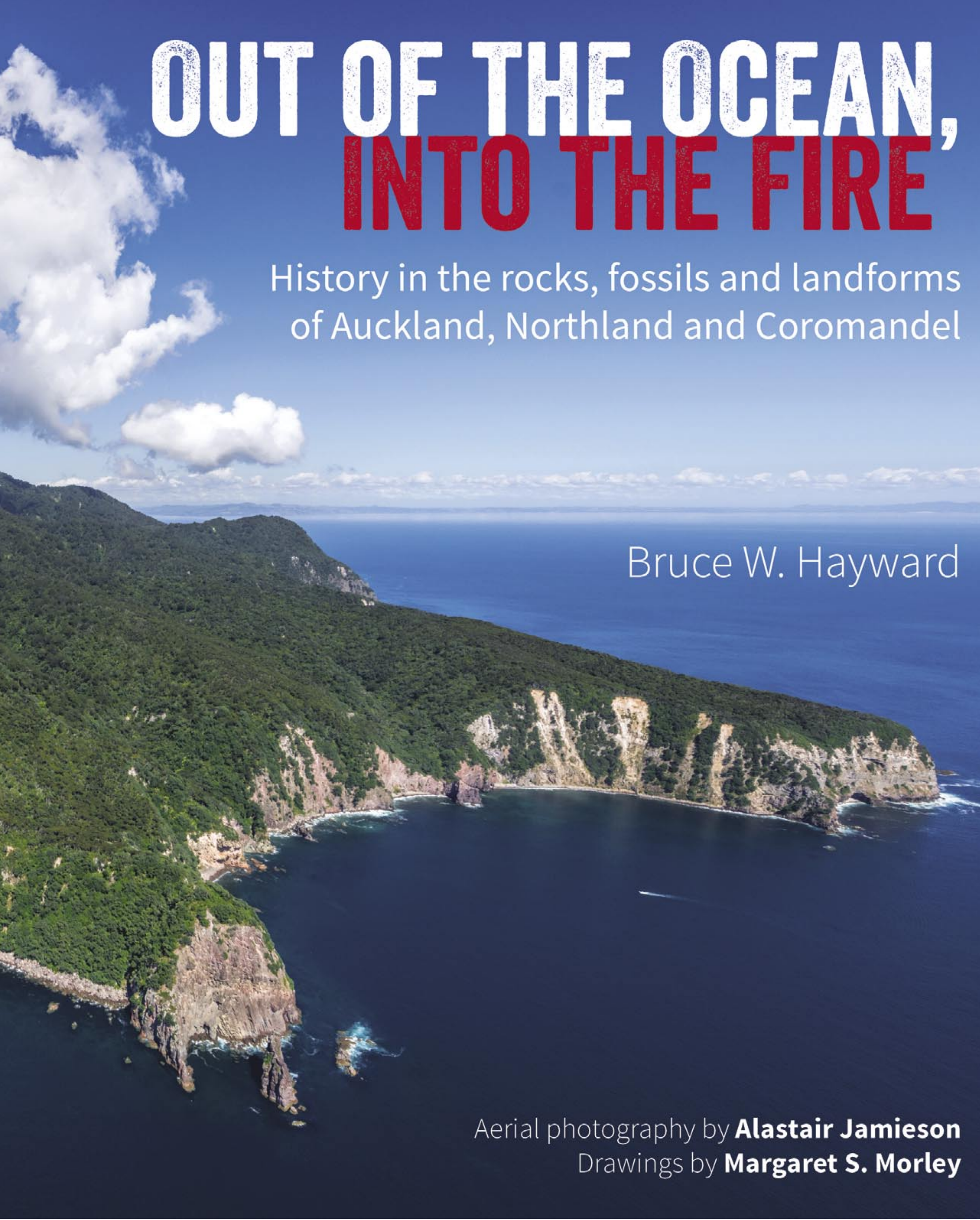
OUT OF THE OCEAN, INTO THE FIRE

History in the rocks, fossils and landforms of Auckland, Northland and Coromandel

Bruce W. Hayward



Aerial photography by **Alastair Jamieson**
Drawings by **Margaret S. Morley**

Just as a tree retains a record of its life in its tree rings, the Earth also retains memories of its past development. These memories are preserved in the rocks and in the landforms of northern New Zealand. They have been decoded by geoscientists, and now, for the first time, are made accessible to everyone through this book. Now we can all appreciate and marvel at this region's amazing 270 million-year-long history — initially under the sea and later as a land ravaged by volcanic eruptions.

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Out of the Ocean into the Fire tells, for the first time, the fascinating geological history of the formation of northern New Zealand and the history of its past biota.

The oldest rocks were formed on the deep floor of the ancient Pacific Ocean, between 270 and 25 million years ago. Some were plastered onto the side of the supercontinent of Gondwana about 150–100 million years ago, before they split away to become ancient New Zealand.

Then 25 million years ago, 100,000 cubic kilometres of ocean floor rocks were pushed up out of the ocean and slid hundreds of kilometres southwest to cover all of ancient Northland.

Since then the later history has been dominated by the most violent and diverse volcanic activity to occur in a region of this size anywhere on Earth.

Highlights include:

- NZ's largest cone volcano (Waitakere)
- NZ's largest shield volcano (Waipoua)
- 200 small basalt volcanoes in 7 fields
- Extrusion of 70 viscous volcanic domes
- Massive explosive caldera eruptions
- North Island's oldest rocks and fossils
- World's best fluted basalt (karst)
- NZ's largest sand dunes produce NZ's largest harbours (Kaipara, Manukau)
- NZ's best examples of a butte, lava plug, natural jetty, pillow lavas, lava caves, huge spherical concretions, mud volcano
- NZ's richest goldfields (Coromandel)
- Quartz sand for glass, black sand for steel
- Northland limestone source of NZ's cement
- Geothermal power lights up Northland
- Northland clay makes world's whitest ceramics
- NZ's largest fossil shellfish (1.5 m long)
- Fossil ichthyosaurs, ammonites, coconuts.

About the author: Bruce Hayward is a semi-retired research geologist, paleontologist and marine ecologist, who spent most of his career studying aspects of the natural and human history of northern NZ (as a paleontologist with the NZ Geological Survey, curator of marine invertebrates at Auckland Museum, a James Cook Fellow at Auckland University, and as self-employed principal scientist of Geomarine Research). He is author or co-author of over 280 peer-reviewed articles plus 13 monographs. He is a past President of the Geological Society of NZ, a former member of the NZ Conservation Authority and Auckland Conservation Board, and co-founder of the NZ Geopreservation Inventory and Auckland Geology Club. His studies have been recognised with Fellowship of the Royal Society of NZ and Member of NZ Order of Merit.

Previous books by Bruce Hayward:

On the edge: Celebrating the diversity of NZ's coastal landforms (with Jill Kenny), 2013
Volcanoes of Auckland: The Essential Guide (with Graeme Murdoch, Gordon Maitland), 2010
Karst in Stone. Karst landscapes in NZ: A case for protection (with Jill Kenny), 2010
The Restless Country: Volcanoes and earthquakes of NZ (with Geoffrey Cox), 1999
A Field Guide to Auckland (with Ewen Cameron, Graeme Murdoch), 1997, 2008
Precious Land — Protecting NZ's Landforms and Geological Features, 1996
Volcanoes and Giants (with Brian Gill), 1994
Kauri Timber Days (with Jack Diamond), 1991
Trilobites, Dinosaurs and Moa Bones: The Story of NZ Fossils, 1990
Granite and Marble: Guide to NZ Building Stones, 1987
Kauri Gum and the Gumdiggers, 1982
Waitakere Kauri (with Jack Diamond), 1980
Cinemas of Auckland (with Selwyn Hayward), 1979
Ancient Undersea Volcanoes: A guide to Geological Formations at Muriwai, West Auckland, 1979
The Maori history and legends of the Waitakere Ranges (with Jack Diamond), 1979
Kauaeranga Kauri, 1977
Kauri Timber Dams (with Jack Diamond), 1975

Cover photo: Little Barrier Island/Hauturu is an extinct stratovolcano that erupted in the middle of the Hauraki Gulf in two phases, 3 and 1.2 million years ago.
Photographer Alastair Jamieson

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Crater Hill, in Papatoetoe, is the best preserved of the remaining tuff cones and craters in the young Auckland Volcanic Field. Crater Hill erupted for a short period, 30,000 yr ago.

Aerial photography by **Alastair Jamieson**
Drawings by **Margaret S. Morley**

Geoscience Society of New Zealand, 2017

Motuarohia in the Bay of Islands, consists of a string of greywacke islands and stacks joined together by a sand tombolo. Photographer Alastair Jamieson.

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FOREWORD

We humans recognise the importance and desirability of preserving our cultural and historic heritage. Now the time has come to ensure we also document and protect our geological heritage before it is all destroyed. The past of the Earth is no less important than that of human beings. Earth and human histories are closely linked. The Earth's history is our history and the Earth's future will be our future. In the next few decades we need to make a greater effort to protect the history of our Earth - our geoheritage. To achieve this requires greater public appreciation and understanding of the past history of our part of the planet, how it evolved through to the present day and how it is now being lost and destroyed by thoughtless human actions.

Just as a tree retains a record of its life in its tree rings, the Earth also retains memories of its past history. These memories were preserved in the rocks and in the landforms before humans evolved, a record that can be read by geoscientists and told to us all. This book attempts to bring to life and relate the amazingly complex history of the origins of northern New Zealand and its biota, so that all who read it will have a new appreciation of the rocks and landforms around them and the clues they hold to understanding our land and our place on Earth.

The history recounted here has been sleuthed from our land by several generations of geoscientists. Hopefully there will be sufficient representative examples of our diverse rock exposures and landforms remaining for our grandchildren and great-grandchildren to appreciate and understand that history and for many more generations of scientists to study and extract a far more complete and precise history of our unique part of the World.

I dedicate this book to my family who have had no choice but to travel this alluring road to discovery with me, and to all those geologists whose detective work has contributed to understanding the history of northern New Zealand told in this book.

Bruce W Hayward, 2017

These fingers of rock, called pillow lava, were extruded out onto the seafloor, 17 million years ago, on the slopes of the Waitakere Volcano - the largest stratovolcano ever erupted in New Zealand. Most of its 50 km-diameter cone has been eroded away by the Tasman Sea in the 15 million years since it stopped erupting. The volcano's remains form the Waitakere Ranges, west Auckland.

CONTENTS

Boxes

The following boxes provide additional information about the listed topics

Mt Manaia is the eroded remnants of 20-18 Myr-old Whangarei Heads Stratovolcano (see chapter 6). Photographer Alastair Jamieson.

BOOK SUMMARY

Out of the ocean

Northland, Auckland and Coromandel Peninsula have the most diverse, and complex, geology in New Zealand. This is the first time the story of their 300-million-year (Myr) history has been prepared for a general readership. Almost all of the older rocks (older than 23 Myr) were deposited as sediment or erupted as lava on the floor of the ancient Pacific Ocean. The older basement greywacke rocks (chapter 2) were rafted along on the moving oceanic Pacific Plate and plastered onto the coastal edge of the supercontinent of Gondwana, prior to 110 Myr ago. Between 85 and 50 Myr ago these basement rocks split away from Gondwana as part of the New Zealand continent of Zealandia. Thin deposits of coal measures and limestone accumulated on top of the eroded greywacke, 40-23 Myr ago (chapter 3).

Between 24 and 19 Myr ago, at least 100,000 km^3 of rocks that had been erupted and deposited on the floor of the Pacific Ocean (110-23 Myr old) were pushed up out of the ocean by plate tectonic forces and slid into Northland and northern Auckland (chapter 4). They slid into the northern end of a 1-3 km deep marine basin created by regional subsidence. The southern end of the basin accumulated 1 km thickness of Waitemata Sandstone that was subsequently uplifted to form Auckland (chapter 5).

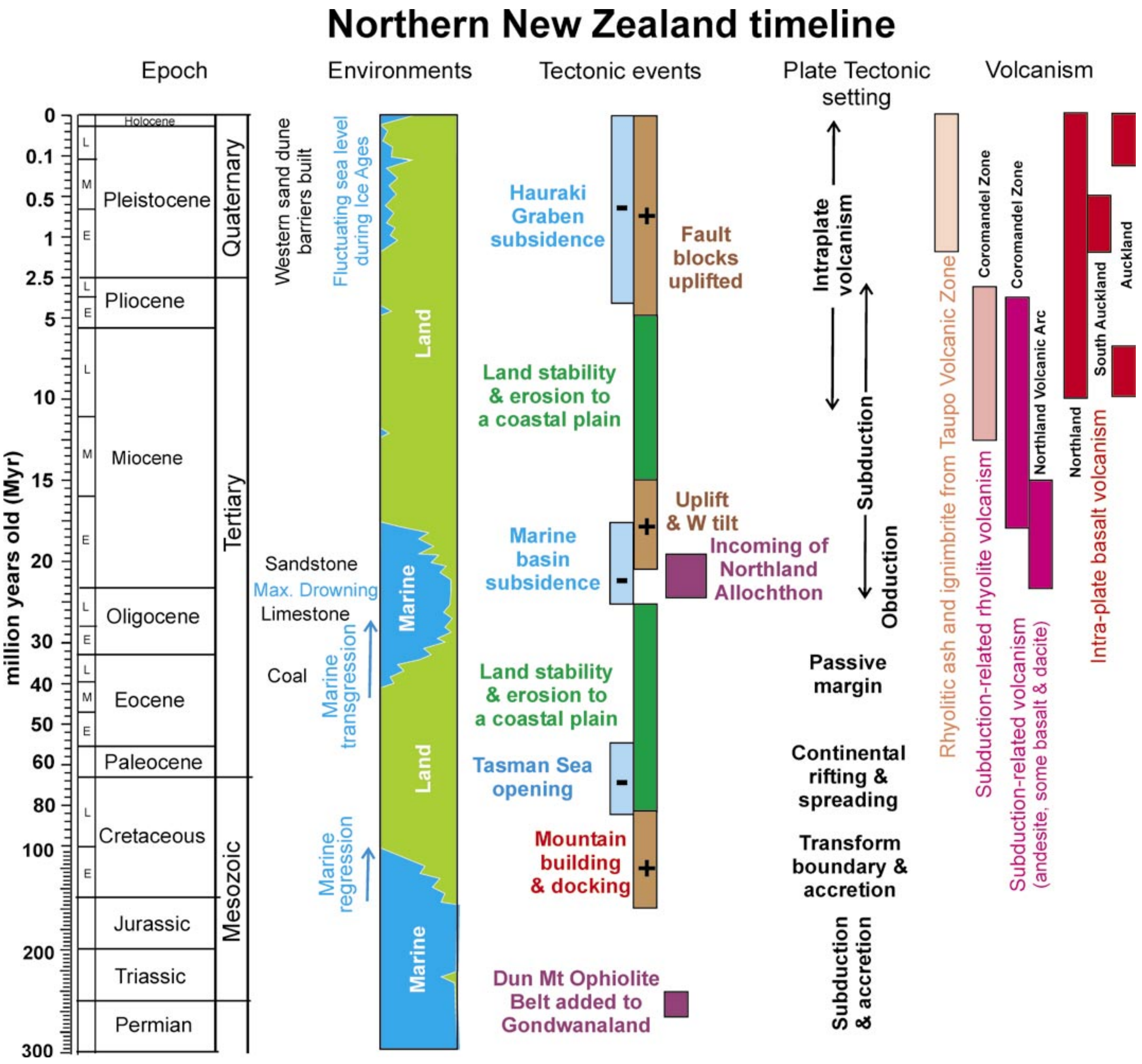
Into the fire

Most of the subsequent history of northern New Zealand was dominated by fiery volcanic activity of greater diversity than any area of similar size elsewhere in the world. There were subduction-related volcanic arcs of andesite stratovolcanoes, giant caldera volcanoes, searing ignimbrite flows and rhyolite domes, including the largest cone volcano (Waitakere) and largest shield volcano (Waipoua) ever to erupt in New Zealand (chapters 6, 7). These were followed by at least 200 small basalt volcanoes (explosion craters, scoria cones, shield volcanoes, plateau basalt flows) that erupted in seven "hot-spot-like" volcanic fields (chapter 9).

The region has been uplifted three times, pulled down once, tilted westwards, eroded down to an undulating coastal plain twice (chapter 8) and torn apart by the recent foundering of the elongate Hauraki Gulf and plains. The present-day shape and landforms of northern New Zealand reflect its history over the last 5 Myr (chapters 10-12) with local uplift, erosion, volcanic activity, the construction of New Zealand's largest sand-dune barriers and harbours, and the moulding of the coast by the oscillating sea levels of the Ice Ages (last 2.5 Myr).

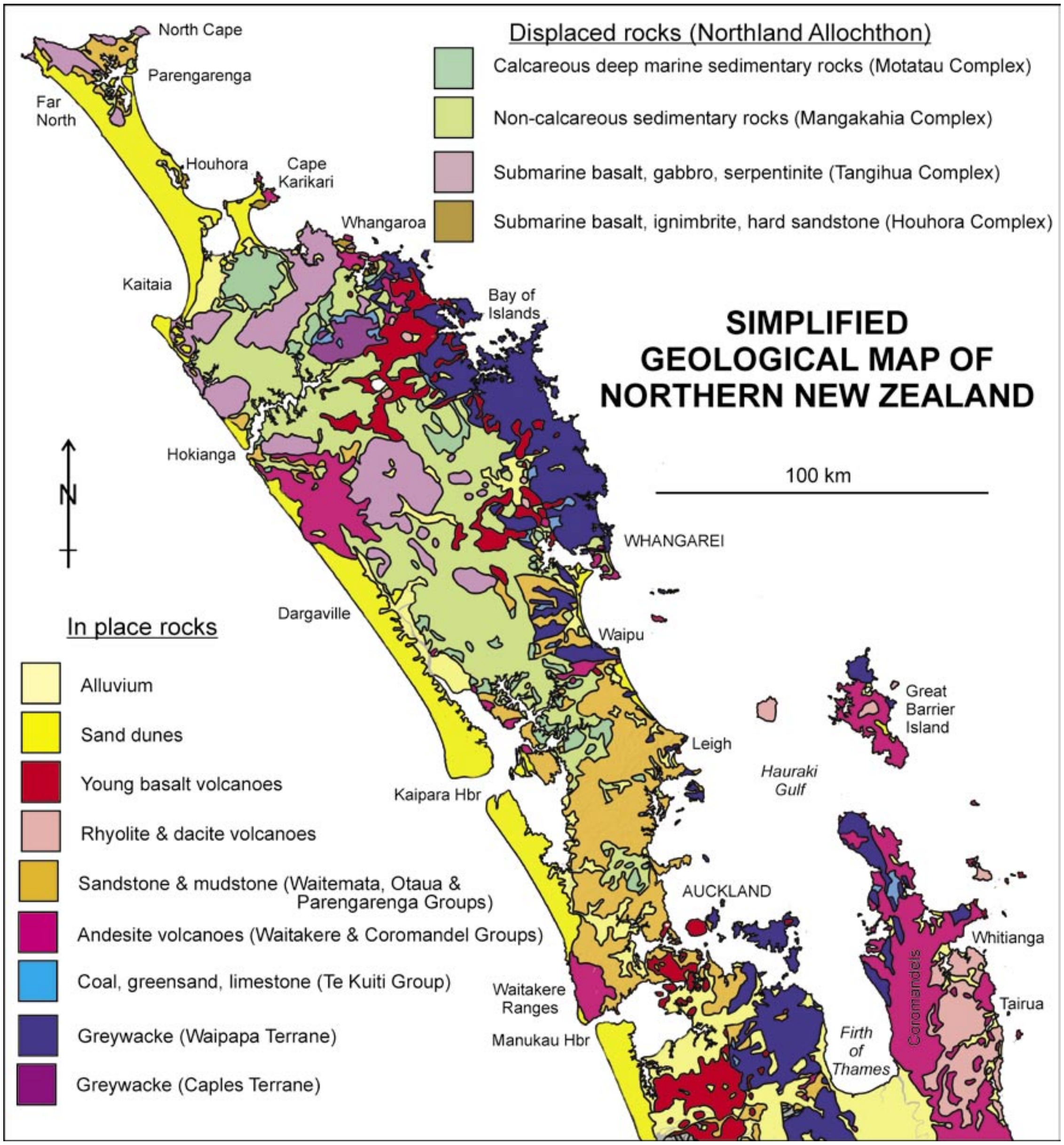
A wide range of fossils documents the evolutionary history of life in the sea and on land and includes fossil ammonites, giant mussels, subtropical seashells, reef corals, soft-bodied fan worms, palms, ferns, miniature coconuts, seeds, leaves and the bones of extinct ichthyosaurs, turtles, lantern fish and moa. The rocks of northern New Zealand have played a pivotal role in the region's infrastructure, buildings and economy – greywacke and basalt for aggregate, limestone for cement and fertiliser, and clay for brick making. Silica sand provides raw material for glass-making, iron sand for the production of steel, halloysite clay for the whitest ceramics in the world. Mining for coal and kauri gum were major industries in early Northland. Gold mining still plays a significant role in the economy of the Coromandel region.

Each chapter in the book (except the introduction) starts with a brief summary of its contents, in less technical language more suitable for those with limited previous exposure to geology. In most chapters, simplified geological maps, cross-sections, stratigraphic columns and paleogeographic maps are developed to help explain the history contained in the region's rocks.



This time line summarises the major events in the geological history of northern New Zealand that are described in detail in approximate chronological order in this book.

Chapter 1. INTRODUCTION TO GEOLOGICAL TERMS AND CONCEPTS



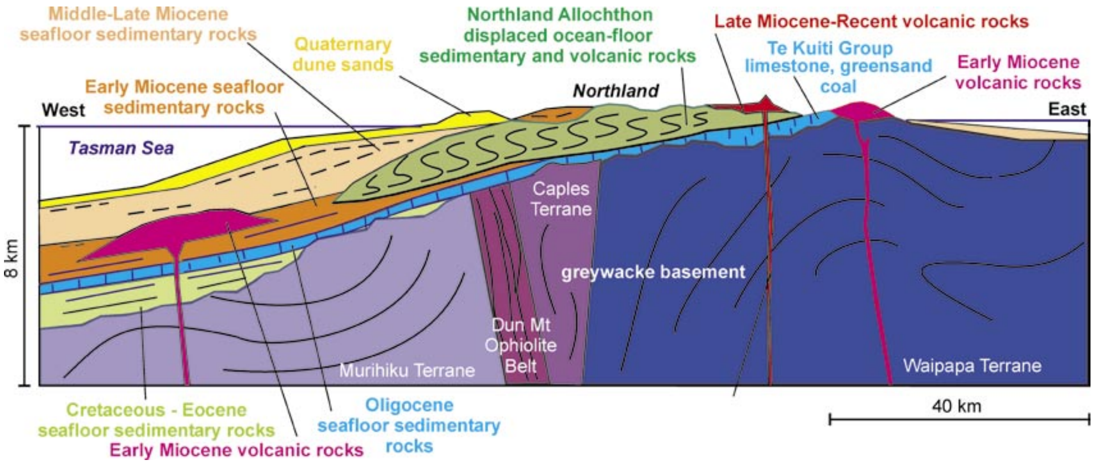
1.1 Simplified geological map of northern New Zealand.

GEOLOGICAL MAPS, CROSS-SECTIONS, COLUMNS

Geological maps (*1.1*)

These use different colours to show where rocks of different kinds and different ages occur at the surface or just below the soil cover. Volcanic and plutonic rocks that formed by cooling of a molten magma are usually shown in red, purple and pink tones. Hardened sedimentary rocks like greywacke are usually shown in dark blue and young sediment like dune sand and alluvium in yellow.

Rocks that are of the same or similar kind and were formed about the same time are often lumped together as a geological formation. These are given formal names, usually the name of a place where they are easily seen. These formations are parcelled together into larger units called Groups, Terranes or Complexes. For ease of reading, no structural features are shown on most of the simplified maps, but in a few more detailed maps, faults are shown as lines with a tick on the downthrown side, the axis of folds are plotted and the tilt of bedding is shown with a standard strike and dip symbol.



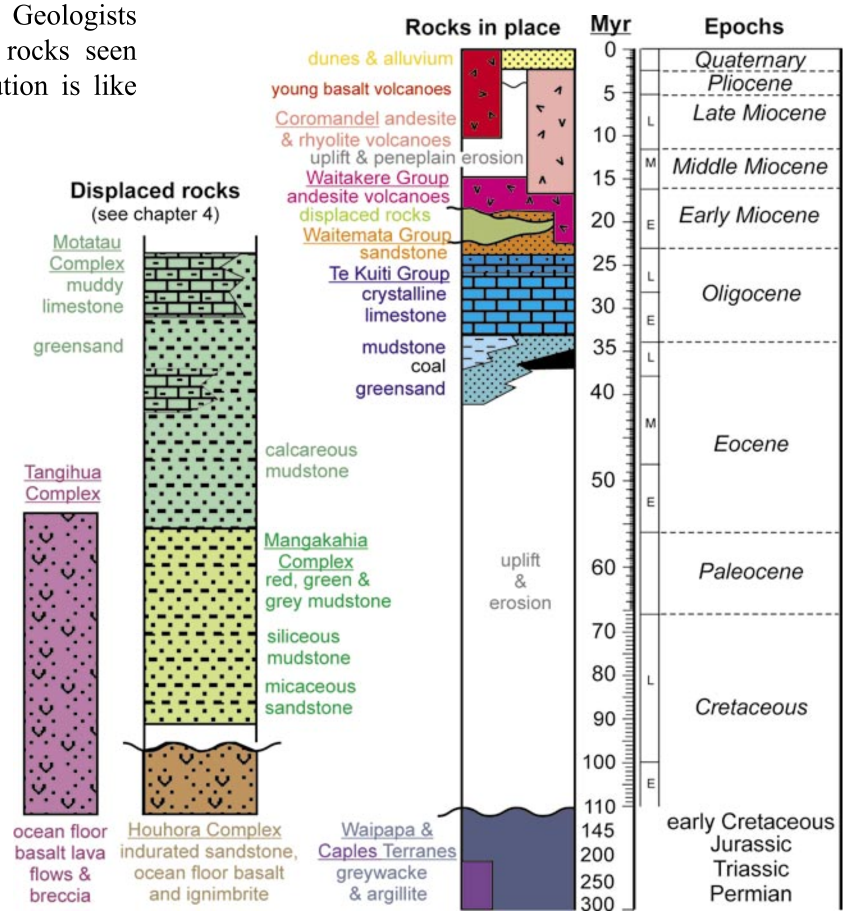
1.2 Simplified geological cross-section through central Northland. Vertical exaggeration 5 to 1.

Geological cross-sections (*1.2*)

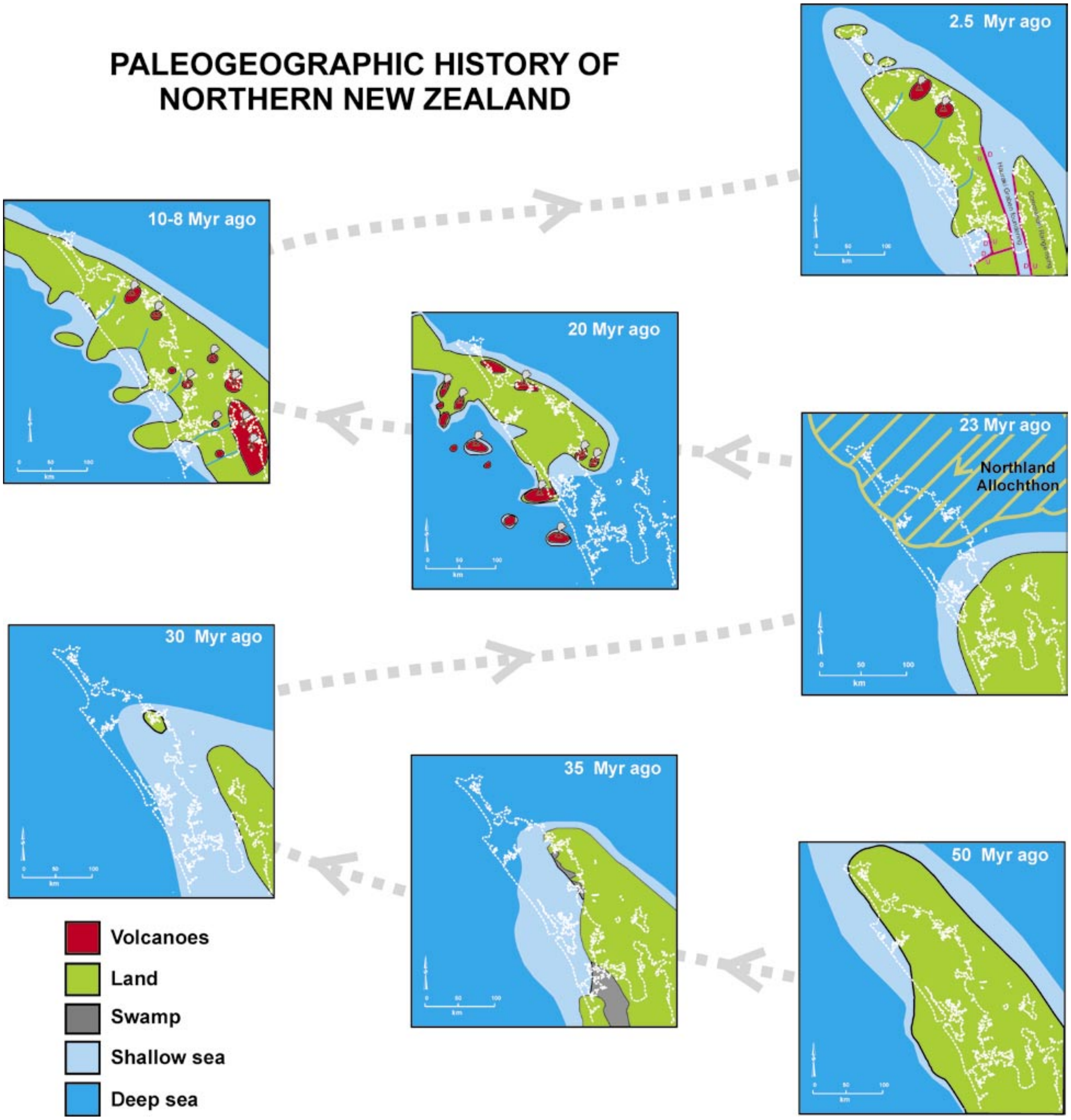
These portray the arrangement of the rocks at depth for several kilometres, like a layered cake beneath the ground, as if a knife has cut down along a straight line so we can see the layers within. In this book the simplified cross-sections are all oriented west-east and viewed from the south. The different rocks are generally shown in the same colours as on the geological maps. To make it easier to see the relationships between the rocks, the cross-sections have an exaggerated vertical scale compared to the horizontal of 5:1. Geologists use the observed structure and pattern of rocks seen at the surface to project what their distribution is like underground. Sometimes they can use the records from rocks encountered in a drill core to help them draw a more accurate cross-section. In offshore areas to the west of northern New Zealand, remote sensing methods (particularly seismic reflection profiling) deployed from a research vessel or aeroplane have been used to create a cross-sectional image of the rocks at depth (*6.7*).

Stratigraphic rock columns (*1.3*)

These show the sequence through time in which the various rock types in the region were formed. They might have been laid down as sediment layers on the floor of the sea, a lake or on a flood plain, or they might have been erupted from a volcano or intruded as liquid magma into the rocks under the ground. The oldest rocks are at the bottom of the column and they get progressively younger up the column, with the youngest (often unconsolidated sediment) at the top. Some stratigraphic columns portray the rock sequence in terms of the thickness of the different rock types, but in this book the sequence is shown on an age scale in millions of years and in terms of the international time periods (e.g. Jurassic, Miocene). The different types of rock have been given the same colours as on the geological maps and cross-sections.



1.3 Stratigraphic column of the rock sequence found in northern New Zealand.



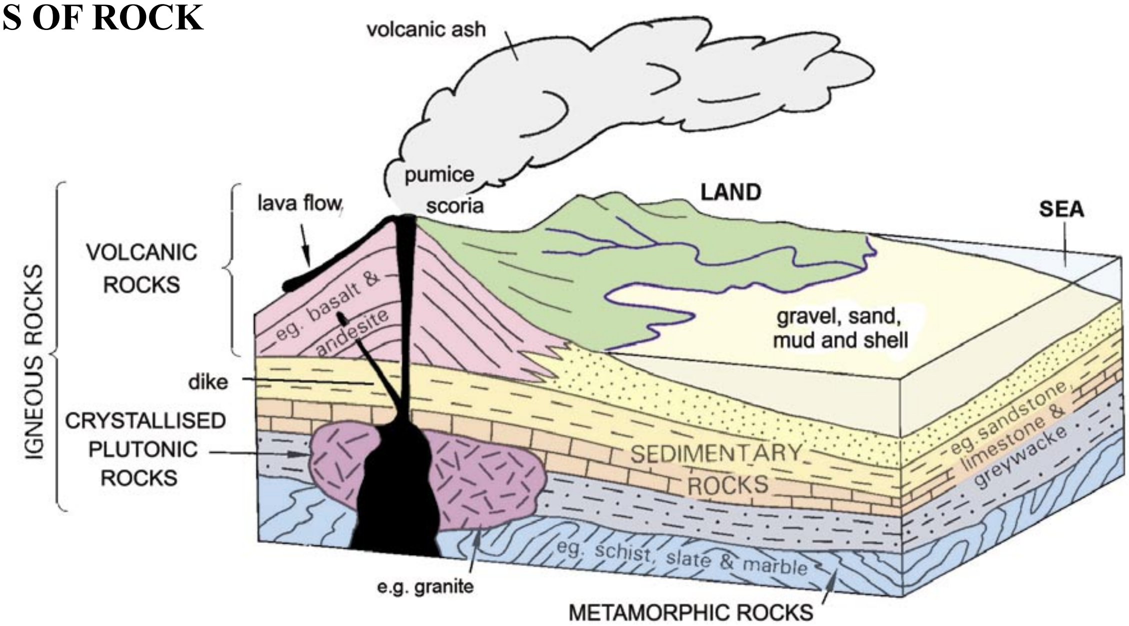
1.4 Summary set of paleogeographic maps showing the geography of northern New Zealand at various times in the past 50 million years (*Myr*). *The present coastline is dashed in white for reference purposes. Each of these maps appears separately in the chapter that describes the geological history of that period.*

Paleogeographic maps (*1.4*)

Paleogeographic maps show the geography of a region at various times in the geological past. The reconstruction of what the geography was like in the past is based on information contained within the rocks of that age in different parts of the region. These paleogeographic maps generally show the approximate position of the coastline, shallow and deep seas, peat swamps and actively erupting volcanoes. The colours used relate to these ancient environments and not to the different rock types.

These maps help us visualise in what environment and places each of the different rock types were deposited and how these relate to other types of rock that were being deposited or erupted from volcanoes at about the same time.

TYPES OF ROCK



1.5 Schematic cut-away diagram showing how the main groups of rock were formed.

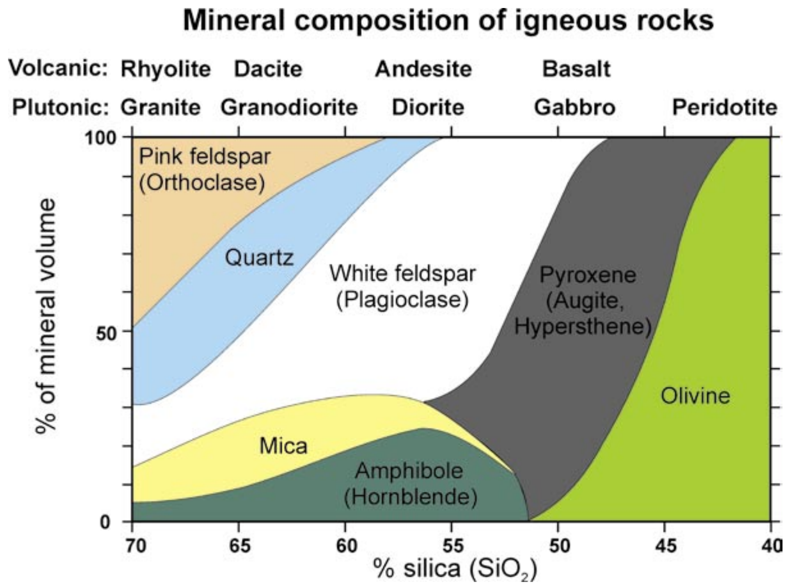
Most rocks are made of minerals, although some are composed entirely of organic matter (coal). Minerals are composed of elements in varying combinations and arrangements and each has its own characteristic properties (e.g. crystal shape, colour, hardness). The most common rock-forming minerals are compounds of silicon and oxygen, called silicates, such as feldspars (potassium, sodium and calcium silicates), micas (sheet silicates), augite, hypersthene and hornblende (iron and magnesium silicates). Quartz (silica) and calcite (calcium carbonate) are major mineral constituents of sedimentary rocks.

The rocks that make up the Earth's crust are classified into three groups depending on their origin.

Igneous rocks (volcanic and plutonic)

Igneous rocks are formed by the cooling and solidifying of molten magma, which originates deep within the Earth. This molten magma moves upwards through the crust, often collecting in large underground chambers. Plutonic rocks are formed when the magma cools slowly, resulting in the growth of large crystals of the various mineral constituents (*1.7*). Magma that rises to the surface erupts lava, which cools and solidifies quickly to form glassy to fine-grained volcanic rocks (*1.8-1.10*). Magma is a mix of liquid rock, crystals (that have grown within the melt as it is cooling) and dissolved gas. Magma with low gas content erupts as lava flows or domes. Magma full of gas might erupt in frothy fountains at the surface then cool to form rocks full of holes such as scoria and pumice. If rising magma encounters cold water near the surface the resulting explosive eruptions might throw out vast quantities of ash that accumulates in layers that harden into tuff.

Igneous rocks are classified on the basis of their chemical composition, mineral components (*1.6*) and



1.6 Diagram illustrating main mineral assemblages present in plutonic and volcanic (igneous) rocks with decreasing amount of silica in their composition.

1.7 A plutonic rock - diorite from Karikari Pluton, Maitai Bay, Cape Karikari. Photo 8 cm across.

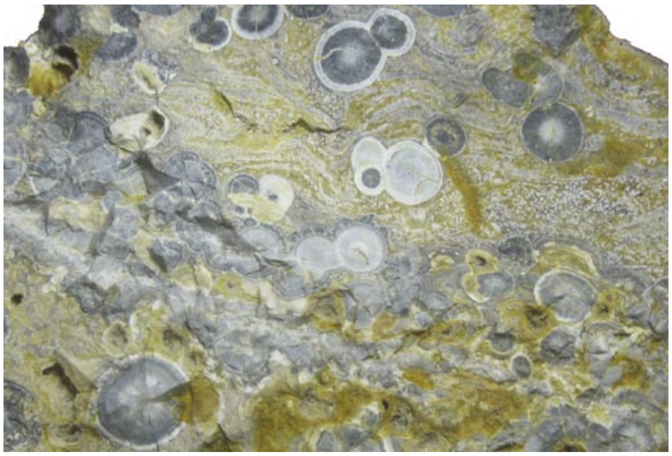
1.8 A volcanic rock – fine-grained basalt with scattered vesicles (gas bubbles) from Pupuke Volcano, North Shore, Auckland. Photo width 20 cm.

texture. Those with a high silica content (more than 63% by weight) are called acidic or felsic. They are usually light in colour with feldspar and quartz as the dominant minerals. Those with low silica content (45-52%) are called basic or mafic. They are dark grey and composed dominantly of augite and feldspar (plagioclase). Igneous rocks with intermediate silica content (52-63%) are usually grey or grey-green with dominant minerals feldspar, augite, hypersthene or hornblende. The table below shows the classification used for naming igneous rocks (present in northern New Zealand).

1.9 A volcanic rock – andesite from Taipa, Doubtless Bay, with white crystals of plagioclase feldspar and black crystals of pyroxene in a fine-grained matrix. Photo width 15 cm.

Table. Naming of igneous rocks.

	PLUTONIC	VOLCANIC	Colour of fresh rock
Texture:	Coarsely crystalline	fine-grained	
ACIDIC or FELSIC (>68% silica)	granite	rhyolite (ignimbrite)	White, pink or orange
ACIDIC or FELSIC (63-68% silica)	granodiorite	dacite	Light grey
INTERMEDIATE (52-63% silica)	diorite	andesite	Medium grey
BASIC or MAFIC (45%-52% silica)	gabbro	basalt	Dark grey
ULTRABASIC or ULTRAMAFIC (<45% silica)	peridotite	nephelinite	Black or green



1.10 A volcanic rock – spherulitic rhyolite from Coromandel Peninsula. Photo width 15 cm.

Sedimentary rocks

Sedimentary rock forms from sediment that accumulated in layers on the floor of the sea, lakes or river valleys. With burial this loose sediment is compacted and sometimes cemented into rock strata (*1.11*). Special kinds of sedimentary rock are limestone and chert, which mostly form by the accumulation, compaction and cementation of deposits of the calcareous or siliceous shells of dead marine organisms. Another kind of sedimentary rock is composed of the organic remains of plants, which initially accumulate in swamps as peat but with deep burial become coal.

Clastic sedimentary rocks are those composed of clasts (rock pieces) and are classified based on their grain-size as shown in the table at top right.

Table. Naming of sediments and sedimentary rocks.

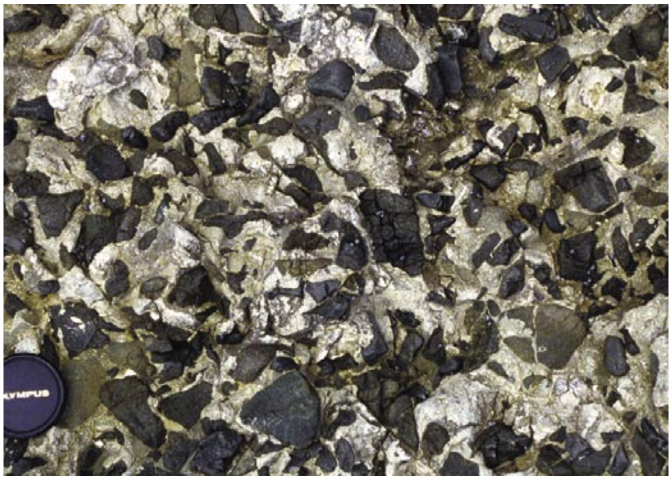
Grain-size	SEDIMENT	ROCK
>25 cm	Boulder	Conglomerate or Breccia
6-25 cm	Cobble	
4-64 mm	Pebble	
2-4 mm	Granule	Grit
0.06-2 mm	Sand	Sandstone
<0.06 mm	Mud (silt & clay)	Mudstone

Metamorphic rocks

Metamorphic rocks (e.g. schist, marble) are igneous or sedimentary types that have been greatly changed by the action of enormous pressures, heat or hot gas and solutions (hydrothermal), usually as a result of deep burial or contact with high temperature magmas.

1.11 A sedimentary rock – beds of brown sandstone and thinner, cream mudstone from the Waitemata Sandstone, Manukau Harbour. Photo 1.5 m across.

1.13 A weakly metamorphic rock – greywacke sandstone (light grey) and argillite (dark grey). Te Arai Pt, Mangawhai. Photo 50 cm across.



1.12 A sedimentary rock – pebble conglomerate in a limestone matrix from basal Waitemata Group, Motuihe Island. Photo width 50 cm.

WHAT ARE FOSSILS?

A fossil is the remains or trace of an animal or plant preserved in rock. Most fossils are the preserved hard parts of organisms, such as shells, bones, teeth and wood (*1.14, 1.16*). Less common are the preserved imprints of the soft parts of organisms, as with leaves, worms and jellyfish. A fossil can also be the track or burrow made by an organism passing over or living within sea-floor sediment and preserved in the rock (*1.15*). By far the majority of fossils are found in sedimentary rocks. Very few occur in volcanic rocks. One exception is Takapuna fossil forest where the shape of the tree trunks and branches was captured in the solidifying lava flow that engulfed them (*9.89*).

When an animal or plant dies its softer parts decay rapidly or are eaten away by bacteria, fungi and other organisms. Most harder parts also break down and disappear, but over a longer period of time. To capture the remains of an organism as a fossil requires special conditions - usually this means rapid burial to protect the fossil from decay, weathering and other damage. The remains of organisms stand a much better chance of early burial and preservation if they are in water (lakes, lagoons, sea) rather than exposed to the air on land.

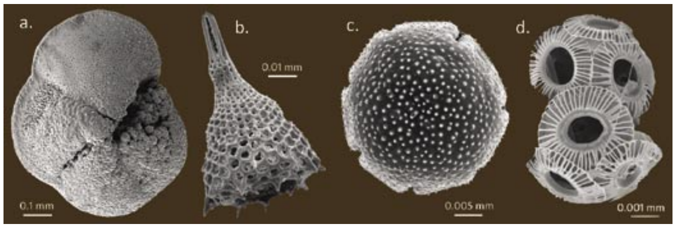
In special conditions, minerals dissolved in percolating groundwater can add to or replace the original skeletal components of the fossil. Petrification is the process where these secondary minerals gradually impregnate and replace the fossil remains, increasing its weight and hardness and literally turning the fossil into stone (e.g. silicified wood). But as we have seen above, a fossil does not need to be petrified to be termed a fossil - it can still be the unaltered original shell or wood of the dead organism. Another way that fossils might be preserved is as casts and moulds of the original fossil (usually a shell). These form once the burying sediment has hardened sufficiently to retain the shape of the fossil if it is dissolved away leaving a mould. If the fossil was hollow inside (like a seashell), it might have filled with sediment during burial. When the hard parts dissolved an internal cast might be left.

The study of fossils is called paleontology, and people who study them are paleontologists. Larger fossils that can be seen with the unaided eye (larger than about 5 mm) are called macrofossils. Fossils smaller than this that must be studied using a microscope are called microfossils (*1.17*) and scientists who study them are micropaleontologists. Scientists who study microscopic pollen and spores are called palynologists.

1.14 Only a few fossils are the bones of vertebrate animals, like these Late Cretaceous (*70 Myr old*) *vertebrae of a mosasaur from Te Kopua, Kaipara Harbour. Photo 12 cm across. Auckland University collection.*

1.15 Trace fossils - feeding burrows (*Scolicia*) *preserved on a bedding plane in Oligocene* (*30 Myr old*) *limestone, Tangowahine, east of Dargaville. These were probably made by a heart urchin burrowing through soft sediment, which has eroded away to expose the burrows. Photo width 60 cm.*

1.16 A 17 Myr old fossil starfish, Pseudarchaster motutaraensis, from the cliffs south of Muriwai, west Auckland. Photo 12 cm across.



1.17 Microfossils are the shells and skeletons of microscopic plankton, pollen, spores and other small organisms. They are studied using microscopes and their evolutionary sequence in the rocks has been used to provide ages for many of the sedimentary strata in northern New Zealand. a. planktonic foraminifer, b. planktonic radiolarian, c. southern beech pollen, d. calcareous nannofossil phytoplankton. Scale bars show different sizes.

HOW ROCKS ARE DATED

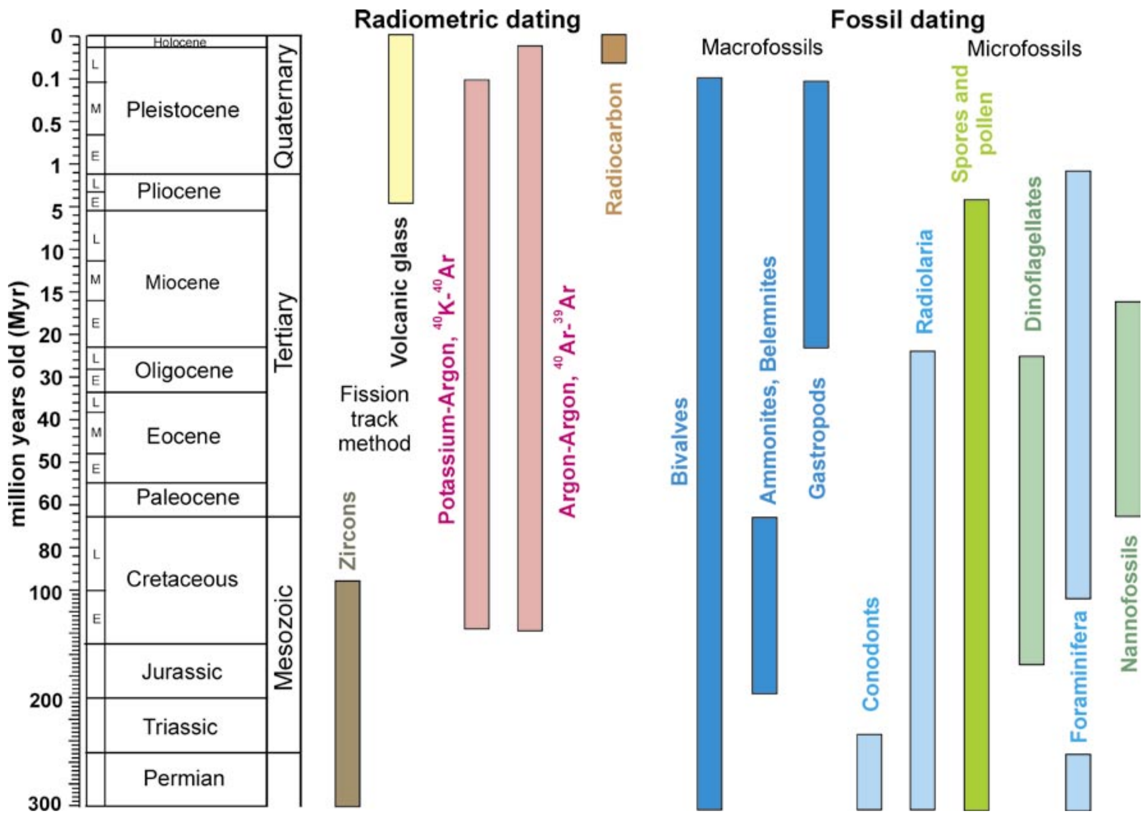
Relative dating using fossils

Fossils are used to date the sedimentary rocks in which they occur. This is the fastest and cheapest method of dating rocks. Sometimes the macrofossils can be identified in the field and the age of the strata are immediately known. Geological time has been divided up into a relative time scale of Eras and Epochs based on the succession (evolution) of fossils in the strata. If dinosaur bones are present in the rocks we know they were deposited during the Age of Dinosaurs (Mesozoic Era). Many fossils only lived in the New Zealand area and thus their succession in the local sequence of strata has had to be documented here. Several groups of microscopic plankton fossils (foraminifera, radiolaria, nannofossils) lived throughout the subtropical and temperate oceans of the world and their documented global succession is used to provide relative ages for rocks around the world. The various units of the geological time scale have been calibrated using absolute dating methods in many places and thus a relative age can be translated into absolute time.

In northern New Zealand, different fossil groups are useful for dating strata of different ages (*1.18*). Macrofossil molluscs for example are mostly used for dating Permian to Cretaceous strata, but can also assist in dating marine Miocene and Pliocene rocks. Microfossil groups are more widely used - conodonts are useful in the Permian-Triassic; spores and pollen date strata of all ages, especially those in freshwater and nearshore sedimentary rocks (because they come from land plants); radiolaria date deep-water marine strata, mostly of Permian-Oligocene age in northern New Zealand; foraminifera date shallow and deep-water marine rocks of Late Cretaceous to Pliocene age.

Absolute dating using radioactive isotopes

An absolute age is the numeric age of the formation or cooling of a mineral or rock given in years. This form of dating is possible because many minerals contain minute radioactive "clocks" preserved within them. These "clocks" consist of unstable forms (isotopes) of certain chemical elements which decay over time and transform into more stable isotopes of the same or different elements. The rate of decay is constant for any isotope and is given as the half-life in years that is the amount of time taken for half the isotope to break down. The half-life of different isotopes varies dramatically between just a few years (^{210}Pb = 22 yrs), a few thousand years (^{14}C = 5730 yrs), to millions of years (^{40}K = 1,251 Myr). Thus different isotopes are used for dating minerals and rocks depending on their age.



1.18 Diagram of the main fossil and radiometric methods used for dating rocks in northern New Zealand and the time span over which they have been useful.

There are two basic ways that radioactive isotopes form and are incorporated into materials used for dating. The first way is during the crystallisation of minerals in igneous or metamorphic rocks. As the parent materials cool and the crystals grow, they capture unstable isotopes from the Earth's interior in their crystal structure and from then on the isotopes begin to decay radioactively. The second way that radioactive isotopes are formed is by the bombardment of extra-terrestrial cosmic rays on elements such as carbon (^{14}C) in the atmosphere and beryllium (^{10}Be) and silicon (^{32}Si) in surface rocks.

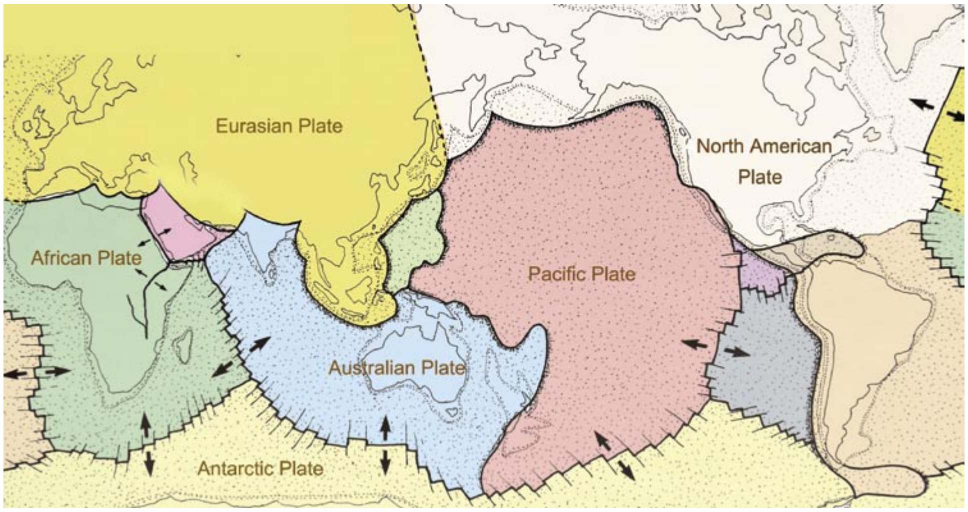
Radiometric dating is undertaken in laboratories in one of several different ways. One method measures the amounts of original unstable and derived (daughter) stable isotopes present with a mass spectrometer. Using the known half-life of the parent isotope, the time since the mineral was formed can be calculated. In northern New Zealand potassium-argon (^{40}K-^{40}Ar) isotopes and more recently argon-argon (^{40}Ar-^{39}Ar) isotopes have been widely used to date Cretaceous to Pleistocene (100 Myr -20,000 yrs old) igneous rocks; uranium-lead (^{235}U to ^{207}Pb) isotopes to date zircon crystals in Permian to Early Cretaceous basement rocks (300-100 Myr old); and radiocarbon (^{14}C to ^{14}N) isotopes to date young Pleistocene and Holocene (0-50,000 yrs old) organic material such as shell, wood and peat.

An indirect radiometric dating method, called fission track dating, determines the density of microscopic damage (called tracks) left in volcanic glass or certain mineral crystals by the fission (radioactive decay) of uranium-238 isotopes. This fission of the nucleus of a single parent uranium atom into two daughter isotopes releases fission fragments which leave trails of damage that are visible and can be counted using a high-powered microscope. Once the uranium content of the material being dated is determined, the decay half-life can be used to calculate the time since the mineral or glass cooled down. In northern New Zealand fission-track dating has been used on volcanic glass to determine the age of rhyolitic ash deposits of Pliocene-Pleistocene age (5 Myr-10,000 yrs old).

All radiometric dating methods give numeric ages with different levels of accuracy that depend on things like the precision of the laboratory measurements and whether the dated crystal, glass or organic matter has suffered from any alteration or weathering since it was formed. Sometimes the mineral clocks have been reset by a period of increased heat and the age determination might date this later event.

PLATE TECTONICS – AN INTRODUCTION

The Earth's outermost layer, the lithosphere, is broken up into 7-8 major tectonic plates (*1.19*) and numerous smaller ones. These plates are slowly moving around the Earth's surface in varying directions and colliding with each other. The plates are composed of two kinds of lithosphere. One is dense oceanic lithosphere (50-100 km thick), which consists of thin (5-8 km thick), mafic crust (basalt and gabbro) and the more rigid upper part of the mantle (peridotite). The second is less dense continental lithosphere (150-250 km thick), which consists of thicker (30-50 km), felsic crust (mostly granite, metamorphic and sedimentary rocks) plus the more rigid upper mantle.

