Towards the calibration of tsunami models in the Auckland Region using paleotsunami deposits

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ABSTRACT

The Auckland region does not have a historic record of any significant tsunamis, but it is exposed to a number of local, regional and distant tsunami sources. Of these potential sources, the largest tsunamis are expected to be generated by large earthquakes on the Kermadec Trench. Tsunami models of large Kermadec Trench earthquakes (M 8.5–9.4) suggest parts of the eastern coastline of the Auckland Region could be exposed to tsunamis with wave amplitudes of up to 10 m on Great Barrier Island and 1–5 m on the mainland coastline. The primary objective of this EQC project is to contribute to the calibration of tsunami modelling by identifying potential paleotsunami deposits in the Auckland region that can inform us of the run-up heights, inundation distances and recurrence of tsunamis in the prehistoric period (pre- AD 1850s). This report presents a review of existing paleotsunami information in the Auckland region, methods and results of new field studies on paleotsunami in the Auckland region (primarily on Great Barrier Island) and outlines future steps toward a better understanding of tsunami hazard in Auckland and the upper North Island.

We reviewed evidence for paleotsunamis at 18 sites within the Auckland region and our review found three sites (Tawharanui, Whangapoua Beach and Harataonga Bay) have robust evidence of paleotsunami. The dating of the inferred paleotsunamis at all sites is relatively poor, and it is currently hard to evaluate if there are temporal correlations (similarities in age) between the records. To undertake new field studies of paleotsunami we evaluated 12 coastal areas and selected sites based on previous paleotsunami research, tsunami modelling, suitability of the coastal depositional environments and accessibility of the site. Field reconnaissance was undertaken at 8 coastal sites but only two had likely evidence of past paleotsunamis, these were the previously identified sites of Whangapoua Beach and Harataonga Bay (Tawharanui could not be revisited). Further data were gathered at Whangapoua Beach and Harataonga Bay to better constrain the age of the inferred paleotsunami deposits. Most sites on the Auckland mainland did not have ideal depositional environments for capturing and preserving paleotsunami sediments, so the lack of paleotsunami information on the mainland is more a reflection of the environment than lack of past tsunami inundation.

We recommend future research to review paleotsunami records in the neighbouring regions of Northland and Coromandel Peninsula, coupled with multidisciplinary paleotsunami field studies with iwi and archaeologists. We also recommend a general investigation to evaluate the potential of sheet gravels within sand dunes as paleotsunami indicators, and tsunami modelling at specific sites to understand local effects on tsunami amplification. Further field studies at three sites on Great Barrier Island and two sites on the Auckland mainland are recommended in order to improve the age precision and reliability of the Auckland paleotsunami record. The coastline of Auckland and its neighbouring regions offer our most promising sites to better understand the size and frequency of large to great Kermadec Trench earthquakes and this information could be of critical importance for understanding tsunami risk in New Zealand.

KEYWORDS

Paleotsunami, Auckland, Great Barrier Island, Kermadec Trench, tsunami hazard.

1.0 INTRODUCTION

Tsunami models of large Kermadec Trench earthquakes (M 8.5–9.4) suggest parts of the eastern coastline of the Auckland region could be exposed to tsunamis with wave amplitudes of up to 10 m on Great Barrier Island and 1–5 m on the mainland coastline (Power et al. 2012). Such a tsunami would have a short warning time (<3 hours) and most likely have a devastating impact on Auckland's coastal inhabitants and infrastructure. However, tsunamis of this magnitude have not been witnessed in the ~180-year historic period. Our current best information on the likely frequency and size of tsunami impacting Auckland comes from probabilistic tsunami hazard models (Power et al. 2012). These are based on estimates of the likely size, location and recurrence of earthquakes on selected seismic sources (Power et al. 2012, 2013). An alternative way to understand tsunami hazard is by looking at the prehistoric record of tsunamis (paleotsunamis) onshore. Sediments entrained and deposited by large tsunamis can be preserved in the geological and geomorphic record of coastlines, this is called paleotsunami evidence. Paleotsunami evidence can be used to understand the size and frequency of past tsunamis, therefore providing insight into future tsunami hazard. To provide best estimates of tsunami hazard, ideally both probabilistic tsunami hazard models and paleotsunami data from coastal locations are used. When probabilistic models are consistent with paleotsunami data, we can have increased confidence that our tsunami hazard models are reliable.

The primary objective of this project is to contribute to the calibration of tsunami modelling by identifying potential paleotsunami deposits in the Auckland region that can inform us of run-up heights, inundation distances and recurrence of tsunamis prior to written and oral records. This report presents a review of existing paleotsunami information in the Auckland region, results of new research on paleotsunami in the Auckland region (primarily on Great Barrier Island) and outlines future steps toward a better understanding of tsunami hazard in Auckland and the upper North Island.

2.0 HISTORIC TSUNAMI RECORD IN THE AUCKLAND REGION

There have not been any large, damaging tsunamis in the Auckland region during the historic period since ~AD1840. In general, large distant earthquakes on the South America plate boundary have produced the largest and most frequently observed historic tsunamis in the Auckland region. The New Zealand Historical Tsunami Database has 59 tsunami observations for the Auckland region and these relate to 30 different events (some events have multiple observations from around the Auckland region, for example the 1868 tsunami was observed at 6 locations). Figure 2.1a shows the location of historic tsunami observations in the Auckland region, these are from Downes et al. (2017) and the New Zealand Historical Tsunami Database (https://data.gns.cri.nz/tsunami/index.html, accessed 31 August 2020).

The most significant historic tsunami, in terms of wave height, was the 1868 tsunami from the M ~9.0 Peru earthquake, observed at six locations (Figure 2.1b). A previous compilation of Auckland historic tsunamis by Goff et al. (2005) listed the maximum 1868 tsunami height as 2.9 m on Great Barrier Island. However, we cannot find the source of this information height estimate. In the New Zealand Historical Tsunami Database, the maximum run-up height is 2.5 m, estimated from this historic source:

> *"Water rose 7 ft vertically above the usual HWM [paper specifically notes that it is vertical not horizontal] (Daily Southern Cross 26 August 1868); On Great Barrier Island, at no specific location, on night of August 14/15 water rushed in and out sometimes going out 3 ft below LWM. On west side of island, water rose 5 ft higher than "usual" [no other detail]. (Daily Southern Cross 22 and 26 August 1868)".*

The 2.5 m estimate is a result of the 7 ft observation and taking account of tide level at the estimated time of arrival. Other Auckland locations recorded run-up of ≤1 m and within Auckland Harbour there were no differences in tides observed (Daily Southern Cross 22 and 26 August 1868, from New Zealand Historical Tsunami Database).

The 1877 MW8.8 northern Chile earthquake generated a tsunami that caused minor run-up in Auckland. It was observed at five locations with run-up heights of <1 m. The 1883 Krakatau eruption in Indonesia generated a meteo-tsunami recorded at three locations in Auckland with maximum run-up of ~1m observed at Warkworth. The 1960 MW 9.4–9.6 Chile earthquake produced a tsunami recorded at four locations in Auckland with run-up heights of <1m but some damage to boats occurred and the sea rose over some low-lying roads on the eastern side of Great Barrier Island. The remainder of the tsunami observations relate to minor tsunami observations of <0.5 m. The frequency of tsunami observations in the New Zealand Historic Tsunami Database increases toward the present day as instrumental measurements from tide gauges are included in the database (Figure 2.1b). It is worth noting that observations from earlier days may have been from a selected audience (i.e. privileged/higher class people whose observations were recorded by newspapers at the time) and it may miss many observations made by other sectors of society.

The overall observations made by Goff et al. (2005) about the historic tsunami record in Auckland are still valid with the addition of another 15 years of data, they stated "Where information exists, Great Barrier Island records the largest wave height in an event. All tsunamis with wave heights >0.5 m in Auckland have been larger in the outer Hauraki Gulf (Great Barrier Island) with the exception of the 1883 event".

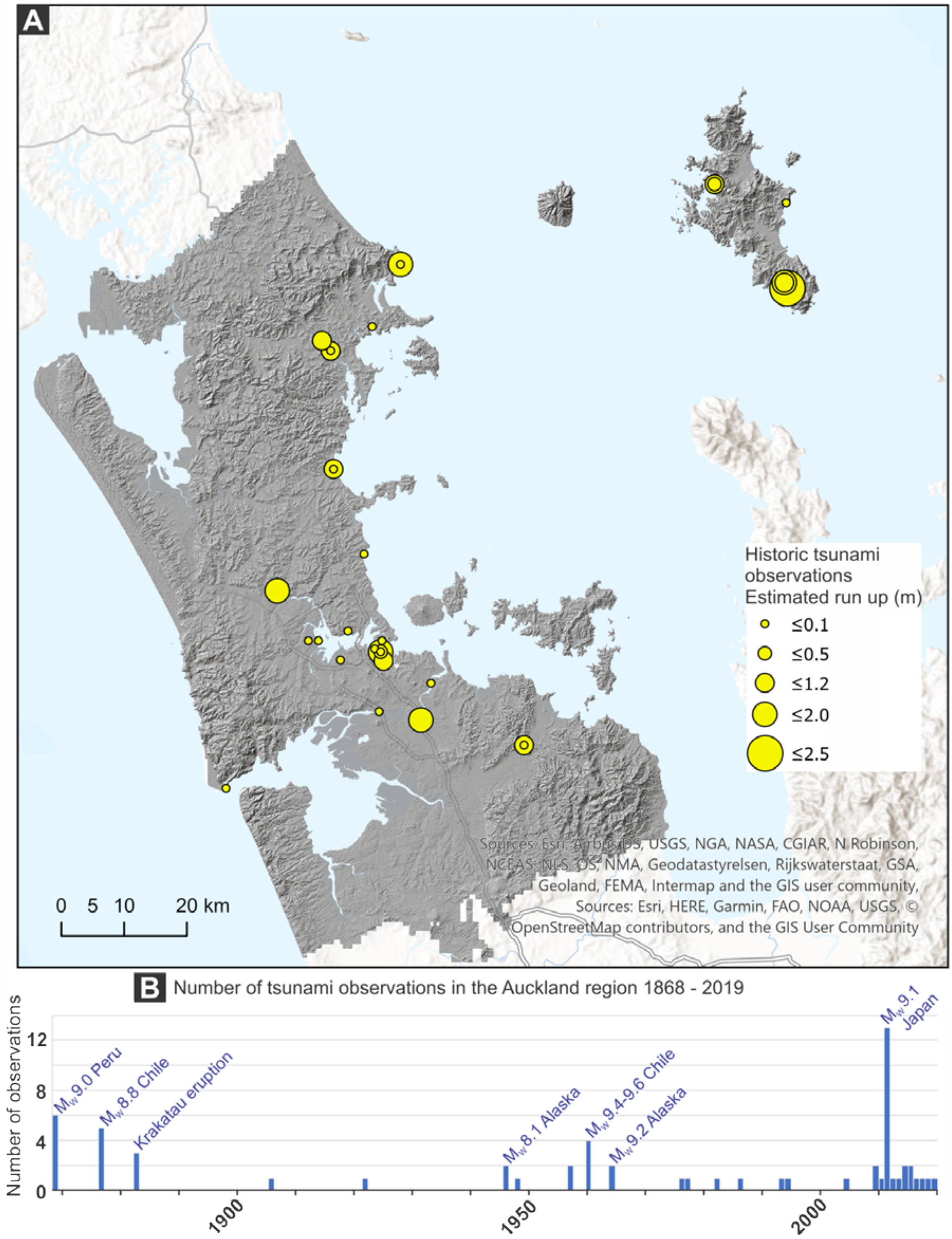


Figure 2.1 Map shows location and estimated run-up of historic tsunami observations in the Auckland region. The graph below shows the number of tsunami observations through time (note that after ~2009 tide gauge observations are more routinely included in the database so lower threshold events are reported. Data source: New Zealand Historical Tsunami Database (https://data.gns.cri.nz/tsunami/index.html, accessed 31 August 2020).

3.0 PREVIOUS PALEOTSUNAMI RESEARCH IN THE AUCKLAND REGION

The Auckland region has a sparse record of paleotsunamis which is probably a consequence of several factors including: few targeted studies to look for paleotsunami deposits, a highly developed and modified coastline, and relatively low tsunami hazard in the last 150 years. In the New Zealand Paleotsunami Database (New Zealand Paleotsunami Database 2017) there are 18 records within the Auckland region, compared to 22 on the Coromandel Peninsula and 44 records in Northland. Tsunamis are typically not just local phenomena. Instead, tsunamis can impact large areas of coastline so to understand tsunami hazard it is relevant to look at paleotsunami records from neighbouring regions as well as local to the area of interest. For the purposes of this report, we restrict our review to sites in the Auckland region, but future work should aim to integrate paleotsunami sites from neighbouring regions for a more complete understanding of tsunami hazard.

3.1 Sources of Paleotsunami Information

The richest compilation of paleotsunami information for New Zealand is in the New Zealand Paleotsunami Database (NZPD, https://ptdb.niwa.co.nz/) and this is the primary source of information for our review. Each entry in the NZPD has an associated data table with up to 35 pieces of information that describe the location, type of evidence and characteristics of the paleotsunami deposit, age information, spatial information such as elevation and inland extent of deposit, validity of the record or observation, source characteristics of tsunami and references related to the site. Of particular importance is the validity ranking which is a proxy measurement for how compelling or reliable the paleotsunami record is at each site. The validity ranking in the NZPD can be either Excellent, Moderate or Poor and this is based on the number of paleotsunami 'proxies' or criteria that each record satisfies. For example, an 'excellent' validity ranking means the record at an individual site satisfies >9 paleotsunami criteria; validity of 'poor' means the record satisfies between 1–4 paleotsunami criteria. The criteria are well-established paleotsunami characteristics compiled from publications such as Chagué-Goff et al. (2011), Goff et al. (2001, 2010, 2012), Goff & McFadgen (2003), McFadgen & Goff (2007) and Morton et al. (2007).

The validity ranking is a useful and transparent method of understanding how reliable the paleotsunami record is at each site and enables a rapid evaluation of the reliability of an area's paleotsunami record. However, we note there is no consideration or evaluation within the NZPD of whether a record may be better explained by processes other than tsunami (e.g. storm surge, strong swell, flood, etc.). For example, a site with a moderate validity ranking may display proxies such as coarse sediment and inland fining, which are also characteristics compatible with storm surge deposits. Furthermore, some of the criteria for an individual site relate to similarity to nearby sites, e.g. criteria 30 "Replication – similar contemporaneous coastal deposits are found regionally giving a regional signal of inundation". Often the establishment of 'contemporaneous' is not rigorously supported by independent age data from individual sites, so 'Replication' is hard to prove yet it is frequently applied as a criteria. This means some sites with relatively weak paleotsunami evidence are given a higher validity ranking because they are inferred to be of similar age to a deposit or record nearby, but this is rarely backed up by age data. Overall, the NZPD is a comprehensive and useful source of information and a good starting place for paleotsunami studies, but some caution should be taken with using the records at face value as each record should be evaluated individually and preferably using the original data source. In the following sections we start by examining the paleotsunami records in each area and evaluate each record individually.

3.2 Paleotsunami Sites in the Auckland Region

New Zealand Paleotsunami Database sites in the Auckland region can be grouped into three spatial areas: (1) Great Barrier Island, (2) east mainland and islands of the Hauraki Gulf, and (3) west coast (Manakau and Kaipara Harbours). Great Barrier Island has the highest density and overall highest validity of data, it is also the coastline most exposed to tsunamis that originate at the Kermadec Trench and South America.

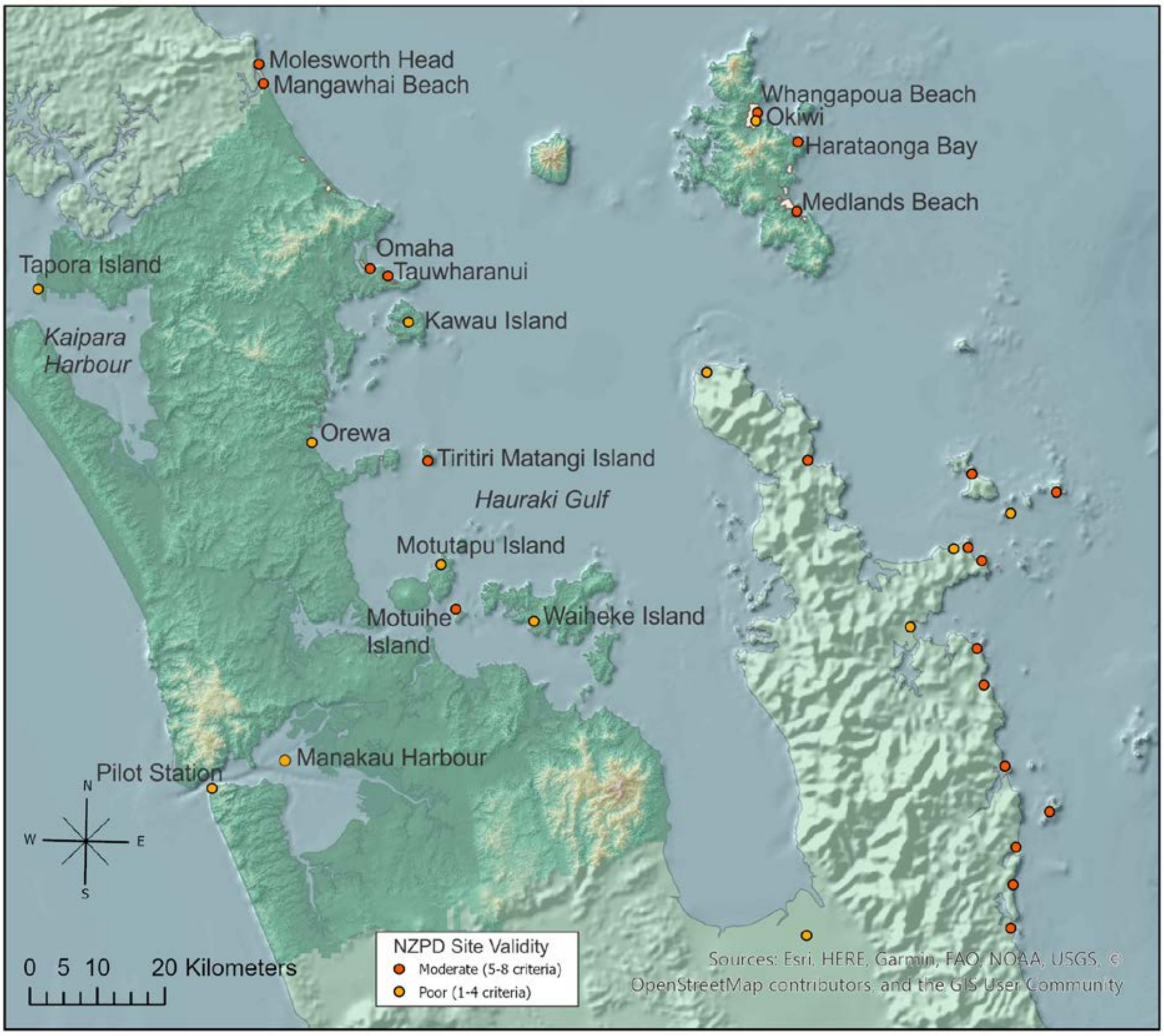


Figure 3.1 New Zealand Paleotsunami Database sites in the Auckland region, coloured by site validity ranking (red = moderate, orange = poor). Sites in the Auckland region are labelled. Also shown are sites on the Coromandel Peninsula but these are not reviewed in this report. Sites from https://ptdb.niwa.co.nz [accessed July 2020].

3.2.1 Great Barrier Island

There are four sites on Great Barrier Island (Figure 3.1) and of these Whangapoua Bay and Harataonga Bay are the most well-known paleotsunami records. At Whangapoua Bay, Nichol et al. (2003) describe a gravel sheet reaching up to 14 m elevation within sand dunes. These authors describe the composition and particle size of the gravel sheet and its spatial distribution, and possible temporal association with nearby midden deposits. The three plausible depositional mechanisms for the gravel sheet that they considered are: storm surge, aeolian winnowing and tsunami, and they concluded the only reasonable depositional mechanism for the gravel sheet is tsunami. Nichol et al. (2003) reason the 14.3 m maximum elevation of the gravel sheet is too high for a storm surge to reach, while aeolian winnowing (a process by which wind removes fine particles leaving a coarse lag in dune deflation basins) still requires the initial deposition of gravel by another process. Nichol et al. (2003) used two methods to date the gravel sheet but dating gravels within sand dunes is an inherently difficult proposition. Optically stimulated luminescence (OSL) samples from under the gravel sheet had ages between ~6700–3700 years before present (yrs BP) and a sample from above the sand was essentially modern (40 yrs ± 470 yrs). They also radiocarbon dated shells within nearby midden deposits and these clustered around the AD 1390–1670 age range. The presence of hearth stones scattered in the gravel sheet was used to argue the gravel sheet must have been deposited during or after Māori occupation, so the tsunami probably occurred around or after AD 1390–1670 (Nichol et al. 2003). The NZPD lists the tsunami inferred age as AD 1450–1480 but it is not clear why this is slightly different to Nichol et al. (2003). Nichol et al. (2003) speculated the source of the tsunami could have been an earthquake on the Hikurangi subduction zone or a submarine volcanic eruption on the Kermadec arc. At the time of their research, there was little understanding or awareness of the potential for large earthquakes to also occur on the Kermadec subduction zone, so this appears to have not been considered as an option.

Harataonga Bay is also on the east coast on Great Barrier Island, approximately 7 km southeast of Whangapoua Bay (Figure 3.1). At this location, unusual sediments within a back-barrier wetland have been interpreted as potential paleotsunami deposits (Nichol et al. 2007). Nichol et al. (2007) collected two sediment cores (collected 1 m apart) from the Harataonga Bay wetland. The wetland is sheltered behind a dune barrier that is ~100 m wide and up to 15 m high. The wetland sediments record progressive infilling of the basin, transforming the location from a wetland at ~6500 yrs BP to a shallow freshwater lake before returning to a wetland environment. During the second wetland phase there was deposition of three coarse sand and gravel beds, interbedded with fine sandy silt. The lowest sand unit is 12 cm thick and displays rounded gravel and an apparent erosional basal contact, this is interpreted by Nichol et al. (2007) as a paleotsunami deposit. The middle and upper sand beds are <10 cm thick and are interpreted as mixed slope-wash and dune sand sediments transported by “run-off events” (presumably heavy rainfall?). The main reasons for interpreting the lower sand bed as a tsunami deposits are (1) the magnetic susceptibility of the sand suggests it was derived from the beach and dune system seaward of the wetland (as opposed to from the landward catchment), (2) there was scouring and erosion of the wetland surface and gravel and mud rip-up clasts incorporated at the base of the sand unit, and (3) storms and floods probably could not directly impact the site as the dune barrier is too high for storms to overtop and floods would be seen more frequently within a ~6500 year record. The authors also note similarity to the tsunami gravels at nearby Whangapoua Bay as additional support for a tsunami hypothesis (although we note there is potentially a large difference in the ages of these two tsunami deposits).

The paleotsunami deposit at Harataonga Bay wetland was dated using a combination of tephra, radiocarbon dating and OSL dating. Tephra layers significantly below and just above Facies C constrain the age to <5590–5490 yrs BP (Whakatane tephra) and > ~600 yrs BP (Kaharoa tephra), respectively. A radiocarbon date on seeds found slightly below Facies C was 3000–2710 yrs BP. Three OSL ages from below, within and above Facies C have ages of ~6,100 yrs BP, ~3540 yrs BP and 2,560 yrs BP respectively, but all have issues with incomplete bleaching or mixed grain populations and the authors suggest all must be maximum ages (i.e. the dated sediment must be younger than the ages yielded). Overall the authors suggest Facies C, the paleotsunami sand is close in age to ~3000 yrs BP, i.e. very close to the radiocarbon age on seeds underlying the sand. As noted above, this is a significantly different age to the paleotsunami deposit at Whangapoua Bay, although there are large uncertainties with the age data at both sites.

The NZPD has an entry for Okiwi, a site located ~2 km south of the Whangapoua Bay gravel deposit. This site has a poor validity ranking because it satisfies only four paleotsunami proxies. There is scant information about the paleotsunami evidence at this site; the NZPD entry describes a sedimentary deposit and the characteristics are described as a "modified soil" with additional notes saying there is a modified soil with a "much disturbed midden" and hummocky topography ("or tsunami geomorphology") was observed. This description is vague thus more information from the primary reference material of Prince and Clough (2001) and Furey (1991) was sought. Prince and Clough (2001) describes a series of archaeological excavations at Okiwi. There are multiple descriptions of soil pits and trenches that contain middens and gardening soil. We cannot find any mentions of a "much disturbed midden" and the modified soils are to be expected given the use of the site for gardening. Furey (1991) describes archaeological excavations at a site on the Coromandel Peninsula, 120 km away. The Furey (1991) report was presumably cited because it provides timing for Māori occupation at the Coromandel Peninsula site of AD 1360–1450 and this may be correlated with Māori occupation at Okiwi. The NZPD lists the age of the Okiwi deposit as AD 1450–1480 based on stratigraphic correlation (i.e. no samples from Okiwi have been dated). Given the considerable uncertainty about what evidence for a paleotsunami exists at Okiwi we consider this an unreliable record.

