Environment Waikato Technical Report 2005/36

Whaingaroa (Raglan) Harbour : Sedimentation and the Effects of Historical Catchment Landcover Changes

Prepared by:
A. Swales, R. Ovenden, R. Budd, J. Hawken
(NIWA)
M.S. McGlone
(Landcare Research Ltd, Lincoln)
N. Hermanspahn, M.J. Okey
(National Radiation Laboratory, Christchurch)

For:
Environment Waikato
PO Box 4010
HAMILTON EAST

ISSN: 1172-4005

Document #: 1036467

Environment Waikato
REGIONAL COUNCIL

Whaingaroa (Raglan) Harbour: sedimentation and the effects of historical catchment landcover changes

NIWA Client Report: HAM2005-070
August 2005

NIWA Project: EVW05278

Whaingaroa (Raglan) Harbour: sedimentation rates and the effects of historical catchment landcover changes

A. Swales
R. Ovenden
M.S. McGlone[1]
N. Hermanspahn[2]
R. Budd
M.J. Okey[2]
J. Hawken

(1) Landcare Research Ltd, Lincoln
(2) National Radiation Laboratory, Christchurch

Prepared for

Environment Waikato

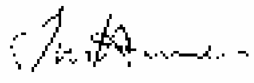
NIWA Client Report: HAM2005-070
August 2005

NIWA Project: EVW05278

National Institute of Water & Atmospheric Research Ltd
Gate 10, Silverdale Road, Hamilton
P O Box 11115, Hamilton, New Zealand
Phone +64-7-856 7026, Fax +64-7-856 0151
www.niwa.co.nz

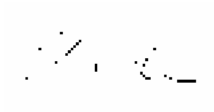
Contents

Reviewed by:



Terry Hume

Approved for release by:



Andrew Swales

Formatting checked

Executive Summary

Whaingaroa (Raglan) Harbour is an important coastal resource for the Waikato Region. The community has expressed concerns regarding perceived environmental degradation of the harbour and its catchment (Environment Waikato, 2002). In response to community concerns and the importance of the harbour to the Waikato Region, Environment Waikato initiated a programme of environmental monitoring and restoration in partnership with the Whaingaroa community. This programme includes the monitoring of catchment sediment loads and sediment accumulation rates (SAR) in the harbour.

Environment Waikato commissioned NIWA to collect and analyse sediment cores from Whaingaroa Harbour. The specific objectives of the study are to: (1) quantify long-term SAR under undisturbed native forest landcover before human settlement; (2) quantify changes in SAR associated with large-scale catchment deforestation (~1880–1925 AD) and subsequent conversion to pasture; and (3) determine differences in SAR and sediment profiles in the Waingaro and Waitetuna arms of the harbour.

Duplicate sediment cores up to four metres in length were collected during May 2002 at six intertidal and three subtidal sites. Cores from five of these sites were analysed (Fig. A). Sampling was designed to differentiate between sedimentation in the Waingaro and Waitetuna arms of the harbour. The cores were dated using pollen profiles and the radioisotopes: carbon-14 (^{14}C); unsupported lead-210 (^{210}Pb); and caesium-137 (^{137}Cs) to determine time-averaged SAR for several historical time periods. Particle-size profiles were also determined.

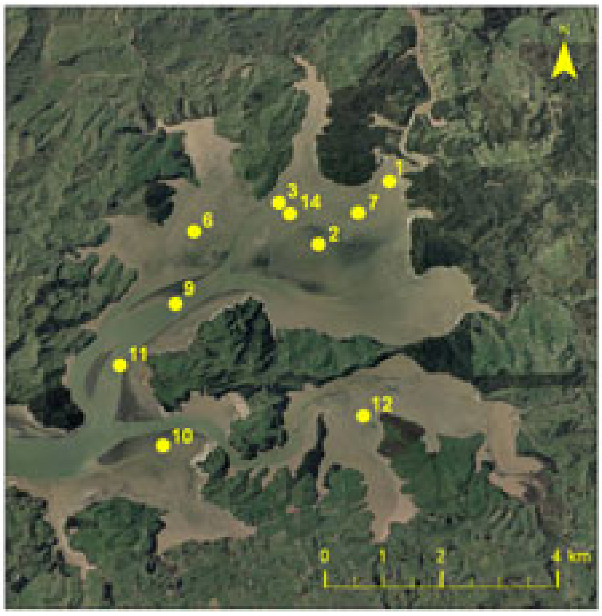


Figure A: Sediment core locations. Cores from sites 1, 2, 6, 10 & 12 were analysed in this study.

Exotic pollen derived from plants, introduced by European settlers since the mid-1800s, and radioisotopes such as lead-210 (^{210}Pb) and caesium-137 (^{137}Cs) are ubiquitous environmental tracers, which are incorporated into catchment soils and estuarine sediments. These tracers were introduced to the environment at different times (e.g., pine pollen) and can be used to quantify harbour sedimentation rates for a number of historical periods. Radioisotopes are created by the radioactive decay of one element into another form and can be naturally produced, such as ^{210}Pb and continuously deposited from the atmosphere (referred to as unsupported ^{210}Pb). ^{210}Pb is attached to sediment particles and decays with age at a constant rate as it is buried through sedimentation and typically displays a negative exponential profile with depth in the sediment column. Thus, the age of the sediment increases as the unsupported ^{210}Pb concentration decreases with depth. Alternatively, radioisotopes are the by-products of nuclear technology, such as ^{137}Cs that was first produced by atmospheric weapons testing in the 1940s and first detected in NZ in 1953. Detailed explanations of these dating techniques are provided in section two.

Key findings of this study are:

- Whaingaroa Harbour began to fill with sediment at least 8000 years before present (B.P.) and before the sea had reached its present level 6500 years B.P. Rapid sedimentation in the harbour before 6500 years B.P. is attributed to the formation of now relict intertidal shore platforms up to 700-m wide and ≤10 m below present-day mean high water level. These coastal landforms were rapidly formed 8000–6500 years B.P. by physical weathering of soft mudstone cliffs and wave action. Consequently, all but the upper two metres of the present day sediment column was deposited before 6000 years B.P. and thousands of years before the arrival of Maori some 700 years ago. Today, the harbour has largely infilled with catchment sediment up to ~8-m thick, with 70% of its high tide surface area being intertidal.

- Harbour-wide sediment accumulation rates (SAR) have averaged 0.3–0.5 mm yr^{-1} over the last 8000–6500 years (section 4.1). The effects of large-scale catchment deforestation (1890–1920s), conversion to pasture and plantation forestry (1985–) on sedimentation have occurred very differently in the Waingaro and Waitetuna arms of the harbour.

- In the Waitetuna arm, ^{14}C dating of shell and exotic-pollen profiles preserved in core 12B indicate that pre-human SAR of 0.35 mm yr^{-1} has increased threefold following deforestation and averaging 1.1 mm yr^{-1} since 1890. Pine pollen, which is produced in large quantities and widely dispersed by the wind, suggests that SAR have further increased to 2.5 mm yr^{-1} since the early 1990s. At Okete Bay (core 10B) pre-human SAR averaged 0.5 mm yr^{-1}. The pine pollen profile indicates that SAR have averaged 8 mm yr^{-1} since the early 1990s. The absence of unsupported ^{210}Pb and ^{137}Cs does not enable independent validation of the pine-pollen derived SAR for Okete Bay.

- In the larger Waingaro arm, the absence of pollen types related to human activities, as well as radioisotopes, in sediment cores indicates that long-term sedimentation has not occurred in this part of the harbour for at least the last 150 years and probably much longer. In particular the absence of: (1) bracken in association with native forest pollens, which is indicative of Maori slash and burn agriculture and (2) exotic plant pollens, ^{137}Cs and ^{210}Pb, which are used to date recent sediment deposits, provides strong support for this interpretation. It is noted that pine pollen is present in small quantities in surficial sediments near the Waingaro stream outlet (core 1A). However, the absence of ^{137}Cs and ^{210}Pb indicates that long-term sediment accumulation has not occurred even near this major sub-catchment outlet.

- The most likely explanation for the absence of 'modern' sediments in the Waingaro arm of the harbour is sediment resuspension by waves driven by the prevailing southwest wind. As the harbour has infilled, small and short-period waves have become effective at remobilising tidal-flat sediments. This process has been observed in other NZ estuaries and results in the winnowing of mud from tidal flats which is redeposited in low-energy environments such as fringing saltmarshes and tidal creeks. The importance of wave processes in controlling sedimentation in the Waingaro arm is also shown by (1) the formation of several-hundred metre wide wave-cut shore platforms facing the prevailing southwest wind; and (2) formation of intertidal beaches near Waingaro Landing composed almost entirely of the heavy mineral titanomagnetite. Thus, a substantial proportion of the catchment fine-sediment load is now exported to the open coast, so that the harbour's sediment trapping efficiency is lower today than during its prehistory. This conclusion is supported by the presence of clay minerals in continental-shelf sediments that were eroded from catchment mudstone and LANDSAT images showing fine-sediment plumes extending up to 20 km offshore from the harbour mouth (section 5).

- The embayments and tidal creeks of Whaingaroa Harbour are less exposed to wave action (e.g., Waitetuna and Okete Bay) and under these conditions long-term sediment accumulation is occurring. Therefore, these sheltered sub-environments are more susceptible to the effects of future changes in the quantity and type of sediment runoff associated with human activities in their land catchments.

1. Introduction

1.1 Study background

Previous studies of sedimentation rates and processes in the estuaries of the Coromandel Peninsula (Hume and Gibb, 1987; Hume and Dahm, 1992; Sheffield, 1991; Swales and Hume, 1994, 1995) and other North Island estuaries (Hume 1983; Vant et al. 1993; Goff, 1997; Swales et al. 1997, 2002a, 2002b, 2003, 2005; Abrahim and Parker, 2002) have shown that historical changes in landcover following European settlement from the mid 1800s have substantially increased soil erosion and sediment accumulation rates (SAR) in these systems. Typically, SAR of <1mm yr^{-1} under native forest landcover have increased to several mm yr^{-1} following large-scale catchment deforestation (mid-1800s onwards). This information has been derived from sediment cores collected from intertidal and shallow subtidal flats. These studies have applied pollen, radiocarbon (^{14}C) and lead-210 (^{210}Pb) dating techniques to estimate time-averaged SAR associated with major historical landcover periods. These studies indicate as much as an order of magnitude increase in SAR following catchment deforestation.

By contrast, little is known about the west-coast estuaries of the Waikato Region. The Whaingaroa (Raglan) Harbour is an important coastal resource for the Waikato Region. Its close proximity to Hamilton City, the region's largest urban centre, makes it an important recreational resource. Mana whenua and local community groups have expressed concerns regarding perceived environmental degradation, including soil erosion, stream and harbour water quality and subsequent effects on the sustainability of kaimoana (Environment Waikato, 2002). In response to these community concerns and the importance of Whaingaroa Harbour to the Waikato Region, Environment Waikato (EW) initiated a programme of environmental monitoring and restoration in partnership with the Whaingaroa community. This programme includes the monitoring of suspended sediment loads being delivered to the harbour and the present study. Environment Waikato also contributes funds to the Raglan Harbour Care Group for riparian management. The Whaingaroa Harbour is also part of the EW Regional Estuaries Monitoring Programme. This monitoring includes intertidal benthic fauna composition, physical, chemical and biological sediment characteristics and intertidal bed elevation changes, which are measured at five sites at 3- (2 sites) and 6-month (3 sites) intervals. Whaingaroa Harbour is also the focus of NIWA's Fine Sediment Study (FSS) which is being conducted as part of NIWA's *Effects-Based Protection and Management of Aquatic Ecosystems* Programme. The primary goal of this research programme is to develop new predictive tools for managing pollution, which includes fine sediments, in streams, rivers, lakes and estuaries. The Raglan FSS is also co-funded by EW.

1.2 Limitations of present knowledge

The most comprehensive study to date of Raglan Harbour's sedimentology to date was conducted by Sherwood (1973) for his M.Sc. thesis research. The results of this work are summarised by Sherwood and Nelson (1979). Lees et al. (1998) analysed sediment cores from coastal wetlands between Auckland and Raglan and have reconstructed catchment vegetation assemblages from pollen profiles dating back 24,000 years before present (B.P). Some information relating to historical changes in catchment landcover following European settlement from the mid-1800s is provided by Henderson and Grange (1926). The focus of the Sherwood (1973) study was on the contemporary sedimentology of the harbour as it relates to surficial sediment grain size and mineralogy. Tidal flow and suspended sediment concentrations (ssc) were also measured at one station in the lower harbour opposite Raglan town. These data were used by Sherwood and Nelson (1979) and to infer sediment transport modes and pathways.

Thus, the key limitation of our present knowledge of sediment processes in Whaingaroa Harbour relates to its long-term evolution and to quantitative information on sediment accumulation rates before human settlement. This information is essential to determine how these SAR may have changed during the last 150 years or so as a result of human activities, in particular catchment deforestation and conversion to pasture.

1.3 Study objectives

The specific objectives of the present study are:

- Quantify long term time-averaged SAR in Whaingaroa Harbour under undisturbed forest landcover before human settlement.

- Quantify changes in time-averaged SAR associated with large-scale catchment deforestation (~1880–1925 AD) and subsequent conversion to pasture.

- Determine spatial variations in SAR and sediment particle-size profiles in the Waingaro and Waitetuna arms of the harbour.

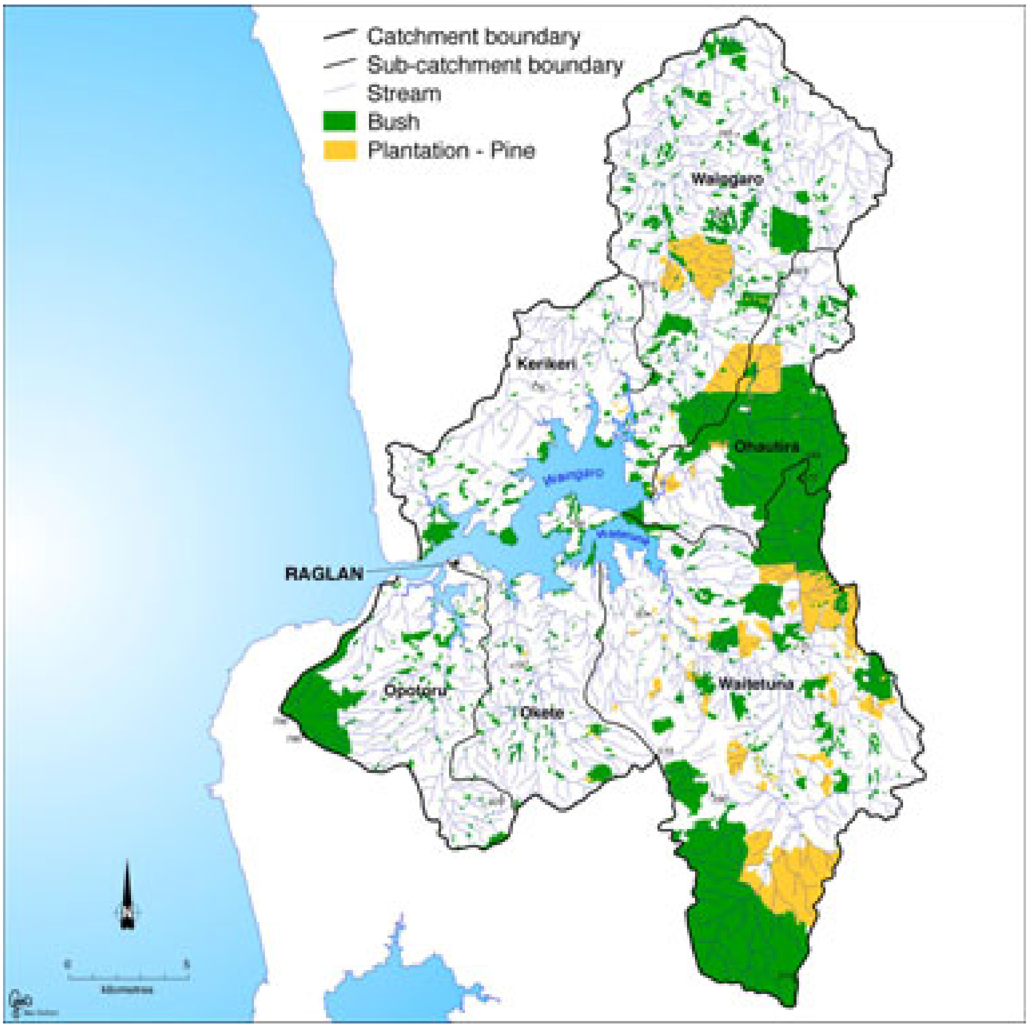


Figure 1.1: Whaingaroa Harbour and sub-catchments.

1.4 Catchment and harbour characteristics

Catchment

Whaingaroa Harbour receives runoff from a 525 km^2 catchment with six main sub-catchments (Opotoru, Okete, Waitetuna, Ohautira, Waingaro, Kerikeri (Fig. 1.1). The geology of the Ohautira and Waingaro sub-catchments is composed of argillaceous greywacke, sandstones and mudstones (Mesozoic), by Upper Pliocene –Lower Pleistocene volcanics in the Waitetuna sub-catchment and by calcareous mudstones and muddy sandstones of Oligocene age in sub-catchments north of the harbour (Henderson and Grange, 1926; Sherwood and Nelson, 1979; Curtis, 1986). The sedimentary rocks are deeply weathered and on steep hillslopes much of this soil has been eroded leaving a shallow regolith (Curtis, 1986).

Average annual rainfall at Raglan (Karioi C74885, 37.8021°S/174.8679°E, elevation 7 m) for the period 1984–2004 was 1354 mm (*s* = 144 mm). Average annual runoff to the harbour is 0.034 $m^3 s^{-1} km^{-2}$ (Heath, 1976). Curtis (1986) has estimated an annual suspended sediment load delivered to the harbour of 55,000 tonnes or 104 t $km^{-2} yr^{-1}$.

History and landcover

Pollen analysis of estuarine sediment in the present study and of cores collected from coastal wetlands (Lees et al. 1998) show that the original catchment landcover was composed of a mixed podocarp-hardwood forest with rimu, rata, beech and tree ferns. Maori settlement of New Zealand is believed to have occurred about 700 ±100 years before present (McGlone and Wilmshurst, 1999). People of the Tainui canoe settled around the shores of Kawhia Harbour and after several generations had established settlements at Aotea and Whaingaroa (Vennell and Williams, 1976). Long cores collected by Lees et al. (1998) at Limestone Downs (north of Whaingaroa) show evidence of bracken cover indicative of Maori slash and burn agriculture. Abel Tasman’s ships, *Heemskerk* and *Zeehaen*, sailed passed Whaingaroa on 28 December 1642 and from their vantage point, some four miles offshore, they noted Mount Karioi but did not land here. During the early 1800s, Ngati Toa of Kawhia under Te Rauparaha were at war with the Waikato tribes, which included Ngati Mahuta, Ngati Hikairo and Ngati Mahanga. The fighting, which continued until 1821 depopulated the southern shores of Whaingaroa. By 1830, Ngati Mahanga had taken procession of the land between Aotea and Whaingaroa Harbours. During the 1820s, flax was cleared and sold to European traders to purchase muskets (Vennell and Williams, 1976). By the early 1830s, a few Europeans from the convict settlements of New South Wales were living with Maori at Whaingaroa. The Wesleyan missionary James Wallace arrived at Kawhia on 19 April 1835 and established the first mission at Whaingaroa. Land purchase by the NZ Government from Maori tribes at Whaingaroa began in 1850. By 1855, some 80,000 hectares of coastal land between Waikato Heads and the Mokau River had been purchased, which included the land between Whaingaroa and Aotea. At this time, Maori were growing wheat on small blocks near Whaingaroa Harbour, however, inland the steepland catchment remained under forest. By the end of 1855, much of the land south of the harbour had been surveyed for farm blocks and European settlers began to arrive (Vennell and Williams, 1976). Large numbers of settlers began to arrive in the 1870s, under the government “Homestead” scheme which provided settlers with several acres of land. By 1876 the European population of 870 inhabiting Raglan County was still modest given that this covered the entire area west of the Waikato River between the river mouth and Aotea Harbour. At least half of these settlers lived in Raglan town itself, which remained isolated from inland Waikato until 1879 when the first Raglan-Waipa road was completed. In 1885, the Waingaro block was purchased and within two years a settlement of twenty-two families had been established. A track between Waingaro and Waingaro Landing was formed at this time to link Waingaro to Raglan town using sailing boats (Vennell and Williams, 1976).

These historical accounts indicate that most of the harbour catchment remained forested as late as the early-1890s, with mixed podocarp-hardwood forest occupying the steeplands and kahikatea on the flats. It is evident that deforestation had not begun at Whaingaroa earlier because of the area's relative isolation. However, over the next 35 years most of the 525 km^2 catchment was deforested and converted to pasture. By the mid-1920s indigenous forest stands were restricted to the steeplands of Mount Karioi, Pirongia and the Moerangi Plateau (Henderson and Grange, 1926). A sawmill on the eastern flank of Mt Karioi supplied timber to Raglan and the Te Mata district. Present-day landcover is dominated by pasture and grassland (~80%), with the largest areas of regenerating native forest occurring east of the harbour in the Whaingaroa and Ohautira sub-catchments. These forest stands are dominated by tawa and rimu (Landcare Research Database, 1995).

Plantation forests of *Pinus radiata* occur in the Waingaro and Waitetuna sub-catchments. In the Waingaro sub-catchment, pine forests have been established near Waingaro Springs. The Putawa Forest (3.5 km^2) was established during 1985–1986, which included burn-off of ~2 km^2 of scrub. The adjacent Bokamp forest (1.2 km^2) was planted in 1994. The 5 km^2 Waingaro Springs Forest was planted in 1994 (source: Mr Collin Maunder, P.F. Olsen and Co.). At Waitetuna, a number of pine forest plantations ranging in size from 0.01–6 km^2 have been established. The 5 km^2 Vela Holdings Forest east of the Mangaokahu Stream was planted on former pasture in 1990–1991. Most of the pine forest established in the Waitetuna sub-catchment was planted during 1991–1994, which coincided with large increases in the value of pine timber (Mr Carl Hanna, Wood Marketing Services, Rotorua, pers comment, 31/8/05). These pine forests, which were 10–18 yrs old when the NIWA sediment cores were taken, have now developed a substantial pollen rain which should be preserved in the estuary sediments.

