Post-tsunami survey of Niuatoputapu Island, Tonga, following the 30th September 2009 South Pacific tsunami

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ABSTRACT

The Tongan island of Niuatoputapu was severely affected by the 30th September, 2009, South Pacific tsunami. Located c. 190 km from the earthquake epicentre, there were 9 fatalities on Niuatoputapu, over half of the houses were destroyed and the healthcare and communications facilities were badly damaged. Post-tsunami surveys were undertaken by Tongan, New Zealand and Japanese teams, this report is a compilation of results from those surveys.

Three basic tsunami wave parameters were measured by the survey teams: inundation distance, runup elevation and flow depths. The inundation distance of the tsunami was measured at 105 locations on Niuatoputapu with a greater density of measurements around the villages. The maximum recorded inundation distance was 910 m on the southeastern coastline of the island. Inundation distances in the villages were typically 200 – 500 m. Interpretation of post-tsunami satellite images suggests there had been inundation up to 1100 m inland at the southeast of Niuatoputapu and that 46% of the island had been inundated by the tsunami. The tsunami runup elevation was measured at 29 locations with a maximum runup of 4.7 m above mean sea level at the village of Falehau in the northwest of Niuatoputapu. Runup elevations were lower on the eastern coastline due to the gentle topography.

The flow height of the tsunami reached a maximum of 16.9 m above mean sea level at Toma, on the southeast coast of Niuatoputapu. Flow heights were typically between 8-15 m along the northern peninsula and eastern coastline of Niuatoputapu. Flow heights decreased by about half, to between 4 – 7 m above mean sea level along the western coastline of Niuatoputapu where the villages of Hihifo, Vaipoa and Falehau are located. Topographic profiles show that tsunami flow depths at Hihifo were 2.5 – 3.5 m above ground level near the shoreline, remained at c. 2 m above ground level up to 300 m inland at Hihifo and then decreased rapidly towards the inundation limit. Flow direction indicators suggest the strongest wave of the tsunami came from a northeast to east direction; the tsunami flow wrapped around the northern and southern points of the island and inundated the west coast from variable directions.

Tsunami impact to the villages of Niuatoputapu was severe but some of the greatest damage was evident in the unpopulated, forested areas of the eastern and northern coastline of Niuatoputapu. In these areas swathes of mature forest were completely destroyed, debris piles of trees and vegetation were built up on land and in the lagoon, the shoreline was significantly scoured and the land surface was stripped of soil.

KEYWORDS

Tsunami, Tonga, 30th September tsunami, Niuatoputapu, Tonga Trench, tsunami runup, tsunami inundation.

1.0 INTRODUCTION

The 30th September 2009 South Pacific tsunami[1] caused nine deaths and widespread damage to the housing, infrastructure and physical environment of the island of Niuatoputapu, Tonga (Fig. 1). Probably due to the remote location, small population and difficulties with communication, the tsunami impact on Niuatoputapu has been given relatively little attention to date by scientists and the mainstream media alike. Nevertheless the tsunami impacts in Niuatoputapu were equal to or of greater severity than those seen in Samoa and American Samoa. For example, 57% of the housing stock was completely or partially destroyed; the hospital, police, government and telecommunications facilities along with the fishing boat fleet were also destroyed or rendered unusable. The severity of impact at Niuatoputapu should not be surprising as it is a similar distance from the earthquake source as the islands of Samoa and American Samoa (approximately 190 km, Fig 1).

In early November the Tongan government, through the National Emergency Management Agency and the Tonga Meteorological Service, initiated a request to the International Tsunami Information Centre (ITIC) for a post-tsunami survey to be undertaken at Niuatoputapu. The aim of post-tsunami surveys is to collect transient evidence of the tsunami impact; the basic parameters recorded are the distance of inland tsunami inundation and the maximum run-up elevation (Fig. 2). Other observations such as flow depths, flow directions, building damage and geological characteristics may also be recorded. These data allow a better understanding of the impact of the tsunami and can be used by disaster management agencies to assist recovery and improve disaster risk reduction planning. Furthermore, the location of Niuatoputapu to the west of the earthquake epicentre provides a valuable contrast to the data obtained from the Samoan islands which lie to the north and northeast of the epicentre. Data on the tsunami wave heights, wave direction and arrival time from Niuatoputapu can help to refine models of the tsunami source event.

In response to the request for a post-tsunami survey an international team of scientists from Japan, New Zealand and Tonga, supported by SOPAC and ITIC, collaborated to conduct the survey on the 11-16 November, 2009. This report details the survey methodology used and the results obtained.

[1] The South Pacific tsunami occurred on the 29th September in Samoa and American Samoa but across the dateline the same event occurred on the 30th September in Tonga.

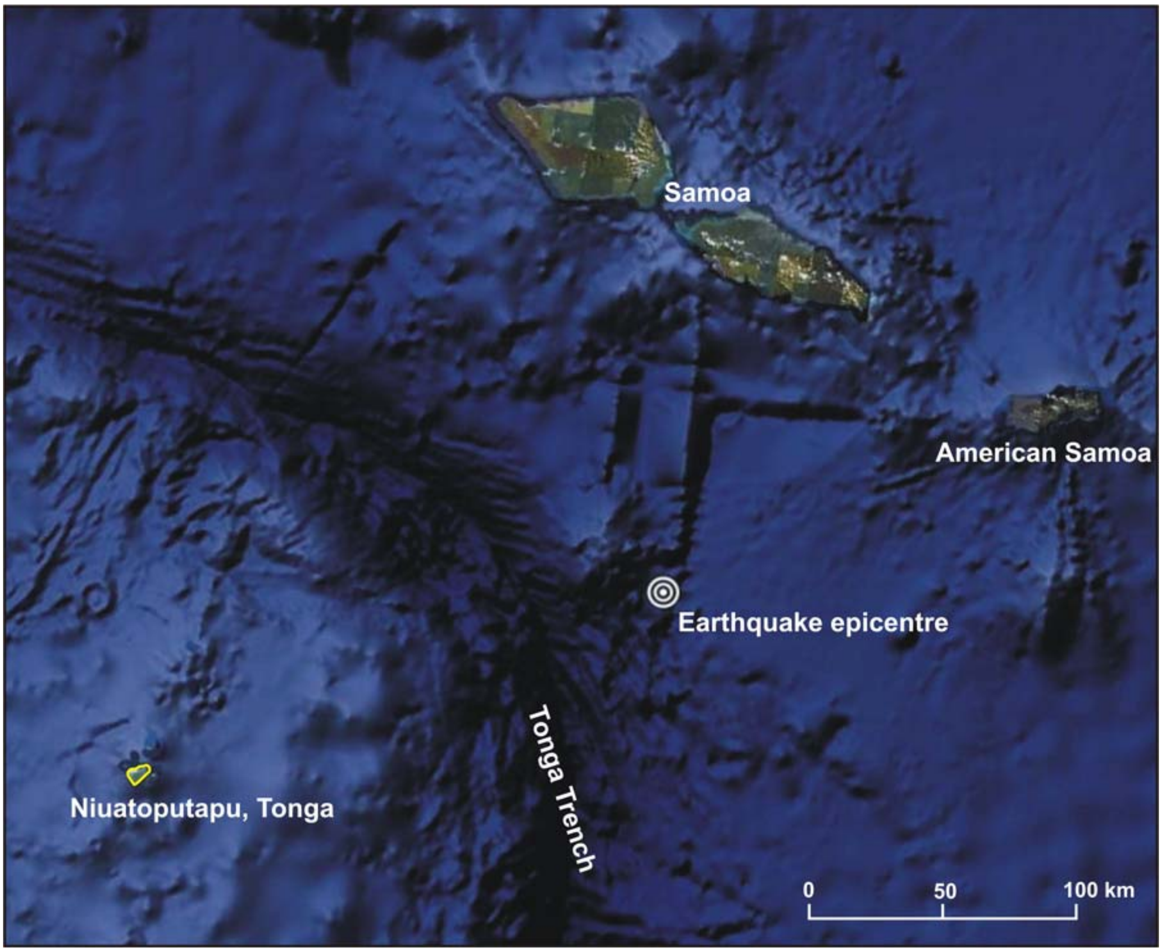

Figure 1. Location map of Niuatoputapu Island, Tonga, and nearby countries relative to the epicentre of the M 8.0 earthquake that caused the tsunami of 30 Sept, 2009 (also known as the 29th September tsunami in Samoa and American Samoa).

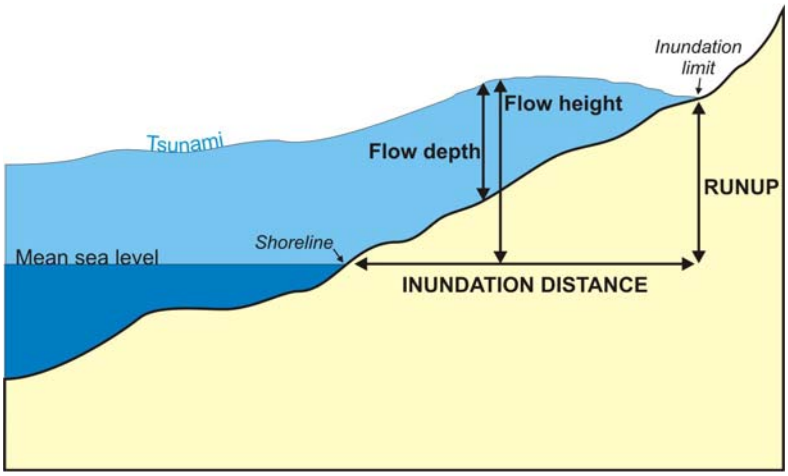

Figure 2. Illustration of features measured during the post-tsunami survey. The main parameters recorded in the field were inundation distance, runup and flow depths. Cartoon adapted from IOC (2008).