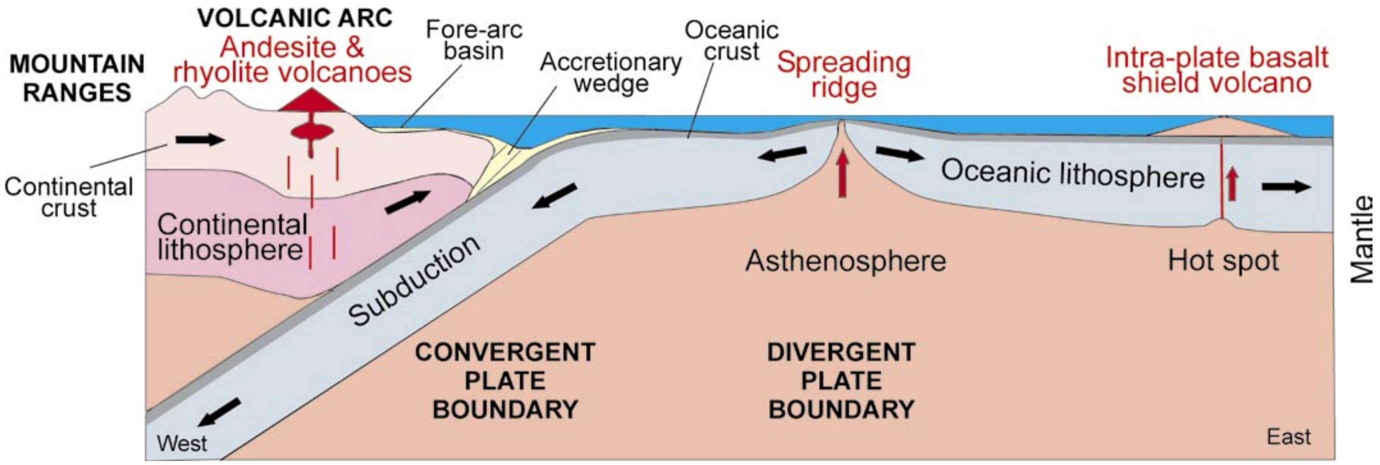


1.19 The major tectonic plates of the world today.

Many of the Earth's earthquakes and volcanic eruptions, as well as mountain building, occur around the margins of the plates, where they interact with the adjacent plates. These plate boundaries can be of three basic types:

1. **Moving apart** (**divergent boundaries**).

Spreading zones often occur between oceanic plates under the ocean, but can also rift apart continental plates



1.20 Schematic cross section through the Southwest Pacific Ocean showing the mid-ocean spreading ridge and the collisional boundary with oceanic lithosphere subducting beneath the edge of the continental plate.

(e.g. formation of Tasman Sea). As the plates move apart, molten magma from the mantle rises through the gap and erupts on the sea floor as basalt lava flows, forming new oceanic crust. The presence of rising molten magma at shallow depths raises the temperature of the lithosphere and it bulges upwards creating a mid-ocean ridge on the sea floor. The erupting magma on the sea floor contributes to building up this mid-ocean spreading ridge that is a lot shallower than the surrounding ocean floor and sometimes basalt volcanoes form islands along it, such as Iceland. As the plates move apart they raft along the newly formed oceanic crust and lithosphere. The further these move away from the spreading ridge the cooler, denser and thicker they get and they gradually subside to the typical depths of the ocean floors (4-5 km).

2. Moving together (**convergent boundaries**).

These collisional boundaries commonly occur around the edge of the Pacific Ocean where the oceanic plate collides with a continental plate, e.g. northern New Zealand. In these instances the dense oceanic plate plunges down into the mantle (subduction) beneath the edge of the less dense continental plate. Numerous earthquakes, large and small, occur along these subduction boundaries. A plot of the location (foci) of these earthquakes shows the path of the downward moving plate. The subducted oceanic plate carries down with it an upper layer of water-saturated marine sediment. With increased temperature and pressure, at about 100 km depth, the water is driven upwards out of the subducted rocks into the overlying upper mantle. The addition of water lowers the melting point of the mantle above the subducting plate, causing partial melting. This magma rises and collects in large chambers in the overlying continental crust. Magma periodically erupts as andesite, dacite or rhyolite from a line of volcanoes that form above the subducted plate and parallel to the plate boundary. These lines of volcanoes are called volcanic arcs and together they form the well-known Pacific Ring of Fire. The water, driven out of the subducted rocks, may also alter some of the overlying upper mantle to serpentinite.

Along these convergent plate boundaries considerable pressure builds up within the rocks in the overlying continental plate, often causing the land to be pushed up as mountain ranges parallel to the plate boundary (e.g. axial ranges of New Zealand). In some places, slices of rock are scraped off the top of the down-going oceanic plate and thrust under the edge of the continental plate. Over time a succession of these slices might be added forming what is called an accretionary wedge (*1.20*).

3. Moving sideways (**transform boundaries**).

Sometimes a plate boundary separates two portions of plate of similar density and neither is pushed under or over the other. In most instances the convergence direction between the two plates is at an angle to the boundary itself and thus the two plates are pushed sideways past each other along a major transform fault. This is happening today through the South Island (Alpine Fault), but is inferred to have occurred through northern New Zealand 200-150 Myr ago (Jurassic).

The interior of plates, away from their boundaries, are usually tectonically stable, but sometimes they are pierced by the eruption of basalt sourced direct from the mantle, 50-100 km below. These are called intra-plate volcanoes and the deep source beneath is often referred to as a hot-spot.

Chapter 2. THE OLDEST ROCKS (300-110 Myr old)

CHAPTER SUMMARY

The oldest rocks in northern New Zealand underpin (form the "basement" of) the geology. Dominant are the greywackes seen eroding at the surface in eastern Northland and Auckland and in parts of the Coromandel Peninsula. They also occur at depths of 2-4 km below the surface, beneath the west side of the Northland-Auckland peninsula where they are buried beneath younger rocks. We recognise four NW-trending belts of basement rocks (terranes) that were formed in different places and progressively brought together by plate tectonic forces and welded into their present configuration onto the side of the supercontinent of Gondwana between 250 and 100 Myr ago.

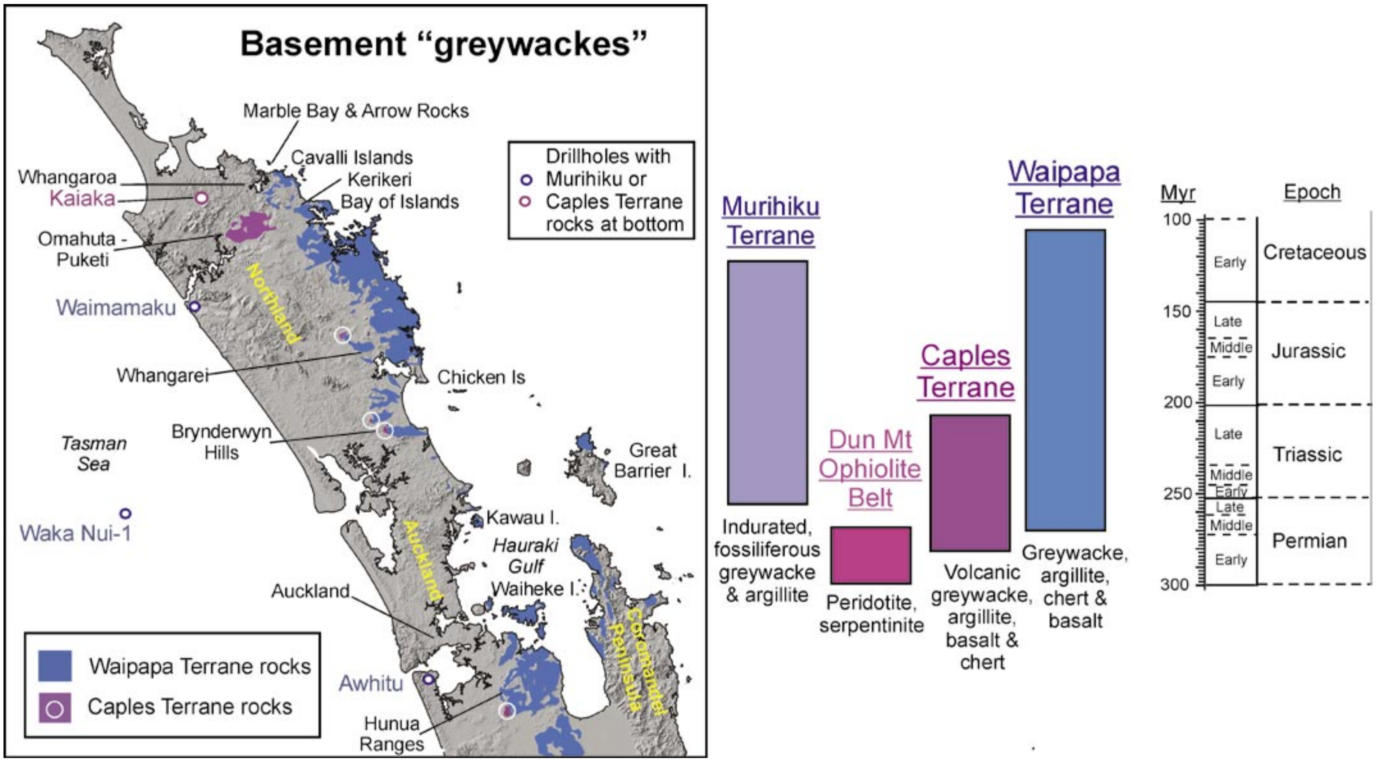
The oldest terrane (Maitai Terrane) consists of a narrow belt of ultramafic peridotite and highly magnetic, green serpentinite rock (Dun Mt Ophiolite Belt) that runs beneath the length of central Northland and Auckland, but is nowhere seen at the surface in this region. This belt is a slice of upper mantle and crust that was formed at a mid-ocean ridge spreading centre in the ancient Pacific Ocean about 285 Myr ago (Permian). It was transported westwards by plate movement and added onto the edge of Gondwana about 260 Myr ago. To the west of this belt are little-deformed, fossil-bearing sandstone and mudstone strata (Murihiku Terrane) that were deposited along the coast of Gondwana, 250-130 Myr ago (Triassic-Early Cretaceous). Murihiku rocks are known from only three drillholes in this region, although though they can be seen at the surface south of the Waikato River mouth.

The easternmost belt (Waipapa Terrane) consists of numerous repeated slices of a rock sequence that was deposited 270-110 Myr ago (Permian-Early Cretaceous). The base of the Waipapa sequences are basalt lava flows that were erupted on the deep ocean floor at the Pacific mid-ocean spreading ridge. The basalt was mantled by thin, multi-coloured chert and mudstone, derived from plankton shells, and from wind-blown dust fallout. Over tens of millions of years the moving oceanic crust transported the thin lower part of the Waipapa sequence, several thousand kilometres to the southeast. As it approached the coast of Gondwana, thousands of metres of mud and sand, eroded from the land, were deposited in layers on the deep seafloor on top of the basalt and chert. Slices of this sequence were scraped off the top of the moving oceanic crust as it started to plunge down beneath the edge of the Gondwana Plate, creating a thick accreted wedge of Waipapa Terrane rocks along the edge of the supercontinent. Here the rocks were hardened and weakly metamorphosed by deep burial (5-12 km beneath the ground).

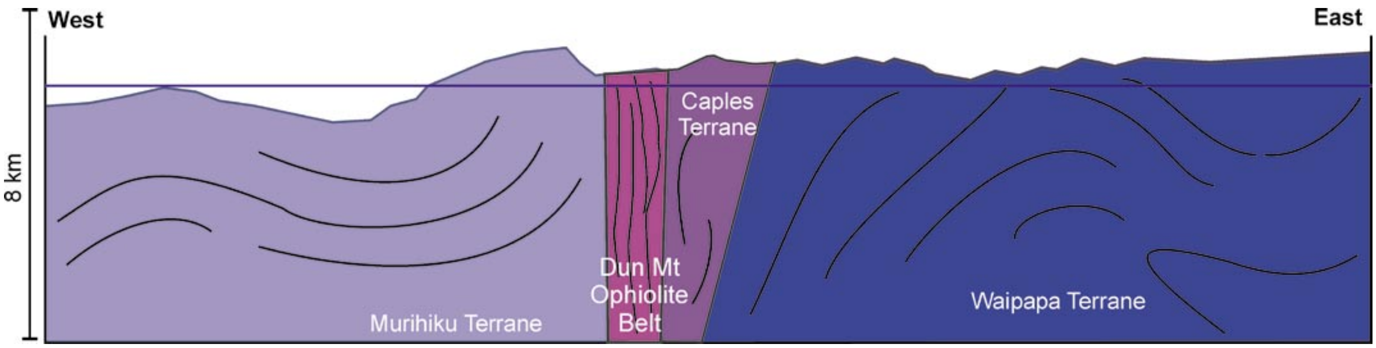
Between the Waipapa Terrane, in the east, and the Dun Mt Ophiolite Belt is a discontinuous series of outcrops of volcanic-rich sedimentary rocks (Caples Terrane), from the Omahuta-Pukeiti ranges in the north to the southwest corner of the Hunua Ranges in the south. It consists of hardened sandstone (greywacke), mudstone (argillite), basalt lava flows and chert that were deposited in the ancient Pacific Ocean, 300-200 Myr ago (Permian-Triassic). The Caples and Waipapa terranes were glued onto the edge of Gondwana between 160 and 105 Myr ago (Late Jurassic-Early Cretaceous). The highly sheared, near-vertical belt of serpentinite and related rocks (Dun Mt Ophiolite Belt) may have been the location of a major transform fault zone (similar to the modern Alpine Fault), along which the Caples and Waipapa terranes were shunted hundreds of kilometres southwards during the final suturing process.

Between 85 and 55 Myr ago (during the Late Cretaceous-Paleocene) a huge area of continental crust, created by the above processes, split off from Gondwana to become the continent of Zealandia.

BASEMENT TERRANES



2.1 Distribution of basement rocks (grouped into terranes) at the surface and in drillholes in northern New Zealand and a stratigraphic column showing the age relationship between these terranes and the Dun Mt Ophiolite Belt.



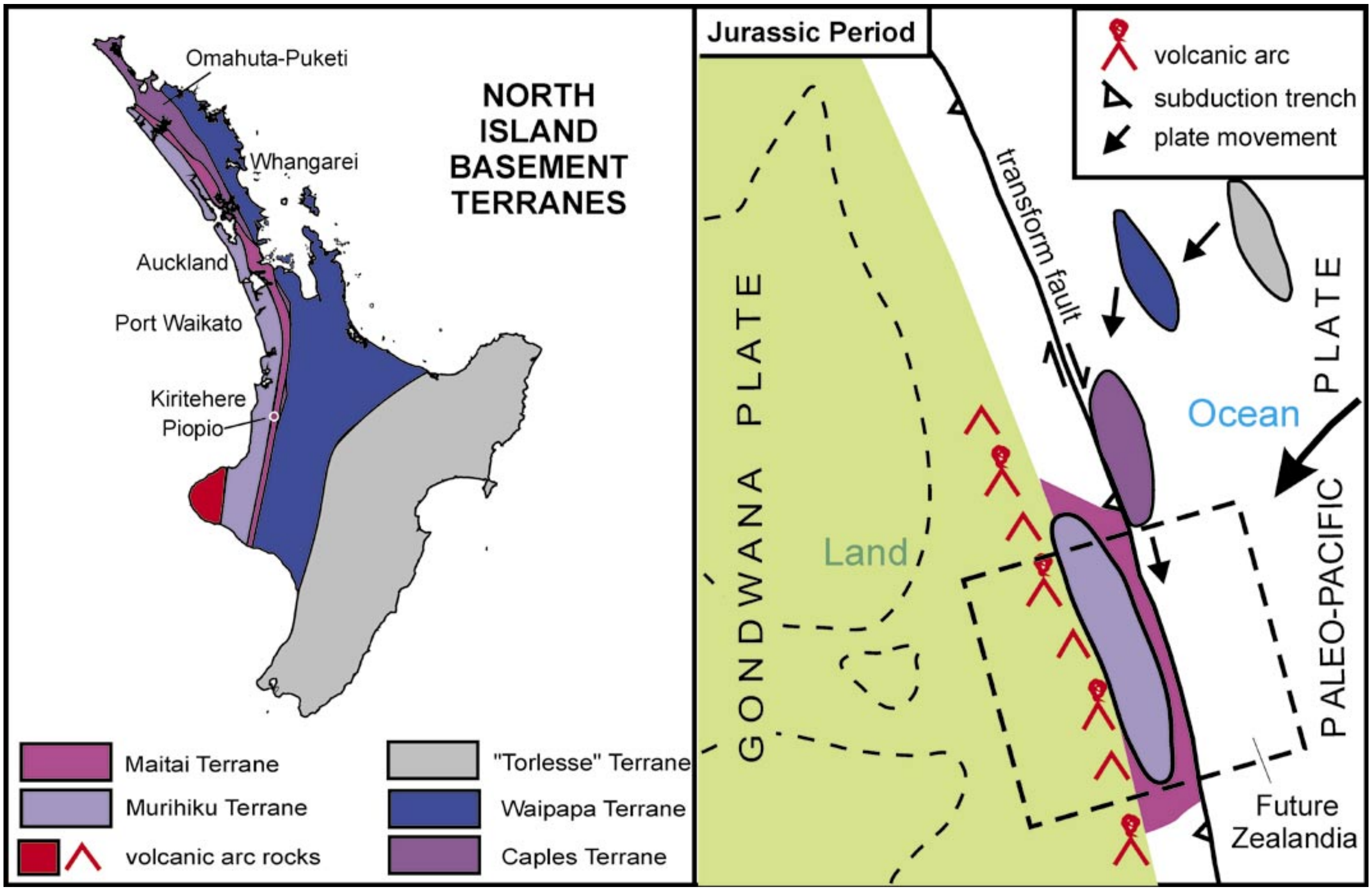
2.2 Simplified cross-section through Northland showing relationship between basement terranes.

The oldest rocks in northern New Zealand are the hard "greywacke" rocks, which are referred to as basement greywackes. As their name implies, these basement rocks underlie all of the younger cover rocks in the region. Along with most of the overlying rocks, the top of the basement rocks has an overall tilt down to the west beneath the Northland-Auckland peninsula and is in places 2-4 km below the surface under parts of western Northland and off the west coast (*1.2*). Greywacke can be seen at the surface along the eastern side of Northland and Auckland forming many of the coastal ranges and the coastline south from Whangaroa (*2.1*). On much of Coromandel Peninsula, the 40-35 Myr old erosion surface on top of the basement rocks is tilted down to the east and south, with greywacke completely buried at depth by the younger volcanic rocks in the east and south, but forming many parts of the western coastline. These rocks can also be seen at the surface in northern and eastern parts of Great Barrier Island and form many of the islands in the Hauraki Gulf (e.g. Waiheke, Motutapu, Rakino, Tiritiri, Kawau, Chickens). The most prominent blocks of basement greywacke have been pushed up to form the Hunua Ranges (south of Auckland), the Brynderwyn Hills (south of Whangarei), Russell Forest range (southeast of Bay of Islands) and the Omahuta-Puketi range (west of Kerikeri).

The basement rocks of northern New Zealand can be divided into four northwest-southeast-aligned belts (called terranes), each of which contains rocks that accumulated or erupted in separate regions off the coast of Gondwana during the Permian to Early Cretaceous epochs (285-105 Myr ago). These basement terranes can be seen at the surface in other parts of New Zealand, with the three westernmost (*2.3*) having been named from their type areas in the South Island – Murihiku, Maitai and Caples terranes. Murihiku and Maitai terranes are completely buried by younger rocks in northern New Zealand. Caples Terrane only outcrops in a few places, but the Waipapa Terrane is the most widespread, forming large parts of eastern Northland and Auckland (*2.1*).

ACCRETION AND SUTURING ALONG THE EDGE OF GONDWANA

During the Permian-Early Cretaceous, the basement rocks of northern New Zealand were erupted or deposited along, and offshore from, the convergent plate boundary between the Gondwana (continental crust) and Paleo-Pacific (oceanic crust) plates. These basement terrane rocks that were formed in different places off the coast were progressively brought together and sutured onto the edge of Gondwana by plate tectonic forces (*2.3*). The main process is called accretion, whereby slices of rock were scraped off the top of the down-going oceanic Paleo-Pacific plate, as it was subducted beneath the edge of the continental Gondwana Plate. These rock slices were usually layers of sediment (up to 1 km or more thick), which had been deposited on top of the oceanic plate as it moved towards Gondwana, but sometimes they included some or all of the oceanic crust and even the top of the mantle, as in the case of the Dun Mt Ophiolite Belt. As the rock slices were scraped off, they were usually thrust



2.3 Left: Distribution of basement terranes in the North Island with all cover rocks stripped off. Right: Schematic map of the eastern margin of Gondwana, 180 Myr ago, showing the Murihiku Basin on top of the Dun Mt Ophiolite Belt accumulating sediment eroded from the adjacent volcanic arc. The Caples and later Waipapa terranes were moved southwards by a plate boundary transform fault and accreted and sutured onto Gondwana by convergent plate forces.

2.4 Much of the east coast of Northland and Auckland is made of highly eroded and deeply weathered basement greywacke of the Waipapa Terrane, like the northwestern part of the Bay of Islands shown here. The greywackes are harder and more resistant to erosion than the surrounding sedimentary rocks and therefore usually form hill country that is deeply dissected by rivers and streams. Rangihoua Bay, Purerua Peninsula.

under the coastal edge of adjacent Gondwanan rocks forming a new accreted tapering rock body. Over time, a succession of these underthrust rock slices were accreted onto the Gondwana coast, creating what is known as an accretionary wedge (*1.20*) of newly-formed continental crust. A modern analogue in New Zealand is the 100 km-wide accretionary wedge that has been added onto the eastern North Island in the last 20 Myr.

By the Late Jurassic-Early Cretaceous (160-105 Myr ago), the convergent motion between the Gondwana and Paleo-Pacific plates appears to have become more oblique, with sideways movement of elongate basement terrane rocks along a major plate boundary transform fault, like the Alpine Fault of today. The Caples and Waipapa terranes were probably moved hundreds of kilometres southwards along this transform fault, before they became stuck (sutured) to the coast of Gondwana. The location of this fault was likely within or adjacent to the extensively sheared Dun Mt Ophiolite Belt.

Associated with these more extreme collisional forces, there was major deformation of the accreted terranes, especially those in the east (e.g. Waipapa and Caples). Within the accretionary wedge, some of the rocks were buried to depths of 5-12 km, which increased temperature, compaction and hardening of the rocks and new metamorphic minerals began to form. Some of the rocks were crumpled, sheared or broken and this can be clearly seen in fresher coastal exposures. Some of the higher slices of rock may have been pushed upwards to build mountain ranges, rather like the axial ranges through the North and South islands today, but all trace of these was eroded away long ago.

MURIHIKU TERRANE

These rocks can be seen at the surface, just south of the region, in a belt along the west coast between Port Waikato and Kiritehere and also in the South Island, particularly forming the Catlins coast in east Southland. The rocks are mostly indurated (hardened) mudstone and sandstone (“greywacke”) and are the least deformed of the basement terranes. They have been folded into several wide synclines and anticlines, which parallel the trend of the linear terrane. Murihiku rocks are also characterised by the occurrence of sometimes rich and diverse well-preserved fossils, particularly molluscs (bivalves, belemnites). This terrane is inferred to have accumulated in a shallow marine to alluvial fore-arc basin (*1.20*), during the Triassic-earliest Cretaceous (250-140 Myr ago). Most of the sediment was derived from an active volcanic arc to the west, which was erupting above the subduction zone that had formed along the convergent boundary between the Gondwana and Paleo-Pacific plates.

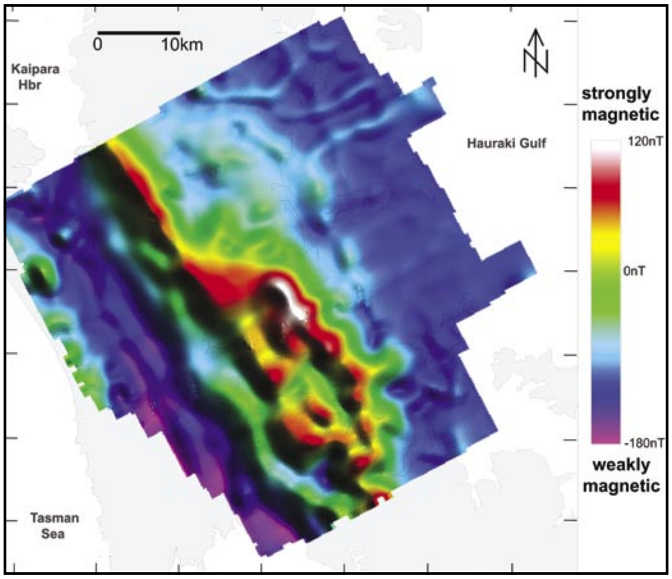
Murihiku Terrane basement is inferred to lie beneath west Northland and Auckland, as the deeply buried northward extension of the sequence seen at the surface, south of Port Waikato. This inference is mostly based on its recognition in the bottom of three drillholes – a water bore at Awhitu (west of Auckland city), and hydrocarbon exploration drillcores in Waimamaku Valley (Hokianga) and Waka Nui-1 (90 km offshore from the Kaipara Harbour entrance), where the rocks have been dated at Jurassic and earliest Cretaceous, based on their fossil pollens and spores.

DUN MOUNTAIN OPHIOLITE BELT

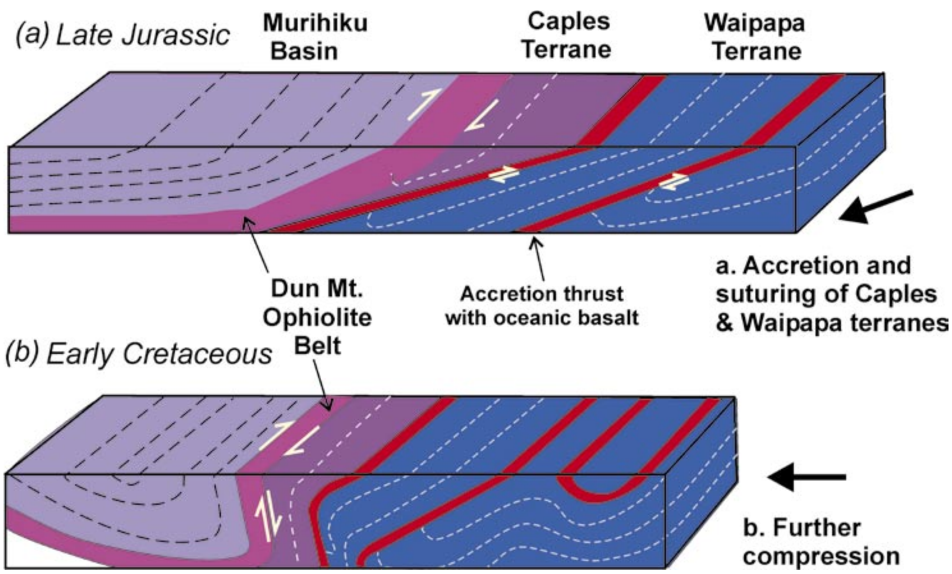
The Dun Mt Ophiolite Belt (DMOB), part of the Maitai Terrane, is exposed at the surface in east Nelson and the southwest South Island, as a band of near vertical rocks, up to 10 km across, separated by 450 km of displacement along the Alpine Fault. In the North Island, this band can only been seen at the surface at Piopio in the King Country. Elsewhere, we can trace it beneath cover rocks through the western North Island, including Auckland and Northland, as a narrow, linear belt with its distinctive high magnetic signature, called the Junction Magnetic Anomaly.

Ophiolites are oceanic basalt crust and gabbro, along with peridotite from the underlying mantle. Much of the peridotite has been altered by hydrothermal fluids in the crust to the slippery green, strongly magnetic rock called serpentinite. Peridotite and serpentinite are ultramafic igneous rocks rich in magnesium and iron (in the minerals olivine and pyroxene). They lack quartz, feldspar and mica, typical of granites. The DMOB is believed to be a slice of ocean floor crust and upper mantle, which formed along a mid-ocean spreading ridge (*1.20*), during the Early Permian Epoch (285 Myr ago). It was rafted away from the spreading ridge by plate movement, then detached from the subducting oceanic plate and finally accreted onto the edge of Gondwana to become part of the continental crust. The Murihiku fore-arc basin sedimentary rocks might have been deposited on top of this accreted slab of DMOB, during the Triassic-earliest Cretaceous.

In the Late Jurassic-Early Cretaceous (160-105 Myr ago) the Caples and Waipapa terranes were also accreted and sutured onto the edge of Gondwana, with their western parts pushed against the eastern margin of the DMOB (*2.6*). With further collisional compression, the Murihiku rocks were folded into broad synclines and anticlines parallel to the plate boundary and the DMOB was folded back on itself around the eastern edge of the Murihiku Terrane as a near vertical belt (*2.6*), which today separates Murihiku from Caples and Waipapa basement terranes beneath northwest New Zealand.



2.5 Colour map of the total magnetic intensity (see p. 106) of the buried rocks highlighting the lineaments within the Junction Magnetic Anomaly beneath Auckland City. White and red colours overlie rocks with the most magnetic minerals and purple and blue areas have the least. Courtesy of Jennifer Eccles.



2.6 Block diagrams illustrating the inferred tectonic evolution of the Dun Mt Ophiolite Belt (DMOB) around Auckland during the Early Cretaceous. (a) Accretion of Caples and Waipapa Terrane slices by thrusting under the edge of the DMOB and Murihiku Terrane. (b) Continued collisional forces between the plates crunch the terranes together resulting in boundary-parallel folding with the DMOB and nearby Waipapa rocks being pushed up to near vertical. Redrawn from Eccles et al. (2005).

The DMOB was likely the location of a major transform fault during the Jurassic-Early Cretaceous and the intense shearing, splintering and mixing within it, possibly results in part from the southwards displacement of Caples and Waipapa terranes along it. Recent, more detailed aeromagnetic and gravity survey work by Auckland University's Jennifer Eccles, Helen Williams and John Cassidy, has shown that the DMOB varies in thickness along its length, bulging out to a width of 10 km or more beneath Auckland (*2.5*). Here the DMOB consists of many subparallel linear slices, with the strongest magnetic lineaments possibly produced by sheared-out serpentinite zones. Auckland's young volcanoes have erupted up through this bulge in the DMOB and the St Heliers Volcano has thrown out numerous blocks of ultramafic and metamorphosed rock, excavated from one of these highly mixed shear zones.

CAPLES TERRANE

Rocks of this terrane form the 25 x 12 km, 500-m-high, "Omahuta-Puketi Range" between Kerikeri and the headwaters of the Hokianga Harbour and were found in the bottom (600 m depth) of the Kaiaka oil exploration drillhole (1957), 15 km east of Kaitaia. They also occur in several small blocks located west of Whangarei, in the western Brynderwyn Hills and southwestern Hunua Ranges. These "greywacke" rocks are hardened and weakly metamorphosed, tuffaceous sandstone, argillite and chert, with massive and pillowed basalt, which are inferred to have accumulated on the ocean floor off the New South Wales part of Gondwana, during the Permian and Triassic Epochs (300-200 Myr ago). They are distinguished from the adjacent Waipapa Terrane by their subtly greater volcanic content, which results in common red and green weathering colour of the sandstones, their slightly higher grade of metamorphism (pumpellyite-actinolite and prehnite-pumpellyite zones; Box 3), and by geochemical differences that indicate separate source areas for the sediment. After formation, they were moved down the edge of Gondwana along a transform fault, deeply buried and metamorphosed during the Jurassic, and then accreted or sutured onto the edge of Gondwana during the Early Cretaceous.

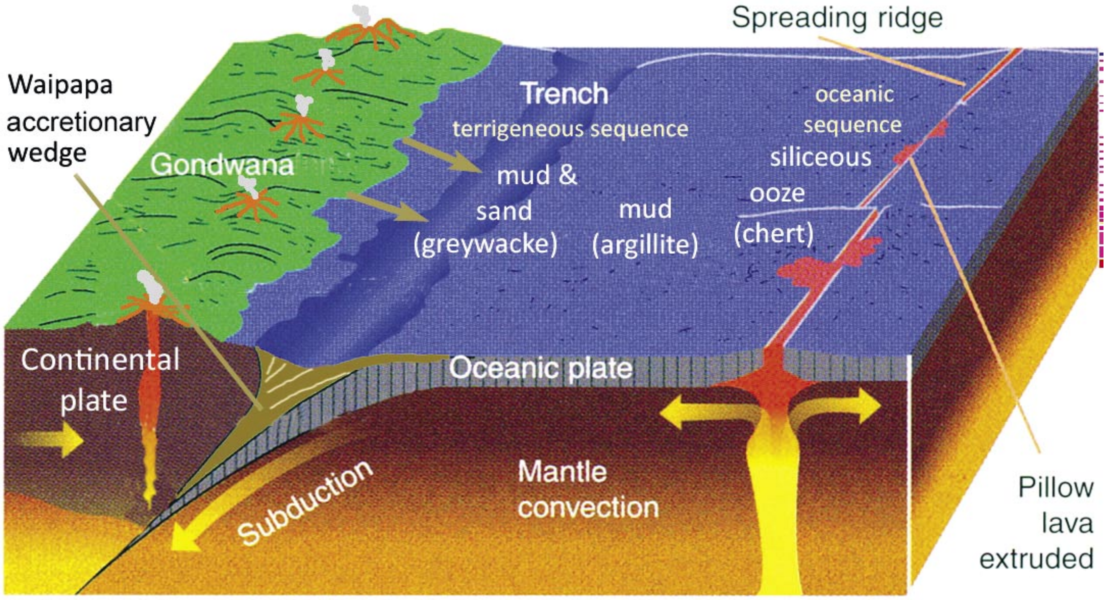
Because of the limited outcrop of Caples Terrane in northern New Zealand, it is not known whether it forms a continuous buried belt between DMOB and Waipapa Terrane through Northland and Auckland. The Caples Terrane is well exposed in the South Island, where it has the same structural position sutured onto the east side of the DMOB.

WAIPAPA TERRANE

The Waipapa Terrane occurs in eastern Northland, Auckland, the northern Coromandel Range and on Great Barrier Island. In Northland, Auckland and the Hunua Ranges, this terrane consists of a number of repeated slices of a deep-sea sedimentary sequence that are inferred to have been scraped off the top of the down-going Paleo-Pacific oceanic plate, as it was being subducted beneath the edge of Gondwana, in the Late Jurassic and Early Cretaceous (160-110 Myr ago). Each slice was partly thrust under the preceding slice and added onto Gondwana, as part of the accretionary wedge. Continued convergent pressure between the two plates appears to have buckled and folded the imbricate slices, so that sometimes the original beds are steeply dipping or even vertical.

The sequence in each slice (2.12) usually consists of thin, ocean-floor basalt pillow lavas, that might have erupted on a seamount at a mid-ocean spreading ridge. In amongst the pillow lavas in northern Northland there are occasional lenses of red or white recrystallized limestone (sometimes referred to as marble; 2.20) derived from the calcareous shells of moderately shallow-water molluscs, corals and foraminifera. Interbedded with and

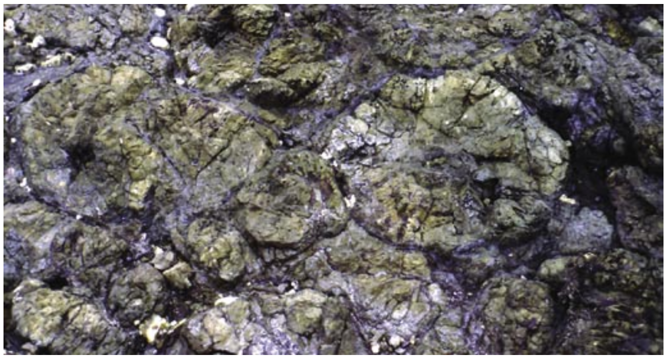
2.7 A 6 m-thick pile of Permian (270-250 Myr old) basalt pillow lavas within the oceanic lower part of the Waipapa Terrane sequence on Motukawanui, Cavalli Islands, near Whangaroa.



2.8 Cut-away diagram illustrating the oceanic Paleo-Pacific Plate being moved by seafloor spreading towards, and then subducted beneath, the edge of the continental Gondwana Plate. As the Paleo-Pacific plate moved along, the thin oceanic sequence of Waipapa Terrane pillow lava, siliceous mud and ooze was overlain by terrigeneous mud, and then sand, from the eroding edge of Gondwana. Slices of this Waipapa sequence were scraped off the top of the down-going oceanic plate and thrust under the growing edge of the growing continent, forming an accretionary wedge.

overlying the upper parts of the pillowed basalt are red, white and sometimes green or grey chert and siliceous argillite beds (2.10). These hard recrystallized rocks originally accumulated very slowly on the floor of the deep paleo-Pacific Ocean, as a siliceous ooze composed predominantly of the skeletons of the zooplankton group, radiolaria. Variable amounts of mostly wind-blown, fine mud might be included and these have been hardened, with deep burial, to siliceous argillite. The pillow lavas, limestone and chert accumulated out near the middle of the paleo-Pacific Ocean well away from land and thus there is no land-derived (terrigeneous) sand and only a little fine mud in the lower part of the sequence.

Over tens of millions of years, seafloor spreading rafted this oceanic sequence closer and closer towards the coast of Gondwana (2.8). As it approached land, it started to receive terrigeneous mud carried in suspension down rivers and out to sea, and this was deposited as multi-coloured grey, red and green mud, which has now been hardened into argillite. Getting closer still, and in the vicinity of the convergent plate margin trench, thin sand beds started alternating with the mud, and up sequence the sand beds became thicker and the dominant part of the sequence. These were probably transported in periodic slurries of sand and mud (turbidity currents)



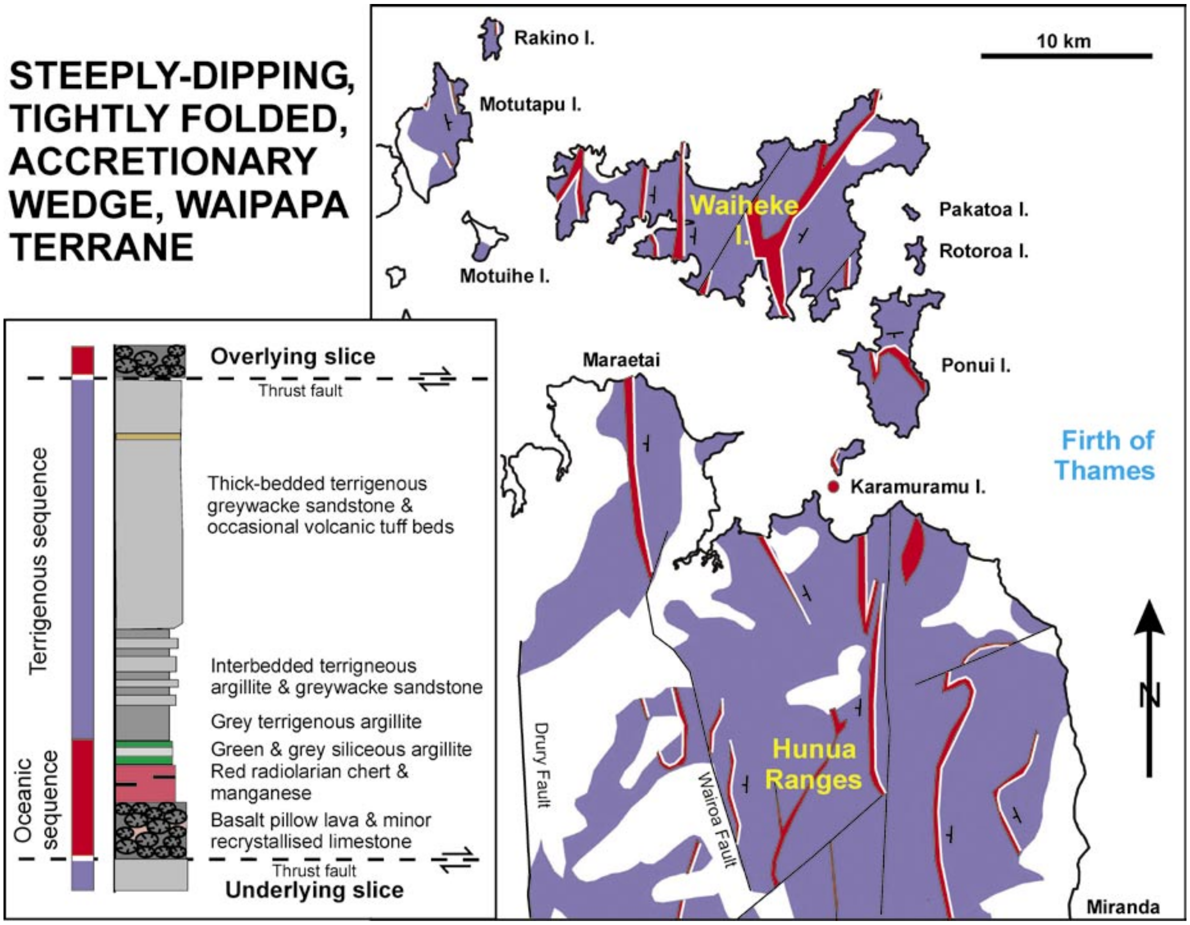
2.9 Cross-section through Late Triassic (230-200 Myr old) pillow lavas in the Waipapa Terrane oceanic sequence near Blackpool, Waiheke Island. Note the black glassy selvedge around individual pillow lava lobes, caused by the quenching of the outside of these lava bodies by cold sea water. Photo width 1.2 m.

2.10 Tightly folded and faulted, red and green chert beds of Late Triassic age (230-200 Myr old) within the Waipapa Terrane oceanic sequence at Administration Bay, Motutapu Island, Auckland. Photo 1 m across.

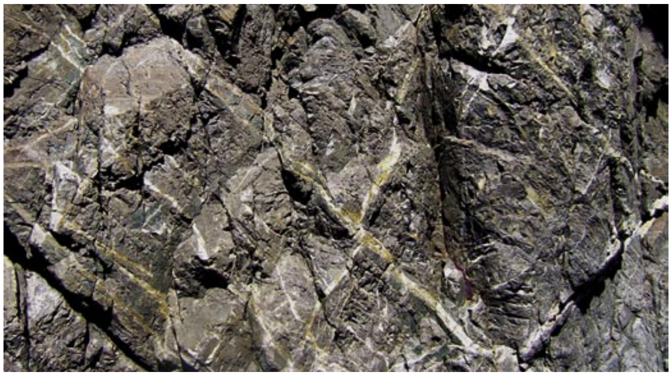
down the continental submarine slope to be deposited as sand beds, which have been hardened with deep burial into greywacke. The sand grains were mostly derived from a volcanic arc that was erupting along the landward margin of Gondwana. Occasional thin beds of volcanic ash (tuff) are present within the greywacke sequence. These terrigeneous (land-derived) clastic sedimentary parts of each slice comprise by far the bulk of the rocks in the Waipapa Terrane in Northland and Auckland.

The greywacke, argillite and pillow lava rocks were squashed and deeply buried to 5-15 km depth, resulting in considerable deformation of their internal features with numerous faults and joints and growth of metamorphic veins and veinlets (2.13-2.15), which distinguish Waipapa

2.11 A 15 cm cobble of spherulitic red chert from the Late Triassic (230-200 Myr old) oceanic sequence of the Waipapa Terrane on Ponui Island, inner Hauraki Gulf.

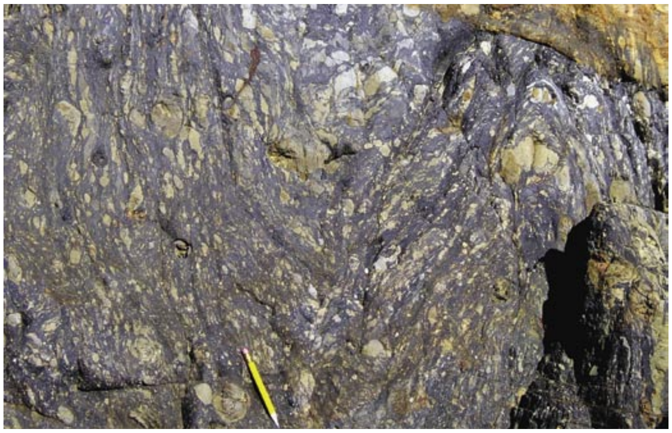


2.12 Map of Hunua Ranges, Waiheke and surrounding islands, east of Auckland, showing the surface distribution of Waipapa Terrane red chert and minor pillow lava (red) that were deposited in the Late Triassic-Early Jurassic (220-190 Myr ago) in the middle of the Paleo-Pacific Ocean. The bulk of the rocks consist of terrigeneous argillite and greywacke (blue) that were deposited during the Late Jurassic (160-145 Myr ago) in deep water close to the coast of Gondwana. Slices of the typical sequence (left) on top of the oceanic plate was scraped off the top of the down-going Paleo-Pacific Plate and thrust under the growing accretionary wedge. The wedge was then compressed into a number of steeply-dipping, tight folds. The chert beds, at the base of at least three accretionary slices, are recognised in this area and some are folded and displaced by faults and repeated at the surface a number of times. Mapping by Schofield (1976, 1979), interpretation from Aita and Sporli (1992).



2.13 Thick, intensely-jointed, Waipapa Terrane greywacke sandstone, with numerous multi-phase veins of quartz, prehnite, pumpellyite and calcite, which were formed during accretion and deep-burial metamorphism. Rakino Island, inner Hauraki Gulf. Photo 1 m across.

2.14 Late Jurassic, thin-bedded greywacke and argillite (Waipapa Terrane) on Pakatoa Island, inner Hauraki Gulf. The less competent, argillite beds are highly sheared and the sequence is cut by faults, causing a top-to-the-right movement. Pencil for scale.



2.15 Deformed Late Jurassic (165-145 Myr old) broken formation of the Waipapa Terrane terrigeneous sequence. Broken formation was formed first, resulting in sheared argillite containing chunks of broken, light-coloured greywacke sandstone. Later it was deformed into the two moderately tight folds. Pakatoa Island.

Terrane rocks from the little deformed Murihiku Terrane. The thrust faults between different slices in the Waipapa Terrane are often marked by a sheet of sheared argillite and greywacke sandstone (broken formation) or contain a mixture of terrigeneous and oceanic rocks (melange), which have been ripped from the quite different rocks on either side of the low-angle fault zone.

From the Bay of Islands northwards in northeast Northland, the oceanic part of each slice has been dated by fossils as Permian to Triassic in age (270-220 Myr old), but from Whangarei southwards to the Hunua Ranges, the oceanic parts are Late Triassic to Early Jurassic (220-190 Myr old). The terrigeneous, upper parts of each slice are Late Triassic (230-200 Myr old) in northeast Northland and Late Jurassic (160-145 Myr old) everywhere to the south. This suggests that the Waipapa Terrane might have been divided in two by another major transform fault (perpendicular or oblique to the convergent plate margin) through the oceanic seafloor, which was being rafted towards Gondwana during the Triassic and Jurassic epochs. The Permian-Triassic northern part was possibly erupted and deposited much further away to the north than the southern part.

The fossils in the oceanic sediments indicate that they accumulated beneath warm waters in low latitudes and were rafted several thousands of kilometres southwards by seafloor spreading before approaching the coast of Gondwana, which at that time was at high latitudes. Fossil radiolaria (studied by Japanese micropaleontologists Yoshiaki Aita, Atsushi Takemura and Rie Hori) in the terrigeneous parts of the sequence that accumulated close to the Gondwanan coast are quite different from those

2.16 Fossils have been found in very few locations in the deep-water, terrigeneous, greywacke sandstone and argillite of the Waipapa Terrane. This 5 cm-long, Late Jurassic bivalve (Retroceramus haasti) comes from the most fossil-rich site, on Tawharanui Peninsula, near Omaha. University of Auckland collection.

in the oceanic sediment and characteristic of the much cooler waters.

A small section of Waipapa Terrane greywacke and argillite sedimentary rocks on Arrow Rocks, offshore from Whangaroa, was deposited before, during and after the most severe extinction event in Earth's history. This occurred 252 Myr ago, at the boundary between the Permian and Triassic epochs. Up to 96% of all marine species and 60% of all land-based species disappeared at this time. This sequence in Northland has attracted a good deal of international research, as it is one of the few places in the Southern Hemisphere where the extinction has been captured in the rock record of fossil microplankton that lived in the middle of the oceans.

Manaia Hill Group

Waipapa Terrane rocks, on Coromandel Peninsula and Great Barrier Island, are placed in the Manaia Hill Group. All are of Late Jurassic-Early Cretaceous age (160-110 Myr old) and are less deformed and less metamorphosed than Waipapa rocks in Northland and Auckland. Their zeolite metamorphic grade suggests that they were only buried to a depth of 2-6 km during the Cretaceous. They contain no oceanic sequences (no lavas nor chert) and are dominated by terrigeneous argillite and lesser thicknesses of volcano-derived greywacke (sandstone) and some conglomerate. Cobbles and pebbles in the conglomerate include granite derived from exhumed magma chambers from beneath the volcanic arc (*2.3*) and occasionally fossil-bearing siltstone eroded from the Murihiku Terrane. They are the youngest greywackes in the north and might have been deposited in a slope basin on top of the older Waipapa Terrane accretionary wedge, as it was being compressed against the side of Gondwana. Like other parts of the Waipapa Terrane they have been compressed and folded into tight folds with many steeply-dipping sections (*2.17*). The greywacke rocks on Coromandel Peninsula and Great Barrier Island have not been well studied and could include some underlying deformed and older Waipapa Terrane similar to that in Auckland.

OPENING OF THE TASMAN SEA: BIRTH AND SUBMERGENCE OF ZEALANDIA

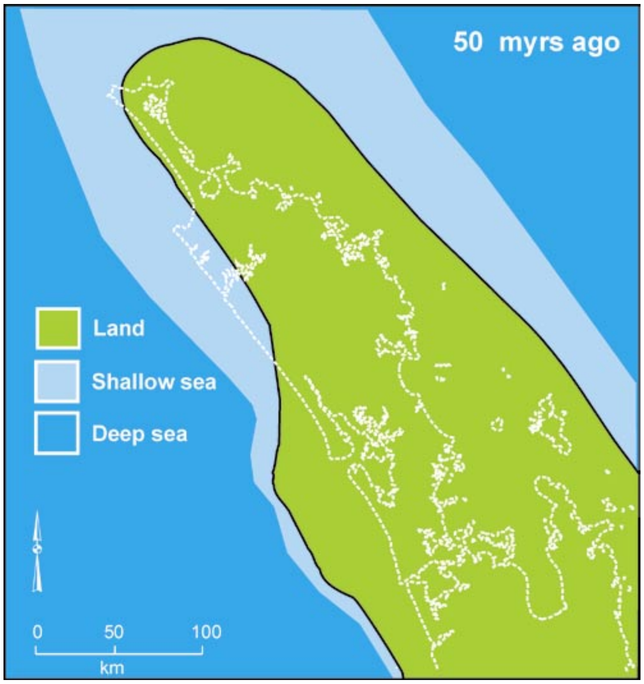
Towards the end of the Early Cretaceous (105 Myr ago), there was a major switch in tectonic forces between the Gondwana and Paleo-Pacific plates from convergence to extension. This stretching thinned the continental crust to 20-25 km thick (usually 30-40 km) along the eastern margin of Gondwana, and eventually the Tasman Sea rift opened up about 500 km inland to the west and parallel to the Gondwana coast. Between 85 and 55 Myr ago, plate tectonic forces moved a 5 million km^2 area of thinned continental crust (the new continent of Zealandia) northeastwards away from the Antarctic and Australian sectors of Gondwana. New oceanic crust was formed by seafloor spreading, widening the gap that was to become the Tasman Sea and the Southern Ocean (Box 1).

The stretching phase allowed the injection of hot igneous rocks into and beneath the thinner crust, which naturally became warmer and more buoyant. At the same time, large elongate tensional gashes (or rifts) opened up

2.17 Thin-bedded Waipapa Terrane greywacke sandstone and argillite (Manaia Hill Group) in a road cutting on Manaia Hill, south of Coromandel township. The beds have been tilted to near-vertical, but like many of these rocks on Coromandel Peninsula and Great Barrier Island, they are otherwise little deformed and little metamorphosed.

on the surface of Zealandia. Extensive valley systems, similar to the present day Hauraki Plains, formed in these subsiding rifts. They filled with large thicknesses of river gravel and flood plain sand and mud, which was eroding off the adjacent mountains. Freshwater swamps and ponds in these valleys accumulated peat that, with deep burial, became coal measures. Several elongate valleys, filled with Cretaceous-Paleocene (100-55 Myr old) alluvial conglomerate and sandstone, occur deeply buried beneath the seafloor west of Northland and Auckland.

As the stretching and rifting phase came to an end (55 Myr ago), the warm, thin continental crust of Zealandia began to cool. As a result, the crust became more dense and started to subside, a process that was to last in northern New Zealand until the onset of fresh collisional tectonic forces in the Late Eocene-Oligocene (35-25 Myr ago). At the same time, the original mountains created in the Early Cretaceous (100 or so Myr ago; Rangitata Orogeny), were eroded down to a low-lying plain by weathering, rain and wind. The eroded sand and mud was transported by rivers to the sea and deposited on the ocean floor to the east and west, on both sides of ancestral northern New Zealand (*2.18*). Some of these deep-water marine sedimentary rocks off the east coast were later uplifted and pushed onto Northland as part of the Northland Allochthon (chapter 4) and can be seen eroding on land today. The sedimentary rocks deposited off the west coast in the Tasman Sea between 80 and 30 Myr ago are still there, buried beneath a thick sequence of younger strata and volcanoes. They can be seen by the remote sensing technique of seismic reflection profiling



2.18 Reconstructed paleogeographic map for northern New Zealand during the Early Eocene, about 50 Myr ago, after the Tasman Sea had finished opening.

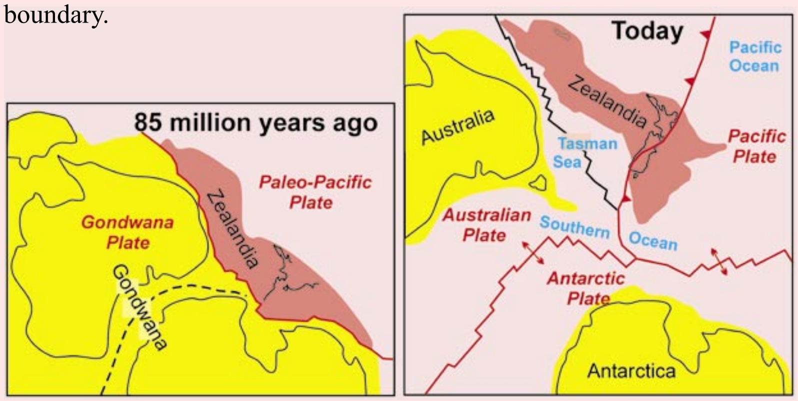
and have been sampled by an offshore petroleum exploration drillhole, Waka Nui-1 (*2.1*).

This erosion, combined with the cooling-related crustal subsidence during an otherwise tectonically quiet period, resulted in much of the land surface of Zealandia, including northern New Zealand, becoming a low-lying coastal plain that was eventually mostly submerged beneath the sea by the end of the

Box 1. THE CONTINENT OF ZEALANDIA

New Zealand sits in the middle of a vast area of thin (mostly 20-25 km thick) continental crust (usually 30-40 km thick) that is regarded as the world's seventh (and smallest and most submerged) continent. Zealandia was once part of the southern supercontinent of Gondwana but split off from it between 85 and 55 Myr ago, during the Late Cretaceous-Paleocene periods. Because the crust is thinner than in other continents, it is less buoyant and over 90% of Zealandia is currently submerged beneath the sea. More would be submerged, if the spine of New Zealand was not being pushed up by collision forces along the plate boundary.

2.19 85 Myr ago, prior to the opening of the Tasman Sea, Zealandia lay along the eastern margin of the supercontinent of Gondwana, next to Australia and Antarctica. Today Zealandia is separated from Australia and Antarctica by ocean-filled rifts that opened up between 85 and 55 Myr ago (Tasman Sea) and since 85 Myr ago (Southern Ocean). Zealandia is now cut in two by the modern plate boundary with northern New Zealand on the western side (Australian Plate).



Oligocene (25 Myr ago). This was the time of maximum submergence and least land in the New Zealand region and would have been a time of greatly reduced terrestrial habitat, resulting in extreme competition faced by the ancestral biota of New Zealand. One hypothesis that has received much attention was that New Zealand might have been completely submerged at this time and that all of New Zealand's modern terrestrial biota is derived from ancestors that must have arrived subsequently and none were Gondwanan relics. Most palaeontologists and evolutionary biologists find this highly unlikely and there is plenty of circumstantial evidence for the existence of small land areas in northern New Zealand throughout the Oligocene-Early Miocene (see later).

