
Wairakei/Te Tumu Tsunami Inundation Study

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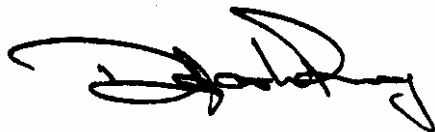
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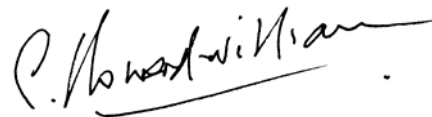
Appendix 1: Some general tsunami information

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Executive Summary

Environment Bay of Plenty contracted NIWA to undertake a tsunami inundation study for the Wairakei/Te Tumu development area. The particular focus of this work was to determine the potential tsunami inundation associated with a credible, locally-sourced, “Worse case scenario” event.

The most likely potential tsunamigenic sources were identified. These included:

- Subduction zone earthquakes along the Tonga-Kermadec-Hikurangi trench associated with the Pacific/Australian plate boundary.
- Regional active faults - primarily normal faults in the offshore Taupo Volcanic Zone.
- Landslide sources in the Hikurangi margin east and north of East Cape
- Offshore volcanic sources in the Bay of Plenty including Tuhua/Mayor Island and Whakaari/White Island.
- Local landslides including sector collapse of seamounts.

The numerical model, RiCOM (River and Coastal Ocean Model), was used to derive the results described in this report. A bathymetric grid was developed spanning longitudes 175.89° to 181.76°E and latitudes 38.05° to 35.08°S. This was combined with a topographic grid, derived from aerial photography, centred on the Wairakei/Te Tumu development area. The finite element model grid used was generated by the program GridGen with the grid adjusted to increase resolution.

Results show that regionally active faults within the Bay of Plenty, offshore volcanic sources, and local sector collapse of seamounts do not generate a large enough tsunami to inundate the Wairakei/Te Tumu development area. Large fault ruptures along the Tonga-Kermadec trench however, can generate large tsunamis.

A “Worse case scenario“ was derived from a M_w 8.5 subduction zone earthquake along the Tonga-Kermadec-Hikurangi trench striking the coast at Mean High Water Spring. Maximum tsunami runup height was 4.2 m on the seaward side of the study area, arriving some 70 minutes or so after fault rupture. Waves did not breach the coastal sand dunes. Part of the wave however travels through the Kaituna River and Maketu Estuary, inundating low-lying areas in the south-east section of the site, penetrating approximately 2km west along Bell Road. Tsunami waves to the north-west (Papamoa) of the site ran up to 5.4 m, marginally breaching coastal dunes but not penetrating south-east into the study area.

An “Extreme case scenario” was also modelled to try and correlate inundation more effectively with geological data. The generating mechanism used was aimed at modelling a complex combination of a large subduction zone earthquake and submarine landslides on the continental shelf slope. Essentially, the “Worse case” fault displacement was increased so that the runup was in better agreement with palaeotsunami data. This differs from the “Worse case scenario” where an attempt was made to determine the maximum source displacement for this area purely from sparse geophysical data. The final outcome is realistic enough to closely approximate landward inundation similar to the geological record.

The tsunami for the “Extreme case scenario” propagates in the same manner as the “Worse case scenario” but with maximum tsunami runup height up to 7 m on the seaward side of the study area, arriving some 70 minutes or so after fault rupture. Waves at this elevation are just starting to breach the coastal sand dunes on the seaward side of the study area. Part of the wave however travels through the Kaituna River and Maketu Estuary and inundates low-lying areas in the south-east section of the site. Inland penetration to the west and north via the Kaituna River is more extensive than in the “Worse case scenario”. Tsunami waves that overtop coastal dunes to the north-west (Papamoa) runup to 9.1 m and inundate dune swales inland of the main residential areas along the dune ridge. The water however is impounded in the swale behind an unsealed road crossing the stream. Impounded water is several metres deep and does not penetrate SE into the study area. It is possible that flows may create new drainage patterns to the southeast through low-lying land. In the absence of detailed LIDAR and drainage data though, this would require careful on-site assessment of micro-topography to interpret likely return flow pathways.

The importance of the coastal dunes cannot be overstated. In the absence of such a natural barrier, or if dune height were reduced, tsunami runup would be extreme and widespread inundation would occur. Some indication of what could happen as a result of coastal dune breaching in the study area can be gleaned from observations of areas to the north-west of the study area. An absence of detailed topographic data makes it difficult to model weak points in the coastal dune system of the Wairakei/Te Tumu development area. It is recommended that this aspect of the dune system be modelled once sufficiently high resolution data are available.

Five animations are produced for the report. Three show the “Worse case scenario” at a regional, intermediate and local scale. Two show the “Extreme case scenario” at an intermediate and local scale.

1. Introduction

Environment Bay of Plenty contracted NIWA to undertake a tsunami inundation study for the Wairakei/Te Tumu development area (Figure 1). The focus of this work was to determine the potential tsunami inundation associated with a credible, locally-sourced, “Worse case scenario” event. The scope and nature of the services include:

- 1.1. Determining a realistic source scenario for the generation of such a tsunami;
- 1.2. Modelling wave propagation from the source and the subsequent inundation of the Wairakei/Te Tumu development area (defined as an area bordered by the Kaituna River to the east and south, and by Parton Road to the west) and identifying and reporting on the main areas of concern.

Background information on tsunamis is provided in Appendix 1.



Figure 1: Topographic map showing limits of the study area – open circles refer to sites discussed in Goff (2002), PR = Parton Road 1 site.

2. Potential sources

The Bay of Plenty faces a diverse range of potential tsunamigenic sources either within the Bay of Plenty, along the crustal plate boundaries, or remotely across the Pacific Ocean. Within the region 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. These sources were summarised in Bell et al. (2004).

The term Return Period is used in this text and can be defined as a qualitative measure of the average recurrence interval. A general methodology to determine these values is to construct a plot of magnitude versus the annual exceedence probability for each of the sources. For a given magnitude event, the corresponding probability then defines an average recurrence interval. However, there is no adequate data to define these plots, except for the detailed assessment of local faults in the Bay of Plenty (Lamarche and Barnes, 2005). Hence, the values for return period are rough estimates based on general knowledge of similar events.

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. Furthermore, with return periods in the 10's-100's of thousands of years, we do not believe that such an event can be modelled as a realistic credible "Worse case scenario". We wish to keep the "Worse case scenario" event to something that could occur or has occurred within a timeframe of 500-1000 years.

For the purpose of this study, the important potential tsunamigenic sources (local and regional) are categorised as:

- ±1. Subduction zone earthquakes along the Tonga-Kermadec-Hikurangi trench associated with the Pacific/Australian plate boundary. This source occurs beneath the eastern margin of the Bay of Plenty and the Kermadec Ridge, where the Pacific Plate underthrusts (subducts) to the west. Historic earthquakes of magnitude M_w 8.0 to 8.3 have occurred along the Kermadec Ridge (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.
- ±2. Regional active faults provide many candidates for sources within the Bay of Plenty (Lamarche and Barnes, 2005). They primarily include normal faults in the offshore Taupo Volcanic Zone. The major zone of active rifting extends between Whakatane and Tauranga, with faults between Matata and

Whakatane accommodating a significant proportion of the total crustal extension (Wright, 1990; Lamarche et al., 2000). Larger faults with significant seafloor traces include the Whakaari/White Island and Rangitaiki Faults in the offshore Whakatane Graben. Normal faulting in the Taupo Volcanic Zone rarely exceeds 2 m single event vertical displacement, but the larger boundary faults may be capable of larger seabed displacements. Typical return periods for these regional faults vary from a few hundred to 1000's of years.

3.3. Landslide sources in the Hikurangi margin east and north of East Cape include giant landslide complexes such as Matakaoa and Ruatoria that may be triggered during large earthquakes. Collot et al. (2001) have shown that the Ruatoria landslide was triggered approximately 170000 years ago and had a volume of about 3000 km³. The Matakaoa landslide on the other hand contained at least three large landslides and probably dates to around 50 000 years ago (Lewis et al., 1999; Carter and Lamarche, 2001). These slides included large slabs that slid down the continental shelf semi-intact and debris flows that inundated the abyssal plain. Such large events have very long return periods of 10's–100's of thousands of years. However, smaller landslides are more likely within the Matakaoa complex and in the submarine canyons of Bay of Plenty.

4.4. Offshore volcanic sources in the Bay of Plenty include Tuhua/Mayor Island and Whakaari/White Island. For Tuhua/Mayor Island, modelling studies indicate that the credible pyroclastic eruptions of a “Mt St Helens” scale (1 km³) could produce a tsunami that would impact an area from Tairua to Maketu, with wave heights peaking at 0.5 m between Whangamata and Tauranga (de Lange, 1998; de Lange and Prasetya, 1999). An eruption ten times larger with a pyroclastic flow of Krakatau scale (10 km³) would peak at around 5 m at the coast (de Lange and Prasetya, 1999). Recent geophysical data from Tuhua/Mayor Island indicates the last caldera collapse, associated with the largest eruption, occurred about 6,300 years ago (Houghton et al., 1992) and included the transport of large pyroclastic flows into the sea. Numerous smaller submarine volcanoes occur on the Bay of Plenty continental shelf and slope closer to the coast (within 100–150 km) (Gamble et al., 1993; Lamarche and Barnes, 2005).

5.5. Local landslides including sector collapse of seamounts, can provide sources within the Bay of Plenty. In particular, landslide sources at the heads of Tauranga and White Island Canyons were considered as possible sources. In addition, a complete collapse of a seamount was considered as an extreme case in order to gauge the relative size of a tsunami that could be generated.