Harbour

The Whaingaroa Harbour was formed by post-glacial flooding of the lower reaches of the river-valley system. Studies of other North Island estuaries indicate that this flooding began at least 10,000 years B.P. (Irwin, 1976; Swales et al. 1997), with the sea reaching it's present level about 6,500 years B.P. The presence of phosphorite (apatite) calcareous nodules in the Waitetuna Arm, associated with a shore platform, has been related to a period of lowered sea level between 6500 and 3600 years B.P. (Cullen et al. 1990). During this period salt marsh and/or mangrove became established across Haroto Bay. Subsequently, biogeochemical reactions in the oxidised sulphide-rich saltmarsh sediments resulted in the precipitation of calcareous nodules particularly at root depth 0.2 m below the platform surface. Radiocarbon dating of the nodules indicate that at about 3600 years B.P. the sea began to rise again to its present level and reinstated anoxic conditions within the former saltmarsh platform. In this reducing environment, apatite was absorbed into the surface layers of the calcareous nodules. Today the platform surface is submerged at high tide to a depth of ~0.5 m. The apparent reduction in sea level between 6500–3700 years B.P. (Cullen et al. 1990) is broadly consistent with decimetre fluctuations in palaeo sea levels around the New Zealand coast over the last seven thousand years (Gibb, 1986). This does not account for tectonic uplift or subsidence which may also have influenced local sea level. The physical significance of these sea-level fluctuations relates to the resulting large-scale changes in estuary morphology and sediment processes. During the apparent sea-level regression 6500–3700 years B.P., large intertidal areas may have been colonised by salt marsh and/or mangroves where muds would have accumulated. The sea-level regression and resulting reduction in water depth may also have enhanced wave-driven sediment resuspension on the tidal flats.

The present-day harbour has a high-tide area of 33 km^2 and has substantially infilled, so that intertidal flats account for ~70% of its area (Sherwood and Nelson, 1979). The harbour is mesotidal (i.e., 2–4 m tidal range), with spring- and neap-tide ranges of 2.8 m and 1.8 m respectively (Heath, 1976). The Paritata peninsula separates the extensive intertidal flats of the Waingaro-Ohautira and Waitetuna arms (Fig. 1.2).

The mean freshwater inflow is small (18 $m^3 s^{-1}$) in comparison to the spring (46 x 10^6 m^3) and neap (29 x 10^6 m^3) tidal volumes (Heath, 1976), so that for most of the time tidal flows dominate circulation in the harbour. The estimated spring-tide residence time of water in the harbour is 1.1 days (Heath, 1976), which indicates that harbour flushing is relatively efficient despite it being indented by numerous bays and arms. This reflects the fact that the harbour is largely intertidal so that a large proportion of the tidal prism is exchanged on each tide. In a shallow estuary like the Whaingaroa Harbour, physical mixing of the water column by tidal currents and waves will reduce the degree of density stratification, particularly under average freshwater flows. Stratification is likely to occur in the harbour during catchment floods when freshwater discharge and the resulting vertical density gradient are sufficient to suppress vertical mixing of the water column. In this case, a salt wedge may develop with the fine sediment initially transported within the surface freshwater layer (Dyer, 1986). In this way fine sediments can be widely dispersed within the estuary. As these fine cohesive particles sink under gravity through the freshwater layer and into the seawater below they flocculate to form larger aggregates with fall speeds that can be orders of magnitude greater than their constituent particles. For example, a 5 μm diameter silt particle has a fall speed of ~0.002 cm s^{-1}, whereas a 500 μm diameter floc composed of similar sized particles will sink at ~0.4 cm s^{-1} (McDowell and O'Connor, 1977). Thus, flocculation is likely to be an important process influencing the fate of catchment sediments in the harbour.

Figure 1.2: Waingaro and Waitetuna (foreground) arms of Whaingaroa Harbour separated by the Paritata peninsula in the middle distance.

Sediment resuspension by waves modifies sediments after initial deposition. Wave characteristics and thresholds for bed sediment remobilisation by wave orbital motions can be estimated from empirical formulae and/or measurements (Rahn, 1986). In the Whaingaroa Harbour, the available fetch (i.e., distance from shore to shore at high tide) in the direction of the prevailing southwest winds is ≤5.5 km. For example, given a 10 m s^{-1} southwest wind at high tide in the Waingaro Arm, wave heights of ≤0.5 m with peak periods of 2–3 s can be expected. These steep and short-period waves are effective at remobilising intertidal and shallow subtidal sediments (Green et al. 1997; Swales et al. 2004). This process results in the winnowing of mud from the tidal flats (particle diameter ≤63 µm), which in turn can result in measurable changes in intertidal-bed elevations. This resuspended sediment can subsequently be redeposited in (1) low-energy environments, such as fringing mangrove and saltmarsh systems; (2) deep subtidal basins (central mud basin); or (3) flushed from the harbour entirely.

Intra-annual changes in tidal-flat elevations are measured as part of Environment Waikato's Regional Estuaries Monitoring Programme. On intertidal flats, these elevation changes most likely result from cycles of wave-driven sediment resuspension and subsequent redeposition. Changes in the average depth, from the sediment surface, to concrete plates buried at 15–20 cm depth have been monitored at Whatitirinui Island and Okete Bay since November 2002. Bed-elevation changes have measured at 3-monthly intervals, with 10 measurements made per plate per survey (Bronwen Gibberd, EW coastal scientist, personal comment, October, 2005). These data show between-survey changes in bed elevation of ±20 mm at Whatitirinui and ±40 mm at Okete Bay. Figure 1.3 shows these between-survey elevation changes for the Whatitirinui Island site, which is located within several hundred metres of NIWA core site 6.

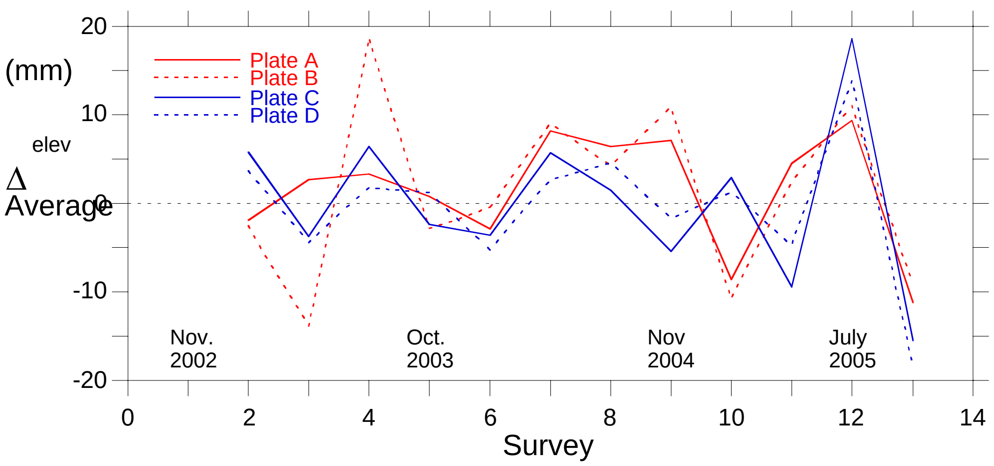


Figure 1.3: Between-survey changes in average bed elevations (mm) relative to the top surface of 4 plates buried on the intertidal flats, Whatitirinui Island (data source: Environment Waikato).

These data indicate that rapid physical mixing of the upper 5-cm of the sediment column is an ongoing process and results from the mass erosion and redeposition of surface sediments. This process is most likely due to wave action.

2. Dating of recent estuarine sediments

2.1 Summary

Radioisotopes, such as caesium-137 (^{137}Cs, ½-life 30 years) and lead-210 (^{210}Pb, ½-life 22.3 years), and plant pollen can be used to reconstruct the recent sedimentation history of an estuary. Heavy metal (i.e., Pb, Zn and Cu) profiles in estuarine sediments have also been shown to provide useful additional information to identify the onset of urban development (e.g., Valette-Silver, 1993; Abrahim and Parker, 2002; Swales et al. 2002a, 2002b, 2005).

Dating of estuarine sediments by several independent methods offsets the limitations of any one approach. This is particularly important when interpreting sediment profiles from lakes and estuaries, given the confounding effects of physical and biological mixing (Robbins and Edgington, 1975; Olsen et al. 1981; Sharma et al. 1987; Alexander et al. 1993; Valette-Silver, 1993; Benoit et al. 1999; Chagué-Goff et al. 2000). A description of the various methods of dating sediments follows. The S.I. unit of radioactivity used in this study is the Becquerel (Bq), which is equivalent to one disintegration per second.

2.1.1 ^{137}Cs dating

^{137}Cs was introduced to the environment by atmospheric nuclear weapons tests in 1953, 1955–1956 and 1963–1964. Peaks in annual ^{137}Cs deposition corresponding to these dates are the usual basis for dating sediments (Wise, 1977; Ritchie and McHenry, 1989). Although direct atmospheric deposition of ^{137}Cs into estuaries is likely to have occurred, ^{137}Cs is also incorporated into catchment soils, which are subsequently eroded and deposited in estuaries (Fig. 2.1). In New Zealand, ^{137}Cs deposition was first detected in 1953 and its annual deposition was been measured at several locations until 1985. Annual ^{137}Cs deposition can be estimated from rainfall using known linear relationships between rainfall and Strontium-90 (^{90}Sr) and measured ^{137}Cs/^{90}Sr deposition ratios (Matthews, 1989). Experience in Auckland estuaries shows that ^{137}Cs profiles measured in estuarine sediments bear no relation to the record of annual ^{137}Cs deposition (i.e., 1955–1956 and 1963–1964 ^{137}Cs-deposition peaks absent), but rather preserve a record of direct and indirect (i.e., soil erosion) atmospheric deposition since 1953 (Swales et al. 2002b). The maximum depth of ^{137}Cs occurrence in sediment cores, corrected for sediment mixing (see section 2.1.2), is taken to coincide with the year 1953, when ^{137}Cs deposition was first detected in New Zealand. We assume that there is a negligible delay in initial atmospheric deposition of ^{137}Cs in estuarine sediments (e.g., ^{137}Cs scavenging by suspended particles) whereas there is likely to have been a small time-lag (i.e., < 1 yr) in ^{137}Cs inputs to estuaries from topsoil erosion, which would coincide with the occurrence of floods.

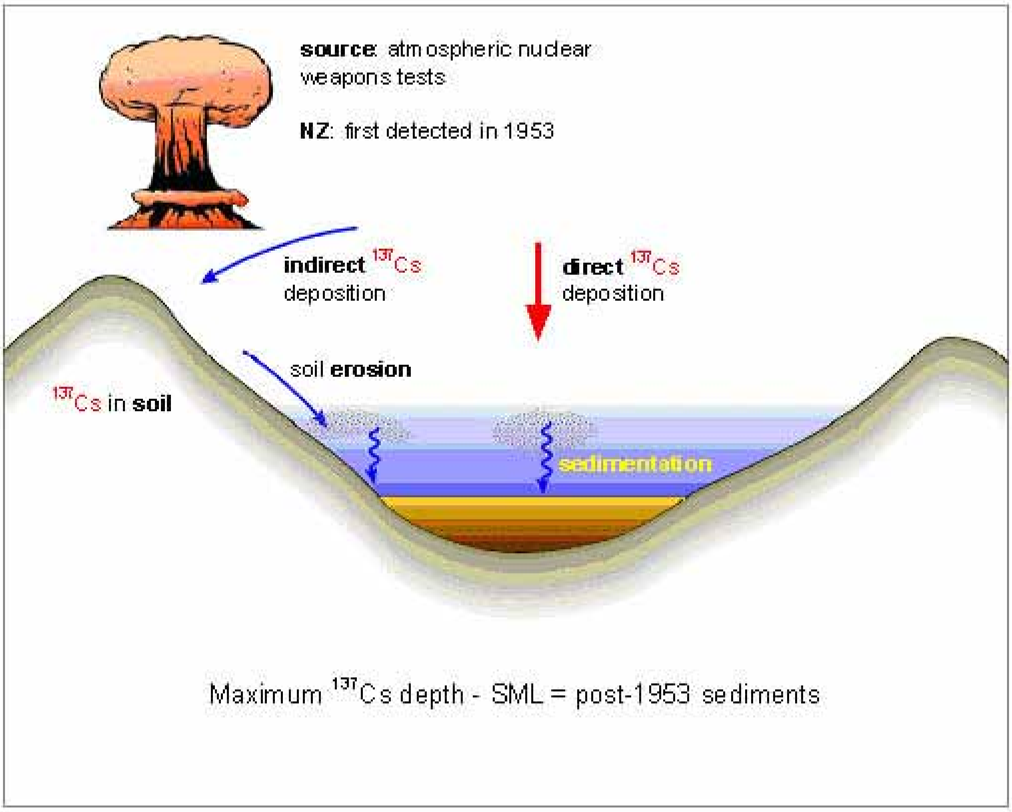


Figure 2.1: ^{137}Cs pathways to estuarine sediments.

If a surface mixed layer (SML) is evident in a core, as shown by an x-ray image and/or a tracer profile (e.g., ^{7}Be, ^{210}Pb) then ^{137}Cs is likely to have been rapidly mixed through the SML. Therefore to calculate time-averaged sedimentation rates, the maximum depth of ^{137}Cs occurrence is reduced by the maximum depth of the SML.

Uncertainty in the maximum depth of ^{137}Cs ($^{137}Cs_{max}$) results from (1) the depth interval between sediment samples and (2) the minimum detectable concentration (MDC) of ^{137}Cs, which is primarily determined by sample size and counting time. The

1963–1964 ^{137}Cs deposition peak was about five-times than the deposition plateau that occurred between 1953 and 1972. Thus, depending on the sample size, there is uncertainty in the age of $^{137}Cs_{max}$ (i.e., 1953–1963). To reduce this uncertainty, we have maximised the sample mass that is analysed (section 3.1).

2.1.2 ^{210}Pb dating

^{210}Pb (half-life 22.3 yr) is a naturally occurring radioisotope that has been widely applied to dating recent sedimentation (i.e., last 150 yrs) in lakes, estuaries and the sea (Fig. 2.2). ^{210}Pb is an intermediate decay product in the uranium-238 (^{228}U) decay series and has a radioactive decay constant (k) of 0.03114 yr^{-1}. The intermediate parent radioisotope radium-226 (^{226}Ra, half-life 1622 years) yields the inert gas radon-222 (^{222}Rn, half-life 3.83 days), which decays through several short-lived radioisotopes to produce ^{210}Pb. A proportion of the ^{222}Rn gas formed by ^{226}Ra decay in catchment soils diffuses into the atmosphere where it decays to form ^{210}Pb. This atmospheric ^{210}Pb is deposited at the earth surface by dry deposition or rainfall. The ^{210}Pb in estuarine sediments has two components: supported ^{210}Pb derived from *in situ* ^{222}Rn decay (i.e., within the sediment column) and an unsupported ^{210}Pb component derived from atmospheric fallout. This unsupported ^{210}Pb component of the total ^{210}Pb concentration in excess of the supported ^{210}Pb value is estimated from the ^{226}Ra assay (see below). Some of this atmospheric unsupported ^{210}Pb component is also incorporated into catchment soils and is subsequently eroded and deposited in estuaries. Both the direct and indirect (i.e., soil inputs) atmospheric ^{210}Pb input to receiving environments, such as estuaries, is termed the unsupported or excess ^{210}Pb.

The concentration profile of unsupported ^{210}Pb in sediments is the basis for ^{210}Pb dating. In the absence of atmospheric (unsupported) ^{210}Pb fallout, the ^{226}Ra and ^{210}Pb in estuary sediments would be in radioactive equilibrium, which results from the substantially longer ^{226}Ra half-life. Thus, the ^{210}Pb concentration profile would be uniform with depth. However, what is typically observed is a reduction in ^{210}Pb concentration with depth in the sediment column. This is due to the addition of unsupported ^{210}Pb directly or indirectly from the atmosphere that is deposited with sediment particles on the bed. This unsupported ^{210}Pb component decays with age (k = 0.03114 yr^{-1}) as it is buried through sedimentation. In the absence of sediment mixing (see below) the unsupported ^{210}Pb concentration displays an exponential decay profile with depth in the sediment column. Thus, the age of the sediment increases as the concentration of unsupported ^{210}Pb decreases with increasing depth in the sediment column. The validity of the ^{210}Pb dating rests on how accurately the ^{210}Pb delivery processes to the estuary are modelled, and in particular the rates of ^{210}Pb and sediment inputs (i.e., constant versus time variable).

At Whaingaroa, large-scale landcover changes over the last 120 years or so, due to catchment deforestation and conversion to pasture, and the planting of pine forests during the last 20 years are likely to have resulted in substantial increases in catchment sediment loads. Consequently, we would expect that sedimentation rates in the harbour are also likely to have increased.

There are two possible models that can be applied to date ^{210}Pb profiles under varying sediment accumulation rates (SAR): (1) constant initial concentration (CIC) and (2) constant rate of supply (CRS) models. The usual output from these dating models are ~annual time series of mass deposition fluxes (i.e., g cm^{-2} yr^{-1}) and sedimentation rates (i.e., mm yr^{-1}). These models have been successfully applied in several Auckland estuaries (Swales et al. 2002b). Methods for validating ^{210}Pb chronologies are discussed in Appendix I.

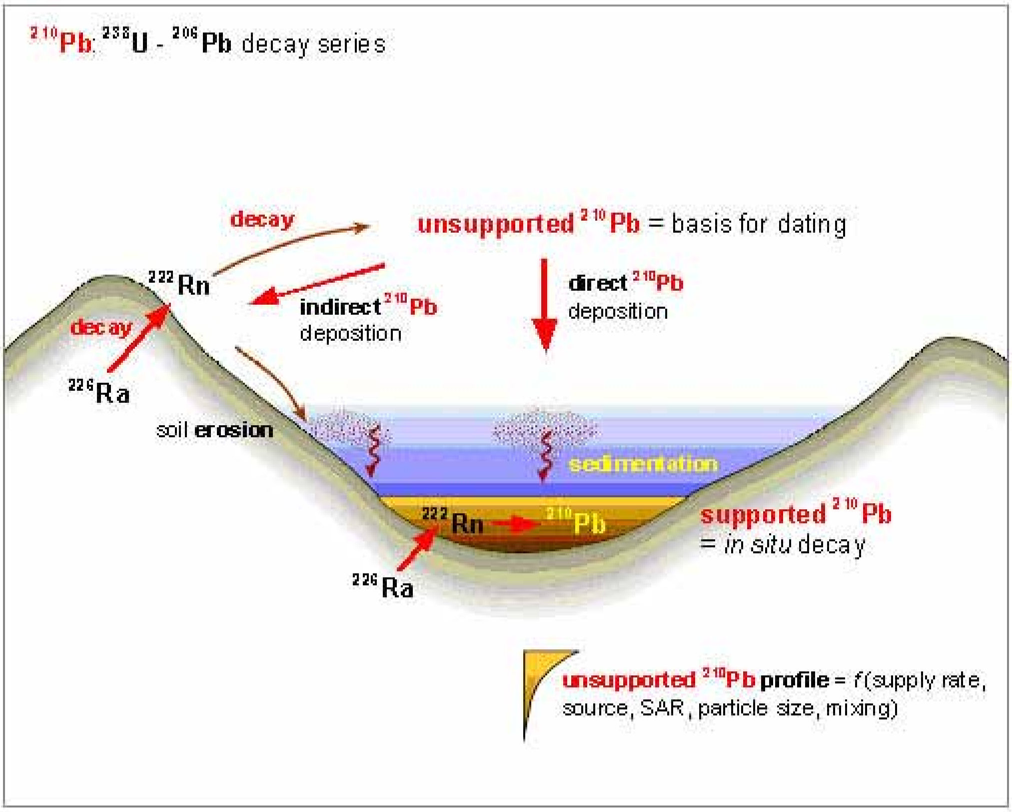


Figure 2.2: ^{210}Pb pathways to estuarine sediments.

Sediment Mixing

Biological and physical processes, such as the burrowing and feeding activities of animals and/or sediment resuspension by waves, mix the upper sediment column

(Bromley, 1996). As a result, sediment profiles are modified and this limits the temporal resolution of dating. At worst, sediment stratigraphy can be completely erased. Various mathematical models have been proposed to take into account the effects of bioturbation on ^{210}Pb concentration profiles (e.g., Guinasso and Schink, 1975). Biological mixing has been modelled as a one-dimensional particle-diffusion process (Goldberg and Kiode, 1962) and this approach is based on the assumption that the sum effect of 'random' biological mixing is integrated over time. In estuarine sediments exposed to bioturbation, the depth profile of unsupported ^{210}Pb typically shows a two-layer form, with a surface layer of relatively constant unsupported ^{210}Pb concentration overlying a zone of exponential decrease. In applying these types of models, the assumption is made that the mixing intensity (i.e., diffusion co-efficient) and mixing depth (i.e., surface-mixed layer, SML) are uniform in time. The validity of this assumption usually cannot be tested, but changes in bioturbation process could be expected to follow changes in benthic community composition.

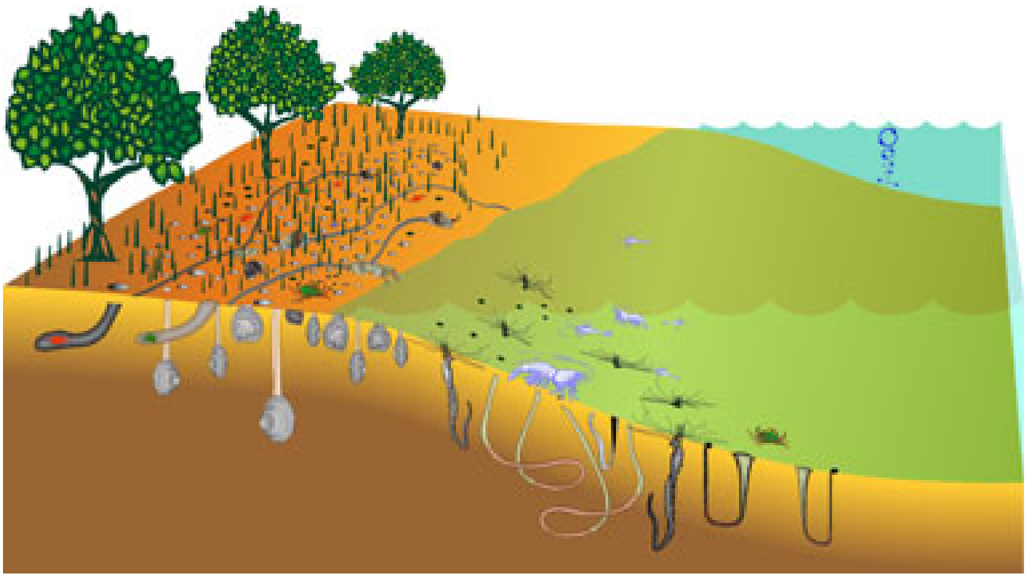


Figure 2.3: Biological and physical processes, such as the burrowing and feeding activities of animals and/or sediment resuspension by waves, mix the upper sediment column. As a result, sediment profiles are modified and limit the temporal resolution of dating. The surface mixed layer (SML) is the yellow zone.

