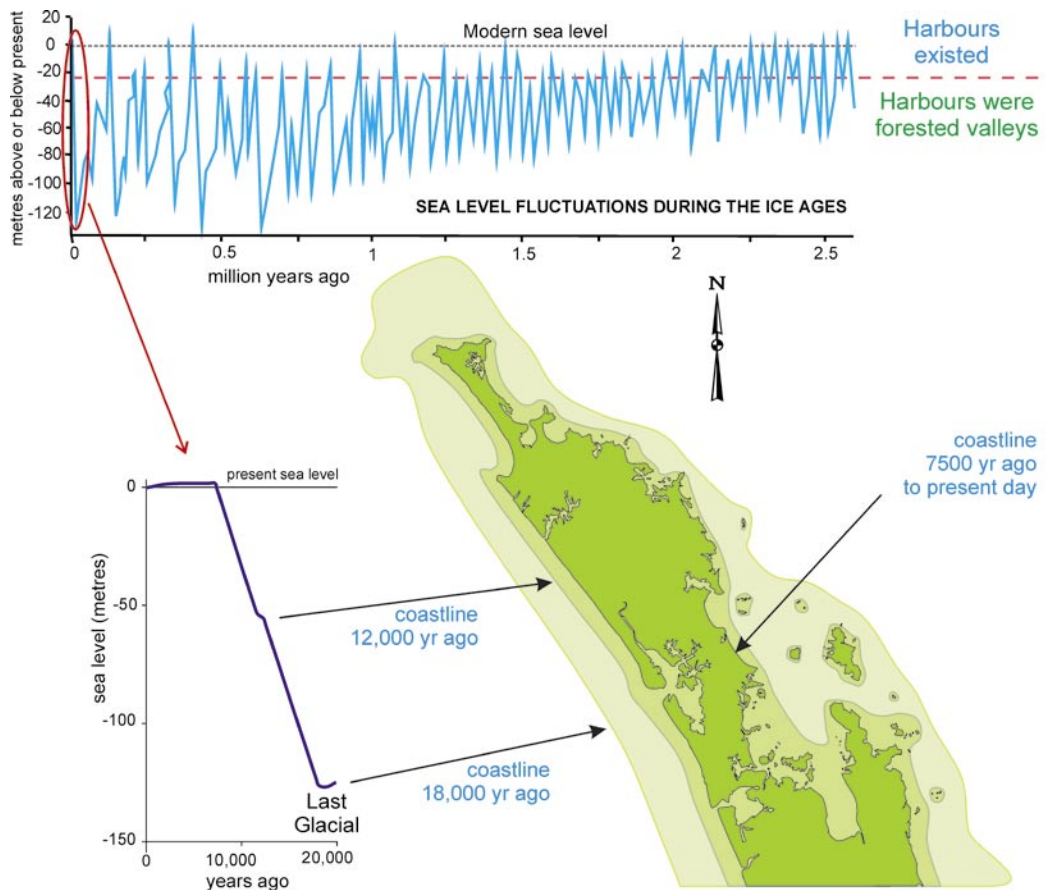


CRAFTING THE COASTLINE (last 2.6 Myr)



11.40 Map of northern New Zealand showing the coastline position at the peak of the Last Glacial period, 18,000 yr ago, and during the rapid sea-level rise 12,000 yr ago. The graph at left records sea level history from 20,000 yr ago through to today. The graph (above) of sea level history throughout the Ice Ages (last 2.6 Myr) illustrates the switch back and forth between forested valleys during low stands and drowned harbours during high stands.

The shape of the present coastline of northern New Zealand has been influenced by a number of factors. The most significant has been the sea-level cycles of the Ice Ages, but contributory factors include the degree of exposure to strongly erosive storms and constant wave action, the amount of sediment in the nearshore coastal system, and the nature of the coastal rocks.

In other parts of New Zealand, nearer the plate boundary, an additional factor is tectonic uplift or subsidence. Northern New Zealand has been subjected to very little, or at least very slow, tectonic activity in recent time and as a result has the lowest earthquake frequency in the country. Continuous GPS measurements of land elevation in five locations around northern New Zealand since 2002, have not detected any significant change in height relative to the centre of the Earth in that short time period. This confirms that this is the most stable part of mainland New Zealand. Other parts of New Zealand varied between uplift rates of ~ 7 mm/yr (eastern Bay of

Plenty) to subsidence of 4 mm/yr (Wellington region).

The Hauraki Plains coast at the head of the Firth of Thames is slowly subsiding. This may be part of the continued tectonic subsidence of the Hauraki Rift or a result of ongoing compaction of the thick pile of young sediment that fills this part of the rift. There is ongoing discussion as to whether other parts of northern New Zealand are stable, rising or falling over a longer time period as a result of tectonic forces or more likely as a result of isostatic adjustment of the crust to loading of the continental shelf by the rapid rise of sea level between 18,000 and 7500 yr ago. The weight of the additional water will depress a wide shelf by several metres over a period of time and will result in land a little further away rising slightly. Is the width and depth of the continental shelf around northern New Zealand sufficient to have impacted the elevation of the land, and if so, is the adjustment still occurring? Currently we do not know the answer to these questions.

COASTAL LANDFORMS FORMED BY DROWNING

Sea level has been lower than present for 80-90% of the time during the Ice Ages of the last 2.6 Myr and thus the shape of the coastline has been strongly influenced by erosion that occurred when the sea was lower. During lower sea levels there was a forested coastal plain around all of the coast, extending 10-50 km beyond the present coastline during the peak low of the Last Glacial (18,000 yr ago). All the main rivers would have carved valleys into the coastal plain and most of these valleys were eroded below modern sea level and extended back into the hills beyond the plain. In many places on this coastal plain there were probably belts of sand dunes that had built up at the back of the beaches as sea level was falling.

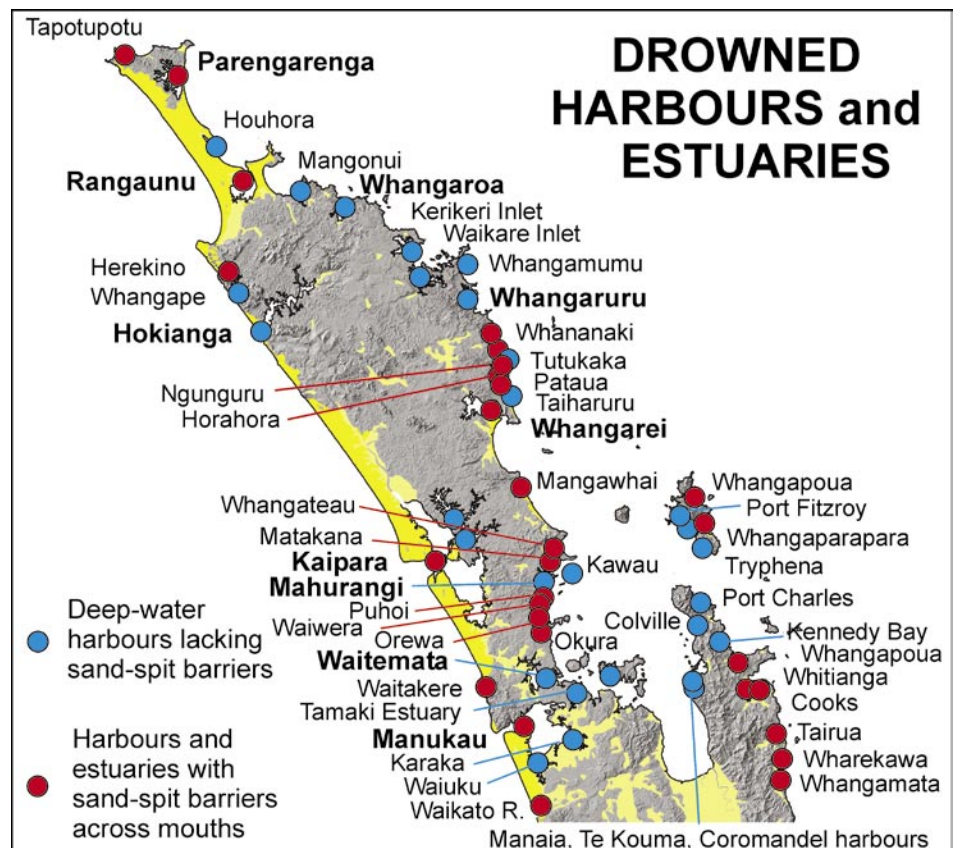
In the most recent climate cycle, sea level rose from its lowest known level of about 130 m below now, to reach its present height about 7500 yr ago (11.27). The average rate of sea-level rise was 1.2 m per century, but rates around 14,000 yr ago were as much as 4 m per century. This was much faster than even the fastest predicted rates for sea-level rise in the next century. Around northern New Zealand, the sea continued to rise to 1-2 m above present by 7000 yr ago and stayed at about that level until about 3000 yr ago. Thereafter sea level fell, reaching a low of 0.6 m below present at the start of the Little Ice Age, 600 yr ago. Then sea level slowly rose again until accelerating its rate of rise after AD1880. Sea level has risen ~30 cm in the last 130 yr or so.

As sea level rose across the coastal plain between 18,000 and 7500 yr ago, the sand from the low-stand beaches and relict sand dunes was moved landward filling in the incised valleys and smoothing out the seafloor profile. On the east coast of northern New Zealand, the

Waikato River had not flowed down the Hauraki Rift since 22,000 yr ago and the supply of new sediment to this coast was limited. Much of the sand on the east coast of Auckland and Northland had probably been deposited as sand dunes on the upper part of the coastal plain as sea level was falling before the Last Glacial (at elevations shallower than ~70 m below present sea level). Thus initially, as sea level began to rise, many of the valleys that had been cut across the lower part of the coastal plain were not completely filled in by the limited amount of moving seafloor sand. Thus, today, there are many rocky outcrops on the seafloor at mid-outer shelf depths off the east coast.

Additional sand was picked up by the slowly rising sea as it inundated the sand-dune belts that had been left higher on the coastal plain, and this tended to fill in most of the valleys at inner shelf depths (0-70 m). As sea level reached its present height, any extra sand in the coastal system on the east coast was thrown up as sandy beaches and started to build sand spits across valley and bay mouths. There was insufficient sand, however, to fill the upper parts of the drowned valleys. The rising sea progressively invaded these eroded valleys, creating the

11.41 Map showing the main harbours and estuaries of northern New Zealand. They were all formed by drowning of valleys as sea level rose after the end of the Last Glacial period.





*11.42 **Drowned hills:** The eastern Bay of Islands was formed as rising sea level drowned a landscape of small stream valleys separated by low greywacke ridges. The higher parts of the ridge crests form the numerous large and small islands and peninsulas in the photograph. View east over Te Rawhiti Inlet with Urupukapuka Island in the mid distance on right. Photographer Alastair Jamieson.*

indented coastline of bays, harbours and estuaries (ria coastlines) of the Coromandel Peninsula, east Auckland and east Northland. Even the middle sections of the major river valleys of the west coast were not filled up with sand and were drowned, creating the intricate waterways of the inner Manukau, Kaipara and Hokianga harbours.

As the land was progressively drowned, the tops of some of the coastal hills were completely surrounded by water, creating islands, particularly in the Hauraki Gulf, Mercury Bay and Bay of Islands (11.42). All our valued wildlife islands were surrounded by the sea and isolated from the mainland as sea level rose. The deep water between the Three Kings Islands and northernmost Northland, suggests that these may have been the only islands that have not had a land connection to the mainland at all during the Ice Ages. The Poor Knights Islands were probably joined by dry land to the mainland for only a few thousand years during the peak lowest sea levels. Other significant islands like Great and Little Barrier and the Hen and Chickens lost their land links to



*11.43 **Drowned river valley:** View southwest down the Hokianga Harbour – which until it was drowned by rising sea level between 12,000 and 7500 yr ago was the forested valley of the Hokianga River. This is about the fiftieth version of the Hokianga Harbour in the last 2.6 Myr. Each harbour lasted only a few thousand years during the high sea levels of the warmest part of each climate cycle. Photographer Alastair Jamieson.*



11.44 Drowned ridge crest: Whangaparaoa Peninsula, on the east coast north of Auckland, was a narrow ridge between the Orewa and Weiti Rivers before their valleys were drowned by sea-level rise between 12,000 and 7500 yr ago.



11.45 Left. Drowned river gorge: This narrow, 200-m-wide waterway is a former river gorge that was eroded during cooler climate periods of low sea level and was drowned by rising sea level about 8000 yr ago, after the end of the Last Glacial. The drowned gorge now forms the entrance from the Tasman Sea (foreground) into Whangape Harbour (distance). Photo by Lloyd Homer, GNS Science.



11.46 Left. Drowned crater: Orakei Basin is one of a number of explosion craters of the young Auckland Volcanic Field that were drowned by rising sea level between 9000 and 7500 yr ago. Subsequently it filled with intertidal muddy sand. It remained that way until the main trunk railway embankment was built across it in the 1920s, creating an artificial salt water lake.

the North Island most recently, around 14,000 yr ago.

Like the islands, the harbours and estuaries of today are extremely young features geologically, having been created by drowning only 10,000-8,000 yr ago. For 100,000 yr prior to that they had been forested valley floors. These harbours and estuaries are only the latest in a long succession of similar waterways that have been

formed during the higher sea levels of warm interglacial periods and then drained and reforested again during the lower sea levels of glacial periods (11.40). Indeed in the last 1 Myr there may have been 10-11 versions of each of the main harbours and estuaries, each of which has only existed for less than 10,000 yr before disappearing again.

11.47 Drowned branching valley: View south down the lower portion of Mahurangi Harbour, on the east coast of Auckland, clearly showing three original branches of the drowned valley. The crests of the narrow ridges between the branches now form the finger-like peninsulas, with Scott Pt the most prominent.



COASTAL LANDFORMS FORMED BY SEDIMENT ACCUMULATION

Sand spits

Where there was a more plentiful supply of coastal sand, it filled all the eroded valleys in the drowned coastal plain as sea level rose. The excess sand started accumulating as sand-dune spits just inside the sheltered mouths of drowned valleys. In some instances, like at Parengarenga, the young sand-dune spit built up on top of an old spit from previous high sea-level stands. Elsewhere, earlier spits had been completely eroded

away and completely new elongate sand-dune spits were constructed in the last 7500 yr. These sand spits created partial dams across the drowned valley mouths and sediment has since accumulated in behind, creating muddy or sandy tidal estuaries, such as Herekino, Whananaki, Ngunguru, Horahora, Puhoi, Waiwera, Cooks Beach, Whitianga, Tairua, Wharekawa and Whangamata harbours and estuaries (11.41).

In some places, the excess sand built up as a

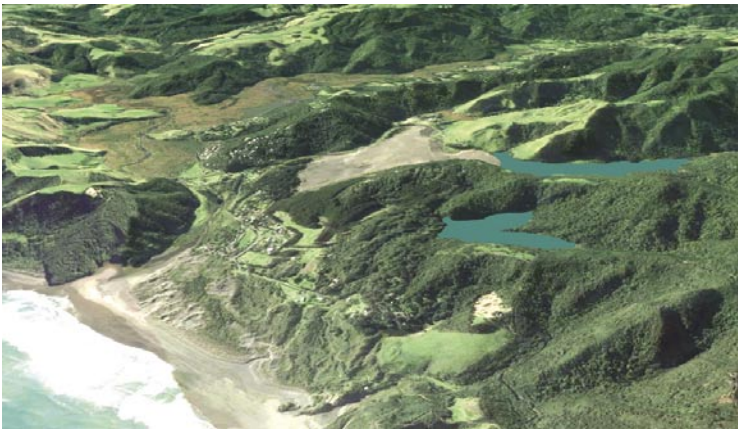


11.48 Sand spit: The Ngunguru sand-dune spit, east of Whangarei, has grown inside the sheltered mouth of the drowned Ngunguru River valley since sea level reached near its present height, about 7500 yr ago. Photographer Alastair Jamieson.



11.49 Sand spit: View south over the Pauanui sand-dune spit, eastern Coromandel Peninsula, that built up across the mouth of the flooded Tairua Valley in the last 7500 yr, creating the sand- and mud-filled tidal estuary behind.

11.50 Dune-dammed lakes: Where there has been excess sand in the coastal system, it has been thrown up on the back of the beach, forming a shore-parallel foredune belt, or it has migrated inland forming areas of parabolic dunes. Here, a belt of high foredunes, now planted in exotic pine forest, has built up behind Pakiri Beach, east of Wellsford, and in behind it has ponded Tomarata, Spectacle and Slipper dune lakes.



11.51 Dune-dammed lakes and swamp: Sand dunes accumulated across the mouth of the drowned Waitakere Valley (left foreground) in the last 7500 yr have dammed several valleys, creating Lakes Kawaupaka and Wainamu (middle right) and the large Bethells Swamp (top left and centre). Bethells Swamp was a tidal estuary between 7000 and 2000 yr ago and subsequently became a freshwater swamp, as sea level fell and swampy peat accumulated. Photograph from Google Earth.

11.52 Sand tombolo: This narrow spit of sand behind Bland Bay, Northland, is called a tombolo. It built up in the last few thousand years and joins the former island of Whangaruru North Head to the mainland. Photographer Alastair Jamieson.

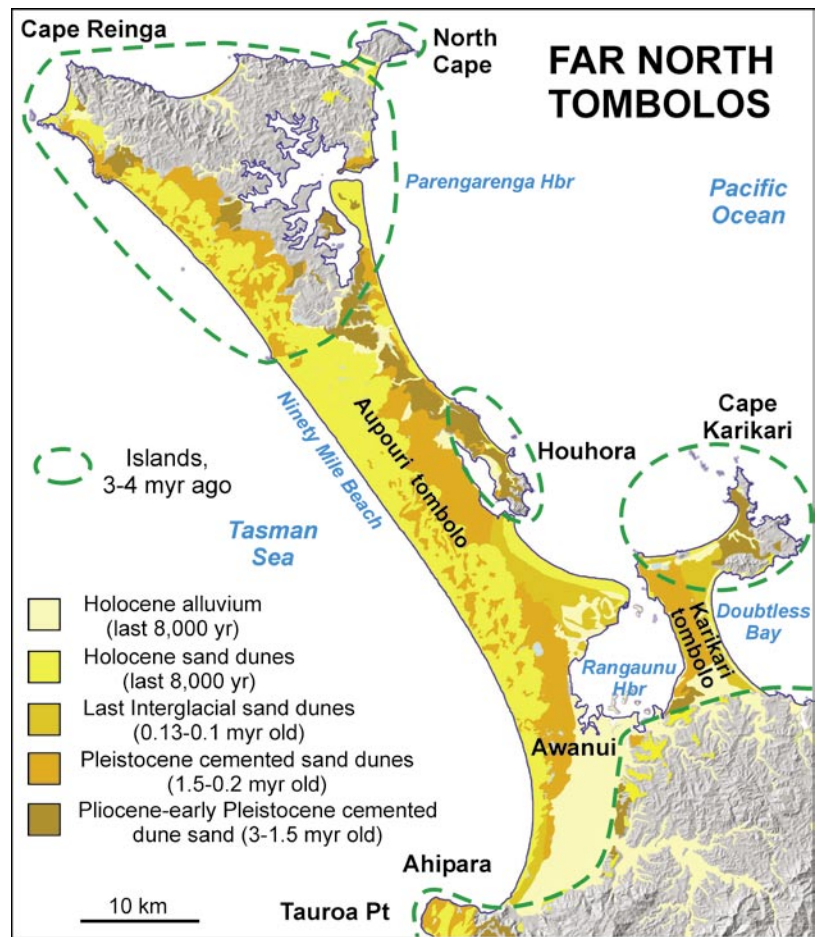


11.53 A number of islands in the Far North have been joined to the main part of Northland by the growth of sand-dune tomboles, over the last 2-3 Myr. Base map from GNS Science's QMAP.

sand-dune spit or barrier across the mouth of a large embayment, enclosing a wide tidal harbour in behind, such as Parengarenga, Rangaunu, Whangarei, Mangawhai, Omaha, Orewa, Whangapoua (Great Barrier) and Whangapoua (Coromandel Peninsula). The shape of these sand-dune spits indicates how they grew and the direction of local longshore movement of sand. From Waiwera northwards to Whananaki on the east coast, longshore drift has been primarily northwards. Elsewhere on the east coast longshore drift has been locally more variable. As mentioned previously, it is likely that a lot of the sand on our modern beaches, and in the sand dunes behind, was thrown up as sea level fell after the Middle Holocene high stand, 7000-3000 yr ago.

Sand beaches

Some sections of coast have a more plentiful supply of sediment, much of which is quartz-rich sand that had been delivered to the east coast by the Waikato and Bay of Plenty rivers, during the last few climate cycles. In these places there are numerous sandy beaches often backed with low foredunes. They include the east coast of Coromandel Peninsula and Great Barrier and the east coast of Auckland and Northland from Tawharanui to Whangaruru and from Doubtless Bay north. On the west coast, some sand



11.54 **Sand beaches:** As sea level has fallen in the last 3000 yr, the excess sand in the coastal system off Ocean Beach, Whangarei Heads, has accumulated on the beach and blown inland to form a belt of foredunes. The white sand is mostly derived from erosion of the ignimbrite and rhyolitic volcanic ash in the central North Island, which was transported down rivers to the east coast, especially prior to 22,000 yr ago, when the Waikato switched its course back to the west coast. Photographer Alastair Jamieson.

has been swept into the three large west coast harbours (Manukau, Kaipara and Hokianga) by flood tides creating sand beaches near their mouths, with excess sand thrown

up to form a large sand-dune flat at Tapora, opposite the mouth of the Kaipara Harbour.



11.55 Top. **Coastal sand plain:** Marsden Point oil refinery, Marsden Cove, One Tree Point and Ruakaka are all built on the coastal plain behind the northern half of Bream Bay. The plain is composed of two belts of sand that accumulated during the Last Interglacial 120,000 yr ago and during the present Holocene interglacial. The higher belt of sand, underlying One Tree Point (far right), consists of a series of sand-beach ridges and foredunes that were left behind as sea level fell after its peak height of 6 m above present, at the end of the Last Interglacial period. Most of the sand flat in the photograph is the 2.5 km-wide seaward belt of sand dunes that has been thrown up in the last 5000 or so years. Photographer Alastair Jamieson.

11.56 Lower left. **Last Interglacial beach and foredunes:** These 6 m-high cliffs at One Tree Point, on the south side of Whangarei Harbour, expose a sequence of beach sands passing up through high-tide beach ridges to a belt of foredunes, which were deposited as sea level began to fall at the end of the Last Interglacial, about 120,000 yr ago. The dark peaty soil at the top of the cliff, in the middle of the photograph, accumulated in a swampy hollow between the low dunes on either side. High tide beach deposits occur in the middle of the cliff and indicate that sea level at the time was 3 m higher than today.

11.57 Lower right. **Last Interglacial beach sand:** These Last Interglacial beach sands in the cliffs at One Tree Point, near Marsden Point, consist of bands of white quartz sand and black titanomagnetite-rich sand, both derived from the volcanic eruptions in the centre of the North Island. The alternating bands beautifully display the layers of sand that were deposited on the beach, with evidence of some erosion between layers and of animals that have burrowed into them. Photo 20 cm across.

Gravel beaches

Where sand is less plentiful in the coastal system, there are eroding rocky shorelines and deep, navigable harbours such as Whangaroa, Bay of Islands, Whangaruru, Tutukaka, Mahurangi, Waitemata, Coromandel and Port Fitzroy (Great Barrier). On some of the more exposed sand-poor coasts, locally derived gravel beaches have

accumulated, as on the west coast of Coromandel Peninsula, the greywacke shores of the Hunua Ranges and many of the islands of the inner Hauraki Gulf, as well as around Little Barrier Island. If exposure to waves has been sufficient to jostle and tumble the cobbles and pebbles on the beach, they will have become rounded and polished.



11.58 Top left. **Gravel beach:** Sand supply is limited in the Firth of Thames. The cobble and pebble beaches along its Coromandel shore are derived by erosion of the local hard volcanic and greywacke rocks. Port Jackson Rd.

11.59 Top right. **Gravel delta:** When rivers discharge sediment into a water body, such as the sea, they may form a delta. There are few deltas in northern New Zealand, because most rivers flow into drowned river valleys and the sediment is dumped in the estuary. An exception is along the uplifted west coast of the Coromandel Peninsula, where short steep streams transport vast quantities of gravel down to the Firth of Thames, during short-lived rain storms. On the coast, they have built up a number of classic, fan-shaped gravel deltas, such as this one at Te Puru, 10 km north of Thames. Photographer Alastair Jamieson.

11.60 Lower. **Gravel tombolo:** Motukioire Island at the entrance to Parua Bay, Whangarei Harbour, is joined to mainland Manganese Point (left) by a shell and gravel tombolo that disappears beneath the waves when the tide is in. The shells and pebbles have been moved here by a combination of strong tidal currents and periodic storm waves. Photographer Alastair Jamieson.



11.61 Intertidal harbour flats: The sheltered embayments and upper reaches of many of the larger harbours in northern New Zealand have filled with sediment to form extensive intertidal flats, such as these at Takahiwai on the south shore of Whangarei Harbour. These intertidal flats are underlain by a combination of eroded rocky shore platforms and sediments deposited in the last 7500 yr.

Intertidal flats and shell spits

In more sheltered places, sand or mud may have accumulated to form extensive intertidal flats, such as around the heads and arms of many of the harbours, in estuaries and around the head of the largest estuary – the Firth of Thames. Shellfish, particularly the cockle *Austrovenus stutchburyi*, often live in vast numbers on these intertidal mudflats and when they die the shells are swept across the mud by strong tidal currents or onshore waves in large storm events. These shells build up linear shell ridges, called cheniers, that move around on the mud flats as in the upper Manukau and Kaipara harbours. At Miranda they become attached to the coast and form a series of shore-parallel shell banks, creating a coastal chenier plain (box 50).



11.62 Braided river delta: The drowned lower valley of the Waikato River has filled with sediment since sea level rose to its present elevation, and a braided, estuarine delta has been formed 8-20 km from its mouth. Most sediment passes through the delta and reaches the exposed Tasman Sea coast. Photo from Hamilton and Waikato Tourism.



11.63 Sediment-filled estuary: Horahora River, east of Whangarei, is a small waterway, whose mouth was partially dammed by a sand-dune spit after it was drowned by rising sea level, 9000-7500 yr ago. Because of this it has not been able to flush out all the accumulating sediment inside its tidal estuary, which has become a network of meandering channels and sandy mud flats among mangrove forest and salt marsh. Ngunguru Estuary beyond to the north. Photographer Alastair Jamieson.



11.64 Above. **Shell spit and cusped foreland:** View north down the Tamaki Estuary towards Rangitoto Island. Extending most of the way across the estuary is the Tahuna Torea shell spit made of dead shells of cockles from the surrounding mudflats. The shells are moved up the estuary across the mud by strong flood tidal currents and northerly waves and moved down the estuary by strong ebb tidal currents and waves from the south. The spit is located where these opposing forces balance out. The spit is attached to the western shore by a cusped (arrow-shaped) foreland, margined by the arcuate shell spits on each side, with mud flats in between.



11.65 Right. **Shell banks:** These shell banks (cheniers) on the mud flats of the southern Manukau Harbour, move around and change shape during major storm events. Northeast of Clarks Beach. Width of photo 500 m.

Box 50. MIRANDA CHENIER PLAIN

A chenier is a beach ridge made of gravel, shell or sand, resting on top of mud and separated from the shore by a belt of intertidal mudflats. The southwest corner of the Firth of Thames is fringed by a 15 km-long and up to 2 km-wide coastal plain that accumulated in the last 4000 yrs (11.67). It is one of the best examples in the world of a combined gravel and shell chenier plain that has built up by the progressive addition of gravel and shell beach ridges on top of tidal mud flats. The gravel beach ridges form the narrower northern part of the plain, with greywacke cobbles and pebbles, eroded from the adjacent Hunua Ranges, coming down streams to the coast. Once on the beach, the gravel was moved progressively southwards by longshore drift during storms, which threw up a succession of storm beach ridges (11.67). Moving south, the pebbles became progressively smaller and less numerous, and were replaced by shells, mostly cockle, south of Kaiiua.

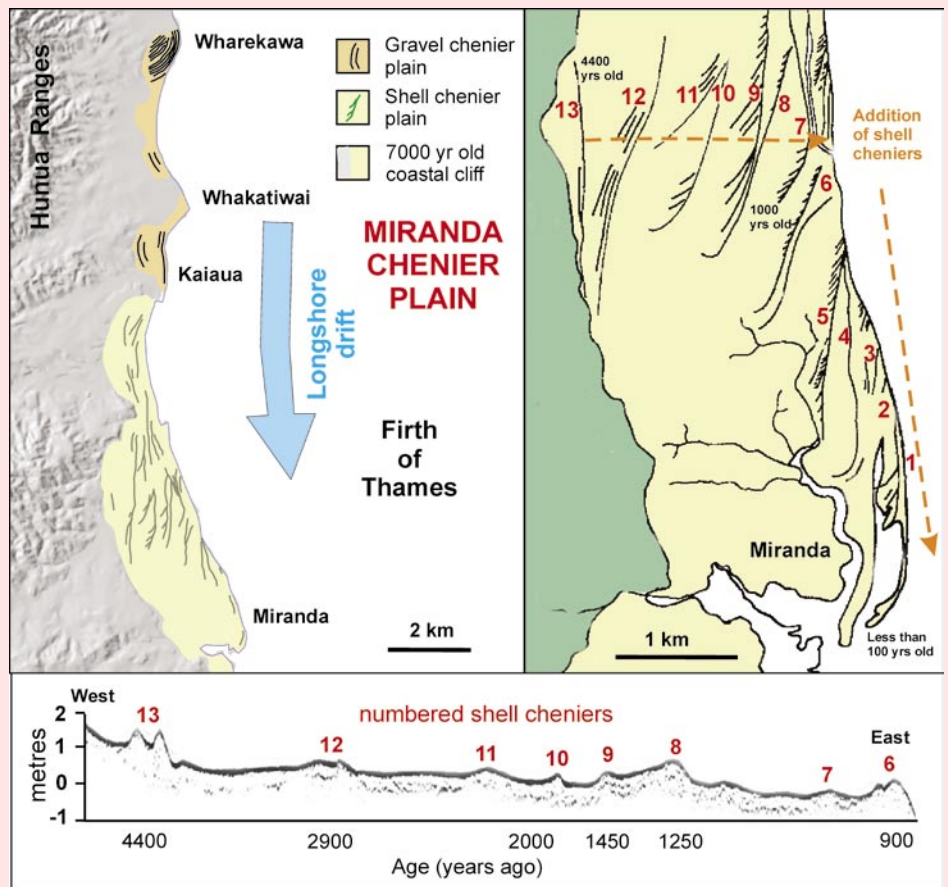
The shell ridges originated intertidally, as sand and shell banks, during major northeast storms, which swept away the mud and concentrated the coarse material into a heap. These offshore banks were driven shoreward by later storms and eventually attached to the existing shell beach at their northern ends. From here, they developed into narrow shell spits that grew southwards, parallel to the coast, separated from the previous shell beach by a 50-200 m-wide depression (11.69). In the shelter of the shell spit, this elongate depression progressively filled with intertidal mud that may have been colonised by mangroves and eventually by high-tidal salt marsh, thereby adding new land to the plain. During high spring tides, some storm waves washed over the shell spit spreading feathery lobes of shell into the mud depression. These characteristic feathery lobes can still be seen in many places on the grazed older parts of the chenier plain today (11.68).



