Auckland Regional Council
TE RAUHITANGA TAIAO

Tsunami Overview Study

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GeoEnvironmental Consultants

TSUNAMI OVERVIEW STUDY

Prepared for

Auckland Regional Council

Tsunami Overview Study

GeoEnvironmental Consultants

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EXECUTIVE SUMMARY

Auckland Regional Council (ARC) requested a study to assess the risk that tsunami hazards pose to the Auckland Region, and to update elements of the 1994 report prepared by de Lange and Hull. The report is summarised below:

Potential tsunami sources for the Auckland region

Distant sources:

- Chilean sources (have been long recognised as the most common source for distant events.
- Little is known about Pacific Northwest and Alaskan events, although they are still not believed to be a source of large tsunami for the region.
- Recent work, discussed in this report, points to the need to consider closer northern sources, perhaps the Fiji Basin and Solomon Sea.

Local sources:

- Subduction and upper plate earthquakes and submarine landslides associated with the Tonga-Kermadec Trench-Hikurangi Trough system.
- Recently active faults in the Firth of Thames, along eastern Coromandel, offshore Taupo Volcanic Zone and eastern Bay of Plenty.
- Submarine volcanism in the Tonga-Kermadec system and in offshore Bay of Plenty.
- Fault, volcanic and mass movement sources in the Auckland region.
- Local sources within the Hauraki Gulf, however, do not appear to generate significant tsunamis. In this instance it is more likely that the hazard of the generating event will be of greater concern to the council.

Historic and Prehistoric tsunamis

- The historic tsunami database has seen some additional detail added in recent years, but the addition of significant past events is unlikely.
- Important advances have been made with the recognition of prehistoric tsunamis for which several primary (studied) and secondary (not studied for tsunami origin) sites have been identified. The present record may record evidence for as many as two local and three region-wide events that have affected the Auckland Region in the last ~2600 years. The most significant of these being in the late 14th and early 15th centuries (max. runup to 14m and <10m respectively). It is speculated that the former was possibly from a distant source to the north of New Zealand, the latter from a more local source outside the Hauraki Gulf.

Magnitude, frequency and source estimates:

- Small (<1 m): 1 in 13 years (historic events)
- Medium (1-5 m): 1 in 42 years (historic events), distant sources only
- Large (>5 m): 1 in 870 years (prehistoric events only)

These data are based on maximum wave height within the region, time periods over which these estimates are based vary. Estimates of magnitude and frequency derived from the palaeotsunami database must be considered a minimum. It is reasonable to assume that several events will remain unrecorded. Both local (outside the Hauraki Gulf) and distant sources appear to have produced large tsunamis in the Auckland Region.

NOTE: Maximum wave heights between Great Barrier Is. (GBI) and Auckland city areas show significant variation – this affects the results of one historic tsunami - 1960 - which is placed in the Medium category (based upon GBI data), as opposed to the Small category (using Auckland data). A similar situation is most likely represented in the prehistoric data, particularly for tsunami sourced from the east. Estimates for the region may therefore slightly overestimate the frequency of higher magnitude events.

General summary of wave interaction with the coast

A model is used in a general sense to evaluate the effects of a ***small*** subduction zone earthquake along the Hikurangi Trough and a remote tsunami from South America. This event produces a tsunami with a wave height of 1m at source. A "reference time" used in these results is the time at which the wave starts onto the continental shelf. This time is approximately 15 hours after a remote tsunami is generated in Chile, or the same time as the earthquake for a local subduction zone event.

The tsunami impacts the east coast of Great Barrier Island approximately 70 minutes after the "reference time". The runup height is spatially variable with a maximum of approximately 4 m (for this small event). A few minutes later the wave encounters the open mainland coast north of the Auckland Region and has a maximum local runup height of 3 to 4 m. Approximately 3 minutes later, the tsunami comes ashore at Tawharanui Peninsula with maximum local runup height of 2 to 3 m. The tsunami propagates down the coast toward Auckland with diminishing height. A large reflected wave arrives at Waiheke island at about the same time as the tsunami enters Waitemate Harbour nearly 3 hours after the earthquake. Model parameters for a large event, with runup heights at least three times higher, are within the range of geological observations from the east coast of Great Barrier Island.

Most likely damaging source for a distant and a local event

- Distant: Chile is the key distant source (3 tsunami since 1868, 2 medium, 1 small), BUT Identification of source areas (and their effects) to the north of the country also needs to be investigated.
- Local: Preliminary modelling suggests that a subduction earthquake along the Tonga-Kermadec Trench-Hikurangi Trough system could be the most damaging source. A tsunami generated by a subduction zone rupture could have an amplitude around Auckland of about 3 metres and a wavelength of 30 to 100 km. There have probably been at least 2 in the last 2600 years.

Assess uncertainties in the available information and identify gaps in current knowledge:

- There is an incomplete source record. Source characteristics, implications for subsequent wave propagation, and tsunami inundation in the Auckland region are poorly understood.
- Significant amounts of palaeotsunami data have been collected. This database will never be complete, but the record of larger, prehistoric tsunamis needs to be interrogated in greater detail in order to improve and complement mathematical modelling of potential source areas.

Recommendations:

- Characterisation of offshore fault and landslide/volcano sources, including fault dislocation modelling for local (outside the Hauraki Gulf) and distant sources (Chile and to the north), and estimation of frequency/magnitude relationships.
- Wave propagation modelling to evaluate the potential tsunami hazard of the sources identified above.
- Local runup and inundation need to be evaluated in the Auckland region using numerical models with more detailed source data.
- To support co-ordinated geological and geoarchaeological investigations of secondary verification sites within the Auckland region, and to extend the palaeotsunami tsunami record back in time.
- An evaluation of the resource consenting process. A requirement for developers to undertake and report upon a robust scientific survey for physical evidence of past historic and prehistoric coastal hazards (e.g. tsunamis, storm surge) is recommended.
- Develop a more detailed record of recurrence intervals for South American tsunamis based upon their longer historic record.

An integrated programme using most recommendations listed above could be:

Distant tsunami:

- Characterisation of subduction earthquake sources in South America and to the north of New Zealand.
- Wave propagation modelling to evaluate the potential tsunami hazard of the sources identified.
- Produce local runup and inundation measurements for Auckland region using numerical models based upon the most likely damaging sources.
- Investigation of geological and geoarchaeological sites on the west and east coast of the Auckland region.
- Iteration between local runup and inundation model and geological data to improve resolution of model.
- Produce inundation maps/mitigation procedures based upon iterated data and field survey of coastline.

Local tsunami:

- Follow similar procedures for subduction earthquakes (and volcanoes) from most likely damaging sources outside the Hauraki Gulf.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

Auckland Regional Council (ARC) has requested a study to assess the risk that tsunami hazards pose to the Auckland Region, and to update elements of the 1994 report prepared by de Lange and Hull. The objectives, as we see them, are to:

- Identify and assess potential local and distant tsunami sources (inc. fault, volcano, landslide, etc.).
- Provide information on prehistoric and historic tsunamis in and around the Auckland Region of relevance to the study – giving pertinent source information (with an indication of the veracity of the data).
- Develop magnitude, frequency and source estimates.
- Provide a generic summary of resonance.
- Identify the most likely damaging source for a distant and a local event.
- Assess the uncertainties in the available information and identify gaps in the current knowledge.

This report represents the output prepared in response to the required objectives listed above. It includes relevant data from within and outside the Auckland Region.

1.1. Caveat

This report is written on the basis of the contemporary scientific knowledge about tsunamis. Every attempt has been made to provide as comprehensive an interpretation of available data as possible, although there is always the possibility that some data have been missed. In many instances much of the interpretation is based upon professional intellectual property and as such this type of information cannot be referenced. Studies of tsunamis indicate that the effects along a coastline are extremely variable. Therefore, where necessary, a general approach has been adopted acknowledging that, for example, while runup height is controlled by many variables, a general runup is chosen based upon known site-specific conditions.

2. IDENTIFY AND ASSESS POTENTIAL LOCAL AND DISTANT TSUNAMI SOURCES

This section focuses mainly on local sources because there is considerable new information since the 1994 report.

2.1 Potential distant tsunami sources for the Auckland region

For distant sources we draw mainly on evidence from the historic and prehistoric tsunami record (Table 1, Appendix I). Chilean sources (the 1868 tsunami source is now in N. Chile) have been long recognised in the historic record as the most common source for distant events. Little is known about Pacific Northwest and Alaskan events, although they are still not believed to be a source of large tsunami for the region. Recent work, discussed in Section 3.3. this report, however, points to the need to consider closer northern sources, perhaps the Fiji Basin and Solomon Sea.

2.2 Geological Setting

The east coast of the North Island is characterised by high seismic activity and land instability, both offshore and onshore (Figure 1). For example, large-scale avalanches of sea-floor sediments have been discovered recently along the sections of the Tonga-Kermadec Trench-Hikurangi Trough (e.g., Collot et al., 2001; Lamarche et al., 2004).

Active volcanism and faulting is also associated with subduction along the Tonga-Kermadec Trench and includes a 40 km-wide zone of actively rifting continental crust that lies ~200 km west of the plate boundary. Active volcanism in the zone extends from the Taupo Volcanic Zone in central North Island (e.g., Ruapehu, Ngaruahoe, Tongariro, Edgecumbe), offshore to Tonga and Fiji in the north (Figure 1). The offshore zone also comprises White and Mayor Islands and a number of active submarine volcanic cones and structures that have been discovered over the last 10-15 years (e.g., Wright, 1990, 1992; Wright and Gamble, 1999; Wright et al., 1996, 2003, 2004, in press).

Since Auckland City and the Hauraki Gulf lie ~400 km northwest of the plate boundary, they are characterised by low levels of earthquake seismicity and fault activity (de Lange and Healy, 2001; Edbrooke et al., 2003). Basement rocks in the Auckland area are Mesozoic greywackes, overlain by younger marine sediments and volcanic rocks. It is these young volcanic landforms and rocks (<140 000 years old: Wood, 1991) that dominate the Auckland landscape, with the most recent eruption sequence forming Rangitoto Island about 600 years ago (Nichol, 1992). These are clearly potential tsunami sources.

