# TSUNAMIGENIC SOURCES IN THE BAY OF PLENTY, NEW ZEALAND

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## ABSTRACT

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 prehistoric information indicates that large tsunamis have inundated the coastline several times in the past. A part of our work has been directed toward using historic and prehistoric tsunami data to evaluate possible sources. Several types of dislocation models and submarine landslide models are used to simulate the displacement of the sources. A finite element numerical model is used to simulate generation, propagation and runup of the resultant tsunami. As an example, we present results for the Bay of Plenty, northeast coast of the North Island, New Zealand. The range of source types includes local faults, subduction zone rupture, volcanic eruptions, sector collapse of seamounts, and submarine landslides. A likely major source is a subduction zone event along the Tonga-Kermadec Trench. Data from paleotsunami deposits have guided the model in determining appropriate source characteristics and establishing the most significant event for this region.

## Introduction

In a geophysical sense, New Zealand sits in a precarious position astride the boundary between the Pacific and Australian Plates (Figure 1). To the north in the Tonga-Kermadec-Hikurangi trench, the Pacific Plate is subducting from the east at a rate of ~40 mm/yr. To the south in the Puysegur trench, the Australian Plate is being subducted from the west with a convergence rate of ~35 mm/yr. Hence, there are a wide range of potential tsunamigenic sources including upper plate and subduction zone fault movements, submarine landslides on the oversteepened continental shelf slope, volcanic activity in the volcanic arc stretching northeast from the North Island, sector collapse of seamounts, and other mechanisms.

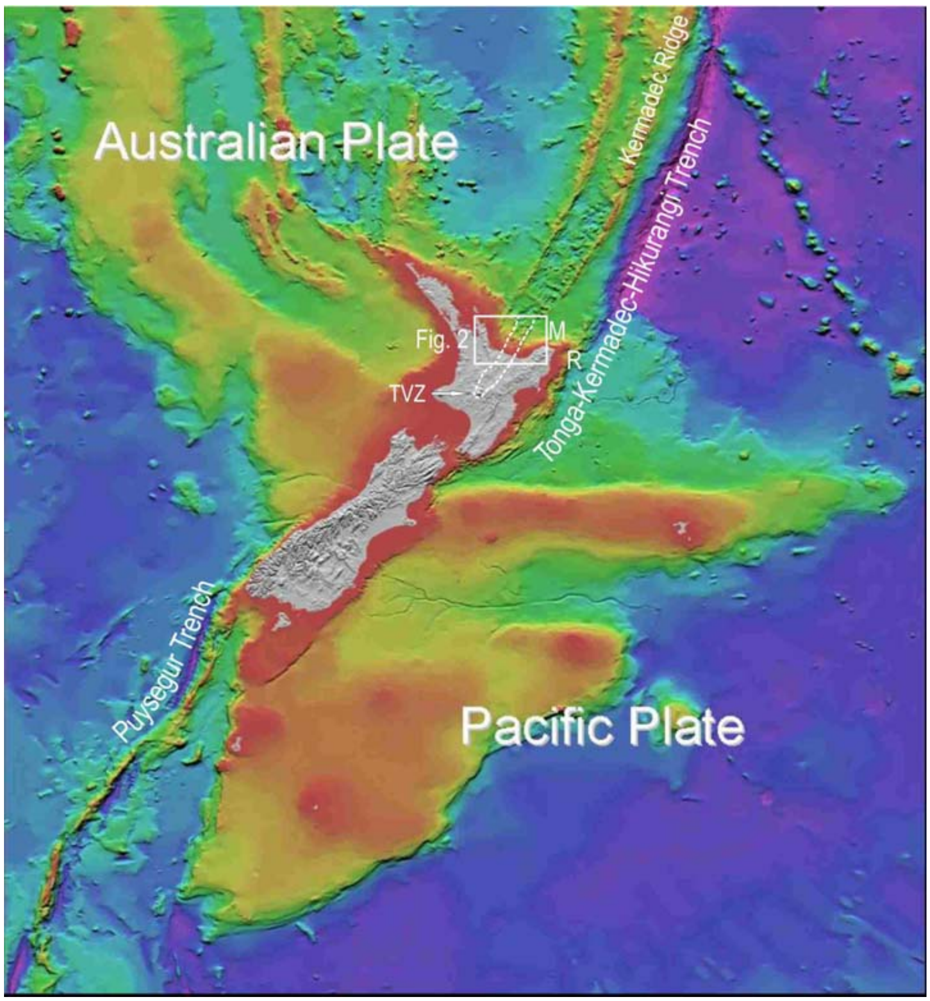


**Figure 1: Geophysical setting for New Zealand. Note the plate convergence that crosses from east to west in central New Zealand. The white box indicates the study area of this paper. , (TVZ = Taupo Volcanic Zone; R = Ruatoria landslide; M = Matakaoa landslide)**

As a result, it is not surprising that tsunamis have occurred relatively frequently along the coast of New Zealand in historic and prehistoric times (de Lange and Fraser 1999; Goff et al., 2001a). The record of prehistoric events has grown markedly over the past decade to include sites on the main and several offshore islands (e.g. McFadgen and Goff, in press; 2005; Goff et al., 2004; Bell et al., 2004; Nichol et al., 2004; Chagué-Goff and Goff, 2003). These geological data are useful for developing estimates of tsunami magnitude and frequency. They are also useful however as data points to compare with, and complement, hydrodynamic models (Walters and Goff, 2003).

In the end, tsunami runup effects depend on the initial or incident wave amplitude and direction, the wave period (or more generally the spectral content of the wave), and how the wave interacts with the ocean and shoreline topography. Where a harbor or coastal bay resonates with a similar period as the incident wave, large amplification of incident waves can be expected. In addition, offshore islands can cause a convergence of the waves and result in large amplitude waves on the adjacent coastal margin. In theory, hydrodynamic models should be able to provide realistic approximations of tsunami runup along the whole coastline. In the absence of groundtruthing it is difficult to know how close these approximations are to reality.

