NIWA
Taihoro Nukurangi

Tsunami source study

NIWA Client Report: CHC2006-082
August 2006

NIWA Project: EWR06502

Tsunami source study

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Prepared for

Environment Waikato

(on behalf of Environment Waikato, Auckland Regional Council, Environment Bay of Plenty, Northland Regional Council)

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Executive Summary

New Zealand sits in a precarious position astride the boundary between the Pacific and Australian Plates. There is a wide range of potential tsunamigenic sources in this area including fault movements, submarine landslides, volcanic activity, and other mechanisms. In addition, considerable palaeotsunami information indicates that large tsunamis have inundated the coastline several times in the past.

NIWA was engaged by the combined councils of Northland Regional Council, Auckland Regional Council, Environment Waikato and Environment Bay of Plenty to undertake a tsunami source investigation. Part of this study has been directed toward using palaeotsunami and some historic data to evaluate possible tsunami sources. Dislocation and submarine landslide models were used to simulate the displacement of the sources, and a finite element numerical model was used to simulate generation and propagation of the resultant tsunami.

The initial aim of the project was to identify the three most significant tsunami sources for the combined region. During the investigation process it was decided to expand this to four. Based upon available data, the identified sources included a distant one from South American, distant/regional tsunamis from the Solomon Sea and New Hebrides areas, a subduction zone event along the Tonga-Kermadec Trench, and selected local sources. The local sources investigated included those from the Bay of Plenty which have been previously published and some poorly-defined ones north and east of the North Island that may explain traces in the palaeotsunami record. The report discusses the general settings for each source and presents results for the areas encompassed by the four regional councils: Northland, Auckland, Environment Waikato, and Environment Bay of Plenty.

Using a combination of an inverse solution (palaeotsunami data guiding source selection) and source modelling, we determined that a subduction zone event along the Tonga-Kermadec Trench represented the most significant tsunami source for the combined region. In some cases, surface water elevations were in excess of 10 m. The distant South American, Solomon Sea and New Hebrides source areas generated maximum water surface elevations around 3 m, although there was considerable variability. The eastern coast of the Northland region records the highest elevations from all sources, with a marked signal also noted along the western coastline.

Some of the focus of the project was determined by unusually high runups recorded from events such as the Krakatoa tsunami in 1883. Such northern sources were inferred as being potentially problematic particularly for the north-facing Bay of Plenty and Hauraki Gulf. However, this does not appear to be the case.

High elevations and distinctive depositional records from some sites noted in palaeotsunami evidence, particularly in Northland and eastern Coromandel Peninsula, indicated that these could not have been laid down by any of the scenarios modelled for regional and distant sources. Unknown or poorly studied local sources were probably the cause. We modelled three potential local source scenarios. These scenarios were based upon an examination of all available data including bathymetric data and palaeotsunami records.

The source models produced account for the majority of tsunami evidence recorded for the combined region. In most cases the "worst case scenario" model to be considered would be that from the Tonga-Kermadec Trench, although other sources provide for some local variability. It is therefore suggested that all the major distant and regional scenarios proposed in this report be considered for inundation modelling at any one site.

Palaeotsunami data and inverse modelling would suggest that a Mw 8.5 to 9.0 event on the Tonga-Kermadec Trench is not unreasonable, although this is larger than current geophysical consensus. Moreover, the larger runup events in the Northland region are still lacking a definitive geophysical explanation. It is worth noting that this study points out that marine geophysics and the description of the subduction zones still present major limitations in the knowledge base. With regards to local tsunami sources, more continental shelf work on landslides and submarine faults needs to be carried out.

1. Introduction

Environment Waikato (EW), acting on behalf of four regional councils [Auckland Regional Council (ARC), EW, Environment Bay of Plenty (EBOP), Northland Regional Council (NRC)] commissioned a tsunami source study for locations most likely to produce damaging tsunamis for the combined coastlines of EW, ARC, EBOP, and NRC.

The main aim of the study was to produce tsunami source data for input into inundation models that can be run for the individual regional councils concerned. Combining the financial resources of each region allowed a more comprehensive compilation of source data to be used for input into initial model runs in this financial year. It was decided that the best cost-benefit and tsunami source coverage could be achieved by considering distant and regional sources for the most part.

In this report, a standard definition of source type is used. Distant sources refer to tsunamis that take longer than 3 hours from their time of generation to time of runup along New Zealand shores. Regional sources take between 1 and 3 hours to propagate to New Zealand, and local sources take less than 1 hour.

2. Background

The study area of the combined regions faces a diverse range of potential tsunamigenic sources either locally on the continental shelf and slope, regionally along the crustal plate boundaries where subduction zone earthquakes occur, or remotely across the Pacific Ocean. Within the local and regional categories a range of potential tsunamigenic sources have been reported in geophysical investigations that include seafloor mapping and seismic profiling of fault systems, underwater volcanism and sector collapse, and underwater landslides. Large submarine landslides will undoubtedly produce large tsunamis, but these are highly complex events and much of the required data for modelling purposes are not available. With limited data it is difficult to estimate return periods, although for large submarine landslides these are believed to be in the 10's-100's of thousands of years. For smaller, but potentially locally catastrophic submarine landslides, there are no existing useful data, but these events have undoubtedly occurred in the past and with a higher frequency than their larger counterparts.

In general terms, the patterns and magnitudes of tsunami runup recorded place constraints on the possible locations and strengths of various sources. Since the aim is to determine the most significant sources for the combined regions we have, where possible, used palaeotsunami deposit and historical data to help groundtruth and guide modelling efforts. The use of palaeotsunami data has proved to be a successful tool in other studies (Walters et al., 2006a).

A key point concerning the available palaeotsunami data is that it usually only records events which have had run-up heights around 5 m or more (Goff, 2003). This lower height limit is not fixed, and deposits have been found where runup could not have exceeded 4 m, but it works as a useful "rule of thumb". Palaeotsunami evidence spans most of the Holocene, with most covering the period from when sea levels stabilised about 6000 years ago or so. There are several apparently contemporaneous groupings of palaeotsunamis that have occurred during this period, the most significant of which was in the 15th Century (e.g. Goff and McFadgen, 2002). It is believed that there was not one, but several, large tsunamis that inundated the New Zealand coast around this time (Goff and McFadgen, 2002). Evidence for these inundations is particular marked along the coast of the combined regions and these will form the bulk of the palaeotsunami data used as part of this investigation.

Conversely, historical data for the most part do not record evidence for large tsunamis. There are rare local exceptions, but the historical record suffers from two fundamental problems. Firstly, it is only extends back about 180-200 years, containing only details of the relatively higher frequency, lower magnitude events. It is not a reliable as an indicator of all potentially significant tsunami sources. Secondly, much of the information is anecdotal and lacking in scientific rigour. This type of information is of little value to an investigation of the nature and extent of potentially significant tsunami sources. At best these data offer an indication of the general effects from distant South American sources. The most recent moderate tsunami from this region occurred in 1960 but much of the information from this event was not measured. In the almost total absence of physical evidence, and with limited instrumental data, it is unwise to place too much reliance upon this data source.

We have treated this study in two ways. Firstly, we see it as an inverse problem where the palaeodata (and some historical data) helps determine the most credible sources out of all the possibilities. Numerical models then fill in the information between the physical data points. Secondly, numerical models are used to determine "worst case scenario" events from known sources. The worst case scenarios from some sources may not be significant to the combined region and will therefore not have produced any notable tsunamis. Alternatively, they may be significant, but simply not yet recorded in any database. Without running the models we would not know.

From this exercise, we identified four source areas believed to be the most significant to the regions encompassing EW, ARC, EBOP, and NRC:

1. Distant – Eastern source: South America (Chile/Peru) subduction zone.

2. Regional/Local – Eastern source: Tonga-Kermadec Trench.

3. Distant/Regional – Northern source: Solomon Sea/New Hebrides Trench (these represent two source areas, but are considered jointly under the heading of a Northern source).

4. Local - Various.

There are numerous potential local sources which are likely to be catastrophic for only one or two regions as opposed to all four regions. In general terms, by covering key eastern and northern sources we are finding out about how distant and regionally sourced tsunamis would affect any stretch of coast within the combined region. Locally-sourced tsunamis however can be much larger than their regional or distant counterparts but affect only a short stretch of coastline. With this in mind, some consideration was also given to local sources within the Bay of Plenty, and also to areas around the edge of the continental shelf to the north and east of the combined region. Potential local northern sources could generate catastrophic tsunamis for the Northland region, but the possible impact of these waves on coastlines to the south is largely unknown. Both the Hauraki Gulf and Bay of Plenty are open to the north. While not exhaustive, it was felt important to initiate additional investigations of this exposure to locally-sourced tsunamis, with particular reference to submarine landslides.

As discussed, the main aim of this study is to produce tsunami source data for input into inundation models. This rationale was based primarily upon the need to assimilate and critically review data from a wide range of research, and to liaise widely with workers from many countries. During the course of this contract we have held discussions with researchers from Australia, United States, Canada, New Zealand, Chile, and France. Much of the original data collected has been from overseas sources including Australia, Japan, Chile and French Polynesia.

During the data collection and interpretation exercise we ran a complementary project to improve bathymetric data. A global search was undertaken to improve resolution of the data with particular emphasis placed upon areas to the northwest, north and east of the North Island. The aim was two-fold: To improve our understanding of the propagation of tsunamis produced from the various sources, and also to provide geophysical source information for local and regional areas. To this extent we were also able to identify key gaps in the existing information.

2.1. Source description

2.1.1. Distant – Eastern source: South America (Chile/Peru)

The plate boundary along the west coast of South America has a relatively high rate of convergence and is seismically very active. The size of a tsunami that is generated in a subduction zone rupture depends on a number of factors including the magnitude and location of the event. The location determines the primary direction that the wave will propagate and hence whether the wave will hit or miss New Zealand. Historically, there have been three moderately large tsunamis from South America; 1868, 1877, and 1960. The largest estimated runup recorded within any of the four regions was 3.6 m at Port Charles (EW) in 1877 (Fraser, 1998). The only known geological evidence for any of these events is in Lyttelton Harbour, outside the combined region, where wave heights of 4.3 m (1960) and 7.6 (1868) were recorded (Goff, 2005). Previous reports have detailed the most significant historical runup information for individual regions (Northland Region: Chagué-Goff and Goff, 2006; Auckland Region: Goff et al., 2005; Environment Waikato/Environment Bay of Plenty: Bell et al., 2004).

2.1.2. Distant/Regional – Northern source: Solomon Sea/New Hebrides Trench

Subduction zone earthquakes occur from the New Hebrides trench east of New Caledonia up to the Solomon Sea and beyond. Eastward between the New Hebrides trench and Tonga, the plate convergence is along the direction of the faulting so that the seabed deformation is greatly reduced. Northward from New Caledonia, the fault direction is highly variable and any tsunamis that are generated are not directed at New Zealand. However, there are two underwater ridges that can act as wave guides to direct tsunamis to the far north of New Zealand and to the northwest coast of the South Island (Figure 2.1.2-1).

The extent to which tsunamis sourced from the north can affect the combined region's coastline has largely been ignored, although it has been noted that moderately large runups up to 1.8 m (Auckland and Bay of Plenty regions) were recorded as a result of the Krakatoa eruption in 1883. Recent work around the Northland coast however, has produced palaeotsunami deposit evidence for runups well in excess of 10 m at many sites (Chagué-Goff and Goff, 2006). Many of these Northland sites have a north facing aspect and serious consideration was therefore given to identifying potential local, regional and distant northern sources.

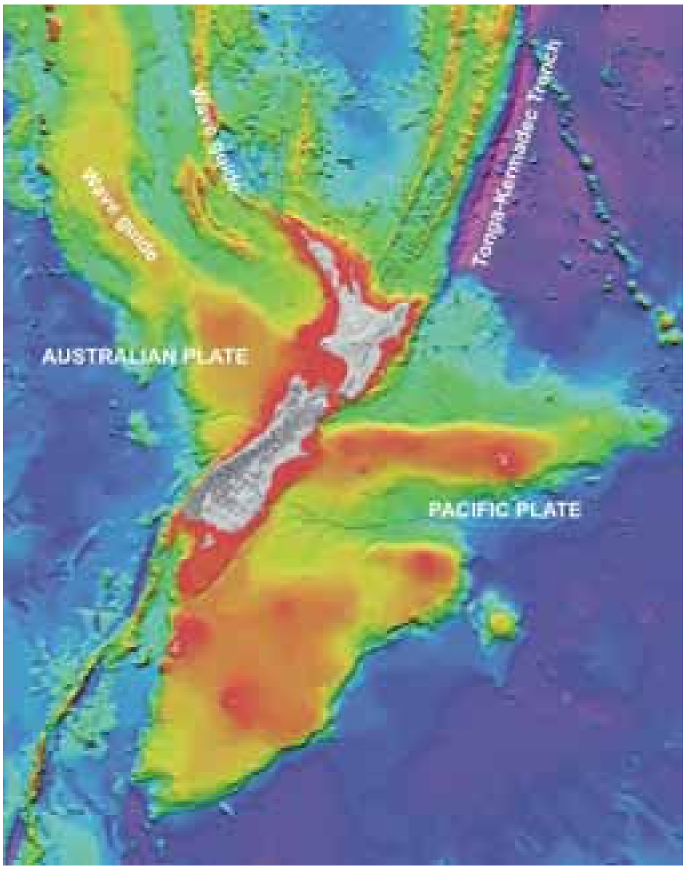


Figure 2.1.2-1: Geophysical setting of the North Island showing two bathymetric wave guides to the northwest (the Chatham Rise acts as a wave guide to tsunamis approaching from across the eastern Pacific Ocean).

2.1.3. Regional/Local – Eastern source: Tonga-Kermadec Trench

.Subduction zone earthquakes occur along the Tonga-Kermadec trench associated with the Pacific/Australian plate boundary (the Hikurangi Trough is a southern extension of the Tonga-Kermadec trench) (Figure 2.1.2-1). This source occurs beneath the eastern margin of the continental shelf and the Kermadec Ridge from the east coast of the North Island to Tonga, where the Pacific Plate underthrusts (subducts) to the west. Historic earthquakes of magnitude Mw 8.0 to 8.3 have occurred along the Kermadec boundary (ITDB/PAC 2004) in the early 1900's. As a general rule of thumb, large subduction zone earthquakes in a particular area have return periods of 300 to 1000 years.

Palaeotsunami data have been used successfully to groundtruth models of local tsunami inundation from this source for some parts of New Zealand (Walters et al., 2006a). In this study of the combined region there is a considerable amount of data available incorporating records accumulated from a series of studies (e.g. Nichol et al., 2003; 2004; Bell et al., 2004; Goff et al., 2005; Chagué-Goff and Goff, 2006). Undoubtedly, there is an impact from this source on the eastern and north-eastern facing coasts that comprise much of the combined region. The extent to which either this or a northern source(s) has contributed to some of the larger runups recorded however, has yet to be resolved. The effects of these sources on the western coast of the combined region are also unknown.

2.1.4. Local – various

The range of local tsunami sources from East Cape around the north tip of the North Island to Taranaki is substantial. Most of the sources that are known in some detail occur around the Bay of Plenty and include giant submarine landslide complexes such as Matakaoa and Ruatoria, local normal and reverse faults, and volcanic activity associated with the Taupo Volcanic Zone. Large submarine landslides will undoubtedly produce large tsunamis, but these are highly complex events and much of the required data for modelling purposes is not yet available. Furthermore, they have long return periods in the region of 10's-100's of thousands of years. However, smaller landslides are possible along many parts of the combined region's coastal margin. Local normal and reverse faults and volcanic activity are generally confined to the Bay of Plenty and northward along the Kermadec Ridge.

Local tsunamis tend to be larger but affect a shorter length of coastline that those from more distant sources. This is evident from the recent Indian Ocean tsunami in 2004 where coastlines along Indonesia immediately adjacent to the fault rupture received large wave runups in excess of 30 m, but with runup elevations tapering off markedly at short distances along the coast (Borrero et al., in press). In Africa, maximum wave runups only 2-3 m were noted, but were recorded along the whole length of the east African coast (Fritz and Borrero, in press).

Local sources cannot therefore be ignored. While some bathymetric data have been collected around New Zealand, there are many regions where coverage is minimal. With the exception of some areas of the Bay of Plenty this generally applies to the combined region. Poor resolution bathymetric coverage means that we only have a vague indication of the larger geomorphological features on the seafloor. The nature and extent of palaeotsunami evidence, particularly around the Northland region (see Section 2.1.2), indicates that locally sourced tsunamis must have been responsible for some of the higher elevation sites. Similarly, evidence in the western Bay of Plenty is indicative of larger, local events. We have used all available data to start to address this issue of locally sourced tsunamis.

2.2. Model description

The numerical model used in this study is a general-purpose hydrodynamics and transport model known as RiCOM (River and Coastal Ocean Model). The model has been under development for several years and has been evaluated and verified continually during this process (Walters and Casulli, 1998; Walters, 2005; Walters et al., 2006b; 2006c). The hydrodynamics component of this model was used to derive the results described in this report.

The model is based on a standard set of equations - the Reynolds-averaged Navier-Stokes equation (RANS) and the incompressibility condition. In this study, the hydrostatic approximation is used so the equations reduce to the nonlinear shallow water equations.

To permit flexibility in the creation of the model grid across the continental shelf, a finite element spatial approximation is used to build an unstructured (irregular) grid of triangular elements of varying-size and shape. The time marching algorithm is a semi-implicit numerical scheme that avoids stability constraints on wave propagation. The advection approximation is a semi-Lagrangian scheme, which is robust, stable, and efficient (Staniforth and Côté, 1991). Wetting and drying (inundation) of intertidal or flooded areas is included in this formulation and is defined by the finite volume form of the continuity equation and method of calculating fluxes (flows) through the triangular element faces. At open (sea) boundaries, a radiation condition is enforced so that outgoing waves will not reflect back into the study area, but instead are allowed to realistically continue through this artificial boundary and into the open sea. The equations are solved with a conjugate-gradient iterative solver. The details of the numerical approximations that lead to the required robustness and efficiency may be found in Walters and Casulli (1998) and Walters (2005).