The final site on Great Barrier Island in the NZPD is Medlands Beach (Figure 3.1), where the description says "pebbles in sand" and it has a moderate validity ranking. The primary reference is an archaeological report by Butts and Fyfe (1978) and the deposit is dated by correlation to other nearby sites and given the estimated age of AD 1450–1480 (we presume the correlation was made to the Whangapoua Bay gravels which are assigned the same age). Butts and Fyfe (1978) describe numerous archaeological sites in the southern Great Barrier Island area, and we can deduce the paleotsunami entry for Medlands Beach relates to sites N30-1/152 and N30-1/153 which are described as: "[site 152]: Midden. Shell (primarily tuatua), oven stones, obsidian, waste flake, scattered over a 30 sq. m. area of sand dunes, 55 m from sea. [site 153]: Shell (mainly tuatua), chert waste flake, oven stones, obsidian, covering 35 sq.m. Marble also present." These descriptions have some similarity to the gravel sheet at Whangapoua Bay and they have clearly been deposited post-Māori occupation as oven stones and flakes are incorporated. However, it is not compelling from the description that the Medlands Beach deposit is a tsunami deposit because it is also consistent with a large midden, and most proxies assigned to this site are fairly generic such as "replication" (i.e. it is similar to other deposits nearby) and presence of tsunami geomorphology. Given the sparse information about this site, we consider it an unreliable record of paleotsunami. If the deposit could be relocated, an experienced archaeologist would be required to understand if the deposit is anomalous or not.

One paleotsunami record is in the NZPD from the Mokohinau Islands, an isolated island group 25 km northeast of Great Barrier Island (100 km NNE of Auckland city, not shown on Figure 3.1). The paleotsunami observation is of moderate validity and is described as “pebbles and gravel overlie soil on hillside”. The primary reference is an archaeological report by Moore (1985). We presume the inferred paleotsunami evidence relates to the descriptions of “Scatter of obsidian, charcoal, shell over area of at least 50 m x 20 m” and “well-rounded cobbles, minor obsidian on flat area”. The islands have a history of occupation for mutton birding and there are natural outcrops of obsidian. This record is hard to assess because the archaeological observations are very brief, but it seems most scattering of pebbles and gravels is explained by middens, gardening and areas of obsidian working.

3.2.2 Auckland Mainland and Hauraki Gulf Islands

The NZPD lists 10 sites on the east coast of the Auckland mainland and three on the west coast (Figure 3.1). We review each of these sites from north to south.

Paleotsunami evidence at two sites at Mangawhai (Mangawhai Beach and Molesworth Head) relates to archaeological evidence and both sites are considered “moderate” validity. At Mangawhai Beach there is a pebble layer in sand dunes and archaeological evidence shows a change in midden shell species. Changes in shell species within middens has been proposed by McFadgen and Goff (2007) as a potential indicator of tsunami: “[extract from McFadgen and Goff 2007] Middens are the repositories of food refuse left over from the consumption of animals, by far the greater part of which will be the remains of food collected nearby. Tsunamis can create new environments, erode existing sandy environments, and change the depth and extent of coastal lagoons and estuaries, and as such, they can eliminate or severely curtail some animal species, and enhance the availability of others.” McFadgen and Goff (2007) also acknowledge several other processes can change the availability of shellfish including overfishing and environmental changes. Pearce (2001) describes the midden at Mangawhai Beach in an archaeological report. There is a change from cockle-dominated midden to tuatua-dominated midden and the author attributes this to a change in gathering location from the estuary to the open beach. Stratigraphic descriptions in Pearce (2001) do not show a sand or pebble layer intervening between the different middens, so we assume the pebble layer is located elsewhere. Overall the strength of paleotsunami evidence at Mangawhai Beach is equivocal and largely hinges on a change in midden composition, for which there are other explanations aside from tsunami. At Molesworth Head, the paleotsunami evidence consists of sand and Loisels pumice overlying a Māori occupation horizon and it is suggested that a tsunami caused remobilisation of the sand, although there could be other explanations. The primary reference is Wellman (1962) which gives a brief description of a stratigraphic section with “light yellow sand” above a “earthy sand” with “rare charcoal and shells” (presumably an occupation layer?) and below a “occupation layer” (Figure 3.2). Loisels pumice is often referred to in archaeological and geological studies along the northern New Zealand coast, it is a sea-rafted pumice sourced from Tonga-Kermadec arc volcanoes. Early research suggested it has an age of ~650 yrs BP but later research found the Loisels pumice has multiple sources and may have varying ages between 1500–600 yrs BP. The use of Loisels pumice as a stratigraphic correlation marker or reliable indicator of post-Maori era in New Zealand is questionable (Shane et al. 1998), but there remains debate about this (Lowe et al. 2000).

SECTION 33.—*Molesworth Headland* (*N29, 108539*)

Loose blown sand	2.0ft
Occupation layer, weak, grading into dark soil	0.7ft
Light yellow sand with shells and charcoal	2.0ft
Loose sand with rare Loisels Pumice at base	0.2ft
Earthy sand, rare charcoal, and shells	0.2ft
As above, no shells or charcoal. Very rare Leigh pumice	0.4ft
Brown dune-sand. Road level 50ft above sea level	4.0ft

Figure 3.2 Screenshot of a description of the stratigraphy at Molesworth Head by Wellman (1962).

At both Mangawhai sites, the paleotsunami age is inferred in the NZPD to be AD 1450-1480 by correlation to nearby sites. There is no direct radiocarbon dating at Molesworth Head but at Mangawhai Beach shells from the middens were dated by Pearce (2001) at 452 ±44 yrs B.P. and 349 ± 35 yrs B.P. This implies the change in midden composition occurred between AD 1450–1540 and AD 1570–1640, consistent with the age inferred in the NZPD.

At Omaha Beach, a moderate validity paleotsunami record is described as “gravel/pebbles in sand” with the further description of “Pebbles in association with early (Archaic) occupation. These were large middens nearer the sea as opposed to later ones that were further inland”. In the primary reference material, an archaeological report by Campbell and Clough (2002), ovenstones were described as part of middens but we cannot find any reference to pebble layers in sand. We assume the reference to an age-pattern in the spatial distribution of middens implies that occupation may have moved landward following a tsunami. Campbell and Clough (2002) say there were “interesting patterns” in midden distribution but partly attribute this to historic sand dune quarrying that may have destroyed some midden sites and note they did not have radiocarbon ages on the middens to determine spatial variation with age. A later more detailed and final report on Omaha archaeology by Bickler et al. (2003), which had the benefit of 17 radiocarbon ages stated: “there is no obvious trend in the distribution of sites in time with the sites scattered across the landscape covering the range of dates”. We suggest the Omaha Beach record of paleotsunami should have a lower validity ranking than moderate or be removed from the database as there is no compelling evidence of paleotsunami in the primary reference archaeological reports.

At Tawharanui two large sand washover lobes have been identified and dated in the back-barrier wetland (de Lange and Moon 2007). This is one of the more robust studies of paleotsunami in the Auckland region and the study incorporates extensive mapping, augering and sedimentology, with tephrochronology for age control. The sand lobes partially infill wetlands behind a sand dune barrier, the lobes extend up to 450 m inland and decrease in elevation further inland. The lobes are composed of well-sorted medium to fine sand with very few shell fragments; the sand is similar to the dune ridge but differs from the modern beach by the lack of shells. The sand lobes overlie Loisels pumice, charcoal and Kaharoa tephra, therefore they are interpreted to be <~600 yrs BP (post-dating Kaharoa tehpra). De Lange and Moon (2007) suggest tsunami is the most likely process by which the sand lobes were deposited, and they reason that Tawharanui is particularly positioned to amplify tsunami wave heights. Alternative processes considered are dune destabilisation and storm surge. Dune mobilisation is discounted because the orientation of the sand lobes differs from the orientation of recent dune blowouts and a water-borne process is required to transport the Loisels pumice seen in the margins of the sand lobes. Storm surges are discounted because they reason the dunes are too high (at 5.5 m elevation) and storm wave heights are not particularly high in the Hauraki Gulf due to limited fetch. The authors tentatively attribute the tsunami source to a submarine volcano, possibly the same eruption that produced the Loisels pumice (although, as discussed above the precise age of the Loisels pumice is not well constrained). Evidence for paleotsunami in the NZPD at Tawharanui is also obtained from archaeological records (Judge et al. 2005; Lawlor 2004); the NZPD notes “gravel/pumice over occupation”. Our examination of Judge et al. (2005) cannot find reference to gravel and pumice over an occupation horizon but two pits certainly show sand overlying midden/occupation layers (charcoal and oven stones). There is no mention within the archaeological report of anything anomalous or unusual about the stratigraphic sequence. Overall, we agree with the NZPD that Tawharanui is a “moderate” validity site; the sand lobes are compelling evidence of paleotsunami, but we are not as confident with dismissing dune blowout and storm surge as plausible processes given the dune field may have changed in height over time.

There are four locations in the inner Hauraki Gulf islands that have potential paleotsunami evidence attributed to the eruption of Rangitoto in ~AD 1400, these are on Motutapu Island, Waiheke Island, Tiritiri Matangi Island and Motuihe Island. The evidence for paleotsunami consists of gravel or shell layers within sand, reworked occupation layers and gravel layers in between occupations horizons. Three sites have radiocarbon dates on material above or below the inferred tsunami deposit. The record for Waiheke Island is of “poor” validity within the primary reference material of an archaeological report (Law 1975): it is difficult to distinguish what “gravel/shell” layer has been interpreted as a potential tsunami deposit. The report describes one soil profile that has evidence of multiple phases of reoccupation for Māori gardening. Gravel lenses are described in the section, but the accompanying discussion suggests gravel and sand was moved by Māori for gardening purposes. Evidence for paleotsunami on Motuihe Island, described as “shell and gravel in sand”, and the event notes say “beneath poorly developed soil on windblown sand. Could be anthropogenic”. We cannot locate the primary reference material for this record, it is in a 2005 conference abstract that cannot be found online so it is hard to re-evaluate the quality of this paleotsunami record. Similarly, the primary references for Tiritiri-Matangi Island and Motutapu Island cannot be located so these are also difficult to thoroughly evaluate. The Tiritiri-Matangi Island paleotsunami evidence is gravel (described as “lumps of coastal platform”, McFadgen 2007) between occupation horizons and bracketing radiocarbon ages suggest there is an age correlation to the ~AD 1400 eruption of Rangitoto. However, the primary references are a 2001 conference abstract and a “pers. comm.” and neither of these can be verified. The paleotsunami evidence on Motutapu Island is “Reworked occupation/ash layers” and the primary reference is a 1988 PhD thesis from the University of Auckland (Nichol 1988). This thesis is not accessible online so the evaluation of this paleotsunami record is incomplete. Motutapu Island has a rich archaeological history and other well-documented coastal archaeology sites show complex occupation histories and highly variable sediment sequences (e.g. Davidson and Leach 2017) but we could not find any other documentation of possible tsunami deposits or reworking of archaeological horizons near the time of Rangitoto eruption. McFadgen (2007) described the distribution of Rangitoto ashfall on Motutapu Island but indicates there is no recognition of tsunamis within the archaeological deposits even though McFadgen (2007) is listed as a primary reference for the Motutapu Island paleotsunami site in the NZPD. Overall, we find the reliability of the four sites with paleotsunami evidence attributed to the eruption of Rangitoto to be very weak. All records appear to relate to archaeological evidence and none could be substantiated through the primary references.

The final two sites on the east coast of Auckland are at Orewa and Kawau Island. The Orewa paleotsunami record relates to a pūrākau and the primary reference is a magazine article from 1997 that we cannot locate. The notes for this record in the NZPD say it is “a Māori prophecy that one day a tidal wave will sweep Orewa off the earth". The Kawau Island record is a "pers. comm." observation of "gravels on surface" with a note that it "needs further work". We consider both of these records unreliable as evidence of paleotsunamis. The Kawau Island record cannot be verified and the source of knowing about the pūrākau related to Orewa and the context from which it probably has been removed, make this record unreliable.

There are three records of paleotsunami from the west coast of the Auckland mainland; two are from within Manakau Harbour and one from Kaipara Harbour. All three records have a "poor" validity ranking in the NZPD. One record from Manakau Harbour is a pūrākau and primary reference material for this is inaccessible (an email), but it was included in a review of Māori oral traditions and natural hazards science by King and Goff (2010). The other record from Manakau Harbour is an observation of stacked boulders at Pilot Station by Ferdinand Hochstetter, published in a magazine in 1862. Our re-examination of Hochstetter's writings about New Zealand showed he stayed at the pilot station at Whatipu and he writes that at the foot of the cliffs north of Whatipu "deep caverns are seen washed out, in the background of which large masses of boulders are deposited. This would indicate a former period, when the surge washed the rocks themselves and piled up these masses." The caverns are sea caves separated from the Tasman Sea by sand dunes and beach and any boulders formerly observed inside them are now beneath the windblown sand. We agree with Hochstetter's original assessment that the boulders would have been washed in by the sea when the sand barrier was not in front of the sea cave, i.e. they are probably a high tide boulder beach, similar to other boulder beaches seen along the west coast such as at O'Neill Bay. Tsunami deposition, as inferred in the NZPD, is an unlikely explanation for the boulder accumulations at the back of the sea caves.

The Kaipara Harbour paleotsunami entry relates to a pūrākau of an eroded island, the NZPD notes say "Māori oral record tells that soon after arrival of Mahuhu canoe the land was shaved off by the sea (storm/tsunami/natural processes?)" and more detail is given in King and Goff (2006) where it says people settled at Taporapora around AD 1300 and lived there for many years but "then the place was 'shaved off by the sea', the land disappeared and 'all were carried away by the sea'". King and Goff (2006) discuss how this record could relate to a large storm, but a tsunami cannot be ruled out. We agree with the NZPD that each of these three west coast paleotsunami records are of poor validity. There are few tsunamigenic sources on the west coast of the upper North Island and combined with the low veracity paleotsunami records, it is hard to evaluate the tsunami hazard for the west coast from paleotsunami evidence.

3.2.2.1 Other Paleotsunami Studies in the Auckland Region

The NZPD was created in 2017 and is the most recent compilation of paleotsunami evidence in Auckland but there is some earlier literature about paleotsunami in Auckland and some additional paleotsunami evidence that is not in the database. The Goff et al. (2005) study is a consultancy report for the Auckland Regional Council that updates an earlier report on Auckland tsunami hazard by de Lange and Hull (1994). Specific to the Auckland region, Goff et al. (2005) provide an overview of potential tsunami sources, a discussion of historic and prehistoric tsunamis, estimates of magnitude and frequency, a general overview of wave interaction with the coast, an assessment of uncertainties and gaps in knowledge, and recommendations for further studies. Goff et al. (2005) describe evidence for five prehistoric tsunamis affecting the Auckland region in the past ~2600 years. However, the paleotsunami sites relating to three of these events are located in the Bay of Plenty and the tsunamis are inferred to have impacted Auckland because the events were interpreted as region-wide events, i.e. there is no physical evidence for these paleotsunamis reaching the Auckland region. One paleotsunami is inferred from archaeological evidence of land subsidence in the Hauraki Gulf (no evidence for the paleotsunami associated with the subsidence was recorded) and one of the paleotsunamis was inferred to be from the eruption of Rangitoto. Six paleotsunami sites in the Auckland region were described in an Appendix in Goff et al. (2005) and these sites have been incorporated into the NZPD (reviewed above). In the course of our field reconnaissance site selection we also found evidence of a paleotsunami deposit at Kaitoke, Great Barrier Island, and this is further discussed in the following section.

3.2.2.2 Summary of Previous Paleotsunami Research in the Auckland Region

Our review of paleotsunami evidence for the Auckland region has found three sites that have relatively strong evidence of paleotsunami: Tawharanui, Whangapoua Beach and Harataonga Bay (Figure 3.3). The dating of paleotsunamis at each of these sites is relatively poor, and it is currently hard to evaluate if there are temporal correlations between each of the records. The Tawharanui paleotsunami observation may correlate with the Whangapoua Beach gravel as both may have occurred post-Māori occupation and both have been tentatively correlated with the Tonga-Kermadec arc volcanic eruption that produced the Loisels pumice. There is, however, uncertainty about the age of the Loisels pumice and the Whangapoua Beach gravel. The Harataonga Bay paleotsunami deposit is significantly older at ~3000 yrs BP and does not appear to correlate with the Tawharanui or Whangapoua Beach records, unless the interpretation that the Whangapoua Beach gravel was deposited after Māori occupation is incorrect. The remainder of the sites have very weak evidence of paleotsunami, but part of the reason for this is the reliance on re-interpretation of archaeological records. The expertise of an archaeologist would be helpful in understanding how robust some of the paleotsunami evidence related to archaeological sites is. Our brief summary of the NZPD sites in the Auckland region is presented in Figure 3.3.

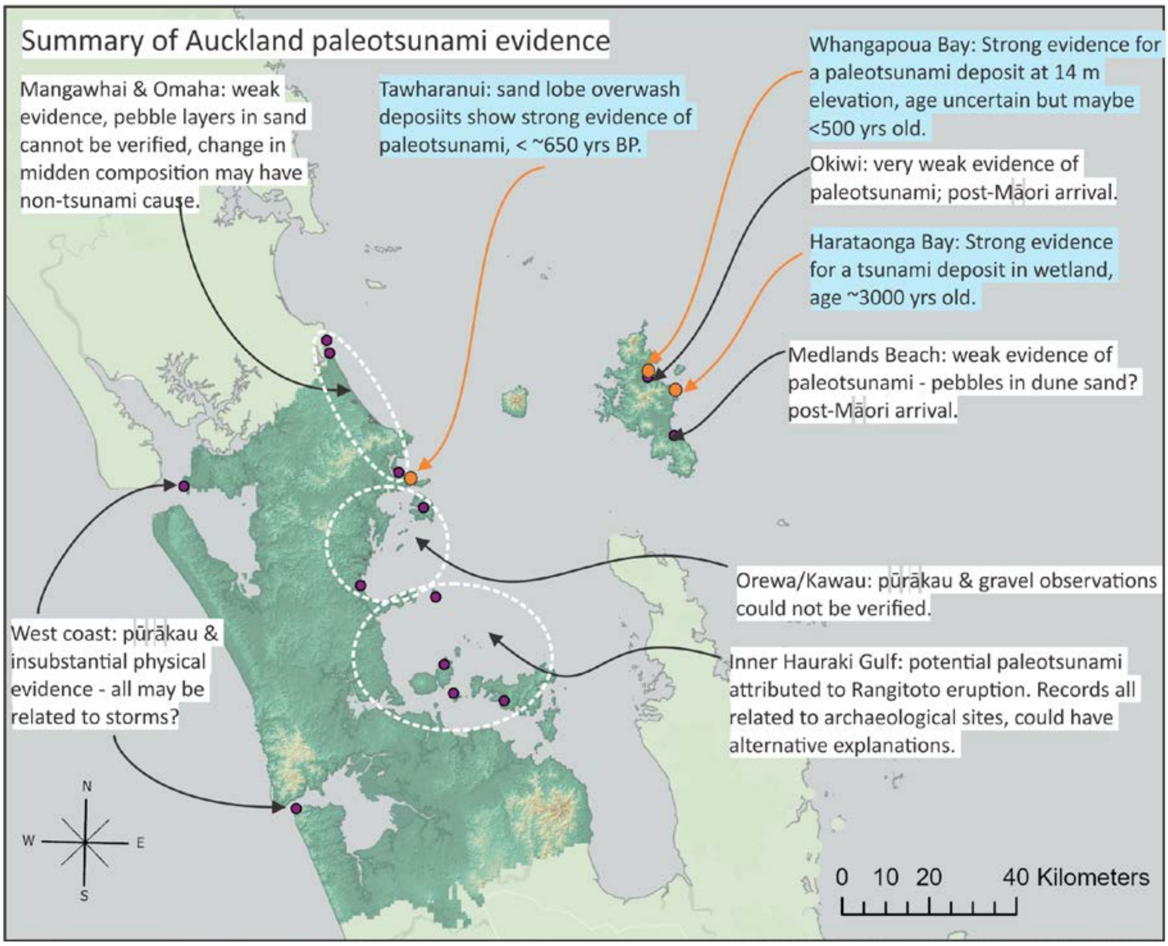


Figure 3.3 Summary of the NZPD sites in the Auckland region.

4.0 PALEOTSUNAMI FIELD WORK SITE SELECTION

4.1 Objectives

An objective of this project was to undertake reconnaissance-level field work at 3 to 4 locations around Auckland to better assess paleotsunami evidence. Although we have reviewed 18 sites listed in the NZPD, only three of these sites were purposely studied and evaluated for paleotsunami evidence (Whangapoua Bay, Nichol et al. 2003; Harataonga Bay, Nichol et al. 2007; Tawharanui, de Lange and Moon, 2007). To our knowledge, there has not been a targeted field search for paleotsunami deposits in the Auckland region. This means that potentially some ideal paleotsunami preservation sites may have been overlooked. The Auckland coastline is 3700 km long and traversing every bit of coastline is impractical. The following section describes our method of rationalising a shortlist of locations for field study.

4.2 Field site selection method

Field study sites were evaluated on the basis of three main factors:

1. Previous work: where previous work (reviewed in section 3) indicated a site has significant potential for credible paleotsunami evidence, we considered this evidence and evaluated whether the site should be re-examined. In some cases, we decided it was important to try to gather more data (e.g. select more radiocarbon samples) to better constrain an identified paleotsunami deposit, or we decided to look at more locations in the same area to see if an identified paleotsunami deposit was preserved elsewhere.
2. Tsunami modelling: Tsunami modelling of Kermadec Trench earthquakes was used to identify parts of the Auckland coastline along which tsunami wave heights are expected to be particularly high. These coastal areas were considered a higher priority for field study as they may be more vulnerable to inundation than other areas, thus more likely to preserve a paleotsunami record. The tsunami models are further described below.
3. Depositional environment: Using local knowledge, aerial photography and satellite imagery we sought coastal locations that may preferentially preserve paleotsunami sediments. Preferred depositional environments are: back-barrier coastal wetlands, dune swale wetlands, lagoons and coastal lakes. These sheltered, low-energy depositional environments act as sediment sinks for material transported landward by tsunamis.

A final practical consideration for each site was the accessibility of the site and any permits that would have to be obtained before undertaking field work. On Great Barrier Island we found that most sites we considered for field work were either private land or Department of Conservation (DOC) land. The DOC granted us a Research and Collection Authorisation (Authorisation 64103-GEO) for all sites on Great Barrier Island and we consulted with Ngāti Rehua Ngātiwai ki Aotea about this field work. On the Auckland mainland most sites were either private land or in Auckland Regional Parks. We tried twice to obtain a permit for undertaking research within the following regional parks: Tawharanui Regional Park, Wenderholm Regional Park, Mahurangi Regional Park, Shakespear Regional Park. The first application in 2016 was stalled due to the Kaikōura earthquake response. The second attempt in 2019 progressed further but Auckland Council Parks representatives asked us to consult with Heritage New Zealand. Our enquiries to Heritage NZ in regard to the Auckland Regional Parks permit were unanswered. Our previous experience in consulting with Heritage NZ has shown that obtaining archaeological authorities is a lengthy (and costly) exercise and it was considered well beyond the scope of this project, so we did not progress the application with Auckland Council any further. In advance of all field work we consulted the ArchSite database of New Zealand archaeological sites and made sure we were aware of nearby known archaeological sites but most of our coring was in wetlands and estuarine margins where the risk of accidentally disturbing archaeology is exceptionally low. Although we were not granted a permit for the Auckland Regional Parks we include them in our site selection report below for completeness.