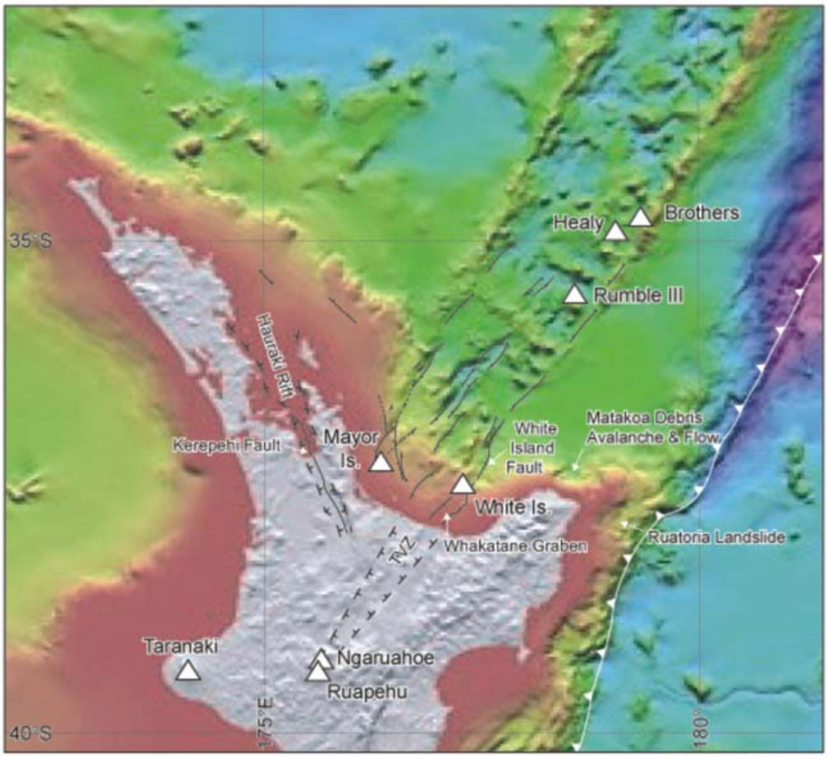

Figure 1: Locality map showing the Tonga-Kermadec Trench-Hikurangi Trough (toothed line – the Hikurangi Trough starts approx. south of the Ruatoria landslide, the Tonga-Kermedec Trench to the north), and potential local tsunamigenic sources for the Auckland region. Major volcanoes are denoted by triangles. Known active faults and those with sea-floor expression are shown by dark, thin lines with notches indicating the downthrown side of the fault. Landslides are also indicated (Matakaoa debris avalanche and flow, Ruatoria Landslide). TVZ = Taupo Volcanic Zone.

2.3 Potential local tsunami sources for the Auckland region

Sources that require further evaluation (since the 1994 report) as posing a potential hazard to Auckland City and Hauraki Gulf include:

- i) Subduction and upper plate earthquakes and submarine landslides associated with the Tonga-Kermadec Trench-Hikurangi Trough system.
- ii) Recently active faults in the Firth of Thames, along eastern Coromandel, in the offshore Taupo Volcanic Zone and eastern Bay of Plenty.
- iii) Submarine volcanism in the Tonga-Kermadec system and in offshore Bay of Plenty.
- iv) Fault, volcanic and mass movement sources in the local Auckland region.

Many of these potential local tsunami sources were reported in the previous report by de Lange and Hull (1994), but as far as possible, information regarding these sources is updated here. It should be noted that de Lange and Hull (1994) indicated that tsunamis generated from distant, rather than local, sources such as the west coast of South America, were responsible for the largest tsunami heights of 1-3 m observed historically in the Hauraki Gulf, as confirmed also by de Lange and Healy (2001).

2.2.1. Subduction and upper plate earthquakes and submarine landslides associated with the Tonga-Kermadec Trench-Hikurangi Trough system

Historic earthquakes in 1947 (M_W 7.1 and 6.9) off Poverty Bay (Downes et al., 2001) indicate that subduction-interface earthquakes and seismic activity associated with upper plate faulting and folding (e.g., Barnes et al., 2002) represent a significant seismic and potentially tsunamigenic hazard for parts of the Tonga-Kermadec Trench-Hikurangi Trough system (e.g., Chagué-Goff et al., 2002; Walters and Goff, 2003; Cochran et al., in press). For such Hikurangi events to impact the Auckland region, would require propagation of the wave along the east coast (North Island) and around East Cape. Such events are considered potential tsunami sources for the Bay of Plenty (Walters and Goff, 2003; Bell et al., 2004). In the absence of more detailed research, Hikurangi events should be considered potential sources for Auckland City and Hauraki Gulf as well.

Potential Hikurangi margin landslide sources for tsunamis include large-scale landslides, such as Ruatoria and Matakaoa, which lie to the east and north of East Cape, respectively (Figure 1). While these events resulted in the mass movement of substantial amounts of sea-floor material (i.e., >3000 km^3 for Ruatoria, and 500-1000 km^3 for Matakaoa), they are likely to have very long return times in the order of 10’s to 100’s of thousands of years (e.g., Collot et al., 2001; Carter, 2001; Lamarche et al., 2004). Smaller scale, though more frequent, landslides in other seismically active regions, such as offshore Bay of Plenty, are recognised in recent mapping (P. Barnes and G. Lamarche, NIWA unpublished data), although their contribution to tsunami generation has yet to be fully evaluated.

Size and Frequency estimates (refer Table 2):
Small – 1 in 4 years; Medium – None; Large – 1 in 1300 years

2.2.2. Recently active faults in the Firth of Thames, along eastern Coromandel, in offshore Taupo Volcanic Zone and eastern Bay of Plenty

The most active offshore fault structure recognised in the Auckland region is the Kerepehi Fault in the Firth of Thames (e.g., de Lange and Lowe, 1990; Chick et al., 2001) (Figure 1). This fault has vertical slip rates of

~0.13 mm/yr and is capable of generating earthquakes of M 6.5-7.1 with a mean recurrence interval of ~2500 years (Chick et al., 2001; Edbrooke et al., 2003). Chick et al. (2001) suggested, however, that the tsunami hazard to Auckland City associated with the Kerepehi Fault was minor, although coastal settlements around the Firth of Thames were considered vulnerable. Further discussion of this source in Section 3.2. reassesses the tsunami hazard with reference to palaeotsunami data.

Active faults have been mapped on the continental shelf in offshore Bay of Plenty and deeper waters of the southern Havre Trough. These faults are associated with rift structures, such as the Whakatane Graben, as well as offshore extensions of the North Island Dextral Fault Belt (e.g., Wright et al., 1996; Lamarche et al., 2000) (Figure 2).

One of the major rift-bounding faults in the Whakatane Graben is the White Island Fault, which is >140 km in length and has sea-floor scarps that are up to 80 m in height with maximum vertical slip rates of 2.3-3.5 mm/yr over the last 20 000 years. Numerous other fault structures occur in the offshore Bay of Plenty and in deep water areas in the Havre Trough (>1000 m depth; Wright, 1992, 1993; Wright et al., 1996) (Figure 2). Based on historical seismicity data, preliminary analysis of fault sources and empirical equations for calculating tsunami height (e.g., de Lange and Moon, 2004), it is suggested that many of these faults may be capable of producing earthquake magnitudes of 6-6.5, which could result in tsunami heights of 1-1.5 m (e.g., Abe, 1995).

Faults with sea-floor expression have also been mapped at low resolution on the continental shelf and slope of Hauraki Gulf and off eastern Coromandel (Hochstein et al., 1986; Thrasher, 1986, 1988) (Figure 1). Similarly, faults that are less than 5 million years old with no sea-floor expression have been identified in preliminary studies off the west coast of Auckland (e.g., Isaac et al., 1994; de Lange and Healy, 2001). To the best of our knowledge, there has been no new offshore data collection to the west and east of Auckland since de Lange and Hull’s (1994) and de Lange and Healy’s (2001) reports. Thus, it is not possible to identify potential tsunamigenic sources (e.g., active faults, submarine instabilities) in these regions with any confidence without additional data collection.

In order to ascertain the frequency of occurrence and the scale of active faulting and mass movements as potential tsunami-generating sources that pose a hazard to the Auckland region, detailed sea-floor mapping of offshore regions in Bay of Plenty/Coromandel/Hauraki Gulf and west Auckland are needed.

