Waikato Regional Council Technical Report 2016/37

Fan delta development on the western coast of the Coromandel Peninsula

www.waikatoregion.govt.nz
ISSN 2230-4355 (Print)
ISSN 2230-4363 (Online)

Waikato
REGIONAL COUNCIL
Te Kaunihera ā Rohe o Waikato

Prepared by:
Dr Mark Dickson & Dr Jon Tunnicliffe
Auckland Uniservices Limited

For:
Waikato Regional Council
Private Bag 3038
Waikato Mail Centre
HAMILTON 3240

November 2016

Document #: 8786980

Peer reviewed by:
Dr Stephen Hunt Date November 2016

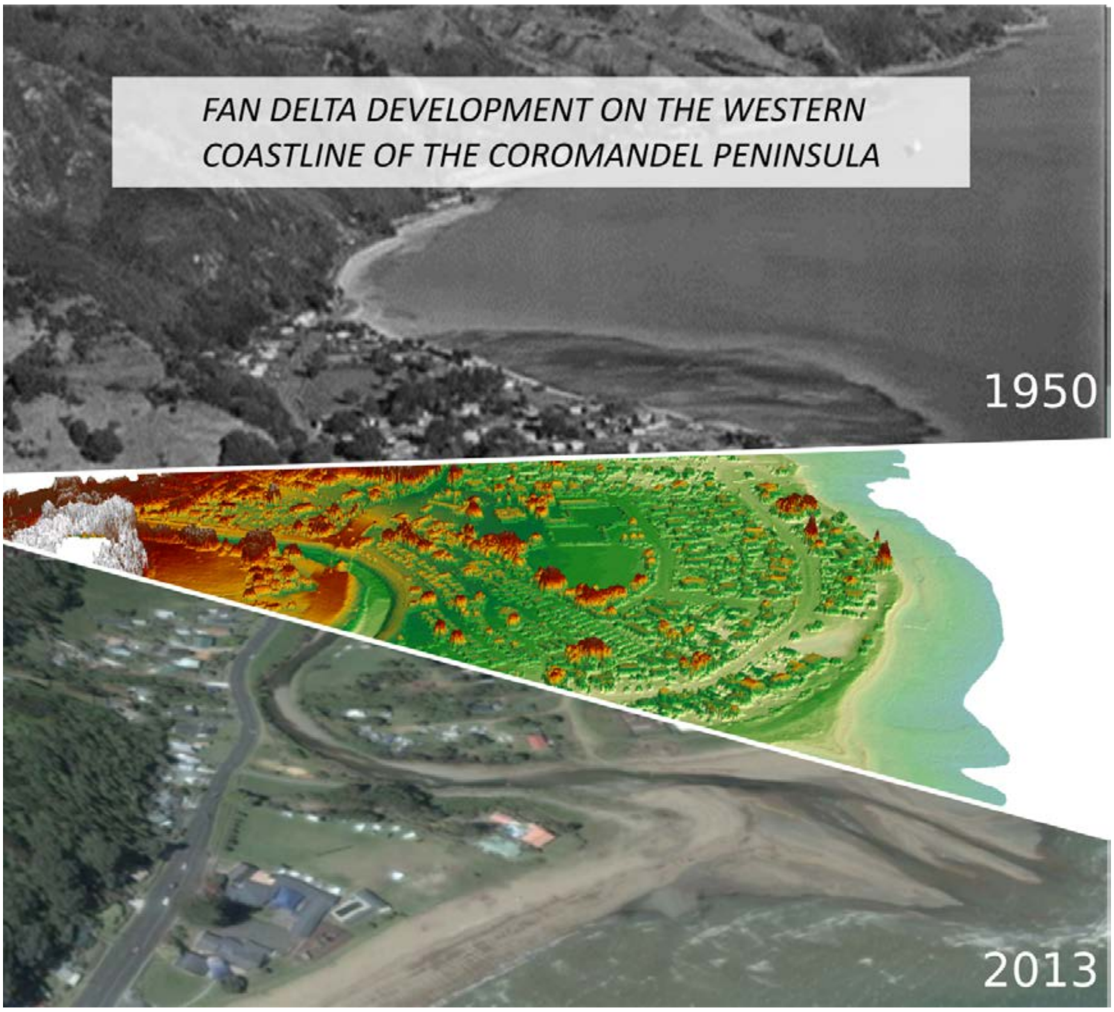
Approved for release by:
Dominique Noiton Date February 2017

Disclaimer

This technical report has been prepared for the use of Waikato Regional Council as a reference document and as such does not constitute Council's policy.

Council requests that if excerpts or inferences are drawn from this document for further use by individuals or organisations, due care should be taken to ensure that the appropriate context has been preserved, and is accurately reflected and referenced in any subsequent spoken or written communication.

While Waikato Regional Council has exercised all reasonable skill and care in controlling the contents of this report, Council accepts no liability in contract, tort or otherwise, for any loss, damage, injury or expense (whether direct, indirect or consequential) arising out of the provision of this information or its use by you or any other party.



AUCKLAND UNISERVICES LIMITED

a wholly owned company of

THE UNIVERSITY OF AUCKLAND

Prepared for:
Waikato Regional Council
8 July 2016

Prepared by:
Dr Mark Dickson & Dr Jon Tunnicliffe
School of Environment
The University of Auckland

EXECUTIVE SUMMARY

Waikato Regional Council commissioned a report to summarise the pilot research undertaken on the fan deltas on the western coast of the Coromandel Peninsula by the School of Environment, The University of Auckland between 2013 and 2015. The 'Coromandel Deltas' research project included sonic drilling, sedimentological logs, radiocarbon dating, catchment mapping, gravel sediment tracer measurements, and geophysical surveys with CHIRP and ground penetrating radar (GPR). An approximate chronology and morphostratigraphy of fan-delta deposition was developed, and a first attempt made to describe the influence of changing sea-level and other controls on small bedload-dominated fan-delta development.

The purpose of this report is to (1) summarise what is known about how the deltas have developed over long (Holocene) and medium (decadal) timescales; and (2) identify knowledge gaps that are important with respect to the management of the fan deltas. The report focusses on summarising the results of the 'Coromandel Deltas' research project, including some of the results reported in the Masters theses by Allison (2014) and Longstaff (2016), but overview of other previous research is also provided to give context, as appropriate.

The Coromandel Deltas project provides a broad understanding of the timing of delta formation, the dependency of delta development on sea-level change, approximate rates of delta development, and some aspects of the modern process environment. Previous research has suggested that delta progradation is on-going. However, our research shows that the vast majority of delta development occurred during conditions of sea-level stability and probably sea-level fall. Post-glacial sea-level rise was associated with delta flooding rather than delta building. It is unclear whether current sea-level rise is counter-acting the effects of continued sediment delivery.

Six points are highlighted as knowledge gaps: (1) detailed characterisation of climatic boundary conditions, and possible future changes to incident wave height, angle, and storm frequency; (2) local tectonics and sea-level history, because current understanding is grounded on an uncertain assumption of local tectonic stability; (3) building on our initial dating to provide a detailed chronology of delta development and sediment yield; (4) hazard characterisation of the fan-deltas, including liquefaction potential during seismic events and flood inundation; (5) rates of sediment production, including understanding the debris flow hazard and flood accommodation; (6) future trajectories of coastal flooding and coastal erosion during storm events under the influence of sea-level rise. Some brief thoughts are provided on research that could target these knowledge gaps.

CONTENTS

FIGURES

1. Introduction

Gravel fan deltas consist of a ‘prism of sediments, delivered by an alluvial fan, and deposited mainly or entirely subaqueously at the interface between the active fan and a standing body of water’ (Nemec and Steel, 1988). They are distinguished from alluvial fans by their deposition into a body of water (Van Dijk et al., 2012), and from ‘braid’ deltas and ‘common’ deltas owing to their coarser sediments, smaller steeper catchments (usually <10^3 km^2), dominant bedload transport, and a high proportion (often more than 90%) of their delta area above sea level (Orton and Reading, 1993; Blair and McPherson, 1994). Figure 1A shows an example of a fan-delta (Tararu) on the Coromandel coast; the subaerial delta and steep catchment are apparent.

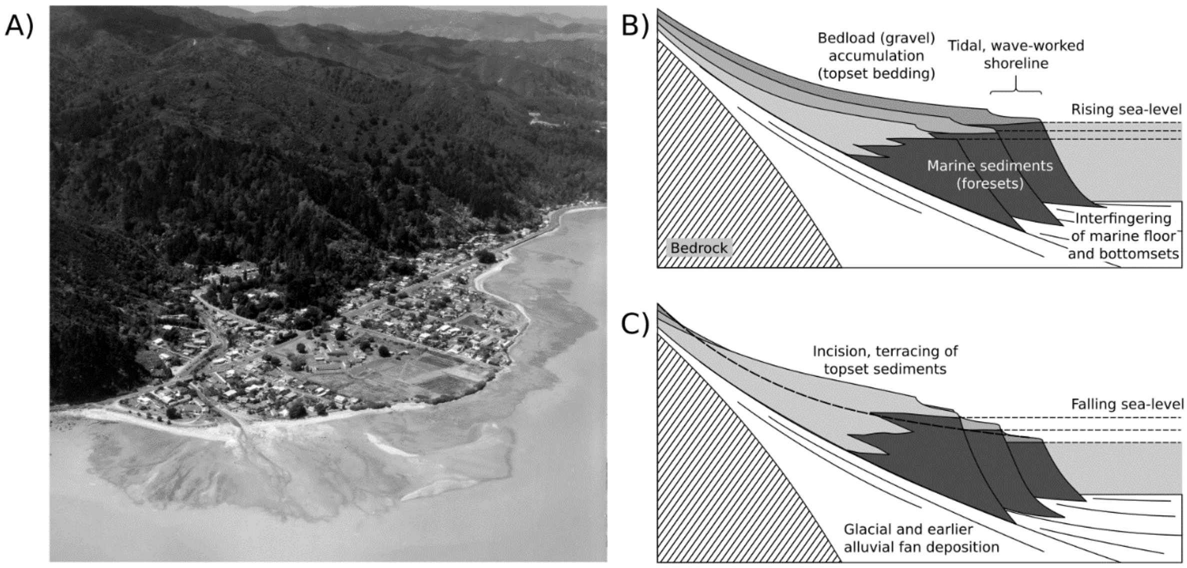


Figure 1. (A) Delta morphology at Tararu Fan-Delta in 1983, Coromandel Coast (White’s Aviation Ref: WA-76704-F). Fan-delta development during the course of (B) sea-level rise and (C) fall. Note the Firth is shallow, so the vertical scale is exaggerated.