2.0 METHODS

Three parameters were routinely measured by all teams during the post-tsunami survey of Niuatoputapu, these being (1) inundation distance and runup elevation, (2) flow depths, (3) flow direction. Each of the parameters was measured using either a GPS, total station, laser range finder or level and staff. The survey methods will be described in Section 2.1.

The inundation distance is the maximum inland distance reached by the tsunami flow (Fig. 2), which was typically recognised in the field by the boundary between dead or damaged vegetation, and healthy vegetation (Fig. 3). Dispersal of debris and damage to buildings could also be used as a guide to inundation extent, along with eyewitness observations. Where the surveying method allowed, the runup elevation was also measured, this being the height above mean sea level that the tsunami flow reached at its maximum inland extent.

Figure 3. Example of the distinguishing features of the tsunami inundation limit. Note the stark contrast between the dead vegetation and the healthy vegetation. Photo taken at the southeastern corner of Niuatoputapu, grid reference 844081E, 8230634N (UTM Zone 1 South coordinates).

Flow depth is the height above ground level of the tsunami flow. Flow depths could be estimated by features such as watermarks inside buildings, damage to structures (e.g. levels to which windows were broken), gouge marks from entrained debris on the exterior of buildings and up tree trunks, broken branches and vegetation stripping on trees, and the presence of debris caught in tree branches (Fig. 4). Each of these indicators has varying degrees of reliability, for example, watermarks within houses may indicate the level to which water ponded rather than the flow depth, or gouge marks on trees may be higher than the flow depth due to the entrained debris floating above the water level. Some features were useful only to constrain a minimum or maximum flow height. Where possible inferences were made on the reliability of the flow depths and recorded in our field notes, with “A” being the

most reliable, and "C" being less reliable. In most cases the GNS team collected photos of the measured features. Flow depths can be converted to flow heights (flow elevation relative to mean sea level) when the ground elevation at the measurement point is also known.

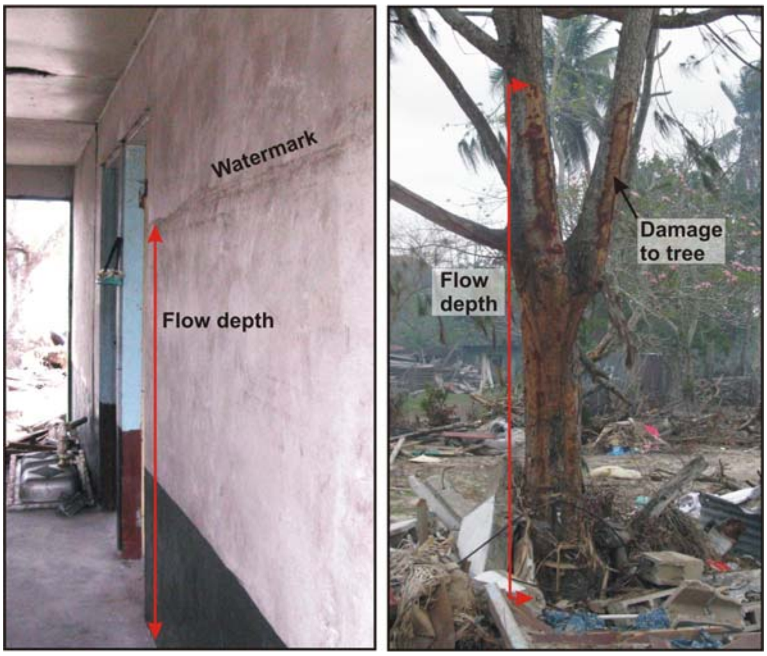

Figure 4. Examples of flow depths indicators. Left photo shows a watermark within a house at Hihifo. Right photo shows gouge marks and bark stripped from a tree trunk in Hihifo village.

Flow directions were measured from the alignment of damaged features. For example, the direction that plants were bent, the direction that uprooted or snapped trees had fallen, the direction of movement of large objects (e.g. the displacement of boats), or debris piles preferentially aligned in particular directions (Fig. 5). There is also variability in the reliability of flow direction indicators, and there can be uncertainty regarding which wave the flow direction records. For example, groups of large, snapped trees all aligned in the same direction probably represent the flow direction of the *strongest* wave. More fragile features such as bent shrubs and small debris piles possibly represent the flow direction of the *last* wave or even the backwash flow. For these reasons we tried to collect as many flow direction indicators as possible so that different populations of flow directions may be identified.

Figure 5. Examples of flow direction indicators, red arrows indicate the alignment of debris. Left photo the alignment of fallen trees, this photo was taken at Toma on the eastern coast of Niuatoputapu (grid reference 845358E, 8231327N). The right photo shows wire fencing and other debris caught around a coconut tree trunk in Hihifo village, the direction of the wire fencing shows the flow direction.

2.1 Survey methods

Surveying was undertaken using different methods by each team.

- The GNS team used a real-time kinematic (RTK) GPS unit and a laser range finder. The RTK GPS unit obtains detailed topographic data and within each survey the horizontal and vertical accuracy of each point relative to another is less than 0.02 m. The elevation accuracy relative to mean sea level depends upon the quality of the calibration points. Where possible the GNS team surveyed known geodetic benchmarks, which have elevations known relative to mean sea level. For surveys where geodetic benchmarks were not available the GNS team surveyed natural tide markers such as the debris line at the high water mark and tide levels at various times of the day. On the leeward side of the island there is little to no wave action therefore the high water mark accurately represents high tide. From comparing the high tide marks with low tide water levels the GNS team calculated an average tide range of 0.55 m. No tide tables or tide gauges exist for Niuatoputapu Island therefore our own calculations of the tide range are the best available data. On the windward (eastern) side of the island wave action means that the high tide water mark is typically 0.5 – 1 m higher than the high tide level (we estimated this by comparing all our measurements for the high water mark around the island). With the combination of geodetic benchmarks and natural high water marks we estimate that all elevation points in the GNS survey have an uncertainty of ±0.25 m relative to mean sea level. Where features such as flow depths many metres above the ground could not be measured with the GPS the GNS team used a laser range finder to calculate the heights of these features relative to ground level.
- The joint Japanese-Tongan team led by Yuichi Nishimura used a handheld GPS and a total station survey system. The inundation heights were measured from sea level at the measurement time. As there are no tide tables for Niuatoputapa, tide corrections of each measured data were done by using theoretical tide data at Apia, Samoa, and it is assumed that the tide pattern is similar in Niautoputapu and Apia.
- The Tongan team from the Ministry of Lands, Survey and Natural Resources (MLSNR) used a handheld GPS, and an automatic level and staff to carry out the

surveying. The MLSNR team carried out a number of topographic profiles from the high water mark to the inundation limit.

2.2 Satellite image analysis

Post-tsunami satellite imagery of Niuatoputapu was supplied to GNS Science by the National Science & Technology Centre for Disaster Reduction in Taiwan. The imagery was obtained by the Formosa 2 satellite, a Taiwanese-operated satellite that provides imagery for post-disaster recovery purposes. The imagery was passed onto GNS Science by Wei-Sen Li, the Deputy Executive Secretary of the National Science & Technology Centre for Disaster Reduction.

3.0 RESULTS

3.1 Tsunami inundation

The limit of tsunami inundation was measured in the field at 105 locations by the three survey teams in Niuatoputapu (Fig. 6). Point density is greatest around the three villages where the inundation limit could be walked along completely, but there are fewer points along the eastern coast due to dense forest and limited accessibility. The maximum inundation distance measured in the field was 910 m near along the northeastern part of Niuatoputapu. The minimum amount of inundation was seen along the western side of Niuatoputapu where no tsunami inundation was seen along the southern side of Nukuseilala Island (Tafuna Island was not accessed). In the village of Hihifo the inundation varied between approximately 200 – 570 m, a topographic ridge near the southwestern side of the island affected the inundation pattern. In Vaipoa the inundation distance varied from 120 – 180 m, and in Falehau inundation was between 190 – 310 m. In Vaipoa, the maximum inundation distances were significantly shorter in the eastern part of the village than in the western part. It suggests that the beach forest in the eastern part of the village has worked to reduce the tsunami energy.

To supplement the field measurements we also used the Formosa 2 satellite images to remotely locate the inundation limit. The satellite images show the tsunami inundation line clearly in most parts of the island, except in the villages. Along the west coast of the island the panchromatic satellite images are darker in the regions of tsunami inundation and in the multispectral images the zone of inundation is a light brown shade representing the dead vegetation. We are confident that the satellite images are a true representation of tsunami inundation for two reasons: (1) there is a precise match between the GPS data collected in the field and the inundation limit indicated by the satellite imagery along the east coast (Fig. 7); and (2) oblique aerial photographs over the east coast show a distinctive pattern of dead tress which matches the pattern of the inundation line estimated from the satellite image (Fig. 8).

Calculations of inundation distance from the dataset including the satellite interpretation indicates that the maximum inundation distance was 1100 m near the southwest corner of Niuatoputapu (Fig. 7). The inundation distance may have been greater slightly to the north of Falehau village where the tsunami inundation zone bridges the whole island (a width of 1.5 km) but the wave inundated from both sides and we cannot determine at what point in the

middle the tsunami met. Using the GIS map of tsunami inundation we calculate that 46% of the land area of Niuatoputapu was inundated by the tsunami (Fig. 7).

