are mostly generated by earthquakes. However, over history 6% of tsunamis have been caused by volcanic eruptions. On 15 January 2022 Tonga's Hunga Volcano erupted in a sudden and explosive way. The giant ash plume reached the height of 30 km stratosphere, and sonic booms were heard in several countries and as far north as Alaska, 10,000 km away. Pressure disturbances travelled around the globe several times in the form of a Lamb wave. A destructive tsunami hit Ha'atafu, Tongatapu in less than 10 minutes and then travelled across ocean basins.

On the day before (14 January 2022), a smaller eruption with 'volcano natural warnings' of ash dust clouds and sulphur odours, explosive boom sounds, and abnormal and erratic tides and sea level fluctuations were reported by town officers and locals on Fonoi and Mango islands. This prompted the Tonga Meteorological Service (TMS) to issue a Tsunami Marine Warning on January 14th, which was finally cancelled for all of Tonga at 10 AM local time on 15 January after visual confirmation that volcanic activity was ceasing and sea-level fluctuations on the Nuku'alofa gauge had decreased.

Starting from 5:13 PM local time, a huge mushroom ash cloud was observed, with sound blasts lasting a couple of minutes, and so loud that eardrums hurt, shock waves were felt on the ground, thunder was heard, lighting strikes seen, and sea birds were seen flying en masse inland. Based on these natural warning signs, and the knowledge gained from the previous day, the TMS issued an Urgent Tsunami Warning at 5:21 PM advising people to evacuate inland.

Unbeknownst to them, tsunami waves were already flooding the northwestern coast of Tongatapu where runups of up 20 m were measured. Eyewitness accounts noticed waves around 5 PM, and a tsunami bore of white water at 5:14 PM in Ha'atafu. At the same time, many shared through social media, images, videos, and descriptions of the volcanic eruption and of the tsunami waves hitting in different places, and the evacuations that ensued. The sharing happened in real time until about 6:30 PM when the submarine telecommunications cable between Tongatapu and Fiji was severed, resulting in a near blackout in communications that lasted for 10 days.

Documentation of these and other aspects of this event for lessons learned is essential for improving tsunami preparedness, mitigation, and the warning system. The post-event collection of tsunami wave runups, flow depths, inundation, and damage to the built and natural environment records the quantitative impact. These are complemented by eyewitness descriptions detailing the wave's arrival (its timing, character, strength, direction, recurrence, etc.), and powerful accounts of people reacting to and escaping the sudden tsunami.

The communication blackout added to the ongoing COVID-19 pandemic, which had closed Tonga's borders to visitors from the outside and made it all but impossible to conduct a comprehensive post-tsunami science survey. Following past significant tsunamis, the IOC, working through its Tsunami Information Centres such as the International Tsunami Information Centre (ITIC), facilitated International Tsunami Survey Teams (ITST) of international scientists who worked with the impacted country to collect tsunami data (runup and inundation, eyewitness accounts, and impact) – normally within the first week and month.

Due to unprecedented logistical challenges including COVID sanitary restrictions, this time national teams led by the Tonga Geological Service, and remotely assisted by international technical experts through virtual meetings conducted Post tsunami reconnaissance from 25 January to June 2022. At the request of the Tongan Government and the Tonga Meteorological Service, the ITIC provided active coordination support and expertise for monitoring and assessment to strengthen the Tonga Tsunami Warning capability including facilitation to ensure that post-tsunami runup and inundation assessments would be used for improved tsunami forecasting.

The data report presented here represents a coordinated, collaborative effort of the Tongan government, eCoast Maine Consulting and Research, ITIC and IOC, New Zealand, Pacific Community (SPC), and University of Auckland - working together. That cooperation enabled conducting the assessment relatively smoothly, given the enormous logistical, transportation, and communications challenges.

This work is a result of the trust and good working relationships built over the last 10-20 years between the participants and partners in the IOC-led Pacific Tsunami Warning and Mitigation System principals. The ITIC, SPC and New Zealand have been working together since the early 2000s in disaster risk reduction and tsunami training - the most recent being tsunami inundation modelling for Southwest Pacific countries and tsunami warning centre operations for Tonga in 2019. With Dr. Jose Borrero of eCoast, we had a very experienced tsunami scientist who has been involved in ITSTs' activities since 1992 and acted as the IOC's principal for the ITST-El Salvador in 2012. Finally, we save our last appreciation for Dr. Shane Cronin, for his willingness to stray from his Hunga Volcano investigations to help collect in-situ tsunami runup and inundation data starting in April.

Our warmest appreciation for all of them for their contribution to the noble goal of saving people's lives across the whole Ocean.

Vladimir Ryabinin
Executive Secretary, IOC
Assistant Director-General, UNESCO

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1.0 INTRODUCTION

From January 15th, 2022, at approximately 4:47 pm local time (0347 UTC), several weeks of heightened activity at the Hunga volcano (Cronin et al., 2017) 65 km northwest of Tongatapu (Figure 1.1), culminated in an 11-hour long violent eruption. During the first 45 minutes of this eruption a massive atmospheric pressure wave and a series of tsunamis were generated and observed around the world (Carvajal et al., 2022, Lynett et al., 2022). The eruption severed an undersea telecommunications cable resulting in a near-blackout in communications between Tongatapu and the world as only satellite phones and HF radio were able to work. Restoration of communications through the repair of the cable took until 22 February 2022 (5.5 weeks).

The first successful science / tsunami warning centre communications with the Tonga Meteorological Service (TMS) was 25 January, 10 days after the eruption. when the International Tsunami Information Centre (ITIC) Director was finally able to connect to TMS by satellite phone. This communication resulted in three requests from the Government of Tonga for support to repair and re-strengthen their tsunami warning and weather forecasting operations. The requests were to the USA for supplies to fix their 'Chatty Beetle' remote communication system. to Australia and New Zealand for deployment of seismic stations for earthquake monitoring, sea level stations for tsunami monitoring, communications equipment, access to the NZ Tsunami DART buoy data, replacement of automated weather station, and tsunami scientists to urgently conduction post-tsunami inundation assessments, and to the ITIC for coordination and technical expert assistance.

Over the next three months through April 2022, the ITIC and IOC convened 30 regular check-in phone and videoconference calls with the Tonga Meteorological Service and Tonga Geological Services (TGS), and international partners working together to response to Tonga's requests. The primary partners included the Pacific Tsunami Warning Centre (PTWC, USA), NZ GNS Science, Geoscience Australia (GA) and Bureau of Meteorology (BOM), and Pacific Community (SPC), with additional experts joining for inundation modelling (Univ of Southern California), volcano and earthquake monitoring and long-term deployments (US Geological Survey).

Due to the immediate post-disaster needs of the community and because of travel restrictions to and within Tonga caused by the ongoing COVID-19 pandemic, a comprehensive field survey of the impacts and effects of tsunami runup and inundation was not conducted in the immediate aftermath of the event. Unlike for past damaging tsunamis, no International Tsunami Survey Teams were able to deploy to work with Tongan government officials to conduct detailed surveys although local investigators (i.e., the Tonga Geological Service and Tonga Meteorological Service) did provide important information regarding the magnitude and effects of the tsunami, there was nevertheless a strong need for detailed information on the impacts and effects of the tsunami in Tongatapu and outlying islands. These surveys are important because they increase tsunami risk knowledge, strengthen support for community recovery, support future improvements to the Tsunami Early Warning System (TEWS) and contribute to the fundamental understanding of the tsunami phenomenon itself.

To address this need, the Government of Tonga first officially requested support from New Zealand or Australian scientists to conduct a post-tsunami survey. Given the travel restrictions, New Zealand, USA and SPC, sent in lieu surveying equipment (laser ranger, survey poles, handheld GPSs) to the Tonga Geological Services (TGS) to assist in collecting runup and inundation data. Additionally, the ITIC requested that The Pacific Community (SPC) engage an experienced international tsunami scientist (Dr. Jose C. Borrero) to provide remote training and assistance on post-tsunami field data collection techniques and to compile the results of a series of surveys into a technical report. Serendipitously, volcanologist Professor Shane Cronin of The University of Auckland was permitted entry to Tonga in early March 2022 for an extended mission to conduct field investigations related to understanding ongoing volcanic threats. He also oversaw the ground training and tsunami field surveys with local scientists and TGS staff.

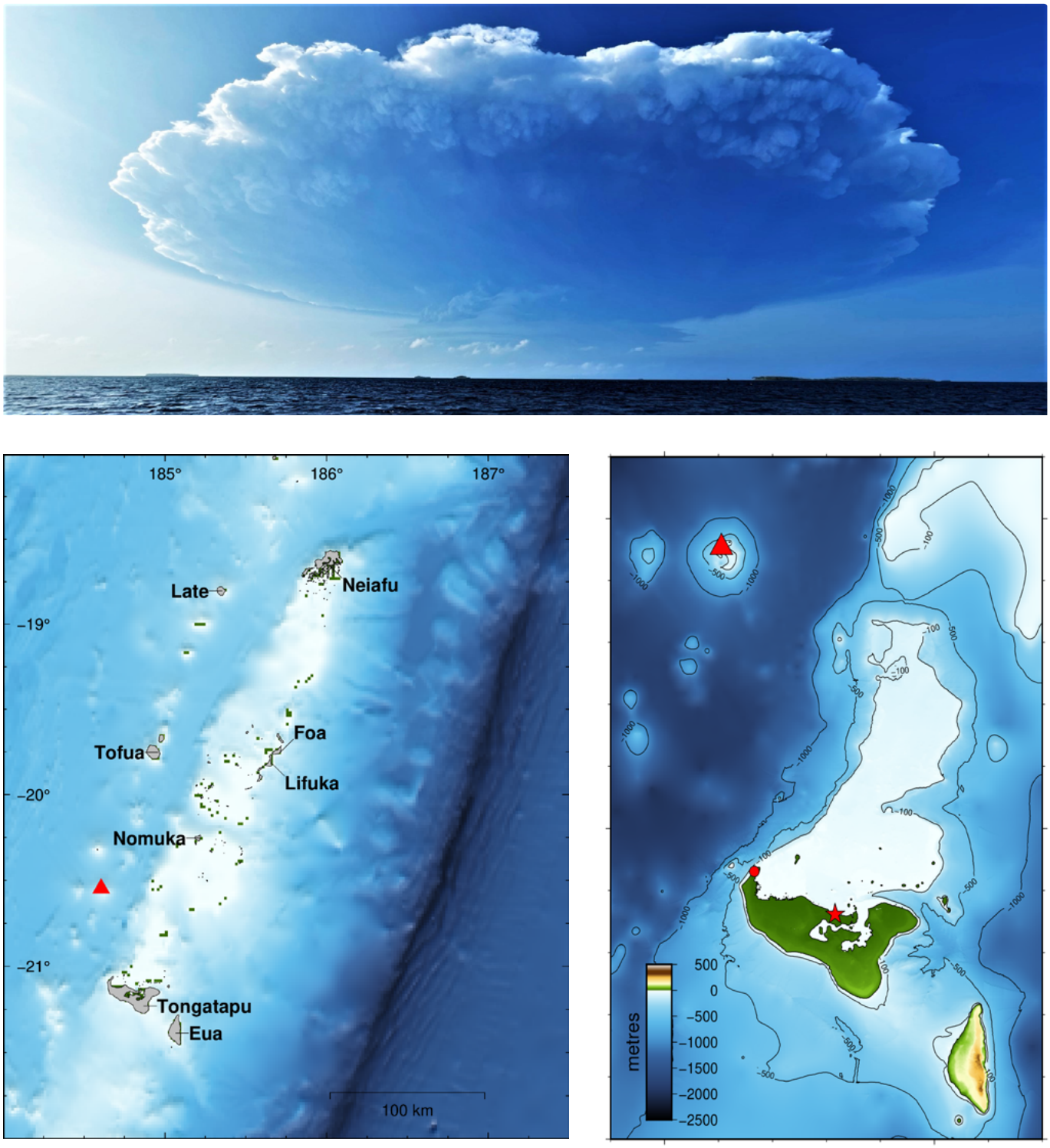


Figure 1.1 **(top)** The eruption rising to its climax at 5.24 pm (0424 UTC) January 15th from ~10 km north of Tongatapu (Photo: Branko Sugar); the upper plume is already >100 km wide. **Lower left** shows the location of major islands in the Kingdom of Tonga, with Hunga volcano indicated with a red triangle. **Lower right** shows the bathymetry around Tongatapu and Eua islands.

1.1 HISTORICAL TSUNAMI OVERVIEW

Globally, approximately 80% of tsunami have been caused by earthquakes. Of the remainder, 7% were caused by tectonically induced landslides, 6% by volcanic eruptions, 5% by landslides alone and 2% by other causes (NGDC/WDC 2022).

NOAA's historical tsunami database (NGDC/WDC 2022) lists 32 tsunami events affecting Tonga (see: https://www.ngdc.noaa.gov/hazel/view/hazards/tsunami/runup-data?country=TONGA). Of these 27 have a validity ranking of '3' or '4' (definite or likely tsunami), four have a validity of '2' (questionable tsunami) and one with a ranking of '1' (doubtful tsunami).

Of the 27 definite or likely tsunami, three have been damaging (events in 1865, 1917 and 2009) with the 2009 event causing fatalities. 65% of the events were from distant sources and 37% were from local or regional sources. 89% were caused by earthquakes and 11% by volcanic activity. The tsunami source locations for events affecting Tonga are broken down in Figure 1.2 while source locations of damaging or deadly regional tsunami events is shown in Figure 1.3. A more detailed discussion of Tonga's tsunami history is presented in Borrero et al. (in review).

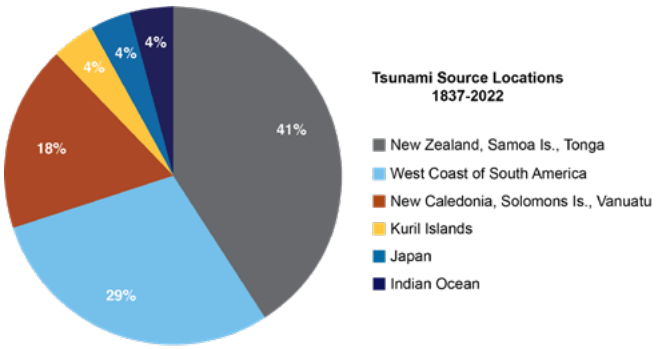


Figure 1.2 Breakdown of source locations for tsunami affecting Tonga.

In addition to the events listed in the database, in the late 1990's the Tonga Geological Services investigated reports of unexplained wave-related destruction occurring overnight along beaches in western Tongatapu. At Good Samaritan Beach the beach was eroded by 50 m and marked by a sharp escarpment along the tree line behind the storm berm over 2 meters high. The 'Utukehe Beach resort, now known as White Sands Beach, had trees removed from the beach side and pushed through concrete resort accommodation 50m behind the storm berm and tree line.

Additionally, in 2016 serious damage was caused by a series of waves occurring over a span of a few hours early one morning along a beach in southern Tongatapu. At Fua'amotu Beach and Nakolo Beach the waves reportedly removed cemetery decorations that were located at 7 m elevation above sea level and levelled out the sand mounds positioned above each grave site. While these events have not been fully investigated, they are nevertheless a reminder of tsunami or tsunami-like damage from other sources occurring near Tonga.

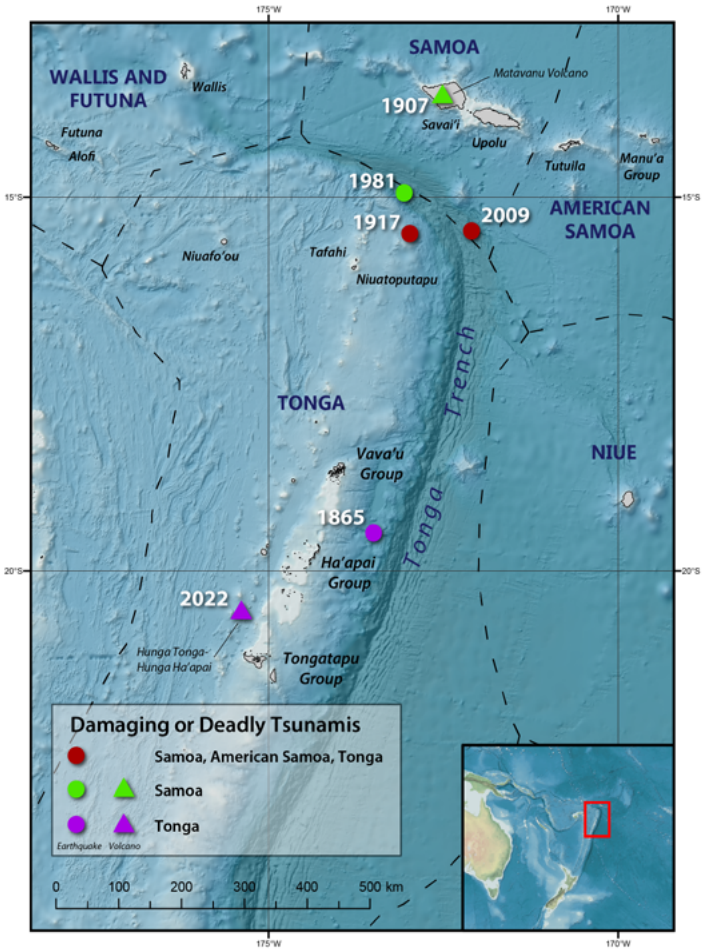


Figure 1.3 Location map for sources of damaging or deadly regional tsunami affecting Samoa, American Samoa and Tonga.

1.2 SURVEY DETAILS

The tsunami runup and inundation survey was conducted as per standard methodologies (i.e. IOC/UNESCO 2014). Data was collected by visiting the tsunami affected sites and collecting coincident transects of local topographic elevation and tsunami flow traces along each transect. The quantities measured in the survey are named according to Figure 1.4. In this case, 'flow depth' is a measure of a water mark above ground level. The total 'tsunami height' is the sum of the flow depth plus the topographic elevation at that location. Runup height is the elevation of the tsunami at the point of maximum inundation. The runup height is not necessarily the maximum tsunami height as there can be tsunami height markers along a transect that are higher than the runup. This generally occurs in areas with relatively flat topography or ground that slopes downward further inland resulting in large inundation distances.

Survey lines were run perpendicular to the coast and in each site a minimum of two and up to four survey lines were measured. Position and elevation data were collected using survey grade RTK GPS receivers (Figure 1.6) and heights were corrected to the Tongatapu local mean sea level on Tongatapu and Eua. On the Ha'apai Group islands heights were measured directly by difference along GPS survey lines and checked against satellite LiDAR based measurements where available (the latter courtesy of James Garvin, NASA). While the positional precision for the measurements was generally within a few centimetres, the overall accuracy of the absolute heights may vary up to several tens of cm, partly due to measurement error, but also to local irregular topographic conditions along the coastlines.

Surveys were collected from the most-recent high-tide mark (wetted limit or detritus limit) up to the interpreted run-out of the tsunami. Maximum run-up was identified by floated debris, evidence of wetting through staining or vegetation die-back, deposits (rarely), and most commonly, by floated pumice, which formed distinctive marker lines. Survey transects were targeted, where possible, to areas where true-run-ups could be measured (i.e., un-affected higher slopes beyond the runup). Transects were also targeted to maximise the possibility for flow-height measurements – e.g., by choosing places where trees were standing. In areas of near-total destruction, typically only a few coconut trees remained. Flow height measurements were taken from trees or other tall obstacles either directly along the transect line or projected from up to 20 m perpendicularly on either side of the line. Flow markers included, in order of reliability: rafted/floated debris within trees, impact/damage marks on bark/trees/structures, freshly broken tree branches, debris piles, stain marks on walls and debris lines. Where possible residents from the survey areas were interviewed and were able to point out many additional flow-height markers that they had seen soon after the event. Flow heights were estimated using a laser-range finder. Flow height measurements have inherent great variability due to the serendipity of the presence of trees, whether they were distinctively marked and whether the marks represent the maximum flow height. In most cases the flow-heights are considered an underestimate of the true water levels.

Due to the relatively small tide range (~0.75m typically) the data presented here have not been adjusted to account for difference in the tide level at the time of the tsunami. However, as shown in Figure 1.11 the tide level at the time of the tsunami was approaching high tide, thus the tsunami heights reported here could be reduced by ~0.4 m. However, given the relatively large tsunami heights and the uncertainty inherent in interpreting the flow traces this correction can be neglected at some sites. At other sites such as northern Tongatapu where the tsunami heights are smaller, the 0.4 m correction can be applied.

Tsunami runup and inundation surveys were conducted between April 4 and 17 June 2022 as listed in Table 1.1. The tide levels on the day of the tsunami and on the days of the field surveys are presented in Table 1.2.

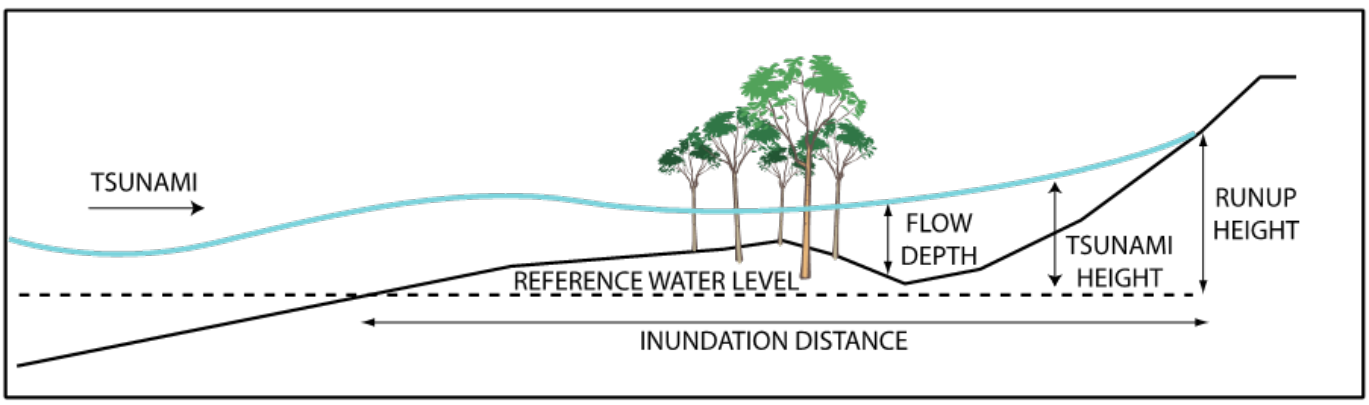


Figure 1.4 Definition sketch for tsunami flow terms.

Figure 1.5 Examples of field indicators used to deduce flow depths and inundation distances (left) evidence of debris impact on a concrete water tank and (right) deposited debris near the limit of inundation (Photos: Shane Cronin and TGS).

Figure 1.6 Collecting position and elevation using a Trimble Geo7x RTK GPS receiver with additional Zephyr3 Antenna (GNSS data were collected in rover mode and differentially corrected using the Tonga base-station using Trimble Data Office software). (Photos: Shane Cronin and TGS).

Table 1.1 Dates and locations of surveys around Tongatapu and Ha'apai Islands.

Tongatapu	
Date	**Sites**
4-Apr-22	Kolovai
6-Apr-22	Otuhaka, Kanokupolu
7-Apr-22	Ha'atafu
8-Apr-22	Likualofa
11-Apr-22	Utukehe
13-Apr-22	Kala'au, Fanga Piliki
24-Apr-22	Samaletane, Keleti
25-Apr-22	Hufangalupe, Ahononou, Katea, Emeline, Fanga Taupo'ou
26-Apr-22	Kolonga, Manuka, Patangata, Popua
29 Apr-22	Talafo'ou, Lapaha, Ha'ateiho, Halaleva
5-May-22	Atata, Fafa
11-May-22	Nukualofa, Sopu, Nukunuku, Te'ekiu

Ha'apai	
Date	**Sites**
18-Apr-22	Nomuka, Mango, Fonoifua
19-Apr-22	Tonumea, Tungua
'Eua	
Date	**Sites**
13-Jun-22	Ohonua 1, Tufuvai, Ohonua Wharf
14-Jun-22	Blue-Water, Ohonua SOT
15-Jun-22	Eua Bridge,
16-Jun-22	Ha'atua
18-Jun-22	Ta'anga
Tofua	
Date	**Sites**
13 -oct-2022	Tofua

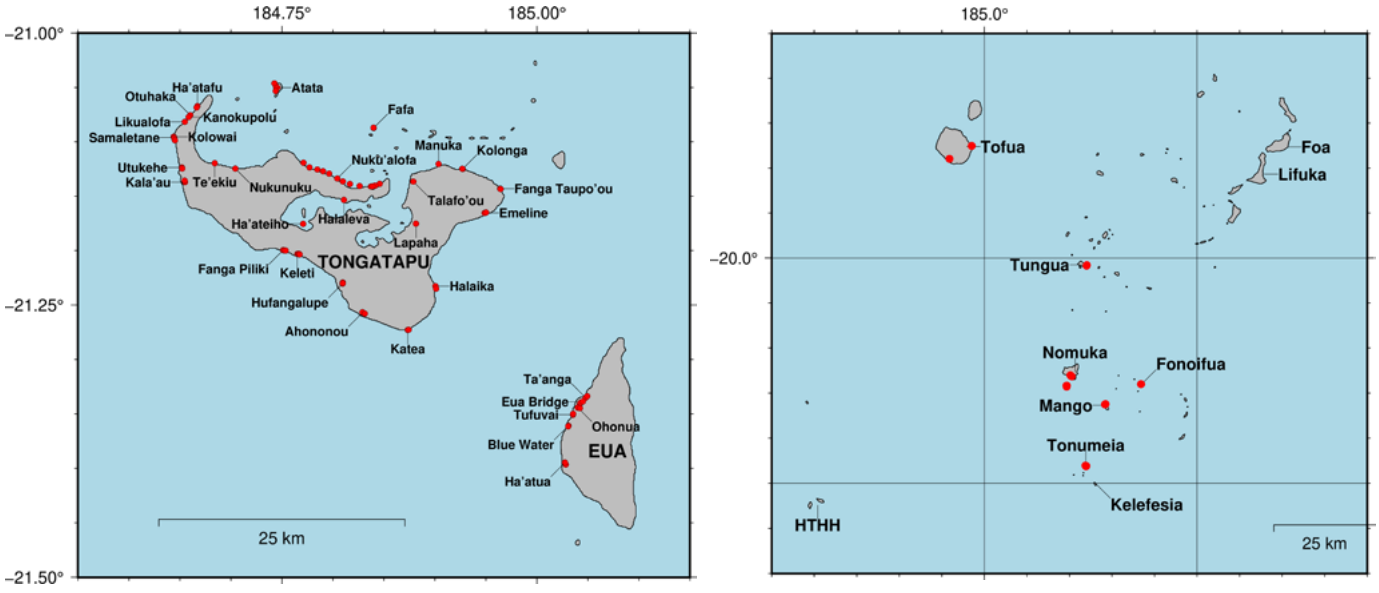


Figure 1.7-Locations where tsunami runup data was collected and listed in Table 1.1.

Table 1.2 Forecast tide levels on the days of the tsunamis and the subsequent field surveys. Times are given in Tonga Local Time.

Tsunami	
Date	**Tides**
15 Jan 2022	0600 1.42 1144 0.77 1759 1.57

Surveys: Tongatapu, Ha'apai					
Date	**Tides**	**Date**	**Tides**	**Date**	**Tides**
4-Apr-22	0331 0.57 0944 1.65 1600 0.51 2212 1.56	6-Apr-22	0456 0.68 1107 1.56 1730 0.57 2344 1.45	7-Apr-22	0541 0.72 1151 1.51 1816 0.60
8-Apr-22	0031 1.41 0628 0.76 1239 1.47 1906 0.63	11-Apr-22	0306 1.38 0903 0.78 1517 1.45 2144 0.64	13-Apr-22	0446 1.45 1048 0.72 1701 1.51 2319 0.59
18-Apr-22	0213 0.48 0825 1.76 1445 0.39 2059 1.67	19-Apr-22	0300 0.48 0912 1.78 1535 0.36 2151 1.66	24-Apr-22	0149 1.56 0748 0.61 1358 1.62 2029 0.46
25-Apr-22	0250 1.56 0852 0.61 1501 1.60 2130 0.48	26-Apr-22	0350 1.57 0955 0.60 1604 1.60 2229 0.49	5-May-22	0424 0.70 1031 1.51 1656 0.53 2314 1.41
11-May-22	0315 1.43 0918 0.72 1529 1.44 2146 0.59				

Surveys: 'Eua					
Date	**Tides**	**Date**	**Tides**	**Date**	**Tides**
13-June-22	0549 1.71 1220 0.35 1833 1.57	14-June-22	0027 0.47 0642 1.76 1314 0.27 1928 1.61	15-June-22	0122 0.45 0736 1.79 1407 0.22 2024 1.64
16-June-22	0219 0.44 0831 1.80 1500 0.19 2120 1.65	17-June-22	0317 0.44 0928 1.79 1556 0.20 2217 1.65	18-June-22	0417 0.45 1025 1.75 1651 0.24 2315 1.64

1.3 INSTRUMENTAL DATA

Two tide gauges were in operation on the Nuku'alofa waterfront during the tsunami, the 'nkfa' sensor at Queen Salote Wharf and 'nkfa2' located 1.8 km to the west at the Vuna Wharf (see Figure 1.8 with station details in Table 1.3). Water level data was also recorded at Neiafu on Vava'u some 300 km north of Nuku'alofa (see Figure 1.1). In Nuku'alofa, at the time of the tsunami, only the 'nkfa' (Queen Salote Wharf) sensor was transmitting data to the IOC Sea Level Monitoring Facility website in real time (https://www.ioc-sealevelmonitoring.org/) and this gauge failed during the tsunami event as shown in Figure 1.9. After the event the Australian Bureau of Meteorology (BoM) released the complete data from the station at Vuna Wharf (nkfa2).

Inspection of the data from the day before the tsunami shows a period of sea level agitation commencing at approximately 1800 hours on 13 January (UTC) and lasting for approximately 24 hours. The main tsunami event commenced at approximately 0425 hrs (UTC) on January 15 with the highest tsunami water level reaching just under 3.0 m relative to the tide gauge datum. The data from nkfa and nkfa2 closely mirror each other with the tsunami signal on nkfa2 slightly preceding that of nkfa due to its more westerly location.

Figure 1.8 Locations of the nkfa and nkfa2 tide gauges along the Nuku'alofa waterfront. (Google Earth)

Table 1.3 Tide gauge details for Nuku'alofa. Information obtained from **https://www.ioc-sealevelmonitoring.org/**.

Station	Location	Lon	Lat	Sensor	Sampling Rate
nkfa	Nuku'alofa_TO (Queen Salote)	-175.1807	-21.1368	Aquatrak	1 min
nkfa2	Nuku'alofa Harbour Vuna Wharf	-175.1967	-21.1303	radar	1 min

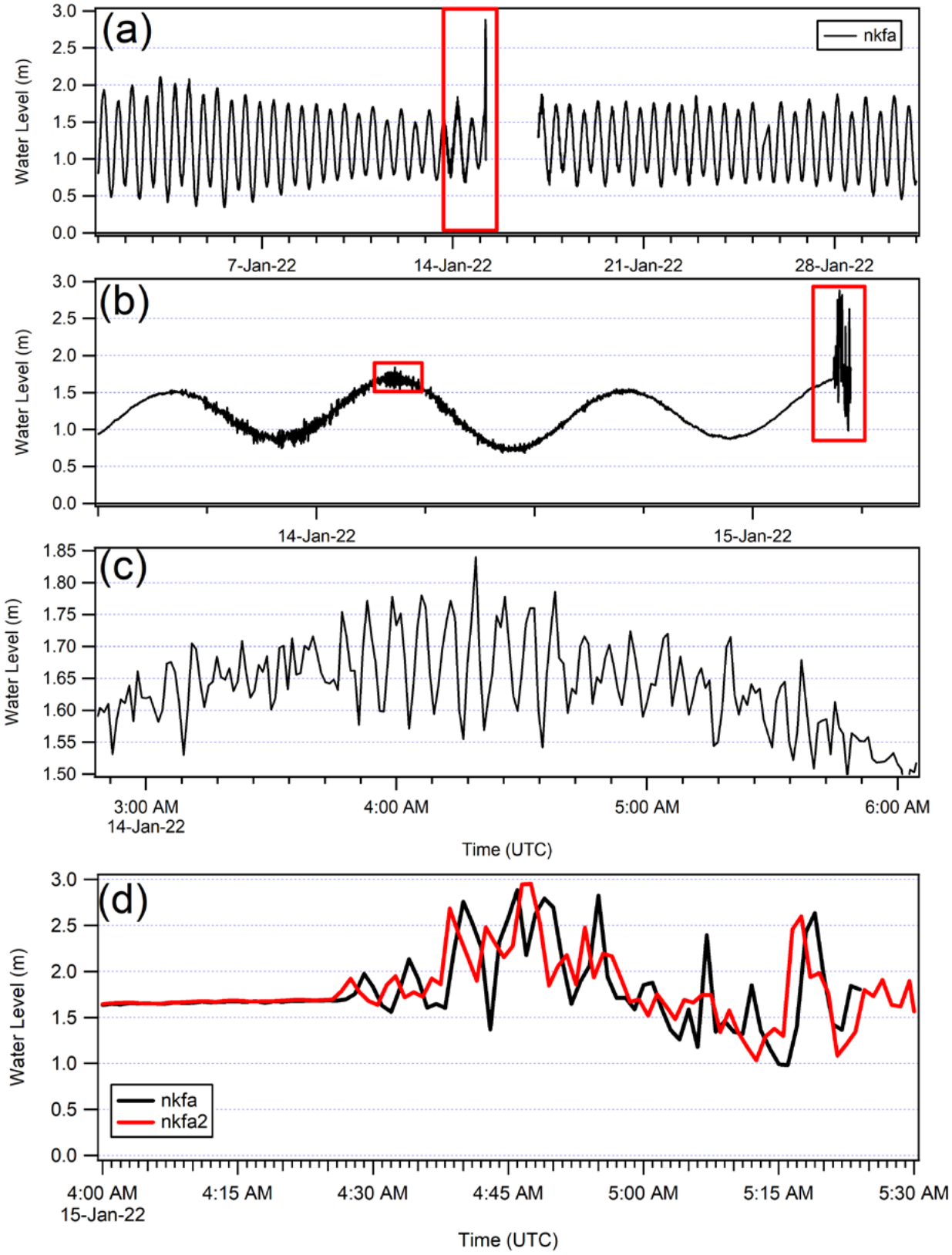


Figure 1.9 Tide gauge water level data from Nuku'alofa. Panel A shows data from the month of January 2022, note the gap in the record commencing shortly after the tsunami arrival. Panel B shows an enlargement of the time span indicated with the red box in A. Small tsunami activity can be seen commencing at ~1800 hrs on from 13 January 2022. Red boxes indicate areas enlarged in Panels C and D. Panel C shows a close-up of this early tsunami activity with tsunami amplitudes of +/-15 cm. Panel D is a close-up of the main tsunami on 15 January with the data from nkfa2 included.

The Neiafu and Nuku'alofa (nkfa2) data sets were detided using a predicted tidal curve derived from tidal constituents (Cyprien Bosserelle pers. comm,) at their respective stations and presented in Figure 1.10. The figures show that the main tsunami of January 15th occurred during the high tide period on Tongatapu and shortly after high tide at Neiafu. At Neiafu tsunami amplitudes are generally smaller than the tide range while at Nuku'alofa the tsunami amplitudes are more than twice the tide range. The plots also show the rapid onset of tsunami activity at Tongatapu and the ~1.5 hr travel time to Neiafu. Also, at Neiafu we see that the tsunami signal is more periodic in nature, suggestive of resonance in the complex bathymetry and dendritic channel characteristic of southern Vava'u where the tide gauge is located.

Figure 1.11 shows the first ~3.5 hours of the de-tided tsunami record at Nuku'alofa (nkfa2). In this plot the vertical red line is the time of the largest magnitude explosion of the eruption sequence, which occurred at 0415 UTC (equivalent to a M5.8 earthquake in energy). We see that tsunami activity is present on the gauge at ~0425 UTC, just 10 minutes after the explosion – which is too early for water waves generated by it. The implications of this timing are discussed in the discussion section below.

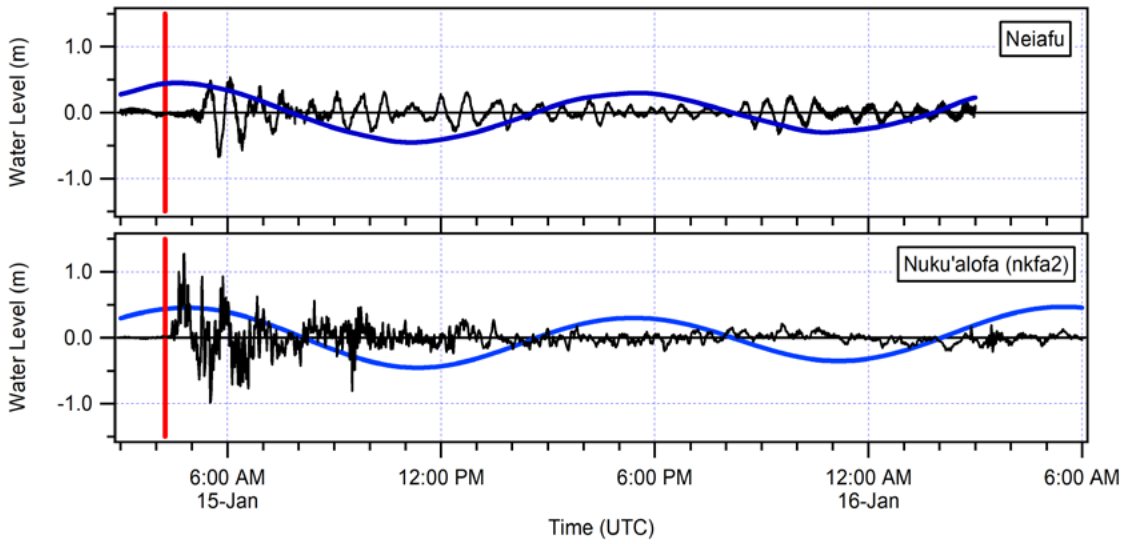


Figure 1.10 The detided (black) water level and the predicted tide (blue) at Neiafu (top) and Nuku'alofa (bottom). Vertical red line indicates the time of the large explosion from the erupting volcano (0415 UTC).

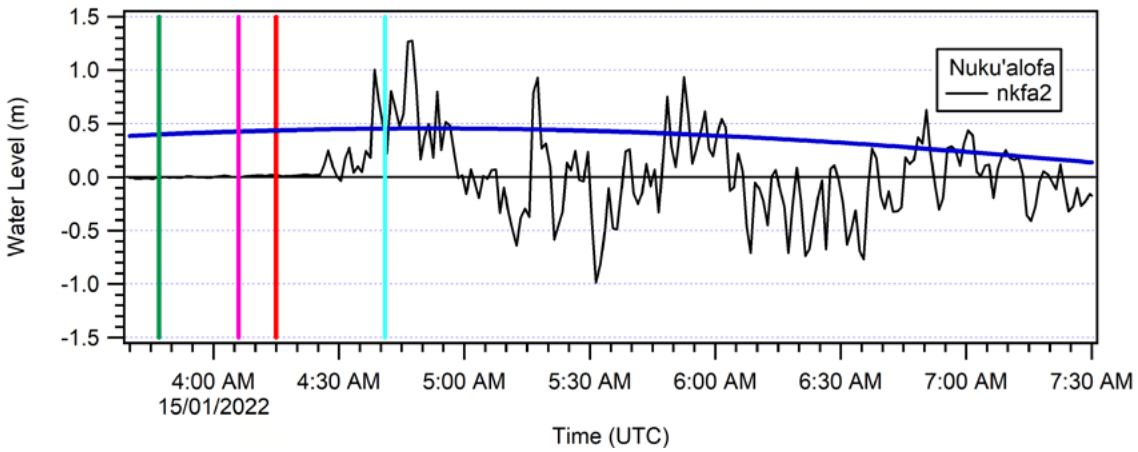


Figure 1.11 Detail of the first 3.5 hours of tsunami activity at Nuku'alofa. Vertical lines indicate key times; green (0347) the start of the surface eruption, pink (0406) eruption plume visible on satellite imagery, red (0415) the time of the large explosion and green (0441) the ~26-minute tsunami arrival time from the volcano to Vuna Wharf.

2.0 FIELD DATA SUMMARY

The overall maximum measured tsunami heights are plotted against location in Figure 2.1 below. On Tongatapu, tsunami waves caused catastrophic damage to the western part of the island with runup heights greater than 15 m along the Hihifo Peninsula from Ha'atafu south to Utukehe with maximum measured total tsunami heights of 18 -19 m in the vicinity of Kanokupolu and Liku'alofa. Inundation distances varied greatly ranging from less than 200 m on steeper coasts where there was no overtopping, to more than 1000 m where the tsunami overtopped and inundated across the entire peninsula.

In the capital of Nuku'alofa media reports showed videos of waves crashing over sea walls and flooding houses, suggesting tsunami runup heights of the order of 3-5 m. These heights were confirmed during this survey.

The southwest facing coast of Tongatapu experienced tsunami runup heights of 10 to 15 m with inundation distances generally less than 100 m due to the steep, terraced and cliffed topography. Some of these runups may be over-estimated due to splash-zones against the steep cliffs. Despite facing directly away from the tsunami source, sites on the east coast of Tongatapu nevertheless experienced tsunami heights greater than 6 m with inundation distances varying from ~20 m at Emeline to ~80 m at Halaika. On Eua the survey was constrained to the central west coast. Tsunami runup heights were generally of the order of 4-8 m with one measurement up to 18 m.

In the Ha'apai island group, the survey visited the islands of Tungua, Nomuka, Fonoifua, Mango, Nomuka-iki and Tonumea, focussing on the inhabited areas for the first four islands listed. Tsunami effects were severe in the islands with tsunami heights greater than 10 m. The islands of Nomuka Iki, Mango and Tonumea were particularly hard hit with extreme surges washing over low-lying areas causing extreme erosion and completely stripping coastal forests, effects reminiscent of those seen in the Mentawai Islands after the October 2010 earthquake and tsunami (Hill et al., 2012) and on islands in the Sunda Strait following the tsunami generated by the eruption and flank collapse of Anak-Krakatau volcano in December 2018 (Borrero et al., 2020).