Fan deltas are important indicators of sediment yield over time; they are a summary record of gravel and sand delivery from the mountain range to the coast. The distribution and morphology of gravel fan deltas is largely determined by wave and storm climate, characteristics of the receiving basin, sea level history, and the texture of the debris delivered from the river upstream. Gravel fan deltas are common along the shores of glacial lakes in the South Island, but are rare around New Zealand’s coastline, which generally has high exposure to wave energy that can redistribute sediments alongshore.

There are a dozen fan-deltas along 32 km of western Coromandel coastline between Thames and Coromandel town. They debouche from relatively small catchments (10-

33 km^2) and owe their preservation to a combination of a sheltered receiving basin (i.e. low wave energy within the Firth of Thames) and the lithological and hydrological characteristics of the steep Coromandel hill country. The fan-deltas provide relatively flat land in an otherwise rugged terrain. For this reason, they are highly valued for coastal settlements (O'Regan et al., 1995; Schneider, 2010). Six of the larger fan-deltas - Waikawau, Te Mata, Tapu, Waiomu, Te Puru, and Tararu (Figure 2) – have infrastructure such as roads, domains and residential properties. These fan-deltas are exposed to high hazard risks. River floods and debris flows are particularly concerning (Collen and Hessel, 1981, 1982; McSaveney and Davies, 2005; Davies and McSaveney, 2008; Welsh and Davies, 2011), and several historical events have caused significant damage, including Cyclone Bola in 1988 and Cyclone Drena in 1997 (Naish, 1990; Schneider, 2010). The most recent of several recorded storm-related fatalities occurred in a flood event at Waiomu in June 2002 (Munro, 2002; White, 2003). Hazards associated with coastal erosion and coastal flooding will continue to increase given projections of accelerating sea-level rise. A further item of concern is susceptibility of marine sands and silts to seismic shaking. Fan deltas build out (prograde) out into lake and marine environments by depositing fine-grained slope deposits known as foreset beds (Figure 1B, C) consisting of fine sands, silts and clays. These sediments make up the core of most fan-delta deposits. The upper alluvial beds, known as topsets, are built from channel switching over time, and may also have fine-grained channel fills. Liquefaction occurs when sediments are shaken, and lose their ability to stay cohesive. As the sediments are shaken they may settle, deform and/or spread.

Previous research in the Firth of Thames region has described aspects of Holocene climate and sea level history (Pocknall et al., 1989; Newnham et al., 1995), sedimentation patterns (Naish et al., 1993), the development of a bayside chenier plain along the western Firth margin (Schofield, 1960; Woodroffe et al., 1983; Dougherty and Dickson, 2012), and recent shoreline progradation associated with mangrove expansion (Lovelock et al., 2010), but there are no published studies of the small fan-deltas along the eastern margin.

This report is structured to first provide an understanding of long-term (Holocene-scale) fan-delta development through review and discussion of what is known about the basic long-term controls on delta development, and identifying where our existing knowledge is lacking. This understanding is an important prerequisite for understanding long-term rates of landscape evolution and anticipating future changes. The report then focuses on providing an overview of recent research (2014-2016) undertaken during the Coromandel Deltas project. The methods used in this project are summarised in the box below.

Methods employed in the School of Environment Coromandel Deltas Project

The project, internally funded by the School of Environment, utilised several techniques:

- The sub-bottom stratigraphy of the marine portion of the fan-deltas, as well as their relation to the larger Firth of Thames basin, was imaged using a single-channel 3kHz CHIRP sounder (Figure 2A). Transects were taken across the Firth, as well as radial transects from six fan-deltas along the Western boundary of the Firth. Penetration was generally good, though there were significant portions of the stratigraphy that were masked by intermittent layers of coarse-grained, shelly materials or possibly gas-rich layers.
- A PulseEkko GPR system with 50- and 100-MHz antennae was used to image the stratigraphy of Te Puru delta (Figure 2B). Conditions for ground penetrating radar varied from good to quite poor. Seasonal fluctuations in groundwater, as well as the presence of coarse-grained (cobble) facies, and salt water intrusion at the outer distal extent of the fan-delta degraded signal quality.
- Drilling was carried out at Te Puru using a sonic drill with a 3" barrel (Figure 2B). Drilling extended to roughly 15 m depth at two locations on Te Puru Delta before retrieval of additional core material became difficult, perhaps owing to a basal contact between marine and Last Glacial terrestrial sediments. The core material was retrieved relatively intact, though there were minor losses due to the agitating action of the drill.
- Sedimentological logs of the cores were prepared by Dr. Lorna Strachan and grain-size analyses were carried out at 10-cm intervals using a Malvern Particle Analyser.
- Radiocarbon dating was carried out on 6 samples, 3 from each core, at the Waikato Radiocarbon Laboratory.
- A program of high-resolution surveys using Structure-from-Motion was initiated at Te Mata delta, with the aim of understanding grain-size facies changes in response to storm events (Figure 2A).
- Gravel sediment tracer measurements were undertaken at Te Mata delta

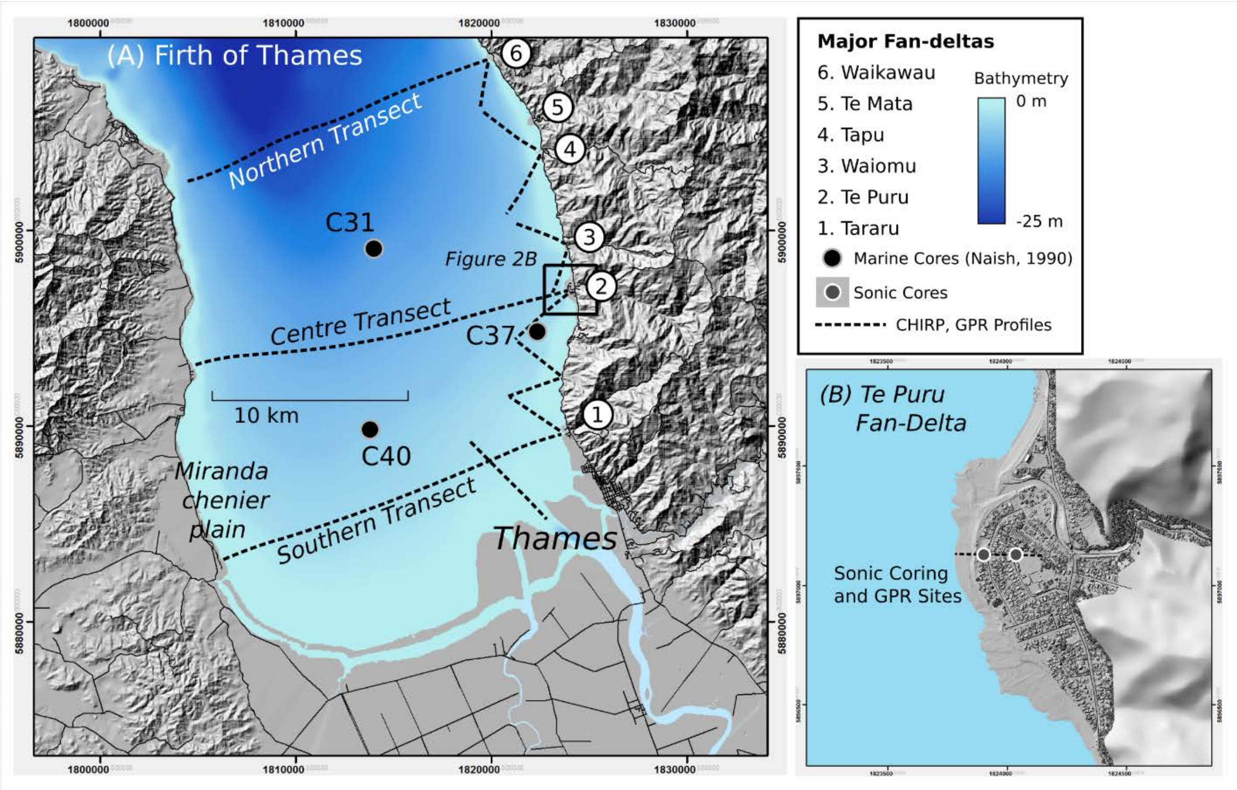
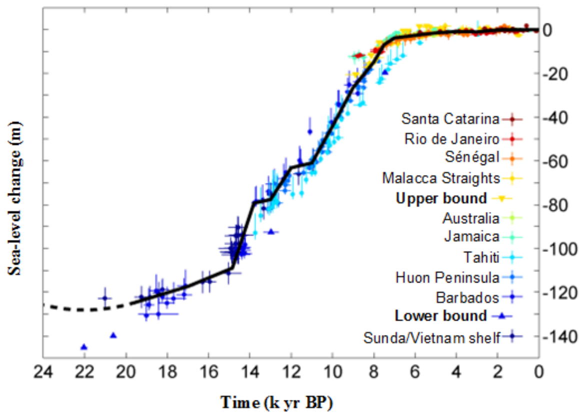


Figure 2. (A) Firth of Thames study area, showing the six major deltas, Miranda Chenier Plain, and the location of CHIRP profiling and drill cores from Naish (1990). (B) A more detailed picture of the Te Puru delta, where GPR and sonic drilling studies have been carried out to characterize delta stratigraphy.

2. Review: Holocene sea-level and sedimentation history in the Firth of Thames

Globally it is understood that multiple factors influence fan-delta development, such as ground level movements (tectonic and isostatic), climatic characteristics, river catchment characteristics, sediment discharge, and sediment redistribution by waves and tides. These factors vary with location, but global deceleration in sea-level rise has imparted an overriding control on the timing of the onset of Holocene delta development (Stanley and Warne, 1994). Around the world it is understood that deltas began to develop around 8,500 to 6,500 years BP. Recent evidence points toward a progressive decrease in the rate of sea-level rise after about 8,200 years BP (Lambeck et al., 2014). Decelerating sea-level rise provided the opportunity for the rate of fluvial sediment input to become dominant, resulting in the onset of Holocene delta succession accumulation.