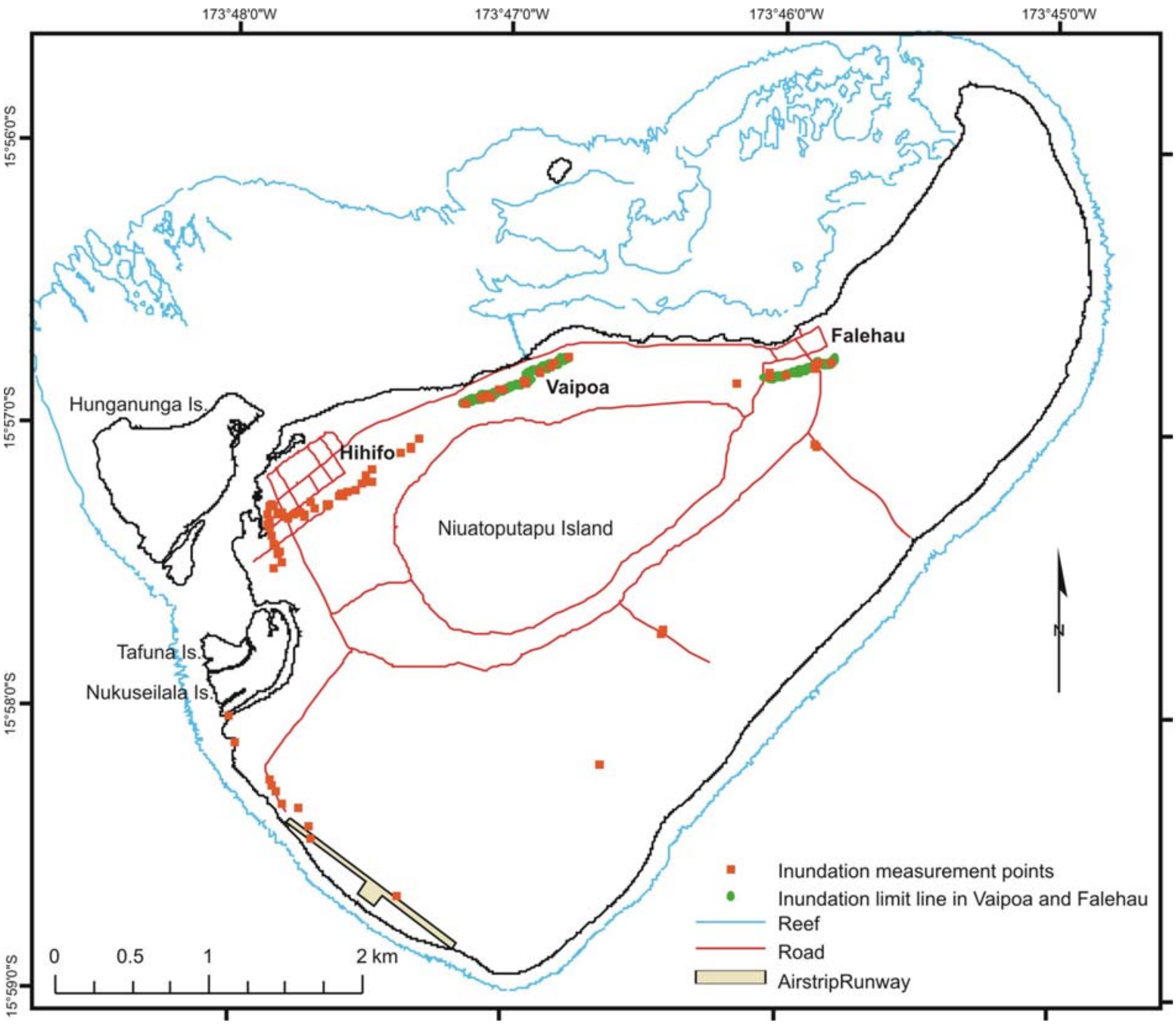

Figure 6. Inundation limit points measured in the field using handheld or RTK GPS.

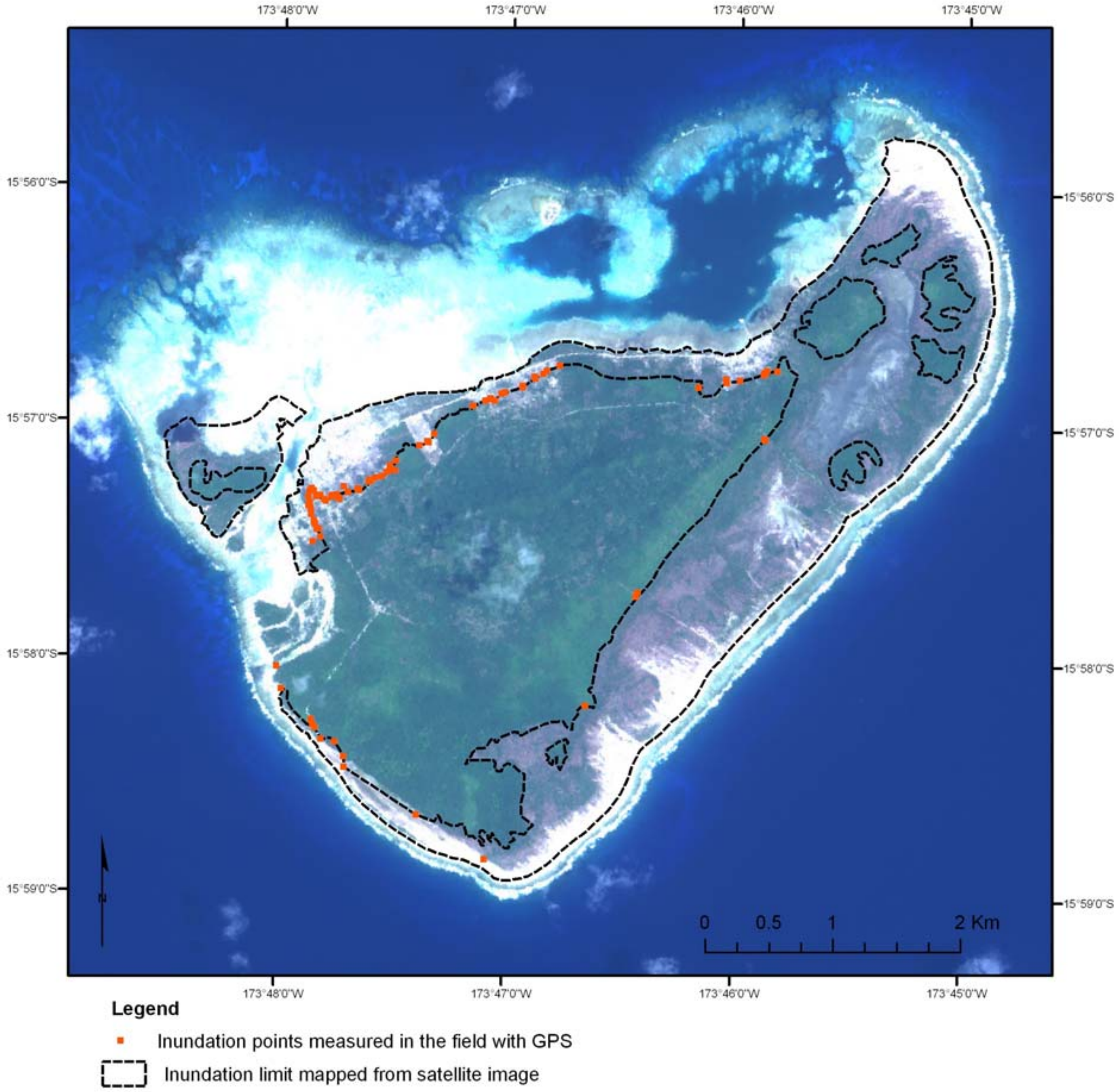

Figure 7. Inundation line mapped on the island of Niuatoputapu from a combination of Formosa 2 satellite images and GPS points collected in the field. Along the east coast there is a precise match between the GPS points and the zone of dead vegetation on the satellite image.