2.1.3 Pollen dating

Historical landcover changes, such as catchment deforestation, establishment of pasture, plantation forestry or urbanisation, alter the composition of the pollen assemblage. Pollen is delivered to estuaries by direct atmospheric deposition and by eroded catchment soil. Thus, changes in the abundances of plant pollen in estuarine sediments can be used for dating deposits if the history of catchment landcover change is known. The uncertainty in dating sediment cores using pollen largely depends on two factors: (1) the degree of *in situ* sediment mixing, the efficiency of which declines as sedimentation rate increase and (2) the time lag between the initial introduction of new plant species and the production of sufficient pollen to be detectable in the stratigraphic record. The time lag for pollen production varies between plant species. New Zealand native trees take up to 50 years to reach full reproductive maturity whereas the introduced pine, *Pinus radiata*, develops a substantial pollen rain within 10 years. Grasses, weeds and other short-lived plants flower immediately and enter the stratigraphic record quickly. We assume a pollen dating uncertainty of ~10 yr, based on the time lag for pine pollen production and detection in estuarine sediments.

Pollen grains and spores (palynomorphs) are produced in huge numbers by conifers, flowering plants, ferns, and fern allies. Most palynomorphs are in the size range 5–120 µm, and thus can be easily transported by wind or water. In the presence of oxygen and moisture the cytoplasm decays rapidly, but the tough, decay-resistant outer wall tends to persist, although it will eventually break down. If sediments are water-saturated, and thus oxygen levels are reduced to very low levels, the outer walls can persist indefinitely. A cubic centimetre of most soils and estuarine sediments will contain thousands of pollen grains and spores. Palynomorphs are most often identified to a familial or generic level, although a substantial number can be attributed to one or several closely related species.

There are three main pathways by which palynomorphs are incorporated into the estuarine stratigraphic record (Fig. 2.4):

- airborne palynomorphs may fall directly onto the estuary sediment (low tide) or the overlying water mass (high tide);

- palynomorphs drop directly onto the surface of catchment soils and waterways and are delivered to the estuary by fluvial processes;

- palynomorphs accumulated in catchment soils, rocks and other sediments are reworked (10^1–10^6 yr after initial deposition) and eroded and transported by fluvial processes to the estuary.

The final palynomorph assemblage will always reflect varying proportions of these three pathways. Airborne palynomorphs suffer no corrosion and little breakage before incorporation in sediments. Palynomorphs reworked along waterways will show some corrosion or breakage if they spend time in sediments along stream-banks and beds where bacteria are active. Soils, however, have a dramatic effect on palynomorphs. Fern spores are highly resistant to corrosion, but flowering plant pollen is highly susceptible and conifers have intermediate resistance to corrosion. The longer a collection of palynomorphs is in the soil, the more fern spores and, in particular, tree-fern spores will dominate. A well-drained (aerated) soil will lose nearly all palynomorphs except for extensively corroded tree-fern spores. Thus, an estuarine sediment dominated by tree-fern spores is nearly always the result of a pollen source dominated by eroded catchment soils.

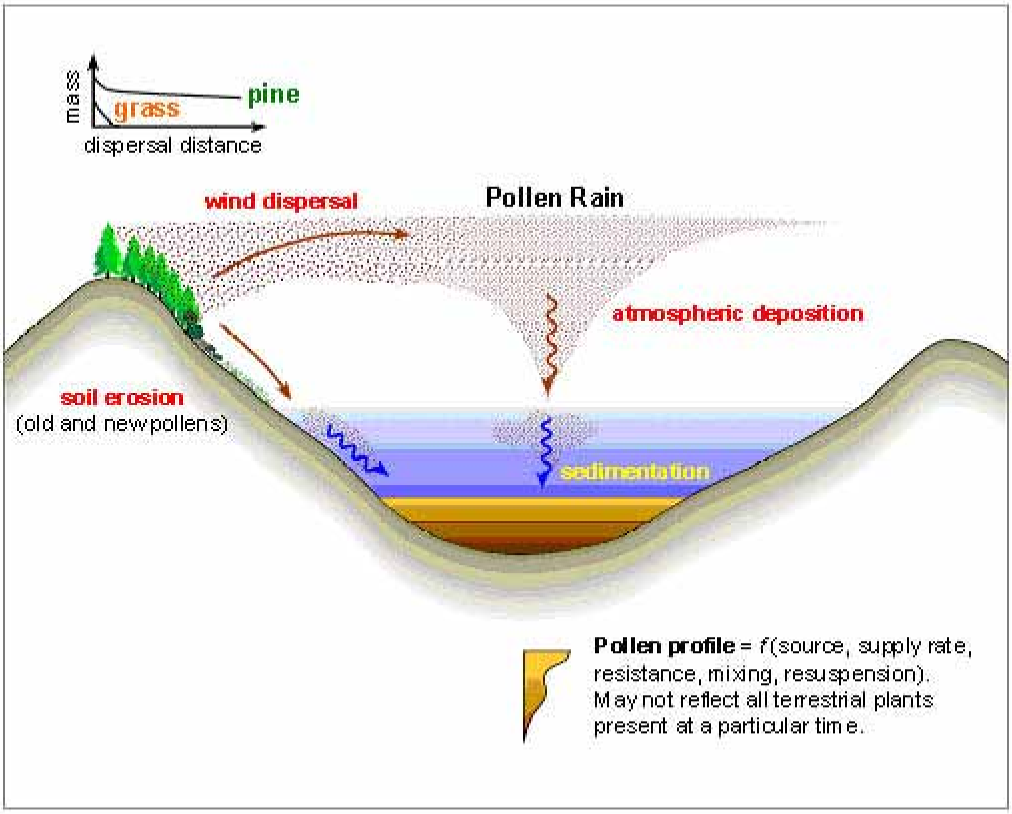


Figure 2.4: Pollen pathways to estuarine sediments.

Major pollen assemblages and their interpretation

At Whaingaroa, catchment landcover was originally composed of a podocarp-hardwood forest dominated by totara (*Podocarpus totara*), matai (*Prumnopitys taxifolia*), rimu (*Dacrydium cupressinum*), kahikatea (*Dacrydium dacrydioides*); rata

(*Metrosideros robusta*); maire (*Nestegis* spp.) and tree ferns. Pollen data indicate that kauri (*Agathis australis*) was present but not abundant (Lees et al. 1998; present study). Unlike many areas of New Zealand, Maori had made little impression on the continuous bush cover of the Whaingaroa catchment before European settlement began in the 1850s (section 1.4). Consequently, the clearance of relatively small areas for cultivation by Maori had a minimal impact on the pollen rain delivered to the harbour.

Bracken (*Pteridium esculentum*) spores are produced in large numbers, and are wind-dispersed and corrosion-resistant. In the Auckland region, bracken and scrub covered large areas after Maori settlement and forest clearance. Soils rich in bracken spores can continue to provide a steady influx of bracken spores to estuaries even when bracken has been nearly eliminated from the local area (Wilmshurst et al. 1999). By comparison, the bracken content of the Whaingaroa Harbour sediments is negligible and even in the aftermath of catchment deforestation, bracken is only common at one core site in the Waitetuna arm of the harbour.

Pine (*Pinus*) pollen is probably the most abundantly produced and widely distributed of all types (exotic and native) in the New Zealand flora. Slicks of yellow pollen that are sometimes noticeable after rain on suburban streets are often derived from pine plantations many kilometres distant. Pine trees begin to flower as soon as five years after planting. However, pine pollen production depends on tree size and the distance pollen is dispersed is proportional to the height above the ground at which it is released. Pollen production from a pine plantation therefore gradually increases over time, reflecting the number of saplings coming into flower (as all the trees are not planted at once), tree height and the foliage coverage. Pollen contributions from a plantation should first become apparent after 5 years, but the full effect is delayed until ~10 years after planting. In interpreting pine pollen profiles, it is reasonable to assume a typical sigmoidal growth curve, with an initial period of rapid increase followed by a decline in growth rate that eventually plateaus as maturity is reached. This sigmoidal growth pattern is mirrored in the pollen production, with an initial rapid increase, which eventually stabilises to roughly uniform level of year-to-year pollen production. This pattern has been observed in a regional study of sedimentation in Auckland estuaries (Swales et al. 2002b). At Whaingaroa, pine plantations account for less than 5% of present-day landcover, so that they have a relatively minor impact on the local and regional pollen rain. Pine pollen production would have substantially increased from initial planting in the mid-1980s.

Pasture is now the predominant landcover in the Whaingaroa Harbour catchment (Fig. 1.1). The pollen of grass species are often not well represented in estuarine sediments, which likely reflects relatively low pollen dispersal rates in comparison to other exotic species such as pine.

Changes in the abundance in the pollen profiles of these indigenous and exotic plants, in association with the catchment landcover history, are the usual basis for pollen dating of sediment cores. Typically, several historical time periods are identified in North Island estuarine cores: (1) pre-human indigenous forest; (2) Maori settlement (1350 AD ±100 years) identified by indigenous forest with bracken and charcoal increasing; (3) European settlement (mid-1800s onwards) with a rapid reduction in native forest species; (4) Modern sediments (typically post-1945) distinguished by a rapid rise in exotic grass and tree species (e.g., *Pinus*).

2.1.4 Radiocarbon dating

Radiocarbon (^{14}C) dating has been widely applied to sedimentation studies in NZ estuaries and is suitable for dating the remains of plants and animals older than about 500 years. Atmospheric carbon dioxide is composed of carbon-12 (^{12}C), and a small proportion of radioactive ^{14}C. ^{14}C radioactively decays to nitrogen-14 with a half-life of 5,730 years, so the measured $^{14}C/^{12}C$ ratio remaining in a sample is used to estimate the radiocarbon age. Any material that was at one time living can be dated using ^{14}C to a limit of about 70,000 years before present (B.P., "present" = 1950 AD).

In estuarine and marine environments, carbonate shells of bivalves and molluscs are particularly suitable for ^{14}C dating. As little as ~5 g of shell can be dated, although larger samples are preferred. Samples smaller than 1 gm can be dated by Acceleration Mass Spectrometry (AMS). Caution is required in selecting samples for dating because 'old' shell can be reworked from old sediments and re-deposited at a higher level in the stratigraphic record. This results in an over estimation of the age of sediments. Reworking of old shell occurs when channels migrate, and on intertidal flats where waves are energetic. Also, shellfish that burrow to substantial depths in the sediment column and subsequently die will result in under-estimation of the age of sediments at that depth. As such, whole, disarticulated and un-abraded (i.e., no transport) shell valves are most suitable for radiocarbon dating. ^{14}C dating provides a useful tool to estimate long-term average SAR for estuaries based on dating of suitable samples buried at depth in the sediment column. More detailed information on radiocarbon dating is provided in Appendix II.

2.2 Sediment accumulation rates (SAR)

Changes in sedimentation rates in estuaries provide by far the strongest evidence for the effects of catchment sediment runoff on estuarine systems.

Sedimentation rates are measured by calculating the thickness of sediment between dated layers in cores. The layers are dated ideally using complementary methods as previously discussed in this report. Sedimentation rates calculated from cores are ***net average* sediment accumulation rates (SAR)**, **which are usually expressed as mm yr^{-1}**. These SAR are net values because cores integrate the effects of all the processes, which influence sedimentation at a given location usually over years, decades or centuries. However, at short time scales (i.e., seconds–months), sediment may be deposited and then subsequently re-suspended by tidal currents and/or waves. Thus, over the long term, sedimentation rates derived from cores represent net or cumulative effect of potentially many cycles of sediment deposition and re-suspension. However, less disrupted sedimentation histories are found in depositional environments where sediment mixing due to physical processes (e.g., resuspension) and bioturbation is limited. The effects of bioturbation on sediment profiles and dating resolution reduce as SAR increase (Valette-Silver, 1993).

Net sedimentation rates statistics also mask the fact that estuary sedimentation is an episodic process, which largely occurs during catchment floods, rather than the continuous gradual process that is implied.

Although sedimentation rates are usually expressed as a sediment thickness deposited per unit time (i.e., mm yr^{-1}) this statistic does not account for changes in dry sediment mass with depth in the sediment column due to compaction. Typically, sediment density (ρ = g cm^{-3}) increases with depth and therefore some workers prefer to calculate dry mass accumulation rates per unit area per unit time (g cm^{-2} yr^{-1}). These data can be used to estimate the total mass of sedimentation in an estuary (tonnes yr^{-1}) (e.g., Swales et al. 1997). However, in our experience of estuarine cores (up to 4 m long) the effects of compaction are often offset by changes in bulk sediment density reflecting layering of low-density mud (i.e., dry density (ρ_d) <1 g cm^{-3}) and higher-density (i.e., ρ_d >1 g cm^{-3}) sand deposits. Furthermore, the significance of a SAR expressed as mm yr^{-1} is more readily grasped than a dry-mass sedimentation rate in g cm^{-3} yr^{-1}. For example, the rate of estuary aging due to sedimentation (mm yr^{-1}) can be directly compared with the potential mitigating effect of local sea level rise (mm yr^{-1}).

2.2.1 SAR from ^{210}Pb dating

In this study, we calculate an average sediment accumulation rate for the zone of exponential ^{210}Pb concentration decrease. The rate of ^{210}Pb concentration decrease with depth can be used to calculate a net sediment accumulation rate. Given an initial unsupported ^{210}Pb concentration (C_0), the value of C (Bq kg^{-2}) will decline exponentially with age (t):

$$C_t = C_0 e^{-kt} \qquad \text{Eq. 1}$$

Assuming that within a finite time period, sedimentation (S) or SAR is constant then $t = z/S$ can be substituted into Eq. 1 and by re-arrangement:

$$\frac{\ln\left[\frac{C_t}{C_0}\right]}{z} = -k/S \qquad \text{Eq. 2}$$

For an exponential decay model, a depth profile of natural log(C) should yield a straight line of slope $b = -k/S$. We fitted a linear regression model to natural-log transformed ^{210}Pb concentration data to calculate b. The sedimentation rate over the depth of the fitted data is given by:

$$S = -(k)/b \qquad \text{Eq. 3}$$

An advantage of this method is that the sedimentation rate is based on the entire ^{210}Pb profile rather than a single layer, as is the case for ^{137}Cs. Furthermore, if the pollen or ^{137}Cs tracer is present at the bottom of the core then the estimated SAR is a minimum value. The SAR found by the ^{210}Pb method can also be used to estimate the residence time (R) of sediment particles in the surface mixed layer (SML) before they are removed by burial. For example, given an SML (L) depth of 40 mm and S of 2 mm yr^{-1} then $R = L/S$ = 20 years. Although this greatly simplifies the process (i.e., the likelihood of particle mixing reduces with depth in the SML), this approach provides a useful measure of the relative effect of sediment mixing between cores, sub-environments and estuaries.

3. Methods

3.1 Sediment cores

Sediment cores were collected during 29–31 May 2002, with locations determined in consultation with Environment Waikato. Duplicate cores were collected at six intertidal sites (1–3, 6, 10, 12) and three subtidal (channel) sites (7, 11, 14) using a Livingston piston-corer to drive 50-mm diameter PVC pipe into the sediments (Fig. 3.1). Cores were collected within ±3 hours of high tide from R.V. Rangitahi, a 6 metre catamaran, using a three-point anchor system to maintain position on site, with location fixed to ±5 m using differential global positioning (DGPS). Sampling was designed to differentiate between sedimentation in the Waingaro and Waitetuna arms where the major sub-catchments discharge to the harbour. Sediment cores from sites 1–2, 6, 10 and 12 have been analysed in the present study. Typically, two cores were collected at each site (cores A & B) and the core exhibiting the least compression was subsequently analysed. Details for each core are summarised in Table 3.1.

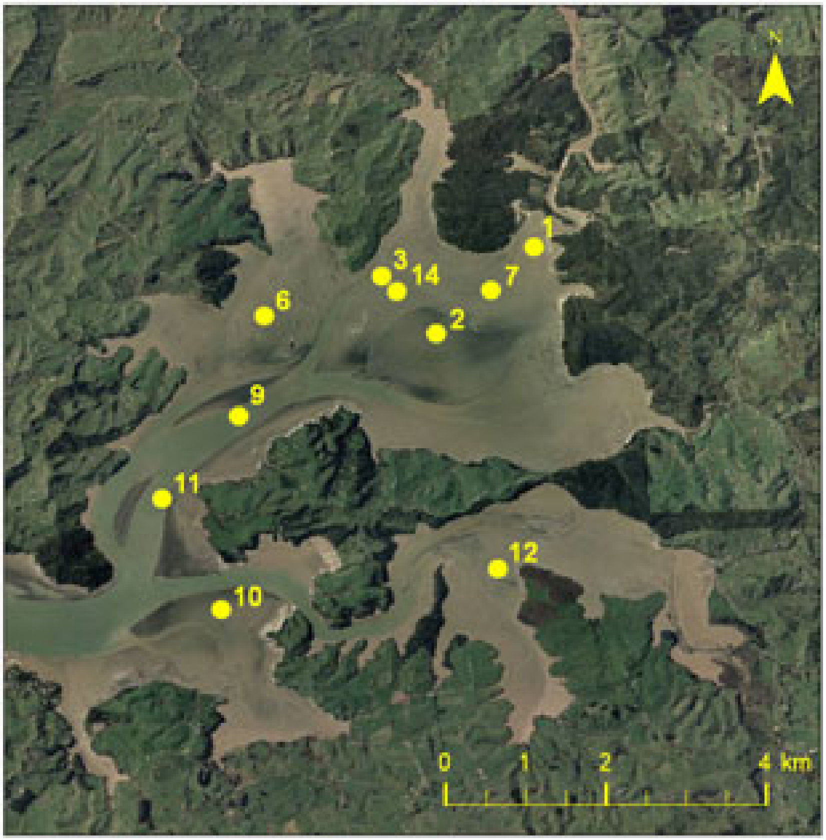


Figure 3.1: Sediment core locations. Aerial photograph taken 10 June 2002 (source: Terralink International Ltd).

Site 6 was selected because of earlier work by Sherwood (1973), who surveyed a SE–NW 800 m transect between Whatitirinui Island and the harbour shore. Steel rods were used to determine the thickness of unconsolidated estuarine sediment on the underlying palaeo shore platform. Sherwood (1973) found that the surface of the rock platform rapidly drops to 10m below mean high water level and extends up to 500 m from the present-day shore.

Table 3.1: Whaingaroa Harbour Livingston core site locations and details. Cores from sites in bold analysed in the present study – (s) denotes subtidal core site and (A/B) denotes duplicate core identification, with the core analysed denoted in bold in the table.

Site	Latitude	Longitude	Water Depth[1] (m)	Length of Core Driven (m) (A/B)	Length of Core Retained (m) (A/B)	Compression (%)[2]
1	37 °45.181'S	174°56.948'E	1.8–1.8	**3.8**/4.0	**3.8**/3.83	**0**/4
2	37 °45.762'S	174°56.291'E	1.6–1.2	4.1/**4.1**	3.80/**3.86**	7/**6**
3	37 °45.483'S	174°56.032'E	1.0–1.4	3.95/4.08	3.42/3.63	13/11
6	37 °45.645'S	174°55.133'E	0.8–1.1	**4.2**/4.4	**3.77**/3.95	**10**/10
7(s)	37 °45.470'S	174°56.659'E	3.5–3.0	2.1/2.1	1.98/1.90	6/10
10	37 °47.619'S	174°54.848'E	2.2–1.6	4.05/**4.1**	3.94[3]/**3.73**	11/9
11(s)	37 °46.878'S	174°54.448'E	3.6–3.9	2.0/2.1	1.84[4]/2.05	8/2
12	37 °47.342'S	174°56.492'E	2.1–1.5	4.1/**4.1**	3.94[5]/**3.8**	4/7
14(s)	37 °45.379'S	174°55.925'E	3.9–4.5	2.1/3.0	1.98/2.9	6/3

Notes: (1) Range of water depth (m) during sediment core collection; (2) linear core compression assumed. Compression (%) = ((driven – retained)/driven)*100; (3) Core 10A: 0.41 m of core lost from base of core – actual length retained = 3.53m; (4) Core 11A: 0.10 m of core lost from base of core – actual length retained = 1.74m; (5) Core 12A: 0.24 m of core lost from base of core – actual length retained = 3.70m.

Waingaro Cores 1A, 2B & 6A

Cores were split in half, logged and samples taken from 1-cm thick slices for pollen and particle size analysis. The Waingaro cores 1A, 2B & 6A, which were analysed during 2003/2004, were sub-sampled at 0.25-m intervals from the surface to the base of each core. In 2004/2005 these cores were re-sampled in the upper 0.5m for radioisotope (i.e., ^{137}Cs & ^{210}Pb) and particle-size analyses to more finely resolve sedimentation chronology over the last 150 years. Sediment samples were taken as 2-cm thick slices at 1–3, 5–7, 9–11, 13–15, 17–19, 22–24, 30–32, 35–37, 40–42 and 45–47 cm depths. The 2 cm slices provided enough dry sediment to minimise counting errors in the radioisotope analyses while not averaging over such large depth increments that temporal resolution is lost. In addition, a radiocarbon age (^{14}C) for a cockle shell (*Austrovenus stutchburyi*) valve deposited at 2.0 m depth in core 2B, was determined to calculate a long-term average SAR in the Waingaro arm of the upper harbour.

Okete & Waitetuna Cores 10B & 12B

Waitetuna cores 10B and 12B were analysed during 2004/2005. Based on earlier findings for the Waingaro arm cores, we intensively sampled the top-most 0.5m of both cores. Samples for radioisotope and particle size analyses were taken as 2-cm thick half-slices at 13 depth increments between: 0–12, 14–16, 20–22, 24–26, 30–32, 34–36, 40–42 and 46–48 cm depths. Sediment samples for pollen and particle-size analysis were taken from 1-cm depth increments between: 0–3, 5–6, 7–8, 9–10, 15–16, 35–36, 50–51 cm then at 0.25-m increments to the base of both cores. Samples of shell were also taken from cores 10B (*Macamona lilliana*, 3.69–3.7-m depth) and 12B (*Austrovenus stutchburyi*, 2.54–2.58-m depth) for ^{14}C dating to estimate a long-term average SAR in the Waitetuna arm of the harbour.

3.2 Particle size

Particle size was determined using a Galai CIS-100 'time-of-transition' (TOT) stream-scanning laser particle-sizer operated by NIWA. The sediment sub-samples were wet-sieved through a 2 mm sieve to remove leaf and twig fragments and shell hash. Approximately 3 cm^3 of sediment was mixed in a 1000 ml cylinder and mixed into a homogenised suspension, from which ~200 ml was sub-sampled for particle-size analysis. The samples were dispersed by ultra-sonic dispersion for four minutes before and then during particle size analysis. Typically 10^5–10^6 particles were counted per sample. Particle volumes, for spheres, were calculated from the measured particle diameters, which were used to determine the particle-size volume distribution for each sample.