General observations of damage show an overall correlation to flow-height/runup between sites, as well as a clear gradient of destruction from the coast landward. The between site overall damage states are as follows:

1. **Near-Total destruction** – runups >15-20 m, or local flow heights >8-11 m: soils and trees eroded from roots 100-500 m inland, all complex trees gone, many coconut trees destroyed, and all structures and low-vegetation removed up to 700 m from the coast (depending on local topography), very large debris piles (>6 m high). Concrete building foundations, ripped up, undermined and damaged. Examples: Kanokupolu-Liku'alofa, Tonumea and Nomuka-iki.
2. **Building-concentrated destruction** – runup >8 m, or local flow heights >4-6 m: Soils and trees eroded <50 m from beach edge, all houses stripped off foundations and either floated or totally destroyed up to 300 m from beach edge. Concrete foundations remain. ~50% of complex trees toppled, large debris piles (>4 m high). Examples Nomuka, Mango.
3. **Flooding Only/Non-Structural Damage** – Runup of 1-3 m and low depths generally of 1 m. Structures were flooded, but there was no structural damage. Some fences or unreinforced block walls were toppled. Examples of this were along the Nuku'alofa waterfront.
4. **No damage or inundation** – Examples of this occurred at sites along the shore of the Fanga'uta Lagoon and along the north facing, mangrove dense, intertidal coastline of Tahi Toafa (Maria Bay) between Hihifo Peninsula and Nuku'alofa.

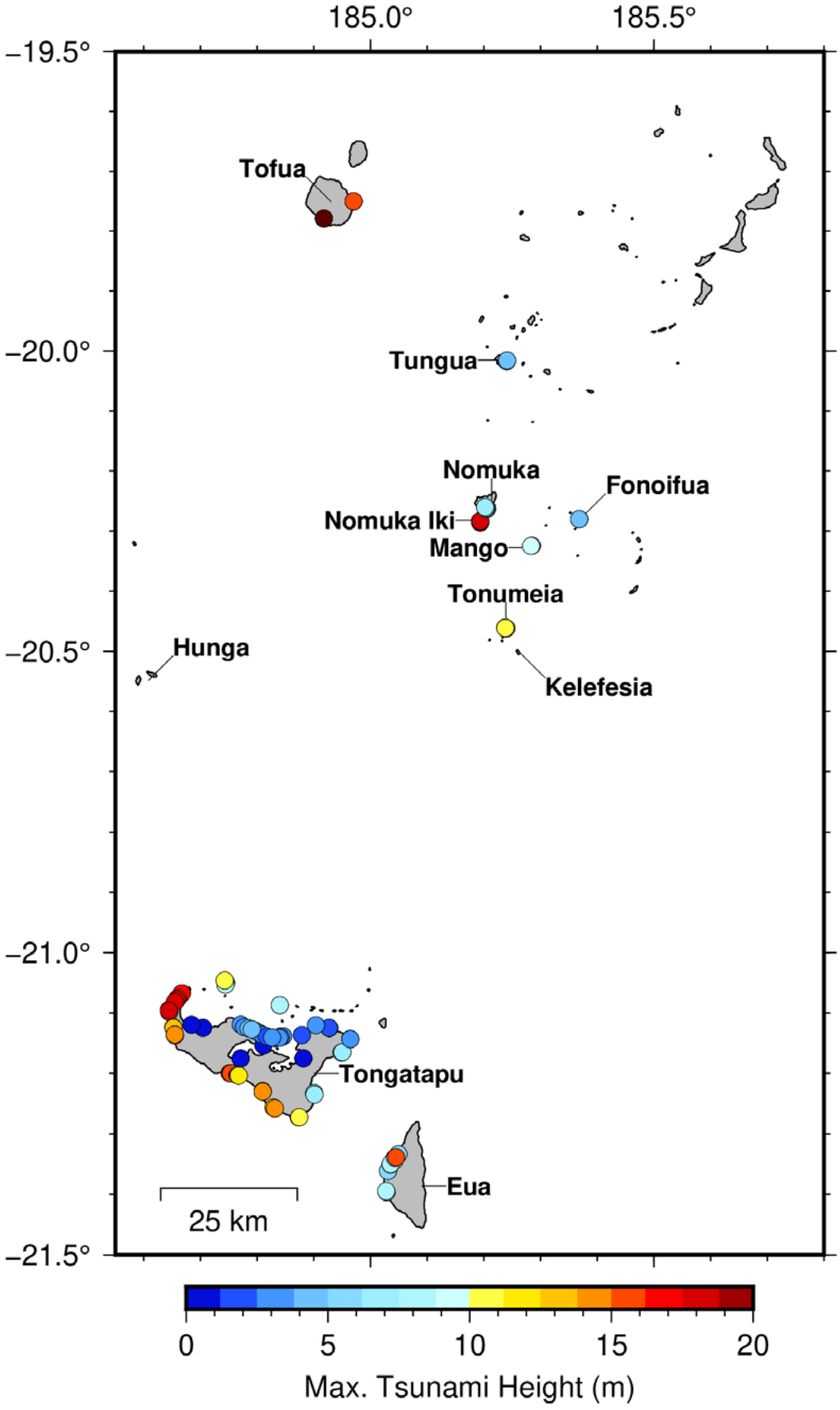


Figure 2.1 Summary data plots of maximum tsunami height for Tongatapu and 'Eua (left) and Ha'apai islands (right). HTHH = Hunga Volcano.

2.1 DATA DELIVERY AND AVAILABILITY

The data collected in this survey has been compiled and collated into tables with the latitude/longitude of the shoreline location at each site, the maximum runup, the maximum tsunami height measured along each transect and the maximum measured inundation distance. At some site the maximum tsunami height is greater than the maximum runup. At other sites there is no measure of true 'runup' as the tsunami flowed over an area and into another body of water, likewise, these sites would not have an inundation distance associated with them either. These complete summary tables are presented in Appendix A, Table 7.1 to Table 7.3.

The data has been organized into separate spreadsheet files containing the detailed cross shore profiles of topography and measured tsunami height at each site. Plots of these transects are presented in Appendix B through Appendix G. Photographs from the survey and other reconnaissance missions have also been compiled and organized into folders for each location. This data is all available for download upon request and is available at the ITIC website:

http://itic.ioc-unesco.org/index.php?option=com_content&view=category&layout=blog&id=2709&Itemid=3327

3.0 DETAILED SURVEY RESULTS

The following sections will provide more details from each of the surveyed locations.

3.1 WEST COAST TONGATAPU

Eight sites were surveyed on the west coast. These are indicated in Figure 3.1. This region experienced the most extreme tsunami effects Along this section of coast the tsunami overtopped the narrow peninsula with the tsunami spilling over into the lagoon. Peak tsunami heights were of the order of 20 m with runup heights reaching ~17 m. The inundated areas shown in Figure 3.1were estimated based on UAV (drone) imagery and preliminary surveys conducted shortly after the tsunami.

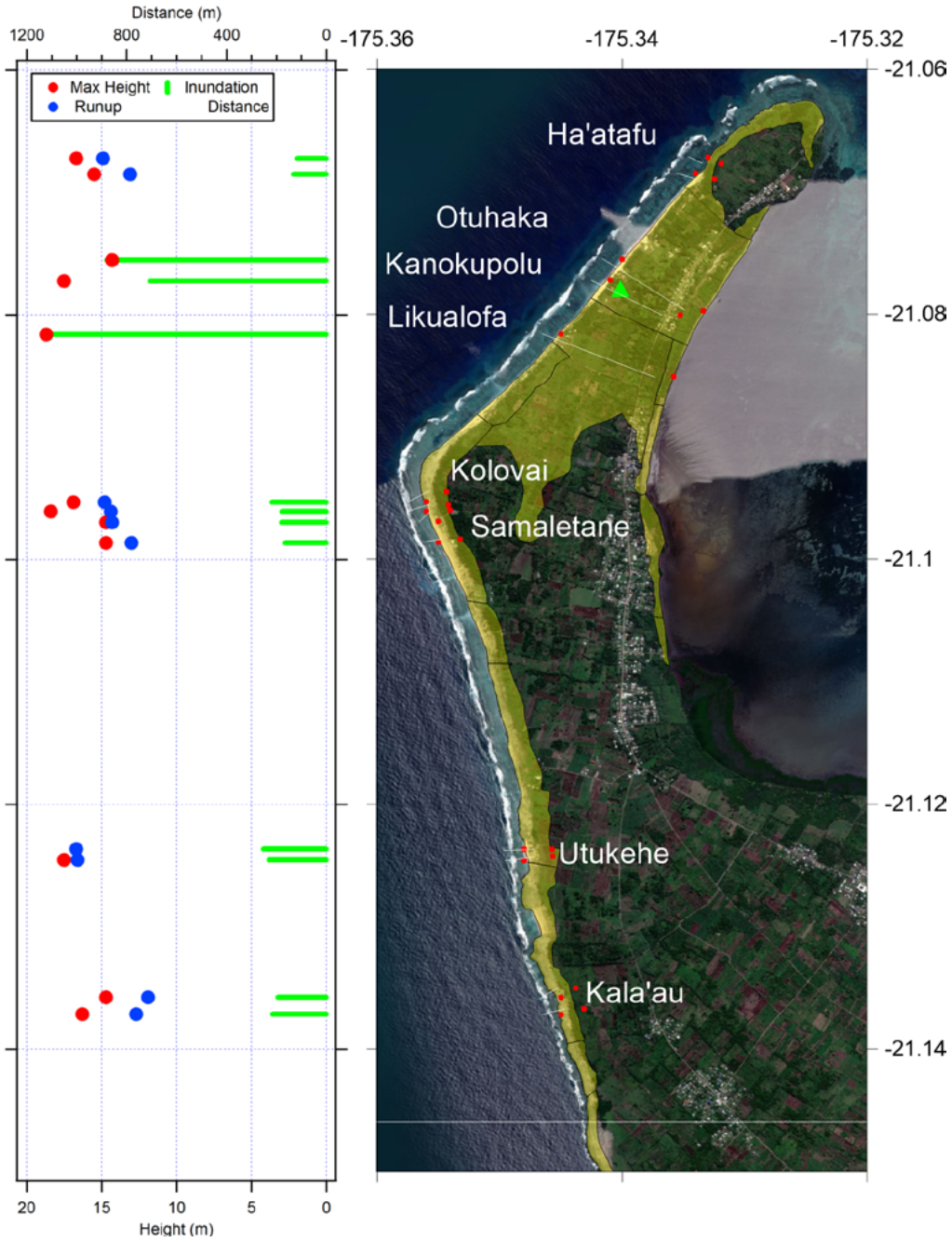


Figure 3.1 Locations surveyed along the western coast of Tongatapu. The start and endpoints of each transect are indicated with the red dot. Green tringle indicates the location of the NIWA weather station. Yellow shaded area indicated extents of inundation. Left plot shows maximum tsunami trace height and maximum runup height along each transect, right plot shows maximum inundation distance.

At Ha'atafu near the northern tip of the peninsula, locally high topography did not allow for complete overtopping with runup stopping at 13-15 m. Just south of these transects, several beach resorts were located on land at elevations of ~5-7 m. This area was completely overrun by the tsunami which destroyed every structure, reducing reinforced concrete buildings to bare foundations (Figure 3.3). The force of the tsunami also stripped away nearly all the coastal vegetation as shown in Figure 3.4.

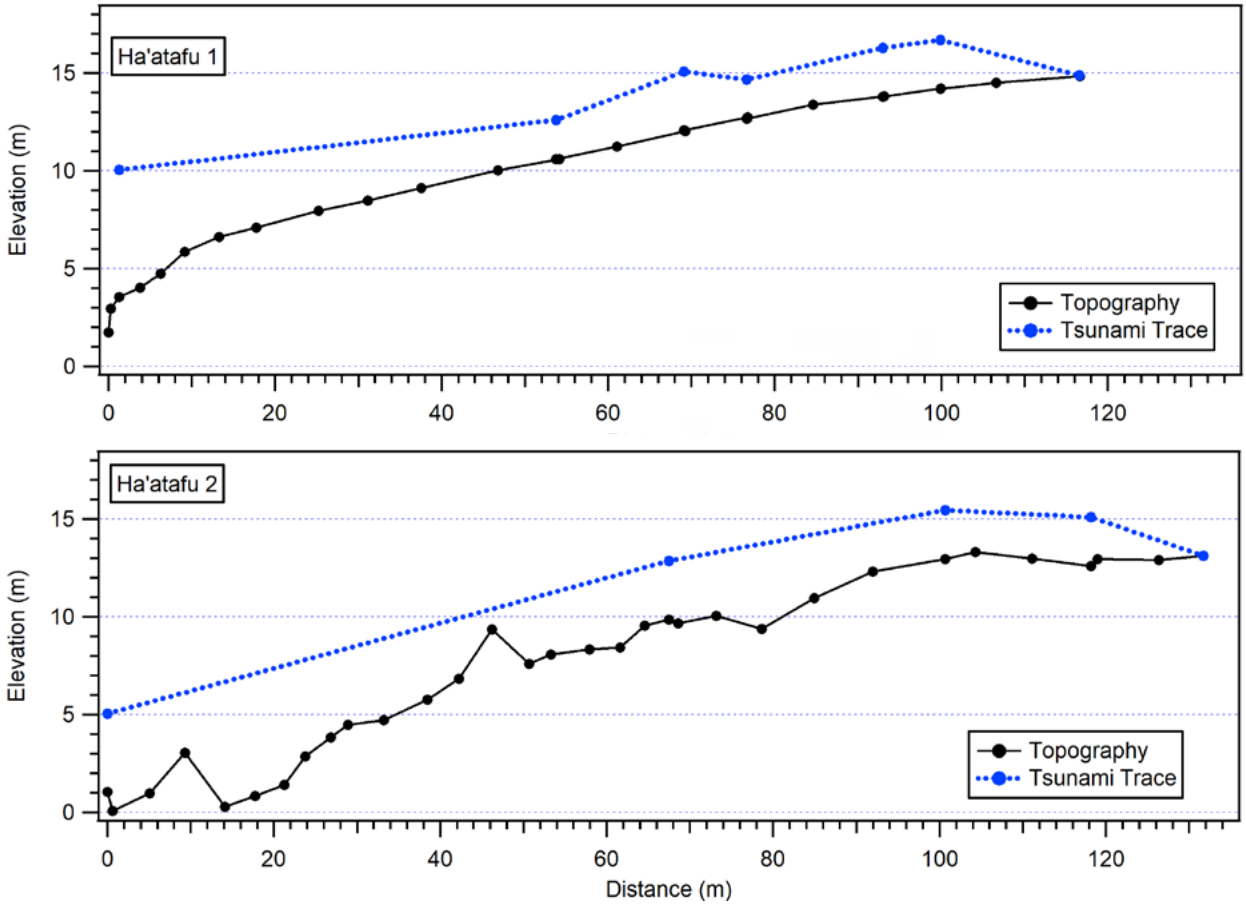


Figure 3.2 Transects of topography and tsunami height at Ha'atafu.

Figure 3.3 Buildings reduced to concrete foundations at the Ha'atafu Beach Resort (photos courtesy Moana Paea).

Figure 3.4 The beach at Ha'atafu after the tsunami (top) and as it looked in 2015 (bottom). Top photo courtesy Moana Paea, bottom photo Jose Borrero.

3.1.1 Eyewitness Accounts from Ha'atafu

3.1.1.1 Moana Paea: Proprietor Ha'atafu Beach Resort

An interview conducted with an eyewitness[1] from the Ha'atafu area shed some light on how the tsunami wave manifested along the west coast of Tongatapu. According to her, there was noticeable tsunami activity along the west coast on January 14th, the day before the major eruption and tsunami. They were aware that a tsunami advisory or warning had been issued by the Tongan government that day and were mindful of the sea conditions. She noted that the sea was agitated all day on the 14th of January, and this prompted them to move their boats out of the water. The description of the sea state is supported by the tide gauge record shown in **Figure 1.9**.

Overnight the sea and weather calmed, and she noted that on the morning of January 15th there was no noticeable surge and that it was a 'beautiful day'. However, there was still a tsunami advisory in place, and radio messages advised that people should not swim due to the possibility of unusual waves or surges. As such, throughout the morning she or a staff member periodically checked the beach area to try and keep guests out of the water. Around mid-day, she went down to the beach and noticed that the water appeared unsettled, guests that were swimming were asked to get out of the water. After this she returned to work at the kitchen of the resort.

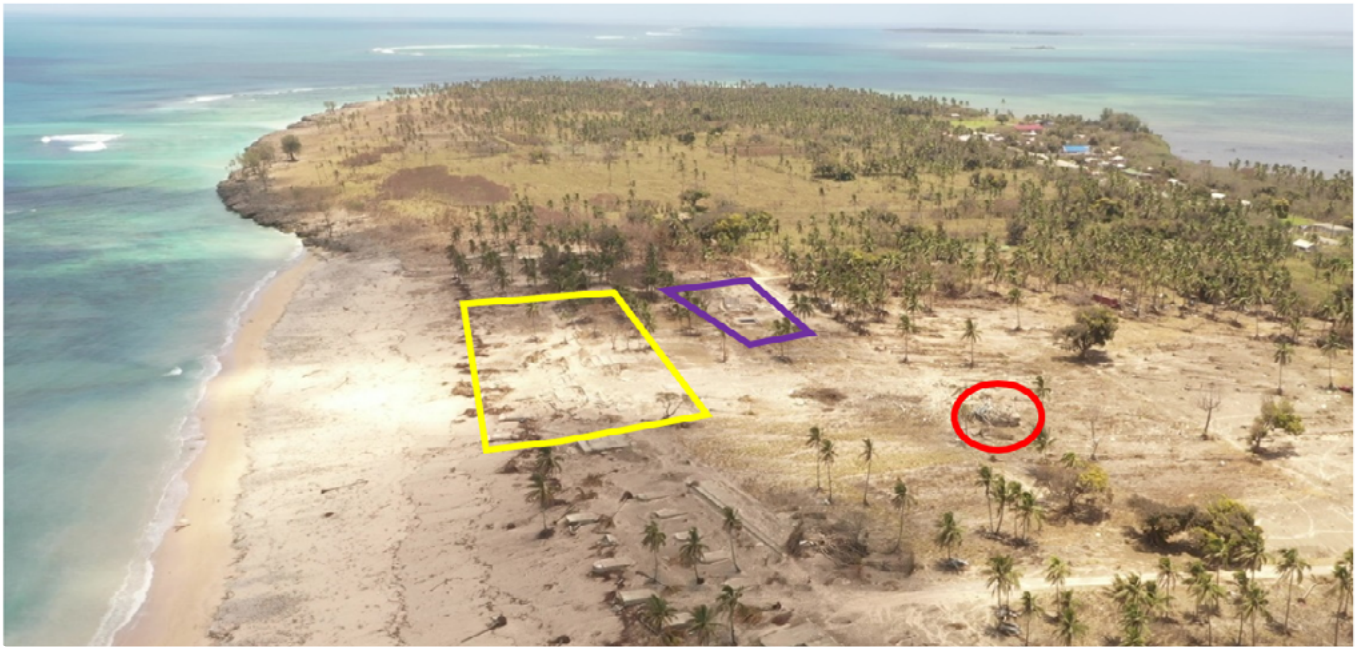


Figure 3.5 The Ha'atafu section of the Hihifo Peninsula. Yellow is the site of Ha'atafu Beach Resort, Purple Holty's Hideaway and red circle is the 'tsunami rock'. (Photo: TGS)

Her recollection of the tsunami begins just before 5 pm local time (0400 UTC). While working in the kitchen, she heard yelling and commotion from the beach area. She was alerted by staff and looked up to see a 'gushing of water' coming into the resort property. She immediately thought 'tsunami' and yelled for people get out. According to her account, that first surge came up to the fence line of property, then the water retreated. During that time, they went around the resort area to try and warn guests and get them to evacuate.

During this time a family member was attempting to retrieve things from the beach area and move them to high ground, but it was then that they noticed the second surge coming in. In her account she notes that the surge was clearly from the north or northwest as it was sweeping laterally from right to left when looking out to sea in a westerly direction. She then ran back to the kitchen and then on to the car park area when she saw cars reversing back into property because they were encountering the incoming tsunami surge at the end of the driveway. Since it was too late to use cars for evacuation, they started to run towards the east through the bushes to escape.

1 Moana Paea, proprietor of the Ha'atafu Beach Resort, which was destroyed by the tsunami

A video circulating on news and social media shows a surge of water coming up a narrow street, ripping down a fence as it advances. This video was recorded at about the same time that the eyewitness reached the car park and saw the cars reversing. Frame grabs from that video are presented in Figure 3.8 below. This is the second wave as described by the eyewitness.

By her estimate at a 'quarter past five or twenty past 5' while running, she got a phone call from a family member and that all of this occurred before the large explosion from the eruption but that the waves had already gotten into the resort. A minute or two later as they were running through the bushes, they heard a large explosion. She noted: "It felt like a bomb. Pretty much knocked all of us on the ground. We all got thrown on the ground when we were running through the bushes." After getting up, they could still hear the ocean or waves coming. During their escape, they couldn't find a large rock that had been previously identified by them as a tsunami evacuation point. They came to a Mango tree and started to climb up it when she received a phone call from her brother on another part of the island who had heard the explosion as well. At that time, the noise from sea abated and things seemed calmer, so they decided to continue moving towards Ha'atafu village on foot. Those that had already climbed the tree got down and they ran to the road. At this point they looked back towards the beach and saw that the water had already reached 'Holty's Hideaway', a small hotel located adjacent to but slightly inland of their resort.

They then ran down to the main road and by this time it started to rain down with rocks and black dust. When they reached the main road on the lagoon side of the peninsula, they climbed on to the roof of 2 storey house where other people were congregating. The roof had a view over the lagoon to the east and from this vantage point she could see the tsunami swell wrapping around into the lagoon. At this point the rain of ash, dust and debris was stronger and they had to cover their nose and mouth.

At this point, her brother arrived by car from the south. Her and her family got into the car and drove away. According to those who remained, it was just after they left when the big surge came across the peninsula and inundated the village. She recounted that she could hear the roar of the ocean as they got in the car and as they drove off it felt like they were being chased out by the ocean.

Other notable observations from this eyewitness were that vehicles from their property were washed across the peninsula to the lagoon side. Also, that no debris remained on their property, this it was all washed to the neighbouring Vakaloa Resort some 500 m to the south.

Figure 3.6 The rock that the witness and family planned to use as a tsunami evacuation point. Fortunately, they did not find the rock during their escape as it was overtopped by the tsunami as indicated by the debris present on top of it. (Photo: Moana Paea)

Figure 3.7 The Ha'atafu-Kanokupolu area before (December 2021, top panel) and after (March 2022 bottom). Red circle indicates the location where the video discussed in the interview was filmed (Figure 3.8). Yellow and purple polygons are the Ha'atafu Beach Resort and Holty's Hideaway respectively. Blue arrow indicates the path run by the eyewitness and family to escape. The pale-yellow ovals along the route are the mango trees they climbed before moving on to the 2-storey house where they climbed up on the roof. The green dashed circle is the large rock shown in Figure 3.6. (Imagery from Google Earth)

Figure 3.8 Tsunami wave advancing up the access road just north of the Ha'atafu Beach Resort. View is towards the west with the ocean approximately 150 m away. This scene occurred shortly after Ms. Paea, family and staff evacuated on foot and just before one of the large explosions was heard.

3.1.1.2 Rachael Moore: Australian High Commissioner to Tonga

A second interview was conducted with Ms. Rachael Moore the Australian High Commissioner to Tonga. Ms Moore was at the Ha'atafu beach resort on the day of the tsunami where she and her family had intended to spend the weekend. They had originally intended to be there on Friday afternoon (January 14th), but the tsunami advisory from the Tongan Meteorological Service due to the eruption and tsunami activity kept them away. On Saturday morning, the advisory was lifted, and the day was calm, so the family continued with their plans. Ms. Moore reported that on the 15th, they had a short swim in the ocean shortly after 4 pm (local time), but that they got out quickly as the ocean became unsettled or 'washy'. She and her son moved up the beach into the shaded area and were doing other beach activities. By 5:15 pm Ms Moore noticed that the water level had risen considerably and just reached the vegetation line of the resort. After this, Ms. Moore returned to their room and began preparing to leave as she did not feel comfortable staying at the resort given the agitated ocean. Her husband was still outside with the children but returned to the room to get Ms. Moore for immediate evacuation after being alerted by the resort staff. It was around this time that she reported felling her ears popping, likely the result of the pressure disturbances from the volcano. Ms Moore and her family then left the resort in two vehicles, one driven by her and the other by her husband.

The images on the following pages (Figure 3.9) are provided by Ms. Moore and show the transition of the sea state as the first tsunami waves affected the Hihifo Peninsula. The sequence starts at 4:41 pm with the ocean looking relatively normal. 33 minutes later at 5:14 an advancing bore of white water can be seen. Over the next minute, the leading edge of the bore can be seen to just reach the edge of the vegetation as her sons look on (3rd and 4th images). The final image 2 minutes later shows the agitated nature of the sea.

Figure 3.9 (following pages) Photos provided by Ms. Rachael Moore of the first of the early arrival tsunami waves affecting the Ha'atafu Beach area. The time stamp is taken directly from the photo file metadata.

4:41:32 PM: Playing on the upper beach, the sea state appears relatively normal.

5:14:32 PM: A bore can be seen advancing towards the beach between the offshore reef and the beach face.

5:14:57 PM: The bore has reached the beach

5:15:11 PM: The bore interacting with the beach.

5:17:38 PM: A few minutes later, ocean still appears agitated.

3.1.1.3 Shane Egan: Blue Banana Homestay

The following account is from and email exchange with Shane Egan, the proprietor of the Blue Banana Beach House located some 500 m south along the beach from the Ha'atafu Beach Resort. It has been lightly edited.

SHANE: I can't say how many bigger waves washed over the peninsula - only that they must have been huge to leave nothing of our solid buildings left vertically standing. I watched the first few arrive (perhaps three)- from just a shore dump, that unsettled the beachgoers, to the one that chased me up the road.

At around 5:00pm there were only thin bands of low cloud on the horizon and from the beach I could not make out any plume at all. This was the first day, after a month of activity, there was clearly no plume emanating from the Hungas.

A few minutes later the plume began to rise rather suddenly so I ran to the house for my camera- just to record it. These first photos (Figure 3.1) are about 6 minutes from the time there was nothing. There is already a small tsunami, tidal surge arriving at the beach - as indicated by the turbulence in the lagoon and the sudden shorebreak (Figure 3.1, Panel E, F). Minutes earlier the lagoon was calm, and it normally takes a large swell to form shorebreakers along this beach. There was otherwise only a small wind swell breaking on the fringing reef. It was pretty much right on high tide so that would not help.

At this time there had been no explosion sounds.

The people on the beach, who were forewarned the day before, realised there was something wrong and swiftly left the area. The next wave (no photo) came further up the beach to the grass line on the beach, so I ran for the car and threw my laptop & camera in it.

There was perhaps a third wave coming up over the beach and on to our property. At this time the loud crack sounds started but they sounded so close I first thought they were fireworks in the property next door. This, though, confirmed that the volcano was getting serious, so I did not return to the house.

By the time I opened the gate and drove out (around 5:15pm) the waves were already coming further up our property and up the road. This was probably the same wave that was filmed at Ha'atafu and the same wave that washed our good friend Ange away.

I did not see the waves receding. They just appeared to arrive in rapid succession, one on top of the other. It was all so fast.

From nothing to this and the crack sounds were getting louder as I drove away.

I made a couple of stops in the village and warned people on the way but they were already aware & had begun to evacuate.

I assumed the waves would be a threat to the low lying village (washing in from the bay side, rather than over the rise of the peninsular) and perhaps making the main road impassable.

'Edi (a friend from town) was coming from Nuku'alofa and arriving at the village as we were all evacuating- so he turned & followed me. As we drove along the high western road, toward the centre of the island, the expanding mushroom cloud was racing us and the cracks became very loud & scary. I'm not sure how many crack sounds there were, perhaps 6 or many more- by this point it was all too surreal.

The pressure waves made our ears pop, like being in an aeroplane & it was necessary to equalise them. It began hailing pumice stones averaging 1 to 3 cm in size. As the mushroom cloud covered the sky the day turned to night and the light rain drops on the windscreen were milky from the ash.

After we arrived at some friends' house at Vaini a strong wind blew up. By morning everything was covered in a thick layer of heavy, black ash- covering cars & houses like black snow and wilting the foliage.

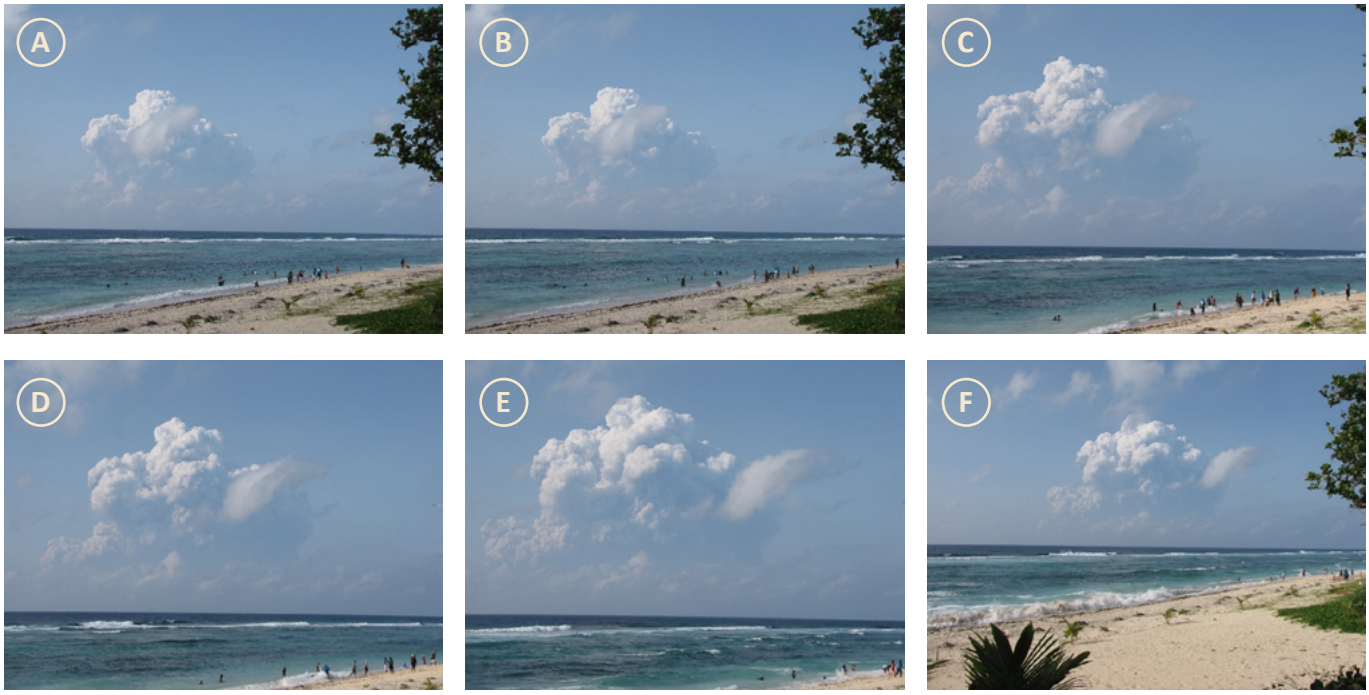


Figure 3.10 Photos from Shane Egan. They form a sequence of about 10 to 15 minutes and start some 6 minutes after the plume was first visible from the beach.

3.1.2 Kanokupolu

At Kanokupolu the tsunami overtopped the peninsula flowing across into the lagoon. A weather station positioned on a cell phone tower with base at a ground elevation of approximately 13 m above sea level was destroyed by the tsunami. The station observed the onset of the eruption and reported data until 05:00 UTC (18:00 local time). Three days after the tsunami, a site visit revealed that the tower had been toppled and transported approximately 20 m from its original location, suggesting tsunami flow elevations significantly greater than 13 m above mean sea level. One woman, Angela Glover (51) a British national, was killed in Kanokupolu (Matai Tonga, 2022, Reuters, 2022)

Figure 3.11 UAV image of Kanokupolu. Red line shows the approximate location of the transect depicted in Figure 3.12. (Photo; TGS)

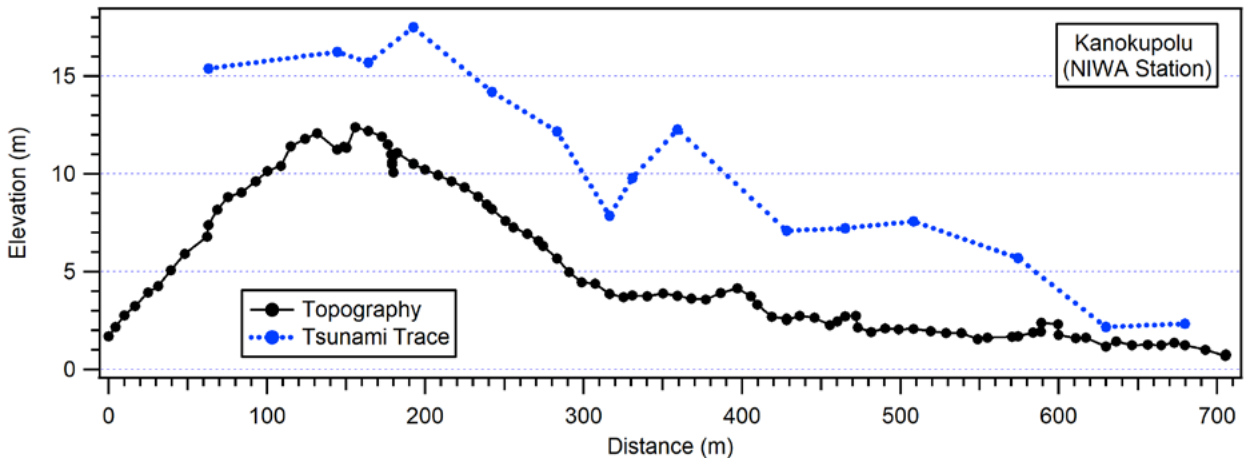


Figure 3.12 Kanokupolu transect.

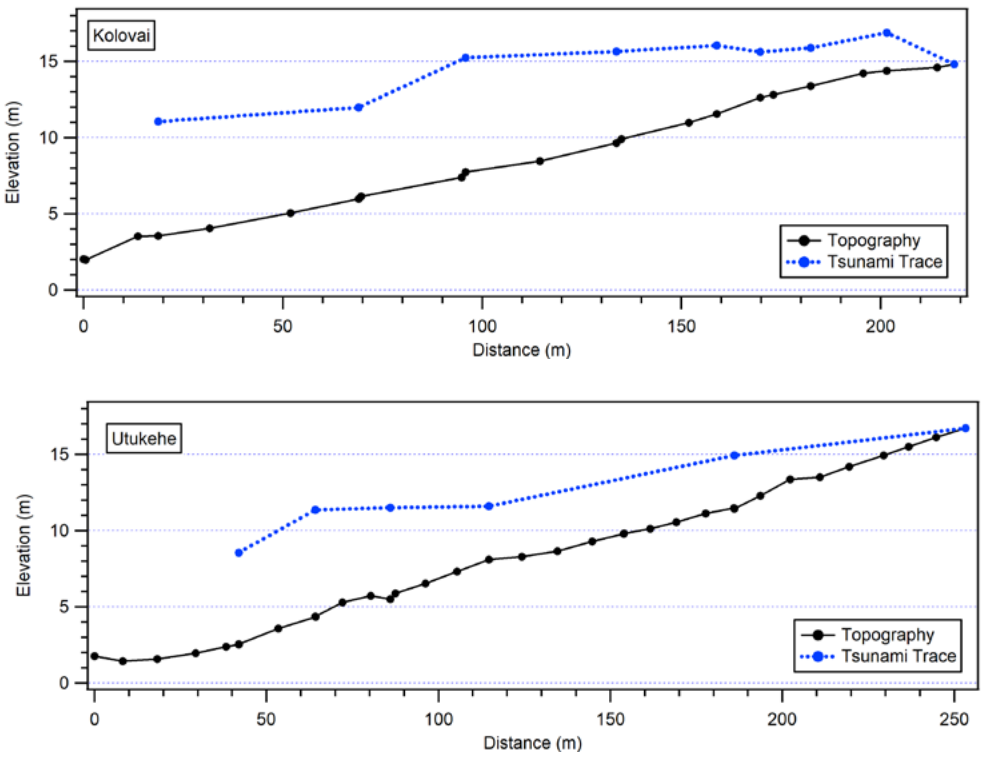
Figure 3.13 (top) The weather station prior to the tsunami and (bottom) after. (Photos: Shane Cronin and TGS).

3.1.3 Other West Coast Sites

The western peninsula was overtopped from Ha'atafu to approximately 2.5 km south (see Figure 3.1 for inundation extents). South of this, higher and steeper topography prevented the tsunami from overtopping the peninsula and measures of true runup could be obtained, i.e. runup against a steep slope where the point of maximum inundation is also the height of the tsunami runup. An example of this is shown in Figure 3.14 at Utukehe, where a clear demarcation of the inundated area can be seen. with representative transects for Kolovai and Utukehe shown in Figure 3.15. In these areas runup was measured to be 15-16 m above MSL.

Figure 3.14 Aerial view of the Utukehe area. The tsunami inundation extent is clearly visible in the agricultural field and indicated with the dashed line. (Photo: Taaniela Kula TGS)

Figure 3.15 Representative transects from the west coast of Tongatapu.



3.2 NORTH AND EAST COAST TONGATAPU

Along the northern coast of Tongatapu in the vicinity of Nuku'alofa tsunami heights were of the order of 3-4 m (Figure 3.16) with inundation distances from 100 to >300 m. The tsunami heights and runup levels were relatively consistent across the entire northern coast from Sopu to Fanga Taupo'ou. In the eastern villages (Manuka, Kolonga, Fanga Taupo'ou) the tsunami heights were generally smaller and did not cause any significant damage and relatively little inland inundation.

The smaller tsunami hights on the north and northeast coast of Tongatapu can be attributed to the tsunami directivity, approaching from the west and hitting this coast obliquely. This area is also shadowed by Tongatapu's western peninsula and by a complex series of reefs and shallow areas to the north which acted to dissipate the tsunami energy.

Maximum runup heights were generally lower owing to the tsunami surge hitting this area indirectly after interacting with the built-up area and flowing over relatively flat topography.

3.2.1 Nuku'alofa

Buildings in the built-up areas of Nukualofa suffered damage typical for a tsunami of this size, that is, toppled walls made of unreinforced masonry (Figure 3.17) and the lower portions of walls being blown out (Figure 3.17.)

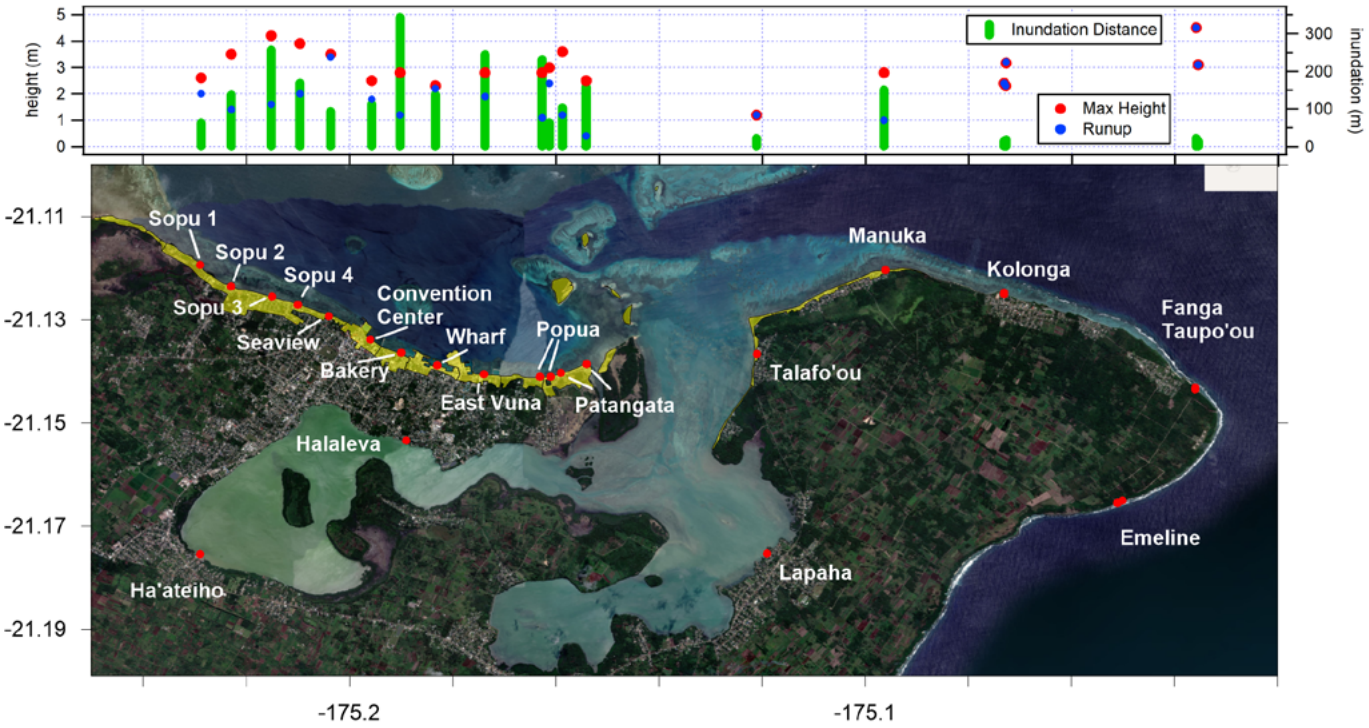


Figure 3.16. Maximum tsunami trace elevation (red) and run up height (blue) along the north coast of Tongatapu.

Figure 3.17 Toppled wall in Nuku'alofa. (Photos: Shane Cronin and TGS).

Figure 3.18 (top) Damaged house with the lower portion of that walls blown out, caused by the tsunami surge. (bottom) A coastal revetment and walkway in Nuku'alofa survived largely intact. (Photos: Shane Cronin and TGS).

Figure 3.19 Tsunami surge coming ashore on the grounds of the Royal Palace of Tonga in Nuku'alofa. Photo is taken from the government offices adjacent to the Vuna Wharf.

3.2.2 Atata and Fafa

Atata and Fafa are small islands located off the northern coast of Tongatapu (Figure 3.20). Due to their relatively exposed location, they were strongly affected by the tsunami waves. The low-lying peninsula protruding southward from Atata (Figure 3.21) was completely overtopped with tsunami heights of ~6 m (~4 m flow depth). Runup heights on the higher topography of the island were 6-8 m (Figure 3.22). The island of Fafa was (Figure 3.25) also completely overtopped, also with tsunami heights of 6-8 m flowing over the low-lying topography (Figure 3.26).

Figure 3.20 Location of Atata and Fafa, north of Tongatapu.

Figure 3.21 Locations surveyed on Atata. Before tsunami on left, after on right.