2.3. Model grid and bathymetry

Several model grids were developed for the various source scenarios. For the distant source (Chile) a refined version of the EEZ was used. This grid spans from approximately 157 to 210 degrees east Longitude and 22 to 65 degrees south Latitude. Another grid was developed for the Tonga-Kermadec source from just south of East Cape to 22 degrees south Latitude. Finally, the latter grid was extended northward to include the Solomon Sea and New Hebrides subduction zones. Bathymetric data were derived from a number of sources. For the EEZ area, existing data were used. For the northern area, GEBCO data were used (IOC, IHO, and BODC, 2003).

The finite element model grid has a number of requirements to ensure that model calculations will be accurate and free from excessive numerical errors (Henry and Walters, 1993). The primary requirements are that the triangular elements are roughly equilateral in shape and their grading in size is smooth from areas of high resolution (small elements) in the coastal zone to areas of low resolution (large elements) offshore. The grid was generated using the program GridGen (Henry and Walters, 1993) according to the requirements described above. A layer of elements is generated along the boundaries using a frontal marching algorithm (Sadek, 1980). The remaining interior points are filled in using the cluster concept described in Henry and Walters (1993). The grids were then refined by a factor of four by subdividing each grid triangle into 4 new triangles using vertices at the mid-sides of the original triangle. This refinement continued until the target resolution was obtained. Water depth values were interpolated at each node from the reference datasets.

3. Results

3.1. Distant - Eastern source: South America (Chile/Peru)

There are three primary factors that determine the response of New Zealand to tsunamis that travel across the Pacific Ocean: source location and geometry, wave transformations that occur when the tsunami crosses the ocean, and the effects of the bathymetry and geometry of the continental shelf and coastal region.

Source geometry can be determined in a general sense from empirical formula that relate fault length, width, and slip to the moment magnitude (Mw) of the earthquake. The location of the plate boundaries and convergence rates are found in Bird (2003) and information on the fault geometry is found in Pacheco et al (1993). The faults are typically 100 km in width along the dip and extend down to 45 km below the surface. Here we focus on the great earthquakes with Mw from 9.0 to 9.5. Among these are the 1960 Chile earthquake (Mw 9.5) and the 1868 Peru (now Chile) earthquake (Mw 9.0) which generated two of the largest distant tsunamis to reach New Zealand over the last 200 years of historical records. An important factor is the location of the fault rupture as the trend of the subduction zone determines the direction that a tsunami is propagated. As an example, the 1960 event was larger but was directed north of New Zealand and generally had a smaller effect than the 1868 event which was almost a direct hit on New Zealand.

The direction of tsunami propagation across the Pacific Ocean generally follows a great circle route, but the wave is modified by reflection and refraction when the water depth changes and by diffraction when the wave passes through island chains. Usually, trans-Pacific tsunami propagation is modelled using nonlinear shallow water theory with dissipation of short wavelengths, or by linear shallow water theory where all waves travel at the same wave speed. However, this latter approach is not strictly correct since over this great distance the waves are dispersive (long waves travel faster than short waves) and the result is that a wave train is generated rather than a single wave. This behaviour is important when the runup is considered.

When a tsunami encounters the continental shelf slope, it is partially reflected and the wave speed slows due to the decreased water depth. As the wavelength becomes shorter the wave height increases. In some locations where there is an abrupt change in water depth such as at the Chatham Islands, the shoaling and wave height increase can be very abrupt with tsunamis several times larger than are experienced on the mainland. Finally, it is the detailed coastal geometry and bathymetry that controls how a given wave affects the shoreline. A typical tsunami represents a superposition of waves of many frequencies and amplitudes. Hence, a section of the coast amplifies parts that are in resonance and dampens others. For instance, Mercury Bay (EW) will typically oscillate at about 45 minutes in response to that part of the tsunami whereas there are 10 minute current surges in small bays and a characteristic 2 to 3 hour resonance in Pegasus Bay and the Port of Lyttelton. As a result there is a wide range of observed frequencies and amplitudes for a single tsunami as it interacts with the coast.

For the purposes of this report, we have chosen to specify an incident tsunami at the eastern edge of the model grid (210 degrees east Longitude) that represents a "direct hit" scenario similar to the 1868 event. We have used the concept of inverse modelling to groundtruth this scenario using the more reliable historical data for the 1868 event and to a lesser degree the 1960 event. In effect, the model fills in the missing information along the coast using the historical data as a rough guide. A plot of the maximum water surface elevation for the entire simulation is shown in Figure 3.1-1.

The incident wave has a maximum elevation of about 0.15 m. When the wave encounters the Chatham Rise, the wave amplitude abruptly increases to over 5 m in places around the Chatham Islands. Note that the legend in Figure 3.1-1 ranges up to 3 m. Thus any elevations higher than 3 m would just be indicated by the highest colour on the scale. We have made a decision about what is the best visual representation of the wave, but the largest water elevations can be higher – in some cases much higher – than the upper increment. It should be noted that there is no land topography in these images and so these are water surface elevations with a "wall" at the shoreline. These results are therefore accurate if the coast is a steep cliff but are an over-prediction for relatively flat coastal topography. As a result, we have erred on the side of caution and have avoided stating the highest water elevation at the coast for any region as a result of any of the scenarios presented since this would introduce bias to the interpretation.

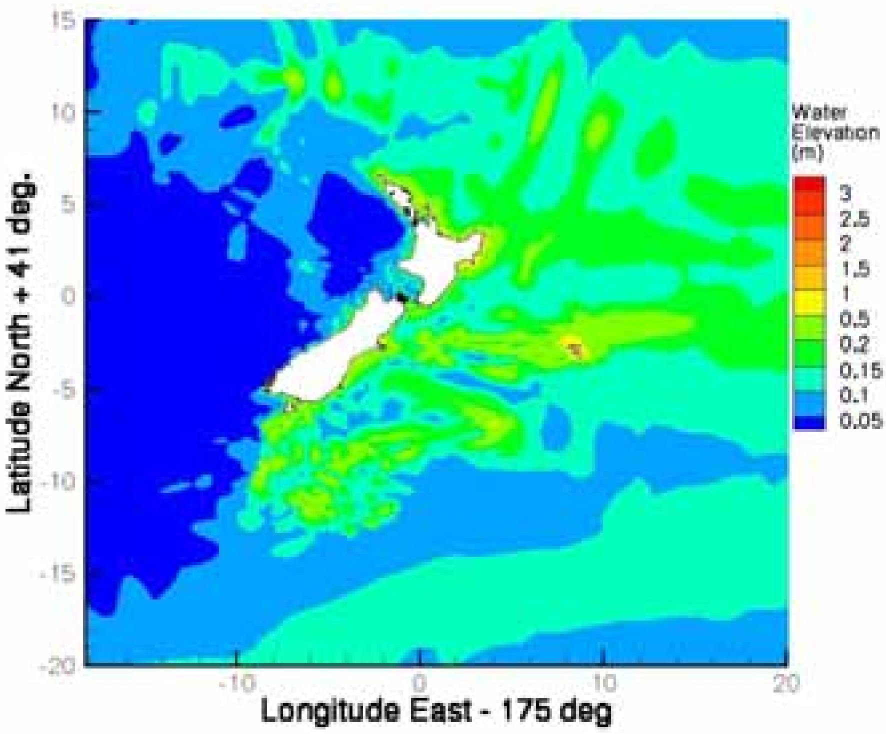


Figure 3.1-1: Maximum water surface elevations for a tsunami that represents the "direct hit" scenario.

After the Chatham Islands the tsunami then makes landfall along the east coast of the North Island due to deep water allowing the waves to travel faster in deep water. When the tsunami reaches East Cape, the crest is aligned roughly with the Kermadec Ridge. Hence the tsunami has a similar spatial pattern to tsunamis caused by subduction zone ruptures along the Tonga-Kermadec trench, but the amplitude is less with the distant tsunami.

As the tsunami passes East Cape, the wave front stretches and refracts into the Bay of Plenty. Wave height at the shoreline is typically 1 to 2 m with larger heights toward the west and north. The wave has a large impact on Great Barrier Island but diminishes in amplitude as it enters Hauraki Gulf. There are mixed effects as the tsunami arrives at more northerly locations. The wave heights at the shoreline are generally 1 to 2 m with larger values of approximately 3 m in a few bays. (These values for wave height are only approximate as there is no land topography in the model).

3.2. Regional/Local – Eastern source: Tonga-Kermadec Trench

Although the Tonga-Kermadec-Hikurangi trench extending north along the east coast of the North Island to Tonga is a prominent feature in the seabed topography, there is a paucity of definitive geophysical information for the area north of East Cape. South of East Cape along the Hikurangi subduction zone, Reyners (1998) suggests that the subduction zone area decreases between Wairarapa and East Cape and events of about Mw 6.9 are estimated for the northern part of this segment

Up to a distance of approximately 250 km north of East Cape, the Hikurangi Plateau is being subducted beneath the Kermadec margin. At the northern edge of the plateau is the Rapuhia Scarp where there is an abrupt transition from the Hikurangi Plateau volcanics to oceanic crust (Collot and Davey, 1998; Davey and Collot, 2000). The Rapuhia Scarp is approximately 1 km high and results in an increase in depth of approximately 1.5 km to the north. This implies that the shelf slope is oversteepened and there is a possibility of large submarine landslides and slumps. In addition, the scarp may act as a termination point for subduction zone ruptures to the north and south. Moreover, the change in fault dip across the scarp suggests that surface deformation caused by fault rupture may vary between sections to the north and south of the scarp.

For the area to the north along the Tonga-Kermadec trench, Pacheco et al. (1993) provide information for estimating the fault geometry. We have used this information as input to the fault dislocation model of Okada (1985) to define the seabed displacement used in this study.

Since the magnitude and location of subduction zone events is not well defined for this area, we have explored a range of events and compared the results with elevations of palaeotsunami deposits primarily from the 15^{th} century (e.g. Walters et al., 2006a). The first set of events are for an Mw 8.5 event placed south and north of the Rapuhia Scarp, and an additional location in the next northern section of the fault (Figures 3.2-1, 3.2-2, and 3.2-3). As shown in the wave elevation patterns, the southern section mainly impacts the Bay of Plenty to Great Barrier Island, the next northern section mainly impacts Northland, and the far north section has minimal impact as the tsunami is directed north of the North Island. Events generated farther north have even less effect. An Mw 8.0 to 8.5 would be considered a reasonable magnitude event for the Tonga-Kermadec subduction zone. However, the Boxing Day event serves notice that these are probably underestimates for the maximum magnitude that could occur.

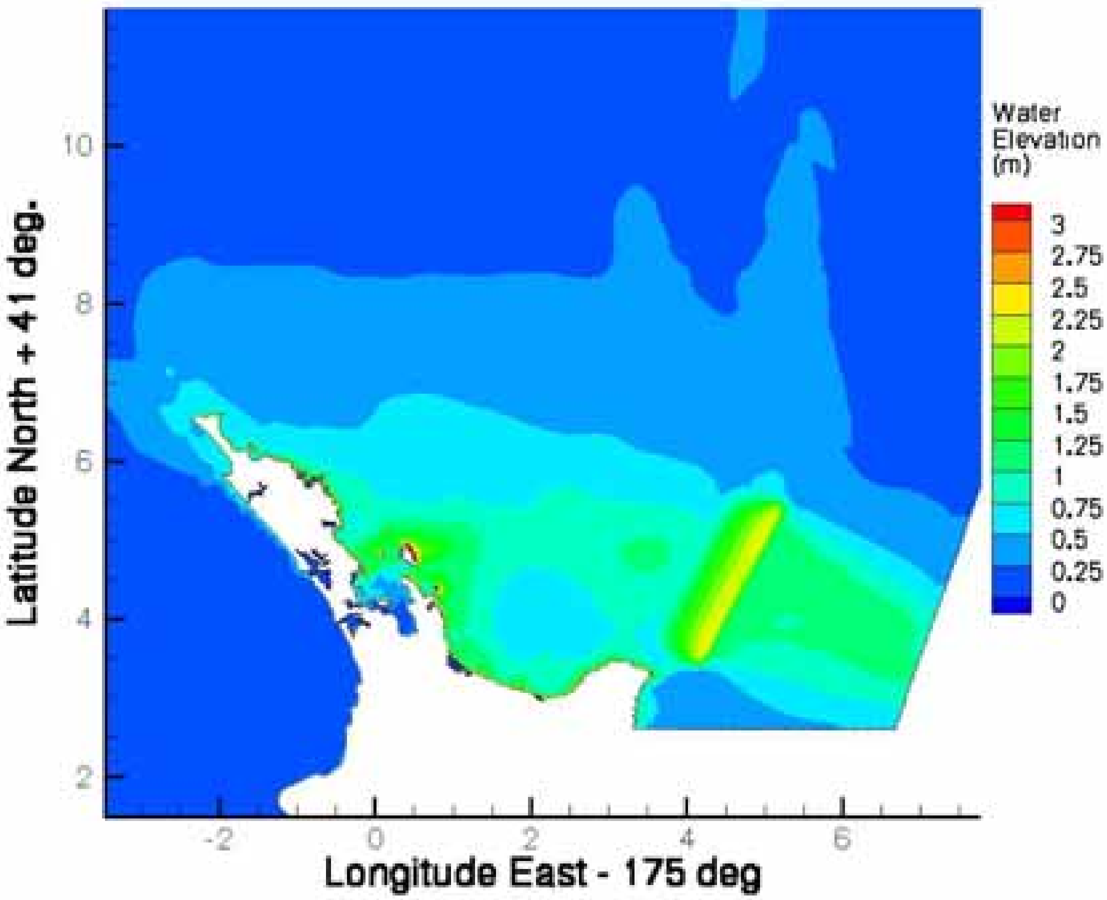


Figure 3.2-1: Maximum water surface elevations for the Tonga-Kermadec source- southern location with Mw 8.5.

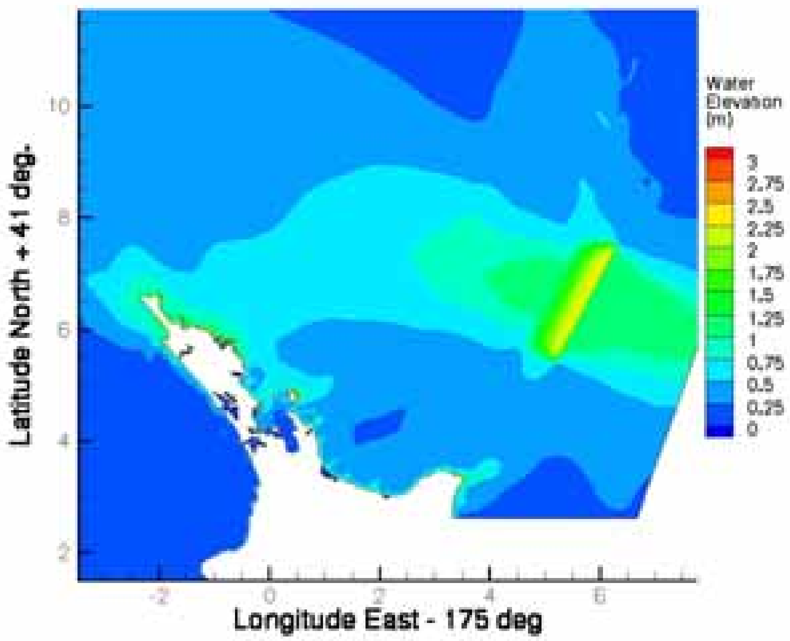


Figure 3.2-2: Maximum water surface elevations for the Tonga-Kermadec source- central location with Mw 8.5.

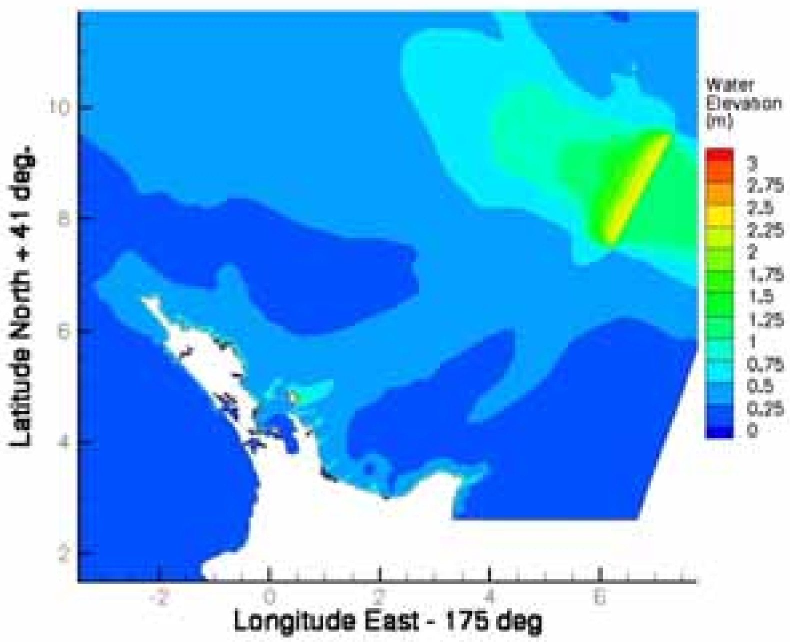


Figure 3.2-3: Maximum water surface elevations for the Tonga-Kermadec source- northern location with Mw 8.5.

Hence, we have also included an Mw 9.0 event which is twice as long and has twice the slip of the Mw 8.5 event. The faults were placed south of the Rapuhia Scarp, across the scarp, and to the north of the scarp (Figures 3.2-4, 3.2-5, and 3.2-6). For locations farther north along the Kermadec trench, the tsunami passes north of North Cape and the impacts on the Northland coast are reduced considerably. As shown in the wave elevation patterns, the southern section mainly impacts the Bay of Plenty to Great Barrier Island. As with the Mw 8.5 event, the section across the scarp impacts all the study area, and the northern section mainly impacts Northland.