Time	Landscape
18 k BP	Sea level -120m, Firth is dry, rivers cutting down and infilling Firth basin
12-10 k BP	Initial flooding (assuming a depth of 30m)
10 - 7 k BP	Rapid flooding and marine sedimentation
7 - 4 k BP	Possible ~+2m(?) highstand, marine sedimentation
4 - 1 k BP	Rapid coastal progradation
1 - 0 k BP	Alongshore chenier extension (western Firth)

Figure 3. Sea level history (after Robert A. Rohde, Wikimedia Commons) and coastal response in the Firth of Thames.

A declining rate of post-glacial sea level rise may have controlled the timing of the onset of delta building along the eastern Firth (Figure 3). Previous work around New Zealand indicates that sea level was situated between 55 and 70 m below the present level at roughly 12,000 years BP (Carter et al., 1986), rising to about 33.5 m below present by around 10,000 years BP (Gibb, 1986). Core data from the Firth of Thames deviates somewhat from this general pattern, with evidence suggesting that about 11,900 years BP sea level in the Firth was ~35 m below its present with the coastline was in the vicinity of the northern end of Ponui Island and present day Coromandel town (Pocknall et al., 1989). Post-glacial sea level rise continued rapidly around New Zealand between 10,000-6,500 years BP, with stillstands likely between 9,500-8,500 and 7,500-7,000 years BP (Gibb, 1986). It is generally thought that Holocene sea level has been relatively stable around New Zealand since about 6,500 years BP (Gibb, 1986).

Reasonable postulates, given a declining rate of post-glacial sea-level rise from about 7,500 years BP, and sea-level stability from about 6,500 years BP, are that (i) the onset of fan-delta development within the Firth likely occurred between 7,500-6,500 years BP, and (ii) delta development may have progressively occurred during the Holocene sea-level still stand. However, late Holocene sea-level stability cannot be assumed within the Firth. In fact, evidence from the chenier plain preserved along the western side of the Firth indicates that mid- to late-Holocene sea level movements may have been significant.

On the western margin of the Firth north of Miranda a sequence of thirteen cheniers (shell ridges) is preserved. Radiocarbon dating by Schofield (1960) shows that they progressively reduce in age from the oldest, landward-most ridge (chenier 13, ~3,900 years BP) to the youngest, seaward-most ridge (chenier 6, ~980 years BP) (younger ridges are distributed alongshore rather than across-shore). There is a clear decreasing trend in ridge surface elevation from chenier 13 to chenier 6, which Schofield (1960) attributed to a +2m drop in sea level between about 4,000 and 1,000 years BP. (Woodroffe et al., 1983) noted that the modern chenier varies in elevation between +1.7 and 3.1 m above MSL, and on this basis suggested that a better sea-level proxy is provided by a continuous sub-surface band of sub-fossil shells, preserved in growth position, which they dated at 3650 ± 60 years BP to landward and 1260 + 50 yrs BP to seaward. The elevation of this shell layer implies higher sea level of +0.7-0.9 m above MSL around 3,600 years before present, falling gradually to present levels around 1,200 years BP.

A third approach was taken by Dougherty and Dickson (2012), who used GPR to image the basal contact between the shell chenier and the sand-mud foreshore sediments. Their assumption is that the continuity of this stratigraphic boundary forms a more reliable sea-level proxy than the surface of the ridge, which could have been influenced by compaction and a range of human effects. On the basis of a continuous radar transect from chenier 13 to chenier 6, Dougherty and Dickson (2012) concluded that sea level likely reached a maximum of +2 m above MSL around 4,000 years BP (Figure 4B) and then fell toward present sea level, probably reaching present level around 1,000 years BP.

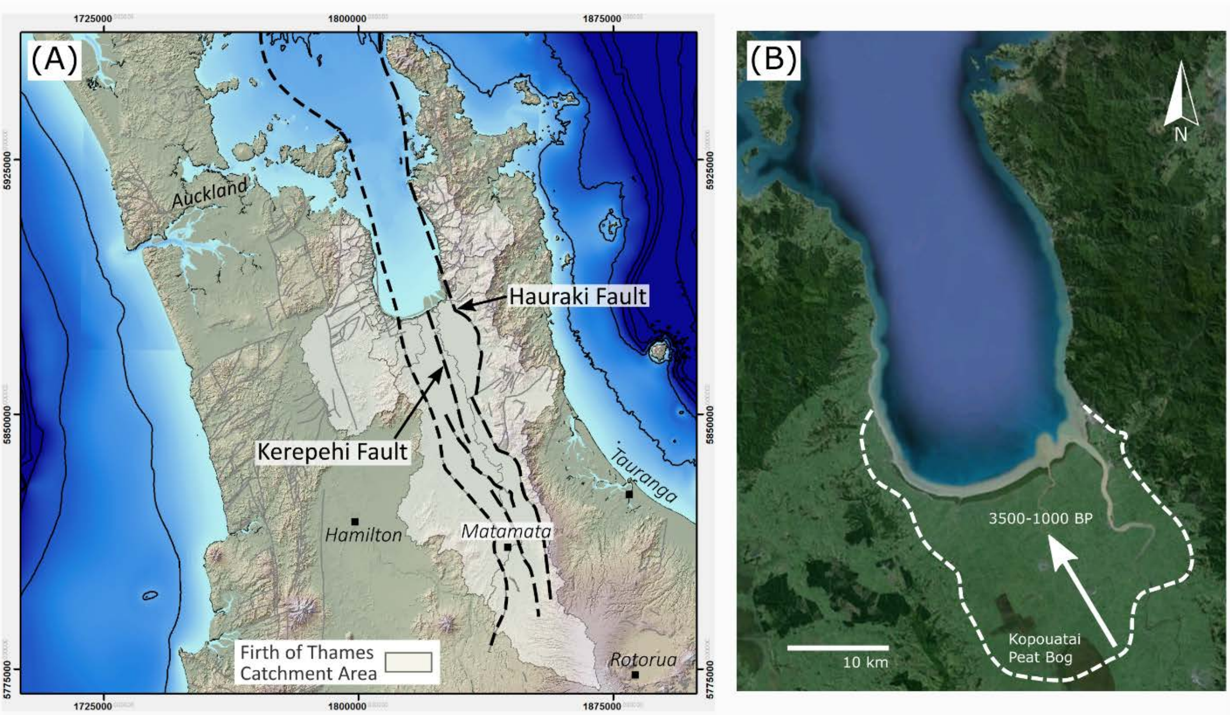


Figure 4. Firth of Thames environs; (A) geologic structure of the Hauraki depression and catchment area. (B) Approximate maximum extent of sea level incursion, following the mid-Holocene high-stand.

2.1 Tectonic and geologic setting

A major uncertainty in the above work is whether there has been tectonic stability over the period during which these sea-level reconstructions are inferred. Some researchers have assumed the Firth area to have been a region of relative tectonic stability throughout the Holocene (e.g., Schofield, 1960; Woodroffe et al., 1983). However, Gibb (1986) suggested, on the basis of preserved of Pleistocene and Holocene terraces, that there may have been uplift in the vicinity of the Firth of Thames at a rate of ~0.10 m per 1,000 years. The Kerepehi Fault (Figure 4A) is active in the central Firth and is thought to have a vertical displacement of ~0.13 $mm \cdot a^{-1}$ with an average recurrence interval of ~2,500 years (De Lange and Lowe, 1990). Chick's (2001) analysis indicates a possible event vertical displacement of around 2.1 m some time after the end of the postglacial transgression. Greig (1990) cited evidence of seafloor and sub-bottom features strongly suggesting recent tectonic activity in the outer Firth of Thames/inner Hauraki Gulf. In attempting to reconcile a depth discrepancy in paleo sea level data recovered from the outer Firth (versus the global record), Pocknall et al. (1989) suggested that the difference might reflect local and aberrant tectonic uplift in a region of otherwise unquestioned longer term rapid subsidence (Hochstein et al., 1986). If there has been uplift within the region then that process could largely account for raised chenier ridges, implying that late Holocene sea level may not have been higher than present. However, raised beach ridges are also preserved further north at Omaha (Dougherty, 2014), an area that is thought to be stable tectonically. Clearly, Holocene vertical tectonic movements in the Firth of Thames remain a major source of uncertainty that restricts our ability to decipher sea level history, and that limitation has significant flow-on effects to understanding the evolution of coastal landforms.

Tectonic movement within the Hauraki rift is an area of on-going research at The University of Auckland under the new project 'Hauraki Rift – Bridging the Gulf' led by Dr. Jennifer Eccles, School of Environment.

2.2 Sediment yield

The Firth of Thames is shallow and was subaerially exposed during the last glaciation when sea-level was lower. Analyses of peat extracted from cores taken on the northern seaward opening of the Firth suggest that in pre-Holocene times the Firth basin was covered in lowland swamp or marshland and surrounded inland by rainforest dominated by conifers, beech, and tree ferns (Pocknall et al., 1989). At this time the Coromandel fan-deltas were entirely sub-aerial and relatively unconstrained, progressively building out onto the lowlands. Toward the south sediments were being supplied from rivers draining the Hauraki Lowland and southern catchments. At present the dominant southern rivers are the Waihou and Piako/Waitoa, with sediment discharge rates of about 3.5 x 10^6 $t{\cdot}a^{-1}$ and 0.8 x 106 $t{\cdot}a^{-1}$, respectively. More than 90% of the load is suspended sediment (Griffiths and Glasby, 1985) leading to modern sedimentation rates of about 0.8-1.0 $mm{\cdot}a^{-1}$ in the centre and 1.8-2.0 $mm{\cdot}a^{-1}$ in the southern nearshore regions of the Firth respectively (Naish, 1990). During the Last Glacial, the southern rivers were supplying pumiceous sands and gravels in a thick wedge of prograding, braided fan sediments (Kear and Tolley, 1957; Cuthbertson, 1981; Houghton and Cuthbertson, 1989). These sediments are volcaniclastic in nature, dominated by pumice and glass shards from erosion of the mid-Pleistocene ignimbrites of the Taupo Volcanic Zone (TVZ), but also the erosion of Neogene andesite-dacite volcanics of the Coromandel-Kaimai Range.