The objective of the work presented here is to evaluate potential tsunamigenic sources in the Bay of Plenty and determine the most significant source by comparing and contrasting independently obtained model and paleotsunami data. The potential sources are identified through existing geophysical data. Fault ruptures were simulated with elastic dislocation models (Okada, 1985; Wang et al, 2003), and sector collapse of seamounts and submarine landslides were simulated with a dynamic landslide model (Walters et al, 2006b). A high-resolution hydrodynamic model was used to simulate the effects of the resultant tsunami (Walters, 2005; Walters et al, 2006a). Finally, the results of paleotsunami studies were compared with model predictions to determine the most significant sources.

## Potential Sources

The Bay of Plenty faces a diverse range of potential tsunamigenic sources either within the Bay of Plenty (Figure 2), along the plate boundaries (Figure 1), 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, mapping underwater volcanism and sector collapse, and mapping underwater landslides. These sources were summarized in Bell et al. (2004).

Return period is defined here 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.

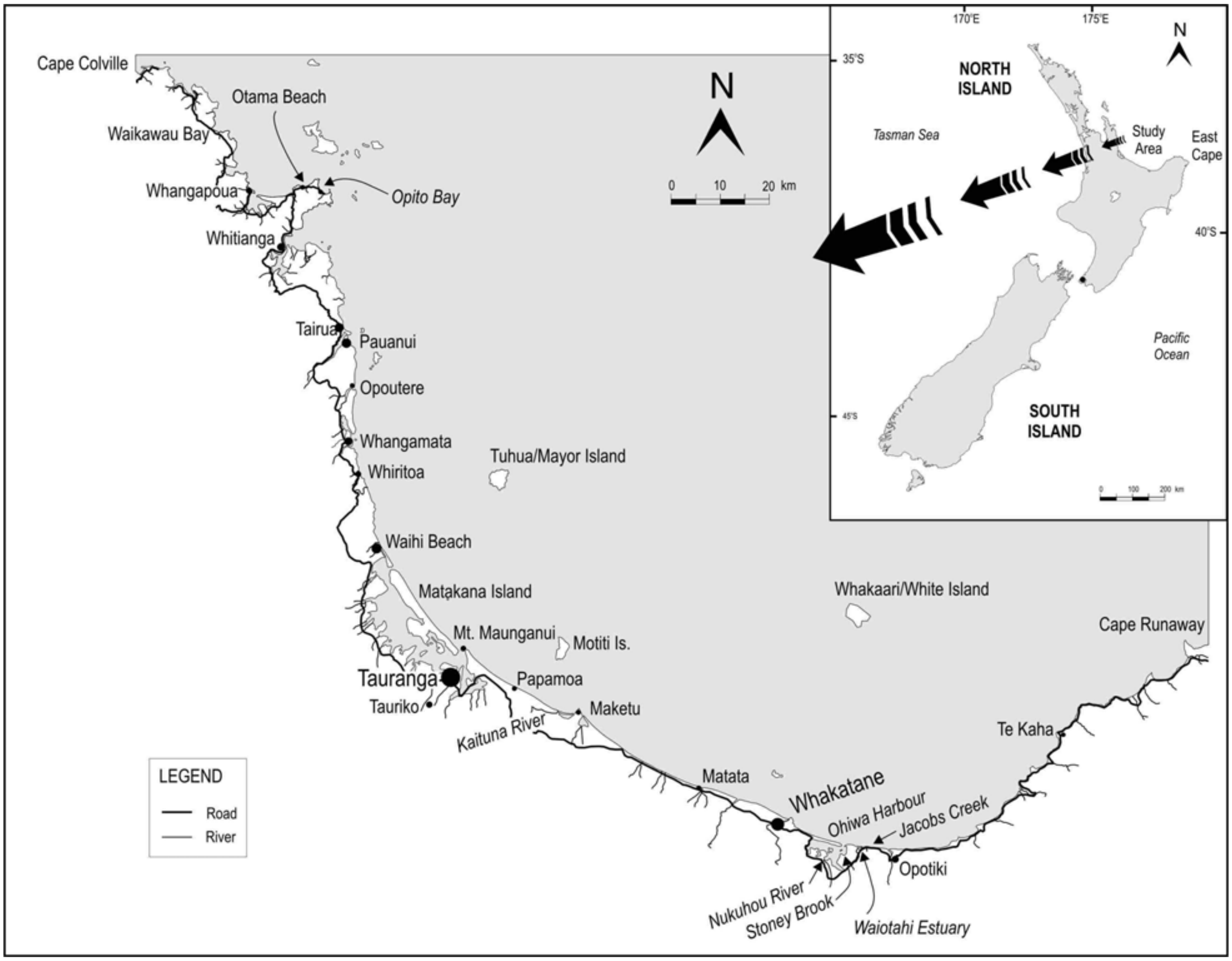


**Figure 2: The Bay of Plenty – showing location of mainland paleotsunami sites and locations mentioned in the text**

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

1. Subduction zone earthquakes along the Tonga-Kermadec-Hikurangi trench associated with the Pacific/Australian plate boundary (Figure 1). 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 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.

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 (Figure 1). 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 (Figure 2) (Wright, 1990; Lamarche et al., 2000). Normal faulting in this area 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 (Lamarche and Barnes, 2005).