3.3 Bulk density

The 2-cm thick sediment slices for radioisotope analysis were weighed and dried at 105°C for 24 hours and then reweighed after 30 minutes cooling. These data, along with the slice volume (39.3 cm^3), were used to calculate sediment dry bulk density (g cm^{-3}), which is required to derive unsupported ^{210}Pb areal fluxes.

3.4 Pollen

Sediment samples (2–3 cm^3) for pollen analysis were prepared as described by Moore and Webb (1978). Following acid digestion, resistant minerals, pollen and spores were mounted on glass slides. A minimum of 150 pollen grains and spores of terrestrial plants (i.e., all species combined) were counted on regular transects across each slide. The results are presented as percentages of a palynomorph sum including all types.

3.5 Radioisotopes

Radioisotope concentrations were determined by high resolution, low-level gamma ray spectrometry using a Canberra Model BE5030 50% broad energy range hyper-pure germanium detector. Samples were counted for 23 hours to minimise uncertainties in radioisotope concentrations. The ^{226}Ra concentrations of the sediment samples were determined from the emissions of the short-lived daughters of the noble gas ^{222}Rn gas by embedding samples in epoxy resin. An in-growth period of 30 days allows equilibrium to be reached between ^{226}Ra and its daughter ^{222}Rn. Gamma spectra of ^{226}Ra, ^{210}Pb and ^{137}Cs were analysed using Genie2000 software (ver. 3). Radioisotope concentrations are expressed in S.I. units as Becquerel (disintegration s^{-1}) per kilogram (Bq kg^{-1}).

The uncertainty ($U_{2\sigma}$) of the unsupported ^{210}Pb concentrations is given by:

$$U_{2\sigma} = \sqrt{(^{210}Pb_{2\sigma})^2 + (^{226}Ra_{2\sigma})^2} \quad \text{Eq. 4}$$

where $^{210}Pb_{2\sigma}$ and $^{226}Ra_{2\sigma}$ are the two standard deviation uncertainties in the total ^{210}Pb and ^{226}Ra concentrations at the 95% confidence level. The primary source of uncertainty in the measurement of radioisotope concentrations relates to the counting statistics (i.e., variability in the number of detected decay events). This source of uncertainty can be reduced by increasing the sample size. The $U_{2\sigma}$ values of sediment samples in the Whaingaroa cores were in the range 3.6–5.2 Bq kg^{-1}.

In cases where the ^{226}Ra concentration was higher than the total ^{210}Pb concentration (i.e., supported and unsupported ^{210}Pb) we assumed that unsupported ^{210}Pb was absent in that particular sample and excluded it from the regression analysis. The unsupported ^{210}Pb profile and time-averaged SAR for each core were calculated, using the fitted regression relationship, from the surface to a maximum depth based on Equations 5 and 6. Figure 3.2 shows an example of a linear regression fit to a ^{210}Pb profile measured in an estuarine sediment core. It can be seen that the decline in unsupported ^{210}Pb concentration with depth in the sediment column is well described by the log-linear regression equation (r^2=0.96). Note the absence of a surface mixed layer in this example.

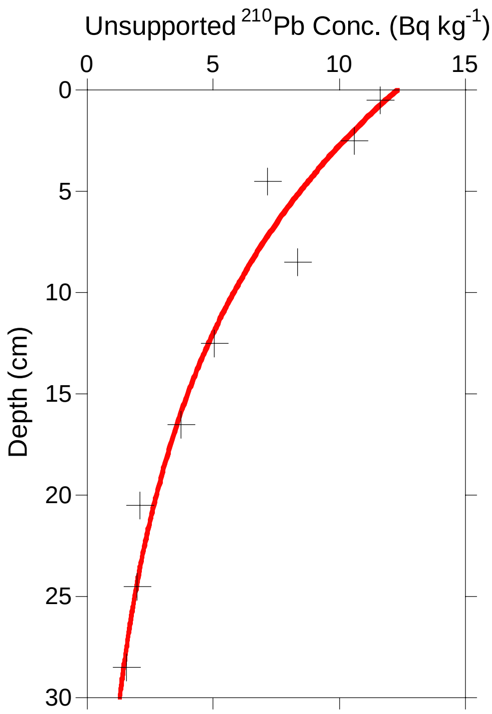


Figure 3.2: Example of log-linear regression fit (r^2 = 0.96) to ^{210}Pb concentration profile in an estuarine core.

4. Results

4.1 Overview

The sediment profiles preserved in the Whaingaroa Harbour cores are atypical of sediment cores collected in other North Island estuaries. Pollen analyses show an almost complete absence of exotic plant species that we would expect to see in the sediment cores following European settlement and subsequent catchment deforestation from the 1890s onwards. Radioisotope analyses also show an unprecedented absence of ^{137}Cs and unsupported ^{210}Pb in the sediment cores, with the exception of core 12B (Waitetuna arm). ^{210}Pb occurs in the top 8 cm of core 12B. ^{137}Cs and ^{210}Pb are ubiquitous environmental tracers which are found globally in terrestrial and aquatic ecosystems. The almost complete absence of both exotic pollens and radioisotopes in the harbour sediments indicates that long-term sediment accumulation has not occurred in the main body of the harbour for at least the last 150 years and probably much longer. In particular the absence of: (1) bracken in association with native forest pollens (indicative of Maori slash and burn agriculture) and (2) exotic plant pollens, ^{137}Cs and ^{210}Pb, which are used to date recent sediment deposits, provides strong support for this interpretation.

Table 4.1 summarises the results of the core dating and analytical results (i.e., ^{210}Pb, ^{137}Cs, ^{14}C) are present in Appendix III. Radiocarbon dating of shell valves taken from three cores provides a very consistent picture of harbour sedimentation over the last ~8000 years. Long-term SAR have averaged $\leq$ 0.5 mm yr^{-1} since the sea reached its present level about 6500 years B.P. and is consistent with pre-human SAR estimated for other North Island estuaries with forested catchments. The pollen profiles show no evidence of Maori habitation, which reflects: (1) the fact that large-scale deforestation did not occur until the 1890s after the arrival of Europeans and/or (2) sediments indicative of this historical period have not been preserved in the stratigraphic record.

European-era sediments are restricted to the top 15cm of the sediment column and in core 12B exotic grass and weed pollen profiles indicate an average post-1890 SAR of 1.1 mm yr^{-1} in the Waitetuna arm. We conclude that the post-1890 ^{210}Pb SAR of 5 mm yr^{-1} estimated for core 12B is unreliable based on the analysis (section 4.6). Pine-pollen profiles were used to estimate a post-1990 SAR of 2.5–8 mm yr^{-1}. There is some uncertainty in these estimates because we have no information from the cores on sediment mixing depths due to physical and biological processes, which mix pollen and radioisotopes in the surface mixed layer. Environment Waikato's bed-elevation change data for the harbour indicates physical mixing to ≤5-cm depth due to wave action (Fig. 1.3). We have also used data from other North Island estuaries (Swales et al. 2002b, 2005) to estimate mixing depths and thereby conservative SAR estimates. The post-1990 SAR of 2.5–4.0 mm yr^{-1} in cores 1A and 12B are consistent with present-day sedimentation rates in other North Island estuaries. The pollen data suggest that average annual sedimentation rates in the Waitetuna arm of the harbour have increased in the last decade or so in comparison to last 100 years following deforestation. The absence of ^{210}Pb and ^{137}Cs does not enable independent validation of these pollen-derived SAR for the recent sediments. Furthermore, relatively few cores were collected and analysed in this study so that there is limited information on the spatial variability in sedimentation rates.

Table 4.1: Sedimentation rates for historical time-periods estimated by dating methods.

Core	Historical Era	Dating Method	SAR (mm yr^{-1})
1A	post-1990	pollen	4.0
2B	post-6300 B.P.	^{14}C	0.34
10B	post-7900 B.P.	^{14}C	0.5
	post-1990	pollen	8.0
12B	post-7900 B.P.	^{14}C	0.35
	post-1890	pollen	1.1
	post-1890	^{210}Pb	5.0
	post-1990	pollen	2.5

In the following sections, the sedimentary characteristics of each core are discussed in detail. This includes interpretation of the particle size, bulk density, pollen, ^{210}Pb profiles and radiocarbon data. In this report we will discuss observed changes in the sediment profiles in a chronological sequence from the past (bottom of core) to the present day (top of core).

4.2 Core 1A: Waingaro Landing

Core 1A was collected from the intertidal flat close to Waingaro Landing (Fig. 2.1) in two metres of water (28 May 2002, 1200 NZST). The intertidal sediments at this site are composed of homogeneous dark green-grey (colour 4/1) fine sandy mud and grey-olive (6/2) sandy mud below 1.8-m depth. Leaf and twig fragments occur in the upper part of the core and become rare below 2.5-m depth. Cockle shell (*Austrovenus stuchburyi*) valves and fragments are abundant in the top 5 cm of the core and common throughout the core length. Figure 4.1 plots the particle-size distribution (PSD) for selected sample depths between the surface and the base of core 1A. The sediments are bi-modal, with fine silt (~15 µm) and very-fine sand (~100 µm) modes. These data show a change over time from predominantly mud to fine–coarse sand accumulation on the tidal flat.

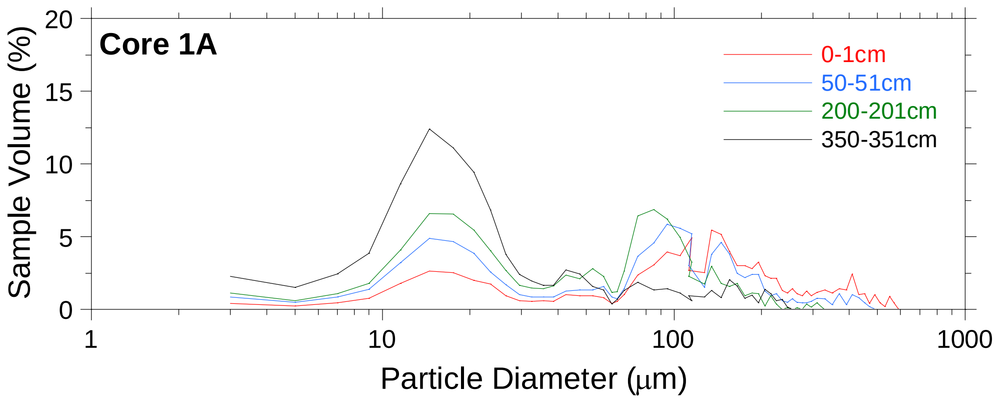


Figure 4.1: Core 1A (Waingaro Landing) particle-size distribution plotted on a log scale for surface (0–1 cm), intermediate depths, and basal (350–351 cm) sediments.

Sediment profiles also record this trend of increasing particle size towards the top of the core, as characterised by changes in median and mean particle size (Fig 4.2a). The apparent increased variability in particle size in the top 50 cm is an artefact of the increased sampling density in this part of the core (section 3.1). At the base of the core, sediments are composed entirely of mud (Fig 4.2b). The mud content rapidly reduces over time (towards surface) in the lower part of the core, so that mud accounts for 50% of the sediment mass at 250-cm depth. The mud content gradually declines to 25% at the sediment surface. Dry bulk density values of 0.75–1.25 g cm^{-3} in the upper 50 cm of core 1A are typical of estuarine mud (Fig. 4.2c).

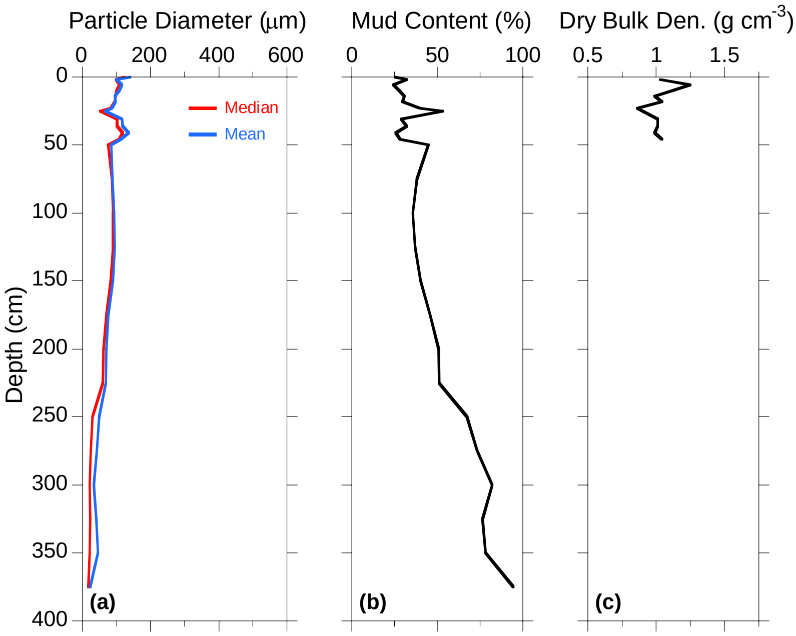


Figure 4.2: Intertidal Core 1A (Waingaro Landing) sediment profiles: (a) median and mean particle diameter (microns); (b) mud content (%) and dry bulk density (g cm^{-3}).

The pollen profiles for core 1A are dominated by native tree pollen (rimu, other podocarps and rata) and tree-fern spores (Fig. 4.3). The dominance of corrosion-resistant tree-fern spores, which account for ~60% of the terrestrial pollen, strongly suggests that the primary pollen source is eroded catchment soil. Pine pollen and exotic grasses and weeds occur in the top 20 cm of the sediment column. The pine pollen abundance at the sediment surface of ~10% is indicative of the pollen rain that could be expected within 10–15 years after initial planting of local pine forests. The initial production of pine pollen in substantial quantities would typically occur ~5 years after planting. This is consistent with the planting of the pine forests in the Waingaro catchment from 1985 onwards.

Based on this information, a time-averaged SAR for core 1A can be estimated from the maximum depth of pine-pollen (~15 cm) and the forest history, assuming that initial pollen production began no earlier than 1990. In this case, the post-1990 SAR would be ~12 mm yr^{-1}. Unfortunately, we have no information from the core about the mixing depth of near-surface sediments due to physical and biological processes. Sediment mixing is ubiquitous in most estuarine environments and this process results in downward mixing of tracers, such as pine pollen, and therefore over-estimation of sedimentation rates.

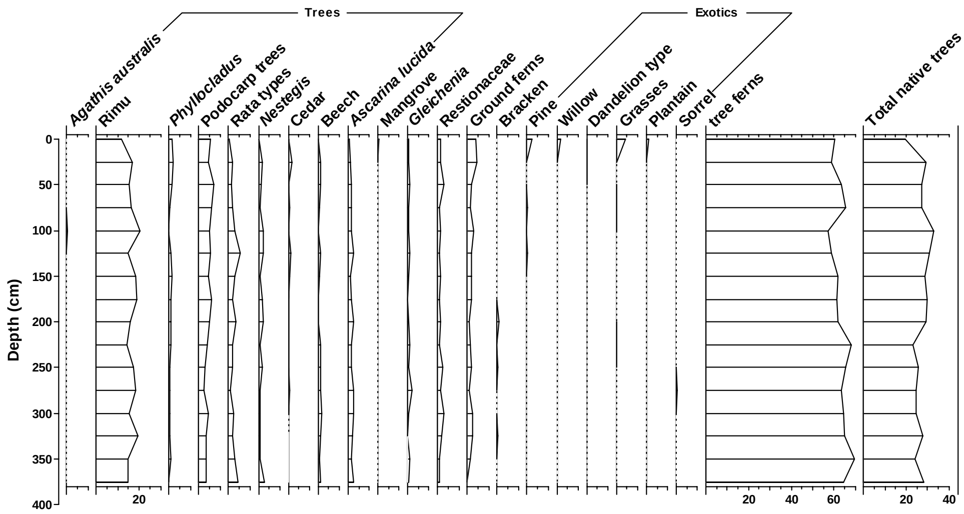


Figure 4.3: Core 1A (Waingaro Landing), pollen and spore profiles for major plant groups expressed as a percentage of the terrestrial pollen sum.

The bed-elevation data from surveys conducted at 3-month intervals at the EW monitoring sites (Fig. 1.3) indicate short-term physical sediment mixing to ≤5-cm due to mass erosion and redeposition. The depth of this surface mixed layer, which is due to physical and biological processes, can also be deduced from x-ray images and the vertical distribution of short-lived radioisotopes, such as Beryllium-7 (^{7}Be, half-life = 53.3 days). These methods were used in a recent study of the Pauatahanui Inlet, Porirua (Swales et al. 2005). The Pauatahanui Inlet and Whaingaroa Harbour are similar in that they are exposed to prevailing westerly winds and have sufficient fetch for wave generation to occur. At Pauatahanui, ^{7}Be profiles and x-radiographs showed that short-term (i.e., days–months) sediment mixing occurred to ≤5-cm depth. The ^{210}Pb profiles showed that deeper sediment mixing to ≤15-cm depth occurred over years–decades. Thus, the maximum depth of pine-pollen in core 1A, corrected for surface mixing could be ≤5-cm, in which case the post-1990 SAR would be ≤4 mm yr^{-1}. Present-day sedimentation rates in North Island estuaries are averaging 2–4 mm yr^{-1} (e.g., Swales et al. 2002b; 2005).

4.3 Core 2B: Waingaro (intertidal flat)

Core 2B was collected near the centre of the large intertidal flat south of the main tidal channel (Fig. 2.1) in 1.2 m of water (30 May 2002, 1330 NZST). The intertidal sediments at this site are composed of dark green-grey (colour 4/1) fine sandy mud. The stratigraphy of this core is more complex than for Core 1A. Leaf and twig fragments are common in the upper two metres of the core, with a thin layer of terrestrial plant fragments at 157–158-cm depth. A discrete shell-rich fine–coarse sand unit occurs at 192–251-cm depth. The shell is dominated by cockle and the deposit-feeding wedge shell *Macomona liliana*. Below 251-cm depth, the sediments to the base of the core at 386 cm are largely similar to sediments above the shell/sand unit. Another layer of cockle shell occurs at 339–344 cm and another thin layer of terrestrial plant fragments occurs at 367–368-cm depth.

Figure 4.4 shows the particle-size distribution (PSD) at several depths between the surface and the base of core 2B. The sediments are similar to those sampled in core 1A, being composed of a bi-modal fine silt (~15 μm) and very-fine sand (~100 μm). Unlike core 1A, there is no general trend of increasing particle size towards the sediment surface. The PSD for 200–201 cm samples the top of the shell/sand layer at 192–251-cm and shows that this layer is composed of poorly sorted fine–coarse sand. The PSD above and below this layer in the green-grey sandy mud unit are very similar, whereas surface sediments contain more fine sand.

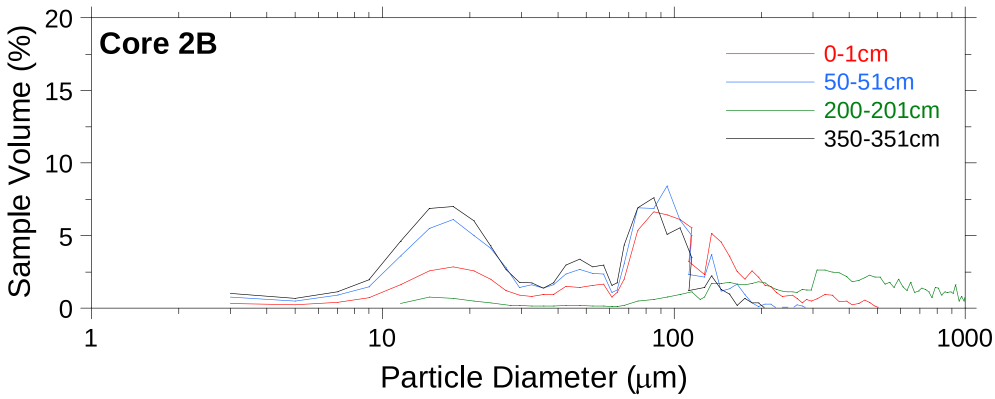


Figure 4.4: Core 2B (Waingaro arm) particle-size distribution plotted on a log scale for surface (0–1 cm), intermediate depths, and basal (350–351 cm) sediments.

Sediment profiles reflect the down-core heterogeneity of core 2B described above, with the dominant feature of this core being the shell/sand unit at 192–251-cm depth (Fig 4.5a). Figure 4.5b also shows that this shell/sand unit is capped by a mud-rich layer between 180–192-cm depth. Above 150-cm depth there is a gradual increase in median/mean particle diameter from about 50 to 100 μm (Fig 4.5a). Dry bulk density values of 1.0–1.2 g cm^{-3} in the upper 50 cm of core 2B are typical of estuarine muds (Fig. 4.5c).

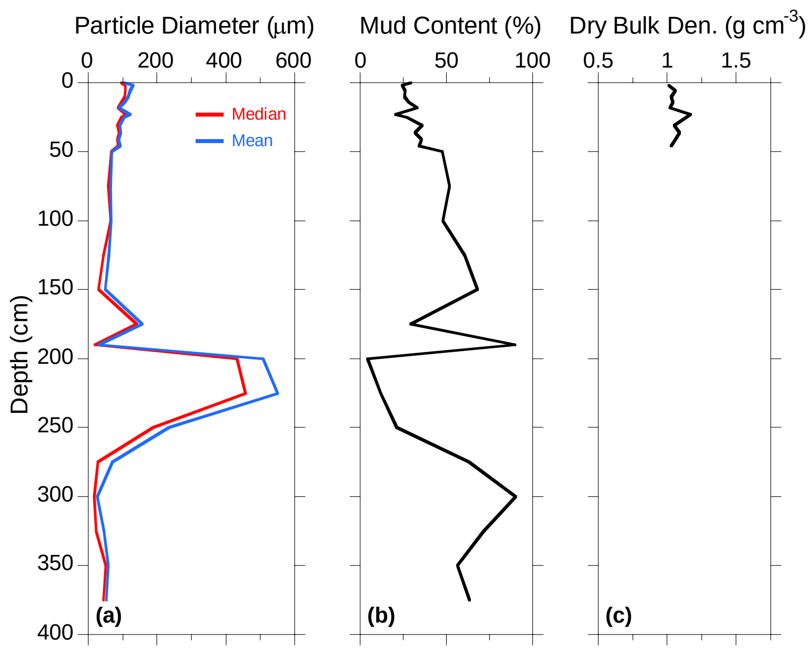


Figure 4.5: Intertidal Core 2B (Waingaro tidal flat) sediment profiles: (a) median and mean particle diameter (microns); (b) mud content (%) and dry bulk density (g cm^{-3}).