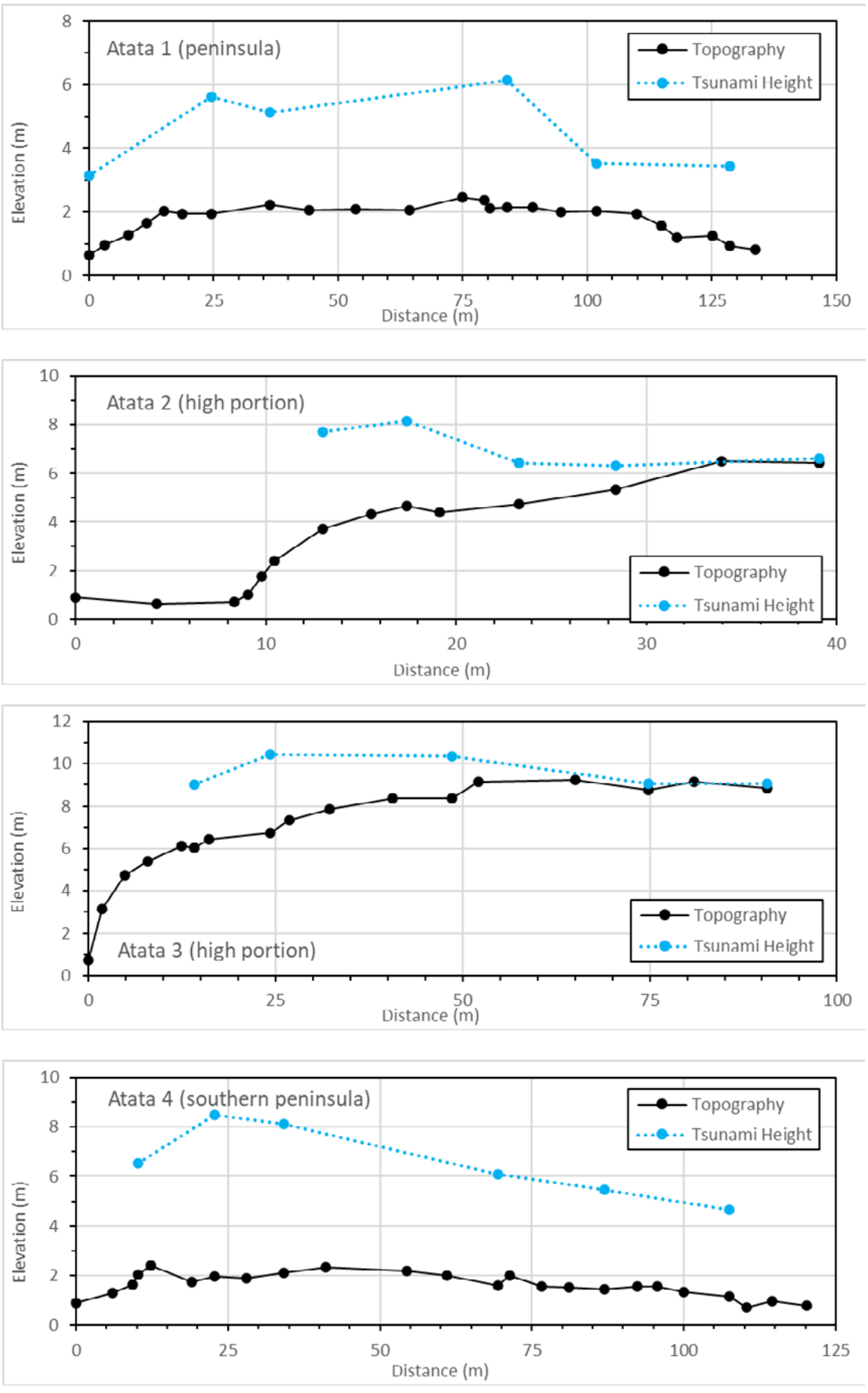


Figure 3.22 Profiles of measured topography and tsunami heights on Atata.

Figure 3.23 (top) The overtopped spit on Atata and (bottom) damage to structures on the island. (Photos: Taaniela Kula TGS).

3.2.2.1 Lisala Folau's Survival Story

Atata Island was the site of another remarkable tale of survival. This one by Lisala Folau a resident of Atata. The tsunami swept Mr. Folau out to sea at approximately 6 pm on Saturday and he was forced to swim and float on debris, before eventually making his way to the main island of Tongatapu at Sopu at 10 pm on Sunday night. Mr. Folau's path is shown in Figure 3.24 and the extended version of his story is reproduced from Facebook posts in Appendix I.

In his account, Mr. Folau describes an initial surge that alerted people on the island to the tsunami, prompting their evacuation. This was followed by a large surge approaching from the northwest that split around the island, wrapping around and meeting on the low peninsula protruding to the south (see Figure 3.21). This surge is described as being 7 m high and highly destructive destroying houses and washing across the island. Mr. Folau and others climbed a tree to escape this surge. After this, there was a period of calm with no waves when they came down from the tree and started to walk to higher ground, helping others to safety as well. After some time, as they were moving, they were alerted by others that another large wave was coming. This surge, also estimated at 6-7 m, washed Mr. Folau into the sea. He grabbed on to debris and floated near the island, hearing people calling for him, but he did not reply, for fear of putting them into danger. After this, he recalls another large surge taking him further from land. He floated through the night before landing on Toketoke around dawn. That morning, from land, He saw police boats going by, but they did not see him despite his signalling. Taking matters into his own hands, he used a piece of plywood as a float and essentially paddled along the shallow reef edge to Polo'a arriving there at dusk on Sunday to find the area abandoned. He carried on, making it to Sopu, west of Nuku'alofa by 10 pm Sunday night where he finally found help and made contact with his family.

Figure 3.24 Lisala Folau's path after being washed off Atata by a tsunami wave. He floated and swam for 28 hours before coming ashore at Sopu, west of Nuku'alofa.

Figure 3.25 Locations surveyed on Fafa. Before tsunami on left, after on right.

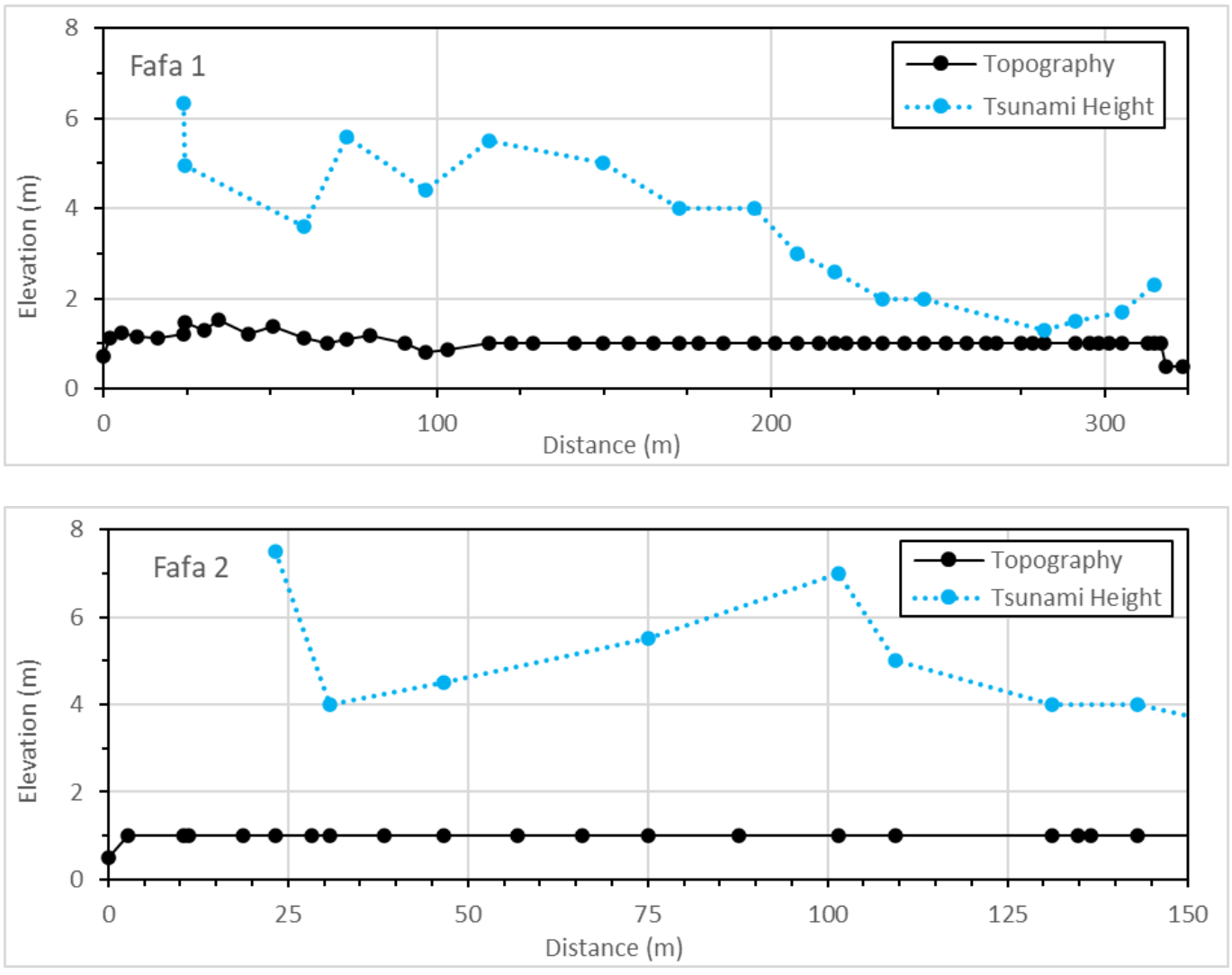


Figure 3.26 Profiles of measured topography and tsunami heights on Fafa.

3.2.3 East Coast Tongatapu

Two sites were visited on the east coast of Tongatapu, Emeline and Halaika (Figure 3.27). Despite these locations being on the sheltered eastern side of the islands runup height was of nevertheless more than 6 m with horizontal distances of 80 – 90 m at the southern site (Halaika) and ~20+ m at Emeline to the north (Figure 3.28).

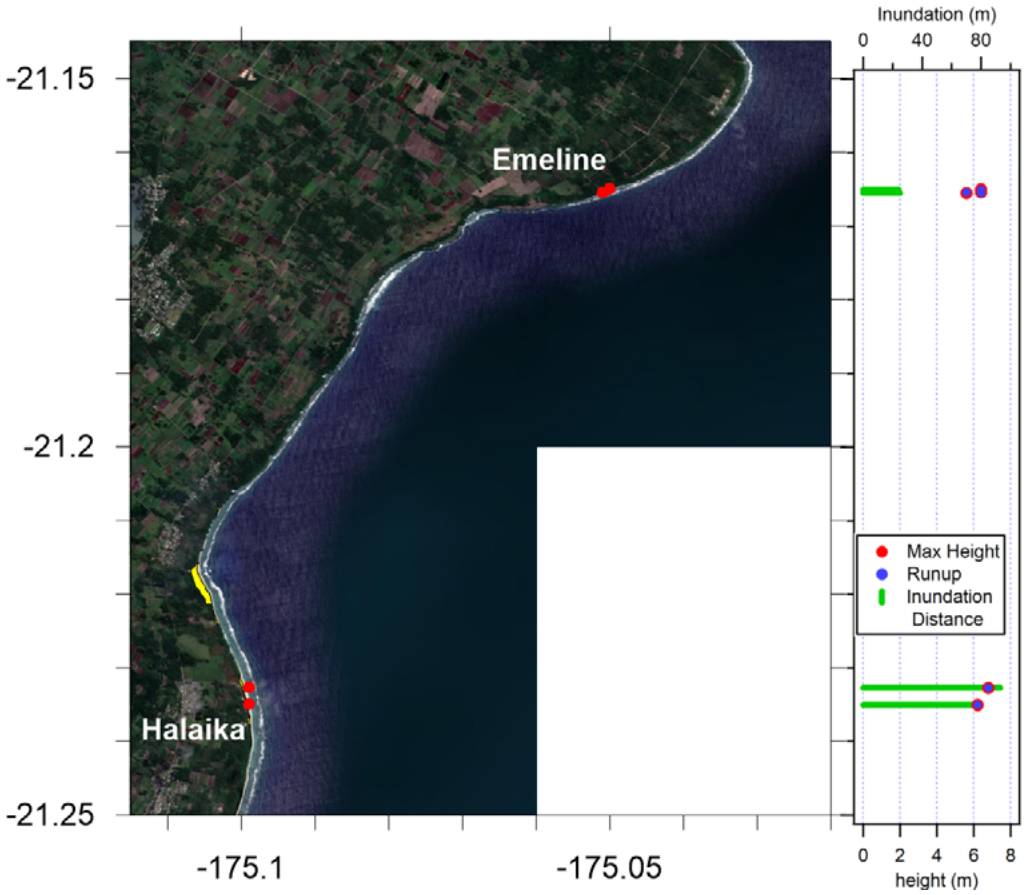


Figure 3.27 Sites surveyed on the east coast of Tongatapu. Right panel shows maximum tsunami height, runup height and inundation distance.

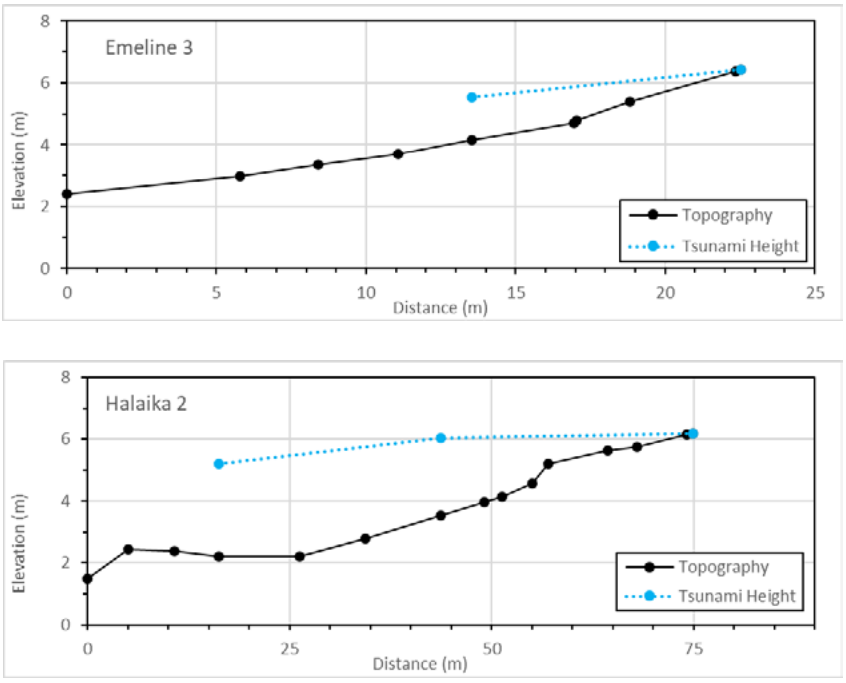


Figure 3.28 Representative transects of tsunami height and topography at Emeline (top) and Halika (bottom)

3.3 SOUTH COAST TONGATAPU

Tsunami flow and runup heights along the southern coast were greater than 10 m with >15 m runup measured at Fanga Piliki and Hufangalupe (Figure 3.29). Inundation distances were less than 100 m and as small as 15 m at one of the Katea sites owing to the steep cliff-backed topography there.

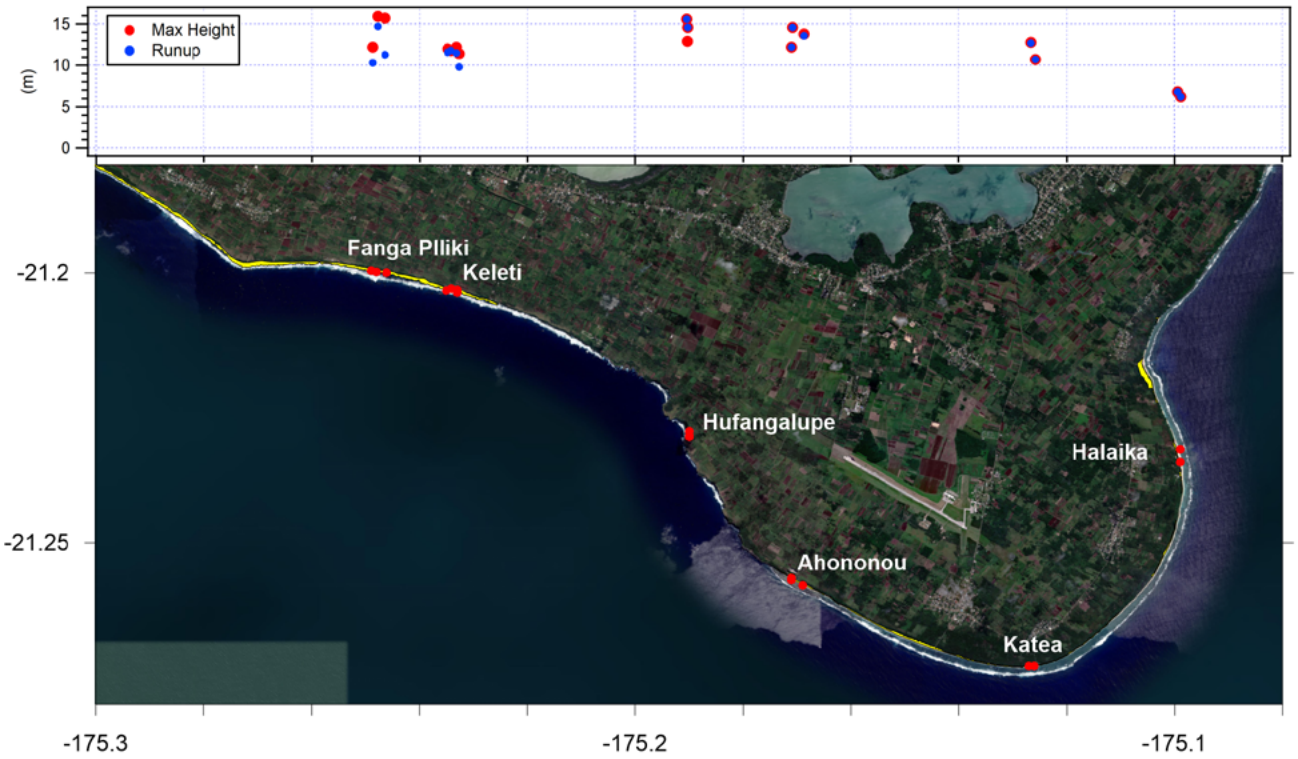


Figure 3.29 Sites surveyed along the southern coast of Tongatapu

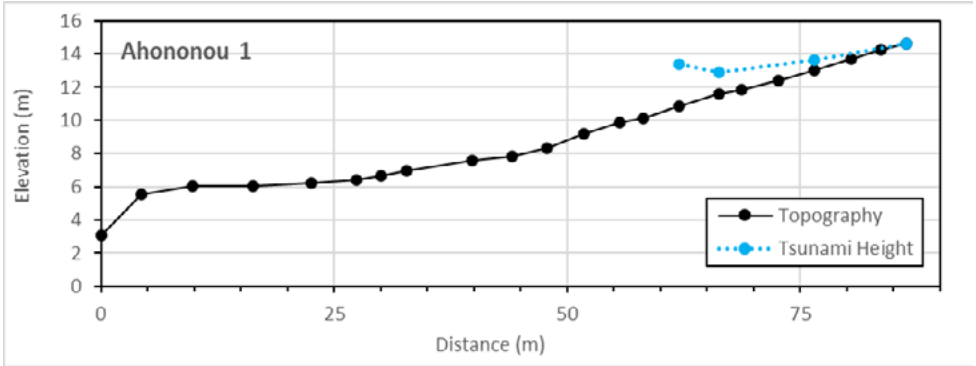


Figure 3.30 (top) Photo of Ahononou and (bottom) transect of topography and tsunami height. (Photos: Shane Cronin and TGS).

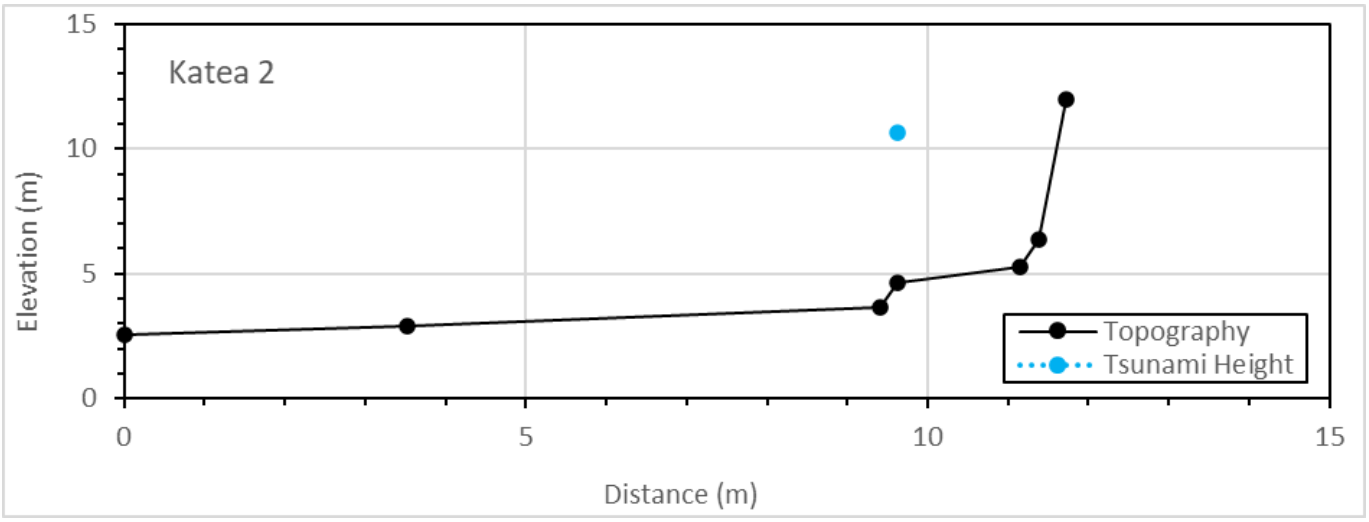


Figure 3.31 (top) Photo of Katea and (bottom) transect of topography and tsunami height. (Photos: Shane Cronin and TGS).

3.4 ʻEUA ISLAND

On Eua the survey was constrained to the central west coast. Tsunami runup heights were generally of the order of 4-8 m with one measurement up to 18 m.

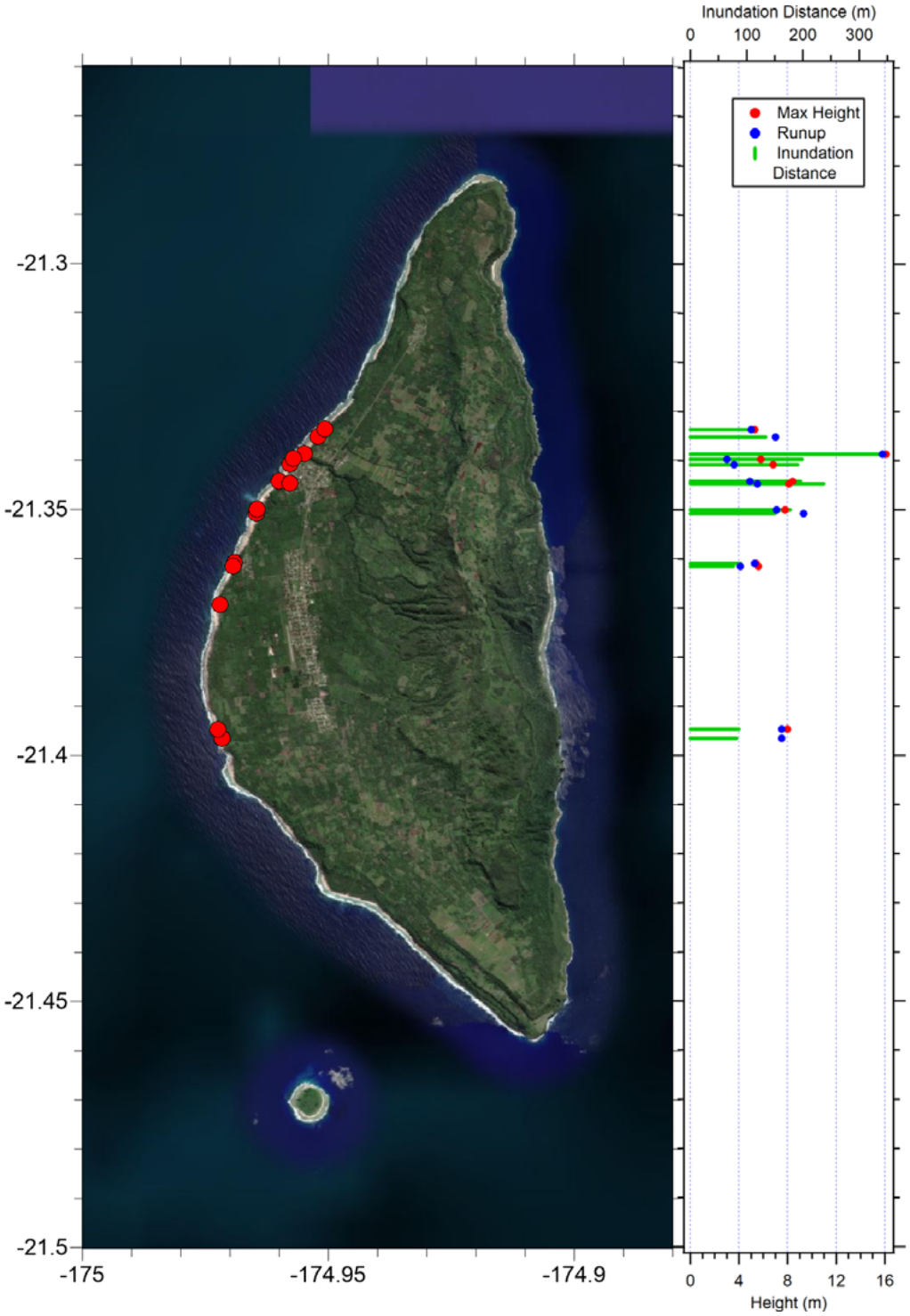


Figure 3.32 Measured runup, maximum tsunami height and inundation distance along the western coast of Eua Island.

3.5 NOMUKA AND SOUTHERN HA'APAI ISLANDS

The survey team visited the Nomuka and southern Ha'apai Islands on 18-19 April 2022. Transit to the island was by boat with the Tongan Navy. The team visited Tonumea, Mango, Fonoifua, Nomuka, Nomuka-Iki and Tungua islands as shown in Figure 3.33.While all the islands were affected, the strongest tsunami effects were seen on Nomuka-Iki, Mango and Tonumea Islands. Each of these islands as well as Kelefesia, which was not visited by the team, had sections of land that were completely over washed with the tsunami surge. The extreme inundation resulted in drastic changes to the coastal morphology and shape of these islands. Two of the three casualties caused by the tsunami occurred in this area, one on Nomuka (Maumi Lauaki) and one on Mango (Telai Tutu'ila, age 65) (Matai Tonga, 2022a,b, Reuters, 2022).

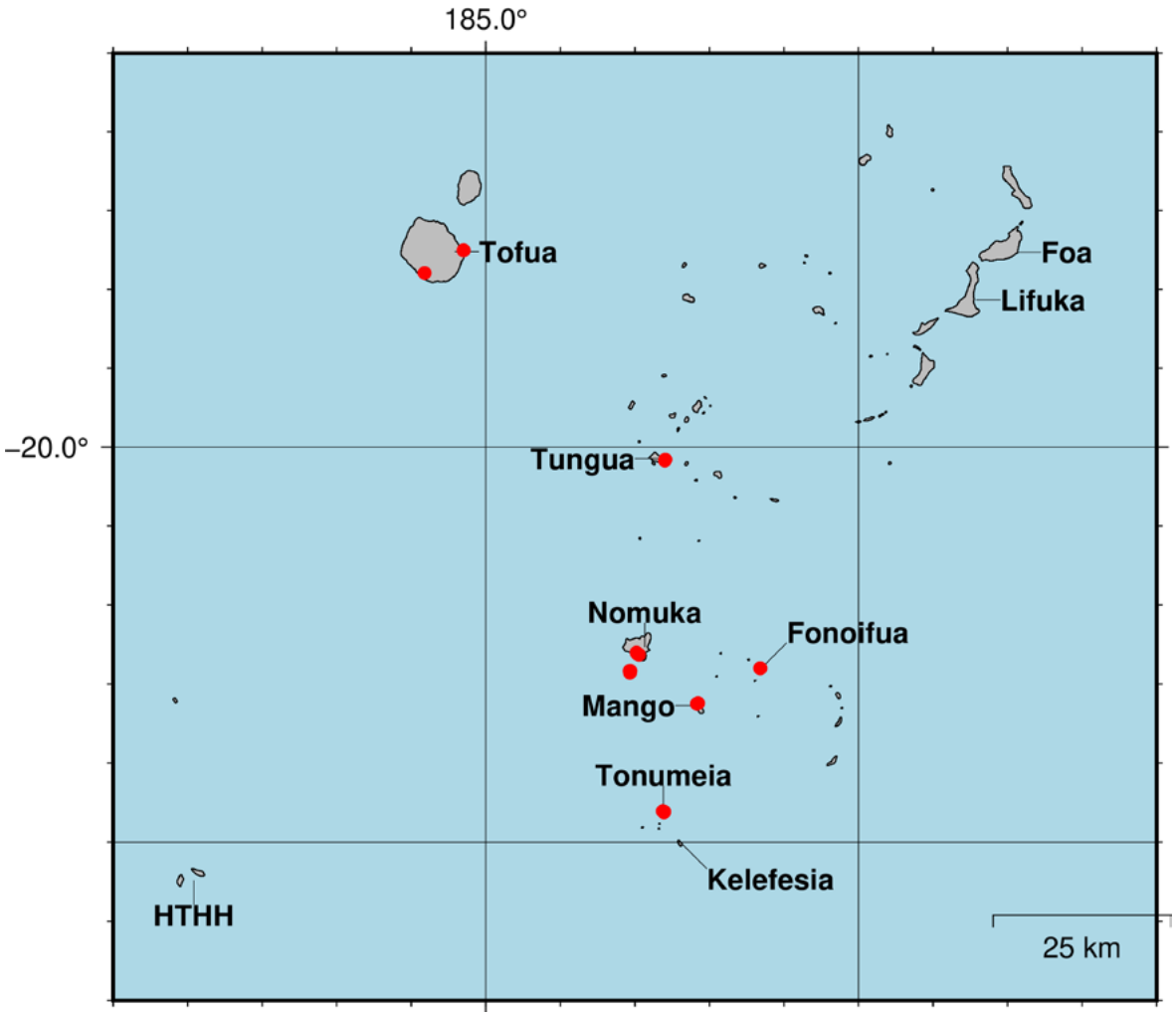


Figure 3.33 Locations visited in the southern Ha'apai Islands (red dots) and other locations for reference. Right panel shows maximum measured tsunami height at each location.

3.5.1 Tungua

The village on Tungua is located on the eastern side of the island away from the direction of approach of the tsunami. Furthermore, the island is surrounded by a relatively wide and shallow reef shelf (Figure 3.34) which would have acted to reduce tsunami impacts. Despite these factors, the tsunami inundated over 175 m inland and caused significant damage. Two profiles were measured at Tungua with flow depths of 1-3 m observed along the transect indicating a maximum total tsunami height of ~4 m. Damage on Tungua include a collapsed wood-frame building, concrete structures destroyed, a moved and damaged concrete water tank, damage to a solar panel array and boats damaged and pushed ashore.

Figure 3.34 Locations surveyed on Tungua. (Google Earth)

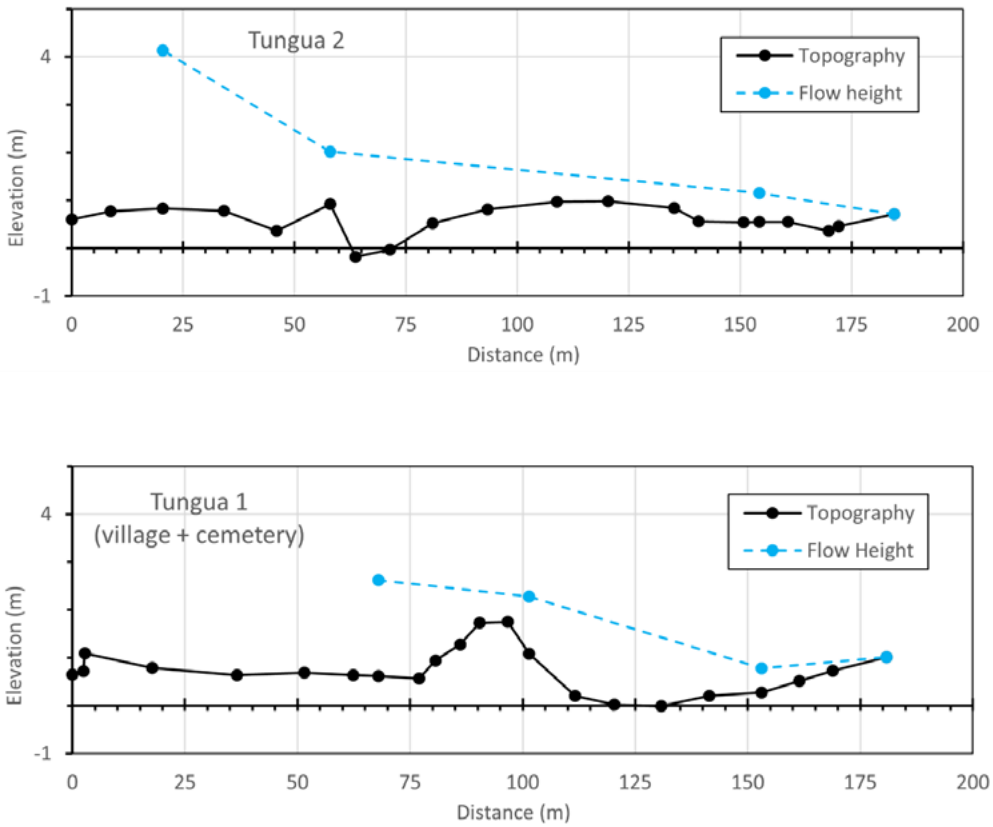


Figure 3.35 Profiles of measured tsunami height and topography at Tungua.

Figure 3.36 Tsunami damaged structure on Tungua. (Photos: Shane Cronin and TGS).

Figure 3.37 Tsunami damage on Tungua. (Photos: Shane Cronin and TGS).

3.5.2 Nomuka and Nomuka Iki

Nomuka and Nomuka Iki are located approximately 65 km northeast of Hunga Volcano. Although the tsunami strongly affected Nomuka, the presence of Nomuka Iki likely protected the village on Nomuka from the full force of the tsunami (Figure 3.38).

Figure 3.38 Nomuka and Nomuka Iki islands. The location of Nomuka Iki sheltered the village on Nomuka from the full brunt of the tsunami. (Google Earth)

In the village on Nomuka (Figure 3.39), tsunami flow traces were measured at up to 10 m near the shoreline on Profile 1 with tsunami heights more typically of the order of 4-6 m on the other three profiles (Figure 3.40). On Profile 3, the tsunami surge crossed over the land area and flowed into the small pond and surged across to the other side. Inundation distances ranged from 80 to more than 150 m. There was significant damage to some structures and several boats and vehicles were entrained in the surge and destroyed (Figure 3.41). The tsunami flow caused significant scour and erosion around building foundations (

Figure 3.39 Locations surveyed in Nomuka Village. (Google Earth)

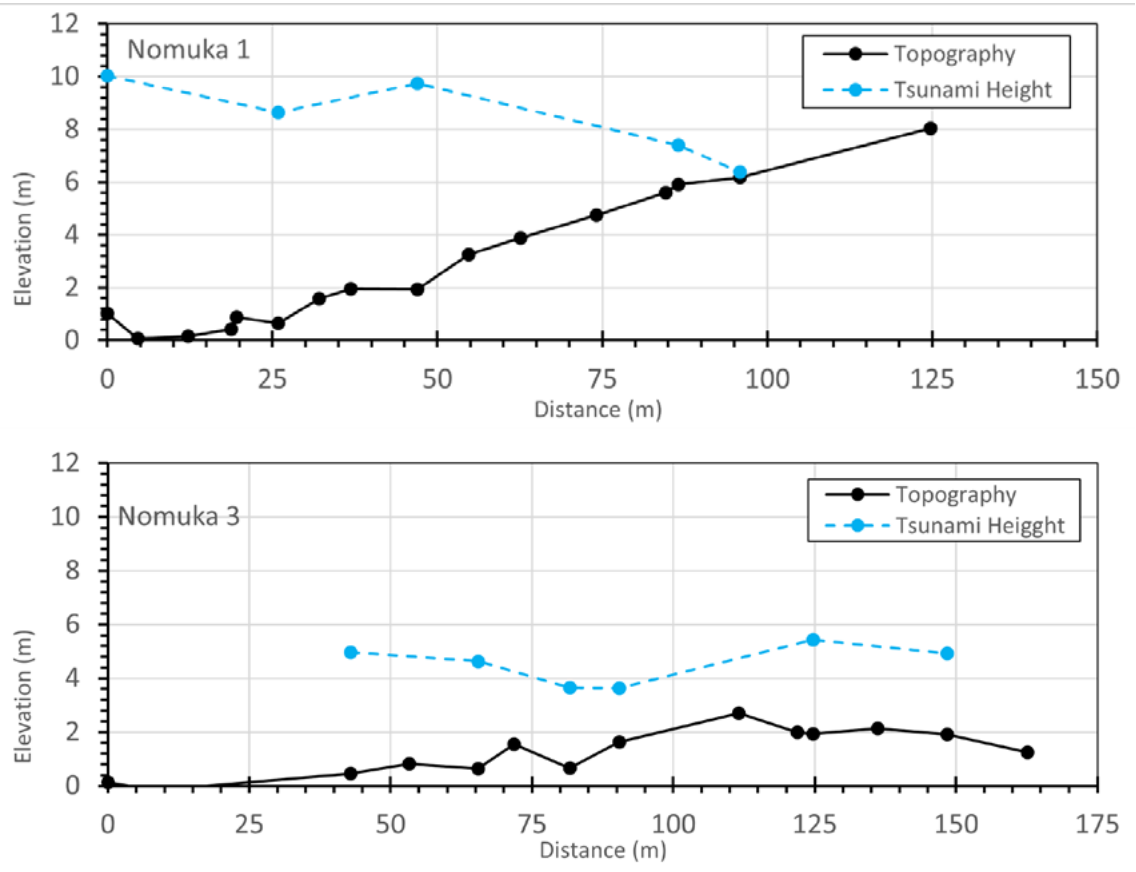


Figure 3.40 Surveyed profiles from Nomuka.

Figure 3.41 (top) Damaged boat (bottom) the inundated area. (Photos: Shane Cronin and TGS).

Figure 3.42 (top) Tsunami flow caused the damage to the lower portion of the walls and (bottom) scour around a building foundation. (Photos: Shane Cronin and TGS).

In contrast to Nomuka, Nomuka-Iki was affected by a much larger tsunami surge. The tsunami flowed across a broad flat area destroying a coastal forest with flow depths greater than 12 m. Measured runup was up to 20m along the face of a small hill located on the island (see Figure 3.44).

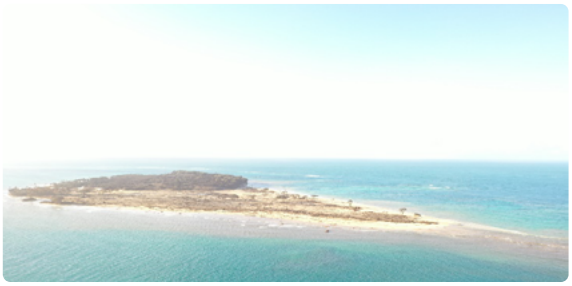


Figure 3.43 Locations of the profiles surveyed on Nomuka Iki. Profile 1 crossed the northern section of the island from southwest to northeast. Profile 2 ran towards the south from the flat area up onto a topographic high. The green line indicates the location of the cliff face along which runup was measured. Red arrow indicates the direction of tsunami approach. Inset photo shows Nomuka after the tsunami with the forest stripped away from the low-lying land area. (Google Earth and Taaniela Kula TGS)

Figure 3.44 View of Nomuka Iki from offshore. Note the broad flat coastal area with few trees (red arrows) on the right and the elevated area on the left. (Photos: Shane Cronin and TGS).

Figure 3.45 Tsunami over wash on Nomuka Iki stripped the coastal forest. Inset image shows impact scars on the tree trunk used to quantify the tsunami flow depth. (Photos: Shane Cronin and TGS).

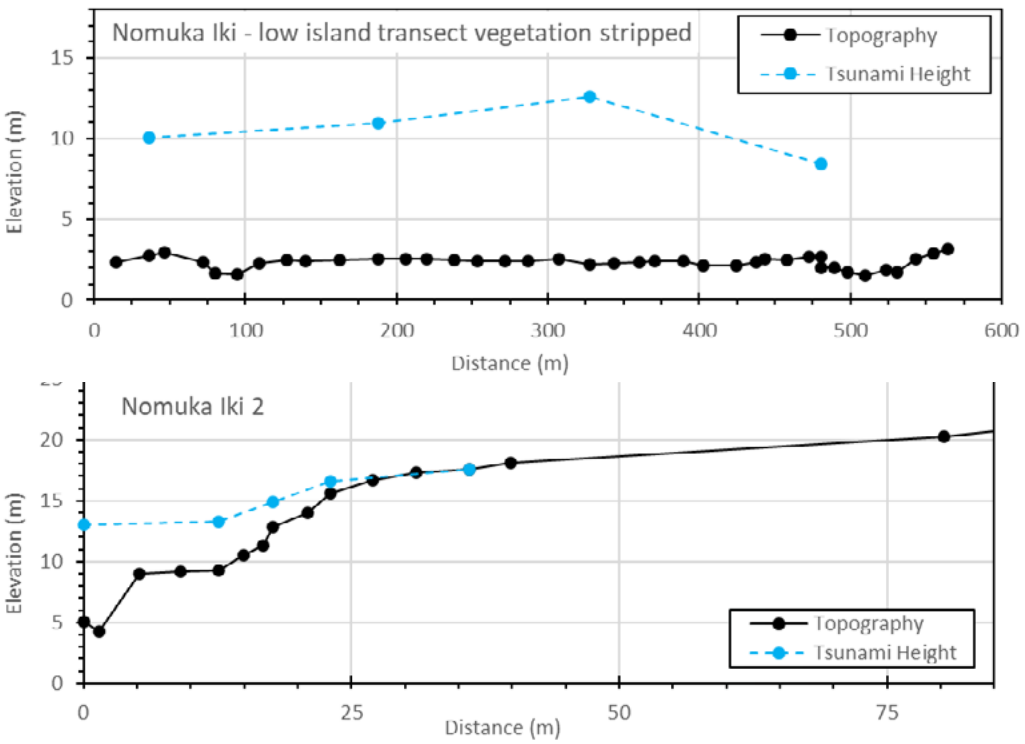


Figure 3.46 Profiles 1 and 2 from Nomika-Iki (see Figure 3.44).