3. Landslide sources east and north of East Cape include giant landslide complexes such as Matakaoa and Ruatoria (Figure 2). Collot et al. (2001) have shown that the Ruatoria landslide was triggered approximately 170000 years ago and had a volume of about 3000 $km^3$. The Matakaoa landslide on the other hand contained at least three large landslides and probably dates to around 50000 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. Large submarine landslides will undoubtedly produce large tsunamis, but these are highly complex events and much of the required data for modeling purposes are not available. Furthermore, with return periods in the 10's-100's of thousands of years, these events occur on a longer timeframe than the 500 to 1000 years considered here. However, smaller landslides are possible within the Matakaoa complex and in the submarine canyons of Bay of Plenty.

4. Offshore volcanic sources in the Bay of Plenty include Tuhua/Mayor Island and Whakaari/White Island. For Tuhua/Mayor Island, modeling studies indicate that the credible pyroclastic eruptions of a "Mt St Helens" scale (1 $km^3$) could produce a tsunami that would impact an area from Tairua to Maketu (Figure 2), 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 $km^3$) would create waves that 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 pyroclastic flows into the sea. However, an examination of the detailed bathymetry (Figure 2) does not reveal any areas where large pyroclastic flows (>1 $km^3$) have occurred. 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). As a result, volcanic sources do not seem to have a significant impact.

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 (Figure 3). 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. Instead, a complete collapse of a seamount was modeled as an extreme case in order to gauge the relative size of a tsunami that could be generated. These could be a source of large amplitude waves because of the short distance to shore.

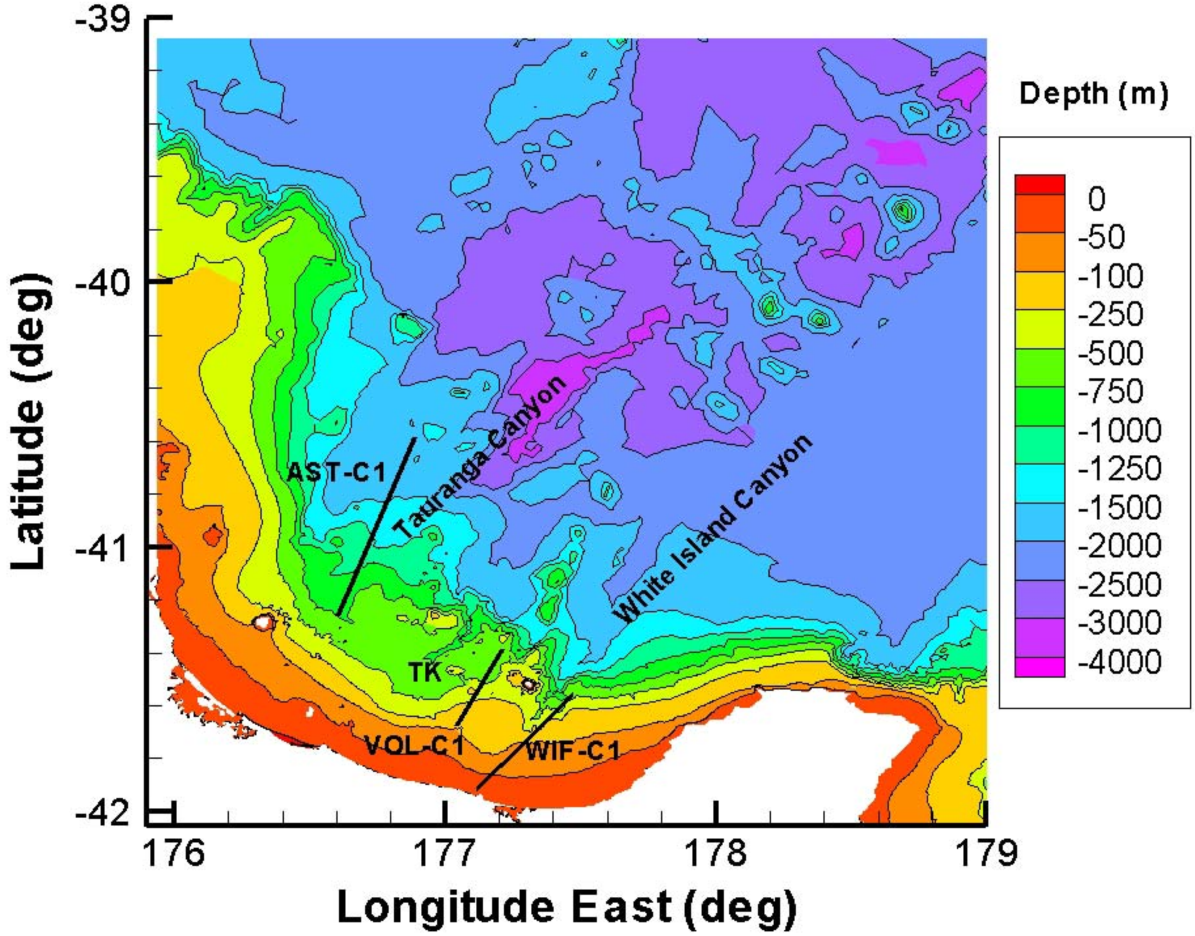


**Figure 3: High resolution bathymetry of the Bay of Plenty. AST-C1 = Composite Astrolabe fault, VOL-C1 = Composite Volkner fault, WIF-C1 = Composite White Island fault, TK=Tumokemoke Knoll.**

Of the remaining sources:

1. Upper plate faults along the Tonga-Kermadec-Hikurangi 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.

2. Undersea volcanic sources in the Tonga-Kermadec-Hikurangi 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.

3. Pressure waves or pyroclastic flows from large onshore volcanic eruptions in the Taupo Volcanic Zone were not considered.

4. The primary source for a remote tsunami is South America. The historic record indicates that these events are unlikely to generate tsunamis of comparable size to local and regional events (de Lange and Fraser, 1999), so they too are not considered here.