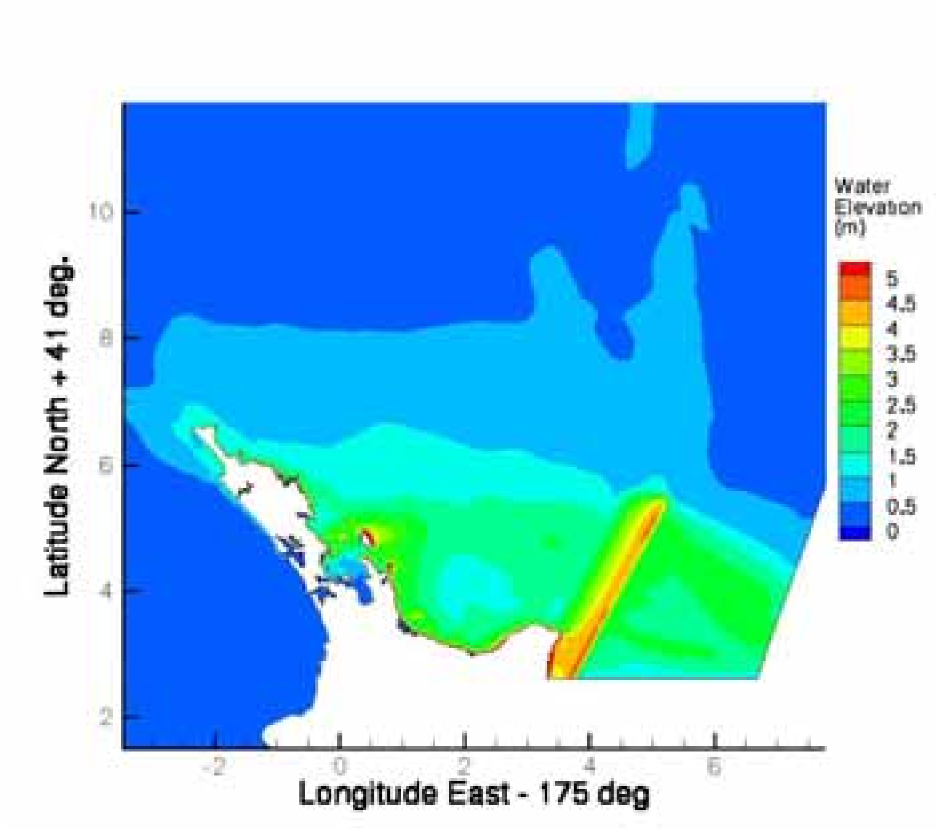


Figure 3.2-4: Maximum water surface elevations for the Tonga-Kermadec source- southern location with Mw 9.0.

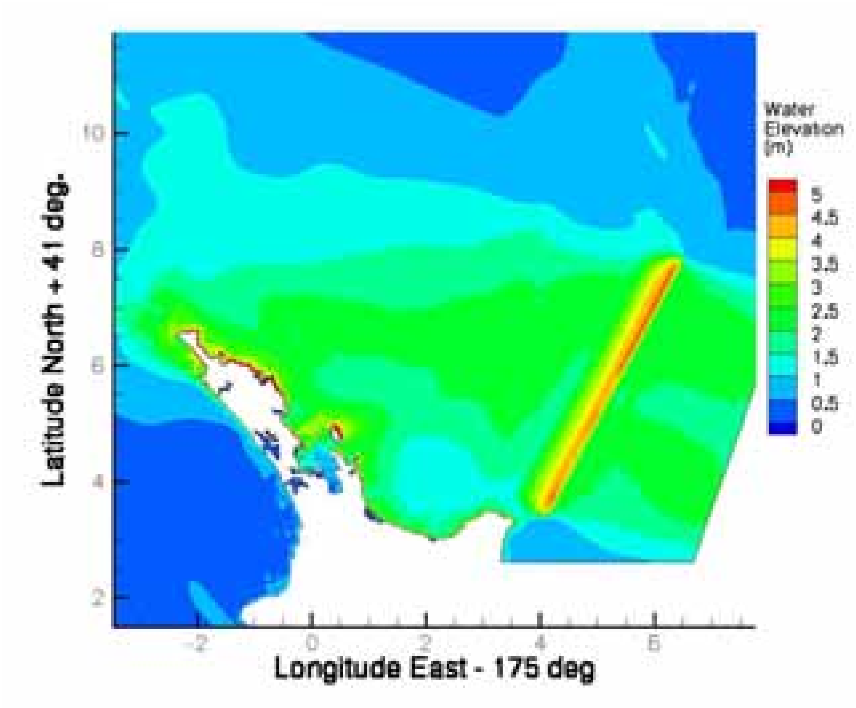


Figure 3.2-5: Maximum water surface elevations for the Tonga-Kermadec source- central location with Mw 9.0.

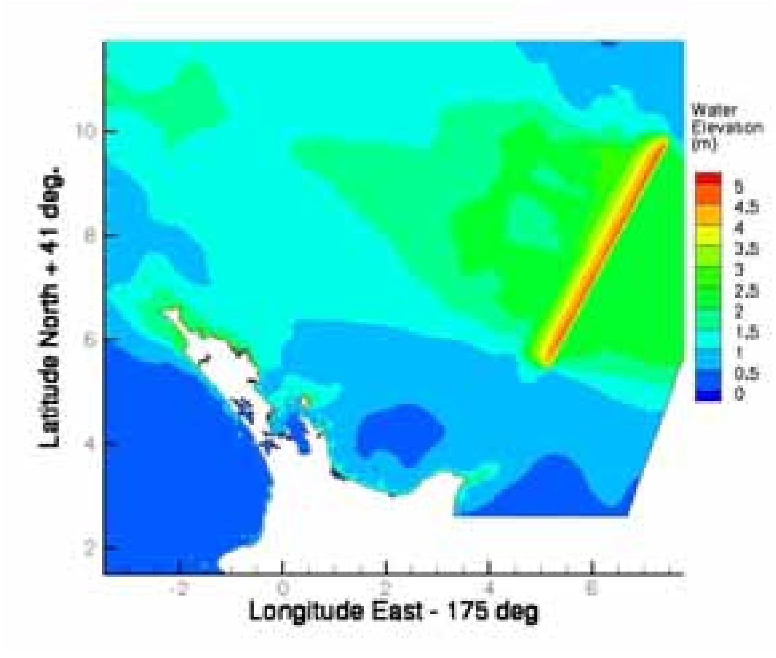


Figure 3.2-6: Maximum water surface elevations for the Tonga-Kermadec source- northern location with Mw 9.0.

3.3. Distant/Regional – Northern source: Solomon Sea/New Hebrides Trench

Between Tonga and Indonesia, the plate boundary between the Pacific and Australian Plates takes a sinuous path along a number of small plates (Bird, 2003). For the purposes of this study, we will focus on the subduction zone extending from the edge of the New Hebrides Plate near New Caledonia to the Solomon Sea. While this may seem far afield, Burbidge (pers. comm., 2006) has shown that fault ruptures at the southern end of the New Hebrides trench and near the Solomon Sea will generate tsunami that can travel along underwater ridges to New Zealand. These ridges act as a wave guide, similar to the Chatham Rise for tsunamis generated in South America (Figure 2.1.2-1).

We have used the data in Bird (2003) to locate the subduction zone for the Solomon Sea and New Hebrides Trench sites, and used the data from Pacheco et al. (1993) to define fault geometry. From these data, we have defined Mw 8.5 and Mw 9.2 events. An event with Mw 8.0 to 8.5 is considered a reasonable magnitude for this part of the plate boundary. The larger event was adopted for two reasons: recent events have indicated that these estimates are probably too conservative, and we wanted to determine the maximum potential tsunami impact in New Zealand. This is the largest event that could be expected.

The maximum water surface elevation for these two events is shown in Figures 3.3-1 and 3.3-2 for the New Hebrides source, and in Figures 3.3-3 and 3.3-4 for the Solomon Sea source. The wave guide effects of the undersea ridges are readily apparent with the New Hebrides tsunami propagating primarily down the ridge to Northland, and the Solomon Sea tsunami propagating primarily down the ridge to the northwest of the South Island.

3.4. Local – Various

3.4.1. BOP faults and submarine landslides

The Bay of Plenty is somewhat unique in that it has a large number of important local tsunamigenic sources owing to its position astride the Taupo Volcanic Zone and base of the Kermadec volcanic forearc (Bell et al, 2004; Walters et al, 2006a). These sources include normal and reverse offshore faults, volcanism, submarine landslides, and subduction zone faults (refer Section 3.2.). Of these, subduction zone events generated the largest runup (Walters et al, 2006a), although de Lange et al. (2001, 2006) suggest that volcanic island edifice failure might have similar impacts. At this time, these local events are reasonably well understood and have impacts that may reach as far as Coromandel Peninsula. We do not propose to address these any further in this report.

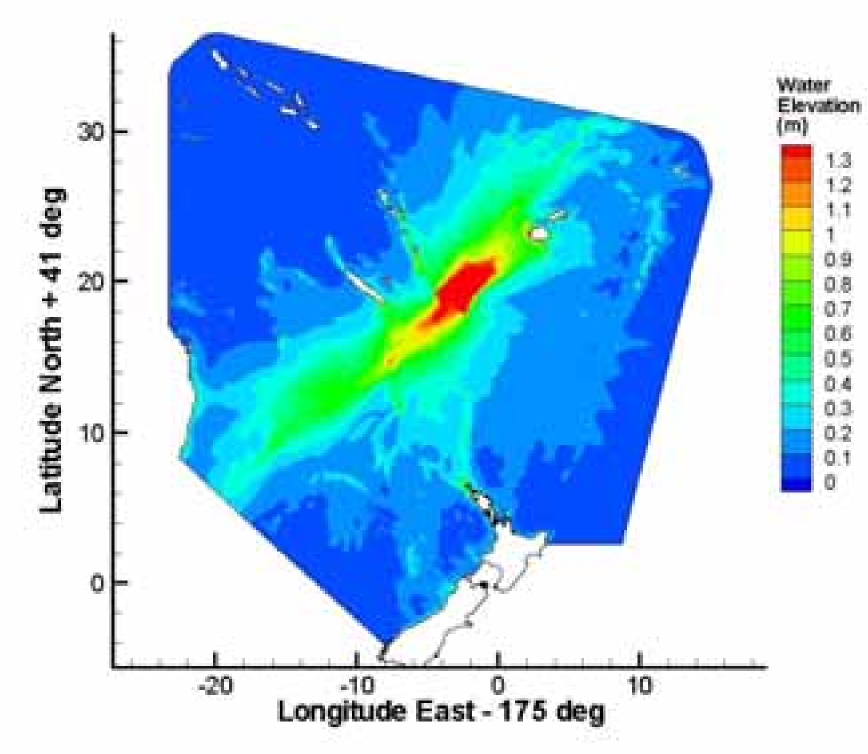


Figure 3.3-1: Maximum water surface elevations for the New Hebrides source with Mw 8.5.

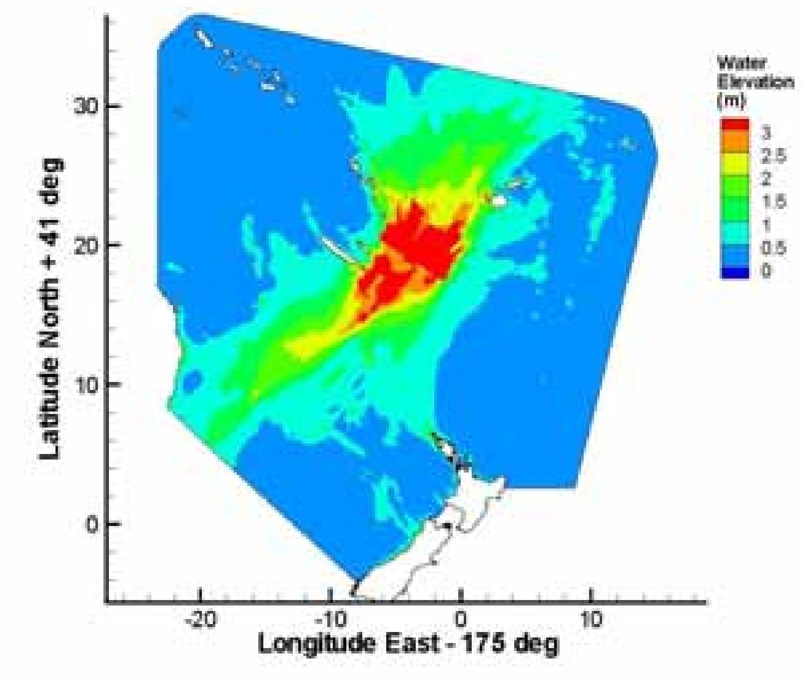


Figure 3.3-2: Maximum water surface elevations for the New Hebrides source with Mw 9.2.

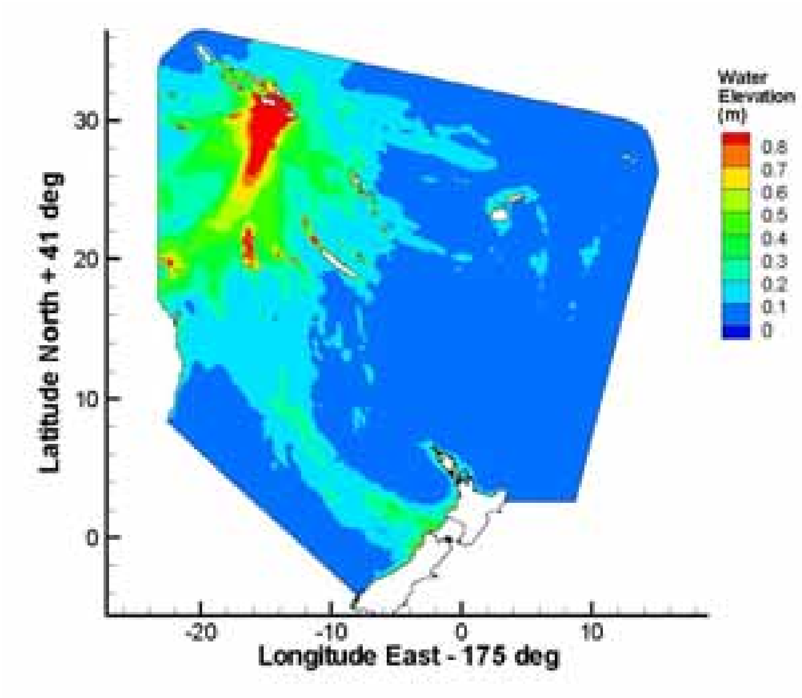


Figure 3.3-3: Maximum water surface elevations for the Solomon Sea source with Mw 8.5.

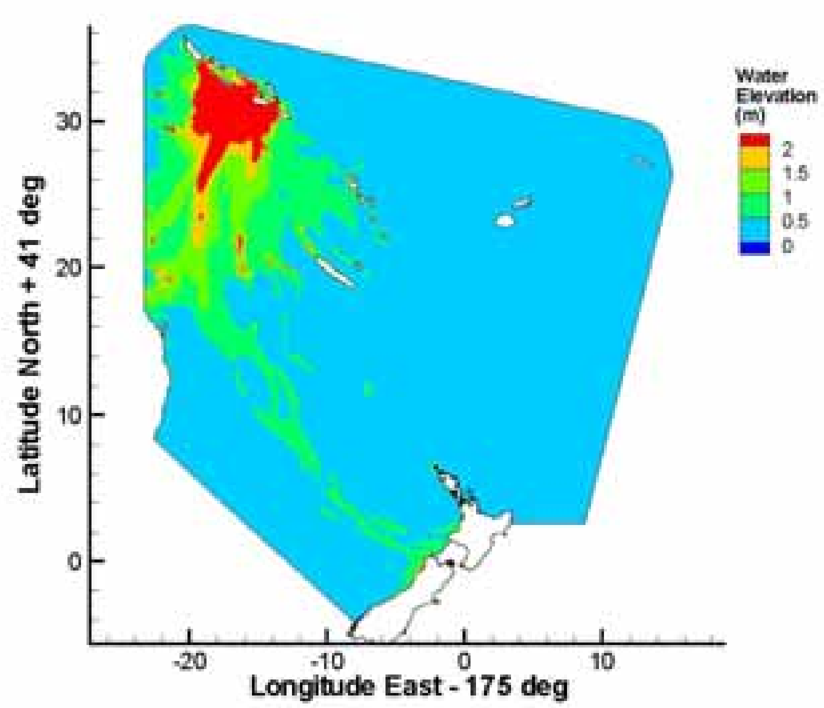


Figure 3.3-4: Maximum water surface elevations for the Solomon Sea source with Mw 9.2.

3.4.2. Mystery sources

There is a mystery event (or events) that shows up in the palaeotsunami deposit elevations from the 15th century. Some, such as those on Great Barrier Island, have been successfully modelled from a Tonga-Kermadec subduction zone event (see Section 4.2.2). There are several sites in Northland however where the runup exceeds 20 to 30 m above MSL (e.g. Nichol et al., 2004). These values are much too large to have been caused by the largest regional subduction zone or distant events that are considered in this study. The local grouping and the large runup of these events suggests that there is an unknown local source north to northeast of the North Island. However, this area is not considered to be active tectonically so there are few clues as to the source. With limited information available, a potential source could be submarine landslides east of Three Kings Islands, presently unknown faults or submarine landslides, or a combination event (e.g. a Tonga-Kermadec subduction zone event combined with large scale submarine landsliding or slumping). In lieu of more information, we have chosen to experiment with local sources to attempt to replicate the observed runup and thus gain a better understanding of potential source locations.

Three general sources were considered: a generic submarine landslide travelling north from Three Kings Islands, a submarine landslide northeast of North Cape, and a slump off the continental shelf near the Rapuhia Scarp (Tonga-Kermadec trench). The third one is not produced below as a figure, but an animation is provided on the CD. There are other possibilities, but these provide a basic framework of potential events.

A tsunami generated by the Three Kings Island source has its main impact on the north and northwest of Northland and little impact elsewhere. The wave height pattern can match part of the palaeotsunami data, but not on the east coast around Henderson Bay (Figure 3.4-1). The second source has a better spatial pattern on the east coast (Figure 3.4-2) but seems to be too weak on the west coast. The third source is somewhat distant and has the major impact at Great Barrier Island. The third source could be moved farther north and superimposed with the Tonga-Kermadec subduction zone event to have a greater impact at the Northland sites. However, this would involve additional work which is outside the scope of this study.