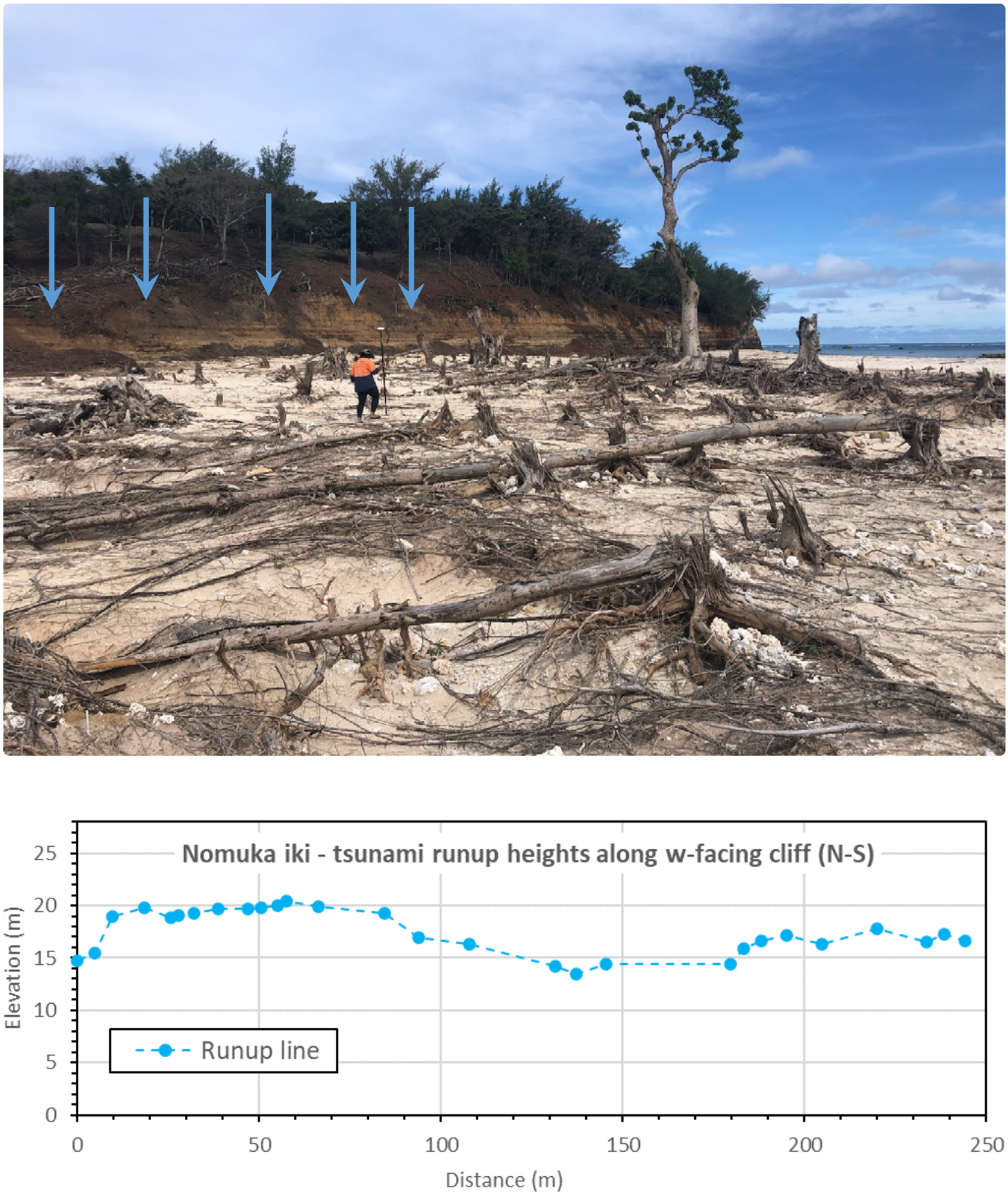


Figure 3.47 (top) The hillside on Nomuka Iki where the runup heights (bottom panel) were measured. Blue arrows indicate approximate tsunami runup height. (Photos: Shane Cronin and TGS).

3.5.3 Fonoifua

Two transects were surveyed on Fonoifua. Peak tsunami runup heights were measured at 2.9 m and 4.9 m on each transect.

Figure 3.48 Locations surveyed on Fonoifua Island. Google Earth)

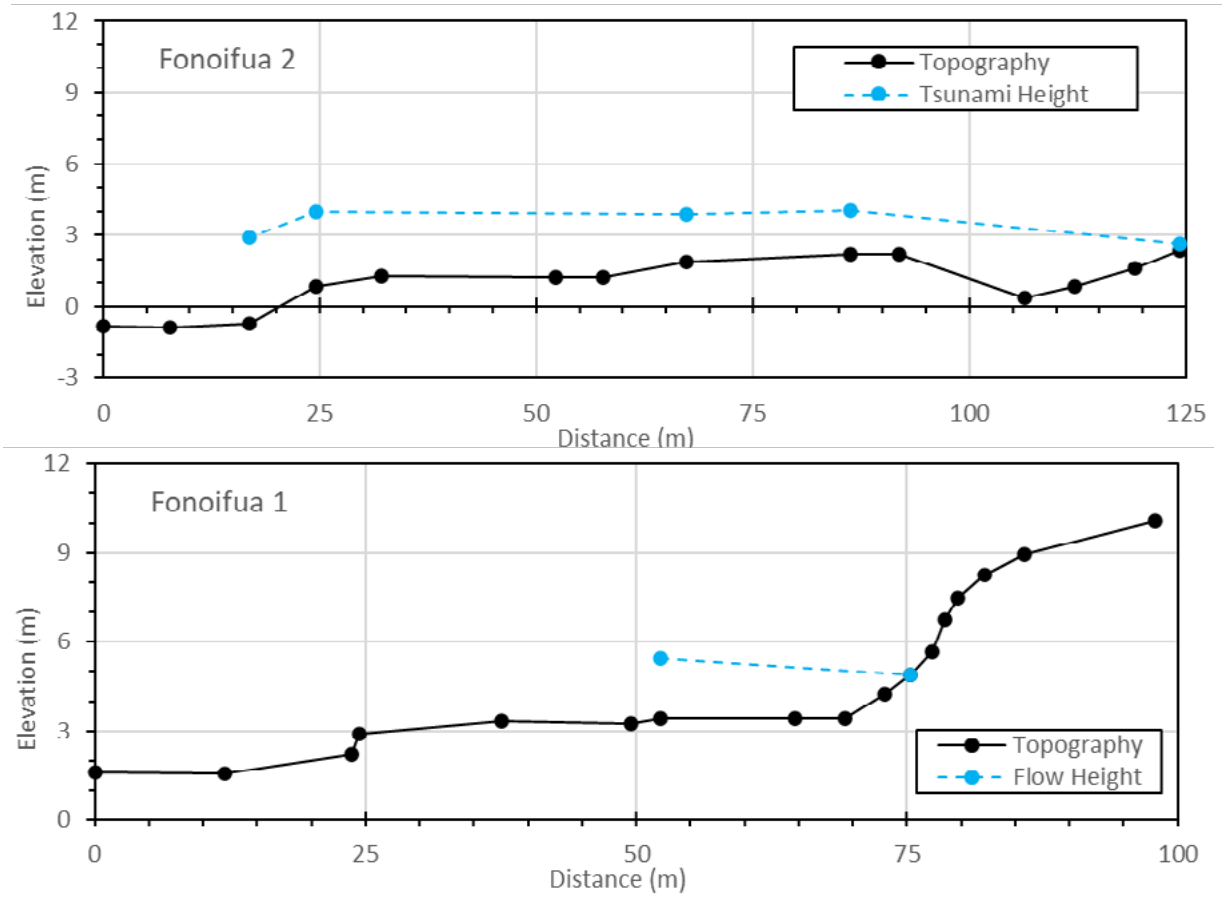


Figure 3.49 Transects for Fonoifua.

Figure 3.50 Tsunami damage on Fonoifua. (Photos: Shane Cronin and TGS).

3.5.3 Mango

Mango Island was heavily damaged by the tsunami with measured tsunami heights of just under 10 m from two transects taken in the village at the northern end of the island (Figure 3.51 and Figure 3.52). With the tsunami approach from the west, the village on the north coast was not protected as the wave wrapped around the island. It is also possible that the high tide allowed for stronger refraction and some amplification over the offshore reef platform on the north-western side of the island. News accounts report that all of the residents from Mango were evacuated to Tongatapu after spending the night outdoors. A detailed account of their ordeal was described in news reports (Matai Tonga, 2022b) and is reproduced in Appendix J.

Figure 3.51 Locations surveyed on Mango Island. Images from before the tsunami (left) and after (right). Red arrow indicates the direction of tsunami approach. The heavily damaged village on the north coast is circled in red and shown in more detail in Figure 3.53. Google Earth.

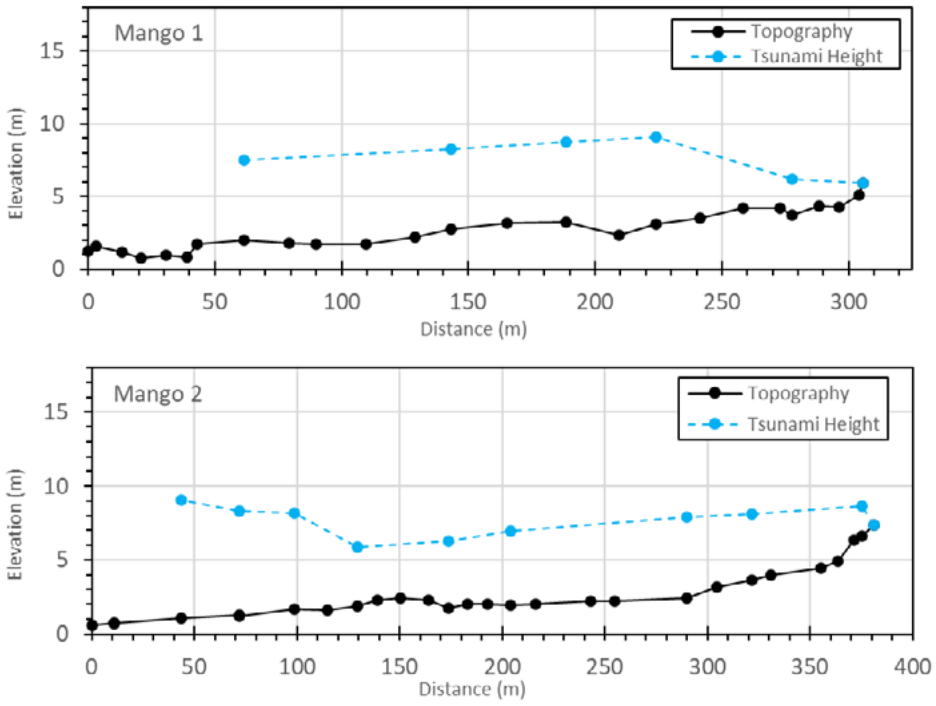


Figure 3.52 Tsunami height transects at Mango.

Figure 3.53 Aerial view of the damage to the Mango Village. The remains of the structure circled in red (lower panel) is shown at ground level in Figure 3.54. (Photos: Taaniela Kula TGS).

Figure 3.54 Tsunami damage on Mango Island. (Photos: Shane Cronin and TGS).

3.5.4 Tonumea

Tonumea Island (Figure 3.55) was strongly affected by the tsunami. Runup heights more than 10 m were measured on the steep face of a hill in the centre of the island (Figure 3.56, Figure 3.57). The tsunami completely washed over the low-lying fringe of land on the southern side of the island with flow depths of 6-8 m, toppling most of the trees and stripping away large areas of beach. Although not surveyed, aerial imagery from Google Earth suggests that similar effect occurred on the northern part of the island.

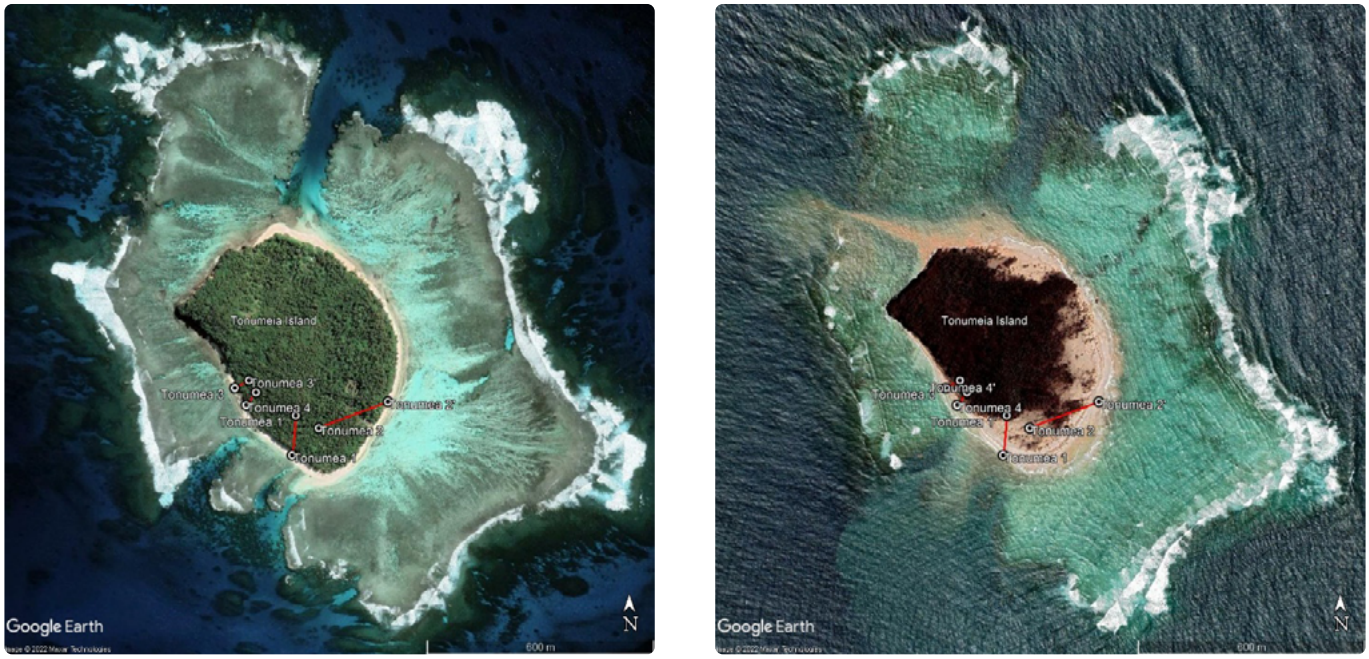


Figure 3.55 Survey locations on Tonumea Islands. Google Earth images from before the tsunami (left) and after (right). (Google Earth)

Figure 3.56 Photos from Tonumea Island. (Photos: Shane Cronin and TGS).

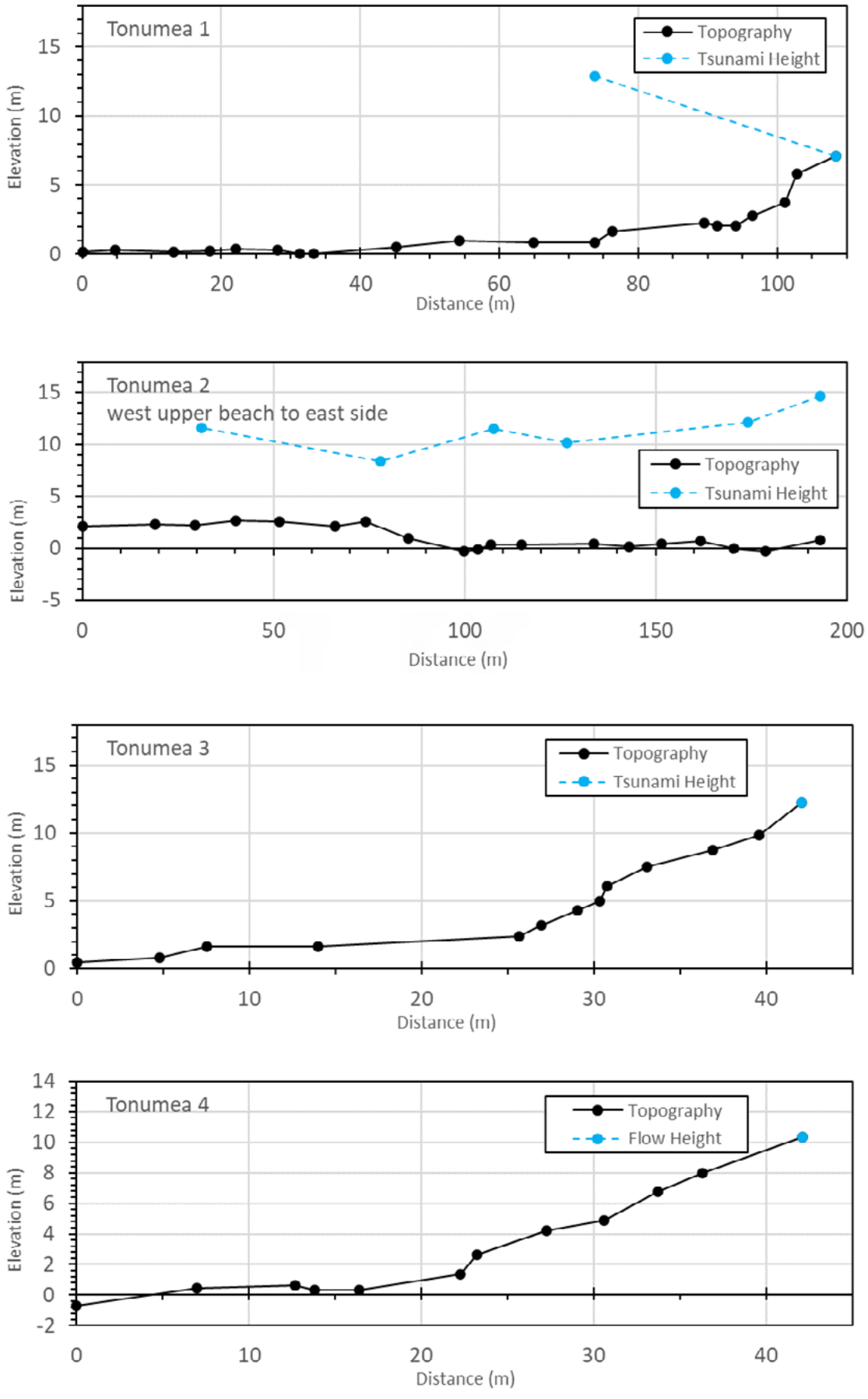


Figure 3.57 Transects from Tonumea.

3.5.5 Kelefesia

Due to time constraints, the survey team was not able stop at Kelefesia island. However Aerial imagery from Google Earth (Figure 3.58) shows that the island was heavily eroded and was changed significantly by the tsunami.

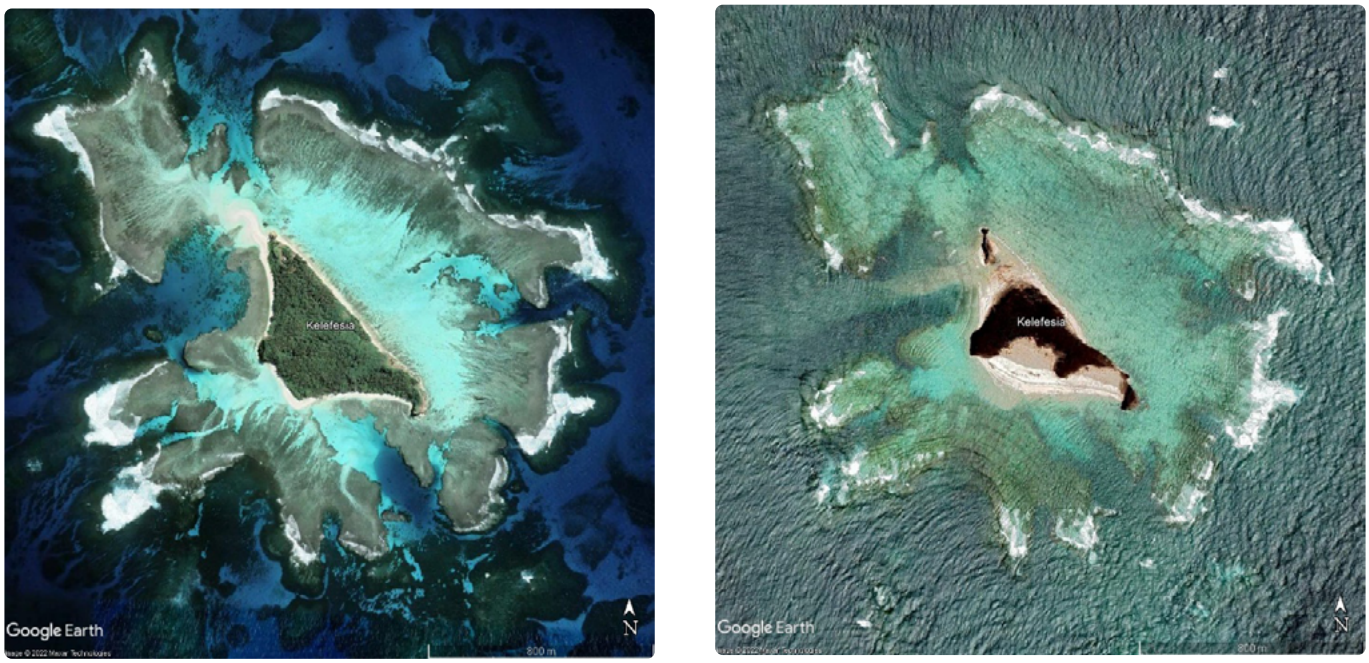


Figure 3.58 Google earth imagery of Kelefesia from before and after the tsunami. (Google Earth)

4.0 DISCUSSION

The tsunami caused by the eruption of the Hunga-Tonga Hunga Ha'apai volcano was an unprecedented event in the Pacific basin - this despite the large number of volcanoes present around the so-called 'Ring of Fire'. Its only historical analogue was the 1883 eruption of Krakatau in Indonesia which caused a similarly large and globally observed tsunami, albeit with a much higher death toll. Indeed, the extraordinarily low number of casualties given the extreme devastation caused by this tsunami is a marvel in itself. Below we discuss some of the factors that contributed to the low casualty rate.

4.1 TSUNAMI ARRIVAL TIMES

Tsunami arrival times along the coastline of Tonga were determined through numerical modelling by Lynett et al. (2022) using a nonlinear, dispersive hydrodynamic code. Their results predict tsunami travel times of ~8 minutes to Ha'atafu, ~26 minutes to the King's Palace/Vuna Wharf and ~28 minutes to the tide gauge on Queen Salote Wharf. The 26-minute arrival time, relative to a 0415 UTC source origin time, is plotted in Figure 1.11. In that plot we see that there is significant tsunami activity prior to the predicted arrival time. This suggests that tsunami waves were being generated by other mechanisms at the volcano prior to the large explosion at 0415 UTC. These early waves would have been generated at approximately 0400 UTC and arrived on the western facing beaches of northwest Tongatapu at 0408 UTC; seven minutes before 0415 UTC explosion occurred and 10 minutes before residents would have heard the explosion. This timing is consistent with the eyewitness accounts at this location described in Section 3.1.2.

One puzzling aspect of the tsunami arrival times is the timing of the destruction of the weather station at Kanokupolu. The station transmitted data until 6 pm local time (0500 UTC), as such it must not have been hit by the largest tsunami surge until after 6 pm. This is inconsistent with numerical models of the tsunami that generally predict one large surge on the west coast of Tongatapu occurring much earlier than 0500 UTC.

4.2 LOW NUMBER OF CASUALTIES

Despite the total destruction of several beach resorts along western Tongatapu and significant inundation along the populated northern coast, only three deaths were attributed to the tsunami. This low number of casualties can be attributed to multiple factors including: the event occurred during the day, the early arrival of moderate tsunami waves prior to the largest and most destructive wave, the low number of tourists in Tonga and the effectiveness of tsunami awareness education and outreach campaigns conducted in recent years.

The occurrence of the tsunami during daylight hours on a weekend afternoon likely helped to reduce the number of casualties. People would have been out and about, generally aware of their environment and able to react despite the lack of at least one of the normally discussed 'natural warnings' associated with tsunami disasters, i.e., strong ground shaking. This is in contrast to the effects of the 2010 southern Mentawai earthquake and tsunami, an event that occurred at night, during a period of unsettled and rainy weather. The causative earthquake was also anomalous in that it only caused weak ground shaking and residents did not generally feel the need to spontaneously evacuate. Ultimately a tsunami with heights greater than 10 m tore through numerous coastal villages and resulted in hundreds of deaths (Hill et al., 2012).

The early tsunami waves were also undoubtedly a mitigating factor for the residents of the western coast of Tongatapu. Based on information from eyewitnesses, the first waves arrived largely without warning. These waves were large enough to inundate the western beaches and penetrate to the boundaries of the coastal properties, but they did not cause extensive inundation or damage. It was the effect of these waves that prompted the locals into action to evacuate guests and staff from the resorts. Due to the quick response following the initial surges, by the time the larger and more destructive surge arrived the evacuation was well under wave allowing locals to get out of the area or to reach high ground or elevated vantage points.

A third mitigating factor was the near complete absence of international tourists in Tonga due to travel restrictions from the ongoing COVID-19 pandemic. Although resorts on the west coast were operating, they were at reduced capacity and catering only to domestic patrons. Despite this, the tsunami did occur on a weekend when domestic usage of beach and resort areas would have been higher, however as discussed able the afternoon/weekend timing of the event could have also helped to limit casualties.

Finally, the Government of Tonga and other international agencies can be credited with reducing tsunami casualties through their ongoing efforts of tsunami hazard mitigation through education and outreach. These efforts have been steadily increasing world-wide since the 2004 Indian Ocean tsunami and were significantly ramped up in Pacific Island nations following the 2009 Samoa-Tonga earthquake and tsunami. After the 2009 tsunami, which caused seven fatalities Niuatoputapu, Tonga, the Tonga Broadcasting Commission (TBC) produced a documentary and book (TBC and ITIC, 2013) sharing 55 survivor stories with artist drawings; these materials were made available to schools and the public as a reminder of the dangers of tsunamis. Additionally, education and outreach activities were conducted in association with World Tsunami Awareness Day (WTAD), designated as the 5th of November each year by the UN General Assembly. In Tonga, WTAD was commemorated through a series of educational and outreach initiatives just 2.5 months before the Hunga-Tonga event. Activities included art and poetry competitions and exhibitions in schools during the weeks preceding WTAD, discussions on Tongan radio stations, prayers and reminders during church services on the Sunday prior to WTAD and a series of activities on the day itself – although this event was held a week later due to a COVID lockdown that was in effect on November 5th. The rapid self-evacuation by large numbers of people after experiencing 'natural' warnings for tsunami was paramount in the small number of casualties. This behaviour was undoubtedly prompted in some capacity by the ongoing education and outreach activities.

4.3 RECOMMENDATIONS

The Kingdom of Tonga should continue to work aggressively towards mitigating tsunami hazards and raising tsunami awareness and education throughout the archipelago. Tonga is and always will be highly vulnerable to tsunami from both volcanic and tectonic origin. The Kingdom should continue to leverage international support to enhance tsunami education and outreach activities. While these efforts should continue to reinforce that while the volcanic tsunami threats are real and significant, earthquake generated tsunami remain a much more likely possibility. Historically only 2 of 30 tsunami events recorded in Tonga (prior to the 2022 Hunga event) were associated with volcanic sources, the rest were generated by earthquakes, from either distant or local sources (NGDC/WDC 2022). The population needs to be made aware that Tonga lies astride the enigmatic Tonga-Trench Subduction Zone and that earthquakes from this region have produced several tsunamis in historical times including the deadly and highly destructive Samoa-Tonga event of September 29, 2009. Future tsunamis from this source region would approach Tonga from the east and have the potential to produce highly destructive tsunami particularly on the east and north coasts of Tongatapu and the Ha'apai Islands. Awareness and recognition to evacuate immediately based on the natural tsunami warning signs are key for local tsunamis, which have made up approximately 1/3rd of Tonga's recorded tsunami events.

Despite efforts to increase public education and awareness on tsunami hazards in Tonga, one key message that may not have been effectively communicated however was to not evacuate by vehicle. Attempts to evacuate by vehicle were a compounding factor that resulted in increased tsunami deaths in Samoa after the September 2009 earthquake and tsunami. In that event, people attempting to evacuate by car encountered traffic congestion along roads running parallel to the coast and were subsequently swept away when the tsunami came ashore. (Okal et al., 2010, Fritz et al., 2011). The cruel irony was that safe ground was reachable on foot by simply running to the coastal hill slopes less than 500 m inland. Future tsunami education campaigns should continue to reinforce the need to heed natural warning signs – particularly those related to strong and long ground shaking or unusual fluctuations in water levels – while stressing the importance of moving as quickly as possible – without the use of vehicles - to high ground or inland.

In areas outside of Nuku'alofa this may be more practical given the existence of relatively high topography, however in Nuku'alofa, the low-lying topography and relatively densely populated area presents challenges for evacuation. The Kingdom of Tonga should consider the feasibility of vertical evacuation structures for the urbanised population centre of Nuku'alofa and develop these areas as part of a comprehensive tsunami evacuation strategy for the capital city.

The large number of photos and videos recorded and shared via social media presents an excellent opportunity for education and outreach. A program should be initiated to systematically collect and archive this material and to conduct additional interviews with survivors – particularly individuals from western Tongatapu and from the northern islands who experienced the strongest effects. These interviews can then be combined with the collected videos and imagery to produce high-quality, impactful media products such as posters, short videos and social media posts which can be used in Tonga and throughout the Pacific Region as part of tsunami awareness campaigns.

As discussed in Section 1.1, records of tsunami hazards in Tonga are dominated by tectonic sources, whether from nearfield events along the Tonga Subduction Zone to the east of the Kingdom or from far-field sources around the Pacific Ring of Fire. Modelling of tectonic tsunami sources from the Tonga Subduction Zone shows that the west coast of Tongatapu is less vulnerable to tsunami from these sources than the eastern or northern coasts (Borrero et al, 2021), however, as we have seen, the most affected area from this volcanically generated tsunami was western Tongatapu.

That there have been unexplained destructive wave events along the western beaches of Tongatapu in the past raises questions about the frequency of tsunami generated from volcanic or other sources (i.e., submarine landslides) and suggests that western Tongatapu may have a greater tsunami hazard than is presently appreciated.

This in turn raises questions about rebuilding of resorts, residential areas and social infrastructure. Such projects should be based on sound environmental assessments and structural engineering designs that will minimise risk from equivalent impacts. Furthermore, such proposed reconstruction should be submitted under the Spatial Planning Act 2012 to obtain Development Consent. Hazard Zones should be redefined for all areas in the Kingdom and relevant development consent procedures be enforced.

5.0 CONCLUSIONS

On January 15, 2022, the eruption of the Hunga volcano generated a series of massive tsunamis causing large-scale destruction along the western shores of several Tongan Islands. The tsunamis were likely generated by a combination of sources including evacuation of water by explosive eruptions, flank collapse, pyroclastic density currents entering the water, caldera collapse and atmospheric pressure waves radiating out from the volcanic explosion. These sources combined to produce a highly complex tsunami with catastrophic effects in the near field as well as unusually persistent and damaging effects at distant locations around the Pacific and Atlantic Oceans.

A quantitative survey of tsunami runup and inundation in affected areas of Tonga by international scientists was impossible due to travel restrictions due to the ongoing COVID-19 pandemic. The Government of Tonga officially first requested in-person technical assistance to Australia, New Zealand, and the ITIC to conduct post-tsunami inundation assessments. When this was not possible, New Zealand, the USA, and SPC sent in lieu surveying equipment to assist the Tonga government officials in collecting the data. Additionally, the ITIC requested to the Pacific Community (SPC) to engage an experienced international tsunami scientist to provide remote training and assistance to Tongan officials on post-tsunami field data collection techniques and to compile the results of a series of surveys into a technical report. Serendipitously, a volcanologist from the University of Auckland was permitted entry to Tonga in early March 2022 for an extended mission to conduct field investigations related to understanding ongoing volcanic threats and this researcher took part in the effort by coordinating surveys and overseeing training and tsunami field surveys with local scientists and staff from the Tongan Geological Services (TGS).

On Tongatapu, the survey recorded a peak tsunami height of approximately 19 m on the western coast of the Hihifo Peninsula near Liku'alofa. Around Tongatapu, tsunami heights were generally in excess of 15 m along the west coast, 2-4 m on the north coast, 10-15 m on the south coast and ~7 m on the east coast. On the west coast of 'Eua tsunami heights were of the order of 5-10 m while the Nomuka and southern Ha'apai Islands, tsunami heights ranged from 5-20 m. The largest measured tsunami height from these surveys was tsunami runup along a cliff face at Nomuka-Iki island where a height of 20.5 m was recorded amongst several flow marks in excess of 13 m.

Inundation extents were in excess of 100 m where the tsunami surge crossed the Hihifo Peninsula but were more generally of the order of 200 m in the west and 100-200 m in Nukualofa. Shorter inundation distances were measured along the southern coast where steeper, cliff-like topography is prevalent.

The tsunami was recorded on two tidal stations in Nuku'alofa. While the primary station failed during the tsunami, a full record of the tsunami was captured on a second station located 2 km to the west. This gauge recorded a peak tsunami height of 1.2 m at 0446 UTC (5:46 PM local time). The gauge also captures the signal of tsunami waves affecting the coast of Tongatapu that were generated prior to the large explosion which occurred at 0415 UTC and is believed to be the source of the largest tsunamis. These early waves were experienced by witnesses on the west coast of Tongatapu as two distinct

surges that inundated over the beach and up to the shoreward property lines and served as an unintentional early warning for people to evacuate the area immediately. Fortunately, everyone in the area did evacuate the beach front prior to the arrival of the largest surge a few minutes later, overtopping section of the peninsula and causing complete destruction of the numerous beach resorts along the coast there.

While this event can serve as an unambiguous 'teachable moment' for the hazard presented by volcanically generated tsunami, this should not be done at the expense of continued vigilance against tsunami generated from the Tonga Trench Subduction Zone to the east. Given the relative frequency of earthquake generated tsunamigenic events in the region, the Tonga Trench presents a much greater hazard relative to volcanic sources. In contrast to this event, tsunami generated on the Tonga Trench will cause impacts that are more severe on the eastern and northern coasts of Tongatapu and the eastern coasts of the islands to the north. As such tsunami hazard mitigation efforts should be reinforced in these areas and use the lessons learned from the recent event to educate residents of the likely effects if a large-scale tectonic tsunami were to occur.

6.0 ACKNOWLEDGEMENTS

The authors would like to acknowledge the people of Tonga who suffered during and after this unfortunate event. The production for this report was funded by the Secretariat of Pacific Communities (SPC). Professor Shane Cronin's mission to Tonga was supported by the University of Auckland, the Kingdom of Tonga and the New Zealand High Commission to Tonga (special thanks to Peter Lund). Litea Biukoto (SPC) and Jiuta Krovulavula (UNESCO) provided invaluable logistical and administrative support. Liz Sullivan (Waterfront Lodge) provided vital local logistical support for Cronin in the field amidst COVID-19 lockdowns and post-disaster disruption. The Nuku'aofa tide gauge data 'nkfa2' is part of the Australian Aid 'Climate and Oceans Support Program in the Pacific' (COSPPac) and was made available by Jeff Aqualina of the Pacific Sea Level and Geodetic Monitoring (PSLGM) and the Australian Bureau of Meteorology (BoM). Anurah Chandra of NIWA provided information on the Kanokupolu weather station. Nic Arcos (NOAA NCEI/WDS for Geophysics) confirmed information on the tsunamis affecting Tonga.

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APPENDIX A. DATA TABLES

Table 7.1 Tsunami runup, maximum tsunami heights and inundation distances on Tongatapu.

Site	Long.	Lat.	Runup (m)	Max Elev. (m)	Inund. Dist. (m)	Comment
TONGATAPU						
Atata 1	-175.25458	-21.05021		6.1	>134	Crossed entire peninsula 134 m distance
Atata 2	-175.25590	-21.04887	6.6	8.2	39.0	
Atata 3	-175.25733	-21.04630	9.1	10.5	91.0	
Atata 4	-175.25610	-21.05333		8.5	>120	Crossed entire peninsula
Fafa 1	-175.16006	-21.08732		6.3	>330	Crossed entire island
Fafa 2	-175.16013	-21.08708		7.5	>200	Crossed entired island - wave reinforced from two directions
Ha'atafu 1	-175.33282	-21.06721	14.9	16.7	117.0	
Ha'atafu 2	-175.33355	-21.06851	13.1	15.5	132.0	
Otuhaka	-175.33987	-21.07553		14.3	880.0	Passed from east to west across peninsula
NIWA/Weather Station	-175.34132	-21.07722		17.5	706.0	Passed from east to west across peninsula
Likualofa	-175.34516	-21.08161		18.7	1120.0	Passed from east to west across peninsula
Kolowai	-175.35609	-21.09531	14.8	16.9	218.0	
Samaletane 1	-175.35579	-21.09608	14.4	18.4	179.0	
Samaletane 2	-175.35549	-21.09695	14.3	14.7	180.0	
Samaletane 3	-175.35483	-21.09863	13.0	14.7	166.0	
Utukehe 1	-175.34799	-21.12366	16.7	16.7	253.0	
Utukehe 2	-175.34774	-21.12456	16.6	12.8	230.0	
Kala'au 1	-175.34502	-21.13716	12.7	16.3	216.0	
Kala'au 2	-175.34537	-21.13576	11.9	14.7	195.0	
Fanga Piliki 1	-175.24876	-21.19962	10.3	12.2	71.0	

Site	Long.	Lat.	Runup (m)	Max Elev. (m)	Inund. Dist. (m)	Comment
TONGATAPU						
Fanga Piliki 2	-175.24778	-21.19983	14.7	15.9	83.0	
Fanga Piliki 3	-175.24637	-21.19997	11.3	15.7	80.0	
Keleti 1	-175.23484	-21.20315	11.6	12.0	47.0	
Keleti 2	-175.23415	-21.20294	11.8	11.8	57.0	
Keleti 3	-175.23313	-21.20309	11.5	12.2	44.0	
Keleti 4	-175.23266	-21.20361	9.8	11.4	70.0	
Hufangalupe 1	-175.19048	-21.23039	15.6	15.6	40.0	
Hufangalupe 2	-175.19037	-21.22933		12.9	13.0	
Hufangalupe 3	-175.19032	-21.23013	14.6	14.6	14.0	
Ahononou 1	-175.17081	-21.25691	14.6	14.6	86.0	
Ahononou 2	-175.17103	-21.25663	12.2	12.2	106.0	
Ahononou 3	-175.16877	-21.25793	13.6	13.8	67.0	
Katea 1	-175.12662	-21.27294	12.7	12.8	13.0	
Katea 2	-175.12574	-21.27276	10.7	10.7	12.0	
Halaika 1	-175.09944	-21.23269	6.8	6.8	93.0	
Halaika 2	-175.09886	-21.23504	6.2	6.2	75.0	
Emeline 1	-175.05101	-21.16539	6.4	6.4	24.0	
Emeline 2	-175.05126	-21.16546	5.6	5.6	24.0	
Emeline 3	-175.04981	-21.16502	6.4	6.4	25.0	
Fanga Taupo'ou 1	-175.03595	-21.14310	4.5	4.5	22.0	
Fanga Taupo'ou 2	-175.03556	-21.14348	3.1	3.1	14.0	
Kolonga 1	-175.07281	-21.12499	2.3	2.3	13.0	
Kolonga 2	-175.07277	-21.12502	3.2	3.2	18.0	
Kolonga 3	-175.07314	-21.12481	2.4	2.4	14.0	
Manuka	-175.09645	-21.12041	1.0	2.8	150.0	
Talafo'ou lagoon	-175.12118	-21.13663	1.2	1.2	22.0	eyewitness

Site	Long.	Lat.	Runup (m)	Max Elev. (m)	Inund. Dist. (m)	Comment
TONGATAPU						
Lapaha (lagoon)	-175.11855	-21.17528	0.9	0.9	12.0	eyewitness
Ha'ateiho (lagoon)	-175.22920	-21.17554	0.4	0.2	1.0	eyewitness
Halaleva (Lagoon)	-175.18917	-21.15344	0.7	0.7	3.0	eyewitness
Patangata 1	-175.15416	-21.13865	0.4	2.5	158.0	eyewitness
Patangata 2	-175.15874	-21.14032	1.2	3.6	102.0	eyewitness
Popua - North 1	-175.16267	-21.14112	1.1	2.8	230.0	
Popua - North 2	-175.16129	-21.14095	2.4	3.0	63.0	
Nukualofa Seaview	-175.20365	-21.12926	3.4	3.5	93.0	eyewitness
Nukualofa Convention	-175.19570	-21.13377	1.8	2.5	112.0	eyewitness
Nukualofa Villa/Bakery	-175.19025	-21.13640	1.2	2.8	343.0	eyewitness
Nukualofa Wharf	-175.18336	-21.13879	2.2	2.3	138.0	eyewitness
Nukualofa East Vuna	-175.17372	-21.14062	1.9	2.8	244.0	
Sopu 1 - West	-175.22880	-21.11935	2.0	2.6	63.0	eyewitness
Sopu 2	-175.22294	-21.12358	1.4	3.5	137.0	eyewitness
Sopu 3	-175.21522	-21.12551	1.6	4.2	256.0	eyewitness
Sopu Captain Cook	-175.20963	-21.12705	2.0	3.9	168.0	eyewitness
Nukunuku	-175.29567	-21.12463	1.2	0.3	3.0	
Te'ekiu	-175.31586	-21.11967	2.2	0.6	29.0	eyewitness

Table 7.2 Tsunami runup, maximum tsunami heights and inundation distances in the northern islands.