## Paleotsunami Data

A definitive identification of a paleotsunami deposit hinges on the use of as many data sources as possible. In most cases this relies largely on the recognition of as many paleoenvironmental characteristics as possible, including geological, archeological, and geomorphological parameters (c.f. McFadgen and Goff, in press; Goff et al., 2004; Witter et al., 2001). It is also useful to be able to identify a probable tsunami source. This task is made easier for areas with one coastline and a major offshore seismic source (e.g. west coast of North America, Chile), but is less clear cut for countries such as New Zealand with potential tsunami sources and coastline at all points of the compass. It is worth noting though that sufficient data now exist in New Zealand to allow tsunami sources to be estimated from palaeotsunami records.

Even a standard conception that a paleotsunami deposit represents ‘a deposit out of place’ (e.g. a sand layer sandwiched between peat) must be treated with caution since this visible identification is dependent upon the nature of both the material available for entrainment and the depositional environment. Therefore, perhaps counter-intuitively, a mud layer in sand can represent a paleotsunami (or paleostorm) deposit (Goff and Chagué-Goff, 1999).

The absence of some paleoenvironmental characteristics does not negate a paleotsunami interpretation, but rather it can be indicative of the particular context. For example, the absence of buried soil or vascular plants might mean that either the underlying material was devoid of vegetation, or that the nature of inundation removed the material prior to deposition of a ‘clean’ sediment. Hence it is useful to understand paleoenvironmental conditions at the time of deposition. In general terms, if the study site was relatively exposed to the sea it is possible that the last inundation removed evidence of earlier events and also has a limited number of potential paleoenvironmental characteristics. A more sheltered, low energy coastal wetland would be more likely to preserve evidence of multiple inundations and have more paleoenvironmental characteristics (e.g. Goff et al., 2001b).

The New Zealand paleotsunami database currently consists of over 200 sites (J. Goff, unpublished data). The database contains a range of information including archeological, geological, and geomorphological material. Each site contains details of location, age, elevation, distance inland, forms of evidence, possible/probable tsunami source, relevant references, general comments concerning the evidence, and an indication of the veracity of the data. It is possible to differentiate between relative event magnitudes in the broad categories of <5.0 m (small), '>5.0-10.0 m (large)' and '>10.0 m (extreme)'. The latter category should be considered a catch-all for events greater than 10.0 m. In New Zealand the record of these extreme events ranges in height up to possibly 60.0 m. above mean sea level (Goff, 2003), although this should not be considered a maximum. The New Zealand record is far from complete and will continue to grow as more sites are studied and new analytical techniques are developed. Following a recent study of the Bay of Plenty area however (Bell et al., 2004), there is sufficient information available to undertake a comparison between independently obtained model results and geological data.

Paleotsunami deposits reported from the Bay of Plenty range in age from 9500 years BP to 1600-1700 AD. At least two of these events have had a significant region-wide impact, the most recent occurring in the 15$^{th}$ century (Bell et al., 2004). Data from the 15$^{th}$ century event are extensive, and include evidence collected from all mainland sites shown in Figure 2. These data were used to map estimated wave crest height around the Bay of Plenty. Estimated wave heights are based upon the maximum elevation of the deposit above sea level, estimated distance inland from paleoshoreline, and the wave height required for transport of the coarsest material (after Jaffe and Gelfenbaum, 2002).

# Models

### Tsunami 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 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 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 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 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).

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. The coastline and contour data were combined to form a depth reference grid.

The model grid was generated using methods described in Henry and Walters (1993). 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. Depth values are interpolated at each node from the reference dataset described above. The resulting model grid contains 365787 nodes and 722852 elements for the subduction zone events, and local, more refined grid for the remaining sources.

### Fault Dislocation models

There were two dislocation models used in this study. The first is an analytical solution for a rectangular dislocation in an elastic media (Okada, 1985). The width, depth, strike, dip, and displacement are all considered constant. This type of model is more appropriate for the local normal faults in the Bay of Plenty where these parameters have been tabulated in Lamarche and Barnes (2005).

The second model is a more general numerical model developed by integrating Okada's (1985) point-source dislocation solution (Wang et al, 2003). This model is more appropriate for the curved dislocation surface and variable slip in a subduction zone fault.

### Landslide Model

Laboratory experiments (Fleming et al, 2005) and models studies (Walters et al, 2006) have guided the creation of a series of dynamic landslide models. The models range from solid sliders, to viscous fluids, and to mixtures. For this study, the viscous fluid approximation was used where the landslide has internal Newtonian stresses and basal sliding with friction (Walters et al, 2006).

## Results and Discussion

It is important to recall that the coastal effect of a tsunami depends on both the source characteristics and the coastal response characteristics. For remote tsunamis, maximum amplitudes and spectral content of the waves can be determined from historic data. This information combined with admittance information derived from the response patterns leads to reasonable estimation of effects (Walters and Goff, 2003). For local tsunamis, the situation is very different. In particular, the source characteristics are generally not well defined along the New Zealand coast.

**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 (Figure 1). 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 (Figure 2). 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.