The discrete layers of terrestrial plants in core 2B are indicative of flood deposits and are particularly common in tidal creeks close to catchment outlets (Swales et al. 1997; 2002a). The shell-sand unit at 192–251-cm depth, occurring within the ubiquitous estuarine sandy mud suggests an episode of substantial environmental change in the harbour. ^{14}C dating of cockle shell (sample *Wk-13978*, University of Waikato Radiocarbon Lab.) taken from the top of the shell/sand unit at 200-cm depth provides a calibrated age of 6090–6330 years B.P. (95% probability). Thus, the top of the sand unit corresponds with the sea reaching its approximate present level 6500 years B.P. (Gibb, 1986). The sand unit likely reflects local *in situ* conditions rather than changes in sediment source characteristics because we do not see similar units in the other Waingaro cores. The sand unit may represent a shallow subtidal sand/shell bank formed during the period of rapid sea-level transgression before 6500 years B.P. The sand unit contains abundant shell valves of the intertidal *Austrovenus stutchburyi* and intertidal–subtidal *Macomona liliana*, which indicates that this shell material was also likely to have been transported to the site. A time-averaged SAR can be estimated from the ^{14}C age and correcting the sample depth for 6% core compression (Table 3.1), yields a long-term SAR of 0.34 mm yr^{-1}.

The core 2B pollen profiles are similar to core 1A, being dominated by native tree pollen (rimu, other podocarps and rata) and tree-fern spores (Fig. 4.6). The dominance of corrosion-resistant tree-fern spores, which account for ~50% of the terrestrial pollen signal, again strongly suggests that the primary pollen source is eroded catchment soil. There is no discernable change in the pollen profiles through time, towards the top of the core or above or below the ^{14}C-dated shell at 200-cm depth. These profiles largely reflect the fact that the native-forest landcover was relatively undisturbed until very recently (1890s) in terms of the harbour's history. A trace of pine pollen occurs in the surface sediment, whereas exotic grasses and weeds are absent from the sediment column. The absence of modern sediments containing exotic pollens, ^{137}Cs and ^{210}Pb suggests that long-term accumulation of eroded soils has not occurred for at least the last 150 years.

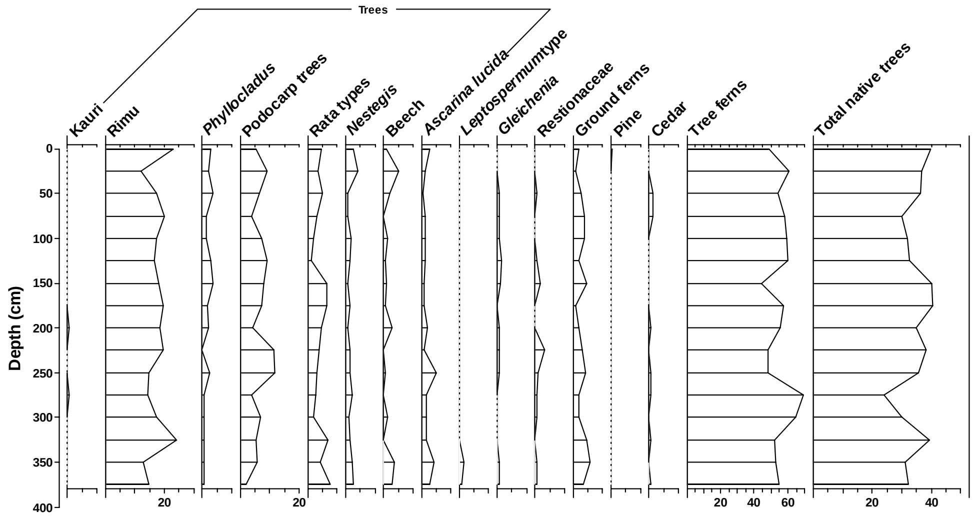


Figure 4.6: Core 2B (Waingaro intertidal flat), pollen and spore profiles for major plant groups expressed as a percentage of the terrestrial pollen sum.

4.4 Core 6A: Waingaro

Core 6A was collected in 0.9 m of water on the intertidal flat 370 m north-west of Whatitirinui Island (31 May 2002, 1300 NZST) (Fig. 2.1). Sherwood (1973) survey data show that the unconsolidated sediment column is about 10 metres thick at this site. The sediment core is composed of homogeneous dark green-grey (colour 4/1) fine sandy mud. Small plant fragments (≤3 mm) are common in the upper two metres of the core. Occasional cockle-shell fragments occur throughout the core.

Figure 4.7 shows the particle-size distribution (PSD) at several depths between the surface and the base of core 6A. The sediments are similar to previous cores, being composed of a bi-modal fine silt (~15 μm) and very-fine sand (~100 μm). Unlike cores 1A and 2B, the mud fraction increases over time towards the top of the core from 200-cm depth.

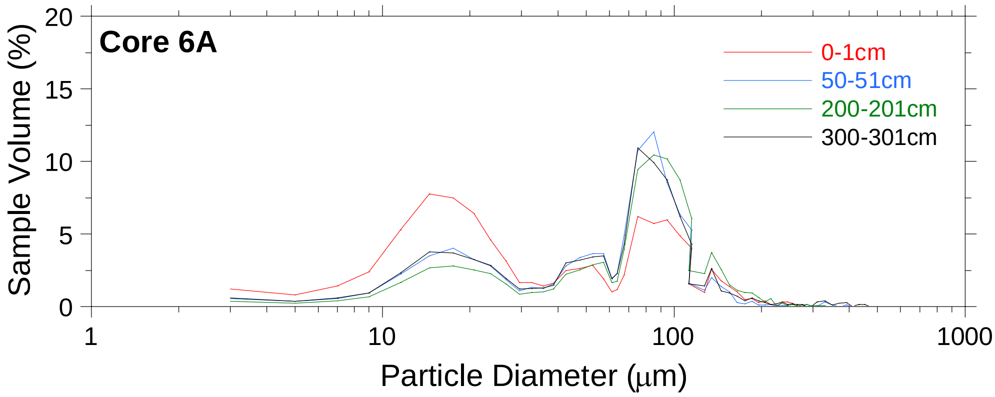


Figure 4.7: Core 6A (Whatitirinui Island, Waingaro arm) particle-size distribution plotted on a log scale for surface (0–1 cm), intermediate depths, and basal (300–301 cm) sediments.

Sediment profiles demonstrate the relatively homogeneous nature of the sediment deposits sampled by core 6A (Fig. 4.8a). Median particle diameter decreases from ~80 μm (very fine sand) at the base of the core to ~50 μm (coarse silt) at the surface. This reflects an increase in mud content over time, from about 180-cm depth (Fig. 4.8b). Dry bulk density values of 0.7–1.3 g cm^{-3} in the upper 50 cm of core 6A are typical of estuarine muds (Fig. 4.8c).

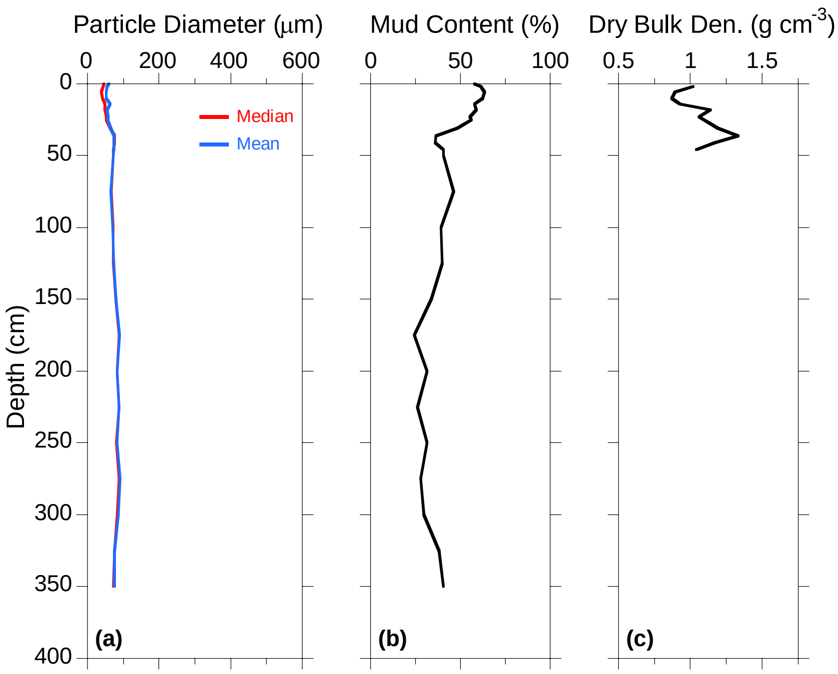


Figure 4.8: Intertidal Core 6A (Whatitirinui Island) sediment profiles: (a) median and mean particle diameter (microns); (b) mud content (%) and dry bulk density (g cm^{-3}).

The core 6A pollen profiles are similar to the previously described Waingaro cores, being dominated by native tree pollen (rimu, other podocarps and rata) and tree-fern spores (Fig. 4.9). Again, the dominance of corrosion-resistant tree-fern spores, which account for ~50% of the terrestrial pollen signal, indicates that the primary pollen source is eroded catchment soil. There is no discernable change in the pollen profiles through time, towards the top of the core. The absence of modern sediments containing exotic pollens, ^{137}Cs and ^{210}Pb renders it impossible to calculate SAR but does suggests that long-term sediment accumulation has not occurred for at least the last 150 years.

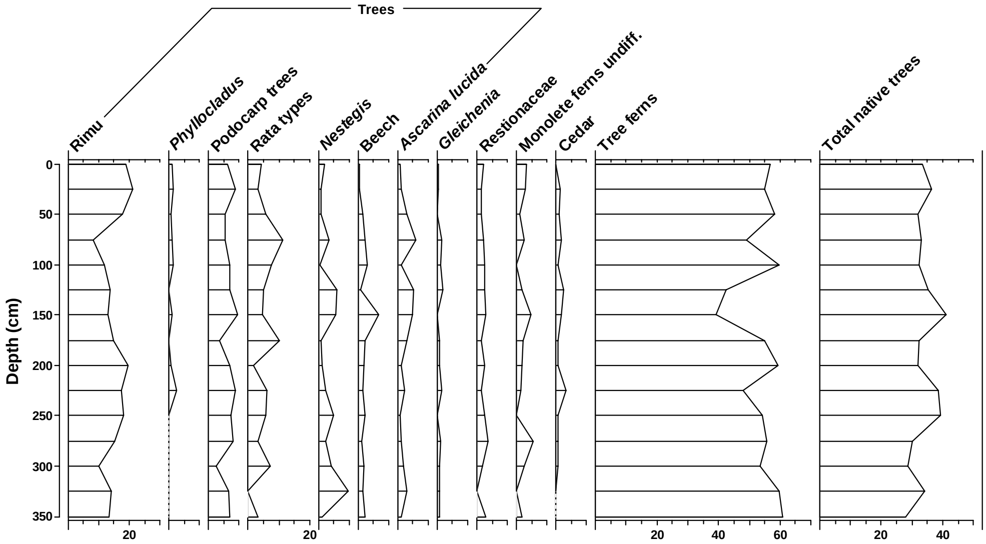


Figure 4.9: Core 6A (Whatitirinui Island, Waingaro arm), pollen and spore profiles for major plant groups expressed as a percentage of the terrestrial pollen sum.

4.5 Core 10B: Okete Bay

Core 10B was collected in 1.6 m of water at the mouth of Okete Bay (30 May 2002, 1545 NZST) (Fig. 2.1). The sediment core is composed of muddy fine sand. Figure 4.10 shows the particle-size distribution (PSD) at several depths between the surface and the base of core 6A at 366-cm depth.

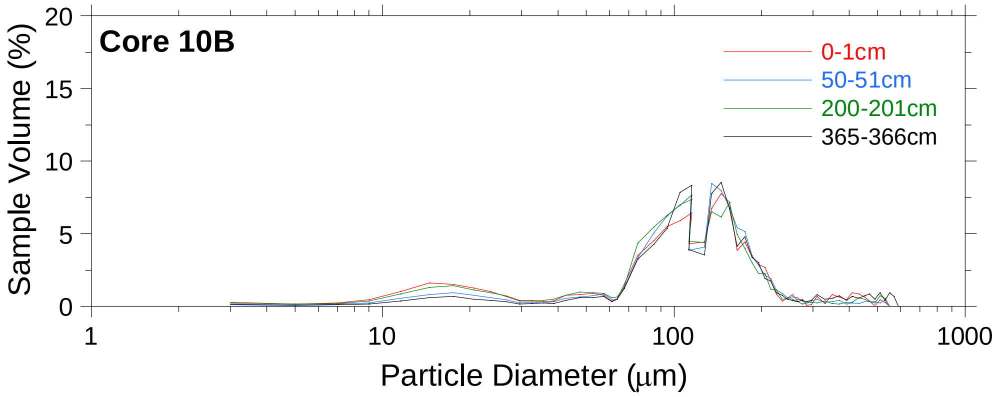


Figure 4.10: Core 10B (Okete Bay) particle-size distribution plotted on a log scale for surface (0–1 cm), intermediate depths, and basal (365–366 cm) sediments.

These sediments differ from those in the Waingaro arm, being composed of a bi-modal fine-sand (100 μm & 140 μm). The fine-silt mode (~15 μm) is almost absent so that the total mud content is ≤15% in comparison to ≤80% in the Waingaro cores.

Sediment profiles for core 10B show little variability with depth. Median and mean particle diameter vary about 140 μm (fine sand) throughout the core (Fig. 4.11a). Mud content also does not substantially vary over time towards the top of the core (Fig. 4.11b). Dry bulk density values of 0.7–0.95 g cm^{-3} in the upper 50 cm of core 10B reflect the relative porosity and water content of these estuarine sands (Fig. 4.11c).

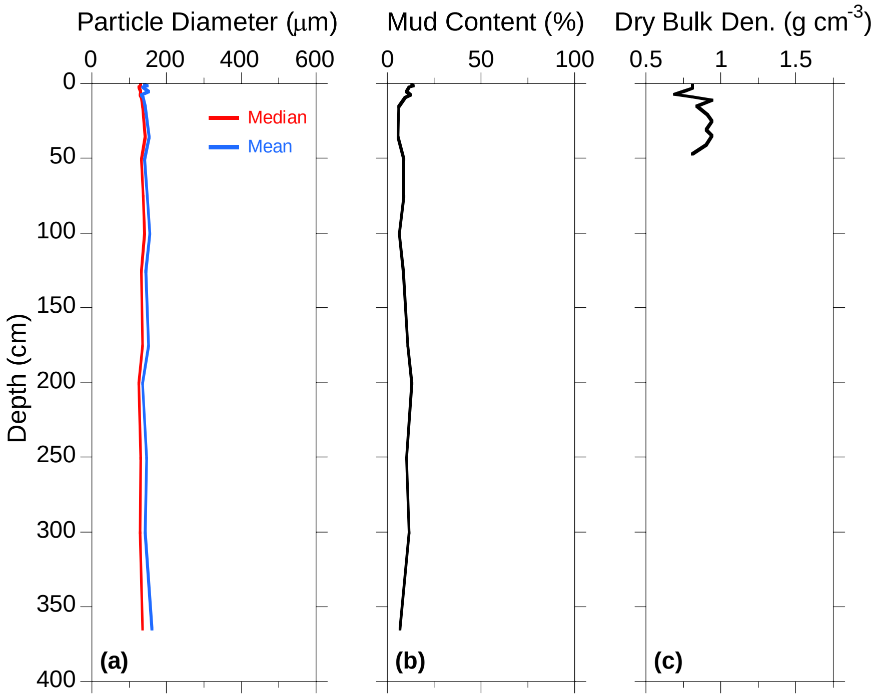


Figure 4.11: Core 10B (Okete Bay) sediment profiles: (a) median and mean particle diameter (microns); (b) mud content (%) and dry bulk density (g cm^{-3}).

^{14}C dating of wedge shell, *Macomona liliana*, (sample *Wk-15938*, University of Waikato Radiocarbon Lab.) taken at 369–370-cm depth provides a calibrated age of 7710–7940 years B.P. (95% probability). A time-averaged SAR estimated from the ^{14}C age and correcting the sample depth for 9% core compression (Table 3.1), which yields a long-term SAR of 0.5 mm yr^{-1}.

The core 10B pollen profiles again show that catchment landcover was formerly dominated by native tree pollen (rimu, other podocarps and rata) and tree-fern spores (Fig. 4.12). The abundance of corrosion-resistant tree-fern spores (i.e., ~50% of the terrestrial pollen signal), again indicate that the primary pollen source is eroded catchment soil. In the top 15 cm of the core, pine and exotic grass and weed pollens appear, which is shown in more detail in Figure 4.13.

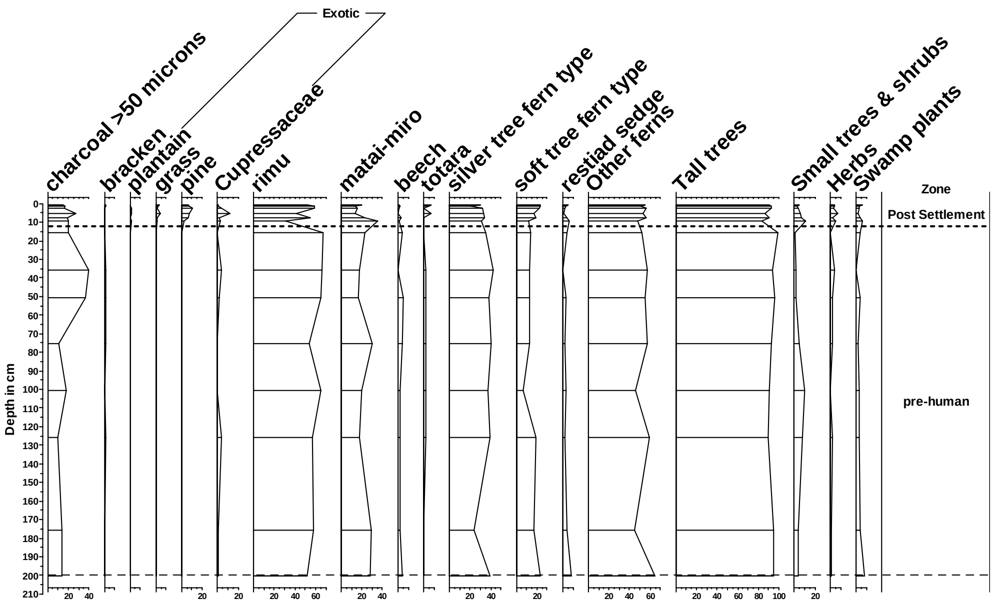


Figure 4.12: Core 10B (Okete Bay), pollen and spore profiles for major plant groups expressed as a percentage of the terrestrial pollen sum.

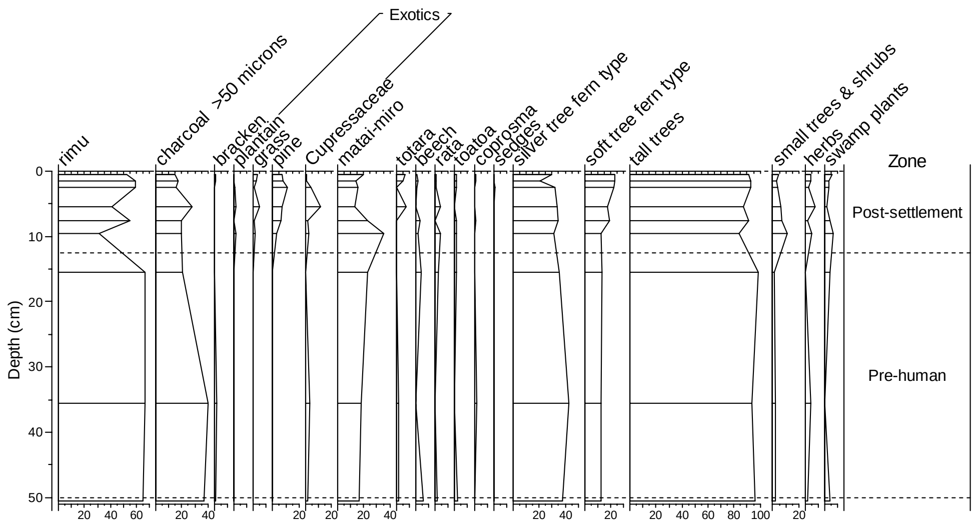


Figure 4.13: Core 10B (Okete Bay), top 50-cm of the pollen and spore profiles for major plant groups expressed as a percentage of the terrestrial pollen sum.

Figure 4.13 shows trace quantities of pine occur between 10–15-cm depth, which can result from down-core sediment mixing, particularly by benthic fauna (Swales et al.

2005). In this case the estimated post-1990 SAR is 8 mm yr^{-1}. The absence of ^{137}Cs and ^{210}Pb in the core does not enable independent confirmation of this pine-pollen SAR.

4.6 Core 12B: Waitetuna

Core 12B was collected in 1.5 m of water at the mouth of Horoto Bay (31 May 2002, 1500 NZST) (Fig. 2.1). Figure 4.14 shows the particle-size distribution at several depths between the surface and the base of core 12B at 376-cm depth. The sediments are largely composed of a bi-modal fine silt (15 µm) and fine sand (95 µm), as observed in the Waingaro arm. However, an abrupt change in particle-size distribution occurs in the upper 50-cm of the core. The ubiquitous green-grey fine-sandy mud is replaced by poorly-sorted muddy fine–coarse sand. Mud accounts for ≤ 20% of this near-surface layer.

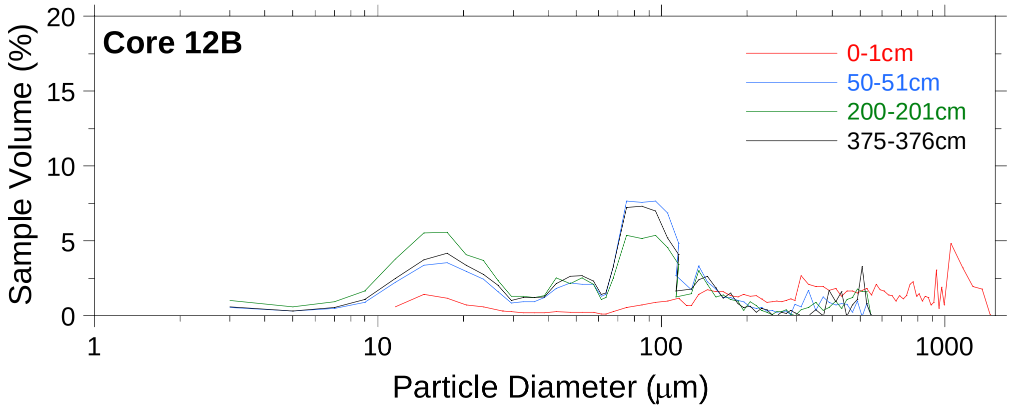


Figure 4.14: Core 12B (Waitetuna arm) particle-size distribution plotted on a log scale for surface (0–1 cm), intermediate depths, and basal (375–376 cm) sediments.