Size and Frequency estimates (refer Table 2):
Small – 1 in 400 years (Hauraki graben)

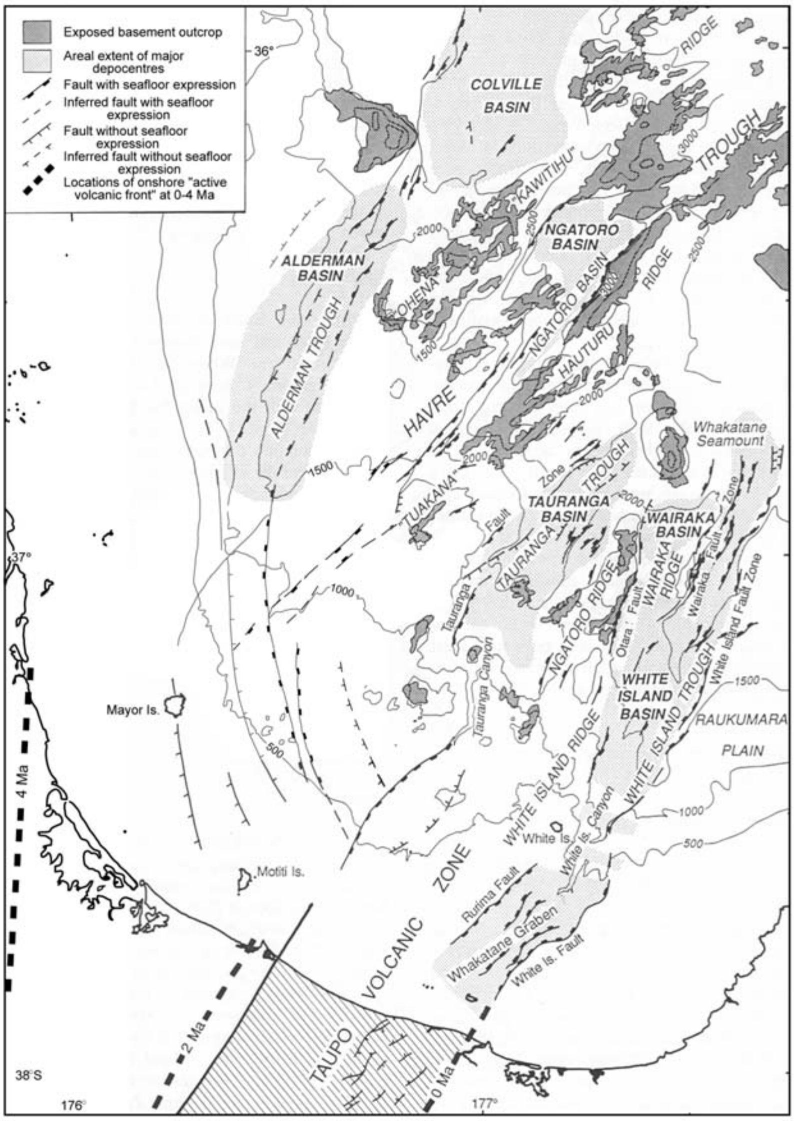

Figure 2: Detailed map showing faults in offshore Bay of Plenty and Havre Trough). Exposed basement outcrop and sediment depocentres are also shown (from Wright, 1993). Refer to Figure 1 – this area is to the west of the White Island Fault Zone.

2.2.3. Submarine volcanism in the Tonga-Kermadec system and in offshore Bay of Plenty

There are 28 offshore volcanoes along the active Taupo-Kermadec-Tonga arc that are >10 km in diameter and lie within 1000 km of Auckland City. Potential tsunamigenic sources in this region include the southern Kermadec volcanoes and White and Mayor islands in the Bay of Plenty (Figures 1 and 3).

Tsunamis could be generated from the southern Kermadec volcanoes (Figure 3) during explosive submarine eruptions (specifically as hot, gas-rich pyroclastic flows) and/or catastrophic sector collapse of the volcanic cone and crater (e.g., Latter et al., 1992; Lloyd et al., 1996). Healy volcano is interpreted to have formed by a catastrophic submarine pyroclastic eruption that is correlated tentatively with part of the widespread Loisels Pumice (Wright and Gamble, 1999; Wright et al., 2003) and tsunami inundation from North Cape to the eastern Bay of Plenty (Nichol et al., 2003; 2004). Eruptive volumes of ~5-100 km^3 have been estimated for these volcanoes, with most recent events occurring within the last 10000 years (Wright et al., 2003, in press).

Mass failure and landslides of volcanic material on the slopes of the southern Kermadec volcanoes are common features observed on recently collected multi-beam data. The landslides range from <1 km^3 for smaller landslides to over 4 km^3 for a substantial collapse feature on the western flank of Rumble III (Wright et al., 2004). The frequency of occurrence of such catastrophic events is poorly known, but range from 10 years for more common, small-scale landslides to >10000 years for larger mass failures (Wright et al., in press). The tsunamigenic potential of eruptions, landslides and sector collapse at the southern Kermadec volcanoes, however, has not yet been evaluated fully.

The largest eruption of Mayor Island (Tuhua) occurred 6300 years ago and was associated with both catastrophic caldera collapse and the transport of pyroclastic flows into the sea (Houghton et al., 1992, 1994). While the volcano is considered inactive, the last eruption occurred only 2000 years ago. Numerical modelling of a credible 1 km^3 pyroclastic flow entering the sea from Mayor Island would produce a <0.5 m high tsunami on the adjacent Bay of Plenty coast (de Lange and Healy 1986; de Lange et al., 2001).

White Island (Whakaari) is the emergent summit of a larger, active submarine volcanic edifice. While the volcanic history of White Island is poorly documented, the active hydrothermal system weakens the edifice structure and enhances potential sector collapse on both the outer sub-aerial (as in 1914) and submarine flanks. The generation of significant tsunamis sourced from White Island, however, is considered low (de Lange and Healy 1986; de Lange 1997). Other small caldera volcanoes occur on the outer Bay of Plenty continental slope (Gamble et al., 1993; NIWA unpublished data).

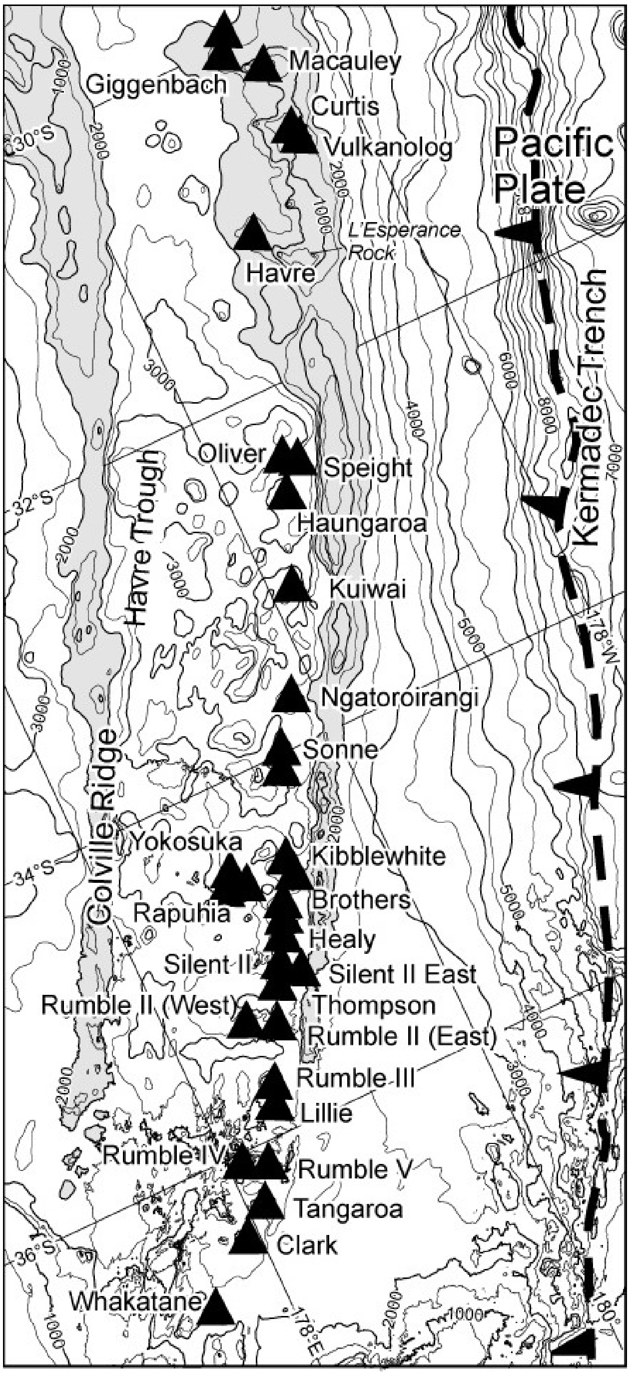

Figure 3: Detailed map showing the recently discovered southern Kermadec submarine volcanoes associated with the Tonga-Kermadec Ridge (toothed line) (from Wright et al., in press). The location of Brothers, Healy, and Rumble III is shown in Figure 1.

Volcano-meteorological tsunamis arise from atmospheric pressure waves associated with large, explosive volcanic eruptions, such as those generated during the AD 1883 Krakatau eruption and postulated to have occurred during the c. AD 200 Taupo eruption in central North Island (Lowe and de Lange, 2000). The Krakatau tsunami was 1.8 m in Tamaki Estuary, the largest recorded on the Auckland City coast in over 180 years (Lowe and de Lange, 2000). The Taupo tsunami was about 5.0 m on the Kapiti coast. Possible onland eruptive centres capable of generating such phenomena are located in the Taupo Volcanic Zone.

Size and Frequency estimates (refer Table 2):
None (as stated above, existing publications indicate the Healy volcano as the possible source for a tsunami that inundation from North Cape to eastern Bay of Plenty – this deposit is recorded on Great Barrier Island. Recent modelling suggests that a tsunami from this point source would not generate large waves. A Tonga-Kermedec Trench scenario is a more likely source)

2.2.4. Fault, volcanic and mass movement sources in the local Auckland region

The active Auckland Volcanic Field comprises 49 discrete basaltic volcanoes. De Lange and Hull (1994) suggested that the volcanic hazard associated with the Auckland Volcanic Field is likely to be greater than any tsunami hazard related to local volcanic earthquakes, submarine explosions, basal pyroclastic surges and landslides. The absence of a significant local tsunami hazard is due mainly to the shallow water depths present in the Auckland Volcanic Field. Similarly, mass failure of coastal cliffs is unlikely to be important due to the shallow water depths around Auckland (de Lange and Hull, 1994; de Lange and Healy, 2001).

The most credible tsunami scenario within the Auckland Volcanic Field is one where explosive eruptions occur within the Manukau or Waitemata harbours. Numerical modelling of such scenarios suggests tsunamis with wave heights of <2.5 m and mostly <0.8 m respectively could be generated by such local volcanic processes (de Lange and Prasetya 1997; de Lange and Healy, 2001).

Size and Frequency estimates (refer Table 2):
Medium – 1 in 600 years (Rangitoto)

3. HISTORIC AND PREHISTORIC TSUNAMIS IN AND AROUND THE AUCKLAND REGION

3.1. Historic Tsunamis

de Lange and Hull (1994) report what they acknowledged to be an incomplete dataset of historical tsunamis. Any such dataset, historic or prehistoric, will always be incomplete but data continue to be added on a regular basis. A table including the most recent updates by Fraser (1998) is given below (Table 1). There are no new tsunamis recorded, but some additional detail has been added, including information from Great Barrier Island. For 19th century events additional sites from the Coromandel are included in the table to provide some context for the responses recorded within the region.