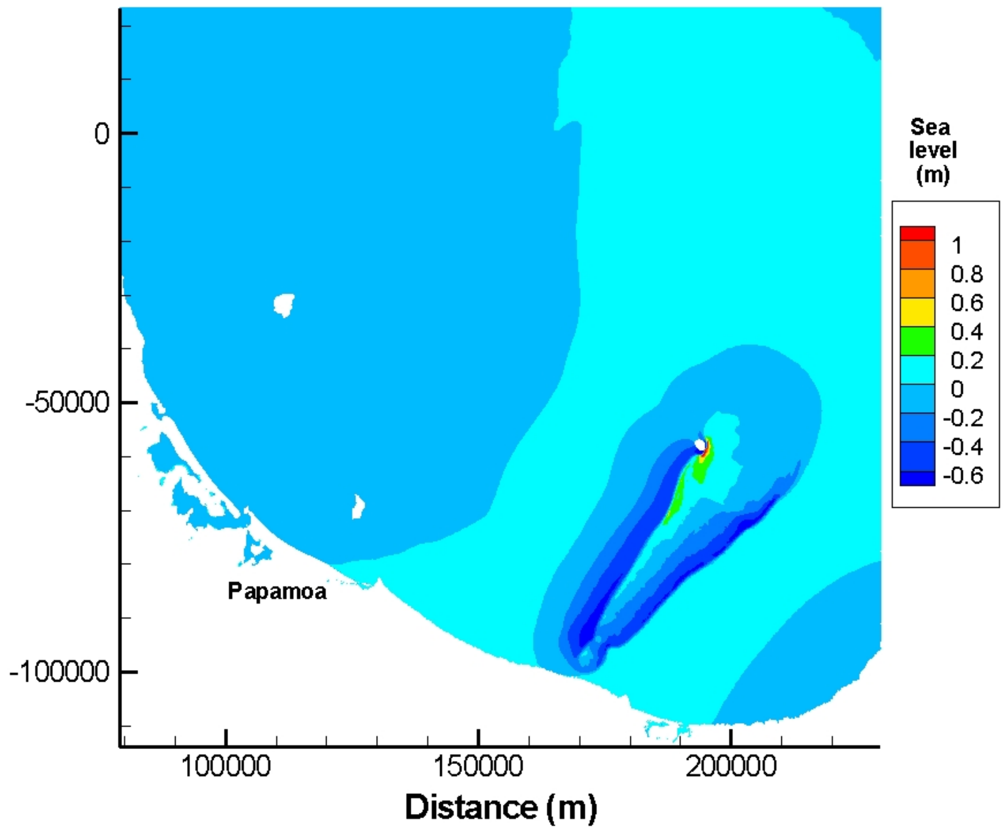


**Figure 4: Composite White Island faults – 140 seconds after maximum single event displacement (note westward moving wave has just struck east coast of White Island).**

Three representative faults were chosen based on their potential for producing relatively large wave heights (Figure 3). These included a composite of the White Island faults (WIF-C1), the composite Volkner faults (VOL-C1), and the composite Astrolabe faults (AST-C1). All the necessary parameters for an elastic dislocation model are provided in the report by Lamarche and

Barnes (2005). The rectangular-fault 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.

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 tsunamis with a negative leading wave, the positive peak is amplified and the runup in local areas can be up to 2 m. The illustrations in Figures 4 and 5 show snapshots in time near the start and end of the tsunami sequence for the White Island Fault composite fault (WIF-C1).

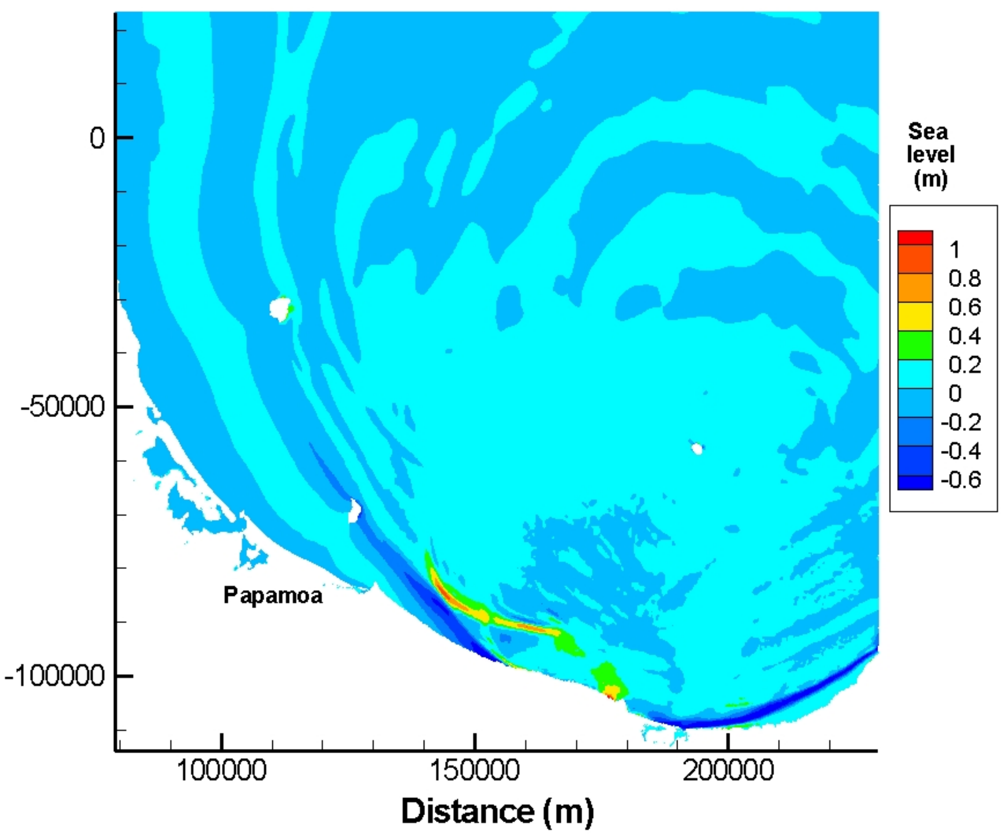


**Figure 5: Composite White Island fault – 1500 seconds after maximum single event displacement. Note the westward traveling wave with a leading trough has the largest positive wave crest height.**

**Seamount collapse**

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 collapses, and the direction and depth of the collapse.