4.3 Tsunami models

The Auckland region could be affected by tsunamis from a number of sources but the largest tsunamis are expected to be generated by large earthquakes on the Kermadec Trench and the southern New Hebrides subduction zone (Figure 4.1 and Figure 4.2, Power et al. 2013). The tsunami models show that of these two source regions, the Auckland region is more affected by Kermadec Trench tsunamis. Southern New Hebrides tsunamis are expected to have a greater impact north of Auckland. Figure 4.2 shows the east coast of Great Barrier Island is likely to see the largest wave heights from Kermadec Trench sources. Figure 4.3 shows that on the Auckland mainland, sites north of Tawharanui are likely to see the largest wave heights from Kermadec Trench sources and the embayments of Pakiri-Mangawhai Heads, Omaha, Tawharanui and Orewa show some amplification of wave heights. We used these tsunami models as a guide to site selection, but low modelled tsunami wave heights at a certain location was not considered enough on its own to rule out a site. At a local scale numerous factors such as bathymetry, coastal geomorphology, offshore island wave refraction, local resonance phenomena and wrap-around effects can influence tsunami wave height and these complexities are not shown by the coarse models we have used here.

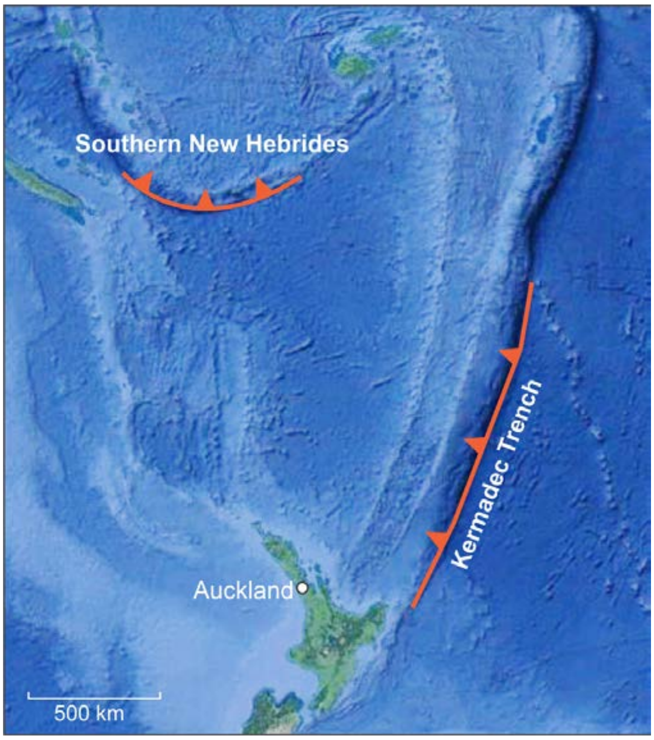


Figure 4.1 Location of the southern New Hebrides subduction zone and the Kermadec Trench, the sources of the largest tsunamis to impact northern New Zealand.

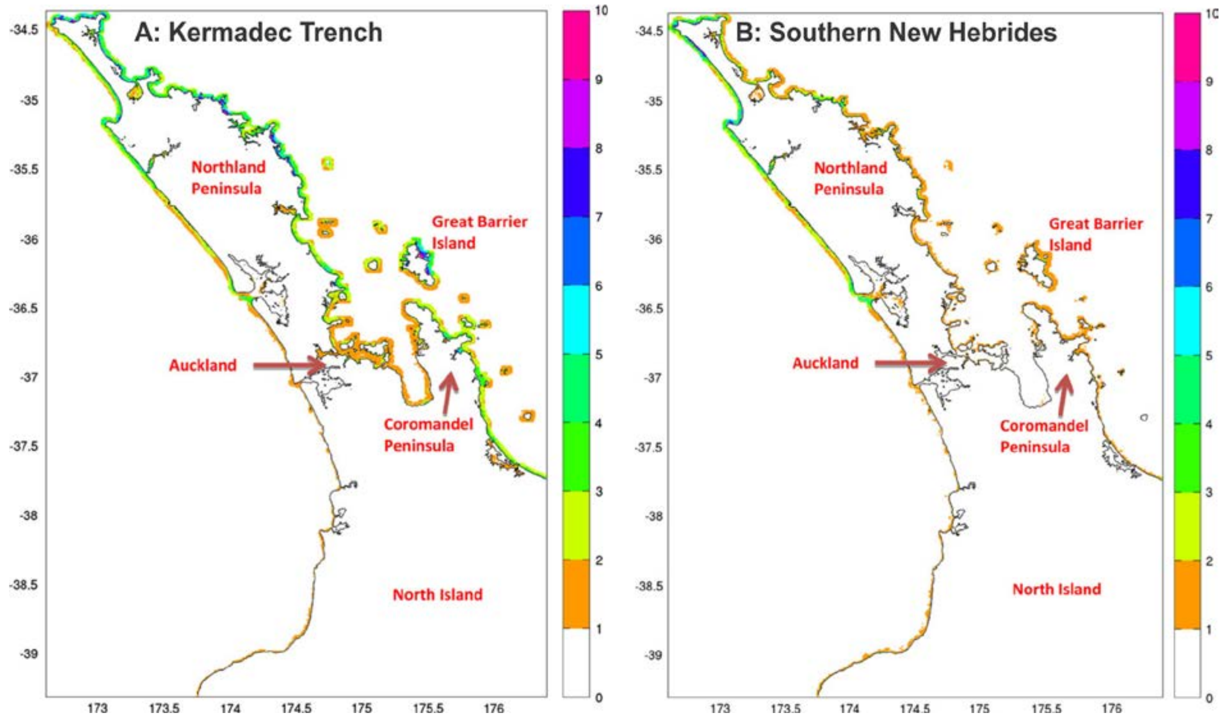


Figure 4.2 Estimated 2,500 year 84th percentile tsunami hazard from the Kermadec Trench (A) and the southern New Hebrides Trench (B), expressed in terms of the maximum water level in metres. Figures from Power et al. (2013).

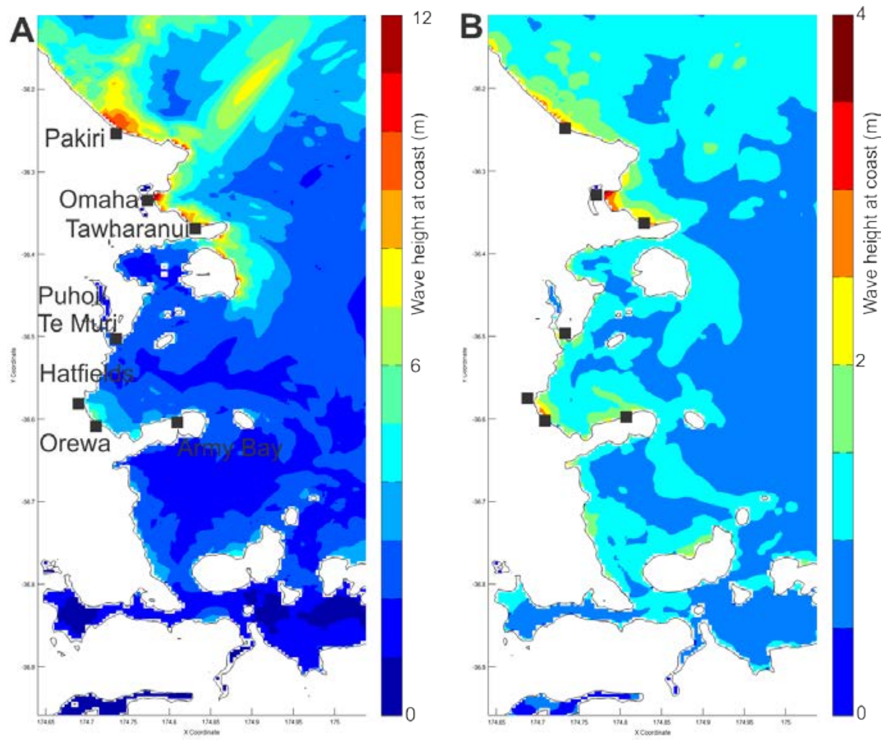


Figure 4.3 Two tsunami models of Kermadec Trench subduction earthquakes showing the wave height around the Auckland mainland coastline. Black squares show the locations of potential field study locations. A: Mw 9.2–9.3 earthquake on the southern Kermadec Trench; B: Mw 9–9.1 earthquake near Raoul Island. Note the difference in scale. These two scenarios illustrate that coastal sites from Tawharanui and north are likely to see greater wave heights from Kermadec Trench sources compared to the coastline further south which is somewhat shielded by Great Barrier Island. Source: William Power, GNS Science.

4.4 Potential Field Sites: Great Barrier Island

In the following section we describe each potential field site and discuss reasons why each was considered suitable for paleotsunami research. At the start of each site is a table that summarises the main selection criteria as follows:

- **Previous paleotsunami research** (has previous work been undertaken at this site related to paleotsunami?): Yes/No.
- **Tsunami modelling** (does tsunami modelling indicate the site is exposed to significant tsunami wave heights? (tsunami models referred to are described in previous section): High (generally wave heights > 5 m), Moderate (generally wave heights 1–5 m, Low (wave heights < 1m).
- **Suitable depositional environment** (is there an area that is likely to preserve paleotsunami sediments?): Yes (good sites present)/Moderate (sites are moderately suitable)/No
  (no suitable depositional environments).
- **Accessibility/permissions**: Notes related to land ownership and whether research permits are required.
- **Suitable?** (Our conclusion about whether a site was considered suitable for paleotsunami field work when taking into account all the factors listed above): Yes/No.

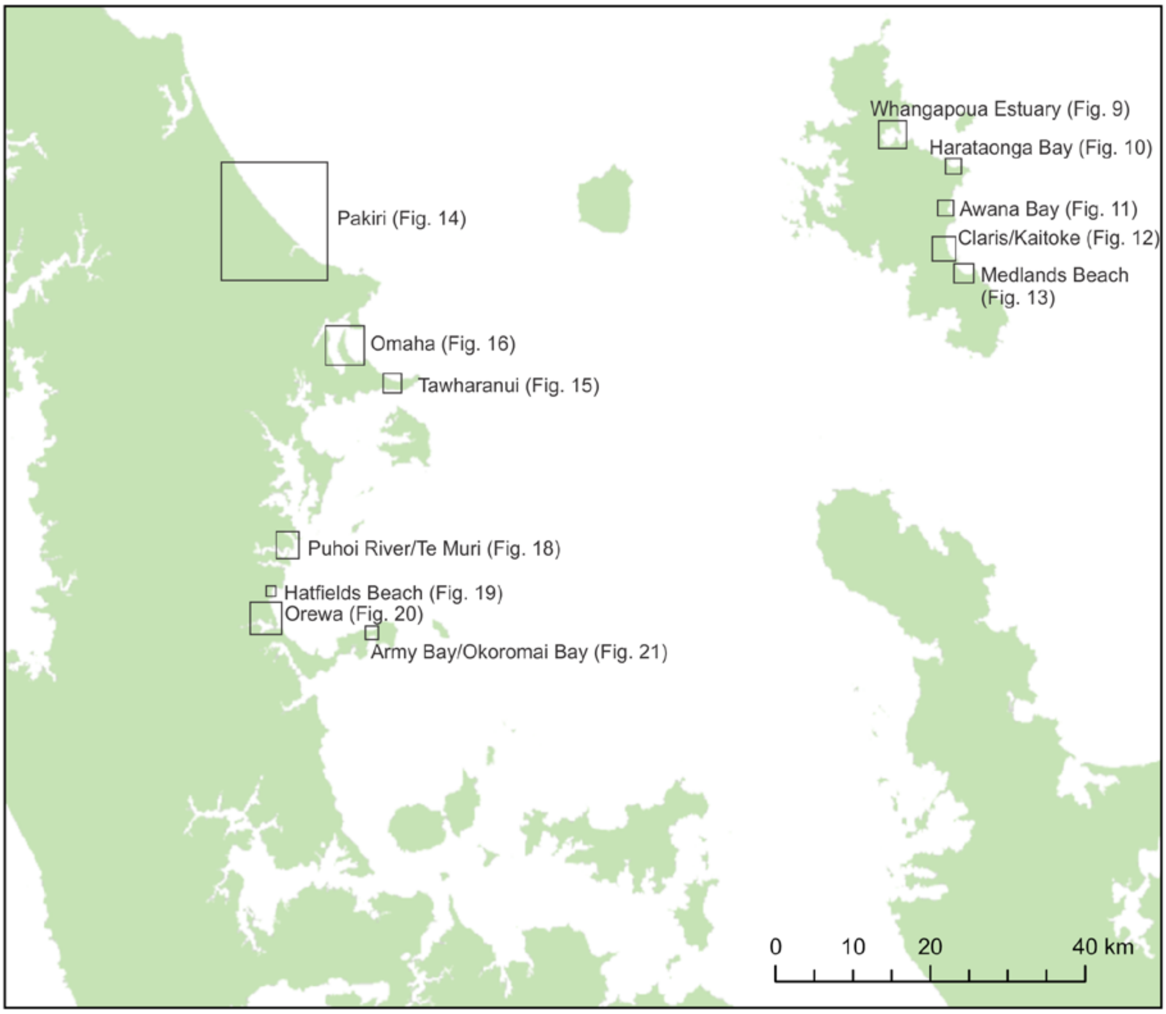


Figure 4.4 Locations evaluated for paleotsunami field work in the Auckland region. Each box shows the map extent of Figure 4.5–4.17.

4.4.1 Whangapoua Estuary, Whangapoua Bay and Okiwi Area

Previous paleotsunami research	Tsunami modelling	Suitable depositional environment	Accessibility / permissions	Suitable?
Yes	High	Yes	DOC Permit required	Yes

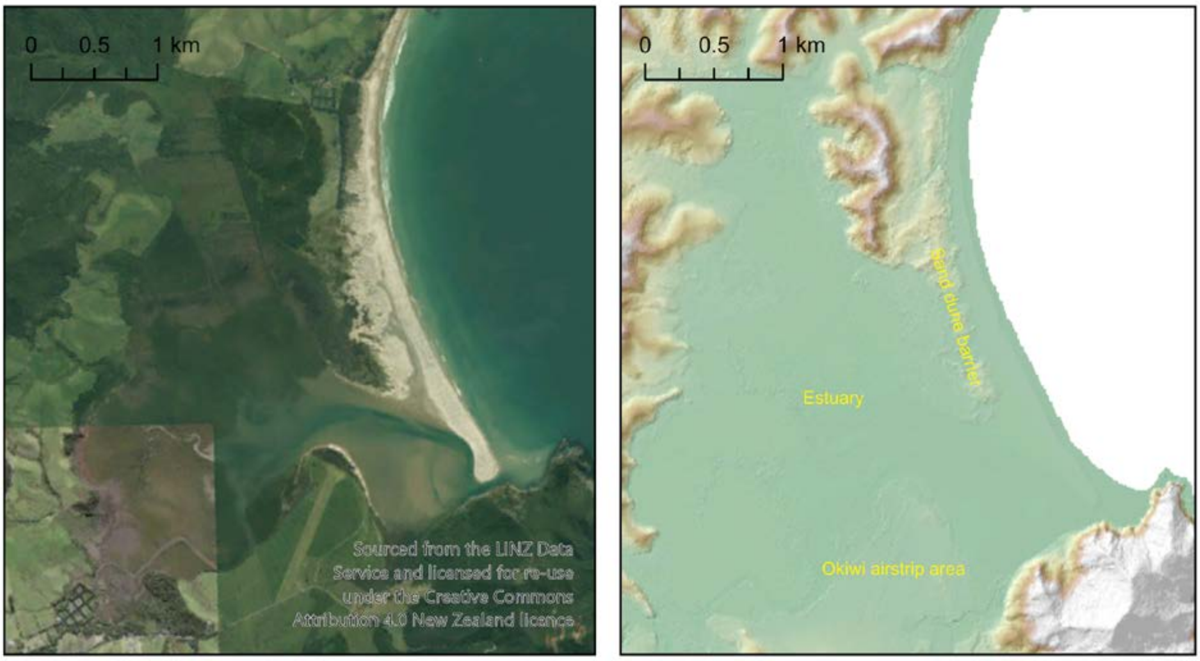


Figure 4.5 Whangapoua Bay area (including Okiwi airstrip). Left: satellite image, right: shaded hillshade lidar image.

Previous work at Whangapoua Beach (Figure 4.5) has shown an extensive gravel sheet within sand dunes that has been attributed to a tsunami (Nichol et al. 2003, see discussion above). Tsunami models show northern Great Barrier Island is especially prone to large wave heights (>7 m at the coast) from Kermadec Trench sources (Figure 4.2). Compelling reasons to revisit the Whangapoua area include:

1. search for additional material to constrain the age of the Whangapoua Beach gravel sheet,
2. explore in the sheltered Whangapoua inlet behind the sand dune barrier for evidence of tsunami, and
3. check the Okiwi airstrip area. The Okiwi airstrip area is aligned with the Whangapoua Estuary entrance so any tsunami that enters the inlet may wash over the airstrip.

Reviewed paleotsunami evidence from this site is unreliable. The estuary was considered prospective for paleotsunami because if a large tsunami washed gravel up to 14 m above sea level (Nichol et al. 2003) then it may have also entered the inlet and left sedimentary evidence of disturbance within estuarine sedimentary sequence. A tsunami could also potentially wash over the dune barrier in places where the dunes are low enough. Sediment cores have been collected from Whangapoua estuary but the purpose of these was to understand the impacts of Māori and European people on estuarine vegetation and the rate of estuarine sedimentation

(Ogden et al. 2006). We cannot find stratigraphic logs of the cores, but the description mentions some anomalies:

> *"......sediment accumulation appears to have been continuous. However, two sites nearer the present estuary entrance (E1 and E3) contain hiatuses and evidence of periods of sediment disturbance. The sand spit may have been breached once by a tsunami surge during the Polynesian period (Nichol et al. 2003). Such events would probably have caused changes in sediment accumulation patterns and successional processes, but there is no evidence that the infilling process has been affected at sites in the upper estuary."*

A permit was acquired for the Whangapoua sites from the DOC.

4.4.2 Harataonga Bay

Previous paleotsunami research	Tsunami modelling	Suitable depositional environment	Accessibility / permissions	Suitable?
Yes	High	Yes	DOC Permit required	Yes

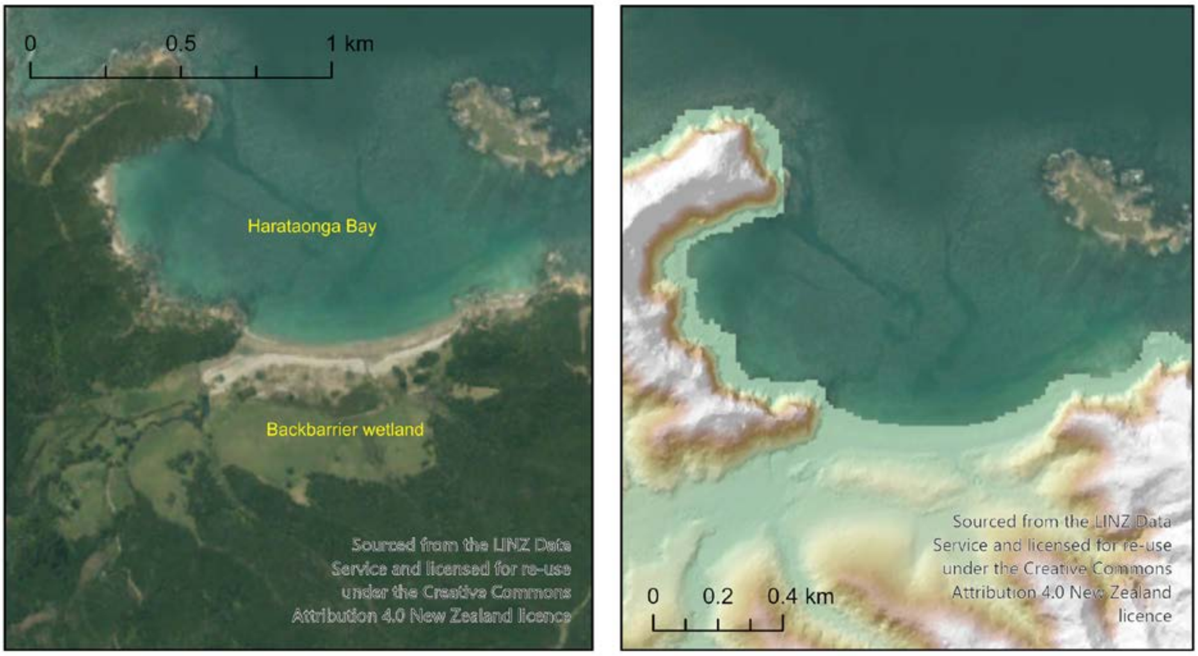


Figure 4.6 Harataonga Bay area. Left: satellite image, right: shaded hillshade lidar image and digital elevation model.

Previous work at the back-barrier wetland in Harataonga Bay (Figure 4.6) found evidence for a paleotsunami. Our reasons for wanting to revisit this site were (1) to obtain more material for dating because there was sparse age control in the first study and the paleotsunami age was inconsistent with the gravel sheet age at Whangapoua Bay, and (2) replicate the original findings across more sediment cores. The study by Nichol et al. (2003) collected two cores 1 m apart. We wanted to trace out the paleotsunami deposit to see if its spatial distribution was consistent with a marine source. Tsunami modelling indicates the site is exposed to large waves from Kermadec Trench tsunami sources (Figure 4.2) and a permit was obtained from DOC.

4.4.3 Awana Bay

Previous paleotsunami research	Tsunami modelling	Suitable depositional environment	Accessibility / permissions	Suitable?
No	Moderate	Yes	DOC Permit required / private land	Yes

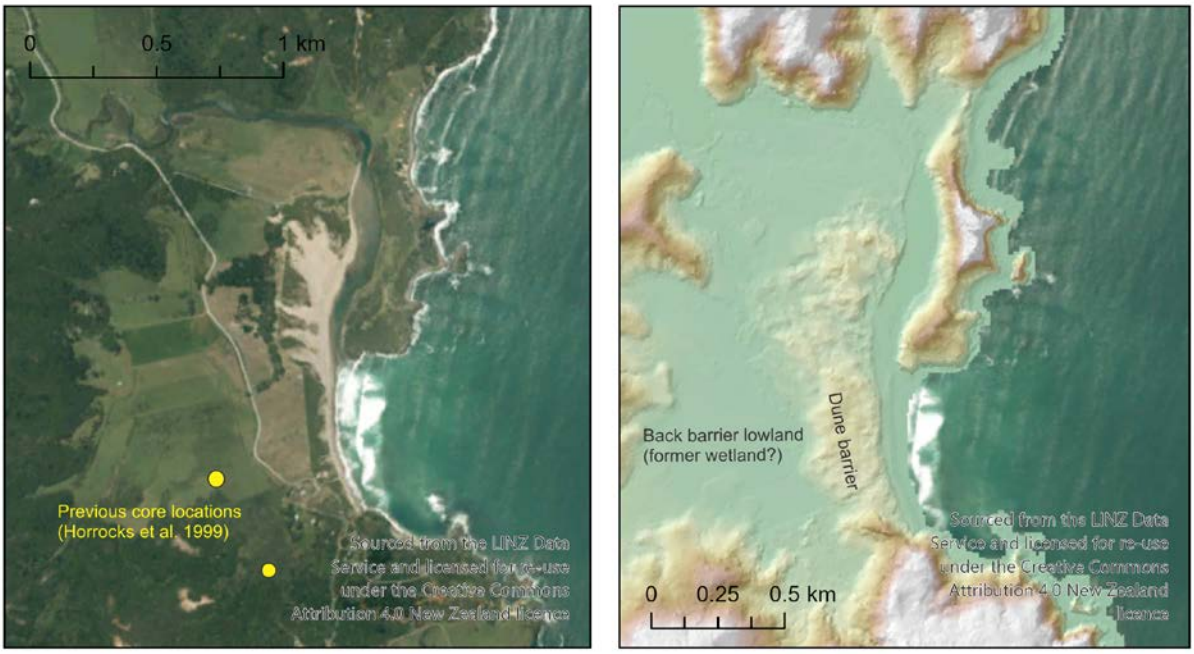


Figure 4.7 Awana Bay area, locations of sediment cores collected by Horrocks et al. (1999) shown in yellow. Left: satellite image, right: shaded hillshade lidar image and digital elevation model.

Awana Bay has not been the subject of previous paleotsunami research, but it has an extensive low lying back-barrier wetland that is a suitable depositional environment for paleotsunami sediments (Figure 4.7). Like most of the east coast of Great Barrier Island, relatively high wave heights at the coast are forecasted for Awana Bay due to large Kermadec Trench tsunamis (Figure 4.2). However, the sand dune barrier is relatively high at 15–20 m at the barrier crest so tsunami heights would have to be exceptionally high to overtop it. Tsunamis could potentially flow up the river, but the convoluted shape of the river mouth means tsunami energy would probably be rapidly dissipated. Previous work related to understanding the paleoecological history of the back-barrier swamp was undertaken by Horrocks et al. (1999). They collected two sediment cores from the back-barrier swamp, the cores were up to 5.5 m deep and dated back to ~7000 yrs BP (Figure 4.7). Most of the cores were freshwater peat deposits but near the top of one core were beds of medium sand:

> *"the preservation of thin beds of medium sand within the upper 2 m is evidence of episodic fluctuations in depositional energy. In the context of the geomorphic setting for this site, it is therefore probable that these deposits are the product of aeolian processes, and variations in sand size are a record of major fluctuations*

(storm related?) in wind energy and/or changes in vegetation cover on the nearby dunes".