Of the remaining sources:

- Upper plate faults along the Hikurangi-Kermadec shelf margin were not judged capable of generating large tsunamis within the Bay of Plenty as compared to large subduction zone earthquakes due to their shorter wavelength, short fault length, and moderate vertical displacement.
- Undersea volcanic sources in the Tonga-Kermadec system can be represented as a point source for tsunamis. The amplitude of the waves from these volcanoes decreases rapidly with distance from the source and hence is not considered to be an issue here.
- Sector collapse of seamounts within the Bay of Plenty was considered. These could be a source of large amplitude waves because of the short distance to shore.
- Pressure waves or pyroclastic flows from large onshore volcanic eruptions in the Taupo Volcanic Zone were not considered.

The primary source for a remote tsunami is South America. The historic record indicates that these events are unlikely to generate “Worse case scenario” tsunamis of comparable size to local and regional events, so they too are not considered here.

The basic definition of wave runup requires some explanation. A tsunami’s runup distance is the distance from the normal tide line, or shoreline, at the time of the tsunami’s arrival to its maximum extent inland. The runup height is the elevation of the point of maximum runup above the normal ocean surface at the time of the tsunami. This is shown diagrammatically in Appendix I. Onshore topography has a significant control over wave runup, with coastal dunes reflecting or absorbing much of the wave energy. Any reduction in dune height increases the risk from tsunami inundation (see Appendix I for examples).

3. Historical and palaeotsunami record

Maximum runup of historical tsunamis in and around the Wairakei/Te Tumu development area has not exceeded 2 m (Bell et al., 2004). The historical record for the region dates back as far as 1840. During this time there have been no large, locally-generated tsunamis. Maximum runup heights in the historical database relate

solely to large, distant events from South America and Indonesia and provide little indication of “Worse case scenario” events from more local sources.

The palaeotsunami record is more revealing. This is summarised in Bell et al. (2004) and in Figure 2 below. Of particular note are the most recent region-wide events which occurred around 500-600 years ago. Some geological evidence for these events is preserved in wetlands around Papamoa, and just south of Bell Road, far inland from anything recorded in the historical record. A brief reconnaissance of the Hickson property (part of the Wairakei/Te Tumu development area) in 2002 also indicated possible tsunami inundations dating to this time period on the seaward dune system (Goff, 2002). These data provide tangible evidence of realistic “Worse case scenario” tsunamis and help guide the development and groundtruthing of the model.

4. Modelling tsunami inundation

4.1. Numerical model

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., 2006a; 2006b). The hydrodynamics part 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 shallow water equations.

To permit flexibility in the creation of the model grid across the continental shelf, finite elements are used to build an unstructured grid of triangular elements of varying-size and shape. The time intervals that the model solves for are handled by a semi-implicit numerical scheme that avoids stability constraints on wave propagation. The advection scheme is semi-Lagrangian, which is robust, stable, and efficient (Staniforth and Côté, 1991). Wetting and drying of intertidal or flooded areas occurs naturally with this formulation and is a consequence of 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

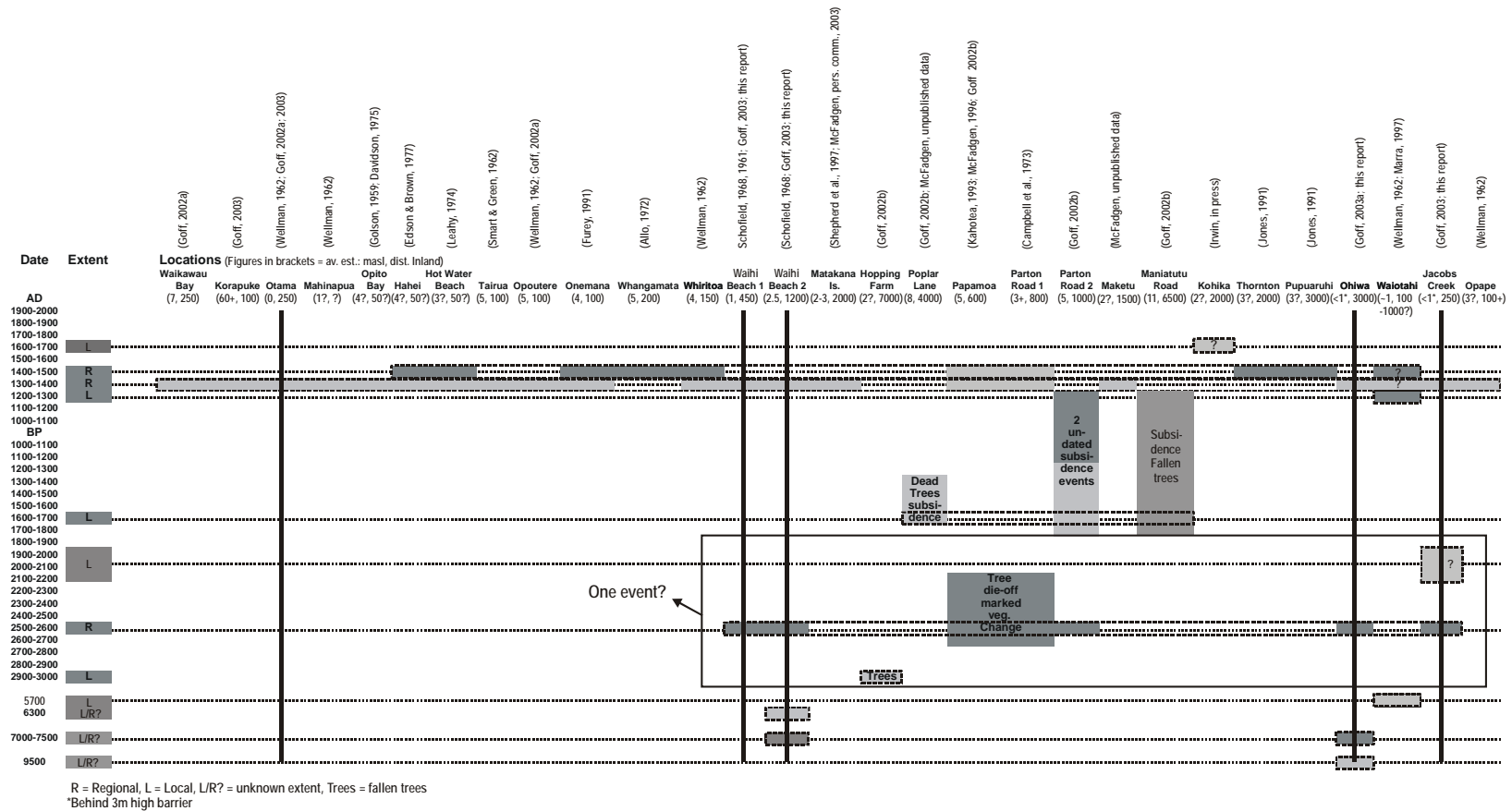


Figure 2: Palaeotsunami data from Bell et al. (2004). Region-wide events occurred in the 14th and 15th centuries, and 2500-2600 years BP. Runup of at least 5 metres was recorded in the Papamoia area.

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).

4.2. Model Grid – Topography and Bathymetry

A bathymetric grid was developed spanning longitudes 175.89° to 181.76°E and latitudes 38.05° to 35.08°S. This was combined with a topographic grid centred on the Wairakei/Te Tumu development area, extending from beyond Parton Road to Maketu Estuary, and inland approximately two kilometres (see below). The topographic portion of the grid allows for realistic modelling of wave runup and also provides an indication of the level of inundation. Coastline data were retrieved from the LINZ high resolution New Zealand coastline dataset which follows a boundary defined by the mean high water line. Bathymetric data were derived from surveyed data of coastal coverage with 10 m isobaths (to approximately 150 – 200 m depth) and 50 m contours at greater depths off the continental shelf. No topographic data in the form of a DTM or LIDAR data were available for the Wairakei/Te Tumu development area. Instead, topographic data for the land portion of the grid were obtained from a photogrammetric dataset supplied for the project by Environment Bay of Plenty. Detailed aerial photographs in electronic form were only available from Topomap. These composite images do not include the most easterly point of the area and to compensate for this we have also included animations and imagery at an intermediate scale (extending from beyond Parton Road to Maketu Estuary). Animations and imagery for the credible, locally-sourced, “Worse case scenario” are given at a Regional (Bay of Plenty wide), Intermediate (as above), and Local (approximating the boundaries of the Wairakei/Te Tumu development area) scales.

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). This grid was subsequently refined by a factor of four by subdividing each

grid triangle successively into 4 new triangles using vertices at the mid-sides of the original triangle. Height/depth values are interpolated at each node from the reference datasets described above.

5. Results

The results for the modelling of potential tsunamigenic sources are discussed in the subsections that follow. Of these, the events that generated the largest tsunamis for the Wairakei/Te Tumu development area were a subduction zone earthquake and offshore volcanism such as described by de Lange and Prasetya (1999) for a Krakatau-sized event.

As the focus of this report has been the Wairakei/Te Tumu development area, tsunami inundation of the coastline outside those boundaries has not been discussed in detail except when relevant to the study area. Additional work would need to be done to fully investigate other sections of the BOP coastline.

5.1. Subduction zone event

The Wairakei/Te Tumu development area (and most of the Bay of Plenty) is directly exposed to tsunamis generated by subduction zone earthquakes immediately north of East Cape (the Tonga-Kermadec Trench). A fault-dislocation model was used to model seabed displacement for events ranging from M_w 8.3 to M_w 8.7 (see Lamarche and Barnes (2005) for definitions). An event of M_w 8.5 however, seems likely to be the maximum credible event for this source (Worse case scenario – vertical displacement of 3 m). For comparison, events with M_w 8.0 and 8.3 occurred farther north on the Kermadec trench early in the 20th century.