11.66 The youngest gravel chenier (beach ridge) at the northern end of the Miranda chenier plain, north of Kaiiua. The gravel cheniers are made of rounded pebbles of greywacke eroded out of the Hunua Ranges and transported southwards by longshore drift.

Box 50 continued

11.67 Left side. Map of the internationally-famous Miranda chenier plain that has formed along the west coast of the Firth of Thames in the last 4000 yr. Right side. Map showing numbered shell chenier ridges around Miranda: 13 is the oldest (4000 yr) and 1 the youngest (less than 50 yr); modified from Schofield (1960). Bottom. West to East cross-section through the 4000-1000 yr-old portion of the shell chenier plain, showing the drop in sea level (chenier crests) of 1.5-2 m, during this time; from Dougherty and Dickson (2012).



Between 7000 and 4000 years ago, when sea level was 1.5-2 m higher than today, the coastline at Miranda was up to 2 km further west, right up against the foot of the hills. Between 4000 and about 1000 yrs ago, as sea level dropped to its present level or slightly lower, much of the shell chenier plain, between Miranda and Kaiaua, and the gravel plain further north, was constructed. Each successive shell or gravel ridge was added seaward of the preceding one and the plain built out across the intertidal mud. The 4000 yr-old chenier up against the hill is 1.5-2 m higher than the 1000 yr-old one, and those of today (11.67). Together they document the decline in sea level since 4000 yr ago. In the last 1000 yr there has been little growth of the gravel plain, but in the south, additional shell spits have been added, as the chenier plain has grown southwards rather than seawards. This is believed to be the result of the previously stable (and more recently rising) sea level.

11.68 Part of the 2 km-wide Miranda chenier plain. Some of the shell cheniers and their feathery overbank shell ribs can be seen in the grazed pasture. Image from Google Earth.



11.69 This recently formed shell chenier had just formed and attached to the Miranda chenier plain when photographed in 1980. Within ten years, it had migrated landward to form a new shore-parallel, south-migrating beach ridge.

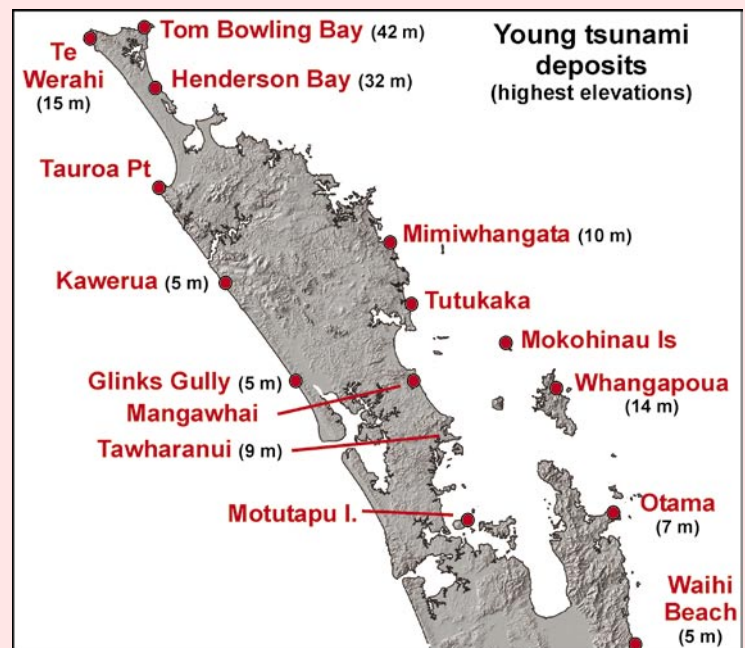


Box 51. TSUNAMI DEPOSITS

Tsunami (Japanese, from *tsu*, 'harbour,' *nami*, 'wave') refers to long-period waves generated by a sudden event, such as a submarine earthquake, submarine landslide, explosive undersea eruption, giant sea-floor collapse or meteorite crashing into the sea. New Zealand experiences about 12 tsunami waves greater than 1 m in height per century. It is the very largest that cause the most damage and potential loss of life, as we have seen in recent years with earthquake-generated tsunamis in Japan, the Indian Ocean, Chile and Samoa. New Zealand has not experienced one of these really large tsunami in historic times, but there is geological evidence that they do occur occasionally and have impacted northern New Zealand at least once in the past 1000 yr.

The most likely sources of large tsunami that might impact northern New Zealand are megathrust earthquakes on the subducting boundary between tectonic plates along the Tonga-Kermadec trench near New Zealand or much further away along the coast of South America. Another potential source could be a large eruption of an undersea volcano on the Tonga-Kermadec Volcanic Arc. The height of a tsunami wave reaching the coast will vary greatly from place to place depending upon its source direction and local features that may amplify it. Thus places like the inner Hauraki Gulf, Waitemata, Kaipara and Manukau harbours are unlikely to receive large tsunami whereas the eastern shorelines of Coromandel Peninsula, Great Barrier Island and Northland are more exposed to waves arriving from the east and north, which could have run-up heights in excess of 20 m.

Evidence of past tsunami comes from deposits of marine-sourced sediment or shells that have been left behind in places well inland or on the coast well above the height that could be reached by the largest king-tide storm waves. These deposits are usually recognisable as beach-rounded pebbles and shells high up in coastal sand dunes or coastal terraces, or sometimes as a layer of marine-sourced sediment and salt-water microfossils deposited in an inland freshwater lake or swamp. Significant tsunami deposits have been recognised at various elevations above sea level right around the coast of northern Northland (11.70). Dating of the time of emplacement of some of these, suggests that a major tsunami inundated the coast of Northland about 600 yr ago, with run ups as high as 30-40 m above sea level in the Far North. Likely sources of this tsunami include an eruption that occurred about that time from the submarine Mt Healy caldera volcano, located ~500 km east of the Bay of Islands on the Tonga-Kermadec Volcanic Arc; or a major megathrust earthquake on the plate boundary in the same region.



11.70 Map showing distribution and highest elevations, above MSL, of inferred tsunami deposits preserved mostly in sand dunes around the coast of northern New Zealand. Some have been dated to about 600 yr ago. A large tsunami, at that time, could have been generated by a huge eruption 400-500 km away at Mt Healy submarine caldera volcano or by a megathrust earthquake on the plate boundary in the same region. Many of these deposits have not been directly dated and so not all of them may necessarily have been emplaced by the one tsunami. Based on de Lange and Moon (2007) and Goff (2008).



11.71 Deposit of rounded pebbles and thick shells located up to 14 m above MSL in the sand dunes behind Whangapoua Beach, northeast Great Barrier Island. They are inferred to have been picked up from the 20 m-deep sea floor, between Rakitu Island (left) and Haratounga (right), by a large tsunami about 600 yr ago and carried landward up into the dunes.

COASTAL LANDFORMS FORMED BY EROSION

Sea cliffs

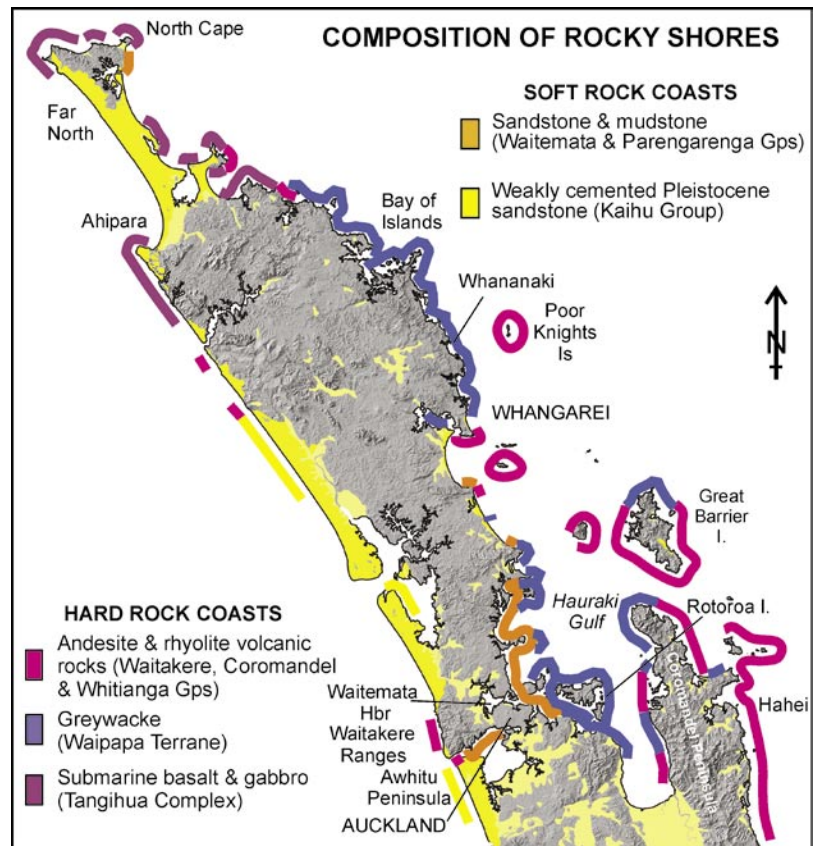
The shape of the cliffed coasts of northern New Zealand has been influenced by a number of factors. The ridges and valleys that were flooded by rising sea level at the end of the Last Glacial determined the location of cliffed headlands, peninsulas and islands. The shape of the rocky shorelines has been determined by a combination of the hardness and structure of the rocks, the degree of exposure to storm waves and swells, and the tidal range and height of the sea.

The shape of many of the higher cliffs made of harder rocks has been inherited to a certain degree from sea cliffs eroded during earlier interglacial high sea levels. In the last 700,000 yr or so, these higher sea levels have recurred every 100,000 yr and each lasted 5000-10,000 yr. The last was 120,000 yr ago during the Last Interglacial period. In the long intervening cooler periods, when sea level was mostly more than 20 m lower than present, the high-stand sea cliffs would have weathered back to forested, scree-covered slopes. Each time sea level returned to near its present level, the soft clays and scree would have quickly been eroded away, exhuming the hard rock of the steep cliff behind.

How far hard-rock cliffs have retreated since sea level uncovered them most recently (about 8000 yr ago) can often be estimated by the width of the shore platform



11.73 Slowly-eroding cliffs: This 15 m-wide shore platform on the exposed eastern side of Rotoroa Island, inner Hauraki Gulf, provides an estimation of how much erosion of the greywacke cliffs has occurred since they were exhumed by sea-level rise, about 7500 yr ago.



11.72 Map showing the distribution of eroding hard and soft rock coasts around northern New Zealand.

at their feet. These platforms are often 5-20 m wide on the harder volcanic rock shores right around northern New Zealand (11.72). Eroding back at a similar rate are the greywacke rocks of the Waipapa Terrane that occur along parts of the east coast. Cliffs made of softer rocks are mostly eroded out of the Waitemata Group sandstone and mudstone that form many of the sea cliffs around Auckland. The maximum widths of Waitemata Sandstone shore platforms are highly variable, but mostly within the range 40-200 m (11.78) - this is an indication of the amount of erosion of their backing cliffs in the last 7500 yr. Thus erosion rates for hard rocks have been ~0.1-0.3 m/100 yr and for the softer Waitemata Sandstone ~0.6-3 m/100 yr. These are minimum estimates as some erosion occurs at the seaward edge of the shore platforms, particularly those made of softer sandstone. Potentially the fastest-eroding cliffed coasts are those cutting into the soft Pleistocene sandstones of the Awhitu and Kaipara barriers, particularly along the more exposed western coasts of northern Awhitu (11.75) and North Kaipara peninsulas (11.7), where there are no Holocene foredune belts deposited in front of them.



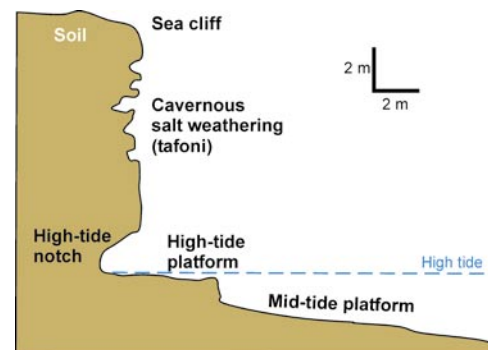
11.74 Eroding sandstone cliffs: The east coast of Auckland from Beachlands to Warkworth consists of rapidly eroding, near vertical cliffs of Waitemata Sandstone separating a series of small sandy beaches, each of which fills the mouth of a small drowned stream valley. The width of the shore platforms in front of the cliffs indicate cliff retreat rates of 1-3 m/100 yr. View south from Browns Bay, North Shore.



11.75 Rapidly eroding cliffs: The 160 m-high cliffs on the exposed Tasman Sea coast of northern Awhitu Peninsula are probably eroding faster than any other cliffs around northern New Zealand at the present time. They are composed of weakly cemented Pleistocene dune sands that are too unconsolidated to maintain a vertical cliff face. View south from Hamiltons Gap.



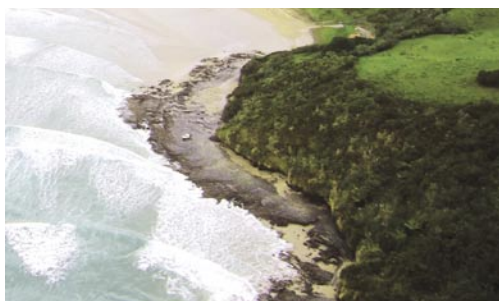
11.76 Rapid erosion: The north side of Rangitoto Volcano illustrates the speed of marine erosion on a relatively sheltered coast exposed to only periodic storm waves. In little more than 500 yr since they were erupted, the hard basalt lava flows have been cut back, forming 5 m-high cliffs. During storms, the waves have forced their way along cooling joints, releasing blocks of basalt that have been tossed around and thrown up onto the back of the beach, as rounded boulders, as seen here at Wreck Bay. In the same time period there has been almost no erosion on the sheltered southern coast of the volcanic island.



11.77 Sketch of main elements of an eroding cliff with intertidal shore platforms.

Shore platforms

Subhorizontal tidal platforms often form at about mid- to high-tide level as a result of the increased resistance to erosion of water-saturated rocks. The surface layers of rocks at higher tidal levels often dry out between successive tides, allowing them to weather and erode much faster than those at lower levels, which remain water-saturated throughout the tidal cycle. Intertidal platforms were initially formed during the Middle Holocene (7000-3000 yr ago), when sea level was



11.78 Upper. **Mid-tide shore platforms:** These 100-200 m-wide shore platforms have formed at mid-tide on the relatively soft Waitemata Sandstone. Musick Pt, Waitemata Harbour, Auckland. Photographer Alastair Jamieson.

11.79 Bottom left. **High-tide shore platform:** High-tide platforms like this, have been eroded into most of the harder rocky shorelines (here Tangihua Terrane basalt) since sea level rose to near its present height after the end of the Last Glacial period. Shipwreck Bay, Ahipara, west of Kaitiaki. Vehicle on shore platform for scale.

11.80 Bottom right. **Old-hat islet:** Several “old-hat” islets occur around northern New Zealand. They have eroded out of soft Waitemata Sandstone (as seen here in Watchman Island, near Auckland Harbour Bridge) or harder greywacke (14.1). Each consists of a central remnant islet with steep cliffs surrounded by a wide high tidal shore platform.

1.5-2 m higher than present. Many of these platforms, especially those in softer rocks, appear to have eroded down as sea level fell. In some places, there is a relict shore platform at high tide level and a younger one forming 1-2 m lower on the shore (11.83-11.84). Many of the higher platforms cut in Waitemata Sandstone around Auckland have already eroded down and been replaced by extensive mid-low tidal platforms, but in a few places thick beds of more-erosion-resistant sandstone still retain the earlier platform on top of them.

In general, the most rapid cliff and shore platform erosion occurs in the zone of constant wetting and

drying of the rock. In softer, more porous sandstone and mudstone on sheltered shores, this zone is more likely at mid-tidal level. With harder, less porous rocks, this zone may be somewhat higher, and on exposed shores it is higher still. On the most exposed west coast shores the constant surging waves and salt spray keep the rocks wet at higher levels and the shore platform in hard rocks may be even higher than mean high water level (11.79). In some circumstances this kind of erosion in harder, more massive rocks can result in the creation of a high tidal notch cut into the foot of the cliffs with an overhang above (11.81-11.83).



11.81 Above left. **High-tide notch and shore platform:** A high-tide notch has eroded into volcanic conglomerate on the sheltered side of Paratutae Island, Whatipu, Waitakere Ranges. This used to be the location of a wharf in the 1860s-1910s, where scows pulled up alongside to load sawn kauri timber.



11.82 Above right. **Mushroom-rock stack:** This “mushroom” rock stack at Cathedral Cove, Coromandel Peninsula, is made of relatively soft, massive ignimbrite rock. The zone of fastest erosion is just below high tide level where the rock alternates between wet and dry on most tidal cycles.



11.83 Above left. **High-tide notch:** This 5 m-deep, high-tide notch on the west side of Shakespeare Cliff, Whitianga, has eroded into massive ignimbrite. Note the two levels of shore platform – the upper one may be relict from when sea level was higher several thousand years ago.



11.84 Above right. **Two-tiered shore platform:** At Motuihe I, Auckland, there are two levels of shore platform - one at low-tide level and another 1 m higher near high-tide level. They have been eroded into massive Parnell Grit rock during two different sea-level heights in the last 6000 yrs.

Erosion along joints and faults

The structure of the coastal rocks can also strongly influence erosion rates and the smaller-scale topography of the shore. Joints and faults that cut through even the hardest volcanic or greywacke rocks are planes of weakness that are exploited by the pounding waves, eroding-out open crevices, guts and sea caves along them. This is particularly true for joints that are perpendicular to the cliff. Almost all sea caves and arches have eroded along joint or fault planes. These may gradually erode larger and larger, until the roof collapses and they become blowholes or deep guts cut into the cliffs. If the sea caves erode out along planes of weakness in a headland, they may carve their way right through to become a sea arch

(11.86). Collapse of arch roofs may create sea stacks or small coastal islands.

In the case of columnar or planar cooling joints in volcanic rocks, the wave energy gets focussed along the joints, until the pounding loosens a block of hard rock, which eventually drops out of the cliff. Sometimes the more rapid erosion of the rocks around mid-high tide undercuts part of the cliff, which may suddenly fail along a cliff-parallel joint plane and come sliding down. The shapes of many cliffs are controlled by rock failures along steep joint planes like these (11.91). Where there are intersecting sets of joints, it is possible that steep-sided pinnacles may be produced.

The layering (bedding) of the alternating sandstones



11.85 Above. **Coastal pinnacles:** The hydraulic forces of pounding waves have opened up many of the numerous vertical joints in the greywacke (Waipapa Terrane) that forms The Needles off the northern tip of Great Barrier Island. This has loosened many blocks which have fallen away, creating these spectacular pinnacle rock stacks that rise up to 75 m out of the sea.

11.86 Right. **Sea arch:** Some hard-rock cliffs, like these at Archway Island, Poor Knights, drop straight down into deep water with little or no shore platform. They were clearly exhumed and eroded when sea level was much lower than today and present-day marine erosion is relatively slow and concentrated along joints, with large blocks falling off into deep water. The archway has eroded along joints through the ignimbrite rock.



11.87 Below. **Joint-controlled erosion:** A typical section of rocky greywacke coastline on the east coast of Northland, with high tidal platforms cut by numerous guts, which have eroded along several sets of near vertical joints. Motutara Pt, with Whananaki sand spit and harbour beyond. Photographer Alastair Jamieson.





11.88 Top left. **Intertidal gut:** This large 6 m-wide intertidal gut has been formed by erosion along two parallel joint planes (one on either side) in volcanic sandstones at Tirikohua Pt, south of Muriwai, Waitakeres west coast.



11.89 Top right. **Blowhole:** Marine erosion along joint planes in ignimbrite rocks, has resulted in roof collapse and formation of blowholes in a number of places along the east coast of the southern Coromandel Peninsula. This blowhole, south of Hahei, is 80 m across at the top and can be entered by small boat through a sea tunnel at the base of the cliff, 50 m below.

11.90 Right. **Sea caves:** Erangi Pt, between Te Henga and O'Neills beaches on the Waitakere west coast, is cut by two sets of joints at right angles to each other. The pounding Tasman Sea waves have eroded along many of these joints to create an extensive network of sea caves and tunnels. Speleologist Peter Crossley, has mapped and measured their combined length to be just over 1 km, which makes it the third longest sea-cave system in the world. The largest tunnel (200 m long and up to 40 m high) can be seen in this photograph, passing right through the heart of the point.



11.91 **Joint-plane failure:** The steeply-sloping, northeast face of 63 m-high Taitomo Island, Piha, is a joint plane. Large blocks have been undercut by erosion at high tide level and then have failed, sliding down the plane to the base of the cliff, where some still sit. Note also the shore platform above high tide level on the extremely exposed right side of the island.

and mudstones of the Waitemata Sandstones around Auckland can influence the local shape of the rocky shoreline. The sandstone layers are always more resistant to erosion than the thinner mudstone beds between. Thus the sandstone layers project out slightly from the face of the cliff and above the surface of the shore platform. The layering is often tilted and the eroded off ends of the tilted beds often define the shape of the shore platform (11.92). The most resistant thicker sandstone beds and the massive Parnell Grit layers often project higher above the surrounding shore platform than the thinner beds.



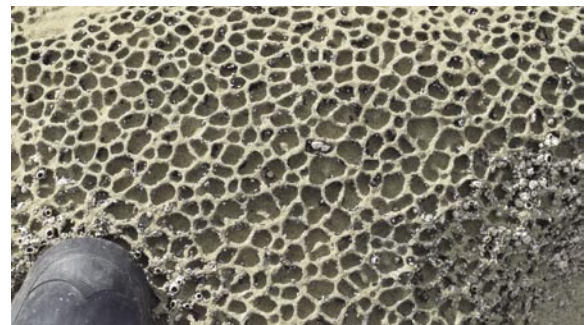
11.92 Ridged shore platform: The striped pattern in the shore platform is produced by the layers of alternating harder sandstone and softer mudstone (Waitemata Sandstones) that have been tilted up to vertical and eroded down. Whangaparaoa Head, east Auckland.



11.93 Cavernous weathering: Cavernous weathering (tafoni) on the higher parts of 90 m-high cliffs on the exposed western side of Lion Rock, Piha. The cavernous surface has developed over a long period of time as a result of the growth of salt crystals within the surface of the porous rock, as sea spray dries. The crystals growth releases small fragments of rock that fall out or are blown away.

Tafoni

Another form of coastal cliff erosion is salt weathering (honeycomb weathering) whereby the cliffs are periodically wetted with salt spray that accumulates in slight depressions and penetrates into the more porous rocks. As the moisture evaporates, salt crystals grow, pushing apart the grains or crystals in the rock. The loosened grains or crumbs of frittered rock blow or wash away and, as the wetting and drying continues, an irregular cavernous cliff face develops, sometimes resembling a honeycomb (called tafoni) (11.93).



11.94 Small-scale tafoni: Small-scale honeycomb weathering (tafoni) in a thick Waitemata Sandstone bed at mid-tide level, near Sandspit, Warkworth. The precise mode of formation is unknown but may have included a combination of salt-crystal growth, sea-snail grazing and micro-climate effects inside each cell.

COASTAL TERRACES

Coastal terraces are usually flat surfaces that slope gently towards the coast and have been created by erosional and/or depositional processes. Coastal terraces created by erosion were cut in the intertidal zone as shore platforms. Coastal terraces created by deposition may be former intertidal mud or sand flats, former high-tidal salt marsh surfaces or storm benches at the back of beaches. They may also be alluvial terraces, where sediment was dumped by streams, at the heads of estuaries or in small deltas, as they lose energy and drop their sediment load on reaching the sea.

Coastal terraces are recognised on land at levels above the influence of present-day sea level processes. Thus these terraces were either deposited when sea level was higher than it is now, or there has been uplift of the land since the terrace was formed. In chapter 8 the extensive Late Miocene erosion surface has already been described. It is inferred to have been formed predominantly by erosional processes that were related to sea level over many millions of years and has subsequently been pushed up and tilted to varying degrees in different parts

of northern New Zealand. In places where this surface is at lower elevations today, such as around Auckland, we may not be sure whether terraces and flat ridge crests are remnants of this older erosion surface or have been made more recently.

The most definite coastal terraces that we can see around many parts of northern New Zealand are those that were made during the Middle Holocene, 7000-3000 yr ago, when sea level was 1.5-2 m higher than it is today (11.27). These terraces (which used to be called Flandrian terraces) have been left stranded above the influence of the sea as the water level has fallen. Their height today depends on where they were formed. The best example is the Miranda chenier plain on the west side of the Firth of Thames (box 50) created by a series of beach shell ridges, called cheniers. Other storm beach deposits can be seen 2-3 m above high tide level today at many places, like Bucklands Beach (eastern Auckland) and Paihia (Bay of Islands). In many places around the edges of sheltered harbours and estuaries there are lower coastal terraces, only 1 m or so above present high-tide level, which are former intertidal flats that were left stranded as land, as the sea level fell (11.95-11.99). Because of the lack of any significant tectonic uplift in northern New Zealand, none of these young Holocene highstand terraces are higher than 2-4 m above present mean high tide level.

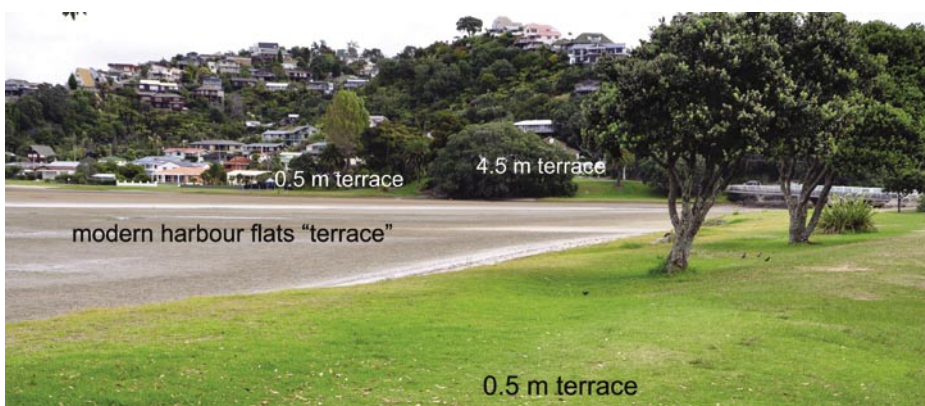
The second-most recent occasion when sea level has been as high as, or higher than, present was 125,000-115,000 yr ago during the warmest peak of the Last Interglacial period. Studies from around the world indicate that sea level was up to 5-7 m higher than present during some of this period. Many intertidal and high tidal terraces were undoubtedly formed around northern New Zealand at this time, but since then the vast majority have been eroded away by streams and more recently by the sea. There are, however, a number of coastal terraces within the range 3-6 m above present around parts of northern New Zealand, that were most likely made during



11.95 Okahu Bay, on Auckland's Tamaki Drive, is backed by a gently-sloping flat that is 500 m-wide, extending 800 m inland and is 0.5 m-2 m above spring high tide. The terrace, now used as sports fields, is the former surface of intertidal muddy sand flats, which accumulated in the mouth of this small drowned valley, between 7000 and 3000 yr ago. It has been left high and dry as sea level has fallen 1.5-2 m since then. Similar low coastal terraces occur right around northern New Zealand's sheltered coastlines.

this Last Interglacial period. Where present, they indicate little if any tectonic uplift or subsidence occurred in these areas in the last 100,000 yr or so. In the Far North, former intertidal sand flats within Houhora Harbour now form a flat coastal terrace that is 4-6 m above the approximate elevation at which it accumulated (mid tide). There are a number of distinct coastal terraces at elevations of 5-6 m above Mean Sea Level inside the sheltered mouths of coastal valleys on Coromandel Peninsula (11.96, 11.98), which were undoubtedly formed during the Last Interglacial period.

Around Auckland city, there are many gently-sloping terraces located 6-9 m above present mean sea level. Examples of these on the Waitemata Harbour side can be seen at Point England, Edgewater and Highbrook on the Tamaki Estuary, and at Kawakawa Bay. Around the Manukau Harbour, on the west coast side, examples can be seen at Favona, Puhinui and Weymouth. One of Auckland's



11.96 Much of the township of Tairua, on the shore of Tairua Harbour, is built on two coastal terraces that were formerly intertidal harbour sand flats. The terrace 0.5-1 m above spring high tide was formed during the most recent high sea level ~7000-3000 yr ago. The 4.5 m terrace was formed during the Last Interglacial high sea level, ~120,000 yr ago.



11.97 Several extensive flat terraces, about 2 m above present high tide level, occur around the western shore of Parengarenga Harbour in the Far North. They appear to have been eroded during the Middle Holocene high sea level, 7000-3000 yr ago, out of the weakly cemented intertidal sediments that were deposited in the harbour during the Last Interglacial period. Photographed at Paua.



11.98 Above. The Port Jackson Road passes over two distinct coastal terraces that fill the mouth of the Waiaro Valley, 7 km north of Colville, Coromandel Peninsula. The higher, Last Interglacial terrace is separated from the lower in the foreground, by a 4-5 m-high riser. This was the embayed coastal cliff when the lower terrace was being formed, 7000-3000 yr ago.



oldest volcanic craters, Boggust at Favona on the Manukau Harbour, has been breached by the sea and filled with intertidal sediment during the Last Interglacial high stand. The flat crater floor is now 6-7 m above the mid- to high-tide level at which it was deposited. These terrace heights suggest that there may have been a slight uplift of 1-2 m of the Auckland area in the last 120,000 yr, but there is still considerable uncertainty in this.

There are many other coastal terraces at greater heights around much of northern New Zealand. Our knowledge of global sea level indicates that the only other period in the last 1 Myr when sea level was above present, was during an exceptionally warm interglacial 400,000 yr ago. At that time sea level is understood to have risen to 6-10 m higher than today and it has not been higher than this at any time in the last 2 Myr. Some of these higher terraces have clearly been formed intertidally during the last 1-2 Myr. Their occurrence now at elevations higher than 10 m indicate that there has been uplift of the land (11.99), albeit at much slower rates than many parts of New Zealand that are closer to the plate boundary. Not surprisingly, there are no consistent elevations for these higher terraces, which reflect the different amounts of uplift that there has been around the north.

The Far North, north of Kaitaia, is one area that has no solid evidence of tectonic uplift in the last 1-2 Myr. Other places that have definite uplifted Pleistocene harbour-side terraces preserved are on the sheltered eastern sides of the South Kaipara and Awhitu Peninsulas and the east side of Coromandel Peninsula.