Our aim at Awana Bay was to explore the back-barrier wetland, relocate any sand beds and date them to see if there was an age correlation to any other paleotsunami evidence. Land ownership is a mixture of private land and DOC land and a permit from DOC was acquired.

4.4.4 Claris / Kaitoke Area

Previous paleotsunami research	Tsunami modelling	Suitable depositional environment	Accessibility / permissions	Suitable?
No	Moderate	Moderate	DOC Permit required / private land	Yes

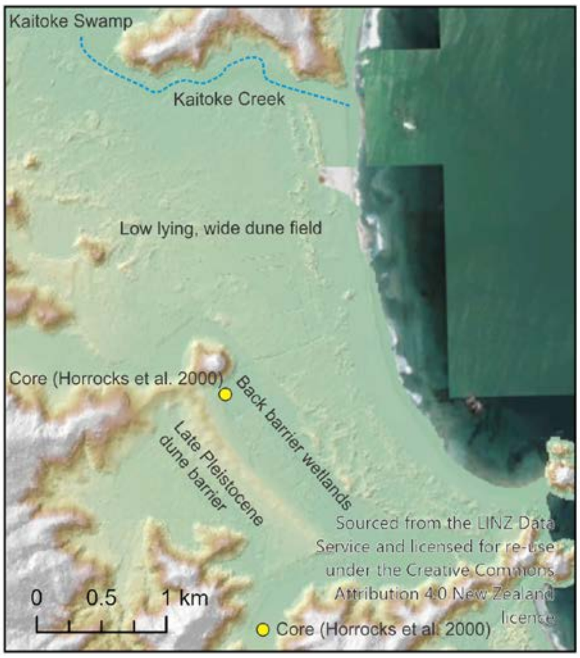


Figure 4.8 Claris and Kaitoke area, locations of sediment cores collected by Horrocks et al. (2000) shown in yellow. Left: satellite image, right: shaded hillshade lidar image and digital elevation model.

The Claris/Kaitoke area (Figure 4.8) has a variety of coastal environments from a wide, relatively low lying Holocene dune field, back-barrier wetlands in the south (now partially drained), a large freshwater swamp up the Kaitoke Creek (called the Kaitoke Swamp) and relict late Pleistocene coastal landforms at the landward margins of the coastal flats (Figure 4.8). Like at Awana Bay, cores have been collected from the southern Kaitoke swamp by Horrocks et al. (2000) for the purposes of understanding paleoecology. The cores track the Holocene progression of the embayment from an estuarine environment to an enclosed freshwater wetland. The southernmost sediment core has some evidence for anomalous sand deposition; at 5.8 m depth Horrocks et al. (2000) describe "....a well-defined erosional contact, marking the transition to a 30 cm-thick bed of fine sand….mixed with angular shell fragments and isolated rip-up clasts of silty mud." This sand is dated somewhere between 7570–7410 yrs B.P. and 5560–5120 yrs B.P. They interpret the sand as "the product of a high energy event, possibly a storm or tsunami surge, that scoured the finer grained estuarine deposits and deposited marine-sourced sand. A flood event is considered unlikely in this instance given the small catchment behind Forsythes' Paddock (<2 km2)”.

Shallower in the core, there were some other slightly anomalous sand units that Horrocks et al. (2000) interpreted as higher energy phases of deposition. These paleoenvironmental histories suggested the Kaitoke swamps may be suitable for paleotsunami studies and tsunami modelling shows moderate wave heights from Kermadec Trench sources (Figure 4.2). The Claris and Kaitoke swamps are a mixture of private and DOC land and a permit from DOC was acquired.

4.4.5 Medlands Beach

Previous paleotsunami research	Tsunami modelling	Suitable depositional environment	Accessibility / permissions	Suitable?
Yes	High	Yes	Private land	Yes

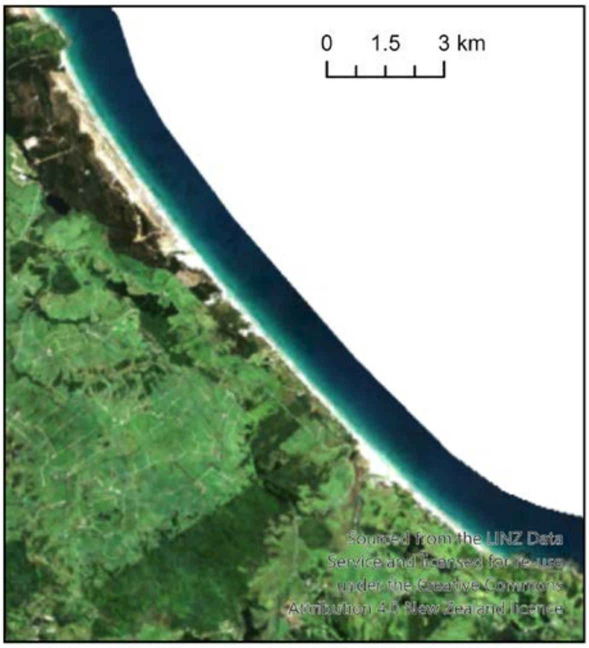
Figure 4.9 Medlands Beach area. Left: satellite image, right: shaded hillshade lidar image and digital elevation model.

The Medlands Beach area (Figure 4.9) has a prominent dune barrier and behind this are low lying swampy wetlands and drained paddocks. The site offers a combination of suitable depositional environments, exposure to Kermadec Trench tsunamis, and some previous work that interpreted paleotsunami evidence from the archaeological record. The dune barrier is relatively high at 10–15 m elevation but inlets at the northern and southern ends of the embayment offer a pathway for tsunamis into the back-barrier environment. The dune barrier has many houses on it so relocating the “pebbles in sand” observed by Butts and Fyfe (1978) is not feasible, particularly without an archaeological authority. The Medlands Beach area is almost entirely in private land ownership.

4.5 Potential Field Sites: Auckland Mainland

4.5.1 Pakiri

Previous paleotsunami research	Tsunami modelling	Suitable depositional environment	Accessibility / permissions	Suitable?
No	High	Moderate	No issues	Yes



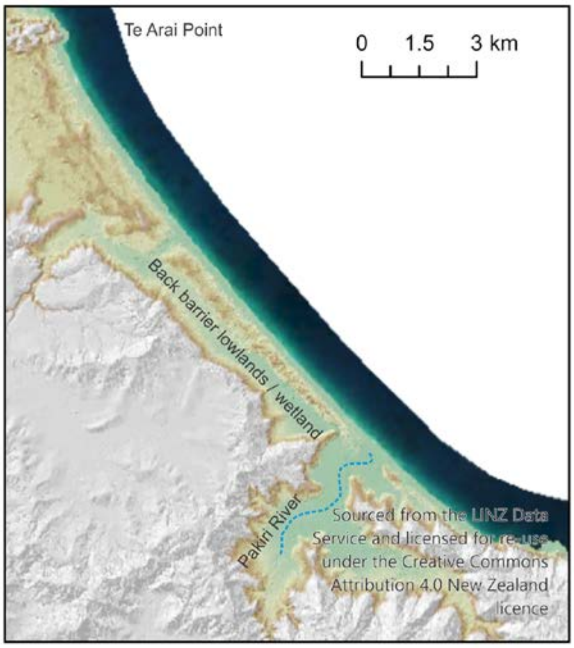


Figure 4.10 Pakiri area. Left: satellite image, right: shaded hillshade lidar image and digital elevation model.

Tsunami modelling suggests the Pakiri coastline (Figure 4.10) could be exposed to relatively high wave heights (>8 m) from Kermadec Trench tsunamis and moderate to low wave heights from southern New Hebrides tsunamis (Figure 4.1 and 4.2). The NZPD has no records from this stretch of coastline but sites exist in the database to the north at Mangawhai and south at Tawharanui. Most of the Pakiri coastline is characterised by a high dune barrier (generally >30 m elevation at the crest) with low elevation (1–2 m) back-barrier flats and wetlands behind the barrier. Tsunamis are highly unlikely to wash over the dune barrier in most places but there are a few gaps in the barrier where streams and rivers cut through to the coast. Most of the land at Pakiri is in private ownership and it is one of the few coastal locations on the Auckland mainland that is not in a Regional Park or highly developed.

4.5.2 Tawharanui

Previous paleotsunami research	Tsunami modelling	Suitable depositional environment	Accessibility / permissions	Suitable?
Yes	Moderate	Moderate	Auckland Regional Park permit required	No

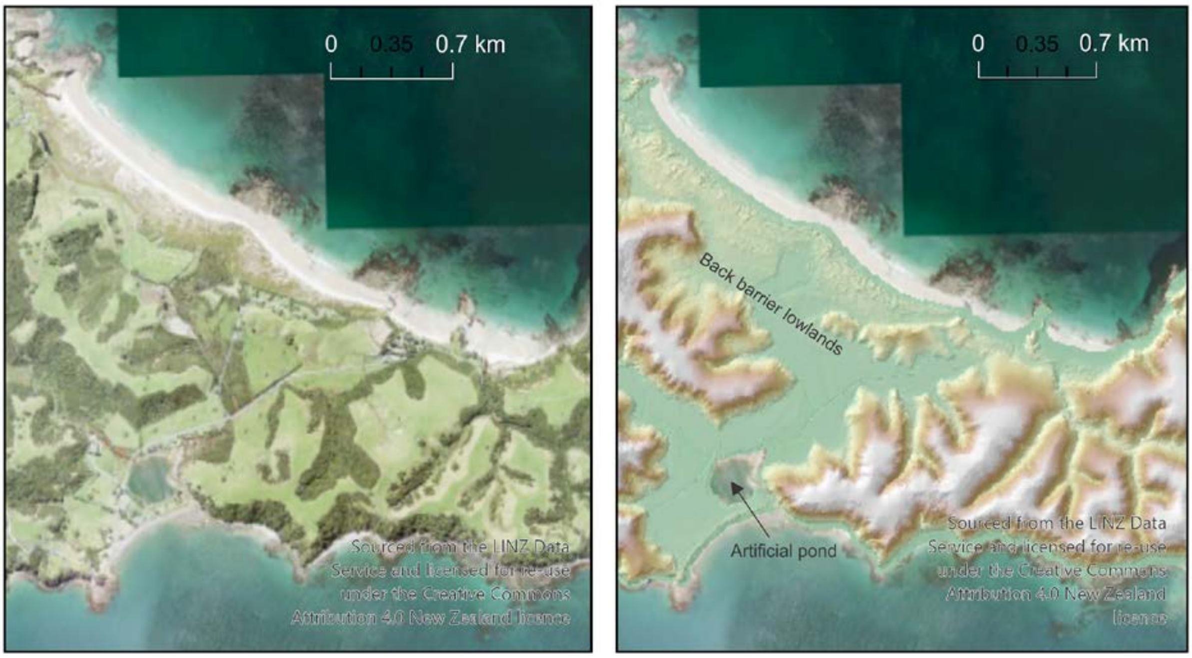


Figure 4.11 Pakiri area. Left: satellite image, right: shaded hillshade lidar image and digital elevation model.

Tawharanui (Figure 4.11) is the site of a previous study of sand lobes attributed to paleotsunami and tsunami modelling shows moderate wave heights from Kermadec trench sources (Figure 4.2). The purpose of revisiting Tawharanui would be to obtain more precise age control on the sand lobes (they are only constrained as post-Kaharoa tephra, < 650–680 yrs BP) and determine if any further analysis on the sand lobes could better resolve their depositional mechanism. A permit for this site could not be obtained and there is relatively dense archaeology, so an archaeological authority would probably be required, so further work at Tawharanui was not possible within this project.

4.5.3 Omaha

Previous paleotsunami research	Tsunami modelling	Suitable depositional environment	Accessibility / permissions	Suitable?
Yes	Moderate - High	Moderate	No issues	Yes

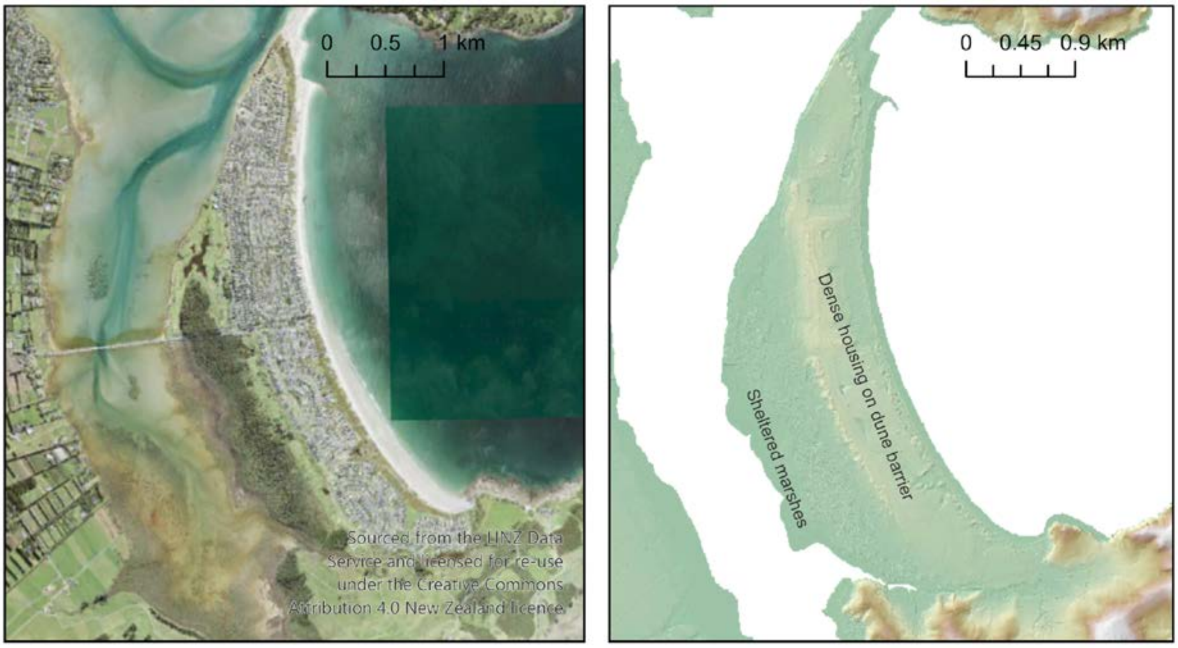


Figure 4.12 Omaha area. Left: satellite image, right: shaded hillshade lidar image and digital elevation model.

Tsunami modelling shows Omaha Bay amplified tsunami waves, and inundation modelling has shown significant inundation hazard for parts of the sandspit (Figure 4.13). The sand spit is formed of moderately high sand dunes (10–13 m elevation at the crest) but the dunes have been heavily modified by housing developments. In addition to being developed, the sandspit has many archaeological sites. Paleotsunami depositional sites at Omaha are not ideal; there are no natural back-barrier wetlands or dune swales remaining. However, the relatively high tsunami risk at this location due to a combination of coastal development and wave amplification means that Omaha is an important location for understanding of tsunami hazard. Land ownership at Omaha is mostly private ownership and there are many archaeological sites; for this reason, we identified the saltmarsh on the western side of the sand spit as the only viable location for paleotsunami reconnaissance (Figure 4.12).

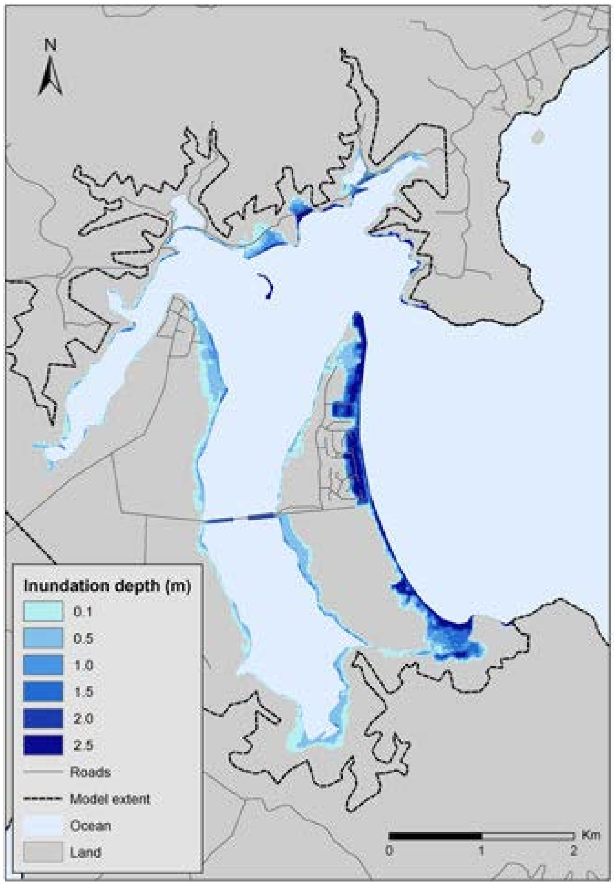


Figure 4.13 Probabilistic inundation modelling for the Omaha area by Lane et al. (2013). The figure shows the 2,500-year annual return interval exceedances for regional probabilistic tsunami inundation for Omaha at mean high water springs.

4.5.4 Puhoi River / Te Muri Beach & Estuary

Previous paleotsunami research	Tsunami modelling	Suitable depositional environment	Accessibility / permissions	Suitable?
No	Low	Moderate	Auckland Regional Park permit required	No

Figure 4.14 Puhoi River mouth and Te Muri Beach. Left: satellite image, right: shaded hillshade lidar image and digital elevation model.

The Puhoi river mouth area (part of Wenderholm Regional Park) and Te Muri Beach area (part of Mahurangi Regional Park) were considered potential field sites as they have moderately suitable paleotsunami depositional environments in the back-barrier salt marshes and on the low coastal area backing Te Muri Beach (Figure 4.14). No previous work indicates there are tsunami deposits at these sites and tsunami models show very low wave heights from regional sources, however this area was considered as a field site due to its undeveloped nature which becomes rarer proximal to Auckland city. A permit could not be obtained for either site and given the low tsunami hazard the Puhoi/Te Muri Beach site was not considered for further work.

4.5.5 Hatfields Beach

Previous paleotsunami research	Tsunami modelling	Suitable depositional environment	Accessibility / permissions	Suitable?
No	Low	Yes	No issues	Yes

Figure 4.15 Hatfields Beach. Left: satellite image, right: shaded hillshade lidar image and digital elevation model.

Hatfields Beach was considered a reasonable site for paleotsunami studies primarily due to the low beach barrier and low-lying saltmarsh back-barrier area (Figure 4.4). The tsunami models indicate low to moderate wave heights from a Kermadec Trench source and there has not been previous paleotsunami research at the site. It is relatively undeveloped and most of the land is a public reserve or in private ownership.

4.5.6 Orewa

Previous paleotsunami research	Tsunami modelling	Suitable depositional environment	Accessibility / permissions	Suitable?
No	Moderate	No	High level of land development	No

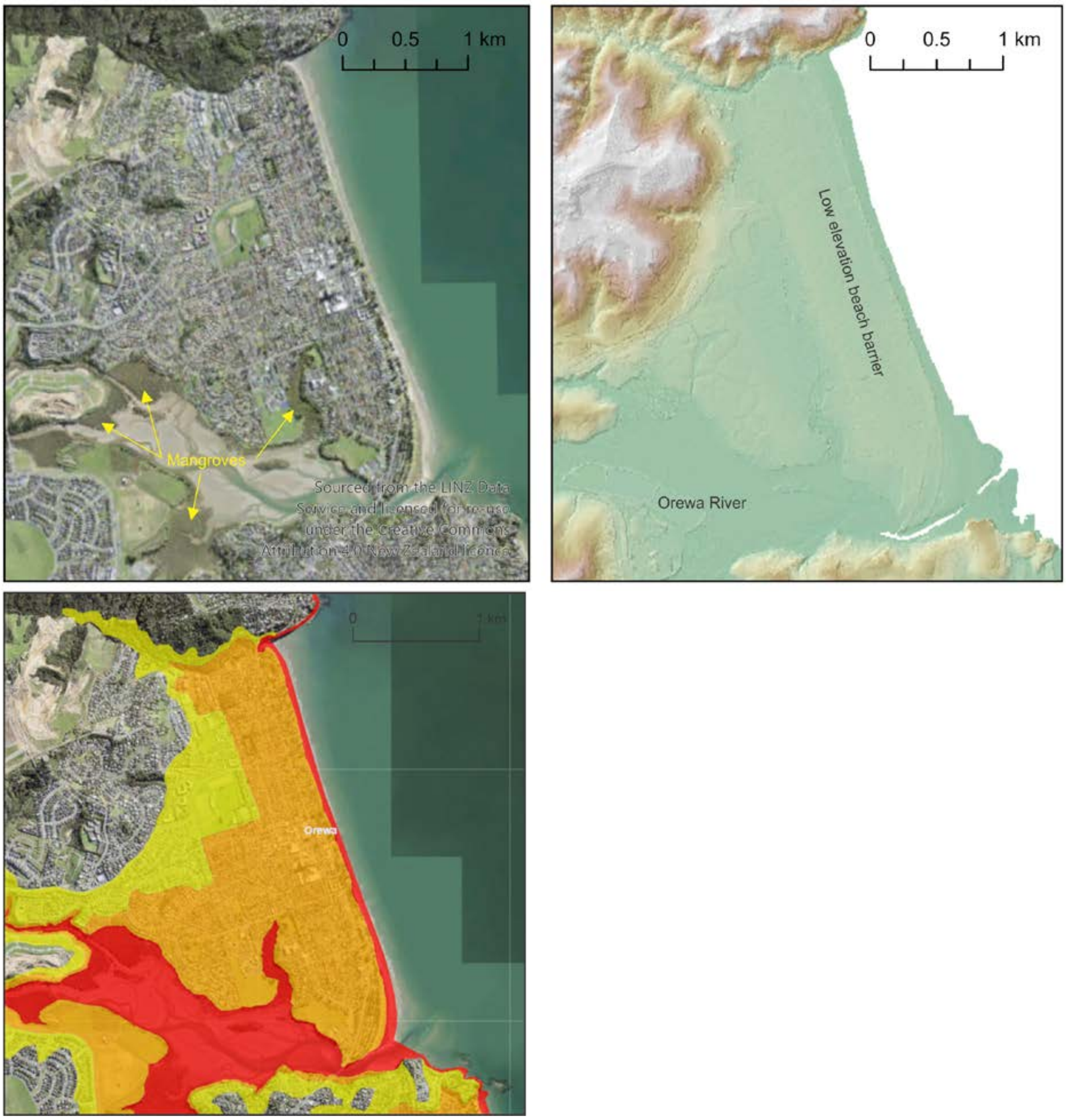


Figure 4.16 Orewa. Upper left: satellite image; upper right: shaded hillshade lidar image and digital elevation model; lower left: tsunami evacuation zones from Auckland Emergency Management Hazard Viewer (https://aucklandcouncil.maps.arcgis.com/apps/MapSeries/index.html?appid=81aa3de13b114be9b529018ee3c649c8, accessed 26 August 2020).

Orewa was considered a high priority for paleotsunami studies because there is a large population within the tsunami evacuation zones (Figure 4.16) so it is an important site for calibrating tsunami models with paleotsunami deposits. The beach barrier is low and the whole coastal plain is only 3–5 m above sea level. If the coastal plain was undeveloped it would probably be quite prospective as a tsunami depositional area, but the high level of modification and development means there are few sites available for paleotsunami field studies. The Orewa River has a large estuary, but the margins are covered in mangroves. Mangroves are difficult to work in and the sediment is often intensely bioturbated by vegetation and crabs. There are some reserves adjacent to the estuary, but these have been modified into flat playing fields. Due to the intense development and modification, we did not consider Orewa suitable for paleotsunami field work at this point in time.