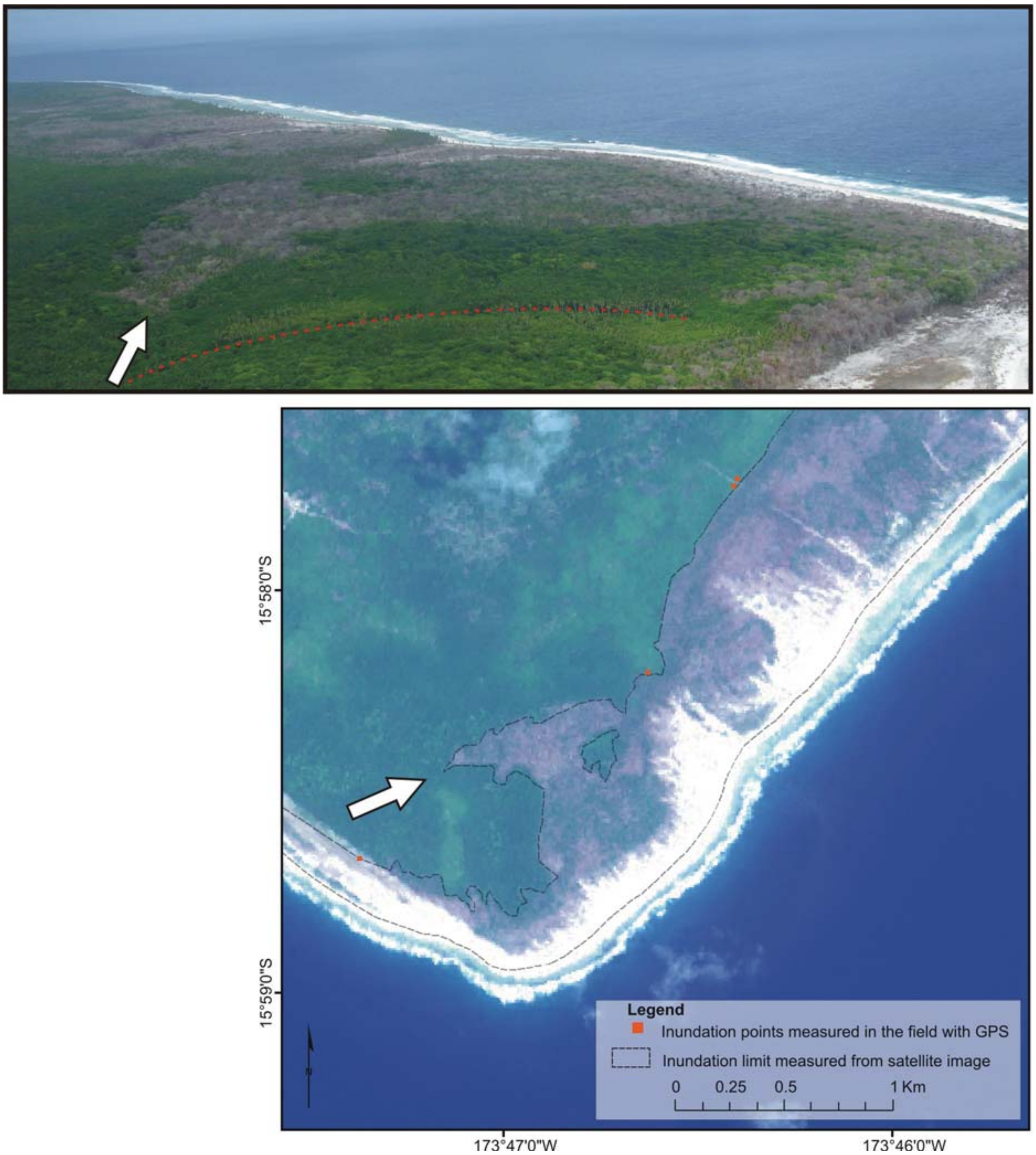

Figure 8. A comparison between an oblique aerial photograph of the zone of tsunami inundation and the satellite image of tsunami inundation. Both images are of the southwestern corner of Niuatoputapu. The white arrows point out the comparable features in each image. The dashed red line in the top image shows a road that was checked in the field for tsunami inundation and where none was found, confirming that inundation probably did not extend beyond the region of dead trees.

3.2 Tsunami runup

Tsunami runup elevation (i.e. the ground elevation at the maximum inland extent of inundation) was measured at 29 locations (Fig. 9). A maximum runup elevation of 4.7 m above mean sea level (AMSL) was measured at Falehau village. Vaipoa village had tsunami runup up to 4.5 m AMSL and the maximum runup at Hihifo was 4.3 m AMSL. The highest runup elevations were all recorded along the western side of Niuatoputapu. However, it is likely that higher runup elevations were attained at the southern tip of Niuatoputapu because topographic profiles collected there (to be discussed in Section 3.5) showed tsunami inundation up to elevations of 5.8 m AMSL. The topographic profiles could not reach the inundation limit due to dense forest and debris piles but runup was probably at least 5.8 m AMSL in this area. Along the western coast of Niuatoputapu, where the greatest inundation distances were, runup elevations area relatively moderate at 0.8 – 3.1 m AMSL.

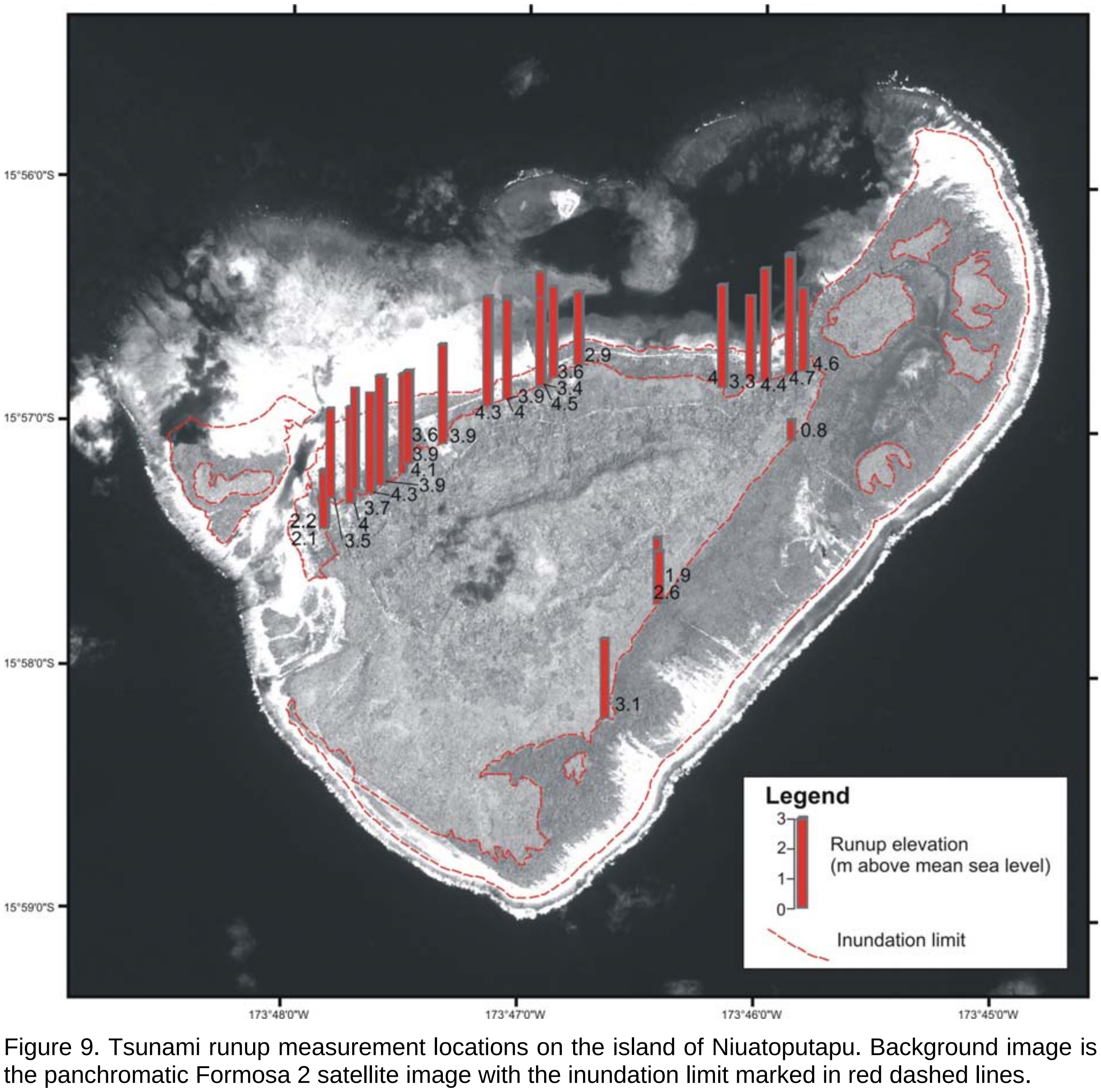

Figure 9. Tsunami runup measurement locations on the island of Niuatoputapu. Background image is the panchromatic Formosa 2 satellite image with the inundation limit marked in red dashed lines.

3.3 Tsunami flow directions

Tsunami flow direction measurements were taken at 98 locations on Niuatoputapu Island (Fig. 10). Flow directions are variable but the general pattern is of the tsunami coming from the northeast direction and “wrapping” around the northern and southern tips of the island. At the northern tip of Niuatoputapu the flow direction indicators were typically 250º - 270º indicating that the waves came from the northeast. Most flow direction indicators in this region were swathes of large snapped or uprooted trees all aligned in the same direction, undoubtedly representing the direction of the strongest wave. Further around the northern tip the flow directions trended parallel to the coast and then bent landward (140º) near the village of Falehau. A similar pattern was seen at the southern tip of Niuatoputapu where the flow directions were directly from the east along the east coast, bent approximately parallel with the coast at the very southern promontory and then turned inland (flow directions from the south-southeast) once the flow had turned the corner.

The few flow direction measurements obtained along the eastern coast of Niuatoputapu that indicate the dominant flow direction was directly onshore (flow from the east-southeast). At Atatuka, on the east coast, flow directions were dominantly c. 300º but two measurements were almost the opposite of this at 156º and 180º. It is likely that the latter two measurements represent return (offshore) flow of the tsunami waves.

At Hihifo village the flow directions were generally complex and variable, but it is likely that the tsunami waves came from two directions. The northern part of village appears to have been inundated by waves from north and northeast directions, and the southern part by waves from the southwest. Flow directions at Hihifo may also have been influenced by the small scale topography. A small tidal channel indenting the coastline at the north of the Hihifo and a ridge along the southern part of the village probably caused some of the flow variability.