Historical data are of variable reliability:

i) 20th century events are of increasing reliability up to the present day as more sophisticated recording technology has become available. This accounts for an increasing number of small tsunamis recorded in the recent historical record, a record terminated for the purposes of this report in 1994 (the last significant wave height being recorded in 1960).

ii) 19th century data vary in veracity but, whether or not wave height information is entirely correct, the recording of personal observations is usually indicative of a significant event. A review of these data indicates:

Summary of historic tsunami

- All wave heights >1m have been generated from distant sources.
- There have been THREE tsunamis greater than 1m. high.
- The largest tsunami was in 1868 - max. wave height recorded = 2.9m.
- Where information exists, Gt. Barrier Island records the largest wave height in an event.
- All tsunamis with wave heights >0.50m in Auckland have been larger in the outer Hauraki Gulf (Gt. Barrier Island) with the exception of the 1883 event. The 1883 tsunami was volcano-meteorological as opposed earthquake-generated.

YEAR	DATE	OBSERVED	HEIGHT (m)	Est. No. WAVES	SOURCE	CAUSE	COMMENTS
1868	15-Aug	Gt. Barrier Is.	2.90	1	Chile	Quake	Rosalie Bay, tide 2m >NHW. Tryphena Har., boat lifted 1.5m >NHW.
1868	15-Aug	Tamaki Est.	1.50	2-5			Bore on upper reaches of estuary, then 1.2-1.5m water fluctuations.
1868	15-Aug	Orewa	1.80				Unusually high tide.
1868	15-Aug	Port Charles	1.80	1			
1877	11-May	Auckland	0.20		Chile	Quake	0.2m fluctuation recorded.
1877	11-May	Thames	0.90	2-5			Bore in Thames River
1877	11-May	Port Charles	3.60	20+			Tide ebbed/flowed every 20min all day. Ave height =2.5m, Max=3-3.6m.
1883	29-Aug	Auckland	1.80	1	Krakatau Volcano	Rissaga	Water rose 1.8m in 30min, back to normal in 30min.
1883	29-Aug	Thames	1.50	1			Tide became full during ebb flow.
1883	29-Aug	Coromandel	0.90	2-5			Wave was seen at low tide, then tidal fluctuations.
1952	5-Nov	Auckland	0.10	20+	Kamchatka, Russia	Quake	Minor oscillations continued for days.
1960	23-May	Gt. Barrier Is.	1.50	>1	Chile	Quake	Waves were surging across the roads at Tryphena.
1960	23-May	Auckland	0.60	6-10			Tide fluctuations started late on the 23rd.
1964	29-Mar	Auckland	0.45	>1	Alaska, USA	Quake	
1976	14-Jan	Auckland	0.10		Kermadec Islands	Quake	
1977	22-Jun	Auckland	0.10	>1	Kermadec Ridge	Quake	
1982	19-Dec	Auckland	0.10		Kermadec Islands	Quake	
1986	20-Oct	Auckland	0.10		Kermadec Islands	Quake	
1993	Jun	Auckland	0.10		Kermadec Islands	Quake	
1994	6-Oct	Auckland	0.10		Kuril Islands	Quake	

TABLE 1: Historic tsunami from 1868-1994 (after Fraser, 1998)

3.2. Prehistoric Tsunamis

Good progress has been made in the Auckland region on the identification of prehistoric tsunamis (palaeotsunamis) since the report of de Lange and Hull (1994). These data provide some context for the present historical database and, in particular, show evidence for lower frequency, higher magnitude events not recorded over the last 180 years or so (Appendix I).

A recent tsunami study in the adjacent Bay of Plenty identified five or six known palaeotsunamis, two of regional impact (AD1302-1435 and 2500-2600 yrs. BP), and four of local (AD1600-1700, AD1200-1300, 1600-1700 yrs. BP, and 2900-3000 yrs. BP) (Bell et al., 2004). Further progress has now been made while preparing this report.

If one assumes that regionally significant events in the Bay of Plenty would have affected the Auckland region, then those of AD1302-1435 and 2500-2600 yrs. BP must be considered. Further interrogation of archaeological evidence however, introduces another significant regional tsunami. The Bay of Plenty work identified a local tsunami dated to approximately AD1200-1300. This was based primarily upon archaeological data. We recalibrated the age range of this event to the late 14th century and identify it as a markedly more region-wide tsunami. As a result of recalibration, elements of the region-wide event dated to AD1302-1435 are split – some are incorporated into the late 14th century, the remainder are combined with additional data from the 15th century to produce a distinctly separate region-wide tsunami in the early 15th century.

The main confounding factor in separating out these two events in the Bay of Plenty report (Bell et al., 2004) was chronological control. It was difficult to separate these events using radiocarbon dating and, not surprisingly, they have rarely been preserved together at any one site (the latter destroying evidence of the former), although rare stratigraphic sequences recording both have been reported (e.g. Smart and Green, 1962; McFadgen, in prep.). In brief, the earlier, late 14th century tsunami, was a larger event, affecting both the west and east coasts of the northern half of the North Island including the Auckland region. The later, early 15th century tsunami, was more focused on the tsunami crescent (North Cape to eastern Bay of Plenty) (Walters and Goff, 2003).

It is important to recognise that much of the data collected for the above interpretation is based upon "work in progress" and while the overall regionality of the two events is apparent, the dating of individual sites relies as much upon stratigraphic correlation as it does upon radiocarbon dating. The occurrence of the Ohuan Sand phase, sand dune advances, and the presence of Loisels pumice are all useful stratigraphic markers when considered in association with archaeological data (e.g. McFadgen, 1985; Goff and McFadgen, 2002).

The veracity of palaeotsunami data must be viewed in a different a context to historic events. Some of the sites have been studied by researchers and are verified palaeotsunami deposits (e.g. Whangapoua, GBI; Nichol et al., 2003); whereas others are based upon either the interpretation of past archaeological data, similarities in sedimentary evidence, or as yet unpublished work. Those verified by appropriate geological field research are considered Primary sites (1 in the 'verify' column of Appendix I), others are secondary (2 in the 'verify' column of Appendix I).

Three small events are noted in Appendix I. The earliest event is related to the Rangitoto eruption. Interestingly, archaeological data indicate a disturbance of the second ash eruption by a tsunami (Nichol, 1988). This physical evidence contradicts other workers who have suggested that this event was unlikely to have been tsunamigenic (e.g. de Lange and Prasetya, 1999) or that no evidence of a past tsunami related to the eruption has been found (www.gns.cri.nz/what/earthact/volcanoes/ nzvolcanoes/aucklandprint.htm).

The second event, *c* mid 16 century, is a single secondary site at Mangawhai. At such an early stage of investigation it is difficult to assess whether this represents a regionally or locally significant event with a local source, or some other environmental driver. The most recent event, early 17th century, is not recorded as a tsunami, but rather as a subsidence event in the archaeological record of the Hauraki Plains (Phillips, 2000). Several prehistoric Maori occupation sites, including for example a large area about 10km north of Paeroa, had the living floors raised at least 40cm or more in response to subsidence of the area. This took place around AD1600-1650. It is presumed that this was a locally significant event, although a more regional impact cannot be discounted given the record of what is reported to be a "local" tsunami in the Bay of Plenty around AD 1600-1700 (Bell et al., 2004).

Acknowledging a possible regional impact, it seems most likely that the event is related to subsidence associated with Hauraki graben, and to rupture of the Kerepehi Fault (Chick et al., 2001; de Lange and Healy, 2001). de Lange and Lowe (1990) infer that the fault scarp is the result of several sudden displacements in association with earthquakes rather than slow creep. Given the archaeological evidence this would seem to be the case (this example clearly shows the usefulness of interrogating all available data, and archaeological data in particular. Modeling of the fault rupture would undoubtedly have been assisted by this information). This is even more significant if one considers that much of the Auckland Region's coast is now under urban development, and that for many lengths of coast all we have remaining is early archaeological information. Obvious questions arise from the Hauraki Plains data, such as how variable was the subsidence across the region, and what are the implications for tsunami hazard within the Hauraki Gulf? These cannot be answered in this report but, if required, further geoarchaeological research combined with resonance modeling is a logical first step to addressing the issue.

Archaeological data also give some indication of runup height (the vertical distance from the pre-event tide level to the maximum elevation that the tsunami attains, regardless of how far inland). Maximum elevations of deposits are indicated in brackets under the evidence column in Appendix I. Of particular note are previously unknown (secondary) sites of Mangawhai and Waiheke Is., the latter being well inside the Hauraki Gulf. The deposits have an elevation of 8m and <10m respectively. These warrant further investigation.

It should be noted that the absence of a location report does not mean that it has not been affected by past tsunamis, but rather that information is not available (e.g. no written data, data not found or inaccessible, no research undertaken, the site is inappropriate for preserving palaeotsunami data).

Summary of prehistoric tsunami

In summary, there appears to be evidence for two local and three region-wide events that have affected the Auckland Region in the last ~2600 years:

2500-2600 yrs. BP	**>5m** high (Bell et al., 2004) SOURCE: Bay of Plenty Region-wide event
Late 14th century	Up to **14m** (Appendix I) Auckland region (west and east coasts) SOURCE: Bay of Plenty Region-wide event
15th century	**height unknown** Auckland Region SOURCE: Rangitoto eruption (Appendix I) Local event
Early 15th century	**<10m** (Appendix I) Auckland region (east coast only?) SOURCE: Bay of Plenty Region-wide event
AD1600-1650	**<1m** (Appendix I) Auckland Region SOURCE: Subsidence in Hauraki Gulf (Appendix I) Local event

Data indicate that runup heights of up to at least 14m have occurred on the outer edge of the Hauraki Gulf, and possible as high as nearly 10m inside. Where unknown, and in the absence of a reasonable alternative, local sources have been inferred for region-wide events. The source for the late 14th century event was most likely to the north of New Zealand, either in the Solomon Sea (Agnew and Smith, 1973) or Fiji Basin (Walters et al., 2005); although a closer, local source cannot be discounted. Further work is needed to clarify source information.