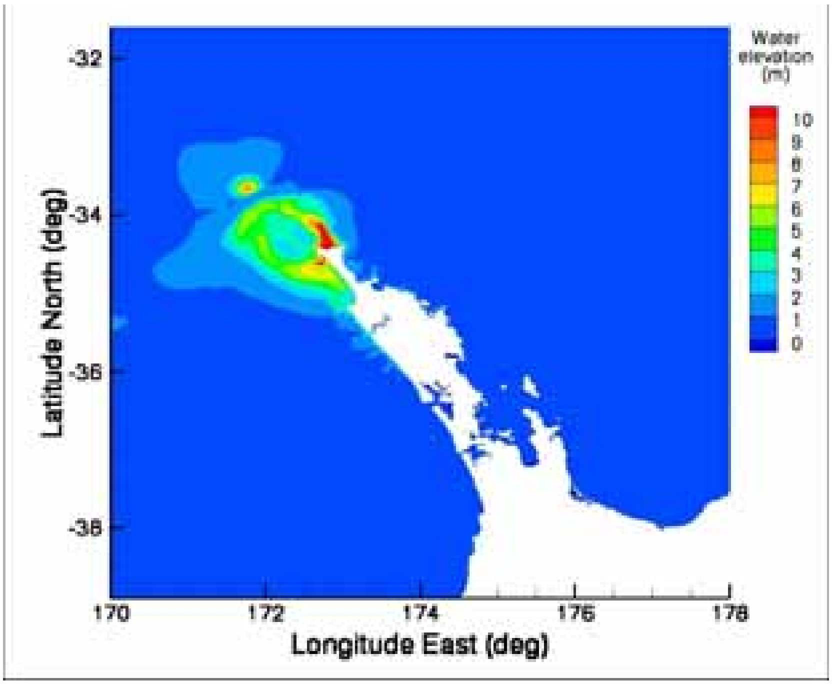


Figure 3.4-1: Maximum water surface elevations for a submarine landslide near Three Kings Islands.

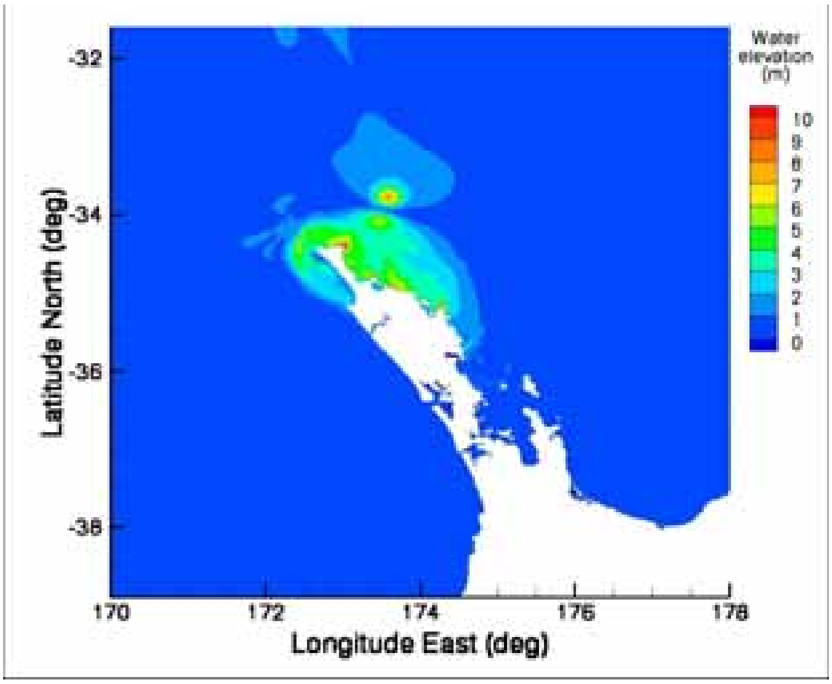


Figure 3.4-2: Maximum water surface elevations for a submarine landslide northeast of North Cape.

4. Regions

Maximum water surface elevation images are presented below for tsunamis generated from the sources discussed above; Distant – Eastern source: South America (Chile/Peru), Regional – Eastern source: Tonga-Kermadec Trench, and Regional/Distant – Northern source: Solomon Sea/New Hebrides Trench. In addition, selected images are shown for local source options.

To provide some useful visualisations for presentation to interested parties, we have provided a CD for each region which contains animations of tsunamis generated from a selection of the sources discussed. This is not a comprehensive collection of all the sources discussed, but it complements much of the information contained in this report. (n.b. It should be noted that there is no land topography in these animations so these are water surface elevations at the shoreline only. These results are accurate if the coast is a steep cliff but are an over-prediction for relatively flat coastal topography. Refer to Section 3.1. for more information).

4.1. Northland Region

4.1.1. Distant – Eastern source: South America (Chile/Peru)

The incident tsunami crosses the Kermadec Ridge and refracts into the Northland coastline. The wave slows down as the water shoals with the result that the wavelength decreases and the height increases. The main factors controlling the wave height are the shoaling along the coastline and selective amplification in some of the bays (Figure 4.1.1-1).

The wave height is largest along the east coast as would be expected. However, the wave refracts around the northern coast and becomes a coastally-trapped wave that travels southward along the west coast. The tsunami tends to be smaller on the west coast, with a maximum of about half the height of the maximum on the east coast.

4.1.2. Regional/Local – Eastern source: Tonga-Kermadec Trench

As in the case of the distant South American source, the incident tsunami crosses the Kermadec Ridge and refracts into the Northland coastline. The wave height pattern at the shoreline is similar to the South American event but the heights are considerably larger for the Tonga-Kermadec source. Again, the main factors controlling the wave height are the shoaling along the coastline and selective amplification in some of the bays (Figure 4.1.2-1).

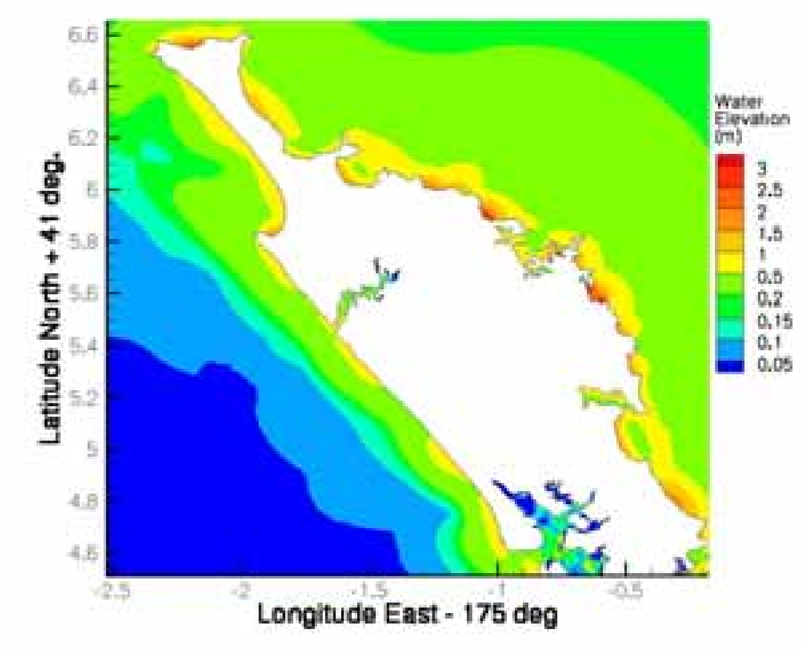


Figure 4.1.1-1: Maximum water surface elevations for an eastern distant source.

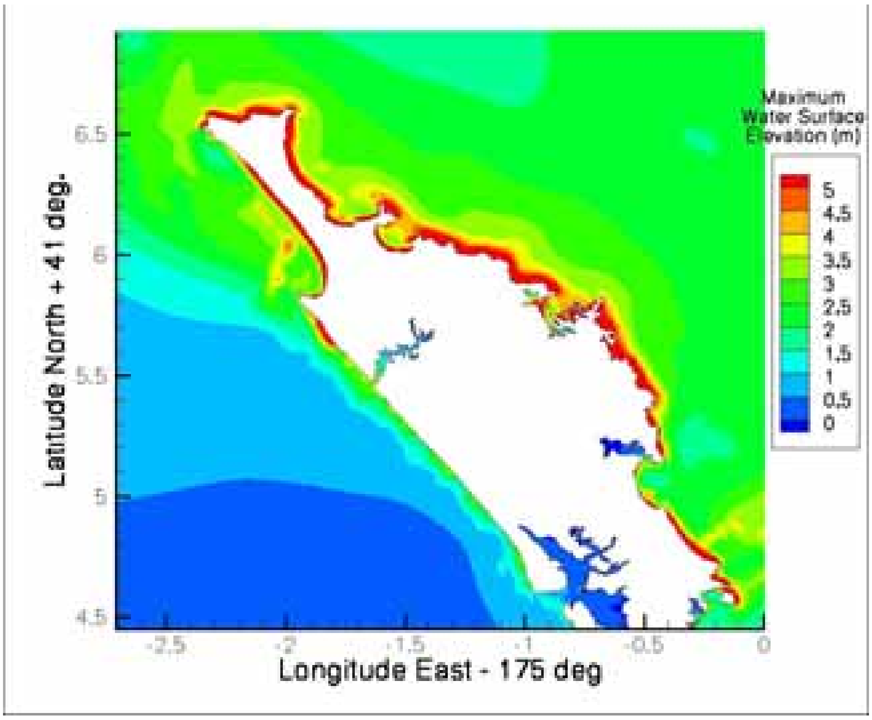


Figure 4.1.2-1: Maximum water surface elevations for the Tonga-Kermadec source- central location with Mw 9.0.

The wave height is largest along the east coast as would be expected. However, the wave refracts around the northern coast and becomes a coastally-trapped wave that travels southward along the west coast. This wave has relatively large amplitude.

Overall, these wave heights have a similar pattern and magnitude compared to the general pattern shown by the palaeotsunami deposit data (Chagué-Goff and Goff, 2006). There are however, several sites in the palaeorecord where runup heights appear to be in excess of those achievable by the maximum water surface elevations recorded here.

4.1.3. Regional/Distant – Northern source: Solomon Sea/New Hebrides Trench

Exposed northern coasts are the most affected by waves originating from events in the Solomon Sea and New Hebrides trench areas. In general, the New Hebrides event is more significant to the combined region, whereas the Solomon Sea event is more significant to the area in the northwest of the South Island (Figures 3.3-1 to 3.3-4). This behaviour is due to the different ways in which these events interact with the underwater ridges shown in Figure 2.1.2-1. The tsunami from the New Hebrides event is directed into the region by undersea ridges and is especially focussed by the Norfolk and Three Kings ridges resulting in wave heights of up to 3 m (Figure 4.1.3-1). Note that the results shown in the figures are for the Mw 9.2 event which is really the maximum possible and sets an upper bound on what may be expected in water surface elevations. Figure 4.1.3-2 shows maximum water surface elevations from the Solomon Sea source.

4.1.4. Local – Mystery source

Three general sources were considered: a generic submarine landslide travelling north from Three Kings Islands, a submarine landslide northeast of North Cape, and a slump of the continental shelf near the Rapuhia Scarp. There are other possibilities, but these provide a basic framework of potential events.

The first of these, a submarine landslide travelling north from Three Kings Islands, generates a tsunami that primarily affects the north coast between Cape Reinga and North Cape, and travels down the west coast (Figure 4.1.4-1). This event does not produce the high wave heights responsible for the deposits seen in Henderson Bay.

The second of these, a submarine landslide northeast of North Cape, produces a spatial pattern that matches the palaeotsunami data on the east and north coasts but is a little small on the west coast (Figure 4.1.4-2).

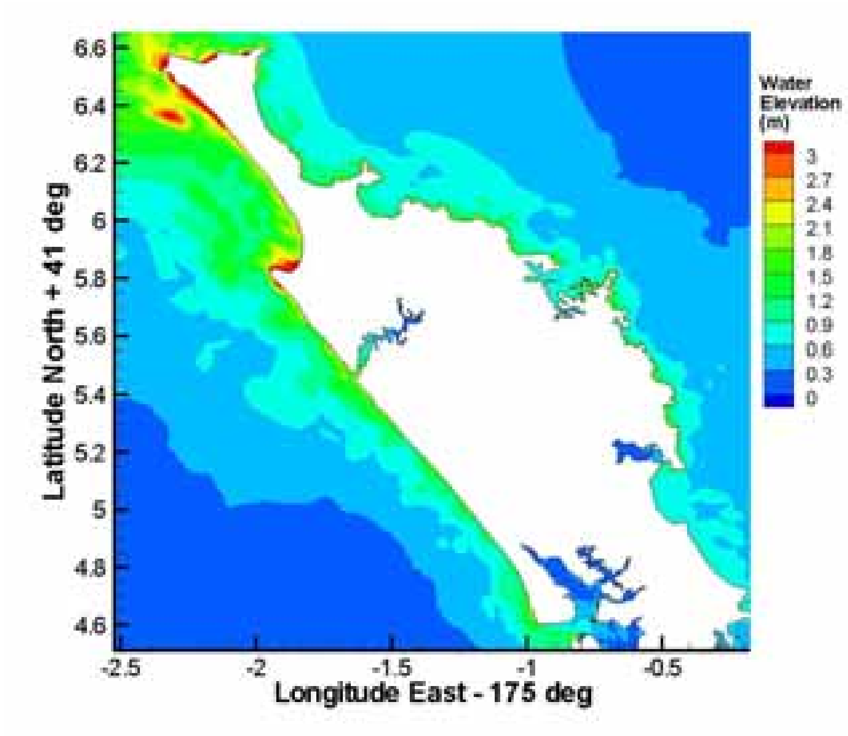


Figure 4.1.3-1: Maximum water surface elevations for the New Hebrides source with Mw 9.2.

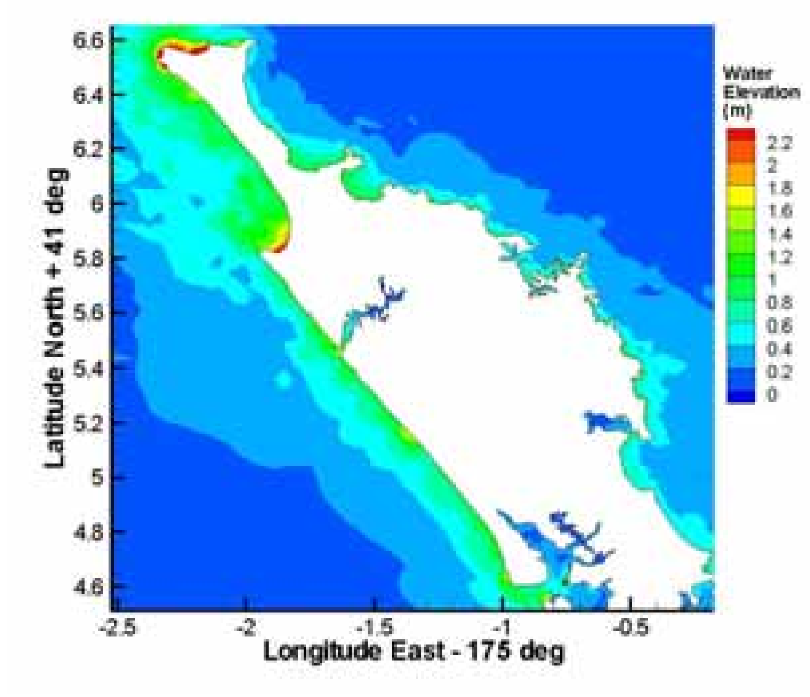


Figure 4.1.3-2: Maximum water surface elevations for the Solomon Sea source with Mw 9.2**.**

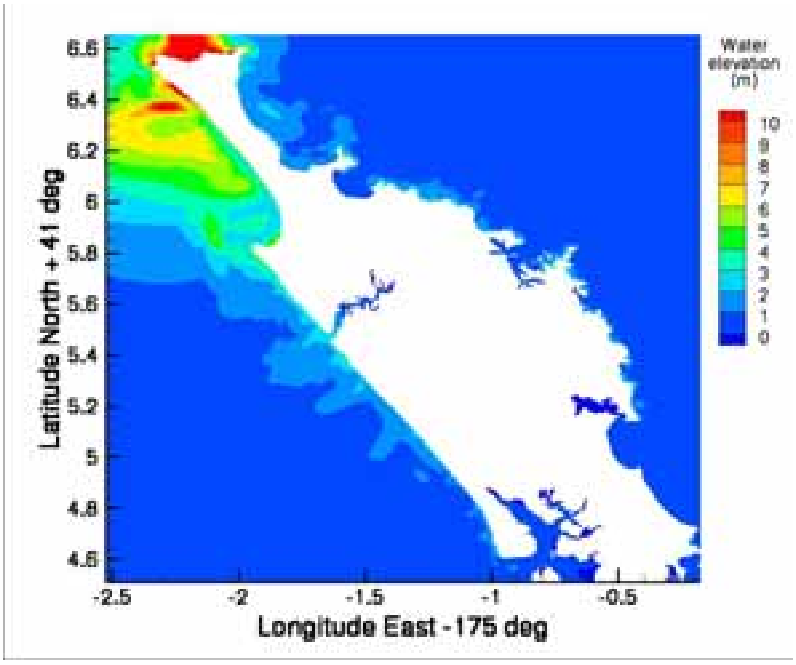


Figure 4.1.4-1: Maximum water surface elevations for a submarine landslide near Three Kings Islands.