Sediment profiles illustrate the abrupt increase in particle size from 35-cm depth, with median particle diameter increasing from ~90 µm in the sandy-mud to between 500 and 1100 µm in the surface sand layer (Fig. 4.15a).

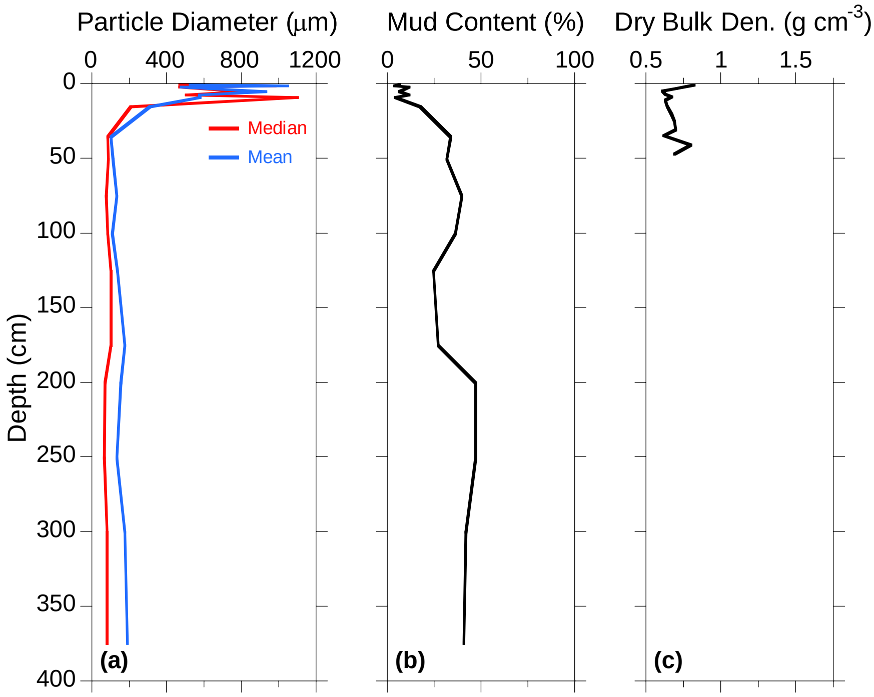


Figure 4.15: Core 12B (Waitetuna arm) sediment profiles: (a) median and mean particle diameter (microns); (b) mud content (%) and dry bulk density (g cm^{-3}).

Mud content reduces from ~30% to 6% at the surface (Fig. 4.15b). Dry bulk density values of 0.6–0.75 g cm^{-3} in the upper 50 cm of the core reflects the relatively high water content of the surface sand unit (Fig. 4.11c).

^{14}C dating of cockle shell (sample *Wk-15939*, University of Waikato Radiocarbon Lab.) taken at 255–256-cm depth provides a calibrated age of 7680–7920 years B.P. (95% probability). A time-averaged SAR estimated from the ^{14}C age and correcting the sample depth for 7% core compression (Table 3.1) yields a long-term SAR of 0.35 mm yr^{-1} for the last ~8000 years. This dated cockle-shell sample also indicates that sedimentation began in the Waitetuna arm at least 1000 years before the sea reached its approximate present level 6500 years B.P.

The core 12B pollen profiles provide the most detailed information on catchment landcover changes of any of the harbour cores that we analysed. The core shows that catchment landcover was formerly dominated by native tree pollen and tree-fern spores (Fig. 4.16). The abundance of corrosion-resistant tree-fern spores (i.e., ~50% of the terrestrial pollen signal), again indicates that the primary pollen source is eroded catchment soil. In the top 15 cm of the core, bracken, pine and exotic grass and weed pollens appear, which is shown in more detail in Figure 4.17. The rise of bracken occurs at the same time as the appearance of exotic weeds, which shows that this relates to European-era land clearance from the 1880s. The large increase in pine pollen abundance at 3-cm depth most likely relates to the recent period of pine planting since 1985. Assuming a 5 year lag between planting and a substantial pollen rain, the post-1990 SAR for core 12B is 2.5 mm yr^{-1}.

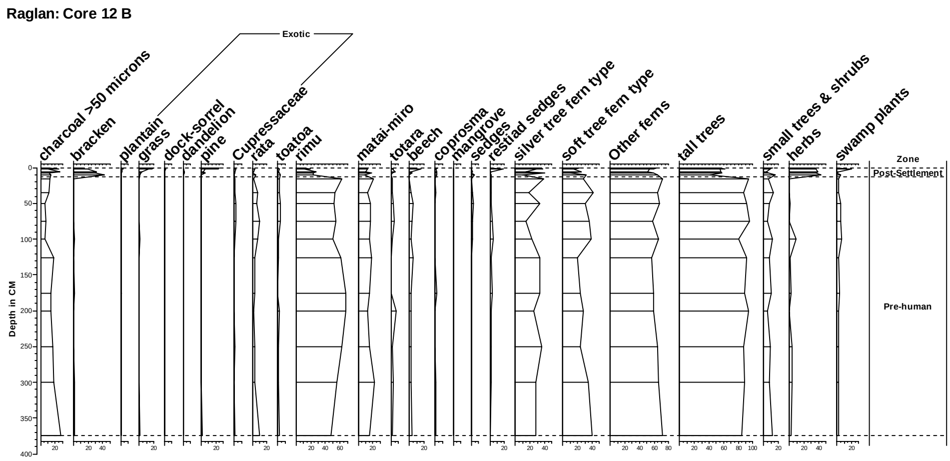


Figure 4.16: Core 12B (Waitetuna arm), pollen and spore profiles for major plant groups expressed as a percentage of the terrestrial pollen sum.

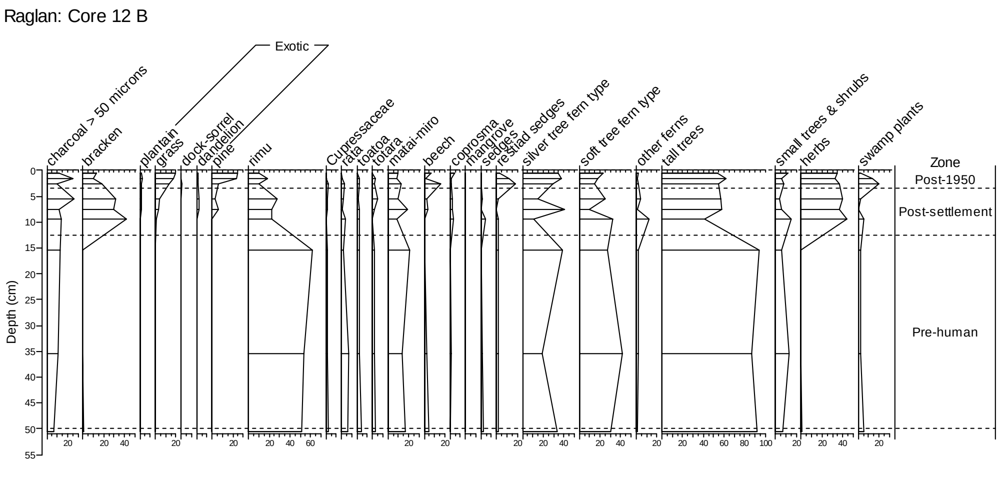


Figure 4.17: Core 12B (Waitetuna arm), top 50-cm of the pollen and spore profiles for major plant groups expressed as a percentage of the terrestrial pollen sum.

Unsupported ^{210}Pb was detected in the top 8 cm of core 12B and these data were used to estimate a time-averaged ^{210}Pb SAR of 5 mm yr^{-1} (Fig. 4.18).

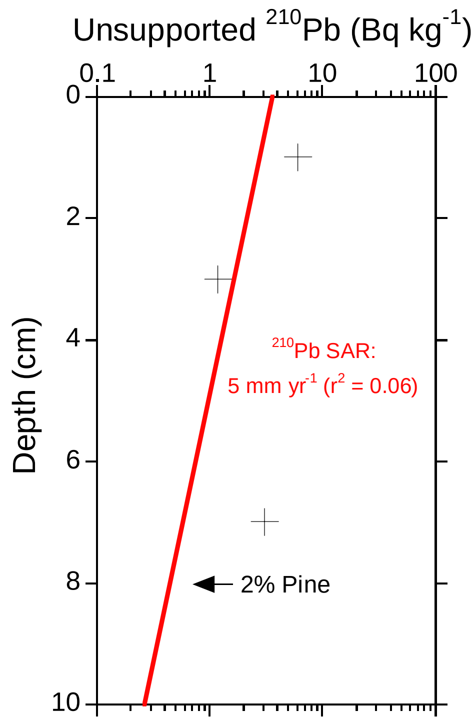


Figure 4.18: Core 12B unsupported ^{210}Pb profile (Bq kg^{-1}) with fitted log-linear regression line.

The fit of the log-linear regression to the unsupported ^{210}Pb data is based on only three values and the resulting fit is poor ($r^2 = 0.06$). A likely reason for this result is the low and variable mud content of sediments in the top 15 cm of the core (Fig. 4.15). Radioisotopes such as ^{210}Pb and ^{137}Cs are primarily adsorbed by clay and fine silt particles. Another indication that the ^{210}Pb SAR is unreliable is that the catchment was converted to pasture between 1890–1920s, which would have been accompanied by the rise of exotic grass and weed pollens. The maximum depth of these exotic species in the core is 12-cm so that the estimated post-1890 SAR is 1.1 mm yr^{-1}. The pine-pollen SAR of 2.5 mm yr^{-1} for the last decade or so suggests an increase in sedimentation at the site. Experience in the Whangamata and Wharekawa estuaries has shown that pollens can accumulate and be preserved in sand (Swales et al. 1994, 1995). Based on these considerations, we conclude that the pollen-derived SAR's are more reliable than the ^{210}Pb SAR.

5. Sedimentation in Whaingaroa Harbour

5.1 Harbour creation – shore platforms

Whaingaroa Harbour was formed by the post-glacial flooding of the lower reaches of the river-valley system. A distinctive feature of the harbour are the broad, low-angle (0.4°) palaeo shore platforms underlying the unconsolidated estuarine sediments and ≤10m below present-day mean high water level. These features have formed in the soft Whaingaroa siltstone along southwest facing shoreline in the Waingaro and Waitetuna arms of the harbour (Sherwood, 1973; Sherwood and Nelson, 1979). This type of shore platform is common in estuarine settings and develops in soft Tertiary sedimentary rocks in the intertidal zone. Wave action is less important than water-layer weathering which occurs at sea level. Physical disintegration of the rock occurs by continual cycles of salt-crystal expansion and wetting and drying. At high tide, wave action removes the rock fragments and exposes fresh rock surfaces (Balance and Williams, 1976; Healy and Kirk, 1982).

The Whaingaroa shore platforms formed as sea level rose at the end of the last glaciation and have subsequently been buried as the harbour filled with sediment (Fig. 5.1).

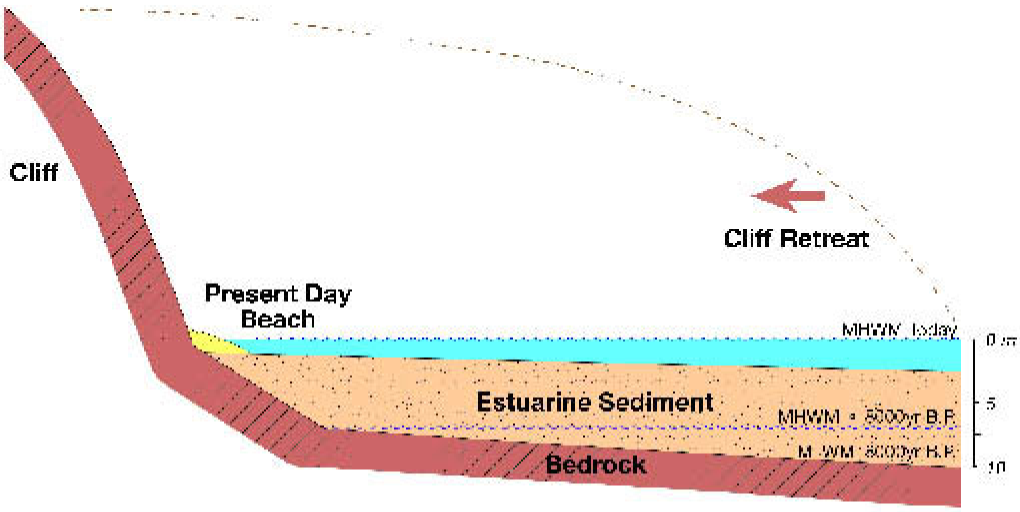


Figure 5.1: Conceptual diagram of palaeo intertidal shore platform formation.

These shore platforms must have formed rapidly 8000–7500 years B.P. when the sea was ~9 m below its present-day level (Gibb, 1986). This reconstruction is based on: (1) the low-angle of the shore platform; and (2) assuming a similar mean tidal range as today (Heath, 1976) so that; (3) the potential intertidal zone 8000 yr B.P. was about 400-m wide. The effects of this shore platform formation process were:

- Rapid erosion and delivery of large quantities of silt and sand to the harbour. Present-day cliff-tops along the northern shore of the harbour are ~20 m above mean sea level (MSL). For Sherwood's (1973) Whatitirinui cross-section and conservatively assuming an average land elevation of ~10 m MSL then some 14,000 m^3 m^{-1} of shoreline was eroded.

- Rapid sedimentation in the harbour between 8000–6500 years B.P as the shore platforms formed, with the sea rising ~10 m to its present level. This deduction is supported by ^{14}C dating of the sediment cores which show that: (1) sedimentation began in the harbour at least 8000 years B.P. and (2) all but the upper two metres of the present-day sediment column had been deposited by about 6000 years B.P.

- Increase in the surface area, depth, tidal volume and wave fetch so that the hydrodynamic properties of the harbour substantially and rapidly changed as sea level rose by flooding the river valley and forming the shore platforms.

5.2 Sedimentation processes

Radiocarbon dating shows that long-term SAR have averaged ≤ 0.5 mm yr^{-1} over the last ~8000 years. However, much more rapid sedimentation occurred in the harbour between 8000–6500 years B.P. given that about 70% of the harbour sediment had been deposited by about 6000 years B.P. For example, sedimentation rates in the Pauatahanui Inlet (Porirua) varied between 1–11 mm yr^{-1} as the sea rose and eroded alluvial terraces in the river valley (Healy, 1980). At Whaingaroa, this process of rapid infilling before 6500 years B.P. was the result of shore platform creation and catchment soil erosion.

The reconstruction of the shore platform formation as well as evidence preserved in sediment cores indicates that Whaingaroa Harbour had already substantially infilled by the time Maori arrived some 700 years ago. From the type of pollen preserved, most of the sediment in the cores was deposited after 5000 years B.P., which is consistent with ^{14}C dating. This conclusion is based on the fact that the pollen assemblage is typical of the late-Holocene forest type that occurred in this area. This forest was dominated by rimu and other podocarps but also with *Knightia excelsa* (rewarewa), beech and *Phyllocladus toatoa* (toatoa). This is consistent with the absence of *Ascarina* (hutu) pollen, which was common in the early Holocene.

A key finding of the present study is that there has been negligible long-term sediment accumulation in the Waingaro arm of the harbour for at least the last 150 years. This time period coincides with European settlement and the large-scale environmental changes that accompanied catchment deforestation. Previous studies in North Island estuaries have shown that deforestation has resulted in substantially increased catchment sediment loads and sedimentation in estuaries (Goff, 1997; Hume, 1983; Hume and Gibb, 1987; Hume et al. 1989; Hume and Dahm, 1992; Vant et al. 1993; Oldman and Swales, 1999; Sheffield, 1991; Swales et al. 1994, 1995, 1997, 2002a, 2002b, 2003, 2005). Exotic plant pollen, unsupported ^{210}Pb and ^{137}Cs are ubiquitous environmental tracers, which are incorporated into catchment soils and estuarine sediments. These tracers have been successfully used to study sedimentation and sediment processes in other North Island estuaries. Unsupported ^{210}Pb and ^{137}Cs are entirely absent from the Waingaro arm cores and pine pollen is only present in trace quantities in the upper 3 cm of core 1A taken near the Waingaro stream outlet. Unsupported ^{210}Pb and ^{137}Cs are also absent from Okete Bay (core 10B) and pine pollen is restricted to the top 10 cm of the sediment column.

In the Waitetuna arm (core 12B), unsupported ^{210}Pb, pine grass and weed pollen is present in the top 8 cm of the sediment column whereas ^{137}Cs is absent. These data (section 4.6) indicate that: (1) long-term sediment accumulation has been occurring in the Waitetuna arm over the last 8000 years; and (2) unlike the Waingaro arm this process continues to the present day.

This spatial distribution of radioisotope and exotic pollen in the harbour shows that 'modern' sediments are accumulating in some parts of the harbour and not others. In estuarine sediments, ^{210}Pb and ^{137}Cs are strongly adsorbed by clay particles so that post-deposition desorbtion and diffusion is highly unlikely (Wise, 1977). In fact, the core sediments do contain ^{210}Pb produced by *in situ* radioactive decay, but not unsupported ^{210}Pb supplied by atmospheric deposition or indirectly by eroded catchment soils. Furthermore, the absence of exotic pollen shows that chemical processes are an unlikely explanation for the absence of unsupported ^{210}Pb and ^{137}Cs. These observations indicate that an *in situ* physical mechanism for the absence of these tracers is a much more likely explanation.

In shallow estuaries with sufficient fetch, such as the Whaingaroa Harbour, waves, rather than tidal currents, control sediment resuspension on intertidal and subtidal flats. This process results in the winnowing of mud from wave-exposed areas, mixing of the sediment column and subsequent dispersal by tidal currents and redeposition in low-energy environments. Such environments include fringing mangroves and salt marshes, deeper subtidal basins and embayments. Furthermore, the clay fraction (≤2 µm diameter) of the inner shelf sediments directly offshore and north of the harbour mouth are largely composed of smectite (50–60%), illite (20–30%) and kaolinite (10–15%) (Hume and Nelson, 1986). The similarity of these shelf sediments to the adjacent Whaingaroa, Aotea and Kawhia harbour sediments indicates that the source of these fine sediments are the readily erodable Oligocene-age catchment mudstones. This interpretation is supported by LANDSAT satellite images, which clearly shows plumes of fine sediment extending as much as 20 km offshore from the harbour mouths (Hume and Nelson, 1986).

Sediment cores often preserve evidence of sediment resuspension by waves and sediment mixing by benthic fauna (bioturbation), which modifies the distribution of tracers in near-surface sediments. Figure 5.2 shows radioisotope profiles resulting from wave-driven resuspension and bioturbation of sediments collected from a wave-exposed subtidal flat in the Pauatahanui Inlet (Porirua). A surface resuspension layer is clearly shown in the upper 4-cm of the core by the x-ray image as low-density sediment (i.e, low density is black and high-density is white). A light-coloured thin sand layer can be clearly seen at the base of this unit. A large infilled burrow can also be seen at 17–28-cm depth (Fig. 5.2a). The short-lived radioisotope ^{7}Be (½ life = 53.3 days) occurs to 3-cm depth, which shows sediment mixing within this layer occurs over days–months (Fig. 5.2b). The unsupported ^{210}Pb profile also displays deep sediment mixing, with uniform ^{210}Pb concentrations to 14-cm depth that is largely due to bioturbation. The ^{210}Pb profile below the surface mixed layer indicates a SAR of 1.7 mm yr^{-1}. As a result of this deep sediment mixing and relatively low SAR the residence time of sediment particles in the SML is ~50 years. Wave and optical backscatter measurements at this core site also clearly demonstrated that sediment resuspension was controlled by waves. These processes resulted in the winnowing of clay and silt from wave-exposed sites and redeposition in the central mud basin and at up-wind sites where waves were less effective (Swales et al. 2005).

The Pauatahanui Inlet, with a maximum wave-fetch of 2.5 km, is much smaller than Whaingaroa Harbour. Despite this size difference, experience from the Pauatahanui Inlet demonstrates that waves can be an important physical process controlling sedimentation and resuspension even in small shallow estuaries. The fact that the Pauatahanui remains largely subtidal today despite having a catchment area 24 times larger in size is largely due to wave resuspension and flushing of fine sediment (Swales et al. 2005).

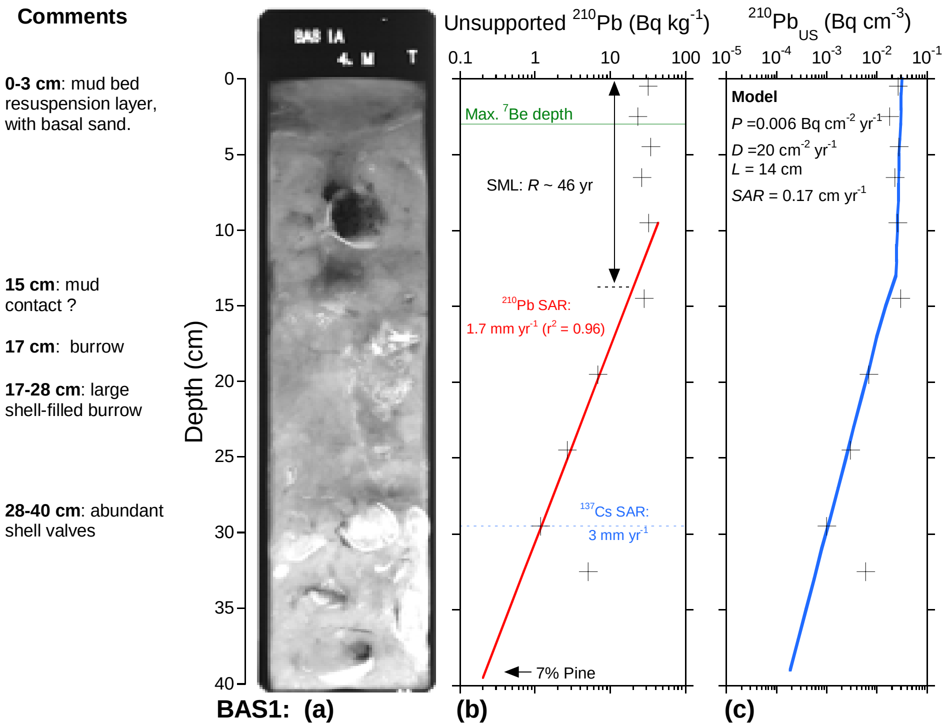


Figure 5.2: Sediment resuspension and mixing on a shallow subtidal flat, Pauatahanui Inlet (Porirua): (a) x-radiograph; (b) unsupported ^{210}Pb profile (Bq kg^{-1}), maximum depths of ^{7}Be (green) and ^{137}Cs (blue)occurrence and time-averaged SAR (*R* is the average residence of sediment particles in the surface mixed layer - SML); and (c) analytical model fitted to the measured ^{210}Pb profile with fitted parameter values, where *P* is the average annual ^{210}Pb atmospheric flux, *D* is the bio-diffusion coefficient and *L* is the mixing depth.