3. Holocene sedimentation in the Firth of Thames

The post-glacial sea-level transgression flooded the plains and reworked fan-delta sediments around the Firth. Rising sea level caused the rivers of the Hauraki Plains to aggrade, prograding the shoreline roughly 13 km seaward (Figure 4B), reworking the cap of earlier braided alluvial sediments and delivering large amounts of volcanic glass-dominated suspended sediment to the Firth. The Firth of Thames was fully inundated by the time the sea reached a high stand by roughly 6,500 years BP. As discussed above, the high stand may have been as much as +2 m above MSL, perhaps persisting until around 4,000 years BP before dropping back to present level by around 1,000 years BP; however, considerable uncertainty exists owing to lack of knowledge of the tectonic setting.

Marine fan-delta deposition along the western Coromandel coast ensued around the time of the sea-level high-stand, before terrestrially derived fan-delta sediments began to again build out on top of the former sub-aerial alluvial fans at the outlet of their catchment valleys. This conceptual model implies a basic stratigraphic succession (see Figure 1B, C) for the Coromandel fan-deltas in which basal pre-Holocene terrestrial sediments are overlain by marine sediments deposited during the postglacial transgression and highstand, which are again overlain by surficial terrestrial sediments deposited during late Holocene still-stand (or falling sea level).

In addition to the Coromandel fan-delta development, progressive winnowing of mud sediments offshore by tidal currents during the late Holocene has produced an actively prograding submarine wedge within the Firth which reaches a maximum thickness in the central Firth of Thames basin, and thins significantly northward (Figure 5; Naish, 1990). Naish (1990) estimates that at least 10 m of silicic volcaniclastic mud accumulated in the basin during the Holocene. The large proportion of volcanically-derived (tephra-rich) sediments in the Firth of Thames (>90%) presents a marked lithological contrast with most sediments found along the New Zealand coastline, and indeed, with most sedimentary systems worldwide (Healy, 2002). More commonly, the bulk of these accumulations consist of quartz, feldspar, and other more resistant lithologies. The total yield to the Firth thus more strongly reflects the significant loading of the landscape by historic tephra falls, and rather less than the detachment and wear of bedrock.

Figure 5 shows two seismic transects across the Firth of Thames from the Te Puru fan-delta in the east, to Whakatiwai Point on the western shore. There is a prominent reflector at roughly 5-10 m depth which is interpreted as the post-glacial Holocene transgressive surface. Layers of suspected shell hash and gravels limit visibility below this reflector across much of the survey line. The overlying seismic unit (I) is interpreted as the prograding Holocene mud blanket. The thickness of seismic unit I is consistent with long-term rates of sedimentation (0.5 to 1.9 $mm \cdot a^{-1}$) established by Naish (1993) from radiocarbon dating of core material. The lower unit was deposited early in the post-glacial era.

Sediments from the Te Puru fan-delta in the east extend roughly 2 km offshore (Figure 5), and interfinger closely with the much larger Holocene mud blanket. The western coastal area of the Firth in the vicinity of Whakatiwai is notably steeper than the east, and the Holocene mud blanket does not extend to the coast. The present day coastal morphology in this area is steep, with greywacke boulder beaches. It is not clear why the maximum thickness of the Holocene mud blanket (and maximum water depth) is offset toward the western Firth coast, but the morphology may be partly inherited from the alignment of major rivers during Glacial times.

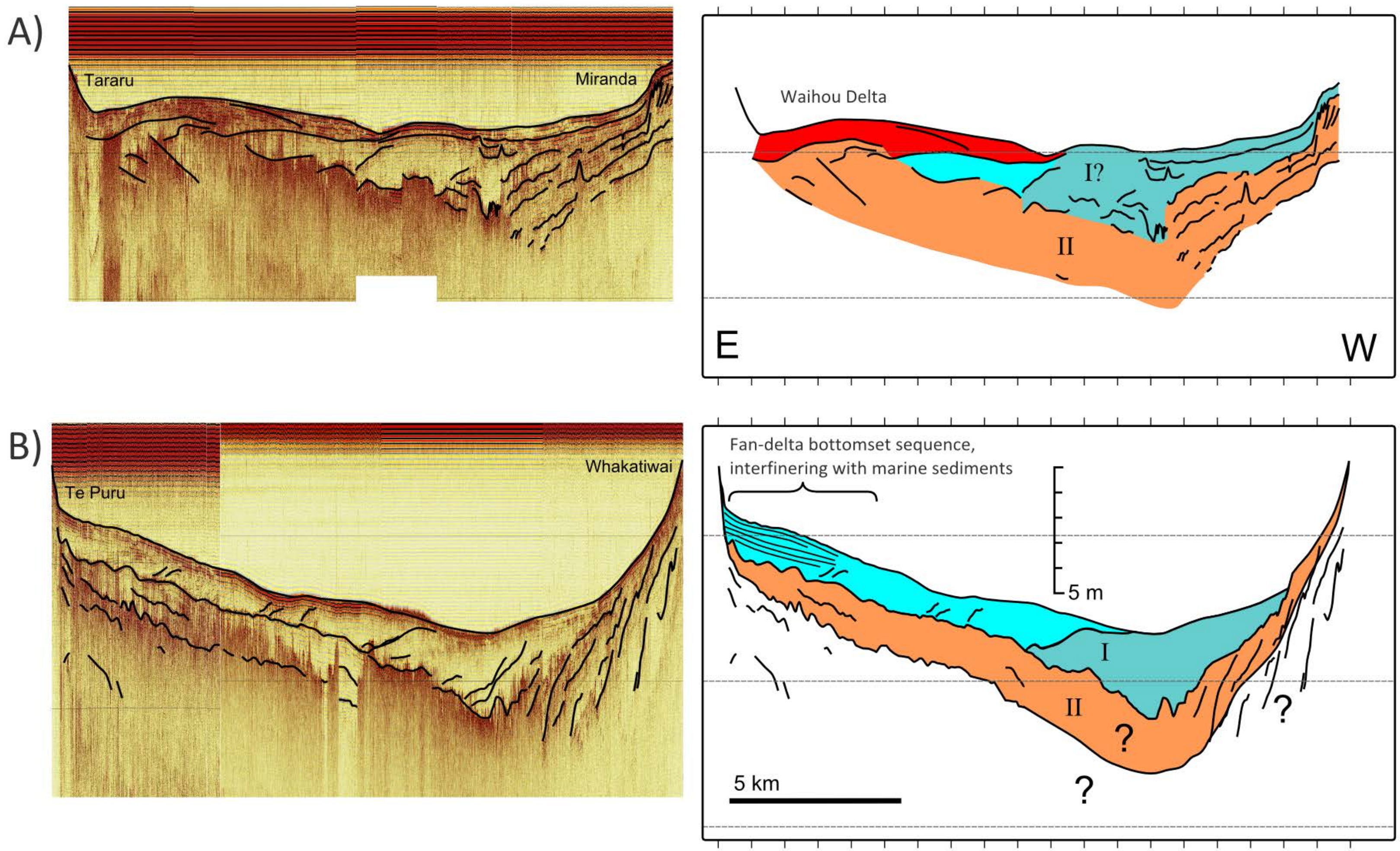


Figure 5. Firth of Thames stratigraphy at (A) southern and (B) center transects (Figure 2A, looking southward), revealed using sub-bottom 3 kHz CHIRP sub-bottom profiler. Units I and II are thought to be mainly post-glacial marine sediments, overlying older (opaque) terrestrial sediments.

4. Model of fan-delta growth

Prior to the Coromandel Deltas project there was very little understanding of the chronology and morphostratigraphy of fan-delta deposition in the area, and little understanding of the primary controls on delta development. This section describes the subsurface stratigraphy of the Western Coromandel fan deltas, their relationship to sediments in the Firth of Thames, and ultimately provides a new conceptual model of Holocene delta development based on our results from the project.

The sub-bottom transects at the distal edges of the fan-deltas (locations indicated in Figure 2A) indicate the nature of the relationship between stratigraphy within the larger Firth of Thames and the smaller fan-deltas. Figure 6 shows two radial sections off the edge of the northernmost Waikawau fan-delta (Figure 2A), showing distal bottomset sediments and their interbedding with marine sediments on the floor of the Firth of Thames. Notably, distal accumulations are entirely fine grained (fine sands and silt), suggesting that the constituent gravels and cobbles delivered to these landforms are essentially ‘trapped’ on the intertidal and sub-aerial fan delta. It appears that the only way they can leave the delta is through swash-zone abrasion processes, but as discussed below, these processes are probably very slow.

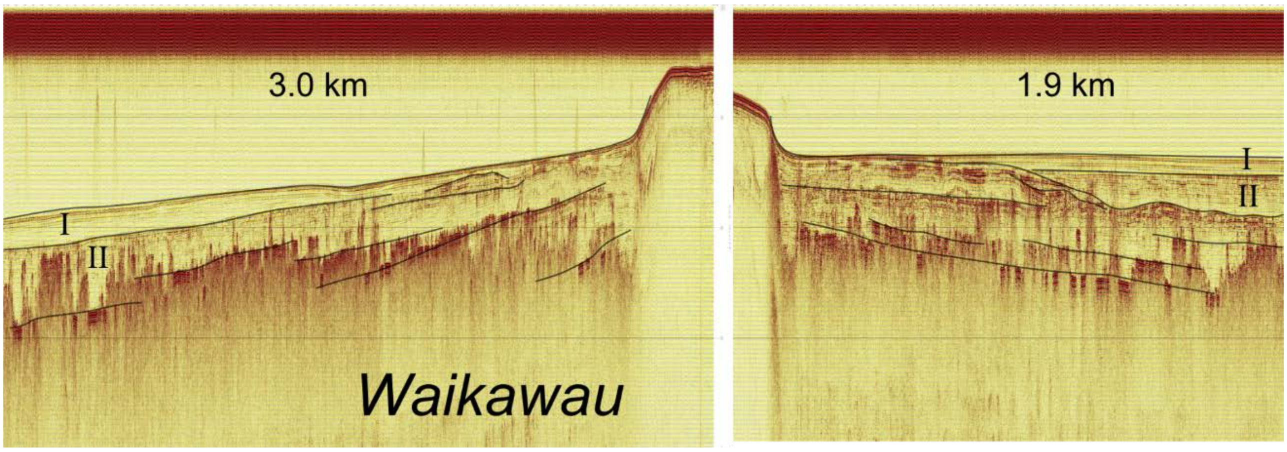


Figure 6. Fan stratigraphy at Waikawau, highlighting the nature of fan-delta bottomset sediments interfingering with marine sediments on the floor of the Firth of Thames.