For the most likely maximum credible event, a M_w 8.5 fault rupture was modelled to strike the coast at Mean High Water Spring (MHWS). Because fault movement is rapid with respect to surface wave propagation in this case, the seabed displacement was used as the initial water displacement for the tsunami that was created. The initial wave separates into two waves of roughly equal size - one propagating onshore and the other propagating offshore to become a remote tsunami elsewhere. The wave directed onshore is partially refracted around East Cape and comes ashore in the Bay of Plenty (refer to Regional Animation - **WCS Reg** – on CD). The main part of the wave travels westward to the area around Tauranga and to the north. At the Wairakei/Te Tumu development area coastline (seaward side), the wave crest is stretched by refraction in the bay. Waves converge around Motiti Island amplifying the tsunami immediately to the north-west around Papamoa. Hence the runup effects

in the Wairakei/Te Tumu development area are somewhat reduced by the geometry of the Bay of Plenty (refer to Intermediate and Local Animations -*WCS Int*, *WCS Loc* – on CD).

Maximum tsunami runup height was 4.2 m on the seaward side of the study area, arriving 70 minutes or so after fault rupture. Waves did not breach the coastal sand dunes as shown by a plot of maximum water surface elevation for the inundated areas (Figure 3). Maximum water surface elevation represents the envelope of the wave crests or equivalently the maximum water surface elevation at a given location during the passage of the tsunami. Part of the wave however travels through the Kaituna River and Maketu Estuary, inundating low-lying areas in the south-east section of the site, penetrating approximately 2km west along Bell Road. Tsunami waves to the north-west (Papamoa) of the site ran up to 5.4 m, marginally breaching coastal dunes but not penetrating SE into the study area (Figure 3). Water velocities are markedly slower on the landward side of the study area (Kaituna River) of the site (Figure 4).

Modelled tsunami inundation does not match geological sites on the landward swale adjacent to Parton Road and to the south of Bell Road (Goff, 2002). Some of this mismatch is undoubtedly related to errors in the source magnitude and historic changes in nearshore bathymetry, coastal topography, vegetation, and shoreline position. However, the overall pattern of inundation approximates that of the geological data, and in particular the unusual location of the Bell Road site.

5.2. Landslide at or near the shelf break

There is abundant evidence for submarine landslides on the east coast of the North Island, particularly between Hawke's Bay and eastern Bay of Plenty. The larger events such as Ruatoria and Matakaoa (discussed above) would seem to be capable of sending large tsunamis into the Bay of Plenty. These have extremely long return periods (in the order of 10's-100's of thousands of years). While such large events are not likely to occur in the immediate future, there is a possibility of further collapse of the northern scar of the Ruatoria avalanche and smaller landslides within the Matakaoa complex. Another area of possible submarine landslides and slumps is along the southern Kermadec Ridge where the Hikurangi Plateau is being subducted.

It is worth noting though that these large submarine landslides are highly complex events that may well be generated by processes associated with seismic activity along the subduction zone. If this is the case, then (excluding bolide impact) the combination of a large subduction zone event and a major submarine landslide at or near the shelf break could be an "Extreme case scenario". With this in mind, and acknowledging that there are currently insufficient data to model these landslides in a useful manner, we

chose to generate larger events by increasing the magnitude of the “worse case” event. In particular, the source was a subduction zone event with M_w 8.7 (a vertical displacement of 4.5m) striking the coast at MHWS. The modelled landward inundation is remarkably similar to the geological record (see below).

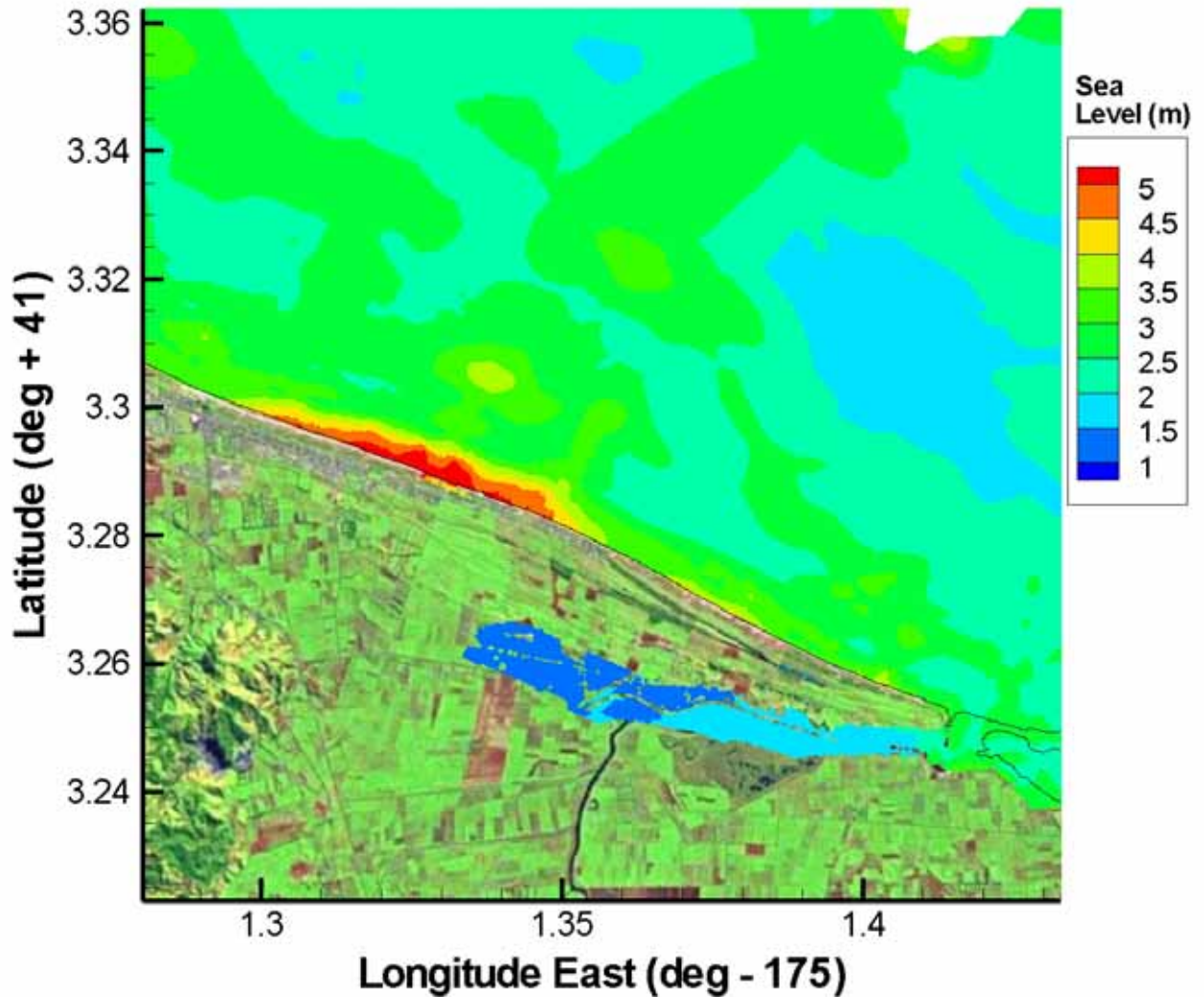


Figure 3: Worse case scenario: Maximum water surface elevations during the time of the tsunami simulation. Note inundation of the Wairakei/Te Tumu development area from the Kaituna River side. The black line delineating the coast in all model figures is the Mean Sea Level (Mean High Water Spring is 1.2 m higher). Add 175 to the longitude scale range for correct longitude, and subtract 41 from latitude scale range for correct latitude – the existing scales are a function of the model program. This is applicable to Figures 3-6.