11.99 Left. These terraces are erosional remnants of high-tidal sand flats that once filled the floor of the mouth of the small Pataua Valley (Te Rau Puriri Regional Park), on the sheltered harbour side of the South Kaipara Peninsula. The lowest terrace (foreground), is the 1-2 m high Middle Holocene high stand terrace. The middle terrace (on left) is 7-9 m above present high tide level and was probably formed during the Last Interglacial period. If so, it is 2 m higher than sea level maximum at that time and indicates uplift at a rate of 2 mm/100 yr for this area in the last 120,000 yr. The highest terrace (middle right) is 16-18 m above present high tide and may have formed 400,000 yr ago during the highest tide level of the last 2 Myr, with subsequent uplift of ~8 m.

Chapter 12. MOULDING THE LAND

Chapter Summary

The shape of the land in northern New Zealand comprises many different surfaces that have been uplifted, weathered and eroded to varying degrees, depending upon their age and history. Recognisable in the landscape are: exhumed remnants of the Late Eocene erosion surface; uplifted portions of the Auckland Erosion Surface (Late Miocene-Pliocene); volcanic landforms, both young and pristine or old and eroded; old eroded sand dune barriers with remnant deflation (Stokes) surfaces and younger sand dune hills; coastal terraces - formed as shore platforms when sea level was higher, or subsequently uplifted; and modern alluvial plains or abandoned fluvial terraces at higher levels. Weathering in the subtropical north has been rapid, producing thick layers of clay over many of the more slowly eroding hills.

All the highland areas are made of harder rocks that have been uplifted in the last 5 or so million years. They are characterised by short, youthful, V-shaped valleys with fresh bedrock, gorges and waterfalls in their upper parts and gravel-filled lower reaches. Lowland areas are mostly underlain by softer rocks. Those with more erosion-resistant sandstone beds often have prominent ridge crests, with their shape influenced by the direction of layering. In both high- and lowland areas, there are many examples of straight streams that have eroded along the crushed rock of fault lines. The lowest hills are often underlain by the soft mudstone and muddy limestone of the Northland Allochthon, which causes them to be highly prone to slides and slumps that produce characteristic lumpy topography.

The largest alluvial flood plains have formed just above sea level, where meandering mature rivers dumped fine sediment at the head of large drowned estuaries, forming the Hauraki, Ruawai and Awarua plains. Lava flows and ash from young volcanic eruptions have dammed valleys, creating lakes and swamps in Auckland and Northland - the largest of which are Lake Omapere and Hikurangi Swamp.

Northern New Zealand's most valuable export commodity in the 19th century was kauri gum, mostly dug out of the ground and swamps and used for the manufacture of high quality varnish and later linoleum. The remains of some of the giant kauri trees that grew over this land in the past 100,000 years or so are preserved in swamp peat and provide clues to the region's past climate and vegetation history. Until recently, most bricks used in the region were made from locally-derived kaolinite clay, largely from deposits in west Auckland.

WEATHERING AND EROSION OF THE LAND

The surface of the land of northern New Zealand is composed of many different elements, most of which have already been described in this book. The oldest in origin is the exhumed and weathered surface that was eroded into basement rocks by about 35 Myr ago, prior to deposition of the Te Kuiti Group sediments (chapter 3), and is now seen on the uplifted and tilted Omahuta and Brynderwyn blocks in Northland and parts of the Hunua Ranges further south. Other older flat tops that occur on parts of the Poor Knights and Great Barrier islands and Table Mt (chapter 7) are inferred to be remnant volcanic surfaces (sinter flats, lava lake) from 10-7 Myr ago (Late Miocene). More extensive are the remnants of the ~5-Myr-old Auckland Erosion Surface (chapter 8) that have been uplifted to various heights throughout Northland and Auckland, and are commonly recognisable by the congruence of flat-topped ridge crests. Yet another set of uplifted planar surfaces are the partly eroded remains of Late Miocene-Pliocene basalt lava flow sheets at Puhipuhi and between Kaikohe and Kerikeri, all in Northland

(chapter 9).

Volcanic cones, domes, craters, calderas, lava flows and flow-dammed lakes and swamps are recognisable throughout all of the younger basalt volcanic fields (younger than ~3 Myr) of Northland and Auckland (chapter 9) and also in a few of the younger volcanoes of the southern Coromandel Volcanic Zone (chapter 7). These landforms are fresh and pristine in the youngest volcanoes and progressively more weathered and eroded the older they are.

The block faulting and general westward tilt of Northland and Auckland, and southeast tilt of Coromandel Peninsula in the last 5 Myr or so (chapter 10), has had a major impact on the shape of the land. Fault scarps between blocks sometimes form prominent linear disjunctions across the land surface. The foundering of the Hauraki Rift and its partial filling with sediment from the south has defined the landforms in the south and east of the region.

Coastal sand dune barriers and belts, dune-dammed lakes and inter-dune lakes and swamps are

prominent along the west coast and in the Far North, and in places down the east coast, where narrower coastal sand spits are more common (chapter 11). Some of the flat terraces around the coastline are uplifted or relic intertidal shore platforms or sand flats - the most prominent of which date back to the high sea-level stands of the Last Interglacial (125,000-115,000 yr ago) and the middle part of the present interglacial (7000-3000 yr ago) periods.

As fast as all these various landforms were forming, the processes of chemical weathering and erosion were doing their best to remove them. When rocks are exposed to oxygen from the air, most of their minerals, except quartz, start to oxidise and weather to clays. Clay and rusty-stained iron oxide (limonite) are the usual weathering products, whereas silica and lime dissolve in water and are carried away in solution to the sea. Chemical weathering works its way into the rocks from the outside, as oxygen or oxygen-bearing water penetrates through pores, or along faults and joints in denser rocks. In rocks with widely-spaced joints, the weathering attacks the rock between the joints from all sides, creating onion-skin effects with weathered rock on the outside of each block and hard fresh rock in the centre (a corestone). If these blocks are exposed by erosion, their weathered outsides are quickly removed leaving behind rounded boulders on the hillsides (9.23).

Chemical weathering is faster in warm moist climates like that of northern New Zealand than in colder, drier climates like the central and eastern South Island. Thus in greywacke basement areas of the north, a 5-20 m-thick weathered zone may be present between the surface and fresh greywacke rock at depth (12.1). It takes many thousands of years for such a thick weathered carapace of clay to develop. The nearer to the surface, the more advanced the stage of weathering and the weaker the rock and the more susceptible it is to erosion. Conversely, the faster the rate of hillside erosion, the thinner the zone of weathering that will be present. Erosion is usually fastest on steeper slopes and on exposed coastlines, and thus it is in the incised stream valleys and coastal cliffs where the freshest rocks can be seen, and where they are most often studied and sampled by geologists. Most land erosion in northern New Zealand occurs by water removal of weathered rock and soil particles.



12.1 The 5-20 m-thick orange clay that overlies fresh blue-grey greywacke in the Glenbervie Quarry, Whangarei, indicates the extent of deep weathering that has occurred in northern New Zealand.

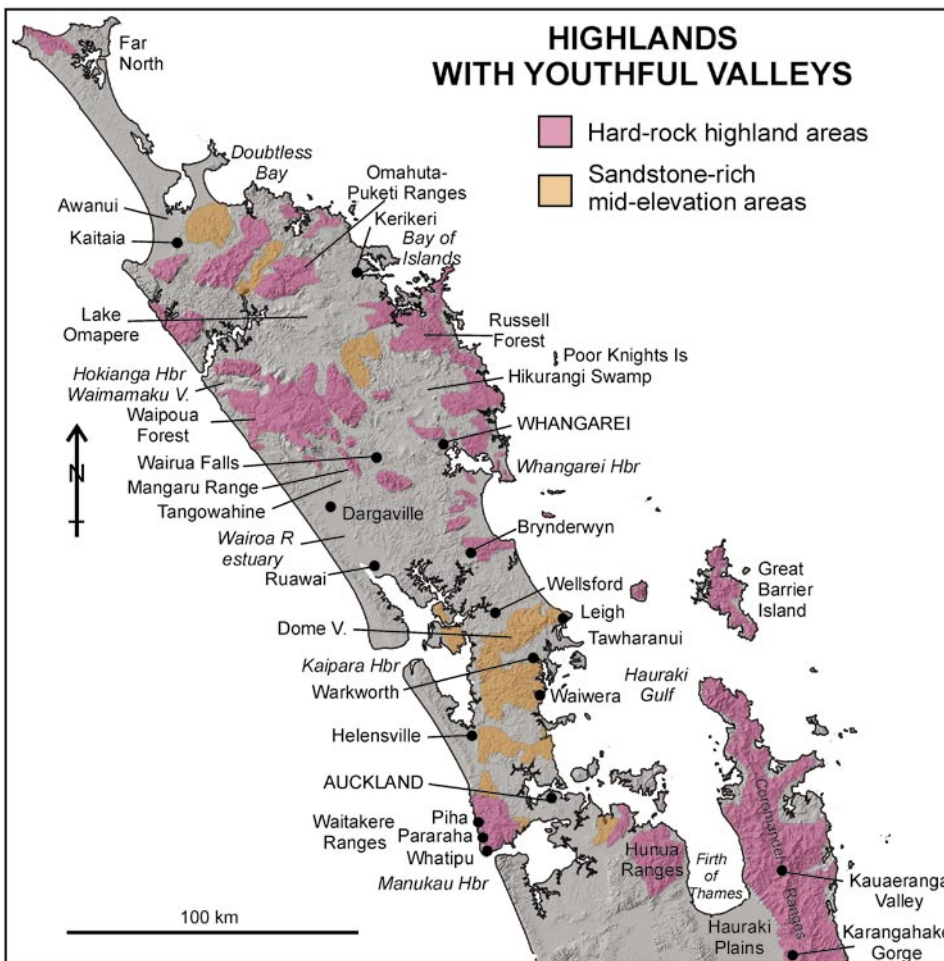
Hard rock underlies the high country

All the uplifted highlands of northern New Zealand are composed of hard rocks - igneous or greywacke. On the other hand, most of the flat and rolling lowlands of Northland and Auckland are underlain by softer sedimentary rocks of the Northland Allochthon (Mangakahia and Motatau Complexes), or the Otatau and Waitemata Groups.

All the hard greywacke highlands once had a thick cover of softer sedimentary rocks, which has been stripped off by erosion, mostly during the formation of the Auckland Erosion Surface. On top of the uplifted and tilted greywacke of the Omahuta-Puketi, Brynderwyn-Whangarei Harbour and Hunua blocks, there are remnants of soft Te Kuiti, Northland Allochthon or Waitemata Sandstone strata, which are still in



12.2 Uplifted high-country blocks in northern New Zealand are dissected by numerous short, youthful stream valleys with gorges, rapids and deep V-shaped profiles. Pararaha Valley, Waitakere Ranges.



12.3 Left. Distribution of hard-rock highlands and sandstone-dominated areas that have youthful valley landforms.

Hunua and Coromandel ranges and Great Barrier Island. All these have been logged in the past, but their steeply-incised stream valleys have not been strongly impacted by increased soil erosion. Thus in the high country the stream valleys are youthful in character, usually with V-shaped profiles. Occasionally there may be near-vertical-sided gorges, where the streams have cut through particularly strong or joint-free rocks (12.7). The uplifted land blocks in northern New Zealand are relatively small and thus they have many short, steep, swiftly-flowing streams and tributaries. The direction of flow of many streams and rivers that drain these highlands reflects the initial uplift and tilt

of the blocks, although a few have antecedent rivers that flow right through them (10.15).

In the high country, most streams have relatively steep courses, often with fresh rocky beds or rapids. Waterfalls are frequent, especially where there are places with harder and softer rocks that have influenced different rates of down-cutting, or where small tributaries join much faster-eroding major streams (12.11). Water flow in a mountain stream may vary from a normal trickle to a raging torrent during high rainfall events. It is during these times of major flood that most erosion and sediment transport occurs (12.5). Much of the sand and mud is carried down to the lowlands and deposited, whereas larger boulders and cobbles are generally left behind and fill the lower reaches of the upland valleys (12.6). Remaining ridge crests and peaks are often composed of the hardest rock types - like the chert and siliceous mudstone units of the eastern greywacke blocks, or thicker lava flows, domes and plugs in the volcanic Coromandel and Waitakere ranges.



12.4 A few stream valleys in central Northland are full of huge basalt boulders that have slid down the valley slopes from eroding basalt bluffs overlying softer allochthonous sedimentary rocks. Wairere Boulders.

the process of being removed by erosion.

The majority of the high country is in forested reserves, particularly the Tangihua blocks in central and western Northland, also Waipoua and Russell forests, the Waitakere,



12.5 Top left. The bed of this small, steep stream has been eroded down to fresh rhyolite bedrock by a flash flood just a few years prior to the photograph. Most erosion and sediment transport out of the uplifted hard-rock blocks in northern New Zealand occurs during high rainfall events. Webbs Stn, Kauaeranga Valley, Coromandel Peninsula.

12.6 Lower left. The beds of streams and rivers draining high-country blocks are often filled with rounded boulders and cobbles, transported down to their lower reaches in flash floods. Kauaeranga Valley, Coromandel Peninsula.

12.7 Right. The Piha Gorge, Waitakere Ranges, is a narrow, 30-80 m-deep, near-vertical-sided cutting through massive volcanic conglomerate with very few joints or other planes of weakness.



12.8 The shape of the rounded high points on Omanawanui ridge, Whatipu (Waitakere Ranges), has been determined by the 40 degree dip to the north (left) of the bedded volcanic conglomerate that they are made of. They have a smooth dip slope to the north and steeper, more-jagged scarp slope on the right.



12.9 Left. The 90 m-high, Waitakere Falls, west Auckland, are held up by hard volcanic conglomerate. The top of the falls may be a nick point that has been slowly migrating back upstream for hundreds of thousands of years. If this interpretation is correct, then the stream profile above the falls was eroded down to a tidal base level, and it and the surrounding Waitakere Ranges have been uplifted subsequently by about 100 m.

12.10 Top right. In this photo the high country hills are composed of erosion-resistant volcanic rocks of Tangihua Complex, whereas the low-lying land is underlain by softer sedimentary rocks of the Northland Allochthon. The whole area was once uplifted to the same height and the present difference in elevation and topographic youthfulness is inferred to be due to much faster erosion of the softer rocks, Tangowahine Valley, near Dargaville.

12.11 Lower right. Owharua Falls, southern Coromandel Peninsula, are held up by erosion-resistant welded ignimbrite. They possibly also exist because the rate of down-cutting of the Ohinemuri River in the Karangahake Gorge, 300 m downstream, is faster than in this small tributary stream.

Many of the valleys in both the harder rocks of the mountains and the softer Waitemata Sandstones that form lower areas, have eroded along fractured fault planes that cut through the rock. This is often recognisable by straight sections of stream valleys, commonly extending across catchments, or by a pattern of numerous parallel streams where there are one or two sets of parallel faults and fractures. Indeed geologists often use the stream pattern to help them recognise and map major faults.

Softer rock underlies the low country

The softer Cretaceous and Tertiary (100-3 Myr old) sedimentary rocks of northern New Zealand can be placed into two land-forming groups – those that contain a significant proportion of more erosion-resistant beds, like conglomerate and cemented sandstone (e.g. Waitemata, Otatau and Parengarenga Groups; Punakitere Sandstone and Tupou Complex in the Northland Allochthon), and the softer, nearly homogeneous mudstone and muddy

limestone of the Northland Allochthon.

Landforms developed in the first group are often influenced by the structure and dip of the more erosion-resistant beds. Smaller streams may flow down-dip through the sequence of strata, but many of the larger streams flow parallel to the strike of the bedding in asymmetric valleys, with gentle dip slopes on one side and steep scarp slopes on the other. Particularly good examples of these asymmetric valleys occur in the gently north- and northwest-dipping Waitemata Sandstone between Waiwera and Wellsford, north of Auckland (5.51). Exceptionally thick and erosion-resistant Waitemata Sandstone beds form the backbone of a high, 25 km-long ridge of land between Leigh, Kaipara Flats, Warkworth and Wellsford. The best known features on this upstanding ridge are the numerous sandstone bluffs and the high points of Tamahanga (behind Matakana) and The Dome (above the Dome Valley on Hwy 1). Another place where sandstone beds (this time in the Motatau

Complex) have helped maintain the elevation of an area of hilly land is between Kaitaia and Doubtless Bay. Early Miocene (20 Myr old) conglomerate beds form ridges and sometimes inland bluffs near North Cape (5.69), south of Hokianga Harbour mouth (13.10) and north of Kaukapakapa.

The second group of softer sedimentary rocks have eroded down much faster, to low-lying rolling countryside. Many of the mudstones in the Allochthon (Mangakahia Complex) contain swelling clays that lubricate downslope movement of the rocks when they are wet. Thus many of the valley slopes underlain by these rocks have characteristic low hummocky topography, produced by widespread low-angle slumping and soil flowage (12.12). This is one of the reasons why many roads in Northland are forever needing repair. In other places, large slumps and slips have blocked valleys, creating natural swamps.

Most of the land underlain by these two groups of sedimentary rocks has been cleared of forest since the arrival of humans. This has greatly increased rainwater runoff and decreased the stability of the soils, which were previously protected and bound together by the forest canopy and roots. As a result, erosion, soil creep and landslides have greatly increased in the last century or so. Eroded mud and sand has built up on the valley floors and stream banks have crept inwards, creating steeper-sided and narrower stream channels that are more prone to flooding. Much mud that has been carried down to the sea has accumulated in the drowned arms of the harbours and helped promote a ten-fold increase in the area of intertidal mangrove forests.

The morphology of the lower reaches of most of the lowland streams and all the larger rivers in northern New



12.12 Hummocky topography produced by slumping and soil flowage of weathered clay-rich mudstone of the Mangakahia Complex is widespread in lowland and hilly areas of central and western Northland. 3 km east of Tangowahine.

Zealand has been strongly influenced by the oscillating base level of the Ice Age sea-level cycles (12.14). The base level is the lowest point to which a stream can flow. In the absence of a major hard-rock impediment, the base level has been sea level. As discussed earlier, the lower reaches of streams and rivers eroded down well below modern sea level during the long periods of lower base level of the climate cycles.

The present character of the lower reaches of these stream valleys, which were drowned by rising sea level after the end of the Last Glacial, has been determined by the local availability of sediment to partly or completely fill them. Initially, about 8000-5000 yr ago, most of the sediment was coastal sand that was thrown up as barriers across the valley mouths. Subsequently, the majority of sediment fill has come from land erosion, with mud and sand transported down the rivers and deposited progressively at base (sea) level at the head of the inlets and estuaries. After heavy rain, rivers flooded right across their low-lying valley floors, depositing fine-grained



12.13 The rounded ridge crests between the stream valleys on Tawharanui Peninsula, east of Warkworth, are probably remnants of the Auckland Erosion Surface that has been uplifted to 70-80 m above sea level. Much of the surface is still present because here it is underlain by hard greywacke with a weathered clay carapace.

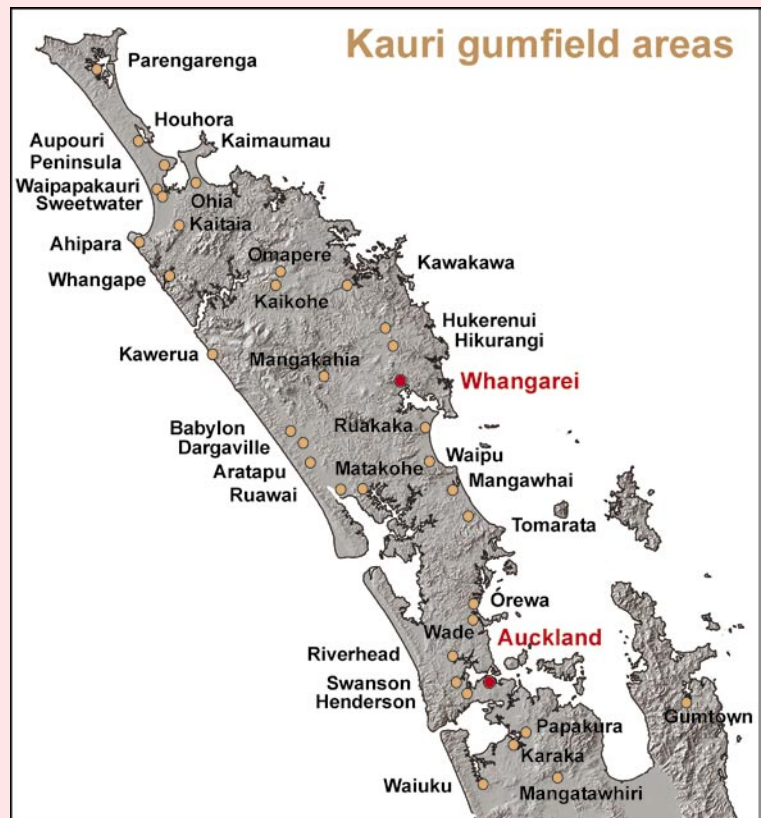


12.14 4 m-high Oakley Creek waterfall in Waterview is the largest waterfall on the Auckland Isthmus. It is held up by several thick Waitemata Sandstone beds and could be the upstream-migrating nickpoint (former base level) from the Last Interglacial high sea level, 120,000 yr ago.

Box 52. KAURI GUM AND THE GUMDIGGERS

Kauri gum is the solidified resin from kauri trees that once grew in vast forests over much of northern New Zealand. The resinous sap slowly oozed through fractures in the bark or even fractures in the centre of the trunk, caused by gales. The gum congealed to form lumps, which eventually fell to the ground and collected in the soil around the base of the trees, or was washed away and floated down streams to accumulate in peaty swamps. The highest quality kauri gum was that collected on the surface or at shallow depths on the hillsides where it had fallen. This was exported to Europe and North America in the 19th century for the production of the highest quality of furniture varnish in the world. Just as the supply of this pure gum was running out, about 1910, it was discovered that the vast supply of discarded lower-quality gum chips and waterlogged gum from the swamps was a suitable ingredient in the manufacture of linoleum, and so the life of the gumfields was extended by several decades. In the 1930s, kauri gum's importance in the manufacture of varnish and linoleum was displaced by synthetic alternatives, and the industry declined through to the 1950s.

Between the 1850s and 1950s, 450,000 tons



12.15 Above. Location of many of the more important gum digging areas in northern New Zealand, 1850s-1950s.



of kauri gum had been exported out of Auckland, and for 50 years prior to 1900, gum was Auckland Province's most valuable export, ahead of kauri timber, gold and wool. During the peak of the gumdigging industry, about 1900, there were 20,000 gumdiggers on 300,000 ha of gumfields in Northland and Auckland.

The larger lumps of gum were usually the purest and highest value and so, prior to the 1910s, most buried gum was located by gumdiggers working alone or as partners. They used a gum spear that was plunged into the ground until it hit a hard lump of gum, which was then dug out with a spade. On the hillsides, most gum was less than a metre below the surface, but on the alluvial flats and in the peat swamps gum could be found 5 m or more below the surface. Once the smaller pieces of gum also became saleable, the whole scale of gumdigging changed. Teams of gumdiggers were formed and together they would systematically dig through

12.16 The search for kauri gum was rather like a gold rush and attracted many itinerants and new immigrants. This group of Dalmatian gumdiggers have dug a 4 m-deep hole in swamp sediment in their search for high quality kauri gum, near Awanui. Photograph from *Weekly Graphic*, 1909.

Box 52 continued

the sedimentary deposits of an entire swamp or alluvial flat. The pay-dirt was shovelled into engine-driven tub washers, which had steel agitators to break up the soil, and a stream of pumped water to wash away the fines that passed through the sieve in the bottom of the tub. The coarse material retained on the sieve was further “refined” by drying it in the sun and then winnowing it by tossing it into a gentle breeze, which blew away the lighter foreign material.

The kauri gum-digging industry brought many Dalmatian immigrants to northern New Zealand. It also resulted in the



12.17 A large piece of high quality kauri gum.

permanent draining of much of the swampy land, which was then turned into pasture for farming.

sediment that has gradually built up the fertile alluvial flood plains, just above sea level (12.18). Aggradation and seaward extension of these coastal flood plains has been accelerated by clearing of the forests since the arrival of humans, 800-700 yr ago. Seaward extension of these flood plains has largely halted today, as a result of the rapidly rising sea level of the last century or so.

FLOOD PLAINS

Many of the valleys in low-lying country, and those flowing through wide coastal plains, have the characteristic form of mature rivers and streams. They have wide, flat alluvial plains traversed by meandering, tidally-influenced rivers and streams with steep muddy sides (12.19). In some places, humans have tried to lessen the impact of floods by constructing banks beside the river, or by straightening its course with artificial channels dug to bypass large meander loops. The largest alluvial plain in northern New Zealand is the Hauraki Plains (12.20). Here the northern part of the plain has built seawards under the control of modern sea level by

at least 40 km in the last 10,000 yr. Other large coastal alluvial plains are at Ruawai at the mouth of the Wairoa River (12.18), and north of Kaitaia at the mouth of the Awanui River.

In some valleys there may be a modern flood plain and one or more river terraces at higher levels. These are eroded remnants of earlier flood plains formed when the base level was higher relative to the land, or the stream profile was gentler due to much greater sediment supply. The most recent period of much higher base level was during the Last Interglacial peak, 125,000-115,000 yr ago, when sea level was 5-6 m above present. Parts of some streams around northern New Zealand still retain profiles and features inherited from this, or earlier times of higher base level (12.14). Well upstream, above modern base level, some valleys have remnant sections of fluvial terrace of even, flat-topped ridge and spur crests on the valley sides. These may relate to much earlier times when higher sediment supply filled the valley, or when the stream erosion level was controlled by sea level, and the whole area has subsequently been uplifted.

12.18 View north up part of the tidal estuary of the mature Wairoa River, where it flows through its fertile alluvial plain south of Dargaville. This plain was built by sediment deposited by overbank floods in the last 7000 yr. These Ruawai plains are now the centre of kumara growing in New Zealand. Photographer Alastair Jamieson.





12.19 The meandering courses of the mature lower sections of the Kaipara (foreground) and Kaukapakapa rivers (left) as they flow across their alluvial flood plains (less than 7000 yr old). The town of Helensville is in the centre.



12.20 View east across the Hauraki Plains, with the uplifted Coromandel Ranges beyond. This 100 km-long by 20 km-wide plain is underlain by sediment that has been deposited in the head of the actively-subsiding Hauraki Rift in the last 2-3 Myr. The alluvial and estuarine sediment that forms the surface of this northern end of the plain was deposited by floodwaters over the past 7000 yr, under the influence of the modern sea level.

INFLUENCE OF VOLCANIC ERUPTIONS ON STREAM VALLEYS

In addition to the primary volcanic landforms created by young volcanicity in northern New Zealand, the eruption of lava, scoria and ash also influenced some non-volcanic landforms. For example, the eruption of Tank Farm and Onepoto tuff rings (9.70) about 200,000 years ago, at Northcote in Auckland, dammed the Wairau Valley that previously had flowed into Shoal Bay (Waitemata Harbour). A 3 km-long shallow lake (later a swamp) was formed, and the stream was diverted east around the north side of Lake Pupuke tuff ring, to flow into the Hauraki Gulf at Milford Beach.

Lava, erupted from a number of Northland and Auckland's younger basalt volcanoes, flowed down valleys before stopping, cooling and leaving a ribbon of solid basalt rock filling the former stream course. If the water flow in the lava-filled valley was relatively small, it took to flowing underground through the cooling cracks of the solidified flow. Where the water flow was larger, the stream sometimes started flowing down one or other side of the flow and carving a new course into the softer rock of the valley sides (e.g. Oakley, Meola and Motion creeks in Auckland; Wairua River (12.25), west of Whangarei. In other places, the larger rivers have continued to flow on top of the lava flow. Over tens to hundreds of thousands of years these rivers have eroded the lava flow back in an upstream direction, with a waterfall over the retreating scarp. Being an erosion-resistant, but jointed rock, most retreat has been by erosion of softer valley-floor sediment beneath the flow. This has undermined the basalt, and joint-surrounded blocks have progressively fallen out and been carried away. Prominent examples of this are Rainbow (12.21) and Haruru falls (9.18) in the Kaikohe-Bay of



12.21 Rainbow Falls, Kerikeri, flow over the edge of a 4 Myr-old basalt lava flow.

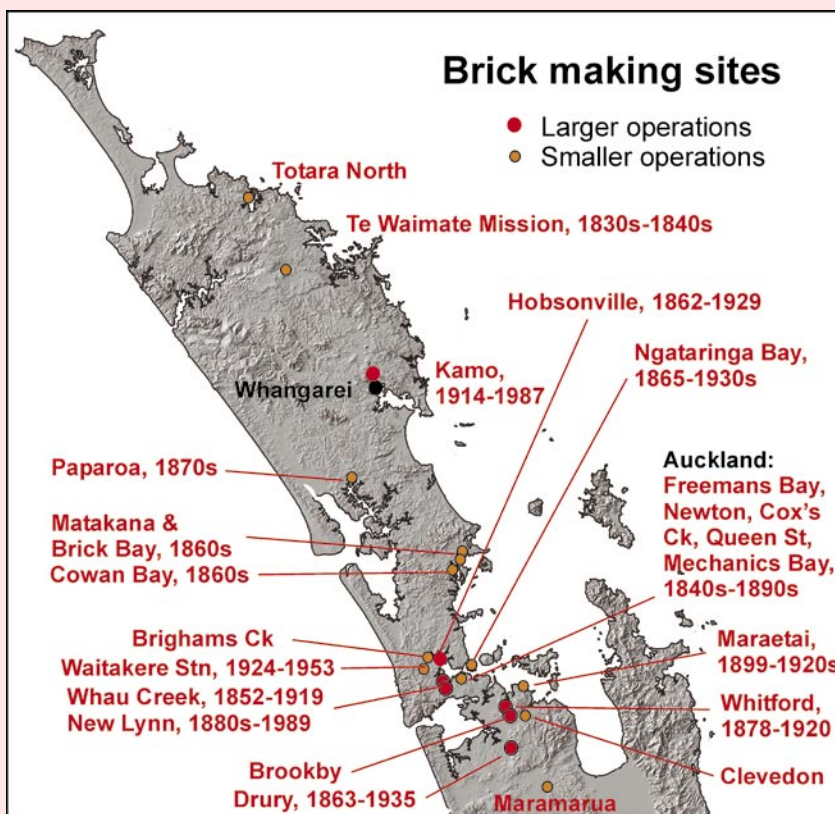
Islands Field, and Whangarei (9.43) and Paranui falls in the Whangarei Field.

Some lava flows created dams across tributary valleys, or between the flow and a valley's side. In Auckland city, there are many examples of lava-flow-dammed ponds and wetlands that were unsuitable for development, but have now been drained for use as reserves or major sporting arenas (e.g. Waiatarua Reserve, Eden Park, Ellerslie Racecourse). More substantial lava flow-dammed lakes occur in Northland with Lake Ora (13.17) in the Whangarei Field and Lakes Omapere (9.63), Owhareiti (9.33) and Tauanui (9.36) in the Kaikohe-Bay of Islands Volcanic Field. Perhaps the most significant result of basalt lava damming a major river valley was the creation of the huge 20 km-long Hikurangi Swamp (12.24), when lava flows from Whatitiri shield volcano poured down the Wairua River valley, west of Whangarei.