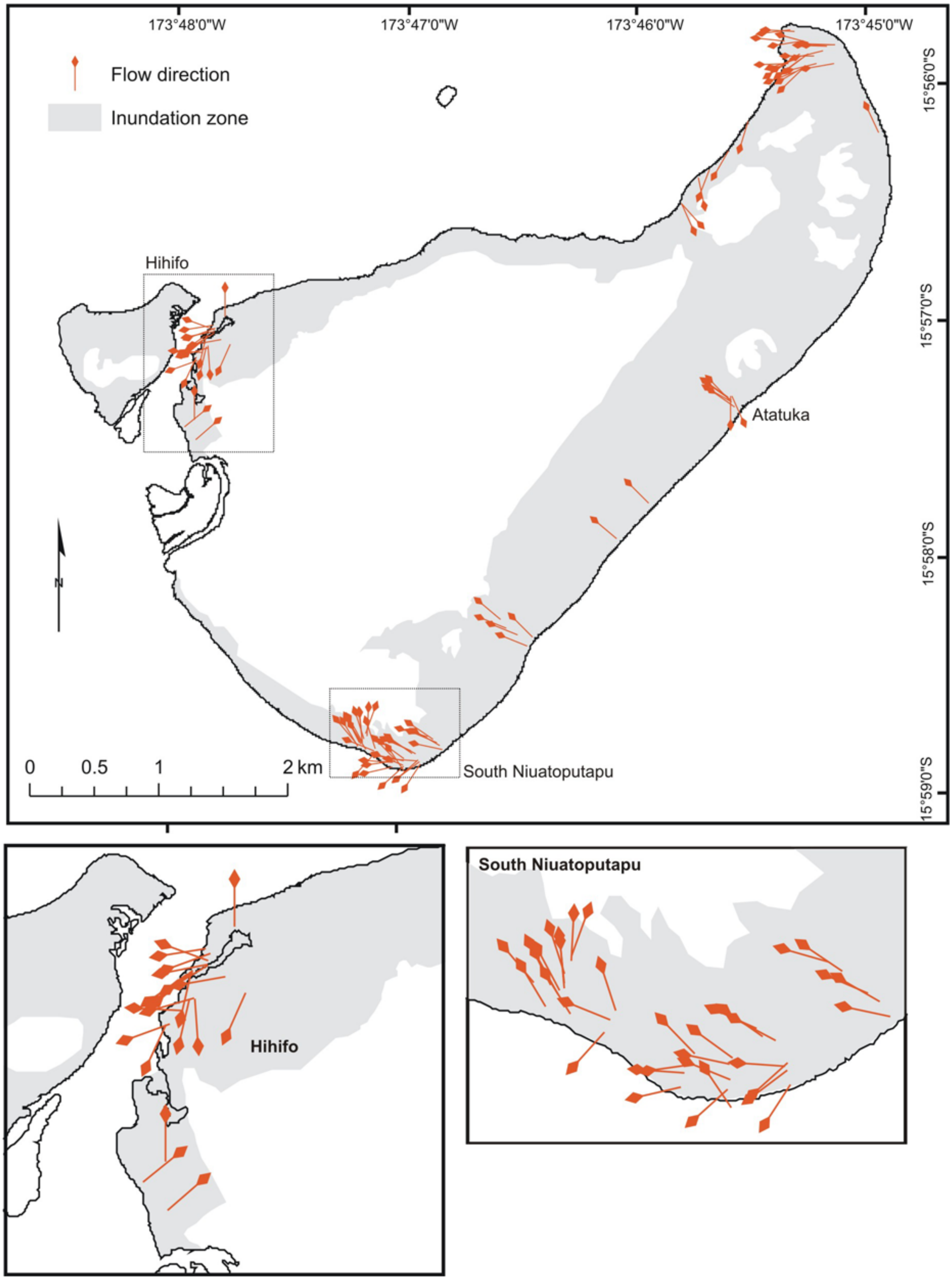

Figure 10. Flow direction measurements around Niuatoputapu Island.

3.4 Tsunami flow depths

The flow heights of the tsunami were highest at the along the western coast and northern tip of Niuatoputapu (Fig. 11). The maximum flow height was 16.9 m AMSL at the coastline at Toma, in the southeast of Niuatoputapu (Fig. 11). Generally the flow heights around southeast of the island were between 8.5 – 15 m AMSL. At the northern tip of Niuatoputapu flow heights varied between 6 - 10.8 m AMSL. Flow heights decreased by approximately half along the western side of the island.

In the village of Hihifo flow heights were typically 5.4 – 7 m AMSL, which equates with inundation depths of 1.5 – 3.3 m above ground level. Flow depths generally tapered off inland as will be discussed in Section 3.5. In Falehau flow heights were between 5.4 – 7 m AMSL (inundation depths of 1 – 3.4 m above ground) and in Vaipoa flow heights were 4.5 – 5.3 m AMSL (inundation depths of 0.5 – 1.4 m above ground).

3.5 Topographic profiles

Thirty-seven topographic profiles were collected at Niuatoputapu by the GNS, MLSNR sand Japanese-Tongan survey teams (Table 1). All profiles, except for those at south Niuatoputapu, extended from the high water mark to the inland limit of inundation. Some profiles also extended from the high water mark into the intertidal zone. Profiles acquired by the GNS team were obtained using the RTK GPS system, with points automatically collected every 1 metre. Wherever possible along a transect route flow depths were measured. The Japanese-Tongan team used a total station to measure the topography. The MLSNR survey team used a level and staff survey method and collected ground elevations every 100 m, at places of significant gradient change or where flow depth measurements were recorded. In this report we present and discuss only the topographic profiles collected by the GNS team (Fig. 12).

Table 1. Location of topographic profiles obtained at Niuatoputapu.

Team	Number of profiles	Location
GNS	3	North Niuatoputapu
GNS	5	Hihifo village
MLSNR	5	Hihifo village
MLSNR	4	Falehau village
Japan-Tonga	2	Falehau village
MLSNR	4	Vaipoa village
Japan-Tonga	3	Vaipoa village
GNS	8	South Niuatoputapu
MLSNR	3	East coast, Nuiatoputapu

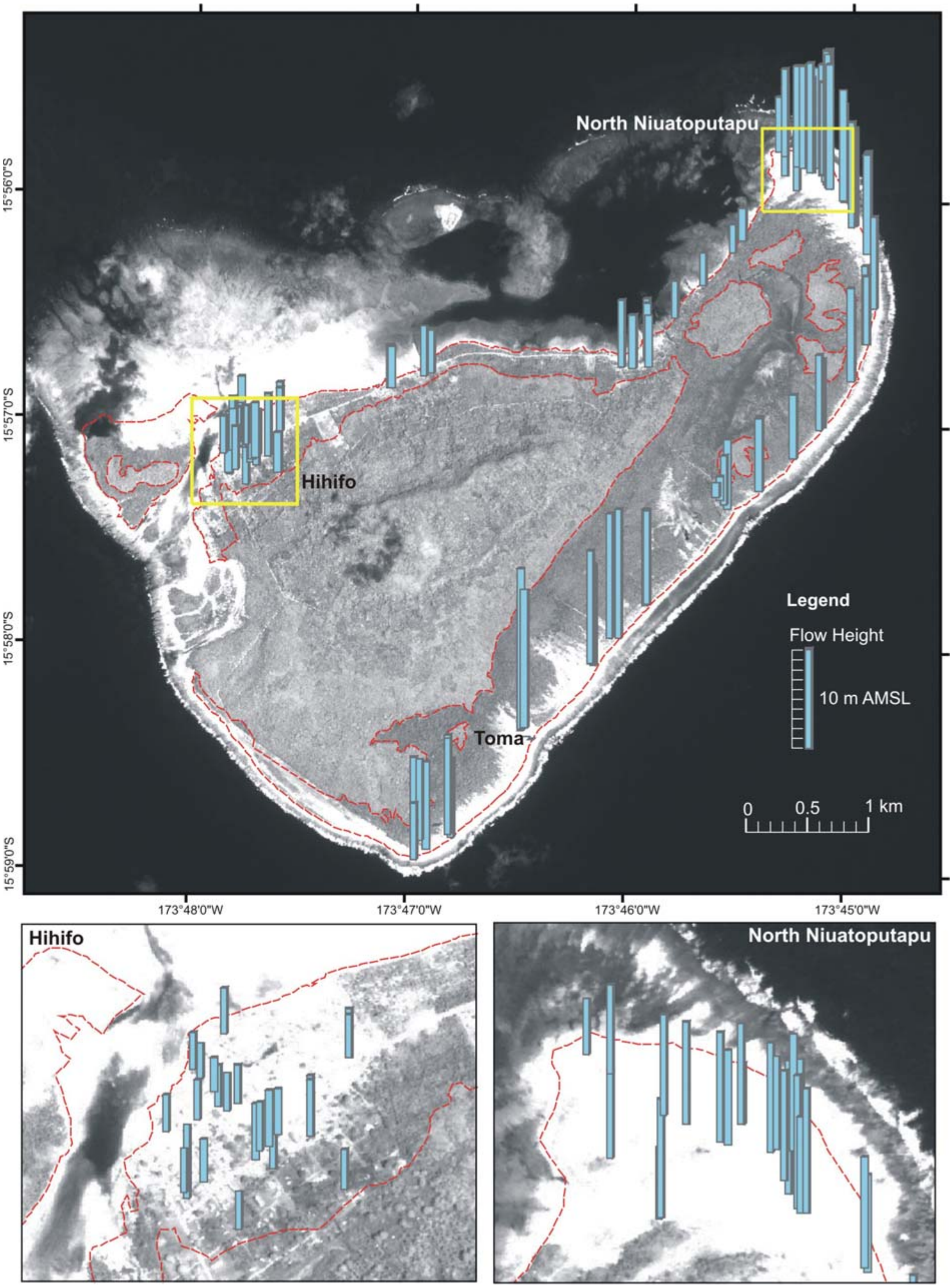

Figure 11. Tsunami flow heights at Niuatoputapu, measured in metres above mean sea level.