Longstaff (2016) used the sub-bottom records to estimate the extent and thickness of the six major fan-deltas, with volumes of post-glacial sedimentation found to be on the order of 10-50 x 10^6 m^3. She also carried out ground penetrating radar surveys at Te Puru fan delta to extend the offshore seismic record across the terrestrial delta (Figure 7). GPR surveys across the fan-delta topset units suggest a relatively complex, disordered stratigraphy. Coarser units up-slope grade to sandy beds and then to finer, layered deposits at the beach face. The outer distal sediments were obscured by saline waters in the substrate. The upper stratigraphy was sandy, with some signs of anthropogenic disturbance and filling. The gravel facies was roughly 8-10 m thick, with comparatively opaque marine beds below that.

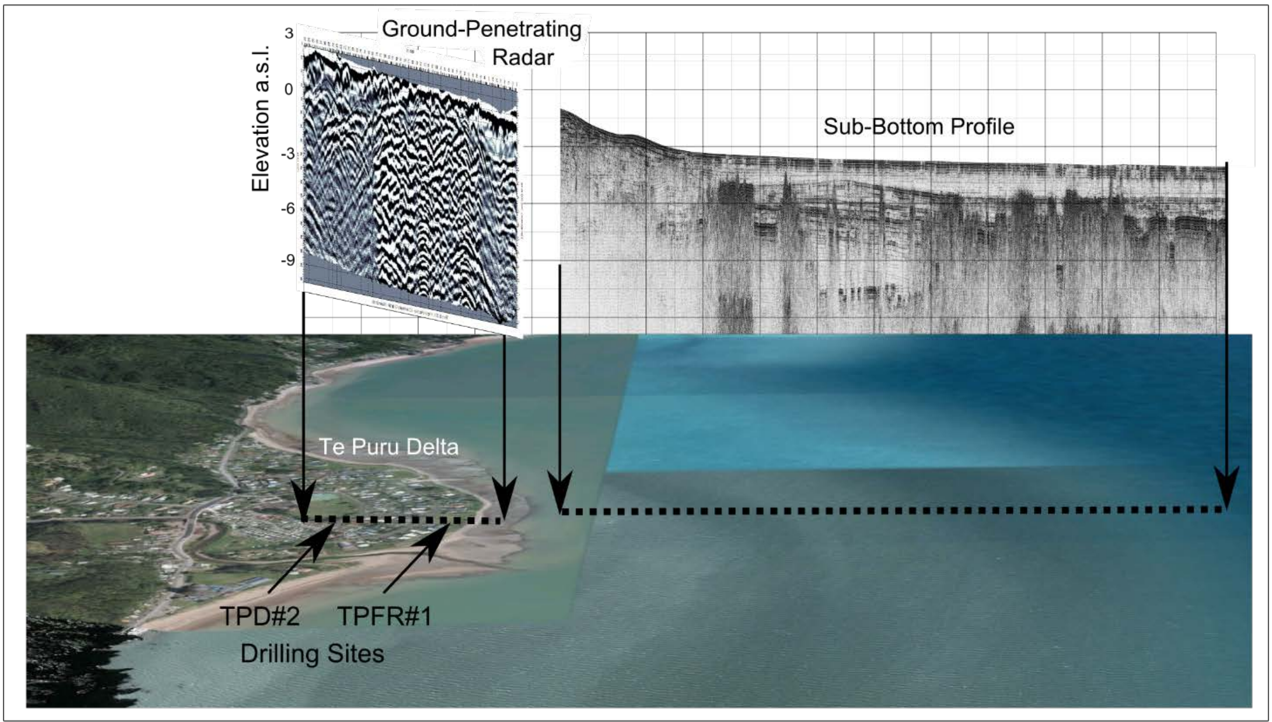


Figure 7. Comparison of GPR and CHIRP seismic surveys at Te Puru fan-delta

Two sonic drill cores ground-truth the GPR survey and provide a coherent picture of the Holocene evolution of the fan-deltas. TPD#2 was extracted at mid-fan, whereas TPFR#1 was sited at a more distal point, toward the modern shoreline. At roughly 9 m and 6 m depth, respectively, there was an abrupt transition from river gravels to marine sediments, indicative of the approximate stage where bedload material from the river had prograded to that point on the fan-delta. The stratigraphy of the two cores is shown in Figure 8.

The upper sedimentary layers of the cores show mainly fluvial gravels, with some indications of marine reworking, most notably shell content. The sonic coring process tends to disrupt bedding to some extent, but there is evidence of sandy deposition near the center of the fan, with interdigitating sheets of gravel. The terrestrial package (i.e. topset deposition) is 9m thick at the center of the fan, tapering to about 5 m closer to the coast.

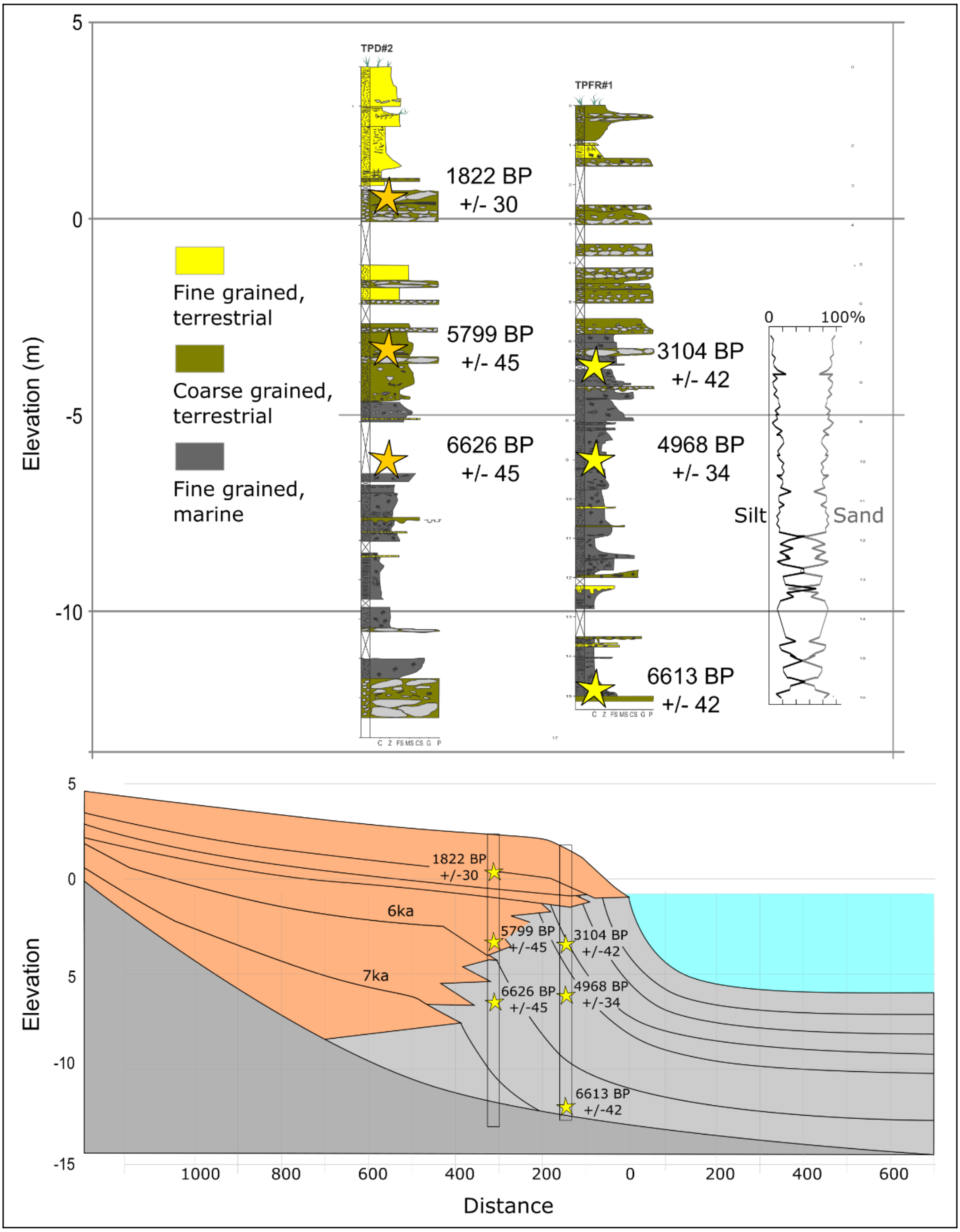


Figure 8. (A) Drilling core logs from TPD and TPFR. (B) Conceptual picture relating core strata to fan-delta stratigraphy

Delta-development at Te Puru appears to have begun when the post-glacial sea-level rise terminated around 6,500 years BP. The timing is constrained by core TPFR#1 on Te Puru delta which has a lower boundary radiocarbon age of 6,613 ± 42 years BP (Figure 8). This contact captures the point at which the fan-delta had prograded over the older Pleistocene fan: below the contact are Pleistocene gravels, above the contact are marine muds. The core from mid-fan (TPD#2) also bottoms out in alluvial gravels (Figure 9), and is overlain with a complex suite of coarse, reworked marine sediments with broken shells. These sediments are likely older than 7,000 years BP, but there is poor dating control here.

Around the time that sea-level began stabilising (e.g. 7,000 to 6,000 years BP) the coastal basin began rapidly filling with marine muds and Te Puru fan-delta started building out into the Firth in about 6-7 m of water. The lower portion of the more distal core (TPFR#1, Figure 8) exhibits a marine foreset sequence that coarsens upward (see inset sand/silt ratio chart), reflecting the change in delta front setting, from deep water to relatively shallow, higher energy flows, transitioning to subaerial fluvially transported material at the top.