Box 2. OLDEST FOSSILS IN THE NORTH ISLAND

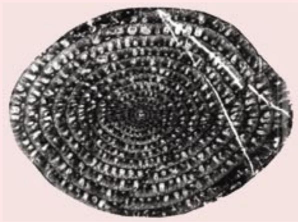
The oldest fossils in northern New Zealand, indeed in the North Island, have been found in coastal rocks at Wherowhero Point, at the east end of Marble Bay, Whangaroa. They are approximately 265 Myrs old (mid Permian Epoch). These fossils are deeply embedded in lenses of recrystallized limestone associated with red and green argillite and basalt pillow lava, which is part of the older oceanic sequence of the Waipapa Terrane.

2.20 Light-coloured lenses of marble (containing the oldest fossils in the North Island) occur within dark pillow lava at Wherowhero Pt, Marble Bay, Northland.

The largest of these fossils are 5-10 cm pieces of reef-forming coral that would have lived at shallow water depths (less than 100 m) in warm tropical waters. Also present are at least 24 different species of an extinct group of large, calcareous-shelled protists (single-celled organisms) called fusulinid foraminifera. Like the reef corals, they also lived on a shallow, tropical seafloor. Much smaller, microscopic fossils (about 0.1 mm across) of the zooplankton group radiolarian, are present in the slightly younger overlying argillites. These fossils have a spherical or conical skeleton made of silica and are extracted from the hard rocks by delicately dissolving them out of the rock with acid. The assemblage of radiolarian species present are also typical of those that lived at that time in warm tropical waters (Tethys region).

It would appear that the reef corals and fusulinid foraminifera colonised the upper parts of a volcanic seamount that had erupted in the low latitude, tropical parts of the Paleo-Pacific Ocean. At that time the portion of coastal Gondwana that was to become Zealandia was located in cool water close to the South Pole. Over a period of about 40 Myrs the warm-water fossils and seamount were rafted by seafloor spreading about 2000 km southwestwards before they started entering the cool temperate zone and began accumulating terrigeneous sediment eroded off Gondwana.

2.21 A 2 cm piece of the reef-building coral, Wentzelella maoria, from Permian limestone within Waipapa Terrane, at Marble Bay. These are the oldest fossils in the North Island, dated at 265 Myrs old. Photo from Leed, 1956.



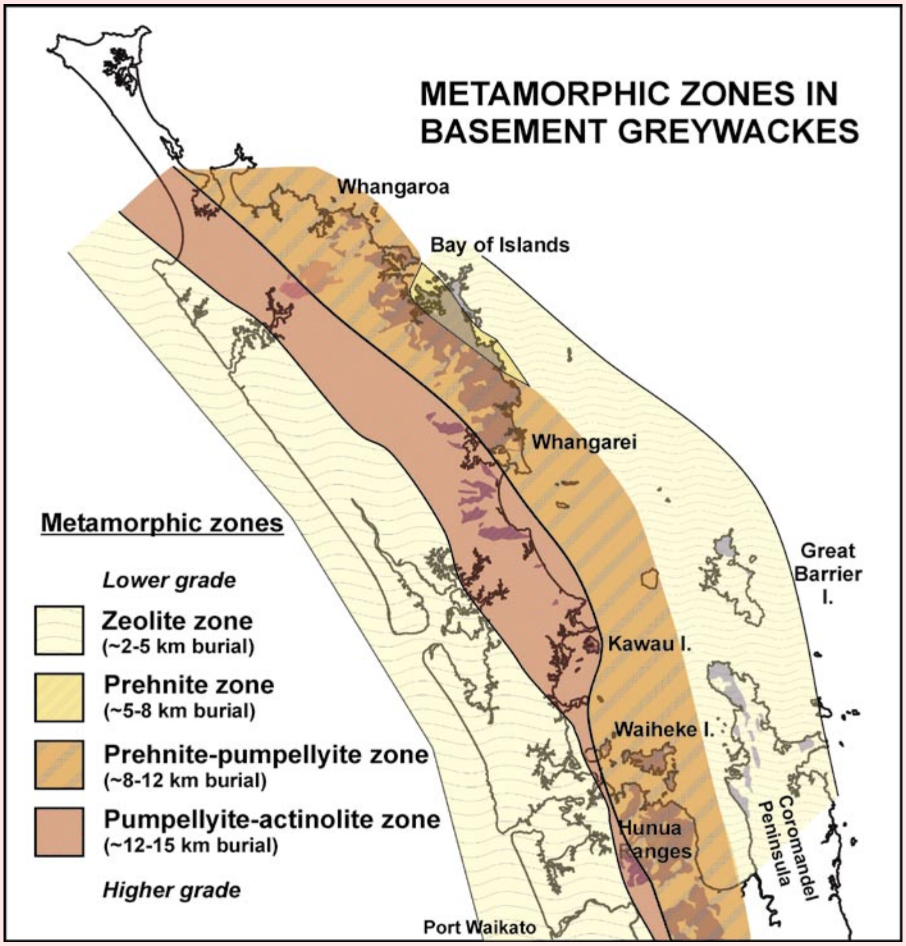
2.22 This 1-cm-long, spindle-shaped (fusiform) fossil is an extinct 265-Myr-old fusulinid foraminifer (shelled protist) from near Marble Bay, Northland. They are identified by examining their structure in a thin section of the limestone in which they are embedded, as seen above. This specimen has been cut by two white veinlets formed during deformation and deep burial metamorphism. Fusulinid foraminifera have also been found in similar rocks on Arrow Rocks and in three places in the Bay of Islands. Photo from Leven & Grant-Mackie, 1997.

Box 3. GREYWACKE ROCK TYPES AND METAMORPHISM

Greywacke is a general term for the hard, slightly metamorphosed, dominantly grey rocks that comprise the Murihiku, Waipapa and Caples terranes. In a strict sense the term is used for the hard, muddy sandstone rocks of these sequences. Another important rock type is argillite (hardened, slightly metamorphosed mudstone), often interlayered with the greywacke sandstone beds. Minor rock types are chert, basalt lava flows, often pillow lava, and recrystallised limestone or marble.

These rocks were deeply buried, in part by the accumulation of a thick pile of sediment on top of them, but mostly when they were thrust beneath more and more rocks in the accretionary wedge (*1.20*) as they were added onto the edge of Gondwana. Pressure and temperature increase with increasing depth of burial and produce increasing amounts of metamorphism that eventually produces truly metamorphic rocks like schist and slate, although there are none of these in northern New Zealand. With increasing metamorphism, a succession of different metamorphic minerals form in the clay between grains and in veins within the rocks. The presence of varying associations of these minerals can be used to determine how much metamorphism has occurred and estimate how deeply the rock was buried during the Late Jurassic-Early Cretaceous, before the process of uplift and erosion began to unearth them. These microscopic metamorphic minerals are identified by petrologists, like Auckland University's Philippa Black, who examine thin sections of the rocks through a microscope and analyse the minerals with X-ray.

Professor Black has recognised four zones of low grade metamorphism in the greywacke basement rocks of northern New Zealand. From lowest to highest metamorphic grade these zones are (with approximate burial depths): zeolite (2-5 km burial), prehnite (5-8 km), prehnite-pumpellyite (8-12 km) and pumpellyite-actinolite (~12-15 km). There is a general trend of increasing metamorphic grade from east to west within the Waipapa and Caples terranes, and this correlates with increased uplift and erosion from east to west during the Cretaceous. The least deformed and metamorphosed of these rocks are the Waipapa terrane greywackes of Coromandel Peninsula and Great Barrier Island, which belong in the zeolite zone, as do the Murihiku rocks exposed at the surface south of Port Waikato and beneath the younger cover rocks in a belt beneath west Northland-Auckland. Prehnite zone rocks occur in northeast Northland in a NW-SE belt centred on the Bay of Islands. West of these is a belt of the next highest grade of metamorphism, prehnite-pumpellyite, which forms the hills from Whangaroa to Whangarei and from Waiheke Island through most of the Hunua Ranges, and south towards Hamilton. The highest grade of local metamorphic rocks, pumpellyite-actinolite zone, form a 10-20 km-wide belt closest to the former margin of Gondwana (Junction Magnetic Anomaly). These rocks occur in the western block of Caples Terrane in the north, in Waipapa blocks west of Whangarei, forming the Brynderwyn hills south to Kawau Island, and a small southwestern part of the Hunua Ranges.

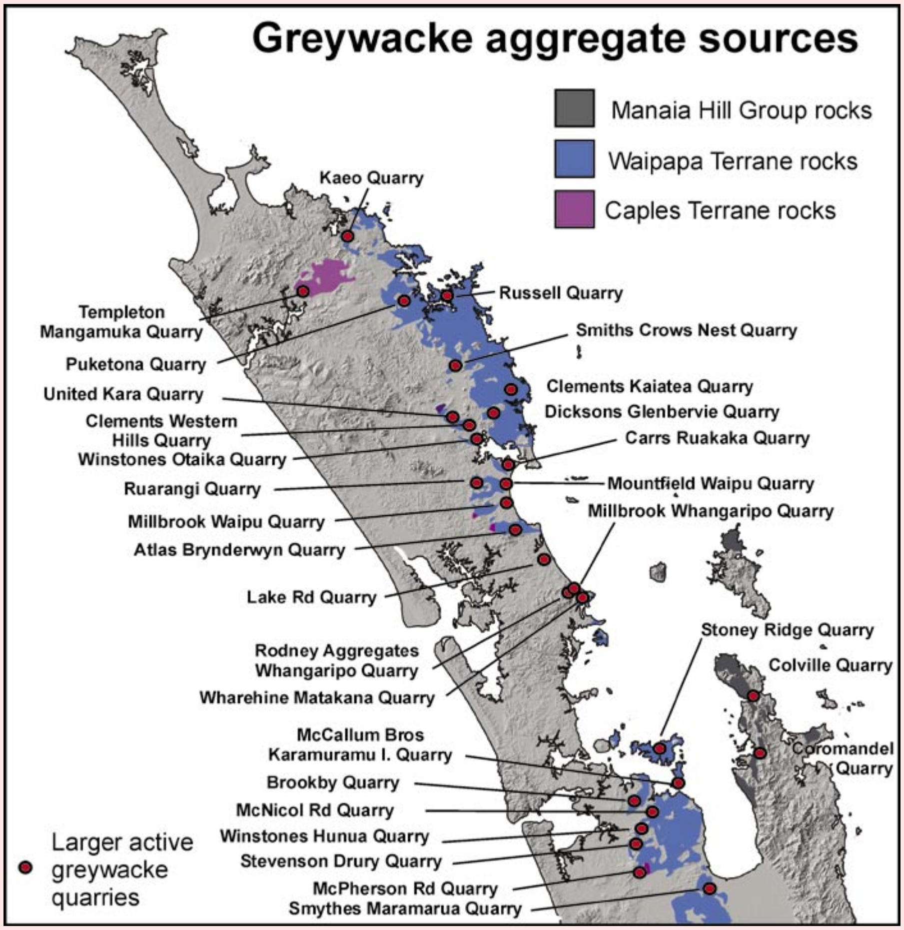


2.23 Map showing increasing metamorphic grade from east to west within the Waipapa and Caples basement terranes in northern Northland, consistent with deeper burial and greater subsequent uplift in the western part of the Late Jurassic-Early Cretaceous accretionary wedge.

Box 4. GREYWACKE AGGREGATE QUARRYING

Crushed rock, or aggregate, is an essential material for building, roading and other construction projects. Basement greywacke rocks provide more than 75% of the aggregate used in northern New Zealand and around the rest of the country. Waipapa Terrane is the main source in the north, although lesser quantities of Tangihua Complex and young volcanic basalt are also significant in some areas. Aggregate is high in bulk and low in value. The cost of transport from the quarry and crusher plant to where the aggregate is used is a vital economic factor. As a result, there are many small quarries scattered throughout Northland and Coromandel and larger quarries close to Whangarei and Auckland.

Providing the huge Auckland market with aggregate from nearby quarries is a major problem, as the traditional rock sources from the Auckland volcanoes are now used up, built over or in public reserves, and the hard rocks in the Waitakere Ranges are also protected in natural heritage areas. Thus, four huge quarries are now extracting Waipapa Terrane greywacke from the western Hunua Ranges, between Brookby and Pokeno and another at Maramarua is rapidly expanding. Northern parts of the greater Auckland City are now supplied with greywacke aggregate from three quarries in Waipapa Terrane in the hills north of Matakana, near Leigh.



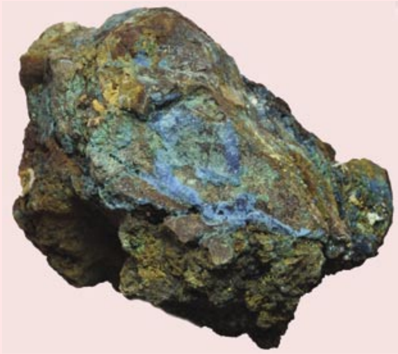
2.24 The main operating quarries that extract and crush basement greywacke aggregate for use around northern New Zealand.

The most important properties for a high quality aggregate are strength and durability. These properties are only present in Waipapa Terrane rocks that are fresh, thick-bedded, greywacke sandstone and argillite. Generally only the larger quarries can supply aggregate of sufficient high quality for use in concrete or road sealing chip, as they have dug down through the thick weathered zone into the fresh, hard greywacke sandstone (*2.25*). Sheared, veined and weathered basement greywacke, and those high in swelling clays, provide low quality and cheaper aggregate, for such uses as unsealed roads and fill. The less metamorphosed Waipapa Terrane rocks of Coromandel are slightly weaker and have more swelling clays and zeolites than their Northland and Auckland counterparts.

For many decades, a large deposit of red siliceous argillite and chert from the Waipapa Terrane has been quarried on small Karamuramu Island (McCallums Island) in the inner Hauraki Gulf and widely used as the distinctive McCallum's red chip on Auckland's footpaths.

2.25 Winstone's Hunua Quarry near Papakura, is one of the largest suppliers of greywacke aggregate to the Auckland building and roading industries. The grey portions are relatively fresh rock, the brown parts are weathered and stained by iron-rich groundwater.

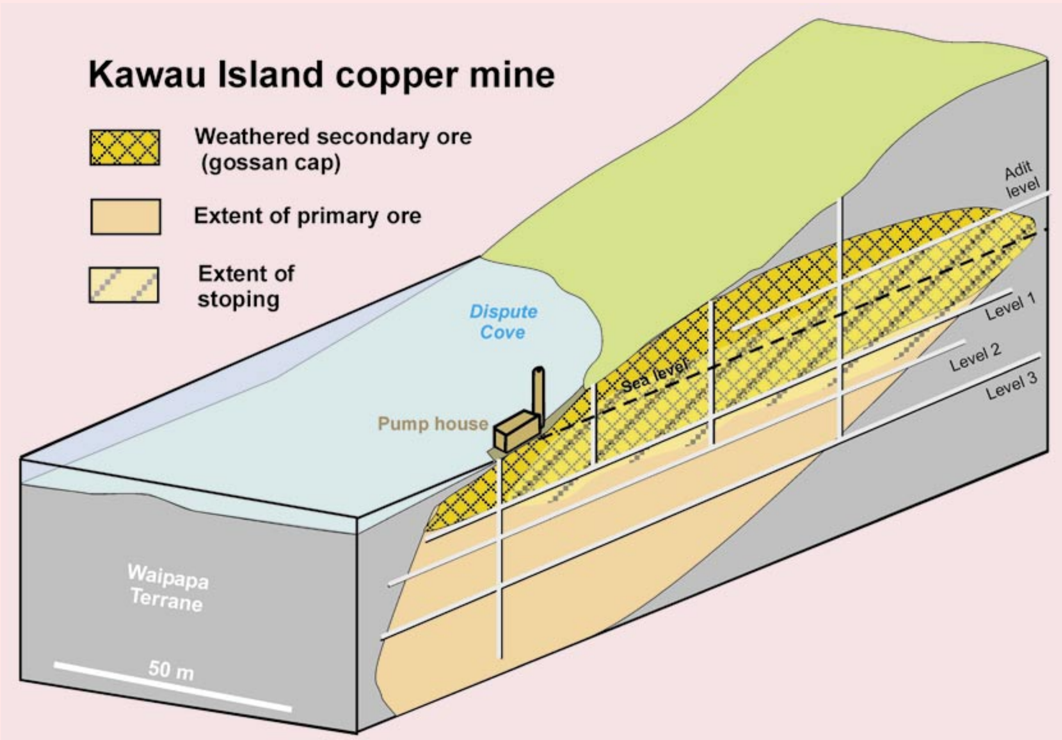
Box 5. COPPER MINING ON KAWAU ISLAND



2.26 *Blue azurite and green malachite (copper hydroxyl carbonate) from the weathered secondarily-enriched zone in the Kawau copper mine. Specimen 10 cm across. University of Auckland collection.*

A small copper deposit, associated with pillow lava, chert and siliceous argillite, was mined on Kawau Island in the early European period. Stonework from part of the mine pump house and chimney still remains (*2.28*), as do the partially restored stone remnants of the smelter in Bon Accord Harbour. The mine manager's residence was the historic Mansion House, which was later bought and extended by Sir George Grey and still stands today. Originally started as a manganese mine in 1843, the Kawau copper mine had started producing copper by 1844, and by the end of the decade there were around 300 people living on Kawau associated with the copper industry. The mining endeavour was plagued with flooding problems, which eventually led to its closure in 1852 and frustrated attempts to reopen it in 1854-55 and again around 1900.

The copper mine was small by world standards and focused on a 3-6 m thick, near vertical, ore-bearing lode or sheet within the lower, oceanic part of one of the rock sequence slices that comprise the Waipapa Terrane. It is no coincidence that the lode is in close proximity to ocean floor lava flow rocks. It is thought that submarine hydrothermal springs called "black smokers" (derived from hot magma beneath the sea floor) spewed plumes of hot mineral-rich water out into the cold water. Precipitating from these plumes and collecting around them on the sea floor are multi-coloured deposits of metal sulphides, oxides and silica, rich in iron, manganese and copper. Kawau's "black smoker" mineral deposits extended over several hectares of seafloor. They were mostly iron



2.27 Section along the 3 to 6 m-thick Kawau copper lode showing the extent of the ore and pattern of shafts, levels and stoping used to mine it. The richest copper mineralisation was obtained from along the base of the weathered cap.

Box 5 continued

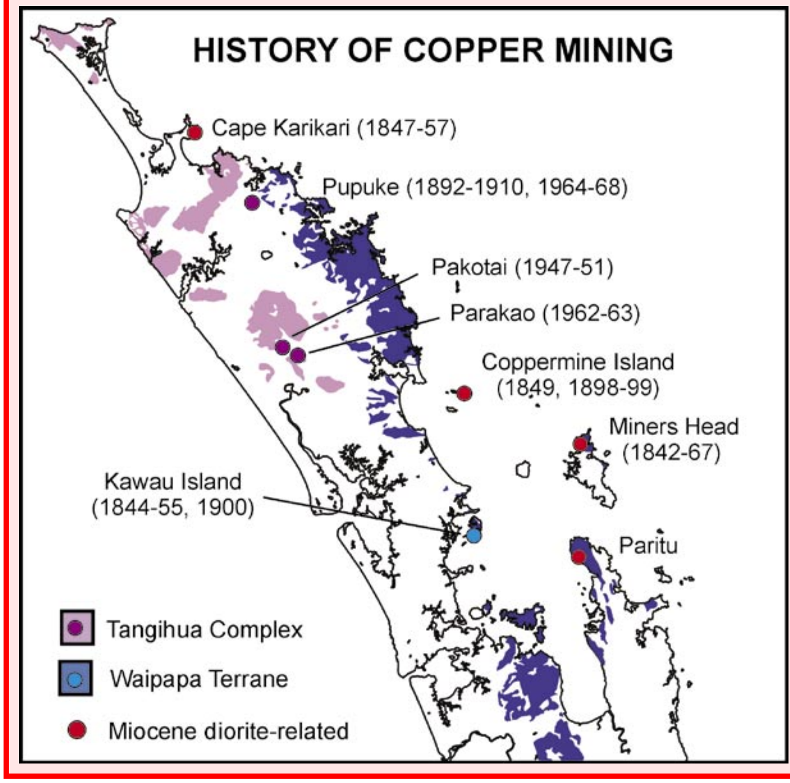
2.28 Remains of the old copper mine pumphouse and chimney on the south shore of Kawau Island. They were built out of Waitemata Sandstone blocks originally obtained from the shoreline at the south end of Pakiri Beach in 1854.

and copper sulphide minerals, especially the gleaming metallic pyrite ("fool's gold") and brassy chalcopyrite. The strata and enclosed copper-bearing lode were tilted up to near vertical during accretion and compression of Waipapa Terrane onto the coast of Gondwana in the Early Cretaceous (150-100 Myrs ago).

In recent millennia, erosion has been relatively slow on this sheltered coast and deep surface weathering of the lode had formed a 10 to 20 m-deep gossan cap on top of it. In this cap, the sulphide ore has been oxidised and sulphur and most of the metals have been leached out, leaving rust-coloured, hydrated iron oxide (limonite mineral) and sporadic blue and green copper carbonates (azurite and malachite minerals; *2.26*), which can be seen staining the cliff above the mine entrance today. The unweathered primary ore in the Kawau lode contained 1 to 2% copper. The leaching resulted in copper enrichment (up to 20%) in the zone along the base of the iron-oxide-rich gossan cap.

The near vertical lode was mined by sinking four shafts into it at various distances along its length, and linking these with a series of horizontal tunnels at different levels (*2.27*). Those parts of the lode that were richest in copper sulphide, particularly in the secondarily enriched zone, were completely mined out (stoped). The ore was transported along the tunnels in small hand-pushed railway trucks and hauled to the surface up the shafts using horse-powered whims (windlasses). Most of the mine was sunk below sea level and water seepage was a major problem, requiring constant pumping using wood-fired pumps. The richest ore in the small Kawau lode was removed prior to the early failure of the venture. In its brief seven years of operation it extracted about one hundred thousand pounds worth of copper - the most productive copper mine ever to operate in New Zealand.

Other small deposits of copper minerals occur in northern New Zealand, mostly as sulphide lenses at the contact between seafloor lava flows and mudstone in the allochthonous Tangihua Complex volcanics (see later) at Pupuke, Parakao and Pakotai, or as widely dispersed copper mineralisation (porphyry-style) associated with hydrothermally-altered diorite and granodiorite intrusive rocks of Miocene age, on the Coromandel Peninsula, northern Great Barrier, Coppermine Island (Chickens Group) and Cape Karikari.



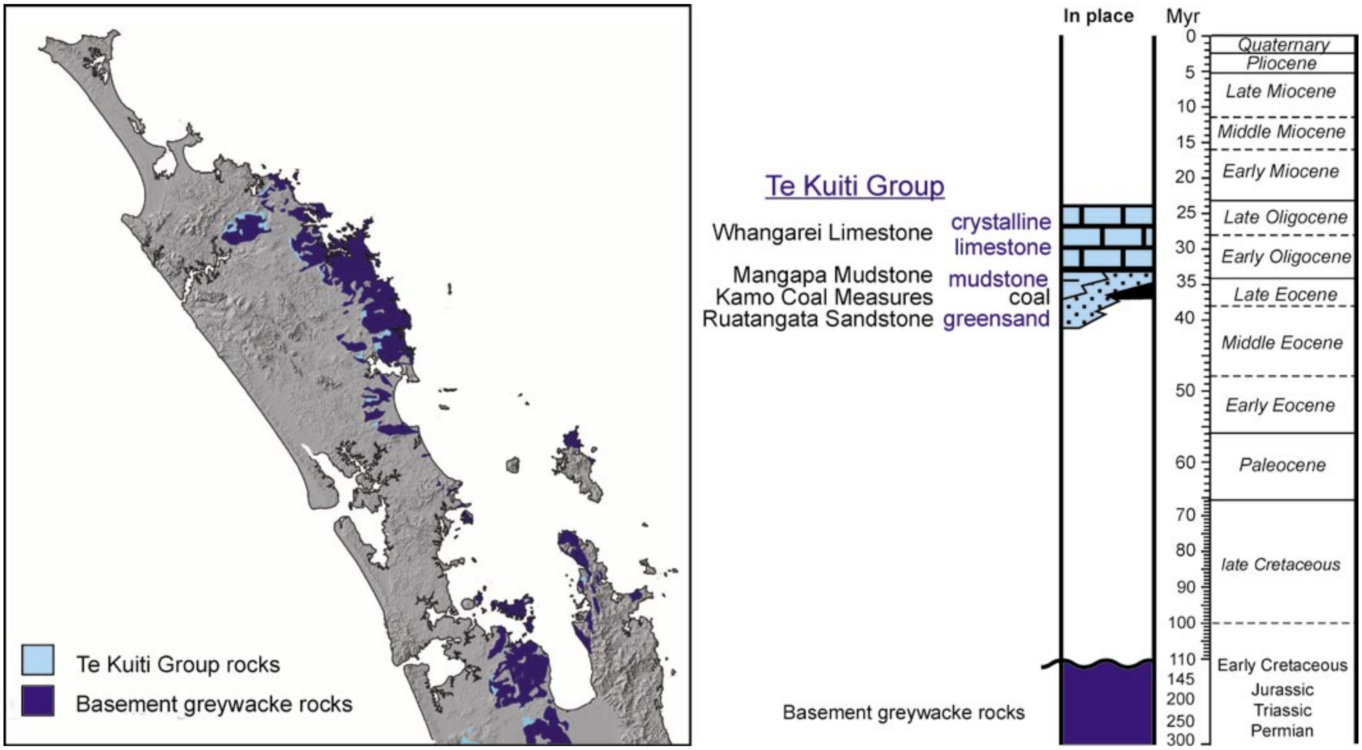
2.29 Location of historic copper mining operations in northern New Zealand.

Chapter 3. COAL, LIMESTONE AND KARST

(Te Kuiti Group: 40-25 Myr old)

Chapter Summary

During and after Zealandia's split away from Gondwana (80-40 Myr ago) there was a long period of tectonic stability in northern New Zealand. Several kilometres of basement greywacke rocks were eroded away, reducing the mountains to a low-lying plain. Renewed tectonic activity began slowly in the Late Eocene (38-33 Myr ago) as a few areas were pushed up and others slowly subsided, creating hills and valleys. River gravels were deposited in these valleys and peat accumulated in adjacent swamps. With later burial, the peat was turned into coal, which was mined at Kawakawa, Hikurangi, Kamo, Kiripaka and Drury between the 1850s and 1950s. Subsidence became more widespread and most of the land was drowned by the sea between 33 and 23 Myr ago (Oligocene). In the absence of land-derived sand or mud, sediment accumulation on the shallow sea floor was slow, with initial greensand deposits overlain by more extensive shell banks. With later burial, these shells were cemented together and recrystallized into hard limestone. Limestone near the surface today has dissolved into beautiful karst landforms and pinnacles (e.g. Waro Rocks) and accessible caves with stalactites (e.g. Waiomio, Waipu, Abbey caves). Amongst the more interesting fossils preserved in these sedimentary rocks are leaves and ferns in coal measure sequences, crabs and turtles in the green sandstone, and a complete lanternfish in the limestone.

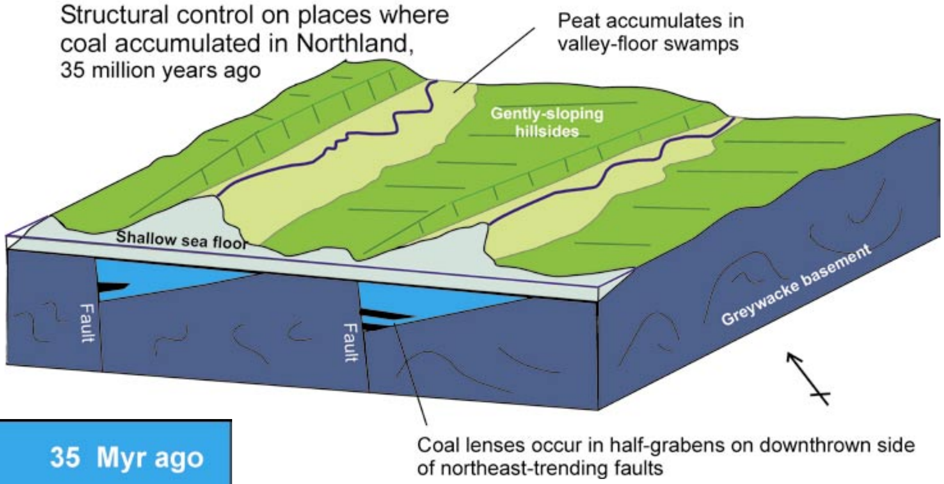


3.1 Distribution of Te Kuiti Group rocks in northern New Zealand and stratigraphic column showing the relationship between the different rock types and the greywacke basement.

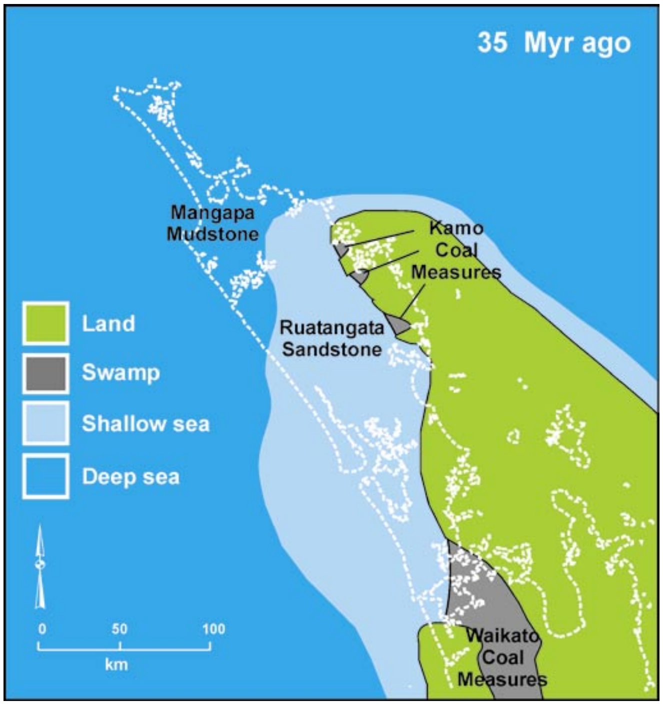
COAL (Kamo and Waikato Coal Measures)

What is now northern New Zealand was land throughout the Cretaceous, Paleocene and most of the Eocene epochs (145-40 Myr ago). The eroding mountains and hills were made of uplifted greywacke basement rocks that shed gravel, sand and mud down rivers into the sea on either coast.

In most parts of Northland, Auckland and the Coromandel, the oldest rocks sitting directly on top of this eroded greywacke surface were deposited during the Late Eocene period around 36-33 Myr ago. These rocks are thin alluvial and coal measure sequences (Kamo Coal Measures and Waikato Coal Measures). They consist of gravel, mud and sand that was deposited in river beds



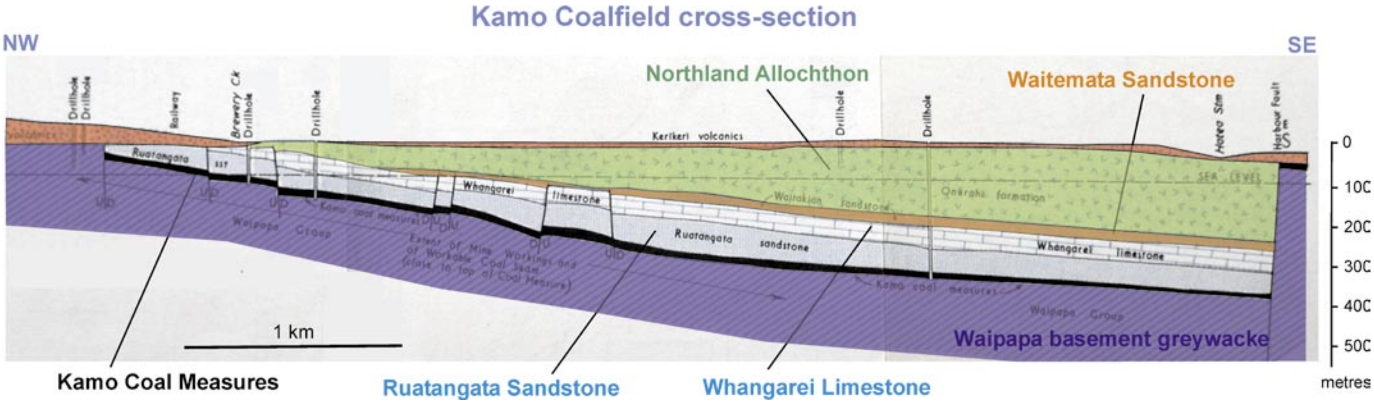
3.2 Reconstruction of the setting in which peat accumulated along the east side of Northland during the Late Eocene. With later deep burial it was transformed into marginally bituminous brown coal.



3.3 Reconstructed paleogeographic map for northern New Zealand during the Late Eocene, 35 Myr ago.

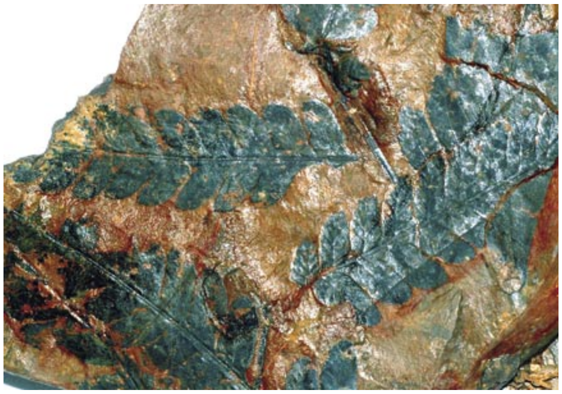
and on alluvial plains, sometimes with interbedded layers of coal (*3.2*). This coal was plant material that accumulated as peat in freshwater swamps and shallow lakes in depressions on these river plains. The plant material was a mix of swamp plants and also leaves and branches washed down into the swamp from surrounding forest during rain storms and floods. In a few places, like Drury, leaf fossils (*3.7, 3.8*) and even freshwater mussels (*7.20*) have been preserved as fossils in the mud that accumulated with the peat in these settings. The peat was converted to sub-bituminous coal (brown coal) by the increased pressure and heat associated with later burial beneath approximately 1-2 km of sediment that was deposited on top of it over the succeeding 15 Myr.

These non-marine sediments are up to 50 m thick, except at Kiripaka, where there is up to 100 m of dominantly fluvial conglomerate and sandstone. They can



3.4 Northwest-southeast cross-section through the Kamo Coalfield based on mining records and drillholes. Note that the recognition of older rocks (green) overlying the Te Kuiti Group rocks (light blue) in this area was one of the key observations that led to the recognition of the displaced Northland Allochthon (see next chapter). Modified from Kear, 1959.

3.5 A thin seam of coal (Waikato Coal Measures) is exposed in this road cutting on Ponga Rd, southeast of Papakura. Inset. Close-up of coal, showing a lump of fossil kauri gum, Ponga Rd.



3.7 Fossil impressions of fern pinnae from the Late Eocene coal measures at Drury. Width of photo 10 cm. Photographer John Conran.

3.6 Coal and alluvial mudstone and conglomerate of the Kamo Coal Measures in a hillside cutting at the back of the old brickworks at Springs Flat, just north of Kamo, Whangarei (currently Greenfingers depot). The yellow colour comes from the sulphate mineral jarosite, produced by weathering of pyrite. Width of photo 5 m.

3.8 Fossil leaves of extinct trees from the Late Eocene coal measure sequence near Drury. The largest leaf is from the laurel family and the two smaller ones are beech (Nothofagus). Width of photo 12 cm.

be found today in eastern Northland around Kawakawa, Hikurangi, Kamo (*3.4, 3.6*), Kiripaka and Waipu, and also southeast of Papakura (*3.5*) near Auckland and south of Colville on the Coromandel Peninsula (*3.9*). The thickest coal seam is up to 8 m thick, but most are much thinner. They are of the same age as the enormous coal deposits of the northern Waikato basin centred around Huntly. While the northern Waikato coal was deposited in a large complex river plain environment, it appears that the more northern coal measure deposits each accumulated in its own small river valley as it approached the coast (*3.3*). These were mostly NE-trending valleys or half grabens bounded on their northern sides by a fault, with the land being downthrown to the south and uplifted and tilted on the northern side (*3.2*).

3.9 Fluvial (river-deposited) pebble conglomerate (centre) and dark grey carbonaceous mudstone overlying an erosional unconformity on the underlying steeply-dipping greywacke (Manaia Hill Group), south of Waitete Bay, Coromandel Peninsula. The conglomerate and mudstone are part of the coal measure sequence (Torehina Formation) that was deposited here about 35 Myr ago. Width of photo 8 m.

Box 6. COAL MINING

European colonists in the mid-nineteenth century were well aware of the value of coal for cooking and heating. By the 1870s, coal-fired steam engines were becoming widely used, especially in timber mills, for the spreading rail network and for newly introduced steam engines on ships. Early on, most coal was imported from Newcastle in Australia at considerable expense. Each settlement in New Zealand was keen to find and open up their own local and preferably easily accessible source of coal. Near Auckland, the Rev Guyon Purchas is reported to have discovered (with the help of local Maori) coal in stream beds of the hills east of Drury in 1858. Auckland Provincial Council was keen to have this coal resource assessed, as its potential value to the fledgling capital would be enormous. When the Austrian *Novara* Expedition arrived in Auckland in December 1859, budding young geologist Ferdinand Hochstetter was asked to undertake a survey of the extent and economic value of the coal at Drury. He recognised just a single coal seam (up to 2 m thick), but was reasonably optimistic that sufficient coal extraction was possible. Soon afterwards, the Waihoihoi Mining Company commenced operations and a tramway was laid from the mine to the Manukau Harbour tidewaters at Drury. Unfortunately, coal reserves proved to be rather small and in many small pockets. These were mined intermittently until 1935, when the last coal mine in the Drury field (near Coal Mine Rd) closed. The average life of each underground mine was only 3 years with a miniscule average production of 750 tonnes per mine.

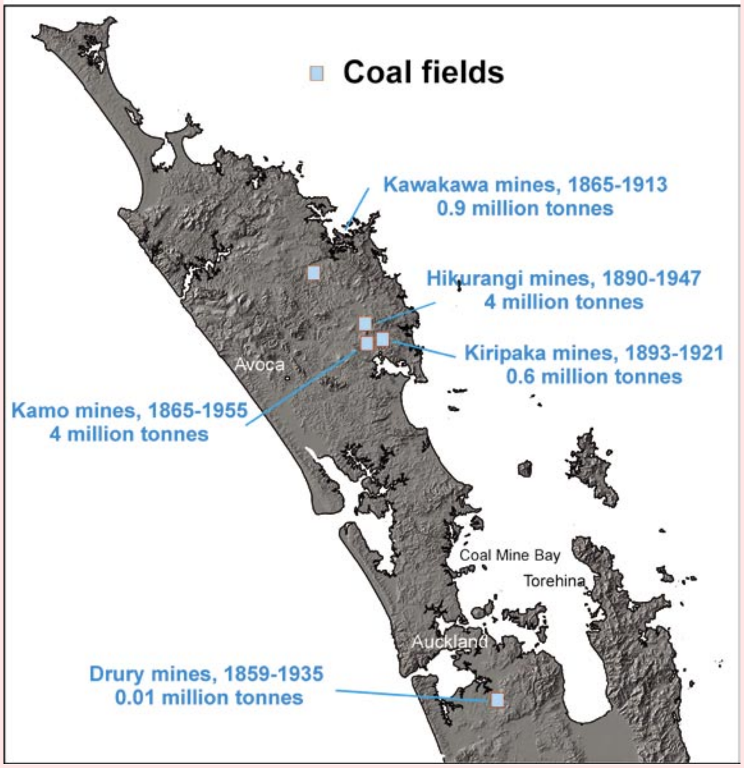


Fig. 3.10 Location, total production and years of operation of coalfields in northern New Zealand.

By the early 1860s, potential coal fields had also been found in Northland, and their assessment was the main reason for Dr James Hector's first extensive field trip after his appointment to establish the NZ Geological Survey in 1865. Underground mining of the coal (discovered early in 1865) was already underway at Kamo, with a rail line being constructed from there to the tidewaters above Whangarei. Hector then moved north to survey the recently discovered coal at Kawakawa and concluded it was of similar sub-bituminous character to that at Kamo and likely the same age. He reported favourably on the prospects of underground mining of coal in this part of Northland, and by the end of 1866 the mine at Kawakawa, with a 2.5 km tramway to the Bay of Islands tidewaters, was the largest in New Zealand and supplying Auckland's needs. From then on coal was mined almost continuously in at least one of the four separate coalfields in this part of Northland (Kamo, Kiripaka, Hikurangi, Kawakawa) until 1955, when the last mine in Kamo was flooded by underground water out of the overlying cavernous limestone. At its peak in the late 1940s, the Kamo mine employed 200 men and there was 50 km of underground tramway. Kamo and Hikurangi coalfields were the most productive coalfields in Northland with at least 4 million tonnes of coal taken from each.

Following closure of the last underground mines in Northland, drilling campaigns were undertaken by the Mines Department in the 1950s and 1980s, which concluded that there was ~2.5 million tonnes of in-ground coal left at Hikurangi and Kamo, but this was unlikely to be economic to extract.

Small amounts of Eocene coal occur elsewhere in northern New Zealand (e.g. Avoca, Torehina) but were insufficient to warrant mine establishment. The presence of large pieces of carbonised wood within the Waitemata Sandstone sequence on the north side of Whangaparaoa Peninsula led to the name Coal Mine Bay, but this was wishful thinking.

Fig. 3.11 Surface remnants of the entrance to Hikurangi Shaft Coal Mine can still be seen in a paddock near the foot of Mt Hikurangi. It closed in 1947, following major underground flooding.

GREENSAND AND MUDSTONE (Ruatangata Sandstone, Mangapa Mudstone)

3.12 In Otaika Quarry, Whangarei, dark green-grey glauconitic sandstone (Ruatangata Sandstone), containing a 2m-thick lens of algal limestone (cream-yellow), overlies basement greywacke. Both were deposited in shallow marine conditions in the Late Eocene, 35-33 Myr ago.

The oldest marine sedimentary rocks that were deposited over the greywacke basement of Northland are 40-35 Myr old (Late Eocene Epoch, Te Kuiti Group) glauconitic sandstone (Ruatangata Sandstone) and calcareous mudstone (Mangapa Mudstone), which can be seen in stream beds between Whangaroa and Omahuta. In this region there are no coal measures present. The sand and mud accumulated on the shallow sea floor as northern Northland began to subside – the earliest evidence for the onset of compressive forces between the Pacific and Australian plates along the line of the modern plate boundary.

The slightly younger localised subsidence that formed the half-grabens in which the coal measures accumulated further south, was followed by more widespread foundering throughout Northland in the Oligocene (33-23 Myr ago). The low-lying coastal hills, which had supplied the fluvial gravels to the coal measure sequences, disappeared beneath the waves and little land remained. Thus there was little mud or sand washing into the sea and sediment build up was slow. In many places the green-black mineral glauconite (iron-potassium

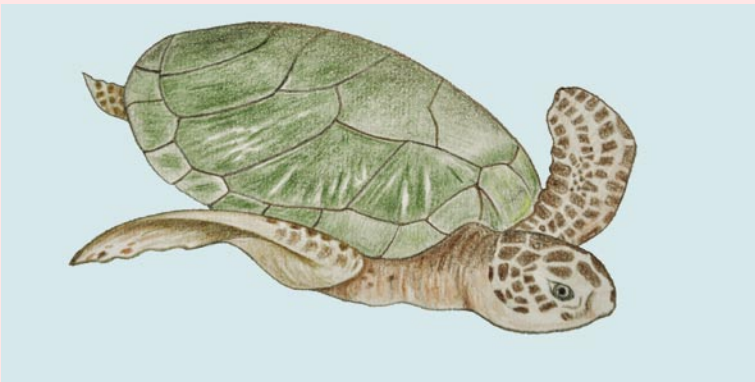
3.13 A fossil Late Eocene (35 Myr old) crab (Tumidocarcinus giganteus) found inside a cannonball concretion in Ruatangata Sandstone on the shore of Whangarei Harbour.

3.14 Algal (rhodolith) limestone near Takahiwai, south side of Whangarei Harbour. The white spheres are made of concentric layers of calcite (below), precipitated by red algae that lived on the floor of shallow seas in the Late Eocene, about 35 Myr ago. They often have a knobbly surface. The centres of most of the rhodolith spheres are pieces of greywacke rock that the algae first settled on. When deeply buried, the deposit of rhodoliths was cemented into this hard crystalline limestone.

silicate) grew slowly as small pellets on the sea-floor surface in relatively shallow water settings (less than 100 m water depth) and the resulting greensand (Ruatangata Greensand, *3.12*) accumulated on top of the sunken coal measures. Glauconite is widespread and abundant today on the Chatham Rise, which is a modern area with similar low supply of land-derived sediment.

Exposed along parts of the coast of the Whangarei Harbour, there are outcrops of Late Eocene sandstone that has only small amounts of glauconite. In one place a bed of this sandstone is full of 10-15 cm-diameter hard concretions that have formed around fossil crabs (*3.13*). On the north side of Whangarei Harbour at Reserve Pt, the bedded sequence of sandstone includes a lava flow of a dark-grey kind of basalt, called nephelinite. This lava flowed across the sea floor and in places formed small pillow-lava lobes (Box 10) that can be seen exposed on the foreshore.

Box 7. FOSSIL SEA TURTLES



3.15 Right. An Eocene sea turtle. Drawing by Margaret Morley.

*3.16 Fossil vertebrae (bottom), broken humerus (left) and broken manus (top) bones of the extinct, 35 Myr-old turtle (*Eochelone monstigris*) from near Whangarei. Width of photo 25 cm. University of Auckland collection.*

The partial remains of two 35 Myr-old (Late Eocene) sea turtles have been found in greensand in Northland. Each consists of a collection of ribs, vertebrae, limb bones and pieces of carapace (shell). They belong to two distinctly different extinct species of warm-water sea turtle, each about 1 m long when alive. One was found in greensand at Pahi in the Kaipara Harbour and the other on Mt Tiger Rd near Whangarei. Fossil turtles are not common in New Zealand, with the remains of fewer than ten having been found. These fossil turtles were described by paleontologist Jack Grant-Mackie

CRYSTALLINE LIMESTONE (Whangarei Limestone)

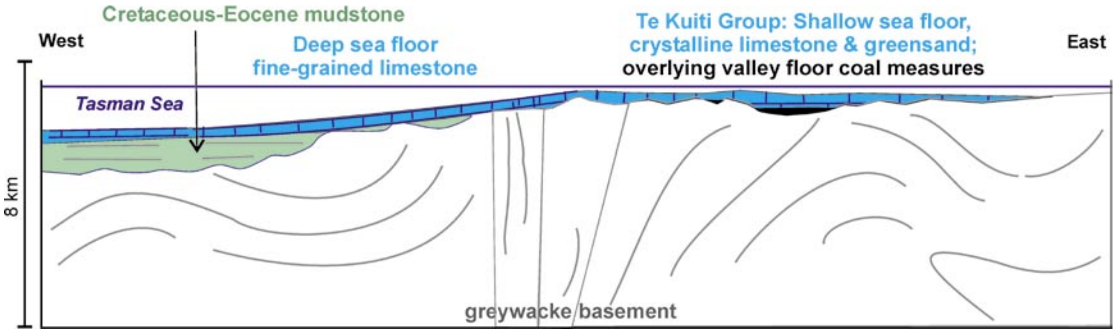
3.17 Eroding flaggy limestone (Whangarei Limestone, Oligocene) forms a spectacular section of coastline between Waipu Cove and Langs Beach, south of Whangarei.

A little later in the Oligocene, there was no sand supply at all, and banks of sea shells and the skeletal remains of other marine organisms accumulated beneath the clear, shallow seas that covered the region. These organisms included bivalves, gastropods, sea eggs, foraminifera and calcite-secreting algae. The shell bank deposits were cemented into hard crystalline limestone (Whangarei Limestone) when they were buried beneath 500-1000 m of younger strata. At these burial depths warm percolating groundwater dissolved some of the shell and then redeposited the calcite as crystals in the spaces within the porous shell banks. This created a strong, erosion-resistant, crystalline limestone with wavy laminae of dark glauconite grains. One deposit of this limestone, next to the railway line at Hikurangi, was quarried in the 1930s and used as a facing stone of polished yellow to pink "Waro Marble" in many government buildings throughout the North Island. This former quarry is now flooded as a recreational lake east of Waro Rocks Scenic Reserve.

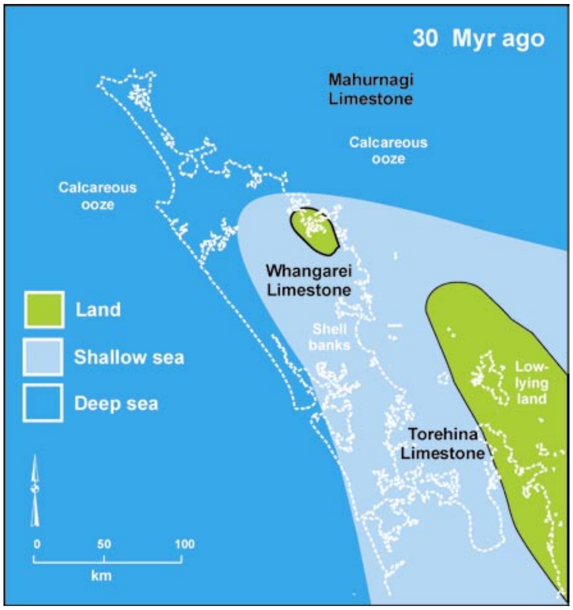
Discontinuous patches of this crystalline limestone occur in eastern Northland between Waiomio (Kawakawa) and Waipu (up to 100 m thick), and another small patch of more sandy limestone (up to 50 m thick) occurs around Waitete Bay, Coromandel Peninsula (Torehina Limestone). The shell banks that formed this crystalline limestone are thought to have been far more widespread over the region than suggested by the present limestone occurrences. Boulders of limestone have been thrown out of Maungataketake Volcano near Mangere Airport on the Manukau Harbour and support the inference that it was once widespread across Auckland, but in many places in that area it was eroded away within a few million years of deposition.

While these shell banks were accumulating in shallow marine depths over ancestral Northland-Auckland-Coromandel, the sea was much deeper out to the east and west (*3.20*). In the absence of mud and sand supply from an eroding nearby land, the only sediment to accumulate on this deeper ocean floor during this Oligocene period was the skeletons (mostly made of

3.18 Erosion-resistant Oligocene limestone (Torehina Limestone) forms the small headland in Waitete Bay on the west coast of Coromandel Peninsula between Coromandel and Colville. This is the only significant exposure of limestone on the peninsula. Slightly older conglomerate that underlies the limestone can be seen in the intertidal rocks in the foreground.



3.19 Simplified cross-section through Northland showing geographic setting as Te Kuiti Group sedimentary rocks were deposited during the Late Eocene and Oligocene, 35-24 Myr ago.

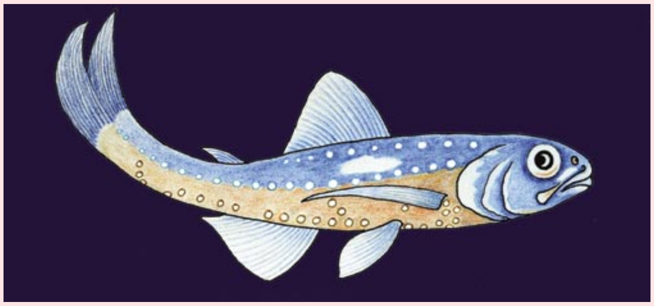


3.20 Reconstructed paleogeographic map for northern New Zealand during the Late Eocene, 30 Myr ago.

3.21 Right. An 8 m-high, vertical-sided pinnacle of crystalline Whangarei Limestone near Kamo.

calcite) of phytoplankton (nannofossils) and zooplankton (planktic foraminifera). These accumulated as a blanket of calcareous ooze several hundred metres thick. With burial by younger strata, this ooze was converted to chalk or a muddy limestone (Mahurangi Limestone), some of which was later displaced onto Northland where we can see it on land today.

Box 8. FOSSIL LANTERN FISH



3.22 A modern lanternfish. Length about 10 cm. Drawing by Margaret Morley.

3.23 This fossilised lanternfish (7.5 cm long) preserved in latest Oligocene (25 Myr old) sandy limestone from Paradise Quarry, near Whangarei, is one of just a handful of complete fossilised marine fish found in New Zealand.

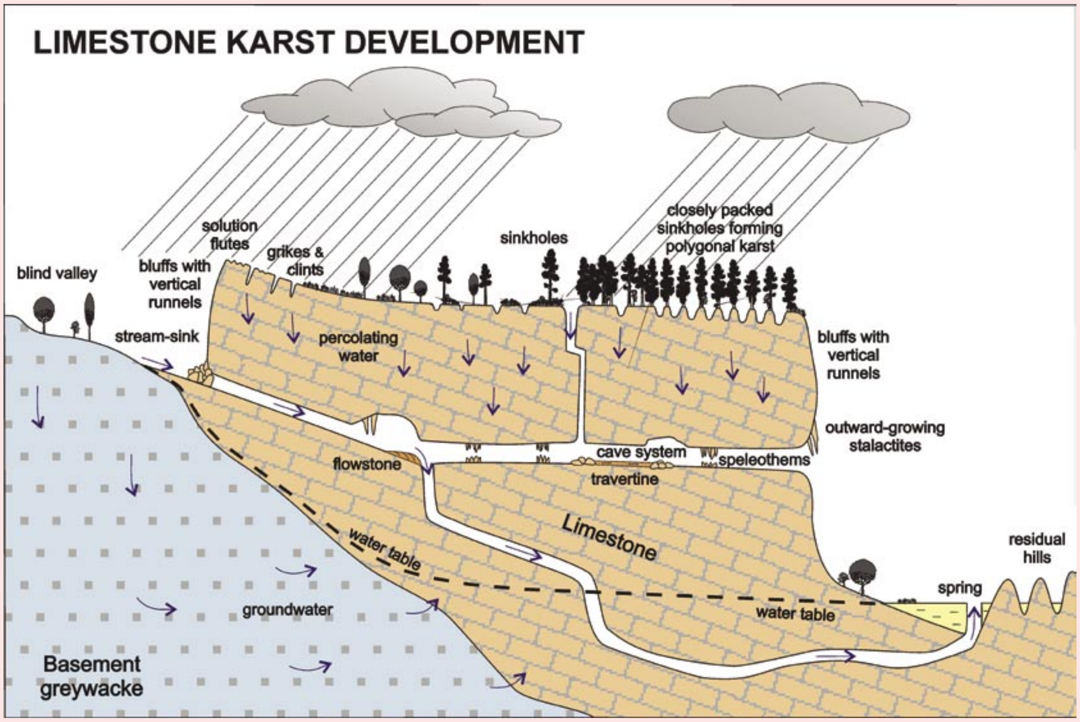
Fish teeth, scales and ear bones (otoliths) are commonly found fossilised in sedimentary rocks, but the remains of a complete fish have rarely been found in New Zealand. One rare find was made by Brian Sharp of Portland, Whangarei in 1991. While splitting flag stones in his sandy limestone quarry (Te Kuiti Group, Paradise Quarry) he uncovered a complete fossilised adult lanternfish. The fossil is well preserved with much of the skin intact. It possesses a distinctive highly regular, lineal pattern of light organs (photophores), which place it in the lanternfish family, Myctophidae. Myctophids live in the open mid-waters of all oceans. During the day most live in low light at depths of 400-1500 m, but at night migrate up towards the surface following their zooplankton prey. The bioluminescence is thought to help with camouflage, whereby they regulate the brightness of the bluish light from the photophores to match the ambient light level above. Lanternfish are the most abundant deepwater fishes and their calcified ear bones are often fossilised. Whole lanternfish fossils are extremely rare and this is the only one known from New Zealand.

Box 9. LIMESTONE KARST

Karst is a term for landforms produced by solution of water-soluble rock, usually limestone, which is composed of calcium carbonate. Karst landforms are characterised by solution caves, subterranean drainage, sinkholes, springs, pinnacles and fluted rock surfaces. Pure, hard, recrystallised limestone, like the Whangarei Limestone of eastern Northland, dissolves most readily to develop the best karst features. Muddy limestone with more than a minor amount of mud or sand, like the muddy limestones (Motatau Complex) of central and west Northland, do not develop karst because voids produced by solution are soon clogged with insoluble mud and sand residues.

3.24 The pinnacles in Waro Rocks Scenic Reserve, Hikurangi, are densely fluted – a result of weakly acidic water dribbling down the sides and dissolving the limestone.