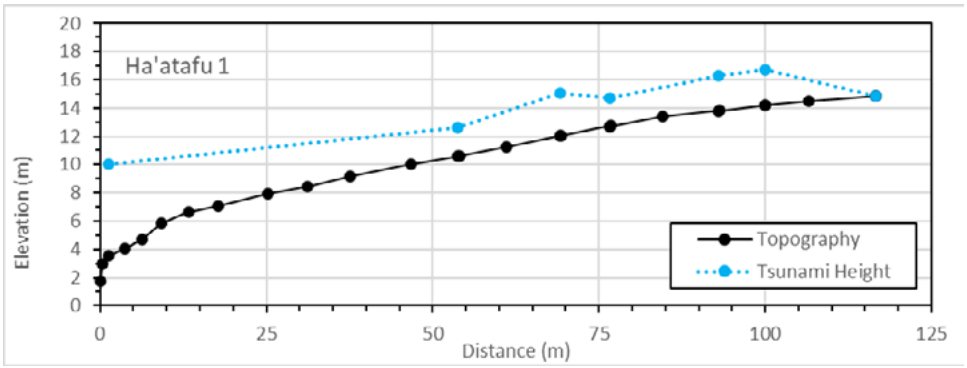
Site	Long.	Lat.	Runup (m)	Max Elev. (m)	Inund. Dist. (m)	Comment
HA'APAI						
Nomuka iki cliff	-174.80653	-20.28584	20.5	20.5		Flow heights measured along cliff (variable wave edge) 13.5-20.5
Nomuka iki 1	-174.80712	-20.28382		12.6	565.0	Flowed across the low forested part of the island (stripped forest)
Nomuka iki 2	-174.80629	-20.28358	17.5	17.5	115.0	
Tonumea 1	-174.76109	-20.46245	7.1	12.9	108.0	
Tonumea 2	-174.76042	-20.46180		14.6	>193	Flowed across peninsula and two waves met
Tonumea 3	-174.76255	-20.46085	12.2	12.2	42.0	
Tonumea 4	-174.76226	-20.46126	10.3	10.3	45.0	
Nomuka 1	-174.79465	-20.26324	6.4	10.0	125.0	
Nomuka 2	-174.79542	-20.26281	5.0	7.3	141.0	
Nomuka 3	-174.79658	-20.26212		5.4	163.0	Passed through the village into the lake behind
Nomuka 4	-174.79785	-20.26051	5.9	6.6	75.0	
Mango 1	-174.71530	-20.32444	7.5	9.1	306.0	
Mango 2	-174.71682	-20.32512	7.4	9.1	380.0	
Fonoi 1	-174.63166	-20.28020	4.9	5.4	98.0	
Fonoi 2	-174.63192	-20.28030	2.6	4.0	124.0	
Tungua 1	-174.75969	-20.01728	1.0	2.6	181.0	
Tungua 2	-174.75919	-20.01580	0.7	4.1	185.0	
Tofua East 1	-175.02990	-19.75069	14.0	14.0	30.0	Measured via pole and pace
Tofua East 2	-175.02992	-19.75031	16.0	16.0	30.0	Measured via pole and pace
Tofua SW 1	-175.08223	-19.77932	20.6	20.6	54.5	Measured via pole and pace
Tofua SW 2	-175.08223	-19.77932	22.0	22.0	35.0	From GPS

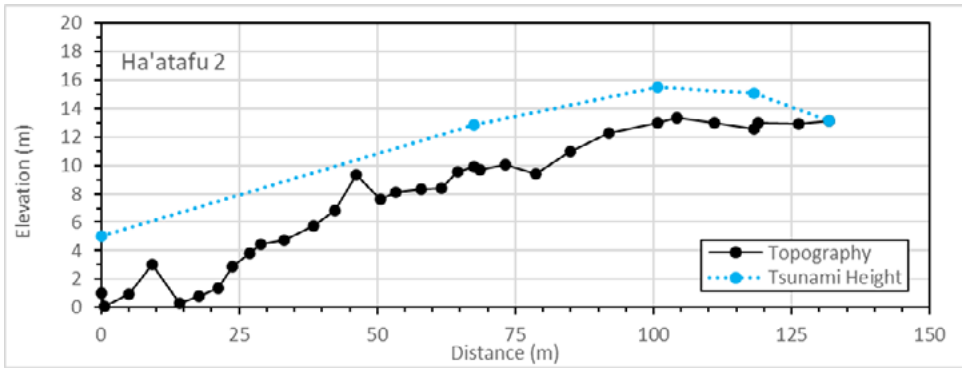
Table 7.3 Tsunami runup, maximum tsunami heights and inundation distances on Eua..

Site	Long.	Lat.	Runup (m)	Max Elev. (m)	Inund. Dist. (m)	Comment
EUA						
Blue Water Retreat 1	-174.96908	-21.36090	5.3	5.4	89.4	
Blue Water Retreat 2	-174.96936	-21.36151	4.1	5.6	76.2	
Ohonua Trench	-174.95495	-21.33871	15.8	16.1	342.8	end of transect, but not end of inundation. Couldn't continue along path
Ha'atu'a 1	-174.97163	-21.39650	7.5	7.5	82.2	log pile at runup
Ha'atu'a 2	-174.97247	-21.39468	7.5	8.0	86.3	debris pile
Ohonua 2	-174.95780	-21.34080	3.6	6.8	191.1	
Ohonua 1 -1	-174.95999	-21.34422	4.9	8.4	195.8	
Ohonua 1-2	-174.95787	-21.34473	5.5	8.1	237.2	
Ta'anga 1	-174.95214	-21.33521	7.0	7.0	133.5	
Ta'anga 2	-174.95068	-21.33369	5.0	5.3	102.5	
Tufuvai 1	-174.96470	-21.35079	9.3	9.3	149.8	
Tufuvai 2	-174.96448	-21.34999	7.1	7.8	177.7	debris pile on huge coral terrace
Ohonua 3	-174.95709	-21.33970	3.0	5.8	198.7	

APPENDIX B. TONGATAPU WEST COAST PROFILES

Ha'atafu





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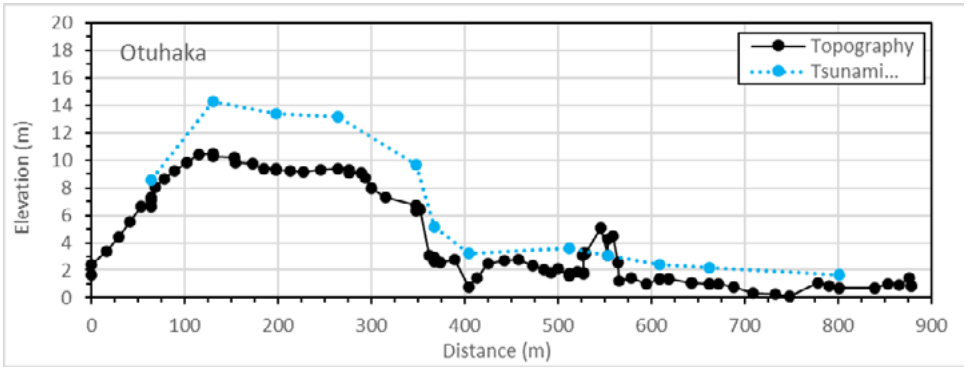
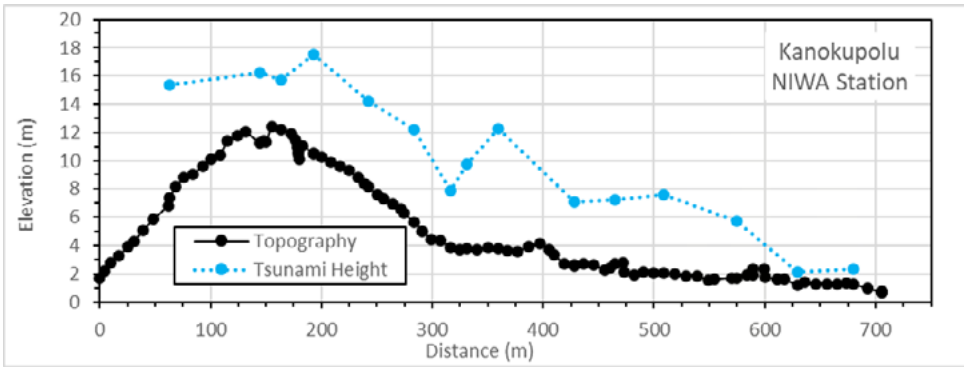
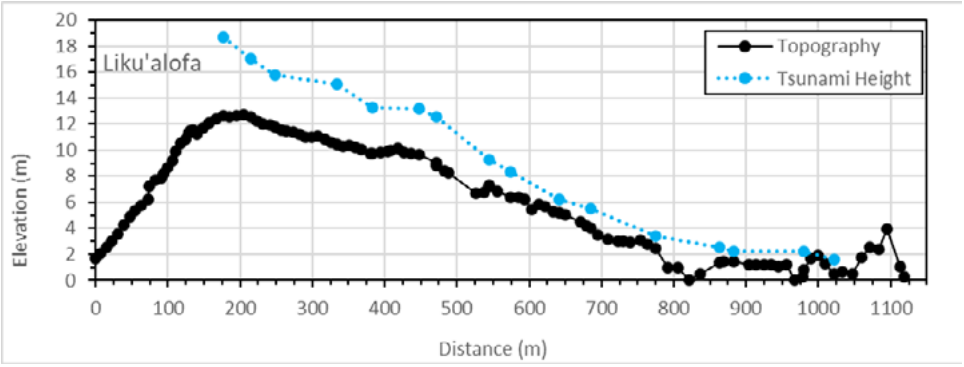


Kanokupolu NIWA Station



Liku'alofa



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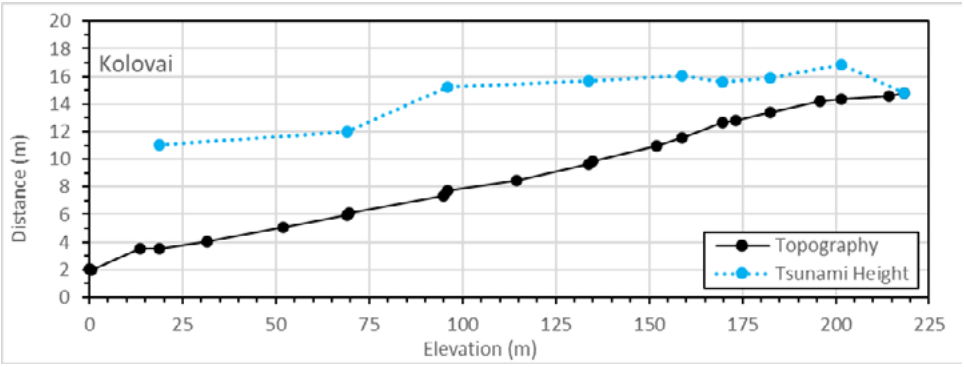
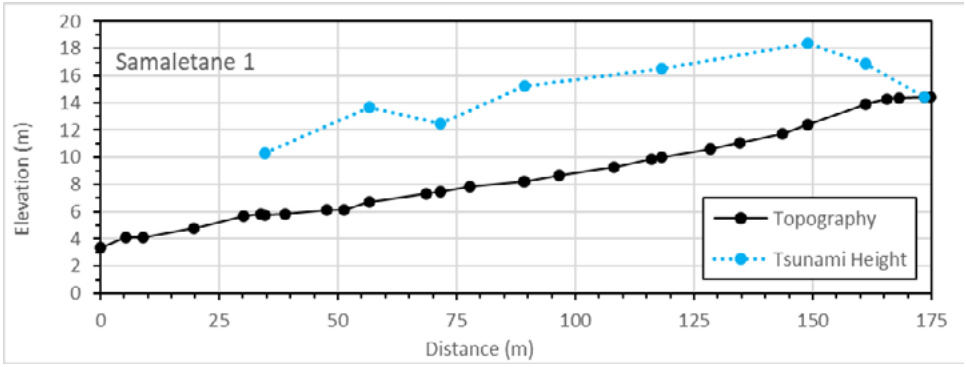
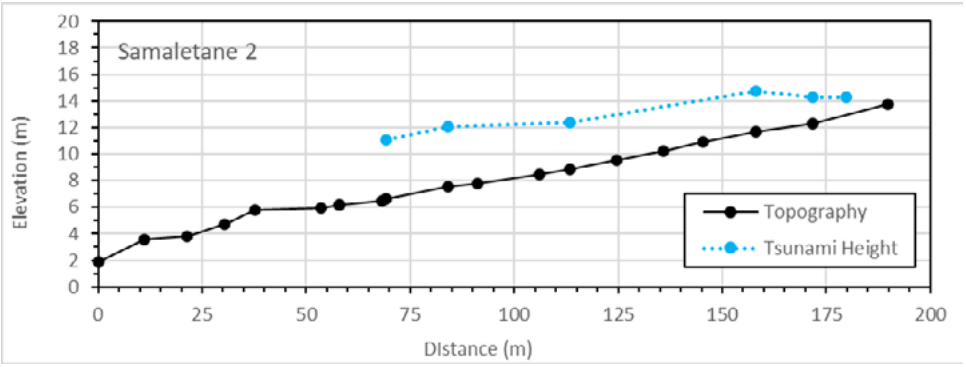
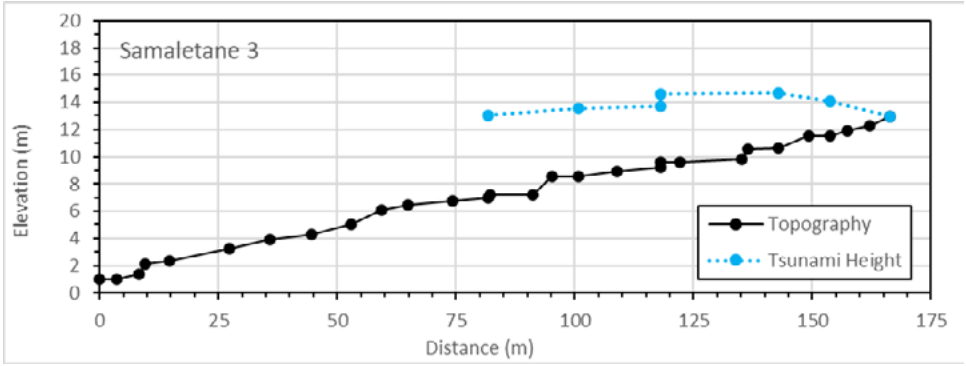


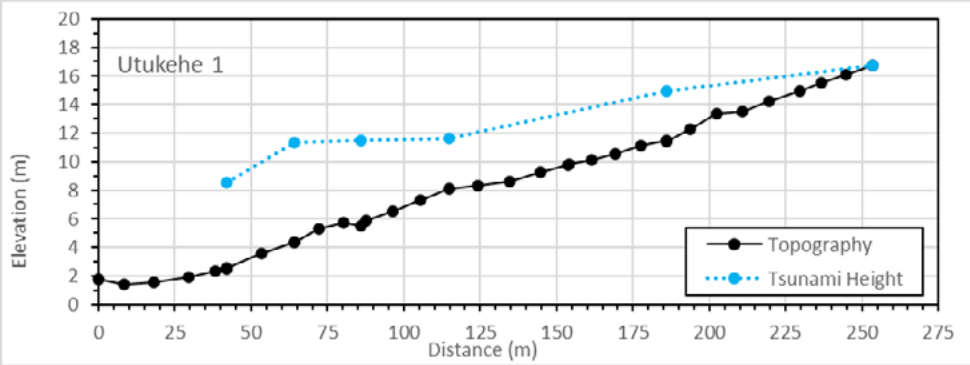
Samaletane

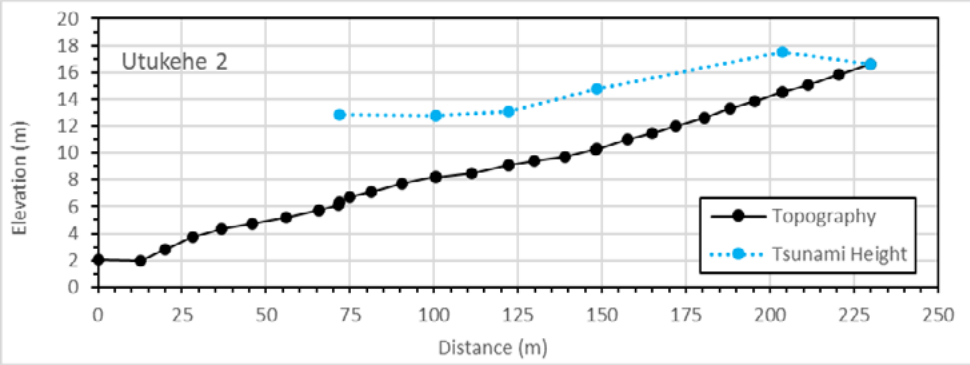




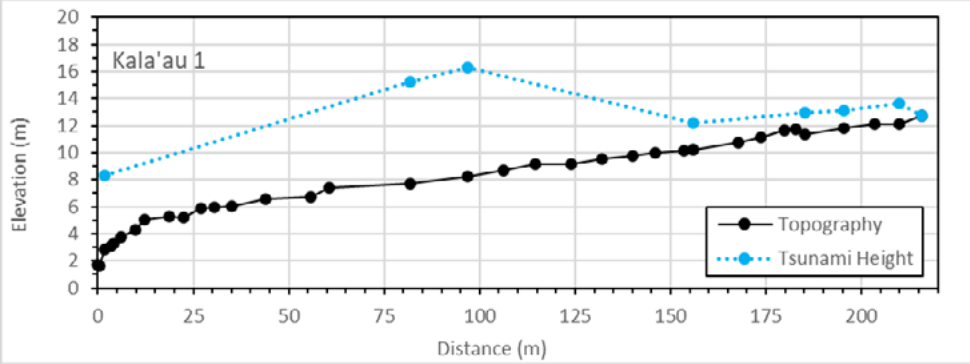


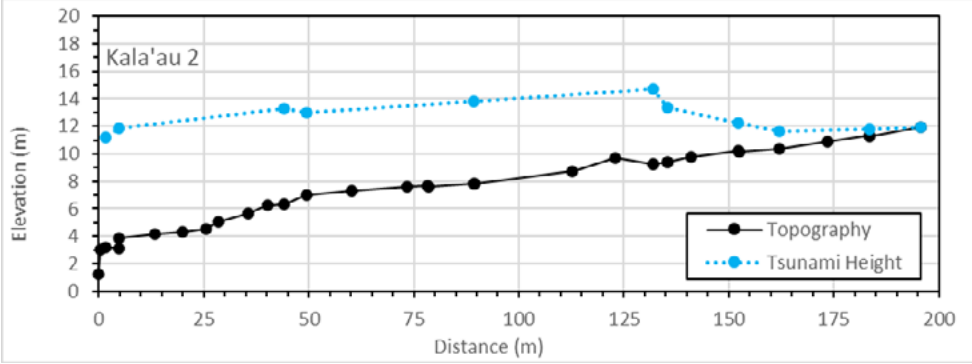
Utukehe





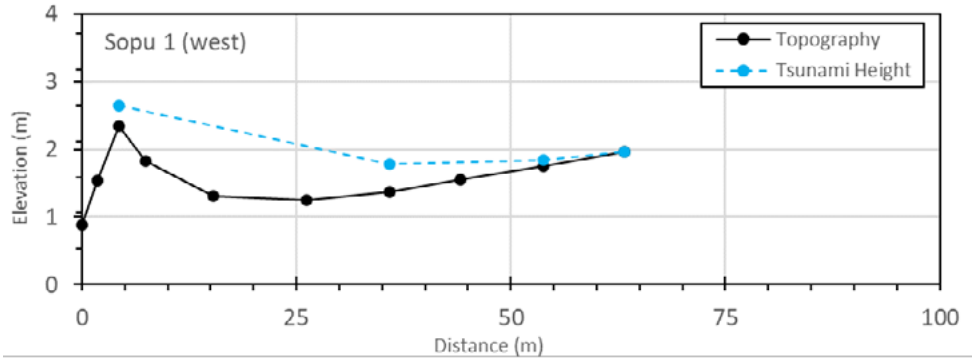
Kala'au

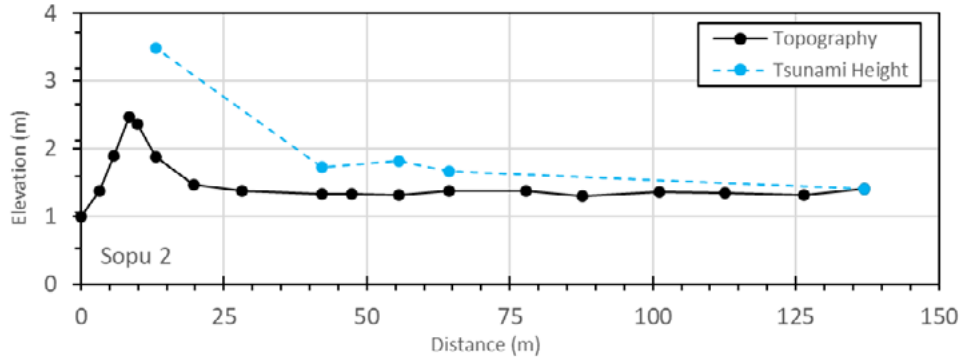


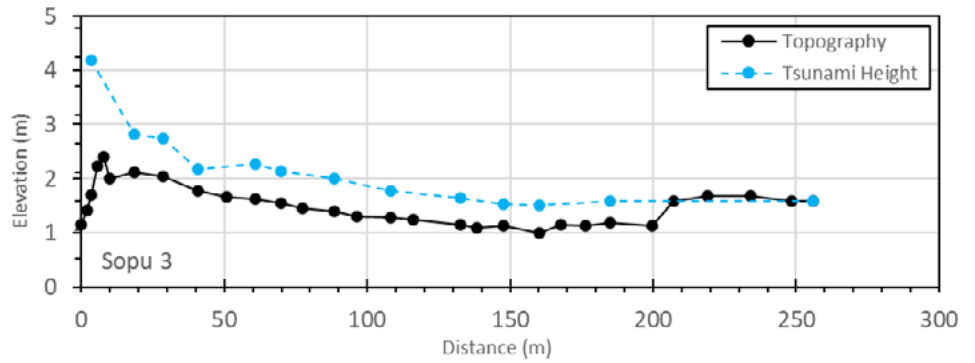


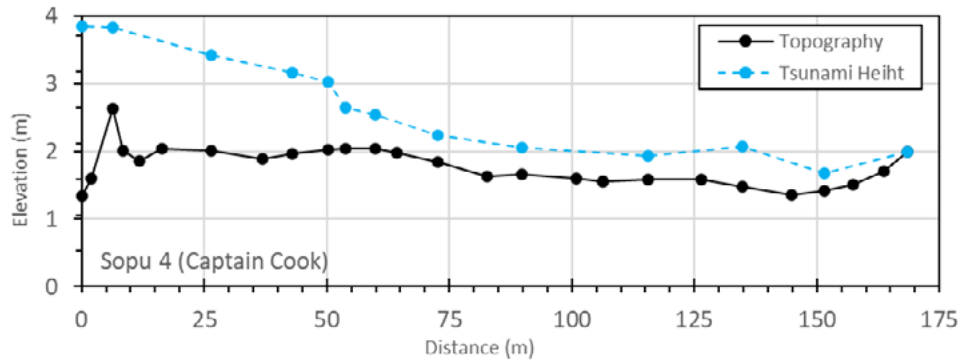
APPENDIX C. TONGATAPU NORTH COAST PROFILES (INCLUDING ATATA AND FAFA)

Sopu

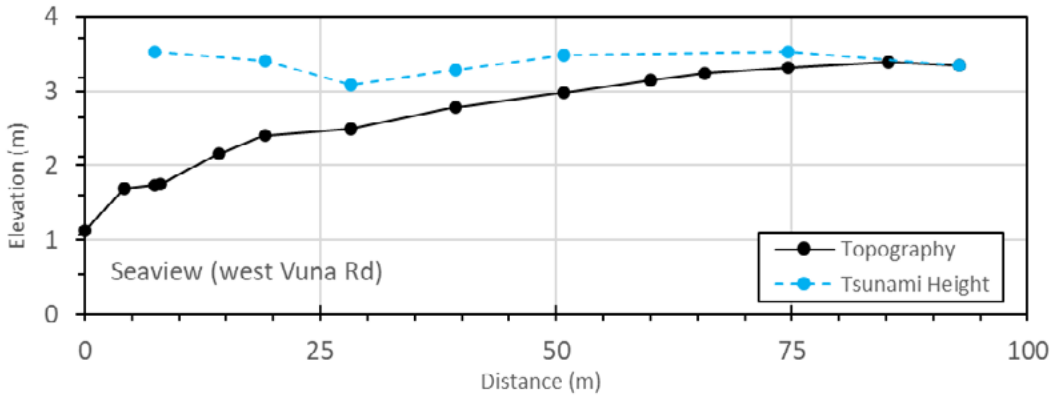




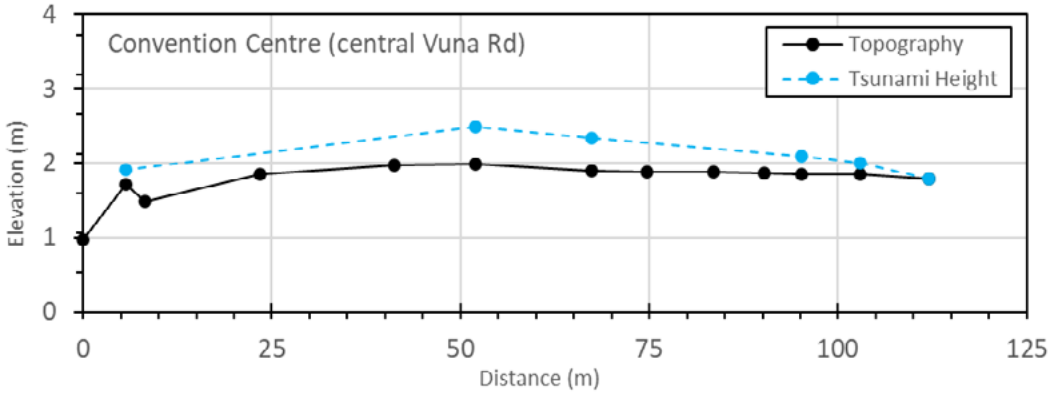




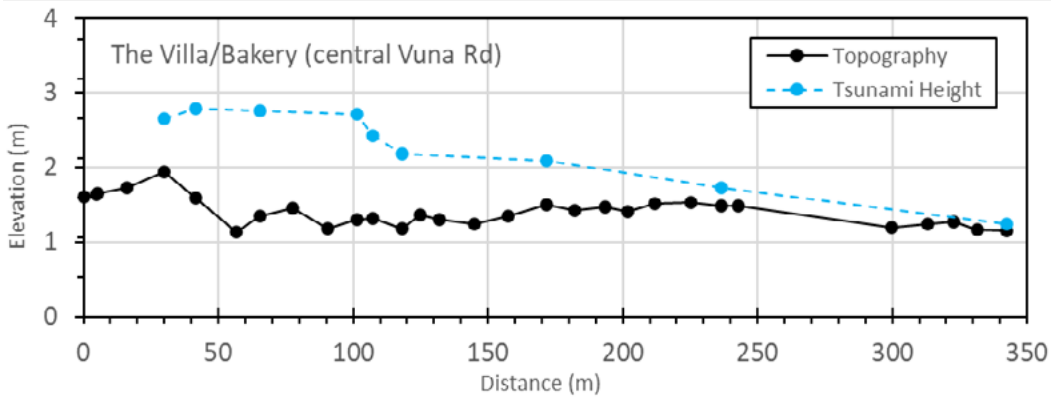
Seaview (west Vuna Rd)



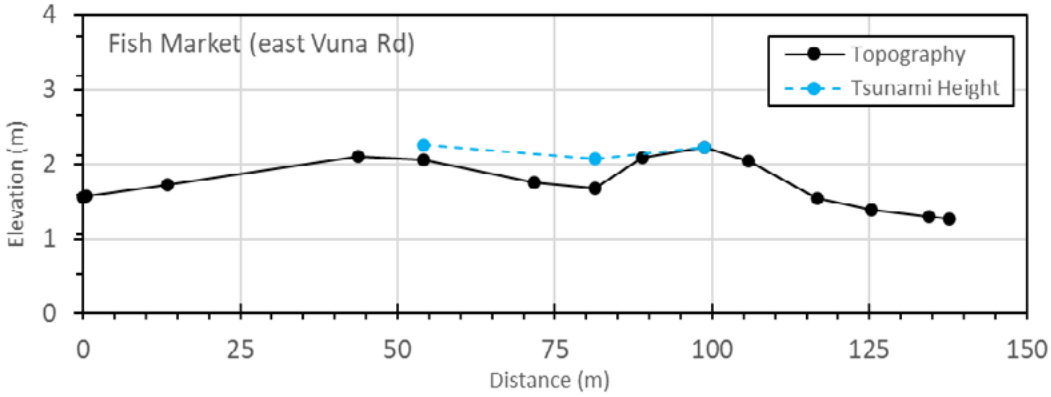
Convention Centre (central Vuna Rd)



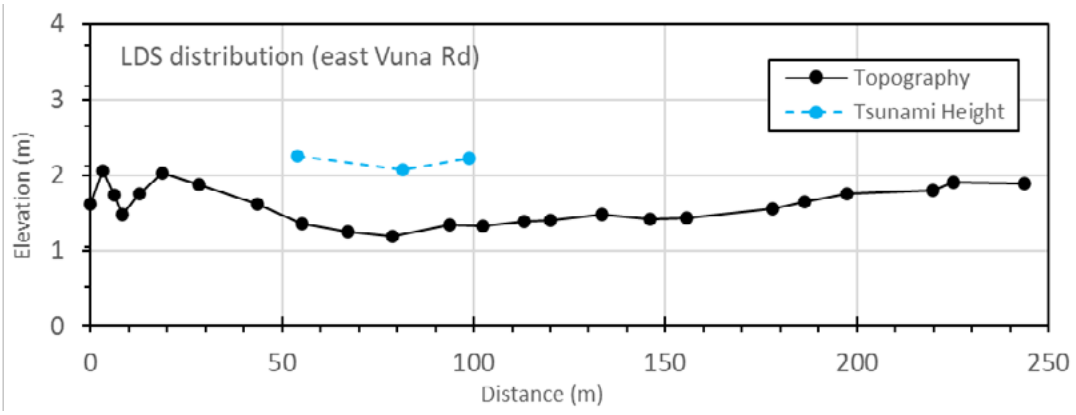
The Villa/Bakery (central Vuna Rd)



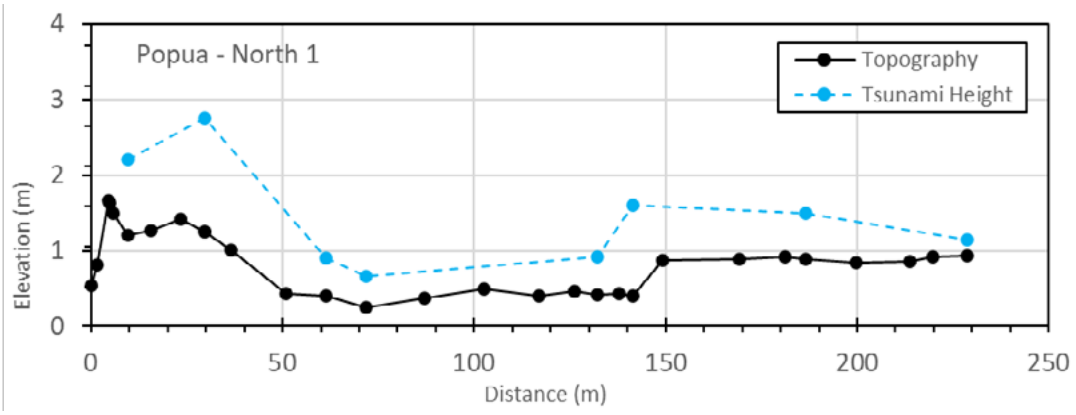
Fish Market (east Vuna Rd)

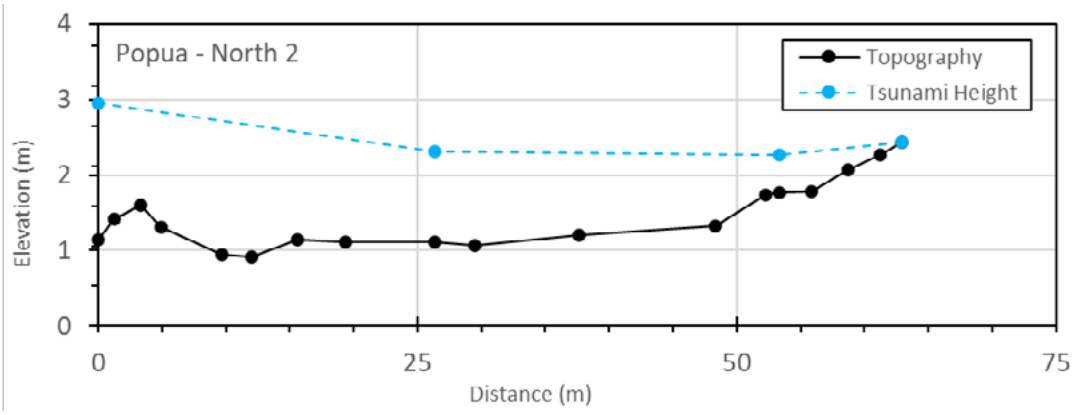


LDS distribution (east Vuna Rd)

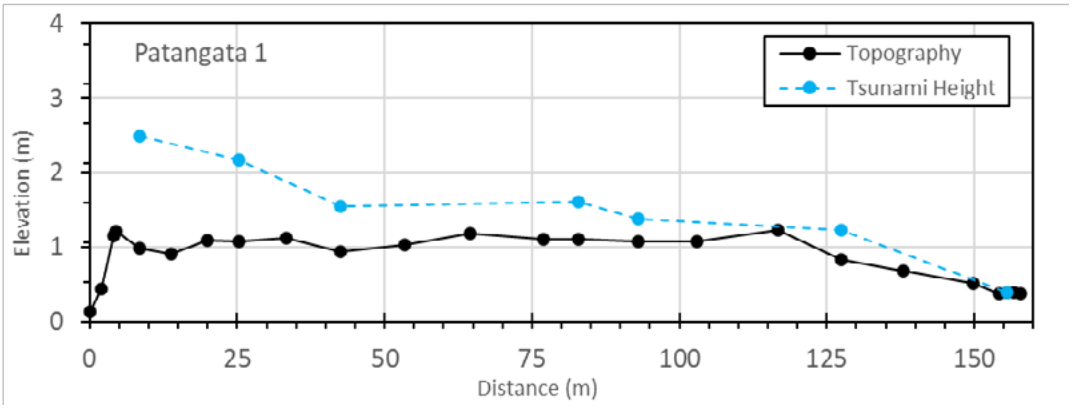


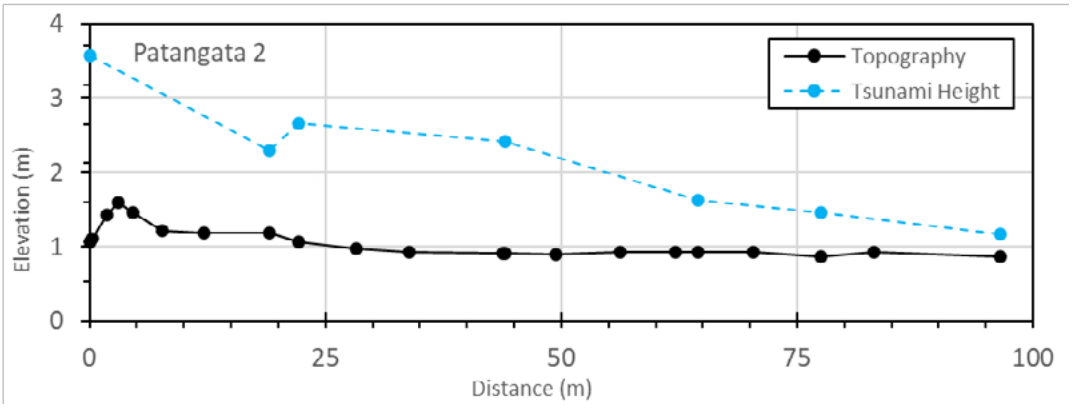
Popua



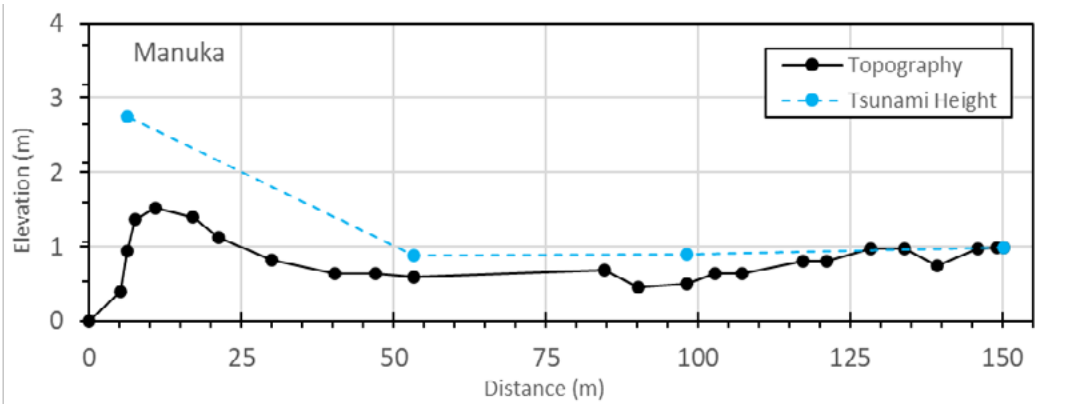


Patangata

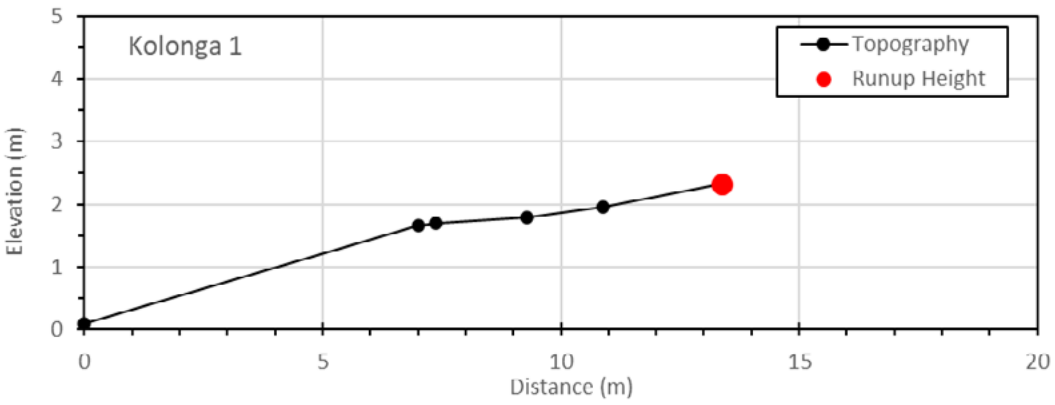


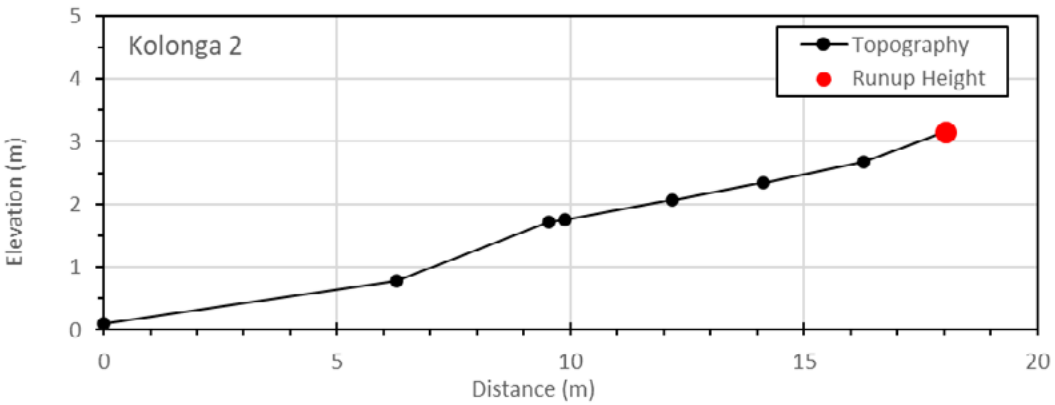


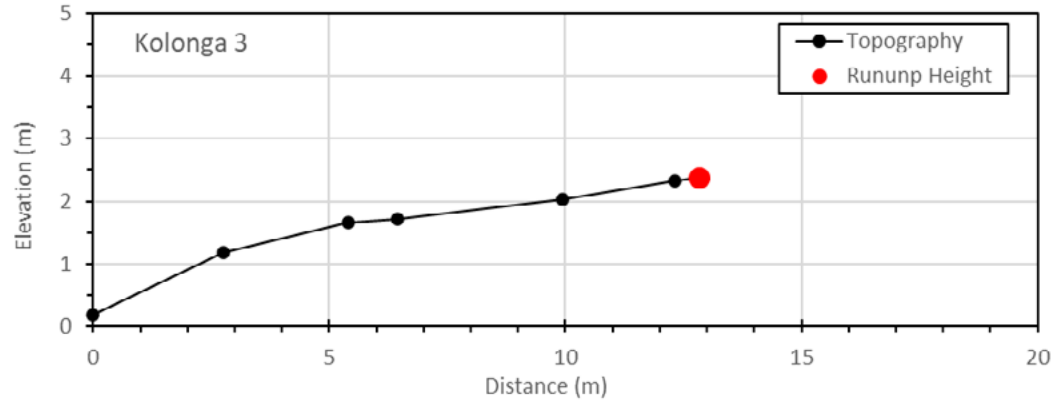
Manuka



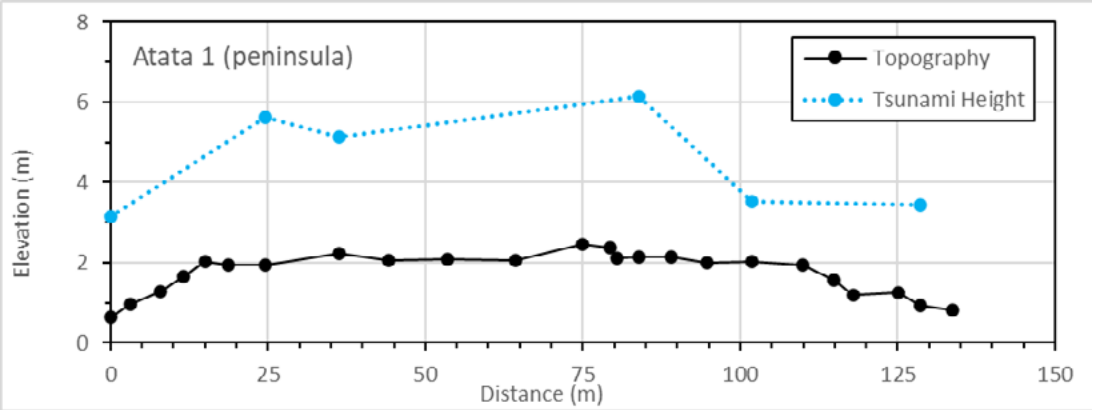
Kolonga

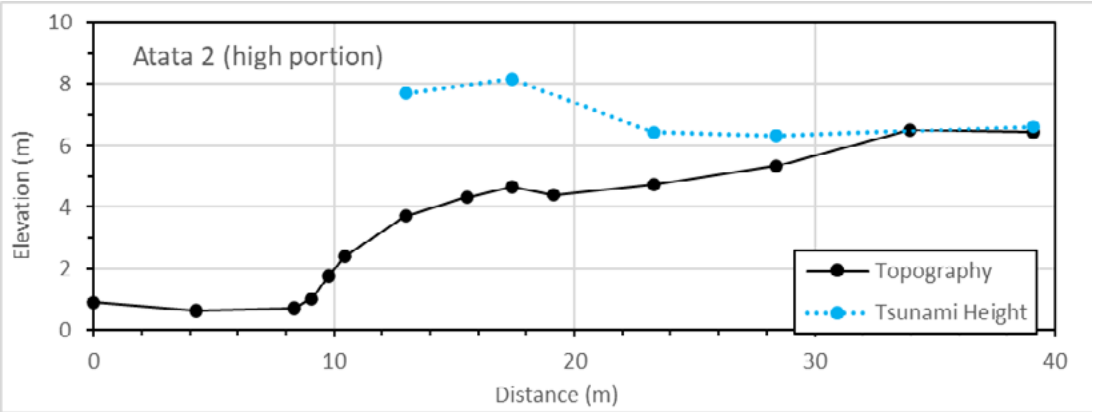

Kolonga 1
Topography
Runup Height
Elevation (m)
Distance (m)
0
1
2
3
4
5
0
5
10
15
20