Box 53. CLAY AND BRICK MAKING

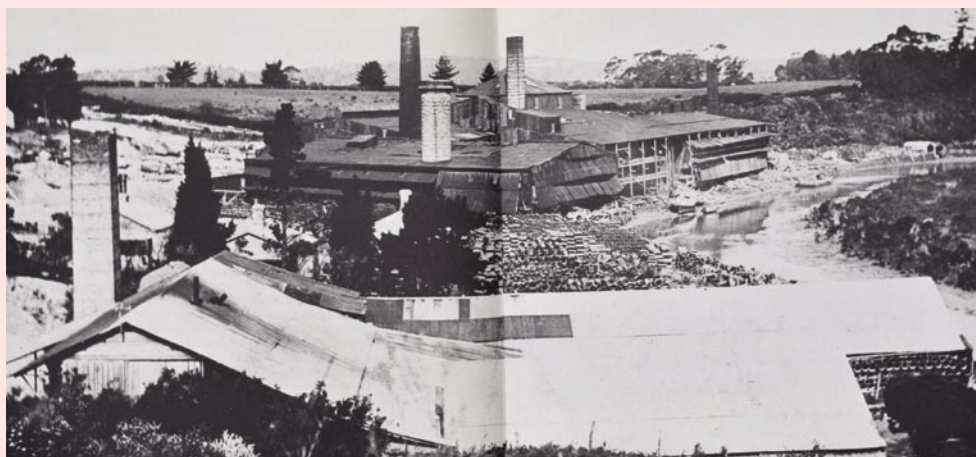
Kaolinite is the main clay that has been used for the manufacture of bricks, tiles, pipes, ceramics and pottery in northern New Zealand. Clay is a soft, fine-grained material which, when mixed with water, can be made plastic and moulded into shapes. When dried and fired, it hardens into the various products we use. Kaolinite is a hydrous aluminium silicate, $Al_4(OH)Si_4O_{10}$. In northern New Zealand, it has been formed by weathering of clay-rich basement argillite (e.g. Whitford, Maraetai, Brookby), weathering of Waitemata Sandstone (e.g. early Auckland), weathering of softer Pleistocene mudstone (e.g. New Lynn, Hobsonville, Ngataringa Bay) or by acid leaching of mudstone associated with coal measures to produce fireclays (e.g. Kamo, Drury, Maramarua).

Bricks are made from a mixture of kaolinite clay and sand with some iron-containing matter. In the early period of European colonisation of Northland and Auckland (1800s-1840s), most bricks were imported from Australia and England, but small-scale temporary brick kilns were used wherever



12.22 Location of significant brick-making yards in northern New Zealand since the 1830s.

there was suitable clay and demand for bricks. The first permanent brick kilns were probably established about 1833 at Te Waimate Mission Station in Northland, and 1847 in Freemans Bay and the Queen Street valley, Auckland. In the 1850s-1860s, larger brickworks were established around the shoreline of the upper Waitemata Harbour at Whau Creek and Hobsonville, on kaolinite deposits derived from weathering of Pleistocene non-marine mudstone. The opening of the railway line north of Auckland in 1881 started a shift to clay mining in the headwaters of the Whau in the New Lynn-Avondale area, and establishment of New Zealand's largest brick-making and pottery centre, which finally closed as suburbia overtook it, in 1989. Many other brickworks were established and operated around Auckland in the late 19th and early 20th century. There were 105 brick, tile and pottery works in Auckland between 1840 and 1930. The best known brickworks in Northland was at Kamo, where the coal measure clays were used to produce high quality crucibles and firebricks.



12.23 Clarks pottery on the shore of Limeburners Bay, Hobsonville, Waitemata Harbour, in the 1910s. John T. Diamond collection.

12.24 Right. Hikurangi Swamp, northwest of Whangarei, is the largest swamp in northern New Zealand. It was created by the damming of the Wairua River valley by lava flows from Whatitiri shield volcano, about 500,000 yr ago. Photographer Alastair Jamieson.



12.25 Left. Wairua Falls, 20 km west of Whangarei, flow over the edge of a hard basalt lava flow erupted from Whatitiri shield volcano. The Wairua River which flowed down over the valley-filling lava flow, subsequently shifted sideways off the basalt and eroded a 3 km-long gorge in the softer rock on the eastern side of the former valley. The falls are where the river currently runs over the edge of the flow and into the gorge. Since 1920, most river water has been diverted around the falls to a hydroelectric station, to generate electricity for Portland Cement Works, and the falls only flow in wet weather.

Box 54. SWAMP KAURI DEPOSITS

Kauri (*Agathis australis*) is New Zealand's longest-living (up to 2200 yrs) and largest (up to 5 m diameter trunks) native tree. When humans arrived in New Zealand, it was one of the dominant forest types in northern New Zealand, with a natural southern limit from Kawhia across to the Kaimai Ranges (38°S). Its long, straight trunk, lacking knots, made it a favoured timber for building, and most of the forests were logged in the 19th and early 20th centuries. Today most felling of living trees is prohibited, but valuable logs are still being extracted from peaty swamp deposits, mostly in Northland. These logs contain perfectly preserved wood from trees that lived many thousands of years ago.

In forests there is a natural procession of old trees dying, falling over and rotting away, and being replaced by new trees. Only in special conditions is the wood of fallen trees preserved, usually by being submerged in water, often in a peat swamp, where all oxygen is excluded and decay does not occur. In northern New Zealand, there are many examples of logs (late Quaternary, younger than 1.5 Myr) that have been preserved in peaty swamps and not buried deep enough to become carbonised. These swamps usually occurred on valley floors or in sand-dune hollows, mostly in the west coast sand-dune barriers. Some of the oldest examples (~1 Myr) occur around Auckland as in-situ fossil forests and logs within peat and rhyolitic ash sequences at Te Atatu, Takapuna Beach, Tamaki Estuary, Takanini and Waiuku (10.30). None of these contain large kauri-tree logs or stumps. One of the oldest swamp kauri deposits, in which large fallen kauri trunks predominate, is eroding out of peat at Ihumatao on the Manukau Harbour flats near the airport (12.27).

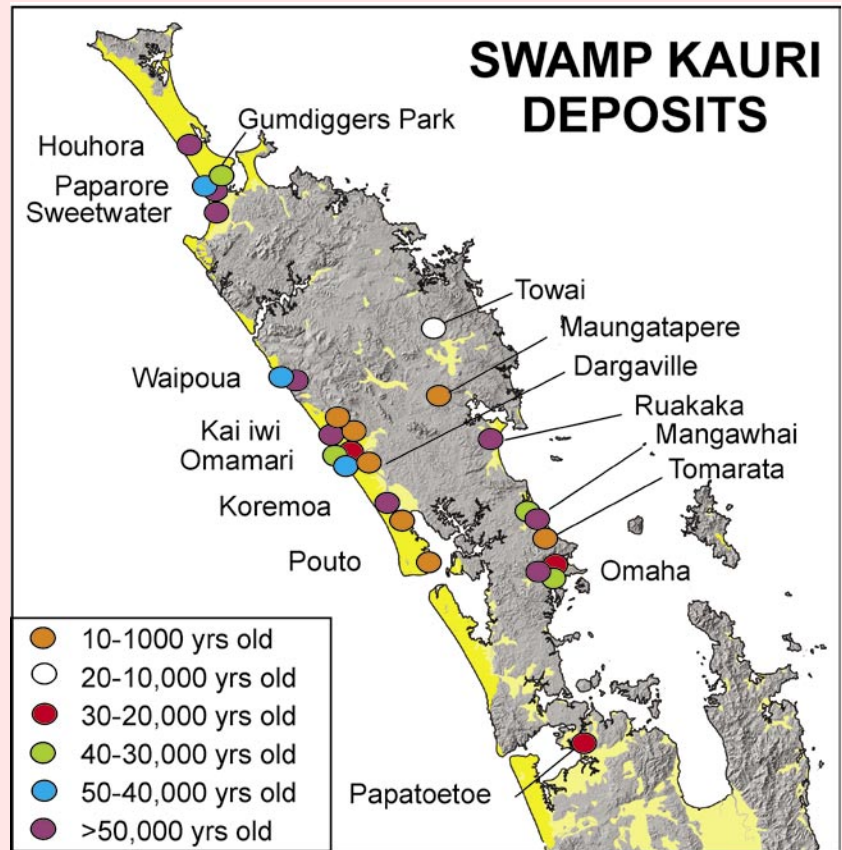
The swamp kauri deposits, from which kauri logs have been harvested, are all thought to be younger than 100,000 yrs. Many are young enough (less than 50,000 yr old) to be reliably dated by modern radiocarbon methods. The age range and distribution of swamp kauri logs (12.26) shows a wide spread of ages older than 30,000 yrs and younger than 10,000 yrs. There are few logs dated between 25,000 and 12,000 yrs old, undoubtedly because this was the peak cold of the Last Glacial

Box 54 continued

period, and the northern kauri forests were reduced to a few small surviving remnants, probably confined to northern Northland. Kauri requires a mean temperature of 17°C or more for the majority of the year. The composition of the northern forests changed during the Last Glacial, with southern forest types replacing the more subtropical.

The discovery and extraction of swamp kauri logs from one or more distinct layers within swamps has led to many hypotheses as to how and why these kauri forests died. Many of the local explanations have grown into Northland folklore and invoke giant tsunami waves, mega-hurricanes, meteor impacts or giant volcanic eruptions and ash clouds. One reason for these explanations is that often it appears that a single event has felled the trees at one site. Radiocarbon dating of the logs usually shows, however, that the death of the trees in each deposit occurred over several thousand to tens of thousands of years, and the peat accumulation that buried them was extremely slow. In a few places, there are several distinct periods of kauri growth, death and recolonisation that show that the forest history was not just an even-paced continuum.

Hurricane winds, tsunami and meteor impacts would be expected to knock most trees over in one direction, but studies show that this was seldom the case, although there is sometimes a preferred orientation that could correlate with the dominant local direction of strong gales. To be preserved in the swamp peats, kauri trees need to have fallen into the water and been submerged.



12.26 Distribution of swamps containing kauri logs that have been radiocarbon dated. Data from Turney et al. (2007), Boswijk et al. (2014).



12.27 The parallel-sided trunk of a 2 m-diameter kauri log eroding out of an old peat swamp deposit on the foreshore at Ihumatao, Manukau Harbour. The preserved logs and stumps in this locality are legally protected and should be viewed but not sampled.

There are no rivers large enough to have transported these fallen giants into the swamps, so they must have been living on or directly beside the swamps. Kauri do not generally grow in water-logged swamp conditions, and thus the most likely explanation for most of the kauri swamp deposits of logs and in-situ stumps appears to be that they result from periodic changes in local drainage. Blocked drainage could create a swamp that might flood through a growing kauri forest, resulting in the death of the trees, which could then blow over in strong winds with some ending up part submerged and preserved by the water. A subsequent period of dryer conditions, possibly a result of drainage changes, would allow for another generation of trees to colonise the site.

Chapter 13. LOCAL MAP GUIDES TO FEATURES OF INTEREST

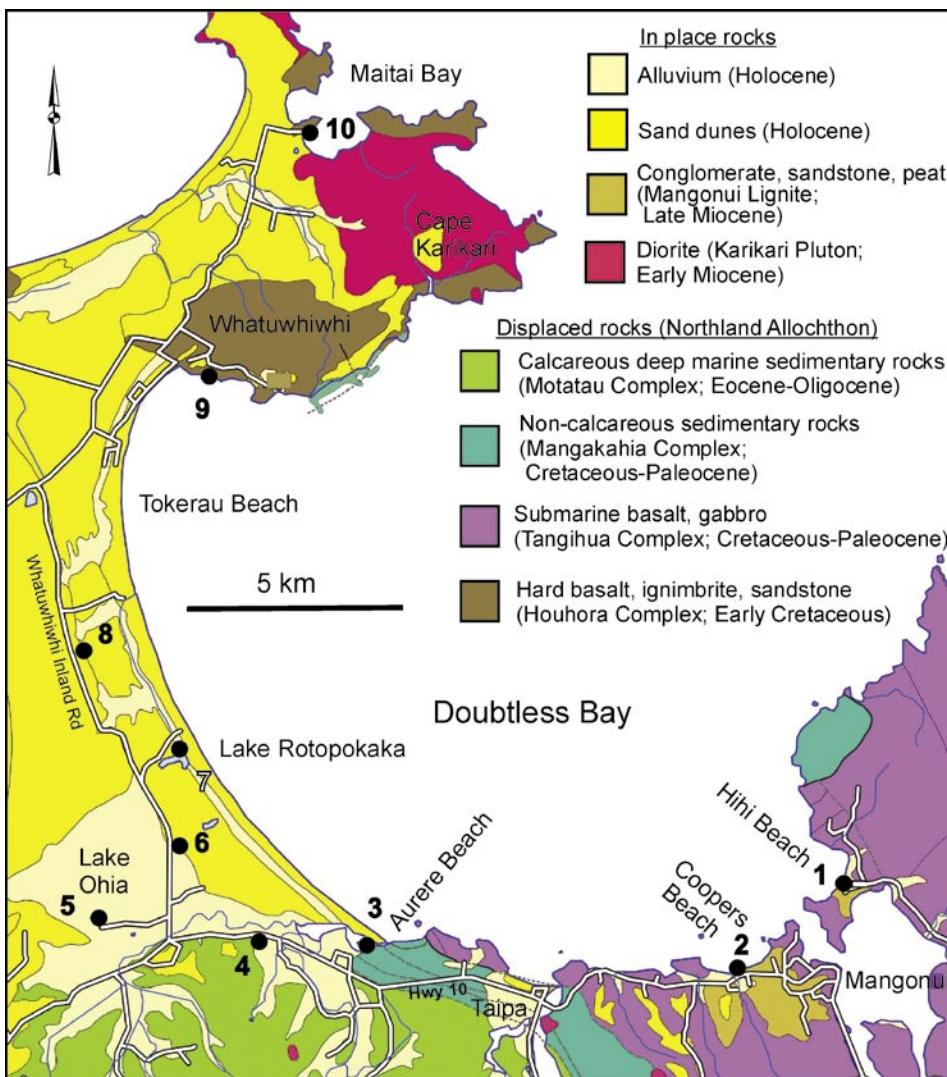


13.1 Location of local guide maps.



13.2 The rocky cap of St Paul's Rock towers above the small seaside town of Whangaroa. It is easily ascended to give panoramic views of Whangaroa Harbour and district (13.7).

DOUBTLESS BAY



sometimes exposed in the beach when the sand shifts.

3. Aurere Beach (4.16, 13.4)

From end of Aurere Beach Rd, walk on firm sand around seaward side of mangroves and alongside estuary to Aurere Beach. Late Cretaceous pebble conglomerate just inside estuary mouth; sandstone, mudstone and spherical concretions (Maungakahia Complex) across front of beach; pillow lava (Tangihua Complex) with intercalated red argillite at southeast end of beach. Only accessible 2 hrs either side of high tide. Allow 2 hrs return.

4. Ohia black shale (13.3)

Pull off Hwy 10 at entrance to old quarry, 2 km east of Whatuwhiwi Rd turnoff. Easily accessible cuttings on eastern side of entrance to old quarry are composed of Waipawa Black Shale, about 60 Myr old. Rub two bits of the dark chocolate mudstone together and get the hydrocarbon smell, like kerosene.

1. Hiji Beach Late Miocene fluvial valley fill (8.14)

In cliffs and shore platform at low tide behind southern end of Hiji Beach. A 100 m-wide valley cut into the underlying hard Tangihua Complex. Valley filled with Late Miocene bedded conglomerate and minor sandstone with occasional fossil logs. Scattered knobbly, rusty brown, siderite concretions have formed in the upper parts of Tangihua rocks.

2. Coopers Beach fossil coconuts and Late Miocene fluvial sediments (8.12, boxes 32, 33)

Fossil coconuts and other seeds are sometimes found washed up at the east end of Coopers Beach. They erode out of a Late Miocene (12-8 Myr old) sequence of sandstone, gravel, woody lignite and mudstone that forms the banks at the back of the beach and are



13.3 Dark mudstone of Paleocene (60 Myr old)
Waipawa Black Shale is exposed in old quarry cuttings beside Hwy 10.



13.4 Sandstone beds of Mangakahia Complex form the intertidal platform at Aurere Beach. A small gravel tombolo connects Puketū Island to the beach at low tide.

5. Ohia gum holes

On the east side of Whatuwhiwhi Inland Road, 2 km from turnoff from Hwy 10. Small parking area and 5 min walk through area of holes left by kauri gum diggers.

6. Lake Ohia drowned kauri forest (13.5)

Signposted on north side of Lake Ohia Rd, 1.5 km from junction with Whatuwhiwhi Inland Rd. Short walk to bed of seasonal Lake Ohia, where there are numerous protruding stumps of kauri trees that lived in the Late Pleistocene. They were killed when Lake Ohia formed and have been preserved by the winter water cover. Visits best in summer when lake bed is dry.

7. Lake Rotopokaka (Lake Coca-Cola)

Near end of Ramp Rd, on east side of Whatuwhiwhi Inland Rd. A Holocene dune lake named for its tea-like tannin-rich waters derived from the surrounding peatland.

8. Karikari tombolo and sand dunes (11.53)

View as you drive along Whatuwhiwhi Inland Rd. The tombolo is a composite of sand dunes that has been built during stands of higher sea level over many Ice Age climate cycles. The oldest part of the tombolo, built more than 200,000 yr ago, is on the west side of the road, whereas the east side has two dune belts from the Last Interglacial and the Holocene.

9. Whatuwhiwhi Early Cretaceous sedimentary rocks and pillow lavas (4.4)

Rocks at west end of Parakerake Bay are composed of hard, thin-bedded sandstone and mudstone (Tokerau Formation, Early Cretaceous) overlain and interfingering with beautiful basalt pillow lava. Section is intruded by 4 m-thick dike of microdiorite (Early Miocene age).

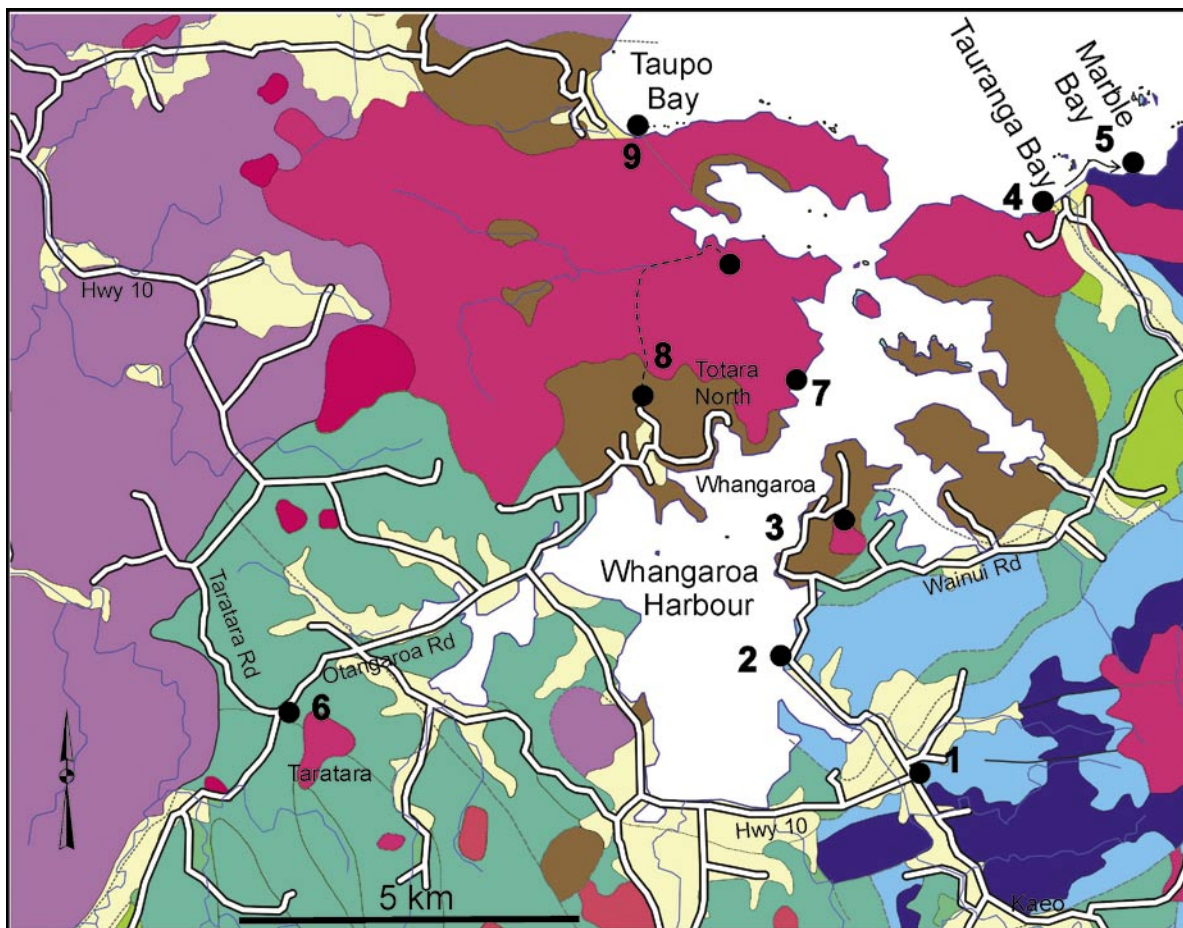
10. Maitai Bay Early Miocene pluton (6.55)

Walk south along beach to rocky points composed of quartz diorite (speckled black and white crystals) of Karikari pluton. Mid-low tide, 30 mins-1 hr return. Point between the two main beaches is hard Early Cretaceous sandstone and mudstone (Houhora Complex).



13.5 The stump of a large kauri tree is one of many in the 30,000 yr-old Lake Ohia drowned kauri forest.

WHANGAROA



In place rocks	Displaced rocks (Northland Allochthon)
Alluvium (Holocene)	Calcareous deep marine sedimentary rocks (Motatau Complex; Eocene-Oligocene)
Andesite volcanoes (Early Miocene)	Non-calcareous sedimentary rocks (Mangakahia Complex; Cretaceous-Paleocene)
Greensand, mudstone (Te Kuiti Group; Late Eocene-Oligocene)	Submarine basalt, gabbro (Tangihua Complex; Cretaceous-Paleocene)
Greywacke (Waipapa Terrane; Permian-Jurassic)	Hard sandstone, conglomerate, mudstone (Houhora Complex; Early Cretaceous)

1, 2. Greensand near Kaero (13.6)

In road cutting opposite east end of Kaero River bridge on Hwy 10 (1) and in low seacliff on bend of Whangaroa Rd (2). Thick beds of 35 Myr-old (Late Eocene) glauconitic sandstone (Ruatangata Sandstone, Te Kuiti Group).

3. St Paul's Rock, Whangaroa (13.2, 13.7)

30 min climb on steep formed track to top from crest of Old Hospital Rd. An erosional remnant of the ring plain of the 20 Myr-old Whangaroa stratovolcano. Panoramic views over harbour and hinterland.



13.6 A thick bed of 35 Myr-old greensand in a road cut by the bridge turnoff on Hwy 10, 2 km north of Kaero.



13.7 View north over the Whangaroa Harbour from the top of St Paul's Rock. All the forested hills in the distance are composed of laharic breccia from the 21-18 Myr-old Whangaroa Volcano.

4. Tauranga Bay lava flow and lahar breccia (13.8)

Halfway up the cliffs above the west end of Tauranga Bay and campground. Subvertical columnar-jointed andesite lava flow in a paleo-gully eroded in laharic breccia deposited on the Whangaroa stratovolcano ring plain.

5. Marble Bay Waipapa Terrane (2.20)

Clamber around greywacke rocks at the east end of Tauranga Bay and along the beach to the east end to see Permian pillow lava, and cream, pink and green marble containing the oldest fossils in the North Island. 1 hr return. Only visit 2 hrs either side of low tide.

6. Taratara butte (6.52)

Remnant of Early Miocene (20 Myr old) Whangaroa stratovolcano ring plain composed of layers of andesitic lahar breccia. Track starts 200 m east of junction of Otangaroa and Taratara roads. Follow bulldozed track through scrub and private farmland around to east side of Taratara, then up grass trail to saddle and steep track through scrub to top (slippery when wet). Panoramic views to Late Miocene erosion surface on skyline in most directions. For experienced trampers only, 2 hrs return.

7. Whangaroa Harbour lake beds (6.53)

Access by boat at low tide. Bedded lake sediments with tightly-folded slumped bed, deposited in a small lake early in the history of eruption of Whangaroa Volcano (20 Myr ago).

8. Dukes Nose track (6.54)

Track starts at end of Wairakau Rd, off Campbell Rd. 2 hrs tramp over 200 m-high ridge to Lane Cove on Whangaroa Harbour. 15 mins more to top of Dukes Nose with spectacular views of Pekapeka Arm, which is surrounded by bluffs and rocky knolls of Early Miocene laharic breccia. Alternative access to Lane Cove, one or both ways by water taxi from Whangaroa.

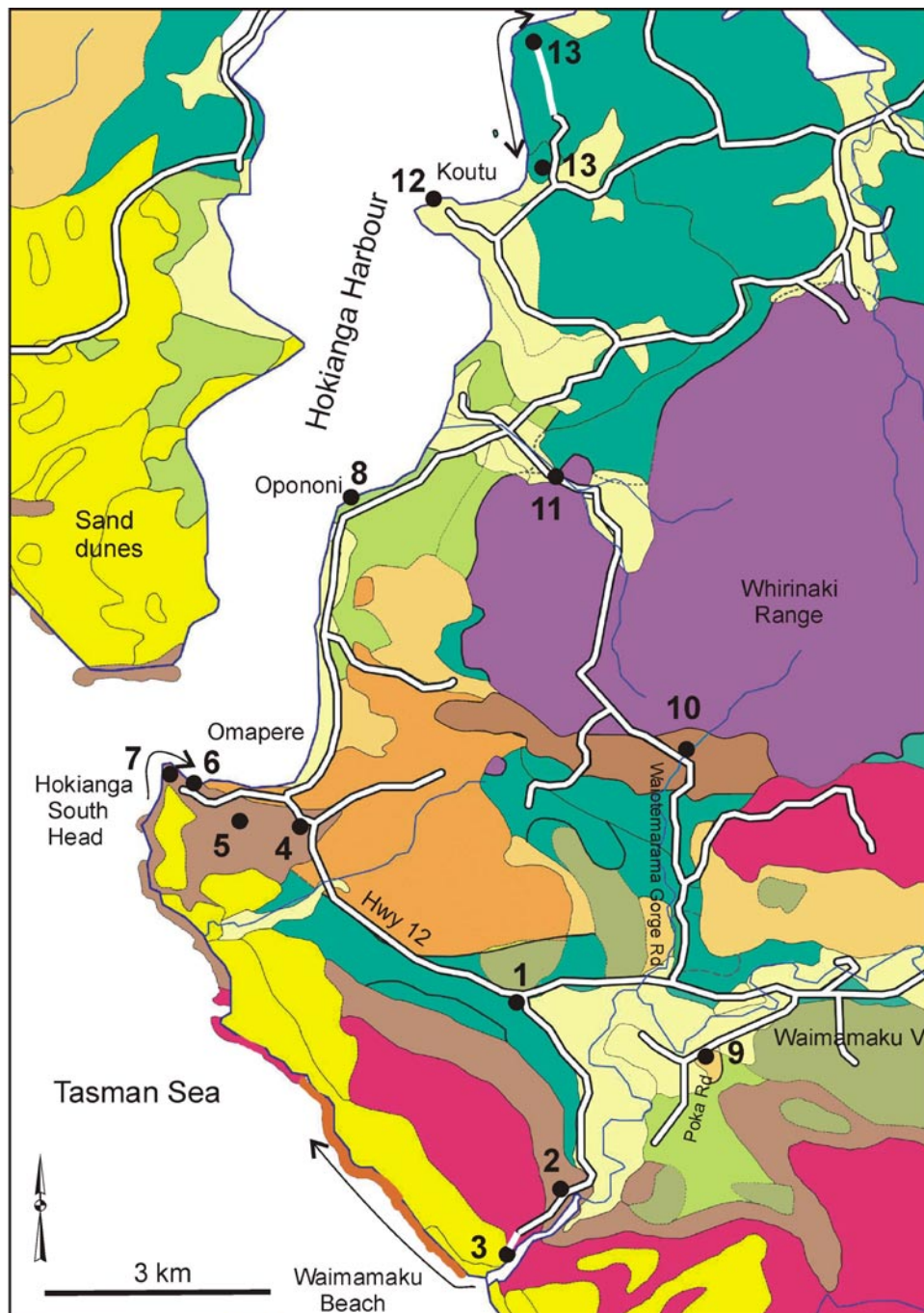
9. Taupo Bay laharic breccia (6.51)

Low tide clamber around rocks at the south end of bay to see andesitic breccia deposited by lahars on the ring plain of the Early Miocene Whangaroa stratovolcano. The breccia contains cobbles and pebbles of coarse- and fine-grained andesite, as well as those derived from the underlying rocks, especially Tangihua Complex.



13.8 Cliffs at the west end of Tauranga Bay, with columnar-jointed lava flow filling a paleo-gully (white line) in the ring plain of the Early Miocene Whangaroa stratovolcano.

COASTAL HOKIANGA



Alluvium	Sand dunes	In place rocks	
Landslide deposits		Conglomerate & lignite (Pukorukoru Formation; Early Miocene)	
Displaced rocks (Northland Allochthon)		Basalt lava flows (Waipoua Basalt; Early Miocene)	
Calcareous deep marine sedimentary rocks (Motatau Complex; Eocene-Oligocene)		Omapere Conglomerate (Otatau Group; Early Miocene)	
Non-calcareous sedimentary rocks (Mangakahia Complex; Cretaceous-Paleocene)		Waiwhatawhata Conglomerate (Otatau Group; Early Miocene)	
Submarine basalt, gabbro (Tangihua Complex; Cretaceous-Paleocene)		Mudstone & sandstone (Otatau Group; Early Miocene)	

1. Waimamaku Beach Rd – Hwy 12 junction

The bumpy land extending up Hwy 12 to the northwest is slowly slumping Cretaceous-Paleocene sedimentary rocks (Mangakahia Complex) of the Northland Allochthon.

2. Waimamaku Beach Rd gorge (5.73)

As you approach the coast, the Waimamaku River passes through a gap in the hills. Here you can clearly see the southwest-dipping Early Miocene sequence of allochthon-derived Omapere Conglomerate overlain by three basalt flows from the Waipoua shield volcano.

3. Waimamaku Beach fluvial conglomerate and fossil trees (6.47-6.49)

Walk north up beach from Waimamaku River mouth, 3 hours either side of low tide. Shore platforms are conglomerate and sand (Pukorukoru Formation) with cross-bedding, lensing and some silicified logs, all deposited on a coastal flood plain during the Early Miocene (~18 Myr ago). These were deposited on top of Waipoua Basalt flows and contain abundant basalt pebbles. Between 30 mins and 1 hr walk up the beach the sequence contains more sand, laminated mud and some peat. There are numerous small tree stumps in growth position where they have been buried by flood gravels.