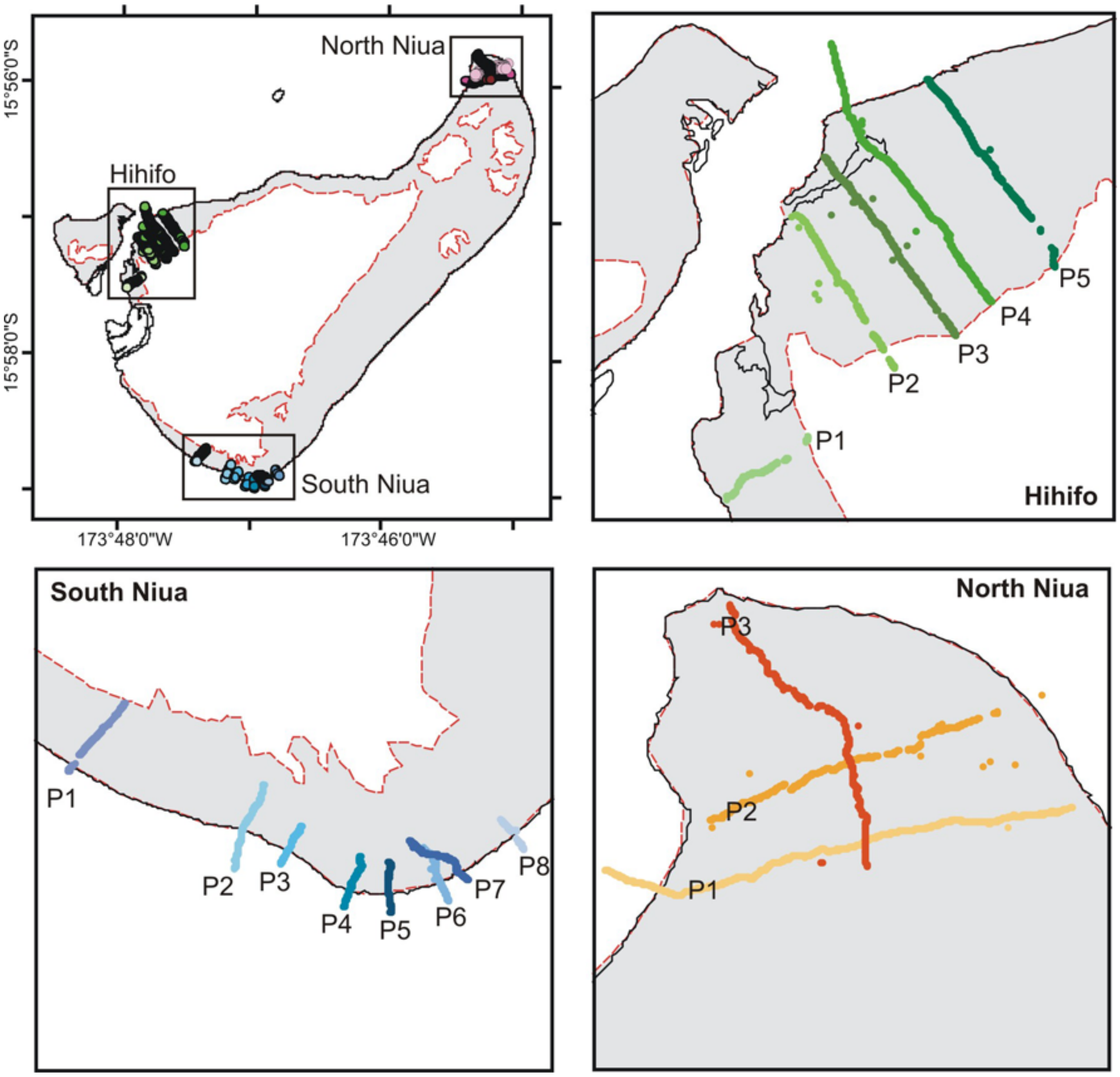

Figure 12. Location of topographic profiles collected by the GNS survey team at Niuatoputapu.

In the village of Hihifo five profiles were obtained, along with approximately 30 flow depths, along or near the profiles (Figures 12 and 13). Plots of topography and flow depths show, as expected, a general decrease in flow depth with increasing distance inland but there is some variability. Hihifo Profile 2 shows a rapid decrease in flow depth at approximately 190 m inland while Hihifo Profile 3 shows flow depths consistently c. 2 m above the ground surface up to 300 m inland. At 400 inland on Hihifo Profile 4 flow depths on the seaward and landward side of a church were obtained. The landward flow depths were 1.6 m lower than those on the seaward side of the church; this data may be used in future to calculate a flow velocity.

The topographic profiles across the northern point of Niuatoputapu show relatively uniform flow depths of c. 8±2 m above ground level across the peninsula (Fig. 14). Flow directions on the peninsula were almost parallel with Profiles 1 and 2, and perpendicular to Profile 3 (Fig.

10). Profiles 1 and 2 indicate that the tsunami flow depth decreased very little as it crossed the peninsula, despite encountering dense forest which was completely destroyed and uprooted by the force of the tsunami.

Eight topographic profiles were obtained from the southern point of Niuatoputapu, however due to dense forest and debris piles only one of these profiles (South Niuatoputapu Profile 1) reached the inundation limit (Fig. 15). The South Niuatoputapu profiles all display the steep shoreface characteristic of this area and flow depths are typically 3 – 4 m above ground level.

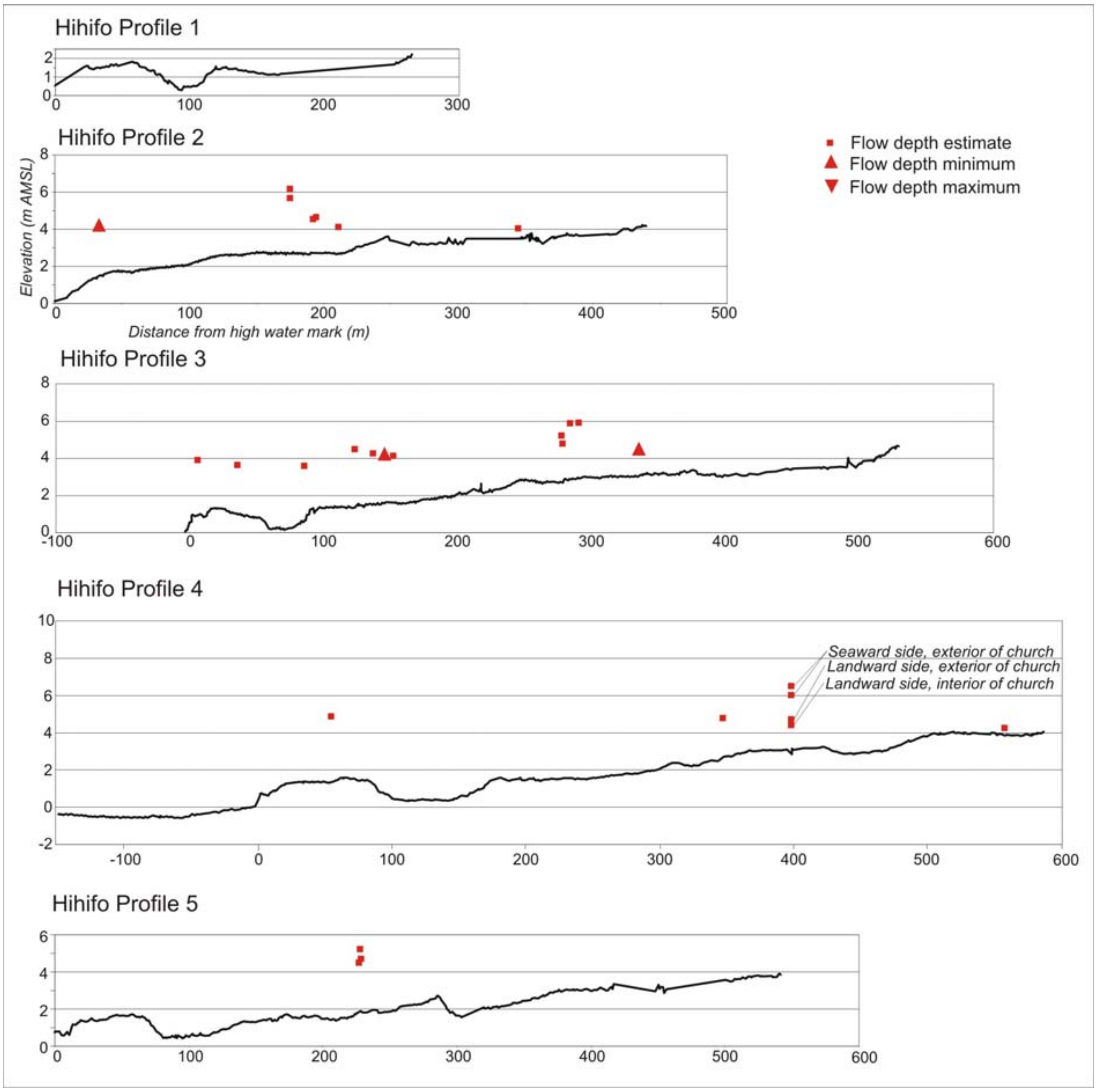

Figure 13. Topographic profiles and flow depth measurements from Hihifo village, Niuatoputapu.