4.5.7 Army Bay / Okoromai Bay (Shakespear Regional Park)

Previous paleotsunami research	Tsunami modelling	Suitable depositional environment	Accessibility / permissions	Suitable?
No	Low	Yes	Auckland Regional Park permit required	No

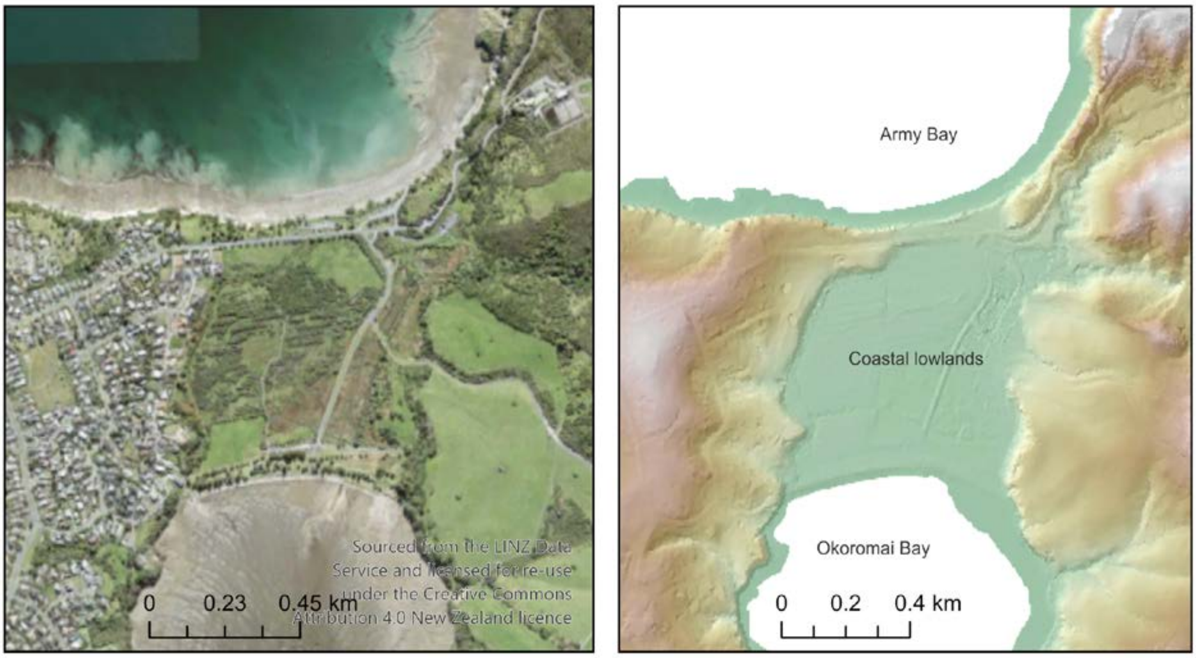


Figure 4.17 Army Bay and Okoromai Bay, Whangaparoa Peninsula. Left: satellite image, right: shaded hillshade lidar image and digital elevation model.

Army Bay/Okoromai Bay was considered as a possible paleotsunami research site because it is one of the few areas on the Whangaparoa Peninsula that is not developed and has suitable paleotsunami depositional sites (Figure 4.17). Tsunami modelling indicates low wave heights from all sources but complexities in wave dynamics due to the Peninsula and offshore islands mean that wave heights could potentially be higher than expected from the coarse resolution models available. The coastal lowlands between Army and Okoromai Bay is only 2–3 m above sea level and looks to be relatively unmodified. There is relatively dense archaeology at the site and a permit for research could not be obtained so further work at this site was not possible within this project.

5.0 FIELD SITE RECONNAISSANCE

5.1.1 Whangapoua Estuary, Whangapoua Bay and Okiwi Area

Figure 5.1 Location of gouge cores and sampling locations around the Whangapoua estuary.

Our field work concentrated on three areas in the Whangapoua area: the Okiwi airstrip, the back-barrier wetland and the gravel sheet within the dune barrier (Figure 5.1). The Okiwi airstrip area is modified by farming and airstrip levelling and a substantial portion of the northern tip of the area is dense with archaeological sites. One gouge auger core collected near the airstrip showed 0.35 m of sand at the top, underlain mostly by silt or clay to a depth of at least 2.2 m (all core locations are shown in Appendix 1 and detailed core logs are in Appendix 2). This appears to be a typical low-energy estuary infill sequence. There were no anomalous units indicative of high energy marine inundation. No further work was undertaken at this site.

In the saltmarsh area of Whangapoua Estuary directly behind the sand dune barrier we collected 6 cores (WhW 1 to 6 on Figure 5.1) that reached up to 1.8 m depth; the simplified stratigraphy is shown in Figure 5.2. The purpose of coring in this area was to test if any marine overwash made it over the sand dune barrier or through the inlet mouth. The sand dune barrier is lower in this area at <9 m so if a tsunami deposited gravel up to an elevation of 14 m in the dune just to the north then it may have overtopped the lower dunes on the southern part of the barrier (Nichol et al. 2003 observed the gravel in localised dune slacks and perched on eroded remnants of Pleistocene dunes in the southern half of the Whangapoua dunes). The saltmarsh sediments showed some alternation of peat and sand units (Figure 5.2) but no units stood out as highly anomalous or indicative of high-energy deposition. There is an interesting sand unit near the top of cores WhW1, 2, 5 and 6 that could potentially represent a marine influx but may equally be aeolian. Two radiocarbon ages from immediately below the sand date the sand layer to <300 years BP (Figure 5.2, Table 5.1). The base of each core is well-sorted medium sand. The general sand to peat sequence is a typical estuary fill sequence where intertidal sands transition upwards to high tide salt marsh organic-rich sediments. The sand unit in cores WhW1, 2, 5 and 6 may reflect an alternating paleoenvironment or it could be aeolian (blown into the estuary from the dune barrier). It has no compelling characteristics of paleotsunami.

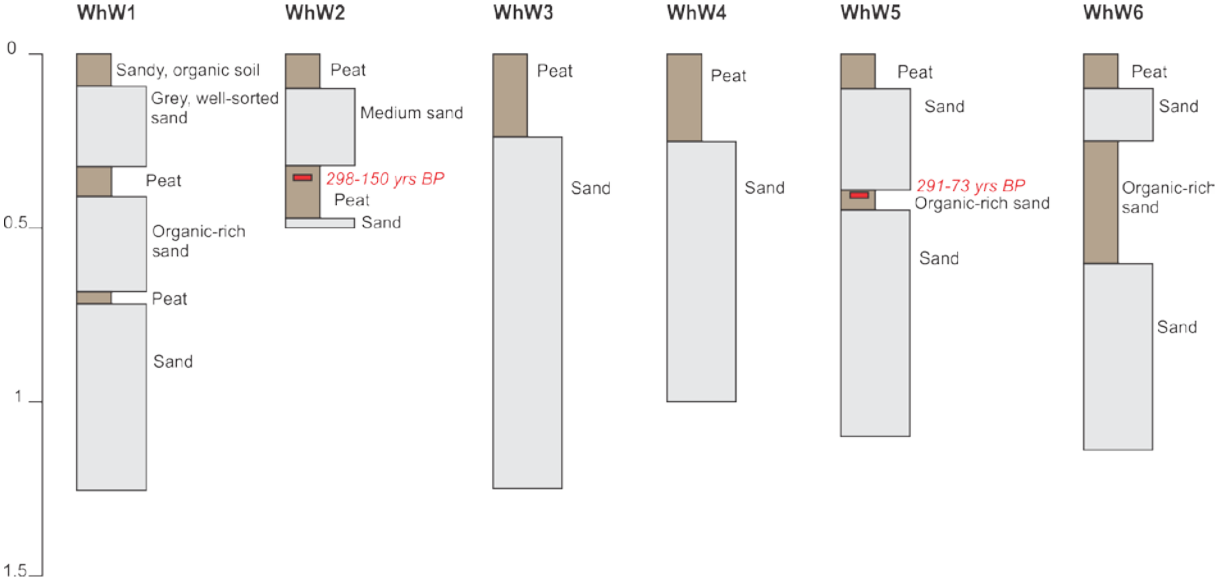


Figure 5.2 Core descriptions from the Whangapoua estuary gouge auger cores with radiocarbon ages.

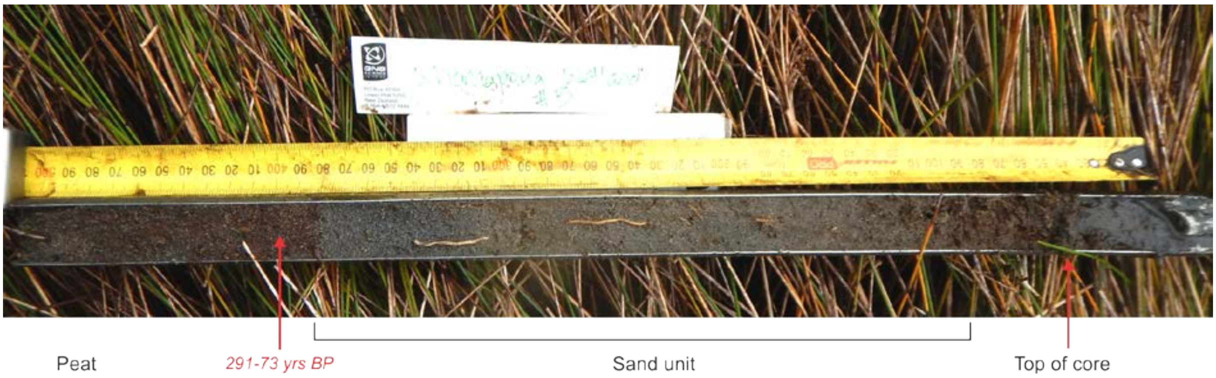


Figure 5.3 Photo of the top 50 cm of core Whangapoua Wetland 5 (WhW5) showing sand unit and location of radiocarbon sample below the sand.

Table 5.1 Radiocarbon ages from paleotsunami reconnaissance around the Auckland region.

Sample	Fraction Dated	95% calibrated age range (yrs BP)	
Whangapoua Dune Shell 1	Shell	424	128
Whangapoua Dune Shell 2	Shell	521	311
Awana 2/52-54	Wood	1988	1431
Awana 2/58-60	Plant Material	2080	1929
Awana 2/208-210	Plant Material	135	124
Whangapoua wetland 2/35-37	Plant Material	298	150
Whangapoua wetland 5/39-41	Plant Material	291	73
Harataonga 2/140-143cm plant fragments	Plant Material	1823	1637
Harataonga 2b/188-190	Wood	2349	1930
Harataonga 2b/193-195	Wood	3056	2860
Harataonga 3/152-154	Plant Material	2677	2342
Harataonga 5/202-204	Wood	3229	3005
Harataonga 5/210-214	Plant Material	3364	3181

We revisited the gravel sheet in the Whangapoua Beach sand dunes, as described by Nichol et al. (2003). The purpose of this was to see if additional evidence or data could be collected to help better understand the depositional process and better constrain the age of the deposit. Sand dune barriers are highly dynamic environments and new exposures may have been created since the original study. The gravel sheet could be easily relocated (Figure 5.4) and it's extent was consistent with previous descriptions by Nichol et al. (2003). In several places we could observe the gravel layer within the dunes and often this was slightly higher (by a metre or so) than the gravel sheet on the dune surface (Figure 5.5). This difference shows the gravel sheet on the dune surface is a lag deposit that has accumulated as the gravel has dropped out of sand dune above or as the dune sand has been winnowed away from around the gravel. Where we could see the gravel layer within dune sand, there was a stark colour difference between the sand below and the sand above the gravel layer (Figure 5.5).

The darker orange colour of sand below the gravel layer indicates it has been through a longer period of weathering and there is, by inference, a reasonable difference in the age above and below the gravel. This age difference is consistent with the OSL dating of Nichol et al. (2003) that found sand under the gravel with ages between ~6700–3700 yrs BP and a sample from above the sand was essentially modern (40 ± 470 yrs BP). However, we are not certain that where the gravel layer is found within dune sand, it is its primary depositional setting. There could be several generations of dune winnowing, gravel lag formation, and dune re-deposition on top of the gravel layer.

Within the surface gravel we found numerous shells, but we did not consider these trustworthy for dating. At sites WhG 1 and WhG 2, where the gravel sheet was within dune sand, we extracted several very small shell fragments. Although we cannot be sure if the gravel layer within dune sand at WhG 1 and WhG 2 is the primary depositional site, we considered it was worth dating the shells. Both shell samples returned ages of <500 yrs BP. Nichol et al. (2003) dated four shells from midden deposits close to the gravel sheet, all shells were <600 yrs BP, consistent with the ages we obtained from shell fragments.

Nichol et al. (2003) observed that cobble-sized hearth stones were scattered throughout the Whangapoua gravel and midden shells were dispersed landward from the primary middens. They reasoned the middens must have existed prior to tsunami inundation so the tsunami must have occurred after Māori occupation (i.e. <600 yrs BP). Our observations of the surface exposures of midden (observations made without disturbance of the midden material) was that the middens contained both large oven stones (mostly shattered andesite cobbles) and many smaller rounded pebbles, several of which were fractured and most had the orange colouration of having been baked in high heat (Figure 5.6). The smaller rounded pebbles were similar in size, lithology and roundness to the clasts of the gravel sheet. If the pebbles in the middens were collected from the gravel sheet it means the gravel sheet must have been emplaced prior to Māori occupation. There do not appear to be accumulations of well-rounded pebbles elsewhere nearby, so the simplest explanation is that the gravel sheet pre-dates, rather than post-dates Māori occupation.

Two options emerge for age constraints on the Whangapoua Beach gravel sheet:

1. The gravel sheet pre-dates Māori occupation and the only reliable age constraint is given by OSL samples from sand beneath the gravel sheet. This constrains the age to <~3700 yrs BP. In this scenario, we trust that observations of well-rounded pebbles within middens show the sheet gravel must have been emplaced prior to Māori occupation. It means the shell fragments we dated from the gravel sheet within the sand dunes are unreliable and probably date post-depositional reworking of the gravel layer.
2. The gravel sheet post-dates arrival of Māori. In this scenario, we trust that dispersed hearth stones and midden shells must have been moved by the tsunami that emplaced the gravel sheet and the rounded, baked smaller pebbles observed within middens must have been collected from elsewhere. The shell fragments we dated from the gravel sheet within the sand dunes may be a reliable indicator of tsunami age at <420 yrs BP.

We are uncertain which of these scenarios is more likely, but we favour (1) as it is hard to explain the presence of well-rounded pebbles within middens other than by emplacing the gravel sheet earlier than Māori arrival. Dispersion of hearth stones and shells from middens can be explained by aeolian and gravity processes (Figure 5.6). Further study on the age of the gravel sheet would probably require small excavations in the sand dunes, significantly more OSL dating and collaboration with archaeologists and iwi.

Regardless of its age we agree with the conclusion of Nichol et al. (2003) that the most reasonable explanation for the sheet gravel is emplacement by tsunami as it is beyond the likely elevation reached by storm waves (although this assumption has not yet been tested by any storm wave modelling). The lithological composition of the gravels means they could only have been sourced from offshore, as the only place where all these rounded pebbles are known to occur together in great quantities is the seabed 20–30 m deep between Rakitu Island (Figure 5.4) and Harataonga Bay (Hayward et al. 1982). In particular, the presence of rhyolite clasts in the gravel sheet (spheroidal rhyolite, flow-banded rhyolite, silicified tuff and silicified ignimbrite) indicates a marine source as the rhyolite is derived from Rakitu Island and there is no rhyolite in the Whangapoua catchment or on the headlands adjacent to Whangapoua Bay.

Figure 5.4 Oblique aerial views of the Whangapoua Beach gravel sheet.

Figure 5.5 Close up photos of the gravel sheet at Whangapoua Beach and radiocarbon sampling locations. Features to note: (i) the difference in sand colour above and below the gravel layer in the right-hand photos, this colour change indicates the sand below is significantly older than the sand above; and (ii) the gravel layer within the sand dune at site WhG 2 is about 1 m higher than the gravel accumulation on the dune surface. This indicates most of the gravel sheet on the dune surface is a lag deposit rather than an *in-situ* deposit.

Figure 5.6 Middens near the Whangapoua gravel sheet. Photo on the left shows the variety of stones in the midden from the larger, orange, heat-fractured hearth stones to the smaller, well-rounded pebbles, similar to those within the gravel sheet. Photo on the right shows dispersal of hearth stones due to gravity.

5.1.2 Harataonga Bay

The aim of field work at Harataonga Bay was to relocate the inferred paleotsunami deposits identified by Nichol et al. (2007), obtain more material for dating to better constrain the age, and to see if the paleotsunami deposit could be replicated across more sediment cores. At Harataonga Bay we collected 5 sediment cores from the wetland (H1 to H5, Figure 5.7), these reached up to 3.5 m below the surface (Figure 5.8). In general, the sediment infill of the wetland is dominated by silt with some more organic-rich units at >1.5 m depth in several cores. Fine sand layers are relatively common throughout all the cores. Core H1 closely resembles the cores collected from the wetland by Nichol et al. (2007). Nichol et al. (2007) proposed the lowest sand bed seen in their cores (equivalent to sand 1.5–1.43 m depth in core H1.Figure 5.8) was a paleotsunami deposit. In two of our cores (H1 and H2) at the base of this sand were small pebbles, similar to the description of Nichol et al. (2007). We tentatively correlated the lowest fine sand unit across the 5 cores in the wetland and we see quite a bit of variation in the thickness of the sand (between 3–50 cm thick). There is a general trend that it thins inland although this is not well constrained due to few data points (Figure 5.9).

We were able to collect a number of radiocarbon samples from above and below the sand (Figure 5.8) and these are all <3400 yrs BP. We could use the radiocarbon ages to model the age of sand emplacement at 2970–2393 yrs BP (this assumes that sample Harataonga 2b/188–190 from below the sand is an outlier, Table 5.1, Figure 5.10). The age is consistent with the age constraints of Nichol et al. (2007) who estimated a sand emplacement age of c. 3,000 yrs BP but only used two radiocarbon ages from below the sand and two OSL ages from above the sand and the OSL samples only provided maximum ages. The additional radiocarbon ages provide a more robust age of sand emplacement that is slightly younger than the estimate of Nichol et al. (2007).

In general, our coring shows more sand layers and more variability in sedimentary fill across the Harataonga wetland than is shown by the more limited core data set of Nichol et al. (2007). However, similar to Nichol et al. (2007) we do not see any sand layers between the Whakatane tephra (5526 ± 145 yrs BP) and the lowest correlated sand unit, so like Nichol et al. (2007) we see a long period of quiescence prior to the inferred tsunami deposit, and then after the inferred tsunami there appear to be 2–3 subsequent episodes of sand emplacement. Nichol et al. (2007) explain the post-tsunami sand units as slope wash (i.e. flood deposits). Our observations are that all sand layers have similar characteristics and it is hard to justify why the lowest sand unit would be a tsunami, but not the higher sand units. The only unique feature of the lowest sand unit is that in some places it has pebbles at the base. Some pebbles were observed in the sand dunes at Harataonga Bay (located on Figure 4.4) and understanding if these also represent paleotsunami and whether they were deposited at the same time as the inferred paleotsunami sand in the wetland would be useful. Overall, we think the evidence for paleotsunami at Harataonga Bay is fairly robust. The reliability of this paleotsunami record could be increased by (1) high resolution paleoenvironmental studies on multiple sediment cores, particularly focusing on techniques to determine the provenance of each sand unit, and (2) correlation of the paleotsunami to other records, in particular determining if the Harataonga Bay deposit is the same age as the Whangapoua Beach gravel sheet.

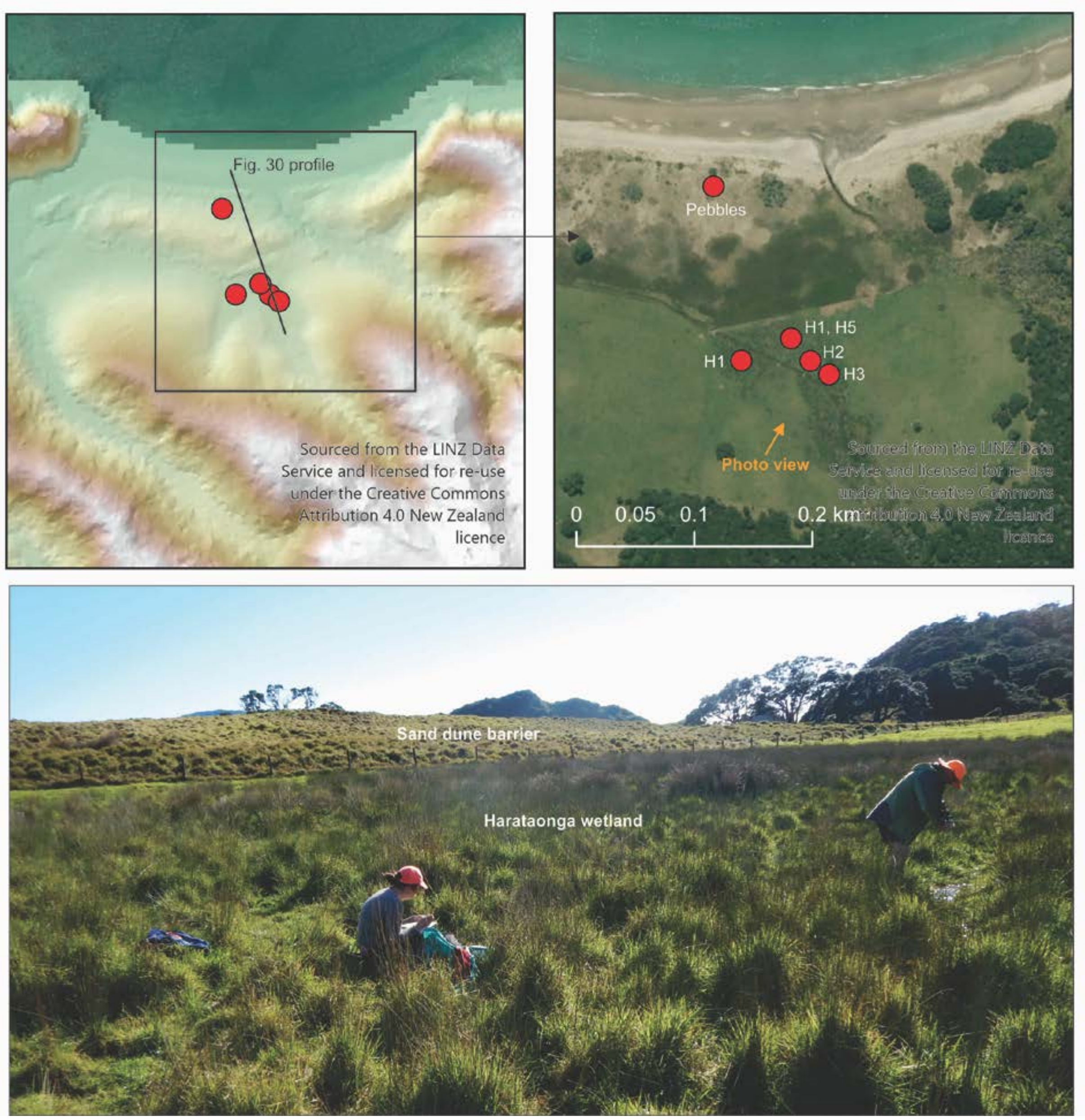


Figure 5.7 Coring locations at Harataonga Bay and a view across the wetland toward the sand dune barrier.