13.9 Across the Hokianga Harbour entrance from Omapere, these quartz and feldspar sand grains have been blown inland from the back of the exposed west coast beach to create this spectacular, 150 m-high orange sand dune barrier.

4. Omapere Hill view of sand dunes and Warawara Range (8.6, 13.9)

High sand dunes on the north side of Hokianga Harbour mouth have been thrown up by the sea and wind in the last 7000 yr. Beyond is the uplifted Warawara Range composed of Tangihua Complex (Northland Allochthon). The flat topped portion is a remnant of the Late Miocene Auckland Erosion Surface.

5. Patipatiarero rock, Hokianga South Head (13.10)

Best viewed from the Signal Station Rd turnoff from the main Hwy. Narrow, steep-sided, rocky knoll on ridge crest, composed of layered Early Miocene Omapere Conglomerate. Vertical northern face is where large blocks broke off the ridge along a vertical fracture plain and long ago rolled down the hillside.

6. Martins Bay Early Miocene fossils (13.11)

Take walking track from carpark at end of Signal Station Rd down to Martins Bay to the north. See fossil fan corals and broken up shell (Early Miocene, 20 Myr old) in mudstone at back of beach. Beds rich in large foraminifera (1 cm diameter discs; “Orbitolite sandstone”) occur at east end of beach next to small stream gully. Mid-low tide.

7. Hokianga South Head conglomerate (13.12)

Walk from carpark at end of Signal Station Rd to lookout over Hokianga Harbour mouth with views up and down coast. Headland is composed of layered conglomerate (20 Myr old) that accumulated on the submarine front of a small river delta. Cobbles were eroded from Northland Allochthon (mostly altered basalt and diorite from Tangihua Volcanics). Take Waimamaku Coast Track



13.10 Patipatiarero (“the upthrust tongue”) is a steep-sided rocky knoll composed of layered Early Miocene Omapere Conglomerate that towers over Hokianga South Head.



13.11 Above left. View of Martins Bay, with Hokianga South Head (right) eroded out of Early Miocene Omapere Conglomerate. The “Orbitolite Sandstone” occurs in the intertidal rocks at the west end of the bay (lower left). Photographer Alastair Jamieson.

13.12 Above right. Omapere Conglomerate can be seen close up around the foreshore of Hokianga South Head. It was composed of a wide range of cobbles and pebbles eroded from Northland Allochthon and the active Hokianga Volcano.

down to first beach on outside of head to see conglomerate close up. If tide is low, turn right and walk around rocks back to Martins Bay inside harbour. Note presence of interbedded thin-beds of mudstone and sandstone that contain marine microfossils and shell fragments.

8. Opononi wharf limestone and sandstone (4.54)

In mid-tide foreshore, 50 m northeast of boat ramp opposite Opononi Hotel. Exposure of laminated muddy limestone that accumulated as calcareous ooze on the floor of the ocean during the Oligocene (~30 Myr ago). It also contains a 2 m-thick unit of bedded glauconitic sandstone that had slid down into the deep ocean floor from shallow water on the edge of ancient Zealandia. These beds are part of the Motatau Complex of the Northland Allochthon.

9. Poka Rd Late Oligocene sandstone (13.13)

Roadside bluff and farm road cutting made of hummocky cross-bedded sandstone (24 Myr old) with small fossils and pebbles of allochthonous sedimentary rock. This was deposited in a submarine channel on the front of the advancing Northland Allochthon before being overridden and swept up into the allochthon itself.

10. Waitemarama Waterfall (13.14)

10 min walk each way from carpark on Waitemarama Gorge Rd. Waterfall pours over Early Miocene Omapere Conglomerate.

13.13 Roadside bluff of Late Oligocene (24 Myr old) hummocky cross-bedded sandstone that is inferred to have accumulated in front of the advancing front of the Northland Allochthon.





13.14 Above left. Waiotemarama Falls and boulders of 20 Myr-old Omapere Conglomerate.



13.15 Above right. The intertidal rock platforms at Koutu Pt are composed of 30 Myr-old muddy limestone of the Northland Allochthon. Uninterrupted views west to the mouth of Hokianga Harbour with high sand dunes of young age (last 8000 years) on north side (right).

11. Waiotemarama Rd Tangihua Complex rocks

Two former quarries on either side of road bridge worked altered basalt of allochthonous Tangihua Complex that has been pushed up to create the Whirinaki Range to the south and east.

12. Koutu Point muddy limestone (13.15)

Access to the coast at mid-low tide via boat ramp at end of Koutu Pt Rd. Intertidal reefs of steeply-dipping Oligocene muddy limestone (Motatau Complex).

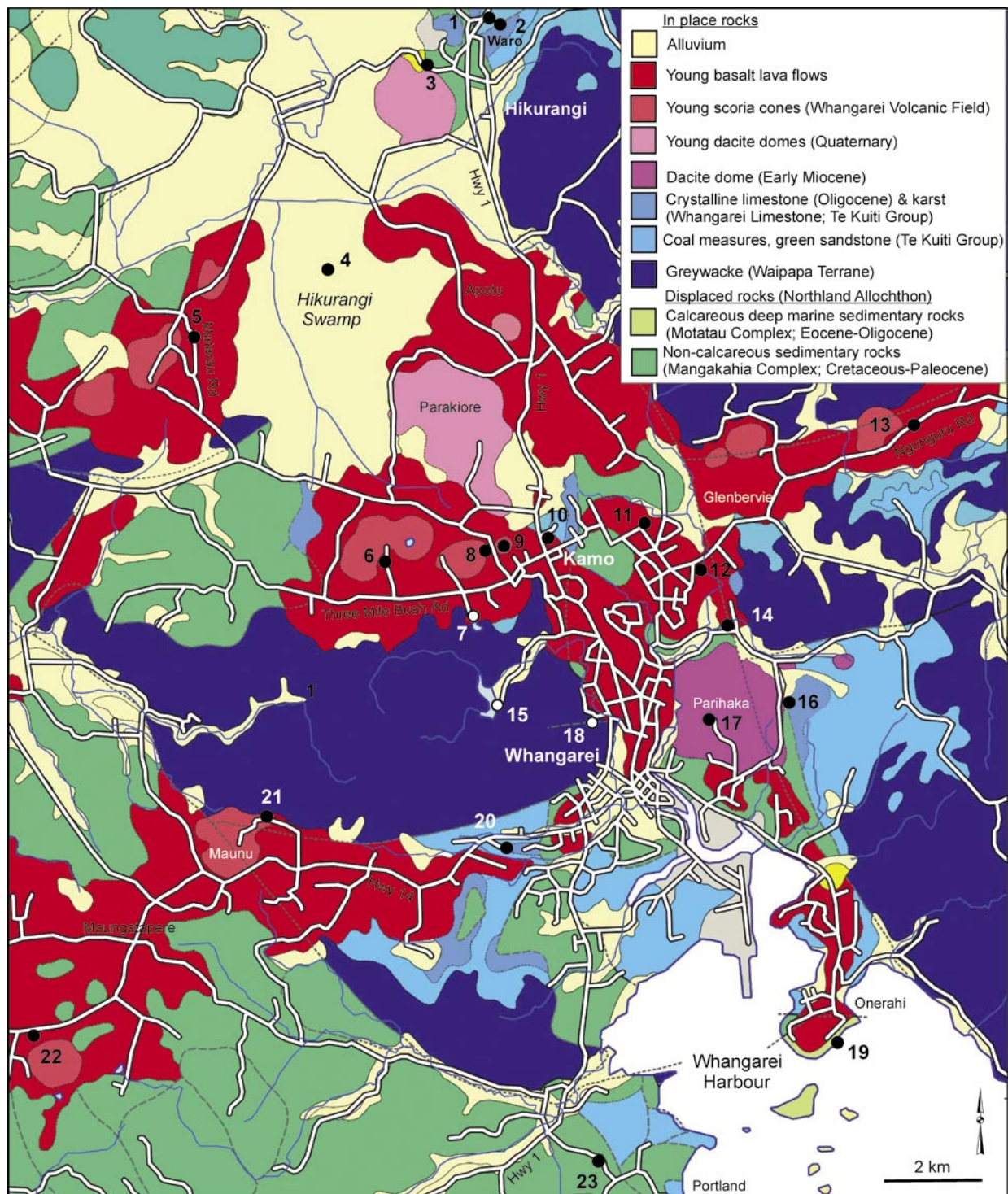
13. Koutu concretions (4.21, 4.26, 13.16)

Take Koutu Loop Rd off Hwy 12, 4 km east of Opononi. Park in carpark on Waione Rd or further on at the end of Cabbage Tree Bay Rd. Walk around the coast, 2 hrs either side of low tide. See some of the largest spherical concretions in New Zealand. Also see exposures of Cretaceous sedimentary rocks (Punakitere Sandstone, 70 Myr old) in which the concretions grew.



13.16 A 1 km-length of shoreline north of Koutu is lined with numerous spherical concretions, including some that are much larger and more impressive than the Moeraki Boulders in the South Island.

WHANGAREI



1. Waro Rocks limestone karst (3.24)
 Park in signposted carpark on Hwy 1, 1.5 km north of Hikurangi township. 30 min walk on loop track right around spectacular cluster of Whangarei Limestone (Oligocene) pinnacles and karst landforms.

2. Waro Lake Reserve lime quarry
 Drive in to reserve at back of Waro Rocks, along sealed drive from King St, 200 m south of junction with Hwy 1. Parking area between railway line and artificial lake. The lake occupies the original quarry for lime used in cement-making at Portland. In the early 20th century,



13.17 Lake Ora was formed when a small valley was dammed by lava flows from nearby Hurupaki Volcano.

Whangarei Limestone, from here, was also taken out in blocks and railed around New Zealand to be used as a building and facing stone.

3. Mt Hikurangi & Wilsonville Quarry view (9.61)

Drive along Boundary and Mountain View roads off Hwy 1, 1-2 km north of Hikurangi township. View north from Mountain View Rd across Wilsonville Quarry, with Northland Allochthon overburden above in-situ Te Kuiti Group Whangarei Limestone, which is quarried for Portland Cement (box 16). Road is on the northern slopes of Mt Hikurangi, a 1.2 Myr-old dacite dome.

4. Hikurangi Swamp (12.24)

Drive through and view from many roads. Huge swamp was formed when a major valley was dammed by lava flows from Whatatiri shield volcano, about 0.5 Myr ago.

5. Matarau basalt karst

View areas of basalt boulders with solution flutes and basins (karst), in paddocks alongside Matarau Rd, 400-800 m north of junction with Going Rd. Basalt boulders are remnants of flows from Matarau Volcano, one of the oldest ones in the Whangarei Volcanic Field (9.41).

6. Ngararatunua Volcano (9.50)

From Rotomate Rd (off Three Mile Bush Rd), the view to the west is of low mounds of scoria in the paddocks. These were rafted away from Ngararatunua's scoria cone by lava flows, late in the volcano's eruptive history. Only half a cone was left behind. View the numerous freestone walls built out of basalt rocks from the surface of the lava flows.

7. Lake Ora (13.17)

View from end of Lake Ora Rd (off Three Mile Bush Rd). This small lake was formed when a stream valley was dammed by lava flows from nearby Hurupaki Volcano.

8. Hurupaki (9.42)

This prominent scoria cone can be viewed from many places, or climbed via a steep walking track from Dip Rd (30 mins to top), through totara and taraire forest. The top has ditch and bank defences, terraces and pits from when it was used as a defensive pa in pre-European Maori times. From the north end of the crest beyond the trig, there are good views to the west, over the quarry and nearby volcanoes.

9. Onoke Scenic Reserve (13.18)

Access along track from Dip Rd (opposite Hurupaki Track entrance). This is a small, partly quarried scoria cone just west of Kamo. It was the site of NZ Railways Onoke Ballast Pit, used in 1880s-1920s to obtain scoria for ballast under Northland railway line. Remains of old boiler engine still on site.



13.18 Onoke scoria cone, viewed from Crawford Cres, Kamo, Whangarei.

10. Kamo Brickworks coal measures (3.6)

Adjacent to Greenfingers Landscape supplies carpark in the former Kamo Brick Refractory site (on Kamo Rd, 500 m N of centre of Kamo). Carpark cutting exposes lenses of coal, carbonaceous sediment (with yellow mineral jarosite) and conglomerate of the Kamo Coal Measures (Late Eocene age). This is the best place to see an example of the coal rocks that were mined around Kamo and Hikurangi in the 19th and 20th centuries.

11. Puketotara and Glenbervie volcanoes view (9.49)

From Corks Rd, 100 m N of Tikipunga High School. View east to Puketotara and Glenbervie scoria cones.

12. Whangarei Falls (9.43)

Carpark on Boundary Rd, just off Kiripaka Rd. Take 40 min loop walk across top of the falls, down to bottom and back up other side. Falls flow over eroding basalt lava flow from Vinegar Hill Volcano, one of the oldest volcanoes in the Whangarei Field. Note the beautiful columnar jointed basalt near the base of the falls.

13. View of Pukepoto Volcano and lava flows (9.81)

This small scoria cone can be viewed alongside Ngunguru Rd. It is at the eastern end of an east-west line of seven volcanoes on either side of Kamo.

14. Paranui Falls

Park at top carpark on Whareora Rd (Clapham Rd turnoff). 5 min walk to lookout. Falls flow over same basalt flow as Whangarei Falls, with columnar-jointed basalt overlain by planar-jointed. Canopy walk through forest and large kauris of AH Reed Reserve downstream, can be reached from lower carpark or steep muddy track from falls.

15. Whau Valley Dam

Waipapa Terrane greywacke for the dam was quarried from the ridge where carpark now sited. Exposures of greywacke can be seen close to carpark.

16. Abbey Caves

Access from Abbey Caves Rd. 45 min loop walk on grass track past spectacular fluted limestone (30 Myr-old Whangarei Limestone), often in forest settings. Entrances to three limestone caves for experienced cavers.

17. Parihaka lookout

At top of Memorial Drive off Riverside Drive. Spectacular views over Whangarei from 241 m-high eroded top of 20 Myr-old Parihaka dacite dome.



13.19 Whangarei Quarry Gardens, Kensington, have been planted inside a disused greywacke aggregate quarry.

18. Whangarei Quarry greywacke gardens (13.19)

Old greywacke quarry with falls over walls, and lake in workings. Tunnels by picnic area housed conveyor belts. Access from Russell Rd, Kensington, Whangarei.

19. Onerahi greensand

35-40 Myr-old (Late Eocene) greensand (Te Kuiti Group, Ruatangata Formation) can be seen forming the intertidal shore platform in front of 100-170 Beach Rd.

20. Ngahere Drive limestone karst

Beautifully fluted Whangarei Limestone blocks and pinnacles occur in middle of Ngahere Drive and in small reserve at No. 47, Horahora, Whangarei.

21. Maunu view and dammed lakes (9.46)

View 395 m-high Maunu scoria cone from Millington Rd, off Hwy 14. Near the end of the road, view wetlands and lake dammed between the cone, lava flows and the greywacke highland to the north.

22. Maungatapere scoria cone (9.47)

Parking inside gate at Groves Broadleaf Forest, opposite junction of Hwy 14 with Watrous Downs Rd. Follow marked trail across private land and climb steep zig-zag track in tairare forest reserve on scoria cone. Swamp maire forest fills former summit crater. No views. For experienced trampers only. 2 hrs return.

23. Portland Quarry view (4.52)

From Portland Rd, off Hwy 1, view of huge quarry in 25-30 Myr-old muddy limestone (allochthonous Motatau Complex). This is the major source material of all of NZ's cement (box 16).

WHANGAREI HEADS

1. Parua Bay red chert

Park at boat ramp carpark and walk 100 m north to intertidal rocks, composed of crudely-layered red-brown chert (Waipapa Terrane basement rocks). The chert originally accumulated as layers of the microscopic siliceous skeletons of planktonic radiolarian, on the deep seafloor in the middle of the Pacific Ocean (~200 Myr ago).

2. Parua Bay basal allochthon contact (4.63)

Take public access to the beach down Bayside Lane, off Muritai Rd off Kiteone Rd. Walk 500 m east through reserve behind mangroves and over boardwalk to beach then south another 400 m. Exposure in low cliff and high tide foreshore, of sheared mudstones at the base of the Northland Allochthon, overlying 1 m of Early Miocene sandstones, which in turn sits on 0.5 m of Oligocene Whangarei Limestone deposited unconformably on basement greywacke. All contacts were originally flat-lying, but are now tilted up to vertical.

3. Reserve Pt Eocene sandstones (13.20)

Park at end of narrow Nook Rd. Take public access to beach. Walk around shoreline to south then east (left), 2 hrs either side of low tide. Bedded rocks forming the point are 35 Myr-old (Late Eocene) sandstone with scattered fossils (14.6).

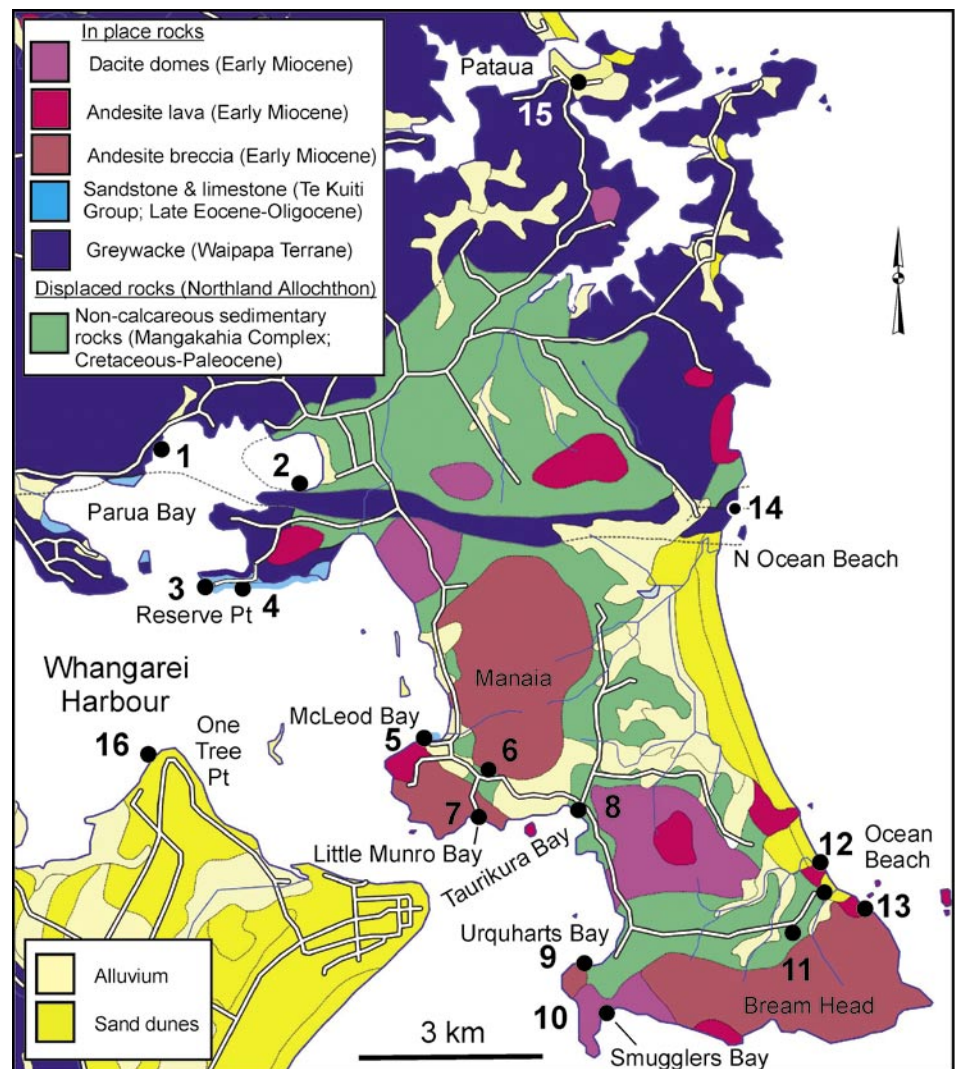
4. Reserve Point pillow lava flow and garnet andesite intrusion (13.20)

About 500 m east of end of Reserve Pt, the sandstone sequence (3, above) contains a pillow lava flow of black nephelinite. A further 100 m to the east, the low sea cliffs are composed of light grey andesite with small crimson crystals of garnet. This is a shallow intrusion of magma beneath part of Whangarei Heads stratovolcano, which

erupted through the sequence of Late Eocene rocks, 20-17 Myr ago (Early Miocene).

5. McLeod Bay allochthon blocks

Park on side of Stuart Rd, about 100 m before McLeod Bay wharf. The adjacent mid-low tide shore platform consists of a 50 m-wide block of Oligocene limestone unconformably overlain (to the west) by bedded Early Miocene sandstone and mudstone. The blocks are tilted so that the contact and originally horizontal layering is vertical. They are inferred to be part of the sequence deposited in Northland that was ripped up and carried along by the passing Northland Allochthon. These blocks are separated from the wharf by soft allochthon mudstone.





13.20 View west across the entrance to Parua Bay with Reserve Pt in the foreground. Eocene sandstone (stop 3) forms the light-coloured foreshore rocks near the end of the point, and pillow lava and intrusive garnet andesite (stop 4) forms the darker intertidal rocks lower right. Photographer Alastair Jamieson.

6. Mount Manaia pinnacles (6.61)

Parking area on side of Whangarei Heads Rd. Well-formed track, moderately steep in parts. 2 hrs return. Leads to andesite breccia pinnacles at top (400 m). These are part of the eroded remains of the 20-17 Myr-old Whangarei Heads stratovolcano.

7. Little Munro Bay (13.21)

Park at end of Bay View Rd. At mid-tide level on west (right) side of beach, grey andesite (magma plumbing beneath the volcano) intrudes and partly bakes light-coloured, allochthonous muddy limestone (Oligocene). Large boulders on beach are composed of massive andesite breccia that have rolled down from Mt Aubrey (part of the steep eroded cone of the Whangarei Heads stratovolcano).

8. Taurikura natural jetty (6.58)

On foreshore adjacent to Ody Rd intersection with Whangarei Heads Rd. 1 m-wide vertical andesite dike intrudes softer Mahurangi Limestone, which has eroded

down to leave the dike as a natural jetty at high tide. The best example of this rare landform in NZ.

9. Urquharts Bay

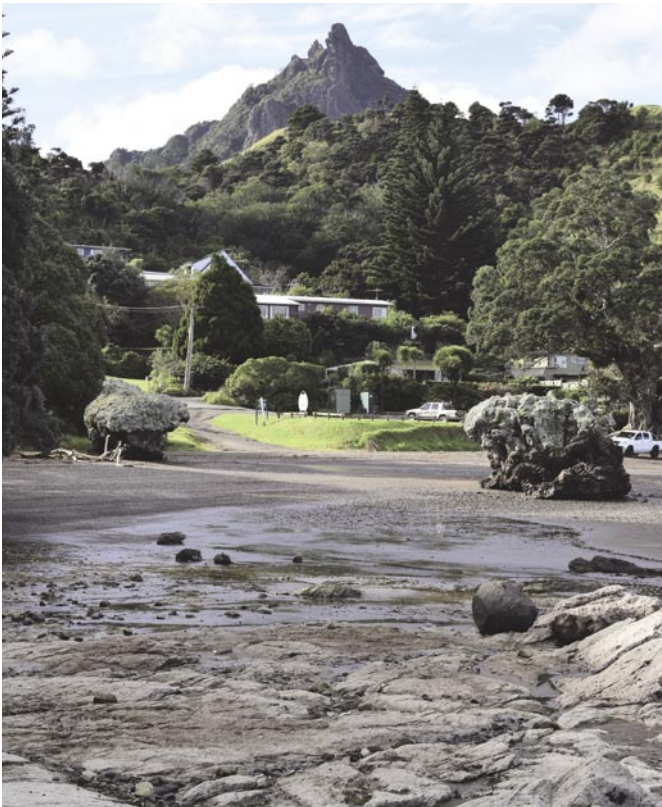
Walk from carpark at end of Urquharts Bay Rd. Intertidally on west side of Urquharts Bay there are Cretaceous sedimentary rocks including spherical concretions, all part of Northland Allochthon.

10. Smugglers Bay dacite intrusion (13.22)

From Urquharts Bay, take Smugglers Bay Loop Track (1.5 hrs), which circum-navigates peaks made of Early Miocene andesite breccia and dacite intrusions. Light grey dacite is best seen in coastal rocks around Smugglers Bay.

11. Bream Head pinnacles (6.59)

Park at start of track to Peach Cove on Ocean Beach Rd. Track leads up to ridge crest and Bream Head-Te Whara Track. Follow this along ridge and down to Ocean Beach and back up road to your car. Spectacular views and pass



13.21 View north over Little Munro Bay with Mt Manaia pinnacles on the skyline. Slightly baked Mahurangi Limestone forms the foreground rocks with two large boulders of andesitic breccia from Mt Aubrey on the beach.

pinnacles of andesite breccia (eroded Whangarei Heads volcanic cone). About 3.5 hrs.

12. Ocean Beach dike and baked limestone (11.54)

White quartz sand is derived from rhyolitic eruptions in Bay of Plenty-Taupo, carried north from the Hauraki Gulf by longshore drift. Rocks at north end (left) are intrusive andesite plumbing from beneath Whangarei Heads Volcano. Clamber round point (mid-low tide) to see irregular dikes intruding allochthonous Mahurangi Limestone, which is baked to black skarn.

13. Ocean Beach andesite, breccia and Hen and Chickens view (6.60, 6.63, 11.54)

Climb up track over point at south end of beach for views of Hen and Chickens Islands, which are the remains of two 19-16 Myr-old volcanoes that intrude and overlie Waipapa basement greywacke. At low-mid tide beyond, see andesite intrusions

that have baked limestone to hard black skarn and angular andesite breccia of Whangarei Heads Volcano.

14. North Ocean Beach (4.37)

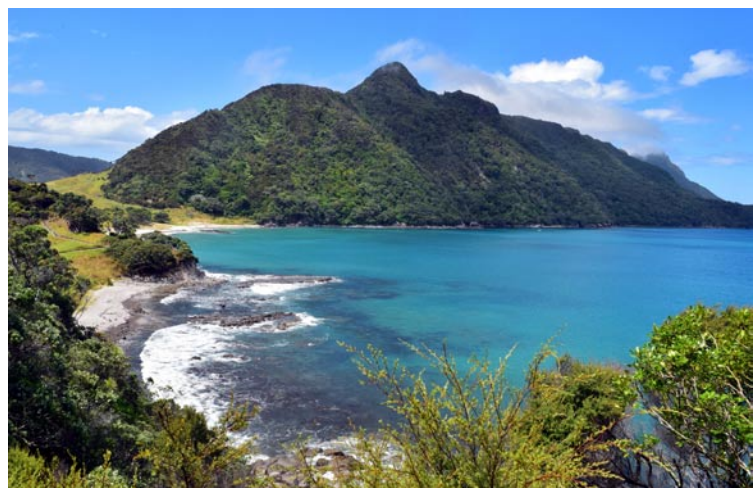
Park at end of Kauri Mt Rd, off Taiharuru Rd, off Pataua Sth Rd from Parua Bay. Take public access track to rocks at north end of Ocean Beach. Disrupted contacts of sheared Northland Allochthon overlying in-situ Waipapa greywacke.

15. Pataua

At end of Pataua South Rd, 8 km from Parua Bay. Between 6000 and 2000 yr ago, the low sand flat with baches was part of a much larger intertidal harbour that linked the Pataua and Taiharuru estuaries. At that time, sea level was 1-2 m higher than present. Surrounding hills and former Pataua Island are made of Waipapa Terrane basement greywacke with erosion-resistant chert bands forming ridge crests.

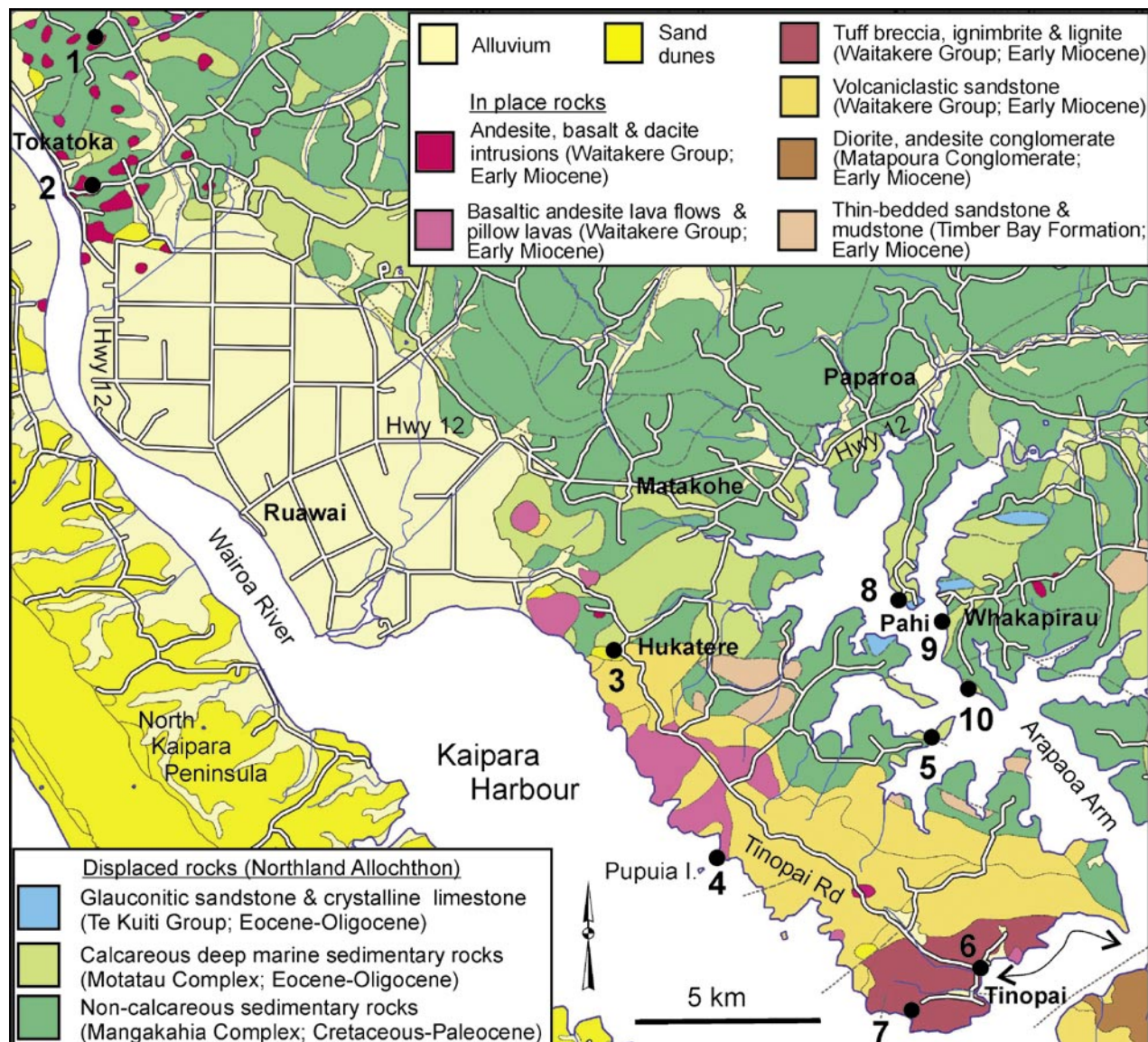
16. One Tree Pt Last Interglacial beach and sand dune sequence (11.56, 11.57)

On south side of Whangarei Harbour. Mid-low tide access from boat ramp or Karoro Rd. High white cliffs consist of sand deposited when sea level was 3-4 m higher than present during Last Interglacial warm period, 120,000 yr ago. Lower part is beach sand with rare fossil bivalve shells and burrows. Upper part is cross-bedded dune sand with lignite in hollows between dune crests at top of cliff.