The timing of delta-development at Te Puru is generally consistent with global data in which the vast majority of deltas began forming as sea-level rise slowed between 8,500 to 6,500 years BP (Stanley and Warne, 1994). Te Puru fan-delta began developing at the later end of that range. This reflects the balance between fluvial-sediment input and sea-level change. Larger deltas with higher sediment supply are able to begin overwhelming rising sea-level at an earlier stage in the decline in the rate of post-glacial sea-level rise. Te Puru has a much smaller sediment supply, such that progradation has been dependent on stable (or even falling) sea-level.

Between roughly 6,000 and 3,000 years BP, the gravel front of the delta prograded across the 260 m between the sites of TPD2 and TPFR1 at a rate of about 8 $cm \cdot a^{-1}$ representing an annual bedload yield of roughly 1,600 $t \cdot a^{-1}$. Looking at it another way, the total post-inundation Te Puru fan-delta sand/gravel package is estimated to be 6.85 $x10^6$ m^3, ± 10%. Dividing this by 6,000 years, and accounting for the densities of sand and gravel, this amounts to roughly 1,900 $t \cdot a^{-1}$. These numbers provide us with some reasonable bounds for considering the long-term, average supply of sand and gravel to the deltas.

5. Modern processes influencing fan delta morphology

The fan-deltas along the western Coromandel are progradational features that have developed over the Holocene. The modern process environment is quite different from the environment during which the deltas developed. The purpose of this section is to review what is known about delta change over short-term and decadal scales.

5.1 The Coromandel catchments

The catchments along the western Coromandel Peninsula are relatively steep and confined, delivering a coarse-grained sediment load to the coast. Slope gradients are on the order of 0.005 to 0.12, and cobble material exceeding 128 mm can be found in the lower river and along the outer fan-deltas. The lower rivers of the major fan-deltas have been engineered to minimise the possibility of river avulsion, with heavy rip-rap reinforcing the current channel configuration. Upstream, the river is supplied by material from steep slopes that are closely coupled with the channel. Thus, bank erosion, shallow slips and larger debris flow material are directly entrained, with little intermediate channel storage (Figure 9A).

At present there is little known about the magnitude and frequency of mass wasting events. There is considerable scope for developing an inventory of mass wasting activity, as well as more directed case studies (e.g., McSaveney and Beetham, 2006), in order to understand the spatial distribution of failures and the potential for debris flows within the valley mainstem. The relationship between fault boundaries, lithologic terranes and slope failures could greatly increase our understanding of failure dynamics in the region. Such studies would help to inform hazard management in the lower valley and fan-delta communities.

Figure 9. Landslips within Te Mata catchment. (A) A landslip is closely coupled with the river. This feature appears to be a complex and chronic slide that reactivates periodically as the river meander erodes the toe zone. (B) Three landslips along the road that are occasionally activated, requiring ongoing road maintenance. Drone photos taken in May, 2016 as part of a study initiated by Martin Brook, School of Environment.

5.2 Sub-tidal sedimentation processes

Fine-grained (suspended) sediment movement and deposition within the Firth of Thames has been studied by Van Leeuwe (1991), revealing some of the basic circulation patterns of sediments emerging from the Waihou and Piako/Waitoa-rivers during tidal cycles. Sediment concentrations of up to 900 $mg \cdot l^{-1}$ were measured at the mouth of the Waihou River. Numerical modelling by Bowman and Chiswell (1982), Greig and Proctor (1988), and Proctor and Greig (1989) provided a more detailed picture of how sediments move in a circulatory pattern, causing most of the suspended load to remain within this semi-enclosed sea, creating extensive intertidal mud flats.

More recently, work by Pritchard and colleagues (2015) employed three-dimensional hydrodynamic and sediment transport models (Delft-3D and SWAN) to simulate circulation within the Firth. Simulations indicate that under calm conditions, decelerating outflow from the Waihou River produces a sediment plume that remains within 1-2 km of the river mouth. By contrast, during NE storm conditions, Waihou sediments are redistributed over larger distances against the southern and southwestern Firth, with deposition occurring on intertidal and shallow subtidal flats. Under SW wind stress, deposition occurs on the eastern shore of the Firth, and so directly influence the development of the western Coromandel gravel fan-deltas. These simulations confirm earlier findings that very little sediment leaves the Firth.

Pritchard et al. (2015) comment that event-driven and long-term sedimentation patterns in the Firth are controlled by the interaction of the prevailing southwest and opposing northeast winds with a buoyant silt-laden river plume. This interaction leads to locally high sediment accumulation rates in depocentres on the upper intertidal (southern Firth) and subtidal zone in the eastern Firth offshore from Te Puru.

It is clear from these results that fine-grained sediment delivery from the southern rivers represents an important constituent of the long-term development on the Coromandel fan-deltas. At the same time that Coromandel river processes are supplying coarse sand and gravel, the Hauraki lowland rivers are supplying silt that is incorporated in the progradation of the distal portions of the delta.

5.3 Fan-delta coastal processes

Two Masters' theses have examined the nature of coastal sediment transport on the gravel fan deltas. Dravitzki (1988) investigated sediment transport and gravel abrasion rates on Te Mata, Tapu, Waiomu and Te Puru fan deltas. Allison (2014) studied sediment transport and abrasion in detail at Te Mata delta as a part of the School of

Environment Coromandel Deltas research project. The studies provide some useful insights into gravel transport on the deltas, but each is limited in a number of respects; overall the coastal morphodynamics of the deltas remains poorly understood, particularly in respect to storm events, which are the most important driver of morphological change.

Dravitzki (1988) studied four of the six fan-deltas along the western coast of the Coromandel peninsula (Te Mata, Tapu, Waiomu and Te Puru). He placed exotic Te Kuiti group limestone clasts on Te Mata and Te Puru fan deltas and visually tracked these over several months. An average net transport distance of 63 $m \cdot a^{-1}$ was determined for clasts of comparable length to native beach sediments. Smaller tracers travelled further, but the trend was not statistically significant and Dravitzki (1988) concluded that littoral processes operate equally for all sizes of indigenous beach gravels. It is not clear whether the limestone clasts had similar transport behaviour to clasts of local lithology (andesite, dacite, and greywacke).

Allison (2014) studied sediment transport at Te Mata fan-delta under calm conditions. The surface of the delta was 52% gravel, 12% fine pebbles, 8% shell and 26% sand. 120 native gravels were sampled proportionately to reflect the lithological make-up of the delta (dominantly andesite with equal smaller proportions of dacite and greywacke), and 12mm RFID tags were inserted in the clasts. Clasts were relocated and their positions measured on days 1, 7, 34, 42, 113, and 188. Wave heights and flow velocities were monitored using pressure sensors and an acoustic doppler current profiler. Significant wave height was <25cm for about 80% of the experiment. Sediment transport rates were quite low during the 6-month experiment. Only 6 of 120 gravels moved more than 15 m and the maximum trajectory was only 36 m. Clasts moved onshore, whereas measured current flows were typically offshore throughout the tidal cycle. Sediment traps 5 cm above the bed even capture only trace amounts of sediment despite current speeds of 50 $cm \cdot s^{-1}$ (30 cm above bed height).

Allison (2014) concluded that at Te Mata, energy levels rarely reach the high threshold for entrainment of coarse sediment (Orton and Reading, 1993; van Dijk et al., 2012). He noted that even during Cyclone Ita, when maximum wind speeds were 100 km/hr, maximum net gravel movement was only 7.3 m. Allison (2014) described Te Mata fan-delta as having a mobile armour layer (Hunziker and Jaeggi 2002), which, while being finer in composition to static armour layers, nonetheless succeeds at being “rather insensitive to changes in the imposed flow strength” (Mao et al., 2011).

Dravitzki (1988) and Allison (2014) each investigated whether gravel fan-delta clasts abrade during transportation. Dravitzki (1988) noted size reductions of 27-30% of the limestone tracer clasts and used these measurements to infer abrasion rates of native clasts; however, this approach is quite unreliable. Allison’s (2014) measurements showed that native gravels did not measurably reduce in size during a 48-day period, indicating that under fair-weather conditions abrasion is likely to be very slow indeed. He investigated further in the laboratory using gravel tumbling experiments which showed that the sand present in the delta likely has an important buffering effect on gravel clast abrasion (e.g. reductions in abrasion rate with sand included were 38, 39 and 61% respectively for andesite, greywacke and dacite).

Allison (2014) concluded that the combined effect of (1) onshore gravel transport, (2) a mobile gravel armour layer, and (3) slow rates of gravel abrasion, means that gravels supplied to the delta by streams likely remain intact on the delta for many years after their initial delivery and imbrication into the armour layer. “This means that only minimal gravel delivery by Te Mata Stream is necessary to ensure the continuing presence of gravels on the delta in the number exhibited. In contrast, the sand present on the fan delta slowly abrades away under fair-weather conditions and is replenished by fluvially derived sand. This creates a prevailing sedimentary equilibrium, where the effects of fair weather conditions and constant sediment supply to the fan delta mute the outcome of sporadic high-energy events.”

5.4 Decadal-scale shoreline changes

Aerial photographs provide one means to evaluate historical (decadal-scale) morphological changes on the fan deltas. Dravitzki (1988) determined from aerial photograph analysis that the western Coromandel deltas have been historically prograding at a rate of about 6 $cm \cdot a^{-1}$, which is reasonably consistent with our Holocene-scale record, above. He assumed for this work that no human influence had taken place, which is a problematic assumption, given that many locals describe quite extensive shoreline modification and land reclamation following the first subdivisions of Te Puru in 1949.

A more detailed analysis of shoreline change was undertaken at Te Puru fan-delta by O’Reagan et al. (1995). Summer (Jan/Feb) photographs were obtained from 1944, 1968, 1983, 1985 and 1991, although the 1944 image was too low in resolution to be useful for planimetric mapping. The images were scanned and rectified and shoreline-change mapping undertaken. Mapping showed that erosion and accretion drove small and non-systematic shoreline fluctuations between 1968 and 1983. The conclusion drawn by O’Reagan et al. (1995, p29) was that “Te Puru delta is a progradational feature formed as a result of the accumulation of sediment from the backing streams, and the inability of wave action and littoral drift to transfer sediments away at the rate it is supplied. As such, there is probably only a minimal risk of coastal erosion placing dwellings in danger of being swept into the sea.”