To produce good karst the limestone rock also needs to be dense, with networks of joints that water can flow through, not soft and porous. Karst develops fastest in warm areas with high rainfall, like Northland. Rainwater that passes through soil and decaying organic matter is enriched with carbon dioxide, becoming slightly acidic, thereby enhancing rock solution. Joints are slowly widened, forming caves at depth or deep trenches on the surface. Solution along criss-crossing vertical joints will, over time, corrode limestone into spectacular pillars and eventually isolated pinnacles, as found in places like Waro at Hikurangi



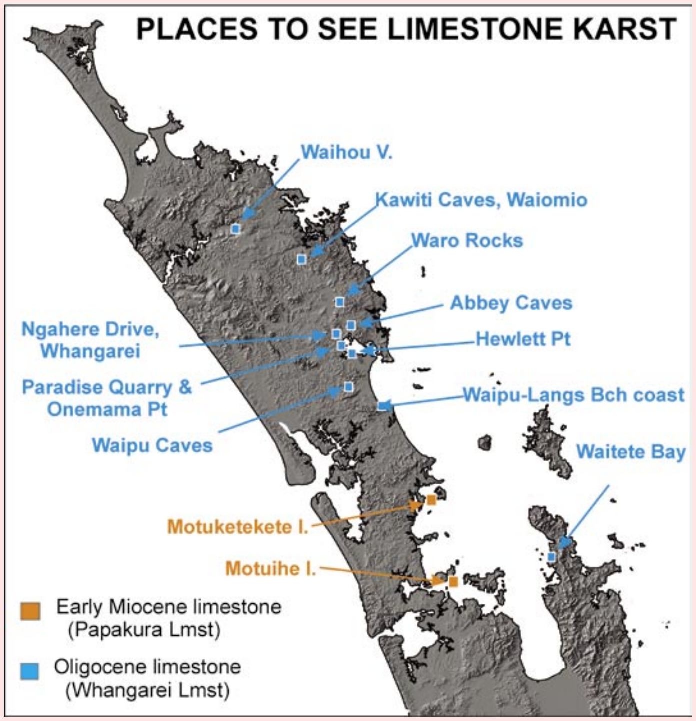
3.25 Cross-section diagram through an area of Whangarei Limestone sitting on greywacke basement, illustrating how water solution along joints produces the variety of karst landforms in Northland. Drafted by Jill Kenny.

Box 9 continued

3.26 Stalactites hang from the roof of the main publicly accessible cavern at Waipu Caves. Photographer Egon Eberle.

(*3.24*) and Abbey Rocks near Whangarei. Other places where spectacular karst can be experienced in Northland are along the coastal track east of Waipu Cove and along Ngahere Drive in the Whangarei suburb of Horahora.

Publicly accessible limestone caves in the region are restricted to east central Northland, with free access at Waipu Caves (*3.26*) and Abbey Rocks. A commercial tour is available at Kawiti Caves, Waiomio, near Kawakawa. A small area of coastal karst, formed in Oligocene limestone, occurs on the point in the middle of Waitete Bay, Coromandel Peninsula (*3.18*). There is no Oligocene limestone near Auckland, but several small areas of Early Miocene limestone (basal Waitemata Group) are present, with flaggy karst development, on Motuihe and Motuketekete islands in the Hauraki Gulf.



3.27 Main locations where limestone karst landforms and caves can be seen in northern New Zealand.

3.28 This spectacularly fluted limestone block, near Kamo, has fallen over so that the fluting is no longer vertical.

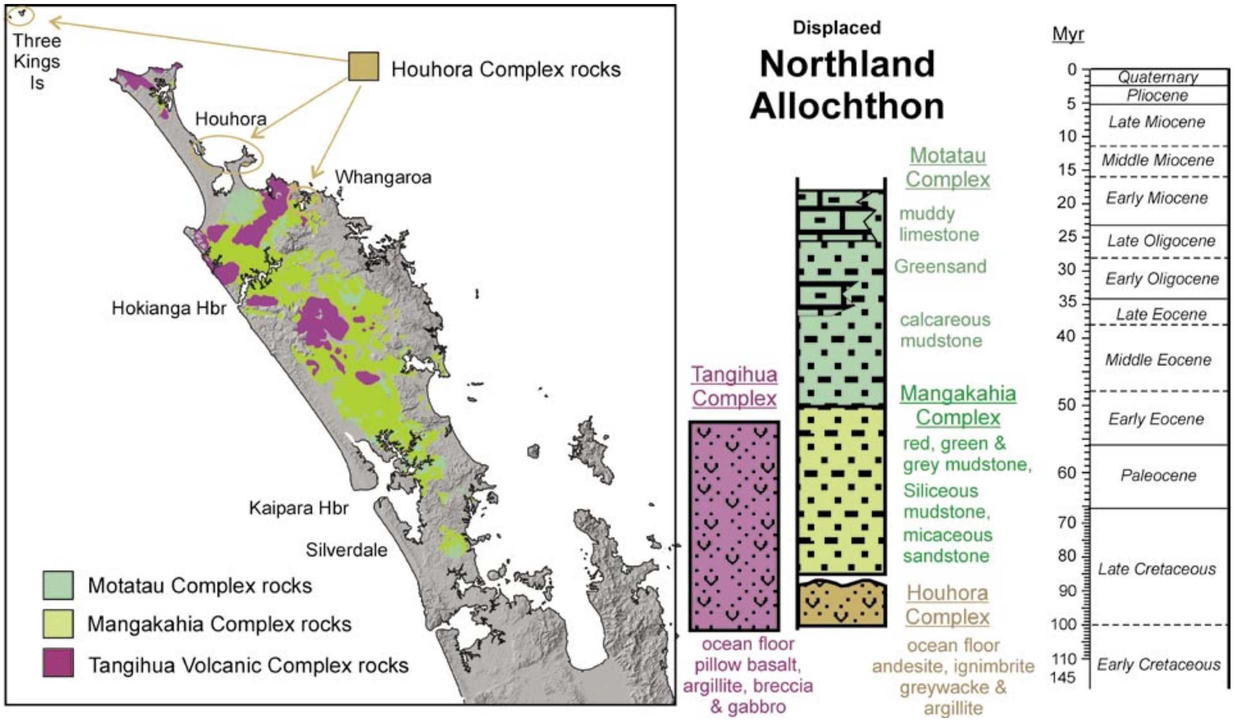
Chapter 4. NORTHLAND'S DISPLACED ROCKS (100-22 Myr old)

Chapter Summary

Many of the rocks of Northland and northern Auckland have puzzled geologists since they were first studied in the 1860s. The rock strata are in no consistent layered sequence and often are mixed and sheared together (once called Onerahi Chaos-Breccia). It was not until the 1970s that geologists began to agree on what had happened. We now know that these problematic rocks accumulated on the floor of the deep ocean northeast of present-day Northland. They consist of rocks that erupted on the floor of submarine rift basins, 100-55 Myr ago (Houhora and Tangihua complexes), plus sand, mud and calcareous ooze that accumulated offshore from ancient Northland 80-23 Myr ago (Mangakahia and Motatau complexes).

About 25 Myr ago northern New Zealand was located west of the collision boundary between tectonic plates, where the Pacific Plate was sliding down under the edge of the Australian Plate. The collision forces between the plates caused deep-sea rocks close to the boundary to be progressively uplifted out of the sea. At the same time, ancestral Northland and the region further west subsided and was flooded by the sea to depths of several thousand metres. Over a few million years, huge slabs of rocks (0.5-2 km thick and up to 100s of square kilometres in area) slid southwestwards off the rising area in the northeast and onto Northland, creating a huge mass of displaced rocks that we now call the Northland Allochthon. The upper (younger) rock layers slid off first, followed later by successively older rocks as they were pushed up, and lastly by the ocean-floor basalt flows that had accumulated further to the northeast. This is why we now commonly find Tangihua lava flow slabs on the top of the sequence forming many of the higher rugged mountain areas, such as the Mangamuka, Herekino, Warawara, Mangakahia and Tangihua Ranges. As the displaced slabs moved further onto Northland and southwards towards Auckland (as far as Silverdale), many broke up into smaller blocks and more mixed, sheared and chaotic layers developed between the cohesive blocks of harder rocks.

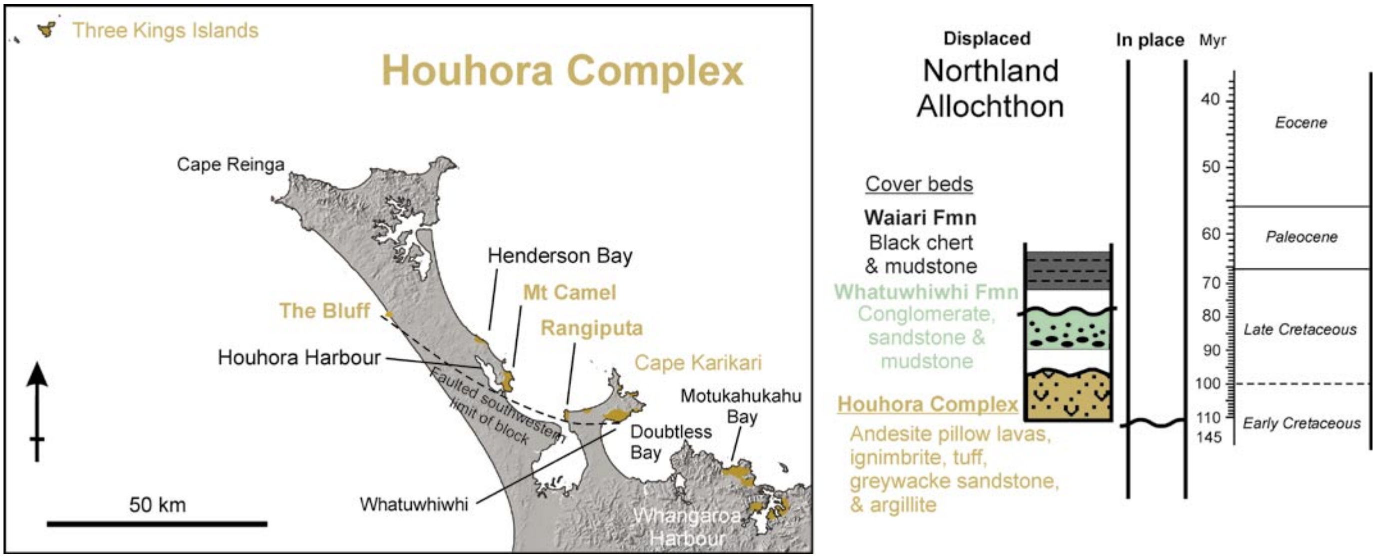
The displaced rocks include muddy limestone, which is quarried on farms in many parts of Northland and is also the main raw material for New Zealand's only cement works, near Whangarei. Spherical concretions that grew within 70 Myr-old sandstones are the largest (up to 6 m diameter) in New Zealand, much bigger than their better known Moeraki Boulder cousins. Among the more spectacular fossils found in these displaced rocks are extinct ammonites, ichthyosaur and mosasaur bones, and New Zealand's largest-ever fossil bivalve (mussel) shell (1.2 m long).



4.1 Stratigraphic column and distribution of the rocks (complexes) in the Northland Allochthon.

Northland's displaced rocks underlie much of central and western Northland and extend from North Cape southwards almost to Auckland City. Trying to understand these rocks was a real headache for early European geologists. It was not until the 1960s-70s that it became clear that they were all jumbled up and had come out of the ocean to the northeast of Northland and slid onto Northland around 25-19 Myr ago. These displaced rocks are now known collectively as the Northland Allochthon, derived from the Greek "allo" meaning other and "chthon" meaning earth. In geology, an allochthon is a mass of rock that has moved tens to hundreds of kilometres from where it was formed.

EARLY CRETACEOUS VOLCANIC AND SEDIMENTARY ROCKS IN THE NORTH (Houhora Complex and its cover beds)



4.2 Stratigraphic column and distribution of Houhora Complex and its cover rocks in northern Northland..

Houhora Complex consists of a mix of altered submarine volcanic rocks of basaltic andesite and rhyolite composition and sediment. Most of the basaltic andesite was extruded onto the seafloor as pillow lava flows (*4.3*), whereas the rhyolite was erupted explosively and deposited as ash, pumice ash and ignimbrite. These volcanic rocks have been altered by percolating hot water (hydrothermal alteration) to spilite and keratophyre, resulting in a mix of green, rusty and grey-coloured rocks. The chemistry of the volcanic rocks indicates that they were erupted in a rift basin, probably on the submarine edge of thinned continental Gondwana crust. This followed close on the heels of the switch in tectonic conditions from plate convergence to extension that occurred about 110 Myr ago (towards the end of the Early Cretaceous).

Associated with these volcanic rocks are indurated, weakly-metamorphosed (prehnite-pumpellyite zone) greywackes (*4.4*), sometimes consisting of thick sandstone beds, sometimes of thinner alternations of sandstone and mudstone (argillite) beds and in a few places, pebble conglomerate. These sediments were eroded from coastal Gondwana and transported as slurries of sand and gravel down submarine canyons into deep water, in the growing rift valley not far offshore. Rare fossil bivalves and radiometric dates indicate that these rocks were erupted and deposited around 105-100 Myr ago.

Houhora Complex rocks form the Three Kings Islands, northwest of Cape Reinga (*4.5*), and a number of hilly blocks between Mt Camel, Houhora and Cape Karikari. These hilly blocks were all individual islands during times of higher sea level, about 3 Myr ago, and appear to be parts of one large eroded block that is about 500 m thick and has an arcuate south-western faulted margin. Geologists are unsure whether these rocks are still located where they were added on to the basement rocks of Northland in the Late Cretaceous (and therefore referred to as Houhora Terrane), or have been displaced as thrust blocks from the northeast as part of the Northland Allochthon (and therefore known as Houhora

4.3 Above. 100 Myr-old basaltic andesite pillow lava flow of the Houhora Complex in the low cliffs on the north side of the entrance to Houhora Harbour.

4.4 Left. Thin-bedded argillite (lower half) and pillow lava (upper half) of the Tokerau Formation, Houhora Complex. 100 Myr old, Whatuwhiwhi.

4.5 Right. Archway Island in the Princes Group, Three Kings Islands, is composed of indurated basaltic andesite and ignimbrite rocks (Houhora Complex) that were erupted on the ocean floor about 100 Myr ago (Cretaceous).

4.6 The rocks in the foreground and middle of Motukahakaha Bay, north of Whangaroa, are made of an allochthonous block of Houhora Complex. The distant hills are made of a slab of allochthonous Tangihua Complex rocks that has been thrust over the top of those in the bay.

Complex). The most likely explanation is that they were indeed the youngest terrane sutured onto the coast of Gondwana, but Houhora rocks that now form parts of northern Northland were moved there by the Northland Allochthon (see later). One reason for this belief is that a block of similar, indurated and deformed Early Cretaceous sedimentary rocks (called Tupou Complex, *4.6*) has been shown by mapping to be one of the lower displaced (allochthonous) rock slabs around Whangaroa Harbour, 20-30 km southeast of Cape Karikari. These rocks have two radiometric dates of ~108 Myr old.

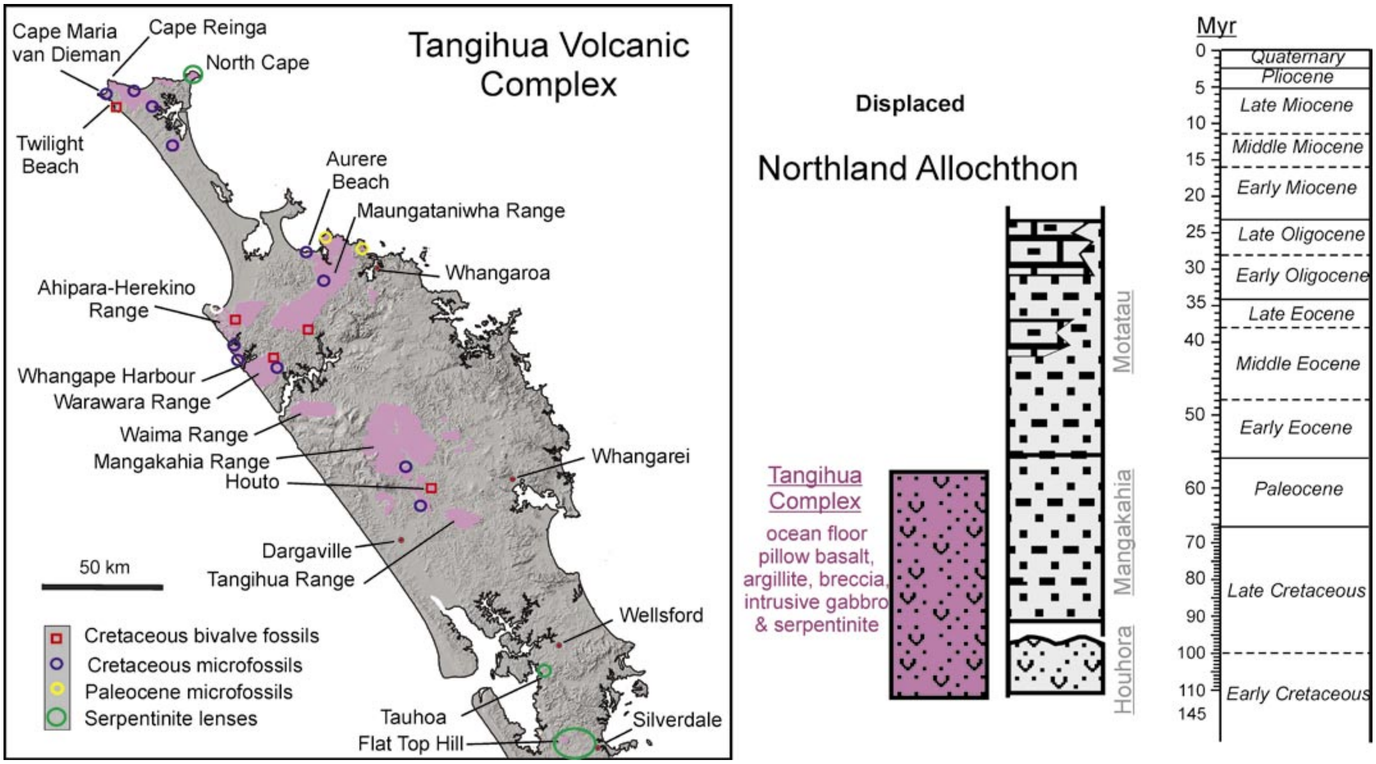
An upwards fining sequence of boulder breccia, pebble conglomerate, sandstone and mudstone (Whatuwhiwhi Formation) unconformably overlies the Houhora Complex rocks along the southern coast of Cape Karikari and a similar, thinner sequence of conglomerate and sandstone also sits unconformably on the allochthonous block at Whangaroa. Fossils indicate a Late Cretaceous age (85-66 Myr old) for the sequence at Whangaroa. These cover beds suggest that during the Late Cretaceous, the seafloor depth increased and/or elevation of the land source decreased as Zealandia broke away from Gondwana.

The youngest cover rocks in the Cape Karikari block are dark grey to black, organic-rich chert and siliceous mudstone (Waiari Formation) of latest Cretaceous or Paleocene age (70-55 Myr old). These were deposited in even deeper water, probably at abyssal depths of 4000 m or more, as siliceous ooze (mostly composed of tiny radiolarian skeletons). They are probably correlative with the Waipawa Black Shale from the east coast of the North Island, which is organic-rich and a possible source for hydrocarbons.

Houhora Complex and their cover beds are highly faulted and folded. Detailed mapping of them around the coast of Mt Camel by structural geologists Bernhard Spörli and Virginia Toy of Auckland University, enabled them to recognise many phases of deformation, including late stage westward followed by southward overthrusting, which they infer occurred during Northland Allochthon emplacement onto northern Northland.

4.7 Early Cretaceous (100 Myr old) broken formation of thinly-interbedded, sheared argillite and greywacke sandstone of the Houhora Complex at Henderson Bay, near Houhora in the Far North. Photo 1.2 m across.

CRETACEOUS-PALEOCENE SUBMARINE IGNEOUS ROCKS (Tangihua Complex)



4.8 Stratigraphic column and distribution of Tangihua Complex rocks in northern New Zealand, showing locations where age-diagnostic fossils have been found.

Tangihua Complex rocks occur in northern and central Northland as many discrete, apparently-displaced blocks or slabs ranging in size from a few square metres up to 500 km^2 (*4.8*). Tangihua rocks are believed to be a slice of oceanic plate comprising thin oceanic crust and a small sample from the top of the mantle - together referred to as ophiolite (Box 10). Here the ophiolite assemblage is predominantly basalt pillow lava flows, non-pillowed flows and associated breccia. Also present are packets of thin-bedded red, green, purple and grey siliceous argillite, and less commonly pink, fine-grained limestone, found between pillow lava lobes, such as at Aurere Beach, Doubtless Bay (*4.15*). The above rocks comprise the upper part of the oceanic crust and were formed on the deep ocean floor.

Present in some blocks are massive or layered bodies of more crystalline plutonic rock such as gabbro or diorite, which are considered to be cooled shallow magma chambers that formed the lower part of the oceanic crust. A slice of green serpentinite occurs within the North Cape block of Tangihuas and is inferred to be hydrothermally-altered peridotite from the top of the mantle. Above this slice at North Cape is a unit of close-spaced basalt and gabbro dikes (vertical sheets of lava) intruding more massive gabbro and overlain by basalt pillow lava of the overlying oceanic crust. This is the most complete section through the Tangihua ophiolite in Northland. The North Cape serpentinite was quarried for many years to supply magnesium for aerial topdressing of

4.9 This glassy basalt breccia (hyaloclastite) was formed when molten lava flowed out into cold sea water, cooling instantaneously to black glass and breaking up into many pieces. Tangihua Complex, Whangape Harbour, Northland.

4.10 At the northern tip of Northland, Cape Maria van Diemen (beyond Te Werahi Beach), Motuopao Island (right distance) and Cape Reinga (foreground) are all formed from eroded allochthonous Tangihua Complex.

4.11 These thin beds of red and green argillite (here tilted to the left) underlie Tangihua basalt pillow lavas at the south end of Twilight Beach, Far North.

4.12 Iconic Houto hill, between Whangarei and Dargaville, is formed of the oldest-known Tangihua rocks (Early Cretaceous, 115-100 Myr old).

farmland. Small lenses of iron, copper and zinc sulphide ore (pyrite, chalcopyrite, sphalerite) within several of the Tangihua blocks (Box 5) were probably formed around black-smoker vents of hot water and gas on the ocean floor, associated with buried molten magma.

The age of the Tangihua rocks has been the subject of considerable debate between research teams led by overseas-based geochemists Kirsten Nicholson and Scott Whattam. Various radiometric dating techniques give a wide range of eruption ages from Cretaceous through to Oligocene (100-25 Myr old). Such a wide spread of ages seems unlikely. Some geochemists have argued that all the younger ages represent geothermal metamorphic events that have reset the radiometric clocks in these rocks, and probably date major changes in their tectonic setting, such as their uplift and emplacement onto Northland in the allochthon, towards the end of the Oligocene (25 Myr ago). The most reliable indicator of the age of these basalt lava flows comes from fossils in the associated seafloor sedimentary rocks (*4.8*). Rare whole and broken bivalve shells of the Cretaceous genus *Inoceramus* occur in a number of the Tangihua blocks, as do deep-water oceanic faunas of microfossil foraminifera and radiolarian, which are also mainly Late Cretaceous in age. The youngest known fossils are Paleocene radiolaria (60 Myr old) from a Tangihua block north of Whangaroa. The oldest known fossil is an Early Cretaceous bivalve fossil (120-100 Myr old) in sediment associated with a block of Tangihua rocks at Houto (*4.12*), between Whangarei and Dargaville. Thus I conclude from fossil evidence and some of the radiometric dates, that Tangihua Complex rocks erupted on the ocean floor during the Cretaceous to Paleocene (120-55 Myr ago), but mostly during the Late Cretaceous (100-66 Myr ago).

The chemistry of the Tangihua basalt and gabbro is quite varied. Many samples have the characteristic geochemical composition of lavas erupted from back-arc basin rifts (*4.67*), with variable amounts of contamination from melted continental crust, or from heated oceanic sediment and fluids from a subduction zone. From this it is inferred that the Tangihua Complex ophiolite assemblage is predominantly oceanic crust

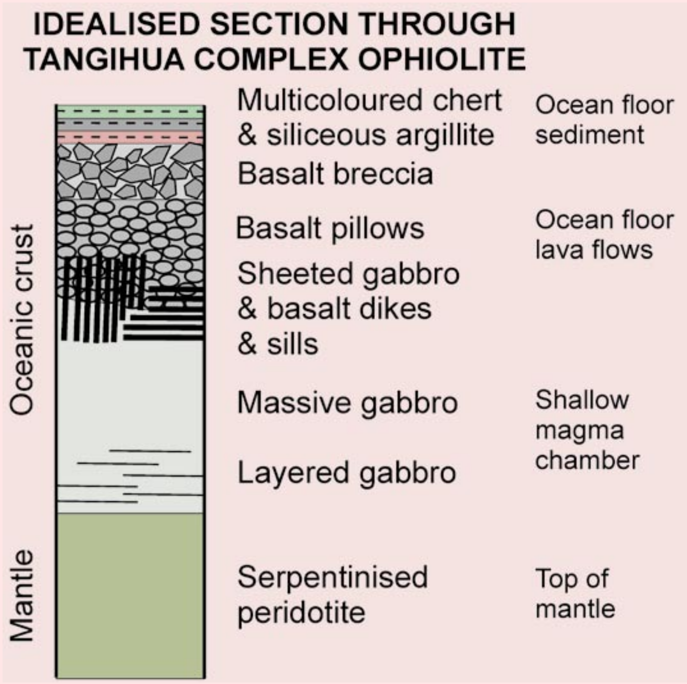
Box 10. OPHIOLITE SEQUENCE AND PILLOW LAVA

The rocks that comprise the Tangihua Complex blocks in Northland are known globally as ophiolites. These are considered to be slices of oceanic crust and upper mantle that been uplifted and exposed on land and often thrust up and onto the edge of continental crust (obduction) during collisional events driven by plate motion. These remnants of the past are important in understanding the Earth's processes because modern ocean plate processes are difficult to study due to their depth beneath the ocean and the ocean floor itself. Exposures of oceanic crust rock sequences are not common on land because they are usually carried down subduction zones and lost.

Typical ophiolites comprise a section through oceanic plate that includes some of the upper mantle peridotite (often altered to serpentinite) and the overlying oceanic crust and its thin covering of oceanic sediment (*4.13*). The igneous oceanic crust generally comprises three zones: a lower zone of massive to layered gabbro - a plutonic rock that cooled within a shallow magma chamber beneath the erupted seafloor lava flows and hence has had time to grow crystals that can be seen without a microscope; an upper zone of ocean-floor basalt lava flows, mostly erupted as pillow lavas (see below); and a middle zone of both gabbro and pillow lavas that has been intruded by numerous, often closely-spaced sheets of lava that have cooled quickly to fine-grained basalt, or cooled more slowly to more coarsely-crystalline gabbro. These sheets are usually either vertically-intruded parallel dikes, or horizontally-intruded sills.

The sediment cover that may occur between and over the ocean-floor pillow lavas is usually siliceous mudstone or chert (derived from the skeletons of planktonic radiolaria). If the sea floor was above the depth at which calcite dissolves (calcium carbonate compensation depth, CCD) the sediment was probably fine-grained calcareous ooze or limestone (derived from the skeletons of planktonic foraminifera and nannofossils).

Most of the gabbros and basalts in the obducted ophiolites on land, including the Tangihua Complex, are geochemically slightly different from those sampled today from mid-ocean spreading ridges and "hot-spot" seamount volcanoes like the Hawaiian Islands. Their silica (SiO_2), titanium (TiO_2) and some of their trace element compositions are more similar to those found in volcanic rocks erupted above a subduction zone (volcanic arc), although they still have a strong signature of oceanic crust. Recent research suggests that most ophiolites were formed during the initial stages of subduction, where the edge of the overlying continental crust is stretched and thinned, sometimes by rift formation of a back-arc basin. This allows new oceanic crust to form by eruption of lavas on the deep-sea floor and the injection of a shallow magma chamber beneath, in much the same manner as occurs at mid-ocean spreading ridges.



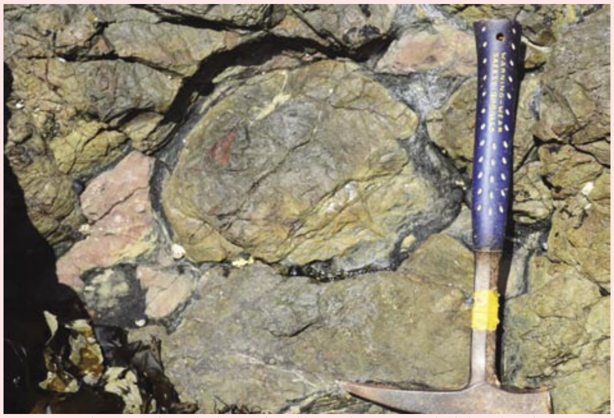
4.13 Diagram illustrating the usual vertical sequence of rock types seen in sections of oceanic plate (ophiolite) that have been pushed up and onto continental crust, like the Tangihua Complex in Northland.

Pillow lava (*4.14-4.16*) only forms when basaltic or andesitic lava is erupted into water, usually on the seafloor. The resulting flows consist of numerous, elongate, interconnecting fingers, each elliptical to circular in cross-section and 0.2-3 m in diameter that may cover the seafloor as an extensive sheet, or grow into a steep-sided heap of overlapping lobes. They are known as pillow lava because when ancient examples have been pushed up out

4.14 Cut-away diagram showing how pillow lava was formed by fingers of lava squeezing out onto the seafloor and building up a heap of overlapping lobes. When eroded through and seen in a vertical cliff section the lobes look like a pile of pillows.

Box 10 continued

4.15 Basalt pillow lavas of the Tangihua Complex, south end Twilight Beach.



4.16 Subcircular lobe of pillow lava with black glassy surrounding selvedge. Pink marble sediment fills the gaps between individual pillow lobes. East end of Aurere Beach, Doubtless Bay.

of the sea and exposed in cliffs, they appear to be composed of a pile of discrete pillow-like forms. Pillow lava lobes have a distinctive structure when seen in an eroded cross-section. Each has a thin, black, glassy outer skin (selvedge) formed by rapid chilling of the surface of the molten lava when it encountered cold sea water. This skin confined the lava to narrow lobes as it flowed along, sometimes breaking through the skin and "budding off" another lobe. Inside the glassy skin, the lava slowly cooled and contracted as it solidified forming a characteristic radial pattern of joints or fractures.

that erupted through stretched continental crust above a young subduction zone in a back-arc rift basin. This rift basin (called the South Loyalty Basin) started opening up parallel to the stretched eastern edge of the Zealandian continental crust above the subducting western edge of the Pacific Plate. Tangihua ophiolite is believed to have erupted to form the deep ocean floor of this rifting back-arc basin to the north of Northland at the same time as the Tasman Sea was opening.

Tangihua rocks have been hydrothermally metamorphosed by circulating hot sea water. This low temperature (200-300°C) alteration changed the composition of many of the minerals within the rock, as well as forming numerous irregular thin veins of zeolite, calcite and green chlorite, and sometimes epidote. The greenish alteration colour of many of the rocks and the presence of thin veins makes it relatively easy to distinguish Tangihua rocks from fresher Miocene basalt and andesite dikes that intrude some of them. Detailed study and dating of this metamorphism by Kirsten Nicholson and Philippa Black indicates that most alteration occurred in two phases, both post-dating their eruption. The first alteration, around 50 Myr ago, is inferred to date the cessation of rifting, and perhaps an early phase of uplift and thrusting onto continental crust, way to the north of North Cape. The second period is dated at around 30 Myr ago and probably coincided with initiation of the main phase of thrusting and sliding of the Tangihua rocks onto Northland.

Tangihua Complex blocks form most of the higher mountain ranges and hills in central and western Northland. Almost all appear to be the last rocks to have been thrust onto Northland as part of the Northland Allochthon. Because these rocks are harder and therefore more resistant to erosion than the more voluminous sedimentary rocks of the allochthon, they remain as the highest peaks in Northland today (e.g. Maungataniwha and Tangihua ranges, *4.17*). The incoming sheet of Tangihua rocks presumably broke up into a number of large slabs as it was emplaced. Today's ranges are their partly eroded remnants. Some of the thicker blocks (500-2000 m thick) appear to be a composite of several overthrust slices separated by thrust planes and broken formation. A few small blocks of altered basalt or gabbro occur within the broken-up mélange zones at the base of the Northland Allochthon in northern Northland. These indicate that some Tangihua Complex blocks were emplaced during the first phase of the Allochthon.

The southernmost occurrence of Tangihuas is a small block (less than 1 km across) at Flat Top Hill, 12 km west of Orewa. This block provided hard aggregate for Rodney District for many decades and will soon be

4.17 Most of the Tangihua Complex slabs in the Northland Allochthon form the higher ranges of central and west Northland. Tangihua Range, southwest of Whangarei is the type locality for these volcanic rocks that were erupted onto the deep ocean floor.

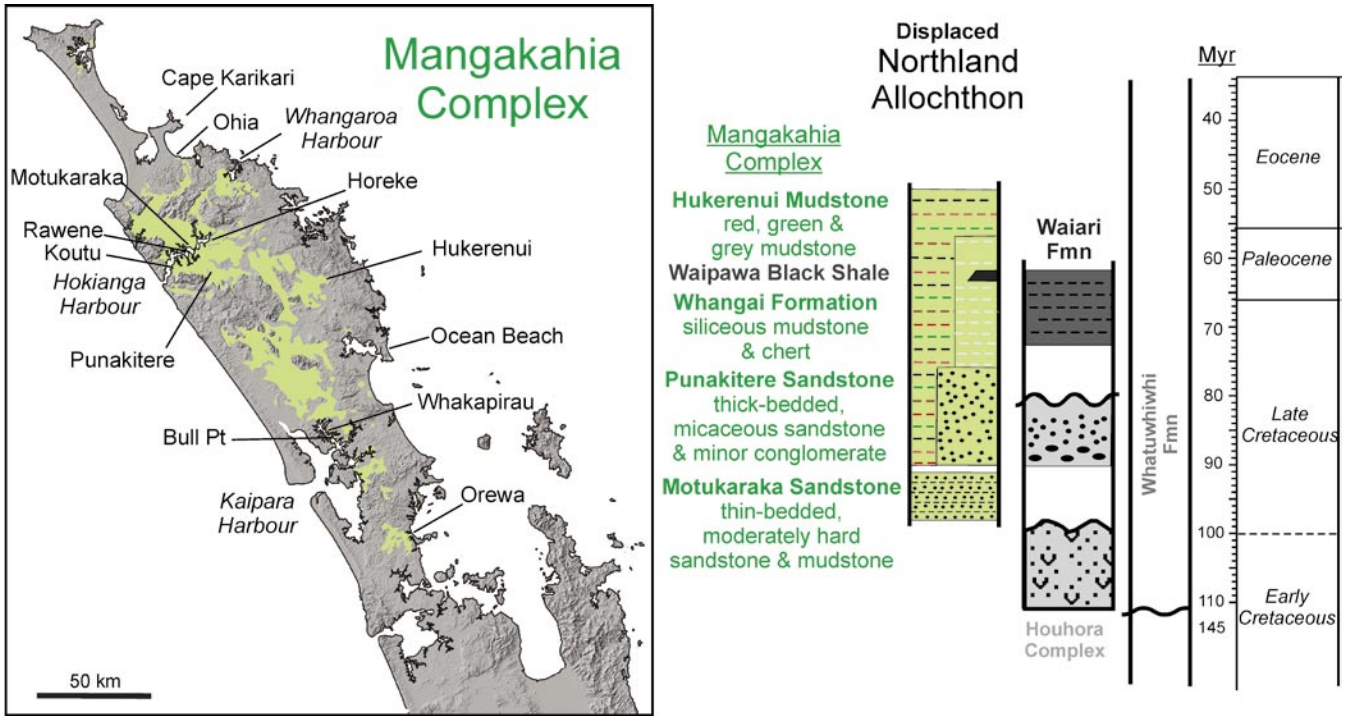
4.18 Left. Badlands erosion of red and orange iron-rich clay, derived by deep subtropical weathering of Tangihua rocks, inland from Twilight Beach in the Far North. Width of photo 25 m.

largely quarried away. As a result, boulders of altered Tangihua Complex can be seen in retaining walls and other projects all around this part of the region. Also within this southern toe of the Northland Allochthon, between Silverdale and Wellsford, there are many small lenses (mostly less than 100 m across) of sheared serpentinite (*4.19*), some of which were quarried out during the 1940s for fertiliser. They are most probably hydrothermally altered peridotite sourced from the top of the mantle and transported in with the Allochthon, just like the serpentinite at North Cape, although in earlier times some geologists contended that they were diapirs (flowing intrusions) of Dun Mt Ophiolite that had pushed up from below about 20 Myr ago.

4.19 A hard boulder of serpentinite from a small lens within Northland Allochthon near Tauhoa, west of Wellsford.

CRETACEOUS-PALEOCENE DEEP-SEA SEDIMENTARY ROCKS

(Mangakahia Complex)



4.20 Stratigraphic column and distribution of Mangakahia Complex and related rocks in northern New Zealand.

The most abundant and widespread rocks within the Northland Allochthon are sediments of the Mangakahia Complex that were deposited in the deep sea off the east coast of Zealandia between 100 and 50 Myr ago during the Late Cretaceous to Early Eocene periods. They consist of a wide range of deep-sea sediment types mostly containing terrigeneous sand and mud derived by erosion from the adjacent continental edge of Zealandia, just before, during and just after it was splitting away from the supercontinent of Gondwana. Many of these sedimentary rocks are siliceous, lack calcite and contain abyssal (deeper than 2000 m) microfossils that suggest they accumulated below the CCD – the depth in the ocean below which all calcite dissolves. Some of the rocks, however, are calcareous and these presumably accumulated higher on the submarine slopes of Zealandia.

4.21 Thick beds of quartz-rich, Late Cretaceous (90-66 Myr old) Punakitere Sandstone, tilted steeply to the right at Koutu, Hokianga Harbour. The sand was transported down the submarine slopes off the coast of Gondwana in dense slurries (turbidity currents).

The rock types in Mangakahia Complex are dominated by micaceous sandstone, siliceous siltstone and multi-coloured mudstone.

Punakitere Sandstone

The oldest of the more common rock types is the quartz-rich, often thick-bedded sandstone called Punakitere Sandstone, which was deposited in the Late Cretaceous (about 90-75 Myr ago) and contains numerous crystalline flakes of the mica minerals muscovite (colourless) and biotite (black). These mica flakes glint in the sun when the rock is broken open and their presence is an easy way to distinguish this sandstone from other sandstones in northern New Zealand. The mica was likely sourced by erosion from Houhora Complex rocks that were eroding on the eastern edge of nearby Zealandia at this time or

Box 11. SPHERICAL CONCRETIONS

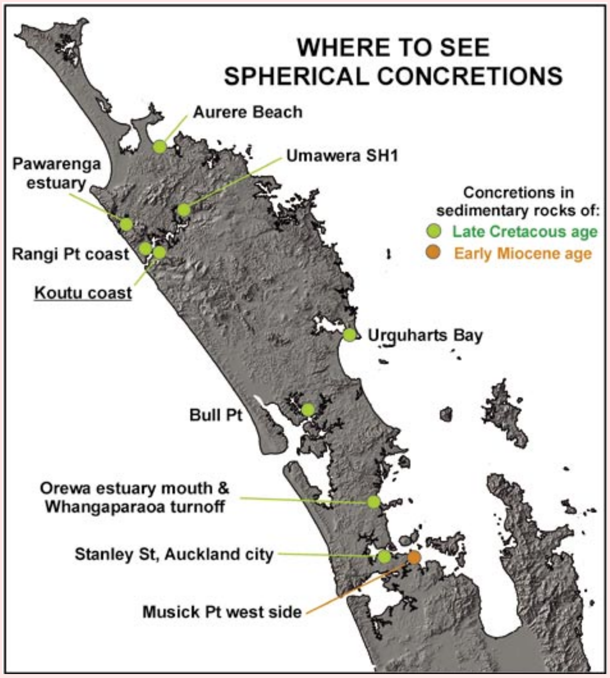
4.22 The largest spherical concretions (4-6 m-diameter) in New Zealand sit with many others on the shores of Hokianga Harbour at Koutu (south side) and Rangi Pt (north side; above). They have eroded out of the Cretaceous sandstone (Punakitere Sandstone) banks at the back of the beaches.

Natural occurrences of spherical boulders and cobbles have attracted attention since earliest human colonisation of New Zealand and today are tourist attractions in several parts of the country, including Northland. Spherical boulders lying loose on a beach, or occasionally on a hillside, have triggered a number of colourful stories to explain their origins - from the Maori traditional stories of the origins of Moeraki Boulders in Otago to the more recent interpretations, such as the unhatched eggs of dinosaurs, or their placement by extra-terrestrial aliens. Geologists know them as concretions that have grown within thick beds of sandstone or mudstone and subsequently have been eroded out by removal of the softer enclosing host rock.

Concretions are hard, cemented, spherical or ovoid bodies of rock that range in size from a pea to 2 m or more across. The cementing mineral is often calcite (calcium carbonate), but sometimes may be quartz (silicon oxide), siderite (iron carbonate) or pyrite (iron sulphide). These concretions grow within layers of sediment some time after they have been buried by additional sediment. In favourable conditions, dissolved minerals in percolating ground water start to crystallise, often around a small pebble, plant fragment or shell, progressively growing outwards over thousands or even millions of years to form the hardened concretion. The crystals grow in the small voids between the grains, cementing them together. If the minerals crystallise at the same rate in all directions, then a spherical concretion forms, otherwise they develop flatter or more elongate shapes. Sometimes the minerals grow around elongate or branching burrows and thus form rounded cylindrical concretions.

Conditions within sedimentary rocks can change over time and the material inside a concretion may begin to dehydrate and contract. As a result radiating shrinkage cracks form, which later are filled by further cementing crystals of a different composition. Thus these concretions developed a regular network pattern of veins through them that has led to them being called "turtle backs", because of their superficial resemblance to turtle shells.

Concretions we see at the surface today have eroded out of the softer surrounding sedimentary rocks in which they were formed. Being made of hard, erosion-resistant minerals, the concretions often end up in dense concentrations of loose boulders on beaches or in stream beds. Most of the larger spherical concretions seen in Northland and Auckland come from Cretaceous micaceous sandstone (Punakitere Sandstone) that is part of the displaced Northland Allochthon rocks. These concretions can be seen alongside the road and in streams and



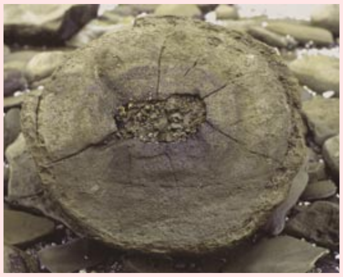
4.23 Ovate, elongate and irregular concretions occur in many places in the sedimentary rocks of Northland and Auckland. Larger, spherical concretions are less common and mainly occur in Late Cretaceous Punakitere Sandstone and Early Miocene Waitemata Sandstone.

4.24 A cluster of concretions lie on the muddy shore of Bull Pt on the Matakohe Arm of the Kaipara Harbour. They have eroded out of the Cretaceous Mangakahia Complex rocks in the hillside behind.

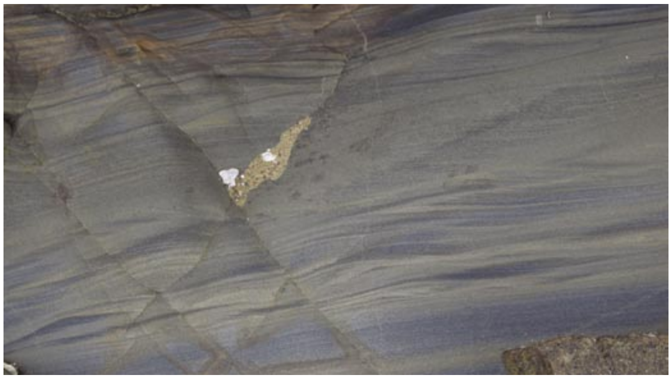
Box 11 continued

paddocks in a number of places in central Northland, with the largest examples along the Hokianga Harbour foreshore at Koutu. The southernmost examples were excavated many years ago by road works at the Whangaparaoa Rd turnoff from Hibiscus Coast Highway, between Silverdale and Orewa. Several still sit in the gardens overlooking the intersection, while others now adorn the traffic island adjacent to Stanley Street tennis courts in the central Auckland city.

4.25 This 30 cm-diameter "cannon-ball" concretion has broken in half, exposing a 5 cm lump of mudstone in the centre, which the concretion started growing around. Musick Pt, Auckland.



Smaller concretions, some spherical, but many of other elongate and irregular rounded shapes, commonly occur in the sandstone cliffs around Auckland (*13.30*). These formed within the layers of sandstone and siltstone (Waitemata Sandstones) that were laid down on the floor of the sea about 20 Myr ago (Early Miocene, see later).



4.26 Punakitere Sandstone close-up with laminations and ripple-drift cross-bedding typical of the upper part of a sandstone deposited from a turbidity current (Box 18). Koutu, Hokianga Harbour. Photo 50 cm across.

from granites slightly further west. Specks of black carbonaceous plant material are also commonly present in these sandstone beds and attest to their erosional source on land.

This sand was carried down rivers to the coast and then in episodic sediment slurries (turbidity currents) down submarine canyons to the floor of the ocean, perhaps 20-100 km offshore. The resulting beds are often 1-2 m thick, but thinner bedded units are also sometimes seen. Between the sandstone beds there is often thin mudstone that was deposited very slowly on the ocean floor between the incoming of each turbidity current.

As these sandstone beds were buried beneath the seafloor, they became transformed into moderately hard Punakitere Sandstone, which was more resistant to deformation and shearing than the softer, finer-grained sedimentary units in the Allochthon. It is also more resistant to erosion and sometimes forms rounded hills and ridges in the rolling Northland countryside. Partly weathered exposures of these friable sandstones often have a yellow-brown colour.

Large slabs of Punakitere Sandstone occur scattered throughout Northland and down into northern Auckland as far as Silverdale. They are generally larger (up to 10 km across and up to 1 km thick) and less deformed internally in northern Northland, and more broken-up and smaller further south. The presence of this sandstone is often signalled by the occurrence of clusters of large spherical concretions (Box 11) at the surface, in stream beds, or along the coast. When all the rest of the sandstone has weathered and eroded away, these hard, cemented concretions often still remain.

Beds of conglomerate with well-rounded cobbles and pebbles are locally present within the Punakitere Sandstone and consist of rock-types eroded from the underlying Houhora Complex and the eastern edge of Zealandia. As with most rock types in the Allochthon, the original relationship of Punakitere Sandstone with other units is seldom seen because the sequence has

4.27 A 1 m-diameter concretion sits where it grew inside its grey host rock, Punakitere Sandstone. The concretion retains some of the original laminations (dipping to the right) that mark the seafloor surface as the host sand was accumulating in the Late Cretaceous. Orewa Estuary, Auckland.

broken up into many displaced blocks. At Whangaroa and Cape Karikari, however, the basal beds of Punakitere Sandstone (known locally as Whatuwhiwhi Formation) are conglomerate-dominated and sit unconformably on Early Cretaceous Houhora Complex. These beds record significant subsidence off the coast of Zealandia that was followed by the deposition of the turbidty current sand beds.

Occasionally present in Punakitere Sandstone, and seen around the fresher coastal exposures of the Hokianga and Kaipara harbours, are fossil bivalves, ammonites and other skeletal remains. Some were the nuclei around which spherical concretions grew.

Whangai Formation

Another of the more common rock groups in the Northland Allochthon is the Whangai Formation which consists of fine-grained, silica-rich sedimentary rocks

Box 12. GIANT FOSSIL MUSSELS

Large fossil mussels of the family Inoceramidae are occasionally found in Cretaceous-age sedimentary rocks (110-84 Myr old) in the Northland Allochthon. Often they occur as broken up shell, recognised by its 0.5-1 cm-thick prismatic structure in cross-section (*4.29*). Broken shells of inoceramids are the most common macrofossil found in Tangihua Volcanic Complex sedimentary rocks. These mussels evolved rapidly into a number of different species that are recognised by their slightly different shapes and particularly by differences in the ribbed ornament on the outside of their two shells (*4.30*). Examples of a number of different species have been found in blocks of Late Cretaceous sedimentary rocks in the Northland Allochthon. Many of these fossil bivalves are 10-15 cm long, but the most spectacular specimen found in New Zealand was a giant 1.2 m-long *Magadiceramus rangatira* exposed in rocks on the intertidal shore of the Kaipara Harbour in the 1970s (*4.28*). This species was in existence for only a short time near the beginning of the Late Cretaceous period (95-94 Myr ago).

Inoceramids were bivalve molluscs (shellfish) with two shells hinged together around the apex. They are an extinct family, related to the modern mussels, which lived on the seafloor at shelf and bathyal depths and fed by straining plankton from the sea water. Like the dinosaurs, marine reptiles, ammonites and belemnites, the inoceramids also died out at the end of the Cretaceous period, during a major extinction event when about three-quarters of all animals and plants on Earth at the time became extinct.

4.28 This huge 1.2 m-long fossil mussel (Magadiceramus rangatira*, 95 Myr old*) *was found in Cretaceous Punakitere Sandstone on the foreshore of the Kaipara Harbour in the 1970s. The specimen was too large and fragmented to remove so a plaster mould of it was made by a University of Auckland team led by palaeontologist Graham Gibson. It is one of the largest bivalve molluscs ever found and larger than the largest living bivalves – the tropical giant clams.*

4.29 This 15 cm piece of rock consists of the thick broken-up fragments of inoceramid mussel shells. It has eroded out of Cretaceous Mangakahia Complex sedimentary rock on the Kaipara Harbour coast near Whakapirau.

4.30 40 cm-wide, slightly broken fossil specimen of an extinct inoceramid bivalve (Cremnoceramus bicorrugatus) *found in a stream bed near Horeke, inland Hokianga. This species was in existence for only a short time and dates the rocks it was preserved in as 94-90 Myr old.*

Box 13. AMMONITES - EXTINCT SHELLED SQUID

4.31 *A live ammonite. Drawing by Margaret Morley.*

When dinosaurs were living on land, the oceans were swarming with ancient kinds of squid, including now extinct, shell-bearing forms known as ammonites and others with a hard bullet-shaped internal skeleton called belemnites. Belemnite fossils are extremely rare in northern New Zealand. In contrast, several hundred fossilised ammonite shells have been found over the years, particularly around the shores of the Kaipara and Whangaroa harbours. Although ammonites lived throughout the Mesozoic Era, those found in Northland are only present in Late Cretaceous rocks (85-66 Myr old), mostly from the Punakitere Sandstone of the Northland Allochthon.

Ammonites belong to the group of Mollusca called Cephalopoda, which includes modern octopus, squid and cuttlefish. All had a ring of arms or tentacles around the mouth and a funnel through which water was squirted to help propel them backwards through the water, just like a jet boat. They had good eyesight and caught their prey with their long tentacles that were dotted with rows of suckers. The closest living relative to the extinct ammonites is the Pearly Nautilus that lives in the tropical west Pacific today. Like the Nautilus, most ammonites are thought to have lived a mobile lifestyle, propelling themselves around at varying depths in the sea.

Nautilus shells are smooth on the outside, whereas most ammonite shells have numerous ribs (*4.31-4.33*). Both have shells (usually planispirally coiled) that are internally divided into many chambers. In ammonites the walls between these chambers are always intricately folded and frilled towards the margin, whereas in Nautilus the walls are smoothly curved. The actual animal lived in the large body chamber at the open end of the shell with its head and tentacles poking out. All the smaller chambers further inside the shell were filled with variable amounts of gas and fluid that could be adjusted by the animal to regulate the shell's buoyancy and enable it to sink or rise through the water like a submarine.

Towards the end of their reign, in the Late Cretaceous period, the ammonites evolved shells with many different shapes, including some straight and some partly-coiled. Ammonites, along with many other creatures, shared the same fate as the dinosaurs, becoming extinct at the end of the Mesozoic Era, about 66 Myr ago – the result of a large asteroid crashing into the Gulf of Mexico.

4.32 Left. 11 cm-diameter Late Cretaceous ammonite (Kitchinites angustus) *from Te Opu, Kaipara Harbour. University of Auckland collection.*

4.33 Centre. 15 cm-diameter ammonite inside a Late Cretaceous concretion from the shore of the Kaipara Harbour. Collection of Les Smith.

4.34 Right. Two straight Late Cretaceous ammonites (Baculites rectus) *from Matakohe Arm of the Kaipara Harbour. Largest specimen 11 cm. University of Auckland collection.*

that were deposited in deep water at abyssal depths (2000-5000 m) during the Late Cretaceous and Paleocene (about 80-56 Myr ago). The dominant, fine-grained sedimentary rock type of the Whangai Formation in northern New Zealand is grey-coloured siliceous mudstone that often weathers to a characteristic cream or white colour. Other less common rocks are thin-bedded, light-grey chert, green glauconitic sandstone beds and laminated, fine-grained limestone, rich in the microscopic calcareous shells of plankton. In Northland, the Whangai rocks occur in slabs up to many kilometres across. The brittle rock in these slabs has often been shattered, sheared and milled to broken formation, presumably during its emplacement onto Northland.

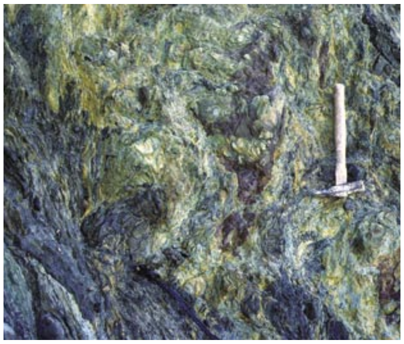
Much of the siliceous mud in these rocks was eroded off the land and carried out into the ocean in suspension before sinking to the seafloor to slowly accumulate. The Whangai rocks are younger than the Punakitere Sandstone and probably reflect both the increasing depth of the seafloor where they were deposited and increased distance from land. They probably also indicate that the topography of adjacent Zealandia had become far more subdued and far less sand was being eroded off it and carried down to the sea.

The Whangai Formation gets its name from the Whangai Range in southern Hawkes Bay, and this group of identical rocks occurs in a 300-500 m-thick belt of undisplaced rocks from the Kaikoura coast northwards up through the east side of the North Island. The silica-rich Whangai rocks are notorious for the impoverished soils that form on them and because of that, often can be easily recognised in the landscape (*4.35*).

4.35 Steep hillsides recently cleared of scrub for pine planting near Whangaroa, appear to have a dusting of snow. In reality, "the snow" is the frittering, white-weathered Whangai Formation that forms the ridge.

Hukerenui Mudstone

This formation consists of Late Cretaceous to Early Eocene (80-50 Myr old) red, brown, green and grey mudstone beds often interlayered or sheared together (*4.36-4.37*). These might occur as discrete blocks or slabs within the Northland Allochthon, or as sheared multi-coloured mudstone between the large slabs of more intact rocks. The sheared zones of clay-rich mud were the lubricating "grease" that helped the giant displaced blocks to slide onto Northland under the pull of gravity. Often these zones contain a mix of small pieces of many different kinds of displaced rock sheared into the Hukerenui Mudstone matrix. Rocks consisting of such a mixture of rock types is called mélange. These soft mudstones weather much faster than the more cemented Allochthon rocks and so fresh exposures of this formation are uncommon and soon turn to clay and get hidden by vegetation. These mudstones are soft and sheared. They become water-logged after heavy rain and



4.36 Left. A temporary roadside exposure of red and green-grey Hukerenui Mudstone (Late Cretaceous-Paleocene). This was the clay-rich lubricant between slabs as they slid into Northland with the allochthon. In wet weather these mudstones remobilise and flow down the hills - a major cause of the notoriously unstable roads of the north.

4.37 Centre. Highly-sheared red, green, grey and yellow-weathered Hukerenui Mudstone forms the lubricating mélange zone at the base of the Northland Allochthon, and contains some small blocks of broken off Waipapa greywacke rocks (top right). North end of Ocean Beach, Whangarei Heads.

4.38 Right. Black and cream chert (intermediate in character between Waiari and Whangai formations) of Paleocene age (66-55 Myr old) exposed in an old quarry at Ohia, Doubtless Bay.

flow off downhill even today.

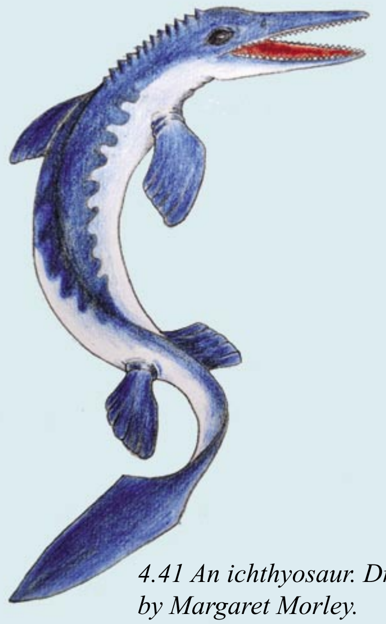
Several other distinctive but relatively rare rock types occur in the Mangakahia Complex. One is a black, organic-rich mudstone of Paleocene age called the Waipawa Black Shale, named from its east coast North Island occurrences, where it is far more common and is considered to be a potential source rock for the generation of oil and gas. This black shale (*13.3*) is inferred to have accumulated in anoxic conditions on the stagnant floor of the deep ocean.