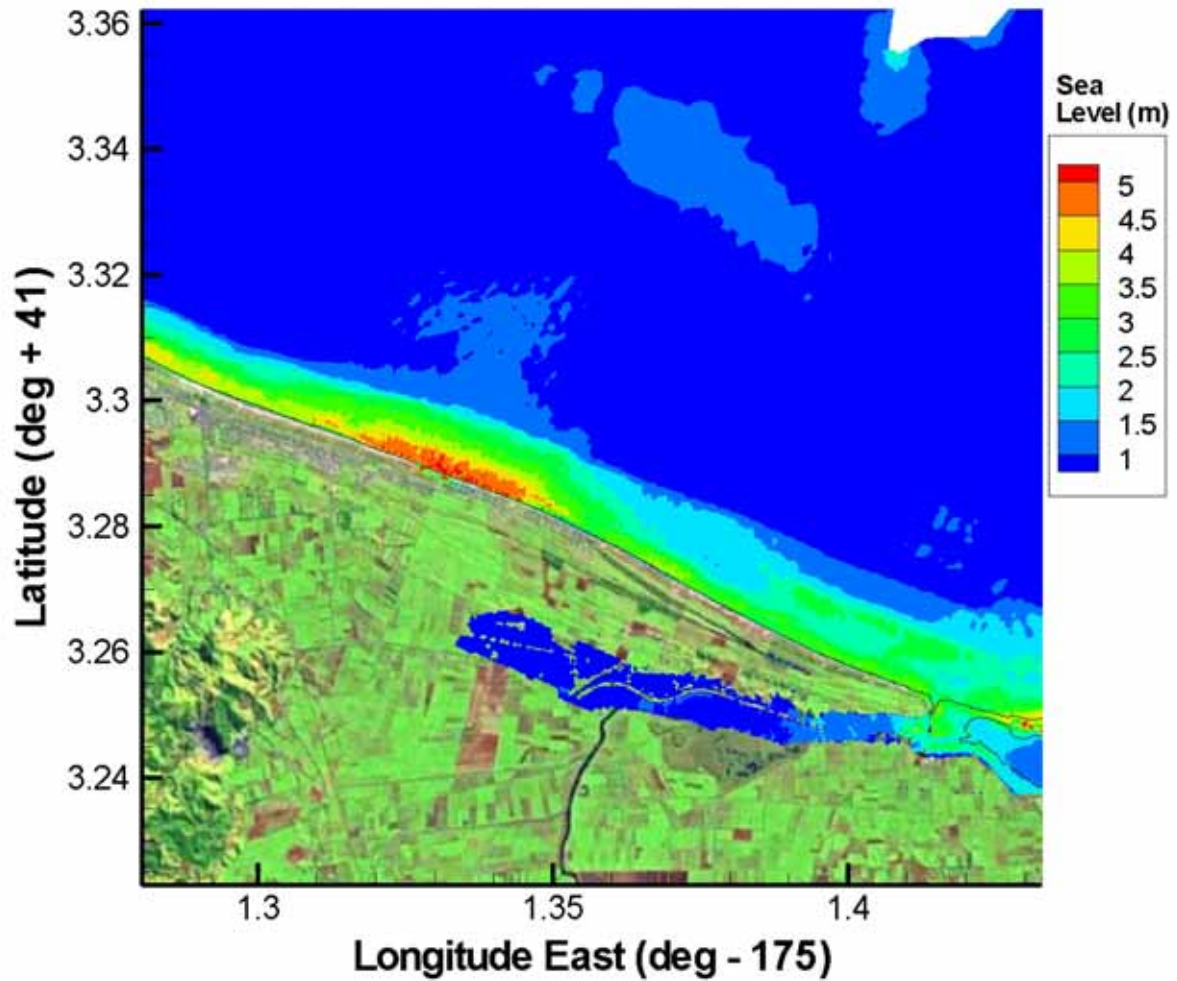


Figure 4: Worst case scenario: Maximum water speeds during the time of the tsunami simulation.

The wave essentially propagates in the same manner as the “Worse case scenario” but with maximum tsunami runup height up to 7 m on the seaward side of the study area, arriving some 70 minutes or so after fault rupture (refer to Intermediate and Local Animations - *ECS Int*, *ECS Loc* – on CD). Waves at this elevation are just starting to breach the coastal sand dunes on the seaward side of the study area (Figure 5). Part of the wave however travels through the Kaituna River and Maketu Estuary and inundates low-lying areas in the SE section of the site. Inland penetration to the west and north via the Kaituna River is more extensive than in the “Worse case scenario”. Tsunami waves that overtop coastal dunes to the north-west (Papamoa) run up to 9.1 m and inundate dune swales inland of the main residential areas along the dune ridge. This inundation occurs outside the study area. The water passes through the residential area into the stream paralleling the dune system. However, water is impounded behind an unsealed road crossing the stream. There is undoubtedly a culvert at this point

although we have no information about it. The impounded water is several metres deep and does not penetrate SE into the study area (Figure 5). It is possible that flows may create new drainage patterns to the southeast through low-lying land. In the absence of detailed LIDAR and drainage data, this would require careful on-site assessment of micro-topography to interpret likely return flow pathways. Maximum velocities are shown in Figure 6.

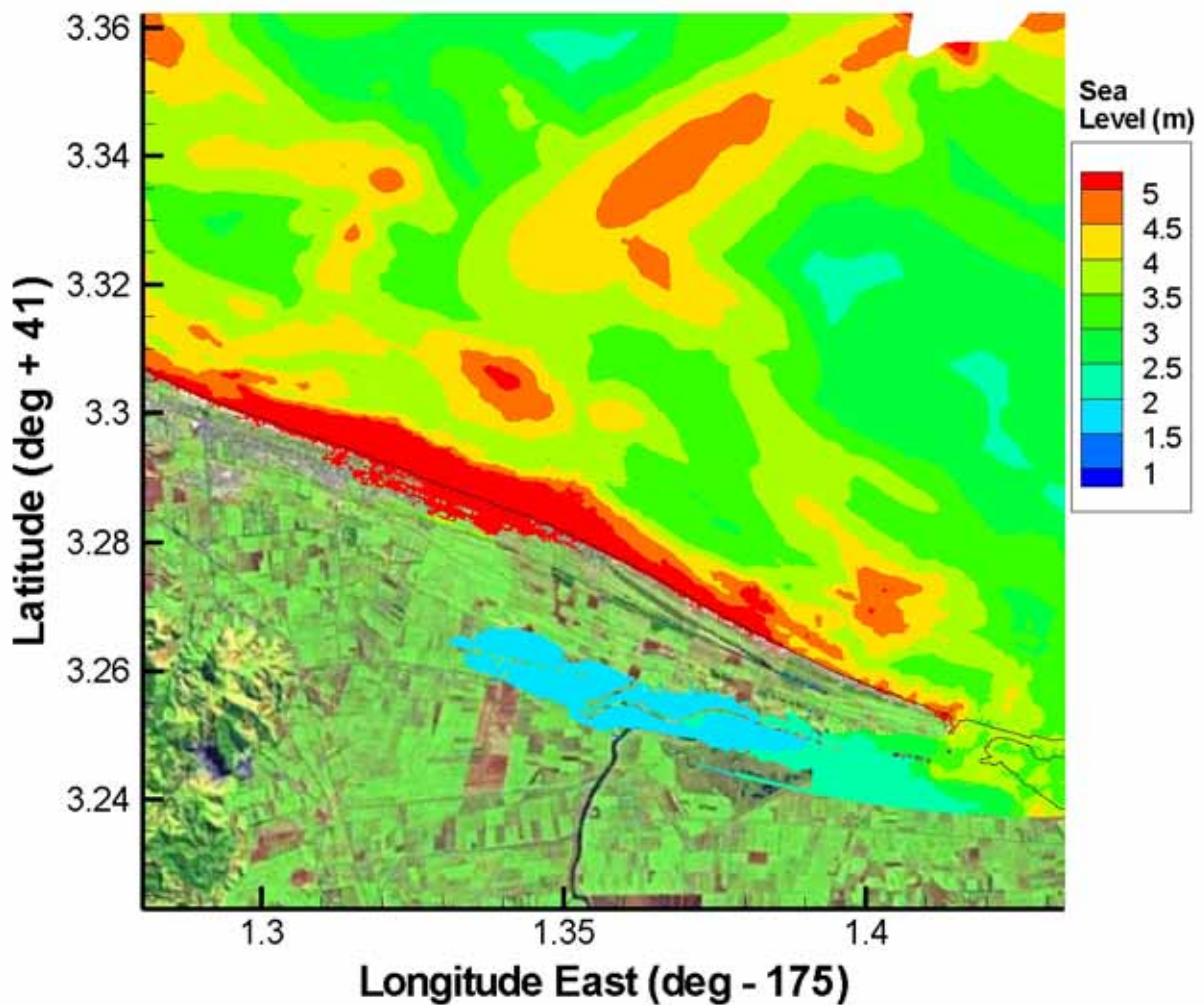


Figure 5: Extreme case scenario: Maximum water surface elevations during the time of the tsunami simulation. Note inundation of the Wairakei/Te Tumu development area from the Kaituna River side, and dune overwash near the Hickson Property.