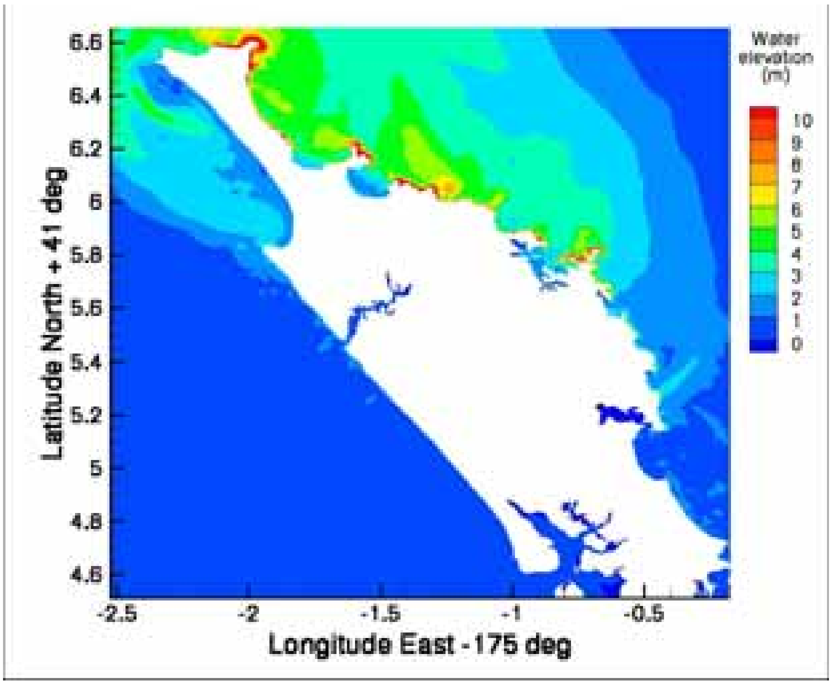


Figure 4.1.4-2: Maximum water surface elevations for a submarine landslide northeast of North Cape.

The third of these, a slump of the continental shelf north of the Rapuhia Scarp which accompanies a subduction zone earthquake produces wave height pattern that mainly impacts

Great Barrier Island. However, the slump size would have to be large (>10 km) and be located at the right place on the shelf slope to superimpose and reinforce the fault-generated tsunami. More numerical experiments are required to refine these estimates.

4.2. Auckland Region

4.2.1. Distant – Eastern source: South America (Chile)

The incident tsunami crosses the Kermadec Ridge and mainly impacts the outer islands and coastline north of Hauraki Gulf. The wave slows down as the water shoals with the result that the wavelength decreases and the height increases as the tsunami approaches the coast. The main factors controlling the wave height are the direct exposure to the incident wave and shoaling along the coastline.

The wave height decreases as the tsunami enters Hauraki Gulf (Figure 4.2.1-1). There are somewhat larger wave heights along the north shore of Waiheke and Rangitoto Islands, and along the shore north of Auckland, and small areas of increased resonance. The wave that refracts around the north end of the North Island can have significant wave height as far south as the entrance to Kaipara Harbour, but is small in Manukau Harbour.

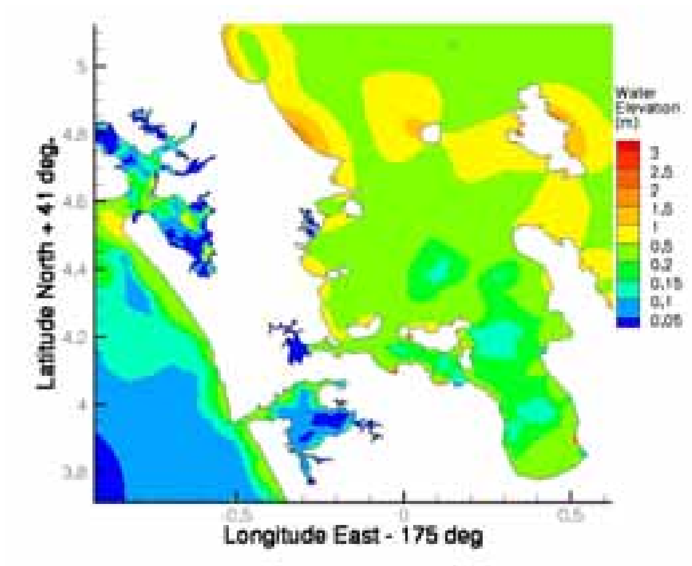


Figure 4.2.1-1: Maximum water surface elevations for an eastern distant source.

4.2.2. Regional – Eastern source: Tonga-Kermadec Trench

The wave height pattern at the shoreline is similar to the South American event but heights are considerably larger for the Tonga-Kermadec source (Figure 4.2.2-1). Again, the main factors controlling wave height are the direct exposure to the incident wave and shoaling along the coastline. Overall, these wave heights have a similar pattern and magnitude when compared to the general pattern shown by the palaeotsunami deposit data (Goff et al., 2005). Of particular note is the effect on the eastern side of Great Barrier Island, Little Barrier Island, Kawau Island, areas of the north shore and Waiheke Island.

4.2.3. Regional/Distant – Northern source: Solomon Sea/New Hebrides Trench

In general, the Solomon Sea and Hew Hebrides Trench sources do not have a significant impact in the Auckland region (Figures 4.2.3-1 and 4.2.3-2). The largest wave heights are at the entrance to Kaipara Harbour and at Great Barrier Island. Elsewhere wave heights are generally less than 1 m.

4.2.4. Local – Mystery source

The northern mystery sources do not have much impact in this area with wave heights less than 1 m**.** The eastern source slump of the continental shelf north of the Rapuhia Scarp which may accompany a subduction zone earthquake has the greatest wave heights at Great Barrier Island (>10 m) These wave heights may not be realistic given the large size of the slump used. There are rare, unresolved palaeotsunami data points, but it seems likely that once more detailed bathymetric data are available, local sources will provide the answer.

4.3. Waikato Region

4.3.1. Distant – Eastern source: South America (Chile)

For distant tsunamis the main area of impact is along the eastern coast of Coromandel Peninsula which has a direct exposure to tsunamis generated along the coast of South America. There are relatively small wave heights along the west coast from the wave that refracts around Northland (Figure 4.3.1-1).

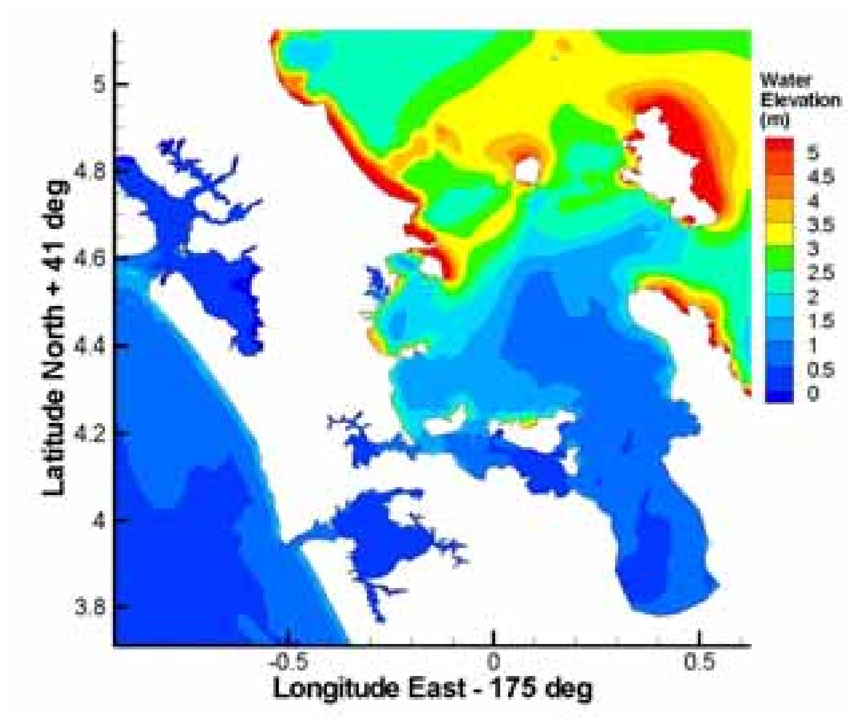


Figure 4.2.2-1: Maximum water surface elevations for the Tonga-Kermadec source - central location with Mw 9.0.

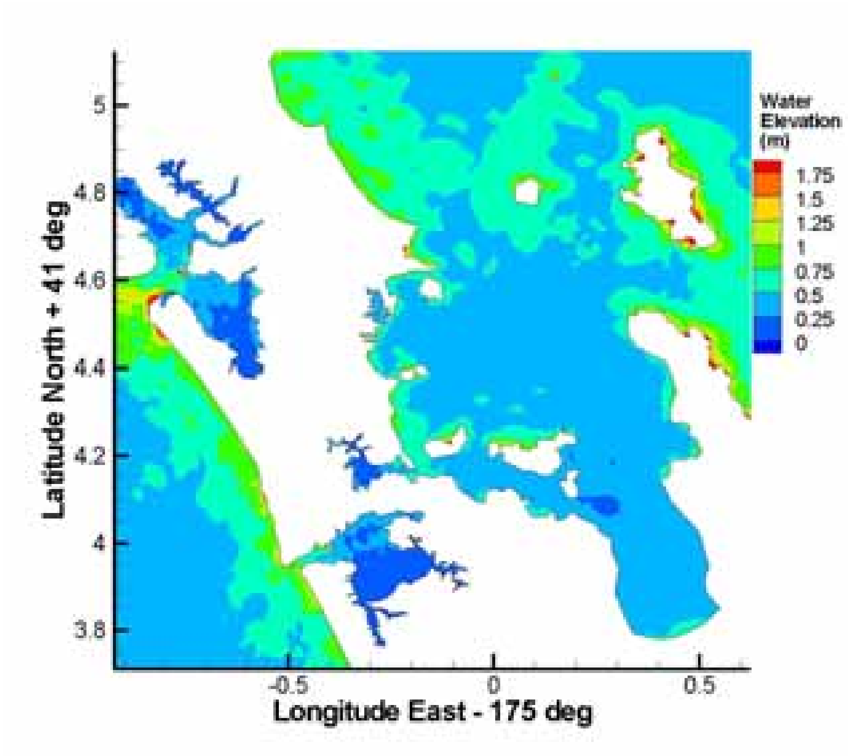


Figure 4.2.3-1: Maximum water surface elevations for the New Hebrides source with Mw 9.2.

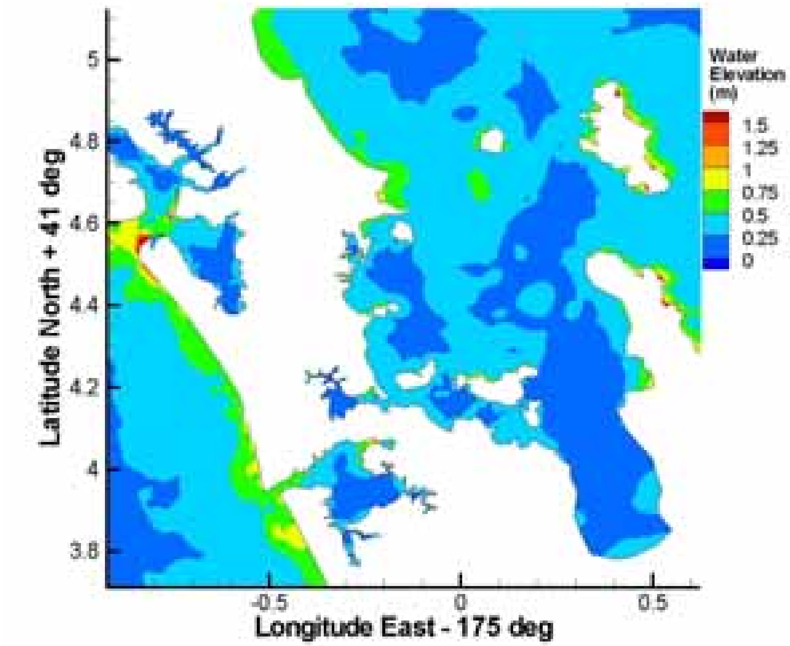


Figure 4.2.3-2: Maximum water surface elevations for the Solomon Sea source with Mw 9.2.

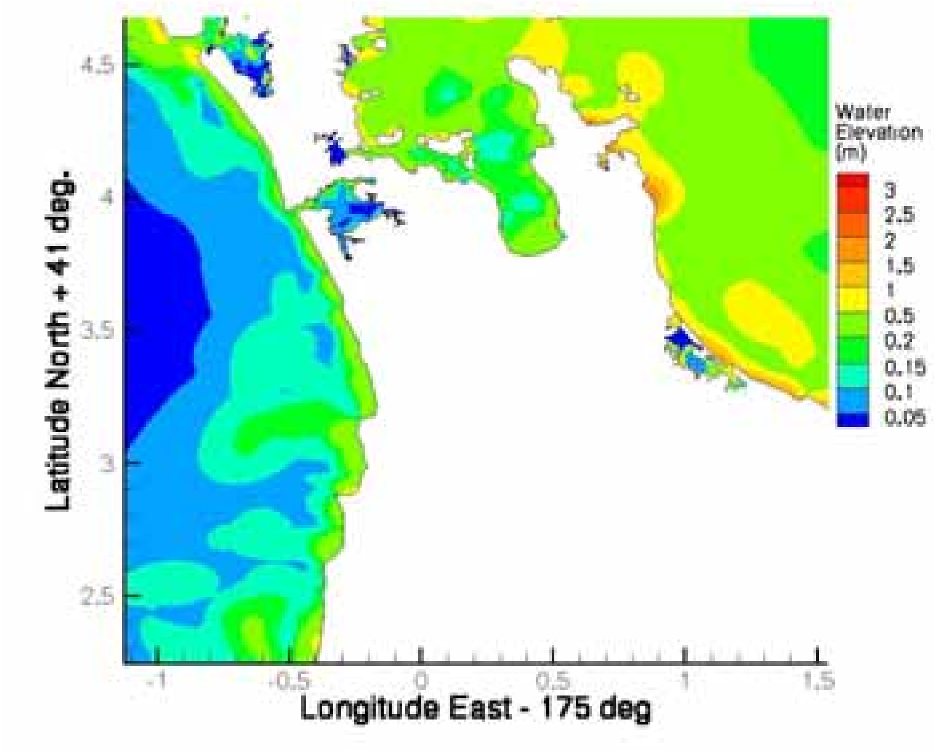


Figure 4.3.1-1: Maximum water surface elevations for an eastern distant source.

Mercury Bay is one area along the Coromandel that has an amplified response to distant tsunamis. The bay has a resonance of approximately 45 minutes which is similar to the primary period of large, distant tsunamis. Hence there can be significant amplification of the tsunami, and strong current surges. Typically, the first wave will arrive with a moderate positive peak and set up the resonance. The following troughs and peaks will be larger and create a "ringing" that lasts for several cycles.Regional – Eastern source: Tonga-Kermadec Trench

For regional tsunamis, the main area of impact is again along the eastern Coromandel Peninsula which has a direct exposure to these tsunamis. There are small wave heights along the west coast from the wave that refracts around Northland (Figure 4.3.2-1).

As with a more distant tsunami, Mercury Bay has an amplified response to this regional tsunami. However, the first wave will arrive with a negative trough in this case. Overall, there is a good match between wave heights and magnitude when compared to the general pattern shown by the palaeotsunami deposit data, at least along the eastern Coromandel Peninsula (Bell et al., 2004).

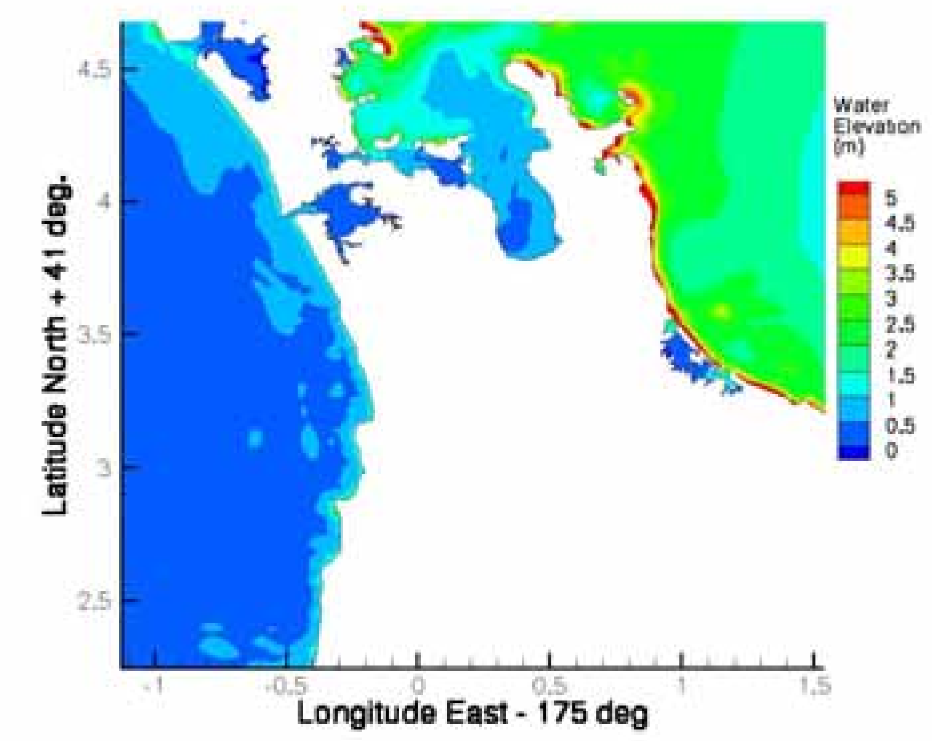


Figure 4.3.2-1: Maximum water surface elevations for the Tonga-Kermadec source- central location with Mw 9.0.

4.3.2. Regional/Distant – Northern source: Solomon Sea/New Hebrides Trench

These regional/distant sources only have a minor effect along the region's coast reaching elevations marginally in excess of 1.3 m (Figures 4.3.3-1 and 4.3.3-2). Waves from the Solomon Sea are noticeably higher along the west coast than those from the New Hebrides trench. This observed response is probably related to a combination of the influence of the offshore wave guide (Figure 3.3-3 and 3.3-4) and local bathymetry. This indicates that tsunamis generated from potential local sources (such as submarine landslides off the continental shelf) may produce large waves along this coast.

4.3.3. Local – Mystery source

The northern mystery sources do not have much impact in this area with wave heights less than 1 m. However, landslides and slumps on the continental slope along the Tonga-Kermadec trench may have an impact on the Coromandel Peninsula.