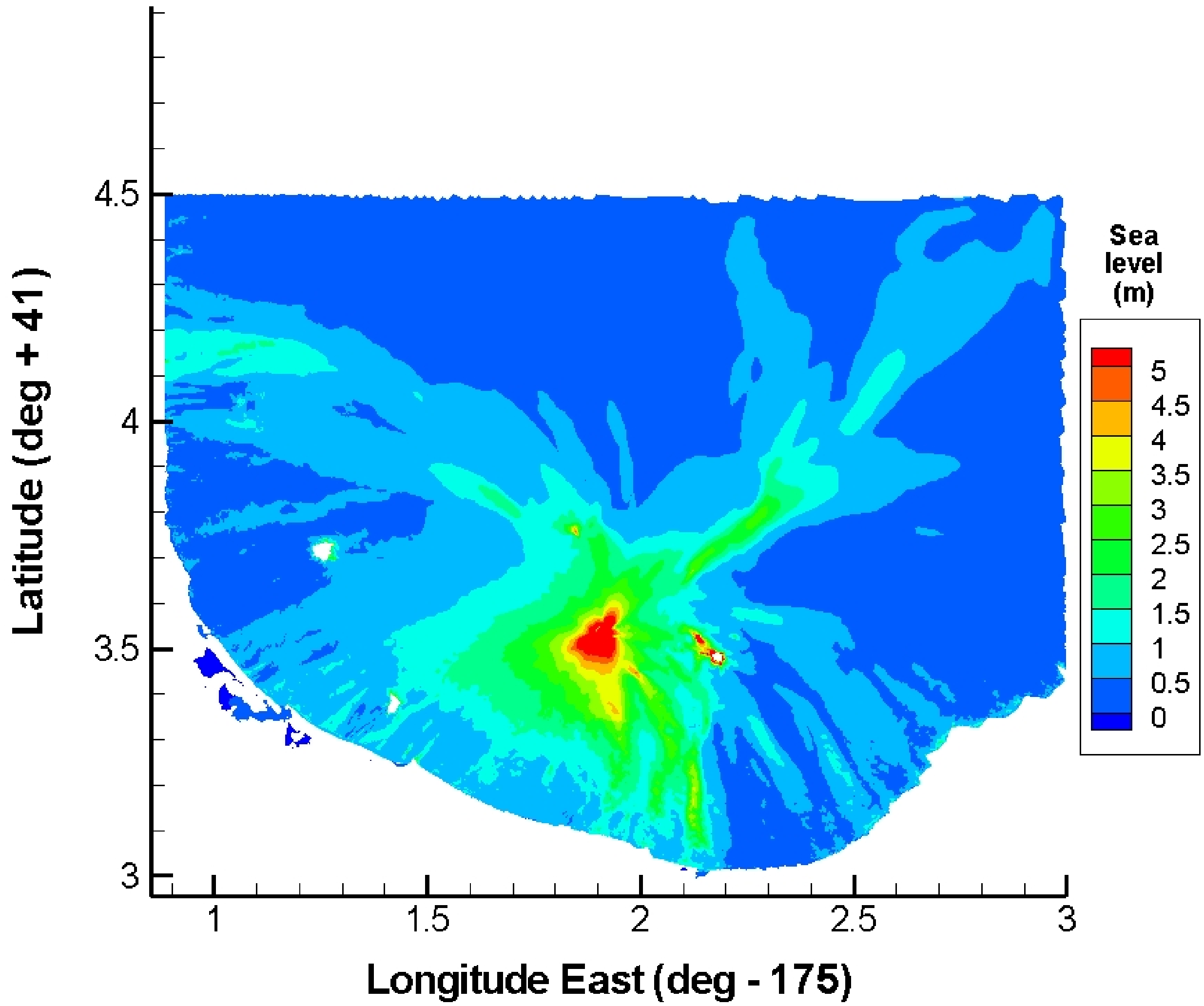


**Figure 6: Maximum water surface elevation for a collapse of Tumokemoke Knoll seamount. Waves peak at less than 1.5 m along the coastline (note change in scale).**

As an example, an entire collapse of the nearest large seamount, Tumokemoke Knoll was simulated as a material failure and subsequent landslide (Figure 3). 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 $km^3$. This can be compared with the 10 $km^3$ of material from volcanic sources that is required to generate a 5 m tsunami (de Lange and Praysetya, 1999).

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 nearest shore (Figure 6).