Interesting anomalous deposits reported by geologists, such as the rocks at the Pilot Station at Manukau Heads (Taylor, 1862), have not been considered in this summary palaeotsunamis section.

4. MAGNITUDE, FREQUENCY AND SOURCE ESTIMATES

Magnitude, frequency and source estimates based upon historic and prehistoric record are given in Table 2. Overall data for tsunamis from all sources indicate:

- Small (<1 m): 1 in 13 years
- Medium (1-5 m): 1 in 42 years
- Large (>5m): 1 in 870 years

These data are based on maximum wave height within the region. Time periods over which these estimates are based vary, and dating control for older events relies primarily upon radiocarbon dating which produces and age range, not a specific date – the oldest date in a range has been taken.

NOTE: Maximum wave heights between Great Barrier Is. (GBI) and Auckland city areas show significant variation – this affects the results of one historic tsunami - 1960 - which is placed in the Medium category (based upon GBI data), as opposed to the Small category (using Auckland data). A similar situation is most likely represented in the prehistoric data, particularly for tsunami sourced from the east. Estimates for the region may therefore slightly overestimate the frequency of higher magnitude events.

Historical data have been used for small and medium tsunamis, whereas the prehistoric (palaeotsunamis) data have been used exclusively for large events. It is well understood in the scientific literature that palaeotsunami deposits deteriorate with time (e.g. Goff et al., 2001). The taphonomy of the deposits is poorly understood, but is undoubtedly driven by local environmental parameters. Researchers are yet to find evidence in the sedimentary record for palaeotsunamis smaller than about 4-5 m in height. In general terms, one can assume that the smaller the wave, the thinner the deposit. Sedimentary evidence for smaller palaeotsunamis (5 m or so) is therefore more likely to be lost over time at any one site. Given this observation, the palaeotsunami database will always be incomplete, more so than the historic one.

Estimates of magnitude and frequency derived from the palaeotsunami database must be considered a minimum, and it is reasonable to assume that several events will remain unrecorded. A particularly good example of this assumption is where the most recent region-wide palaeotsunami (early 15th century) appears to have removed much of the evidence for the previous event (late 14th century) on the east coast.

SOURCE	DATE	HEIGHT (m)
DISTANT		
Alaska	1964	0.45
Chile	1868	2.90 (1.50 at Tamaki Est.)
	1877	0.20 (0.90 at Thames)
	1960	1.50 (0.60 at Auckland)
Fiji/Solomon	14th c	14.00
Kamchatka	1952	0.10
Krakatau Volcano	1883	1.80
Kuril Is.	1994	0.10
SUMMARY		
8 distant events in 700 years = 1 in 88 years		
4 over 1.0 m high (1 over 10.0 m high - in prehistoric record)		
Small (4 in 117 years): 1 in 30 years		
Medium (3 in 126 years): 1 in 42 years		
Large (1 in 700 years): 1 in 700 years		
LOCAL (outside the Hauraki Gulf)		
Kermadecs area	1976	0.10
	1977	0.10
	1982	0.10
	1986	0.10
	1993	0.10
	early 15th c	<10.00
	2500-2600	~5.00
SUMMARY		
7 events in 2600 years = 1 in 370 years		
2 at 5.0m or higher		
Small (5 in 18 years): 1 in 4 years		
Medium (none): 0		
Large (2 in 2600 years): 1 in 1300 years		
LOCAL (inside the Hauraki Gulf)		
Hauraki graben	17th c	<1.00
Rangitoto Volcano	15th c	2.00
SUMMARY		
2 events in 600 years = 1 in 300 years		
1 over 1.0 m high		
Small (1 in 400 years): 1 in 400 years		
Medium (1 in 600 years): 1in 600 years		
Large (none): 0		
SUMMARY OF ALL SOURCES		
Small (1 prehistoric - ignored, see below): 9 in 117 years = 1 in 13 years		
Medium (1 prehistoric - ignored, see below): (3 in 126 years) = 1 in 42 years		
Large 3 in 2600 years = 1 in 870 years		
(Heights estimated where not available; Small = <1.0; Medium = 1.0-<5.0); Large = 5.0+)		

Table 2: Source, magnitude and frequency (based upon max. wave height within the Auckland region (data taken to 1994 to capture representative sample of small, non-catastrophic events).

Local sources within the Hauraki Gulf do not appear to generate significant tsunamis. In this instance it is more likely that the hazard of the generating event will be of greater concern to the council. Distant sources on the other hand have been responsible for medium sized tsunamis (1.0-<5.0m), with a recurrence interval of about once every 42 years (three events). Given the short recurrence interval, and the fact that any tsunamis over about 1.0m should be considered potentially catastrophic (de Lange, 2003), the effects of tsunamis from distant sources on the Auckland Region need to be more fully understood.

Both local (outside the Hauraki Gulf) and distant sources appear to have produced large tsunamis in the Auckland Region. Data are very limited and as a result we have essentially inferred the most likely sources. There has been little or no consideration of tsunami sourced to the north/northwest of New Zealand, and this represents a distinct gap in our knowledge. Similarly, we are largely unaware of the likely magnitude of tsunamis sourced in the Tonga-Kermadec Trench-Hikurangi Trough system. Our limited data on tsunami sourced from distant and local sources has most probably placed an over-emphasis on South American sources, with minor consideration of Pacific Northwest/Alaskan and stratovolcanic sources (e.g. Krakatau volcano). This over-emphasis has been caused by an over-reliance in the historical record, a mere 180 years or so long.

5. GENERAL SUMMARY OF WAVE INTERACTION WITH THE COAST

5.1. Model

In order to evaluate the effects of the source scenarios, model simulations were made for a generalised tsunami from the east. The numerical model is a general-purpose hydrodynamics and transport model (RiCOM, River and Coastal Ocean Model). It has been under development for several years and has been evaluated and verified continually during this process (Walters and Casulli, 1998; Walters, 2002, 2004, 2005a, 2005b). The hydrodynamics part of this model was used to derive the results described in this report.

Model bathymetry is based on the New Zealand Exclusive Economic Zone (EEZ) grid used for the NIWA Tidal Model (Walters et al., 2001). The ARC grid was split from the EEZ grid and refined by a factor of 4 to resolve the tsunami, but no new or more refined bathymetry data were added. Hence, this grid contains a rather coarse resolution of the shorelines, no land areas, and a coarse underlying resolution of the bottom topography. Because no land topography was incorporated into the grid, the edges of the model grid will act as vertical walls. However, this grid is adequate to evaluate the propagation characteristics of the incident tsunami. Proper inundation modeling would require adding the land topography and more detailed bathymetry.

The ARC grid spans the distance from the coast to 182.5^{O} E. longitude, and 33.3 to 33.1^{O} S. latitude. The initial ARC grid that was derived as a subset of the EEZ grid was 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. The resulting grid contains 160880 elements and 53331 vertices. Depths at the vertices were interpolated from original EEZ bathymetry data.

Initial conditions for the model describe a tsunami incident from the east at the continental shelf break. The tsunami has a wave crest height of 1 metre and an approximate wavelength of 50 km. This wave can be used in a general sense to evaluate the effects of a ***small*** subduction zone earthquake along the Hikurangi Trough and a remote tsunami from South America. ***A tsunami generated by a subduction zone rupture could have an amplitude of up to approximately 3 metres and a wavelength of 30 to 100 km. Hence this wave would have similar characteristics to the model results, but would have markedly higher (x3?) wave and runup heights.*** A remote tsunami could have about the same amplitude as the model results but would have a longer wavelength (typically 300 to 400 km at this water depth of 2000 m). Hence the remote tsunami would have slightly higher runup and longer inundation period than the wave modelled here.

The “reference time” used in these results is the time at which the wave propagates onto the continental shelf. This time is approximately 15 hours after a remote tsunami is generated in Chile, or the same time as the earthquake for a subduction zone event.

5.2. Results (Figures 4-10)

An incident wave propagates westward and the wave front is bent due to refraction, hence from East Cape to the Colville Channel the wave comes ashore almost directly in an onshore direction. North of Colville Channel, the wave propagates towards the southwest and impacts the east coast of Great Barrier Island approximately 65 minutes after the “reference time”. The runup height is spatially variable with a maximum of approximately 4 m. 15 minutes later the wave encounters the open coast north of the Auckland Region and has a maximum local runup height of 3 to 4 m (Figure 10) (n.b. this is a small subduction zone earthquake).

Approximately 20 minutes later, the tsunami comes ashore at Tawharanui Peninsula with maximum local runup height of 2 to 3 m. The tsunami propagates down the coast toward Auckland with diminishing height. At 130 minutes after the “reference time” the tsunami encounters the north shore of Rangitoto and Waiheke Islands, and at about 200 minutes reaches the end of the Firth of Thames. There are waves that converge on the south side of the islands and numerous resonances in small bays along the coast line (e.g. waves converge on the south sides of Rangitoto and Waiheke Islands with an increase in wave height, and there is also resonance here between the mainland coast and the islands).

These results describe a ***small*** subduction zone earthquake which could be at least three times larger, with an appropriate scaling up of runup parameters. Model parameters for a large event are therefore within the approximate range of geological observations of palaeotsunamis deposits on the east coast of Great Barrier Island (Nichol et al., 2003).