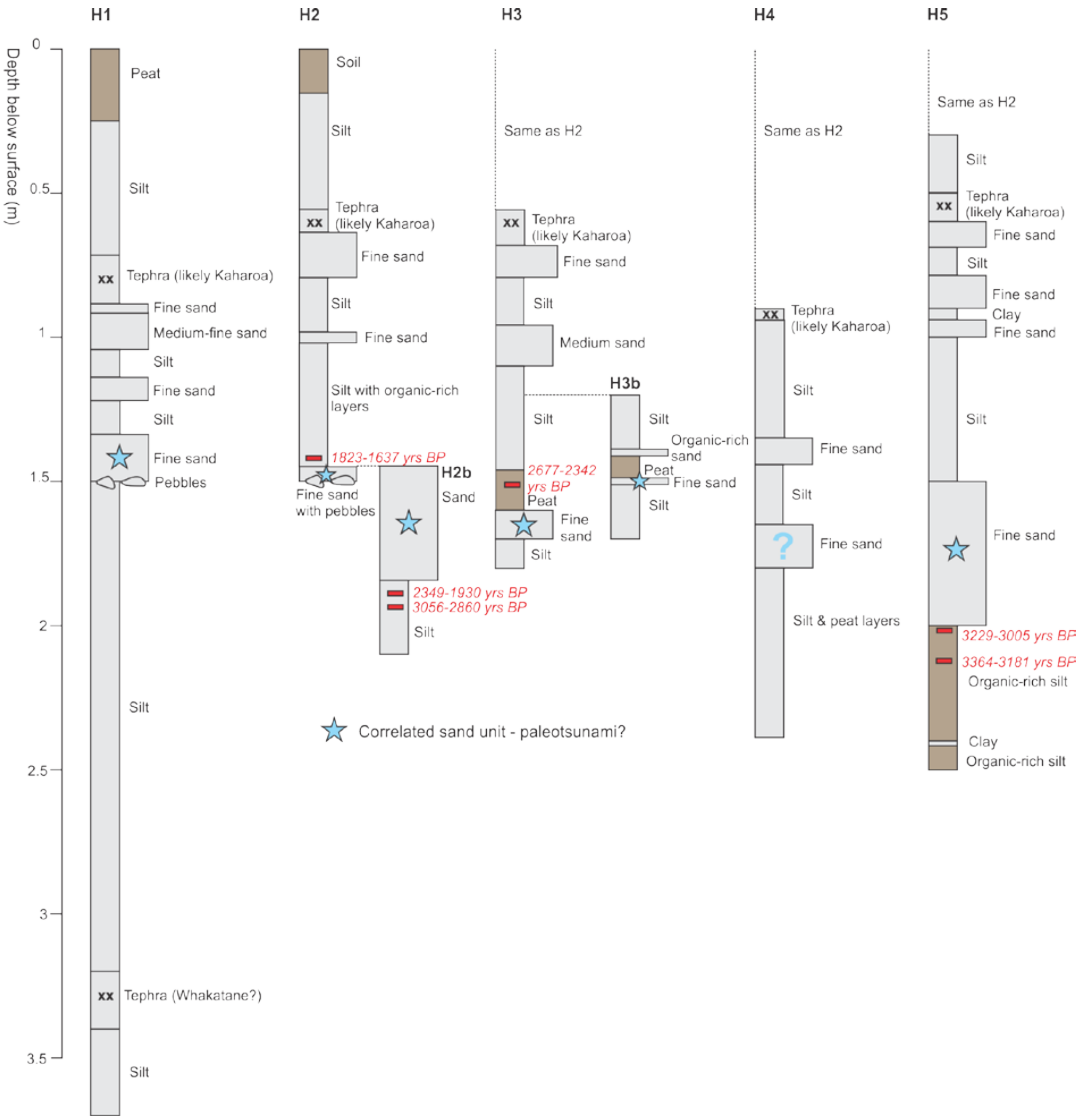


Figure 5.8 Simplified core stratigraphy from the Harataonga wetland. Also shown are radiocarbon ages (see Table 5.1) and our interpretation of the sand unit correlation across the wetland.

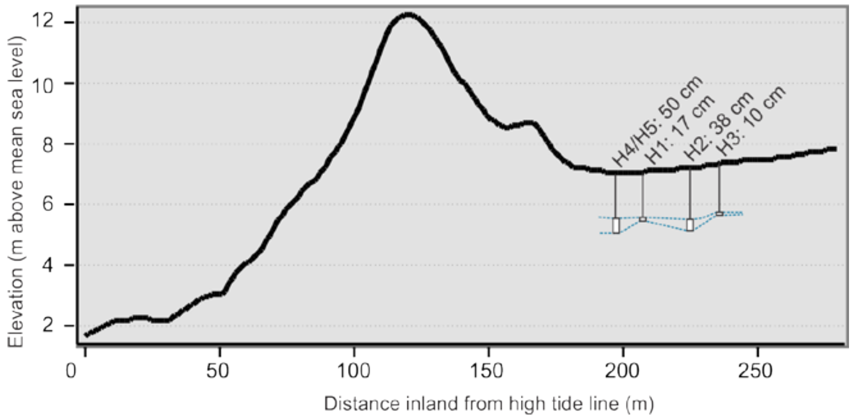


Figure 5.9 Topographic profile across the sand dune barrier at Harataonga Bay (profile location shown in Figure 5.7). This shows the elevation and thickness of the sand unit within the back-barrier wetland.

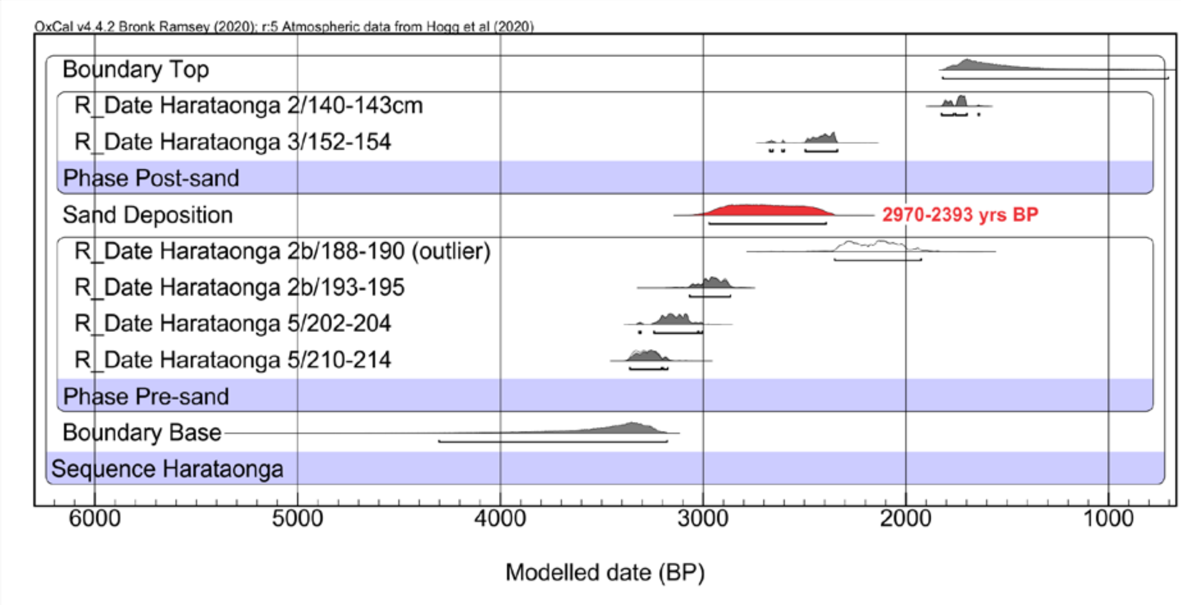


Figure 5.10 Age model for the estimation of the timing of sand unit emplacement (paleotsunami?) at Harataonga Bay. Age model produced using OxCal v 4.4.2 (Bronk-Ramsey 2009).

5.1.3 Awana Bay

At Awana Bay we collected three cores from the back-barrier wetland (Awana 1 to 3, Figure 5.11 and Figure 5.12). All three cores showed a deep sequence of peat, down to ~2 m. Below 2 m was a very compact fine sand. Within two cores we observed a thin (3 cm) fine sand bed at ~0.5 m depth within the peat. The fine sand was of similar particle size and sorting to the nearby dune sand, so the simplest explanation is the sand was aeolian, blown into the wetland perhaps during a particularly severe wind storm. We collected radiocarbon samples from above and below the sand to check if it was a similar age to the Harataonga Bay sand unit. Radiocarbon samples bracketing the sand unit were c. 2000 and c.1800 yrs BP (Figure 5.12, Table 5.1), and they constrain the sand unit emplacement timing to 2040–1650 yrs BP. This does not overlap with the Harataonga Bay sand emplacement (2970–2393 yrs BP) so they cannot be related. We did no further work at Awana Bay.

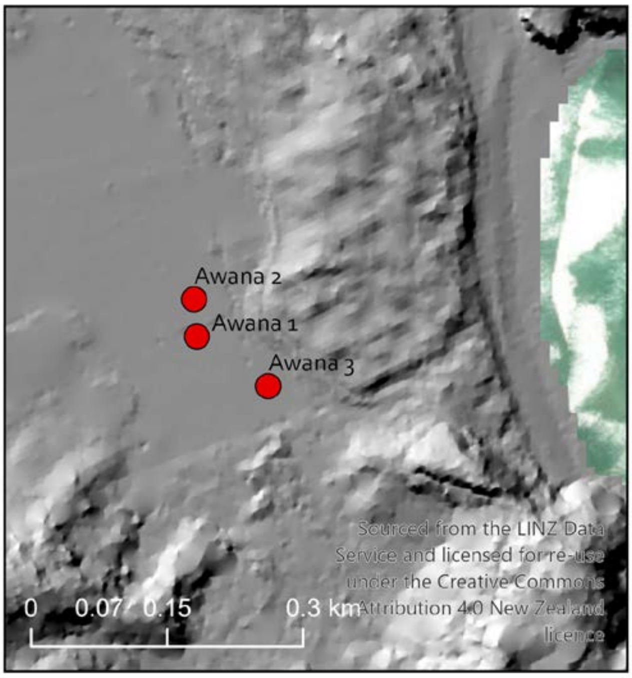


Figure 5.11 Core locations in Awana Bay.

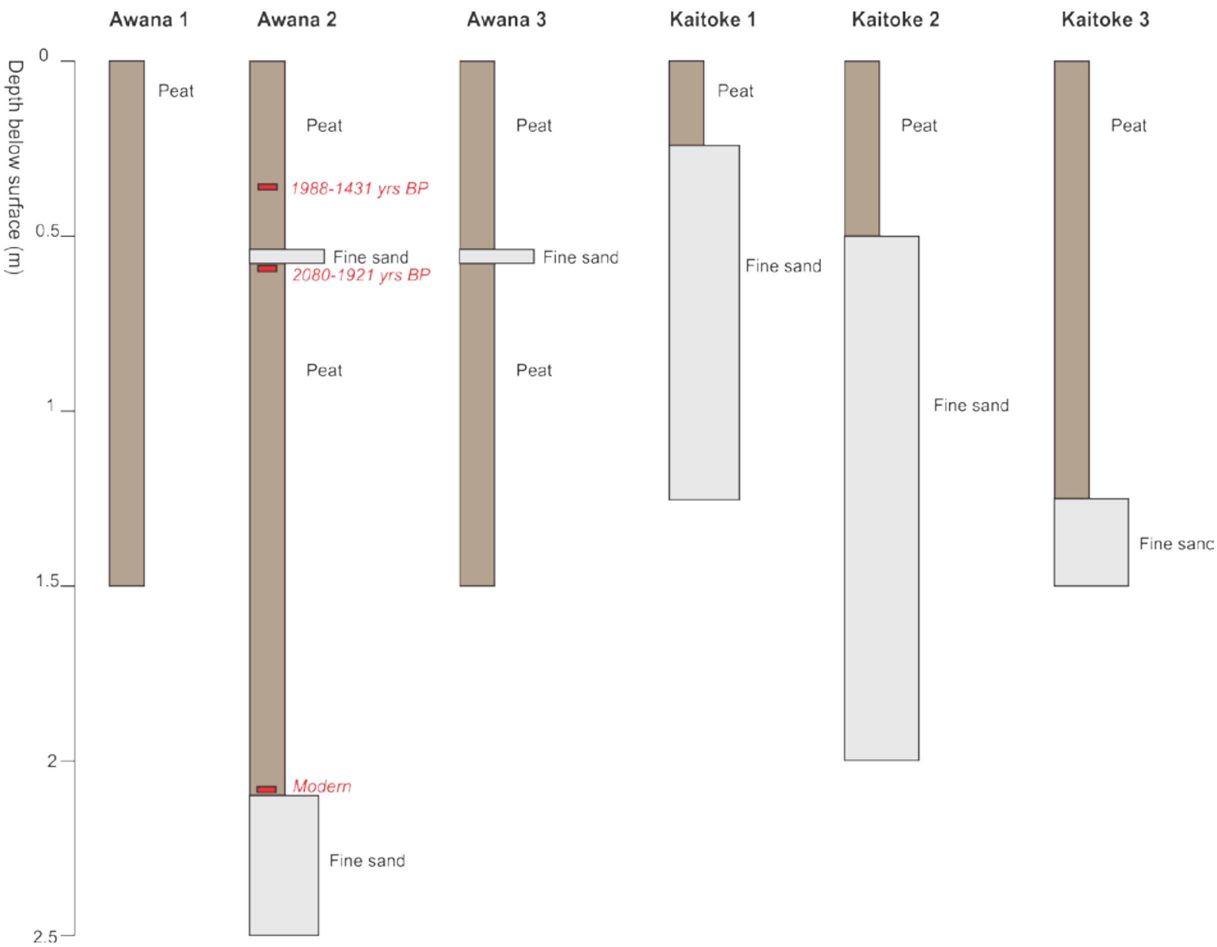


Figure 5.12 Simplified stratigraphy of the Awana Bay and Kaitoke gouge auger cores.

5.1.4 Claris and Kaitoke Area

We assessed the geomorphology around the northern Claris area and near the airstrip, but the sand dune fields were unsuitable for paleotsunami reconnaissance. We concentrated on the southern Kaitoke area and collected three gouge auger cores in the back-barrier lowlands (Kaitoke 1 to 3, Figure 5.13). There are patches of wetland in the back-barrier lowlands but most of the area has been drained for farming. Our three cores showed similar stratigraphy; thick peat sequence on top and well-sorted fine sand below to a depth of >2 m (Figure 5.12). No anomalous units were seen that could be potential paleotsunami deposits. It should be noted that we did not access the same coring location as Horrocks et al. (2000) or get to the same depth (5.8 m) as where they noted a potential paleotsunami deposit. Our coring equipment could not reach that depth, but it is potentially worth follow up research to relocate that anomalous sand unit. Radiocarbon ages above and below the anomalous sand at Kaitoke place it at c. 7500–5500 yrs BP so it is not correlative to the sand at Harataonga Bay (2970–2393 yrs BP) and it is highly unlikely to correlate with the Whangapoua Beach gravel sheet (either <~3700 yrs BP or <420 yrs BP).

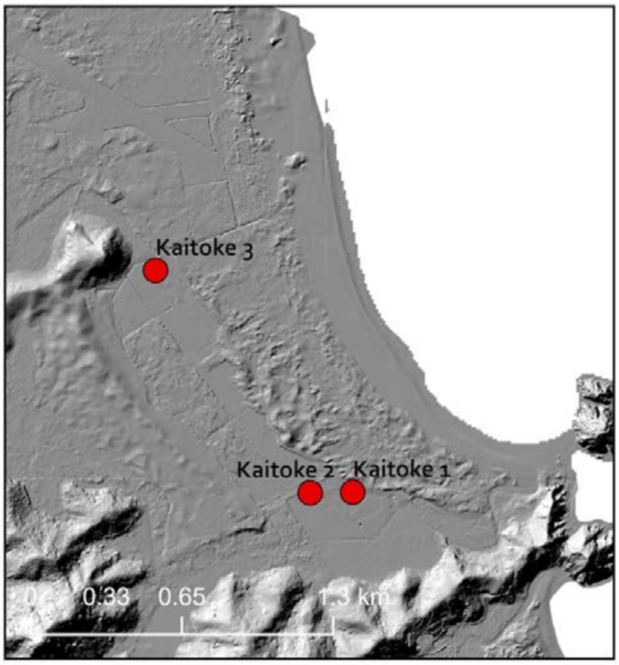


Figure 5.13 Core locations in the southern Kaitoke area.

5.1.5 Medlands Beach

In the Medlands Beach area we cored in multiple locations in the low-elevation swampy back-barrier area (M/Camp, M2 to M5, Figure 5.14). Some sites that we wanted to access at the eastern end of the embayment could not be reached as the landowners were absent, so we could not obtain permission. In our cores we found no anomalous units that we thought could possibly be paleotsunami deposits. In general, the back-barrier sediments are fine grained organic-rich silt and clay. The western end of the back-barrier is sandier (core M/Camp, Figure 5.15) but it is probably we were coring into an older part of the dune barrier at that location. In core M4 we found two very coarse sand layers, they were poorly sorted and had wood fragments throughout. These were interpreted as flood deposits from the nearby stream due to their similarity to modern stream bed sediments. We could not relocate the “pebbles in sand" observed by Butts and Fyfe (1978) because the dune barrier is intensely modified by housing development and an archaeological authority would be required.

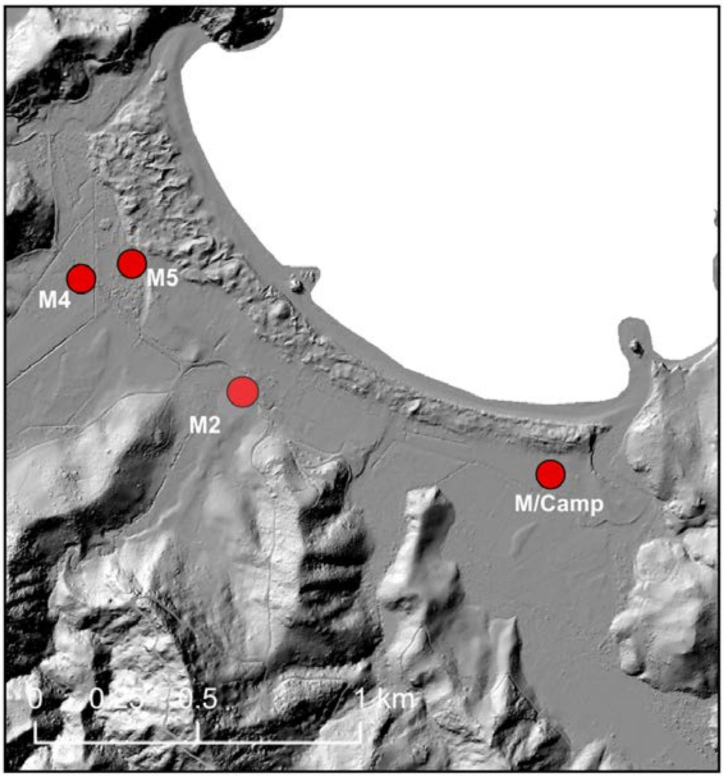


Figure 5.14 Core locations in the Medlands Beach.

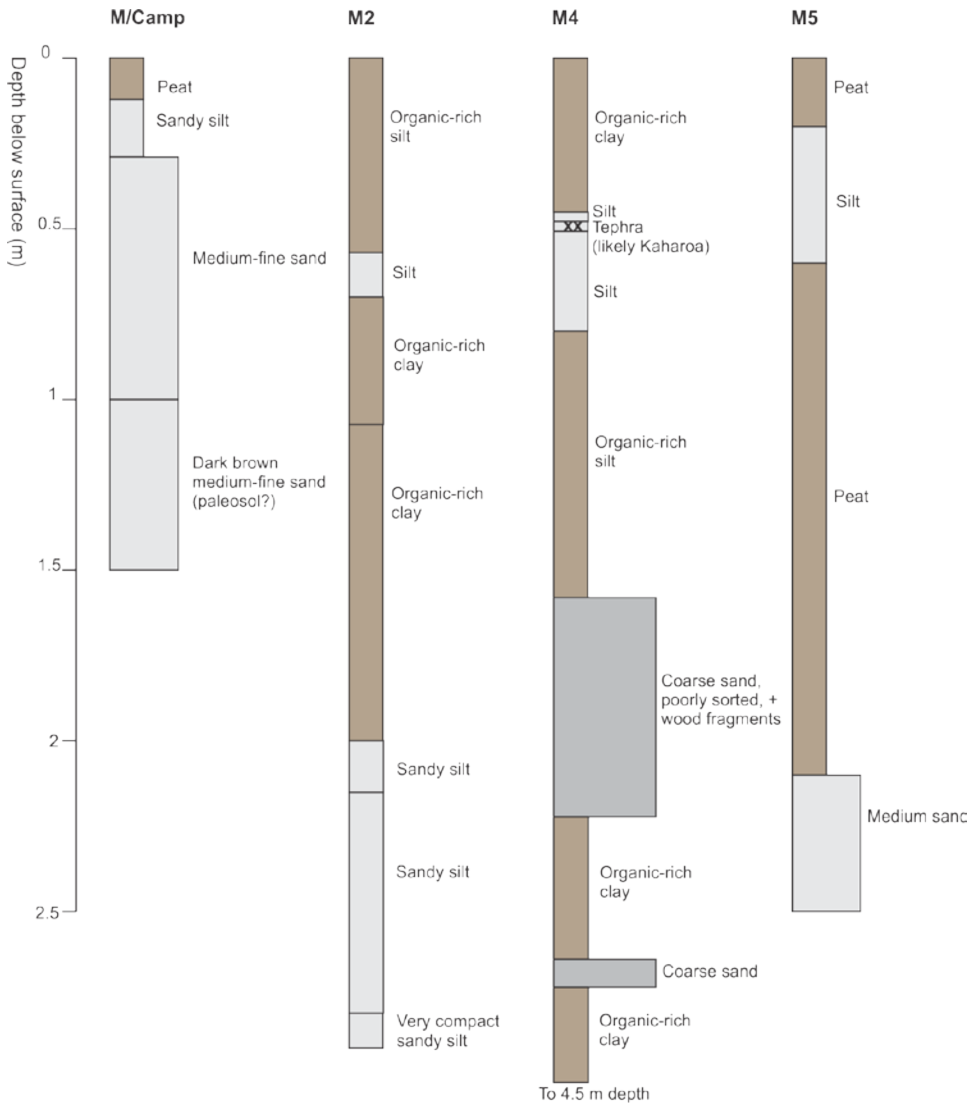


Figure 5.15 Simplified core stratigraphy in the Medlands Beach back-barrier area.

5.1.6 Pakiri

Our series of short (<1.5 m) cores at Pakiri (Figure 5.16) did not yield any evidence of paleotsunami but we concluded the depositional environments we could access were not favourable for recording extreme marine inundation events (storms or tsunamis). The lack of evidence for paleotsunami at Pakiri is therefore not a sign of low tsunami hazard, but instead probably reflects the unsuitability of the locations we could access for recording and preserving geological evidence of past tsunamis. We collected 6 gouge auger cores in the Pakiri River mouth area (Pakiri A to F) but aside from a thin surface cap of sandy soil, we found that cores were dominated by homogenous well-sorted fine sand (Figure 5.16). Our coring equipment could not reach very deep within this type of sediment because the sand quickly became too firm to core through. It appears most of the Pakiri valley fill sequence is sand and distinguishing a marine washover incursion (storm or tsunami) would be very difficult because it would probably be sand emplaced within sand, although potentially geochemical or magnetic susceptibility/anisotropy could be used to detect anomalies that cannot be seen visually. Away from the Pakiri River mouth, the sand dune barrier is very high (>30 m elevation). Tsunamis are unlikely to wash over the dunes to get into the freshwater back-barrier wetlands and lakes that exist north of Pakiri River as they are very high. We aimed to core in some of the small swampy areas south of the Pakiri beach settlement, but the landowners could not be located.

Further south along the coast is Pakiri Regional Park and we did not have a permit for that area. Overall, we did not find Pakiri very prospective for paleotsunami studies but given the high wave heights modelled for large Kermadec Trench tsunamis in the Pakiri area it may be worth further research here with coring equipment more suited for the sandy environment.

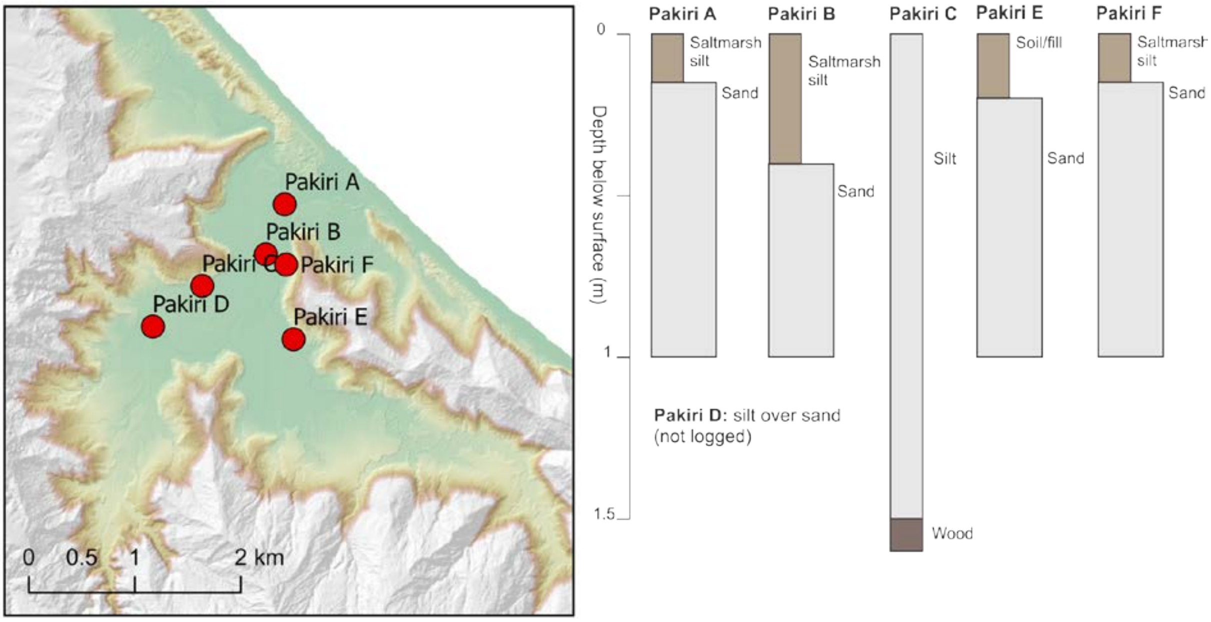


Figure 5.16 Map of core sites at Pakiri and simplified gouge auger core stratigraphy.