13.22 View east across Smugglers Bay with light-coloured dacite rock in the foreground. These are eroded remnants of a 20-17 Myr-old dacite dome associated with the Whangarei Heads Volcano.

NORTH KAIPARA



1. Maungaraho dike (6.38)

Car park at end of Maungaraho Rock Rd, off Mititai Rd. Walking track around base, or rock climb to top, 30-60 mins. Exhumed plumbing of 19-17 Myr-old Tokatoka stratovolcano.

2. Tokatoka intrusion (6.37, 13.23)

Climb steep track to top from Tokatoka Rd. Panoramic views. Andesite plug from beneath completely eroded away Tokatoka stratovolcano.

3. Summer Rd view, Hukaterere (12.18)

Stop on corner, 0.5 km from junction with Speechly Rd. Spectacular view west across estuary of Wairoa River and Ruawai's Holocene alluvial flats, to North Kaipara

sand-dune barrier. Just up the road are views east across the headwaters of the Arapaoa Arm of Kaipara Harbour, which is surrounded by Northland Allochthon rocks.

4. Pupuia Island pillow lava (6.39)

Access down paper road over private farm (get permission) from Tinopai Rd. Mainland and island cliffs made of pillow lava from 18-17 Myr-old Hukaterere pillow lava shield volcano.

5. Kapua Pt muddy limestone

Access from end of Arapaoa Rd, off Neems Rd. Walk round point at mid-low tide. Cliffs and shore platform are made of 30-25 Myr-old Mahurangi Limestone.



13.23 View south to Tokatoka peak, an eroded plug of andesite that congealed deep in the throat of an Early Miocene volcano. It now stands high, as softer rocks have been eroded away from above and around it. Photographer Alastair Jamieson.

6. Tinopai Early Miocene fossil forests (6.41, 6.42)

From the marina at Tinopai, walk east along the coast, past box-weathered basalt to pyroclastic deposits of tuff breccia. See several cycles of soil with lignite and tree stumps (about 17 Myr old) in growth position, buried by wood-bearing pumice breccia around Puketi Pt (1 hr walk), some silicified wood beyond. Access around Puketi Pt is possible only within 2 hrs of low tide. If fast, you can walk on towards Pakaurangi Pt to see abundant shallow-marine, Early Miocene shell fossils (5.50). 3-5 hrs return.

7. Sandy Beach ignimbrite and tree fossils (6.40)

10 min walk from end of Sandy Beach Rd, Tinopai. Cliffs and boulders at south end consist of 18-17 Myr-old ignimbrite containing carbonised or silicified logs.

8. Pahi greensand and limestone sequences (4.55)

Park at end of Dem St, 500 m before campground. At mid-low tide, walk south (left) to see 35 Myr-old (Late Eocene) massive greensand with occasional shallow-water fossil shells. Walk north, up to 1 km, passing 30-25 Myr-old (Oligocene) muddy and sandy limestone, then well-bedded, deep-water, 40 Myr-old greensand interbedded with calcareous mudstone (4.55). Lookout for complex trace fossils (5.31).

9. Whakapirau muddy limestone

The mid-tide shore platform for 1 km south of south end of The Strand, Whakapirau, is composed of allochthonous, 30-25 Myr-old muddy Mahurangi Limestone.

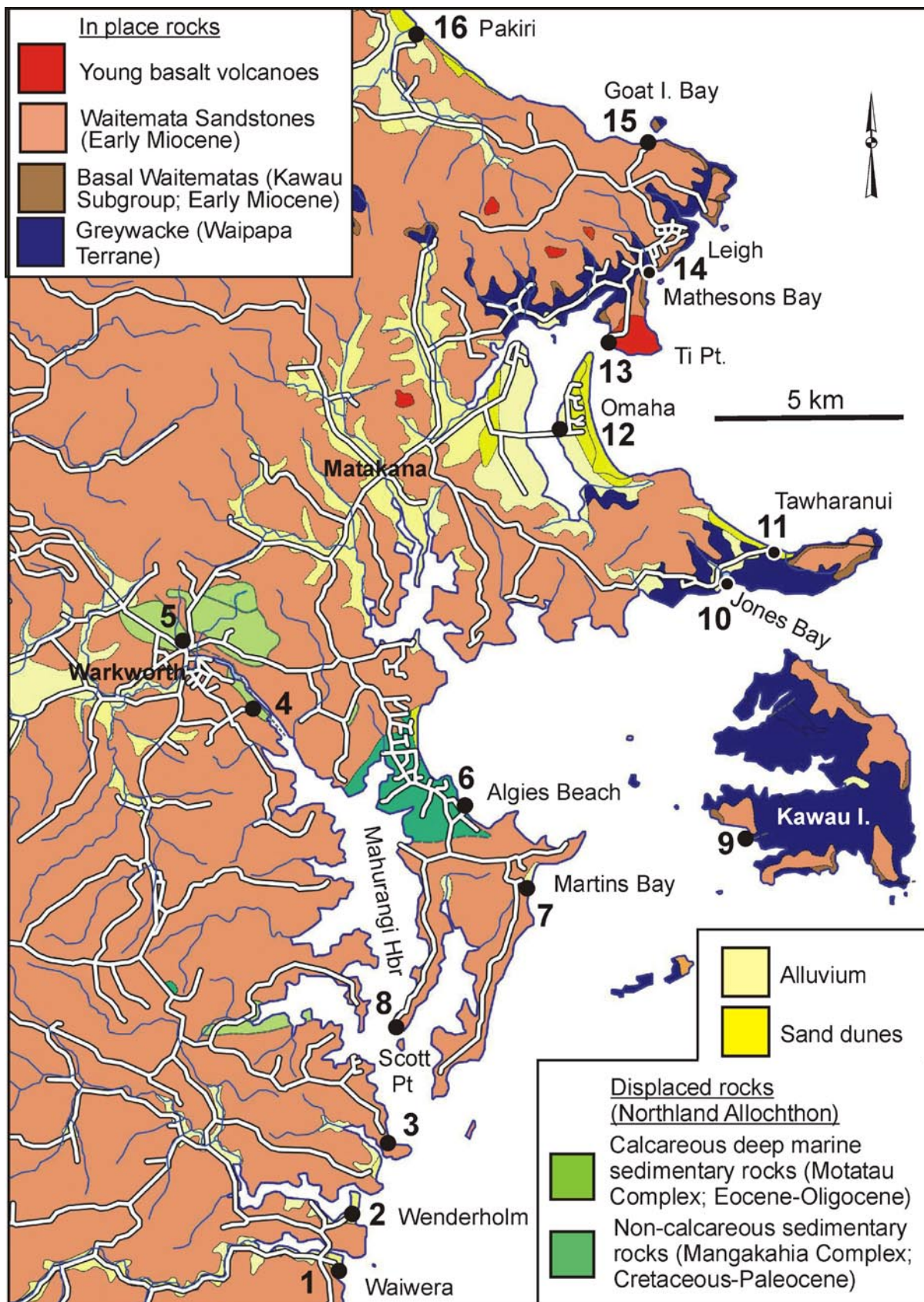
10. Whakapirau Northland Allochthon blocks (4.29)

Walk at mid-low tide, 1-3 km south of Whakapirau (stop 9). Pass and walk over various blocks of 80-55 Myr-old (Cretaceous-Paleocene) sandstone and mudstone (13.24), 30-25 Myr-old Mahurangi Limestone, and 25-23 Myr-old muddy limestone and rhyolitic ash (Puriri Formation, 4.56) – all part of the Northland Allochthon.



13.24 Rippled surface on 70 Myr-old sandstone bed near Page Pt, 3 km south of Whakapirau, Kaipara Harbour.

MAHURANGI





13.25 The carpark and picnic areas in Wenderholm Regional Park are located on a young sand-dune barrier that was thrown up by the sea across the Puhoi Estuary mouth in the last 7000 yrs.

1. Waiwera hot pool remains and Parnell Grit (5.46)

Sandstone remains of first Waiwera thermal bath house at back of beach at south end. Easy walk at mid-low tide around shore platform to south (right) to see classic Parnell Grit bed, with basalt pebbles in base, within 20-19 Myr-old (Early Miocene) Waitemata Sandstone sequence.

2. Wenderholm Regional Park (13.25)

Located on a low sand-dune spit that was deposited most of the way across the mouth of the drowned Puhoi Estuary, 7000-3000 yr ago. Waitemata Sandstone sequence forms cliffs at south end of beach.

3. Mahurangi Regional Park

Parking area located on a coastal terrace formed when sea level was 1-2 m higher, 6000-3000 yr ago. At low tide, clamber round Cudlip Pt (right of beach) with excellent exposures of deformed Waitemata Sandstone and Parnell Grit strata. Te Muri Beach beyond is backed by a young sand-dune spit (7000-3000 yr old).

4. Wilsons Cement Works ruins (4.53)

Beside marina at end of Wilson Rd, off Pulham Rd, Warkworth. Remains of first cement works in Southern Hemisphere (1866-1928) beside Mahurangi lime pit.

5. Kowhai Park lime kilns, Warkworth

Carpark at Hwy 1-Matakana Rd intersection. Short bush walk to remains of old lime kilns (operated 1880s) with natural exposure of Mahurangi Limestone (Oligocene, 30-25 Myr-old) on stream banks.

6. Algies Bay Northland Allochthon

Block of 70 Myr-old (Late Cretaceous), sheared Whangai Siltstone (part of Northland Allochthon) forms cliffs and intertidal rocks between Algies and Snells Beach. Its contact over Waitemata Sandstone can be seen at mid-tide in the beach, in front of main carpark, Gordon Craig Place.

7. Martins Bay Waitemata Sandstones

Walk south from beach carpark, past cliff sections of 20-19 Myr-old turbidite sandstone and thin-bedded siltstone (Waitemata Sandstone). At 3-4 km distance, there are three separate Parnell Grit beds within the sequence. Accessible at mid-low tide, 2-3 hrs return.

8. Scott Pt Waitemata Sandstones (11.47)

Park at end of Ridge Rd, Scott Pt - the crest of a narrow ridge that was partly drowned by rising sea level 7500 yr ago. Walk down beach and around Casnell Island at mid-low tide. Low cliffs and shore platforms of structurally-disturbed Waitemata Sandstone.



13.26 The southwest corner of Ti Pt is made of Waitemata Sandstone, intruded and overlain by 10-7 Myr-old basalt. The sandstone shore platform has eroded down, as a result of daily wetting by the tide and drying in the sun. A basalt boulder, which rolled down the hill onto the shore platform several thousand years ago, has shaded part of the sandstone and prevented it from drying out and frittering down, thereby creating a basalt-capped mushroom rock, with sandstone pedestal.

9. Kawau coppermine (2.27, 2.28)

Walking track from Mansion House Bay to sandstone and brick remains of coppermine (1840s-50s) pumphouse chimney, on foreshore of South Cove, 2 hrs return. Alongside is the collapsed mine with some yellow, blue and green copper sulphate and iron mineralisation around it (box 5).

10. Tawharanui, Jones Bay greywacke (12.13)

Park outside entrance to Tawharanui Regional Park. Greywacke pebbles on beach. Clamber around greywacke (Jurassic, Waipapa Terrane) foreshore to the west (right). Red chert occurs 400 m around. Low tide access only. The lake just inside the entrance was created by a century of extraction of greywacke shingle.

11. Tawharanui, Ocean Beach (2.16)

Main carpark sits behind sand dunes built that were formed in the last 7500 yr. Reefs on main beach are folded Waitemata Sandstone. Basal Waitemata shelly grit forms point to east between Ocean Beach and Anchor Bay. Underlying bedded Jurassic greywacke and argillite (Waipapa Terrane) forms intertidal rocks east from Anchor Bay. Mid-low tide access.

12. Omaha sand-dune barrier

This beach-side suburb is located on a sand-dune barrier that built out across Omaha Bay in the last 7500 yr. Lignite and the fossilised remains of 60,000-20,000 yr-old forest can be seen in the low eroding banks on the west side of Whangateau Harbour on either side of Omaha Flats Rd.

13. Ti Pt basalt volcano (9.21, 13.26)

Park by Ti Pt wharf, at end of Ti Pt Rd. Take walking track around end of Ti Pt to reserve on southeast corner. Basalt boulders line the foreshore. Cliffs are made of intrusive basalt, the exhumed plumbing from beneath a 10-7 Myr-old volcano. 1-2 hrs return.

14. Mathesons Bay basal Waitemata rocks and fossils (5.26)

Walk around the intertidal rocks in both directions from beach carpark, to see unconformable contact of 22-20 Myr old breccia and conglomerate on basement greywacke. Scattered fossil, shallow-water molluscs, barnacles, corals and calcareous algae are present. Also look for fossil

eagle-ray burrows. In the cliff 200 m to the north, there is the top of a small, conical stack of greywacke, buried beneath deeper-water Waitemata siltstone and sandstone. Mid-low tide access only.

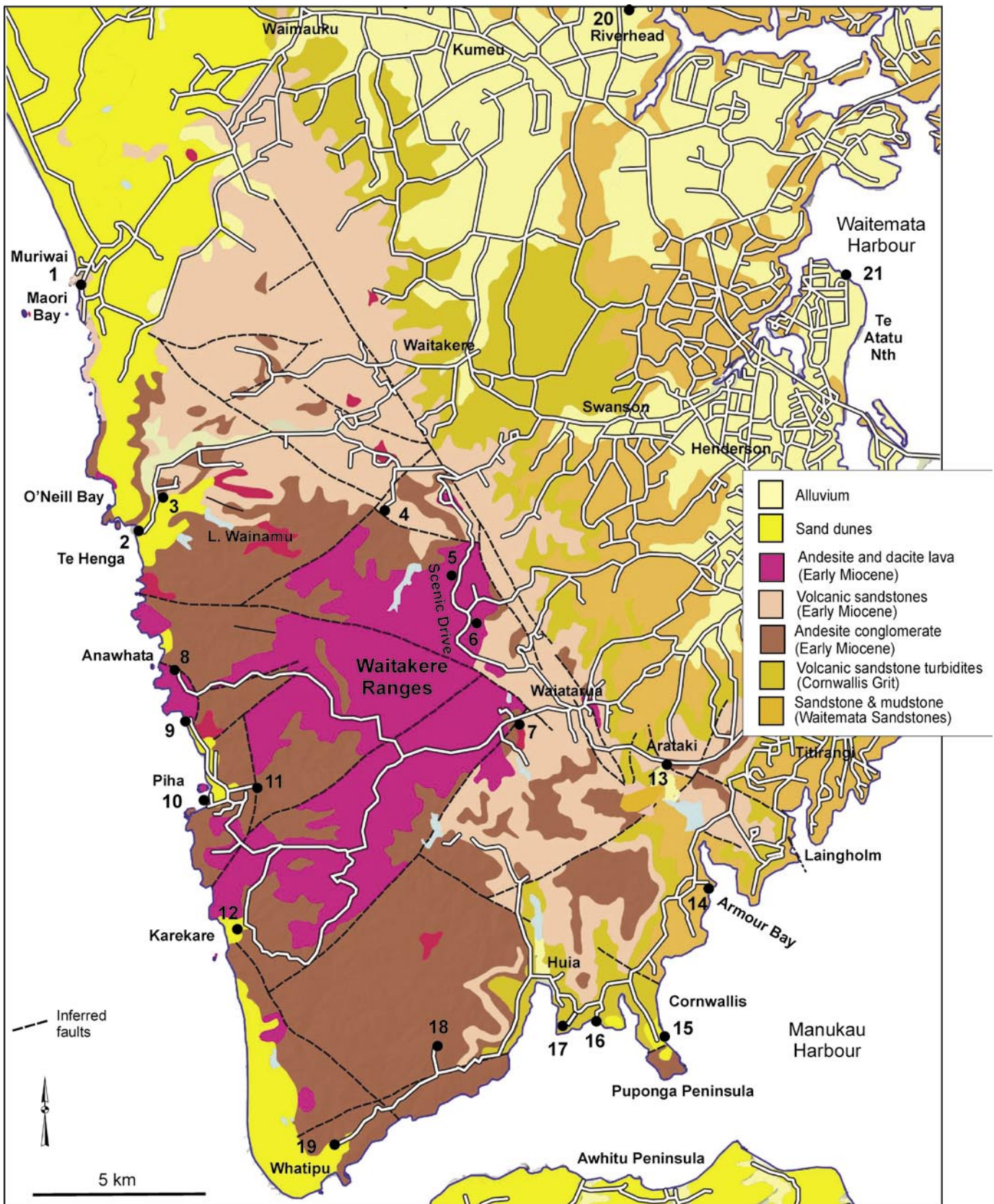
15. Goat Island Bay basal Waitemata grit and Waitemata Sandstone

The rock platform to the right of beach access, and forming most of Goat Island, is made of shelly grit (basal Waitematas). This was deposited in shallow water, unconformably on top of basement greywacke about 21 Myr ago. The high cliffs to the left are composed of a thick sequence of volcanic-rich Pakiri Formation of the Waitemata Sandstone.

16. Pakiri Beach white sand and Waitemata Sandstone cliffs (5.16)

Carpark at end of Pakiri River Rd. The white beach sand predominantly quartz derived from the Taupo Volcanic Zone and carried down to the east coast of Auckland via the Waikato River, prior to 22,000 yr ago, when its course switched from via the Hauraki Plains to its present out to the west coast. Walk 2 km south down beach to see volcanic-rich Waitemata Sandstones.

WEST AUCKLAND – eroded remains of 22-15 Myr-old Waitakere Volcano



1. Maukatia/Maori Bay pillow lava (6.14-6.17)

Carpark above Maori Bay, off Waitea Rd. View pillow lava flow in cliff (6.17) from track to gannet colony on point, or at low tide, walk south along base of cliffs for 2 bays to see bedded volcanic sandstone, conglomerate and more pillow lavas. For detail see “Ancient Undersea Volcanoes”. Geological Society of NZ Guidebook 3. Available from <http://www.gsnz.org.nz/guides.php>.

2. Te Henga pillow lava, ancient crater, sea caves (6.13, 11.90)

At south end of beach, cliffs are made of glassy breccia (hyaloclastite) and pillow lava overlying bedded volcanic conglomerate. Walk north across mouth of Waitakere River, at mid-low tide, and over sandy saddle to O’Neill Bay. High cliffs behind north end are eroded into an ancient crater filled with lava flows. Erangi Pt, between Te Henga and O’Neill Bay, is composed of volcanic conglomerate (Piha Formation) and peppered by numerous sea caves eroded along weak joints within the rock (11.90).

3. Lake Wainamu sand dunes (11.51, 13.27)

Park on Bethells Rd, at track entrance just over stream bridge. Walk beside stream and over high sand dune to edge of Lake Wainamu. Best example of dune-dammed lake in Auckland, all blown inland from the beach in last 7500 yr. 1-1.5 hr return.

4. Cascades

Carpark at end of Falls Rd, through golf course, off Te Henga Rd. Cliffs, beside stream at bottom of picnic area,

are bedded volcanic sandstone. Bluffs, through which the Cascade Falls are eroded, are volcanic conglomerate, 40 mins return walk.

5. Waitakere Falls, Scenic Drive (12.9)

Parking area on Scenic Drive. Walk down sealed vehicle track to Waitakere Dam. Take walking track below falls and around amphitheatre for view back on 95 m-high Waitakere Falls, over bedded conglomerate and sandstone. Only flows when dam overflowing. 1.5-2 hrs return.

6. Fairy Falls, Scenic Drive

Parking area on Scenic Drive. Bush track to top of falls, over thick volcanic sandstone and minor conglomerate, intruded by andesite dike. 1.5-2 hrs return.

7. Upper Nihotupu Dam lava flow, Piha Rd

Parking area at bottom of long hill on Piha Rd. Take walking track to dam. At head of lake, waterfall flows over pillow lava, next to overgrown quarry used for dam construction. Vehicle track cuttings beside reservoir are in volcanic sandstone. Falls below dam, flow over volcanic conglomerate. 2-3 hrs return.

8. Anawhata volcanic conglomerate (13.28)

Take steep walking track down to beach from end of road. Sea cliffs and inland bluffs are made of volcanic conglomerate (Piha Formation). Andesite dikes and mushroom-shaped intrusion in cliffs at north end, accessible at low tide. 2 hrs return.



13.27 Lake Wainamu, inland from Te Henga beach, is a valley that has been dammed by a sand dune that has blown up the valley since sea level rose to its present level 7500 yr ago. Photographer Alastair Jamieson.



13.28 Inland cliffs behind Anawhata Beach are made of volcanic conglomerate that was deposited on the submarine slopes of Waitakere stratovolcano.

9. North Piha sea cave and Whites Beach ancient crater (13.29)

Former sea cave with dune in front, just north of parking area at end of North Piha Rd. Cliffs at north end of beach are volcanic conglomerate intruded by dikes. Take steep walking track over Te Waha Pt to Whites Beach, which is backed by an eroding crater filled with lava flows. 1-2 hr return, at mid-low tide.

10. South Piha volcanic conglomerate and Lion Rock volcanic neck (6.18, 6.31, 11.91, 11.93)

Clamber south around rocks at low tide. Wave attack on jointed andesite dikes has created The Gap and the tunnel through Taitomo Island. Surrounding cliffs are volcanic conglomerate. Erosion along a weak joint through the rocks has created The Blowhole, a little further south. Lion Rock is an eroded volcanic neck, filled with scoria, breccia, volcanic bombs and andesite intrusions.

11. Kitekite Falls and Piha Gorge (13.30)

Parking area at end of Glenesk Rd. Walking track to Kitekite Falls, which cascades in three drops over volcanic conglomerate (Piha Formation) intruded by an andesite dike, 1 hr return. From carpark, take track up Piha Valley to narrow Piha Gorge, cut through volcanic conglomerate. Experienced trampers can wade and clamber through most of gorge. 1.5-2 hrs return.

12. Karekare ancient crater and dacite dome (6.25, 6.29, 6.30)

The Watchman and offshore Paratahi Island are composed of flow-banded dacite that was squeezed

like toothpaste into an ancient crater about 16 Myr ago. Much of the crater has been eroded out to form Karekare embayment (now partly filled with sand dunes). The eroded wall of the crater is visible in the sea cliffs at the north end of the beach.

13. Arataki views, Scenic Drive

Views from decks of information centre of Manukau and Waitemata harbours on either coast of Auckland Isthmus. Dramatic view over lower Nihotupu Valley, mostly eroded into volcanic sandstones.

14. Armour Bay Waitemata Sandstone and Parnell Grit

Parking at end of Armour Rd, off Huia Rd at Parau. Weathered, cobbly Parnell Grit bed on point by carpark. Walk west at mid-low tide along shore platform eroded into Waitemata Sandstone beds.

15. Cornwallis wharf weathered Pleistocene dune sand

Parking beside wharf, near end of Cornwallis Rd. Low cliffs of orange-brown oxidised dune sand 100 m north of wharf and in cutting up road to south. End of Cornwallis Peninsula is composed of down-faulted volcanic conglomerate.

16. Kaitarakihi volcanic sandstones and submarine channel (5.24)

Parking behind beach at end of Kaitarakihi access road off Huia Rd. Sea cliffs and shore platforms at mid-low tide are made of volcanic sandstone, Parnell Grit and thin volcanic ash beds (5.35). 400 m west, see the wall of a 19 Myr-old submarine channel in the cliffs (5.24).



13.29 Whites Beach cliffs are made of crater-filling lava flows overlying conglomerate intruded by lava tongues.



13.30 The lower drop of the 40 m-high, 3-tiered Kitekite Falls, which drop over volcanic conglomerate cut by a 1 m-thick andesite dike (seen on right side of base of falls and in pool overflow).

17. Huia Pt Lookout (13.31)

Parking area at end of Huia Pt Lookout Rd. Panoramic view across Huia Bay to the southern Waitakere Ranges - the uplifted and eroding eastern remnants of the submarine slopes of the 22-15 Myr-old Waitakere Volcano. Across the Manukau Harbour entrance is the northern end of the

Awhitu Peninsula - a sand-dune barrier spit thrown up across the Manukau Bay in the last 1.5 Myr.

18. Mt Donald McLean views

Parking at end of steep Donald McLean Rd, off Whatipu Rd. Walk to top for panoramic views north over the relatively flat top (Auckland Erosion Surface) of the Waitakere Ranges, west to Whatipu sand flats and south to Awhitu sand dune barrier. 30 mins return.

19. Whatipu volcanic conglomerate, abandoned sea caves, sand flat (6.32, 11.32, 11.33, 11.81)

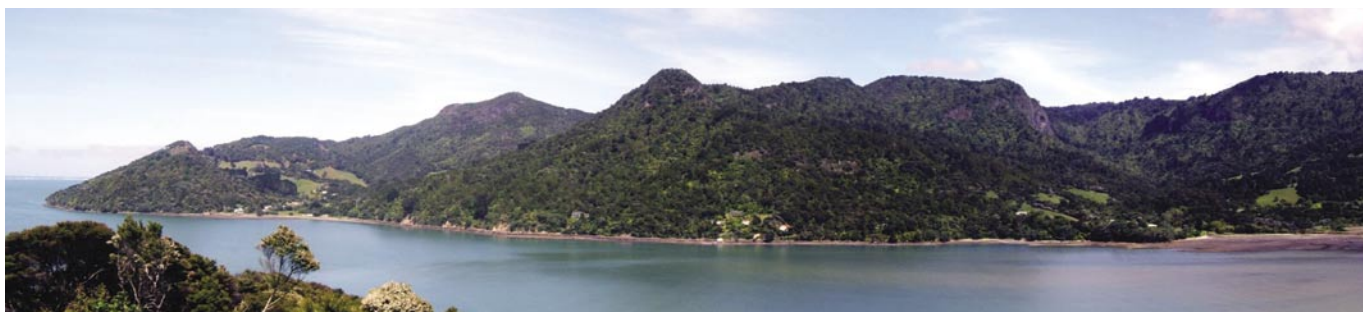
From end of Whatipu Rd, walk south to beach and Paratutae Island with cliffs of volcanic conglomerate intruded by narrow dikes. Ninepin rocks are the eroded remains of a volcanic neck and plug. For the caves, take walk west then north around base of volcanic conglomerate cliffs. Sea caves have been eroded out along weak joints and pyroclastic dikes (6.32) in the cliffs. In the 1910s, waves still surged into the caves at high tide. Since then, the 1 km-wide Whatipu sand flats have accumulated in front.

20. Riverhead bridge conglomerate and reversing waterfall

Parking area beside estuary at west end of Coatesville-Riverhead Hwy bridge. Intertidal reef extends right across estuary and is made of erosion-resistant, sandy Albany Conglomerate. The reef creates a low-tide waterfall under the bridge. It reverses in direction with the change of tide.

21. Te Atatu fossil forest

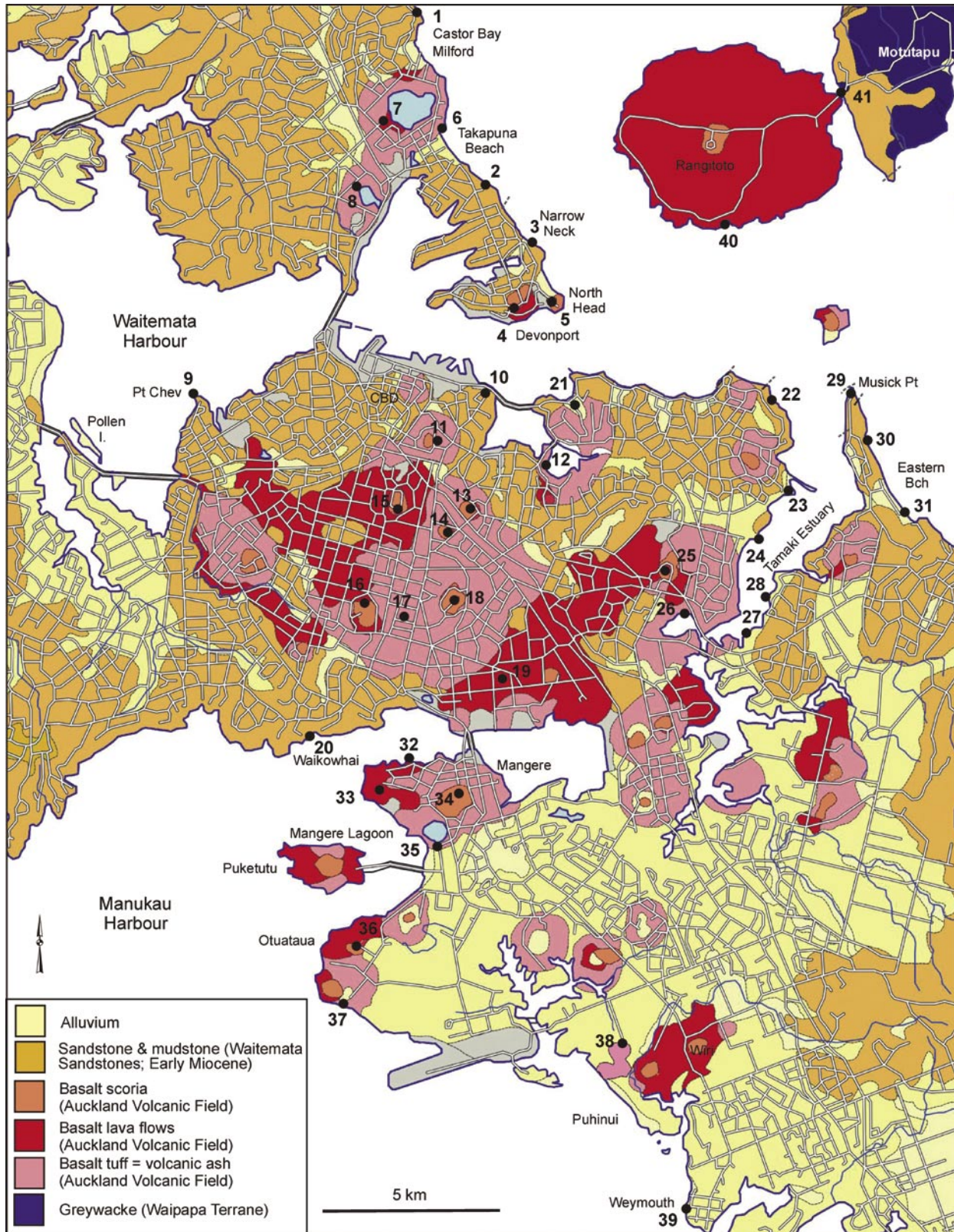
Park at the end of Beach Rd, north Te Atatu. The remains of stumps and logs of a Pleistocene fossil forest can be seen at mid tide level poking out of the black peat that it was preserved in.