Another rarer rock type is moderately indurated dark grey, thin-bedded fine sandstone and mudstone (Motukaraka Sandstone), containing bivalve (inoceramid) fossils, which is mainly seen around the shore of the Hokianga Harbour. This unit is the oldest (about 100-90 Myr old) and has been the most deeply buried of the rocks in the Mangakahia Complex, and thus is the most indurated and the only one that is slightly metamorphosed (to zeolite facies). Motukaraka Sandstone beds are inferred to be the far-travelled, distal deposits of turbidity currents deposited in the deep sea off the coast of Gondwana before Zealandia broke away.

4.39 An unusual Mangakahia Complex rock type on the foreshore at Rawene, Northland, is this red-brown Paleocene mudstone with 5 cm-thick interbeds of white muddy limestone. The mud is inferred to have been deposited slowly as it settled out of suspension onto the floor of the deep sea at abyssal depths below the CCD (below which calcite dissolves, deeper than ~3,500 m). The fine-grained limestone beds are thought to have been calcareous plankton ooze transported in slurries downslope from shallower bathyal depths (1000-2000 m) as small turbidity currents.

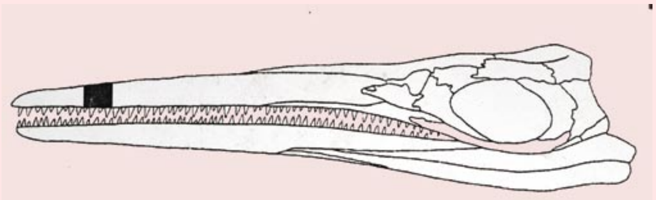
Box 14. FOSSIL ICHTHYOSAUR BONE

No fossilised bones of dinosaurs have been found in northern New Zealand, but what has been found is a bone of one of their large marine reptile cousins – an ichthyosaur. The 11 cm-long piece of jaw bone was found in a stream north of Dargaville and described by paleontologist Jack Grant-Mackie. It is likely to have eroded out of Cretaceous (140-80 Myr old) sedimentary rocks of the Northland Allochthon's Mangakahia Complex. It has been identified by Jack Grant-Mackie as coming from a 3-4 m-long ichthyosaur of the genus *Platypterygius*. Ichthyosaurs or fish-lizards are similar in appearance to modern dolphins. They lived in the oceans around the world during the Age of Dinosaurs (Triassic to Cretaceous) and became extinct about 80 Myr ago. This is the only ichthyosaur fossil found so far from northern New Zealand but the remains of another 20 or so have been found elsewhere in the country. Vertebrae of another kind of extinct marine reptile, a mosasaur, have also been found in Northland (*1.14*).



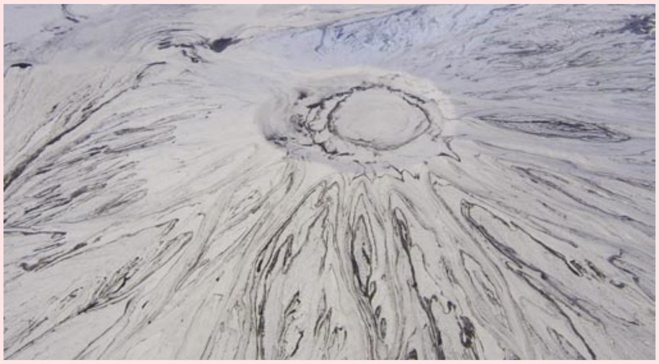
4.41 An ichthyosaur. Drawing by Margaret Morley.

4.40 Fossil jaw bone fragment of a Cretaceous ichthyosaur from near Dargaville, Northland. 10 cm long. University of Auckland collection.



4.42 Sketch of an ichthyosaur skull showing (in black) where the Dargaville jaw bone fragment came from.

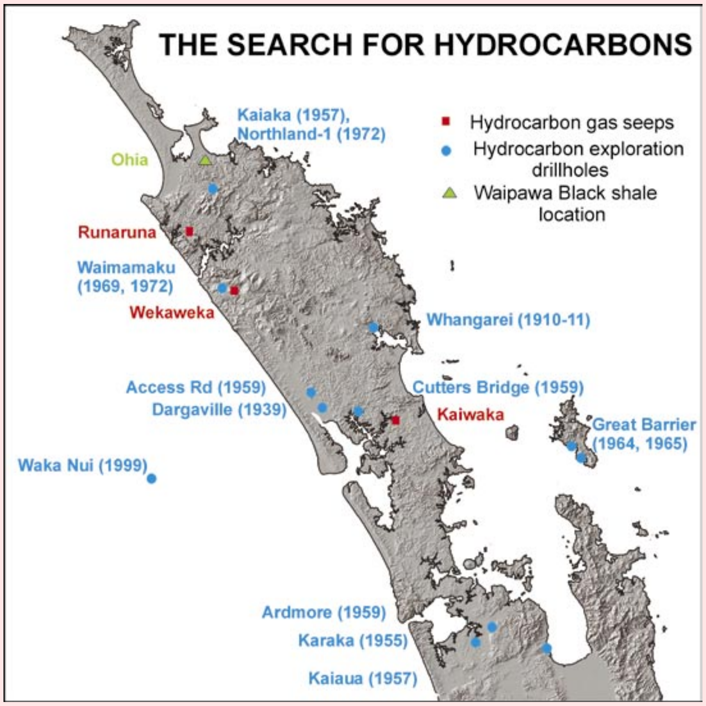
Box 15. RUNARUNA MUD VOLCANO AND THE SEARCH FOR OIL



4.43 *Gas and cold muddy water bubble-up from several vents on the top of the Runaruna mud volcano. Width of photo 1 m.*

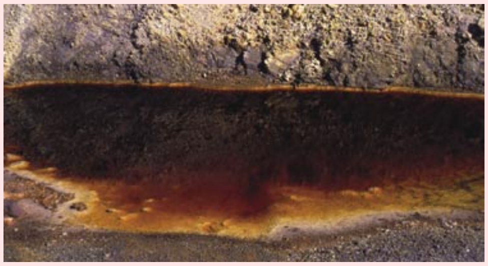
At Runaruna, near the Whangape Harbour, salty water, carbon dioxide, methane and wet mud have found their way to the surface, where they ooze out in a paddock, forming Northland and Auckland's only mud volcano. The water, gas and mud are sourced from clay-rich layers within the Northland Allochthon's Mangakahia Complex and are forced up to the surface under the pressure from hundreds of metres of overlying rock. The mud volcano is active most of the time with bubbles of muddy water and gas breaking the surface of miniature crater lakes on its peak. It is 3-4 m high and 30 m in diameter and one of the two best examples of a mud volcano in New Zealand. Other mud volcanoes in New Zealand are found on the North Island's east coast and in Canterbury.

There are two other hydrocarbon gas seeps in the region, at Wekaweka and Kaiwaka. Together with small quantities of paraffinic wax from Runaruna, these indicate that at depth beneath the Northland Allochthon there are organic-rich rocks that have been buried sufficiently deeply (increased pressure and temperature) to generate hydrocarbons. These seeps gave hope to pioneer oil exploration wells drilled many decades ago at places like Whangarei, Dargaville, Karaka, Kaiaka, and Waimamaku. None found any commercial quantities of hydrocarbons and since 1972 the only oil drilling that has occurred has been one attempt offshore west of Kaipara (Waka Nui). The thick, structurally-simple Jurassic-Cenozoic sedimentary sequence beneath the seafloor west of Northland is similar to that in Taranaki (New Zealand's only known hydrocarbon basin). It has hardly been explored for hydrocarbons, however, and is believed to have potential for a commercial find. Onshore, the sequence over the basement rocks is insufficiently thick and structurally too broken-up to have much potential for generating and storing commercial quantities of gas or oil.



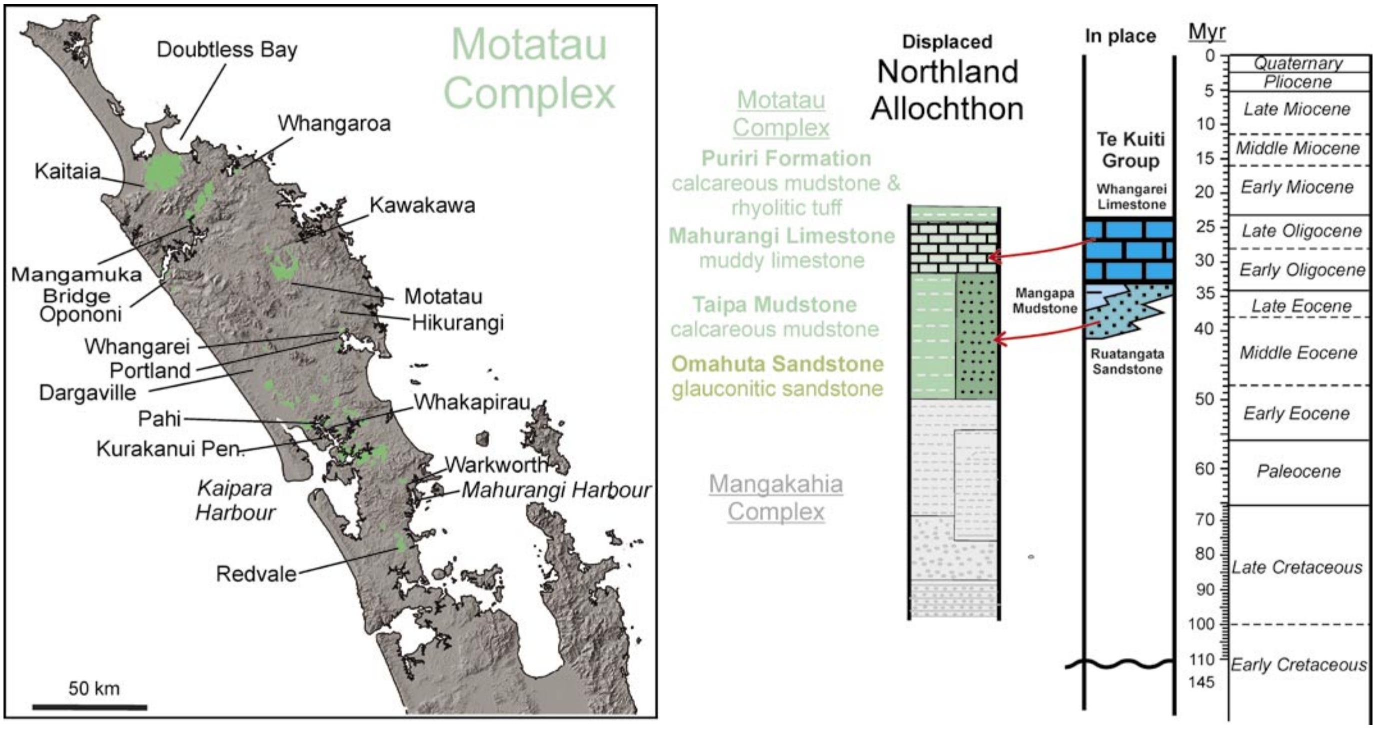
4.44 *Location of natural hydrocarbon seeps, oil shale and drillholes that have been put down in the search for oil or gas in northern New Zealand. Most of the on-land drillholes (except those at Waimamaku) were based on people's hunches and not on any prior geological investigations or remote sensing of underground structures.*

4.45 *The largest mud volcano in the country is at Runaruna, south of Kaitaia. A mix of salty water, mud, carbon dioxide and methane bubbles to the surface and builds up around the vents as a 4 m-high shield.*



4.46 *A pool of oily water has collected on the floor of a disused quarry where the oil has oozed out of exposed Waipawa Black Shale and Whangai Formation (Mangakahia Complex) near Ohia, Doubtless Bay, Northland.*

DEEP-WATER LIMESTONE AND GREENSAND (Motatau Complex)



4.47 Stratigraphic column and distribution of Motatau Complex rocks in northern New Zealand.

In the area where the Allochthon sedimentary rocks came from, northeast of Northland, there was a marked change in the Early Eocene (about 50 Myr ago) from dominantly terrigeneous (land-derived) and siliceous (silica-rich) sediment (Mangakahia Complex) to dominantly pelagic (plankton-sourced) and calcareous (lime- or calcite-rich) sediment. These younger rocks are called Motatau Complex and were deposited during the Eocene and Oligocene (50-23 Myr ago). They presumably accumulated on top of the Mangakahia Complex sequence in deep water offshore from the coast of Zealandia. Their highly calcareous nature indicates that the sediment was deposited in water depths shallower than the CCD (at about 1000-3500 m depth), where the slow rain of calcareous shells of dead phytoplankton (nannofossils) and zooplankton (foraminifera) did not dissolve away when it reached the ocean floor.

The change in composition probably resulted from a combination of world-wide deepening of the CCD in the Eocene, from shallowing of the ocean floor as a result of the progressive build-up of sediment, and from the continued slow subsidence and eroding down of Zealandia, so that there was now little land-eroded (terrigeneous) sediment available to be transported down the continental slope to the ocean depths. By the Late Oligocene (25 Myr ago) the land area of Zealandia had been reduced to perhaps less than 10% of what it is today and probably consisted of just a few low-lying islands. The amount of calcium carbonate within the Motatau Complex rocks also shows an increasing trend through time. The Eocene and Early Oligocene sedimentary rocks (50-30 Myr old) are mainly calcareous mudstone (less than 50% lime) and green sandstone, whereas the Late Oligocene rocks (30-25 Myr old) are predominantly

4.48 Sheared muddy limestone (Mahurangi Limestone) forms extensive rocky hillsides around Motatau, south of Kawakawa in east Northland.

4.49 Sheared muddy limestone (*Mahurangi Limestone, Oligocene age*) *is composed of the calcareous skeletons of microscopic plankton that accumulated on the floor of the deep-sea several hundred kilometres north of their present location in Portland Quarry, Whangarei.*

fine-grained (muddy) limestone (more than 50% lime).

The largest slabs of Motatau Complex rocks occur in northern and central Northland (*4.47*), with numerous smaller blocks widespread further south around Ruawai, Warkworth and as far south as Redvale lime quarry on Auckland's North Shore. The most common rock type is muddy limestone (Mahurangi Limestone) that slowly accumulated on the ocean floor as a carpet of calcareous pelagic ooze, mainly during the Late Oligocene. As the ooze was buried by further sediment, it was compacted down and the calcite shells were partly recrystallised, cementing them together to form a relatively hard limestone rock. When seen in Northland, these rocks are usually highly sheared and cut by numerous faults and veins (*4.49*) - deformation that is inferred to have mainly occurred as the slabs moved into northern New Zealand. In the centres of some of the larger slabs (5-10 km across and up to 1 km thick) these limestone rocks might be less sheared and deformed, and original bedding, sedimentary features and trace fossils might be visible (*4.51*). In other places the limestone is massive with no obvious bedding, or might contain thin beds of sandy limestone.

4.50 Unlike many of the Mahurangi Limestone blocks in Northland, this one forming Kurakanui Peninsula on the Kaipara Harbour, retains most of its original sedimentary features. The thin beds of muddy limestone are steeply tilted to the right (*east*).

Around the eastern shores of the Kaipara Harbour there are a number of 1-2 m-thick beds or lenses of coarsely crystalline, sometimes pebbly, sandy limestone within the deep-water fine-grained Mahurangi Limestone.

4.51 A characteristic deep-water trace fossil (Zoophycus)*, commonly seen in muddy limestone of the Motatau Complex. Redvale Quarry, Auckland. Width of photo 40 cm. University of Auckland collection.*

These are inferred to be lenses of coarse shell hash that were emplaced by submarine gravity flows from shallow marine shelf areas along the adjacent coast of Zealandia. The Mahurangi Limestone is the deep-water, fine-grained limestone equivalent of the shallow-water, coarse-grained Whangarei Limestone (Te Kuiti Group) that was accumulating on the shelf during the Oligocene (Chapter 3).

In places within the Motatau Complex sequence, there are metre-thick beds of moderately hard, glauconitic greensand (Omahuta Sandstone, *4.54- 4.55*). The green mineral glauconite usually grows on sediment-starved parts of the seafloor at shelf depths (0-200 m depth). These sandstone beds have features that suggest they were transported down into deep water as sand and mud slurries (turbidity currents) from the adjacent Zealandia shelf. Thus Omahuta Sandstone is effectively displaced Ruatangata Sandstone (Te Kuiti Group, Chapter 3), which accumulated at shelf depths during the Middle to Late Eocene on the Northland marine shelf.

Box 16. LIMESTONE QUARRYING AND CEMENT

4.52 The huge quarry in muddy Mahurangi Limestone at Portland, near Whangarei, provides most (75%) of the raw material for the production of Portland cement in the nearby plant. Its lime content is augmented by the addition of crushed Whangarei Limestone (20%), quarried at Hikurangi north of Whangarei. All of the cement produced in New Zealand comes from this plant and is transported by ship, road or rail around the rest of the country. Photographer Alastair Jamieson.

The first plant in the Southern Hemisphere to produce "Portland cement" was Wilson & Co. Cement Works, located on a block of Mahurangi Limestone at the head of Mahurangi Harbour, just downstream from Warkworth (*4.53*). This plant operated between the 1880s and 1910s and its ruins and flooded quarry pit are now in a public historic reserve. Initial problems with the low and variable lime content of the local rock were overcome by adding ground up seashells from harbour shell banks. By 1910, 180 people worked at the Mahurangi plant and it was the major employer in Warkworth. Operations were transferred to Portland near Whangarei, which still function under the brand name Golden Bay Cement.

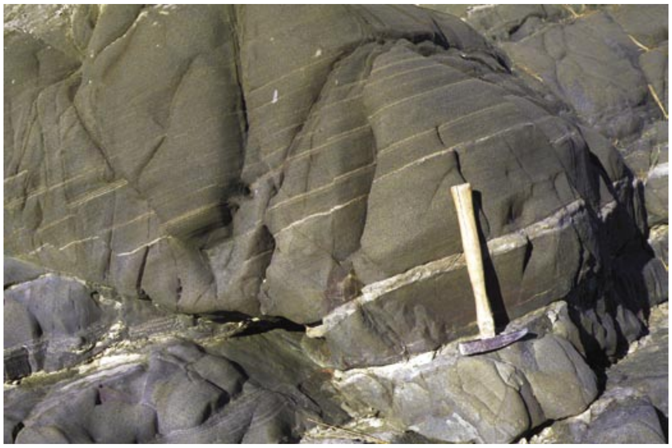
The Portland works has been the only plant in New Zealand manufacturing cement since 2016. Portland cement is a vital ingredient in concrete and therefore in our modern way of life. 95% of the raw material for the manufacture of cement at Portland comes from two nearby limestone quarries - one in coarsely crystalline, near-pure Whangarei Limestone (~96% lime) from the in-situ Te Kuiti Group at Hikurangi (Chapter 3); the other from the muddy Mahurangi Limestone (50-80% lime) in the Northland Allochthon at Portland itself. The cement mix requires lime ($CaCO_3$), silica (SiO_2), alumina (Al_2O_3) and iron oxide (Fe_2O_3). The latter three ingredients come from the clay impurities in the Mahurangi Limestone, which comprises about 75% of raw materials used. The rock is ground into fine particles, mixed together in the correct proportions and heated to 1450°C in a kiln to produce cement clinker nodules, which then are ground down again to produce the fine cement powder used in concrete making. A small amount (4%) of imported gypsum ($CaSO_4$) is also added during the final milling stage to lengthen the time it takes for the concrete to set. The chemical processes in the kiln let off large quantities of the greenhouse gas, carbon dioxide. Technologists are working on ways to reduce emissions and looking for lower carbon dioxide alternatives.

There are numerous other small and medium-sized quarries in northern Northland, north of Redvale, that periodically extract muddy limestone (Mahurangi Limestone) from its displaced slabs in the Northland Allochthon. The lime from these quarries is widely used on farm roads and especially as fertiliser for pasture improvement.

4.53 The remains of Wilson & Co. Cement Works and flooded Mahurangi Limestone quarry near Warkworth. It produced the first Portland cement in the Southern Hemisphere and was used in some impressive early Auckland concrete structures such as the Parnell Rail Tunnel, Rangitoto Beacon and Grafton Bridge.

4.54 At Opononi wharf, gently-dipping muddy limestone (Mahurangi Limestone) includes several beds of glauconitic sandstone. The limestone was calcareous pelagic ooze that accumulated on the ocean floor during the Oligocene (33-25 Myr ago). The sand originated on a shallow marine shelf (shallower than 200 m) and flowed, in turbid slurries, down the submarine slopes of eastern Zealandia to the ocean floor. In the foreground a small fault can be seen crossing the shore platform, offsetting the sandstone beds by 1 m.

The youngest rocks in the Motatau Complex are latest Oligocene-earliest Miocene (25-23 Myr old) calcareous siltstone (Puriri Formation) that was deposited on top of the Eocene-Oligocene Motatau sequence, probably as it was starting to be pushed up and into Northland. The increase in terrigeneous mud signals the onset of the major tectonic movements that were to characterise the Early Miocene (23-16 Myr) period in northern New Zealand. Clearly some land areas were starting to be pushed up and erosion was reactivating. The most characteristic feature of the Puriri Formation is the presence of a number of thick, white, glassy ash beds (tephra) of rhyolitic composition (*4.56*), which signal the initiation of subduction-related volcanic arc eruptions that were to continue in New Zealand through to the present day. In several places around the shores of the Kaipara Harbour, the Mahurangi Limestone can be seen passing upwardsinto the Puriri Formation in a continuous sedimentary sequence. Elsewhere, mainly around the Kaipara and further south, Puriri Formation occurs in small displaced blocks near the top and toe of the Allochthon.



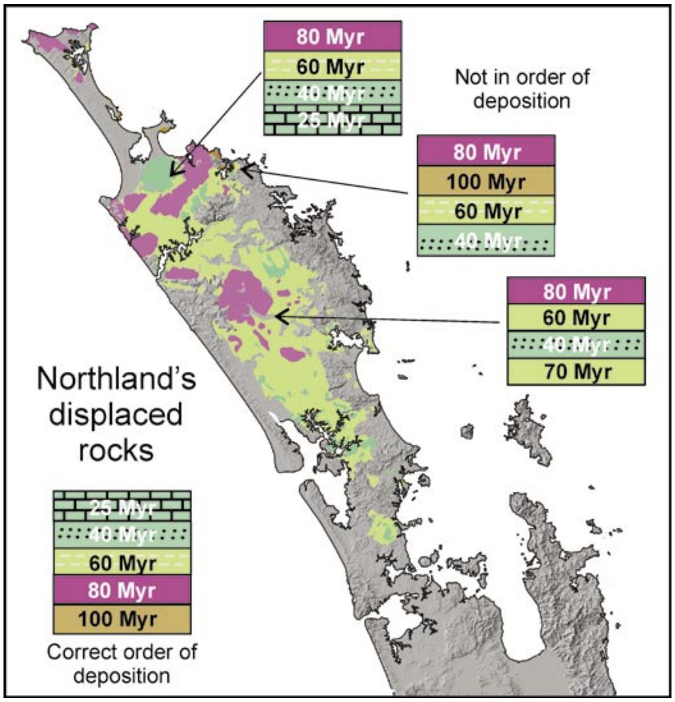
4.55 Well-bedded, laminated, glauconitic sandstone beds (Omahuta Sandstone, Middle Eocene age) near Pahi, Kaipara Harbour. They consist of sand that has been transported from shallow shelf depths down into deep water. The background deep-water sediments are the thin cream beds of calcareous mudstone. Note the numerous small fault displacements of the bedding.

4.56 A 30 cm-thick bed of white rhyolitic tuff sits within cream-coloured, calcareous siltstone (Puriri Formation, latest Oligocene) in a low coastal cliff south of Whakapirau, Kaipara Harbour. The irregular thickness of the tuff bed results from small-scale faulting that probably occurred as the block slid in with the Northland Allochthon.

SOLVING THE MYSTERY OF THE DISPLACED ROCKS

Only since about 1980 has an explanation for the structure and origin of the Cretaceous-Oligocene rocks (110-23 Myr old) of Northland become widely accepted. The main reason why these problematic rocks were difficult to understand was that in different places throughout Northland the various distinctive strata occurred in different orders (*4.57*). The nineteenth century geologists, such as Alexander McKay, James Park and Herbert Cox, who tried to map Northland's geology, argued over the correct sequence of rock strata. Each made their observations in different areas and came up with different answers and, as it turns out, each was correct for their local area.

Other reasons that made it difficult to understand these rocks were that they were deeply weathered and there were few rock exposures large enough to study the sequence. Almost all of these problematic rocks occur inland, with limited coastal exposure that might have allowed the geologists to see more clearly the relationships between the various strata.



4.57 Up until the mid-twentieth century geologists struggled to understand the geology of much of inland Northland. This was largely because the layered sequence of strata was different in different places (*diagrams top right*). *Once the ability to date these strata using microfossils had been developed in the 1940s, it became obvious that these problematic strata were all mixed up and out of order. The actual order of deposition* (*bottom left*) *should have the oldest rocks on the bottom with the sequence of rocks becoming progressively younger upwards.*

First evidence of displaced rocks

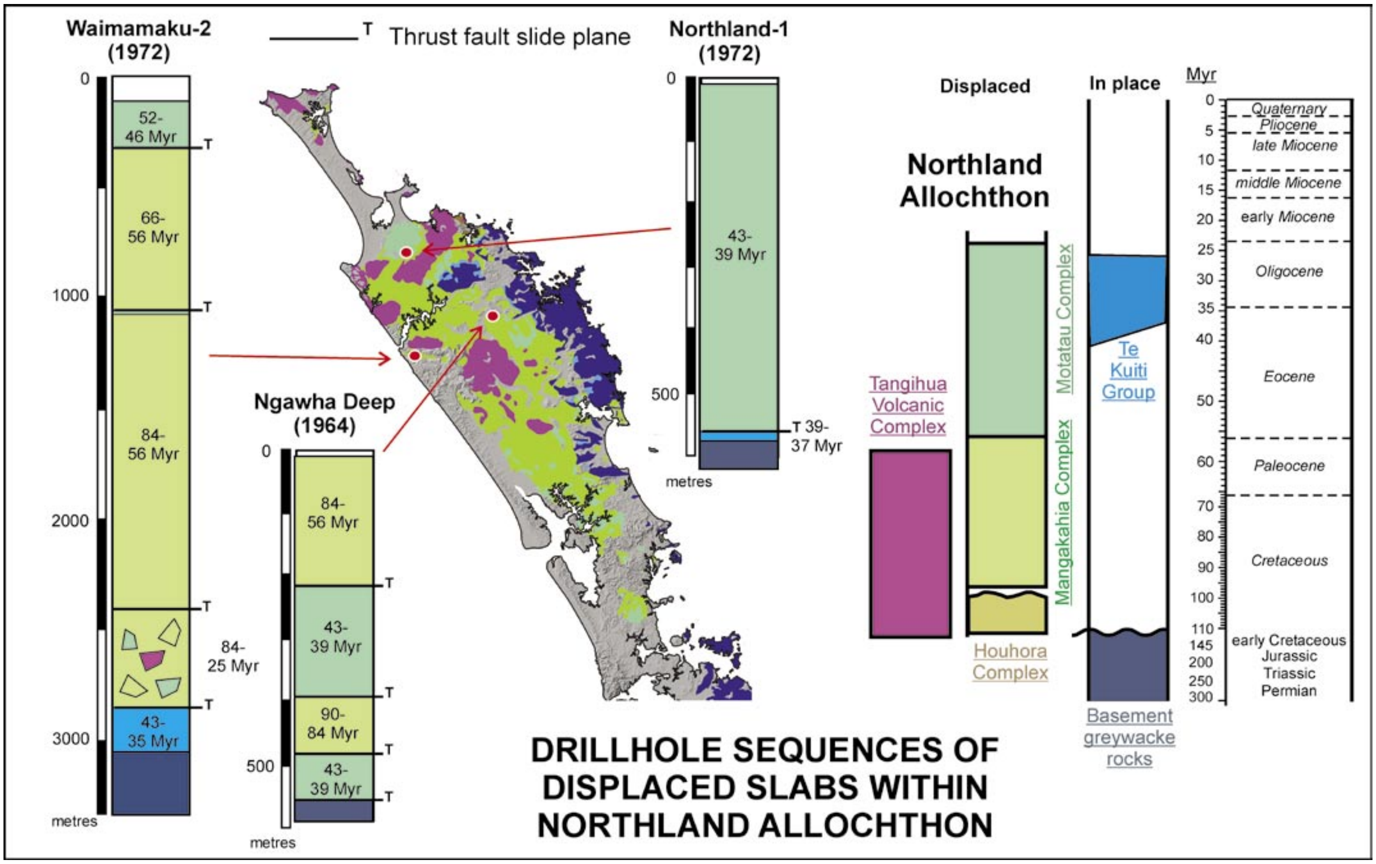
Up until the 1940s, the field geologists had no way of accurately determining the age of these rocks that would have provided answers to their puzzle. There were a few thick-shelled inoceramid bivalves and ammonites, which told them that at least half the rocks were Cretaceous in age. In the late 1930s and 1940s the New Zealand Geological Survey employed paleontologist Harold Finlay to develop the use of microfossil foraminifera for dating New Zealand's Cretaceous and Cenozoic marine sedimentary rocks (younger than 100 Myr old). At this time, geologist Bob Hay was struggling to understand and map the rocks of central Northland and sent samples off to Finlay for dating. He sent back his results and accused Hay of mixing up the samples, as the sequences were in a muddled age order.

To help resolve the problem, the Geological Survey director sent his best and most instinctive field geologist, Harold Wellman up to Northland in 1948. After a couple of days work north of Whangarei, Wellman declared that older strata had been thrust over younger in-situ Te Kuiti Group coal measures and limestone on a low-angle fault that was named the Kawakawa Overthrust. The recognition of a faulted rather than unfaulted sequence was a breakthrough in thinking. Wellman's explanation was accepted by Hay for the eastern strip of his area, but he could not envisage that these problematic rocks were all out-of-place in a rather chaotic order throughout Northland. On the scene soon after, in the early 1950s, were two young geologists Larry Harrington and David Kear, who realised that many large slabs of rock were out of order and independently hypothesised that the problematic rocks were overthrust and displaced throughout various parts of Northland. Both Harrington and Kear had seen similar examples of displaced rocks in Cyprus and Italy and they used these examples to inspire their explanation for Northland's confused sequences. Their ideas were considered to be too improbable at that time by most other New Zealand geologists, who were not prepared to consider any of these heretical ideas and they remained controversial for decades.

Displaced rocks in east Northland

Harrington moved to Australia but Kear remained actively interested in Northland geology, even after he moved to Lower Hutt to become Director of the Geological Survey in 1967. When one of Kear's colleagues, Barry Waterhouse, was having difficulty understanding a chaotic jumble of rocks he was mapping around Silverdale in the 1960s, Kear recognised that this was still further evidence for his controversial hypothesis. He and Waterhouse published a map of Northland and Auckland, showing areas of sedimentary rocks that were "proven" or "probably" "out-of-place", for which they coined the term Onerahi Chaos-Breccia. The name Onerahi came from the type locality on Onerahi Peninsula, Whangarei, of the widespread Cretaceous-Oligocene Onerahi Formation that geologist Hartley Ferrar had defined in the 1920s and 1930s. Like those before him, Ferrar inferred these rocks were in place and had mapped them as such. The term chaos-breccia refers to the chaotic mix of broken up blocks that characterised many of their study sites.

During the 1950s and 1960s Kear and Waterhouse had assembled conclusive evidence from drillholes and outcrops of older rocks sitting on top of younger rocks in at least eight areas. Some drillholes were commissioned by the Geological Survey to specifically investigate the stratigraphic sequence of strata in places, where they suspected they were out of order. In 1967, and more surely in 1977, Kear and Waterhouse speculated that maybe all the Cretaceous-Eocene sedimentary rocks of Northland and Auckland, other than the Late Eocene-Oligocene Te Kuiti Group, could be displaced. Initially (1967) they favoured submarine gravity slumping of Onerahi Chaos Breccia into low-lying areas at various times throughout the last 20 Myr. By the middle 1970s sufficient evidence had been compiled showing that emplacement primarily occurred during the Early Miocene (~23-20 Myr ago) as the northern extent of the Waitemata Basin subsided (Chapter 5).



4.58 Sequence of strata and their microfossil-determined ages encountered in Waimamaku-2 (1972) and Northland-1 (1972) oil exploration wells and Ngawha (1964) deep geothermal exploration drillhole. They show large coherent slabs of older sedimentary rocks of the Mangakahia and Motatau Complexes lying over the top of younger Te Kuiti sedimentary rocks and old basement greywackes. These provide some of the most compelling evidence in support of the Northland Allochthon explanation of displaced rocks in northern New Zealand.

Displaced rocks in west Northland

The 1972, Waimamaku-2 oil exploration drillhole, located just south of the mouth of Hokianga Harbour, provided the first solid evidence that Northland's problematic rocks were also displaced in the west. As previously noted, Northland is tilted down to the west, with the basement greywackes and in-situ Te Kuiti Group cover rocks exposed at the surface in the east. In eastern areas, such as Kawakawa, Hikurangi and Kamo, geologists in the 1950s-60s had been able to see that the older rocks were thrust over the younger in-situ Te Kuiti sequence, either in the hillsides or in shallow drillholes. In central and west Northland, however, the in-situ basement rocks and Te Kuiti strata were deeply buried by several kilometres of problematic Cretaceous-Oligocene strata, and thus only a deep drillhole like Waimamaku-2 could investigate their relationship at depth.

Once again it was the dates provided by microfossils in the rock chips recovered from the circulating drilling mud from Waimamaku-2 that proved crucial. Geological Survey micropaleontologists Norcott Hornibrook and Tony Edwards studied dozens of samples and clearly showed that the drill had passed through at least three thick slabs (each 200-1400 m thick) of deep-sea Mangakahia and Motatau Complex strata of Late Cretaceous to Middle Eocene age (100-40 Myr old), overlying inferred in-situ shallow-water strata of Middle-Late Eocene age (45-33 Myr old), sitting on Early Cretaceous-age (110-100 Myrs old) indurated mudstones. These two in-situ units have since been identified as Te Kuiti Group and young Murihiku Terrane strata. The giant displaced slabs of Mangakahia and Motatau Complex rocks were separated from the apparently in-situ Te Kuiti Group mudstone and glauconitic sandstone by nearly 500 m thickness of chaotically mixed rocks or mélange, containing various rocks ranging in age from Late Cretaceous to Oligocene, and also a piece of dolerite dike, presumably derived from the Tangihua Complex. Thus conclusively for the first time, it was shown that there was at least 3 km thickness of displaced rocks in Northland. Sometimes these occurred as large coherent slabs and sometimes as sheared and chaotically-mixed mélanges between the slabs.

The concept of a Northland Allochthon

Armed with all this evidence of displaced rocks, Auckland University geologists, Peter Ballance and Bernhard Spörli, proposed in 1979 that most of the Cretaceous to Oligocene rocks of western Northland, plus the associated Tangihua Complex, had been displaced onto Northland from the north by gravity sliding about 25 Myr ago. For these displaced rocks, they suggested the term Northland Allochthon. Over time this term has replaced the earlier and more limited concept of Onerahi Chaos-Breccia.

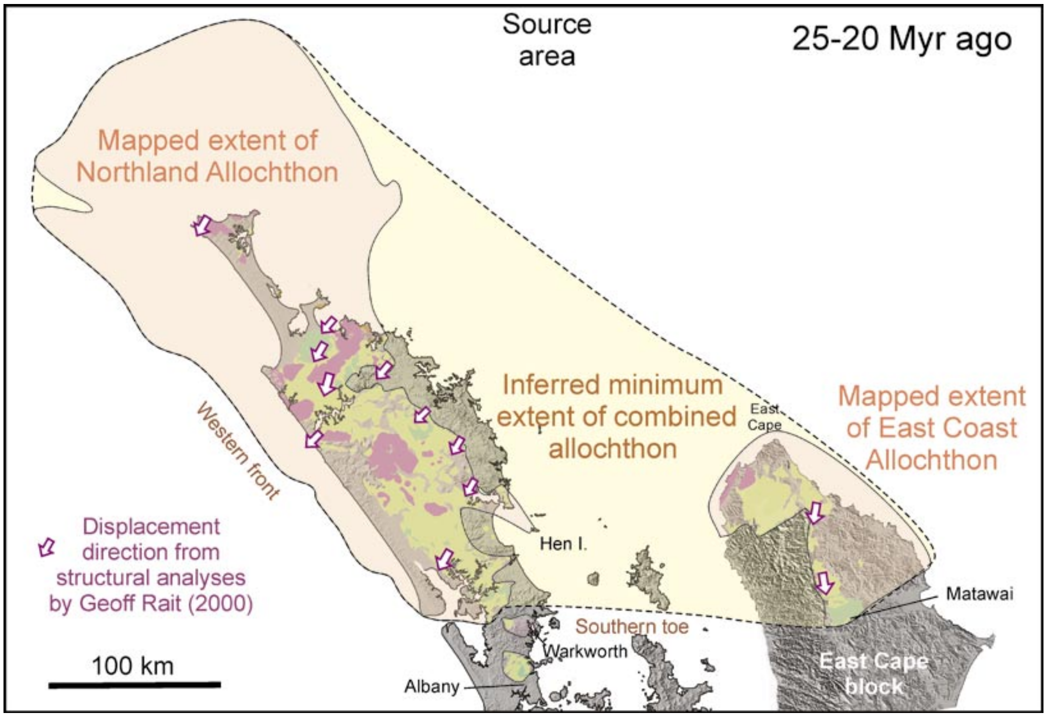
Since 1980, further research involving offshore seismic reflection profiles, extensive onshore mapping, detailed structural analyses, geochemistry and microfossil dating have all served to confirm and better refine understanding of the emplacement of the Northland Allochthon.

Extent of the Northland Allochthon

The Northland Allochthon includes all the rocks that were displaced during the Late Oligocene-Early Miocene (25-19 Myr ago) into Northland-Auckland and surrounding areas that are now under the sea. Clearly large areas of allochthonous rocks have been eroded away since they were emplaced and uplifted to become land. This is especially true along the east coast where basement rocks have been subsequently uplifted high, and almost all the overlying displaced and in-situ cover rocks have been eroded away. Thus the full eastern extent of the Northland Allochthon is unknown. The easternmost remaining visible occurrence is a small outlier of Mangakahia Complex rocks on Hen Island, off Whangarei.

At the time of emplacement of the Northland Allochthon, the East Cape block is believed to have been situated offshore to the east of Northland. Not surprisingly, similar displaced slabs of deep-water Cretaceous-Oligocene sedimentary rocks and Tangihua Complex look-alikes (Matakaoa Volcanics) occur today on the Raukumara Peninsula at least as far south as Matawai. These are known as the East Coast Allochthon, which undoubtedly was the eastern part of the Northland Allochthon before tectonic forces displaced it southeastwards and rotated it clockwise on the East Cape block to its present location.

On land, the Northland Allochthon extends as far west as the West Coast north of Hokianga, and further south presumably underlies the young North Kaipara Peninsula sand dune barrier. The actual western edge of the Allochthon has been imaged by seismic reflection profiling offshore beneath the floor of the Tasman Sea, 40-100 km west of the Northland coast. In these remotely-sensed images of the rock structure beneath the seafloor, the disturbed bedding and individual giant slabs of rock within the Allochthon can often be seen, and the western edge feathers out as a series of 300-500 m-thick thrust wedges that clearly show they came in from the northeast (*4.60*). The distinctive disturbed seismic structure visible within the Allochthon has enabled it to be mapped



*4.59 Map showing present day extent of the Northland Allochthon and its eastern extension, the East Coast Allochthon, which was located east of the Coromandel region when the Allochthon was emplaced about 25-19 Myr ago. The separate areas of displaced rock around Warkworth and north of Albany, are inferred to have broken off the front of the allochthon and slid south into the Waitemata Basin (*Chapter 5*).*

beneath the sea for at least 100 km north of North Cape.

The southern continuous extent of the Allochthon on land is just south of Wellsford, although there are numerous large and small blocks that appear to have slumped off this Allochthon front and into the Waitemata Basin about 20 Myr ago. These slumped Allochthon blocks occur around Warkworth, Wainui and Silverdale, with their southernmost extent close to Albany on Auckland's North Shore.

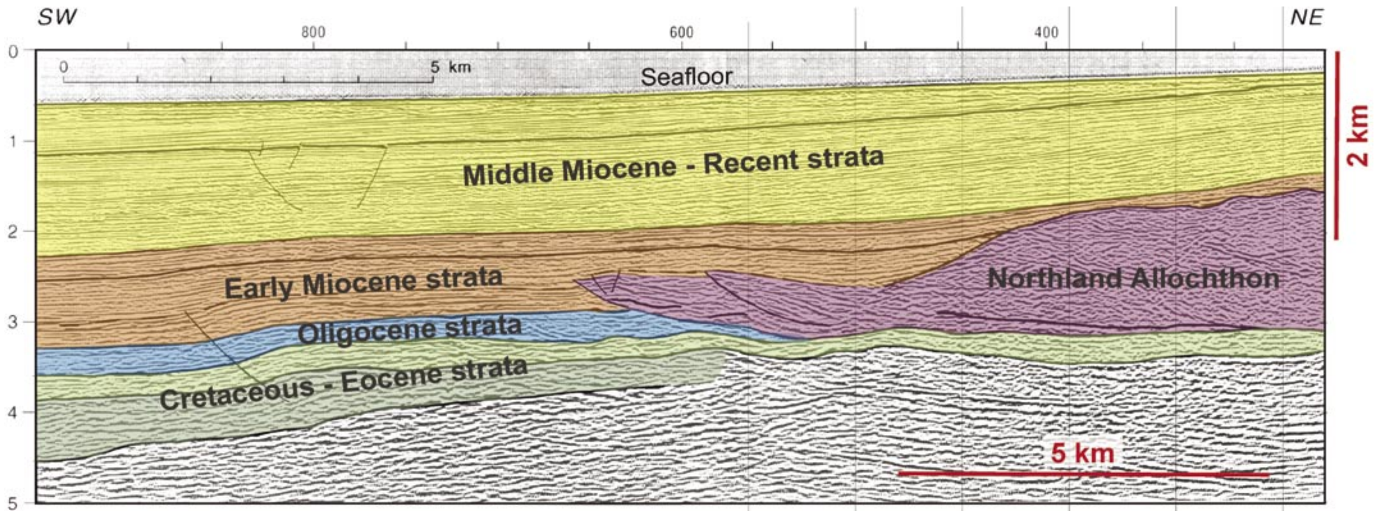
Internal structure of the Northland Allochthon

The pile of displaced rocks not surprisingly varies in thickness, reaching a maximum thickness of about 4 km beneath western Northland. The drilled thickness in Waimamaku-2 drillhole was 2.8 km, but this does not include a minimum 0.7 km of Tangihua Complex that sits on top and forms the adjacent Waima Range. Calculations of the total original volume of the Northland Allochthon are around 100,000 km^3, and this does not include the eastern part (East Coast Allochthon). 100,000 km^3 is sufficient to bury the entire Northland Peninsula today to a depth of more than 2 km with displaced rocks.

The deep weathering and poor on-land exposure of these displaced rocks throughout much of Northland makes it difficult to accurately map them at the surface, and from this infer their structure at depth. Mapping does show that the slabs or blocks of displaced rocks (equivalent to nappes of the Swiss Alps) decrease in size and continuity from north to south. In northern Northland, large slabs of displaced rocks are a minimum of 10-40 km across, each with thicknesses up to 1 km or more. Further south, the mapped slabs in the Kaipara area, and particularly in the far south around Silverdale, are 1-5 km across, with maximum thicknesses of 100-500 m.

One area with better rock exposure, that allows more detailed mapping of the different rock types and sequences, lies between Whangaroa and Kaitaia in northern Northland. It was mapped by three Geological Survey geologists, Fred Brook, Mike Isaac and the author, in the 1980s. Their mapping recognised a sequence of at least five slabs of displaced rocks (labelled i to v in *4.61*) that had slid into that region as part of the Northland Allochthon. Many of the slabs (especially of the Mangakahia and Motatau Complexes) could be seen to be composite, and consisted of a number of smaller sheets sheared against each other. The contacts between the different slabs were often not visible, but when seen consisted of mélange of various rock types in a matrix of sheared, clay-rich, often multi-coloured mudstone (Hukerenui Mudstone) – which presumably helped lubricate the slowly-moving slabs as they slid in.

The sequence of slab emplacement provides clues about the relationship between the displaced rocks in the source area (*4.61*) and how they must have been uplifted and slid in, over several million years, as the source area was progressively pushed upwards and the Northland

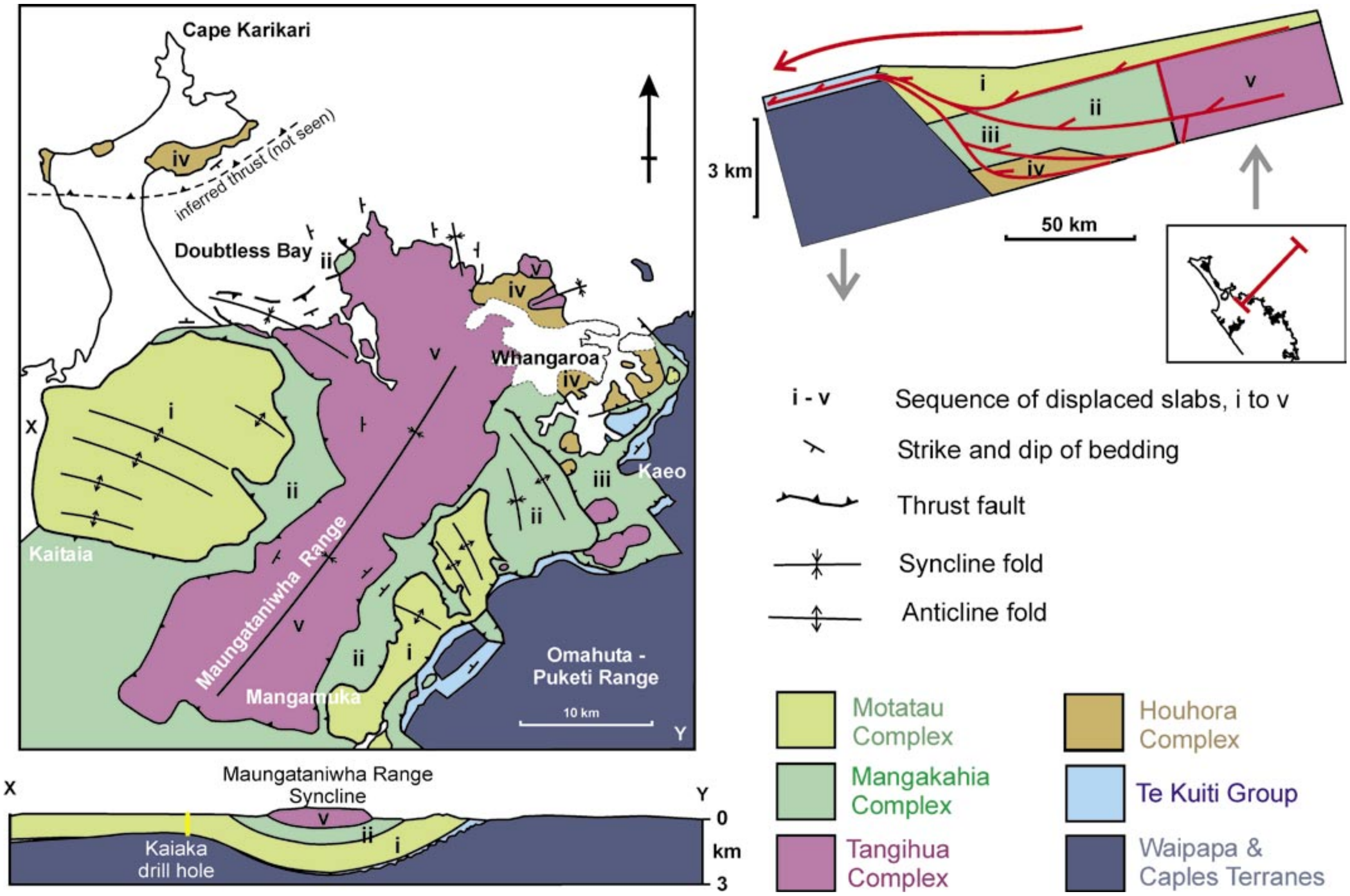


4.60 Northeast-southwest seismic profile off the west coast of northern Northland, showing a nearly 5 km-thick cross-section through the rock strata beneath the seafloor. The profile has been coloured up to show the distribution of the different rock groups. This profile provided key confirmation of the inference obtained from onland structural analysis, that the Northland Allochthon was emplaced across Northland from the northeast in the latest Oligocene-earliest Miocene (*25-20 Myr ago*). *The front of the Allochthon can be seen to consist of several 300-500 m-thick slabs thrust up and onto the strata to the southwest.*

area subsided. An inferred model of the source region of the Northland Allochthon rocks has Houhora Complex to the north partly overlain by Cretaceous-Paleocene Mangakahia Complex, which in turn was overlain by Eocene-Oligocene Motatau Complex. Behind this and further to the north was the Tangihua Complex igneous rocks. As the source region was pushed up, a slab of the youngest rocks (Motatau Complex) uncoupled from the sequence and slid in as the first-displaced slab in this mapped area (i). This was followed by further uplift and a thick slice (ii) of Mangakahia Complex sliding in over the top of (i). Slab (iii) was a mish-mash of broken-up blocks of all the different displaced rocks, but predominantly of Mangakahia Complex. Also present near the base of the allochthon in thrust sheet (iii) is a 2 by 1 km block of Ruatangata Sandstone that had been ripped up from the underlying Te Kuiti Group rocks as the thrust sheet came in. Displaced slab (iv) consisted of Houhora Complex with some of its Mangakahia Complex cover beds still attached. Its emplacement indicates still further uplift of the closest source area, and the sliding in of some of the oldest rocks in the Allochthon. Slabs (iii) and (iv) did not override the earlier displaced slabs but instead pushed in behind them, and might have shunted them forward and compressed them, causing the Mangakahia and Motatau rocks to be rucked up into a series of southwest directed folds. The youngest giant sheet to move in was of Tangihua Complex. This indicates that sufficient uplift had occurred further to the north for these rocks to be able to slide in under the pull of gravity. Indeed this was the last sheet emplaced throughout Northland, although it might have broken up into a number of slabs as it was emplaced.

Less detailed mapping in other parts of central and northern Northland suggests that there might have been at least a further two large displaced slabs (of Motatau and Mangakahia Complex) to slide into Northland, before the ones recognised in the Whangaroa-Kaitaia region. The presence of small blocks (less than 500 m across) of Tangihua Complex rocks within the basal mélange southwest of Whangaroa (*4.61*) indicates that the complex sequence of emplacement outlined above is probably a simplification. It is likely that the various rock units (complexes) had an earlier episode of deformation within an accretionary wedge (*1.20*) in the source area, prior to uplift and gravity emplacement onto Northland.

The mapped sequence of thrust slabs between Whangaroa and Kaitaia has been folded into a large open syncline with a northeast-southwest axis running along the crest of the Maungataniwha Range (*4.61*). This folding probably happened soon after initial emplacement of the allochthon in this area. It appears that the more extensive displaced slabs of northern Northland were dismembered into smaller and more sheared blocks as the southern edge of the Allochthon advanced progressively southwards towards Auckland.



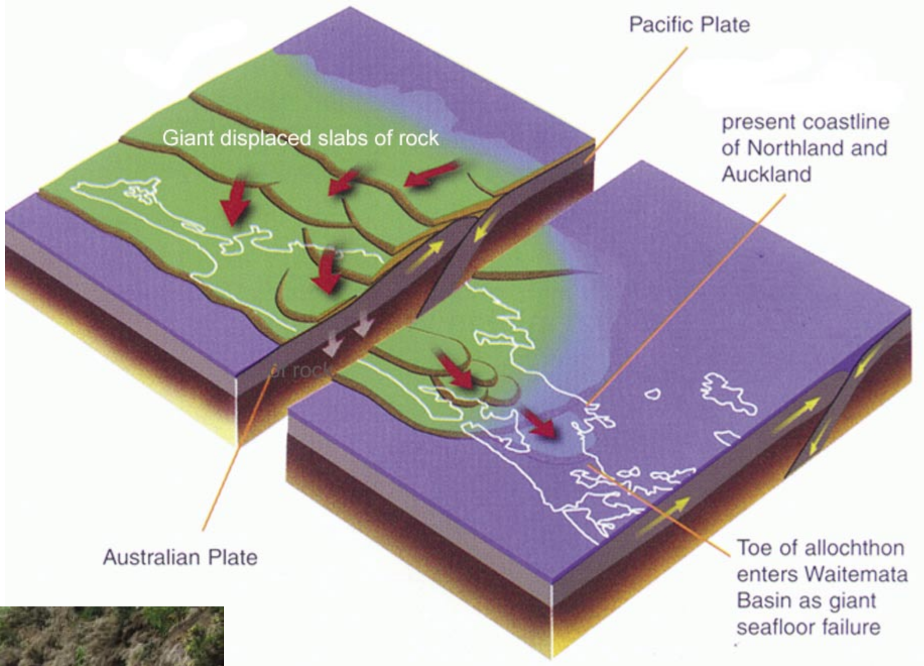
4.61 Simplified geological map of the Whangaroa-Kaitaia area, showing the in-situ greywacke basement rocks overlain by thin Te Kuiti Group sedimentary rocks, and then a sequence of five displaced slabs (i-v) of Northland Allochthon rocks, separated by low-angle slide planes (thrust faults). The northwest-southeast-oriented folds in slabs i and ii are inferred to have been produced during allochthon emplacement from the northeast. The northeast-southwest cross-section (X-Y) shows how the sequence was later folded into the open Maungataniwha Range Syncline. The schematic cross-sectional model (right) illustrates the inferred relationships between the displaced rocks in the source area and how, with progressive uplift, a succession of slabs slid off and into Northland, with the rocks within the slabs generally becoming older as uplift continued.

Timing of Northland Allochthon emplacement

Having established that the problematic rocks of Northland are out-of-place volcanic and sedimentary rocks that were erupted and deposited on the ocean floor and slid over Northland from the northeast as giant sheet-like slabs, there still remain the questions of when and over what time period this occurred. To determine the time of emplacement of the Northland Allochthon, we use a combination of: (a) the age of the youngest rocks overlain by it; (b) the age of the youngest rocks within it; (c) the age of the oldest rocks deposited on top of it, while it was still moving; and (d) the age of rocks that were deposited on it or intruded into it, once it had come to a stop (*4.65*).

The youngest deep-sea rocks within the allochthon are the deep-sea calcareous siltstone with rhyolitic tuff beds (Puriri Formation) that occur in the south and are thought to have accumulated on top of the allochthon as it was moving in. Their age from microscopic fossil dating is latest Oligocene to earliest Miocene (24-22 Myr old).