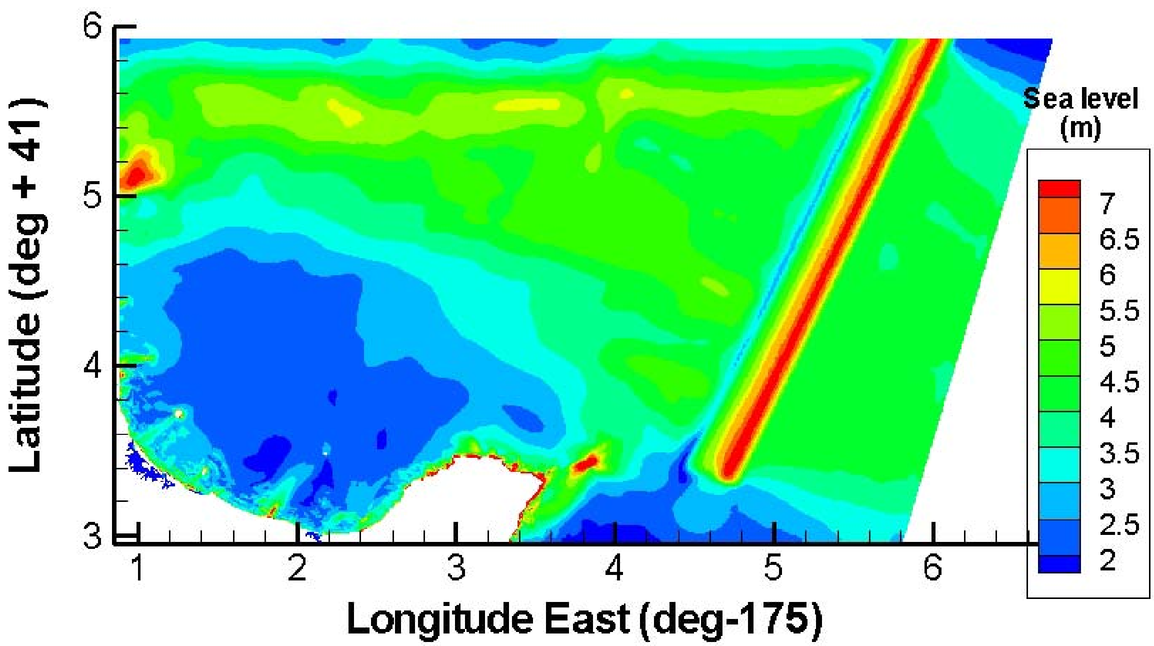


**Figure 7: Maximum water surface elevations during a simulation of a subduction zone event. The reduced elevation on the north boundary is an artifact of the radiation boundary condition.**

**Subduction zone events**

Most of the Bay of Plenty is directly exposed to tsunamis generated by subduction zone earthquakes immediately north of East Cape (the Kermadec-Hikurangi Trench). A fault-dislocation model (Wang et al, 2003) 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 near the maximum credible event for this source. On the basis of an empirical relation between maximum earthquake size, age of subducting plate, and convergence rate proposed by Ruff and Kamamori (1980), the Kermadec subduction zone would appear to be a very unlikely candidate for an event as large as Mw 8.5. Improvements to our knowledge of plate motion rate and age have put this empirical relation in question (Stein and Okal, 2006). The devastating 2004 Sumatra earthquake and tsunami event serve as a wake-up call to remind us that giant earthquakes do occur in what are considered the most unlikely places for them. In fact, events with Mw 8.0 and 8.3 occurred farther north on the Kermadec trench early in the 20th century (ITDB/PAC 2004).

For the most likely maximum credible event, an $M_w$ 8.5 fault rupture was modeled to strike the coast at Mean Sea Level (MSL) (Figure 7). 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. The main part of the wave travels westward to the area around Tauranga and to the north. In the south part of the Bay of Plenty, the wave crest is stretched by refraction in the bay. Waves converge around Motiti Island and other islands, amplifying the tsunami on the adjacent coast (Figure 8).

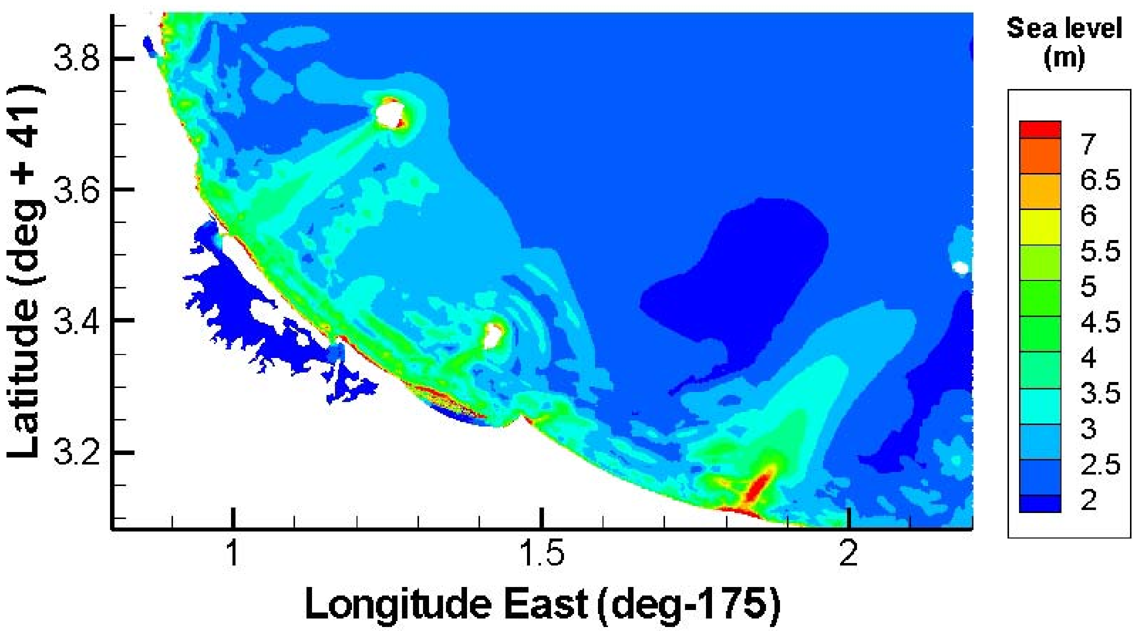


**Figure 8: Maximum water surface elevation showing wave focusing behind Motiki Island.**

The general pattern of tsunami crest height showed low values in the south part of the Bay of Plenty (1 to 3 m) and increasing height toward the north (5 to 8 m). There were local maxima in areas behind offshore islands. One local maximum had a height of 6 m onshore from Motiti Island, arriving 70 minutes or so after fault rupture. Waves breached the coastal sand dunes at this location.

A comparison between elevations derived from the paleotsunami data and the model results is shown in Figure 9. The model contains detailed topography around one of the data sites near Papamoa. Modeling tests indicated that an Mw 8.5 to 8.7 event would overtop the coastal sand dunes and inundate the site. As these are credible-sized events for this area, these results were used for comparison with the elevations derived from the data. Note that these results are preliminary in that other factors such as state of the tide and changes to the coastal dune system over the last 500 years has not yet been taken into account.