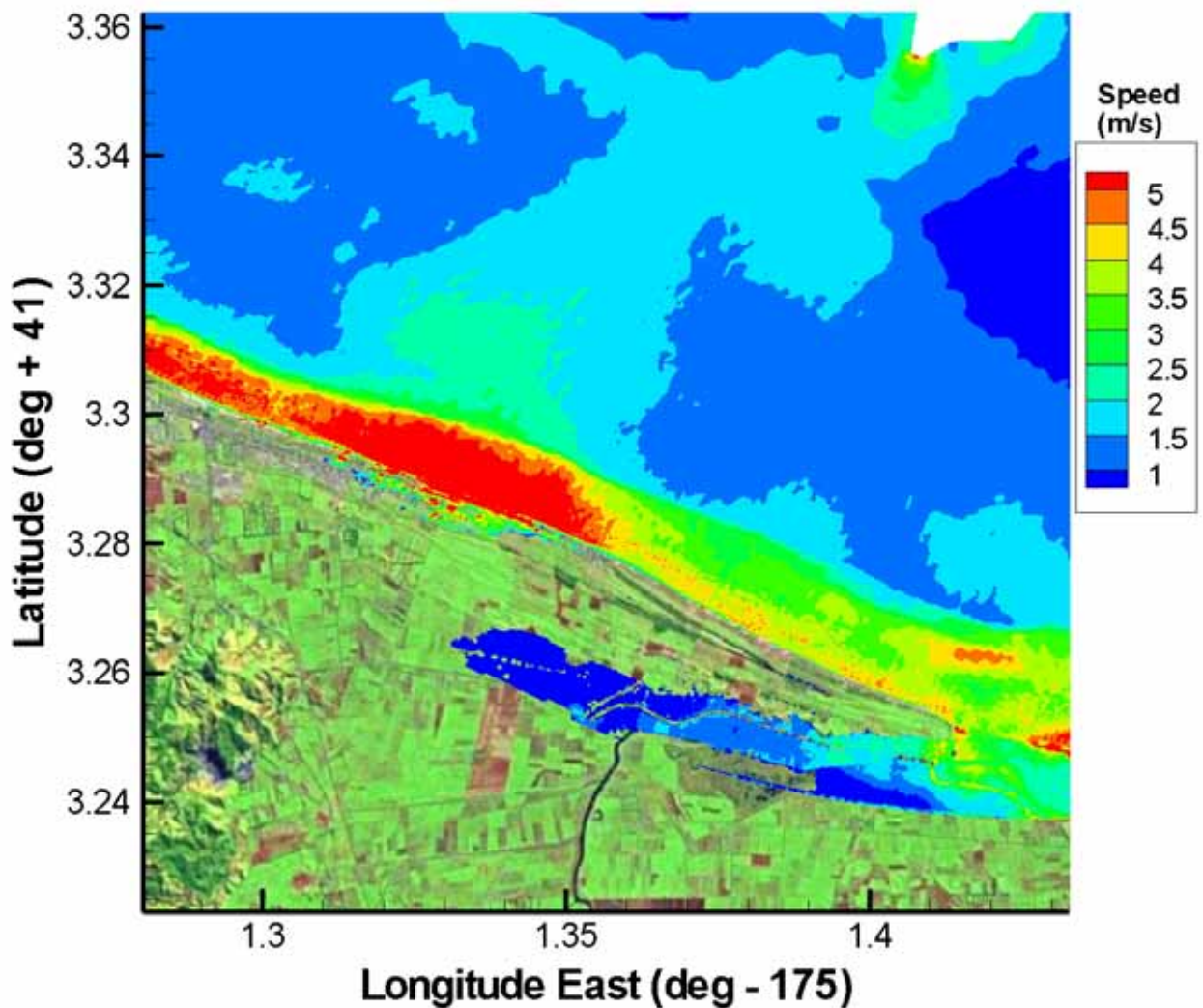


Figure 6: Extreme case scenario: Maximum water speeds during the time of the tsunami simulation.

As mentioned above, the model results are remarkably similar to the geological record. The maximum inland extent is close to or marginally seaward of the Bell Road and Parton Road sites, and matches the Hickson property sites well. The pattern of model inundation is more representative of the physical evidence than the “Worse case scenario”. While the parameters used to model this tsunamigenic event are extreme, the outcomes are a more reasonable facsimile of the physical evidence. Outside the immediate study area there are similar correlations between the model and physical evidence at Newdicks Beach, Maketu, to the east, and Matakana Is. to the west (J. Goff, unpublished data; Bell et al., 2004).

5.3. Volcanism

Previous studies (de Lange, 1983; de Lange and Prasetya, 1999) have shown that the main tsunami risk from volcanism in the Bay of Plenty involves a pyroclastic flow from Mayor Island. Modelling shows that a tsunami with a height of 3 m in the Wairakei/Te Tumu development area is possible from a Krakatau-scale (10 km^3) pyroclastic flow travelling south from Mayor Island. These waves would be comparable to, but smaller than, tsunami generated by a large subduction zone event. They are noted here as a less severe scenario, but modelling has not been repeated as a part of this study.

5.4. Landslides-local

Landslides are possible in the submarine canyons adjacent to the Papamoa coast. Landslide volumes however are relatively small; hence the tsunami that would be generated is also small. Seafloor geometry in the area would also ensure that the tsunami would be primarily directed offshore. As a result, this type of source has not been considered further.

5.5. Local fault events

A comprehensive summary of faults in the Bay of Plenty has been published by Lamarche and Barnes (2005). These faults are primarily normal faults in the offshore Taupo Volcanic Zone. The major zone of active rifting extends between Whakatane and Tauranga, with faults between Matata and Whakatane accommodating a significant proportion of the total crustal extension. The larger faults with significant seafloor traces include the Whakaari/White Island and Rangitaiki Faults in the offshore Whakatane Graben. Normal faulting in the Taupo Volcanic Zone rarely exceeds 2 m single event vertical displacement.

Three representative faults were chosen based on their potential for producing relatively large wave heights at the Wairakei/Te Tumu development area (refer to Lamarche and Barnes (2005), Appendix 3 for details). These included a composite of the White Island faults (WIF-C1) (Figures 7-8), the composite Volkner faults (VOL-C1) (Figures 9-10), and the composite Astrolabe faults (AST-C1) (Figures 11-12). All the necessary parameters for an elastic dislocation model are provided in the report by Lamarche and Barnes (2005). The model of Okada (1985) was used to calculate seabed displacements for the three faults and these displacements were used as an initial condition for the tsunami model.

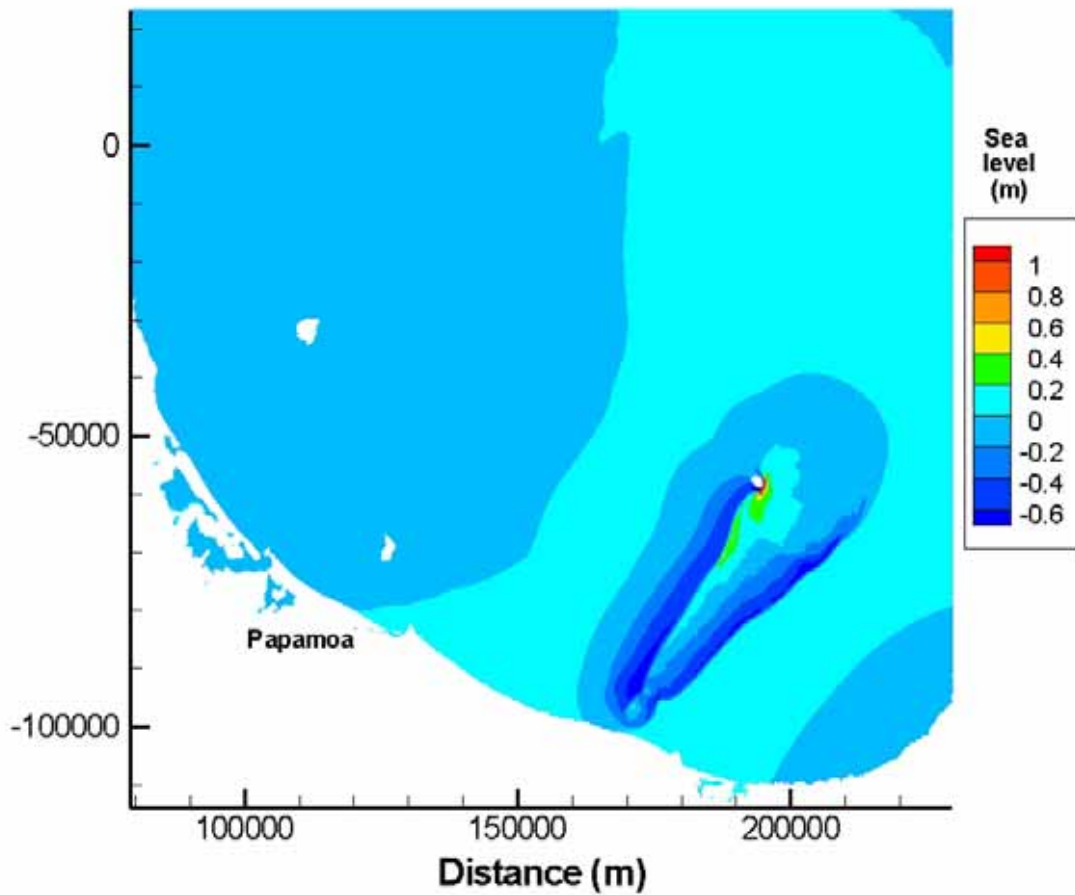


Figure 7: Composite White Island faults – 140 seconds after maximum single event displacement (note westward moving wave has just struck east coast of White Island).

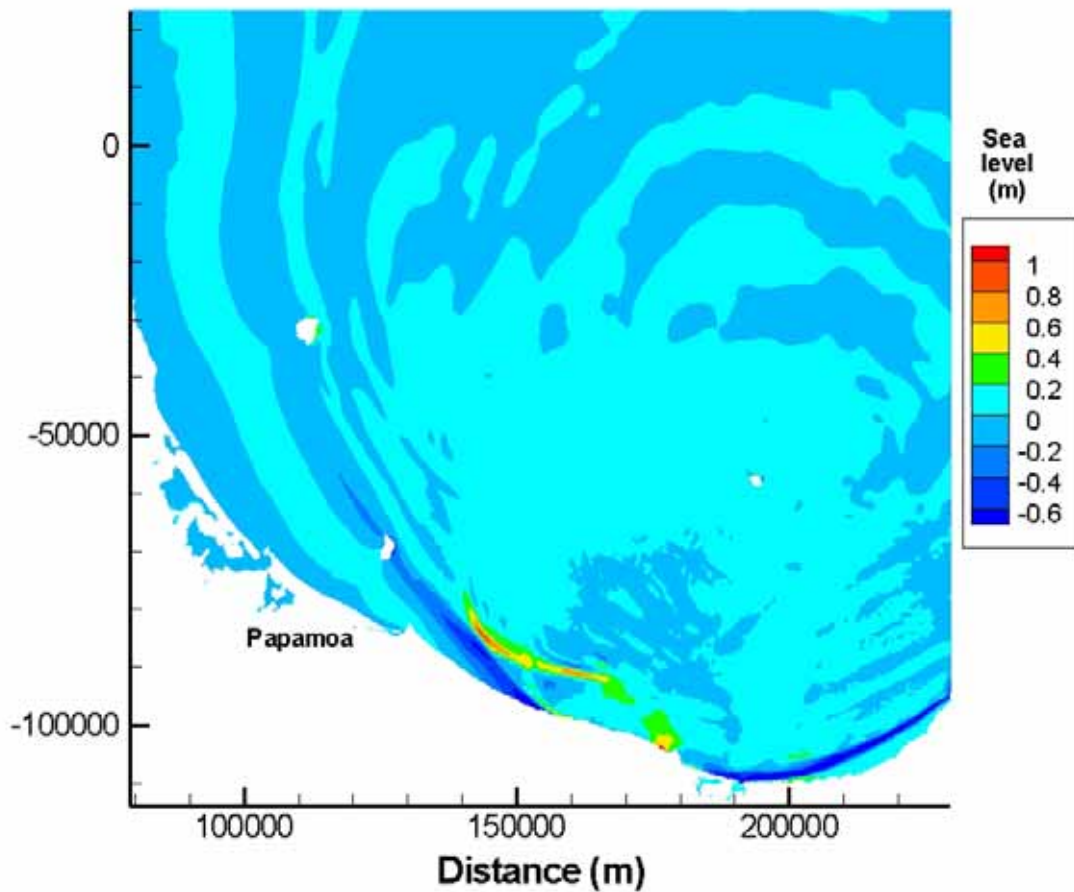


Figure 8: Composite White Island faults – 1500 seconds after maximum single event displacement. Waves in vicinity of the Te Tuma development area eventually peak at less than 1 m.