5.1.7 Omaha

Omaha sand spit is highly developed and there were very few areas of natural geomorphology that were suitable for paleotsunami studies. We collected one core (Omaha 1) in the back-barrier saltmarsh (Figure 5.17) and found ~1 m of sand. Other areas of the sandspit were modified or vegetated by mangroves. Unfortunately, due to the developed and modified nature of the sandspit, further paleotsunami studies at this location would be very difficult.

Figure 5.17 Core location at Omaha.

5.1.8 Hatfields Beach

We collected four cores in the saltmarsh behind Hatfields Beach (Hatfields 1 to 4, Figure 5.18). Cores 1–3 were dominated by sand and core 4 was sand and clay. There were no anomalous units possibly indicative of a paleotsunami. We do not consider the area very prospective for further studies of paleotsunami; much of the estuary is dominated by mangroves and there were few areas of saltmarsh suitable for coring.

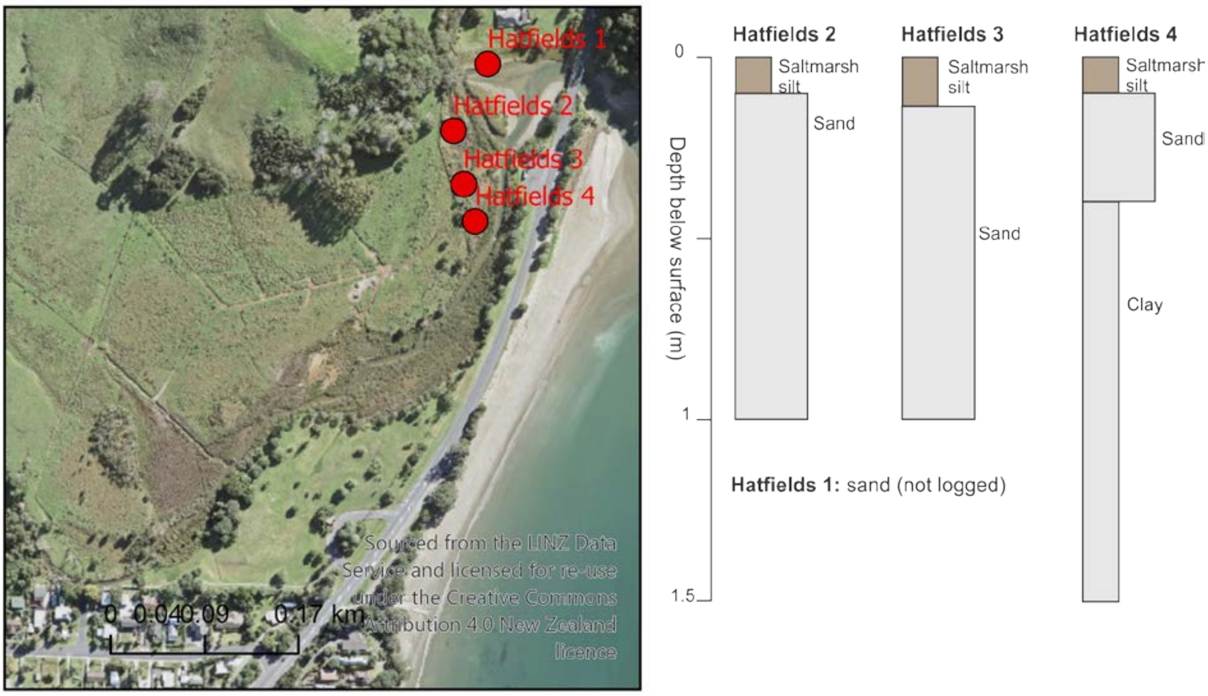


Figure 5.18 Map of core sites at Hatfields Beach and simplified gouge auger core stratigraphy.

5.2 Summary of Field Reconnaissance

A summary of the field reconnaissance is shown in Table 5.2. We recommend several changes to site status in the NZPD and briefly describe further work recommended at each site. The recommendations are further expanded upon in the next section.

Table 5.2 Summary of field reconnaissance outcomes in the Auckland region and suggested updates for the NZPD.

Site	Paleotsunami evidence?	Inferred age	Correlation to other Auckland sites	Updates for NZPD	Recommended future work
Whangapoua Beach	Yes	<~3700 yrs BP *or* <420 yrs BP	Potentially a correlation to Harataonga Bay if age is <~3700 yrs BP. Potentially a correlation to Tawharanui if age is post-Māori occupation.	None at this stage. Recommend Okiwi Airstrip site removed.	Improve age constraint on gravel sheet + tsunami modelling
Harataonga Bay	Yes	2970-2393 yrs BP	Potentially a correlation to Whangapoua Beach	Update age estimate	Paleoenvironmental study on more core + tsunami modelling
Awana Bay	No	Sand deposited at 2040-1650 yrs BP	Sand unlikely to be a paleotsunami, more likely aeolian	None	None
Kaitoke area	Uncertain	7500 - 5500 yrs BP (Horrocks et al. 2000)	No correlation	Add site to NZPD using Horrocks et al. (2000) reference.	Relocate sand deposit using appropriate coring equipment.
Medlands Beach	No			Remove site from NZPD or downgrade validity	None
Pakiri	Uncertain			None	Reconnaissance at a few more locations
Omaha	No			Remove site from NZPD or downgrade validity	None
Hatfields Beach	No			None	None

6.0 RECOMMENDATIONS FOR FUTURE RESEARCH

The objective of this project was to contribute to the calibration of tsunami modelling by identifying potential paleotsunami deposits in the Auckland region. To do this, our aims were to:

1. review existing paleotsunami information in the Auckland region,
2. undertake new research on paleotsunami in the Auckland region, and
3. outline future steps toward a better understanding of tsunami hazard in Auckland by identifying key gaps in our knowledge of Auckland paleotsunamis and outline the opportunities for future research.

This section discusses the knowledge gaps and recommendations for future work. We separate our recommendations into two categories: (1) general recommendations that apply to the whole region, and (2) site-specific recommendations that apply to only one location.

6.1 General recommendations:

Investigate Paleotsunami Records in Neighbouring Regions:

The major subduction zone sources of tsunami for the Auckland region would typically generate tsunamis that also impact the neighbouring regions of Northland and the Coromandel Peninsula. For example, Kermadec subduction zone tsunamis would probably have a large impact from the Bay of Plenty up to Cape Reinga (the relative severity of each area affected would depend on the location of the rupture patch, Power et al. 2012). Southern New Hebrides tsunamis are likely to have greater wave heights in Northland compared to Auckland, although the density of coastal development in Auckland means the impact, even of small waves, could be greater. To better understand tsunami hazard for Auckland, the area of paleotsunami investigation should be widened to Northland and the Coromandel Peninsula.

Several studies have been undertaken at various sites in Northland, predominantly on the east coast (e.g. Goff et al. 2010; Nichol et al. 2004) and there are 44 records in Northland included in the NZPD. Of those 44 Northland records, 39 have an inferred age of AD 1450-1480, most relate to “pebbles in sand” and are often related to archaeological sites. Twenty-one sites are included in the NZPD for the Coromandel Peninsula and among them 19 are of the same inferred AD 1450–1480 age and relate to sand overlying Māori occupation horizons. We recommend a thorough review of paleotsunami evidence in both of these regions. There are also many NZPD recorded sites in the Bay of Plenty, where there are more local tsunami sources (offshore faults, see Lamarche and Barnes, 2005) and the area is more likely to be affected by tsunamis generated at the Hikurangi subduction zone. However, paleotsunami records from the Bay of Plenty are less likely to be applicable to understanding tsunami hazard for Auckland.

Multidisciplinary Study of Paleotsunamis in the Archaeological Record:

Most NZPD records for the Auckland region (and for most of New Zealand) relate to archaeological sites and archaeological evidence. For example, records of sand layers overlying, or in between occupation horizons. The dominance of relatively recent paleotsunami records is to be expected; our coastal sedimentary record will preserve evidence of the youngest, most recent events better than the older events which will be buried deeper and have undergone post-depositional alteration or may be eroded away. Recent paleotsunami

(<~800 yrs BP) are likely to have impacted sites of Māori occupation. The interpretation of paleotsunami evidence from the archaeological record lies at the intersection between the archaeological and geological disciplines and it has largely been through the work of one geo-archaeologist, Dr Bruce McFadgen, that many records of paleotsunamis have been interpreted from archaeological evidence in New Zealand (e.g. McFadgen, 2007; McFadgen and Goff, 2007). Further work on these archaeological records of paleotsunamis is needed in order to verify the records and obtain greater age control on the inferred paleotsunamis. This type of research needs to be undertaken by teams of researchers involving local iwi alongside archaeological and geological disciplines. In part, this is a practical approach as appropriate permissions need to be acquired to investigate archaeological sites, but the different viewpoints and experiences of diverse disciplines are needed to evaluate whether disturbances or changes in the archaeological records are normal or anomalous.

Evaluation of Gravel Layers in Sand Dunes as Paleotsunami Evidence.

Gravel or pebble layers in sand dunes are a problematic type of paleotsunami evidence and a framework on which to evaluate whether certain pebble layers are more or less likely to represent paleotsunamis would be useful to guide future research. Pebble layers in dunes are problematic for two main reasons: they are very difficult to date, and very little multiproxy research can be undertaken on them (e.g. we cannot look at diatoms, foraminifera, pollen, and geochemical signatures of sediment below, within, and above the deposit, as is often the typical approach with paleotsunami sediments in wetland/lagoon sequences). Often the most compelling reason to attribute a pebble layer in sand dunes to a tsunami is that no other reasonable depositional mechanism can be found as they are considered to be out of reach of storm waves. Undoubtedly, some pebble layers will have been deposited by tsunami, but there may also be many that are not. Further research that enables us to better evaluate the depositional mechanisms of pebble layers in dunes would be useful. Such research could incorporate the sediment transport modelling, which is becoming increasingly sophisticated but generally applies to the sand-sized fraction of deposits (e.g. Jaffe et al. 2016; Sugawara et al. 2014; Gusman et al. 2018) and at the other extreme are many models of boulder transport (e.g. Watanabe et al. 2020).

Understanding the processes of transport, preservation and post-depositional changes that pebble layers in sand dunes undergo would help us better evaluate their utility as a tsunami-indicator and potentially allow us to better constrain their age. Although this seems like a very specific area of research, the importance of pebble layers is amplified because in Auckland and Northland pebble layers that reach up to 14 m and 32 m elevation, respectively, have been interpreted as paleotsunami deposits (Nichol et al. 2003; 2004). These quite extreme elevations, particularly 32 m observed at Hendersons Bay in Northland, potentially indicate very high impact tsunamis. Power et al. (2012) note that to explain some of these paleotsunami deposits would require Kermadec Trench earthquakes >MW 9. Evaluating the likelihood that pebble layers in dunes represent paleotsunamis and understanding the frequency of such events is important for calibrating low frequency, high magnitude tsunami events which may not yet be included in tsunami hazard and risk assessment.

High Resolution Tsunami Modelling at Paleotsunami Sites of Specific Interest

At sites with very good evidence of paleotsunami detailed tsunami modelling should be undertaken to understand if the bathymetry and topography of the sites leads to amplification of tsunami waves. For example, if we assume the 14 m high pebble layer at Whangapoua Beach, Great Barrier Island, was deposited by a tsunami, we need to understand if the bathymetry offshore of Whangapoua Beach and the local topography (prominent headlands at either end of the beach and Rakitu Island just offshore) are conducive to tsunami amplification. Understanding localised extremes in tsunami run-up will help better understand hazard elsewhere along the coastline of the Auckland region.

Tsunami modelling can also help to constrain the source of paleotsunamis, although such a modelling exercise is better undertaken when the paleotsunami run-up elevations or inundation distances can be constrained at multiple sites. Trying to model the source of a paleotsunami from a single data point would typically result in very large uncertainties. Multi-site paleotsunami records can only be obtained by having very high-precision age control on paleotsunami deposits at each site. At a single site, if the spatial extent of the tsunami deposit is well understood and can be sampled in many places, tsunami sediment transport modelling can be used to help estimate the tsunami hydrodynamics (flow depth, flow velocity) and size. Such an approach may be particularly useful at Tawharanui where the sand lobes can be sampled in multiple places and the extent of the lobes is well constrained.

6.2 Site-Specific Recommendations:

- **Whangapoua Bay, Great Barrier Island:** The Whangapoua Bay site is important because it has some of the most convincing paleotsunami evidence in the Auckland region (along with Harataonga Bay) and the runup elevation of 14 m is alarmingly high (we note that runup height can be higher than tsunami wave height though). We recommend three main topics that should be investigated at this site:
    - Age control: Current data suggests the pebble layer could be as young as <420 yrs BP or as old as 3700 yrs BP. Better constraint on the age will help with correlations to other sites, which in turn may help understand the tsunami source. The age of the deposit is also important for calculating the run-up elevation because at ~4000 yrs BP, sea level was ~2 m higher than it was at ~400 yrs BP (Clement et al. 2016). Further study on the age of the gravel sheet would probably require small excavations in the sand dunes, significantly more luminescence dating and close collaboration with iwi, archaeologists and DOC.
    - Depositional mechanism: as mentioned in our point above titled “Evaluation of gravel layers in sand dunes as paleotsunami evidence”, we believe we need to better understand how pebble layers in sand dunes can be formed, preserved and altered. Essentially, we need to understand if there are alternative processes aside from tsunami, that could lead to the formation of extensive pebble layers in dunes.
    - Tsunami modelling: Tsunami sediment transport modelling and high-resolution inundation modelling should be employed to better understand the hazard implications of the Whangapoua Beach paleotsunami deposit. Our current hypothesis is that the pebbles in the Whangapoua Beach dunes were sourced from 20–30 m water depth offshore in the shallow gap south of Rakitu Island. Tsunami sediment transport modelling has the potential to help resolve whether this is feasible and what seismic source would be required to generate such a tsunami.

- **Harataonga Bay, Great Barrier Island:** There is compelling evidence for a paleotsunami deposit in the wetland at Harataonga Bay but the reliability of this paleotsunami record could be increased by (1) high resolution paleoenvironmental studies on multiple sediment cores, particularly focussing on techniques to determine the provenance of each sand unit, and (2) improved age control on the inferred paleotsunami deposit. Initial work by Nichol et al. (2003) did involve a high resolution paleoenvironmental investigation but only one sediment core. Our field reconnaissance showed variability across the wetland and we recommend the inferred paleotsunami deposit is examined in multiple cores to better constrain its depositional mechanism. Our work has slightly improved the age control on the inferred paleotsunami deposit but our revised age of 2970–2393 yrs BP still has a 600-year range. This age range is too broad to be useful for correlation to paleotsunami deposits elsewhere.
- **Kaitoke, Great Barrier Island:** In southern Kaitoke, Horrocks et al. (2000) described an anomalous sand deposit at 5.8 m depth that they proposed was potentially a paleotsunami. We recommend collection of long cores at the southern Kaitoke site to relocate the sand identified by Horrocks et al. (2000), a more complete assessment of its paleotsunami-likelihood should be carried out and its age control should be improved (it is currently dated between ~7500 and ~5300 yrs BP). The Kaitoke site near the southern end of Great Barrier Island would provide greater spatial coverage to counter the two closely-spaced sites on northern Great Barrier Island.
- **Auckland mainland sites:** Overall, we found few prospective sites on the Auckland mainland but given the importance of getting tsunami hazard information from sites closer to the main population centres it is worth persisting with paleotsunami studies closer to Auckland city. Our field reconnaissance was hampered by the inability to access several Auckland Regional Parks. We recommend collaborating with iwi and archaeologists to apply for access to Tawharanui Regional Park and Shakespear Regional Park. At Tawharanui, the sand lobes identified by de Lange and Moon (2007) could be relocated and further studies of the depositional process may be able to be carried out along with obtaining more precise age control. Okoromai Bay should be investigated for paleotsunamis because it appears to have suitable depositional environments behind the Army Bay back beach coastal barrier (5 m above MSL). We also recommend some further reconnaissance-level field work at Pakiri, in particular investigating the swampy areas south of the Pakiri beach settlement and use of coring equipment more suited for the sandy environment found at Pakiri.

7.0 CONCLUSIONS

We reviewed the evidence for paleotsunami at 18 sites listed in the NZPD within the Auckland region. Our review found three sites (Tawharanui, Whangapoua Beach and Harataonga Bay) with relatively strong evidence of paleotsunami in the form of gravel sheets in sand dunes and anomalous sand deposits within sheltered back-barrier coastal environments. The dating of the inferred paleotsunamis at each of these sites is relatively poor, and it is currently hard to evaluate if there are temporal correlations between each of the records. The remainder of the NZPD sites in the Auckland region have very weak evidence of paleotsunami.

To undertake field reconnaissance, we evaluated 12 coastal areas, and our process for selecting sites was based on previous paleotsunami research, tsunami modelling, suitability of the coastal depositional environments and accessibility of the site (Section 4). We selected 8 sites for field visits and of these, only two had likely evidence of past paleotsunamis - Whangapoua Beach and Harataonga Bay. At Whangapoua Beach and Harataonga Bay we relocated paleotsunami deposits recorded in the NZPD and collected additional data on the age of the deposits and their spatial extent. At Harataonga Bay we refined the inferred paleotsunami age to 2970–2393 yrs BP. At Whangapoua Beach we re-evaluated the relationship between the gravel sheets and archaeological deposit and we find it is uncertain if the gravel was emplaced before or after Māori settlement in the area. Elsewhere on Great Barrier Island we could not find further evidence of paleotsunamis. At three sites on the Auckland mainland we also could not find evidence of paleotsunamis but on balance the depositional environments were not ideal for capturing and preserving paleotsunami sediments, and some better locations could not be accessed due to permit requirements and the risk of disturbing archaeological sites.

Understanding tsunami hazard and risk in the Auckland region is of importance due to the density of coastal development and number of people living close to the coastline. Paleotsunamis studies are one tool that can help with better understanding hazard as it can provide a record of past tsunami events prior to written and oral records, their magnitude and frequency as well as potentially capture the low-frequency, higher impact events that can be difficult to constrain from tsunami modelling alone. This project has not completed the paleotsunami record for the Auckland region, but we have developed enough insights to propose a list of recommendations for future work to carry on this research. Our two higher priority recommendations are to undertake a thorough review of paleotsunami records in the neighbouring regions of Northland and Coromandel Peninsula, and to approach paleotsunami field studies in a multidisciplinary team with iwi and archaeologists. A better understanding of how gravel sheets within sand dunes form and how to date them, along with a framework to evaluate the likelihood they represent paleotsunami would be helpful. We also recommend high resolution tsunami modelling at certain sites to better understand whether local effects cause tsunami amplification. There are certain sites within the Auckland region that would benefit from further investigation using new tools and dating techniques to better understand the inferred paleotsunami deposits at these sites.

Overall, we find compelling evidence for paleotsunami at some sites on Great Barrier Island (Whangapoua Beach and Harataonga Bay) and northern Auckland (Tawharanui) and these sites approximately co-locate with where the largest tsunami wave heights are expected from Kermadec trench tsunamis. The coastline of Auckland, islands offshore of Auckland, and its neighbouring regions offer our most promising sites to better understand the size and frequency of large to great Kermadec Trench earthquakes and this information could be of critical importance for understanding tsunami risk in New Zealand.

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APPENDICES

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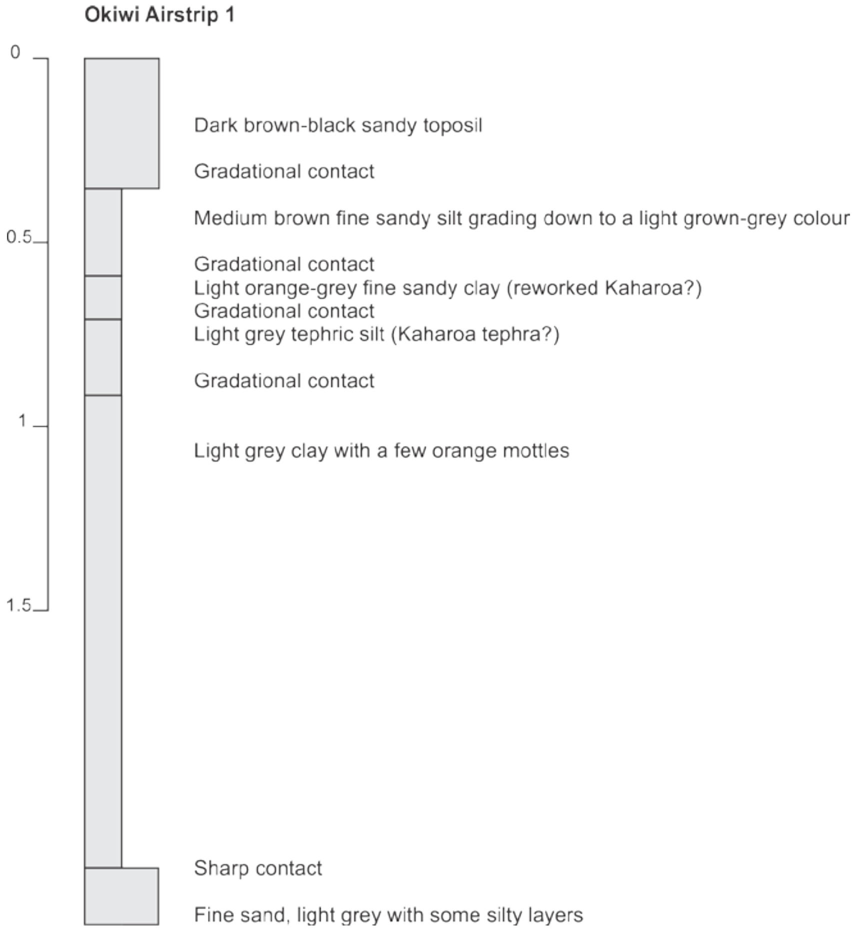
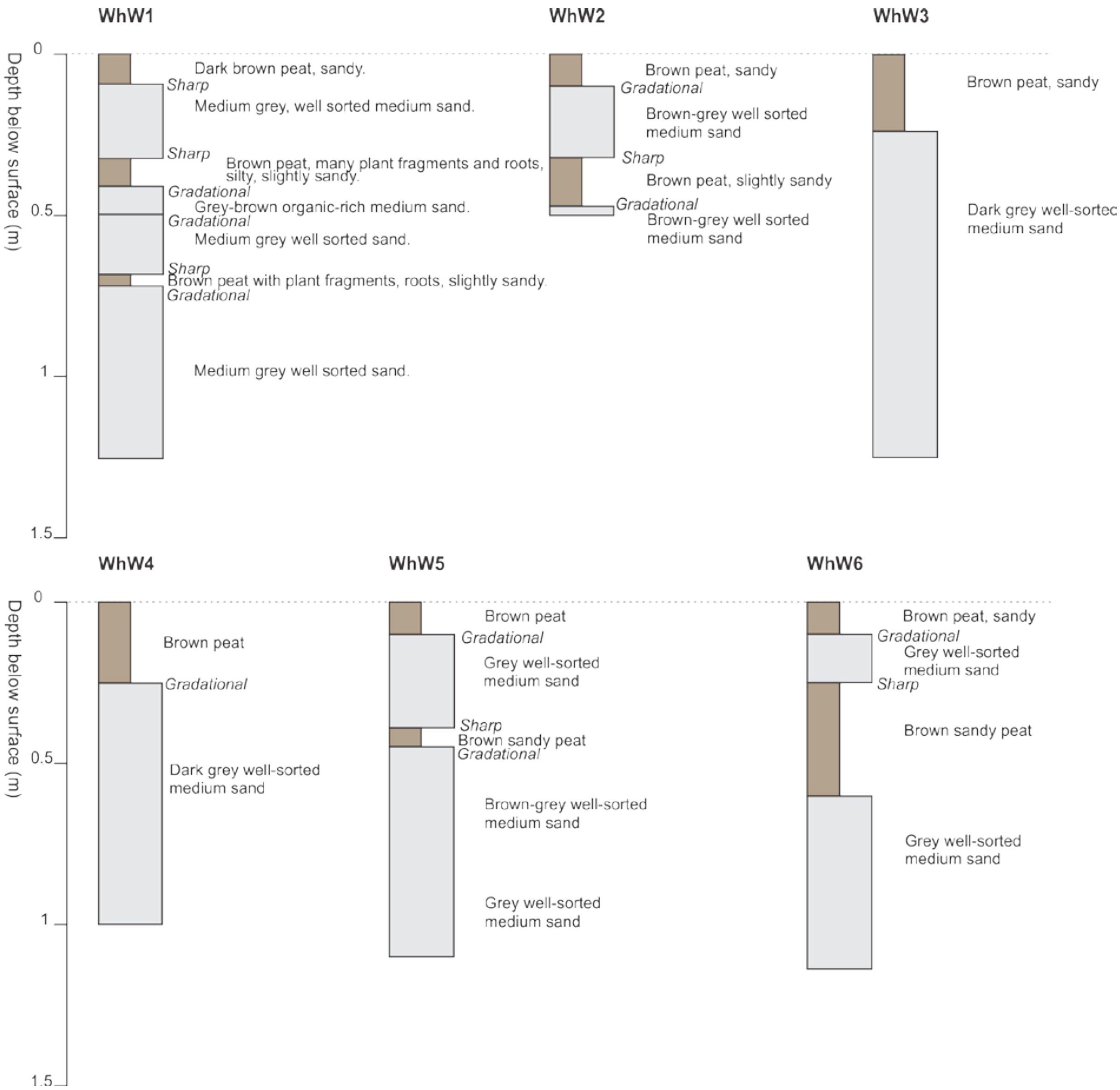
APPENDIX 1 CORE LOCATIONS