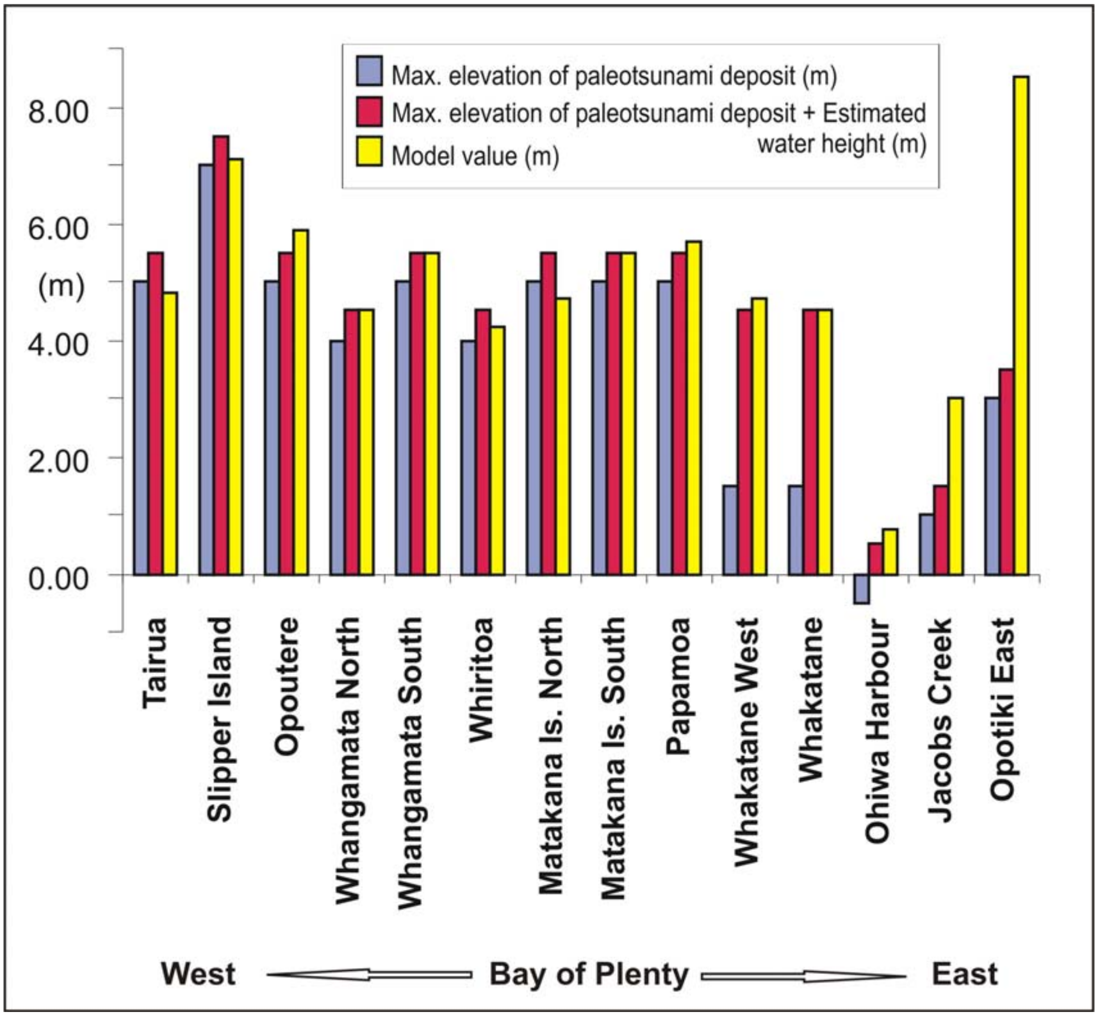


**Figure 9:** **Summary diagram of comparison between model values (maximum water surface elevation at the shoreline) and palaeotsunami-related data.**

There is a striking similarity in the spatial pattern in wave height between the paleotsunami data and the model results. As this pattern is sensitive to the incident amplitude and direction of the tsunami, it provides compelling evidence this data reflects the effects of a large subduction zone event extending north of East Cape. This pattern cannot be reproduced by other combinations of sources in this area, and the wave crest heights are much too large for a remote tsunami.

The largest discrepancy between the data and the model elevations occurs in southern Bay of Plenty near Opotiki. This is an area where there is no coastal topography in the model and the shoreline is rather coarsely resolved. Even so, at Jacobs Creek there is a 2.5 m coastal barrier seaward of the site, hence the wave must overtop this barrier although the data site is at a lower elevation inland. At Opotiki East, the data site is in the lee of a large headland that would have considerably reduced wave height. Adding topographic detail would probably remove these discrepancies.

## Conclusions

This paper presents an evaluation of potential tsunami sources for the Bay of Plenty. These sources include a subduction zone event, local fault ruptures, volcanic sources, seamount collapse, and local submarine landslides. Most of these events can produce tsunamis with crest heights of 1 to 2 m at the shoreline.

However, the most significant source is a subduction zone event along the Kermadec Ridge east of the Bay of Plenty. The pattern of wave height at the shoreline varies from 1 to 8 m and is in good agreement with wave height derived from independently gathered paleotsunami data. This suggests that subduction zone events are the most significant tsunamigenic source over timescales of 500 to 1000's of years.

Local faults described by Lamarche and Barnes (2005) can be locally important and can have a moderate wave crest height of 1 to 2 m.

Volcanic sources and pyroclastic flows are not generally of significance for emplaced volumes less than 1 $km^3$. Larger volumes seem to have a very low probability.

The seabed mapping shows many cases of sector collapse of seamounts. Model experiments with the collapse of Tumokemoke Knoll (1.2 $km^3$) showed that the tsunami decayed rapidly with distance away from the source. The maximum wave crest height at the shoreline was approximately 1.5 m although this was the seamount closest to shore. Hence, sector collapse is not very effective in generating significant tsunamis in the Bay of Plenty.

Submarine landslide volumes within the Bay of Plenty 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 was not considered significant. However, very large landslides (3000 $km^3$) have occurred on the continental shelf but the recurrence intervals were too long for these events to be considered here.

## Acknowledgments

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