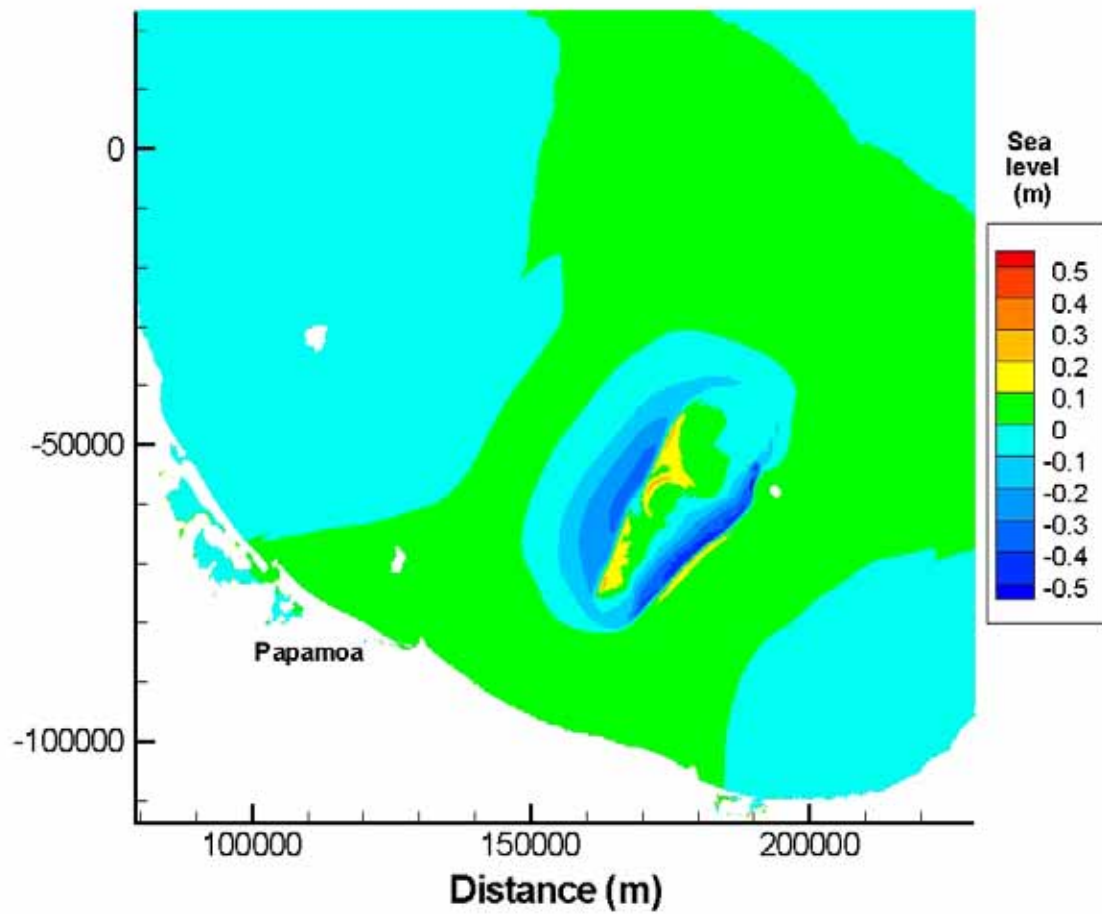


Figure 9: Composite Volkner faults – 140 seconds after maximum single event displacement (note scale change).

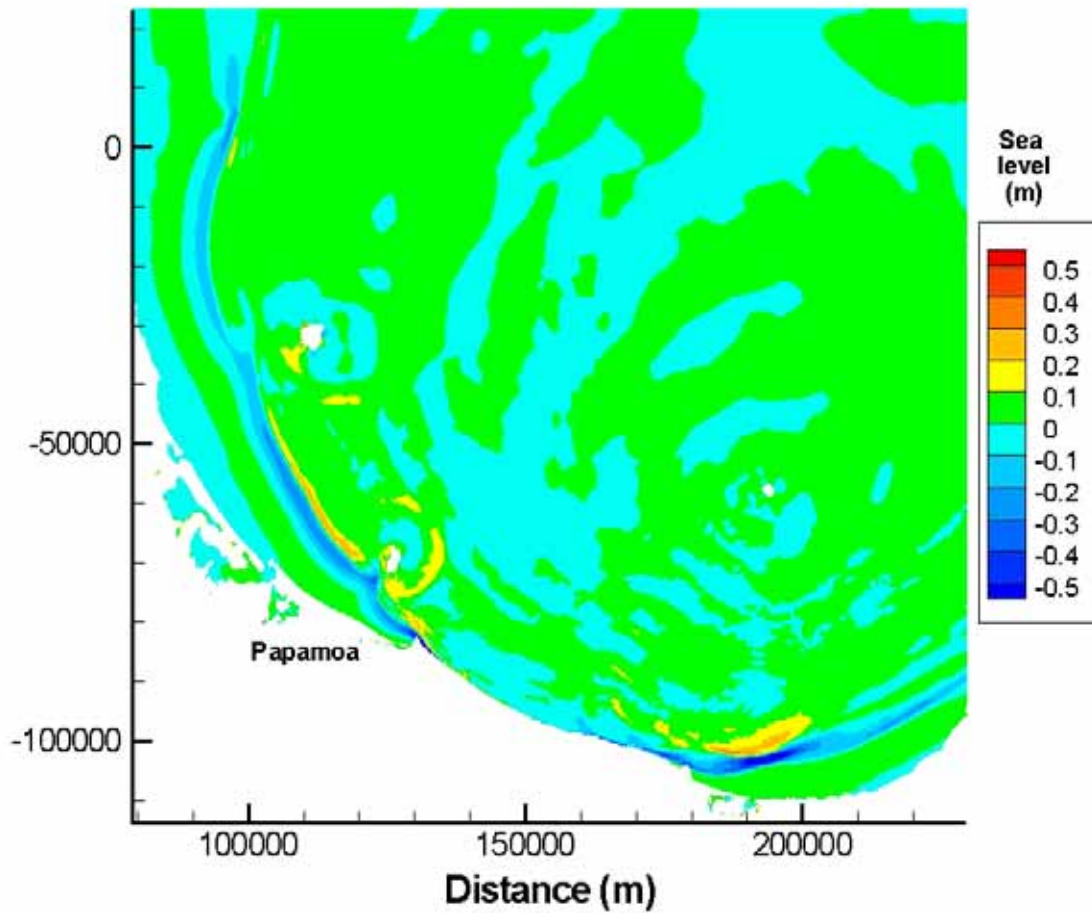


Figure 10: Composite Volkner faults – 1500 seconds after maximum single event displacement. Waves in the vicinity of the Te Tuma development area eventually peak at less than 1 m (note scale change).