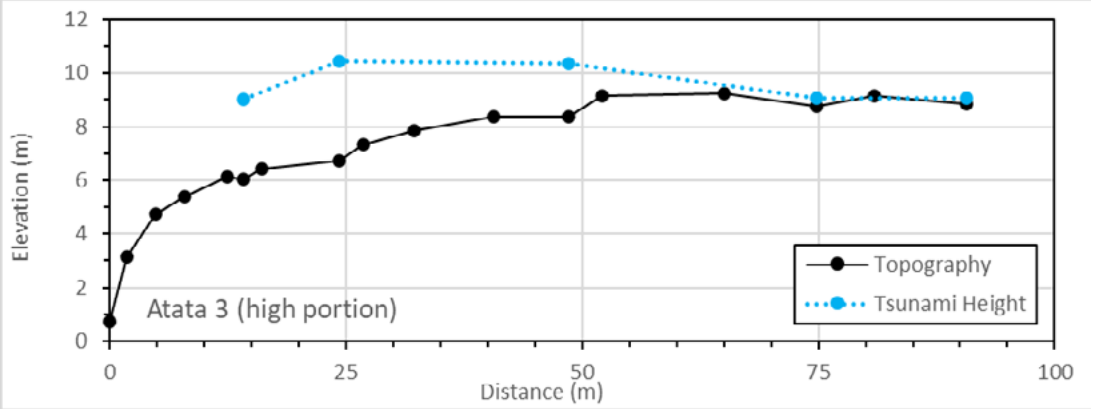

Kolonga 2
Topography
Runup Height
Elevation (m)
Distance (m)
0
1
2
3
4
5
0
5
10
15
20

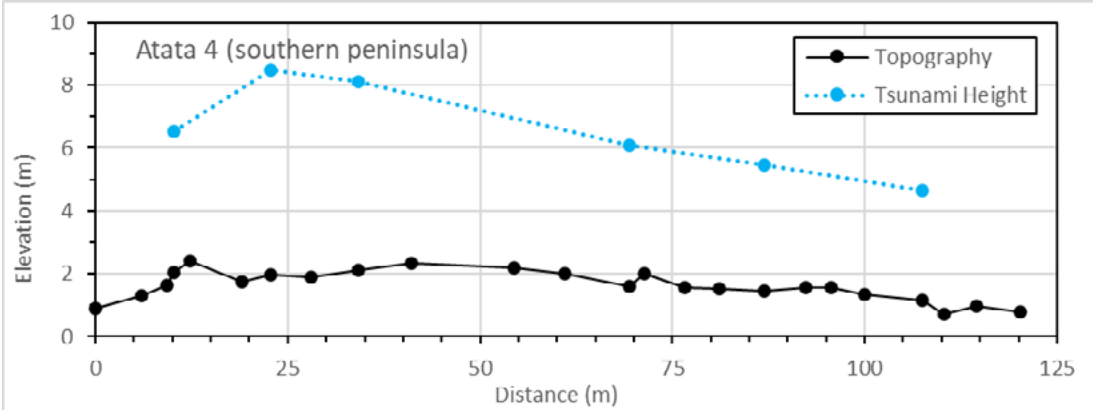

Kolonga 3
Topography
Rununp Height
Elevation (m)
Distance (m)
0
1
2
3
4
5
0
5
10
15
20

Atata

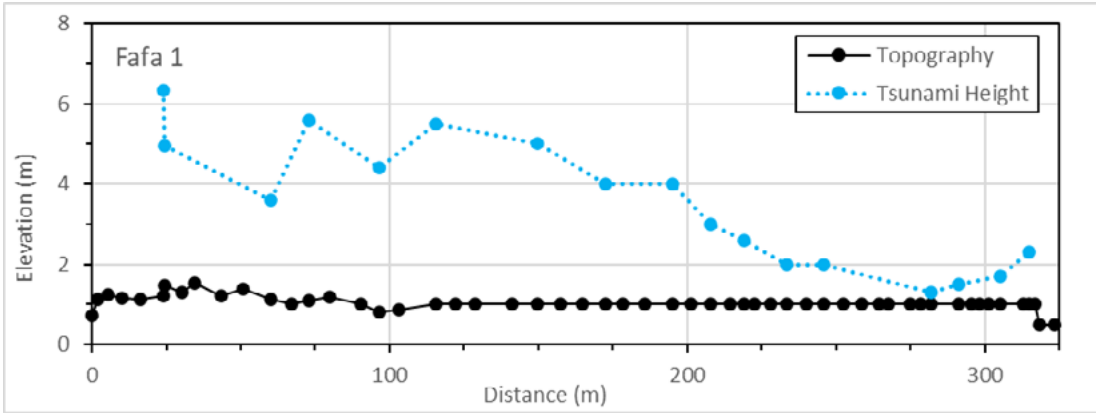

Atata 1 (peninsula)
Topography
Tsunami Height
Elevation (m)
Distance (m)
0
2
4
6
8
0
25
50
75
100
125
150

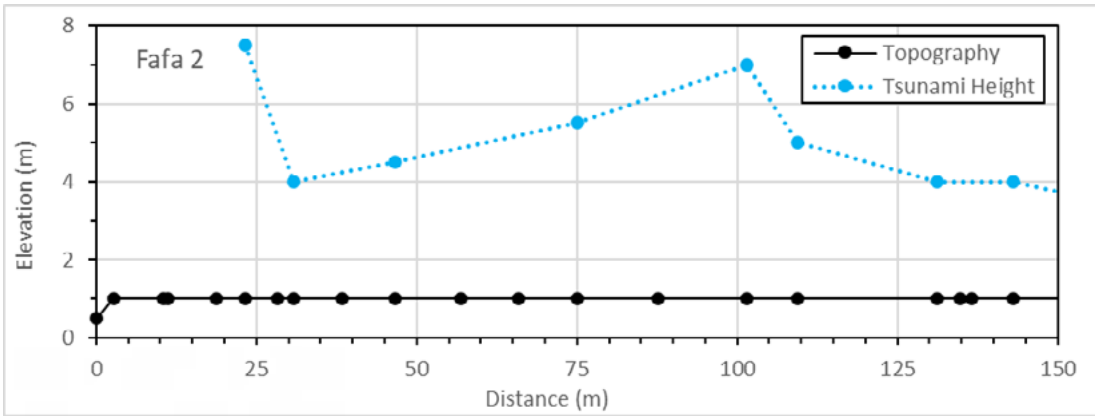

Atata 2 (high portion)
Topography
Tsunami Height
Elevation (m)
Distance (m)
0
2
4
6
8
10
0
10
20
30
40


Atata 3 (high portion)
Topography
Tsunami Height
Elevation (m)
Distance (m)
0
2
4
6
8
10
12
0
25
50
75
100


Atata 4 (southern peninsula)
Topography
Tsunami Height
Elevation (m)
Distance (m)
0
2
4
6
8
10
0
25
50
75
100
125

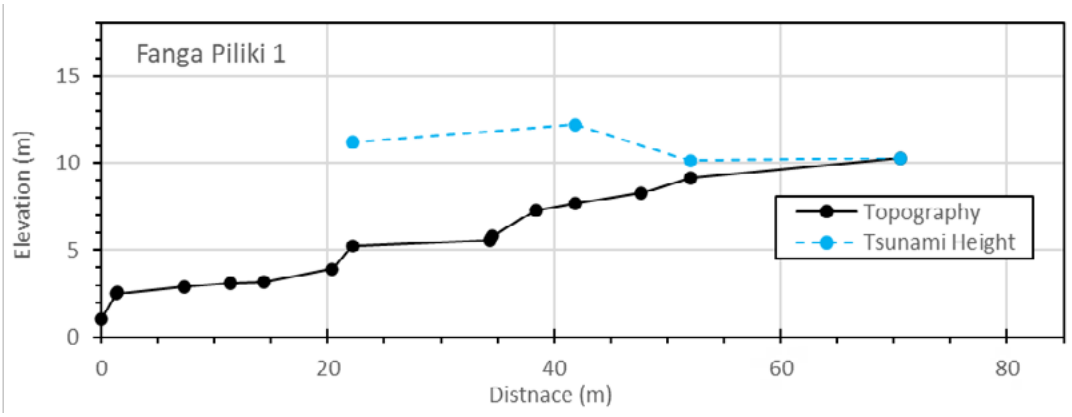
Fafa

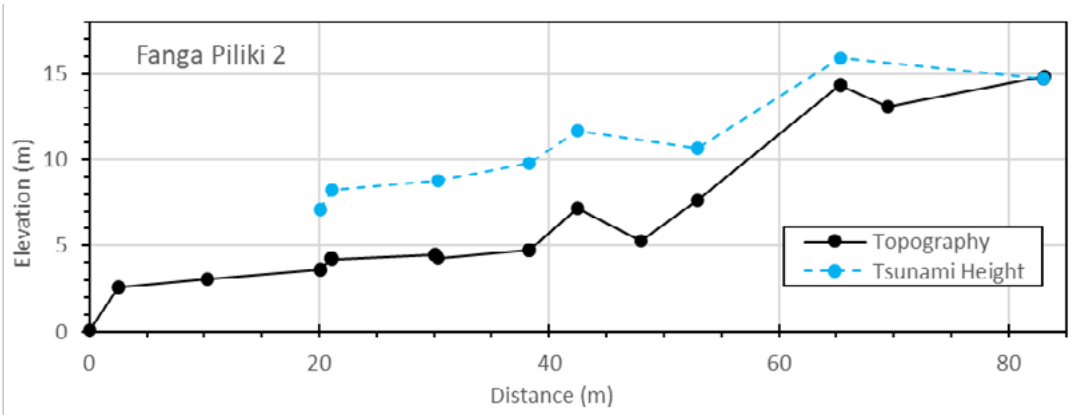

Fafa 1
Topography
Tsunami Height
Elevation (m)
Distance (m)
0
2
4
6
8
0
100
200
300

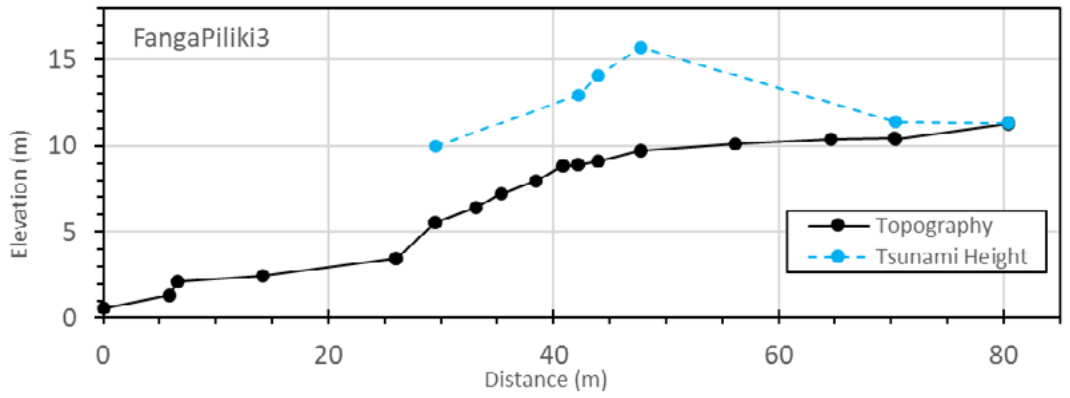

Fafa 2
Topography
Tsunami Height
Elevation (m)
Distance (m)
0
2
4
6
8
0
25
50
75
100
125
150

APPENDIX D. TONGATAPU SOUTH COAST PROFILES

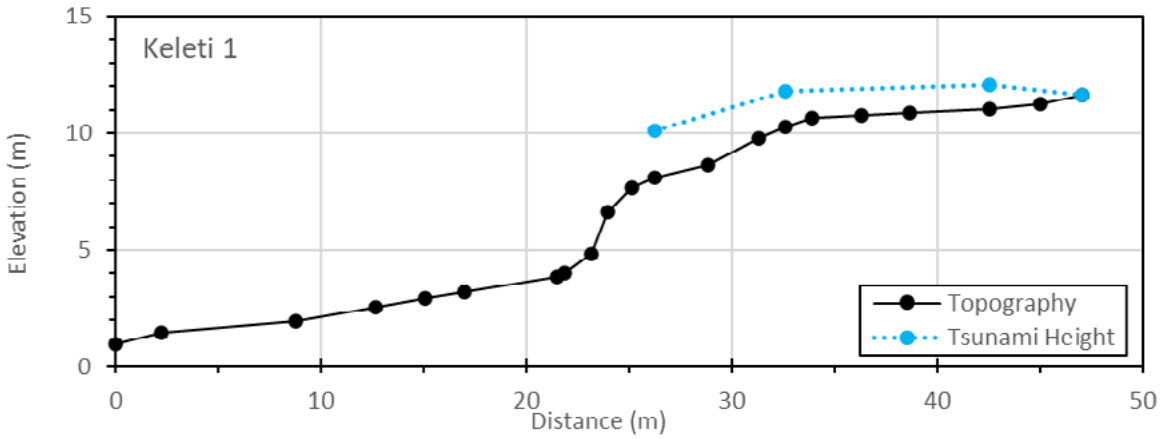
Fanga Piliki

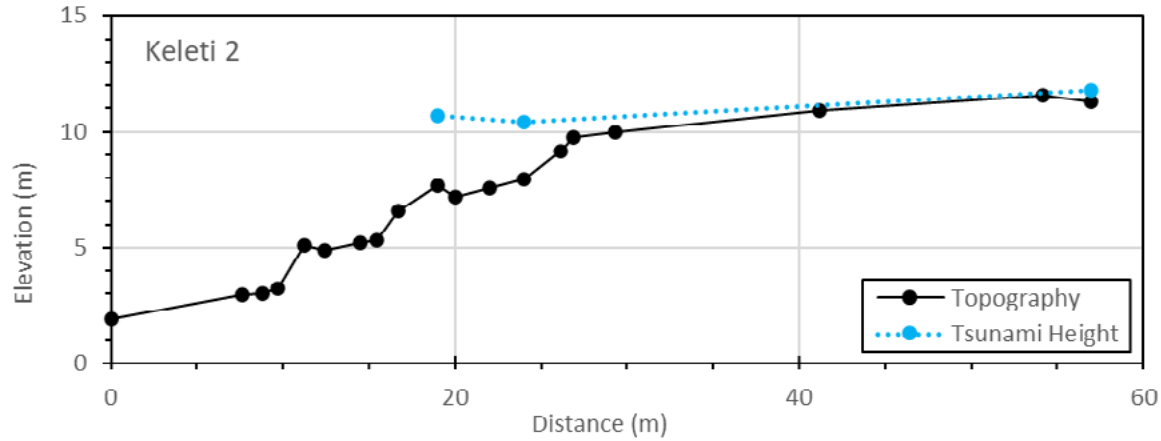


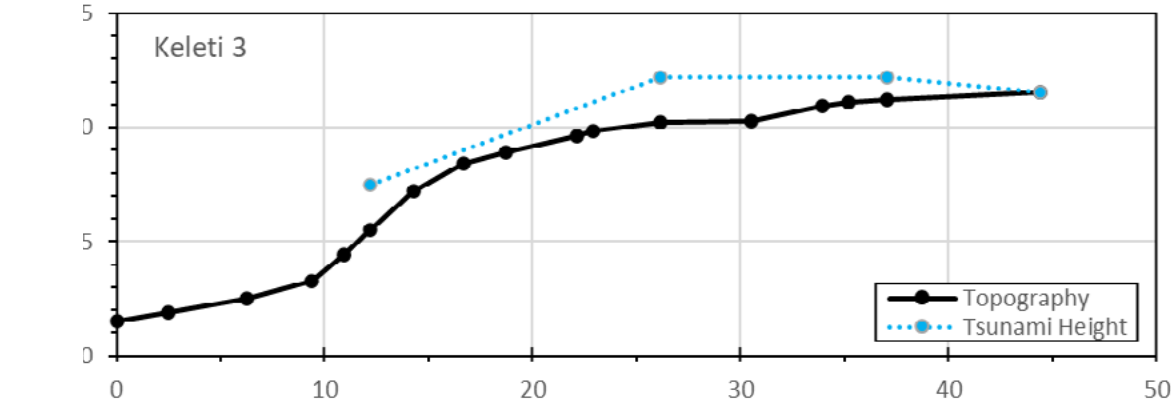




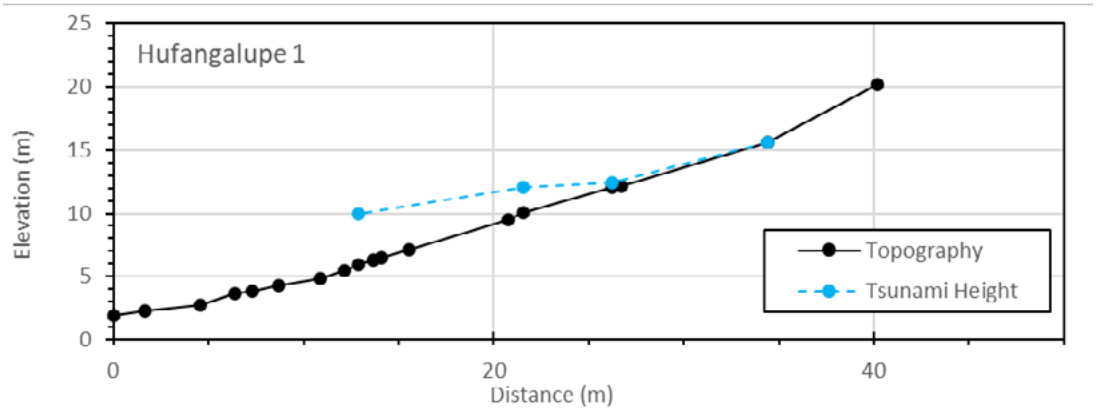
Keleti

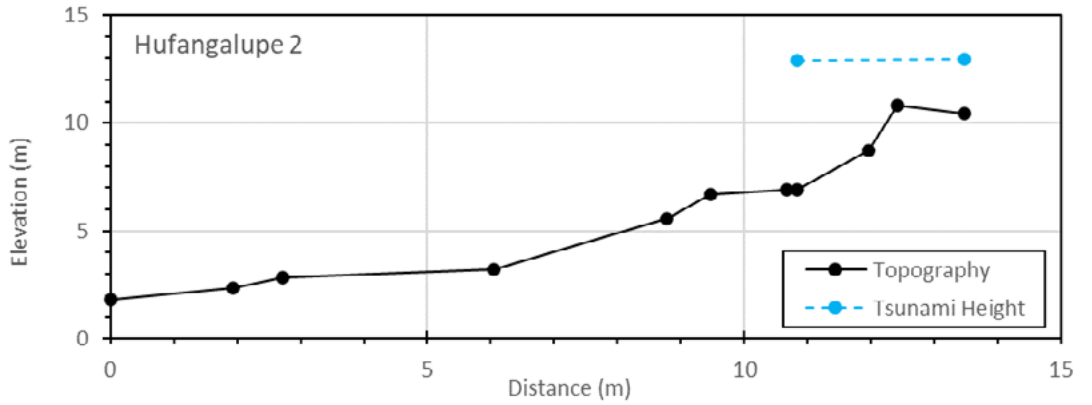

Keleti 1
Elevation (m)
Distance (m)
Topography
Tsunami Height
0
5
10
15
0
10
20
30
40
50


Keleti 2
Elevation (m)
Distance (m)
Topography
Tsunami Height
0
5
10
15
0
20
40
60

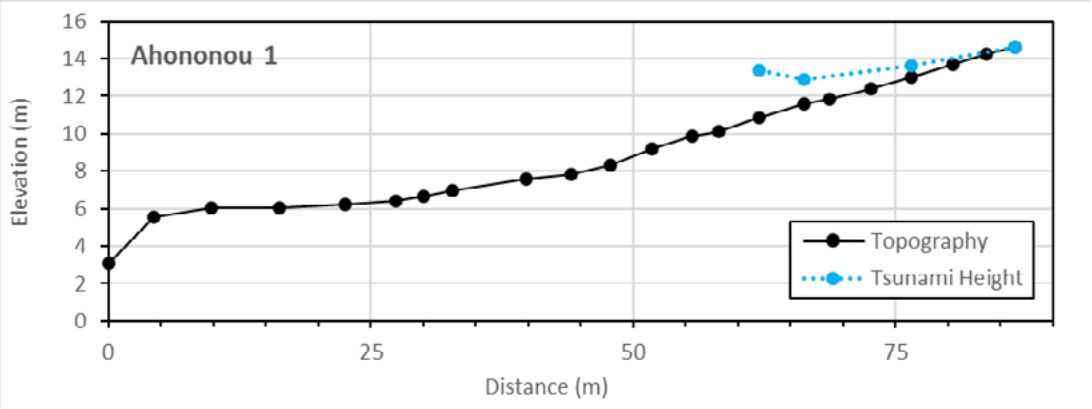

Keleti 3
Topography
Tsunami Height
0
10
20
30
40
50

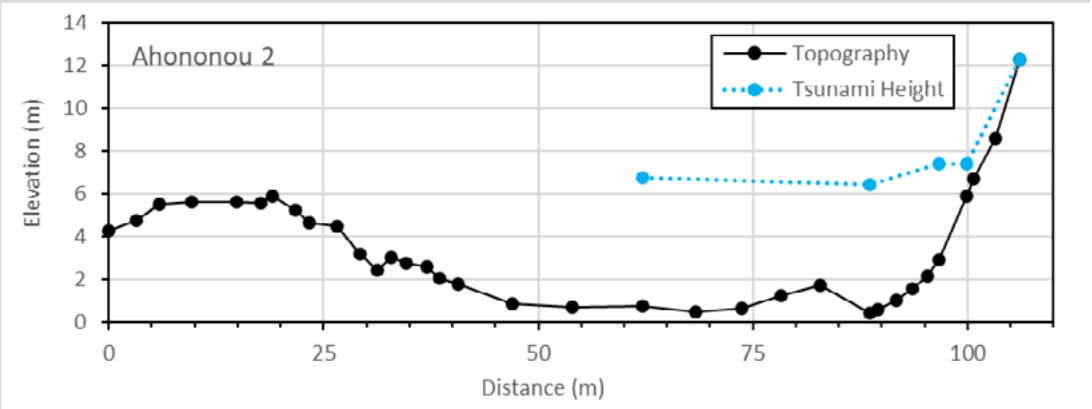
Hufangalupe



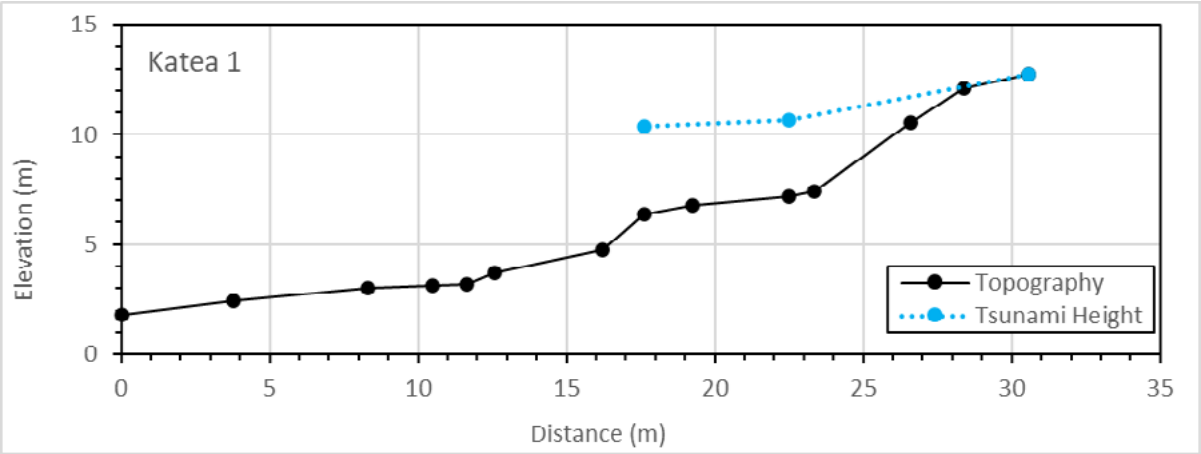


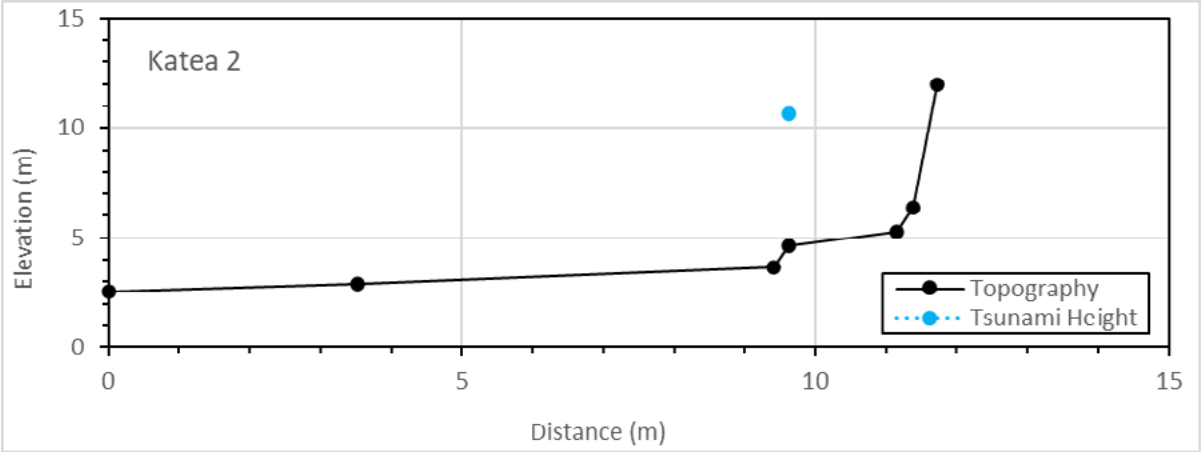
Ahononou





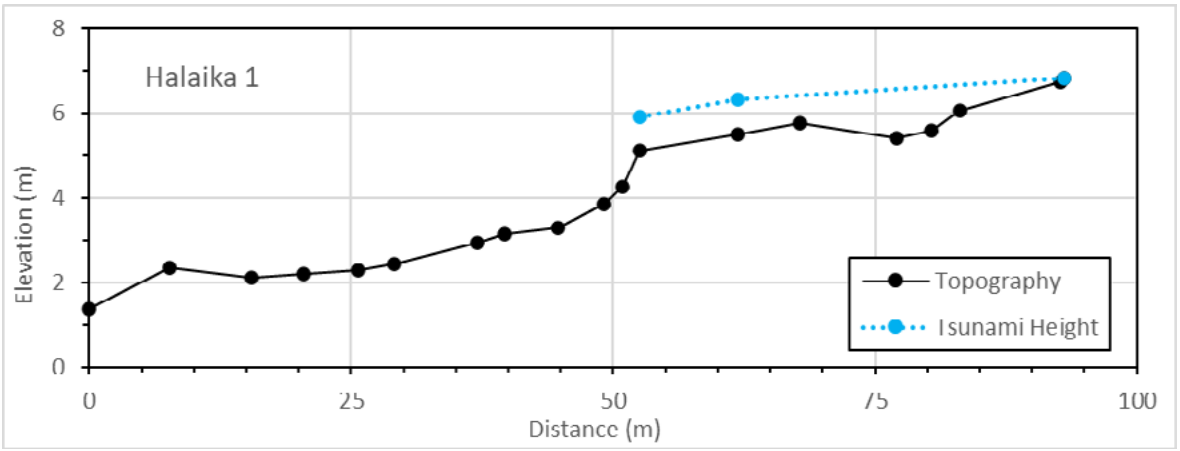
Katea

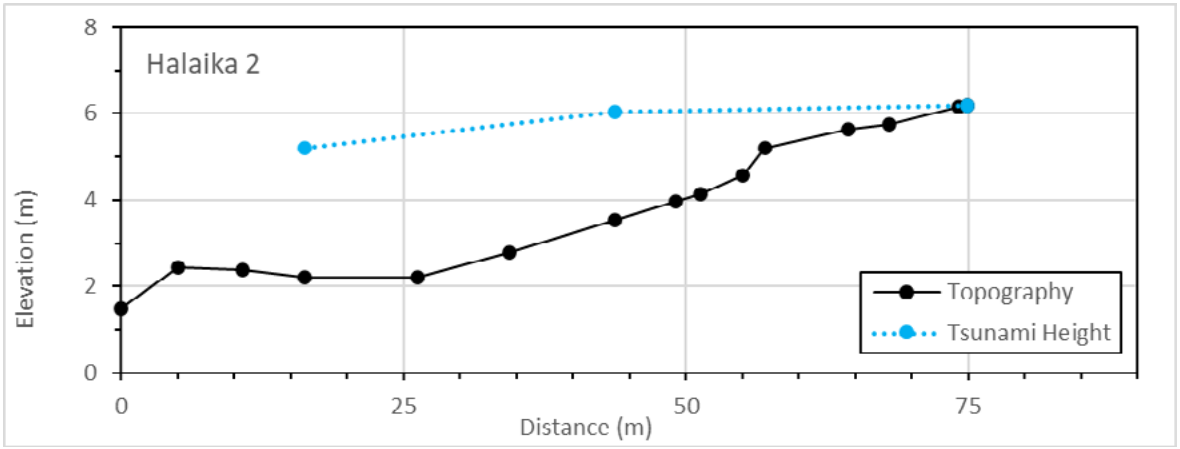

Katea 1
Elevation (m)
Distance (m)
Topography
Tsunami Height
0
5
10
15
20
25
30
35


Katea 2
Elevation (m)
Distance (m)
Topography
Tsunami Height
0
5
10
15

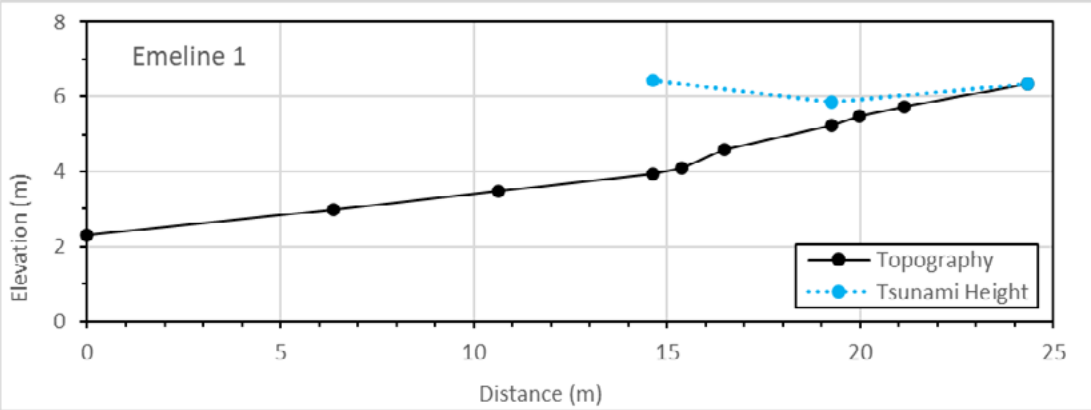
APPENDIX E. TONGATAPU EAST COAST PROFILES

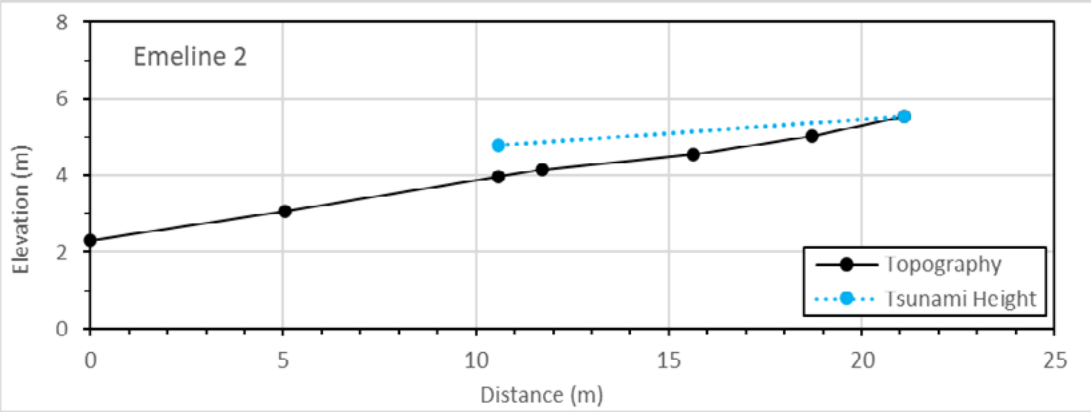
Halaika

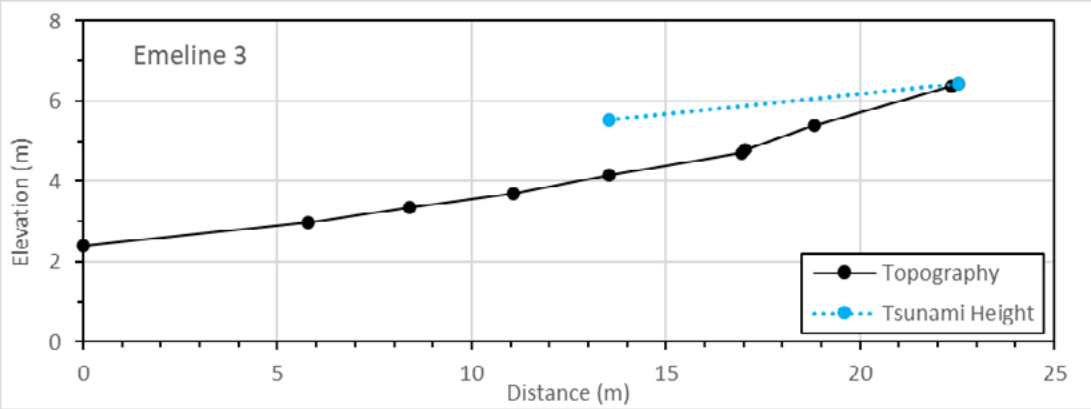




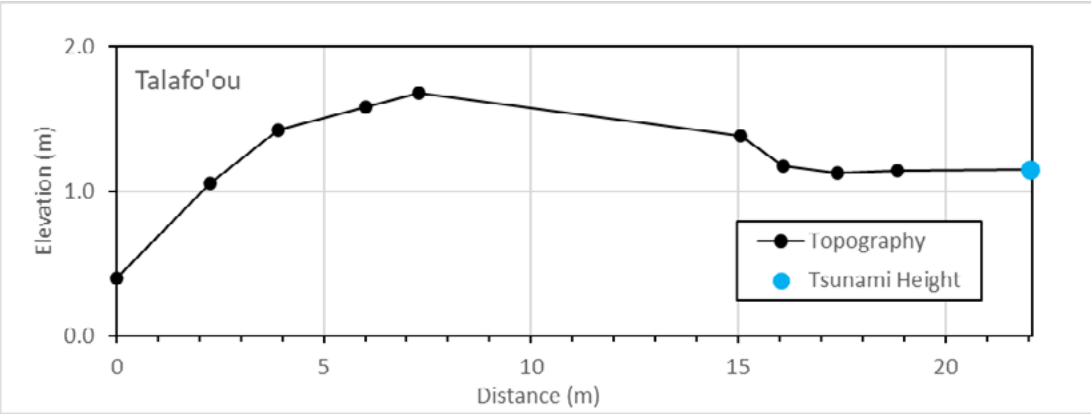
Emeline


Emeline 1
Elevation (m)
Distance (m)
Topography
Tsunami Height
0
2
4
6
8
0
5
10
15
20
25

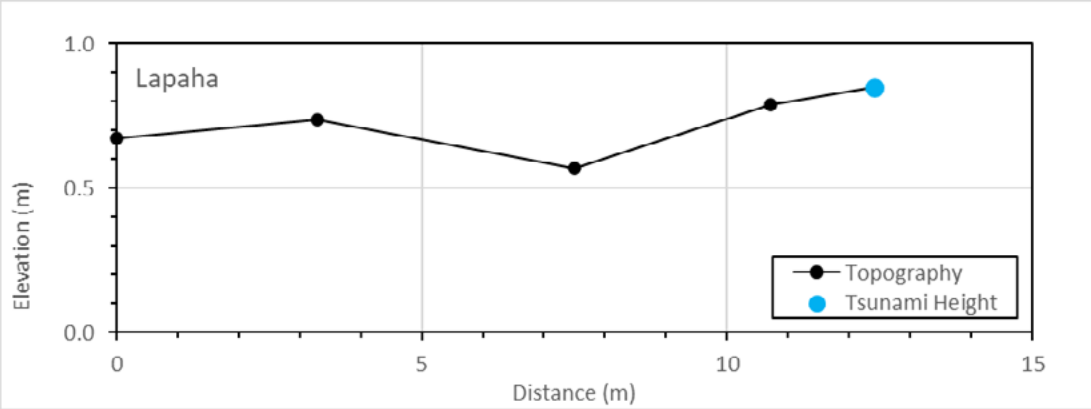

Emeline 2
Elevation (m)
Distance (m)
Topography
Tsunami Height
0
2
4
6
8
0
5
10
15
20
25


Emeline 3
Elevation (m)
Distance (m)
Topography
Tsunami Height
0
2
4
6
8
0
5
10
15
20
25