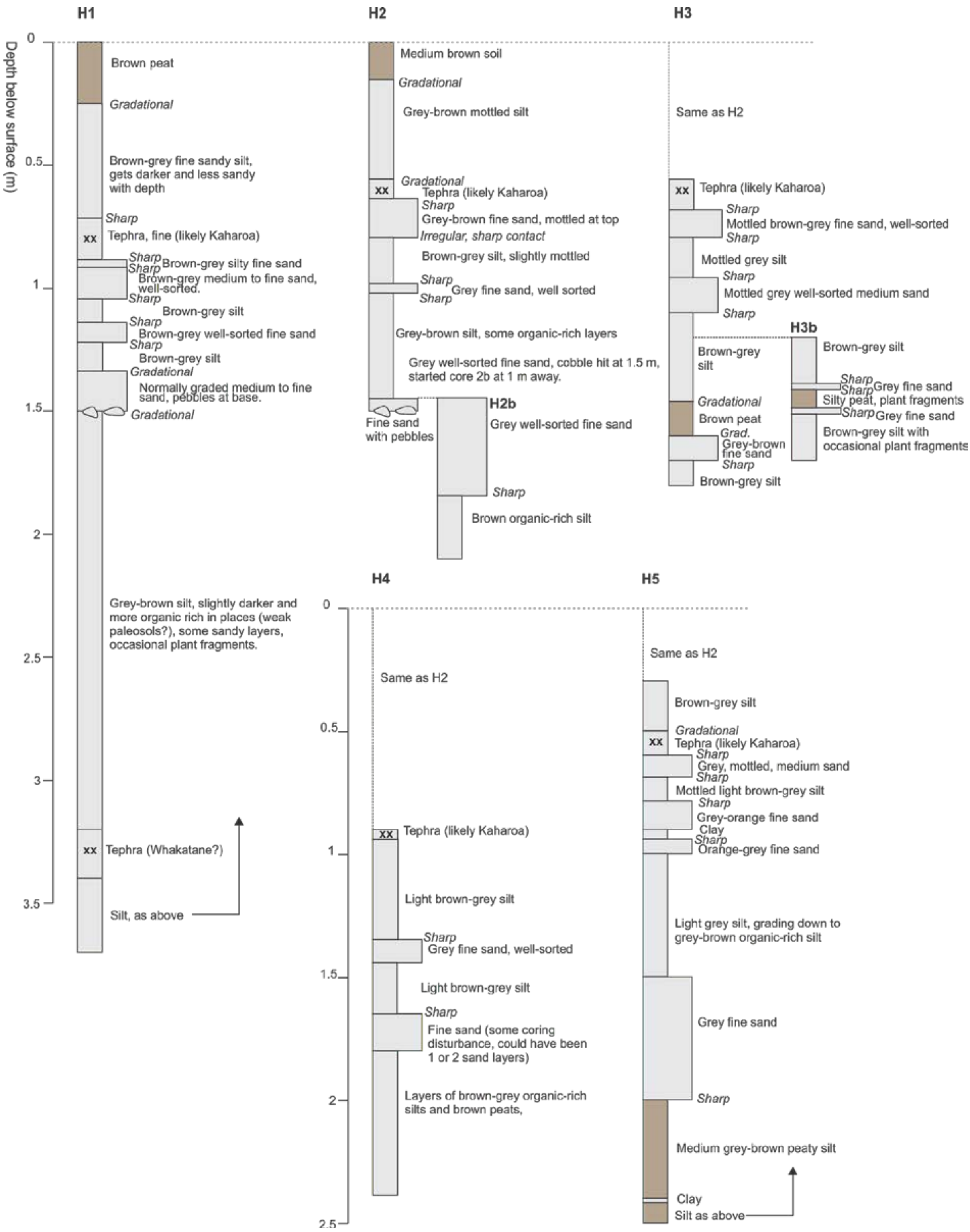
Name	Abbreviated name	Latitude	Longitude	Easting (NZTM)	Northing (NZTM)
Medlands camp	M/Camp	-36.2708	175.5028	1824819.207	5983108.364
Medlands	M2	-36.269	175.4919	1823845.046	5983333.344
Medlands	M3	-36.2687	175.4922	1823872.857	5983365.936
Medlands horse	M4	-36.2657	175.4866	1823378.267	5983711.729
Medlands 5	M5	-36.2653	175.4883	1823532.153	5983752.185
Okiwi airstrip 1		-36.1473	175.4201	1817731.236	5996999.472
Whanga gravel 1	WhG1	-36.1282	175.4216	1817919.06	5999115.206
Whanga gravel 2	WhG2	-36.1264	175.421	1817870.034	5999316.258
Whanga wetland 1	W1	-36.1307	175.4174	1817534.13	5998847.255
Whanga wetland 2	W2	-36.1317	175.4169	1817486.368	5998737.427
Whanga wetland 3	W3	-36.1315	175.4155	1817360.917	5998762.752
Whanga wetland 4	W4	-36.1304	175.4152	1817336.951	5998885.465
Whanga wetland 5	W5	-36.133	175.4175	1817536.779	5998591.852
Whanga wetland 6	W6	-36.1328	175.4184	1817618.332	5998612.024
Harataonga 1	H1	-36.1708	175.4866	1823648.43	5994240.929
Harataonga 2	H2	-36.1708	175.4873	1823711.401	5994239.315
Harataonga 3	H3	-36.1709	175.4875	1823729.108	5994227.759
Harataonga 4	H4	-36.1706	175.4871	1823693.978	5994261.966
Harataonga 5	H5	-36.1706	175.4871	1823693.978	5994261.966
Harataonga stones	Pebbles	-36.1695	175.4863	1823625.138	5994385.856
Awana 1	Awana 1	-36.2099	175.4757	1822557.133	5989927.869
Awana 2	Awana 2	-36.2096	175.4757	1822557.983	5989961.154
Awana 3	Awana 3	-36.2104	175.4766	1822636.638	5989870.327
Kaitoke 1	Kaitoke 1	-36.2558	175.4803	1822840.354	5984824.666
Kaitoke 2	Kaitoke 2	-36.2559	175.4782	1822651.362	5984818.403
Kaitoke 3	Kaitoke 3	-36.2474	175.4706	1821992.48	5985778.935
Pakiri A				1754430	5987539
Pakiri B				1754252	5987067
Pakiri C				1753651	5986769

Pakiri D				1753186	5986385
Pakiri E				1754513	5986265
Pakiri F				1754443	5986970
Omaha 1				1758862	5976763
Hatfields 1				1751731	5952451
Hatfields 2				1751700	5952391
Hatfields 3				1751710	5952342
Hatfields 4				1751720	5952309

APPENDIX 2 DETAILED STRATIGRAPHIC LOGS OF CORES AT OKIWI AIRSTRIP, WHANGAPOUA ESTUARY AND HARATAONGA BAY.




WhW1
WhW2
WhW3
Depth below surface (m)
0
0.5
1
1.5
Dark brown peat, sandy.
Sharp
Medium grey, well sorted medium sand.
Sharp
Brown peat, many plant fragments and roots, silty, slightly sandy.
Gradational
Grey-brown organic-rich medium sand.
Gradational
Medium grey well sorted sand.
Sharp
Brown peat with plant fragments, roots, slightly sandy.
Gradational
Medium grey well sorted sand.
Brown peat, sandy
Gradational
Brown-grey well sorted medium sand
Sharp
Brown peat, slightly sandy
Gradational
Brown-grey well sorted medium sand
Brown peat, sandy
Dark grey well-sortec medium sand
WhW4
WhW5
WhW6
Depth below surface (m)
0
0.5
1
1.5
Brown peat
Gradational
Dark grey well-sorted medium sand
Brown peat
Gradational
Grey well-sorted medium sand
Sharp
Brown sandy peat
Gradational
Brown-grey well-sorted medium sand
Grey well-sorted medium sand
Brown peat, sandy
Gradational
Grey well-sorted medium sand
Sharp
Brown sandy peat
Grey well-sorted medium sand



H1
H2
H3
H3b
H2b
H4
H5
Depth below surface (m)
0
0.5
1
1.5
2
2.5
3
3.5
Brown peat
Gradational
Brown-grey fine sandy silt, gets darker and less sandy with depth
Sharp
Tephra, fine (likely Kaharoa)
Sharp
Sharp
Brown-grey silty fine sand
Brown-grey medium to fine sand, well-sorted.
Sharp
Brown-grey silt
Sharp
Brown-grey well-sorted fine sand
Sharp
Brown-grey silt
Gradational
Normally graded medium to fine sand, pebbles at base.
Gradational
Grey-brown silt, slightly darker and more organic rich in places (weak paleosols?), some sandy layers, occasional plant fragments.
Tephra (Whakatane?)
Silt, as above
Medium brown soil
Gradational
Grey-brown mottled silt
Gradational
Tephra (likely Kaharoa)
Sharp
Grey-brown fine sand, mottled at top
Irregular, sharp contact
Brown-grey silt, slightly mottled
Sharp
Grey fine sand, well sorted
Sharp
Grey-brown silt, some organic-rich layers
Grey well-sorted fine sand, cobble hit at 1.5 m, started core 2b at 1 m away.
Fine sand with pebbles
Grey well-sorted fine sand
Sharp
Brown organic-rich silt
Same as H2
Tephra (likely Kaharoa)
Sharp
Mottled brown-grey fine sand, well-sorted
Sharp
Mottled grey silt
Sharp
Mottled grey well-sorted medium sand
Sharp
Brown-grey silt
Gradational
Brown peat
Grad.
Grey-brown fine sand
Sharp
Brown-grey silt
Brown-grey silt
Sharp
Sharp
Grey fine sand
Silty peat, plant fragments
Sharp
Grey fine sand
Brown-grey silt with occasional plant fragments
Same as H2
Tephra (likely Kaharoa)
Light brown-grey silt
Sharp
Grey fine sand, well-sorted
Light brown-grey silt
Sharp
Fine sand (some coring disturbance, could have been 1 or 2 sand layers)
Layers of brown-grey organic-rich silts and brown peats,
Same as H2
Brown-grey silt
Gradational
Tephra (likely Kaharoa)
Sharp
Grey, mottled, medium sand
Sharp
Mottled light brown-grey silt
Sharp
Grey-orange fine sand
Clay
Sharp
Orange-grey fine sand
Light grey silt, grading down to grey-brown organic-rich silt
Grey fine sand
Sharp
Medium grey-brown peaty silt
Clay
Silt as above

APPENDIX 3 FULL RADIOCARBON RESULTS AND SAMPLE DESCRIPTIONS

Sample ID	Fraction dated	Rafter ID	NZA	CRA[yBP]	CRA error	d13C [‰]	d13C error	F[ ]	F error
Whangapoua Dune Shell 1	Shell	41226/1	66089	653	24	2.28	0.2	0.921882	0.00281
Whangapoua Dune Shell 2	Shell	41226/2	66090	826	24	1.54	0.2	0.902199	0.002783
Awana 2/52-54	Wood	41226/3	66239	1821	106			0.797107	0.01061
Awana 2/58-60	Plant Material	41226/4	66240	2083	22	-27.78	0.2	0.771569	0.002168
Awana 2/208-210	Plant Material	41226/5	66241	Modern				1.018614	0.022112
Whangapoua wetland 2/35-37	Plant Material	41226/6	66242	231	20	-26.48	0.2	0.971647	0.002535
Whangapoua wetland 5/39-41	Plant Material	41226/7	66243	206	20	-25.29	0.2	0.97461	0.002531
Harataonga 2b/188-190	Wood	41226/9	66244	2202	94			0.760173	0.008912
Harataonga 2b/193-195	Wood	41226/10	66235	2878	23	-24.57	0.2	0.698804	0.002036
Harataonga 3/152-154	Plant Material	41226/11	66236	2424	22	-28.83	0.2	0.73944	0.002085
Harataonga 5/202-204	Wood	41226/12	66237	3012	23	-25.86	0.2	0.687273	0.001999
Harataonga 5/210-214	Plant Material	41226/13	66238	3109	22	-27.86	0.2	0.679048	0.00194
Harataonga 2/140-143cm plant fragments	Plant Material	41226/14	66903	1851	20			0.794143	0.002037

Whangapoua Dune Shell 1	71.78 mg of raw sample was received. Description of sample when received: The sample was submitted in a plastic sample bag and consisted of two thin white shell fragments, one which was smaller than the other with some loose sand. The smaller shell was clean on both sides but the larger one had some long strands, perhaps roots or fibres, on one side. There were some tiny brown spots on both shells. Sample prepared by: Cut/Scrape. Pre-treatment description: The contamination was scraped off of the shell using tweezers and a scalpel. No acid etching was done on this shell as it was too thin. Carbon dioxide was generated by carbonate CO2 evolution and 1.1 mgC was obtained. Sample carbon dioxide was converted to graphite by reduction with hydrogen over iron catalyst.
Whangapoua Dune Shell 2	654.29 mg of raw sample was received. Description of sample when received: The sample was submitted in a plastic sample bag and consisted of 5 larger pieces of shell, with a lot of loose sand and smaller shell fragments. The fragments were off white in colour, with some creamy coloured bands. There was some sand embedded in the holes of one fragment. 163.31 mg was subsampled and prepared by: Cut/Scrape. Pre-treatment description: All 5 shell fragments were cleaned using tweezers and a scalpel. The largest/thickest two fragments were selected, and this subsample weighed 96.77 mg. The subsample was acid etched in 0.1M HCl for 1 minute and then rinsed in DI water and dried in the 50-degree oven. Carbon dioxide was generated by carbonate CO2 evolution and 1.1 mgC was obtained. Sample carbon dioxide was converted to graphite by reduction with hydrogen over iron catalyst.
Awana 2/52-54	Description of sample when received: The sample was submitted in a plastic bag containing a small clump of dark damp sediment. Sample prepared by: Wet Sieve, Picking. Pre-treatment description: The sample was sieved to 300 micron. After sieving, the >300 micron fraction was organic rich and contained minerals, a lot of which were quartz. The organic materials were mostly fragile thin cellular sheets, along with a few small woodier looking pieces and root hairs. The paler reed or lake margin plant material was hand-picked. Some pieces of sample that could have been root hairs with bark and additionally a few small woody pieces were separately picked out. All separate sample types were dried to determine the best target for treatment. The reed materials were 9.35 mg, the wood material was 2.38 mg, and the root materials were 2.20 mg. The wood material was selected for treatment, and the other fractions were stored. Chemical pre-treatment was by acid, alkali, acid. Weight obtained after chemical pre-treatment was 0.4 mg. Carbon dioxide was generated by sealed tube combustion and 0.2 mgC was obtained. Sample carbon dioxide was converted to graphite by reduction with hydrogen over iron catalyst.
Awana 2/58-60	Description of sample when received: The sample was submitted in a plastic bag containing a small clump of dark damp sediment. Sample prepared by: Wet Sieve, Picking. Pre-treatment description: The sample was sieved to 300 micron. After sieving, the >300 micron fraction was organic rich with a lot of root hairs and minerals, a lot of which were quartz. The organic materials were mostly fragile thin cellular sheets, along with some darker, thicker cellular sheets and a couple of woodier root hair like materials. The paler reed or lake margin plant material was hand-picked. Separately, some pieces that could be root hairs with bark and the dark cellular materials were picked out. All separate sample types were dried to determine the best target for treatment. The pale reed materials were 4.55 mg, the dark cellular material

	was 8.61 mg, and the root like materials were 7.63 mg. The dark cellular material was selected for treatment, and the other fractions were stored. Chemical pre-treatment was by acid, alkali, acid. Weight obtained after chemical pre-treatment was 1.8 mg. Carbon dioxide was generated by sealed tube combustion and 1 mgC was obtained. Sample carbon dioxide was converted to graphite by reduction with hydrogen over iron catalyst.
Awana 2/208-210	Description of sample when received: The sample was submitted in a plastic bag containing a small clump of dark damp sediment. Sample prepared by: Wet Sieve, Picking. Pre-treatment description: The sample was sieved to 300 microns. After sieving, the >300 micron fraction was loaded with wood fragments, organic flakes, and minerals. A small organic piece thought to be a flower stem was isolated. Separately, several wood pieces were picked out and dried to select the best fraction for treatment. The plant stem was 0.68 mg and the wood materials were 8.28 mg. The stem was selected for dating and the wood materials were stored. Chemical pre-treatment was by acid, alkali, acid. Weight obtained after chemical pre-treatment was 0.3 mg. Carbon dioxide was generated by sealed tube combustion and 0.1 mgC was obtained. Sample carbon dioxide was converted to graphite by reduction with hydrogen over iron catalyst.
Whangapoua wetland 2/35-37	Description of sample when received: The sample was submitted in a plastic bag containing a small clump of dark damp sediment. Sample prepared by: Wet Sieve, Picking. Pre-treatment description: The sample was sieved to 300 micron but organic content clogged the screen. The sample was sieved again to 850 micron. The >850 micron fraction consisted of mats of mixed organic material. The material appeared to be pale reedy material that had been agitated and mixed together into clumps. No obvious macrofossils were observed, so the thick cellular sheets were selected for treatment. Chemical pre-treatment was by acid, alkali, acid. Weight obtained after chemical pre-treatment was 13.1 mg. Carbon dioxide was generated by sealed tube combustion and 1.4 mgC was obtained. Sample carbon dioxide was converted to graphite by reduction with hydrogen over iron catalyst.
Whangapoua wetland 5/39-41	Description of sample when received: The sample was submitted in a plastic bag containing a small clump of dark damp sediment. Sample prepared by: Wet Sieve, Picking. Pre-treatment description: The sample was sieved to 300 micron. The >300 micron fraction consisted of mats of mixed organic material. The material appeared to be pale reedy material that had been agitated and mixed together into clumps. Some wood pieces were picked out and some thick cellular sheets were also isolated. A stem, probably from a macrophyte, was also selected. Each of these fractions was dried to select the best material for treatment. The cellular material was 1.08 mg, the woodish material was 1.21 mg, and the stem was 2.25 mg. The cellular material was selected for treatment, while the other fractions were stored. Chemical pre-treatment was by acid, alkali, acid. Weight obtained after chemical pre-treatment was 0.9 mg. Carbon dioxide was generated by sealed tube combustion and 0.5 mgC was obtained. Sample carbon dioxide was converted to graphite by reduction with hydrogen over iron catalyst.
Harataonga 2b/188-190	Description of sample when received: The sample was submitted in a plastic bag containing a small clump of dark damp sediment. Sample prepared by: Wet Sieve, Picking. Pre-treatment description: The sample was sieved to 300 micron. Very little

	material was captured in the >300 micron fraction which consisted of a lot of tiny pale and also dark organic flakes and some minerals. Materials picked out included part of a presumed seed casing, fine charcoal or wood pieces and pale reed materials. The reed and wood/seed pieces were dried separately to get the mass before measurement. The reed material was 3.83 mg and the charcoal/seed was 1.41 mg. The wood and seed fraction was selected for treatment, while the other materials were stored. Chemical pre-treatment was by acid, alkali, acid. Weight obtained after chemical pre-treatment was 0.5 mg. Carbon dioxide was generated by sealed tube combustion and 0.2 mgC was obtained. Sample carbon dioxide was converted to graphite by reduction with hydrogen over iron catalyst.
Harataonga 2b/193-195	Description of sample when received: The sample was submitted in a plastic bag containing a small clump of dark damp sediment. Sample prepared by: Wet Sieve, Picking. Pre-treatment description: The sample was sieved to 300 micron. Limited material was captured in the >300 micron fraction and consisted of a lot of large organic flakes, fine organic detritus, minerals, and an assortment of small seeds of various type. A lot of root hairs were also observed. Two tiny pieces of flax, some small wood pieces, some flakes of what might be lake margin material, and lots of seeds were picked and dried down to get pre-treatment masses separately. The flax was 0.01 mg, the lake margin material was 5.12 mg, the long black seeds were 0.51 mg, the assorted seeds were 0.32 mg and the wood was 9.35 mg. The wood was selected for treatment, and other fractions were stored. Chemical pre-treatment was by acid, alkali, acid. Weight obtained after chemical pre-treatment was 5.8 mg. Carbon dioxide was generated by sealed tube combustion and 1.2 mgC was obtained. Sample carbon dioxide was converted to graphite by reduction with hydrogen over iron catalyst.
Harataonga 3/152-154	Description of sample when received: The sample was submitted in a plastic bag containing a small clump of dark damp sediment. Sample prepared by: Wet Sieve, Picking. Pre-treatment description: The sample was sieved to 300 micron. Limited material was captured in the >300 micron fraction and consisted of pale reedy materials, minerals, and fine organic detritus. The thick sheets of cellular material, a single small yellow seed and several small pieces of charcoal were picked out and each fraction was dried down separately to determine the best fraction for measurement. The seed was 0.11 mg, the plant material was 1.91 mg and the charcoal was 1.19 mg. The seed and plant material were combined and selected for treatment while the other fractions were stored. Chemical pre-treatment was by acid, alkali, acid. Weight obtained after chemical pre-treatment was 1.3 mg. Carbon dioxide was generated by sealed tube combustion and 0.8 mgC was obtained. Sample carbon dioxide was converted to graphite by reduction with hydrogen over iron catalyst.
Harataonga 5/202-204	Description of sample when received: The sample was submitted in a plastic bag containing a small clump of dark damp sediment. Sample prepared by: Wet Sieve, Picking. Pre-treatment description: The sample was sieved to 300 micron. The >300 micron fraction consisted of a single black seed, minerals, and lots of wood. The wood material appeared to be shattered or splintered from a larger wood piece. There were no obvious twig macrofossils located. A single thin piece of wood was picked for treatment and the remainder was stored. Chemical pre-treatment was by acid, alkali, acid. Weight obtained after chemical pre-treatment was 11 mg. Carbon dioxide was

	generated by sealed tube combustion and 1.1 mgC was obtained. Sample carbon dioxide was converted to graphite by reduction with hydrogen over iron catalyst.
Harataonga 5/210-214	Description of sample when received: The sample was submitted in a plastic bag containing a small clump of dark damp sediment. Sample prepared by: Wet Sieve, Picking. Pre-treatment description: The sample was sieved to 300 micron. Very little material remained in the >300 micron fraction, which contained a single black organic flake possibly from a leaf, some minerals, and fine pale organic root like materials. The surface of the leaf-like piece was scraped free of soil which coated the surface and was caught in the folds of the material. Chemical pre-treatment was by acid, alkali, acid. Weight obtained after chemical pre-treatment was 4.5 mg. Carbon dioxide was generated by sealed tube combustion and 1.1 mgC was obtained. Sample carbon dioxide was converted to graphite by reduction with hydrogen over iron catalyst.
Harataonga 2/140-143cm plant fragments	Description of sample when received: sample submitted as a small plug of light brown damp soil in a plastic bag. Sieved soil to 425 micron. 1.49mg was subsampled and prepared by: Wet Sieve and picking. Pretreatment description: after sieving found that >425micron fraction contained a lot of organic fines and a few larger grained minerals. Collected organic flakes which appeared to come from terrestrial sources and dried down together for a total mass of 1.49mg. Also collected pale orange pieces, which appeared to be hollow in the middle and were soft enough to scrape completely through. These are possibly oxidised twigs based on the internal structure. Dried down a collection of these for a total mass of 15.5mg. Selected organic mix for treatment for this measurement and stored the other fraction. Chemical pretreatment was by acid, alkali, acid. Weight obtained after chemical pretreatment was 1.2mg. Carbon dioxide was generated by sealed tube combustion and 0.4mgC was obtained. Sample carbon dioxide was converted to graphite by reduction with hydrogen over iron catalyst.

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