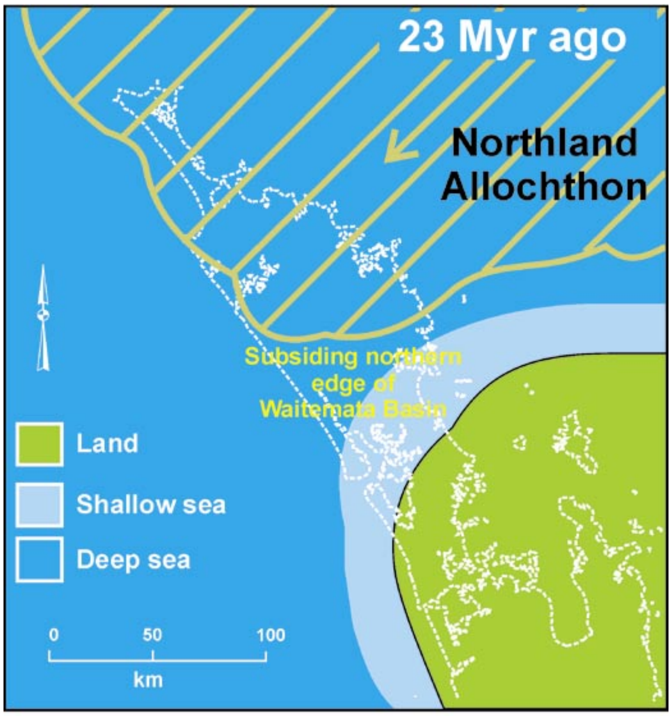
The base of the lowest displaced rocks in the allochthon is seldom visible, but where it is seen, the incoming of the allochthon often appears to have stripped off some of the underlying rocks and those that remain are too old to be of use in dating the time of emplacement. There are a few places, however, where the younger rocks have not been eroded away. In central Northland, between Kamo and Kaitaia, the youngest rocks beneath the allochthon are latest Oligocene (25-23 Myr) and in southern Northland, between Whangarei and Waipu, the youngest rocks beneath are dated at earliest



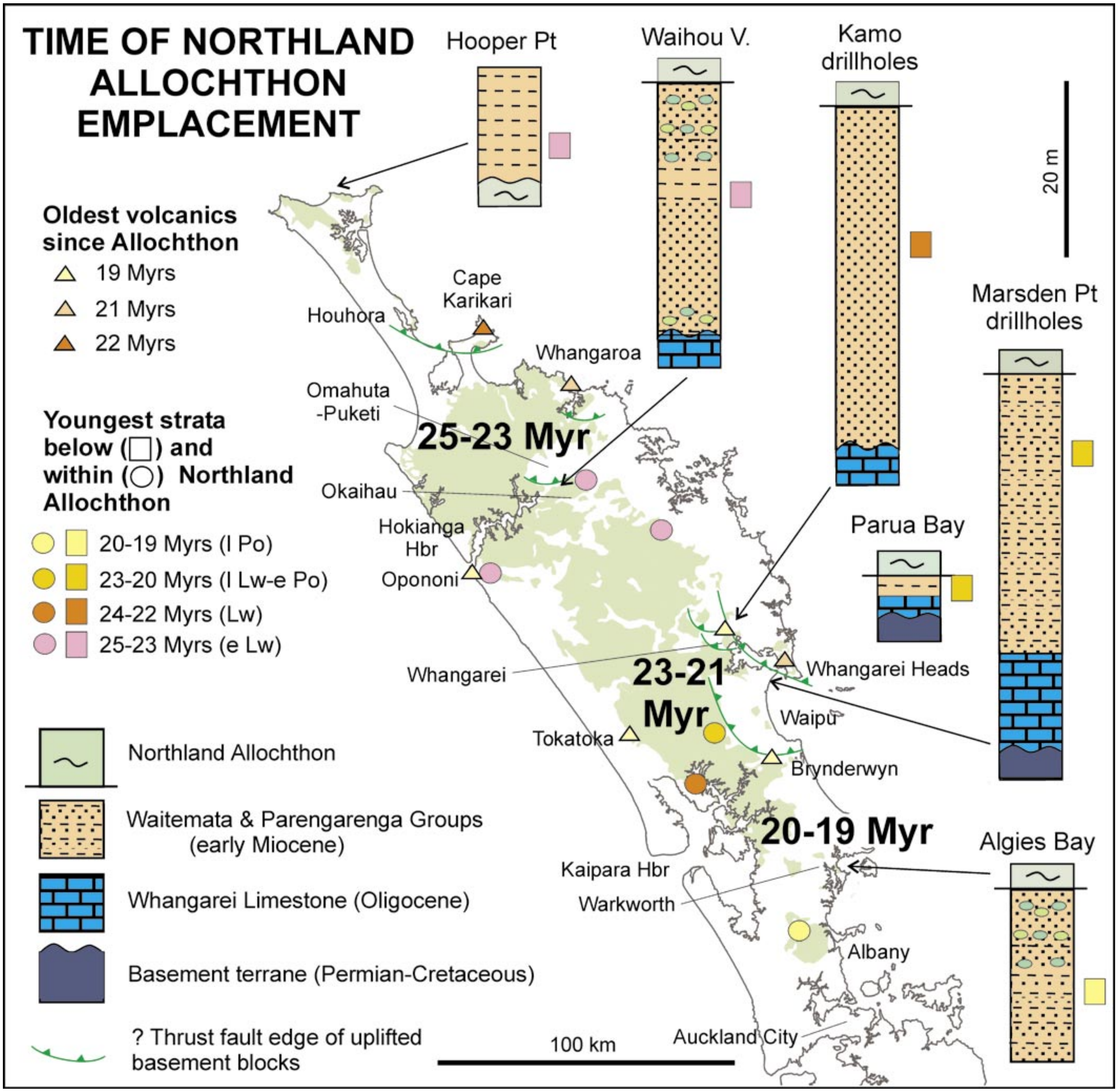
4.62 Cartoon showing how the Northland Allochthon is envisioned to have been emplaced with a succession of giant slabs being pushed up in the northeast and sliding off and down onto a subsiding Northland, between 25 and 19 Myr ago. The East Coast part of the Allochthon is not shown.

4.63 The foreshore of eastern Parua Bay is one of the few places in Northland to see the basal contact of displaced Northland Allochthon sedimentary rocks that slid in over the in-situ rocks about 22 Myr ago. The sequence and contact have been tilted up to near vertical. In-situ basement Waipapa Terrane greywacke, on the far right, is overlain by 0.5 m of shallow-water Oligocene (30 Myr old) Whangarei Limestone, which in turn is overlain by about 1 m of wavy-bedded, Early Miocene deep-water mudstone and sandstone (22 Myr old). The geology enthusiasts are all standing on the sheared allochthonous green-grey mudstones (80-55 Myr old) that lubricated the incoming of the displaced rocks, which lie to the left.

Miocene (23-20 Myr). Still further south, between Wellsford and Albany, the displaced rocks overlie, and are overlain by, Early Miocene Waitemata Sandstones dated at 21-19 Myr.



4.64 Reconstructed paleogeographic map for northern New Zealand during the earliest Miocene as the Northland Allochthon was moving onto Northland, about 23 Myr ago.



4.65 Above. Stratigraphic evidence that documents the timing (large black numbers) of southwards emplacement of the Northland Allochthon, showing the age of the youngest strata beneath and within the allochthon and the oldest strata or volcanoes on top of the allochthon. Most of the sedimentary rocks were dated using microfossils that gave dates in terms of the New Zealand Waitakian (Lw) and Otaian (Po) stages. In turn these stages have been converted into absolute time (Myr) used here.

The oldest sedimentary rocks deposited on top of the allochthon also get younger from north to south. At Hooper Point at the east end of Spirits Bay in the Far North, latest Oligocene (25-23 Myr old) shelly limestone and terrigeneous mudstone and sandstone sit unconformably over Tangihua Complex rocks in the allochthon (*4.66*). Further south in Northland, around Opononi and the Kaipara Harbour, sedimentary rocks derived by erosion from the allochthon and sitting unconformably on top of it, are of Early Miocene age (23-20 Myr). Volcanic rocks, which erupted through and over the allochthon after it came to a standstill in

4.66 Layered, light-coloured, latest Oligocene sedimentary rocks (25-23 Myr old) overlie an eroded unconformity contact on the top of dark grey Tangihua Complex volcanic rocks in the cliffs on the northeast side of Hooper Point, east end of Spirits Bay. This is one of the few places in northern Northland where sediments have been deposited on top of a slab of Tangihua rocks and constrain the time of its displacement in the Far North to before 23 Myr ago.

Northland, constrain the time of the end of emplacement. All these are dated by radiometric methods as Early Miocene with the oldest volcanic rocks at Cape Karikari being about 22 Myr, at Whangaroa and Whangarei Head about 21 Myr, and at Brynderwyn and Tokatoka at about 19 Myr old.

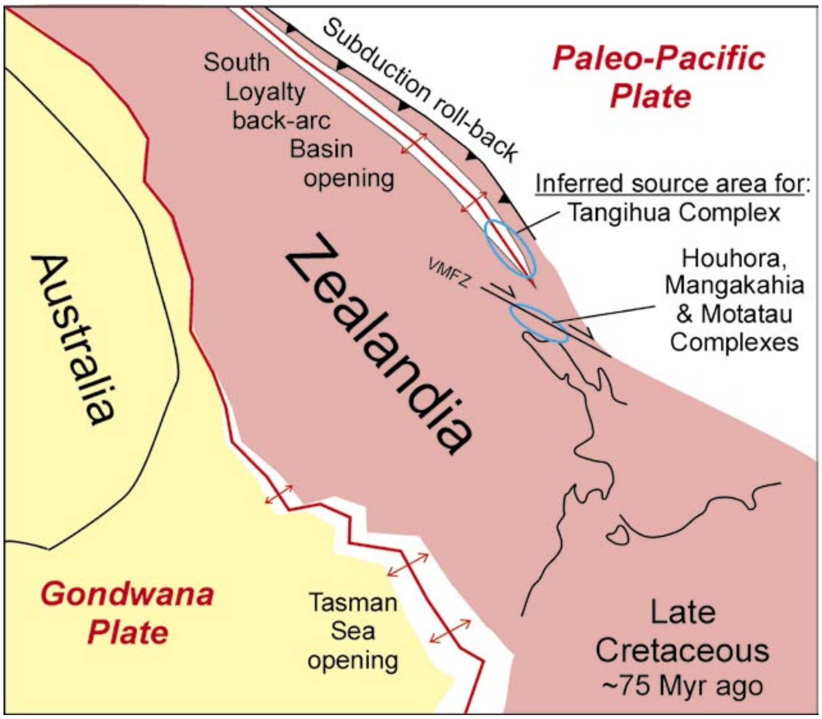
Thus the emplacement of the Northland Allochthon occurred in the latest Oligocene-Early Miocene (between 25 and 19 Myr ago) and movement was probably initiated in the source region even earlier than this. Emplacement in northern Northland occurred between 25 and 23 Myr ago and progressed southwards reaching Whangarei 23-21 Myr ago and finally with the southern toe reaching the outskirts of where Auckland city now stands, about 21-19 Myr ago.

What caused allochthon displacement?

There appear to have been two drivers of the displacement (obduction) of the allochthonous rocks onto Northland. They were pushed up in the northeast by southwest-directed compression from the subduction zone, and then they slid under the pull of gravity into the subsiding basin to the southwest. In the few places (e.g. Parua Bay) where the sedimentary sequence directly beneath the allochthon has not been stripped off, they contain microscopic fossil foraminifera characteristic of lower bathyal-upper abyssal depths (1000-3000 m). These rocks overlie Late Oligocene Whangarei Limestone (30-25 Myr old) that accumulated at shelf depths (shallower than 200 m) and thus there was a rapid deepening in Northland immediately prior to the incoming of the allochthon (25-20 Myr ago). Further south, the Auckland area subsided to similar depths somewhat later (22-20 Myr ago) prior to the allochthon front moving in down there (chapter 5).

The 3-5 km total thickness of the allochthon probably filled up the rapidly subsiding submarine basin that was being created in the Northland region as the displaced slabs slid into it. The rocks that were deposited or erupted on top of the allochthon tell us that the emplacement was followed by a period of considerable tectonic deformation and jostling, with some areas rapidly subsiding (Far North), some areas being pushed up high and still other areas being compressed from the north and northwest, creating southwards-directed thrust faults (Houhora area) or open folds (Maungataniwha Range). Many of the areas uplifted during this later phase of allochthon emplacement appear to have involved in-situ basement greywacke blocks (e.g. Omahuta-Puketi block, Whangaroa, Whangarei-Whangarei Heads, Waipu-Brynderwyn blocks) that were pushed and tilted upwards along their arcuate southern edges as they were nudged southwards. As the blocks were pushed upwards, much of their allochthonous overburden appears to have slid off to continue its journey. Evidence for the timing of this later phase of movement is present at Whangaroa and Whangarei Heads, where terrestrial (on land) volcanic rocks were erupted in the Early Miocene (from about 22-21 Myr ago) and deposited directly on top of the highly deformed and uplifted surface, which in some places had already lost all or most of its allochthonous cover.

In sequences directly beneath the allochthon at Waihou Valley (Okaihau) and Algies Bay (Warkworth), the uppermost 2-3 m of deep-water sandstone strata contain rounded pebbles of Mangakahia and Motatau Complex sedimentary rocks that had eroded off the advancing front of the allochthon as it slowly slid in.



4.67 Reconstructed map of central Zealandia about 75 Myr ago during the Late Cretaceous, showing the possible source area for the four main rock groups (complexes) that were displaced onto Northland in the Northland Allochthon around 25-23 Myr ago. First the Houhora Complex is inferred to have erupted in a continental-rift setting near the edge of Zealandia and was then partly buried by deep-sea sediments of the Mangakahia and Motatau Complexes. Further north, the Tangihua Complex ophiolite assemblage was erupted and accumulated during the Cretaceous and Paleocene, possibly as new ocean-floor in an opening back-arc basin setting (South Loyalty Basin). VMFZ = Vening Meinesz Fracture Zone.

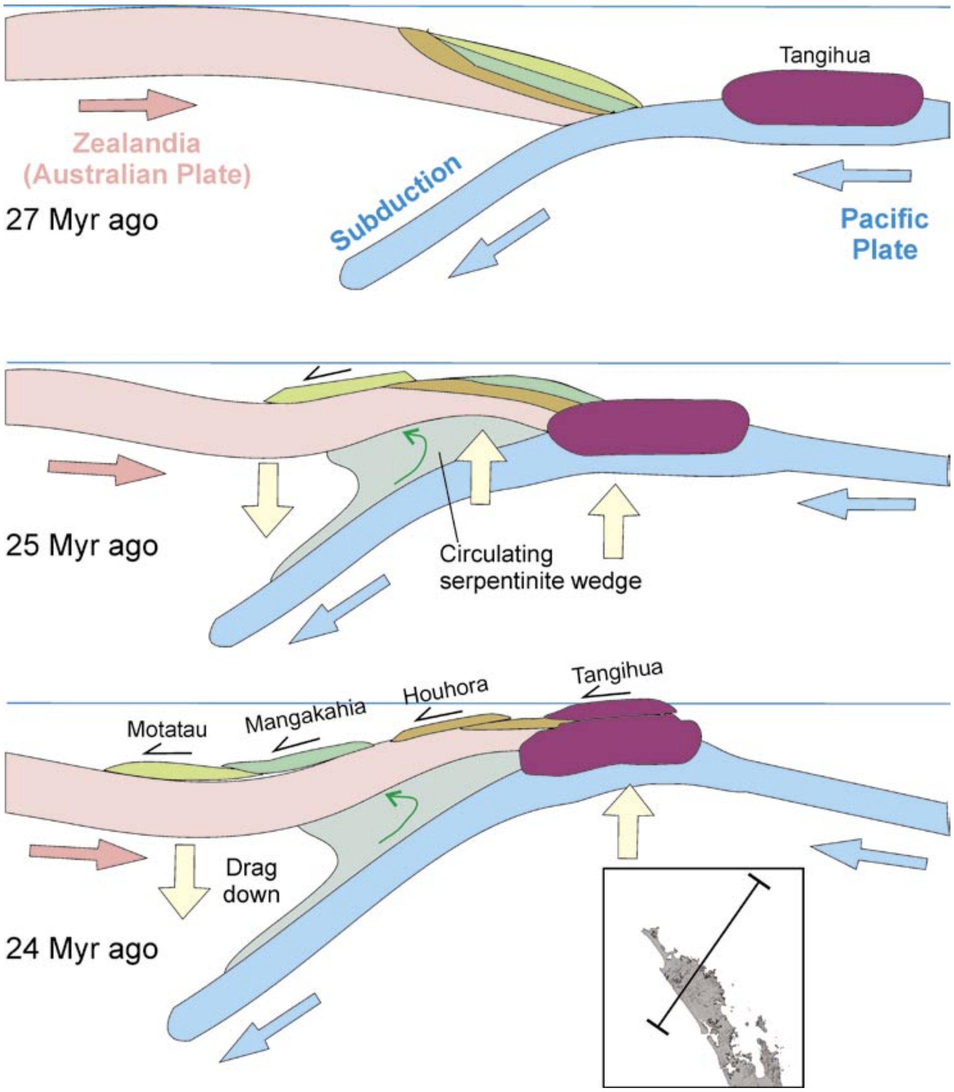
The displaced allochthon slabs clearly did not arrive in overnight landslide events, but slid in slowly or in short bursts, over tens to hundreds of thousands of years.

Since the acceptance of the concept of a Northland Allochthon to explain the north's problematic rocks, there have been a variety of plate tectonic scenarios proposed to explain what happened. To be acceptable, a model has to contain mechanisms that would result in uplifting of the displaced ocean floor rocks by several kilometres in their source area, southwards-progressing subsidence of the Northland receiving area followed a few million years later by southwards-progressing uplift. It also needs to explain the eruption of subduction-related volcanoes in Northland (see chapter 6), which started during early allochthon emplacement (25-23 Myr ago) and continuing on afterwards.

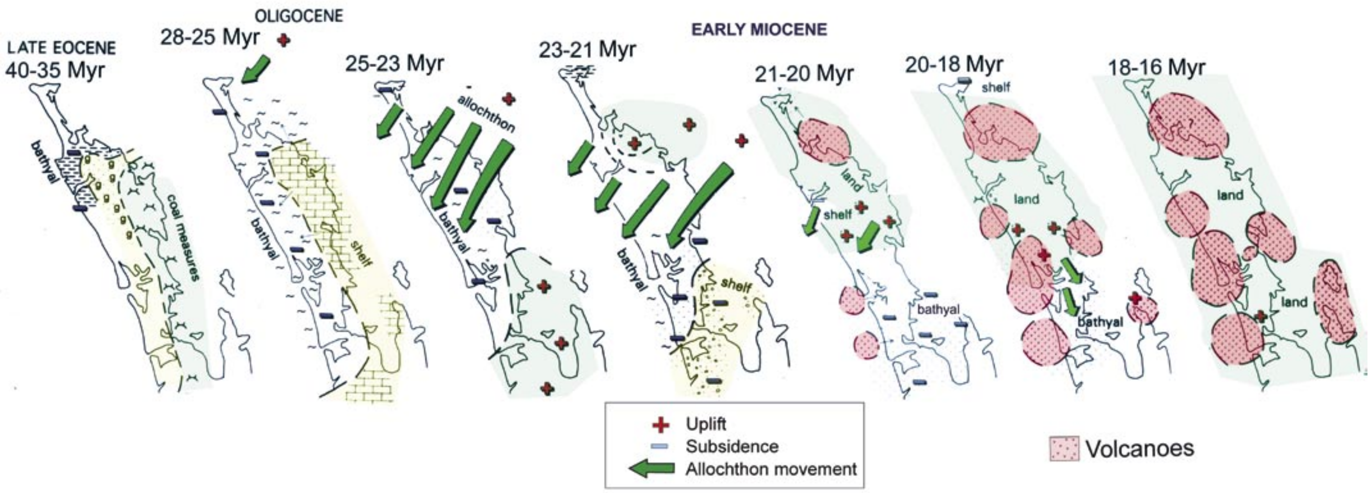
The simplest plate tectonic model that satisfies the above would have inception of a southwest-dipping subduction zone 35-30 Myr or more ago, when Pacific Plate oceanic crust, located northeast of Northland, started to be dragged down beneath the continental crust of the Zealandian coast of the Australian Plate. The Houhora, Mangakahia and Motatau Complex rocks were probably all located on the inboard Zealandian side of the plate boundary and the Tangihua Complex ophiolite assemblage on the Pacific side (*4.67*). Perhaps, about 25 Myr ago, a large mass of Tangihua ophiolites, consisting of the upper portion of the oceanic crust was carried into the upper part of the subduction zone. Being thicker and maybe lower density, these Tangihua rocks were not subducted but were pushed into the overlying continental crust. With continued compression, the Northland Allochthon source rocks in the plate boundary area were progressively pushed upwards (*4.68*).

To the southwest, continental crust could have been dragged down by the descending oceanic plate, or subduction-driven slow circulation within a wedge of altered mantle (serpentinite) could have caused subsidence of the receiving basin. Thus uplift in the northeast and subsidence in Northland provided the slope for the allochthonous slabs to slowly slide down, one after the other, under the influence of gravity – a process that would have taken several million years. Slabs from the top of the source rock sequence (Motatau) slid off first, progressively unroofing the deeper older source rocks (Mangakahia, then Houhora) that followed as the source area continued to rise (*4.68*). Eventually the more distant Tangihua rocks from the uplifted edge of the Pacific Plate came in as the last displaced slabs over the top of all the earlier ones. Some of the 3-4 km subsidence of the Northland Basin needed to accommodate this thickness of Allochthon, was undoubtedly caused by the weight of the incoming displaced rocks pushing down the underlying crust (loading effect).

The southern edge of the subducted oceanic crust, and/or the serpentinite wedge in the upper mantle, moved progressively southwards beneath Northland crust, as did the southern end of the subduction zone itself, and so the phase of subsidence moved southwards. Once the subducted edge of oceanic crust, or serpentinite wedge, had passed beneath an area, the continental crust rebounded upwards and this helped propel allochthonous sheets further into the subsiding basin. Eruptions of the Northland Volcanic Arc (chapter 6) appear to have started during the period of allochthon emplacement, but did not become widespread until a few million years afterwards (*4.69*).



4.68 Right. Cartoons showing a possible plate collisional boundary scenario to explain the displacement of the Northland Allochthon onto Northland. A large mass of Tangihua Complex rocks may have ploughed into the edge of the Zealandian continental crust and caused the plate boundary area to be uplifted. Large slabs of the uplifted rocks slid southwest into the subsiding Northland Basin over several millions of years.



4.69 Series of paleogeographic maps of northern New Zealand during the Late Eocene to Early Miocene showing the inferred changing shape of the land (light green) as different areas were uplifted (red "+") and subsided (blue "-"). These vertical movements of the crust drove the emplacement of the Northland Allochthon (green arrows). Also shown (in pink) are the periods of eruption of the major volcanoes of the Northland Volcanic Arc (chapter 6).

Chapter 5. EARLY MIOCENE SEDIMENTARY BASINS
(23-17 Myr old)

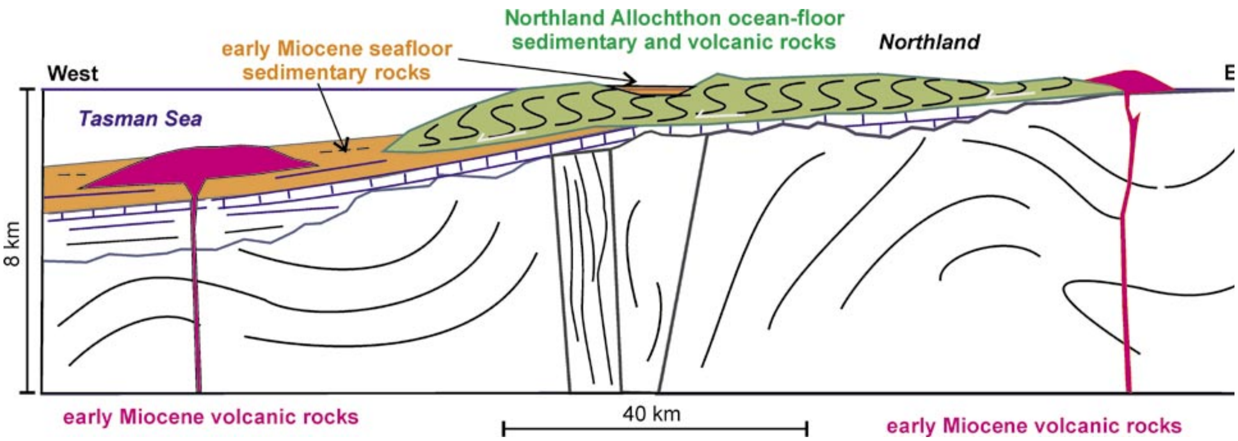
Chapter Summary

About 21 million years ago, the Auckland region began subsiding and the rolling countryside, which existed at that time, was progressively inundated and drowned by the sea. Intertidal and shallow marine gravel, sand and shell banks accumulated along the sinking coastline before the whole landscape disappeared beneath the waves. These fossil-bearing rocks (basal Waitemata Group) can be seen today along the east coast of Auckland.

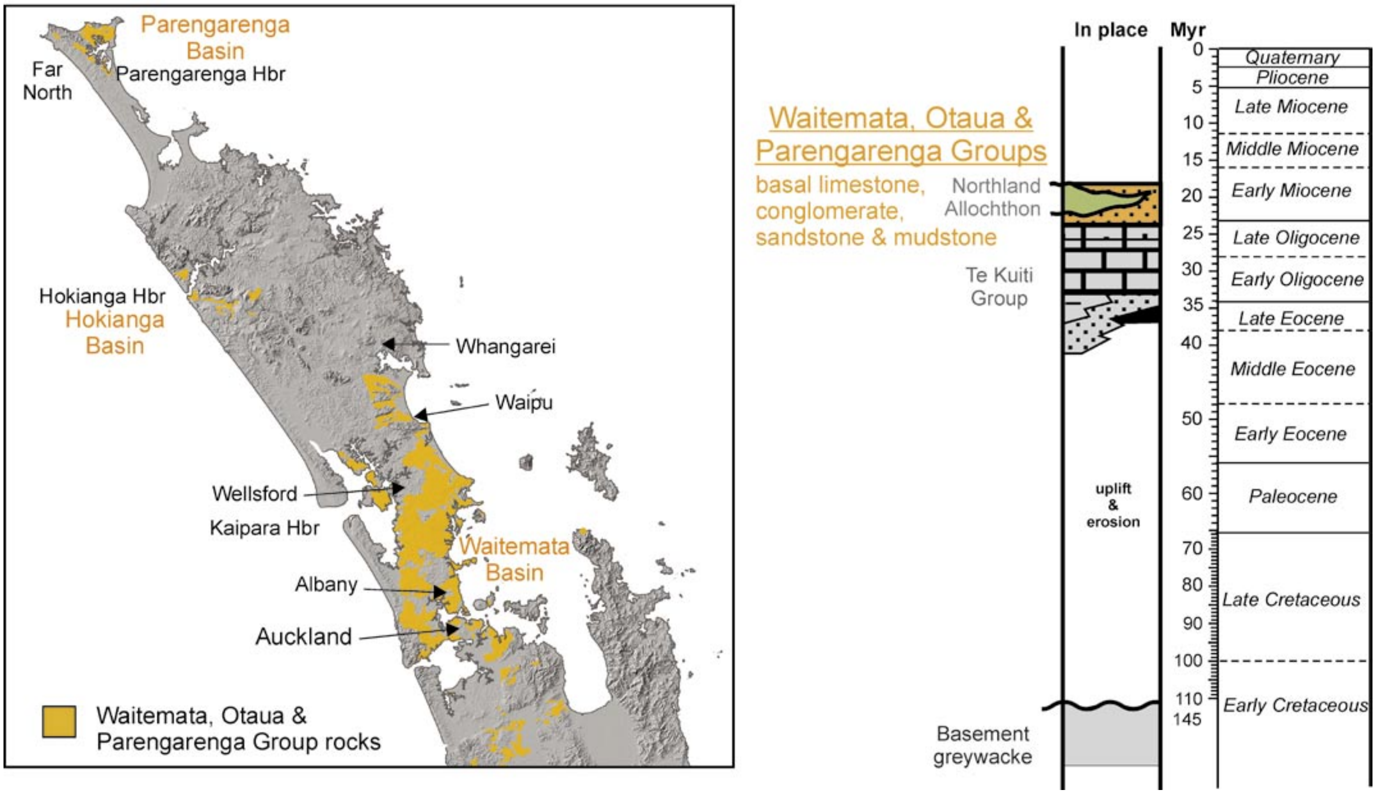
Subsidence continued for several million years, creating the 1000-2000 m-deep Waitemata Basin. The northern slopes of the basin were the southern front of the Northland Allochthon (chapter 4), which by 20 Myr ago had been partly uplifted to form a land area over Northland. Rivers carried sediment from this eroding land down to the shallow marine Kaipara shelf, on the northwestern fringes of the Waitemata Basin. From here, periodic turbulent slurries of sediment (turbidity currents) flowed down submarine canyons and deposited layers of sand (Waitemata Sandstones) on the deep floor of the basin. In the hundreds of years between individual turbidity currents, thin beds of mud, settling out of suspension, were deposited between the sand beds. Eventually 800-1000 m of interbedded sandstone and mudstone accumulated. These beds are now the dominant rock (often weathered to clay) at the surface in the Auckland region.

Between 20 and 19 million years ago, a large part of the southern front of the Northland Allochthon collapsed and slid southwards into the Waitemata Basin, causing major disruption (faulting, folding) to the strata on the basin floor. Occasionally submarine lahars (debris flows) from the active Kaipara and Waitakere volcanoes flowed down into the Waitemata Basin from the west and deposited thick volcanic grit beds (Parnell Grit) within the sandstone sequence. Between 18 and 16 Myr ago, the whole Auckland region was raised up out of the sea again and the ocean receded from the Waitemata Basin.

Even after it had been emplaced and partly pushed up out of the sea to form land, the Northland Allochthon continued to move slowly south and southwestwards. As a result some areas on top of the allochthon subsided to become small piggy-back depressions (Hokianga and Parengarenga basins), which accumulated complex sequences of marine and deltaic gravel, sand, mud and lignite. On-going movement of the underlying allochthon deformed (shunted, faulted and folded) these piggy-back strata as they were being deposited. The Early Miocene sedimentary rocks of northern New Zealand that accumulated in shallow sea water (e.g. basal Waitemata Group, Kaipara shelf, Parengarenga and Kaipara basins) contain the most diverse assemblage of marine fossils in New Zealand. Also noteworthy are the myriad of trace fossils (burrows and tracks), best preserved in the deep-water Waitemata Sandstone sequence.



5.1 Simplified cross-section through Northland in the Early Miocene (about 18 Myr ago) showing sedimentary rocks deposited before, during and after emplacement of the Northland Allochthon and subsequent uplift and west-tilting. Also shown are western and eastern belt volcanoes of the Northland Volcanic Arc that erupted during the Early Miocene (see chapter 6). Left uncoloured are the basement and Te Kuiti Group rocks described in chapters 2 and 3.

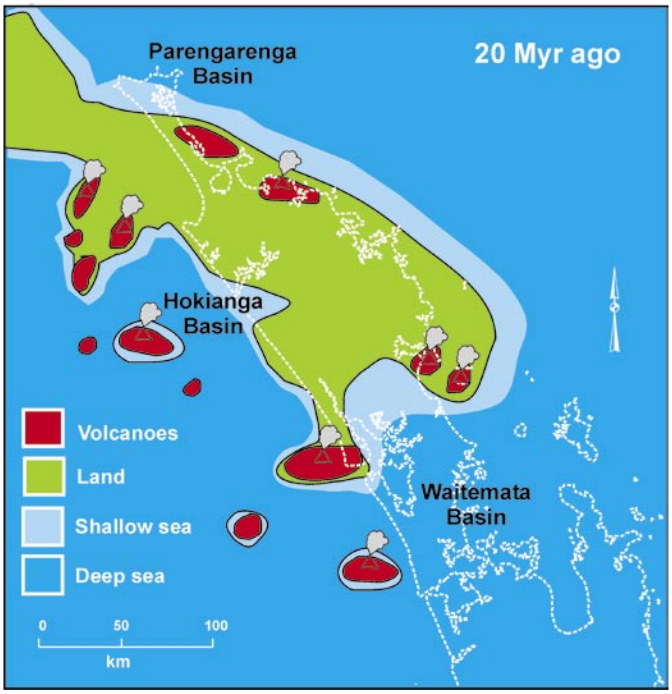


5.2 Distribution of Early Miocene sedimentary rocks in northern New Zealand and stratigraphic column showing their relationship with older rock types.

Today, Early Miocene (23-17 Myr old) sedimentary rocks occur at the surface in the Far North (Parengarenga Group), around the mouth of the Hokianga Harbour (Otaua Group) and are the dominant land-forming rock of the greater Auckland region (Waitemata Group). Small outliers are preserved at the tip of Coromandel Peninsula and between Whangarei and Waipu in southern Northland.

As outlined in the previous chapter on Northland's displaced rocks, a wave of subsidence passed southwards through Northland and Auckland during the Late Oligocene and Early Miocene (*4.69*). This was closely followed by gravity-driven emplacement of the Northland Allochthon that slid into the deep marine depression that was created. Subsidence began in the Far North about 25 Myr ago, occurred in central Northland (Whangarei region) about 23-21 Myr ago and in the greater Auckland and northern Coromandel region about 22-20 Myr ago (*4.64*).

As the various areas subsided there was time for thin sequences of sediment to accumulate on the floor of the rapidly deepening marine depression before the arrival of the displaced slides of older rocks (Northland Allochthon). In a few places these thin sequences can be seen in surface exposures (*4.63*) or have been recorded in drill holes (*4.58*). Elsewhere these Early Miocene sediments were stripped off and carried away by the incoming Allochthon. Throughout Northland, the Allochthon



5.3 Paleogeographic map for northern New Zealand during the Early Miocene, about 20 Myr ago.

largely filled the deep marine depression and thereafter most of the region was above sea level and became eroding land. In two areas, subsequent faulting and southwards movement of the Allochthon created marine depressions on top of the displaced rocks (Parengarenga and Hokianga Basins). These small "piggy-back" basins filled with sediment (Parengarenga and Otaua Groups) eroded from the surrounding Allochthon and nearby active volcanoes and were deformed by the continued slow creep of the underlying rocks.

The main body of the Northland Allochthon reached as far south as Wellsford, with a small part of its southern front breaking up and sliding further south into the Waitemata Basin (as far as Albany) about 20-19 Myr ago. The Waitemata Basin was created by the same wave of subsidence that occurred earlier in Northland, but instead of being filled with displaced Northland Allochthon rocks, 800-1000 m thickness of marine sediment (Waitemata Group) was deposited in it, between 22 and 19 Myr ago. On the northern slopes of the Waitemata Basin, Early Miocene sediment was deposited on top of the southern toe of the main Northland Allochthon, where it is now seen around the Kaipara Harbour.

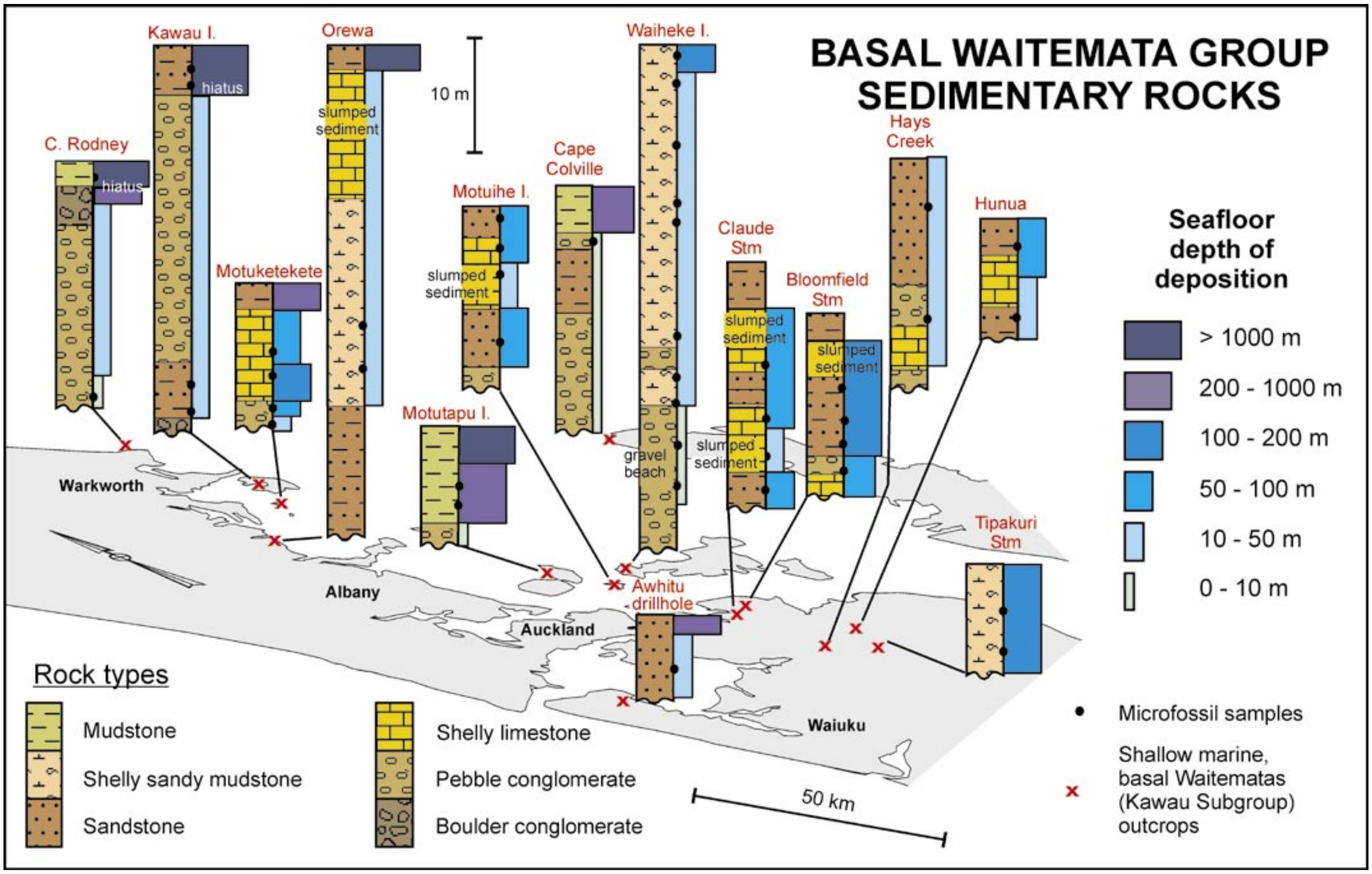
THE WAITEMATA BASIN (Waitemata Group)

Shallow marine sediment (basal Waitemata Group strata)

Prior to the start of subsidence of the Waitemata Basin about 22 Myr ago, the Auckland region was a gently dissected, rolling landscape of hills and valleys eroded into the underlying basement greywacke rocks. The oldest Early Miocene sedimentary rocks (basal Waitemata Group) were deposited in shallow marine conditions as the basin began to founder and drown the ancient greywacke coastlines of boulder beaches, cliffs and sea stacks (*5.4*). Because most of the Auckland region has been gently tilted and faulted up to the east, the basement greywackes and overlying basal Waitemata Group are mainly seen at the surface today in a belt along the east coast. They are deeply buried and hidden beneath younger rocks under central and western parts of greater Auckland. Fossil Early Miocene rocky coastlines and the thin sequence of shallow marine sediment that in places overlies them, are visible in places like Whitford, Waiheke, Motuihe, Rakino, Motutapu and Kawau islands and around Tawharanui Peninsula and Cape Rodney.

As subsidence got underway, only small islands existed above the waves and erosion of these provided limited quantities of greywacke cobbles, pebbles and sand to the coastal environment. As subsidence continued, the islands too were submerged and the supply

5.4 This 15 m-thick sandy conglomerate (basal Waitemata Group) buries an ancient greywacke sea stack on the north coast of Kawau Island. This was an exposed rocky shoreline with a gravel beach about 22-21 Myr ago.



5.5 Stratigraphic columns showing the highly variable sequences of sedimentary rocks that were deposited in shallow water as the Waitemata Basin started to founder. These rocks, known as basal Waitemata Group, outcrop along the east side of greater Auckland. Shades of blue alongside each column indicate the water depths the sediments were deposited at (based on microfossil evidence). Redrawn from Hayward (2004).

5.6 Fallen blocks of flaggy limestone (basal Waitemata Group) line part of the western shore of Motuihe Island, near Auckland. The limestone accumulated as a shallow-water shell bank while the Waitemata Basin was starting to subside 22-21 Myr ago.

of eroded sediment ceased. In places, banks of shells accumulated and these have subsequently hardened and recrystallised into lenses of limestone, such as seen in Hays Creek, near Papakura, and on Motuihe (*5.6*) and Motuketekete Islands in the Hauraki Gulf. These shallow-water sedimentary rocks often contain fossil remains of subtropical shellfish, sea urchins, coralline algae, lampshells and even occasional heads of reef coral. The richest fossil localities are at Fossil Bay, next to Church Bay on Waiheke Island (*5.7*) and at Mathesons Bay, near Leigh.

Over a period of approximately 1 million years, the whole Auckland region subsided, forming the 1000-2000 m-deep Waitemata Basin. After all the greywacke islands were submerged there was a long period of sediment starvation as the basin slowly sank. During this time only thin mudstone accumulated as it settled out of suspension from the overlying waters. In some places, former coastal rock stacks of hard greywacke were still sticking up out of the seafloor and were colonised by deep-marine giant barnacles and branch-shaped octocorals. When they died their shelly plates and skeletal hard parts fell off the rocks and accumulated in heaps in the sediment around the base of these submarine stacks (*5.8*). Eventually the basin subsided to sufficient depth that slurries of sandy sediment (Waitemata Sandstones) could flow down the submarine slopes in the north and across the basin floor, to bury the basal Waitemata Group rocks that now underlie Auckland.

5.7 Top right. This pebbly shelly mudstone (*basal Waitemata Group*) *contains fossilised bivalves* (*white outlines*) *that have been preserved in growth position* (*on edge*) *where they lived buried in seafloor sediment at inner shelf depths* (*10-50 m*)*, 22-21 Myr ago. Fossil Bay, near Church Bay, Waiheke Island, Auckland. Photo 30 cm across.*

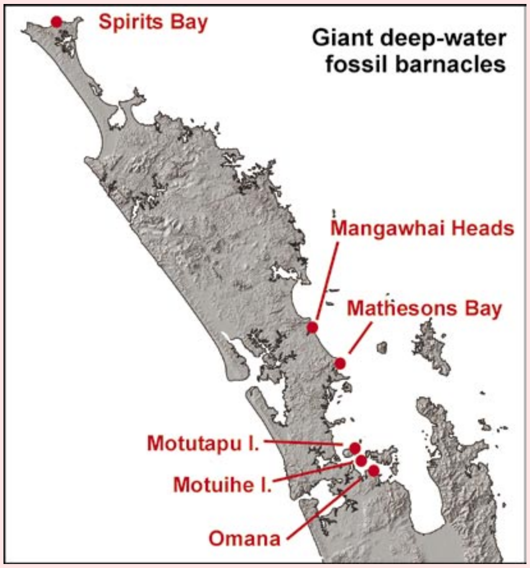
Box 17. GIANT DEEP-WATER BARNACLE FOSSILS

Most of us know of barnacles that grow on intertidal rocks, but some barnacle species live entirely below the waves. One large modern species, *Bathylasma alearum*, lives at depths of 400-1600 m around New Zealand today. They attach themselves to rocky stacks on the floor of the ocean and when they die their plates drop off and accumulate in piles around the base of the submarine rocks. The exceptionally large plates of an ancestor of this modern barnacle can be seen fossilised in 22-20 Myr-old (Early Miocene) basal Waitemata Group rocks in Auckland and Northland. The plates of the extinct barnacle (*Bathylasma aucklandica*) are mostly 10 cm long, but can be up to 17 cm.

Like their modern counterparts, the fossil giant barnacle plates also occur around the bottoms of ancient rocky pinnacles, but they are preserved in mudstone that had subsequently buried them and the pinnacle crests before the incoming of Waitemata Group turbidite sandstones. It seems that these barnacles also lived at bathyal depths on the floor of the Waitemata Basin as it was subsiding down to depths of 1000-2000 m.

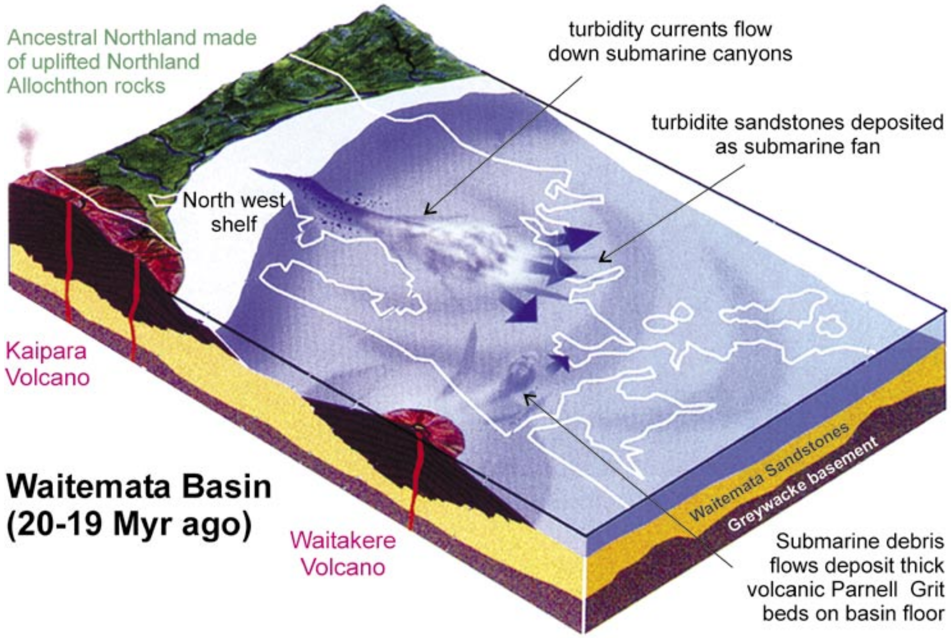
5.8 The best known locality for seeing fossil giant barnacle plates is in the mudstone (*right*) *around the side of an ancient greywacke stack on the west side of Motutapu I.*

5.9 Fossil giant barnacles often occur in heaps of individual plates that had fallen apart when the animal died and collected around the base of the hard substrate they were attached to. Also in this basal Waitemata sandstone from Motuihe Island are cylindrical internodes of the deep-water, tree-like octocoral Keratoisis*. Age: Early Miocene* (*20 Myr*).



5.10 Known localities where fossil giant barnacle plates of Early Miocene age (*~22-20 Myr old*) *can be seen.*

Deep-water, Waitemata Basin sedimentary rocks (Waitemata Sandstones)

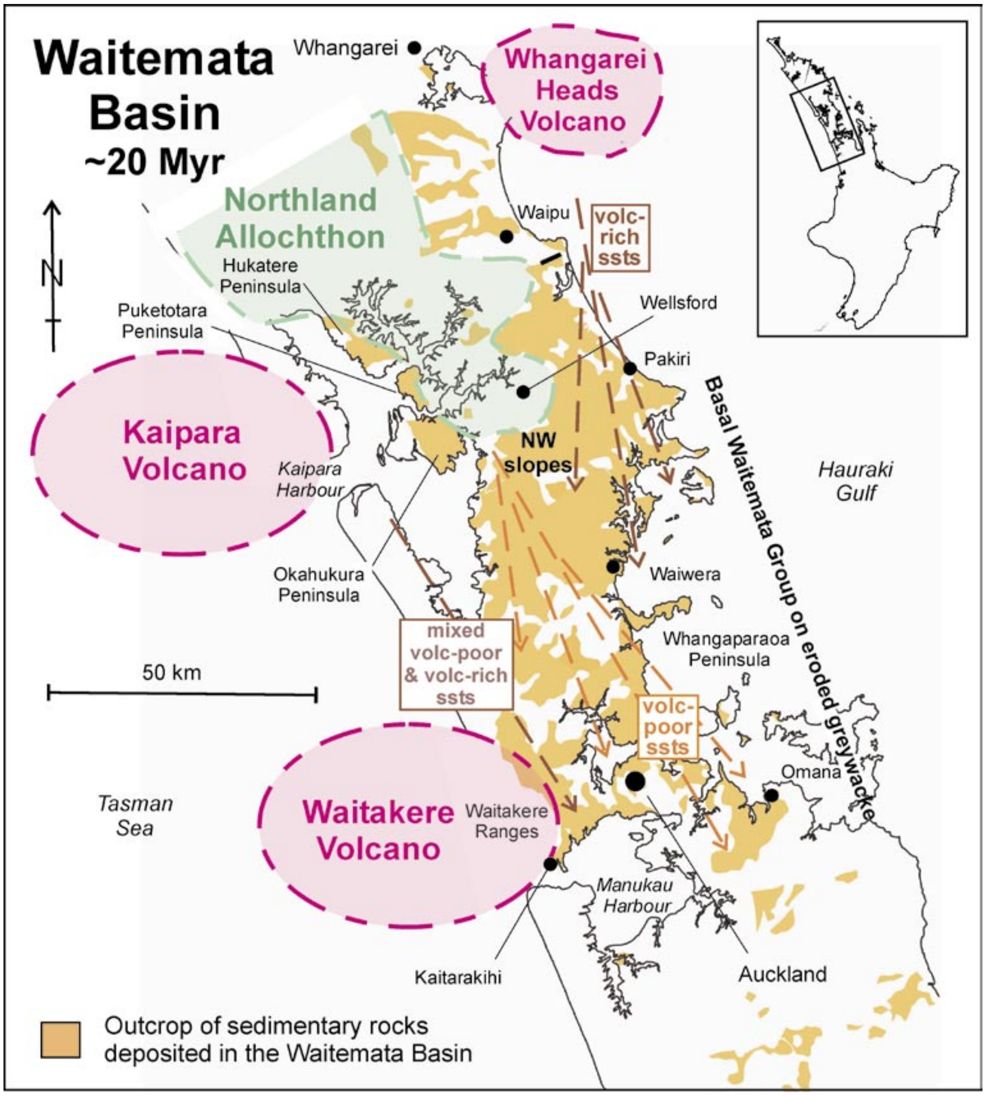


5.11 Cartoon depiction of the Waitemata Basin 20-19 Myr ago when the Waitemata Sandstones were being deposited on its deep seafloor.

Waitemata Sandstones is a general name commonly used for the alternating beds of sandstone and mudstone that underlie much of the greater Auckland region. They are easily seen forming the layered coastal cliffs (*5.12*) along the west coast of the Hauraki Gulf from Beachlands in the south, around the Waitemata Harbour and East Coast Bays as far as Pakiri in the north. They also form the coastal cliffs along the north side of the Manukau Harbour from Onehunga to Huia. Waitemata Sandstones were named after the Waitemata Harbour where they were first described by Ferdinand von Hochstetter in 1860, but otherwise they have nothing to do with Auckland's present day harbour. The sandstones accumulated in the deep marine Waitemata Basin (*5.11*) that extended across all of greater Auckland during the Early Miocene. The Waitemata Sandstones were later uplifted out of the sea to form land and vast quantities removed by erosion over many millions of years. In the east, where uplift has been greatest and where the underlying greywacke now occurs at the surface, the full 800-1000 m thickness of Waitemata Sandstones has been eroded away.

By 20 Myr ago, the whole central part of the Waitemata Basin had sunk to at least 1000-2000 m beneath the sea. The front of the displaced Northland Allochthon had advanced south into the Waitemata Basin as far as Wellsford and most of the Northland area had by then filled up or been pushed up to become land, composed mostly of eroding Allochthon rocks. Some of the streams

5.12 Flat-lying, volcanic-poor Waitemata Sandstones (East Coast Bays Formation) consisting of alternating 0.2-1 m-thick beds of sandstone and 0.1-0.2 m-thick beds of mudstone. The sandstones were transported as turbulent slurries of sand and mud down submarine canyons from the northwest and came to rest on the deep seafloor (1000-2000 m) in the centre of the Waitemata Basin. 20 m-high cliffs north of Long Bay, North Shore, Auckland.

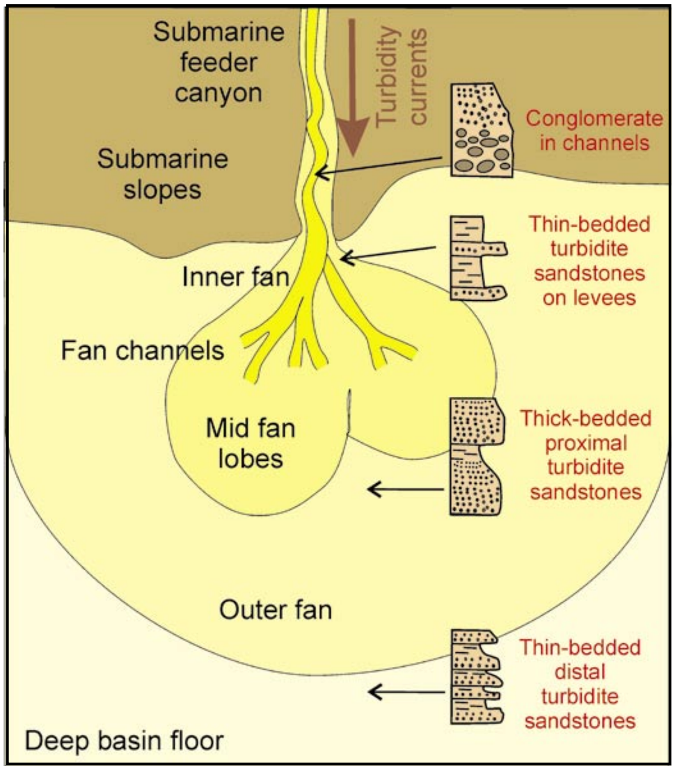


5.13 The outcrop distribution of Early Miocene Waitemata Group sedimentary rocks (*orange*) *and their relationship to the active volcanoes* (*pink*) *and displaced Northland Allochthon rocks* (*green*). *Dashed lines outline the inferred flow direction of turbidity currents that built two submarine fans in the central basin – a northern volcanic-rich sandstone fan* (*Pakiri Formation*) *and a southern volcanic-poor sandstone fan* (*East Coast Bays Formation*). *The older basal Waitemata Group sedimentary rocks* (*Kawau Subgroup*) *outcrop today along the east coast and the younger mixed volcanic-rich and volcanic-poor sandstones* (*Blockhouse Bay Formation*) *outcrop in the west. Redrawn from Hayward* (*1993*).

and rivers that drained this ancient Northland flowed southwards into the northern end of the Waitemata Basin, bringing with them a continuous supply of eroded gravel, sand and mud. This was the major source of sediment that was deposited on the floor of the Waitemata Basin, although active volcanoes also contributed sediment, especially in the north. Some sediment accumulated on the seafloor on top of the southern edge of the allochthon, whereas large quantities were transferred down into the basin in turbulent slurries of sediment called turbidity currents.

These turbidity currents were dense mixtures of sand, mud, water and sometimes gravel that flowed down submarine canyons that had cut into the northern submarine slopes of the Basin. They originated as unstable piles of sediment near the top of the submarine slope and might have been shaken loose by periodic earthquakes. The slurries passed down the canyons to the basin floor, where they dispersed to form a growing submarine fan of sediment. The submarine fan had numerous meandering channels, rather like a delta on the edge of the land. As the submarine slope decreased, so the sediment in the turbidity current began to drop out and be left behind. The largest and heaviest sediment, such as cobbles and pebbles, were the first to be dropped, often in the canyons or channels.

On the deep-sea submarine fan the turbidity currents deposited 0.1-4 m thick beds of sand, sometimes called turbidites or flysch, which hardened with burial by later sediment into the Waitemata Sandstones we see around the Auckland region today. Higher (proximal) on the fan the sandstone beds often consisted of coarse sand and were up to 2-4 m thick (*5.14, 5.16*). Sediment that overflowed the submarine fan channels was usually the finer-grained upper parts of the turbulent flows and these were deposited as thinly-bedded



5.14 Plan of a typical submarine fan formed on a deep marine basin floor at the mouth of a submarine feeder canyon in which the Waitemata turbidite sandstones were deposited.

*5.15 Thin black layers rich in carbonaceous fragments from land plants occur sporadically throughout the Waitemata Sandstone sequence. These woody horizons usually occur in the upper parts of turbidite sandstones (*Bouma horizon D; Box 18*). These carbonaceous fragments were deposited late in turbidite sandstone sequences because their low density kept them in suspension longer than sand grains. This material was presumably carried down flooded rivers to the sea and then transported in turbidity currents down to the basin depths. Location is Achilles Pt, Auckland.*

layers (1-10 cm thick) of fine sand and mud (*5.34*) that often built up banks (levees) along the channel margins (*5.14, 5.24*). Thus in northern parts of the central basin (Wellsford to Waiwera) the Waitemata Sandstones often consist of alternating packets of thick-bedded proximal turbidite sandstones deposited in the channels or their mouths, and thin-bedded fine sandstones and mudstones that built up as over-bank deposits between the channels. Lower (distal) down on the submarine fan the sandstone beds are generally thinner (0.1-1 m thick) and finer-grained (*5.12*), than closer to the source in the north.