Talafo'ou

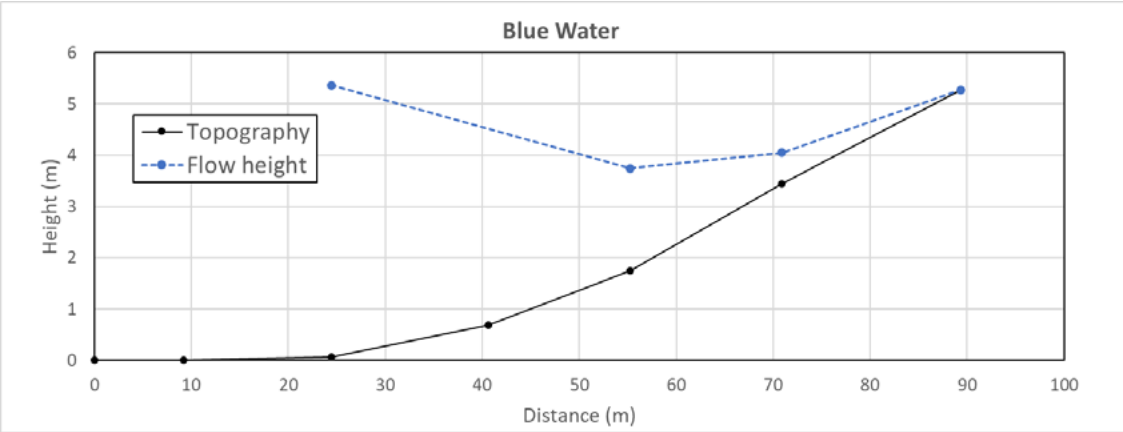


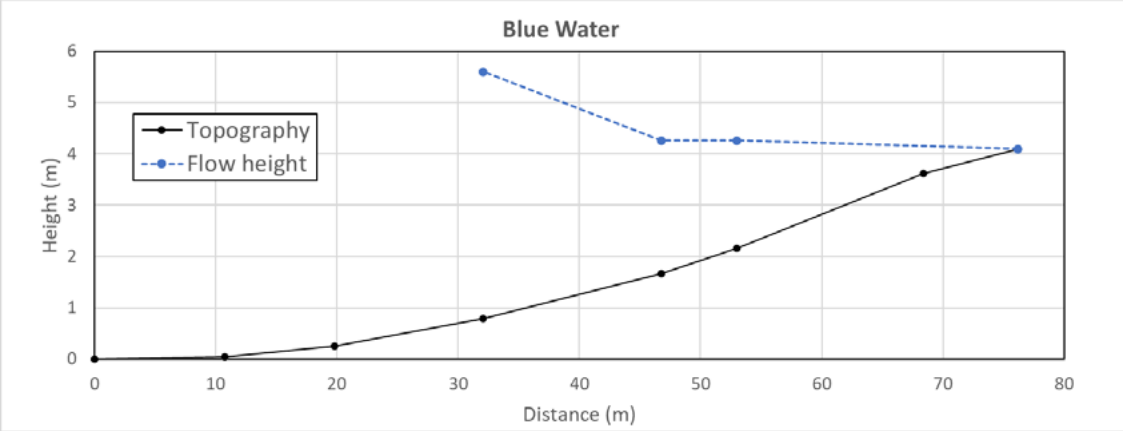
Lapaha



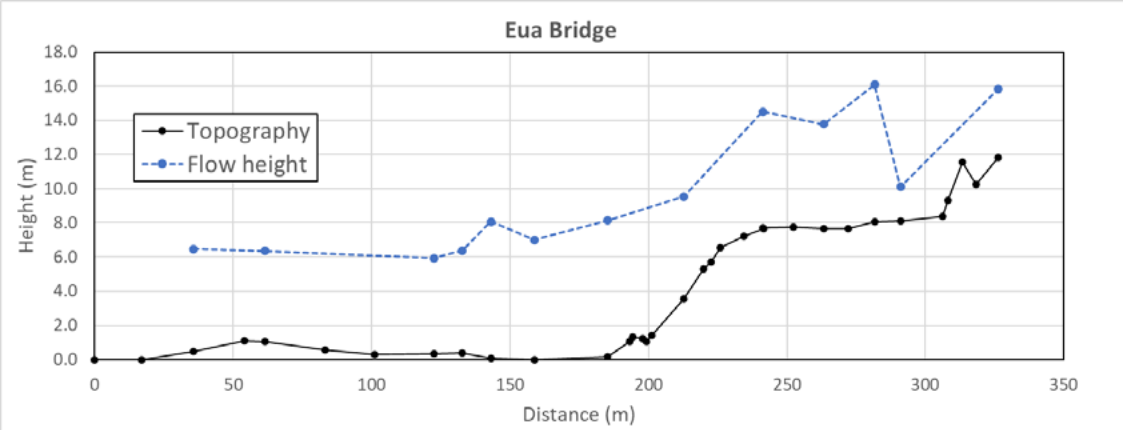
APPENDIX F. ‘EUA PROFILES

Blue Water

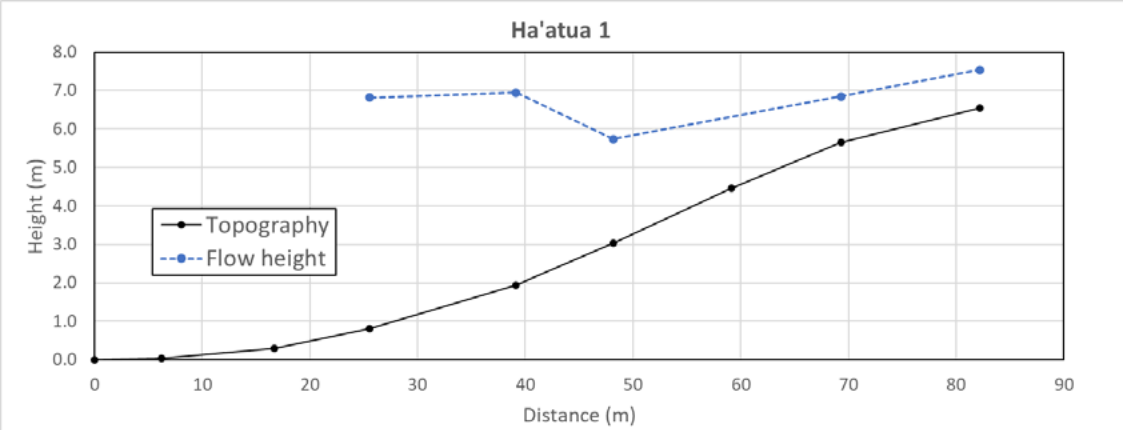


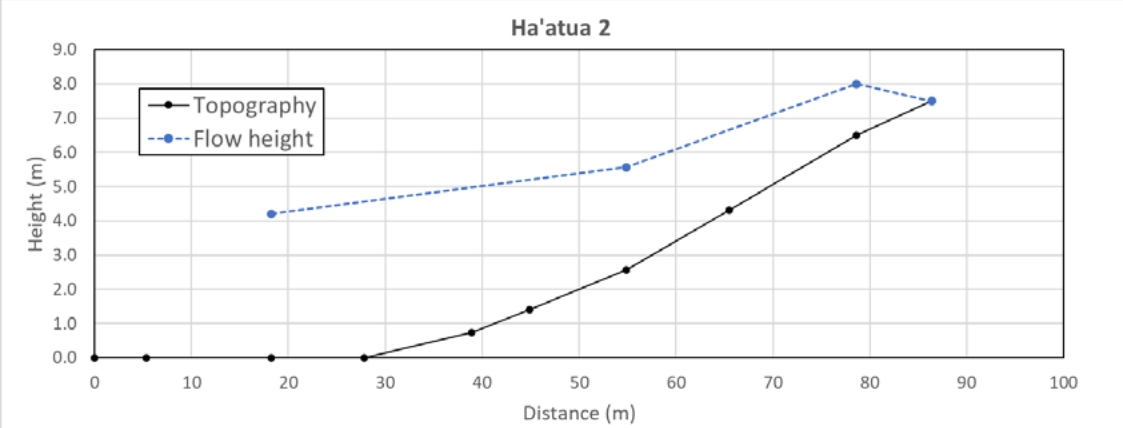


Eua Bridge

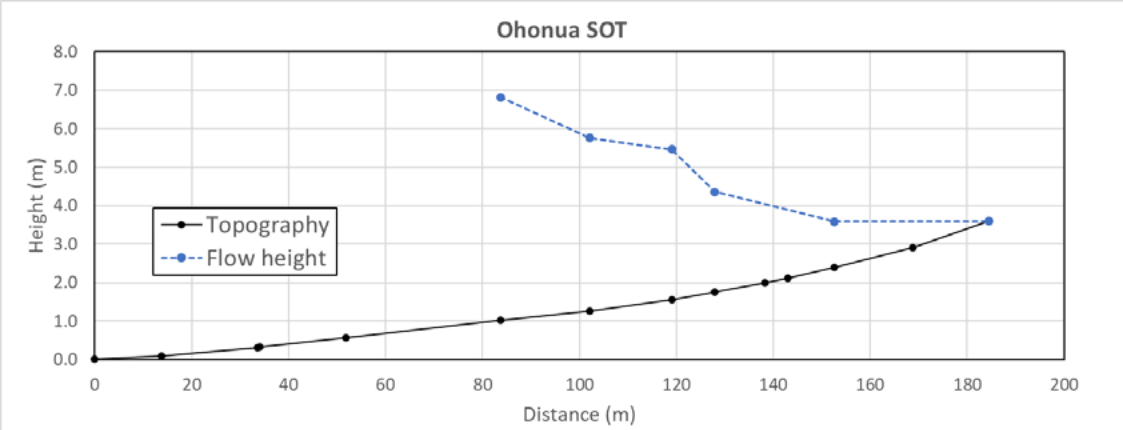


Ha'atua

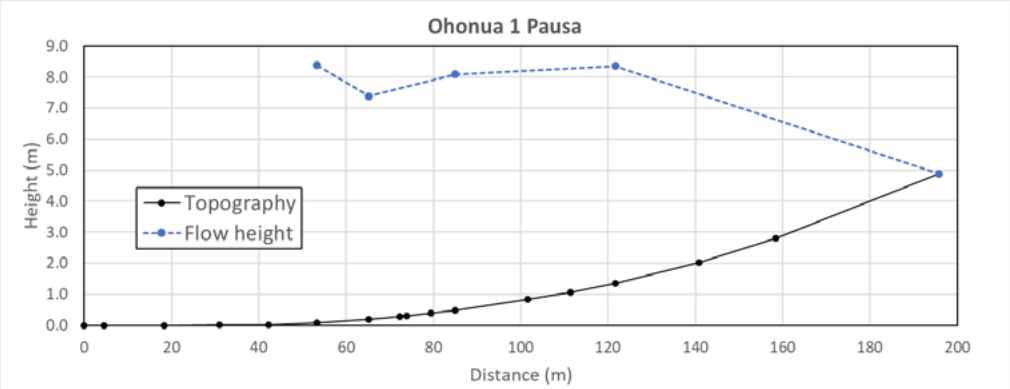


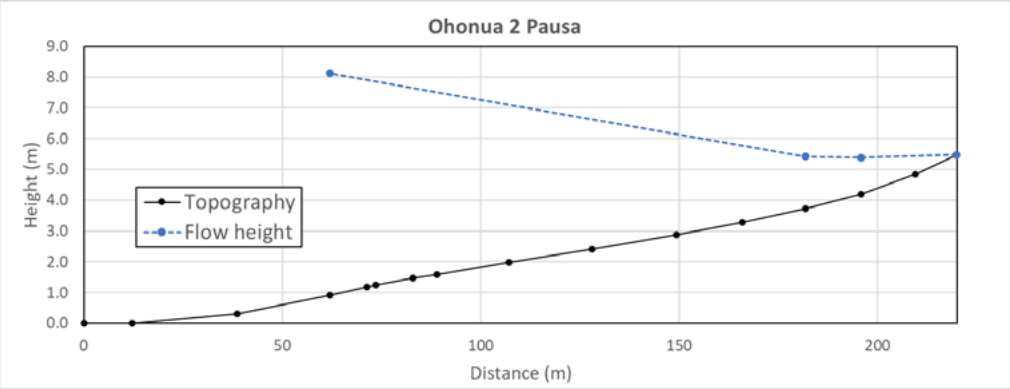


Ohonua SOT

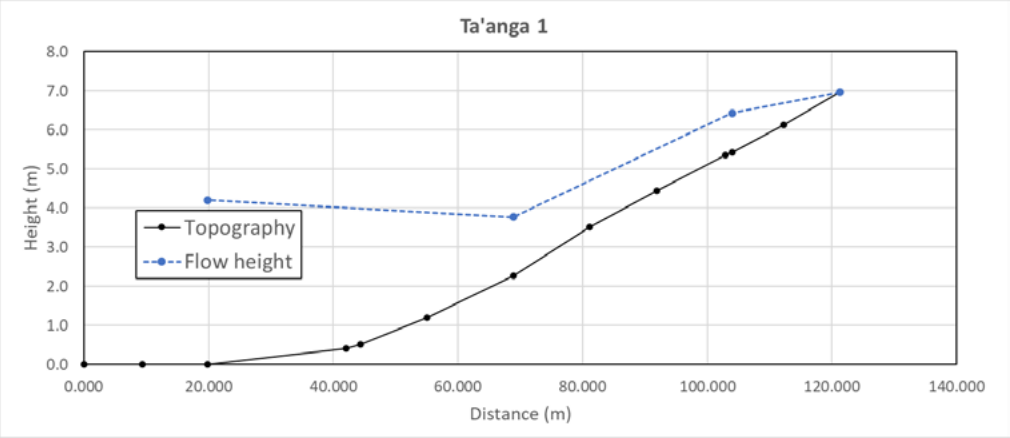


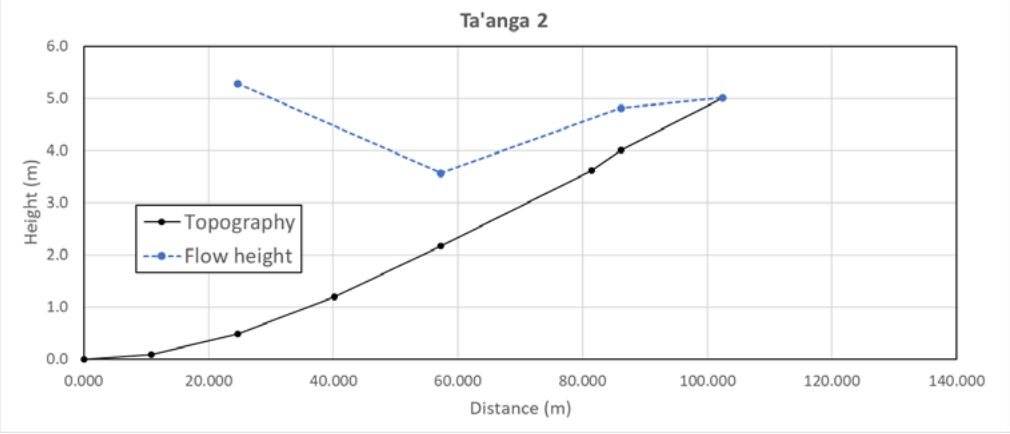
Ohonua



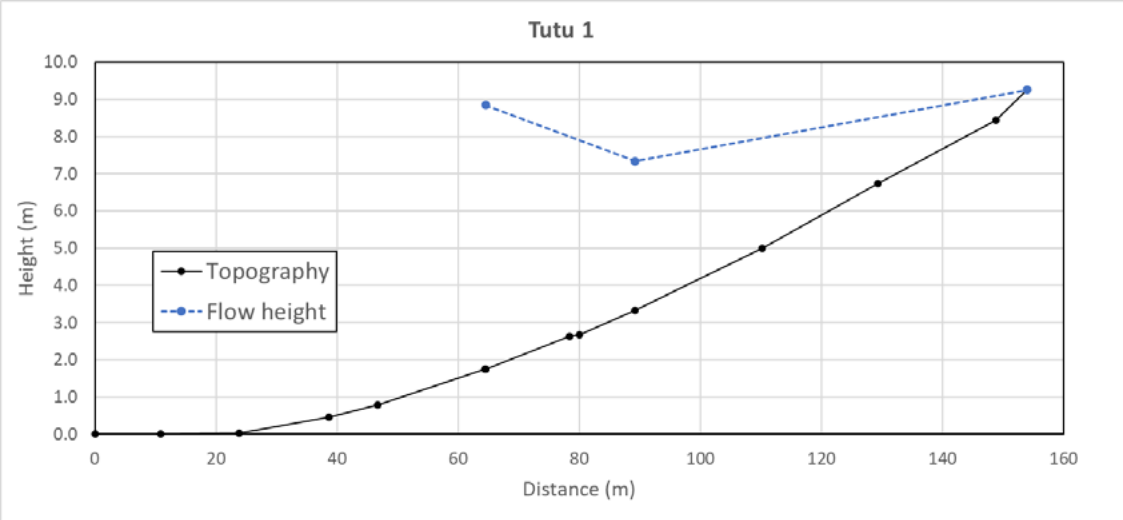


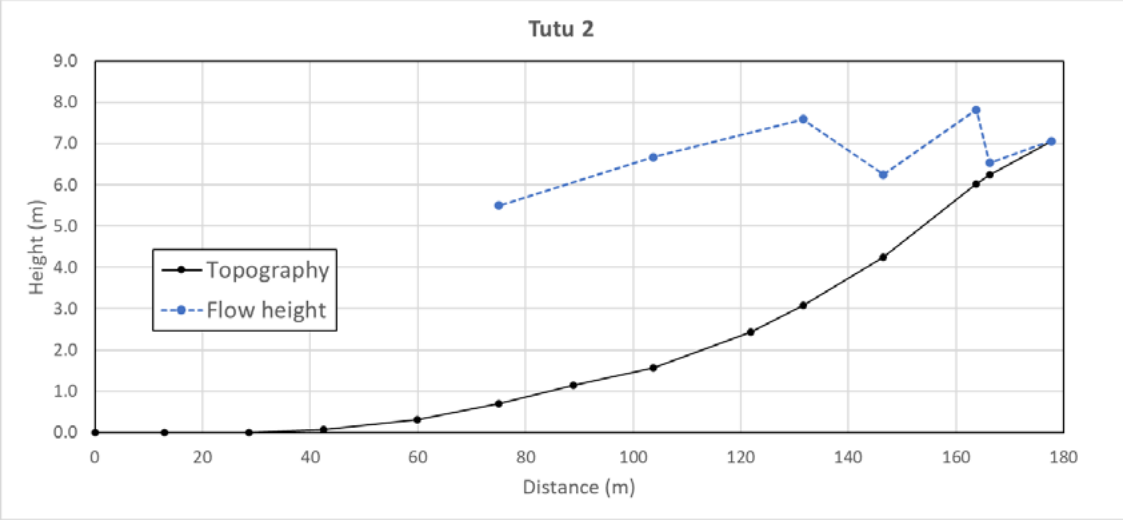
Ta'anga



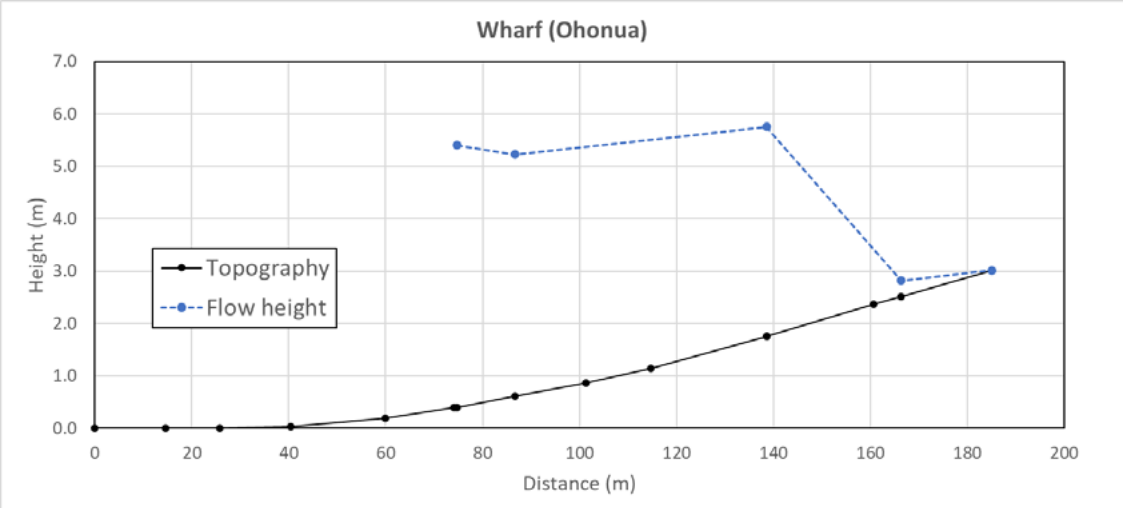


Tutu



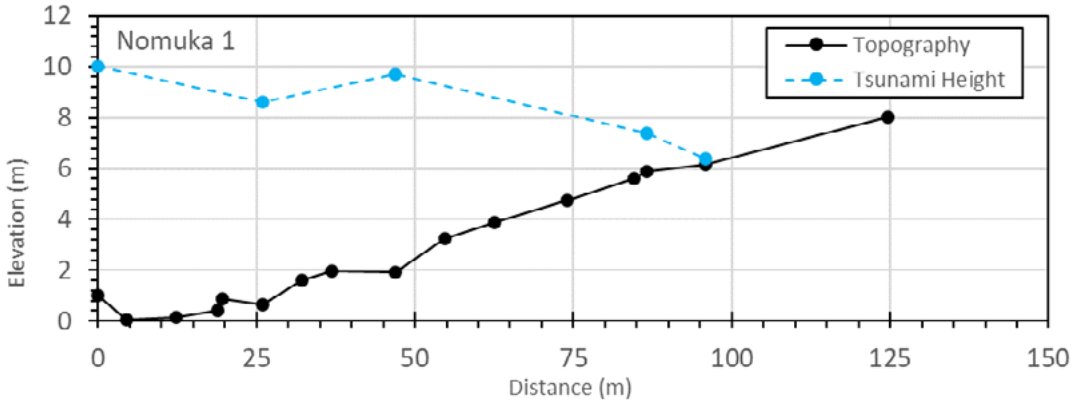


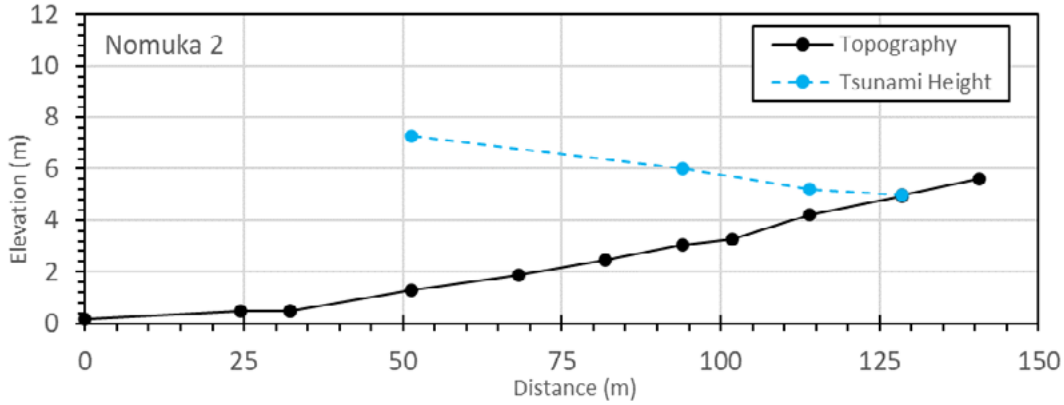
Warf (Ohonua)

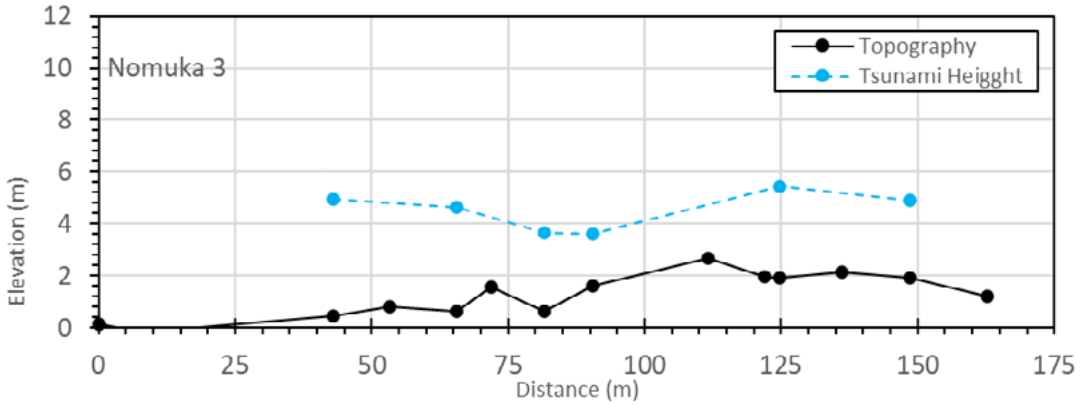


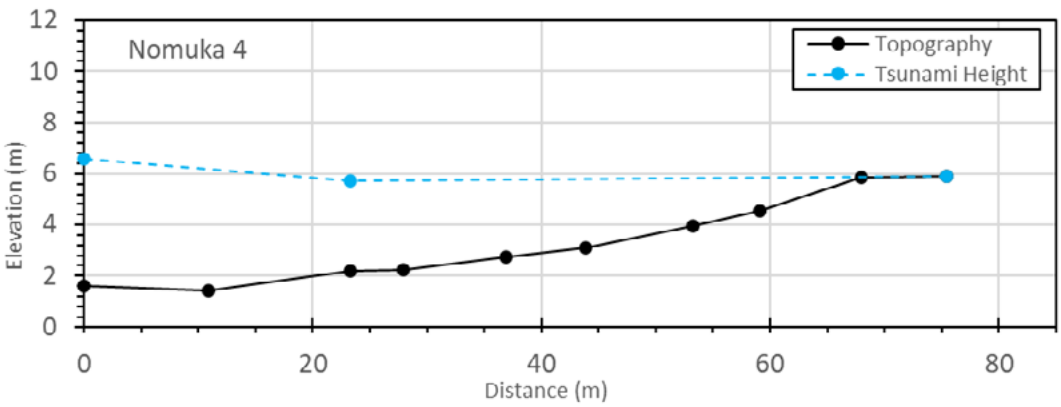
APPENDIX G. HA'APAI SITES

Nomuka

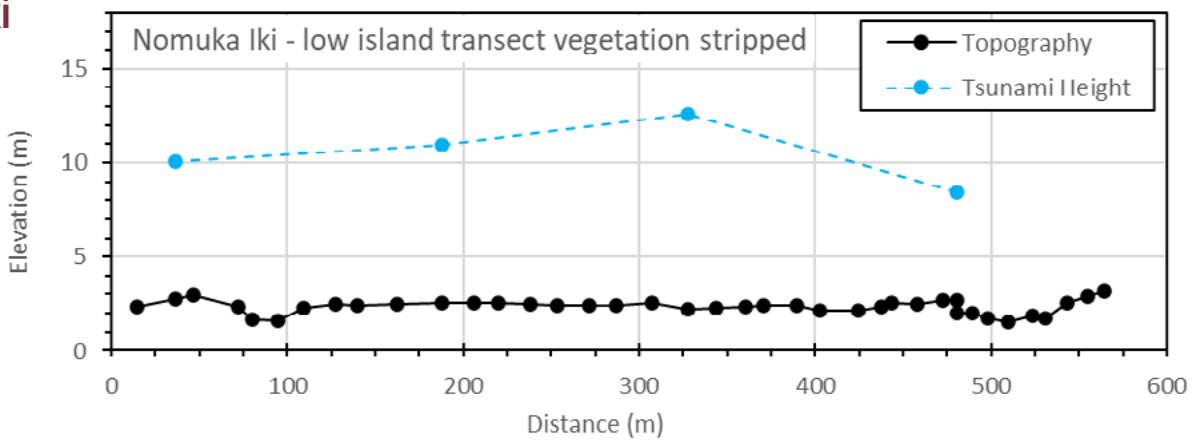


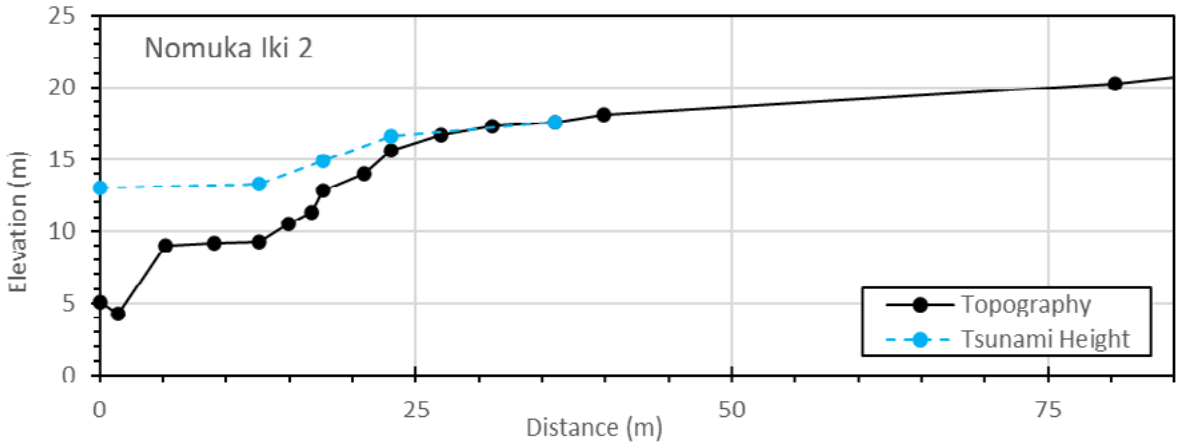


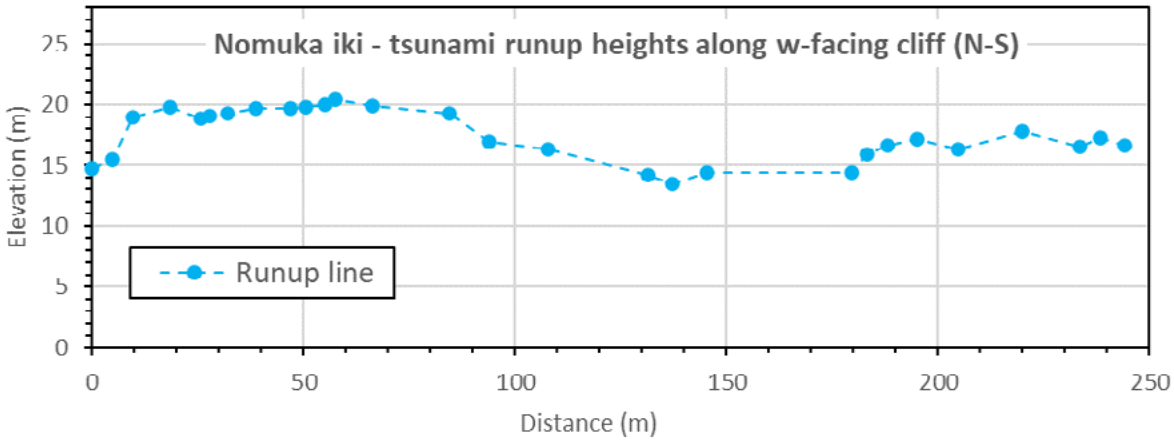




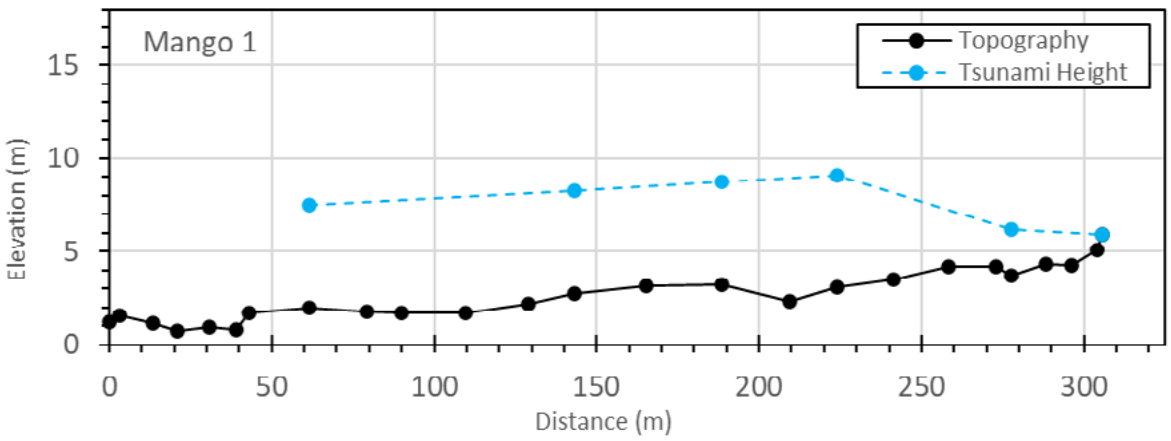
Nomuka Iki


Nomuka Iki - low island transect vegetation stripped
Topography
Tsunami Height
Elevation (m)
Distance (m)
0
5
10
15
0
100
200
300
400
500
600

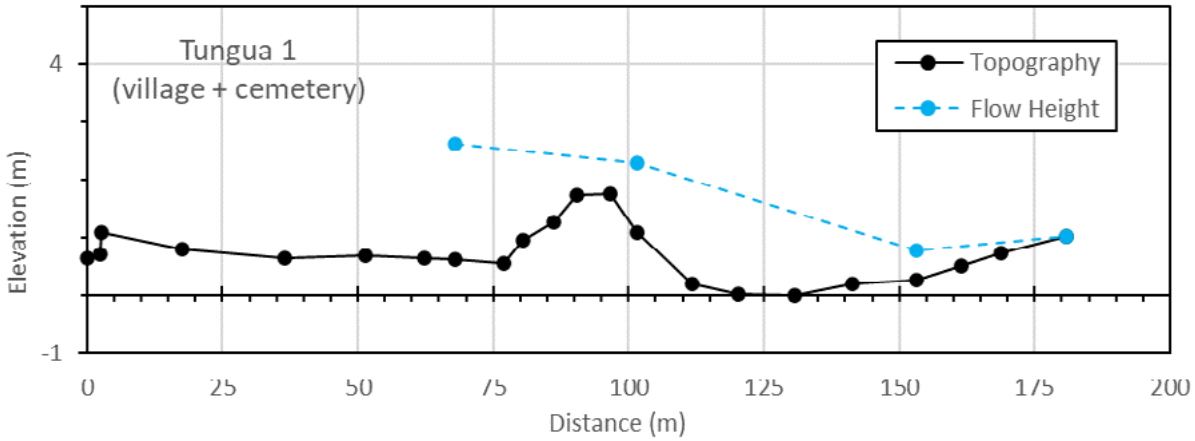

Nomuka Iki 2
Topography
Tsunami Height
Elevation (m)
Distance (m)
0
5
10
15
20
25
0
25
50
75

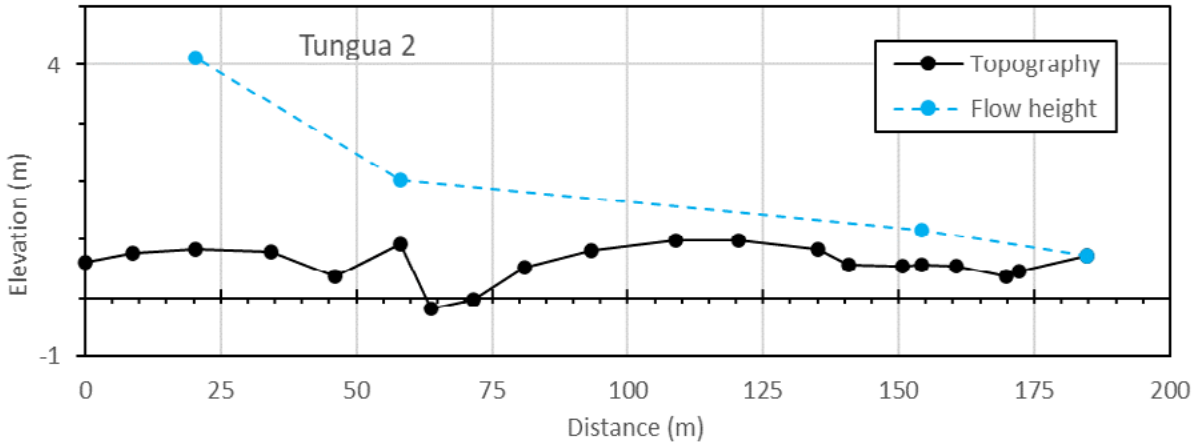

Nomuka iki - tsunami runup heights along w-facing cliff (N-S)
Runup line
Elevation (m)
Distance (m)
0
5
10
15
20
25
0
50
100
150
200
250

Mango

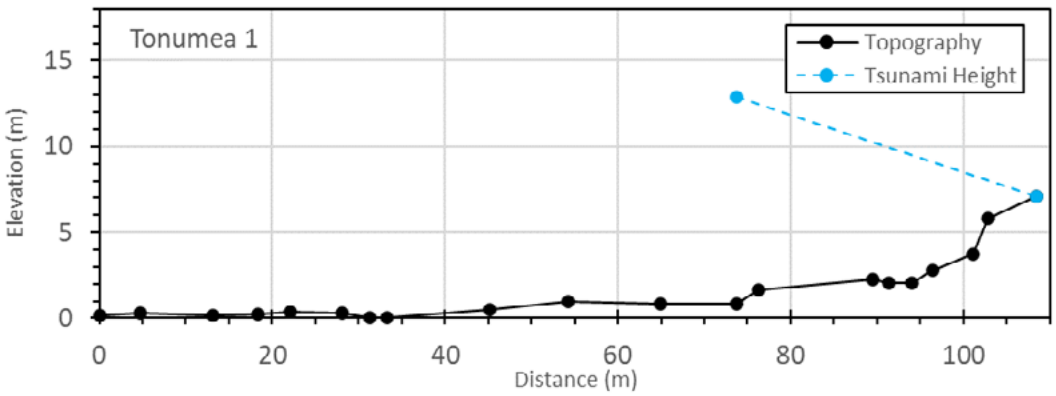


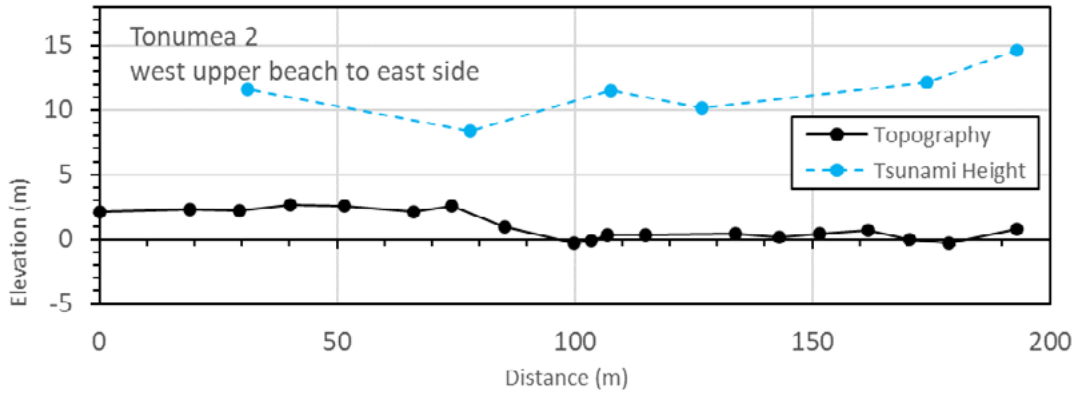
Tungua

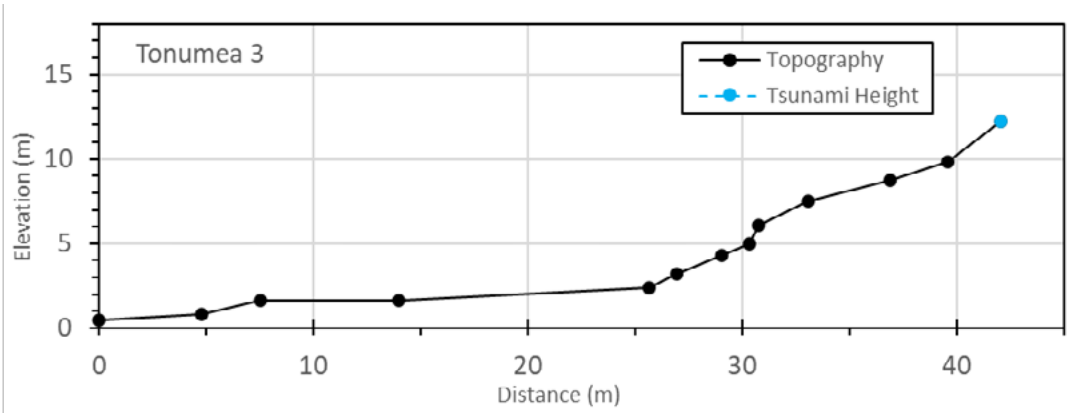


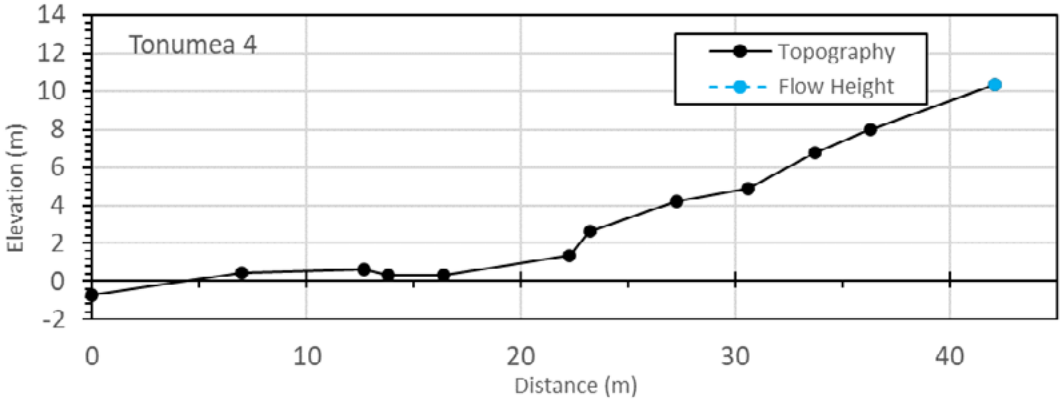


Tonumea

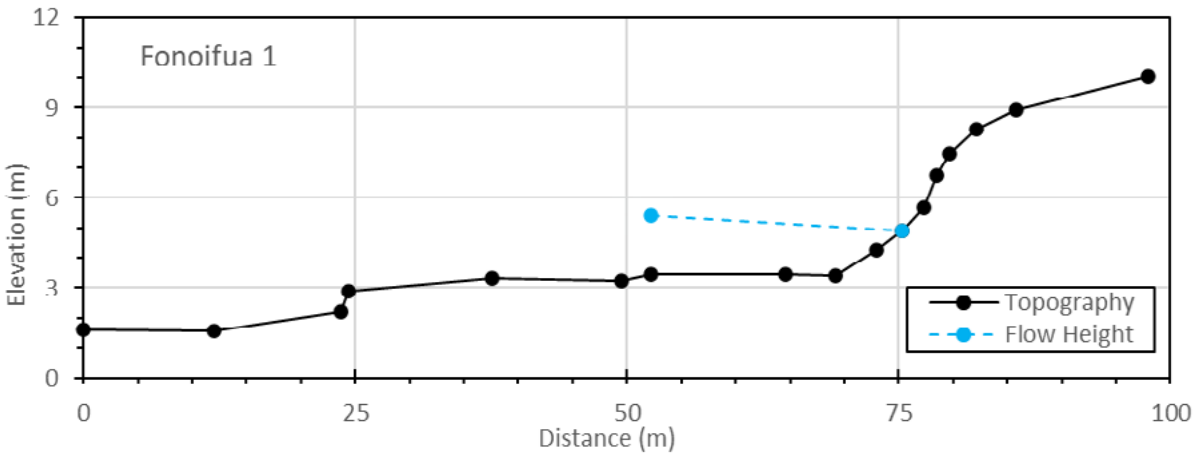

Tonumea 1
Topography
Tsunami Height
Elevation (m)
Distance (m)
0
5
10
15
0
20
40
60
80
100

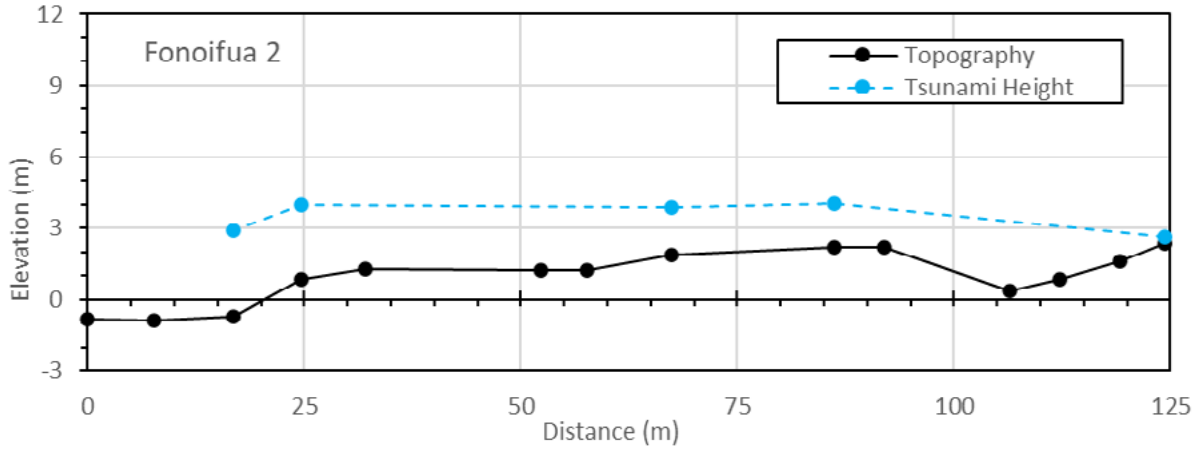

Tonumea 2
west upper beach to east side
Topography
Tsunami Height
Elevation (m)
Distance (m)
-5
0
5
10
15
0
50
100
150
200


Tonumea 3
Topography
Tsunami Height
Elevation (m)
Distance (m)
0
5
10
15
0
10
20
30
40


Tonumea 4
Topography
Flow Height
Elevation (m)
Distance (m)
-2
0
2
4
6
8
10
12
14
0
10
20
30
40

Fonoifua


Fonoifua 1
Elevation (m)
Distance (m)
Topography
Flow Height
0
3
6
9
12
0
25
50
75
100


Fonoifua 2
Elevation (m)
Distance (m)
Topography
Tsunami Height
-3
0
3
6
9
12
0
25
50
75
100
125

APPENDIX H. LINKS TO DATA, PHOTOS AND VIDEOS

Videos of Hunga volcano erupting on January 14th as well as drone footage of the aftermath from around Tongatapu can be seen on the Tonga Geological Services YouTube Page:

https://www.youtube.com/c/TongaGeologicalServices/videos

A compilation of social media and news footage from Tonga can be seen on the 'Disaster Compilations' YouTube Channel:

https://www.youtube.com/c/DisasterCompilations17/search?query=tonga

Photos from the Field Surveys conducted by the Tonga Geological Services and Prof. Shane Cronin Can be downloaded here:

http://xx.xx.xx

The photos are organised by date and location.

Survivor Stories on Facebook: A link to a Facebook Group with the search term 'tsunami' leads to a number of stories from the islands.

https://www.facebook.com/profile/100044168332484/search/?q=tsunami

APPENDIX I. LISALA FOLAU'S STORY

The following text and Images were taken from the Facebook blog 'Ordinary Tongan Lives' It tells the story of Lisala Folau's survival after being washed off of Atata Islands during the tsunami. It has been lightly edited.