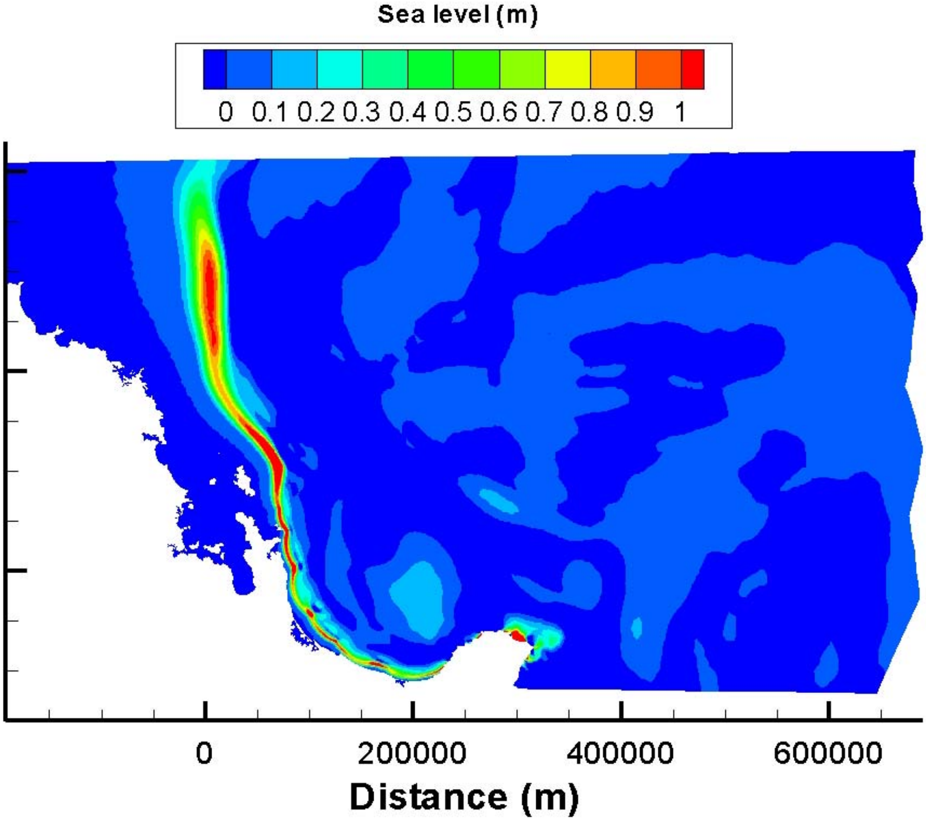

Figure 4: Full ARC grid showing wave approaching Great Barrier Island, 50 mins after the “reference time” the wave is refracting into the shoreline). *NOTE: On the Sea level scale the red bar is greater than 1(>1).*

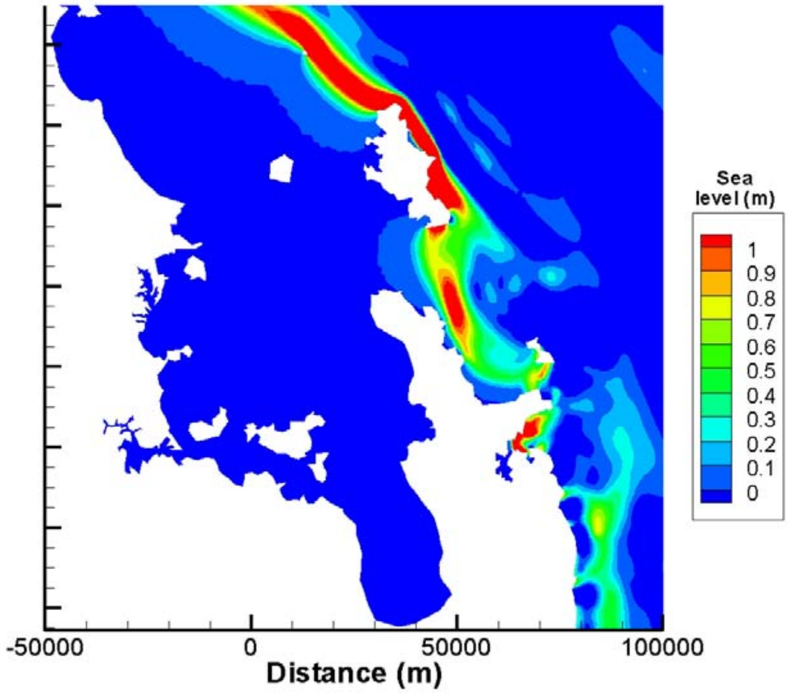

Figure 5: Detail of ARC grid showing wave arriving at east coast of Great Barrier Island, 65 mins after the “reference time” (note wave refracting into the Hauraki Gulf). *NOTE: On the Sea level scale the red bar is >1.*

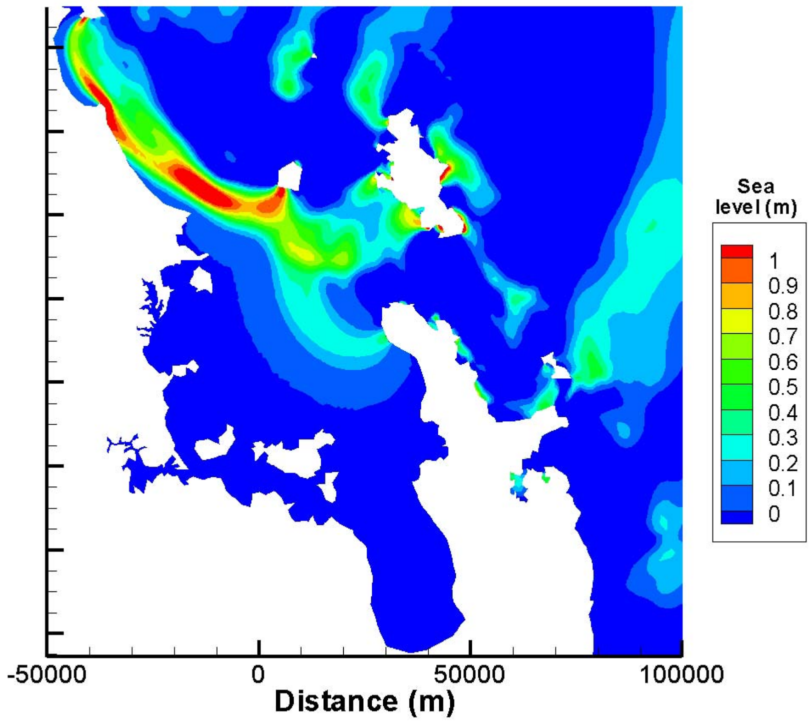

Figure 6: Detail of ARC grid showing wave arriving at northern end of Auckland region’s mainland coast, 80 mins after the “reference time”. *NOTE: On the Sea level scale the red bar is >1.*

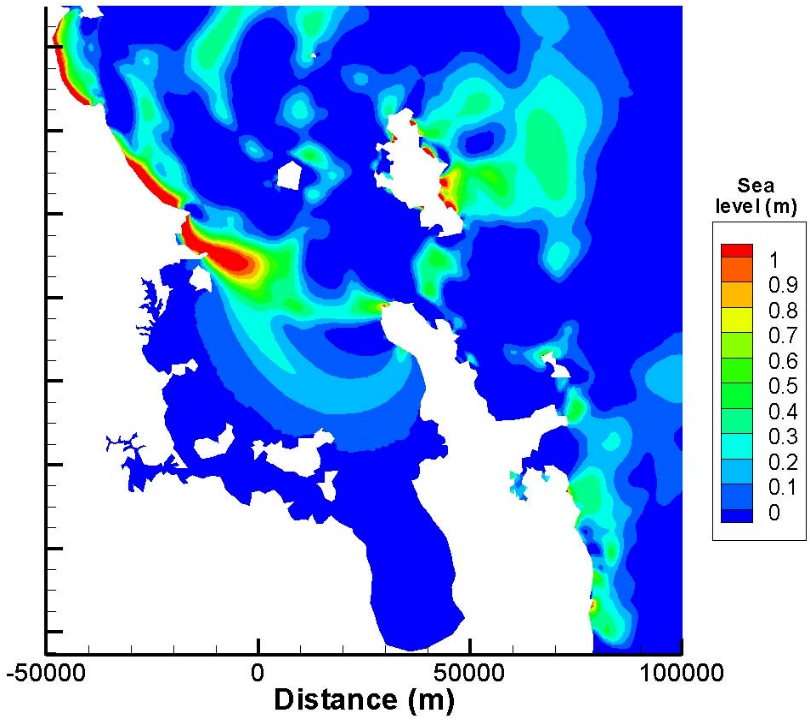

Figure 7: Detail of ARC grid showing wave arriving at Tawharanui Peninsula, 100 mins after the "reference time". *NOTE: On the Sea level scale the red bar is >1.*

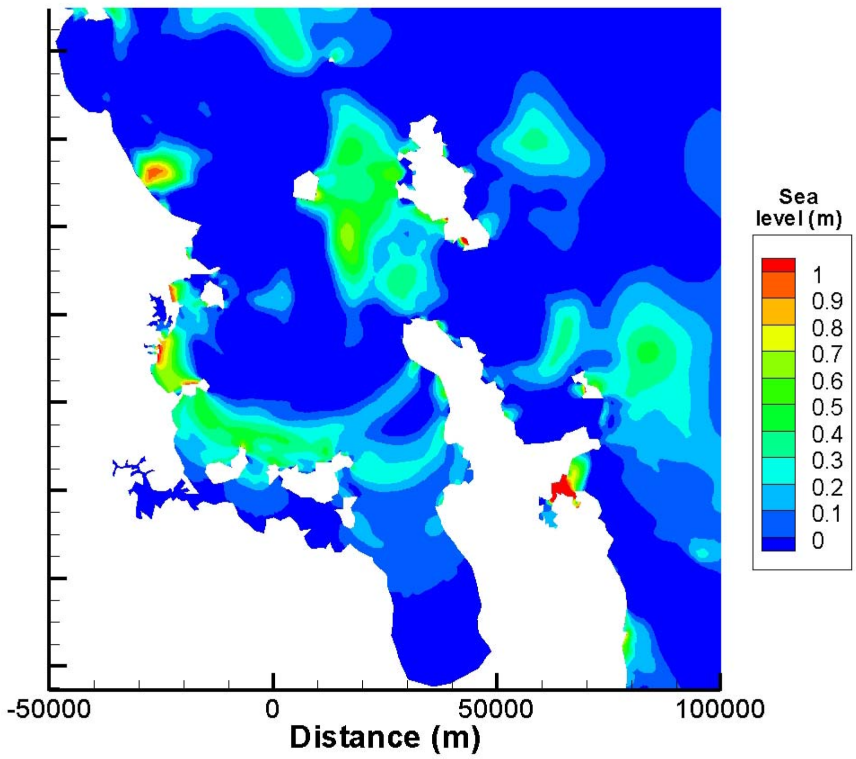

Figure 8: Detail of ARC grid showing wave arriving at Waiheke Island, 130 mins after the "reference time". *NOTE: On the Sea level scale the red bar is >1.*