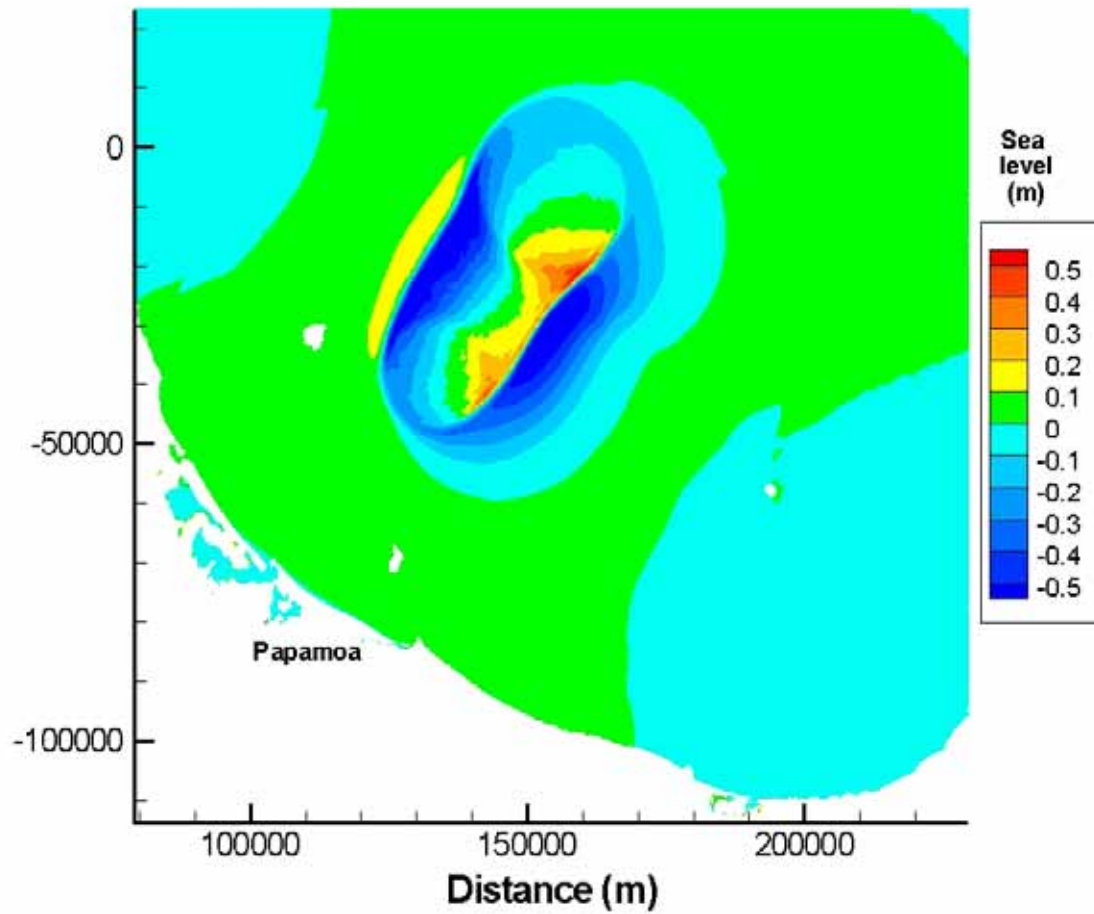


Figure 11: **Composite Astrolabe faults – 140 seconds after maximum single event displacement (same scale as Volkner faults).**

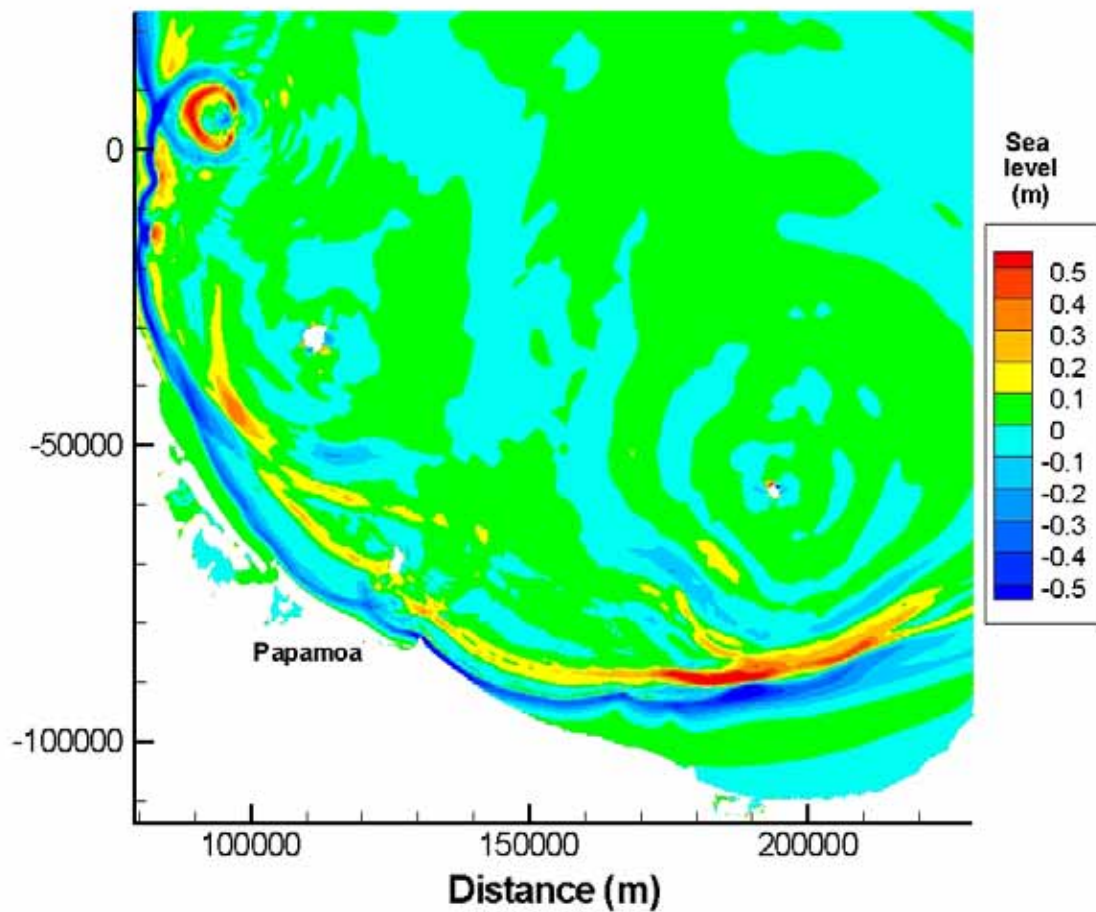


Figure 12: Composite Astrolabe faults – 1500 seconds after maximum single event displacement. Waves in the vicinity of the Te Tuma development area eventually peak at less than 1 m (same scale as Volkner faults).

Because these faults are normal faults, they exhibit the greatest displacement downwards in the direction of dip (typically greater than 1 m), and a smaller positive displacement (typically 0.3 m) on the opposite side of the fault trace. As the wave separates and propagates in both directions away from the fault, the two waves have different characteristics. For the tsunami with a small positive leading wave (initially moving away from the direction of fault dip), the positive peak remains small and runup is not significant. However, for the other tsunami with a negative leading wave, the positive peak is amplified and the runup in local areas can be up to 2 m. The illustrations below show time slices near the start and end of the tsunami sequence for each composite fault.

5.6. Sector collapse of seamounts

The sector collapse of a seamount or submarine volcano acts as a point source and the resultant tsunami tends to decay rapidly with distance away from the source. Important factors that control the size of a tsunami are volume of the material that fails, direction and depth of the collapse.

As an example, an entire collapse of the nearest large seamount, Tumokemoke Knoll was simulated as a material failure and subsequent landslide. The knoll is about 4 km in diameter at the base, about 300 m high from its base, and 200 m below mean sea level. The volume of material is approximately 1.2 km³. This can be compared with the 10 km³ of material from volcanic sources that is required to generate a 5 m tsunami.

As expected, the tsunami decays rapidly with distance from the seamount source and the wave height is less than 1.5 m when it reaches the shore at the Wairakei/Te Tumu development area (Figures 13 and 14).

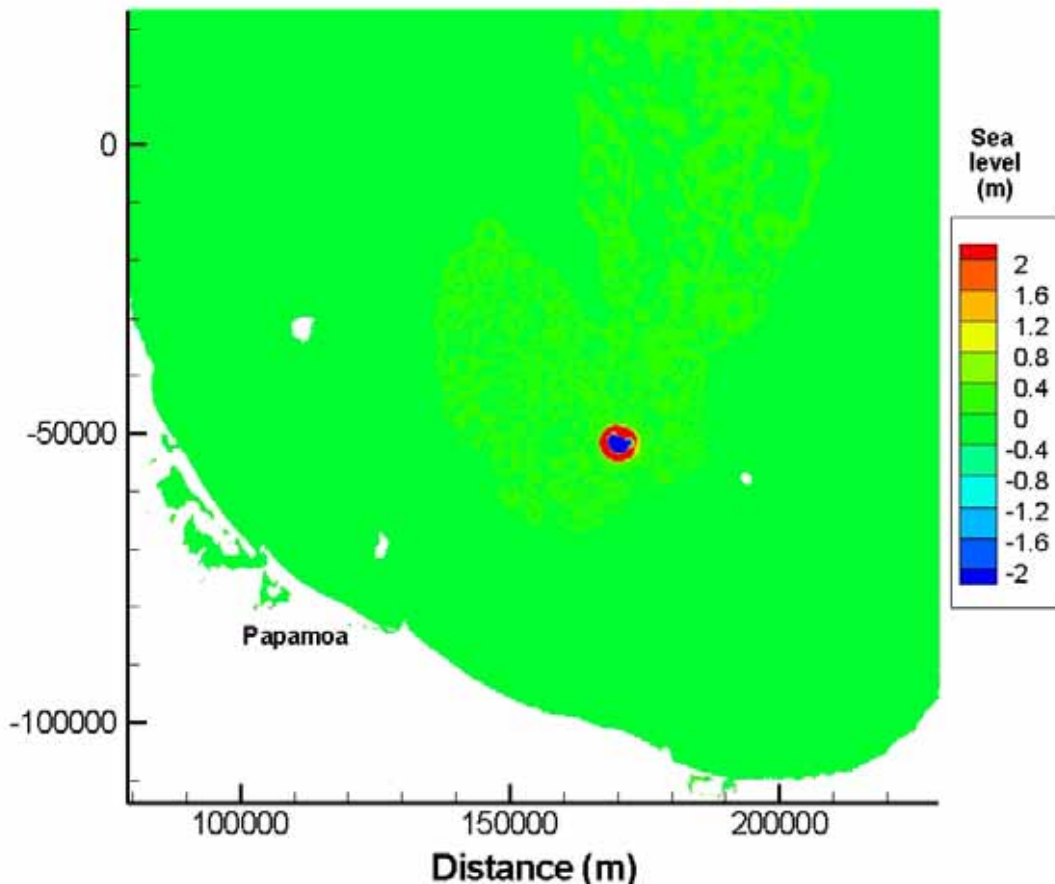


Figure 13: Tumokemoke Knoll seamount – 25 seconds after sector collapse (note change in scale).