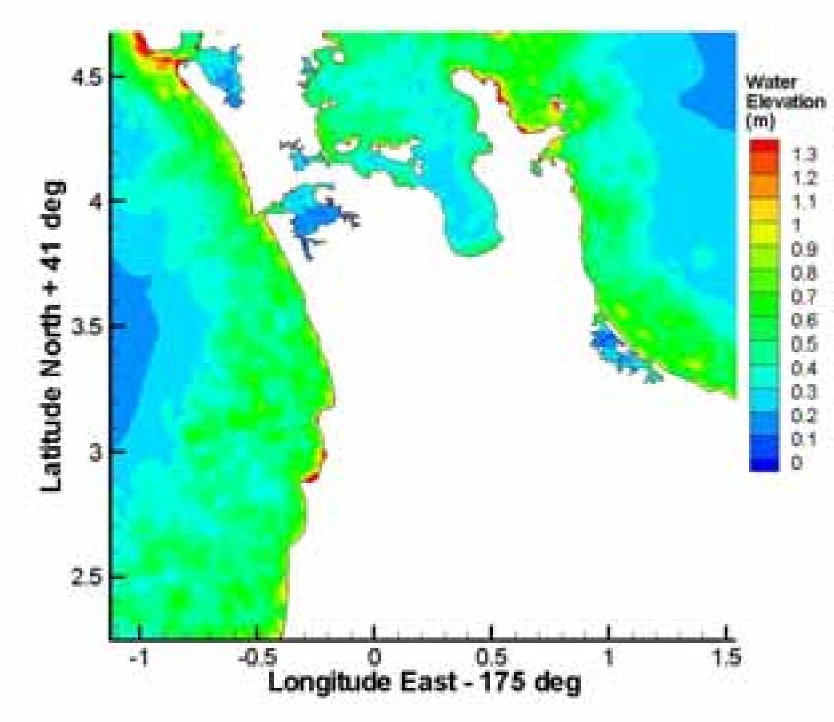


Figure 4.3.3-1: Maximum water surface elevations for the New Hebrides source with Mw 9.2.

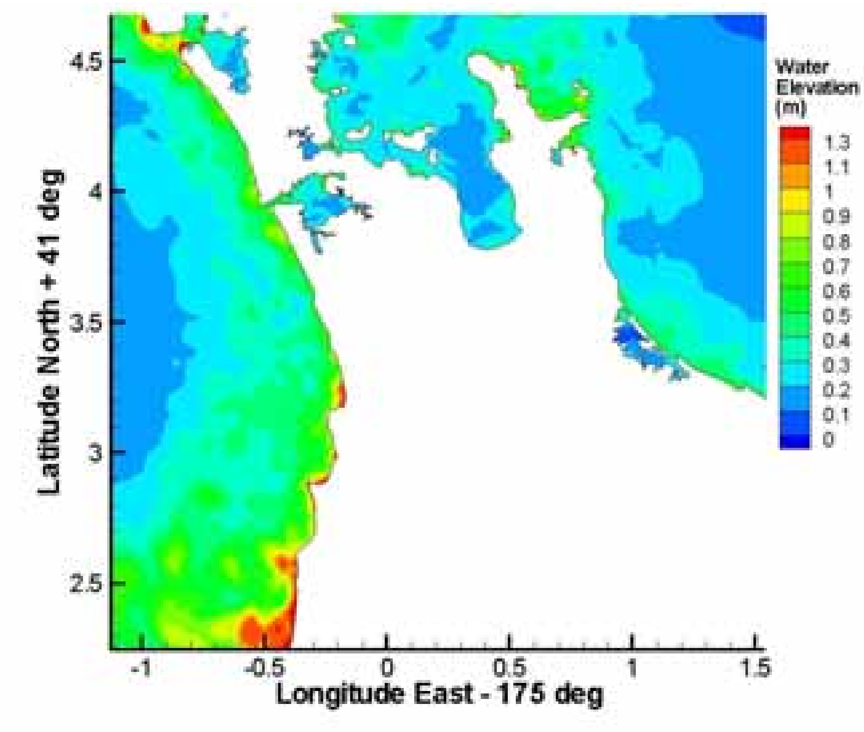


Figure 4.3.3-2: Maximum water surface elevations for the Solomon Sea source with Mw 9.2.

Sources for some of the higher elevation palaeotsunami deposit sites along the west coast of the region remain unresolved. Given the moderate susceptibility of parts of the coast to waves from the Solomon Sea, more local but currently unknown sources will probably provide the answers.

4.4. Bay of Plenty Region

4.4.1. Distant – Eastern source: South America (Chile)

The incident tsunami crosses the Kermadec Ridge and refracts around East Cape into the Bay of Plenty. The wave slows down as the water shoals with the result that the wavelength decreases and the height increases as the tsunami approaches the coast. In addition, there is wave convergence behind islands and along undersea ridges that lead toward the shore. The main factors controlling wave height are the direct exposure to the incident wave, shoaling along the coastline, and convergences. These factors give rise to the wave height pattern shown in Figure 4.4.1-1.

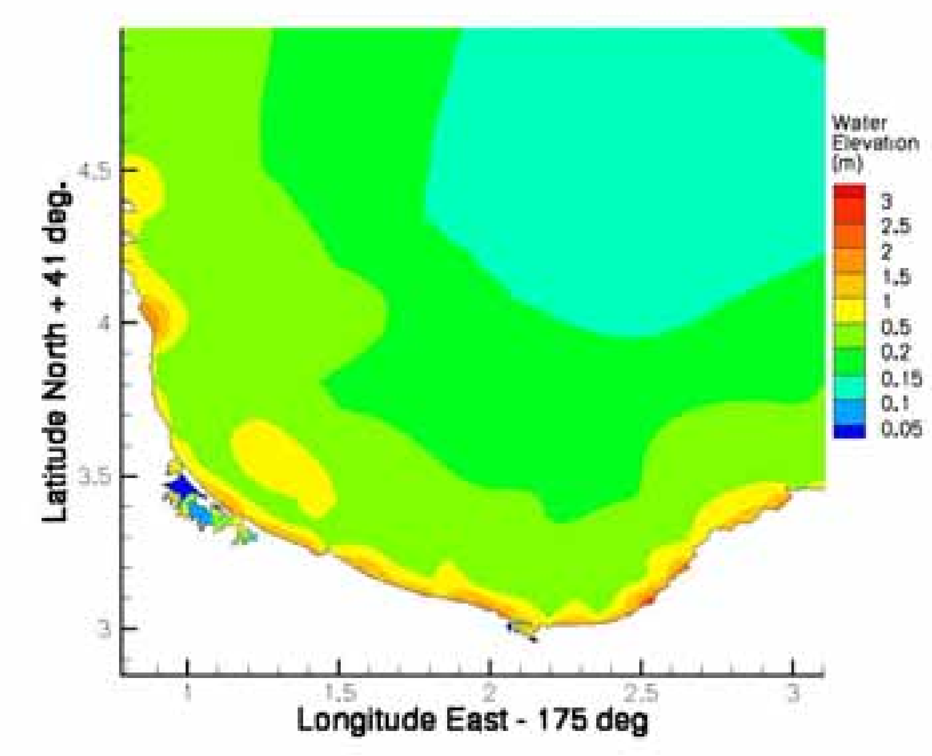


Figure 4.4.1-1: Maximum water surface elevations for an eastern distant source.

4.4.2. Regional – Eastern source: Tonga-Kermadec Trench

The wave height pattern at the shoreline is similar to the tsunami generated by a South American event but heights are considerably larger for the Tonga-Kermadec source (Figure 4.4.2-1). Again, the main factors controlling the wave height are direct exposure to the incident wave, shoaling along the coastline, and convergences behind islands and along undersea ridges. Overall, these wave heights have a similar pattern and magnitude when compared to the palaeotsunami deposit data (Walters et al, 2006a).

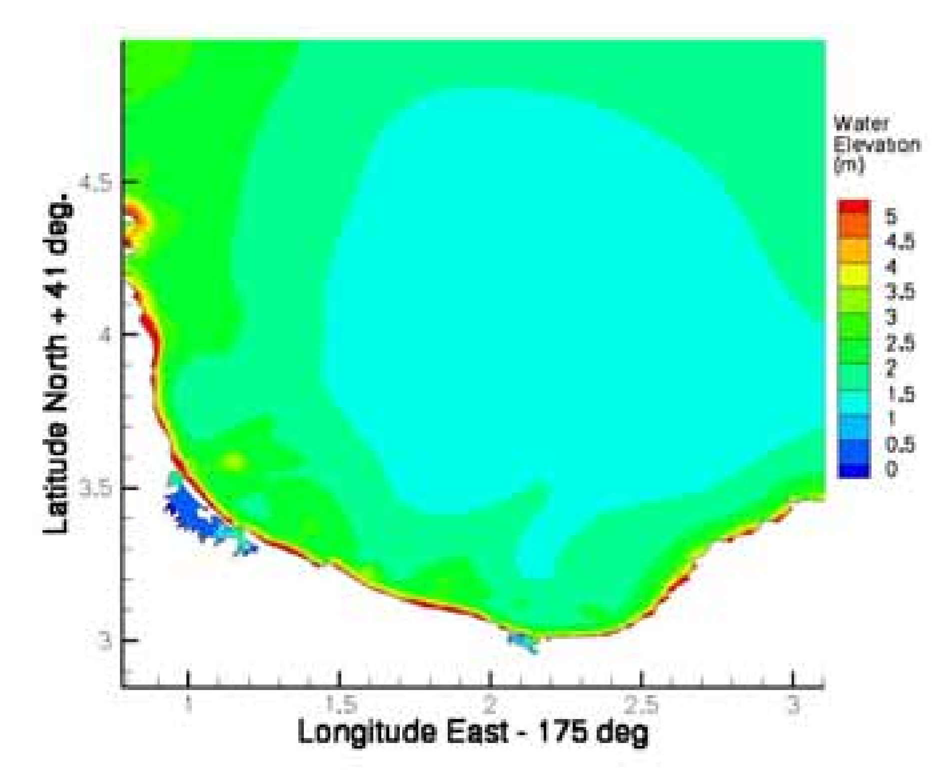


Figure 4.4.2-1: Maximum water surface elevations for the Tonga-Kermadec source- central location with Mw 9.0.

4.4.3. Regional/Distant – Northern source: Solomon Sea/New Hebrides Trench

These regional/distant sources only have a minor effect along the region's coast, with maximum water elevations mainly on the eastern half of the Bay of Plenty (Figures 4.4.3-1 and 4.4.3-2).

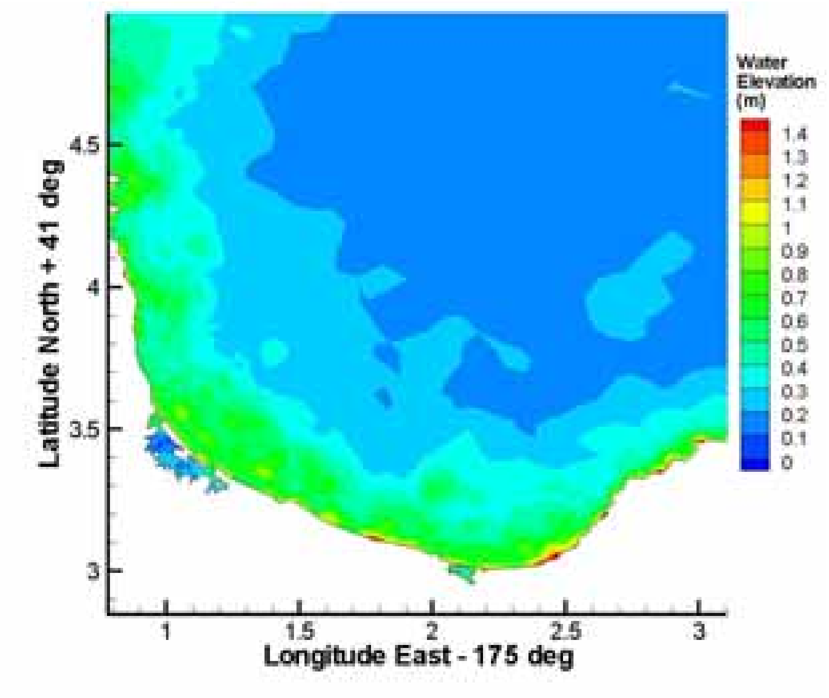


Figure 4.4.3-1: Maximum water surface elevations for the New Hebrides source with Mw 9.2.

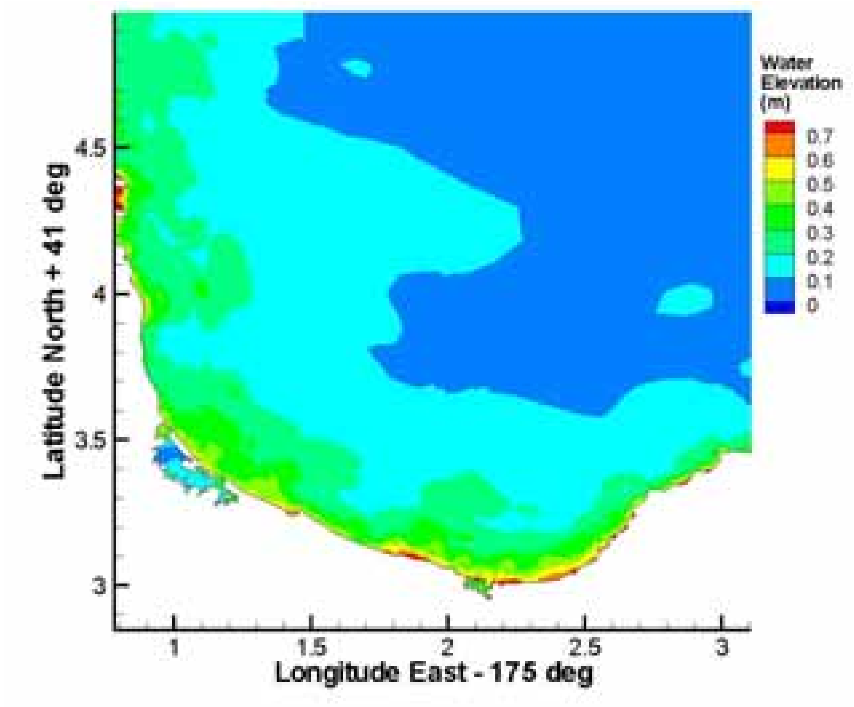


Figure 4.4.3-2: Maximum water surface elevations for the Solomon Sea source with Mw 9.2.

4.4.4. Local – various sources

The northern mystery sources do not have much impact in this area with wave heights less than 1 m. The eastern source associated with a landslide or slump on the Kermadec Ridge may have a more substantial impact, but this has not been assessed.

Walters et al (2006a) present a recent study of local tsunamis generated within the Bay of Plenty. The events included normal and reverse faulting in the Taupo Volcanic Zone, seamount sector collapse, and subduction zone events on the Tonga-Kermadec plate boundary. Typical runup heights were less than 1.5 m, except for subduction zone events which could be as great as approximately 10 m.

A number of studies by de Lange and others have also examined locally-generated tsunamis (de Lange, 1983; de Lange and Presetya, 1999; de Lange et al, 2006). De Lange et al (2006) suggest that an edifice failure at White Island could lead to a local tsunami as large as the subduction zone event considered in this study.

We have not examined the effects of large submarine landslides such as at the Matakaoa complex. However, large landslides and slumps such as these off the continental shelf would undoubtedly have a significant impact in the region.

5. Conclusions

The initial aim of the project was to identify the three most significant tsunami sources for the combined regions. This was expanded to four to allow for a more detailed examination of potential northern sources, including the Solomon Sea and New Hebrides regions, and local areas. The four most significant tsunami sources therefore included a Distant – Eastern source (South America subduction zone), a Regional/Local – Eastern source (Tonga-Kermadec Trench), Distant/Regional – Northern source (Solomon Sea and New Hebrides Trench), and a consideration of Local sources.

The effects recorded in all four regions were similar. Not surprisingly given the orientation of wave approach, the Distant – Eastern source and Regional/Local – Eastern source (Tonga-Kermadec Trench) showed similar patterns of water surface elevation. The latter source however was by far the most significant for all regions.

Northland region experiences the highest water surface elevations for the Distant/Regional – Northern source (Solomon Sea and New Hebrides Trench). However, the waves from a Tonga-Kermadec source are the largest of the known sources and have a marked effect on the western side of the region. Two local Mystery sources - a generic submarine landslide travelling north from Three Kings Islands and one northeast of North Cape - have by far the largest wave heights (but local to NRC) as recorded in the palaeotsunami data. Whilst further work is needed to help determine the characteristics, nature and extent of local sources for the entire combined region, the numerical modelling suggests that the most likely event that can explain the large runups responsible for the palaeotsunami data is potentially a submarine landslide northeast of North Cape, or a combination of events.

In Auckland region, tsunamis from the Tonga-Kermadec source have the largest elevations on the east coast but are not significant on the western shoreline. Both the Solomon Sea and New Hebrides sources create moderately large surface elevations around Kaipara Harbour and Great Barrier Island.

For the Waikato and Bay of Plenty regions, tsunamis from the Tonga-Kermadec source again have the largest elevations of all those considered here. Otherwise, there are similar, less significant, water elevations for the remaining sources, although slightly smaller for tsunamis from the Solomon Sea and New Hebrides areas.

Palaeotsunami data have proven useful for this project. When considered in conjunction with source models they provide a clear indication that the Tonga-Kermadec region is the most significant source for the combined regions. An additional lesson learned from this exercise is that some of the palaeotsunami sites could not have been inundated by credible scenarios from any of the distant and regional sources modelled. These deposits must have been laid down by local tsunamis, or an exceptional event that we have no knowledge of. The local modelling experiments attempt to address this issue.

This study points out that marine geophysics and the description of the subduction zones present major limitations in the knowledge base of potential tsunami sources. Further continental shelf research is required to investigate landslides and submarine faults. This leads to the question of how large could such subduction zone events be? The palaeotsunami data and inverse modelling would suggest that Mw 8.5 to 9.0 is not unreasonable although this is larger than current geophysical consensus. Moreover, the larger runup events recorded in palaeotsunami deposits in the Northland region are still lacking a definitive geophysical explanation. There are also rare palaeotsunami deposits in the other regions where the tsunami source has not yet been identified.

6. References

Not all the references are cited in the text; however, they provide a useful database of references for interested parties.

Adams, C.J.; Graham, I.J.; Seward, D.; Skinner, D.N.B. 1994. Geochronological and geochemical evolution of late Cenozoic volcanism in the Coromandel Peninsula, New Zealand. *New Zealand Journal of Geology and Geophysics 37:* 359-379.