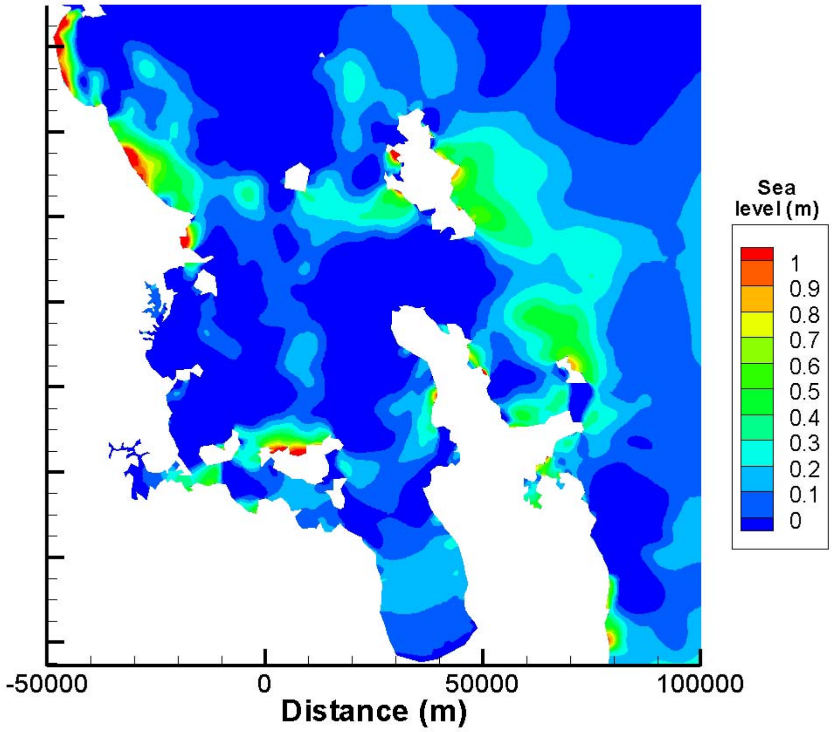

Figure 9: Detail of ARC grid showing large reflected wave arriving at Waiheke Island, and first wave entering Waitemate Harbour, 170 mins after the “reference time”. *NOTE: On the Sea level scale the red bar is >1.*

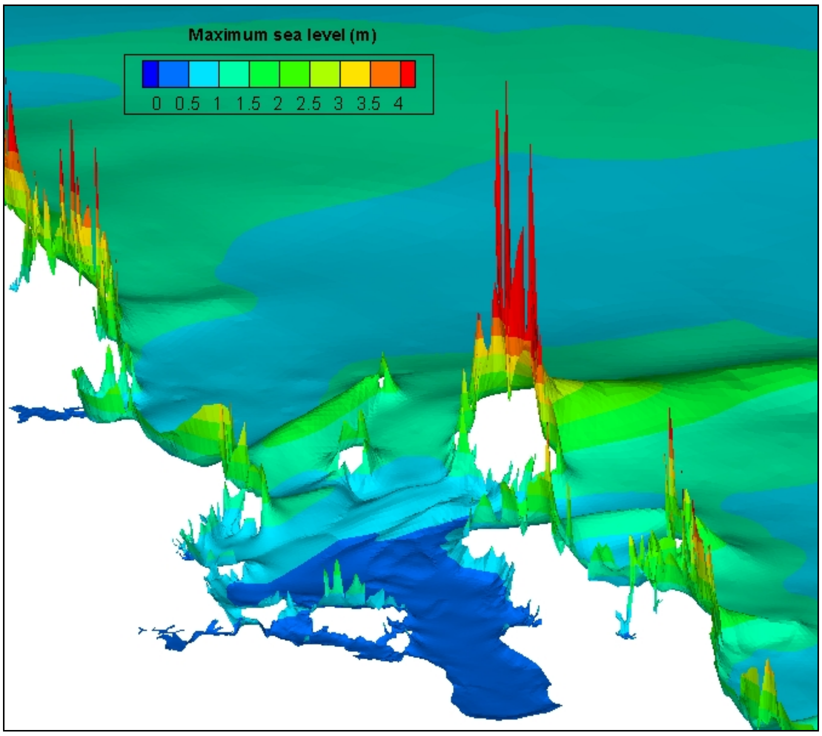

Figure 10: Maximum wave heights produced during model simulation (note different sea level scale from other figures, red bar is >4).

6. MOST LIKELY DAMAGING SOURCE FOR A DISTANT AND A LOCAL EVENT

Interrogation of the historical, palaeo, source and model data indicate that both local (outside the Hauraki Gulf) and distant sources can produce medium to large tsunamis in the Auckland Region:

- Distant: The largest event from a distant source seems likely to be from either South America or to the north of the country. The historic record provides the most reliable information here, and this shows that Chile is the key distant source. Identification of possible source areas (and their effects) to the north of the country needs further urgent investigation. Northern sources may prove to be of more concern than South America.

- Local: Sources can be divided into two distinct groups – inside and outside the Hauraki Gulf.

    - Inside the Hauraki Gulf sources are limited and unlikely to generate a large wave. It is a moot point, but it seems probable that the tsunamigenic source would be more of a concern than the tsunami they might generate (e.g. Rangitoto eruption).

    - Outside the Hauraki Gulf there are numerous sources, none of which has produced a large tsunami in the historic record. Comparison between inferred sources for prehistoric events and model data in this report suggests that a subduction earthquake along the Tonga-Kermadec Trench-Hikurangi Trough system is probably the most damaging source. Little is known about volcanic sources. These sources need further study.

7. ASSESS UNCERTAINTIES IN THE AVAILABLE INFORMATION AND IDENTIFY GAPS IN CURRENT KNOWLEDGE

7.1. Source data

- There is an incomplete source record. Distant sources are defined by the historical database that shows Chile to be the primary source. However, events such as the Krakatau eruption indicate that distant volcanic activity can be a source of medium to possibly large tsunamis. The wave from Krakatau entered the region from the north where it would meet fewer obstacles than waves from the east. The historic record is of no help in defining any additional sources to the north. There are numerous local sources both inside and outside the Hauraki Gulf that are capable of generating tsunamis. Detailed source data, however, are not available in a usable form at the present time.

- Source characteristics, implications for subsequent wave propagation, and tsunami inundation in the Auckland region are poorly understood.

7.2. Historic and prehistoric tsunamis

- The historic database improves with the addition of data, but continues to suffer from being too short to encompass large magnitude events reported in the prehistoric record. Earlier records are less rigorous and more difficult to use for interpreting tsunami characteristics. Assumptions based upon these uncertainties will continue to be made, but need to be recognised in future work. There are most likely few gaps in the overall number of events recorded, but some details will undoubtedly be added over time. Improvements in the historical database however are unlikely to add significantly to understanding the tsunami hazard for Auckland region.

- Significant amounts of prehistoric (palaeotsunami) data have been collected. Data interpretation is at an early stage, but indicates significant inundations have occurred within the region. Published and unpublished data have been used in this report, much of which is based upon personal communications and secondary (non-tsunami geology) source information. These uncertainties have been noted as has the potential for this information to fill our knowledge gaps of prehistoric events. The prehistoric data reported in Appendix I has been update three times during the lifetime of this report. This database will never be complete, but the record of larger, prehistoric tsunamis needs to be interrogated in greater detail in order to improve and complement numerical modelling of potential source areas.

- Physical evidence for possible locally and distantly sourced tsunamis has been discussed in this report. Most, if not all, of this evidence pertains to events that have occurred within the last 1000 years. This evidence needs primary verification in order to provide vital information to guide source investigations and model parameters. BUT almost no data has been collected/studies for earlier events because the focus has been on surficial deposits. This work needs to be undertaken.

7.3. Models

- Tsunami modelling uses data based upon our current knowledge of source characteristics, bathymetry, and nearshore/onshore topography. In this instance we have limited understanding of source characteristics, particularly in local areas outside the Hauraki Gulf, an area which seems most likely to be the source of the largest locally-generated events. Similarly, while we have speculated about a source to the north of New Zealand, for which there appears to be physical evidence of tsunami inundation in the Auckland region, we need to acquire more data to pursue this investigation further.

- Any additional bathymetric and topographic data will serve to improve model parameters. This becomes particularly important in the recognition of local and regional resonance, and serves to improve our understanding of tsunami inundation.

8. INITIAL INTEGRATION OF AVAILABLE DATA

Medium to large tsunamis appear capable of entering the Hauraki Gulf from a number of sources. Those from the east (Tonga-Kermadec Trench-Hikurangi Trough; Chile) interact initially with Great Barrier Island along the eastern perimeter of the region. Those from the north, exemplified in the historic record by the moderately large wave generated by the Krakatau eruption, do not appear to meet such a significant obstacle, and enter the Gulf between Great Barrier Island and Mangawhai. This may be significant.

Modelling shows the progression of a wave from a ***small*** subduction interface event in Tonga-Kermadec Trench-Hikurangi Trough region. This is also analogous to wave interactions that would be experienced by a tsunami from Chile, except that those would have longer wavelengths, longer runup periods and potentially higher runup. There are several key points:

- NE, N, NW sides of Great Barrier Island are struck hard by the wave.
- Little Barrier Island experiences high waves to the N and S sides.
- Mangawhai, Tawheranui, Kawau Island, Waiheke show significant wave heights.
- A wave moves down between Rangitoto Island and the east coast into the Tamaki River, Waitemata Harbour, Maungamaungaroa and Waitopua Creeks areas. There is resonance and amplification on the south sides of Waiheke and Rangitoto Islands.