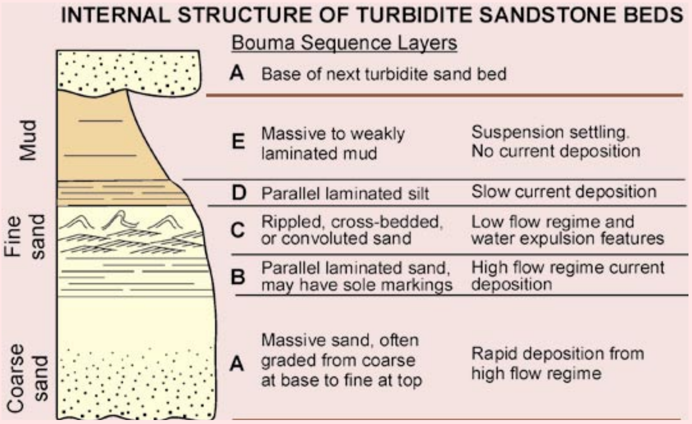
Turbidite sandstone beds almost always alternate with thin softer layers of darker-coloured mudstone. The sandstone beds stick out of the cliff or shore platform because they are more resistant to erosion than the frittering mudstone. Each sandstone bed was deposited in a matter of hours, whereas the mudstone layers were deposited slowly as mud settled out of suspension from

*5.16 1-3 m-thick beds of volcanic-rich Waitemata Sandstones (*Pakiri Formation*), like these in the cliffs at the south end of Pakiri Beach, were deposited in the northern part of the Waitemata Basin during the Early Miocene (*about 20 Myrs ago*).*

Box 18. INTERNAL STRUCTURE OF TURBIDITE SANDSTONE BEDS

Most coarse sedimentary beds (conglomerate, sandstone) that are deposited in relatively quiet deep-water settings, such as Waitemata Sandstones, are transported downslope from shallow water in turbid slurries of sediment known as turbidity currents, a form of underwater avalanche. In 1962, a Dutch geologist, Arnold Bouma, described the sequence of sedimentary structures that were typically found within a bed of coarse sediment that had been deposited by a turbidity current. This internal structure has become known as the Bouma sequence and has five recognised layers - labelled A at the bottom, up to E at the top (*5.17*). Each turbidite bed was deposited over a matter of a few hours as the turbidity current speed was waning and the slurry of material finally came to a stop. The flow regime changed progressively as the current slowed and thus a sequence of different internal structures was produced from bottom to top.

Layer A was deposited first and consists of sandstone that fines upward (normally graded) from coarse-grained sand at the base to fine-grained sand higher up (*5.19*). Layer A sometimes contains pebbles, or rip-up clasts of mudstone (*5.18*) that were eroded from the seafloor as the current passed by and were carried along in the turbulent flow. At its highest speed (about 100 km/hr) the fluid turbulence keeps even the coarsest grains suspended, but as the current slows the largest and densest grains settle out first followed progressively by smaller grains. The base of this layer sometimes has sole markings, which might be elongate scours in the soft underlying seafloor or long grooves made by sticks or shells dragged across the seafloor (*5.20, 5.21*). Sometimes the base of the sandstone bed might have eroded into the underlying strata.

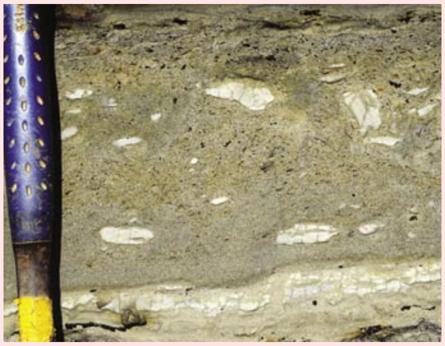


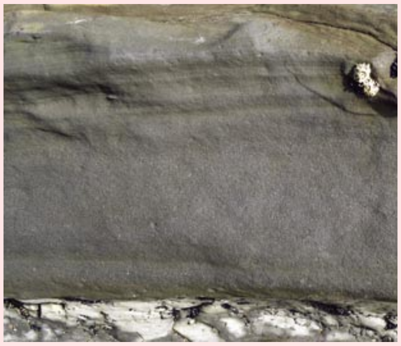
5.17 Diagram summarising the sequence of internal sedimentary structures found in a complete turbidite sandstone bed, such as in the Early Miocene Waitemata Sandstones around Auckland.

Layer B is horizontally-laminated fine- to medium-grained sandstone deposited from traction flow in which the sand grains slid and rolled across the seafloor.

Layer C consists of ripple-laminated fine-grained sandstone (*5.22*) deposited from a slower flow regime where grains bounce along across the seafloor (saltation) and current ripples develop. Often these ripples are deformed into convolute laminations and flame structures by shear and water expulsion (*5.23*), as later turbidites flow over the top or earthquakes shake the seafloor.

Layer D is horizontally-laminated silt deposited by suspension settling from the slowly moving fine cloud of silt that accompanies the tail of the turbidity current. This layer sometimes contains low density carbonaceous material (*5.15*), such as leaves or twigs that had also been carried along.





5.18 Left. Rip-up clasts of mudstone in the basal coarse sand (layer A) of a Waitemata Sandstone turbidite bed. The rip-ups are inferred to have been picked up from the seafloor and carried along by the passing turbidity current. Musick Pt, Auckland.

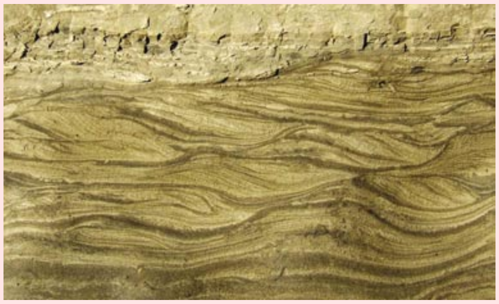
5.19 Middle. A Waitemata Sandstone turbidite bed showing graded massive sand (layer A) overlain by plain laminated sand (layer B) above. Cream mudstone (layer E) at bottom separates this sandstone bed from the one below. Takapuna Cliffs, Auckland.

5.20 Right. Groove casts on the underside of a thin Waitemata Sandstone bed (layer A) that were made by sticks, shells or pebbles being dragged across the seafloor by the passing turbidity current. Flow direction was from bottom right to top left. Whangaparaoa Head.

Box 18 continued

Layer E is massive to weakly laminated mudstone, which accumulated by slow background deposition of suspended mud that occurs between turbidity currents. Layer E and carbonaceous horizons in D are often full of trace fossils made by burrowing organisms that lived in the seafloor sediment (Box 19).

This is the full ideal sequence within any one sandstone bed deposited by a turbidity current, but often not all of the sequence is present in any one bed for a variety of possible reasons such as removal of E by later erosion, or non-deposition of A because the bed was deposited on the bank and not in the main channel of the turbidity current's path.



5.21 Left. Scour marks made by a passing turbidity current are preserved here as casts on the underside of a Waitemata Sandstone bed (layer A). Flow direction was from top right to bottom left. Whangaparaoa Head, Auckland east coast.

5.22 Middle. The upper part of a Waitemata Sandstone turbidite bed showing 30 cm of ripple-laminated fine sandstone (layer C) overlain by 5 cm of planar-laminated siltstone (layer D) and 10 cm of weakly laminated mudstone (layer E). Atiu Creek Regional Park, Okahukura Peninsula.

5.23 Right. The original ripples in this laminated fine sandstone layer (C) within a Waitemata Sandstone turbidite bed have been exaggerated into convolute flames by left to right shear and upwards water expulsion, possibly induced by the arrival of another turbidity current on the seafloor above. Width of photo 75 cm. Atiu Creek Regional Park, Okahukura Peninsula.

5.24 An Early Miocene submarine channel eroded in a deep-sea sandstone-mudstone sequence and filled with several 1 m-thick volcanic-rich sandstone beds. Kaitarakihi, north Manukau Harbour coastline.

the water column above, over hundreds of years between the arrival of each gravity-driven turbidity current. The rate of mud accumulation was in the order of 1 cm per 100 years. To roughly estimate the time taken to deposit all the sediment exposed in a cliff, you can measure the thickness of mudstone between the sandstone beds in centimetres and multiply by 100 years.

Most of the Waitemata Sandstone beds around

Box 19. TRACE FOSSILS

Trace fossils are the burrows, borings, tracks and traces left by organisms and preserved within rocks. They can be present in all kinds of sedimentary rocks, but are most common in mudstone and sandstone deposited in marine settings, especially in deeper water where shell fossils are rare. Almost the only signs of former life preserved within the widespread Waitemata Sandstone turbidite beds and Mahurangi Limestone (Motatau Complex) are trace fossils. Both accumulated at about 600-3000 m depth and contain a wide variety of trace fossils, mostly of soft-sediment-burrowing organisms.

5.25 These 5 cm-diameter burrows have been backfilled with sand as the heart urchin that made them was pushing and eating its way through the seafloor sediment. Note the meniscus structure in the burrow fill (burrows named Scolicia*), which indicates the direction the animal was moving.* Scolicia *burrows are quite common in many of the sedimentary rocks in northern New Zealand. Waitemata Sandstone, ~20 Myr old, Cape Horn, Manukau Harbour.*

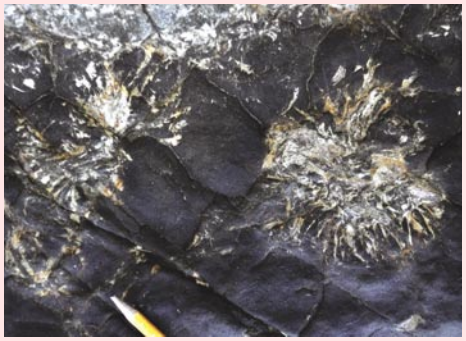
5.26 This 15-cm-deep, steep-sided hole filled with pebble conglomerate is the fossilised feeding burrow of a 20 Myr-old eagle ray (burrows named Piscichnus waitemata*). They occur commonly in the shallow-water, coarse sedimentary rocks (basal Waitemata Group) around Mathesons Bay, Leigh.*

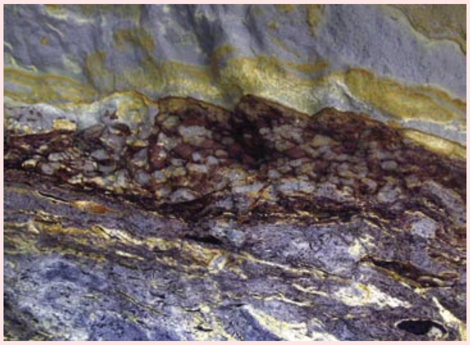
5.27 Trace fossil burrows may be large or small. These are 1-2 mm in diameter and were probably made by marine polychaete worms. ~18 Myr old, Okahukura Peninsula, Kaipara Harbour.

5.28 This 4 cm-diameter burrow is part of a much larger network of branching burrows (Thalassinoides nodosa) *probably made by callianassid shrimps. Note the mud balls that the shrimp has plastered on the inside walls of the burrow to help stop it from collapsing. It is preserved in a Waitemata Sandstone sequence that was deposited at ~600-3000 m depth, about 19 Myr ago. Kaitarakihi Bay, Huia, west Auckland.*

5.29 This siltstone within a Waitemata Sandstone sequence has been extensively burrowed, possibly by sediment-eating worms. Atiu Creek Regional Park, Kaipara Harbour. Photo width 50 cm.

Box 19 continued





5.30 Left. Large vertical burrows and smaller oblique and horizontal ones were excavated by crustaceans into the firm wall of a ~17 Myr-old submarine canyon. Seen at Bartrum Bay, south of Muriwai, west Auckland.

5.31 Middle. Two 10 cm-diameter clusters of radiating burrows (?Radionereites) *preserved in glauconitic sandstone of Late Eocene age* (*~40 Myr old*) *at Pahi, Kaipara Harbour.*

5.32 Right. Shipworm borings (Teredo) *in water-logged wood are sometimes preserved as trace fossils, as seen here within the Waitemata Sandstone sequence at Beachlands, Auckland, ~20 Myr old. Photo width 20 cm.*

5.33 This jumbled heap of broken blocks of bedded sandstone and mudstone is part of a submarine slide deposit that partly filled a submarine canyon on the northwest slopes of the Waitemata Basin about 19 Myrs ago. The cliff near Orongo Pt, Okahukura Peninsula, central Kaipara Harbour is 15 m wide.

Auckland City (south of Waiwera) are composed of sand grains derived predominantly from the erosion of Northland Allochthon sedimentary and igneous rocks in ancient Northland. In this area the sandstones are volcanic-poor and the rocks are formally known as East Coast Bays Formation. Studies of past current direction indicators (*5.20-5.22*) suggest that they mostly flowed down submarine canyons from the northwest, in the vicinity of the present-day central Kaipara Harbour. On the Kaipara peninsulas of Hukatere, Puketotara and Okahukura, there are incised submarine canyons and channels mostly filled with cobble conglomerate (Matapoura Conglomerate) and chaotic piles of submarine slide blocks of sandstone and mudstone (*5.33*). Associated with these, there are considerable thicknesses of thin-bedded over-bank deposits of fine sandstone and mudstone (Timber Bay Formation).

North of Waiwera, most of the sandstones are composed of sand grains derived from andesite or basalt volcanoes that were erupting at the time. Here, many of the Waitemata Sandstone beds are thicker than 1 m and they are said to be volcanic-rich and sometimes referred to as Pakiri Formation (*5.16*). The exact location of the active volcanoes that were the source of the sand in the northern volcanic-rich proximal sandstone beds is not known for sure. They might have been in the area of present day Whangarei Heads and could have been partly over-ridden by later southwards movement of the

5.34 These thin-bedded, rippled, fine sandstone and mudstone beds (Timber Bay Formation) are inferred to have accumulated as overbank deposits of sediment that overflowed submarine channels as turbidity currents (sediment slurries) flowed down the northwestern submarine slopes of the Waitemata Basin. Puketotara Peninsula, Kaipara Harbour.

5.35 Several 10 cm-thick, brown-coloured beds of andesitic volcanic ash (tuff) within a deep-sea sequence of mixed volcanic-rich and volcanic-poor sandstones, Kaitarakihi, north Manukau Harbour coast. These tuff beds are inferred to have been erupted into the air by the nearby Waitakere Volcano.

Northland Allochthon. The eroded Whangarei Heads and Hen Island volcanoes, now present in this vicinity, were erupted through and over the Northland Allochthon and might be younger products from the same volcanic centres.

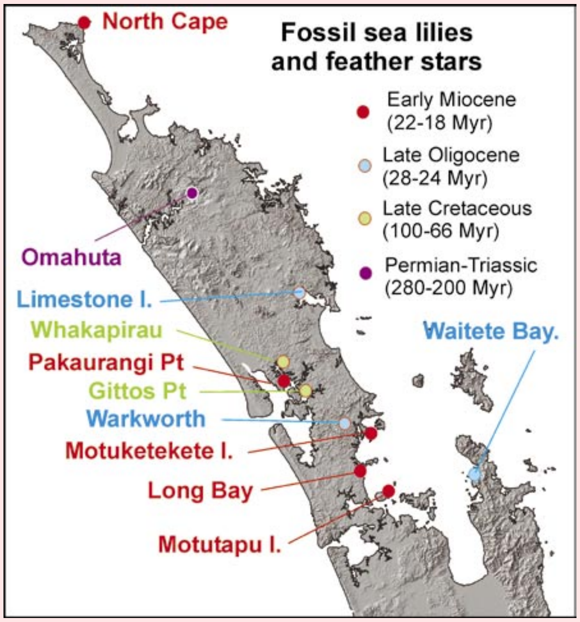
As noted earlier, most of Auckland and Northland is tilted or faulted up to the east and thus the older Waitemata Sandstone beds can be seen exhumed and outcropping at the surface along the eastern side of the peninsula. Further west, in the eastern foothills of the Waitakere Ranges and coastal cliffs of the north Manukau Harbour, the younger Waitemata Sandstones are a mixed bag, with some being volcanic-poor and derived from the erosion of Northland Allochthon, whereas others are volcanic-rich and were presumably derived by erosion of the nearby active Waitakere and Kaipara volcanoes. In some places there are 1-10 cm-thick beds of coarse, sandy volcanic ash (tuff; *5.35*), which were probably erupted into the air from the Waitakere Volcano. The coarse ash landed in the surrounding sea and sank to the deep seafloor, creating a layer composed almost entirely of volcanic, sometimes pumice-rich, ash. These younger Waitemata Sandstones in the west are said to be mixed volcanic-poor and volcanic-rich and have been given the formal name, Blockhouse Bay Formation.

5.36 The easternmost outcrop of Early Miocene sediments that were deposited in the Waitemata Basin occurs at Fletchers Bay, northern tip of Coromandel Peninsula. Here the eroded and east-tilted strata form an extensive shore platform. The oldest rocks (left) are shallow marine basal Waitemata Group pebble conglomerate and cross-bedded sandstone. These are overlain by a deeper-water sandstone and mudstone sequence containing a 10 m-thick Parnell Grit bed (far right, beyond picture).

Box 20. FOSSIL SEA LILIES AND FEATHER STARS

Sea lilies and feather stars are marine animals that belong to the Class Crinoidea in the Phylum Echinodermata, which also includes starfish, sea urchins, sea daisies, and sea cucumbers. Sea lilies are crinoids that possess a flexible column permanantly attached to the seafloor by a cemented holdfast or by a multi-cirried stalk, which holds the animals to the bottom. Feather stars are unstalked crinoids that also possess small cirri (*5.40*) that enable the animal to cling to objects. Crinoids have arms that branch off from the body and spread out in a circular fan around the mouth to facilitate filter-feeding. The long arms have hair-like cilia that trap floating food particles and move them down grooves towards the upturned mouth. Crinoid stalks and arms are composed of calcareous ossicles, usually with five-sided symmetry, and these are the parts most commonly found preserved as fossils.

Crinoids have a long evolutionary history going back 450 Myr (Ordovician). In northern New Zealand, crinoid stem and arm ossicles (rarely whole specimens), have been found fossilised in marine sedimentary rocks of Permian-Triassic (280-200 Myr; sea lily), Late Cretaceous (100-66 Myr; sea lilies), Late Oligocene (28-24 Myr; feather stars and sea lilies) and Early Miocene (20-18 Myr; feather stars and sea lilies) age.

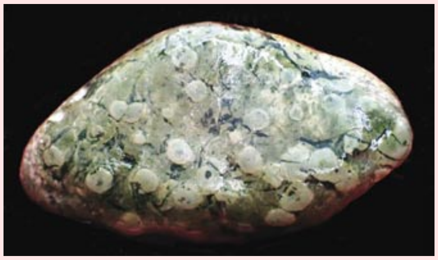


5.37 Localities where fossil sea lilies and feather stars have been found in northern New Zealand.

5.38 A living sea lily.

5.39 The fossilised body and feathery arms of a 20 Myr-old sea lily found in Waitemata Sandstones at Motutapu Island, Auckland. Length of specimen 15 cm. University of Auckland collection.

5.40 Three living feather stars (unstalked crinoids) dredged from 1000 m of water, south of Stewart Island. Photo width 12 cm.



5.41 This small pebble contains some of the fossilised remains of an unidentified sea lily that has eroded out of Caples Terrane rocks in the Omahuta-Puketi block, Northland. It is Late Permian age (280-250 Myr old) and is the only fossil so far found in the Caples Terrane outside of the South Island. Found by Liz Hoskin. Photo width 3 cm.

5.42 Fossil specimen of the body (left) and closed-up arms of a 20 Myr-old (Early Miocene) sea lily from the basal Waitemata Group rocks, near Auckland. Photo width 10 cm. University of Auckland collection.

Parnell Grit

Within the central parts of the Waitemata Basin there are sporadic 1-20 m-thick beds of darker-coloured, volcano-sourced sediment (*5.44*) that often range from pebbles at the base of the bed through grit to coarse and medium sand at the top. These beds are in stark contrast to the thinner-bedded and lighter-coloured Waitemata Sandstone beds around them and have been given the name Parnell Grit after the cliffs at Parnell Baths (*13.33*), where they were first recognised by Ferdinand von Hochstetter in 1860. Parnell Grits are believed to have been sourced from volcanic eruptions on land or islands. They are easily distinguished from the volcanic-poor Waitemata Sandstone beds by the presence of numerous red grains of volcanic rock (*5.43*) that were oxidised when erupted into the air. Many of the older Parnell Grit beds contain pebbles and cobbles and occasionally blocks (up to 20 m across near Army Bay, Whangaparaoa Peninsula) of basalt, with an unusually low amount of silica. The location of the former volcano that was the source for these beds is not known. Younger Parnell Grit beds, which occur within the mixed volcanic-rich and volcanic-poor sandstone area further west, contain cobbles and pebbles of andesite and occasionally rhyolite (Riverhead bridge) that suggest they were sourced from the Waitakere, Kaipara or surrounding smaller volcanoes.

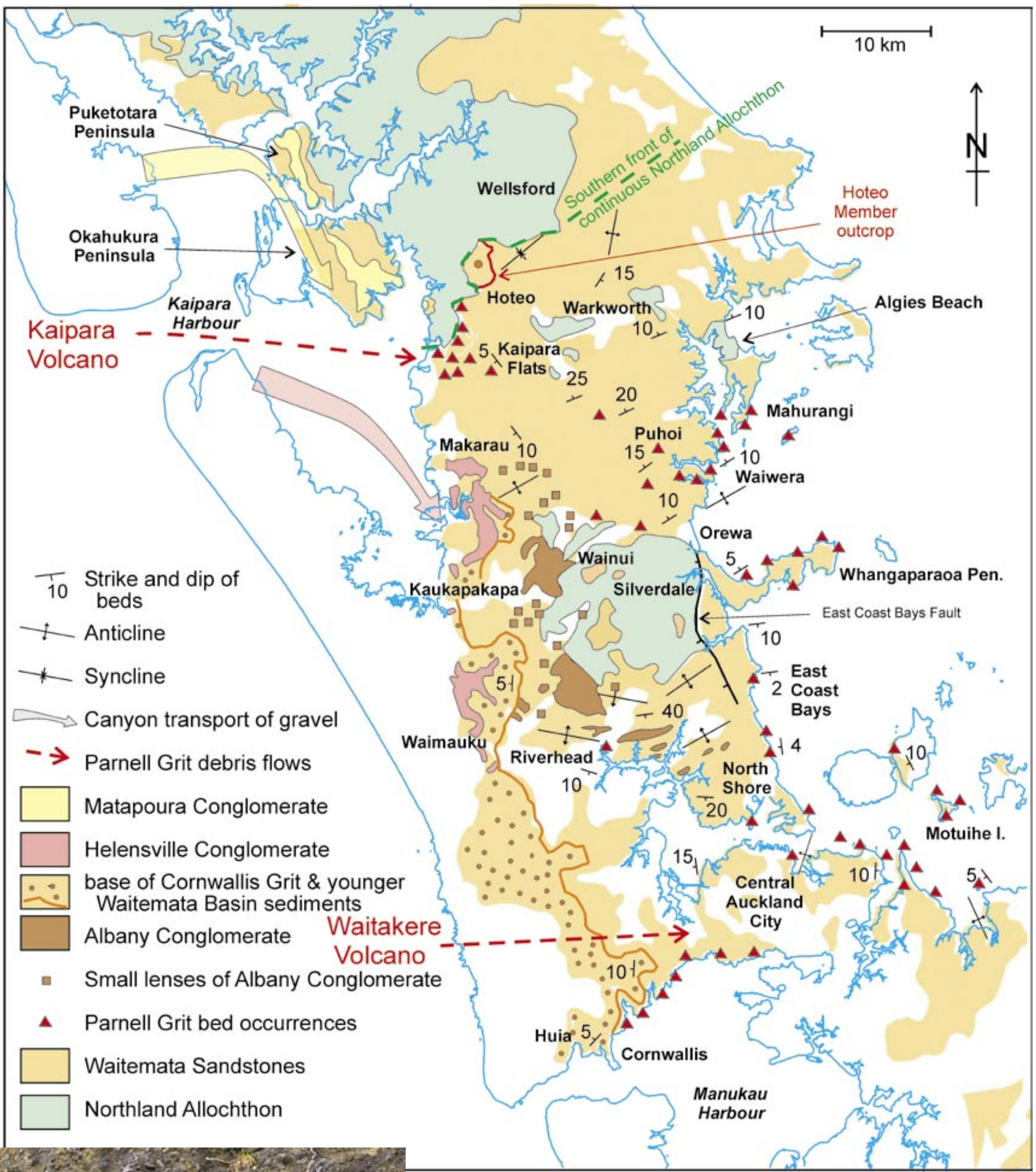
Most of the sediment in the Parnell Grit beds is volcanic in origin, but they often also contain blocks of Waitemata sandstone and mudstone ripped up from the seafloor they flowed across (*5.46*). As these blocks were carried along, they have often been partly rounded, broken apart and sometimes plastically folded into contorted shapes. Some Parnell Grit beds contain numerous pieces of shell, commonly of bryozoa, but also molluscs, foraminifera and occasionally coral. These fossils suggest that some of the grit beds had accumulated as unstable piles of coarse sediment in the shallow seas just off the coast of an active volcano and had possibly been shaken into movement downslope by an eruption-related earthquake.

Like the Waitemata Sandstones, Parnell Grit beds were deposited by submarine sediment gravity flows, but of a different kind. These were non-turbulent and much denser flows called "debris flows" rather like the "wet concrete" lahars that flow down some volcanoes on land. Their density allowed them to carry along large blocks and boulders. As they took up sea water while flowing down the seafloor slopes, the denser particles tended to get left behind and only the finer volcanic grit and sand often reached the central floor of the Waitemata Basin. It has been suggested that collapses of a large sector of an unstable volcanic cone on land might have sent large quantities of chaotic volcanic debris avalanching into the sea and down the submarine slopes as these Parnell Grit debris flows. Some travelled 30-40 km from source, with the most distant occurring at Fletchers Bay (*5.36*) at the tip of Coromandel Peninsula, although the location of its source volcano is unknown.

5.43 Close-up photo of part of a volcanic debris flow deposit (Parnell Grit) that occurs within the Waitemata Sandstone sequence at Castor Bay, North Shore, Auckland. Parnell Grits are characterised by coarse sediment containing both fresh (grey) and oxidised (red) volcanic (andesite and basalt) pebbles and grit. The more rounded, softer pebbles are mostly weathered pumice. Width of photo 25 cm.

5.44 The 20 m-thick darker layer is a typical bed of volcanic Parnell Grit that flowed as a debris flow down the submarine slopes of an active volcano and was deposited on the floor of the Waitemata Basin, about 20 Myr ago. The lighter layers beneath are typical Waitemata Sandstone. Motuihe Island, Auckland.

5.45 Distribution at the surface today of some of the major elements within the Waitemata Basin – Parnell Grit beds; Northland Allochthon rocks; Albany, Matapoura and Helensville Conglomerates; and the base of the Cornwallis Grit and other younger sedimentary rocks that accumulated in the Basin. Also shown are major structural features and the inferred downslope flow directions of gravels and Parnell Grit.



5.46 Left. The coarse, cobbly, lower part of a 15-m-thick volcanic Parnell Grit bed sitting on alternating sandstone and mudstone of the Waitemata Sandstones at Waiwera. The lower contact has been slightly eroded into the underlying beds by the passing of the submarine debris flow. The large, yellow-brown block within the deposit is Waitemata Sandstone that has been ripped up from the seafloor and carried along as the debris flow moved down into the basin.

Conglomerates

Beds of well-rounded cobble and pebble conglomerate occur within the Waitemata Sandstone sequence in the northwestern part of the Waitemata Basin (*5.45*). Their distribution reflects their inferred source, by erosion of harder Northland Allochthon rocks and Kaipara Volcano andesite, which formed land adjacent to the northwest shelf in the central Kaipara area during the Early Miocene. The rounding of the cobbles and pebbles probably occurred as they rolled down streams and rivers enroute to the sea or by tumbling on high energy beaches.

The oldest of the conglomerate units (Albany Conglomerate) is dominated by Tangihua Complex pebbles (especially coarsely crystalline diorite and gabbro and altered ocean-floor basalt; *5.47*). It occurs in thick piles, several hundred metres thick, around Kaukapakapa and Riverhead Forest. Thinner sheets and lenses also occur as far south as Albany. In places it sits directly on top of Northland Allochthon and is overlain by, or interfingers with, Waitemata Sandstones and thin-bedded overbank sandstone and mudstone. The thickest deposits are inferred to have accumulated at bathyal depths (500-2000 m) in and around the mouths of newly formed submarine canyons as they were starting to build up a submarine fan on the flatter basin floor. Many Albany Conglomerate lenses have subsequently been deformed and might have steeply-dipping bedding.

Further west, between Waimauku and Makarau in northwest Auckland, there is another, slightly younger unit of thinner, mostly gently-dipping conglomerate (Helensville Conglomerate), which is dominated by cobbles of andesite with far fewer cobbles and pebbles derived by erosion from the Northland Allochthon. This probably reflects the growth of the andesitic Kaipara Volcano, which by then was providing more eroded rocks to the northwest shelf. Like the Albany Conglomerate, the Helensville Conglomerate beds are inferred to have flowed down submarine canyons from the northwest and were deposited as they reached the gentler slopes on the floor of the central basin.

Another conglomerate (Matapoura Conglomerate; *5.48*) is exposed as lenses in cliffs around Puketotara and Okahukura peninsulas, on the Kaipara Harbour. This conglomerate has a near equal mix of cobbles and pebbles derived by erosion from the Northland Allochthon (igneous and sedimentary sources) and the active Kaipara Volcano (fresh andesite). In some places these lenses can be seen to be filling canyons or channels that were presumably the conduits down which the turbidity currents flowed as they transported gravel, sand and mud from the shelf down into the depths of the basin to the southeast.

5.47 A typical exposure of the gabbro, diorite and altered basalt pebble conglomerate (derived from Tangihua Complex) that is widespread in the Kaukapakapa and Riverhead Forest areas, north of Auckland City. They are inferred to have been deposited in the mouth of submarine canyons at the foot of the northwestern submarine slopes within the Waitemata Basin about 20 Myr ago.

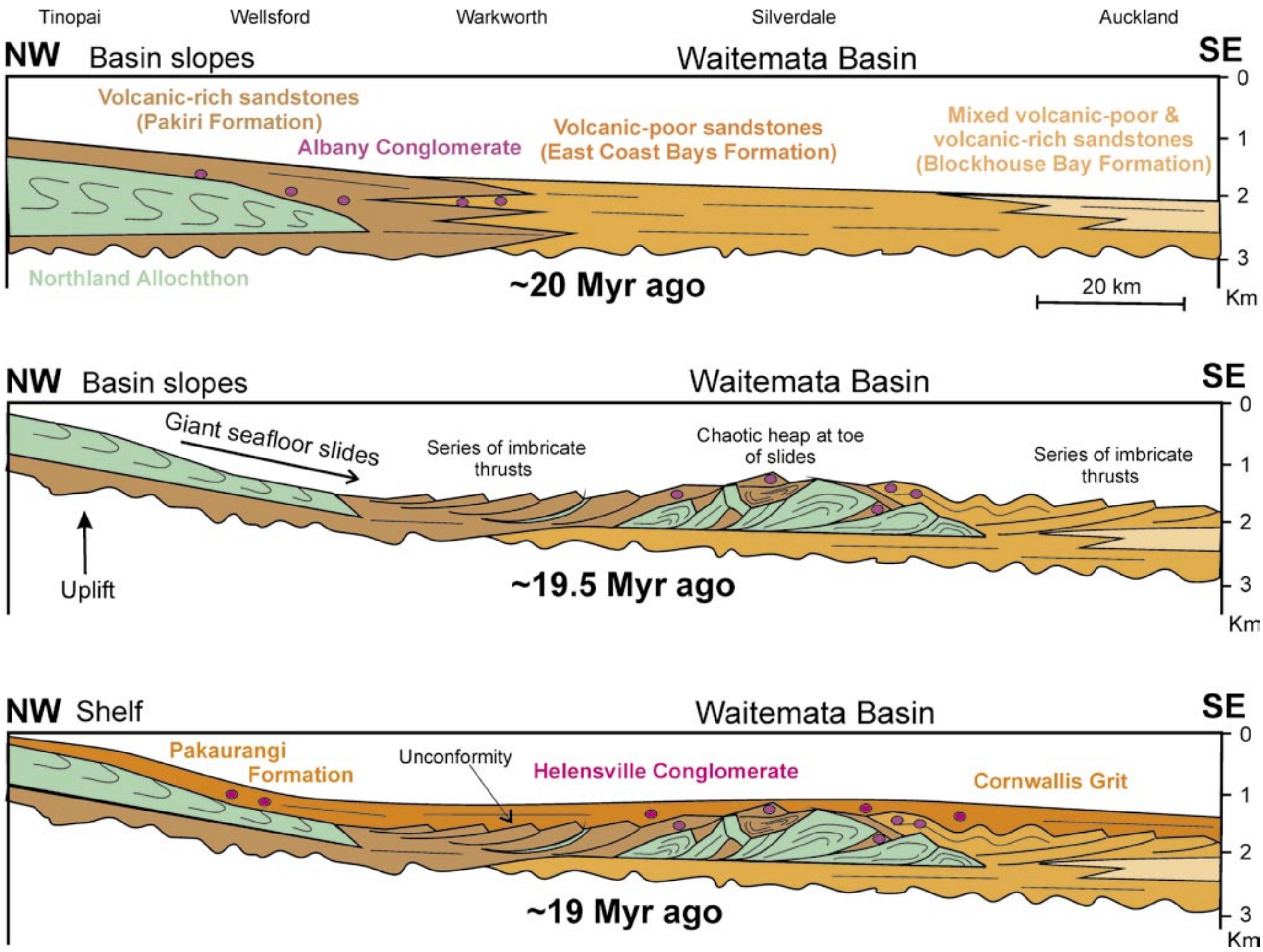
5.48 Matapoura Conglomerate on Puketotara Peninsula, Kaipara Harbour, contains well-rounded cobbles and pebbles of grey igneous rocks eroded from Tangihua Complex and Kaipara Volcano and less rounded cream pebbles of Motatau Complex limestone. Photo 1 m across.

Giant seafloor landslides on the northern slopes

A jumbled heap of fault blocks of Northland Allochthon rocks and Waitemata Sandstone, covering an area of about 200 km^2, outcrops at the surface west of Orewa and Silverdale. This heap occurs within the sequence of Waitemata Sandstones that was deposited on the floor of the deep Waitemata Basin near the foot of its northern submarine slopes. There are also many scattered occurrences of blocks and thrust fault slivers of Northland Allochthon rocks north of the jumbled heap, within the Waitemata Sandstone sequence and seen at places like Algies Beach, Warkworth and Kaipara Flats (*5.45*).

A likely explanation for these displaced blocks is that a portion of the southern toe of the Northland Allochthon, underlying the upper northern slopes of the Waitemata Basin, became unstable and slid down slope into the depths of the basin in one or more giant seafloor landslides, between 20 and 19 Myr ago. The slides carried along, broke up, and folded the overlying Waitemata Sandstones that had been deposited on top of the allochthon before it failed. As the slides moved into the central basin floor, they would also have ploughed into and crunched up the existing sandstone sequence there. This might have caused much of the chaotic deformation within the volcanic-poor sandstones that is seen in many places around the sea cliffs of Auckland and East Coast Bays north to Mahurangi. Detailed study of the direction of folding and low angle (thrust) faulting, by structural geologist Bernhard Spörli, indicate movement from northwest to southeast, which is consistent with a giant seafloor landslide explanation.

Mapping by field geologist Jim Schofield in the



5.49 Three northwest-southeast cross-sections showing how the envisaged uplift of the Kaipara Shelf area, 20-19 Myr ago, initiated giant seafloor failures of Northland Allochthon and overlying Waitemata Sandstones, which slid southwards into the Waitemata Basin causing considerable deformation. This was followed by a resumption of turbidity current deposition (Cornwallis Grit) unconformably on top of the disturbed basin fill.

1980s, showed that the basin floor sandstones in front of the main heap of Northland Allochthon blocks have been rucked up into a series of large folds that swing around its southern front (*5.45*), presumably formed as the slide ploughed into the seafloor. Further north, around Mahurangi and Kaipara Flats, in the area through which the landslide passed, the sequence appears to be a series of northwest-dipping thrust sheets of Waitemata Sandstone and some Northland Allochthon (*5.45, 5.49*). These tabular blocks are inferred to have slid down the northern slopes after the main landslide(s), one after the other, and have become piled up like a skewed stack of cards. The total volume of these seafloor landslides probably exceeded 200 km^3.

In the Kaipara source area of these inferred seafloor slides, there is evidence of uplift about 20-19 Myr ago as the Waitemata sequence shallowed upwards from mid bathyal (600-1000 m) sediment (Timber Bay Formation) into fossil-rich, muddy sandstone and shell grits (Pakaurangi Formation). The numerous molluscs and other fossils in these younger sedimentary rocks indicate that they accumulated at inner to mid shelf depths (0-100 m). This shallowing was probably produced by uplift accompanied by earthquakes, which could have triggered the giant slides. Swelling clays within the Paleocene and Eocene mudstones (Mangakahia Complex) of the Northland Allochthon possibly helped lubricate these slides. Folding, faulting and unconformities are more abundant in the Pakaurangi and older Waitemata Basin strata that still sit on top of Northland Allochthon in the Kaipara area, than in the younger overlying Early Miocene (18-16 Myr old) volcanic-rich sedimentary rocks in the same area. This suggests that the underlying Northland Allochthon was still slowly sliding southwards into the deep Waitemata Basin right up until about 18 Myr ago.

*5.50 Shelly sand (*Pakaurangi Formation*) accumulated on the shallow marine shelf on the northwest margin of the Waitemata Basin about 18 Myr ago. In this photo there are fossil bivalves, gastropods and a tusk shell. Photo width 20 cm.*

The southern front of the continuous Northland Allochthon from which the submarine landslides probably broke off, is today located just south of Wellsford (*5.45*). Between the Waitemata Harbour and

*5.51 Bluffs of a distinctive, thick calcareous sandstone (*Hoteo Member*) within the Waitemata Sandstone sequence can be followed for 5 km west of Wellsford. The sandstone sits unconformably over disrupted blocks of Northland Allochthon and Waitemata Sandstones (*grassed lower slopes*), which are inferred to have been part of a giant seafloor landslide on the northern slopes of the Waitemata Basin about 19.5 Myr ago. As with most of the younger western belt of Waitemata Basin filling sediments, the beds are tilted gently to the west (*left*).*

Wellsford, the Waitemata Sandstones can be seen to occur in three north-south-trending belts with different levels of deformation. The oldest, eastern belt (seen in the coastal cliffs) consists of sections of flat-lying undeformed strata separated every few kilometres by zones of intense folding and faulting. This belt is inferred to have been deposited on the basin floor well before the large landslides came in. The incoming of the landslides appear to have put north-south compressive pressure on these underlying strata; they have broken into separate slabs that have been shunted together creating the intensely deformed zones between them.

The middle belt contains the chaotic landslide blocks, many tilted up at crazy angles, the thrust sheets that came in behind, and also the steeply folded strata in front of the landslide. This belt also contains the Tangihua-dominated Albany Conglomerate deposits, which presumably were also displaced southwards by the landslides and therefore were originally deposited around the mouths of submarine canyons, 20-30 km to the north. Also within the main landslide heap, west of Orewa, are numerous small lenses of serpentinite (Tangihua Complex) that occur in the sheared Northland Allochthon mudstone horizons between individual harder blocks. In the landslide heap is the southernmost occurrence of altered seafloor basalt flows of the Tangihua Complex. It is located at Flat Top Hill, Wainui, and is one of the main sources of quarried aggregate used in northern parts of Auckland.

5.52 The distinctive flaggy, calcareous sandstone (*Hoteo Member*) *that was deposited on top of the jumbled rocks in the seafloor slide has "cross-bedded" horizons* (*angled down to the left*). *These are not sedimentary in origin, but may be cemented shear planes from slight downslope movement of the unit, after it was deposited and partly hardened. Inland bluffs, southwest of Wellsford.*

5.53 Thick beds of grit and sandstone of mixed origin (*Cornwallis Grit*) *can be mapped for 50 km through the younger western part of the Waitemata Basin, between Makarau and the Manukau Harbour. Here in a Huia road cut, thick Cornwallis Grit beds are interbedded with thin beds of fine sandstone and mudstone.*

The youngest, western belt appears to have been deposited on top of the disrupted landslide deposits in the northern half of the Waitemata Basin. They are mostly flat-lying or gently-dipping to the west. Just south of Wellsford, a distinctive, 15-m-thick, calcareous sandstone (Hoteo Member, *5.51, 5.52*) sits directly over the disrupted beds and can be traced as a prominent bluff across the skyline when viewed from SH 1. Further south, between Makarau and the northern shores of the Manukau Harbour, gently-dipping beds of thick-bedded grit and sandstone, called Cornwallis Grit (*5.53*), lie unconformably over the older folded and faulted strata of the middle belt. These grit beds have a mixed composition derived from andesitic and allochthon rocks and appear to be proximal turbidite beds that flowed down into the younger Waitemata Basin from the Kaipara shelf. The rounded boulder and cobble-bearing Helensville Conglomerate has a similar mixed provenance and occurs in lenses probably deposited in channels within the Cornwallis Grit sequence, north of Waimauku (*5.45*).

Deformation

In many places the Waitemata Sandstone sequence has amazingly complex structure, especially for rocks so young. Most of this structure can be classified as folds and faults with different characters and varying orientations. Folds refer to bends in the strata resulting from at least locally compressional forces – an upfold is called an anticline (*13.36*) and a down-fold is called a syncline (*5.57*). Faults are fractures along which the rocks have moved, displacing one side with respect to the other. Displacements can be in a vertical direction (up and down) or sideways (lateral) or often a combination of both. If the overlying side of a sloping fault has moved downwards with respect to the underlying side, it is called a normal fault (*5.54*) and displacement was a result of tension (pulling apart that created space). If, however, the overlying side has been pushed upwards over the underlying (a reverse fault), the movement was produced by compression (reducing the amount of available space). A low angle reverse fault (less than about 45°) is called a thrust fault.

Structural geologists, like Auckland University's Bernhard Spörli and Julie Rowland, make detailed studies of the structure of the rocks (faults and folds) and can determine the sequence of deformation events and the stress directions that produced them. In the Waitemata Basin, the most complex and chaotic structure appears to have formed first and been a result of gravity-driven, southeastwards-directed slope failures within the strata on the northern slopes (between Kaipara and Auckland). Seafloor slumping of the upper tens of metres of strata involved soft rocks that were easily folded and contorted. Sometimes several layers were folded up into a series of tight folds, like a rucked-up mat, while a more coherent slab of strata above stayed together as it slid over them. In other places all the nearby strata have broken apart and been folded into a variety of contorted shapes by the near-surface slumping.

Deeper in the more consolidated sedimentary pile, down-slope movement also occurred and produced more breakup or rupturing of the brittle sandstone beds and thrusting of

5.54 This small normal fault has displaced consolidated Waitemata Sandstone strata downwards on the left, by about 20 cm. Motuihe Island.

5.55 The Waitemata strata on the right have been thrust southeastwards over the sandstones on the left. Road-cutting near Puhoi. Photo width 5 m.

5.56 During its downslope slide, this Waitemata Sandstone bed has rolled up around itself, with the central section breaking off as the fold tightened. Little Manly, south side Whangaparaoa Peninsula. Photo 1.5 m across.

5.57 This upright anticline and syncline leaning to the right in Waitemata Sandstone, were produced during the southward gravity sliding of the upper parts of the sequence. North side of Whangaparaoa Peninsula.

5.58 These rucked-up Waitemata Sandstone strata, sandwiched between undeformed flat-lying beds, were tightly folded as the block of strata above, slid downslope over the top of them. Okura, North Shore.

5.59 These Waitemata Sandstone strata, forming 80-m-high Whangaparaoa Head, have been folded up to near vertical during gravity-driven submarine landsliding.

older strata over younger, in a southeast direction. As discussed above, a great deal of this deeper deformation possibly was the result of one or a series of major seafloor landslides that were possibly enhanced by the plastic swelling clays in some of the underlying Northland Allochthon strata. Some of the larger-scale folds, evident in the central part of the Waitemata Basin, might have formed at this time, whereas other large open folds might have been produced, along with an overall general westward tilt during uplift of the basin, about 18-16 Myr ago.

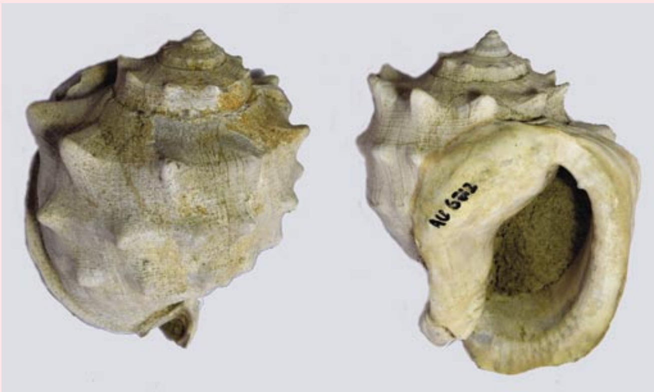
Later still, the structurally complex Waitemata strata were displaced by two sets of steep faults, trending northeast and northwest, some with major displacements. This probably occurred during the block faulting phase of deformation of northern New Zealand, during the last 5 Myr (see chapter 10).

Box 21. EARLY MIOCENE SUBTROPICAL FOSSILS

The most diverse marine fossil assemblages in New Zealand occur in Early Miocene (23-17 Myr old) sedimentary rocks of Northland and Auckland, especially in the shallower marine settings (0-200 m) of the Parengarenga and Hokianga basins and the northwest shelf (Pakaurangi Formation) of the Waitemata Basin. Other quite different assemblages of somewhat rarer fossils are those that lived on rocky intertidal and shallow subtidal coasts and are found in the basal Waitemata Group rocks of east Auckland (especially at Waiheke and Kawau islands and Mathesons Bay).

One of the reasons why the fossils are more diverse than elsewhere is that northern New Zealand was subtropical in the Early Miocene, with sea water about 5-7°C warmer than at present. Warmer subtropical and tropical marine areas have far more species than cooler temperate areas. Another reason for the greater fossil diversity is the wide variety of shallow-marine habitats represented in the sedimentary rock record of northern New Zealand.

5.62 These two, small, Early Miocene (18 Myr old) cone shells (Conus amoricus) *come from the northwest (Kaipara) shelf of the Waitemata Basin. Cone shells are tropical and subtropical shallow marine gastropods (snails). No cones live around the main islands of New Zealand today because it is too cool, although a few specimens colonised Parengarenga Harbour in the 1980s, but did not establish a breeding population. Width of photo 4 cm. University of Auckland fossil collection.*



5.60 Two beautifully ornamented, subtropical, Early Miocene (18 Myr old) helmet shells (Echinophoria hectori) *from the Parengarenga Basin, Te Pokere cliffs. Helmet snails live in seafloor sand at inner-mid shelf depths (0-100 m) and prey on heart urchins. Width of photo 10 cm. University of Auckland fossil collection.*

5.61 This 2-cm-diameter button is the fossilised operculum (cat's eye) of a large Early Miocene cat's eye snail. When the snail retracted its whole body back into the shell, the operculum was pulled tightly shut, like a door, across the shell's aperture (opening) for protection from predators and to prevent drying out. From Kawau Island. University of Auckland fossil collection.

5.63 A large, 15-cm-diameter, subtropical cat's eye snail (Sarmaturbo superba) *from the Early Miocene (20 Myr old) basal Waitemata Group beds on Kawau Island, Auckland. It is related to the much smaller modern cat's eye snail that occurs around New Zealand today. Like its modern descendants, it lived on the rocky shore and grazed on the algal film growing on the rock surface. University of Auckland fossil collection.*

Box 21 continued

5.64 These are the two halves of a giant, 17-cm-long, oyster from Early Miocene (18 Myr old) sedimentary rocks of the Parengarenga Basin exposed in Paratoetoe cliffs, on the northern side of Parengarenga Harbour. Large fossil oysters, like these, are quite common fossils in the Early Miocene rocks of northern New Zealand, where they were able to grow to this size in the warm-subtropical, shallow-marine conditions. University of Auckland fossil collection.

The more abundant and diverse fossils are molluscs – mostly gastropods (snails) and bivalves, but also a few scaphopods (tusk shells), cephalopods (*Nautilus* and cuttlefish) and even some back plates of chitons. Over 1000 species of fossil mollusc have been found in Early Miocene marine sedimentary rocks of Northland and Auckland. Other shallow marine fossils include lampshells (brachiopods), shelly polychaete worm tubes (serpulids), solitary and colonial shelly corals (scleractinians), fish teeth, barnacles, bryozoa, coralline algae (rhodoliths), sea eggs, larger foraminifera, and rare shrimps, crabs and starfish.

5.65 Early Miocene (18 Myr old) sandstone rock at Pakaurangi Point, near Tinopia, Kaipara Harbour, full of the disc-shaped shells (1 cm across) of an extinct tropical-subtropical foraminifera (Miogypsina intermedia). *They accumulated on a small, shallow-marine shell bank on the northwest shelf of the Waitemata Basin. Foraminifera are shell-bearing amoeba. Width of photograph 25 cm.*

5.66 These large flattened discs (up to 4 cm across) are the fossil shells of unicellular amoeba-like protists, known as foraminifera. These Early Miocene (20 Myr old) specimens of the extinct genus Lepidocyclina *are the largest known foraminifera found in New Zealand. Their closest modern relatives are less than half the size and live in shallow marine sediment in tropical and subtropical climates. These specimens come from Hokianga Basin sedimentary rocks in Taita Stream, Waimamaku Valley. University of Auckland fossil collection.*

PIGGY-BACK BASINS (Parengarenga and Hokianga)

Parengarenga Basin

Up to 3500 m thickness of partly eroded, Early Miocene sedimentary rocks (Parengarenga Group) occur in the Far North around Parengarenga Harbour through to North Cape. These sediments were deposited on top of the Northland Allochthon after it had slid into this area, but before it had fully come to a standstill. The continued movement might have been responsible for some of the deformation (folding, tilting, faulting) of the Parengarenga strata, especially as the older rocks are more folded and faulted than the younger ones. The continued movement within the Allochthon might also explain why there were times when same parts of the piggyback Parengarenga Basin were pushed up and other times when parts were forced downwards. In this context piggyback refers to the sedimentary basin being moved along on top of the Allochthon as the basin was accumulating sediment.

The sequence consists of a basal pebbly limestone deposited on top of Tangihua Complex rocks in the latest Oligocene (about 24 Myr ago). It contains numerous, fossilised giant barnacle plate fossils that had lived attached to deep-sea (deeper than 400 m) rocky pinnacles (Box 17). This limestone is overlain by up to 400 m of sandstone and mudstone derived by erosion of adjacent uplifted parts of the Allochthon and then 400-700 m of andesite conglomerate (Kaurahaupo Conglomerate; *5.67, 5.69*). The cobbles and pebbles in this conglomerate appear to have been eroded from active volcanoes to the south, perhaps those near Cape Karikari or Whangaroa (Chapter 6). These gravels would have been transported north by rivers and then down submarine canyons to rapidly fill up the deep-water basin. The upper parts of the conglomerate accumulated in channels in an estuarine and terrestrial delta.

5.67 Well-rounded andesite conglomerate (*Kaurahaupo Conglomerate*)*, derived from erosion of an active volcano to the south, was deposited in deltaic and shallow marine environments in the Parengarenga Basin during the Early Miocene* (*about 22-20 Myr ago*)*. Kaurahaupo Rocks, North Cape.*

Overlying the conglomerate is the thickest part of the basin sediment fill (2000-2500 m), a shell-bearing

5.68 Sea cliffs along the northern shore of Parengarenga Harbour are composed of a thick sequence of shelly sandstone and mudstone (*Paratoetoe Formation*)*, which was deposited at depths of 50-400 m in the subsiding Parengarenga Basin, during the latter part of the Early Miocene* (*20-17 Myr ago*).

muddy sandstone (Paratoetoe Formation; *5.68*). It was deposited on top of the conglomerate 20-17 Myr ago at mid shelf to upper bathyal depths (50-400 m) as the basin was once again sinking, . This last period of subsidence of the Parengarenga Basin appears to have been in northwest-southeast trending down-faulted depressions aligned parallel to the plate boundary. These depressions were possibly related to oblique collision between the tectonic plates, rather than further movement of the underlying Allochthon.

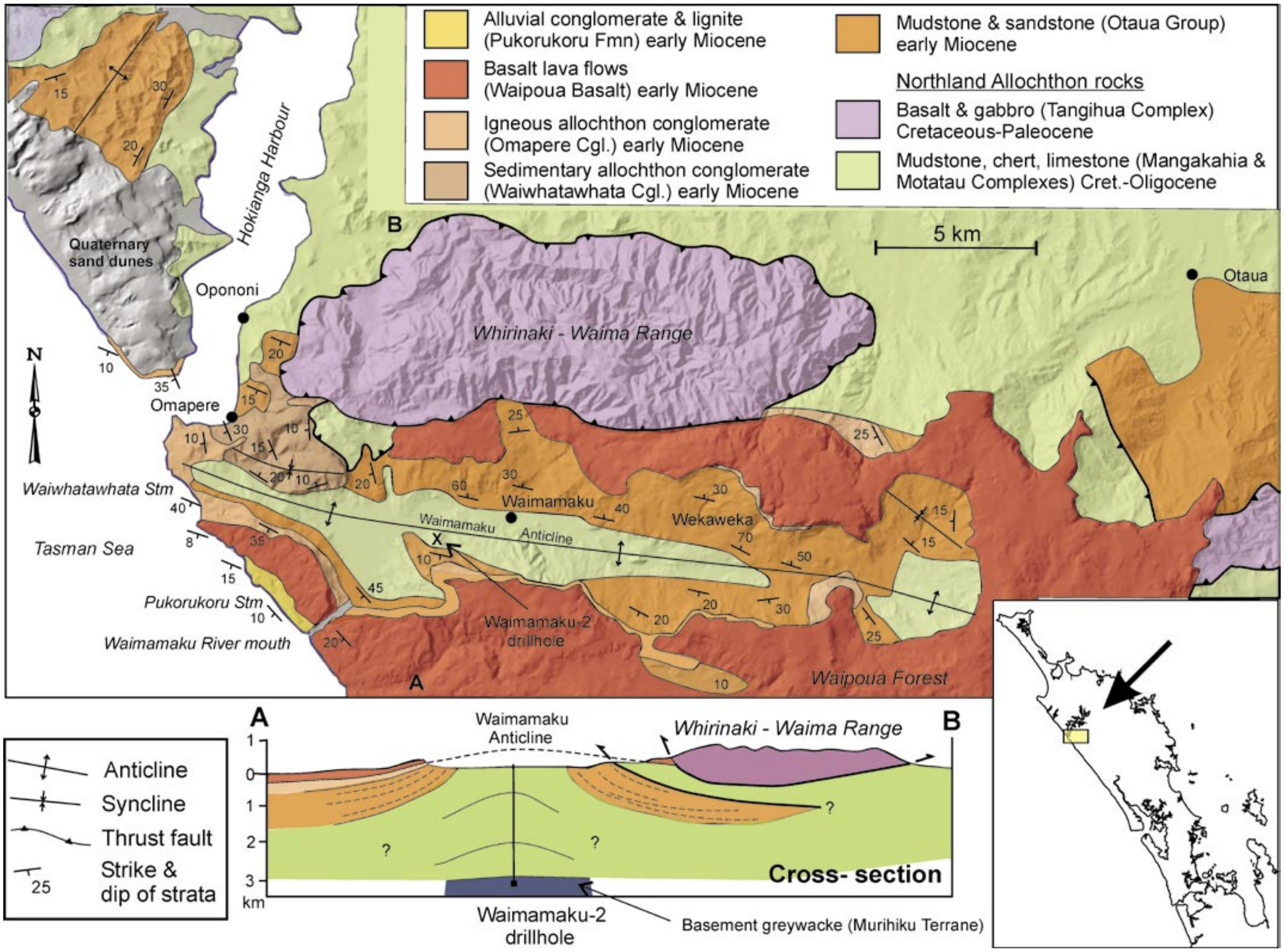
5.69 These rounded hills at the east end of Spirits Bay, are composed of eroded andesite conglomerate (*Kaurahaupo Conglomerate*) *that was deposited in shallow marine and deltaic settings in the Parengarenga Basin, during the Early Miocene. The strata are tilted down to the west* (*right*) *forming the gentler dip slopes on the hills with steep scarp slopes on the east side* (*left*).

Hokianga Basin

Early Miocene sedimentary rocks (23-18 Myr old) can be seen in the area on either side of the mouth of the Hokianga Harbour and extend 30 km to the east up the Waimamaku Valley. They were deposited unconformably on top of various blocks of Northland Allochthon. The oldest of these strata consist of 300-1000 m of mudstone and shell-bearing fine sandstone (Otaua Group; *5.72*), which interfingers with sandy conglomerate and coarse sandstone (Waiwhatawhata Conglomerate). The environment of deposition shallowed upwards from mid bathyal to mid shelf (1000 to 50 m) as the Hokianga Basin filled up with this sediment. The conglomerate was deposited in a submarine fan with a radius of 5-10 km centred around Omapere. The cobbles and pebbles are largely composed of Cretaceous to Oligocene sedimentary lithologies eroded from the Allochthon and indicate that there were no significant Tangihua Complex rocks eroding nearby at the time.

These older Early Miocene strata are more deformed and folded than the sedimentary rocks that were

5.70 Unbedded Omapere Conglomerate fills an ancient stream channel and overlies an irregular surface eroded into the underlying muddy limestone of the Northland Allochthon (*Motatau Complex*). *The cobbles are predominantly composed of altered basalt and diorite, derived by erosion from the Whirinaki and/or Warawara blocks of allochthonous Tangihua Complex. Northern shore of Hokianga Harbour mouth.*



5.71 Geological map showing the surface distribution and structure of the Early Miocene Hokianga Basin rocks and their relationship to the underlying and sometimes overthrust Northland Allochthon rocks. A north-south cross-section of the inferred subsurface geology is shown (A-B). Modified from Hayward (1993) and Evans (1994).