Aitchison, J.; Clarke, G.L.; Meffre, S.; Cluzel, D. 1995. Eocene arc-continent collision in New Caledonia and implications for regional Southwest Pacific tectonic evolution. *Geology 23*: 161-164.

Ali, J.R.; Aitchison, J.C. 2000. Significance of palaeomagnetic data from the oceanic Poya Terrane, New Caledonia, for SW Pacific tectonic models. *Earth and Planetary Science Letters 177*: 153-161.

Andrews, J.E.; Packham, G.; Eade, J.V.; Holdsworth, B.K.; Jones, D.L.; Klein, G. deV.; Kroenke, L.W.; Saito, T.; Shafik, S.; Stoeser, D.B.; van der Lingen, G.J. 1975. *Site 285*. Initial Reports of the Deep Sea Drilling Project, 30: 27-67, Washington, U.S. (Govt. Printing Office).

Ballance, P.F. 1999. Simplification of the Southwest Pacific Neogene arcs: inherited complexity and control by a retreating pole of rotation. *In*: MacNiocaill, C.; Ryan, P.D. (Eds.) *Continental Tectonics*, Geological Society of London Special Publications 184: 7-19.

Ballance, P.F.; Ablaev, A.G.; Puschin, I.K.; Pletnev, S.P.; Birylina, M.G.; Itaya, T.; Follas, H.A.; Gibson, G.W. 1999. Morphology and history of the Kermadec Trench-arc-backarc basin-remnant arc system at 30 to 32°S; geophysical profile, microfossil and K-Ar data. *Marine Geology 159*: 35-62.

Ballance, P.F.; Pettinga, J.R.; Webb, C. 1982. A model of the Cenozoic evolution of northern New Zealand and adjacent areas of the Southwest Pacific. *Tectonophysics 87*: 37-48.

Ballance, P.F.; Scholl, D.W.; Vallier, T.L.; Stevenson, A.J.; Ryan, H.; Herzer, R.H. 1989. Subduction of a Late Cretaceous seamount of the Louisville Ridge at the Tonga Trench: a model of normal and accelerated tectonic erosion. *Tectonics 8*: 953-962.

Bell, R.G;, Goff, J.; Downes, G.; Berryman, K.; Walters, R.A.; Chagué-Goff, C.; Barnes, P.; Wright, I. 2004. Tsunami hazard for the Bay of Plenty and eastern Coromandel Peninsula. *NIWA Client Report HAM2004-084*. 90 p.

Bergman, S.C.; Talbot, J.P.; Thompson, P.R. 1992. The Kora Miocene submarine andesite stratovolcano hydrocarbon reservoir, Northern Taranaki Basin, New Zealand. In, 1991 New

Zealand Oil Exploration Conference proceedings: 178-206. Ministry of Commerce, Wellington.

Bernardel, G; Carson, L.J.; Meffre, S.; Symonds, P.A;, Mauffret, A. 2002. Geological and morphological framework of the Norfolk Ridge to Three Kings Ridge region. *Gesocience Australia Record 2002/08*.

Billen, M.I.; Stock, J. 2000. Morphology and origin of the Osbourn Trough. *Journal of Geophysical Research, B, Solid Earth and Planets 105:* 13,481-13,489.

Bird, P. 2003. An updated digital model of pl;ate boundaries. *Geochemistry, Geophysics, Geosystems 4*: 52.

Blackmore, N.A.; Wright, I.C. 1995. *Southern Kermadec volcanoes*. Scale 1:400 000. Miscellaneous series / New Zealand Oceanographic Institute, 71. NIWA, Wellington, New Zealand.

Bloomer, S.H.; Ewart, A;, Hergt, J.M.; Bryan, W.B. 1994. Geochemistry and origin of igneous rocks from the outer Tonga forearc (Site 841). *J. Hawkins, L.M. Parson, J. Allan et al. (Eds), Proceedings of the ODP, Scientific Results, 135, College Station, TX, USA (Ocean Drilling Programme)*: pp, 625-646.

Bloomer, S.H.; Stern, R.J.; Fisk, E.; Geschwind, C.H.; Box, S.E.C.; Flower, M.F.J.C. 1989. Shoshonite volcanism in the northern Mariana Arc; 1, Mineralogic and major and trace element characteristics Special section on alkaline volcanism in island arcs. *American Geophysical Union 1986 fall meeting, symposium on Alkaline arc magmatism 94*: 4469-4496.

Borrero, J.C.; Synolakis, C.E.; Fritz, H.M. in press. Field surveys northern Sumatra after the tsunami and earthquake of 26 December 2004. *Earthquake Spectra*.

Bradshaw, J.D. 1989. Cretaceous geotectonic patterns in the New Zealand region. *Tectonics 8*: 803-820.

Brathwaite, R.L.; Christie, A.B. 1996. Geology of the Waihi area : part sheets T13 and U13. Scale 1:50 000. *Institute of Geological & Nuclear Sciences geological map 21*. Lower Hutt, Institute of Geological & Nuclear Sciences. 64 p. p.

Burns, R.E.; Andrews, J.E.; van der Lingen, G.J.; Churkin, M., Jr;, Galehouse, J.S.; Packham, G.; Davies, T.A.; Kennett, J.P.; Dumitrica, P.; Edwards, A.R.; Von Herzen, R.P. 1973. Site 205. *Initial Reports of the Deep Sea Drilling Project 21*: 57-102.

CANZ. 1997. New Zealand Region Bathymetry (3rd Ed). New Zealand Oceanographic Institute Miscellaneous Chart Series 73. National Institute of Water and Atmosphere Research, Wellington, New Zealand.

Caress, D.W. 1991. Structural trends and back-arc extension in the Havre Trough. *Geophysical Research Letters 18:* 853-856.

Carter, L.; Lamarche, G. 2001. The large Matakaoa Slide and its impact on the abyssal plain, near Hikurangi Margin, New Zealand. Presented to the European Union of Geosciences XI, Strasbourg, France.

Chagué-Goff, C.; Goff, J. R. 2006. Tsunami hazard assessment for the Northland region. NIWA Client Report CHC2006-069.

Chaproniere, G.C.H. 1994. Middle and late Eocene larger foraminifers from Site 841, Tongan Platform. Proceedings of the Ocean Drilling Programme, Scientific Results Leg 135, College Station, Texas, 231-243.

Cluzel, D.; Aitchison, J.; Clarke, G.; Meffre, S.; Picard, C. 1994. Point de vue sur l'évolution tectonique et géodynamique de la Nouvelle Caléonie. *Comptes Rendus de l'Académie des Sciences Paris 319*: 683-688.

Cluzel, D.; Aitchison, J.C.; Picard, C. 2001. Tectonic accretion and underplating of mafic terranes in the late Eocene intraoceanic fore-arc of New Caledonia (Southwest Pacific); geodynamic implications. *Tectonophysics 340*: 23-59.

Cole, J.W.; Gill, J.B.; Woodhall, D. 1985. Petrologic history of the Lau Ridge, Fiji, Scholl, D.W, Vallier, T.L. (Eds). *Geology and offshore resources of Pacific Island arcs - Tonga region*, Circum-Pacific Council for Energy and Mineral Resources Earth science series e, p. 379-414.

Collot, J.-Y.; Davy, B.W. 1998. Forearc structures and tectonic regimes at the oblique subduction zone between the Hikurangi Plateau and the southern Kermadec margin. *Journal of geophysical research, Solid earth 103(B1)*: 623-650.

Collot, J.Y.; Davy, B.; Lamarche, G. 1996. Forearc structures and tectonic regimes at the oblique collision zone between the Hikurangi Plateau and the southern Kermadec arc, Western Pacific Geophysics Meeting (1996: Brisbane, Australia), pp. W121.

Collot, J-Y.; Lewis, K.B.; Lamarche, G;, Lallemand, S. 2001.The giant Ruatoria debris avalanche on the northern Hikurangi margin, New Zealand: results of oblique seamount subduction. *Journal of Geophysical Research 106*: 19271–19297.

Coombs, D.S.; Landis, C.A.; Norris, R.J.; Sinton, J.M.; Borns, D.J.; Draw, D. 1976. The Dun Mountain ophiolite belt, New Zealand, its tectonic setting, constitution, and origin, with special reference to the southern portion. *American Journal of Science 276*: 561-603.

Crawford, A.J.; Meffre, S.; Symonds, P.A. 2003. 120 to 0 Ma tectonic evolution of the southwest Pacific and analogous geological evolution of the 600 to 220 Ma Tasman Fold Belt System. In: Hillis, R.R. and Muller, R.D. (eds.) *Evolution and Dynamics of the Australian Plate*, Geol. Soc. America Spec. Pp. 372: 383-403.

Davey, F.J. 1982. The structure of the South Fiji Basin. *Tectonophysics 87(1/4)*: 185-242.

Davey, F.J.; Childs, J.; Lewis, K.B.; Hampton, M. 1987. Convergent margin off east coast of the North Island New Zealand, Part I and II. In: R.v. Huene (Editor), *Seismic images of modern convergent margin tectonic structures*. AAPG Studies in Geology.

Davey, F.J., Henrys, S.A., Lodolo, E. 1995. Asymmetric rifting in a continental back-arc environment, North Island, New Zealand Taupo volcanic zone, New Zealand. *Journal of Volcanology and Geothermal Research 68(1-3)*: 209-238.

Davey, F.J.; Henrys, S.; Lodolo, E. 1997. A seismic crustal section across the East Cape convergent margin, New Zealand. *Tectonophysics 269*: 199-215.

Davy, B.W.; Collot, J.-Y. 2000. The Rapuhia Scarp (northern Hikurangi Plateau): its nature and subduction effects on the Kermadec Trench. *Tectonophysics* 328(3/4): 269-295.

de Lange, W.P. 1983. Tsunami hazard–an investigation into the potential tsunami hazards of the Bay of Plenty region using numerical models. Unpublished MSc thesis, Dept. of Earth Sciences, University of Waikato.

de Lange, W.P. 1998. The last wave - tsunami. In: *Awesome forces - The natural hazards that threaten New Zealand*. Hicks, G., Campbell, H. (eds). Te Papa Press, Wellington, 99-123.

de Lange, W.P.; Hansford, A.; Moon, V.G. 2006. Tsunami generation by island edifice failure at White Island and Motuhora Volcanos, New Zealand. Proceedings of the New Zealand Geotechnical Society 2006 Symposium: Earthquakes and Urban Development, Nelson.

de Lange, W.P;, Prasetya, G. 1999. Volcanoes and tsunami hazard-implications for New Zealand. *Tephra 17*: 30–35.

de Lange W.P.; Prasetya G.S.; Healy T.R. 2001. Modelling of Tsunamis Generated by Pyroclastic Flows (Ignimbrites), *Natural Hazards 24*: 251-266.

Delteil, J.; Ruellan, E.; Wright, I;, Matsumoto, T., 2002. Structure and structural development of the Havre Trough (SW Pacific). *Journal of geophysical research. Solid earth, 107(B7)*: doi:10.1029/2001JB000494.

Dupont, J., 1988. The Tonga and Kermadec Ridges. In: A.E.M. Mairn, Stehli, F.G., Uyeda, S. (Eds), *The Ocean Basins and Margins*, Vol 7B. Plenum Press, New York.

Eissen, J.-P.; Crawford, A.J.; Cotten, J.; Meffre, S.; Bellon, H.; Delaune, M. 1998. Geochemistry and tectonic significance of basalts in the Poya Terrane, New Caledonia. *Tectonophysics 284*: 203-220.

Ewart, A;, Bryan, W.B. 1973. The Petrology and Geochemistry of the Tongan Islands. In: Coleman, P.J. (ed.). *The western Pacific; island arcs, marginal seas, geochemistry*, Perth, University of Western Australia Press. pp 503-522.

Exon, N.F.; Herzer, R.H;, Cole, J.W., 1985. Mixed volcaniclastic and pelagic sedimentary rocks from the Cenozoic southern Tonga platform and their implications for petroleum potential. In: Scholl, D.W., Vallier, T.L. (eds) *Geology and offshore resources of Pacific Island arcs - Tonga region*. Circum-Pacific Council for Energy and Mineral Resources Earth Sciences Series 2. American Association of Petroleum Geologists, Oklahoma. 75-107.

Fraser, R.J. 1998. Historical tsunami database for New Zealand. Unpublished MSc thesis, The University of Waikato, Hamilton, New Zealand.

Fritz, H.M.; Borrero, J.C. in press. Somalia field survey of the 2004 Indian Ocean Tsunami. *Earthquake Spectra*.

Fujiwara, T.; Yamazaki, T.; Joshima, M. 2002. Bathymetry and magnetic anomalies in the Havre Trough and southern Lau Basin: from rifting to spreading in back-arc basins. *Earth & Planetary Science Letters 185*: 253-264.

Gaina, C.; Mueller, D.R.; Royer, J.-Y;, Stock, J.; Hardebeck, J.L.; Symonds, P. 1998. The tectonic history of the Tasman Sea; a puzzle with 13 pieces. *Journal of Geophysical Research, B, Solid Earth and Planets 103*: 12,413-12,433.

Gamble, J.A.; Wright, I.C. 1995. The southern Havre Trough: geological structure and magma petrogenesis of an active backarc rift complex. *Backarc basins: tectonics and magmatism*, pp. 29-62.

Gamble, J.A.; Wright, I.C.; Baker, J.A., 1993. Seafloor geology and petrology in the oceanic to continental transition zone of the Kermadec-Havre-Taupo Volcanic Zone arc system, New Zealand. *New Zealand Journal of Geology and Geophysics 36*: 417-435.

Gamble, J.A.; Wright, I.C.; Woodhead, J.D.; McCulloch, M.T., 1995. Arc and back-arc geochemistry in the southern Kermadec arc - Ngatoro Basin and offshore Taupo Volcanic Zone, SW Pacific. In. Smellie, J.L. (ed.) Volcanism associated with extension at consuming plate margins. Geological Society London, Special Publication, 193-212.

Gill, J.B.; Whelan, P., 1989. Early rifting of an oceanic island arc (Fiji) produced shoshonitic to tholeiitic basalts. *Journal of Geophysical Research 94*: 4561-4578.

Goff, J.R.; McFadgen, B.G. 2002. Seismic driving of nationwide changes in geomorphology and prehistoric settlement – a 15th Century New Zealand example. *Quaternary Science Reviews 21*: 2313-2320.

Goff, J.R. 2002. Ancillary tsunami project. GeoEnvironmental Client report: GEO2002/20026. Report for Environmental Bay of Plenty. 43 p.

Goff, J.R. 2003. Joint Tsunami Research Project: Stage 1. GeoEnvironmental Client report: GEO2003/20028. Environment Bay of Plenty and Environment Waikato, 49pp.

Goff, J.R. 2005. Avon-Heathcote Estuary (Ihutai): Palaeoenvironmental changes project – progress report. Christchurch City Council Report GEO2005/20059, 7pp.

Goff, J.R.; Walters, R.; Lamarche, G.; Wright, I.; Chagué-Goff, C. 2005. Tsunami Overview Study. Auckland Regional Council Report GEO2005/20060, 35pp.

Hawkins, J.W. 1995. Evolution of the Lau Basin; insights from ODP Leg 135. Active margins and marginal basins of the western Pacific. *Geophysical Monograph 88*: 125-173.

Hayward, B.W.; Black, P.M;, Smith, I.E.M.; Ballance, P.F.; Itaya, T; Doi, M.; Takagi, M.; Bergman, S.; Adams, C.J.; Herzer, R.H.; Robertson, D.J. 2001. K-Ar ages of Early Miocene arc-type volcanoes in northern New Zealand. *New Zealand Journal of Geology and Geophysics 44*: 285-311.

Henry, R.F.; Walters, R.A. 1993. A geometrically-based, automatic generator for irregular triangular networks. *Communications in Numerical Methods in Engineering 9*: 555-566.

Herzer, R.H.; Exon, N.F.; 1985. Structure and basin analysis of the southern Tonga forearc. In: Scholl, D.W., Vallier, T.L. (eds.) *Geology and offshore resources of Pacific Island arcs - Tonga region*. Circum-pacific Council for Energy and Mineral Resources Earth Sciences Series 2. American Association of Petroleum Geologists, Oklahoma, pp. 55-74.

Herzer, R.H. 1995. Seismic stratigraphy of a buried volcanic arc, Northland, New Zealand and implications for Neogene subduction. *Marine and Petroleum Geology 12*: 511-531.

Herzer, R.H., Mascle, J., Davy, B.W., Ruellan, E., Mortimer, N., Laporte, C., Duxfield, A., 2000. New constraints on the New Zealand-South Fiji Basin continent-back-arc margin. *Comptes rendus de l''Academie des sciences. Serie II, Sciences de la terre et des planetes 330*: 701-708.

Herzer, R.H.; Mortimer, N.; Davy, B.W.; Barker, D.H.N. Laporte-Magoni, C. 2002b. The Pacific margin of northwestern New Zealand. *In* Geological Society of New Zealand. Conference (2002 : Whangarei). Pp. 24-25.

Herzer, R.H.; Mascle, J. 1996. Anatomy of a continent-backarc transform - the Vening Meinesz Fracture Zone northwest of New Zealand. *Marine Geophysical Researches 18:* 401-427.

Isaac, M.J.; Herzer, R.H.; Brook, F.J.; Hayward, B.W. 1994. Cretaceous and Cenozoic sedimentary basins of Northland, New Zealand. *Institute of Geological & Nuclear Sciences monograph 8*. Lower Hutt, Institute of Geological & Nuclear Sciences. 230 pp.

IOC, IHO, and BODC, 2003. *Centenary Edition of the GEBCO Digital Atlas*. Published on CD-ROM on behalf of the Intergovernmental Oceanographic Commission and the International Hydrographic Organization as part of the General Bathymetric Chart of the Oceans; British Oceanographic Data Centre, Liverpool.

ITDB/PAC 2004. *Integrated Tsunami Database for the Pacific.* Version 5.12 of December 31 2004. CD-ROM, Tsunami Laboratory, ICMMG SD RAS, Novosibirsk, Russia.