In Whaingaroa Harbour, the winnowing of fine-sediment by waves has resulted in the formation of estuarine beaches near Waingaro Landing that are composed almost entirely of the heavy mineral titanomagnetite (Sherwood and Nelson, 1979). This observation, in addition to the absence of unsupported ^{210}Pb, ^{137}Cs and exotic pollens in the Waingaro cores indicates that the present day intertidal flats are frequently exposed to intense wave action and sediment resuspension. This process has prevented the long-term accumulation of catchment sediments in the Waingaro arm of the harbour for at least the last 150 years. The presence of small quantities of pine pollen (<5% of terrestrial pollen sum) in the surface ≤5 cm of core 1A, corrected for sediment mixing, near Waingaro Landing (section 4.2) indicates sediment accumulation during the last decade or so. This likely reflects the close proximity to this sub-catchment outlet and deposition of pine pollen associated with eroded soils.

The absence of unsupported ^{210}Pb and ^{137}Cs in core 1A complicates the interpretation, but indicates that long-term sediment accumulation near Waingaro Landing is limited.

Evidence of Maori occupation and in particular slash and burn agriculture is also absent from the pollen record. The characteristic signature of this activity is the rise in bracken (*Pteridium esculentum*) associated with native forest species, which has been observed in other North Island estuaries. Long cores collected by Lees et al. (1998) at Limestone Downs north of Whaingaroa show evidence of bracken cover indicative of Maori slash and burn agriculture. The absence of the bracken/native forest pollen association at Whaingaroa indicates that by the time Maori arrived some 700 years or so ago the harbour had already infilled to the extent that wave-driven sediment resuspension was occurring on the tidal flats. Consequently, undisturbed long-term sediment accumulation was no longer occurring in harbour areas with sufficient wave fetch, such as the Waingaro arm.

In smaller embayments and harbour arms sheltered from the prevailing southwest winds, fetches are insufficient for waves to be effective mechanisms for sediment resuspension. Thus, where long-term sediment accumulation is able to occur, such as in Waitetuna arm (core 12B) we see exotic plant pollen and unsupported ^{210}Pb in the upper 10-cm of the sediment column. The post-1990 SAR of 2.5–8 mm yr^{-1} derived from the pine-pollen profile is consistent with present-day sedimentation rates in other North Island estuaries (2–4 mm yr^{-1}).

5.3 Study limitations

There is some uncertainty in the sedimentation rates that we have estimated from the Whaingaroa sediment cores. Firstly, pollen and radioisotope tracers can be mixed down the core by bioturbation and wave-driven sediment resuspension and redeposition, which results in the over estimation of SAR. We have no quantitative information from the cores on sediment mixing depths or time-scales and we have attempted to account for this mixing effect using the EW bed-elevation change data (e.g., Fig. 1.3) and relevant data from similar estuaries. Secondly, the absence of ^{210}Pb and ^{137}Cs does not enable independent validation of the pollen-derived SAR for recent sediments. Thirdly, relatively few cores were collected and analysed in this study so that there is limited information on the spatial variability in sedimentation rates. For example, it is uncertain how representative the sedimentation history preserved in core 12B is of Waitetuna arm as a whole. Swales et al. (2002b, 2005) addressed the issue of spatial variability in sedimentation process by analysing replicate sediment cores from discrete intertidal and subtidal flats. Figure 5.3 shows an example of this approach for a subtidal flat. It can be seen that the ^{210}Pb- and ^{137}Cs-derived SAR are similar, which indicates that sedimentation processes on this subtidal flat are spatially homogeneous. This is not always the case and substantial between-core differences in SAR can be indicative of heterogeneous sediment processes, such as bioturbation and resuspension (Fig 5.2).

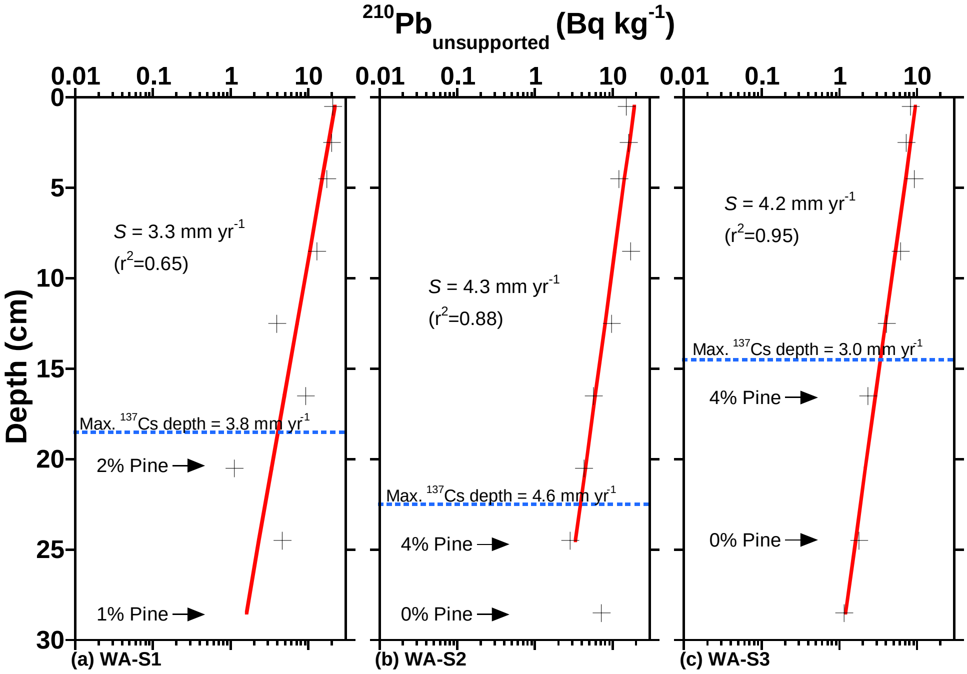


Figure 5.3: Replicate subtidal cores from a subtidal flat (Wairoa Estuary, Clevedon, Auckland). Unsupported ^{210}Pb profiles plotted on a log scale with linear regression fits used to calculate SAR. Also shown is the maximum depth of ^{137}Cs and derived SAR

Lastly, it should be noted that the present study was intended to quantify the Holocene sedimentation history of Whaingaroa Harbour rather than providing a detailed analysis of recent sediment processes and spatial variability. Consequently, we collected 5-cm diameter long cores (≤4 m) rather than large-diameter short cores designed to sample these recent processes. Despite these limitations, the study has shown that Whaingaroa Harbour's sedimentation history has been markedly different from that of other North Island estuaries that have been studied.

5.4 Harbour evolution – controls and changes

Estuaries follow similar evolutionary paths as they infill with sediment. Subtidal areas and water depths decrease over time. As a result, the hydrodynamic, sedimentological and biological characteristics of estuaries change (Roy et al. 2001). The relative influence of the fluvial system increases as the tidal volume shrinks. Sedimentation rates may also increase even if catchment sediment loads remain constant because the size of available depositional areas are reduced. Thus, the longevity of an estuary depends on its original area and storage volume, sediment supply rate, trapping efficiency and rate of sea level rise. In the case of the Whaingaroa Harbour, the original basin was ≤10-m deep and today it is largely intertidal. Sediment cores indicate that much of this infilling occurred before human settlement several hundred years ago. Since that time, long-term sediment accumulation in the Waingaro arm of the harbour appears to have largely ceased as a result of wave-driven sediment resuspension. The presence of small amounts of pine pollen in surface sediments near Waingaro Landing does not substantially influence this interpretation. This conclusion implies that a substantial proportion of the catchment fine-sediment load is now exported to the open coast, so that the harbour's sediment trapping efficiency is lower today than in prehistory. The presence of clay minerals in shelf sediments derived from the eroded of catchment mudstone and LANDSAT images of fine-sediment plumes extending up to 20 km offshore from the harbour mouth (Hume and Nelson, 1986) is consistent with the Whaingaroa Harbour core data.

The long-term evolution of Whaingaroa Harbour has also been affected by historical sea-level changes. Decimetre variations in sea level during the last 6500 years (Gibb, 1986) would likely have resulted in large-scale changes in harbour morphology and sediment processes. For example, during sea-level regressions intertidal areas may have been colonised by salt marsh and/or mangroves (Cullen et al. 1990) where muds would have accumulated. On exposed tidal flats, the reduction in water depth due to sea level lowering could also have enhanced wave-driven sediment resuspension. The historical rate of sea-level rise (SLR) for New Zealand over the last 100 years or so has averaged 1.6 mm yr^{-1} (Hannah, 2004). Tectonic uplift or subsidence also modifies the local rate of sea-level rise observed around the coast. In estuaries, sea-level rise offsets the effects of sedimentation, for example, by increasing the tidal volume and altering the effectiveness of sediment resuspension by waves. In Whaingaroa Harbour, sediment cores indicate that wave exposure is the dominant factor influencing sedimentation patterns and rates in the harbour.

5.5 What does the future hold ? – final comments

The sediment cores indicate that catchment sediment is no longer accumulating on the wave-exposed intertidal flats in the larger Waingaro arm of the harbour. Furthermore, long-term sediment accumulation does not appear to have occurred for at least several hundred years and is unlikely to occur in the foreseeable future. Consequently, accelerated sedimentation resulting from increased catchment sediment loads is unlikely to occur in the main body of the Waingaro arm of the harbour.

By comparison, sheltered harbour arms, such as the Waitetuna arm and Okete Bay, are accumulating recent sediments associated with major landcover changes during the last 120 years. Core 12B taken from the Waitetuna arm of the harbour contains the most complete sedimentation record. Pollen and ^{14}C dating of this core indicate that sedimentation rates have increased by as much as an order of magnitude, following catchment deforestation, conversion to pasture and plantation forest in the last decade or so. These environments are susceptible to the effects of future changes in the quantity and type of sediment runoff associated with human activities in their land catchments.

Sediment cores were not collected from the tidal creeks which fringe the harbour. Present-day SAR measured in Auckland tidal creeks (~20+ mm yr^{-1}) are typically an order of magnitude higher than in the main body of their estuaries (e.g., Vant et al. 1993; Swales et al. 1997, 2002a; Oldman and Swales, 1999). However, the diversity of benthic macrofaunal communities is typically higher in the more sandy substrates found in the main body of estuaries than in tidal creeks characterised by mud substrates and water with strong salinity gradients and high turbidity (e.g., Hewitt et al. 1998, 2001; Norkko et al. 2001; Lohrer et al. 2004; Thrush et al. 2004).

The erosion of a predominantly mudstone geology coupled with episodic fine-sediment resuspension by waves likely results in high turbidity in the harbour. In the Waingaro arm, fine sediments are likely to be deposited on the intertidal flats following catchment floods. However, long-term sediment accumulation is not occurring as indicated by the: (1) substantial short-term changes in the intertidal bed-elevations (±40 mm, section 1.4) shown by quarterly surveys; and (2) absence of radioisotopes and exotic pollen in the sediment cores. The most likely explanation for these observations is that intertidal sediments are being reworked and removed by wave action. This process will result in substantial and rapid changes in near-bed suspended sediment concentrations (SSC) on the tidal flats. For example, typical background SSC values of 20–40 mg l^{-1} in the Manukau Harbour and Pauatahanui Inlet (Porirua) increase within hours to several hundred mg l^{-1}, which is entirely due to wave resuspension (Green et al. 1997; Swales et al. 2004, 2005). Thus, episodic increases in SSC, and sediment erosion and redeposition during floods and wave events are likely to affect the composition of intertidal benthic macrofaunal communities in the Waingaro arm of the harbour in particular. Species sensitive to elevated water turbidity (e.g., suspension-feeding bivalves) and relatively immobile species, such as a number of estuarine shellfish (e.g., cockle), may be under-represented in these intertidal sediments. The types of benthic animals that are better adapted to mobile and muddy substrates include a number of crustacean and worm species. (Dr Simon Thrush, NIWA, Benthic Ecologist, personal comment, November 2005).

6. Acknowledgements

We thank Bronwen Gibberd and Stephanie Turner (Environment Waikato) who initiated the study and took part in field work. Mark Williams (GIS Analyst, Environment Waikato) provided aerial photography of Raglan harbour. Radiocarbon dating of shell samples was carried out by the Waikato Radiocarbon Dating Laboratory (University of Waikato). Mr Steve Soanes (Waikato District Council) provided secure storage for our boat and equipment. Mr Collin Maunder (P.F. Olsen and Co.) and Mr Carl Hanna (Wood Marketing Services, Rotorua) provided historical information on pine forest plantations. We acknowledge Mr Max Oulton (Geography Department, University of Waikato) for drafting Figures 1.1, 2.1–2.3 and 5.1. We thank Auckland Regional Council and Greater Wellington Regional Council respectively for permission to reproduce radioisotope results from the Auckland east-coast estuaries and Pauatahanui Inlet sedimentation studies.

7. References

Abrahim, G. & Parker, R. (2002). Heavy-metal contaminants in Tamaki estuary: impacts of city development and growth, Auckland, New Zealand. *Environmental Geology 42*: 883–890.

Alexander, C.R.; Smith, R.G.; Calder, F.D.; Schropp, S.J.; Windom, H.L. (1993). The historical record of metal enrichment in two Florida estuaries. *Estuaries 16(3B)*: 627–637.

Balance, P.F.; Williams, P.W. (1982). The geomorphology of Auckland and Northland, p. 127–146. *In* J.M. Soons and M.J. Selby (*eds*.) Landforms of New Zealand. Longman Paul, Auckland, 392 p.

Benoit, G.; Rozan, T.F.; Patton, P.C.; Arnold, C.L. (1999). Trace metals and radionuclides reveal sediment sources and accumulation rates in Jordan Cove, Connecticut. *Estuaries 22(1)*: 65–80.

Blais, J.M.; Kalff, J.; Cornett, R.J.; Evans, R.D. (1995). Evaluation of ^{210}Pb dating in lake sediments using stable Pb, Ambrosia pollen and ^{137}Cs. *Journal of Paleolimnology 13*: 169–178. Goldberg, E.D. (1963). Geochronology with ^{210}Pb. In: *Radioactive Dating*, 121–131. International Atomic Energy Agency, Vienna.

Bromley, R.G. (1996). Trace fossils: biology, taphonomy and applications, second edition. Chapman and Hall, London, 361 p.

Chagué-Goff, C.; Nichol, S.L.; Jenkinson, A.V.; Heijnis, H. (2000). Signatures of natural catastrophic events and anthropogenic impact in an estuarine environment, New Zealand. *Marine Geology 167*: 285–301.

Cullen, D.J.; Challis, G.A.; Drummond, G.W. (1990). Late Holocene estuarine phosphogenesis in Raglan harbour, New Zealand. *Sedimentology 37*: 847–857.

Curtis, R.J. (1986). Western coastal catchments condition and sediment yield. Waikato Valley Authority Technical Report No. 86/7, 52 p.

Dyer, K.R. (1986). Coastal and Estuarine Sediment Dynamics. John Wiley and Sons, Chichester, 342 p.

Environment Waikato (2002). The Whaingaroa Environment Catchment Plan. Report 793960, Environment Waikato, Hamilton.

Gibb, J.G. (1986). A New Zealand regional Holocene eustatic sea-level curve and its application to determination of vertical tectonic movements. A contribution to IGCP-Project 200. *Royal Society of New Zealand Bulletin 24*: 377–395.

Goff, J. (1997). A chronology of natural and anthropogenic influences on coastal sedimentation, New Zealand. *Marine Geology 138*: 105–117.

Goldberg, E.D. & Kiode M. (1962). Geochronological studies of deep sea sediments by the ionium/thorium method. *Geochimica et Cosmochimica Acta 26*: 417–450.

Green, M.O.; Black, K.P.; Amos, C.L. (1997). Control of estuarine sediment dynamics by interactions between currents and waves at several scales. *Marine Geology 144*: 97–116.

Guinasso, N.L. Jr. & Schink, D.R. (1975). Quantitative estimates of biological mixing rates in abyssal sediments. *Journal of Geophysical Research 80*: 3032–3043.

Hannah, J. (2004). An updated analysis of long-term sea level change in New Zealand. *Geophysical Research Letters 31*(L03307), 4 p.

Healy, W.B. (1980). Pauatahanui Inlet – an environmental study. New Zealand Department of Scientific and Industrial Research, DSIR Information Series No. 141, Wellington, 198 p.

Healy, T.; Williams, P.W. (1982). Coasts, p. 81–104. *In* J.M. Soons and M.J. Selby (*eds*.) Landforms of New Zealand. Longman Paul, Auckland, 392 p.

Heath, R.A. (1976). Broad classification of New Zealand inlets with emphasis on residence times. *New Zealand Journal of Marine and Freshwater Research 10(3)*: 677–687.

Hendeson, J.; Grange, L.I. (1926). The Geology of the Huntly-Kawhia Subdivision, Pironga and Hauraki Divisions. Bulletin No. 28 (New Series), New Zealand Department of Mines, Geological Survey Branch. Government Printer, Wellington.

Hewitt, J.E.; Cummings, V.J.; Norkko, A. (1998). Monitoring of Okura estuary for biological effects of road construction, December 1997–July 1998. NIWA Client Report ARC80231.

Hewitt, J.E.; Hatton, S.; Safi, K.; Craggs, R. (2001). Effects of suspended sediment levels on suspension-feeding shellfish in the Whitford embayment. NIWA Client Report ARC01267.

Hume, T.M. (1983). Upper Waitemata Harbour sediments and the inferred impacts of future catchment and estuary use change (Specialist report). Water Quality Centre Report No. 3 Prepared for Auckland Regional Authority, 95 p.

Hume, T.M. & McGlone, M.S. (1986). Sedimentation patterns and catchment use changes recorded in the sediments of a shallow tidal creek, Lucas Creek, Upper Waitemata Harbour, New Zealand. *New Zealand Journal of Marine and Freshwater Research 20*: 677–687.

Hume, T.M. & Nelson, C.S. (1986). Distribution and origin of clay minerals in surficial shelf sediments, western North Island, New Zealand. *Marine Geology 69*: 289–308.

Hume, T.M. & Gibb, J.G. (1987). The wooden floor marker bed – a new method of determining historical sedimentation rates in some New Zealand estuaries. *Journal of the Royal Society of New Zealand 17*: 1–7.

Hume, T.M.; Fox, M.E.; Wilcock, R.J. (1989). Use of organochlorine contaminants to measure sedimentation rates in estuaries: a case study from the Manukau Harbour. *Journal of the Royal Society of New Zealand 19*: 305–317.

Hume, T.M.; Dahm, J. (1992). An investigation of the effects of Polynesian and European land use on sedimentation in Coromandel estuaries. DSIR Marine and Freshwater Consultancy Report No. 6104. Department of Scientific and Industrial Research, Water Quality Centre, Hamilton, 56 p + appendices.

Irwin, J. (1976). Morphological stability of Pauatahanui Inlet, Porirua Harbour. *New Zealand Journal of Marine and Freshwater Research 10(4)*: 641–650.

Lees, C.M.; Neall, V.E.; Palmer, A.S. (1998). Forest persistence at coastal Waikato, 24,000 years BP to present. *Journal of the Royal Society of New Zealand 28(1)*: 55–81.

Lohrer, A.M.; Thrush, S.F.; Hewitt, J.E.; Berkenbusch, K.; Ahrens, M.; Cummings, V.J. (2004). Terrestrially derived sediment: response of marine macrobenthic communities to thin terrigenous deposits. *Marine Ecology Progress Series 273*: 121–138.

Matthews, K.M. (1989). Radioactive fallout in the south pacific: a history. Part 1: Deposition in New Zealand. Report NRL1989/2, National Radiation Laboratory, Christchurch New Zealand.

McDowell, D.M. & O’Connor, B.A. (1977). Hydraulic behaviour of estuaries. The Macmillan Press Ltd, London, 292 p.

Moore, P.D. & Webb, J.A. (1978). An illustrated guide to pollen analysis. Hodder and Stroughton.

Norkko, A.; Talman, S.; Ellis, J.; Nicholls, P.; Thrush, S. (2001). Macrofaunal sensitivity to fine sediments in the Whitford embayment. NIWA Client Report ARC01266/2.

Oldfield, F.; Appleby, P.G. (1984). Empirical testing of ^{210}Pb-dating models for lake sediments. In: Lake sediments and environmental history, Haworth and Lund (eds): 93–124.

Oldman, J.O.; Swales, A. (1999). Mangemangeroa estuary numerical modelling and sedimentation. NIWA Client Report ARC70224.

Olsen, C.R.; Simpson, H.J.; Peng, T.-H.; Bopp, R.F.; Trier, R.M. (1981). Sediment mixing and accumulation rate effects on radionuclide depth profiles in Hudson Estuary sediments. *Journal of Geophysical Research 86 (C11)*: 11020–11028.

Rahn, P.H. (1986). Engineering geology – An environmental approach. Elsevier, New York, 589 p.

Ritchie, J.C. & McHenry, J.R. (1989). Application of radioactive fallout cesium-137 for measuring soil erosion and sediment accumulation rates and patterns: A review with bibliography. Hydrology Laboratory, Agriculture Research Service, U.S. Department of Agriculture, Maryland.

Robbins, J.A. & Edgington, D.N. (1975). Determination of recent sedimentation rates in Lake Michigan using ^{210}Pb and ^{137}Cs. *Geochimica et Cosmochimica Acta 39*: 285–304.

Roy, P.S.; Williams, R.J.; Jones, A.R.; Yassini, I.; Gibbs, P.J.; Coates, B.; West, R.J.; Scanes, P.R.; Hudson, J.P.; Nichol, S. (2001). Structure and function of south-east Australian estuaries. *Estuarine, Coastal and Shelf Science 53*: 351–384.

Sharma, K.; Gardner, L.R.; Moore, W.S.; Bollinger, M.S. (1987). Sedimentation and bioturbation in a salt marsh as revealed by ^{210}Pb, ^{137}Cs and ^{7}Be studies. *Limnology and Oceanography 32(2)*: 313–326.

Sheffield, A.T. (1991). The sedimentology and hydrodynamics of the Whangamata harbour. M.Sc. thesis, Department of Earth Sciences, University of Waikato.

Sherwood, A.M. (1973). Surficial sediments of Raglan harbour. M.Phil. thesis, Department of Earth Sciences, University of Waikato.

Sherwood, A.M.; Nelson, C.S. (1979). Surficial sediments of Raglan harbour. *New Zealand Journal of Marine & Freshwater Research 13(4)*: 475–496.