Three points may be made in respect to these historical shoreline mapping analyses:

1. The studies are useful for confirming that no systematic, chronic trend of erosion was occurring in the latter part of the 20th Century.
2. The studies were undertaken at a time when there was little knowledge of the acceleration in rates of sea-level rise currently being experienced. For context, our Holocene sedimentary data clearly show that during the rapid post-glacial sea-level rise there was a period of time during which marine flooding of the fan-deltas occurred (i.e. when sea-level rise overwhelmed sediment supply). We have yet to form a view on the rate of sea-level rise that would be necessary to reverse the progradation history observed in the latter part of the Holocene, but clearly there is some threshold when that would be expected. We are not aware of any shoreline mapping work following O'Regan et al. (1995), but casual inspection of historical photographs in Google Earth supports a general view that the deltas have had relatively small changes in shoreline position over several decades.
3. Historical shoreline mapping does not provide insight on the possible effects of short-term, event-driven changes. Such changes are very unlikely to be recorded within a multi-decadal historical photograph record, but they may be very important events to take into account when considering coastal hazard risk to low-lying coastal properties.

5.5 Event-driven controls on delta morphology

It is well known that occasional NE storm events arising from tropical depressions can deliver significant swell, wind and rain to the western Coromandel fan-deltas. Storm-surge resulting from such event can significantly raise water levels thereby raising the risk of coastal flooding and erosion. Locals describe morphological changes resulting from these events, both in respect to river-forced changes, and also coastal storm waves. Unfortunately, we have no data available to us on the impact of coastal storm waves on the deltas, which represents an important knowledge gap.

6. Knowledge gaps and research required

The Coromandel Deltas project has led us to an improved understanding of the nature of coastal sedimentation in a shallow semi-enclosed sea (Healy and Harada, 1991). The fan-deltas along the coastline of the western Coromandel Peninsula have proven to be of major interest owing to their position at the intersection of several important research threads, namely:

- Risk to communities, owing to floods, debris flow, storm surge and seismic shocks.
- Response to sea-level change, including coastal erosion and sea incursion
- Reconstruction of Holocene sea-level history
- Sedimentation history and sediment budget of the Firth of Thames
- Interactions between delta building and longshore sediment transfer

Through the Coromandel Deltas project we now understand, broadly, the timing of delta formation, the important control of sea-level change on delta growth, approximate rates of late Holocene delta development, and some aspects of the modern process environment. It is clear that hillslope and river processes continue to deliver sediments to the deltas, and that modern coastal processes do little to remove those sediments. Hence, on-going progradation might be expected. However, it is also clear that the vast majority of delta development occurred during conditions of sea-level stability and probably falling sea level. Post-glacial sea-level rise was associated with delta flooding, rather than delta building. Historical photographs are equivocal in respect to shoreline movements over recent decades. It is unclear, therefore, whether current sea-level rise is counter-acting the effects of continued sediment delivery to the deltas. Likewise, human effects on many of the delta’s are significant, and the extent of these effects on modern delta development has not yet been considered.

The most important knowledge gaps identified during the Coromandel Deltas project include:

1. Detailed characterisation of climatic boundary conditions, and possible future changes to incident wave height, angle, and storm frequency
2. Local tectonics and sea-level history: Holocene sea-level fall (based on work from the Miranda chenier plain) appears to have forced delta development, raising important questions about delta change during future sea-level rise; but this understanding is contingent on an uncertain assumption of regional tectonic stability
3. Holocene legacy: building on our initial dating to provide a detailed chronology of delta development and sediment yield
4. Hazard characterisation of fan-deltas, including liquefaction potential during seismic events and flood inundation
5. Sediment production, including understanding the debris flow hazard and flood accommodation
6. Future trajectories of coastal flooding and coastal erosion during storm events under the influence of sea-level rise

7. Event-scale understanding of delta change: erosion, longshore transport and shoreline management
8. The impact that humans have had: catchment clearance, river alignment, bank stability works, shoreline armouring

Some of these research gaps are currently being targeted in other projects. For instance, climatic boundary conditions around New Zealand are being studied in the Natural Hazards Research Platform project ‘Climate change impacts on weather-related hazards’ led by Dr. Coco, School of Environment; and the tectonic stability of the region is the subject of a new project for which funding is likely to be sought in 2017 (led by Dr. Eccles, School of Environment). The other questions in the list above could be addressed via geophysical investigation, monitoring, and numerical modelling work.

6.1 Geophysical investigation

Elucidating the nature of the subsurface architecture of the fans and the larger Firth will be helpful for understanding both the nature of seismic risk, as well as the characteristic rates of sediment yield in recent times and through the Holocene. For the terrestrial extents of fan-deltas, acoustic methods such as seismic reflection and multi-channel analysis of surface waves (MASW) surveys could be used to detail the stratigraphy of these deposits. Further drilling on fan-deltas besides Te Puru would allow us to broaden our understanding of formative processes and rates of channel switching and fan-delta growth. Geotechnical testing, both in-situ and with recovered materials would assist in determining the susceptibility of materials to seismic shaking. Further dating of organic material recovered from drilling would help to complete our chronology of delta evolution, and potential flooding and debris-flow history. From the marine perspective, there is an array of complementary methods to the CHIRP technique we used that could be used to sound out the deeper strata, as well as refining our model of the Firth of Thames post-glacial fill (Figure 5).

6.2 Fan-delta monitoring

Modern sediment production and delivery rates could be studied through a mass wasting inventory. Analysis of mass wasting events in historical photographs could help us build a picture of the spatial distribution of failures and the potential for debris flows within the valley mainstem. Analyses could focus on the relationship between fault boundaries and lithologic terranes to help improve understanding of failure dynamics in the region.

The morphological effect of storms on the fan-deltas could be resolved using new photogrammetric techniques, and a programme of repeat high-resolution drone surveys.

An example of LiDAR data from 2013 is shown in Figure 10A, which was used for assessing the mobility of gravels in different geomorphic settings on the fan-delta surface. On-going high resolution topographic monitoring could be achieved via photogrammetry through drone surveys and structure-from-motion techniques. To-date we have conducted two surveys of Te Mata delta, and have generated 5 cm DEMs of the fan-delta topography (Figure 10C), which provides a quantitative picture of topographic change over time. These surveys, repeated through time, could be very useful for tracking change through major tidal and storm events.

6.3 Numerical modelling

There are a large number of modelling tasks that would be helpful for understanding processes at a range of temporal and spatial scales. From the perspective of delta evolution, it would be of great interest to model the development of fan stratigraphy (Figure 10B) and show how the fans respond to sea-level changes of various rates; one of the fundamental questions addressed at the outset of this report. Flood and debris-flow events could be modelled, in order to understand the geomorphic impacts of sediment-laden flows on fan-deltas, given the configuration of the channel and current engineering works. Further refinement of the large-scale circulation model of Pritchard et al. (2015) could help us to estimate net patterns of longshore sediment transfer. Newly emerging techniques of broad-scale morphological simulation (using behavioural rules) could potentially be used to simulate likely decadal-scale response of the deltas to future sea-level rise.

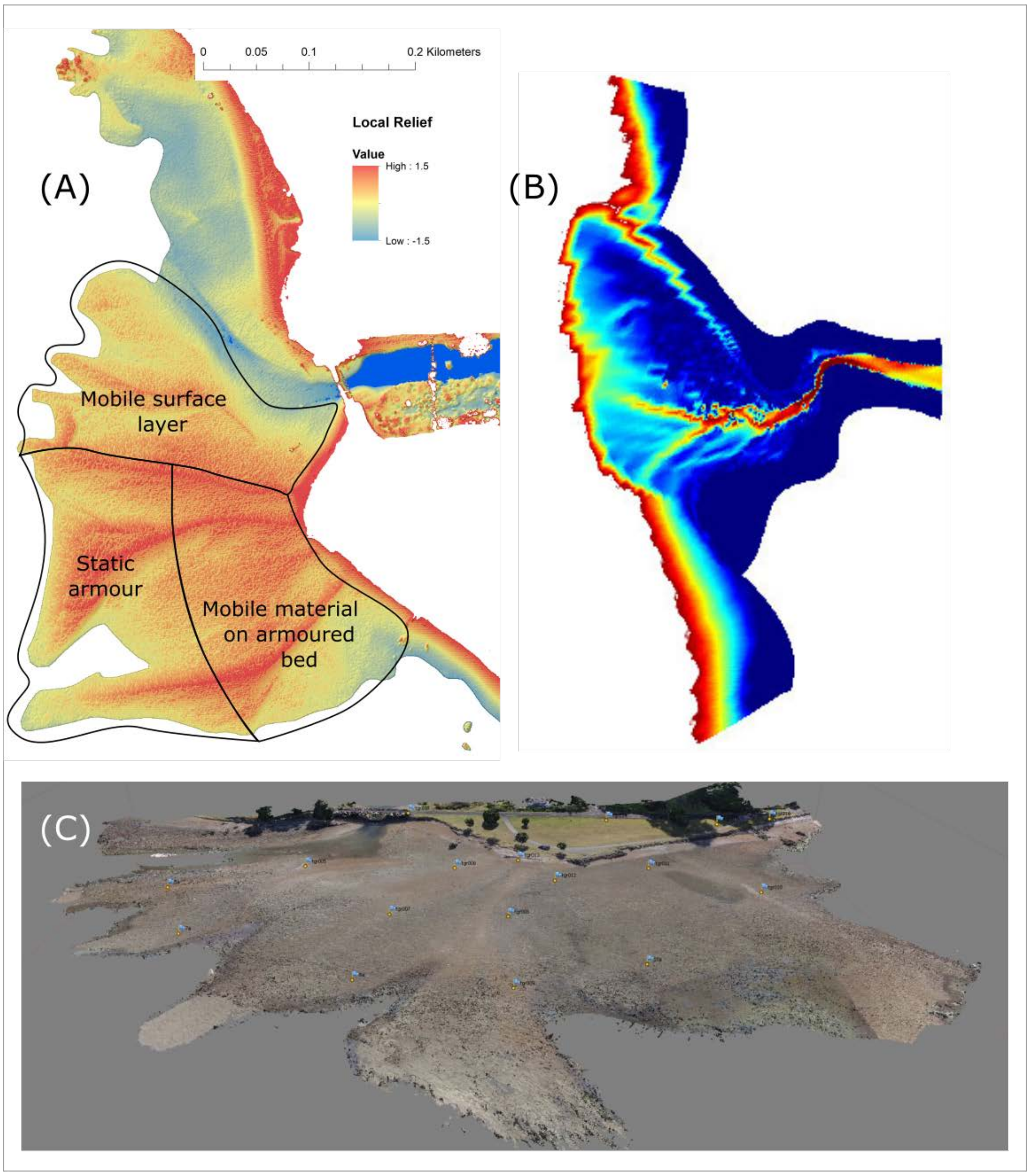


Figure 10. (A) High resolution LiDAR map of Te Mata fan-delta surface, used for mapping patch-scale sediment dynamics (WRC data, 2013); (B) Delft-3D model of Te Puru fan-delta, used to simulate development of Holocene-scale stratigraphy from generalised boundary conditions; (C) Digital elevation model of Te Mata fan-delta captured with drone flight and structure-from-motion techniques.