13.31 View west from Huia Pt Lookout, across the entrance to Huia Bay, to the Marama (left) and Karamatura (right) valleys. Rounded peaks and inland bluffs are made of 19-17 Myr-old volcanic conglomerate (Piha Formation).

CENTRAL AUCKLAND

For more detailed descriptions of individual Auckland volcanoes, see *Volcanoes of Auckland: The Essential Guide*, 2011.



1. Kennedy Park deformed Waitemata Sandstone

Easiest access is down the cliffs using stairs from Kennedy Park, carpark off Beach Rd. View at mid-low tide. Excellent exposures of Waitemata Sandstone that were deposited in the deep sea ~20 Myr ago. Parts of the sequence have been disrupted by seafloor sliding with layering tilted up to vertical.

2. St Leonards Beach Waitemata Sandstone cliffs (5.19)

Access down steep walkway from end of St Leonards Rd beside Takapuna Grammar. View at mid-low tide. Excellent exposures of Waitemata Sandstone. Reef near foot of steps contains bed that has been folded into tight folds on the sea floor. WW2 concrete structure shows erosion rate of cliffs at ~4 cm/yr.

3. Narrow Neck-Takapuna Head deformed Waitemata Sandstones

Parking area on landward side of Old Lake Rd. Cliffs for 500 m southeast, from Narrow Neck Beach to Takapuna Head (mid-low tide access), are made of bedded Waitemata Sandstone and a Parnell Grit Bed near the beach. Near the Head, the bedding is disrupted with some beds vertical, juxtaposed against others that are horizontal.

4. Takarunga/Mt Victoria scoria cone (13.32)

Walking access to top, up former road off Victoria Rd -Kerr St corner. 87 m-high scoria cone. Lava flows from breached crater to south form Devonport foreshore. Superb views of Waitemata Harbour formed by drowning of valley by rising sea level 9000-7500 yr ago.

5. Maungauika/North Head scoria and tuff cone

Road access to parking areas on cone, off Takarunga Rd. Small scoria cone capping tuff mound, erupted about 85,000 yr ago (13.32). Large volcanic bomb beside roadway halfway up. Beautiful tuff exposures alongside track around sea-side bottom of North Head. Panoramic views.

6. Takapuna fossil forest and lava flows (9.89, 9.90)

Seen in reef beside Takapuna boat ramp carpark (end of The Promenade), and alongside high-tide walking track from there to Thorne Bay. Fossilised signs of a forest that was growing here ~200,000 yr ago, when 1-4 m-thick lava flows came through from Pupuke Volcano. The reef is composed of the moulds of the stumps of over 200 trees (many with central holes in them where the wood was located) and some fallen branches and trunks. Further north (beneath grill) is the mould of a 1.5 m-diameter trunk of a kauri and more felled branches that were rafted along and captured in the lava flows.

7. Northcote Rd exposures of Pupuke Volcano tuff and flows

Road cuttings beside the lake end extension of Northcote Rd, composed of Pupuke Volcano tuff and scoria overlying basalt lava flows, also seen in flooded old quarry walls on west side of road.

8. Tank Farm explosion crater (also incorrectly known as Tuff Crater) (9.70)

Easiest access to walking track around 80 % of inside of crater, from end of St Peters St. Middle of three old (~200,000 yr old) explosion craters with surrounding tuff rings that erupted up a fault line between Onepoto and Pupuke volcanoes.



13.32 Three scoria cones erupted at Devonport on Auckland's North Shore. North Head (foreground) and Mt Victoria (left of centre) provide panoramic views from their tops. In between the two, the smaller Mt Cambria cone has been removed by quarrying and is now only remembered by its footprint reserve.

9. Point Chevalier Waitemata Sandstones

Access down steps on far left corner of Coyle Park, at end of Pt Chevalier Rd. View at low tide. Low cliffs contain layers of Waitemata Sandstone with many of features, such as cross-bedding, grading, water escape structures, ripples, trace fossils (*Scolicia*).

10. Judges Bay Parnell Grit (13.33)

Access from Parnell Baths carpark at end of Judges Bay Rd. Best seen from walkway around baths to Tamaki Drive. Cliff above buildings contains 10 m-thick bed of volcanic-rich Parnell Grit overlying volcanic-poor Waitemata Sandstones.

11. Pukekawa/Domain ‘castle and moat volcano’

600 m-diameter explosion crater, with Auckland Museum and Hospital built on crest of tuff ring on opposite sides. Small scoria cone in middle of crater with fernery in old scoria quarry. Flat floor of crater (sports fields) is underlain by a solidified crater lake of lava. Erupted ~105,000 yrs ago.

12. Orakei Basin explosion crater (11.46)

Car access into crater off Orakei Rd. Walking track (1 hr) circumnavigates inside of whole crater. 125,000 yr-old explosion crater and surrounding tuff ring. Railway embankment was built through east side of intertidal crater floor in 1920s.

13. Ohinerau/Mt Hobson breached scoria cone

Easiest walking access to top off Remuera Rd. Scoria cone (143 m above SL) with a crater breached to the southwest and small lava flow that flowed north and south from breach.

14. Te Kopuke/Mt St John scoria cone

Easiest walking access to top off Market or St Johns roads. Scoria cone (126 m above SL) with small ephemeral crater lake in wet season. Source of longest lava flow in Auckland, forming Meola Reef at Westmere (9.76). Erupted about 75,000 yr ago.

15. Maungawhau/Mt Eden double scoria cone (9.79)

Access to parking off Mt Eden Rd. Walk most of way up on sealed roadways. Elongate double scoria cone (28,000 yr old) with bowl-shaped southern crater. Northern crater is breached to north and partly filled with water reservoirs. Source of extensive lava flow field that underlies surrounding suburbs.



13.33 A thick, dark-coloured bed of Parnell Grit overlies layered Waitemata Sandstone in the cliffs above Parnell Baths, Auckland.

16. Te Tatua a Riukiuta/Big King scoria cone and Three Kings crater

Easiest walking access to top from carpark at corner of Mt Eden Rd and Duke St. Big King is the only remaining scoria cone. The other four large cones have been quarried away. All erupted ~30,000 yr ago, within a 1 km-diameter explosion crater and tuff ring.

17. Liverpool St folded tuff (10.39, 13.34)

Road cutting outside 27 Liverpool St, Epsom. Layers of volcanic ash from Three Kings Volcano draped and folded over underlying ridge of hidden sandstone. Look for volcanic hailstones (accretionary lapilli).

18. Maungakiekie/One Tree Hill scoria cone and lava flows (9.78)

Best road access into Cornwall Park and One Tree Hill Domain off Greenlane Rd West or Manukau Rd. Can walk up former roadway to obelisk on top. Complex scoria cone with three fire-fountaining craters. The two horseshoe-shaped craters have been breached by lava flows, which rafted away part of the scoria cone. Surrounded by extensive lava flow field (shield volcano) extending from Onehunga foreshore to Newmarket and underlying many suburbs. Erupted 60,000-70,000 yr ago.

19. Hochstetter Pond collapsed lava cave

In small reserve at 36 Grotto St, Onehunga. Depression formed by collapsed lava cave within lava flow from One Tree Hill. Floor underlain by white diatomite composed of silica skeletons of microscopic algae (diatoms) that lived in a freshwater lake before humans arrived. Up flow, on private land at 5 Puka St, is another, deeper, collapsed lava cave.

13.34 Layers of volcanic ash (tuff) erupted from Three Kings Explosion Crater are folded over the crest of a buried ridge of sandstone. Seen in road cutting on Liverpool St, Epsom.



20. Waikowhai Bay Parnell Grit and Holocene mud crab fossils

Park at back of Wesley Bay at end of Waikowhai Rd, in Waikowhai Park. Walk around rocks to east at low tide. Cliff forming point to east consists of thick bed of volcanic-rich Parnell Grit, that slid down the submarine slopes of the Waitakere Volcano ~20 Myr ago. Bed contains volcanic pebbles and a few lumps of fossil bryozoan (moss animals). Beyond the point is Faulkner Bay beach, which has occasional small concretions containing fossil cockles or mud crabs that were living just offshore within the last 8000 yr (Mid-Late Holocene).

21. Okahu Bay coastal terrace (11.95)

On either side of Tamaki Drive in Okahu Bay. The extensive flats (mostly playing fields) was formed from intertidal mud that accumulated in the bay when sea level was ~2 m higher than today, ~6000-2000 yr ago.

22. Karaka Bay-Tamaki Head Waitemata Sandstones and Parnell Grit

Walking access down steep, sealed path from end of Peacock St, Glendowie. Walk around foreshore to north at mid-low tide on eroded bed of Parnell Grit that also forms West Tamaki Head. Further on, the rocks are Waitemata Sandstone. Blocks of basalt and Coromandel Granite on the beach were brought here in the 1950s as a start for the abandoned Browns Island Sewerage scheme.

23. Tahuna Torea cusped foreland and spit (11.64)

Best access from carpark at end of West Tamaki Rd. Bush and beach walks. Shell spit extends almost right across Tamaki Estuary and has been formed from dead cockle shells concentrated here by wind-driven waves and tidal currents. The cusped (arrow-shaped) land encloses fresh

and salt water ponds and was formed by sand moving north in behind the shell spit.

24. Point England accretionary lapilli

100 m-walk from carpark at end of Pt England Rd. Seen at extreme low tide level around end of small Point England. Bed contains small balls of rhyolitic ash that stuck together inside ash clouds erupted with Potaka Ignimbrite from Mangakino Caldera, ~1 Myr ago.

25. Maungarei/Mt Wellington scoria cone

Walk up former roadway to top from Mountain or Gollan roads. Tallest scoria cone (10,000 yr old) on Auckland isthmus, with three amalgamated fire-fountaining craters - one filled with water reservoir. Source of extensive lava flow field, partly removed by quarrying and now site of new suburb of Stonefields, northwest of the cone.

26. Te Kopua kai a Hiku/Panmure Basin crater and tuff ring

Best access to sealed walking path, which circumnavigates inside of crater (1 hr) from Lagoon Dr, Cleary, Ireland or Peterson roads. 1 km-diameter explosion crater surrounded by tuff ring. Crater lake was breached by rising sea level about 8000 yr ago and now forms an intertidal lagoon. Erupted 25,000 yr ago.

27. St Kentigern cliffs lignite and rhyolitic ash layers (10.37)

400 m-walk on Rotary Walkway around edge of Tamaki Estuary from Kentigern Close. Seen in cliff from small wooden bridge. Stumps of fossil forest (under bridge) overlain by black lignite, which accumulated in a swamp, and layers of reworked cream rhyolitic ash and thin, gleaming-white Ongatiti Ignimbrite (erupted 1.2 Myr ago).

28. Sanctuary Pt ignimbrite (10.36)

Beside Rotary Walkway alongside Tamaki Estuary, accessed from several entrances on Fisher Parade. 2-3 m-high bluff, forming point beside path, is composed of white Potaka Ignimbrite (1 Myr old) that has evidence of still being quite hot when it arrived from Mangakino, 250 km away to the SE.

29. West Musick Pt cannon-ball concretions (11.78, 13.35)

Access via steps down cliff, from lawn in front of historic Musick radio station, at end of Musick Pt Rd (through golf course). Walk 400 m south along the west side at mid-low tide to see cannon-ball concretions that have formed in Waitemata Sandstones.



13.35 A group of 20-30 cm-diameter “cannon-ball” concretions stick out of the shore platform on the northwest side of Musick Point, Auckland. They are partly eroded out of the Early Miocene Waitemata Sandstone rock layers, within which they grew many millions of years ago.

30. Eastern Beach Anticline (13.36)

Mid-low tide walk along foreshore for 1 km, north from north end of Eastern Beach, or faster access down steps opposite 33 Clovelly Rd. Shore platform and cliff face show a perfect anticline (up fold) in Waitemata Sandstone beds.

31. South Eastern Beach Waitemata Sandstone cliffs and Parnell Grit

Cliffs at south end of Eastern Beach, accessed at low tide. Cliffs and foreshore rocks are composed of Waitemata Sandstone and a thick bed of darker, volcanic-rich Parnell Grit. Excellent examples of faults, sedimentary structures and trace fossils can be seen.

32. Kiwi Esplanade pahoehoe lava flows (9.10)

In mid-high tide foreshore alongside Kiwi Esplanade, between Mangere Boating Club and House Ave intersection. Ropey rolls of pahoehoe basalt on the surface of lava flows from Mangere Mt. They are well preserved because they have only recently been exhumed by sea erosion from beneath a covering of volcanic ash.

33. Mangere Mt scoria cone (9.58, 9.74, 9.75)

Road access into reserve off Domain Rd. Walk up farm road to top. Large scoria cone with two craters. Main crater contains a volcanic plug (tholoid) that has been squeezed out of the vent as the eruptions died down.

34. Ambury Park lava flows and lava cave

Road access from end of Ambury Rd. This farm park is built on part of the lava flow field from 50,000-60,000 yr-old Mangere Mt. Parts of lava flows occur in the fields, some with small overhangs and low lava caves, and around the shoreline. Ask the rangers to view the lava cave with locked lid. Moulds of several logs are present at mid tide in coastal flows.

35. Mangere Lagoon ‘castle and moat volcano’

Car park and access to walkway that circumnavigates tidal lagoon inside crater (40 mins) from corner of Creamery and Greenwood roads. A 700 m-diameter explosion crater and surrounding tuff ring that erupted just prior to or at the same time as Mangere Mt. The crater and small central scoria cone have been restored since their modification and use as part of the Mangere Sewage Treatment Plant.



13.36 One of the best examples of an anticline (up fold) in Waitemata Sandstone can be seen in the cliffs north of Eastern Beach.

36. Otuataua Stonefields Historic Reserve (9.55)

Main access (walking) from end of Quarry Rd. Historic Reserve contains largest example of pre-European Maori gardening complex established on the rich soils of the lava flow fields from Otuataua and Pukeiti volcanoes. See quarried stump of Otuataua scoria cone, small Pukeiti spatter cone, and numerous lava flows.

37. Ihumatao fossil forests (9.91, 9.92, 10.38, 12.27)

Access to foreshore and forests down stairs at end of Renton Rd. Fossil wooden remains of several hundred thousand yr-old kauri forest stumps and logs occur intertidally. The low cliffs consist of layered volcanic ash (tuff), erupted ~90,000 yr ago from neighbouring Maungataketake Volcano/Elletts Mt, containing fossil trunks and branches of trees that were killed by the base surges from the eruption. Fossils are seen as wood or hollow moulds where the wood has rotted away.

38. Puhinui craters (9.72)

Walking access from carpark at end of Price Rd. Three, small (200-300 m diameter) explosion craters with low tuff rings occur in farmed reserve. Pond near gate and equestrian arena occupy two craters; the third is eroded and difficult to recognise.

39. Weymouth Pliocene fossils (10.26-10.28, 13.37)

Easiest access from end of Palmers Rd. 200-800 m to the south, the higher intertidal platforms consist of harder Waitemata Sandstone unconformably overlain by softer, lower-lying Pliocene lignite, sandstone and mudstone. The lignites and associated sediment contain fossil wood, seeds, leaves and sea grass. In several places are fossil moulds of many shellfish where the shell has dissolved away.

40. Rangitoto shield volcano, scoria cones and lava caves (9.11, 9.80, 9.84, 9.87, 11.76, 13.38)

Usual public access is by ferry to Rangitoto Wharf. Auckland's youngest (550-600 yr old) and largest volcano. Take walking track or tractor ride to top of high scoria cone with deep crater. Most of circular island is composed of gently-sloping lava flows (shield volcano), many of which are in process of being colonised by pioneer plants. Branch track off Summit walking track (5 mins each way) leads to lava caves (bring torches and mind your head).



13.37 Soft Pliocene (~5-3 Myr old) lignite and fossil shell and leaf-bearing mudstone fills shallow valleys eroded in harder, algae-covered Waitemata Sandstone at Weymouth on the Manukau Harbour.

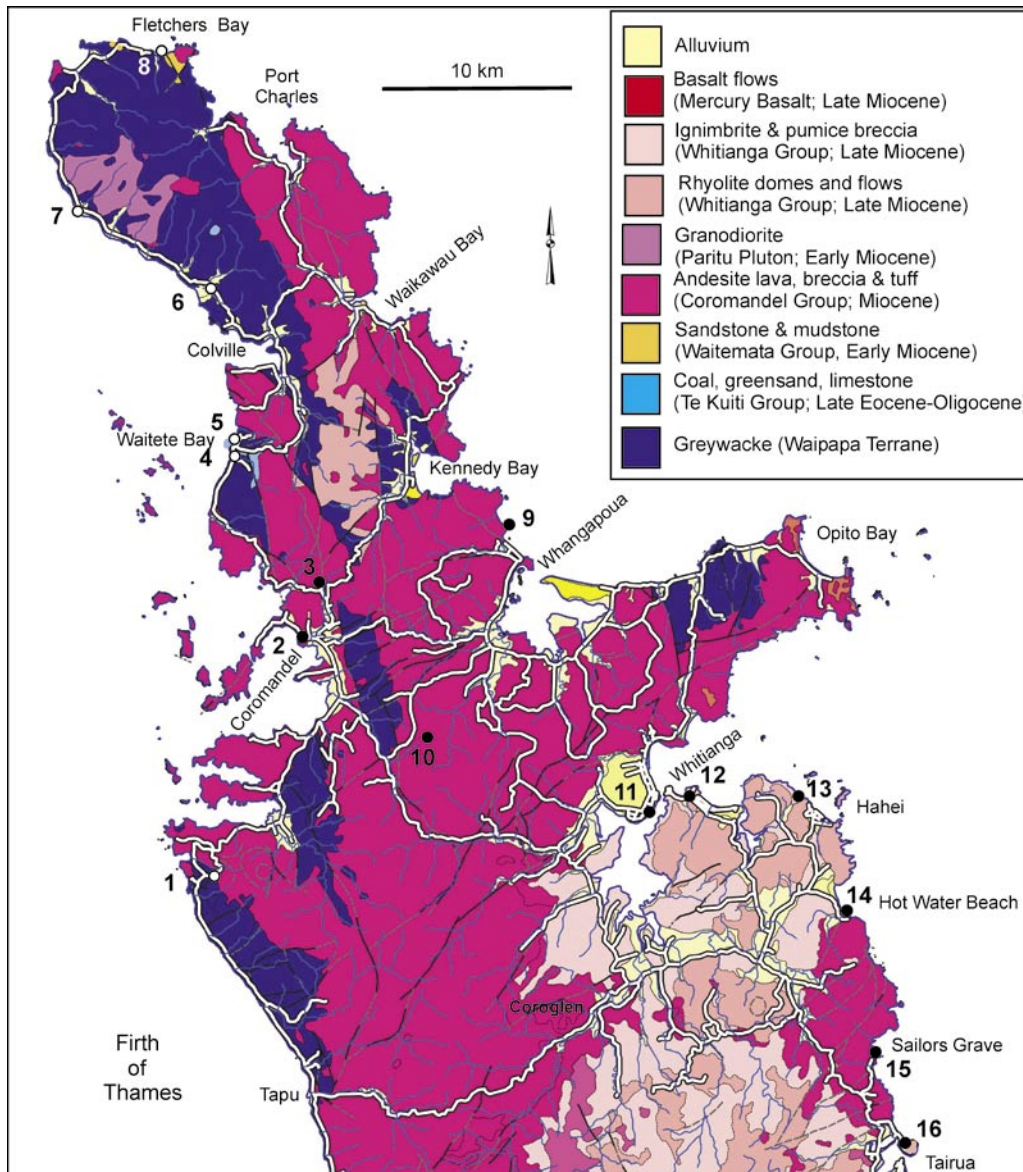
41. Motutapu Island Basal Waitematas and Waipapa chert (2.10, 5.8)

Long walk from Rangitoto Wharf or Home Bay, or shorter from Islington Bay, when ferries land there. Walk around base of cliffs from causeway northwards to Administration Bay at low tide (3.5 km). Pass bedded Waitemata Sandstone with Parnell Grit, overlying buried ancient sea stacks made of greywacke. Large fossil barnacles (5.8) occur in mudstone around base of first stack. See layers of Rangitoto ash that buried coastal village (9.80) in bay west of Administration Bay. At Administration Bay there are intertidal exposures of folded red and green chert within Waipapa Terrane basement greywackes. See "Walks through Auckland's geological past", Geological Society of NZ Guidebook 5, for more detail. Available from <http://www.gsnz.org.nz/guides.php>.



13.38 View across the upper northern slopes of Rangitoto Volcano. In the 550 or so years since eruptions ceased, vegetation has become well-established on the summit scoria cones, but is struggling to colonise some of the inhospitable lava flows. Rangitoto has the world's largest pohutukawa forest.

NORTHERN COROMANDEL PENINSULA



4. Waitete Bay coal

Road cutting, 400 m south of Waitete Bay Rd turnoff. 35 Myr-old pebble conglomerate and carbonaceous mudstone unconformably overlie steeply-dipping Manaia Hill Group greywacke (3.9).

5. Waitete Bay limestone

Point that divides bay into two beaches is made of 30 Myr-old limestone overlying fossil-bearing sandstone (3.18). Cliffs at south end of bay are bedded greywacke unconformably overlain by 35 Myr-old conglomerate.

6. Waiaro Last Interglacial terrace (11.98)

On Port Jackson Rd, 5 km north of Port Charles Rd turnoff. Road descends steeply over 5 m-high riser between Last Interglacial (120,000 yr old) terrace and Mid-Holocene (6000-3000 yr old) high-stand terrace in Waiaro Valley.

1. Manaia Hill thin-bedded greywacke (2.17)

Pull-off area on seaward side of Hwy 25, opp. road cutting with steeply inclined, well-bedded Waipapa Terrane greywacke and argillite (Manaia Hill Group).

2. Coromandel wharf hydrothermal (7.51, 7.57)

On landward side of Wharf Rd, 0.5-1 km west of Coromandel township. Intensely hydrothermally-altered andesite with veining. Kauri Block gold-mining area with abandoned adits beside the road.

3. Coromandel waterwheel and stamper battery

On Buffalo Rd off Rings Rd, north end of Coromandel town. Working waterwheel-powered stamper battery used to crush ore from quartz reefs.

7. Paritu wharf granodiorite (7.10, 7.11)

An old stone wharf, beside Port Jackson Rd, is made of blocks of Coromandel "granite". It was used for loading scows and barges with building stone blocks for shipment around New Zealand. A good place to examine fresh cut faces through this coarsely-crystalline plutonic rock.

8. Fletchers Bay Waitemata section and onset of volcanism (5.36, 7.9, 7.12)

East from Fletchers Bay, clamber around greywacke (Manaia Hill Group) foreshore rocks at low tide, or take track over point at mid-high tide. Intertidal rocks in next bay are 20 Myr-old deepening sequence of Waitemata Group sandstone and mudstone with Parnell Grit beds

near top (east end) of sequence. Intruded by several andesite dikes and overlain by terrestrial andesite breccia and lava flows, which form the Sugar Loaf and Pinnacles, part of the eroding 18-16 Myr-old Port Charles stratovolcano.

9. New Chums columnar jointed basalt (7.44)

Walk at mid-low tide from west end of Whangapoua Beach around back of beach and over track to New Chums Beach. Motuto Pt between Whangapoua and New Chums beaches is made of 9 Myr-old basalt plug with excellent columnar jointing.

10. Castle Rock plug (7.13)

A steep climb up rough trail from parking area, on bend near top of Castle Rock forestry road, which branches off the 309 Rd, just east of The Waterworks tourist attraction. The rock is composed of multiple dacite dikes thought to be the plug of a 12-11 Myr-old stratovolcano. Panoramic views. 1-1.5 hr return.

11. Whitianga ignimbrite buildings and wharf

Three structures on either side of the entrance to Whitianga Harbour are made from ignimbrite rock. One is New Zealand's oldest stone wharf on the east side. South of the wooden wharf on the west side, is a small 1870s stone store. Further south is a disused 1930s cool store, cut out of solid ignimbrite.

12. West end Shakespeare Cliffs high-tide notch and clastic dike (11.83)

Access at mid-low tide at east end of Maramaratotara Bay, across on the ferry from Whitianga. Overhanging cliff eroded out by alternate wetting and drying of the Late Miocene ignimbrite rock at, and just above, high tide level. Also present here is a 1 m-wide vertical sheet of finer ash and pumice (clastic dike) that has been injected up a widening fracture plane after the hot ignimbrite had cooled to a solid rock.

13. Cathedral Cove ignimbrite (11.82, 13.39)

Parking area at end of Grange Rd. Walking track along cliff tops and down to beach. Sea cave and mushroom rock eroded out of 8-6 Myr-old ignimbrite. Note also honeycomb weathering in the cliffs. 1.5 hrs return.

14. Hot Water Beach (10.11)

Walk 200 m north along beach from end of Hot Water Beach Rd. Hot water issues from the beach sand at low tide, just in front of silicified ignimbrite cliff. The hot water rises rapidly to the surface up a buried fault line.



13.39 This large sea cave has eroded along a weak joint through the massive ignimbrite rock. Its arched shape is the basis for the name of this internationally-famous location - Cathedral Cove.

15. Sailors Grave hydrothermally-altered rock (13.40)

Park at end of Sailors Grave Rd, off Hwy 25. Walk 15 mins around foreshore to north at mid-low tide. In the sea cliff around the point is a quartz reef and bright yellow, hydrothermally-altered rock. This is a typical example of the altered rock and reefs that were mined for gold on Coromandel Peninsula.

16. Paku Island rhyolite (7.36-7.38, 11.49)

Panoramic views from top of Paku Hill, 40 mins (return) climb up a walking track from end of Tirinui Cres, off Paku Drive. Paku is the eroded centre of a 8-7 Myr-old rhyolite dome. Intertidal rocks on north side of Paku (walking access at mid-low tide, from end of Hemi Place) are flow-banded and spherulitic rhyolite.



13.40 The yellow-coloured rocks are hydrothermally-altered andesite where the iron sulphides, like pyrite (fool's gold), have been oxidised. North point of Te Karo Bay, at end of Sailors Grave Rd, north of Tairua.

EARLY GEOLOGICAL STUDIES AND THE HISTORY OF GEOLOGICAL MAPPING OF NORTHERN NEW ZEALAND

Both the pre-European Maori and early European colonists undertook extensive searches for earth resources that would assist them to live more comfortably in their newly adopted home of Aotearoa/New Zealand. For example, Maori found and quarried the best sources of hard, fine-grained basalt (e.g. Tahanga, Coromandel) and argillite (e.g. Motutapu and Rakino islands, Auckland) that they could shape into adzes for use in cutting and carving wood. They also found and traded obsidian (from several places in Northland and Coromandel Peninsula, as well as Mayor I.), which was prized for its sharp glassy edge that could cut flesh, flax and other materials. Early Maori also found and fought over the most fertile soils (mostly volcanic) for growing kumara, and used various clays and kauri gum for dyes. They clearly understood that certain landforms were formed by volcanic activity because, in their traditional explanations for their formation and naming, they are often associated with Mataaho, the deity associated with volcanic forces.

The earliest, trained geologist to visit northern New Zealand was Charles Darwin on the *Beagle*, who spent 9 days in the Bay of Islands in December 1835. He found very little to like in New Zealand and noted that the most common rocks of the Bay of Islands were “slate coloured feldspathic (?) stones, ... which in places pass into soft argillaceous stones.” This is the first description of Northland’s basement greywackes. Darwin also described the limestone rocks and their castle-like form at Waiomio, south of Kawakawa. On his way to Waimate Mission Station he noted extensive areas of basalt lava flow and recorded the existence of “two or three truncated, conical hills, that ... clearly at one time have existed as volcanoes.” People brought him lignite from the west coast sand dune sequence that was “used by the inhabitants for their domestic purposes.” He also was the first to describe the top-hat islets in the Bay and to speculate on why the high-tide platform had not eroded down to a lower level. American geologist, James Dana, visited the Bay of Islands on the United States Exploring Expedition in 1840 and made similar observations on the same, small top-hat islet near Russell (14.1).

Ernst Dieffenbach was the next geologist on the scene, as part of a 2-year survey (1839-1841) of the colony by a group employed by the New Zealand Company to find and purchase land for the establishment of British settlements. Dieffenbach travelled widely throughout the north, describing the volcanic conglomerates of the Far North and Whangaroa (Tangihua Complex and Northland Volcanic Arc rocks). He discovered marble, but not the ancient fossils, in Waipapa Terrane greywacke near Whangaroa and Matauri Bay. Dieffenbach and Dana both described the basement greywacke rocks that surrounded the Bay Islands and gave extensive accounts of the young basalt volcanoes of the Kaikohe-Bay of Islands Volcanic Field. Dieffenbach was also the first to describe some of the softer Cretaceous to Oligocene sedimentary rocks of

Northland (Mangakahia and Motatau complexes) that he found around the Hokianga and Kaipara harbours. Among the New Zealand Company party was a young artist, Charles Heaphy, who picked up the rudiments of geology from Dieffenbach. He later applied these skills to producing the first map of the Auckland Volcanic Field, published in London in 1860, and to geological observations on the newly-discovered gold field at Coromandel in 1854.

In December 1858, Austrian geologist Ferdinand Hochstetter arrived in Auckland on the frigate *Novara* and was asked by the Auckland Provincial Council to survey the recently-discovered Drury coal field and advise on its potential to fuel the young city. Hochstetter stayed on in Auckland for a further 7 months. He used Heaphy’s map as a guide to producing his acclaimed map of the Auckland Volcanic Field (1863). He also circumnavigated the Manukau Harbour, visited the Coromandel goldfield with Heaphy, and made an epic overland expedition through the western Waikato, around Lake Taupo, via the Pink and White Terraces, to Tauranga and back to Auckland. On his return to Austria, Hochstetter produced the first geological maps of the Auckland Province and an extensive account of his geological and other observations. He included an account of his understanding of the geology of Northland based on the observations of Dieffenbach, Dana and others (14.2). In his account of the geology around Coromandel gold field, Hochstetter described the andesitic breccias and tuff, and the rich deposits of “chalcedony, carnelion, agate and jasper”, which occurred in thin veins, nodules and silicified wood. He concluded that the gold was derived from quartz veins in the greywacke basement rocks, having not seen occurrences of them in the younger andesite and rhyolites that we know of today.

Next on the scene, in the summer of 1865-66, was geologist James Hector. He had just been appointed the first Director of the New Zealand Geological Survey, based in Wellington. The New Zealand government’s expectation was that he would assist in the search and assessment of mineral resources for



14.1 Both Darwin (1835) and Dana (1840) commented upon how the shape of this small old-hat island, near Russell in the Bay of Islands, was formed. Kaiaara Island, Russell.

the benefit of the fledgling dominion. Hector realised that much of the South Island had been recently surveyed by Hochstetter, Julian Haast and himself, but little had been done in Northland since Dieffenbach and Dana 25 years earlier. Hector's first major field trip was a 4 month expedition (with draftsman John Buchanan), mostly on foot or horseback, from Whangarei to North Cape and down the Hokianga Harbour. At the time, there was a pressing need to open up a New Zealand coal field and Hector's main task was to assess the recently opened coal workings at Kamo and Kawakawa in east Northland. The main outcomes were Hector's optimistic report about the future of coal mining at these locations and the production of the first map of the geology of all of northern Northland (14.3). His map showed the location of nine of the main volcanoes in the young Kaikohe basalt field and several in the Whangarei Volcanic Field.