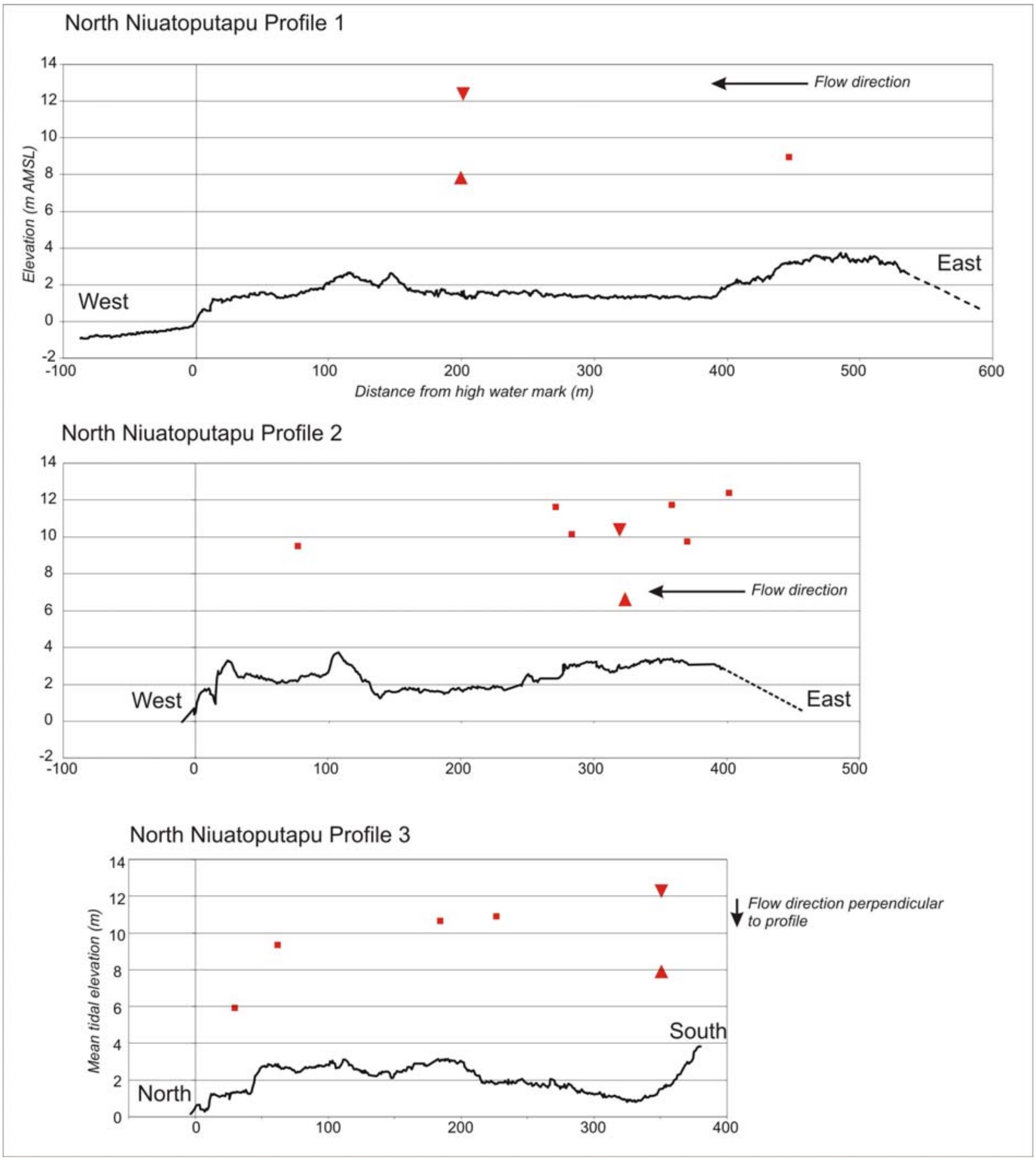

Figure 14. Topographic profiles and flow depth measurements from the northern point of Niuatoputapu Island.

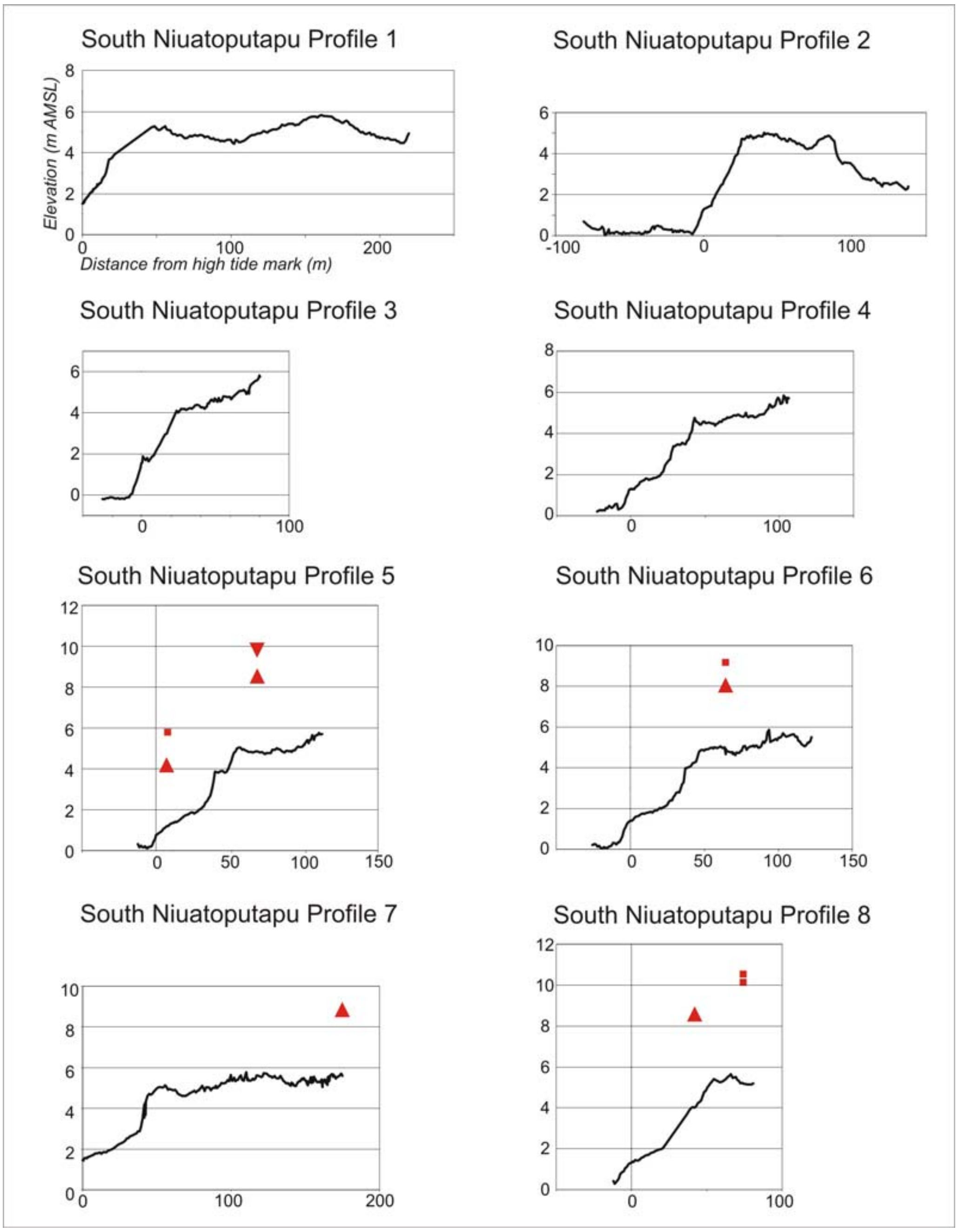

Figure 15. Topographic profiles and flow depth measurements from the southern tip of Niuatoputapu Island.

3.6 Observations of impact on the physical environment

Damage to the natural environment along the eastern and northern coastlines of Niuatoputapu was particularly severe; these were the areas that had the highest flow depths and probably the strongest tsunami flow velocities. Such levels of impact on the natural terrestrial environment were not observed on either Samoa or American Samoa where flow depths were less and most of the coastline was populated. In this section we show examples of the severe damage to the natural environment of Niuatoputapu.

3.6.1 Forest destruction and debris dispersal

Large swathes of forest on Niuatoputapu were destroyed by the tsunami (Fig. 16 and 17). Forested areas were affected in Samoa and American Samoa, but typically the damage was moderate – such as bent trees, trees with snapped branches, and small shrubs uprooted. In contrast, in parts of Niuatoputapu (shaded green areas on Fig. 16) all the trees were uprooted or snapped at the base. All the forest undergrowth was removed and only rare large trees and occasional coconut trees remained standing (Fig. 17). Using satellite images to map the zones of complete forest destruction (confirmed by field visits to most areas, Fig. 16) we calculate that ~0.89 km^2 of forest was destroyed, that is 6% of the total land area of Niuatoputapu. In forested areas of the tsunami inundation zone where there was not complete forest removal, damage was still severe to moderate. In some areas, the forest was still standing but all trees and undergrowth plants were dead, in other areas, particularly near the inland limits of inundation, only small undergrowth plants had been killed by the salt water inundation but larger plants and trees still appeared to be healthy. In the time available we did not gather information on the plant species that were particularly resilient or particularly vulnerable to the tsunami inundation but this may be an interesting topic for future study.