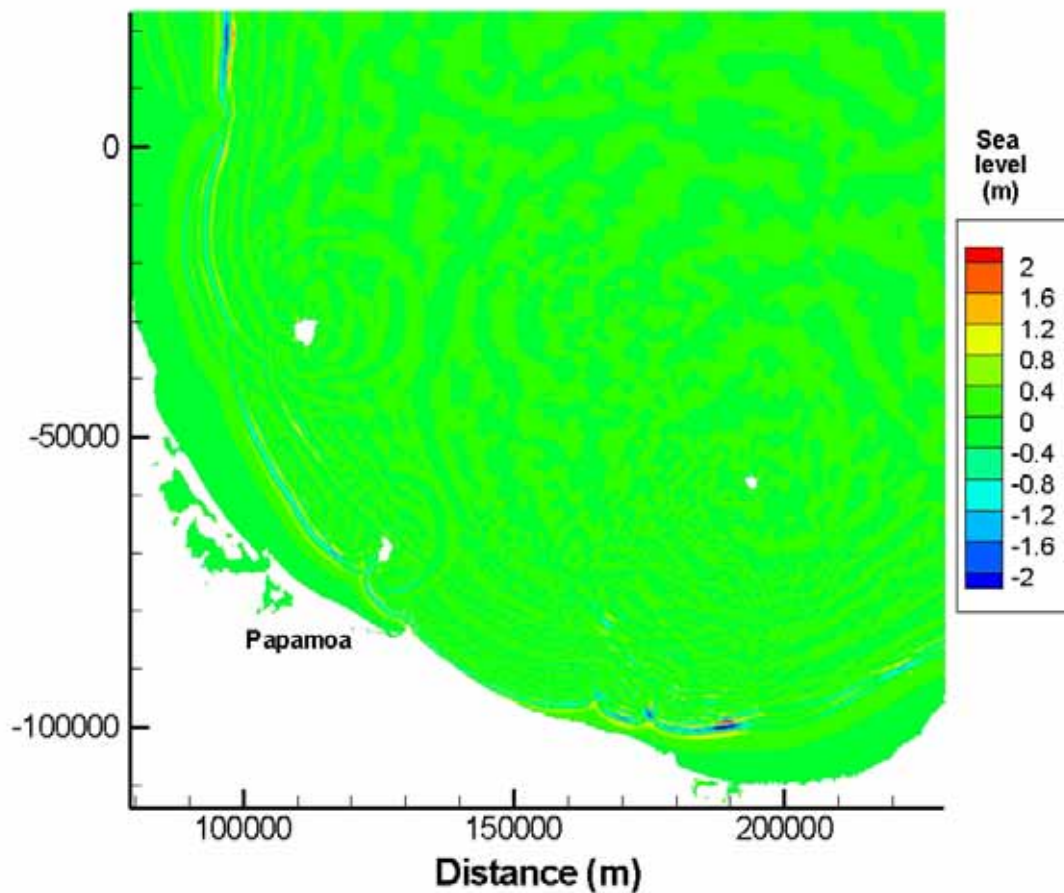


Figure 14: Tumokemoke Knoll seamount – 1500 seconds after sector collapse. Waves in the vicinity of the Te Tuma development area eventually peak at less than 1.5 m (same scale as Figure 13).

5.7. Animations

The attached CD contains five animations. A brief explanation of each animation is given below.

The end points for the local animations differ from the maximum surface water elevation figures above (Figure 3 and 5). This merely reflects a difference in the running time for the animations as opposed to that for generating the maximum surface water elevation data. Water inundating on the landward side of Wairakei/Te Tumu development area takes a long time to accumulate and has been omitted from the local animations. The start of this process can be seen at the end of the “Extreme case scenario” (ECS Loc).

Regional Animation: “Worse case scenario” (WCS Reg): This shows the propagation of the tsunami into the Bay of Plenty. Section of higher amplitude waves are just visible along the Bay of Plenty shoreline. Motiti Island focuses tsunami waves on to the coastline just north-west of the study area. This wave refraction stretches the wave (slightly reducing the height) across the Wairakei/Te Tumu development area coastline. Large scale disturbances in the Bay continue for some considerable time after the first wave strikes the coast, but the scale of the animation is such that the nearshore effects are barely visible.

Intermediate Animation: “Worse case scenario” (WCS Int): This shows the coastline between Kairua and Maketu. The tsunami approaches from the north-east, arriving first at Maketu before striking the coast around Wairakei just to the north-west of the Wairakei/Te Tumu development area. Wave height around Wairakei has been enhanced by waves focussing around Motiti Island just off the frame to the north. A wave propagates SW along the study area’s coastline and combines with a following wave to inundate the Kaituna River and Maketu Estuary. Water runs up the Kaituna River inundating the south-east section of the study area.

Local Animation: “Worse case scenario” (WCS Loc): This provides a more detailed picture of tsunami inundation in and around the Wairakei/Te Tumu development area, indicating the extent of inundation on the Kaituna River side (electronic images did not include the south-east point of the study area).

Intermediate Animation: “Extreme case scenario” (ECS Int): The wave approach is similar to **WCS Int** but waves are markedly higher. Essentially the same scenario is portrayed except inland penetration is greater on both the seaward and landward sides of the study area.

Local Animation: “Extreme case scenario” (ECS Loc): A more detailed picture of the impact on the Wairakei/Te Tumu development area. Inundation and flooding is quite considerable on the landward side and could be a significant issue for evacuation.

6. Conclusions

This study has investigated potential tsunami inundation associated with a credible, locally-sourced, “Worse case scenario” event for the Wairakei/Te Tumu development area to the south-east of Papamoa in the Bay of Plenty. For this area, the most likely potential tsunamigenic sources were identified, which included:

- Subduction zone earthquakes along the Tonga-Kermadec-Hikurangi trench associated with the Pacific/Australian plate boundary.
- Regional active faults - primarily normal faults in the offshore Taupo Volcanic Zone.
- Landslide sources in the Hikurangi margin east and north of East Cape
- Offshore volcanic sources in the Bay of Plenty include Tuhua/Mayor Island and Whakaari/White Island.
- Local landslides including sector collapse of seamounts

The numerical modelling carried out for this study identified that:

- A large subduction zone event on the Tonga-Keramdec Trench represents the most credible ‘Worse case scenario’ for tsunami inundation of the Wairakei/Te Tumu development area, generating waves with a runup of up to 4.2 m along the seaward coast of the study area. The fault rupture directs a tsunami wave train onshore, with the main part travelling westward towards Tauranga and the Coromandel coast. Immediately offshore from the Wairakei/Te Tumu development area the wave crest is stretched by refraction in the bay. Waves converge around Motiti Island amplifying the tsunami immediately to the north-west around Papamoia. Tsunami inundation of the study area is concentrated around the landward (Kaituna River) side which is not protected by large dunes.
- Comparison between this ‘‘Worse case scenario’’ and geological data indicates that tsunami inundation of the area some 500-600 years ago exceeded that produced by the model. An ‘‘Extreme case scenario’’ (explained in the text) more closely approximated existing geological data. In the light of this correlation, the resulting tsunami inundation could be considered as an alternative ‘‘Worse case scenario’’ but we have insufficient data at this time to realistically model the generating mechanisms discussed. Inundation associated with this event is more extensive, again primarily on the landward side of the study area, but with some minor breaching of the high seaward dunes.
- The importance of the coastal dunes cannot be overstated. In the absence of such a natural barrier, or if dune height were reduced, tsunami runup would be

extreme and widespread inundation and damage would occur. Some indication of what could happen as a result of coastal dune breaching in the study area can be gleaned from observations of areas to the north-west (a detailed analysis of the region's coastline outside the Wairakei/Te Tumu development area was not undertaken as part of this work).

- Results show that other potential tsunami sources such as regional active faults, offshore volcanic sources, and local sector collapse of seamounts do not generate a large enough tsunami to inundate the Wairakei/Te Tumu development area.

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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 Bay of Plenty/Coromandel 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:

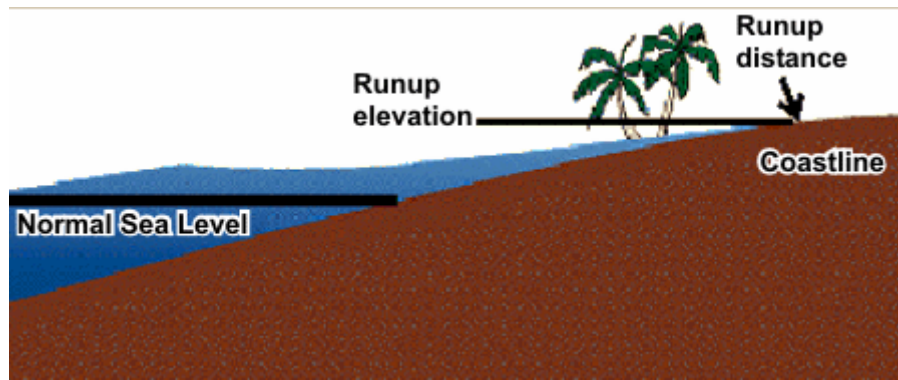
- local source/local impact event (within say 30 to 60 minutes travel time and affecting several 10's of km of coast);
- regional source/regional impact event (within 3 hours travel time and likely to affect most of the Bay of Plenty and eastern Coromandel);
- distant (remote) source/national impact 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>



Appendix I, Figure 1: Yala, Sri Lanka, 26 December 2004 - An example of the trade-off between variable dune heights and runup. 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



Appendix I, Figure 2: 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 tsunami 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.