Swales, A.; Hume, T.M. (1994). Sedimentation history and future impacts of catchment logging on the Whangamata estuary, Coromandel Peninsula. NIWA Consultancy Report CHH003. Prepared for Carter Holt Harvey Forests Ltd.

Swales, A.; Hume, T.M. (1995). Sedimentation history and potential future impacts of production forestry on the Wharekawa estuary, Coromandel Peninsula. NIWA Consultancy Report CHH004. Prepared for Carter Holt Harvey Forests Ltd.

Swales, A.; Hume, T.M.; Oldman, J.W.; Green, M.O. (1997). Holocene sedimentation and recent human impacts in a drowned-valley estuary, p. 895–900. *In* J. Lumsden, *Proceedings of the 13th Australian Coastal and Ocean Engineering Conference*. Centre for Advanced Engineering, University of Canterbury, Christchurch.

Swales, A.; Williamson, R.B.; Van Dam, L.; Stroud, M.J.; McGlone, M.S. (2002a). Reconstruction of urban stormwater contamination of an estuary using catchment history and sediment profile dating. *Estuaries 25(1)*: 43–56.

Swales, A.; Hume, T.M.; McGlone, M.S.; Pilvio, R.; Ovenden, R.; Zviguina, N.; Hatton, S.; Budd, R.; Hewitt, J. E.; Pickmere, S.; Costley, K. (2002b). Evidence for the physical effects of catchment sediment runoff preserved in estuarine sediments: Phase II (field study). Auckland Regional Council Technical Publication 221, 177 p.

Swales, A.; MacDonald, I.T.; Green, M.O. (2004). Influence of wave and sediment dynamics on cordgrass (Spartina anglica) growth and sediment accumulation on an exposed intertidal flat. *Estuaries 27(2)*: 225–243.

Swales, A.; Bentley, S.J.; McGlone, M.S.; Ovenden, R.; Hermanspahn, N.; Budd, R.; Hill, A.; Pickmere, S.; Haskew, R.; Okey, M.J. (2005). Pauatahanui Inlet: effects of historical catchment landcover changes on Inlet sedimentation. NIWA Client Report HAM2004-149.

Thrush, S.F.; Hewitt, J.E.; Cummings, V.J.; Ellis, J.I.; Hatton, C.; Lohrer, A.; Norkko, A. (2004). An over looked pollutant muddies the waters: elevating sediment input to coastal and estuarine habitats. *Frontiers in Ecology and Environment 2*: 299–306.

Tinker, R.A.; Pilvio, R. (2000). Environmental radioactivity in New Zealand and Rarotonga – annual report. National Radiation Laboratory Report NRL-F/80, 24 p.

Valette-Silver, N.J. (1993). The use of sediment cores to reconstruct historical trends in contamination of estuarine and coastal sediments. *Estuaries 16(3B)*: 577-588.

Vant, W.N.; Williamson, R.B.; Hume, T.M.; Dolphin, T.J. (1993). Effects of future urbanisation in the catchment of Upper Waitemata Harbour. NIWA Consultancy Report No. ARC220.

Vennell, C.W.; Williams, S. (1976). Raglan county hills and sea: a centennial history 1876–1976. Wilson and Horton Ltd, Auckland, New Zealand.

Wilmshurst, J.; Eden, D.N.; Frogatt, P.C. (1999). Late Holocene forest disturbance in Gisborne, New Zealand. *New Zealand Journal of Botany 37*: 523–540.

Wise, S. (1977). The use of radionuclides ^{210}Pb and ^{137}Cs in estimating denudation rates and in soil erosion measurement. Occasional Paper No. 7 University of London, King’s College, Department of Geography, London.

8. Appendix I: ^{210}Pb Inventories and mean annual supply rates

The total unsupported ^{210}Pb inventory in the sediment column, $A(o)$ and mean annual supply rate (P) can be estimated from sediment cores and provide important information about sediment processes in estuaries. P (Bq cm^{-2} yr^{-1}) can be estimated from $A(o)$ (Bq cm^{-2}) by:

$$P = kA(o) \qquad \text{Eq. A1}$$

$A(o)$ can be estimated for a core from log-linear regression fits to the unsupported ^{210}Pb profile and the dry bulk sediment density (ρ_d) profile. If sedimentation is spatially uniform and occurs at a constant rate then $A(o)$ and P will be similar in each core. Furthermore, P estimated from sediment cores should also be similar to the measured annual atmospheric ^{210}Pb flux if atmospheric deposition is the primary source. This comparison is also a useful test of the validity of the ^{210}Pb chronology determined for a core. Global atmospheric fluxes of ^{210}Pb are typically 0.0074–0.037 Bq cm^{-1} yr^{-1} (Oldfield and Appleby, 1984). In New Zealand, the mean annual atmospheric ^{210}Pb flux of 0.0117 (range: 0.0086–0.0136) Bq cm^{-2} yr^{-1} measured at Hokitika during 1995–2000 is within the range of global values (Tinker and Pilvio, 2000). The mean annual atmospheric ^{210}Pb flux at Whaingaroa is likely to be less than at Hokitika due to the substantially lower annual rainfall. NIWA has measured monthly ^{210}Pb fluxes in rainwater collected at Pakuranga (Auckland) since June 2002. Measured annual ^{210}Pb fluxes to June 2004 averaged 0.0059 Bq cm^{-2} yr^{-1}. Average annual rainfall at Raglan (station E14199, 1984–2004) of 1354 mm (s ± 144 mm) is similar to that at Pakuranga (station C64983, 1233 mm yr^{-1}, s ±182 mm yr^{-1}). Thus, it is reasonable to apply the measured atmospheric ^{210}Pb flux to validate unsupported ^{210}Pb profiles measured in the Whaingaroa sediment cores.

9. Appendix II: Radiocarbon dating

Secular variations in the production of atmospheric ^{14}C, which relate to solar and geomagnetic influences and the apparent differences (offset) in atmosphere-ocean carbon reservoirs and activity requires ^{14}C dated samples to be calibrated for these effects. Calibration converts a radiocarbon age to a solar (calendar) date. In dating estuarine and marine samples the lag between atmospheric ^{14}C entering the oceans (the global marine offset or reservoir effect) and the mixing of deep 'old' seawater with 'young' surface waters must be taken into account. In the New Zealand coastal marine environment, a reservoir correction of -336 years is required. Consequently, a shellfish that died today would have a radiocarbon age of ~300 years.

The absence of an absolute dating method for the ocean (e.g., c.f. dendrochronology from tree rings on land) requires the modelling of atmospheric-ocean carbon exchange, based on actual variations in the former. Because of the uncertainties inherent in this approach a local correction factor, which in New Zealand is +30 years, is included in the reservoir correction. This is the difference between the radiocarbon age for the modelled surface layers of the world ocean (1950 A.D.) and that derived locally by an independent source, and is applied prior to calibration. The historical fluctuations in atmospheric carbon demonstrated by dendrochronological studies produces characteristic 'wiggles' in the radiocarbon-calendar age curves. Consequently for any given radiocarbon date there may be several calibrated ages (multiple curve intercepts), any of which could be the true date. Given this and other errors inherent in the analysis the 'wiggle effect' can result in substantial total errors and a wide calibrated age range. Consequently, radiocarbon ages less than ~500 years have calibrated (calendar) age ranges (95% confidence intervals) with upper values reported as modern (i.e., present day). Also, burning of fossil fuels has altered the atmospheric $^{14}C/^{12}C$ ratio, so that it is problematic to use radioactive carbon to date samples less than ~500 years old.

10. Appendix III: Analytical results of Radioisotope analyses

10.1 Cores 1A, 2B & 6A Radioisotope results

NRL

National Radiation Laboratory

Report number:	2004-070
Report date:	02.03.2004
Work Order Agreement number:	1517/03

TEST REPORT

Client name:	NIWA	**Order number:**	N/A
Client's address:	Gate 10, Silverdale Road, Hamilton PO box 11115, Hamilton, New Zealand		
Samples submitted by:	Andrew Swales	**Date received:**	8.12.2003
Samples analysed by:	N.Hermanspahn	**Analyses completed:**	02.03.2004
Customer supplied description:	Sediment samples		
Sample received as:	Solid.		
Analyses requested:	Cs-137, Pb-210, Ra-226, Ra-228		
Analytical methods:	Gamma spectrometry.		

Concentration: If the measured value is above background at a level of confidence of 95%, then the concentration of the radionuclide is reported. The reported uncertainty is based on the combined standard uncertainty (u_c) multiplied by a coverage factor (k) = 2 (providing a level of confidence of 95%) as described by International Organization for Standardization, Guide to the expression of uncertainty in measurement, ISO, Geneva (1995).

Minimal Detectable Concentration: Reporting of a 'less than' result means that the measured value was consistent with a background measurement. The minimal detectable concentration with a level of confidence of 95% for both errors of the first and second kind is calculated as described by Currie in: L A Currie, Limits for qualitative detection and quantitative determination: Application to radiochemistry, Anal. Chem. 40(3) (1968) 586-593.

Traceability: Traceability to appropriate national or international standards is maintained. Details are available on request.

Quality Statement: This test report has been produced under the controls established by a quality management system that meets the requirements of AS/NZS ISO9001:2000 which has been independently certified by BVQI under certificate number: 103049.

A centre of excellence in radiation safety

108 Victoria Street P O Box 25099 Christchurch New Zealand
Ph (64) (03) 366 5059 Fax (64) (03) 366 1156 http://www.nrl.moh.govt.nz

Page 1/2 QM template: V 2.0

A specialist business unit of the Ministry of Health

Results

NRL number	Client sample code	Lead-210 (Bq/kg)	Radium-226 (Bq/kg)	Radium-228 (Bq/kg)	Caesium-137 (Bq/kg)
2003-1581	Raglan 1A 1-3 cm	22.1 ± 3.0	23.6 ± 2.2	31.4 ± 1.5	< 0.76
2003-1582	Raglan 1A 5-7 cm	25.8 ± 3.0	26.0 ± 2.4	32.1 ± 1.5	< 0.74
2003-1583	Raglan 1A 9-11 cm	25.9 ± 3.1	28.6 ± 2.6	34.3 ± 1.5	< 0.74
2003-1584	Raglan 1A 13-15 cm	30.1 ± 3.4	30.7 ± 2.8	36.0 ± 1.7	< 0.80
2003-1585	Raglan 1A 17-19 cm	29.5 ± 3.3	30.3 ± 2.8	33.8 ± 1.6	< 0.78
2003-1586	Raglan 1A 22-24 cm	35.2 ± 3.9	34.0 ± 3.1	38.3 ± 1.8	< 0.89
2003-1587	Raglan 1A 30-32 cm	30.7 ± 3.6	32.1 ± 2.9	36.4 ± 1.8	< 0.86
2003-1588	Raglan 1A 35-37 cm	30.0 ± 3.5	31.3 ± 2.9	36.9 ± 1.7	< 0.84
2003-1589	Raglan 1A 40-42 cm	27.4 ± 3.4	31.1 ± 2.8	38.4 ± 1.7	< 0.82
2003-1590	Raglan 1A 45-47 cm	27.4 ± 3.2	30.7 ± 2.8	35.4 ± 1.6	< 0.78
2003-1591	Raglan 6A 1-3 cm	27.5 ± 3.3	29.4 ± 2.8	32.5 ± 1.6	< 0.77
2003-1592	Raglan 6A 5-6 cm	29.5 ± 3.6	28.6 ± 2.8	32.6 ± 1.7	< 0.87
2003-1593	Raglan 6A 9-11 cm	28.7 ± 3.7	29.5 ± 2.8	33.5 ± 1.7	< 0.89
2003-1594	Raglan 6A 13-15 cm	29.6 ± 3.5	29.0 ± 2.7	32.3 ± 1.7	< 0.85
2003-1595	Raglan 6A 17-19 cm	26.6 ± 3.2	28.5 ± 2.7	31.7 ± 1.5	< 0.77
2003-1596	Raglan 6A 22-24 cm	27.9 ± 3.2	29.0 ± 2.6	32.8 ± 1.6	< 0.77
2003-1597	Raglan 6A 30-32 cm	23.3 ± 2.9	27.0 ± 2.4	28.1 ± 1.3	< 0.70
2003-1598	Raglan 6A 35-37 cm	24.1 ± 2.8	25.2 ± 2.3	26.8 ± 1.3	< 0.64
2003-1599	Raglan 6A 40-42 cm	21.9 ± 2.8	24.3 ± 2.3	26.5 ± 1.3	< 0.67
2003-1600	Raglan 6A 45-47 cm	24.2 ± 3.0	26.3 ± 2.4	30.1 ± 1.5	< 0.74

Report date: 02.03.2004 Report No: 2004-070 Page 2/2

2003-1601	Raglan 2B 1-3 cm	24.3 ± 3.2	26.8 ± 2.5	29.2 ± 1.5	< 0.41
2003-1602	Raglan 2B 5-7 cm	24.5 ± 3.0	27.2 ± 2.6	28.8 ± 1.5	< 0.77
2003-1603	Raglan 2B 9-11 cm	26.5 ± 3.2	27.4 ± 2.6	31.0 ± 1.5	< 0.79
2003-1604	Raglan 2B 13-15 cm	23.9 ± 3.1	27.9 ± 2.6	29.4 ± 1.4	< 0.74
2003-1605	Raglan 2B 17-19 cm	23.8 ± 3.1	27.7 ± 2.6	29.9 ± 1.5	< 0.73
2003-1606	Raglan 2B 22-24 cm	24.4 ± 2.5	28.1 ± 2.5	29.2 ± 1.4	< 0.66
2003-1607	Raglan 2B 30-32 cm	25.0 ± 3.0	28.2 ± 2.5	30.0 ± 1.5	< 0.72
2003-1608	Raglan 2B 35-37 cm	26.8 ± 3.1	27.5 ± 2.6	29.3 ± 1.5	< 0.70
2003-1609	Raglan 2B 40-42 cm	23.9 ± 3.0	27.3 ± 2.5	29.3 ± 1.4	< 0.75
2003-1610	Raglan 2B 45-47 cm	26.7 ± 3.2	28.8 ± 2.7	32.6 ± 1.8	< 0.78

Additional information

Results relate only to the samples as received.

This report, or any copy of it, is only valid if it is complete.

Dr. Nikolaus Hermanspahn, Environmental Physicist

Date: 02.03.2004

Report date 02.03.2004 Report No 2004-070 Page 3/3

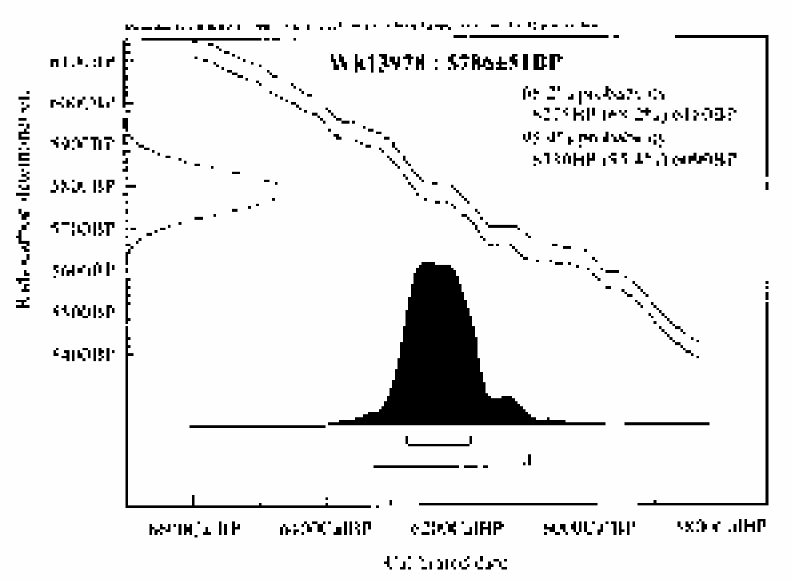


Figure A1: Core 2B ^{14}C-dating result (Wk-13978) for cockle shell (*Austrovenus stutchburyi*) at 200–201-cm depth.

10.2 Cores 10B & 12B Radioisotope results

NRL

National Radiation Laboratory

All tests reported herein have been performed in accordance with the laboratory's scope of accreditation

Report number:	2005-012
Report date:	21/01/2005
WOA number:	1639/04

TEST REPORT

Client name:	National Institute of Water and Atmospheric Research Ltd.	**Order number:**	N/A
Client's address:	P O Box 11-115, Hamilton		
Samples submitted by:	Andrew Swales	**Date received:**	22/11/2004
Samples analysed by:	J-G Decaillon	**Analyses completed:**	18/01/2005
Customer supplied description:	26 sediment samples : Raglan estuary sediments 10 B and 12 B cores		
Sample received as:	Solid		
Analyses requested:	Cs-137, Pb-210, Ra-226, Ra-228		
Analytical methods:	Gamma Spectrometry		

Concentration: If the measured value is above background at a level of confidence of 95%, then the concentration of the radionuclide is reported. The reported uncertainty is based on the combined standard uncertainty (u_c) multiplied by a coverage factor (k) = 2 (providing a level of confidence of 95%) as described by International Organization for Standardization, Guide to the expression of uncertainty in measurements, ISO, Geneva (1995).

Minimal Detectable Concentration: Reporting of a 'less than' result means that the measured value was consistent with a background measurement. The minimal detectable concentration with a level of confidence of 95% for both errors of the first and second kind is calculated as described by Currie in: L A Currie, Limits for qualitative detection and quantitative determination: Application to radiochemistry, Anal. Chem. 40(3) (1968) 586-593.

Traceability: Traceability to appropriate national or international standards is maintained. Details are available on request.

A centre of excellence in radiation safety

108 Victoria Street P O Box 25099 Christchurch New Zealand
Ph (64) (03) 366 5059 Fax (64) (03) 366 1156 http://www.nrl.moh.govt.nz

Page 1/3 QM template: V II.1

A specialist business unit of the Ministry of Health

Results

NRL number	Client sample code	Cs-137 (Bq/kg)	Pb-210 (Bq/kg)	Ra-226 (Bq/kg)	Ra-228 (Bq/kg)
2004-1306	Raglan 10A 0-2 cm	[illegible]	[illegible]	[illegible]	[illegible]
2004-1309	Raglan 10A 2-4 cm	[illegible]	[illegible]	[illegible]	[illegible]
2004-1310	Raglan 10A 4-6 cm	[illegible]	[illegible]	[illegible]	[illegible]
2004-1311	Raglan 10A 6-8 cm	[illegible]	[illegible]	[illegible]	[illegible]
2004-1321	Raglan 12B 0-2 cm	[illegible]	[illegible]	[illegible]	[illegible]
2004-1322	Raglan 12B 2-4 cm	[illegible]	[illegible]	[illegible]	[illegible]
2004-1323	Raglan 12B 4-6 cm	[illegible]	[illegible]	[illegible]	[illegible]
2004-1324	Raglan 12B 6-8 cm	[illegible]	[illegible]	[illegible]	[illegible]
2004-1325	Raglan 12B [illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2004-1326	Raglan 12B 10-12 cm	[illegible]	[illegible]	[illegible]	[illegible]
2004-1327	Raglan 12B [illegible]	[illegible]	[illegible]	[illegible]	[illegible]

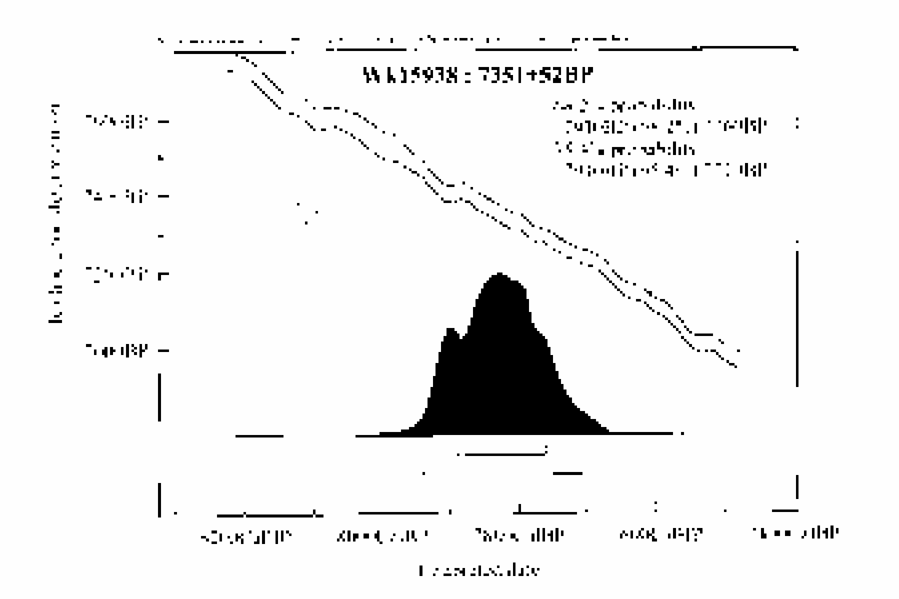


Figure A2: Core 10B [14]C-dating result (Wk-15938) for wedge shell (*Macomona liliana*) at 369–370-cm depth.

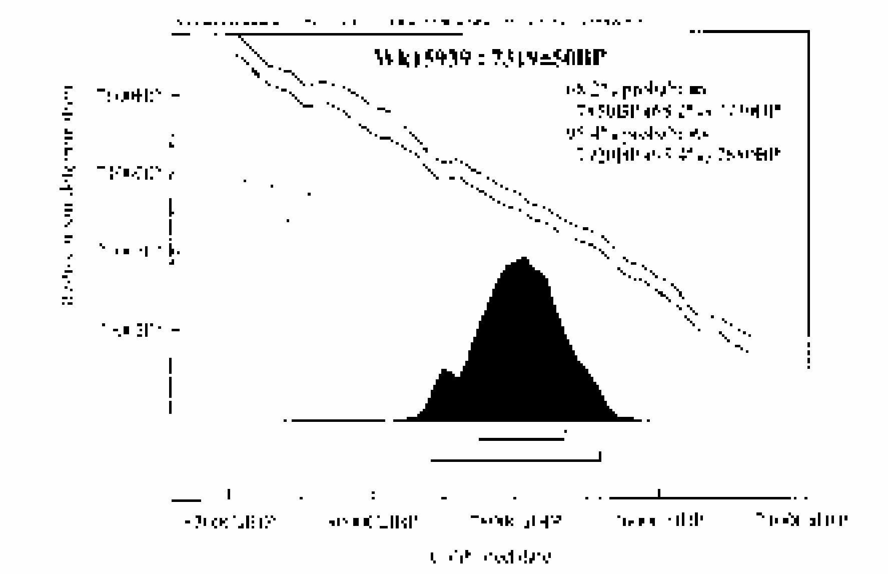


Figure A3: Core 12B [14]C-dating result (Wk-15939) for cockle shell (*Austrovenus stutchburyi*) at 255–256-cm depth.