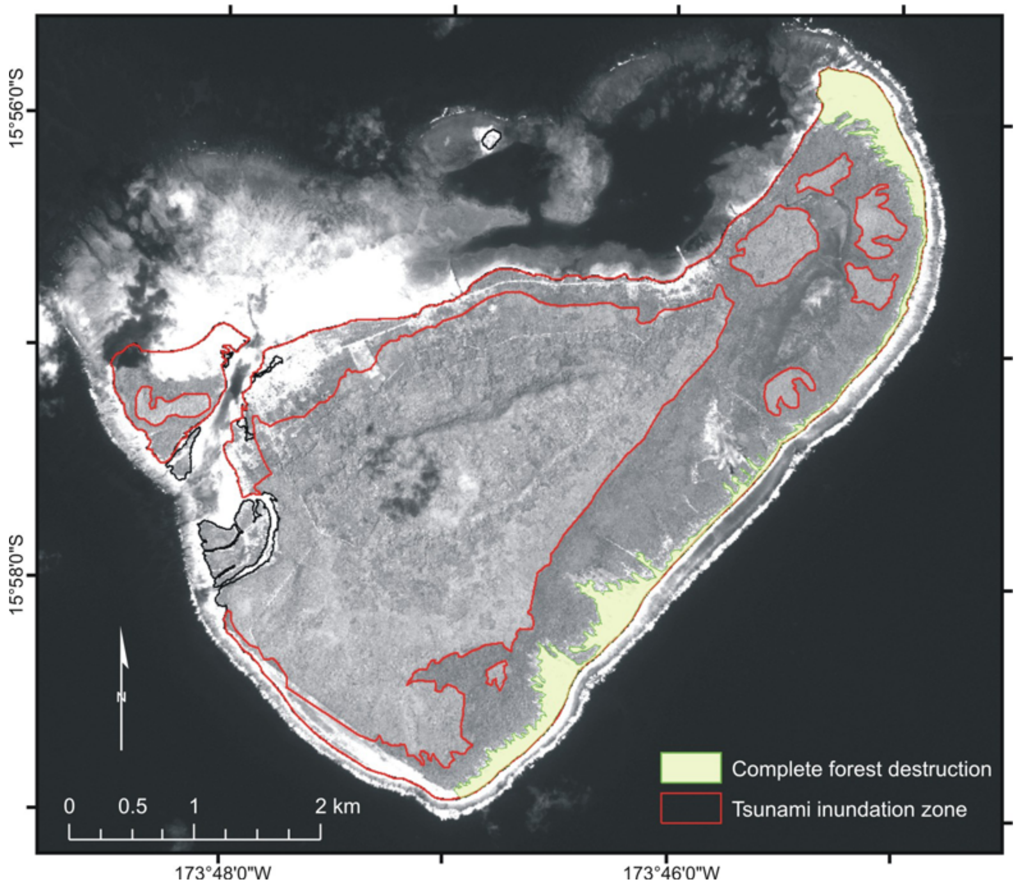

Figure 16. Areas of complete forest destruction on Niuatoputapu Island.

Figure 17. Areas of destroyed forest on Niuatoputapu Island, photos taken 6 weeks after the tsunami. (A) Forest destroyed near Toma, on the east coast. (B) An example of a large tree snapped at the base by the force of the tsunami, photo taken near the shoreline at Toma, east coast, Niuatoputapu. (C) The northern tip of Niuatoputapu, the whole peninsula had been previously forested, now only sparse large trees remain. (D) Photos taken looking across the northern tip of Niuatoputapu from the eastern shoreline.

At the periphery of the zones of complete forest destruction there were typically large debris piles. These debris piles were formed of dead vegetation, often including large trees and packed with small shrubs. The debris piles were up to 4 metres high and are likely to take several months to years to break down naturally. Also observed were significant accumulations of debris within the lagoon on the northwestern side of the island (Fig. 19). This debris will also naturally break down but may linger as a hazard for boating within the lagoon for some time and will probably be remobilised during cyclones.

Figure 18. Debris piles at Niuatoputapu. The upper photo is from the northern point of Niuatoputapu at the southern margin of the zone of forest destruction. The lower photo is from Toma, on the east coast of Niuatoputapu, also at the margins of a zone of forest destruction.

Figure 19. Debris in the lagoon on the northwestern coastline of Niuatoputapu.

3.6.2 Erosion

The shoreline of Niuatoputapu was scoured and eroded by the tsunami along the northern, eastern and southern coastlines (Fig. 20). Scoured indentations into the sand foredunes typically extended 1 – 4 m inland, and most of the vegetation was stripped from the foredune. The shoreline erosion probably would have been worse if there had not been a fringing coral reef offshore; however, the stripping of vegetation means the shoreline is now more vulnerable to further erosion during the cyclone season. Along the western coastline of Niuatoputapu the shoreline is not as steep and no significant erosion was noticed, however, much of the vegetation was removed or damaged therefore the shoreline is now more vulnerable to erosion (Fig. 21).

In places where the forest was completely destroyed by the tsunami (Fig. 16) the land surface was also eroded by the tsunami. All soil was removed and the land surface is now bare coral cobbles and boulders or sand (Fig. 22). At the northern tip of Niuatoputapu, where coral rubble was exposed, it will likely take many years to decades before the forest will recover.

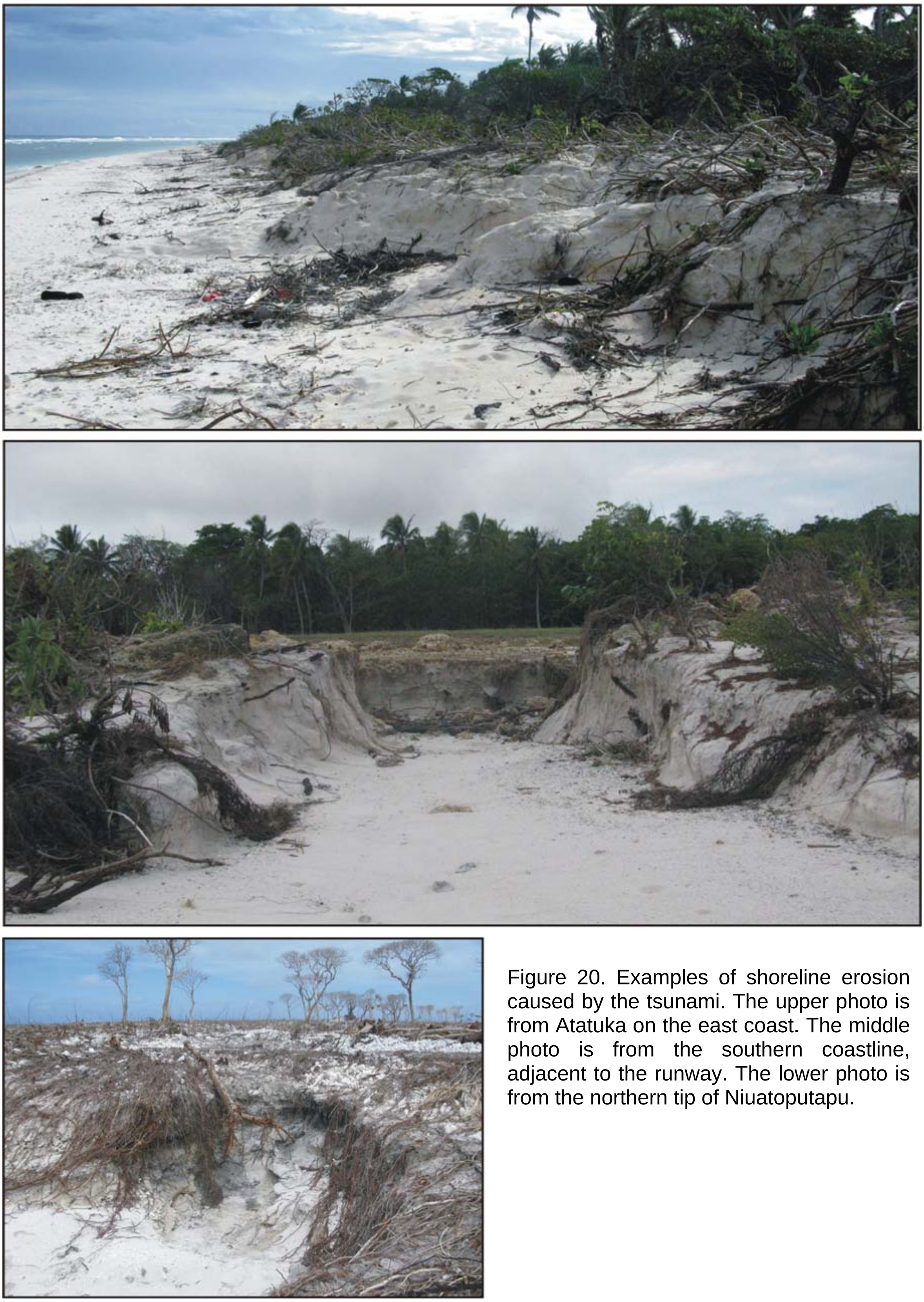

Figure 20. Examples of shoreline erosion caused by the tsunami. The upper photo is from Atatuka on the east coast. The middle photo is from the southern coastline, adjacent to the runway. The lower photo is from the northern tip of Niuatoputapu.

Figure 21. Before and after photos of the Hihifo shoreline demonstrating the extent to which vegetation was stripped from the shoreline, enhancing the areas vulnerability to coastal erosion (Hungahunga Island in the background). Photo on the left is from Google Earth, from Panaramio users Andrey and Irina Popovich (http://www.panoramio.com/user/2347807).

Figure 22. Photos showing the extent of land surface erosion at the northern tip of Niuatoputapu. Photo on the left shows how all soil and organic matter layers were stripped form the surface and bare coral rubble and coral boulders have been exposed. Photo on the right shows a tree formerly rooted on a small hummock of coral boulders. The land all around the hummock has been scoured and eroded by the tsunami.

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