Thus the first extensive geological map of Auckland was produced by Hochstetter (1863) and of Northland by Hector (unpublished 1866). Apart from the 1850s visits to the Coromandel goldfield by Heaphy and Hochstetter, and small surveys of the goldfield areas in 1867 by Hector and Frederick Hutton (on contract to NZ Geological Survey) and in 1883 by Herbert Cox (NZ Geological Survey), the first geological map of the whole Coromandel Peninsula was prepared by James Park (at the time director of the Thames School of Mines) in 1894.

For the first century or more of its existence, the main task of the New Zealand Geological Survey (NZGS) was seen to be to investigate and map occurrences of economically valuable minerals and rocks, which would assist the economic growth of the country. Under NZGS Director James Hector, most parts of northern New Zealand were surveyed for coal, copper, manganese, iron, gold and silver. These surveys were carried out by well-known early NZGS employees, Herbert Cox in Auckland and Coromandel (1870s-1880s) and Alexander McKay in Northland (1870s-1890s) at reconnaissance scales of 1 inch to 5-12 miles.

Hector was succeeded as NZGS director by James Bell (1905-1911), who introduced a systematic geological mapping programme at a more precise scale of 1 inch to the mile. His plan, accepted by the government, was to publish full geological reports and maps of various areas of the country (subdivisions) in NZGS bulletins made available to the public for purchase. All the subdivisions targeted during Bell's tenure were of economic interest to the mining industry. In the north, Bell's Canadian geology colleague, Colin Fraser, who was given the title of Chief Mining geologist, set to work mapping the rugged Coromandel Ranges' goldfield areas. Fraser, with help from a number of assistants, spent over 4 years in the field,

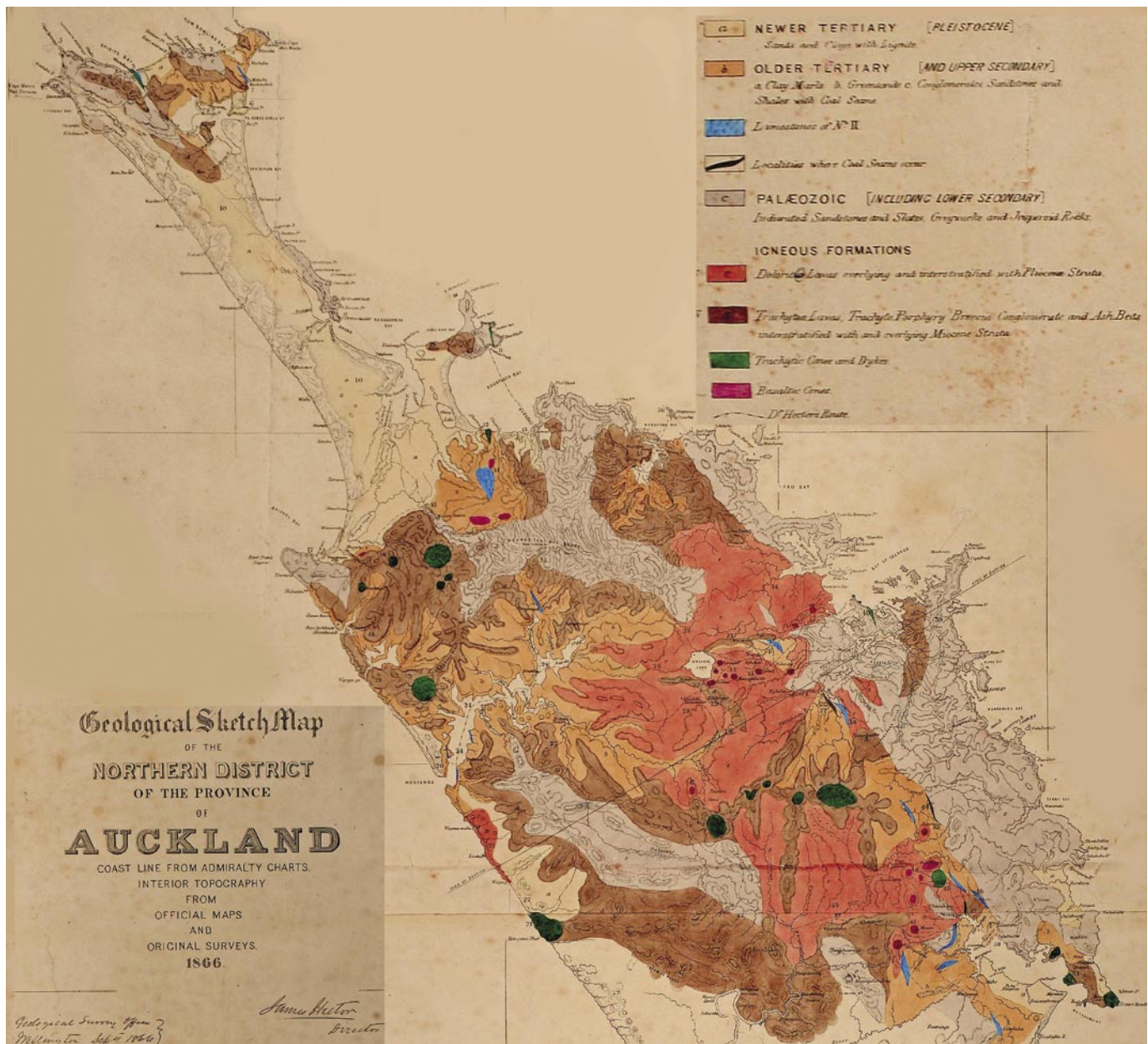


14.2 Watercolour and pencil sketch map of the geology of the Far North District, prepared by Ferdinand Hochstetter while in Auckland in 1859. It is based on the descriptions of Ernst Dieffenbach (1849) and snippets of information provided by others. Image courtesy of Sasha Nolden.

between late 1905 and 1911, mapping most of the Coromandel Ranges and its gold workings. The base maps at the time had reasonably accurate coastlines, but no topography, and the inland streams were poorly defined. Thus the geological mapping parties usually had a chain man and surveyor to improve the base maps and more accurately locate geological observations and samples. The results were published in three NZGS bulletins – Coromandel (1907), Thames (1910) and Waihi-Tairua subdivisions (1912).

The far southern end of the Coromandel Range (Aroha Subdivision, 1913) was mapped by John Henderson, assisted by John Bartrum (later professor at Auckland University College) in 1911-1912, after Bell had been succeeded as NZGS director by New Zealand-trained Percy Morgan. Morgan had been director of the Waihi School of Mines, 1897-1905, and was not at all happy with some of the mapping and conclusions of Fraser and co-author Bell in their Waihi Subdivision bulletin. By 1920, Waihi Mine had produced vast quantities of gold, but there were now questions about whether it was economic to dig deeper or explore more laterally. Morgan himself took the opportunity to remap in much greater detail the geology around Waihi and propose different optimistic hypotheses about the prospect of further gold strikes (NZGS Bulletin, 1924).

Bell's plan of 1 inch-to-the-mile systematic mapping extended to the Whangaroa Subdivision in Northland, which was mapped by Edward Clarke in 1907-08 and jointly written up and published as a NZGS Bulletin by Bell and Clarke in 1909. The justification for working on this area was that it contained evidence of copper, mercury and iron-ore deposits, but had been little explored and further deposits might be



14.3 Most of the unpublished geological map of northern Northland, prepared in 1866 by James Hector and John Buchanan, following a 4-month geological field trip to the north. Image courtesy of Simon Nathan.

found. Further mapping at this scale was undertaken between 1919 and 1925 by geologist Hartley Ferrar, while employed by NZGS. Ferrar is better known as geologist on Scott's first Antarctic Expedition, 1901-1904. His mapping filled in coverage of more of the geologically poorly-known parts of Northland and Auckland. His first Bulletin, on the Whangarei-Bay of Islands Subdivision, was published in 1925, whereas his second, on the Dargaville-Rodney Subdivision, was not published until 1934, two years after his untimely death after an appendicitis operation in Wellington. Much of the remaining unmapped geology of Northland was tackled by a hermit-like geologist, Bob Hay, who undertook fieldwork from 1946 to 1953 for the Mangakahia Subdivision, published as a NZGS

Bulletin in 1960. Bob spent the remainder of his career with NZGS geological mapping in relative isolation in Northland.

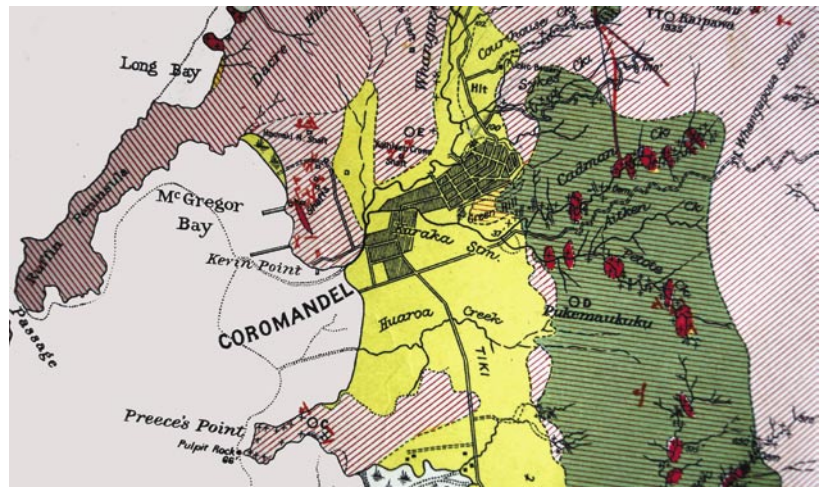
In the mid 1950s, Dick Willett became director of NZGS. He was impatient to see the mapping of all of New Zealand's geology completed, but recognised it would take another 100 years to complete the inch-to-the-mile series started by Bell. He proposed a new rapid-fire mapping programme at 4 mile-to-the-inch scale (1:250,000) as the highest priority for the organisation and to publish 28 sheets covering the whole country within 6-10 yrs. NZGS field geologists were assigned one or two sheets each, and for a few short years they raced around the roads and more easily-accessible exposures making observations and collecting samples for dating using fossils.

Northern New Zealand was covered by four sheets that were produced by Bob Hay, David Kear, Bruce Thompson and Jim Schofield in 1960-67.

After this flurry of activity, geological mapping returned to the more detailed inch-to-the-mile or its metric equivalent 1:50,000 scale. Bob Hay's mapping in the Far North was published as he neared retirement, in three sheets – Parenga, Houhora and Doubtless Bay (1975-1983). After completing the Auckland 4 mile-to-the-inch map in 1967, Jim Schofield, who was based at the NZGS Otago Office at the time, spent his last 20 years of employment producing detailed maps of the geology of the Hunua Ranges and Rodney District, 1976-1989. Also based at Otago in the 1970s-1980s and undertaking geological mapping were field geologists Les Kermode, Barry Waterhouse and David Skinner. David's northern Coromandel map appeared in 1976 and Barry's map of the area inland from Port Waikato followed two years later. Les' long-awaited map of the geology of Auckland was not published until 1992, just after his retirement. David Skinner undertook a great deal of field mapping on the Coromandel Peninsula in the 1970s and 1980s and the results appeared in geological maps of the areas around Coromandel Harbour in 1993 and Mercury Bay in 1995. Yet another map of the Waihi area, this time by Lower Hutt-based NZGS economic geologists, Bob Brathwaite and Tony Christie, was published in 1996. Two further 1:50,000 maps were produced by NZGS geologists in the 1980s - North Cape and Three Kings by Otago-based Fred Brook and Waitakere by Bruce Hayward.

In the 1980s, NZGS adopted another high priority, country-wide programme called the Cretaceous-Cenozoic basin project (CCP). Its aim was to make a significant contribution to the search for hydrocarbons by producing a summary of the known geology, stratigraphy and hydrocarbon potential of each of the sedimentary basins in the New Zealand region. The Northland Basin was assigned to Mike Isaac, Fred Brook and Bruce Hayward, who argued that the first part of the project in the north should be to better understand the recently recognised Northland Allochthon, by geological mapping in an inland area of better exposures between Whangaroa, Omahuta and Kaitaia. This resulted in two maps at scales of 1:25,000 and 1:100,000, published in 1988-1989, and a summary Bulletin in 1994. The latter included mapping of the area offshore of Northland by Rick Herzer, using seismic reflection profiles. Together these studies form much of the basis for chapter 4 and some of chapter 6 in this book.

The most recent geological mapping programme in New Zealand has been GNS Science's production of a new series of revised and updated 1:250,000 scale maps (QMaps) for the whole country. Northern New Zealand is covered by three sheets: Kaitaia compiled by Mike Isaac (1996), Whangarei compiled by Steve Edbrooke and Fred Brook (2009) and



14.4 A small portion of Fraser's 1907 inch-to-the-mile NZGS geological map of the Coromandel Subdivision – the first map at this scale produced in northern New Zealand.

Auckland compiled by Steve Edbrooke (2001). These QMaps are available in hard copy, but they are also available digitally for GIS software manipulation and these have been used throughout this book to create many geological base maps.

Not surprisingly, this account of geological mapping has been entirely about maps produced by the government geological research bodies, NZGS and more recently its successor GNS Science. Geological mapping in northern New Zealand was also widely undertaken by University graduate students for their theses. Indeed, well over 100 theses have produced original maps of parts of the geology of this region and the results have been incorporated into the geological maps published since the 1960s. Most mapping in this region was undertaken by students enrolled at the University of Auckland, but in more recent times, students from the University of Waikato have also contributed, particularly in the Coromandel Ranges. In the 1920s-1940s, some of the MSc geological mapping theses, undertaken under the guidance of Professor Bartrum at Auckland University, covered large areas, and many of the students involved went on to have distinguished geological careers in New Zealand or overseas. Examples of these include maps by: Charles Laws (later University of Auckland lecturer) in northern Hunua Ranges (1924); Frank Turner (later Professor, University of California at Berkeley) in Takapuna-Silverdale area (1925); Cyril Firth (later Chief Engineering Geologist for Auckland Water Supply) in northern Manukau County (1928); Ernie Searle (later Professor, University of Auckland) in southern Waitakere Ranges (1932); Jim Healy (later NZGS volcanologist) in southern Hunua Ranges (1935); Larry Harrington (later Professor, University of New England, Australia) in Hokianga area (1944); Hugh Battey (later Mineralogy Professor, UK) in Tuakau-Mercer area (1945); Nick Brothers (later Professor, University of Auckland) in northern Waitakere Ranges (1948); and Bob Clark (later Professor, Victoria University of Wellington) in Helensville-Kumeu area (1948).

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Finally I thank my wife, Glenys, and our daughters Kathryn, Jessica and Clare, for their support, encouragement and tolerance during the many years taken to prepare this book in all its many aspects.



14.5 Tiritiri Island, off Whangaparaoa Peninsula, is composed of basement greywacke (Waipapa Terrane). Its flat top is an uplifted remnant of the late Miocene Auckland Erosion Surface.

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14.6 A 35 Myr-old (late Eocene) fossil starfish (*Zoroaster whangareiensis*) from Reserve Pt, Whangarei Harbour. Width of photo 10 cm.

GLOSSARY

(if a term is not listed here you will find it on the web – try Wikipedia)

a'a lava – (pronounced ah-ah) lava flow that moves slowly and has a rubbly or blocky surface (p. 173)
abyssal – bottom of the deep sea at 2000-5000 m water depth
accretion – added onto
accretionary wedge – a thick stack of mostly sedimentary rock scraped off the top of the down-going oceanic plate in a subduction zone and added on to the edge of the adjacent continental plate (p.17)
acidic/felsic igneous rock – a rock that has formed by cooling of liquid magma and contains >63% silica, e.g. granite, rhyolite (p.12)
aeromagnetic survey – measuring the magnetic properties of the near-surface rocks with a magnetometer towed behind an aeroplane (p. 106-107)
alkali basalt – a medium to dark grey volcanic rock with 45–49% silica content, the main rock type erupted by Auckland and Kaikohe-Bay of Islands volcanoes
alluvium – sediment deposited by rivers
andesite – a medium to light grey-coloured, relatively fine-grained volcanic rock (1.9) with 52–63% silica composition
antecedent rivers – rivers that retain their course even though the topography around them has altered (p.220)
anticline – upfold
Ar – the inert gas element, Argon
argillite – hardened mudstone, similar to greywacke
ash – mud- and sand-size fragments (less than 2 mm across) of volcanic and other rock that have been fragmented and erupted into the air from a volcano
ASL – above sea level
asthenosphere – weak layer of the mantle below the lithosphere, approximately 80-200 km below the surface
back-arc basin/zone – region of rifting and subsidence behind a volcanic arc
basalt – dark grey-coloured, fine-grained volcanic rock (1.8) with 45–52% silica composition
base surge – a superheated cloud of turbulent steam, volcanic gas, ash and rock fragments that is blasted sideways from a vent during wet explosive eruptions and races across the ground at considerable speed (9.2)
basic/mafic igneous rock – a rock that has formed by cooling of liquid magma and contains 45-52% silica, e.g. granite, rhyolite (p.12)
basin, sedimentary – a large downwarp of the crust that accumulated a thick deposit of sediment
bathyal – sea floor at continental slope depths of 200-2000 m water depth
bedding – layering in sedimentary rocks
benthic – living or deposited on the floor of the sea or a lake
breached crater – a U-shaped crater on a scoria cone with one of its sides rafted away by a lava flow
breccia – rock composed of angular boulders, cobbles or pebbles (fragments greater than 2 mm in diameter)
calcareous – rich in calcium carbonate, CaCO₃ (lime)
calcite – mineral composed of calcium carbonate (lime), the main component of limestone
caldera – large crater formed by collapse during or after an eruption
CCD – calcium carbonate compensation depth = the depth (about 4000 m around NZ today) in the ocean below which all calcium carbonate dissolves
carbon/radiocarbon dating – a method of dating organic material using the natural radioactive decay of the ¹⁴C isotope (1.18)
chenier – a sand or shell beach ridge that has built up on top of mud flats
chert – a hard flinty rock composed of fine-grained silica (SiO₂)
chlorite – a green mineral with soapy feel formed by metamorphism or hydrothermal alteration
clast, clastic sedimentary rocks – particles up to boulder size and rocks composed of them
clinopyroxene – dark-coloured group of crystalline silicate minerals that may occur as small crystals in many of Auckland's basalt rocks
coal – a black, flammable rock composed of compressed and hardened plant remains
Complex – a formal rock unit equivalent to a Group, but composed of a diversity of rock types that are mixed together or have complicated structural relationships, such as the main rocks of the Northland Allochthon
concretion – hard rock formed by precipitation of minerals from solutions passing through the host rocks (box 11)
conduit – pipe or passageway for conveying fluid, such as magma
conglomerate – a sedimentary rock composed of rounded gravel (pebbles, cobbles, boulders)
country rock – the background rock through which volcanoes erupted
cross-section – a vertical slice through rocks or part of the Earth
crust – the outermost layer of the Earth – average continental crust thickness 30-40 km; average oceanic crust thickness 5-10 km (1.20)
dacite – a felsic volcanic rock intermediate in composition between rhyolite and andesite (63-68% silica)
deflation – process of wind erosion within sand dune areas (p.240)
diatoms – microscopic single-celled algae with skeletons made of silica
dike – a narrow sheet-like intrusion of lava or sediment cutting across the rock layers
diorite – speckled black and white, crystalline plutonic rock (1.7) with 52–63%

silica composition

DMOB – Dun Mt Ophiolite Belt (p.22)

epidote – a green silicate mineral formed during metamorphic or hydrothermal alteration

explosion/maar crater – wide, relatively shallow, circular crater remaining after a series of wet explosive eruptions (9.2)

explosive eruption – a violent wet style of eruption that occurs when molten magma encounters cold water and blasts out a cloud of steam, gas and fragmented rock (also known as phreatomagmatic eruption = steam and magma eruption)

fault – a fracture in rocks along which movement has occurred displacing one side with respect to the other

feldspar – the most common group of silicate minerals

felsic/acidic igneous rock – light-coloured igneous rocks rich in feldspar and silica (p.12)

fiery explosive eruption – a violent dry style of eruption of pasty magma powered by gas release with large bursting bubbles throwing out incandescent ragged lumps of magma or aerodynamically moulded bombs (also known as Strombolian eruption)

fire-fountaining eruption – steady fountaining eruption of fluid magma powered by gas release and building up a scoria cone around the vent (also known as lava-fountaining or Hawaiian eruption)

flaggy – rocks that readily split into layers 1-20 cm-thick, that can be used for flagstone paving

fold – curved layering in rocks

fold axis – the hinge line around which the folding occurred

foraminifera – microscopic marine amoeba with chambered shells often found fossilised

fore-arc basin – an elongate depression seaward of a volcanic arc (1.20)

Formation – a formally named unit of rocks with similar properties and age, often used for mapping and named after a place where they can be easily seen and studied

fossil – any remains or trace of a plant or animal that has been preserved in rock (p.13)

geothermal – heat from hot groundwater or steam

glauconite – a green mineral that forms as an alteration product of sediments on the sea floor at 50-300 m depth, where there is little deposition. The green mineral in greensand

graben – a subsided block of the Earth's crust bounded by parallel normal faults

greywacke – hardened sedimentary rock, strictly hardened sandstone. Usually basement rocks

Gondwana – Southern Hemisphere super-continent prior to its break up about 100-50 Myr ago

grit – an informal name for a rock made of granule-sized particles

Group – a formally named large unit of rock formations that have a similar age, origin and/or past geographic setting and have not been moved from one tectonic plate to another (see Terrane and Complex). May be divided into several subgroups.

halloysite – aluminosilicate clay mineral formed by hydrothermal alteration or weathering usually from rhyolite

horst – a raised block of the Earth's crust bounded by normal faults

hydrocarbon – organic compounds of hydrogen and carbon that form oil, natural gas and coal

hydrothermal – hot fluid within the Earth's crust

igneous – rocks formed by the cooling and solidification of molten magma (p.11-12)
ignimbrite – a rock formed from hot ground-hugging flow of volcanic ash and gas (box 29)

indurated – hardened and compressed, as in a rock that has been deeply buried
intermediate igneous rock – a rock that has formed by cooling of liquid magma and contains 52-63% silica (p.12)

intrusion – magma that has intruded into subsurface rocks

joint – a fracture in rock

karst – landscape formed by dissolution of limestone and sometimes basalt rocks, includes sinkholes and caves

K-Ar dating – potassium-argon dating, a method of radiometric dating of the time of crystallisation of igneous rocks and minerals

lahar – a volcanic mudflow consisting of a dense mix of volcanic debris and water
lapilli – pebble-sized pieces (2–64 mm across) of volcanic and other rock that have been fragmented and erupted from a volcano

lava – molten rock (magma) that has been erupted onto the Earth's surface

lignite – low-grade coal containing recognisable plant remains

limestone – a sedimentary rock composed of more than 50% calcium carbonate

lithosphere – the outer part of the Earth that is broken up into tectonic plates; comprises the crust and upper mantle (1.20)

longshore drift – overall movement of sediment along the coast by a combination of processes (p.237)

mafic igneous rock – dark-coloured igneous rock dominated by iron- and magnesium-rich minerals and having 45-52% SiO₂

magma – molten rock occurring under the ground; may erupt at the surface (after which it is called lava but it is essentially the same composition as the parent magma)

magnetic anomaly – local variation in measurements of the Earth's magnetic field as a result of differences in magnetism of the underlying rocks

mantle – part of the Earth's interior between the crust and the core (1.20)

marble – metamorphosed limestone
mélange – a breccia rock composed of a mixture of rock fragments of different kinds
metamorphic – transformed by heat and/or pressure (p.13)
mineral – naturally occurring inorganic substance the components of rocks
mudstone – a rock composed of fine-grained (<0.06 mm) particles (mud)
Myr – million years ago
Northland Allochthon – many oceanic rock types that have been displaced hundreds of kilometres onto Northland, mostly as large slabs
obduction – slabs of oceanic crust and upper mantle that have been pushed up onto the edge of continental crust (box 10)
obsidian – volcanic glass formed by rapid cooling of felsic lava (box 37)
olivine – a green crystalline mineral composed of magnesium iron silicate that sometimes crystallises in the magma underground and is commonly present in basalt
ooze – a soft deposit of sediment on the bottom of the sea
ophiolite – a slice of oceanic lithosphere containing ultramafic and mafic igneous rocks that were formed under the deep sea (box 10)
ore minerals – small dark grains of metal oxide that often crystallise in magma and occur in igneous rocks
pahoehoe lava – (pronounced pa-ho-ee-ho-ee) lava flow that has a rapidly chilled, rolled-up or ropey but otherwise smooth, glassy surface (p.173)
peat – incompletely decomposed deposit of plant material
pelagic – relating to or living in sea or lake water above the bottom
peridotite – iron-magnesium-rich rock that forms much of the mantle and when partly melted produces basalt magma
perlite – a form of obsidian consisting of glassy globules
petrification – the process whereby organic material is replaced by minerals and turned to stone (p.14, box 30)
pillow lava – finger-like lobes of lava erupted under water (box 10)
plagioclase – light-coloured feldspar mineral of sodium-, calcium-, aluminium-silicate that is a common constituent of rocks
plankton – small organisms that float or swim in fresh or salt water
plate – a rigid, mobile segment of the lithosphere (1.19)
plutonic – a coarsely crystalline rock that has formed by slow cooling of magma beneath the ground
podzolisation – an extreme soil-forming process that occurs in acid conditions usually under podocarp forests (p.240)
pumice – solidified frothy, glassy, volcanic rock formed in violent, wet, explosive eruptions, usually pale-coloured and rich in silica
pyroclastic – fragmented material thrown out by an explosive eruption
pyroclastic flow/surge – a hot, fast-moving, gas-rich, ground-hugging flow of pyroclastic debris
quartz – common, inert, variably-coloured mineral composed of silica, SiO₂
radiolaria – microscopic, single-celled plankton having an intricate skeleton of SiO₂, commonly found fossilised in oceanic sedimentary rocks
remote sensing – acquisition of subsurface data by remote means such as using seismic waves or measuring gravity or magnetism
rhyolite – light-coloured, fine-grained volcanic rock with more than 68% silica
ria coast – a coastline characterised by harbours and inlets formed by partial drowning of former river valleys by rising sea level
rift – a linear zone where the lithosphere is being pulled apart; forming a rift basin or valley above it
ring plain – a circular plain mostly of lahar deposits that builds up around the foot of a stratovolcanic cone (6.10)
sandstone – a sedimentary rock composed predominantly of sand grains (0.06-2 mm)
scoria – lightweight volcanic rock full of holes (vesicular) that was erupted by fire-fountaining or fiery explosions of frothy lava which cooled and solidified as it travelled through the air (sometimes referred to as cinders)
scoria cone – relatively small, usually steep-sided (c.30°), volcanic cone made of scoria
seamount – a submarine volcano rising 1000 m or more above the seafloor
sedimentary rock – rocks composed of sediment (rock particles and fossil material) and subsequently cemented into a rock (p.13)
seismic reflection profile – a cross-section of the subsurface rock structure obtained by remote sensing using sound waves bouncing off subsurface layers and features (p.107)
seismometer – instrument used for detecting vibration waves passing through the ground
serpentinite – green rock made of serpentine, formed by hydrothermal alteration of peridotite
shield volcano – gently sloping (c.10°) volcanic cone made of overlapping basalt lava flows erupted from one or more near-central vents (6.8)
siliceous – rich in silica, SiO₂
sill – a narrow intrusion of magma parallel to the layering of the host rock
slump scarp – a steep bank left behind when a mass of rock and earth slides off downhill
strata – layers of rock
stratovolcano – a steep-sided volcanic cone (usually of andesite) consisting of layers of lava flows and volcanic debris (6.10)
strike and dip – horizontal line (strike) and direction of maximum slope (dip) on a planar surface; used to define the slope and direction of bedding/layering
sub-alkali to tholeiitic basalt – a dark grey volcanic rock with 49–50% silica content, richer in aluminium and poorer in potassium and sodium than other

basalts, main rock type erupted by Whangarei, Ti Point, Puhupuhi and Rangitoto volcanoes
subduction – process by which the leading edge of one crustal (usually oceanic) plate pushes down beneath the edge of an adjacent (usually continental) plate (1.20)
submarine canyon – an undersea valley on the seafloor
submarine fan – a delta-like accumulation of sediment deposited at the mouth of a submarine valley
suturing – process in which one terrane is joined to others (p.20)
syncline – downfold
tafoni – weathering of rock surfaces, usually involving the growth of salt crystals by evaporation, that produces a honeycomb on the rock (p.269)
tectonic – forces within the Earth that cause movements of the crust (plate tectonics)
tectonic plates – gigantic slabs of lithosphere that form the surface of the Earth and are slowly moving around and jostling each other (1.19)
tephra – solid material that has erupted into the air by a volcanic eruption and has been deposited on the ground; includes all fragment sizes – ash, lapilli and blocks
tephrochronologist – a scientist who studies the sequence of volcanic ashes
terrane – a block of lithosphere (10s – 100s of km across) broken off one tectonic plate and added to another
terrestrial – on land
terrigenous – derived from land as in sediment eroded off the land and deposited in the sea
Tethys Sea, Tethyan – tropical ocean that existed during the Mesozoic between the supercontinents of Gondwana and Laurasia
thrust fault – low angle fault with the rocks above having been moved across the rocks below
tombolo – a spit of sand or gravel that connects a former island to the mainland
transform fault – a major fracture in the crust with rocks having moved sideways (often hundreds of kms) in opposite directions on either side of it (see p.17)
travertine – a calcium carbonate (limestone) rock that may form around hot springs (box 43)
tuff – volcanic ash that has hardened to become rock
tuff ring – a near-circular rampart of bedded volcanic ash (tuff) built up around an explosion crater (sometimes known as a tuff cone when larger)
turbidity current – a dense, turbulent, underwater flow of sediment-laden water that deposits a graded bed of sand (turbidite) on the seafloor (box 18)
underthrust – pushed beneath with low-angle faults between slabs of rock
vent – the opening through which volcanic material erupts
vesicular – full of holes (vesicles)
viscous – thick, sticky, resistant to flow, like golden syrup
volcanic arc – a chain of volcanoes erupted above a subduction zone, parallel to a plate boundary
volcanic bomb – a glob of magma ejected into the air while still molten and often acquiring an aerodynamic shape as it cools during flight
weathering – the process of altering rock to clay or wearing it away by long exposure to the air
Zealandia – the mostly submerged continent centred around New Zealand today
zeolite – group of silicate minerals formed during rock alteration



14.7 A tight synclinal fold in deformed Waitemata Sandstones has been eroded out on the foreshore of Whangaparaoa Head. Flat-topped Tiritiri I. in background.

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