A larger tsunami (generated by a larger displacement on the Tonga-Kermadec Trench-Hikurangi Trough) could generate waves at least three times higher.

Model parameters are not currently available to chart the progress of a wave entering Hauraki Gulf from the north. There are fewer islands inside the Hauraki Gulf along this path however, and this may permit larger wave heights to be recorded from sources to the north.

Prehistoric data add to the inferences made from the historic record and model. Two distinct region-wide events emerge from the prehistoric data, a late 14th and an early 15th century tsunami. The former appears to affect both the west and east coasts of the region and, if the inference about larger wave heights being produced by waves entering from the north is correct, seems most likely to be responsible for possible high elevation tsunami deposits inside the Hauraki Gulf (e.g. Waiheke Island – Appendix I). The latter, which is only recorded on the top half of the eastern side of the North Island has large runup on Great Barrier Island, which would be expected from a wave approaching from the east. Chronological control of the prehistoric record is poor. No significant dating (or study) has been carried out on many sites, although the Great Barrier Island deposit, dated to post AD1400, fits the proposed model. Further work needs to be carried out to not only investigate the origin of deposits listed in Appendix I, but also to resolve the chronology of events. In general terms though, two distinct events are apparent, an earlier (larger) one that affects both coasts, and a later (relatively smaller) one that affects only the east of the region. Both affect the Hauraki Gulf.

An initial interpretation of sources, modelling and physical evidence points towards the need to better understand the local subduction interface to the east of the region (a small example of which approximates a distant event from South America), and also to investigate distant sources to the north – most probably a megathrust earthquake. Now that we know more about the nature of tsunami approach from the east, it would also be prudent to investigate other possible local tsunami sources to the east such as landslides and volcanoes. Recurrence intervals from all sources are unknown (a more detailed record of pertinent South American tsunamis can be constructed from their longer historic record), but geological studies of tsunami deposits can improve our knowledge, particularly in areas such as Great Barrier Island where multiple sand deposits are present in coastal wetlands (Scott Nichol, pers. comm. 2005). Travel times from the east are fairly well constrained. It takes approximately 3 hours from a Tonga-Kermadec Trench source to Auckland City, with about 100 minutes from Great Barrier Island to the port, and approximately 3-3.5 hours from the nearest potential (distant) northern sites. These time lines alone allow for pragmatic warning/evacuation procedures and planning to be considered for tsunamis propagated to the east (procedures should however, be developed either in tandem with, or after, more detailed studies of source, recurrence interval, runup and inundation).

9. RECOMMENDATIONS

These are not listed in priority order. They are derived from a review of the information gathered above. Some suggested directions, that involve a combination of the points listed below, are given at the end of this section.

- Characterisation of offshore fault and landslide/volcano sources, including fault dislocation modelling for local (outside the Hauraki Gulf) and distant sources (Chile, northern sources), and estimation of frequency/magnitude relationships.
- Wave propagation modelling to evaluate the potential tsunami hazard of the sources identified above.
- Local runup and inundation need to be evaluated in the Auckland region using numerical models with more refined source information.
- One of the most exciting advances since the 1994 report has been the identification of physical evidence for past tsunamis. At present these are all from the prehistoric record. Physical evidence in the geology and geoarchaeology has identified several possible events. Of particular

note are tsunami inundations in the Late 14th (up to 14m) and early 15th (<10m) centuries. Three recommendations are made:
  - To support co-ordinated geological and geoarchaeological investigations of primary and secondary verification sites within the Auckland region, including areas identified by running the initial model (e.g. NE, N, NW Great Barrier Island, Little Barrier Island, Mangawhai, Tawheranui, Kawau Island, Waiheke Island, Tamaki River, Waitemata Harbour, Maungamaungaroa and Waitopua Creeks area). A programme aimed at field survey investigations of key sites is appropriate.
  - An evaluation of the resource consenting process. The paucity of coastal sites for geological and geoarchaeological studies prohibits more accurate interpretation of the tsunami hazard. A requirement for developers to undertake and report upon a robust scientific survey for physical evidence of past historic and prehistoric coastal hazards (e.g. tsunamis, storm surge) is recommended. These data could be added to a database of coastal information help by the council.
  - Develop a more detailed record of recurrence intervals for South American tsunamis based upon their longer historic record.
- Detailed tsunami inundation mapping of Auckland City's coastline should be carried out after detailed modelling has been completed.
- Tsunami warning/evacuation procedures should be developed either in tandem with ongoing research, or as a subsequence of it.

An integrated programme that makes use of most of the recommendations listed above could be:

Distant tsunami:
- Characterisation of subduction earthquake sources in South America (and to the north of New Zealand).
- Wave propagation modelling to evaluate the potential tsunami hazard of the sources identified.
- Produce local runup and inundation measurements for Auckland region using numerical models based upon the most likely damaging sources.
- Investigation of geological and geoarchaeological sites on the west and east coast of the Auckland region.
- Iteration between local runup and inundation model and geological data to improve resolution of model.
- Produce inundation maps/mitigation procedures based upon iterated data and field survey of coastline.

Local tsunami:
- Follow similar procedures for most likely damaging sources outside the Hauraki Gulf (Tonga-Kermadec Trench-Hikurangi Trough system, volcanoes).

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APPENDIX

Date	Elev. ma MHW	Location	Evidence	Reference	Verify
		East Coast:			
late 14C		Parengarenga Harbour	Gravel on sand dunes	Hay, 1981	2
late 14C	32	Henderson Bay	Gravel on sand dunes/wetland	Nichol et al. 2004	1
late 14C	8	Whangarei (Pataua-Ocean Beach)	Gravel on sand dunes	Thorne, 1875; J. Goff, pers. obs. 2003	2
late 14C	<20	Cavalli Island	Gravel on hillside + beach pebbles in soil of Panaki Is.	Hayward et al., 1979; D. Nevin, pers. comm. 2004	2
late 14C	22	Russell, BOI	Gravel on hillside	D. Nevin, pers. comm. 2004	2
late 14C	40	Southwest Is. (Three Kings Group)	Gravel on hillside	Brook, 1999a	2
late 14C	57	Mokohinau Islands	Pebbles/cobbles in soil	Moore, 1985	2
late 14C		Poor Knight Islands	Pebbles in soil on Aorangi Is.	Hayward, 1991	2
late 14C		Tokerau Beach	Shells/Loiselspumice/gravels	Brook, 1999b; J. Goff, pers. obs., 1999	2
late 14C?		Houhora, Mt Camel	Erosion of archaeological deposits	Furey, 2002	1/2
15C		Te Ruatahi, N. Whananaki	Ohuan sand dune advance over occupation layer	Brooks and Goulstone, 1999	2
15C?	**8**	**Mangawhai**	**Ohuan sand + Gravel on sand dunes**	**Wellman, 1962; J.Goff, pers. obs. 2005**	**2**
c mid 16C			**Change in midden shell content between 2 occupations**	**Pearce, 2001**	**2**
15C?		**Molesworth Head, Mangawhai**	**Dune sand - Ohuan? Overlying 1st occupation loisels**	**Wellman, 1962**	**2**
late 14C	**10**	**Tawharanui. Omaha Beach**	**Tsunami deposits with Losiels pumice**	**W. de Lange pers. com. 2005**	**1/2**
15C		**Tiritiri Matangi Is.**	**Gravel between 2 occupation layers**	**J. Goff/S. Nichol, pers. obs. 2001**	**1/2**
15C		**Motutapu Is.**	**2nd ash eruption - disturbance of ash**	**Nichol, 1988**	**1/2**
15C??	**<10**	**Waiheke Is.**	**Gravel and shells**	**Law, 1975**	**2**
15C??	**3**	**Motoiti Is.**	**Gravels/shells in sand**	**Mather, 2004**	**1**
14C	**14**	**Whangapoua, GBI**	**Gravels in sand**	**Nichol et al., 2003**	**1**
early 17C		Hauraki Plains	Large EQ + Subsidence/downdrop/flooding of pa sites	Phillips, 2000	2
15C		Coromandel Pen	Influx Ohuan sand/change shell midden content	Smart and Green, 1962; McFadgen, in prep.	2
15C	8	Waikawau Bay	Gravel in sand	Bell et al., 2004	2
late 14C		Mercury Bay	Shift of prehistoric settlement - beach to hill	Green, 1963	2
??	60+	Korapuke Is	Gravels/boulders on hill	Goff/Nichol/McFadgen, pers. obs, 1980-2003	2
		West Coast:			
14/15C?		90 Mile beach	Major dune advance-tsunami triggered? Inland occupation shift	Hicks, 1975; Coster, 1989	2
14/15C?	10	North Cape-Spirits Bay	Gravels in sand	J. Goff/S. Nichol, pers. obs. 2005	2
14/15C?		Twilight Beach	Gravels in sand	M. Taylor, pers. comm. 2005	2
14/15C?		Te Werahi	Erosion surface	Brooks, 1999c	2
15C?	>5	Tauroa, Ahipara	Gravels in sand dunes	www.arts.auckland.ac.nz/ant/Tauroa_2003	2
14/15C?		Hokianga, Kawerua	Gravel in dunes, Major dune advance? Tsunami triggered?	Hayward, 1974; Hicks, 1975	2
14/15C?	~40	West Waikato Coast	Gravel in sand dunes	Wilkes, 1995; J. Goff, pers. obs. 2003	2
14/15C?		Taharoa/Kawhia/Aotea Harbour	Advance of Ohuan sand burying archaeological sites	McFadgen, 1985; Wellman, 1962	2

Appendix I: Possible/Probable prehistoric tsunami deposits (14^{th}-17^{th}c.) relevant to Auckland region. Bold lines = within region, ma MHW = metres above mean high water