7. References

Allison, A., 2014. Morphodynamics of an armour-layered fan delta, Te Mata, Coromandel Peninsula (MSc). University of Auckland.

Blair, T.C., McPherson, J.G., 1994. Alluvial fans and their natural distinction from rivers based on morphology, hydraulic processes, sedimentary processes, and facies assemblages. Journal of Sedimentary Research 64, 450–489.

Bowman, M.J., Chiswell, S.M., 1982. Numerical Tidal Simulations Within the Hauraki Gulf, New Zealand, in: Jacques C.J. Nihoul (Ed.), Elsevier Oceanography Series, Hydrodynamics of Semi-Enclosed Seas Proceedings of the 13th International Liege Colloquium on Ocean Hydrodynamics. Elsevier, pp. 349–384.

Carter, R.M., Carter, L., Johnson, D.P., 1986. Submergent shorelines in the SW Pacific: evidence for an episodic post-glacial transgression. Sedimentology 33, 629–649. doi:10.1111/j.1365-3091.1986.tb01967.x

Chick, L.M., Lange, W.P.D., Healy, T.R., 2001. Potential Tsunami Hazard Associated with the Kerepehi Fault, Firth of Thames, New Zealand. Natural Hazards 24, 309–318. doi:10.1023/A:1012210314609

Collen, B., Hessel, J.W.D., 1982. Flood Producing Rain In Thames-Coromandel, New Zealand, April 1981. Weather and Climate 2, 30–36.

Collen, B., Hessel, J.W.D., 1981. The Thames-Coromandel Floods of April 1981 (Technical Information Circular No. 183). NZ Meteorological Service.

Cuthbertson, A.S., 1981. The Hinuera Formation in the southern Hauraki Lowland, Central North Island. University of Waikato, Hamilton.

Davies, T.R., McSaveney, M.J., 2008. Principles of Sustainable Development on Fans. Journal of Hydrology (New Zealand) 47, 43.

De Lange, P.J., Lowe, D.J., 1990. History of vertical displacement of Kerepehi Fault at Kopouatai bog, Hauraki Lowlands, New Zealand, since c. 10 700 years ago. New Zealand Journal of Geology and Geophysics 33, 277–283. doi:10.1080/00288306.1990.10425685

Dravitzki, M.L., 1988. Littoral drift of mixed sand and gravel sediments on four gravel delta fans, western Coromandel, New Zealand. Unpublished MSc Thesis, University of Waikato, New Zealand, 181p.

Dougherty, A.J., Dickson, M.E., 2012. Sea level and storm control on the evolution of a chenier plain, Firth of Thames, New Zealand. Marine Geology 307–310, 58–72. doi:10.1016/j.margeo.2012.03.003

Gibb, J., 1986. A New Zealand regional Holocene eustatic sea-level curve and its application to determination of vertical tectonic movements. Royal Society of New Zealand Bulletin 24, 377–395.

Greig, M.J., 1990. Circulation in the Hauraki Gulf, New Zealand. New Zealand Journal of Marine and Freshwater Research 24, 141–150. doi:10.1080/00288330.1990.9516409

Greig, M.J., Proctor, R., 1988. A numerical model of the Hauraki Gulf, New Zealand. New Zealand Journal of Marine and Freshwater Research 22, 379–390. doi:10.1080/00288330.1988.9516309

Griffiths, G.A., Glasby, G.P., 1985. Input of river-derived sediment to the New Zealand continental shelf: I. Mass. Estuarine, Coastal and Shelf Science 21, 773–787. doi:10.1016/0272-7714(85)90072-1

Healy, T., 2002. Muddy coasts of mid-latitude oceanic islands on an active plate margin—New Zealand, in: Muddy Coasts of the World: Processes, Deposits and Function. Elsevier Science BV, pp. 347–374.

Healy, T., Harada, K., 1991. Editorial: Enclosed and Semi-Enclosed Coastal Seas. Journal of Coastal Research i–v.

Hochstein, M., Tearney, K., Rawson, S., Davey, F., Davidge, S., Henrys, S., Backshall, D., 1986. Structure of the Hauraki Rift (New Zealand). Royal Society of New Zealand Bulletin 24, 333–348.

Houghton, B.F., Cuthbertson, A.S., 1989. Geological map of New Zealand 1: 50,000, sheet T14 BD Kaimai.

Hunziker, R.P., Jaeggi, M.N.R. 2002. Grain sorting processes. Journal of Hydraulic Engineering, 128, 1060-1068.

Kear, D., Tolley, W.P., 1957. Notes on Pleistocene and Jurassic beds near Morrinsville. New Zealand Journal of Science and Technology: General Research Section 38, 500.

Lambeck, K., Rouby, H., Purcell, A., Sun, Y., Sambridge, M., 2014. Sea level and global ice volumes from the Last Glacial Maximum to the Holocene. Proceedings of the National Academy of Sciences 111, 15296–15303.

Longstaff, K., 2016. Geomorphic variation of Thames Coast fan-deltas, Coromandel, New Zealand: A sediment budget approach (MSc). The University of Auckland, Auckland.

Lovelock, C.E., Sorrell, B.K., Hancock, N., Hua, Q., Swales, A., 2010. Mangrove forest and soil development on a rapidly accreting shore in New Zealand. Ecosystems 13, 437–451.

Mao, L., Cooper, J.R., Frostick., L.E., 2011. Grain size and topographical differences between static and mobile armour layers. Earth Surface Processes and Landforms 36, 1321-1334.

McSaveney, M.J., Beetham, R.D., 2006. The potential for debris flows from Karaka stream at Thames, Coromandel (No. TR06/17).

McSaveney, M.J., Davies, T.R., 2005. Engineering for debris-flows in New Zealand, in: Debris-Flow Hazards and Related Phenomena, M. Jakob and O. Hungr, Eds. Springer, Berlin; Heidelberg, pp. 635–658.

Munro, A., 2002. The Weather Bomb 21 June 2002 (No. 2002/10). Environment Waikato.

Naish, T.R., 1990. Late Holocene mud sedimentation and diagenesis in the Firth of Thames: Bentonites in the making (PhD). University of Waikato, Hamilton.

Naish, T.R., Nelson, C.S., Hodder, A.P.W., 1993. Evolution of Holocene sedimentary bentonite in a shallow-marine embayment, Firth of Thames, New Zealand. Marine Geology 109, 267–278. doi:10.1016/0025-3227(93)90065-4

Nemec, W., Steel, R., 1988. What is a fan delta and how do we recognize it, in: Fan Deltas: Sedimentology and Tectonic Settings. pp. 3–13.

Newnham, R., De Lange, P., Lowe, D., 1995. Holocene vegetation, climate and history of a raised bog complex, northern New Zealand based on palynology, plant macrofossils and tephrochronology. The Holocene 5, 267–282.

O'Regan, P.R., Morad, M., Chalmers, A. i., 1995. Digital Analysis of Shoreline Change. New Zealand Geographer 51, 25–31. doi:10.1111/j.1745-7939.1995.tb02048.x

Orton, G.J., Reading, H.G., 1993. Variability of deltaic processes in terms of sediment supply, with particular emphasis on grain size. Sedimentology 40, 475–512. doi:10.1111/j.1365-3091.1993.tb01347.x

Pocknall, D., Gregory, M., Greig, D., 1989. Palynology of core 80/20 and its implications for understanding Holocene sea level changes in the Firth of

Thames, New Zealand. Journal of the Royal Society of new Zealand 19, 171–179.
Pritchard, M., Swales, A., Green, M. 2015. Influence of buoyancy- and wind-coupling on sediment dispersal and resuspension in the Firth of Thames, New Zealand. Australasian Coasts and Ports Conference, 2015.
Proctor, R., Greig, M.J., 1989. A numerical model investigation of the residual circulation in Hauraki Gulf, New Zealand. New Zealand Journal of Marine and Freshwater Research 23, 421–442.
Schneider, P., 2010. Current and future climate change adaptation of a vulnerable coastal community on the Coromandel Peninsula, New Zealand (Thesis). Massey University.
Schofield, J.C., 1960. Sea level fluctuations during the last 4,000 years as recorded by a chenier plain, firth of thames, new zealand. New Zealand Journal of Geology and Geophysics 3, 467–485. doi:10.1080/00288306.1960.10422089
Stanley, D.J., Warne, A.G., 1994. Worldwide initiation of Holocene marine deltas by deceleration of sea-level rise. Science 265, 228–231.
Van Dijk, M., Kleinhans, M.G., Postma, G., Kraal, E., 2012. Contrasting morphodynamics in alluvial fans and fan deltas: effect of the downstream boundary. Sedimentology 59, 2125–2145. doi:10.1111/j.1365-3091.2012.01337.x
van Leeuwe, C.M., 1991. Transport of suspended sediments in the southern part of the Firth of Thames. Unpublished M. Phil. Thesis, University of Waikato, New Zealand, p269.
Welsh, A., Davies, T., 2011. Identification of alluvial fans susceptible to debris-flow hazards. Landslides 8, 183–194. doi:10.1007/s10346-010-0238-4
White, R., 2003. Weather Bomb - the Coromandel Experience. Tephra - Ministry of Civil Defence and Emergency Management Journal 20, 12–16.
Woodroffe, C.D., Curtis, R.J., McLean, R.F., 1983. Development of a chenier plain, Firth of Thames, New Zealand. Marine Geology 53, 1–22. doi:10.1016/0025-3227(83)90031-2