LISALA: "Since 2014, I have not been able to walk properly. I can try, but most times I have to lean on someone else to walk. On Saturday, we were doing maintenance work in preparation for my son's wedding for this last Thursday. When my older brother saw the sea rising higher than normal, he alerted me. He knew I'd take a while so he said I should get going. He packed a few things as I left. I barely made it to the main road when my brother and nephew caught up with me, grabbed each arm, and helped me move faster. By that time, a wave from the West had made its way to the main road. Now, the volcano is on the northwestern side of our island. 'Atatā's [shape] is like a tennis racquet. The wider part is where our plantations are. The handle is where we live. When the waves came, it split on the wider and higher end of the island, came east and west, and met up right in the middle of town where most of us live. The first wave I saw was about 7 meters. It came and collapsed right at our house, destroyed it, and flowed straight to the other side of the island. My brother and nephew quickly helped me up a wild hibiscus tree as we waited on the wave to subside. My older brother left to get boys to carry me while I stayed with my nephew on the tree. Then there was this interval with no wave and the ocean ebbed. My nephew said maybe we should get down and walk uphill. We did that when a call came for my nephew to help our other relatives. A mother, her daughter, and an elderly grandma were also trying to get to safety. I held on to the granddaughter, my niece 'Elisiva while my nephew helped the grandma. We all hurried on when I saw my brother coming back. Suddenly, he jumped up a cement water tank and yelled, 'Hold on to a tree!' Tolofī and her elderly mother hid behind a water tank. As for 'Elisiva and I, it was too late."

LISALA: "Another 6-7 meter wave came from the West and collapsed right in the middle of the main road. The current from that wave was up to our waist. It swept me and 'Elisiva away and drove us apart. I was taken east where waves from both sides twirled and tossed me to and fro. As I couldn't use my feet, I only pushed myself up with my hand to breathe. I did that about 8 times. As I went down the 8th time, I told myself my next one will be my last and that'll be it for me. As I came up to breathe one last time, a tree floated right by me, and I grabbed it and held on tightly. That was around 7pm. I heard the village search party then and my son was one of them. He called my name 4 or 5 times. My life was in extreme danger, and I needed the help. But I could not for the life of me, answer my son. I knew if I say something, he will try to get to me, and our lives will both be in danger. Better to lose only one than two members of the family. As he continued calling my name, I floated silently in the dark and cried. But I can also assure you, I trusted in the God I worship that He would help in my hour of need. I said, 'God, would you forsake me at this hour?' Another big wave came and took me further away from land. It was this time that I felt the raining dust. That whole night I was just talking to my God. My family and children were also constantly before my eyes. I was ready to accept whatever God had for me. At around 4am, I felt that I was getting close to land and saw the shadow of an island. At dawn, I was on the reef of Toketoke, the island closest to Ha'atafu. When I made it to the beach, I sat down and again talked to my God. 'Praise thee God, I've made it here. But I am still in the vast ocean. Will you walk with me once more?'

LISALA'S SON: "I was on a boat full of people from Nuku'alofa to 'Atatā when the volcano erupted. Father told me to bring a light bulb for one of our rooms, so I hopped on the boat to bring it over. We were in the deep when we saw the smoke rising. When the big eruption occurred, the waves got bigger. One look from the waters told us our island was in great danger. The town officer who was also the skipper, offloaded the ice blocks and the heavier stuff so we could get home faster. He told me to look out for people who would be swept away and to call him if I see anyone. When the raining dust came, we were close to shore. As soon as we landed, we ran to find family members. My prime concern was my father who can barely walk and his older brother. Uncle said my father was already swept away. I went around with a torch in waist-high waters to look for him. In doing so, I found almost everyone who got swept away except my father. I assisted an elderly woman to safety. I heard there were two more, so I went down again and found Vai. She was clinging to a tree by the seashore and was stuck there. When the others took her up, the wave lowered and out of nowhere, 'Elisiva grabbed my leg underwater. I carried her uphill. All this time, I called out for my father. He had taken me fishing in the deep waters since third grade. He taught me young not to fear the ocean. I knew if he answered me, I would've gone without hesitation. But by Sunday, he wasn't found. I turned every log on the beach and grabbed every coconut in the ocean hoping I'd see him. My uncle convinced me to return to Tongatapu. I pushed the boat from shore and was the last to get on. At Nuku'alofa, most people offered their condolences. By Sunday evening, our extended family decided we'd hold a memorial service for my father on Thursday— the day my wedding was planned for."

LISALA: "It was around 8am on Sunday when I saw the Police boat on its way to 'Atatā. I found a piece of fabric on a tree branch and waved. No one saw me. After a while, they returned. I waved again with no luck. The next thing to do was to evaluate my environment and my capacity to help myself. Other chances of assistance were slim to none. Ha'atafu was close by and so was 'Atatā. My predicament was the deep waters in between. I couldn't possibly swim across with only two hands. Polo'a, the area close to Hōfoa, was the farthest from me. But I knew that area was all reef and then seaweed all the way to Sopu. Shallow waters would be best for my physical abilities. I left Toketoke around 10am. A piece of plywood helped me to float while

I used my hand to paddle. The plywood covered my neck to my waist, protecting it from the corals. As for my feet, they were dragged all the way over the reef. For me, the urgency was making it back to ease the worrying burdens of my family. My sister is highly diabetic. My youngest daughter has heart problems. What's the point of coming back alive if my disappearance caused death within my family? That thought propelled me and I asked God for more strength to keep pushing. At dusk, I made it to Polo'a. People usually fish there so I called for help. None came. It dawned on me that people fled the day before and weren't back yet. Calculating the distance from Polo'a to Sopu, I told myself once more, I'll make it."

LISALA: "At around 10pm Sunday night, I was at Paula Fukofuka's shore at Sopu. Low tide was approaching as I crawled on the sand from there to the shores across the Ministry of Fisheries. Using a piece of timber as a cane, I crossed over calling someone or anyone for help. I was hoping a security guard or staff would be there, but no answer came. People had evacuated. Back on the main road, a vehicle passed by then it turned around and came back. I asked the driver for a phone just to call home. As we chatted, Sione Pālavi—the driver—realized I'm the one man from 'Atatā that the government was out searching for. Pālavi helped me to his vehicle and drove me to my sister's house. My family had just finished devotional and decided to hold a memorial for me. In a kava circle there, friends and family talked of me. Pālavi got off the car and called out a few times, 'Come get your boy'…'Your lost lad is here.' When no one came, he asked for my name, turned on the light then he said, 'Ko Līsala eni, mou ha'u 'o 'oatu.' The cry of relief, joy, and perhaps despiration reverberated as everyone ran over to embrace me. It took a while to respond because they didn't know if I arrived dead or alive. There in my soaked shorts and singlet, we sat on the doorstep and humbly expressed in prayer our ultimate gratitude to our God. Now, we don't talk of injuries or inabilities, we just count blessings. The stories and rumors have spread. But I hope that when people hear my story or talk of me, that they also talk of Jesus. For He alone helped and healed me even in my imperfections. Some say I'm just a skilled fisherman or I was well-acquainted with the area. Others think I'm a courageous man. But I tell you, no amount of courage or strength in me would compare or even begin to withstand the might of God manifested in nature. I pray that people would speak my name as a symbol of divine mercy and grace granted by God through this, our miraculous journey. I know I'm spared because He still has a lot for me to do."

APPENDIX J. MANGO ISLAND SURVIVOR ACCOUNT

The following is reproduced from:
https://matangitonga.to/2022/01/25/62-survivors-mango-island-evacuated-safely-tongatapu

62 survivors from Mango Island evacuated safely to Tongatapu

Tuesday, January 25, 2022 - 14:31

By Linny Folau and Eleanor Gee

Sixty two survivors, including about 18 children and babies, evacuated from Mango Island, Ha'apai Group, were brought to Tongatapu on Saturday Jan. 22 by a Tongan navy patrol boat.

The evacuees were picked up from Nomuka island on the VOEA Ngahau Koula, after being rescued from Mango last week with only the clothes they were standing in.

One man died in the tsunami, on the closest populated island to the submarine volcano in Tonga.

All homes on Mango were destroyed in the multiple tsunamis generated by the powerful eruption of the Hunga Tonga -Hunga Ha'apai volcano, which blackened the island in a thick layer of ash several centimetres deep on Jan.15. The entire population has been evacuated.

Fourteen families are staying at the Free Wesleyan Church Hall in Longolongo, where they were in high spirits Monday, as the church brought in bales of donated clothes and toys for them.

Two Tonga Red Cross trauma counsellors were meeting the families and talking to them after their extraordinary ordeal.

The small community of fisherman and farmers lived on the coastline. Several of them said yesterday that they may never return to live there.

Fled to Open Hilltop

The community ran and scrambled to the top of a hill where they spent a fearful night, sitting in heavy ash fall, with a large pandanus mat, which the women held over their heads - the men out in the open, children in a small tent, and under woven coconut leaves. Rocks and pumice stones were falling with the heavy ash.

When dawn came, they came together on the hilltop, looking out to a grey horizon in a strange new blackened world, and prayed.

FWC Mango community leader, Rev. Kisina Toetu'u, (Free Wesleyan Church) said, "This natural disaster scale of devastation is the first I've seen but although we went through hardships as we fled for our lives, we are thankful that we are alive, all 62 of us."

Two babies, only a few months old, were among them. Their church steward was missing. They called out for him during the night.

Kalisi Levani (81) was the oldest person on the island, "Luckily it did not rain much that night. We are thankful we are alive." she told Matangi Tonga today in Nuku'alofa.

Kalisi said the sound and strength of this volcanic eruption at Hunga volcano was a new experience for her. A second fiery eruption was so strong the whole island was shaking, and the sky turned black as ash was rising.

Rev. Kisina Toetu'u of the Free Wesleyan Church said that on Sunday morning, after the eruption, a search party went down the hill to look for the missing steward, Telai Tutu'ila (65). They found his body.

They also found the church's fishing boat washed up on shore with the emergency beacon, which he turned on.

The Town Officer, Sione Vailea, was with the search party. He was thankful for the support of the church and the government during this evacuation. The community, traumatised by their experience, are recovering.

Rev Toetu'u said the disaster unfolded very quickly.

At 5:00pm on the Saturday he was sitting on the church verandah, engaged in a video call on his phone.

"Then I saw the waves coming inland." He moved quickly to get his family away from the coast.

"We all heard the explosion from the volcano. My family was scared but I wasn't because I was strong for the rest of my family and community, because if I seem discouraged, then they too will feel discouraged," he said.

Rev Toetu'u first carried his 21-year-old sickly daughter, who is too weak to run, on his back, up the hill.

"As I got her safely up, I came back for my wife and other members of my family, as well as fellow churchgoers and we all made it up the hill."

"By 5:30pm it was already dark. ...As I sat up there, I could hear the waves crushing the land."

They put up a small tent to cover around 18 children, younger than 12 years.

Some women and girls sheltered under one pandanus mat.

"But the men had nowhere to hide under during the night, all they had was the clothes on their backs and something to cover their faces."

"We stayed there overnight to be safe, and it was only the next morning that some men as a search party went down to look for our missing person and saw the devastation, and that nothing was left," he said.

The community named the hill that saved them "Mo'unga Saione" (Mount Zion) where they had prayed during the disaster that night.

"We named it as such because we fled to the mountain - God is our refuge and protector."

"We send our love to the small islands in Ha'apai, and we pray that God will get us through these difficult times."

Rev. Toetu'u said they are happy to be taken care of in Tongatapu.

"I was glad to see as we approached Nuku'alofa harbour, that the Prime Minister and some Ministers were there to welcome us, he said.

Will they return to Mango Island?

Rev. Toetu'u said "not in the near future".

"Everything is gone there, our homes, so we are here for now and then we will see what steps to take."

Explosive Fire

Kalisi Levani (81) speaks calmly and smiles, in spite of the difficulty she went through with her family, including the loss of her home and livelihood.

Kalisi said she was at home with family and her grandchildren. She was weaving.

"The first eruption, I knew it was the volcano," she said.

Then the second eruption and the whole island was shaking.

"We all jumped up and stood at the door. I saw in the sky the black smoke rising and within the black smoke there was a glow."

Within minutes the sky turned dark.

"I heard more explosions like shooting sounds."

The town officer, Sione Vailea, shouted out to them to try and get inland because the sea was coming, a tsunami.

Sione is married to her daughter.

"We all ran, and we didn't take anything."

Kalisi held her daughter's hand and ran through the bushes and it was raining and muddy and they reached the side of the hill.

"I told my daughter to leave me here because I'm really tired and I can't climb up. All of you go and I will stay here! She said no, we would all go, and no one will stay here in case the sea gets here.

"We were arguing when her husband arrived and gripped my hand and forcibly pulled me to climb up the mountain with them," she said.

"The three of us fell on the mountain and the path to the top was bushy. But he got my hand and was going to carry me on his back, and we went a few steps, but I told him to put me down, because if I don't die from the tsunami, I'll die from being exhausted."

Kalisi said Sione put her down and they walked a bit then rested on the hill.

"Then we finally reached the very top and found others there already using coconut fronds to make a fale," Kalisi said.

Another family arrived with a plastic tarpaulin and put the children in there. It was starting to rain and getting really dark, and more families were running to the top.

"We stayed there in the dark and the rain fell, it was sad with the ash, and the rocks all falling down. We pulled up a piece of mat to put over us. We heard it all coming down and the ash landed on our faces, and we wiped it off our faces, it was muddy. The saddest part was seeing the men who had nothing to hide under. The rest of us were hiding under trees."

Kalisi said the men were sitting in the mud in the open, some were lying down.

Some were also trying to the find the man that was missing. They were calling for him and using torches to try and find him, but they did not go into the sea.

APPENDIX K. LIST OF NEWS STORIES FROM MATAI TONGA

A summary of news stores from Matai Tonga (https://matangitonga.to/), an online Tongan news website.
This list was compiled by the International Tsunami Information Center (ITIC).

Title	Date	Author	Description
Air NZ funeral flight to Tonga cancelled as Hunga eruption continues	21 December 2021	By Mary Lyn Fonua	Eruption timeline
Tongans told to protect water tanks from acid rain, as eruption continues	21 December 2021		Tonga's erupting Hunga Ha'apai volcano put on a show of lightning at sunset tonight. As a large gaseous cloud continues to rise to 18km altitude and drift over all islands, all Tongan residents were advised by geologists this evening to protect their water tanks from possible acidic rainfall, until the volcanic eruption ceases.
Pyroclastic explosion to 350m recorded by Tonga Navy	23 December 2021	By Mary Lyn Fonua	Taaniela Kula, leading the Tonga Geological Service volcano monitoring, said the important video, uploaded to Instagram by a crew member late yesterday, helped Tongan geologists understand the nature of the explosive basal surge eruption.
Sulphur and lightning on 4th day of Hunga's eruption	23 December 2021		Sulphur dioxide emitted from the Hunga Tonga-Hunga Ha'apai volcano continues to spread over the Ha'apai, Vava'u and Niuatoutapu groups drifting NNE at a high altitude of 8-14km.
Merry Christmas and stay away from Hunga volcano, warns Tonga Geological Services	24 December 2021		Warning that extreme hazards in the area up to five kilometres around the eruption, include possible explosions, surges, ballistic ejecta, tephra, lava domes, laze, vog, pumice shoals, volcanic edifice collapse and tsunamis.
Volcanic eruption in Tonga continues, disrupts flights	29 December 2021		The Hunga Tonga-Hunga Ha'apai volcano continues to erupt intermittently, the Tonga Geological Services said this morning, warning residents in Ha'apai to cover water reservoirs in case of acid rain that may be caused by volcanic emissions in the atmosphere.
Toxic seawater around Hunga volcano may poison fish, TGS warns	4 January 2022		Seawater around the active Hunga Tonga Hunga Ha'apai volcano is contaminated with toxic volcanic discharge and local fishermen should assume that fish in these waters are poisonous or poisonous if consumed, Tongan authorities warned today.
Hunga volcano quietens down, while pumice floats onto Tongatapu beaches	6 January 2022		"Volcanic activity is considered to have ceased, and the volcano has reverted to its normal, non-eruptive state. Monitoring will continue for 7 days from the last detected activity before declaring total n-active."

Title	Date	Author	Description
Marine tsunami warning for Tonga coastal areas, as volcanic eruption likely	14 January 2022		National tsunami marine warning issued at 11:12am, Fri. January 14.
Sea fluctuations, volcanic activity continue after large eruption	14 January 2022		Eruption of the Hunga volcano, continuous for over 12 hours, reached 20km above sea level - the largest in a series of eruptions since December. Tsunami waves of up to 30cm were still being recorded at 6:00pm on the Nuku'alofa tidal gauge.
Tonga Gov't closes due to tsunami warning in force	14 January 2022		Government offices closed at 1:30pm, due to the tsunami warning in force.
Volcanic plume of ash, steam and gas over Tonga	14 January 2022		A plume of ash, steam and gas has dispersed at a radius of 250km from the Hunga-Tonga-Hunga-Ha'apai Volcano over Tongatapu, 'Eua, Vava'u and Ha'apai group, Tonga Geological Services advised.
Tongan geologists observe stunning eruptions at Hunga	15 January 2022	By Mary Lyn Fonua	A team of Tongan geologists who went out to observe the Jan. 14 eruption of the Hunga Tonga Hunga Ha'apai volcano witnessed spectacular explosions on the dangerous mission on Friday afternoon.
We're back, but without full internet	22 January 2022	By Pesi and Mary Lyn Fonua	Our office and place of residence on the Nuku'alofa seafront survived the tsunami waves. Not everyone was so lucky, and many families have lost their homes...
Two national Emergencies for Tonga as new Govt. grapples with disaster	24 January 2022	By Pesi Fonua	The people evacuated from Mango Island in Ha'apai are being brought to Tongatapu, to relieve pressure on Nomuka. Nomuka was also heavily damaged by the tsunami and was having problems catering for its own population. He was informed there were only 30 people on Mango during the eruption. An estimated 62 people live on Mango, but during the Christmas holidays, some people had left the island. The PM confirmed that three people had died in the tsunamis that struck with a devastating impact on some of the coastal areas and low-lying islands of Tonga. The dead included a British national, Angela Glover (51) who was staying at Kanokupolu, Tongatapu. In Ha'apai a man, Telai Tutu'ila died at Mango Island; and a woman, Maumi Lauaki at Nomuka, Ha'apai.
'We must all stand and work for our country', King Tupou VI tells Tonga	25 January 2022		King Tupou VI was thankful that the lives were lost were a few but felt and expressed condolences to their immediate families of those who lost their lives because it is a life.

Title	Date	Author	Description
62 survivors from Mango Island evacuated safely to Tongatapu	25 January 2022	By Linny Folau and Eleanor Gee	Sixty two survivors, including about 18 children and babies, evacuated from Mango Island. One man died in the tsunami, on the closest populated island to the submarine volcano in Tonga. All homes on Mango were destroyed in the multiple tsunamis generated by the the powerful eruption of the volcano....
Tonga restricts sources of drinking water for bottling	25 January 2022	By Pesi Fonua	Only underground water supplied by the Tonga Water Board may be used for bottled water that is processed in Tonga, to sell for public consumption.
King Tupou VI was thankful that the lives were lost were a few but felt and expressed condolences to their immediate families of those who lost their lives because it is a life.	27 January 2022	By Eleanor Gee	COVID - Australian Vessel
Two ships need to assess state of volcano and submarine cable	27 January 2022		Two highly specialised ships need to come to Tonga – one to assess the current state of the Hunga Tonga - Hunga Ha'apai volcano, and another to repair Tonga's submarine fibre optic cable and restore communications with the world.
Emergency support for Tonga in "timely response"	28 January 2022		WB USD $8M donation
Pangaimotu tsunami survivors climbed into fau trees	28 January 2022	By Pesi Fonua	Eleven people on Pangaimotu Island climbed into fau trees as tsunamis ravaged the coast of the low-lying atoll on Jan. 15, following the massive explosion at Hunga volcano.
Nomuka health clinic destroyed by tsunami, relocates to school	1 February 2022	By Eleanor Gee	Nomuka health clinic in Ha'apai and the Maternal Child Health (MCH) clinic at Sopu, Tongatapu destroyed by tsunamis
Reef fish and shellfish may be contaminated by volcanic emission**s**	1 February 2022	By Pesi Fonua	Fishery resources contaminated
Fleet of heavy earthmoving equipment gifted by PRC	14 February 2022		Republic of China donation
30 Containers of relief goods from NZ distributed	15 February 2022		Relief goods - NZ
New UNICEF – Govt. Japan partnership to support Tongan families affected by disaster	15 February 2022		USD$1,250,000 partnership to support the Government of Tonga to ensure about 19,250 people, including 10,000 children, affected by the recent volcanic eruption and tsunami have sufficient access to safe drinking water, a clean environment, as well as good health.

Title	Date	Author	Description
World Bank Tongan Disaster Assessment Report estimates damages at US$90M	15 February 2022		The Tonga Hunga-Tonga-Hunga-Ha'apai volcanic eruption, tsunami and ashfall has caused an estimated US$90.4M (TOP 208 million) in damages – the equivalent of approximately 18.5% of Tonga's Gross Domestic Product (GDP) – a World Bank assessment for the Government of Tonga has found. Full Report:
80km stretch of Tonga Cable blown to bits by eruption	16 February 2022	By Mary Lyn Fonua	Short pieces have been recovered, while a major section of the fibre optic cable, about 55 km long, including an expensive repeater, has yet to be recovered from the seabed.
Elon Musk donates 50 satellite terminals to Tonga	18 February 2022		"These terminals will be deployed at strategic locations throughout Tonga to ensure connection and communications are maintained, particularly for the disaster response operation".
Around 200 small fishing boats wrecked by tsunamis	21 February 2022	By Eleanor Gee	Almost 200 boats were damaged by the tsunamis generated by the volcanic eruption on January 15, the Prime Minister Hon Siaosi Sovaleni said on Friday, Feb. 17.
Torn apart, missing 110km domestic fibre optic cable may take year to replace	1 March 2022		Tonga's domestic fibre optic telecommunications cable was torn apart by tremendous forces and deeply buried under volcanic debris on the ocean floor. It may take up to a year to fix.
Gov't launches rebuild after natural disasters	3 March 2022		The Prime Minister's Office stated today that the Ministry of Infrastructure will coordinate the construction of 468 houses that were damaged during the events of Jan. 15, with 286 houses that will need to be rebuilt, while 182 were damaged. This includes 157 houses in Tongatapu, 36 in 'Eua and 93 in Ha'apai.
Table tennis enjoyed by displaced youth of Mango and 'Atata	3 March 2022		Table Tennis is providing a powerful distraction for the people among the most affected by the volcanic eruptions and tsunamis, which devastated their homes on the islands of Mango and 'Atata.
Nomuka people request evacuation centre, during PM's flying visit	8 March 2022		During the visit, the Nomuka people asked for an evacuation hall to be built at the highest point in the island, to house them should there be similar dangers in the future.
New fishing boats for tsunami-affected communities	10 March 2022		Six boats from Mr Hart and eight boats from Pita were handed over to help people in affected communities get back to their fishing livelihoods.
Loud thunder over Tongatapu "not an eruption"	15 March 2022		"It is NOT RELATED to HTHH volcanic eruption or any eruption. Today's weather will be mostly cloudy and overcast with occasional rain and thunderstorm especially Tongatapu and 'Eua." they stated on the Tonga Met Facebook page

Title	Date	Author	Description
3000 relief kits distributed to affected families	17 March 2022		3,000 family kits donated from China's Red Cross have been distributed this week to affected families on Tongatapu, after the volcanic eruption and tsunamis on January 15. The distribution was carried out by Tonga Red Cross to 75 households at Kanokupolu and 7 households at ‘Ahau on March 15.
Scientific mission to Tonga to study effects of volcanic eruption	1 April 2022		Scientists studying Tonga's seabed expect to find dramatic changes in the underwater topography following the catastrophic eruption of the Hunga Tonga-Hunga Ha'apai sea volcano on January 15, 2022.
Mango island community to rebuild on ‘Eua, under island development program	18 May 2022	By Linny Folau	The island community of Mango in Ha’apai who were affected by the tsunamis and volcano eruption on 15 January will have their homes rebuilt on the outer island of ‘Eua.
Cash assistance for 800 vulnerable households	27 May 2022		IOM said the cash assistance program addresses the urgent needs of 800 families
King and Queen lead $24m project to build new settlements for Kanokupolu and Mango people	11 June 2022		The Crown Estate of Kanokupolu in western Tongatapu, with a population of around 320 people, was among the most severely damaged areas in the natural disaster on January 15. Mango islanders are expected to relocate to temporary shelters at Ta'anga soon, while their new houses are to be constructed.
National early warning project resumes with arrival of Japanese team	1 July 2022		The project aims to provide facilities for swift transmission of warning and safety information on natural disasters by installing an emergency radio communication system, an early warning sound alert system all over Tonga It will also look to improve TBC broadcasting infrastructure and contribute to disaster prevention and measures relating to the environment and climate change.
US$19 Million for safer schools and improved emergency early warning systems in Tonga	4 July 2022		The World Bank’s Board of Executive Directors has approved US $19.5 million (approximately TOP46 million) in additional funding for disaster recovery and resilience projects in Tonga. The new funding will also contribute a further US $5 million to the Tonga component of the Pacific Resilience Program (PREP) - bringing the project to a total of US$39 million - to further strengthen emergency early warning systems and improve disaster preparedness.
Tonga's domestic cable may take a year to replace	7 July 2022	By Linny Folau	...a geological survey showed the seabed around the volcano and along our cable path (near the volcano) is very smooth and as such provides a pretty good surface for laying the new cable over.

Title	Date	Author	Description
Queen presents new truck to Mango Island community	4 August 2022		Government is rebuilding the houses for the Mango community on land allocated by the King in 'Eua.
Unmanned vessel records continuing volcanic activity deep inside HTHH	12 August 2022		Clear signs of continuing volcanic activity were seen inside the deep caldera of the Hunga-Tonga Hunga-Ha'apai (HTHH)volcano by an unmanned remotely operated surface vessel, the (USV) Maxlimer on its first initial survey mission in Tonga.
Japan's new grant aid projects to Tonga include help with clean-up	12 August 2022		The Government of Japan has committed three grant aid projects aimed to improve the waste management and water supply system, while extending the nationwide early warning system in Tonga.
Australia supports Tonga's tide and tsunami station maintenance	19 August 2022		Essential maintenance on Tonga's tide and tsunami station and global navigation satellite system is being conducted by a team from the Australian Government funded Climate and Oceans Support Program in the Pacific. They will decommission the old tide gauge at Queen Salote Wharf and replace it with a new tide and tsunami station at Vuna Wharf.
Psychosocial recovery program after natural disasters	19 August 2022		“Particularly children are more vulnerable because their minds and bodies are still developing. The children we have worked with have experienced traumatic natural events on 15 January and have lost their homes and personal space, changing schools and changing environments.”
Expedition surveying coastal marine habitats in Tongan waters	23 August 2022		A team of scientists is undertaking coastal marine surveys in Tongan waters to evaluate impacts to coral reefs and fisheries following the Hunga-Tonga Hunga-Ha'apai eruption in January 2022.

APPENDIX L. SOCIAL MEDIA LINKS

Assorted links for reference

TSUNAMI EVENT IN TONGA ON 15th January, 2022

1. https://fb.watch/ayifesYXyv/ - Nukualofa, Tonga
2. https://fb.watch/ayihBykx1n/
3. https://www.facebook.com/100005516288157/videos/880677672602532/ - Rennie's Interview
4.

SONIC BOOM FROM TONGA

5. https://www.facebook.com/100006513439385/videos/622698772315823/
6. Loud thundery sounds being experienced in Fiji are from the huge volcanic eruption in Tonga (fijivillage.com)

TSUNAMI WAVES IN VANUATU

7. Steve Govan - One tsunami lo Eton | Facebook - Eton Island, Vanuatu

TSUNAMI WAVES IN FIJI ON 15th January, 2022

1. https://www.facebook.com/IsaiaLawaniyasana/posts/555218582146451 - Tavuki village, Kadavu Island
2. https://www.facebook.com/1339830975/videos/337004624953419/ - Tavuki Village, Kadavu Island
3. https://www.facebook.com/100006513439385/videos/1846800592187351/ - School Compound on Moce Island
4. https://www.facebook.com/disova.vulawalu/posts/3064331900492939 - Naroi village, Moala
5. https://www.facebook.com/734619668/videos/256097386634716/ - Mavana Village, Vanua Balavu Island, Lau Group, Fiji.
6. https://www.facebook.com/100027355037881/videos/2019670241546431/ - Moala Island, lau Group, Fiji.
7. https://www.facebook.com/100027355037881/videos/505993757467192/ - Naroi village, Moala Island, LAU group
8. https://www.facebook.com/mixfm94/posts/4968471466537770 Moce Island
9. https://twitter.com/SirF1shALot/status/1482311307701661704 Galoa, Kadavu
10. https://www.facebook.com/iliesa.w.tupoulahi/posts/10160050048347244 Nukuni Village, Ono-i-Lau

NEWS ON HTHH TSUNAMI

1. https://fb.watch/azcxAdR-UY/ - ABC7 News
2. https://www.facebook.com/ExtremePursuit/posts/1407831022945830 Extreme Pursuit
3. https://www.facebook.com/SismoMundial/posts/4879395458795912 Peru
4. https://fb.watch/aAs1UVOS7c/ - Fiji One News 16th January, 2022
5. https://www.stuff.co.nz/national/explained/127518270/the-most-explosive-eruption-in-30-years-hunga-tongahunga-haapai-rewrites-tsunami-rules?rm=a
6. https://www.chinadaily.com.cn/a/202201/16/WS61e356c7a310cdd39bc81480.html?fbclid=IwAR2kI1Dvzk07UL-QiFQzm23mf_eWgOA6lYwHtrWoJswg0ok1gNFcWQ9rUZtk – Tsunami Reaches Japan

7. https://www.facebook.com/glory.ian/posts/10225493524021808 NZ Defence Force Support
8. https://matangitonga.to/2022/01/15/tongan-geologists-stunning-Jan14eruptions?fbclid=IwAR1OBZvj4gWLOJo4P-Q0I6OuSdayXMzKjS3dq0quGyZ9ihZCDkt5WzniX0sc
9. https://twitter.com/CopernicusEMS/status/1482676574159839233
10. https://www.stuff.co.nz/world/south-pacific/300497165/tonga-eruption-likely-the-worlds-largest-in-30-years--scientist?rm=a
11. https://www.stuff.co.nz/national/127515319/tonga-volcano-photos-and-video-give-first-glimpse-of-tsunamis-impact?rm=a
12. https://www.stuff.co.nz/world/127513001/likelihood-of-tongan-volcano-erupting-again-hard-to-predict-due-to-lack-of-active-monitoring?rm=a – Video footage of HTHH Volcano from TGS.
13. https://www.stuff.co.nz/world/south-pacific/300496316/underwater-volcano-hungatongahunga-haapai-erupts-again?rm=a
14. https://theconversation.com/the-tonga-volcanic-eruption-has-revealed-the-vulnerabilities-in-our-global-telecommunication-system-175048
15. https://twitter.com/UWCIMSS/status/1481764273508524034
16. https://www.stuff.co.nz/world/116676382/underwater-volcano-eruption-near-tonga-could-create-a-brand-new-island?rm=a
17. https://www.stuff.co.nz/world/south-pacific/64548453/big-volcanic-eruption-near-tongas-capital
18. https://www.abc.net.au/news/2022-01-15/tonga-issues-tsunami-warning-after-undersea-volcano-erupts/100759102
19. https://www.abc.net.au/news/2022-01-16/tonga-volcano-could-erupt-again-says-expert-who-visited-the-site/100759390
20. https://www.abc.net.au/news/science/2022-01-18/tonga-volcano-tsunami-hunga-eruption-why-so-big/100761750
21. https://www.abc.net.au/news/2019-02-06/nasa-scientists-pay-first-visit-to-baby-volcanic-island/10784236
22. https://www.abc.net.au/news/2022-01-17/tonga-volcano-eruption-hunga-tonga-hunga-ha-apai-tsunami-/100761966

POST TSUNAMI -IMMEDIATE UPDATES FROM TONGA on 16th January

1. https://www.facebook.com/ngaluope1/posts/1385774405159096
2. https://fb.watch/aIklwpUKxQ/
3. https://www.facebook.com/ngaluope1/posts/1386399198429950
4. https://fb.watch/aIktPFPAYT/
5. https://www.facebook.com/100001699118728/videos/1101859450565257/ Video from Pagai, Haapaii on 16 January, 2022.
6. https://www.facebook.com/radiodateline.tonga/posts/2186375694871318 Ashfall on Nukualofa

SURVIVOR STORY

1. https://www.facebook.com/permalink.php?story_fbid=923477688303434&id=382923949025480 – Lisala Folau
2. https://www.facebook.com/vlavaki/posts/5084924324864700 - Real Life Aquaman – Lisala Folau
3. https://fb.watch/aIptcaAbn4/ - swimming pigs
4. https://www.facebook.com/RoyalSunset/posts/5630412906976135 - Royal Sunset Island Resport – Atata Island
5. https://www.facebook.com/george.lavaka/posts/5024828034202131 - Lisala Latu Story
6. https://www.facebook.com/permalink.php?story_fbid=50995084434137 - Ha'atafu Beach Resort
7. https://www.facebook.com/tevitatai.fukofuka/posts/7206228949417857 - Tevita Tai Fukofuka
8. https://www.facebook.com/HonFredericaTuita/posts/481798933304872 - Hon Frederica Tuita
9. https://www.stuff.co.nz/world/south-pacific/127571008/tonga-tsunami-family-survived-waves-by-tying-themselves-to-a-tree?fbclid=IwAR0K3mNnXwlJtqVLW2jEXJf6bE9nqVOZ2o4UWNoOiDrKOL8zT5Sh7OFVSzo – Fafa Island , Tongatapu
10. https://www.facebook.com/lazzs.fakaoc.1/posts/1013609995859119 - Mango Island, Ha'apai Group

DAMAGE ASSESSMENT

1. https://www.facebook.com/AkiJr/posts/3183836205233109 - Ha'atafu Beach Resort, Tongatapu
2. https://www.facebook.com/permalink.php?story_fbid=5105530512811567&id=203040206393980 – Ha'atafu Beach Resort, Tongatapu
3. https://fb.watch/aHiw4gEXzk/ - Kanakupolu, Nukualofa
4. https://www.facebook.com/ngaluope1/posts/1389529238116946 - Nukualofa
5. https://www.facebook.com/ngaluope1/posts/1389489304787606- Nukualofa
6. https://www.facebook.com/ngaluope1/posts/1387819661621237- Nukualofa
7. https://www.facebook.com/malaumedia/posts/346984737430551 - Ha'afeva Island (Ha'apai Group) – only western side affected
8. https://www.facebook.com/malaumedia/posts/346965850765773 - Nomukeiki Island - uninhabited but vegetation destroyed and completely inundated
9. https://www.facebook.com/malaumedia/posts/346952004100491 - Fonoi Island (Ha'apai Group) – 20 January
10. https://www.facebook.com/malaumedia/posts/346945767434448 -Tungua Island (Ha'apai Group) – 18th January
11. https://www.facebook.com/malaumedia/posts/346887244106967 - Nomuka Island (Ha'apai Group) -16 January
12. https://www.facebook.com/malaumedia/posts/346849007444124 - Nukualofa
13. https://www.facebook.com/RoyalSunset/posts/5630437456973680 - Atata Island - Royal Sunset (Western Tongatapu)

APPENDIX M. TONGA METEOROLOGICAL SERVICES RESPONSE TIMELINE

TONGA METEOROLOGICAL SERVICES

MULTI-HAZARD EARLY WARNING TIMELINE SUMMARY REPORT ON THE VOLCANIC ERUPTION AND TSUNAMI EVENT, OPERATIONS AND RESPONSE

(14th – 17th January 2021)

Date/Local Time	Response Operations	Remarks
14th January 2022 10:30 – 10:50am	Received observations from Mango Town officer, Marine and Ports officer and Fonoi resident about the abnormal tides experienced in their respective shore lines	Updated the Director of TMS and discussion the issuing of the relevant warning
14th January 2022 11:12am	Issued Tsunami Marine Warning No.1 for Tonga (Tongan and English versions). Tsunami operation continued and direct live on-air briefings were being made from the Tsunami Warning Centre on radio Tonga to the people.	Refer to Annex 1 of this report
14th January 2022 03:26pm	Tsunami Marine Warning for Tonga No. 2 (Tongan and English versions). Tsunami operation continued and direct live on-air briefings were being made from the Tsunami Warning Centre on radio Tonga to the people.	Refer to Annex 2 of this report
14th January 2022 06:22pm	Cancelled Tsunami Marine Warning No. 1 for: • Niuafo'ou • Niuatoputapu • Vava'u • Kauvai Ha'ano District, Ha'apai • Pangai Lifuka District • Ha'apai Lulunga Distric	Refer to Annex 3 of this report
14th January 2022 10:00pm	Tsunami Marine Warning for Tonga No. 3 (Tongan and English versions) for: • 'Otumu'omu'a Group • Tongatapu • 'Atataa • 'Eueiki • 'Eua Tsunami operation continued and direct live on-air briefings were being made from the Tsunami Warning Centre on Radio Tonga to the people.	Refer to Annex 4 of this report

Date/Local Time	Response Operations	Remarks
15th January 2022 01:00am	Tsunami Marine Warning for Tonga No. 4 (Tongan and English versions) for: • ‘Otumu’omu’a Group • Tongatapu • ‘Atataa • ‘Eueiki • ‘Eua Tsunami operation continued and direct live on-air briefings were being made from the Tsunami Warning Centre on Radio Tonga (AM Radio) to the people.	Refer to Annex 5 of this report
15th January 2022 04:00am	Tsunami Marine Warning for Tonga No. 5 (Tongan and English versions) for: • ‘Otumu’omu’a Group • Tongatapu • ‘Atataa • ‘Eueiki • ‘Eua Tsunami operation continued and direct live on-air briefings were being made from the Tsunami Warning Centre on Radio A3Z to the people.	Refer to Annex 6 of this report
15th January 2022 07:00am	Tsunami Marine Warning for Tonga No. 6 (Tongan and English versions) for: • ‘Otumu’omu’a Group • Tongatapu • ‘Atataa • ‘Eueiki • ‘Eua Tsunami operation continued and direct live on-air briefings were being made from the Tsunami Warning Centre on Radio A3Z to the people.	Refer to Annex 7 of this report

Date/Local Time	Response Operations	Remarks
15th January 2022 10:00am	Cancellation of Tsunami Marine Warning for Tonga (Tongan and English versions) for: • ‘Otumu’omu’a Group • Tongatapu • ‘Atataa • ‘Eueiki • ‘Eua Due to consistent reductions in the wave amplitude measured from sea level gauges in TBU/Vv/NTT getting lower than 10cm and the reduction in the volcano activity	Refer to Annex 8 of this report
15th January 2022 5:13pm – 5:16pm	First sighting of the development of volcanic ash mushroom cloud from the Fua’amotu MET Office observation site. Duty officers immediately called the Tonga Geological Services via VHF radio and reported the sighting of this volcanic clouds.	Duty Officers: Selusalema Vite and Sitamipa Paea
15th January 2022 5:21pm	Extremely loud volcanic blast and acoustic shock wave observe and experienced on the ground.	Director Instructs Officers on Duty via phone call to issue and Urgent Tsunami Warnings advising people to move inland based on the magnitude of the blast and his observations of a mass sea birds coming inland from the NW direction.
15th January 2022 5:30pm or there about	Duty Officers issue a direct verbal Urgent Tsunami Warning Message on AM Radio after some difficulty in breaking through a congested phoneline to Radio Tonga (A3Z)	This warning was repeated a several times by both the Duty Officers and AM Radio announcer for people to evacuate inland. Director Arrives in Office between 5:35 and 5:40pm.
15th January 2022 5:45pm to 1:48am on 16th	Issued 1st Tsunami Warning Bulletin (written) for Tonga (Tongan and English versions). Tsunami operation continued and direct live on-air briefings were being made from the Tsunami Warning Centre on radio Tonga to the people.	Discussion with Volcanic Ash Advisory Centre (Wellington, NZ) were carried out at every 2 to 3 hours discussing the status of the eruption, ash intensity, coverage and height over the Tonga areas. Refer to Annex 9 of this report

Date/Local Time	Response Operations	Remarks
15th January 2022 6:30pm	Last observation received from the Nuku'alofa tide gauge. Last internet connection received at the Tonga MET Office.	Nuku'alofa tide gauge was online at 2pm,17th Jan 2022 as it was confirmed from Jeff (BOM) that they can view tide gauge reading from Australia but cannot access information from Tonga MET due to internet connection failure.
16th January 2022 1:48am	Downgraded Tsunami Warning for Tonga to Tsunami Marine Warning for Tonga based on direct ocean observations from the Director of Geology and discussion with Tonga Geological Unit. Constant radio briefings on air were carried out via radio to the people of Tonga.	Discussion with Volcanic Ash Advisory Centre (Wellington, NZ) were carried out at every 2 to 3 hours discussing the status of the eruption, ash intensity, coverage and height over the Tonga areas. Refer to annex 10 of this report
16th January 2022 11:00am	Director of Meteorology briefing to NEMC	Presenter: 'Ofa Fa'anunu
17th January 2022 10:00am	Cancelled Tsunami Marine Warning for: • Niuafo'ou • Niuatoputapu • Vava'u • Kauvai Ha'ano District, Ha'apai • Pangai Lifuka District • Ha'apai Lulunga District Tsunami Marine Warning remained in-force for: • 'Otumu'omu'a Group Cancellation template was not send via email to the distribution list because of internet disconnection. • Tongatapu • 'Atataa • 'Eueiki • 'Eua	

Date/Local Time	Response Operations	Remarks
17th January 2022 11:00am	First direct contact from Tonga to Ha'apai in regard to initial damage assessment and reports from Ha'apai based on the volcanic eruption and tsunami wave event. Mode of communication was through channel 5832kHZ between Tonga MET Services, Tonga Airport Limited Tower and Tonga Airport Limited Tower (Lifuka)	Deputy Director of TMS made first contact and then reported to Director of TMS and NEMC
17th January 2022 01:00pm	Cancelled Tsunami Marine Warning for: • 'Otumu'omu'a Group • Tongatapu • 'Atataa • 'Eueiki • 'Eua	Cancellation template was verbal not send via email to the distribution list because of internet disconnection.
17th January 2022 02:30pm	First direct contact from Tonga to Vava'u in regard to initial damage assessment and reports from Vava'u based on the volcanic eruption and tsunami wave event. Mode of communication was through channel 5832kHZ between Tonga MET Services, Tonga Airport Limited Tower and Tonga Airport Limited Tower (Vava'u)	Deputy Director of TMS made first contact and then reported to Director of TMS and NEMC