Lamarche, G.; Barnes, P. 2005. fault characterisation and earthquake source identification in the offshore Bay of Plenty. *NIWA Client Report WLG2005-51*, 57 pp.

Lamarche, G.; Bull, J.; Barnes, P.; Taylor, S.; Horgan, H. 2000. Constraining fault growth rates and fault evolution in the Bay of Plenty, New Zealand. *EOS, Transactions of the American Geophysical Union 81(42)*: 481, 485- 486.

Lewis, K.B.; Collot, J-Y.; Goring, D. 1999. Huge submarine avalanches: is there a risk of giant waves and, if so, where? *Tephra 17*: 21–29.

Maillet, P.; Monzier, M.; Selo, M.; Storzer, D. 1983. The D'Entrecasteaux Zone (Southwest Pacific); a petrological and geochronological reappraisal. *Marine Geology 53*: 179-197.

Malahoff, A.; Feden, R.H.; Fleming, H.S., 1982. Magnetic anomalies and tectonic fabric of marginal basins north of New Zealand. *Journal of geophysical research 87(B5)*: 4109-4125.

Mortimer, N. 2004. New Zealand's geological foundations. *Gondwana Research 7:* 261-272.

Mortimer, N.; Herzer, R., 2002. Report on petrology of New Zealand UNCLOS dredge samples from Bollons Gap and the northern frontier. *GNS Client report, 2002/39*.

Mortimer, N.; Herzer, R.H. 2000b. Diverse SW Pacific Miocene volcanotectonic architecture : New seismic and petrologic data favour simple Miocene model, EOS [Abs.] American Geophysical Union. Fall Meeting, San Francisco, 81(48): F1088.

Mortimer, N;, Adams, C.J;, Campbell, H.J.; Tulloch, A.J.; Graham, I.J. 2004. Investigating geological relationships between New Zealand, Australia and New Caledonia. *In* Geological Society of New Zealand/New Zealand Geophysical Society/26th New Zealand Geothermal Workshop combined conference (2004 : Taupo, NZ); New Zealand Geothermal Workshop (26th : 2004 : Taupo, NZ). Pp. 69-70.

Mortimer, N.; Herzer, R.H.; Walker, N.W.; Calvert, A.T.; Seward, D.; Chaproniere, G,C.H., 2003. Cavalli Seamount, Northland Plateau, SW Pacific Ocean: a Miocene metamorphic core complex? Journal of the Geological Society London 160: 1-13.

Mortimer, N.; Davey, F.J.; Melhuish, A.; Yu, J.; Godfrey, N.J. 2002. Geological interpretation of a deep seismic reflection profile across the Eastern Province and Median Batholith, New Zealand: crustal architecture of an extended Phanerozoic convergent orogen. *New Zealand Journal of Geology and Geophysics 45*: 349-363.

Mortimer, N.; Herzer, R.H.; Gans, P.B.; Parkinson, D.L.; Seward, D. 1998. Basement geology from Three Kings Ridge to West Norfolk Ridge, southwest Pacific Ocean: evidence from petrology, geochemistry and isotopic dating of dredge samples. *Marine Geology 148*: 135-162.

Nichol, S.; Goff J.R.; Regnauld, H. 2004. Sedimentary evidence for a regional tsunami on the NE coast of New Zealand. *Geomorphologie: Relief, Processus et Environnement 1*: 35-44.

Nichol, S.L. ; Lian, O.B. ; Carter, C.H. 2003. Sheet-gravel evidence for a late Holocene tsunami run-up on beach dunes, Great Barrier Island, New Zealand. *Sedimentary Geology 155*: 129-145.

Nishizawa, A.; Takahashi, N.; Ane, S. 1999. Crustal structure and seismicity of the Havre Trough at 26 degrees S. *Geophysical Research Letters 26*: 2549-2552.

Okada, Y. 1985. Surface deformation due to shear and tensile faults in a half-space, *Bulletin of the Seismological Society of America 75*: 1135-1154.

Pacheco, J.F.; Sykes, L.R.; Scholz, C.H. 1993. Nature of seismic coupling along simple plate boundaries of the subduction type. *Journal of Geophysical Research 98:* 14133-14139.

Packham, G.; Terrill, A., 1975. Submarine geology of the South Fiji Basin. *Initial Reports of the Deep Sea Drilling Project 30*: 617-645.

Paris, J.-P. 1981. Geologie de la Nouvelle-Caledonie; un essai de synthese; Geology of New-Caledonia; a synthetic text. *Memoires du B.R.G.M. 113, 81*: 278.

Parson, L.M. ; Wright, I.C., 1996. The Lau-HavreTaupo back-arc basin : a southward-propagating, multi-stage evolution from rifting to spreading. *Tectonophysics 263*: 1-22.

Pelletier, B.; Dupont, J. 1990. Effects of the subduction of the Louisville Ridge on the Tonga-Kermadec Arc. (World circumnavigation of R/V Jean Charot, 1983-1987. 3. Main scientific results.). *Oceanolgica Acta 10*: 57-76.

Pelletier, B.; Louat, R. 1989. Seismotectonics and present-day relative plate motions in the Tonga-Lau and Kermadec-Havre region. *Tectonophysics 165*: 237-250.

Ramillien, G.; Wright, I.C., 2000. Predicted seafloor topography of the New Zealand region: a nonlinear least squares inversion of satellite altimetry data. *Journal of Geophysical Research. Solid earth 105(B7):* 16577-16590.

Reyners, M. 1998. Plate coupling and the hazard of large subduction thrust earthquakes at the Hikurangi subduction zone, New Zealand, *New Zealand Journal of Geology and Geophysics 41:* 343-354.

Ruellan, E.; Delteil, J.; Wright, I.; Matsumoto, T. 2003. From rifting to spreading in the Lau Basin – Havre Trough backarc system (SW Pacific): Locking/unlocking induced by seamount chain subduction. *Geochemistry, Geophysics and Geosystems 4 (5):* 8909, doi:10.1029/2001GC000261, 2003.

Sadek, E.A. 1980. A scheme for the automatic generation of triangular finite elements. *International Journal of Numerical Methods in Engineering 15*: 1813-1822.

Sandwell, D.T.; Smith, W.H.F. 1997. Marine gravity anomaly from Geosat and ERS 1 satellite altimetry. *Journal of Geophysical Research, B, Solid Earth and Planets 102(5)*: 10,039-10,054.

Scholl, D.W.; Herzer, R.H. 1992. Geology and resource potential of the southern Tonga platform. In: Watkins, J.S., Feng, Z, McMillen, K.J., (eds). *Geology and geophysics of continental margins*. M. T. Halbouty continental margins conference, Galveston, Texas, USA. pp 139-156.

Sdrolias, M.; Muller, R.D.; Gaina, C. 2003. Tectonic evolution of the southwest Pacific using constraints from backarc basins. In: Hillis, R.R., Muller, R.D. (eds.) *Evolution and Dynamics of the Australian Plate*, Geol. Soc. Australia Spec. Publ. 22 and Geol. Soc. America Spec. Pap. 372: 343-359.

Sdrolias, M.; Muller, R.D.; Gaina, C. 2001. Plate tectonic evolution of Eastern Australian marginal ocean basins. *In* Hill, K. C.; Bernecker, T. *ed.* Eastern Australian Basins Symposium, a Refocused Enerfy Perspective for the Future. *Petroleum Exploration Society of Australia Special Publication*. Melbourne, Australia, 227-237.

Shor, G.G., Jr.; Kirk, H.K.; Menard, H.W. 1971. Crustal structure of the Melanesian area. *Journal of Geophysical Research 76(11)*: 2562-2586.

Smith, I.E.M.; Black, P.M.; Itaya, T. 1995. Inception and evolution of Cenozoic arc-type volcanism in northern New Zealand. In: Mauk, J.L., St. George, J.D. (eds.) Proceedings of the 1995 PACRIM congress; Auckland. *Australian Institute of Mining and Metallurgy Publication Series 9/95*, 563-567.

Smith, W.H.F.; Sandwell, D.T. 1994. Bathymetric prediction from dense satellite altimetry and sparse shipboard bathymetry. *Journal of Geophysical Research B, Solid Earth and Planets 99(11)*: 21,803-21,824.

Staniforth, A.; Côté, J. 1991. Semi-Lagrangian integration schemes for atmospheric models - a review. *Monthly Weather Review 119*: 2206-2223.

Stern, T.A.; Davey, F.J. 1985. Crustal structure studies within the central North Island: the central volcanic region. *Report / Geophysics Division, 207*: 47 p.

Stern, T.A. 1987. Asymmetric back-arc spreading, heat flux and structure associated with the central volcanic region of New Zealand. *Earth and Planetary Science Letters 85*: 265-276.

Sutherland, R. 1999. Basement geology and tectonic development of the greater New Zealand region: an interpretation from regional magnetic data. *Tectonophysics 308:* 341-362.

Tappin, D.R. 1993. The Tonga frontal-arc basin, South Pacific sedimentary basins, pp. 157-176.

Tappin, D.R.; Herzer, R.H.; Stevenson, A.J. 1994. Structure and history of an oceanic forearc: the Tonga Ridge 22 degrees to 26 degrees south. In. *Geology and submarine resources of the Tonga-Lau-Fiji region*. Pp. 81-100.

Walters, R.A. 2005. A semi-implicit finite element model for non-hydrostatic (dispersive) surface waves. *International Journal for Numerical Methods in Fluid*. *49*: 721–737.

Walters, R.A.; Barnes, P.; Goff, J. 2006b. Locally generated tsunami along the Kaikoura coastal margin: Part 1. Fault ruptures. *New Zealand Journal of Marine and Freshwater Research 40*: 1-17.

Walters, R.A.; Barnes, P.; Lewis, K.; Goff, J.; Fleming, J. 2006c. Locally generated tsunami along the Kaikoura coastal margin: Part 2. Submarine landslides. *New Zealand Journal of Marine and Freshwater Research 40*: 18-34.

Walters, R.A.; Casulli, V. 1998. A robust, finite element model for hydrostatic surface water flows. *Communications in Numerical Methods in Engineering 14*: 931-940.

Walters, R.A.; Goff, J.R.; Wang, K. 2006a. Tsunamigenic sources in the Bay of Plenty, New Zealand. *Science of Tsunami Hazards 24*: 339-357.

Watts, A.B.; Weissel, J.K.; Davey, F.J., 1977. Tectonic evolution of the South Fiji marginal basin. In: Talwani, M., Pitman, W.C., III (eds.) *Island Arcs Deep Sea Trenches and Back Arc Basins*. American Geophysical Union Maurice Ewing Series 1: 419-427.

Wright, I.C. 1990. Late Quaternary faulting of the offshore Whakatane Graben, Taupo Volcanic Zone, New Zealand. *New Zealand Journal of Geology and Geophysics 33*: 245–256.

Wright, I.C. 1993a. Pre-spread rifting and heterogeneous volcanism in the southern Havre Trough back-arc basin. *Marine Geology 113*: 179-200.

Wright, I.C. 1993b. Southern Havre Trough - Bay of Plenty (New Zealand): structure and seismic stratigraphy of an active back-arc basin complex, South Pacific sedimentary basins, pp. 195-211.

Wright, I.C. 1994. Nature and tectonic setting of the southern Kermadec submarine arc volcanoes : an overview. *Marine Geology 118*: 217-236.

Wright, I.C. 1997. Morphology and evolution of the remnant Colville and active Kermadec Arc ridges south of 33 degrees 30 S. *Marine Geophysical Research 19*: 177-193.

Wright, I.C.; Carter, L.; Lewis, K.B. 1990. GLORIA side scan survey of oceanic-continental back arc transition. *Geo-Marine Letters 10*: 59-67.

Wright, I.C.; Parson, L.M.; Gamble, J.A., 1996. Evolution and interaction of migrating cross-arc volcanism and backarc rifting: an example from the southern Havre Trough (35 degrees 20 minutes-37 degrees S). *Journal of Geophysical Research, Solid Earth, 101(B10):* 22071-22086.

Wright, I.C.; Worthington, T.J.; Gamble, J.A. 2006. New multibeam mapping and geochemistry of the 30 degree-35 degree S sector, and overview, of southern Kermadec arc volcanism. *Journal of Volcanology and Geothermal Research 149*: 263-296.

Appendix 1: Some general tsunami information

The word *tsunami* is used internationally, and is a Japanese word meaning "harbour wave or waves". Tsunamis are generated by a variety of geological disturbances, particularly large seafloor earthquakes, submarine landslides (which may be triggered by an earthquake), volcanic eruptions (e.g., under-water explosions or caldera (crater) collapse, pyroclastic flows and atmospheric pressure waves), large coastal-cliff or lakeside landslides, and very occasionally a meteorite (bolide) impact.

In each case, a large volume of water is disturbed suddenly, generally affecting the whole water column from the floor of the ocean to its surface, creating a train of waves radiating outwards (similar to the wave train produced by a pebble thrown into a lake) until the waves either dissipate or they inundate a shoreline. Very large sources are required to cause tsunamis that are damaging at great distances from the source. The most common sources of these tsunamis are very large earthquakes along the subduction zones that ring the Pacific. However, meteorite impact and very large volcanic events are also possible sources. On the other hand, a tsunami that is generated locally (i.e., near the combined region's shores) does not need such a large disturbance to be damaging and life threatening, but it would only affect a limited area of the region's coast.

Tsunamis can be classified into categories either by the distance from their source to the area impacted, or more relevant for emergency management purposes, the travel time to the impacted area and the length scale of impact. For this report, three categories are defined:

- Local source/local impact event (within say 30 to 60 minutes travel time and affecting several 10's of km of coast);

- Regional source/regional impact event (within 3 hours travel time and likely to affect the entire exposed coastal margin);

- Distant (remote) source/national impact event (longer than 3 hour travel time and likely to affect several regions).

Tsunami waves differ from the usual waves we see breaking on the beach or in the deep ocean, particularly in their length between wave crests. In a tsunami wave train, the distance between successive wave crests (or wavelength) can vary from several kilometres to over 400 km, rather than around 100 metres for waves at the beach. The time between successive tsunami wave crests can vary from several minutes to a few hours, rather than a few seconds. As tsunami waves reach shallow coastal waters, they slow down and steepen rapidly, sometimes reaching heights of 10 m or more. Shallow bays and harbours tend to focus the waves and cause them to bounce around and amplify (or resonate). Tsunami waves that overtop or breach natural coastal beach ridges and barriers can surge considerable distances inland in low-lying areas (order of 100's of metres to a kilometre or more depending upon the wave runup height and the "roughness" of the land cover and built environment).

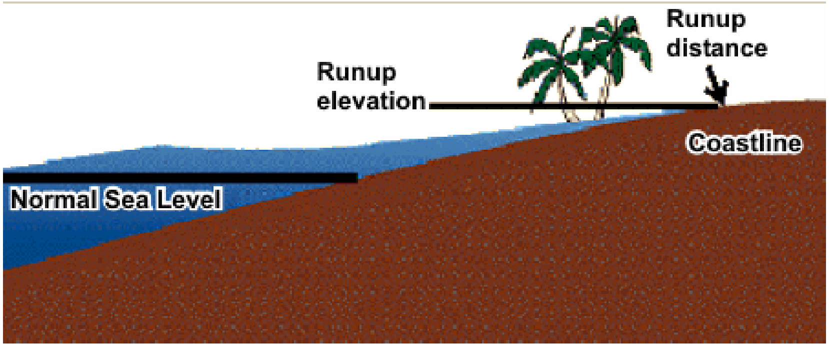
Key definitions to quantify tsunami are:

- Tsunami period (minutes)—the time between successive wave peaks. This can fluctuate during any particular event and vary between different locations within the same region. Periods are usually in the range of a few minutes (e.g., "local source/local impact" tsunami) to an hour or more for a "distant source/national impact" tsunami.

- Tsunami height (m)—taken as the vertical crest-to-trough height of waves, but it is far from constant, and increases substantially as the wave approaches the shoreline. Usually only used in conjunction with measurements from a sea-level gauge to express the maximum tsunami height near shore.

- Tsunami runup (m)—a more useful measure of the tsunami hazard is the maximum runup height, expressed as the vertical height the seawater reaches above the sea level at the time. This measure still has the drawback that it depends markedly on the type of wave (rapidly rising and falling, a bore, or a breaking wave) and on the local slopes of the beach and foreshore areas, so it is highly site-specific.

- Inland penetration (m)—the maximum horizontal distance inland from the shoreline or mean-high-water mark inundated by the tsunami. It depends on the tsunami runup and local topography, barriers and slopes within the coastal margin.



http://www.maine.gov/doc/nrimc/mgs/explore/hazards/tsunami/jan05.htm

Figure 1 App.: Runup and coastal geomorphology a): Yala, Sri Lanka, 26 December 2004 - Dunes in the middle distance were removed when a hotel complex was built, the hotel was completely destroyed. 153 died. Runup onto the intact dune in the foreground was only sufficient to deposit a boat on the dune crest. Live vegetation is visible to the right of the photo.

Figure 2 App.: Runup and coastal geomorphology b): Yala, Sri Lanka, 26 December 2004 – Where dunes had been removed on the coast, the next dune system 500m inland slowed the flow so that only about 0.5-1.0 of water overtopped the 12m high dunes. It still had enough energy however to uproot trees while it overtopped the dune.

The behaviour of any given tsunami wave-field that arrives at any particular coastal locality can vary substantially, depending on several factors, including the generating mechanism, the location, size, and orientation of the initial source, source-to-locality distance, and local seabed and coastal margin topography. Conversely, all tsunamis from the same source area with similar generating mechanisms will propagate to a coastal locality in a similar manner, in which case scenario modelling can be very useful in determining local vulnerability to tsunami hazards.

The arrival of a tsunami wave-train (i.e., it isn't just one wave) is often manifest by an initial draw-down of the level of the sea (much faster than the tide), but for other events, the first sign may be an initial rise in sea level. The waves that propagate towards the coast seldom break before reaching the nearshore area, and the larger waves will appear to have the whole ocean behind them. Thus the larger waves will move relentlessly forward inundating the coastal margin, until they reach maximum runup height before receding temporarily. Other tsunamis occur as an advancing breaking wave front or bore, which is the type of wave most people associate with a tsunami.