5.72 Waimamaku River bank exposure of thinly bedded mudstone and muddy sandstone, which was deposited at 1000-200 m depth in the piggyback Hokianga Basin, during the Early Miocene (23-20 Myrs ago). The originally horizontal seafloor bedding has been tilted up to 45° by forces related to continued movement and emplacement of the underlying Northland Allochthon. Photo 12 m across.

deposited a little later on top of them. This may indicate continued movement of the underlying Allochthon, resulting in considerable compression, particularly towards the end of this first phase of basin filling. Several sheets of allochthonous sedimentary rocks (Mangakahia Complex) appear to have been thrust over these older Early Miocene strata at this time and major anticlinal folding and associated faulting occurred along an axis that now runs up the middle of the Waimamaku Valley (*5.71*). It was this apparent anticline that encouraged oil explorers, in the 1970s, to drill exploration wells near the crest of the fold, as the fold could have been a potential structural trap for hydrocarbons at depth. This phase of deformation might have resulted from the arrival of a large slab of Tangihua Complex rocks from the north or northeast, that now forms the high Whirinaki-Waima Range, on the northern side of Waimamaku Valley.

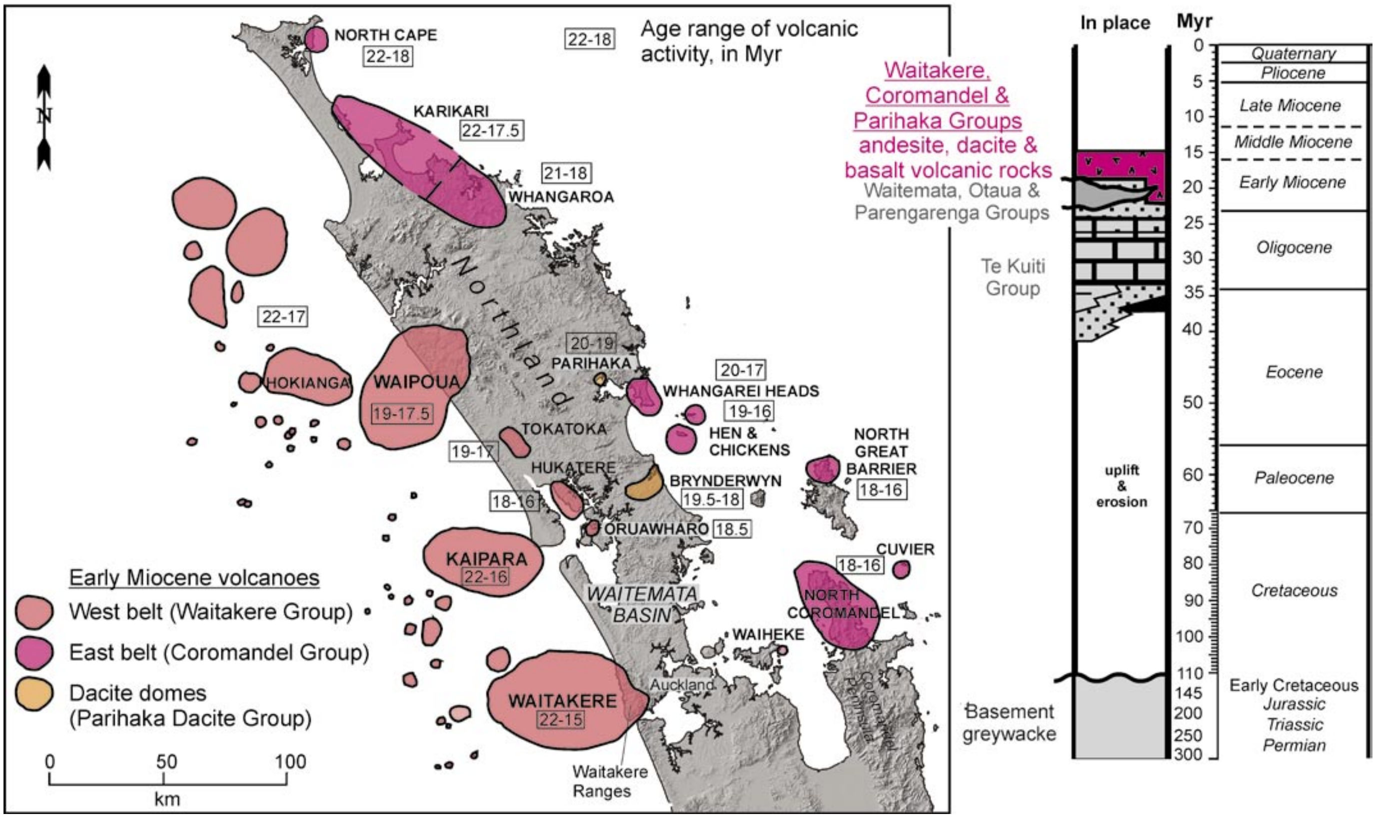
Following this phase of deformation, up to 300 m of bedded, diorite and altered-basalt conglomerate (Omapere Conglomerate; *5.70, 5.73, 13.12*) was deposited over the older Hokianga Basin strata, particularly in the vicinity of the Hokianga Harbour mouth. Unlike the underlying Waiwhatawhata Conglomerate, many of the Omapere Conglomerate cobbles and pebbles were derived by erosion from the newly arrived and high-standing Tangihua Complex slab. The Omapere Conglomerate appears to have accumulated in a rapidly subsiding, shallow marine (0-200 m depth) setting, off the front of a river-fed delta. Further away from the Omapere centre of deposition, thinner lenses of river-deposited (fluvial) Omapere Conglomerate were deposited on a coastal plain around the edge of the filling Hokianga Basin. Folding and thrusting appears to have continued, but with decreasing severity, through the time of Omapere Conglomerate deposition. The Omapere Conglomerate is overlain by basalt flows (*5.73*) from the Waipoua Volcano (described in chapter 6), which coincided with a change from a shallow marine to coastal plain environment.

5.73 The bluffs on the south side of the Waimamaku River mouth gorge, south Hokianga, expose some of the youngest rocks (20-19 Myr old) that accumulated in the Hokianga Basin. The grass slope at the foot of the bluffs on the left is composed of sandstone and mudstone that accumulated at 500-50 m water depth. The clearly bedded strata forming the middle of the bluffs and tilted down to the right (southwest) are Omapere Conglomerate that was deposited along the coastal fringe of a small delta. Overlying the conglomerate and forming the upper part of the bluffs are basalt lava flows from the lower northern slopes of the Waipoua Volcano (see chapter 6).

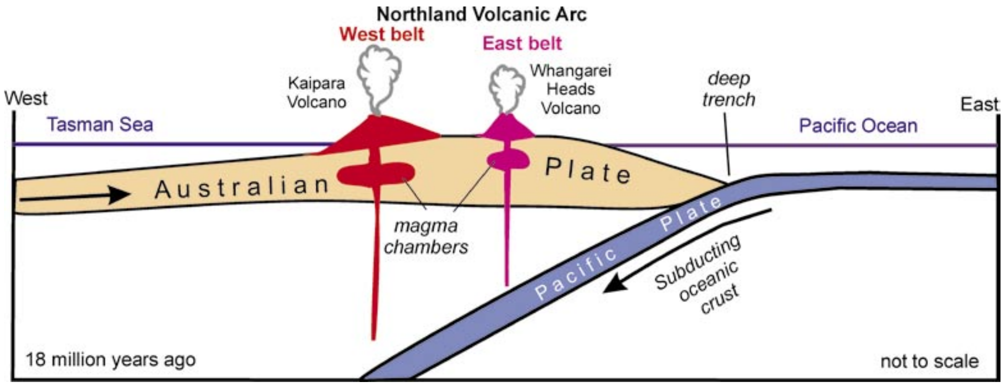
Chapter 6. NORTHLAND VOLCANIC ARC (23-15 Myr ago)

Chapter Summary

The Northland Volcanic Arc comprised two belts of volcanoes that erupted along both sides of Northland and Auckland between 23 and 15 million years ago (Early Miocene). The western belt (Waitakere Group) consisted of the largest stratovolcano in New Zealand's history – Waitakere, the slightly smaller Kaipara Volcano and New Zealand's largest basalt shield volcano – Waipoua. This belt also included four large and at least 35 small volcanoes, all of which are now buried beneath the seafloor off the west coast and have been discovered by remote sensing methods. The eroded eastern slopes of the submarine Waitakere stratovolcano form the Waitakere Ranges today. Its youngest rocks are two lines of volcanic vents and a sheet of lava flows that were erupted on land as the volcano was being uplifted out of the sea. Remains of three small volcanoes located northeast of the Kaipara Volcano can be seen along the eastern shores of Kaipara Harbour, as a large heap of glassy rubble (Okahukura Peninsula), a pillow-lava shield volcano (Hukatere Peninsula) and the subvolcanic plumbing from beneath the completely eroded Tokatoka stratovolcano. The eroded eastern third of Waipoua shield volcano forms Maunganui Bluff and underlies Waipoua Forest. The eastern belt (Coromandel Group) consists of the eroded remains of at least five andesite stratovolcanoes – magma chambers of the completely removed Karikari and Chickens volcanoes, the ring plain and eruptive centres of Whangaroa Volcano, and parts of the steep cones of Whangarei Heads and Hen Island volcanoes. The Northland Volcanic Arc became extinct about 15 Myr ago and volcanic activity moved southeastwards (chapter 7). Notable fossils preserved in sedimentary rocks associated with these volcanoes include reef corals, soft-bodied fan worms, the world's oldest known ram's horn shell and a number of ferns and palms.



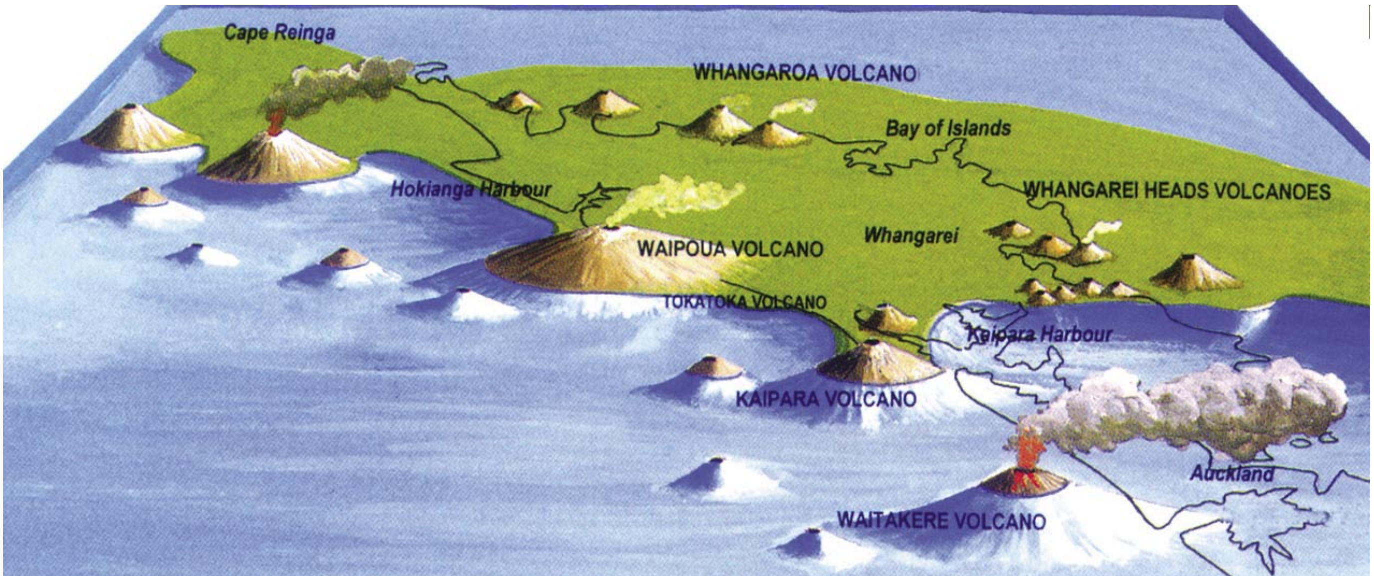
6.1 Early Miocene volcanoes of northern New Zealand with column showing their age relationship to the underlying rocks already discussed. The known eruption periods (in millions of years, Myr) of each volcanic centre are given. Note that the volcanoes are divided into a western Waitakere Group belt and an eastern Coromandel Group belt. The Great Barrier and northern Coromandel volcanoes are described in chapter 7.



6.2 East-west cross-section through southern Northland showing the oceanic Pacific Plate being subducted westwards beneath the edge of the continental crust of the Australian Plate, resulting in the generation of magma bodies and an arc of volcanoes above the subduction zone.

In northern New Zealand there are remnants of two northwest-southeast-oriented belts of volcanoes that erupted during the Early Miocene (23-15 Myr ago) on either side of Northland Peninsula (*6.1*). Together they form the Northland Volcanic Arc. The chemistry of these Early Miocene volcanic rocks confirms that almost all of them were erupted above a plate tectonic subduction zone. This was along the collisional boundary between the Australian and Pacific plates, where denser oceanic crust and its cap of oceanic sedimentary rocks was subducted down a west-dipping subduction zone beneath the more buoyant, lower density, continental crust that underlay the Northland-Auckland-Coromandel region (*6.2*). Subduction zones invariably have a deep oceanic trench marking the plate boundary on the seafloor, where the oceanic crust starts its descent down into the mantle. East of New Zealand there is evidence of much faulting and uplift of the continental crust and a number of potential places where there could have been an oceanic trench. North of New Zealand the geology and distribution of volcanoes of this age appears even more complex than on land and there are a number of different plate reconstruction models that have been proposed to explain them – none of which has yet received anywhere near universal acceptance.

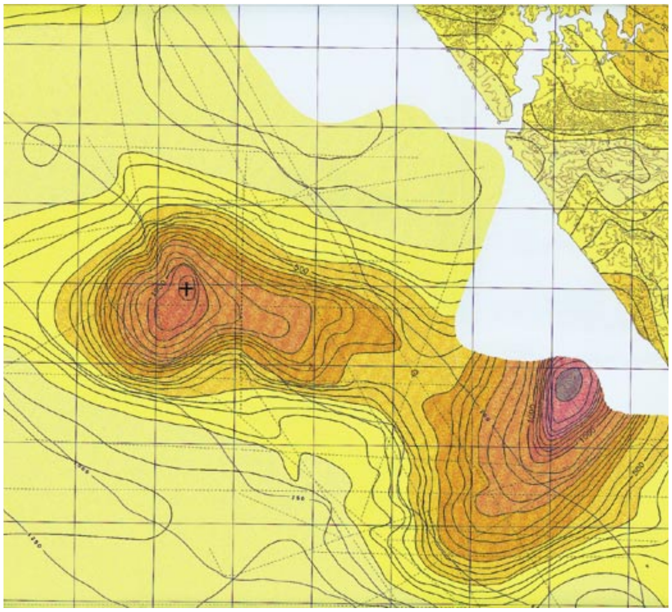
The volcanoes of the western belt are placed in the Waitakere Group. Eruption along this line ceased about 15 Myr ago, although activity shifted southwards along the same line offshore and parallel to the North Island's west coast as far south as Taranaki during the subsequent 10 Myr (Middle-Late Miocene). The volcanoes of the eastern belt are placed in the Coromandel Group, with volcanism along this line beginning in eastern Northland between 23 and 21 Myr ago and progressively advancing southwards to the Hen and Chickens, Great Barrier and northern Coromandel in the latter part of the Early Miocene (18-16 Myr ago). All Coromandel Group volcanism in eastern Northland down to the Hen and



6.3 Artistic impression of the geography and active subduction-related volcanoes of northern New Zealand about 18 Myr ago. Drawing by Geoffrey Cox.

Chickens Islands had ceased by 16 Myr ago and activity shifted southwards into the Coromandel Peninsula proper where it continued on for another 13 Myr (see chapter 7). In the Brynderwyn-Kaiwaka area of southern Northland there is an area of dacite dome volcanism (box 22) that occurred between the two belts during the Early Miocene.

We can clearly see and study the eroded parts of these Early Miocene volcanoes where today they form parts of the land, in places like the Waitakere Ranges, Waipoua, Whangaroa Harbour, and Whangarei Heads. We also know of at least 40 large and small volcanoes of this age that are submerged and buried beneath the seafloor sedimentary rocks off the west coast of Northland and Auckland. From the exposures on land, geologists had suspected the westward extension of the large Waitakere and Waipoua volcanoes beneath the continental shelf to the west and inferred the former presence of another large volcano off the Kaipara coast. It was not until the 1970s-80s that the presence of these was confirmed by remote sensing techniques, but many more Early Miocene volcanoes were also discovered during this oil-exploration survey work. Four more with diameters of 20-30 km were identified and 35 were found with diameters of 1-10 km (*6.1*).



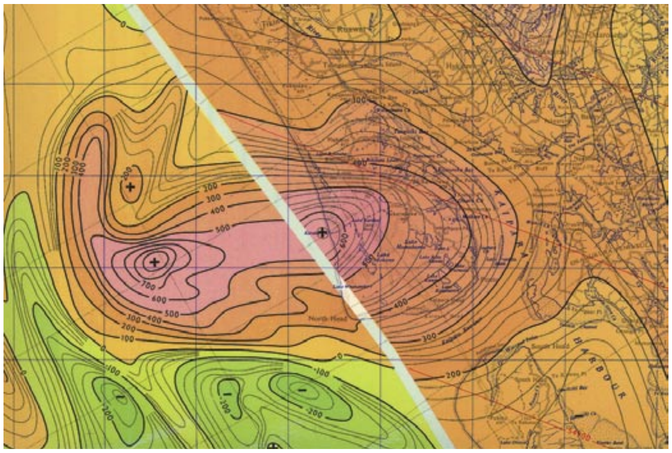
6.4 Part of a gravity anomaly map offshore south of Hokianga Harbour mouth, showing two large ovoid bodies of dense rocks producing strongly positive anomalies. The southeastern body passes northeastwards into the land at Maunganui Bluff and clearly appears to be the buried remains of the Early Miocene Waipoua Shield Volcano. GNS Science map.

REMOTE SENSING TECHNIQUES USED TO IDENTIFY BURIED OFFSHORE VOLCANOES

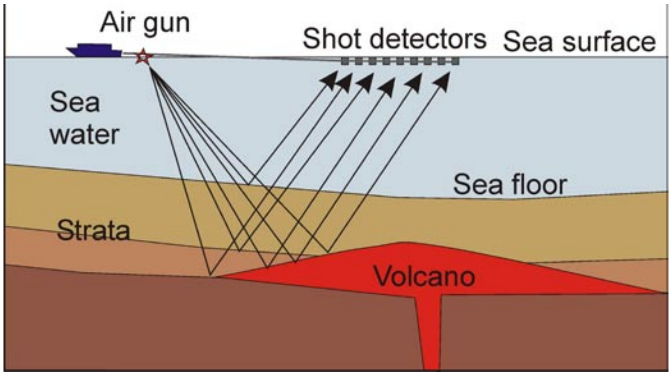
Three remote sensing techniques (Geophysics) were used to identify the location and shape of these buried volcanoes beneath the seafloor off the west coast – gravity, magnetic and seismic surveys.

Gravity and magnetic surveys were undertaken using a small aeroplane flying a grid pattern at relatively low altitude across the land and sea. The instruments that measure the gravity and magnetic fields directly beneath the flight line are either mounted on the plane or towed behind it on a cable. Gravity surveys measure variations in the strength of the Earth's gravitational field and identify differences in the density of the subsurface rocks down to several kilometres depth. When the flight passes over dense subsurface rocks, gravity measurements are raised slightly and positive anomalies are mapped. Thick sequences of low density sedimentary rocks produce negative gravity anomalies. Unconsolidated alluvial sediments typically have the lowest densities and give the largest negative anomalies, followed by mudstones and sandstones. Hard greywacke has the highest density of the sedimentary rocks and can produce similar positive gravity anomalies to the dense igneous rocks. The less silica in an igneous rock the denser it is, so that basalt volcanoes have higher positive gravity anomalies than dacite and rhyolite. The grid patterns of gravity measurements were combined to produce a contoured gravity anomaly map that identified the distribution of buried subsurface dense (igneous and greywacke) and less dense (sedimentary) rocks (*6.4*). The large volcanoes (greater than 20 km diameter) along the west coast of Northland and Auckland were initially identified by this method, but it was not known whether they were igneous in origin or uplifted blocks of dense greywacke.

Aeromagnetic surveys measure variations in the strength of the geomagnetic field and identify differences in the magnetic properties of the subsurface rocks beneath the flight path. Effectively, this method recognises bodies of rock containing magnetic minerals – primarily iron-titanium oxide and iron sulphide minerals such as magnetite and pyrrhotite. Generally igneous rocks are more magnetic than sedimentary. Igneous rocks with lower silica (e.g. basalt) are more magnetic and have larger positive magnetic anomalies than more silica-rich rocks (e.g. rhyolite). All the large bodies off the west coast with positive gravity anomalies were found to have large positive magnetic anomalies (*6.5*), thereby showing



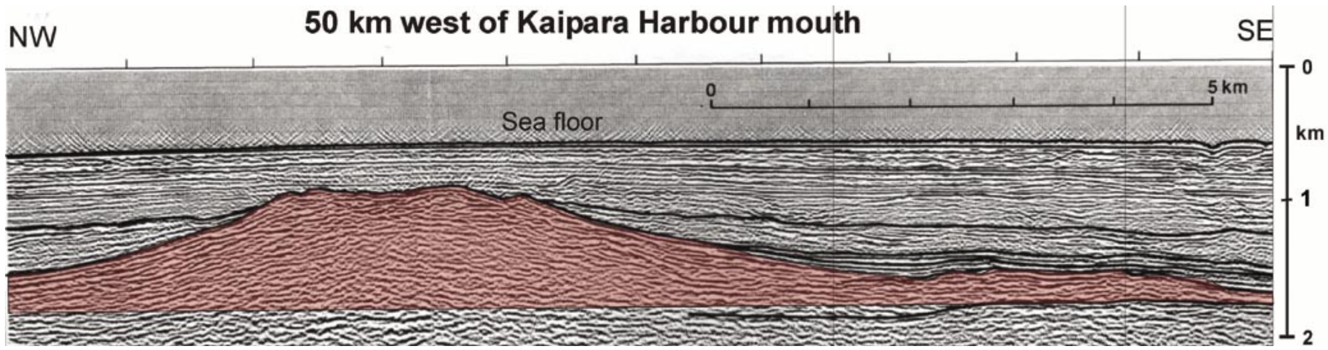
6.5 Part of an aeromagnetic anomaly map at the entrance to Kaipara Harbour (background modern map in grey), showing the location of a strongly positive magnetic anomaly that corresponds to the buried Early Miocene Kaipara Volcano. GNS Science map.



6.6 Cross-section to illustrate how seismic reflection profiling works. A ship fires its air gun sending out seismic waves down through the sea water and into the strata beneath the seafloor. When the waves encounter a hard layer or other significant change within the strata, some of them are reflected back and picked up by the shot detectors at recorded times after the shot was fired. All the results are later combined into a cross-sectional image of the hidden structure (6.7).

that they were igneous in origin and not basement greywacke blocks.

Gravity and magnetic anomaly maps identified large bodies of dense igneous rocks beneath the seafloor out west of Northland and Auckland, but did not indicate whether they were old volcanoes or maybe old magma chambers. It was the third remote sensing geophysical technique, seismic reflection profiling, that answered this question in the 1980s. This method uses a ship, which tows an air gun and a string of detectors out the back. The air gun is fired at set distances along the ship's route, sending seismic waves down through the water and into the rocks beneath the seafloor. Wherever the waves encounter a hard layer or sudden change in rock character, some of them are reflected back up to the surface, where they are picked up by the detectors (*6.6*). The detectors measure the two-way travel time between the air gun shot and the reflectors. The records from all the shots along the ships track are combined and give a two-dimensional seismic reflection profile picture of the seafloor depth and the shape and depth of the major geological reflectors in the rocks beneath the seafloor (*6.7*). It was on these profiles along many different intersecting ship's tracks that seismic stratigrapher, Rick Herzer, identified the 40 plus volcanoes that we now know lie beneath the Tasman Sea floor, west of northern New Zealand. Unfortunately, the dense volcanic rocks of the largest volcanoes are unable to be penetrated by the seismic waves and in these cases the profile looks like a solid line along the tops of the eroded-off stumps of Waitakere, Kaipara and Waipoua volcanoes. Around the fringes of these volcanoes, the volcanic deposits have been imaged where they feather out and interfinger with the Early Miocene seafloor sedimentary rocks.

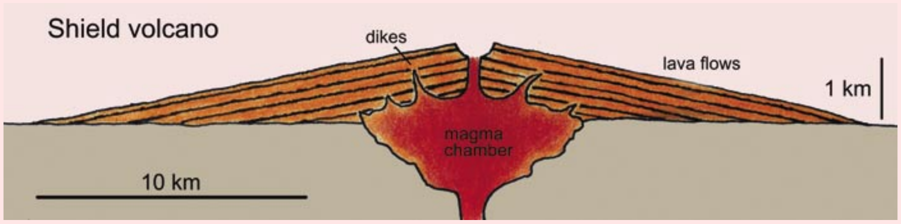


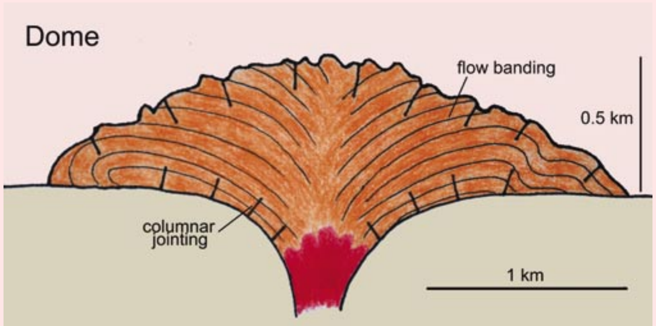
6.7 Seismic reflection profile showing the structure of rocks beneath the Tasman Sea floor west of Northland. Highlighted in red is a medium-sized (10 km diameter) Early Miocene volcano buried by younger seafloor sediment. Modified from Herzer (1995).

Box 22. VOLCANIC SHIELDS, DOMES AND STRATOVOLCANOES

Most of the subduction-related volcanoes of the Early Miocene Northland Volcanic Arc were andesite stratovolcanoes, but there were a number of dacite domes and one huge shield volcano (see Waipoua Volcano). The simple explanation for the different kinds of volcanoes that were formed, is that the magma that was erupted differed in its composition. The magma with the lowest silica in its composition was the mantle-derived basalt. This magma was extremely hot and fluid and when it erupted it spread out quickly and built a gently-sloping (5-10°) cone of solidified lava flows known as a shield volcano (*6.8*). Magma with the highest silica composition was dacite or rhyolite (see p.12), originally basalt magma whose composition had changed markedly in shallow magma chambers due to fractional crystallisation or the addition of melted continental crust. This dacite or rhyolite magma was thick and viscous and when squeezed out onto the surface it did not move very far and built up a steep-sided dome or mound (*6.9*). The magma with intermediate amounts of silica was andesite - also formed by fractional crystallisation of mantle-derived basalt magma possibly with the addition of melted crust. Andesite erupted volcanoes are intermediate in shape between a shield and dome. These had central, steeply-sloping cones made from a mix of relatively fluid lava flows and volcanic breccias and ash. The stratovolcanoes (*6.10*) were generally larger than the domes and often had more than one eruptive centre and several cones. Volcanic lahars were commonplace. They flowed down the stratovolcano cones and over time their deposits built up an encircling, gently-sloping laharic ring plain. Some stratovolcanoes had parasitic domes on their slopes.

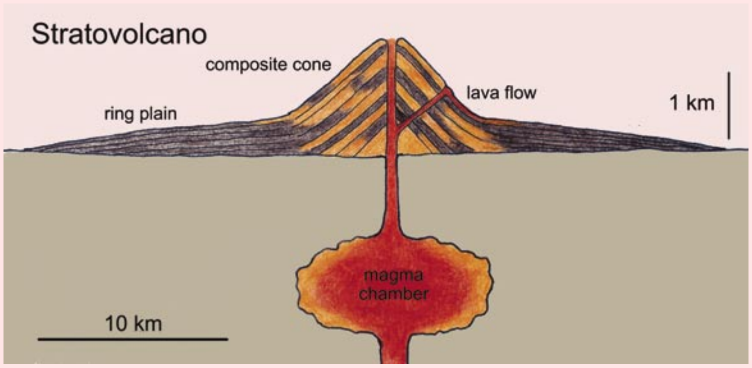
6.8 Right. Cross-section through an idealised shield volcano composed of a pile of gently-sloping lava flows (5-10° slope) that were mostly erupted from the central conduit. Near vertical sheet-like tongues of lava (dikes), fed from the central conduit or a shallow magma chamber beneath, intrude the central parts of the shield. Diameters of New Zealand shield volcanoes are 5-50 km. Drawing by Margaret Morley.



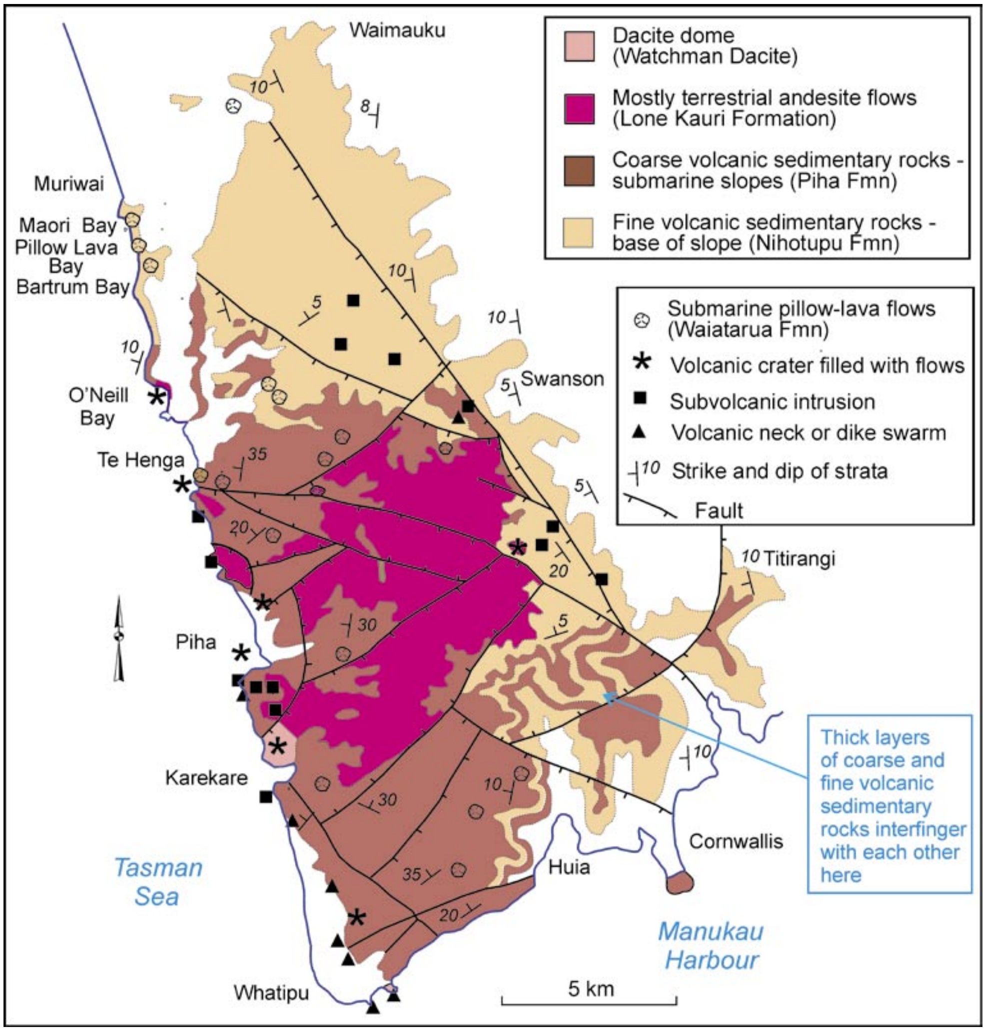


6.9 Left. Cross-section through an idealised dacite or rhyolite dome showing the extrusion of the viscous magma through a flaring conduit out onto the surface. The viscous flows did not move far from the vent. The extruded dome had a high, possibly pinnacle, top. Lines within the dome represent the general direction of flow-banding, whereas more solid short lines perpendicular to the outer surface show the orientation of columnar cooling joints that are often formed as the magma solidifies. Domes are commonly 1-2 km in diameter. Drawing by Margaret Morley.

6.10 Right. Cross-section through an idealised stratovolcano composed of a central, steep-sided volcanic cone surrounded by a gently-sloping ring plain. The cone (sometimes called a composite cone) consists of a mix of lava flows and volcanic breccias and ash. The ring plain has been built up of volcanic breccias and conglomerate deposited by passing lahars that swept down off the cone, together with layers of volcanic ash. Stratovolcanoes and their ring plains are typically 20-30 km across. Drawing by Margaret Morley.



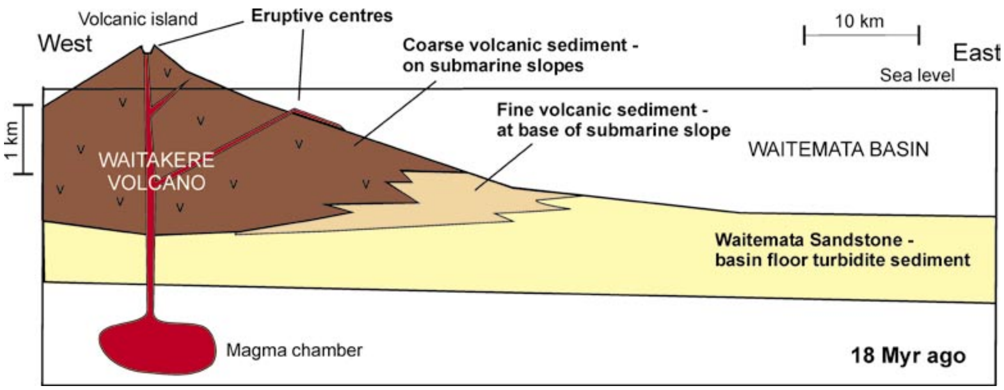
WAITAKERE GIANT STRATOVOLCANO



6.11 Simplified geological map of the Waitakere Ranges, showing the distribution of the main rock types of the Waitakere stratovolcano and the different kinds of eruption centres preserved.

The Waitakere Ranges, west of Auckland, are all that remain of the giant Waitakere Volcano. The rocks that form the Ranges today are the eroded remnants of the lower eastern slopes of this complex stratovolcano. The volcano began erupting on the floor of the deep ocean on the west side of the Waitemata Basin about 22-20 Myr ago and progressively grew in height and size until it became the largest stratovolcano in New Zealand's history, reaching 50 km in diameter and growing at times to elevations of 2500-4000 m above its seafloor base. This was many times the volume of Ruapehu and Tongariro stratovolcanoes combined, partly because the Waitakere Volcano erupted off and on for 5-7 Myr, whereas Ruapehu and Tongariro are both much younger than 1 Myr old. There would have been many different eruptive vents and there is evidence that at times, parts of the upper cones collapsed in dramatic slides, carrying debris down the submarine slopes.

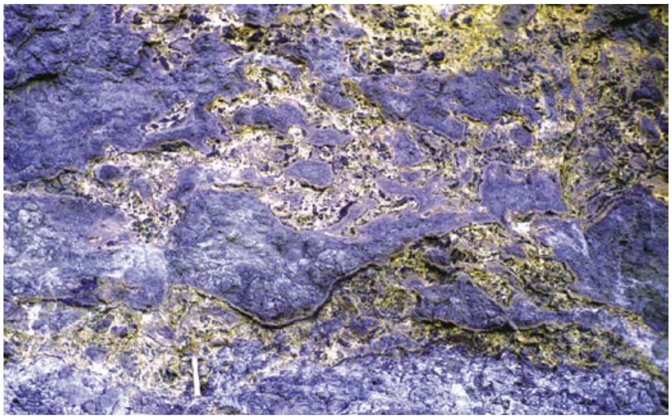
The presence of rare pieces of wood and shallow marine fossils in the Waitakere Ranges rocks, together with red oxidised lumps of volcanic rock (that were erupted hot into the air) and well-rounded volcanic cobbles and pebbles (rounded in streams or in the wave



6.12 Schematic cross-section through the Waitakere stratovolcano after it had built up on the floor of the ocean and was capped by a volcanic island (~18 Myr ago). This predates later uplift and eruption of lava flows and ash over the eastern flanks (now the Waitakere Ranges).

zone), provide good evidence that the Waitakere Volcano was capped by one or more volcanic islands for much of its life. Clearly there were times between major eruptions when forest was able to become established on parts of the island's slopes.

Most of the Waitakere Volcano was located beyond the present west coast and all that remains of it today is its eroded-off stump beneath the seafloor. In the Ranges themselves we can recognise several different assemblages of rocks that provide an insight into how the eastern side of the volcano was formed. The older rocks, erupted and deposited 20-17 Myr ago, accumulated on the growing submarine slopes of the volcano. These are intruded and overlain by younger volcanic rocks (17-15 Myr old) that were erupted on land on the eastern flanks as the volcano and surrounding region was uplifted out of the sea.



6.13 Part of the heap of glassy lava fragments (now altered to yellow and orange clays) and irregular lobes of pillow lava (surrounded by black, glassy selvedges) that accumulated around a submarine volcanic vent on the submarine slopes of Waitakere Volcano about 18 Myr ago. South Te Henga Beach, Waitakere Ranges. Rock hammer for scale.

Undersea lava flows

Within the older rocks that accumulated on the submarine eastern slopes of the volcano, we can see where lava has erupted under the sea, producing one or more lava flows (Waiatarua Formation). Often these flows have the distinctive pillow structure of lava that has been squeezed out as lobes into water and rapidly cooled with distinctive pillow-shaped cross-sections and radiating cooling joints (box 10). As can be seen on the map of the Waitakere Ranges geology (6.11), these pillow lava flows occur in a number of places within the sequence, but are most easily seen in the coastal cliffs south of Muriwai and at the south end of Te Henga Beach.

In the cliffs above Maori Bay (Muriwai), there is a 20 m-thick pillow-lava flow within a sequence of well-bedded volcanic sandstone and conglomerate. The flow is seen in cross-section and has a complex structure (6.16). The sides of the flow are composed of normal 0.5-2 m-diameter pillow lava lobes (6.14), whereas the centre of the flow has several 10 m-or-so-diameter "pillows" of solid andesite with fans of radiating cooling joints (*6.17*). This is one of the few places in the world where we can see such detailed internal structure of a thick pillow lava flow. When this flow was moving down the submarine slopes, the large andesite "pillows" are believed to have been internal tubes of molten lava that were feeding the front of the flow. These internal feeders were insulated from the cooling effects of the sea water by the surrounding carapace of smaller pillow lobes and thus the feeder tubes remained molten for some time. When they eventually cooled from the outside inwards, the radiating cooling joints were formed.

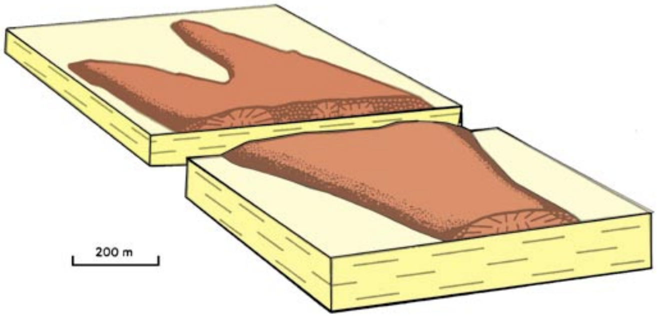
In two places in the coastal cliffs south of Muriwai, we can see sheet-like feeder dikes of solid andesite rock,

6.14 Early Miocene (17 Myr old) andesite pillow lava pile exposed in cross-section in sea cliffs south of Muriwai, Waitakere Ranges. Note the glassy skins around each lobe (pillow) and the radial cooling joints inside each. Width of photo 3 m.

6.15 A dike of columnar-jointed andesite feeding a 2 m-diameter pillow (*top left*) *that was extruded as a roll into unconsolidated seafloor sediment along the upper edge of the sheet-like dike. Pillow Lava Bay, south of Muriwai.*

which in their molten state pushed their way through the sides of the volcano and extruded large, lava pillows into the unconsolidated seafloor sediment. Again this is one of the few places in the world where dikes can be seen attached to, and feeding, a large pillow roll along their upper edges (*6.15*).

At the south end of Te Henga Beach, the extrusion of lava onto the seafloor resulted in the accumulation of a large heap of angular glassy fragments (hyaloclastite) interspersed with irregular pillow-lava lobes and thin irregular intrusive dike feeders (*6.13*). We do not understand exactly why this lava chilled and fragmented as it came in contact with the cold sea water - elsewhere other lava just squeezed out as regular pillow-lava flows with no obvious fragmentation. In some places the lava that was extruded on the volcano's submarine slopes did not even form pillow structures, but spread out as a sheet-like flow over the seafloor, much as they do on land.



6.16 View east of cut-away block diagrams illustrating the inferred shape of the Maori Bay pillow lava flow seen in cross-section high in the cliffs (*middle of diagram*)*. The giant internal fans of cooling joints are solidified andesite lava that once flowed along as large feeder tubes inside the moving flow on the seafloor.*

6.17 Part of the large pillow-lava flow high in the cliffs above Maori Bay, Muriwai. A cooled internal feeder tube with radiating cooling joints (*centre*) *has a pile of more normal pillow lava lobes* (*circular in cross-section*) *on its south side* (*left*)*. Thickness of lava flow 20 m.*

6.18 Volcanic conglomerate (Piha Formation) like this forms much of the western Waitakere Ranges and was deposited on the upper submarine slopes of the growing volcano, between 20 and 17 Myr ago. South Piha. Width of photo 1.5 m.

6.19 A 1 m-thick unit of bedded pumice within the more normal volcanic conglomerate (Piha Formation) that accumulated on the upper submarine slopes of the growing Waitakere Volcano. Farley Point, north end Karekare Beach.

Coarse volcanic sedimentary rocks

Volcanic conglomerate (Piha Formation) forms most of the Waitakere Ranges, except the northern and eastern sides. These rocks can be seen in the coastal cliffs from Te Henga southwards to Whatipu and into the Manukau Harbour as far as Little Huia. They also form the beds and walls of many of the streams and gorges and the rounded tops of the inland knolls. In most places the volcanic conglomerate consists of subangular to subrounded cobbles and pebbles in a granular or sandy matrix. All this material is of andesite composition, but comes from many different lava flows, blocky breccias and ash deposits higher up the volcano. The clasts can vary in colours from various shades of grey (fresh) through yellow-orange (weathered) to red (oxidised when cooling in air). The gravel that forms this conglomerate was transported down the slopes of the submarine volcano, often in debris flows (dense slurries of sediment that can carry along large boulders and cobbles, as well as pebbles and sand). As these sediment flows travelled downslope, they left behind lag layers of larger cobbles and pebbles and as the flows slowed, finer pebbles and sand were deposited on the lower slopes.

The more rounded the clasts in the conglomerate, the longer they must have spent rolling around in stream beds or in the waves on the coast of the volcanic island. In a few places there are whole beds of rounded cobbles and pebbles that must have been derived from these high energy environments. In places, the layering is regular and undisturbed (e.g. south Karekare cliffs), implying that the seafloor sediment was not moved around by bottom currents after it was deposited. Elsewhere (e.g. cliffs of South Piha; 6.18), the layering is less regular with small scours and lenses of sand and sometimes even cross-bedding (seafloor dunes or ripples), all produced by strong bottom-water currents that once swept across the seafloor. In a few places within the conglomerate sequence, there are beds rich in pumice (6.19). The pumice was erupted into the air or sea as gas-rich frothy lava, which would have floated around as pumice rafts.

6.20 The full height of these 100 m-high abandoned sea cliffs, north of the Pararaha Stream mouth on the west coast of the Waitakere Ranges, is composed of an ancient slide of volcanic strata. The slide occurred on the submarine slopes of the Waitakere Volcano, 20-17 Myr ago. Note that the bedding in some blocks has been tilted up towards vertical, whereas several large blocks have been folded over on themselves.

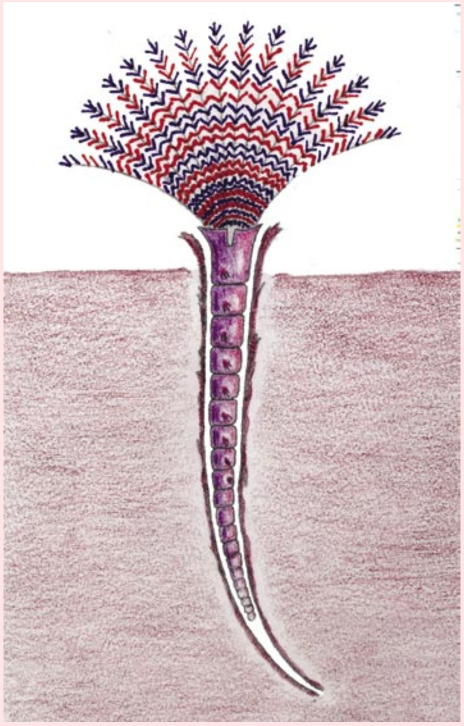
As it became waterlogged it sank to the seafloor, forming pumice-rich deposits.

Interspersed with the conglomerate are chaotic deposits of contorted and twisted blocks of volcanic strata that have slumped down the volcano's side (*6.20*). Some of the larger slump units might have resulted from a partial collapse of a growing cone on the island, whereas others resulted from failure of unstable banks of rapidly accumulated volcanic debris on the upper submarine slopes.

Box 23. FOSSILISED FAN WORMS

In the 1940s, Auckland geologist Professor Bartrum found an unusual segmented tubular fossil (*6.22*) in the volcanic-rich sedimentary rocks on the west coast, south of Muriwai. He was so perplexed by its features that he published a picture of it in the international Journal of Paleontology, calling for suggestions from the palaeontologists of the world, as to what it might be. There is no record that there was any response. In the 1970s more specimens were found by the author at the same bay, which now bears Bartrum's name. By more careful examination, it became apparent that there was an outer tube with the shape of a segmented fossil body inside. Both the tube and the external shape of the segmented body have been accentuated by later growth of calcite inside them. It seems clear that these are extremely rare examples of the fossilised soft bodies of polychaete sabellid fan-worms (*6.21*) preserved inside their parchment tubes. Perhaps the only examples in the world of the fossilised soft bodies of polychaete worms in rocks deposited in the last 100 Myr. These worms were described and named *Archesabella bartrumi* in 1977.

All the specimens found to date come out of several mass-flow beds of coarse volcanic sand that are inferred to have flowed as a sediment slurry down a submarine canyon on the side of the Waitakere Volcano, about 17 Myr ago. Judging by the number of fossil tubes with and without segmented bodies inside them, it appears that thousands of these fan worms were caught up in these submarine sediment slides as they flowed down the slopes. When the slurry came to a standstill, the fan worms were buried within the 1-2 m-thick beds. They had retreated to the innermost parts of their parchment tubes, which filled with sediment, trapping the dying worms inside. The fine sediment that entered the tubes preserved the external segmented shape of the soft-bodied worms as moulds, which have later been lined or filled with secondary white calcite crystals.



6.21 Drawing of a modern marine fan worm living in its parchment tube in sediment, with its fan projecting into the sea water to catch food. Length of tube 10-15 cm. Drawing by Margaret Morley.

6.22 Photograph of the enigmatic fossil specimen originally found by Professor Bartrum in the 1940s and later recognised to be a fossilised segmented fan worm (*left*) *that had retreated down its parchment tube as it was swept down a submarine canyon in a sediment slurry. Total length 13 cm.*

6.23 Fossilised, segmented soft body of a marine fan worm (*sabellid polychaete*) *preserved inside its parchment tube. It, and many others like it, have been found by the author in several beds of 17 Myr-old volcanic sandstone* (6.24) *at Bartrum Bay, Muriwai, Waitakere Ranges. Fossil length 8 cm.*

6.24 Volcanic-rich sandstone beds that accumulated around the base of the submarine slopes of the Waitakere Volcano today form the northern and eastern parts of the Waitakere Ranges. In this photo, on the northern side of Tirikohua Point, south of Muriwai, the cliff is composed of 1-2 m-thick beds of volcanic sandstone, which partly fill a submarine canyon that the sand flowed down in turbulent slurries.

Fine volcanic sedimentary rocks

The coarse volcanic conglomerate passes eastwards into finer volcanic sedimentary rocks (sandstone, grit, mudstone and thinner conglomerate) that were deposited around the base of the submarine eastern slopes of the Waitakere Volcano at water depths of 1000-2000 m. These fine-grained sedimentary rocks (Nihotupu Formation) underlie the northern and eastern parts of the Waitakere Ranges, particularly in the area of the Scenic Drive and the eastern escarpment. Much of this sediment was transported downslope in sediment slurries, as volcanic turbidity currents or the finer, more far-travelled, fronts of debris flows. Some of the sediment was erupted into the air as ash, blown eastwards and fell into the sea, where it sank to the seafloor, 10-30 km offshore from the erupting island. These fine volcanic sedimentary rocks are slightly younger than, and overlie, the Waitemata Sandstones of Auckland city.

6.25 This thick dike of dark grey andesite intrudes older volcanic conglomerate in cliffs at the north end of Karekare Beach, Waitakere Ranges. When molten, this sheet of lava possibly fed lava flows erupted on land above.

Later eruptions on land

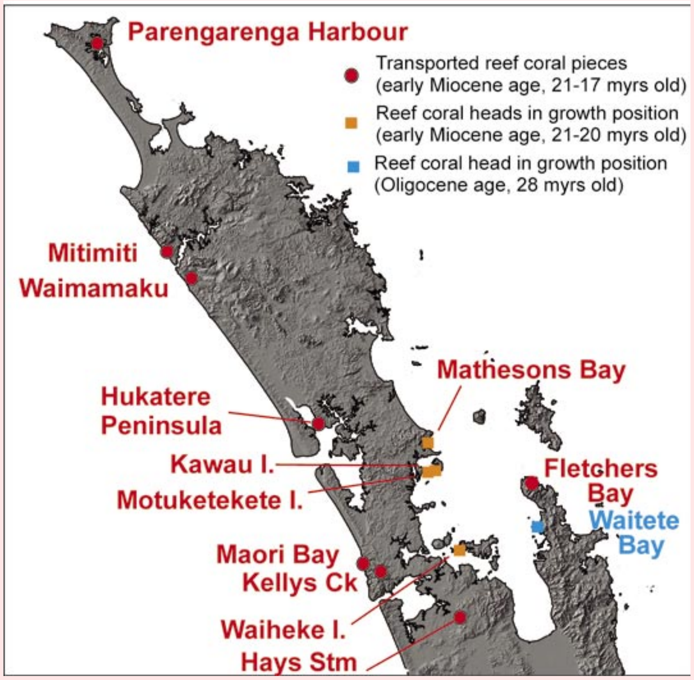
Changes in the deep-seated tectonic forces beneath Auckland resulted in the whole region being uplifted slowly out of the sea, 18-17 Myr ago. This preceded the final stage of eruption of the Waitakere Volcano. In this final stage, two lines of vents (6.11) erupted lava flows over the newly-emerged land on the volcano's eastern flanks. The older rocks, which had been erupted and deposited on the underwater slopes of the submarine volcano, were intruded and overlain by these younger volcanic rocks (Lone Kauri Formation). Eroded remnants

Box 24. FOSSIL REEF CORALS

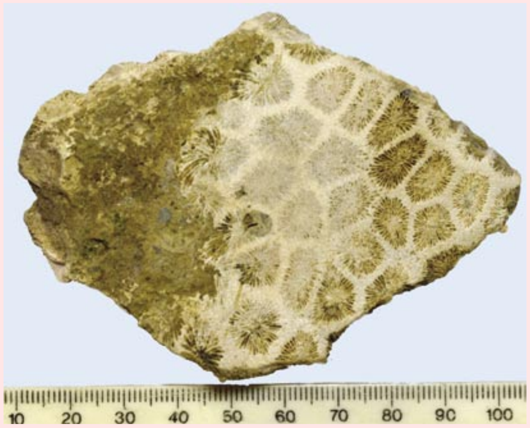
Stony corals (Order Scleractinia) are periodically found fossilised in Eocene, Oligocene and Miocene marine sedimentary rocks of northern New Zealand and a few still live in the waters around New Zealand today. They belong in the Phylum Cnidaria, which also includes jellyfish, sea anemones, hydroids and sea lilies. These corals have an external, calcareous, cup-shaped skeleton, in which an anemone-like polyp lives. Its feathery tentacles comb the water for plankton food to eat. The occurrence of small photosynthesising symbiotic algae within some corals assists in the production of calcium carbonate to build the coral skeletons. Fossil corals are most readily identified by the presence of radiating vertical walls (called septa, *6.28*) extending inwards from the walls of individual cups. Stony corals are often split into two groups – solitary corals that have a single cup attached to something hard or nestled in the seafloor sand, and colonial corals where adjoining cups are joined together and may form deep-sea coral reefs or more solid coral reefs in shallow tropical settings.

6.26 This head of a tropical reef coral (Montastrea *sp.*) *was found in a transported cobble conglomerate of Early Miocene age* (*17 Myr ago*) *at Maori Bay, Muriwai, west of Auckland. University of Auckland collection.*

Tropical coral reefs occur today 30° North and South of the equator, where water temperature does not drop below 16°C. There are no known fossil or living tropical reefs in New Zealand, but single heads of at least 12 different kinds of tropical reef-building coral have been found fossilised in the Early Miocene (23-16 Myr old) sedimentary rocks of Northland and Auckland (*6.27*). Scattered single heads of some reef corals (up to 1 m-across) grow in shallow, slightly cooler water beyond the limits of modern tropical reefs (e.g. around Kermadec and Norfolk Islands). This is the environment inferred for the Early Miocene of northern New Zealand, with surface marine waters being 5-7°C warmer than it is in this area today, but not warm enough for actual coral reefs to have grown. A few of these single heads have been found fossilised in-situ, where they were growing among shallow water cobbles and boulders in the basal Waitemata Group strata (Early Miocene age) now exposed at Mathesons Bay, Kawau, Motuketekete and Waiheke islands (chapter 5). Most fossil reef coral specimens in northern New Zealand grew on harder rocks around the shallow marine fringes of Northland Volcanic Arc volcanoes. Specimens are usually broken pieces that have been transported away by currents from where they were growing. A single small head of a reef coral has also been found in growth position in Oligocene sedimentary rocks of the Te Kuiti Group at Waitete Bay, Coromandel Peninsula.



6.27 Localities where fossil tropical reef corals have been found. There is no evidence that any actual coral reefs developed in New Zealand - only single heads of reef coral species up to 1 m across.



6.28 A 10 cm-piece of reef coral (Goniastrea *sp.*) *that has been sliced through to show the radiating septa in the individual cups. From Maori Bay, west of Auckland. University of Auckland collection.*

6.29 Karekare Beach occupies the eroded out remains of a 1 km-wide Early Miocene crater. The conical peak (The Watchman), near the centre of the crater, is the eroded hardest portion of a dacite dome that was extruded onto the crater floor. This is one of a number of eruption centres that form a belt along the line of the west coast of the Waitakere Ranges today.

of the sequence of young andesite lava flows and thin intervening baked ash, which were erupted over the land at this time, now cap the higher ridges of the Waitakere Ranges. They can be seen in road cuts and small former quarries alongside Piha, Anawhata and Lone Kauri roads They are sometimes seen as fresh, hard, grey rock, but more often they are weathered to purple and red clay.

Remains of the eastern line of vents now form some of the high points of the Scenic Drive ridge, such as Pukematekeo and Parkinsons Lookout. The second line of vents runs along the present-day west coast. Some are recognisable as eroded craters filled with lava flows (Taranaki Bay, Whites Beach, O'Neill Bay). In other places (Ohaka Head, The Gap) there are clusters of volcanic dikes or irregular subvolcanic intrusions — the eroded plumbing from below the vents. Lion Rock at

6.30 17 Myr-old, flow-banded dacite exposed at the foot of The Watchman, Karekare. When molten, the dacite lava would have been thick and viscous and would have been extruded out into the middle of the crater rather like thick toothpaste.

6.31 This 20 cm-long volcanic bomb is preserved in the neck of a volcano that erupted 16 Myr ago. The rocks, through which the neck was blasted, have been eroded away, leaving the harder parts of the filled neck as Lion Rock, Piha.

6.32 The roof of a large abandoned sea cave at Whatipu is composed of volcanic conglomerate that has been intruded by two younger, somewhat irregular, sheet-like pyroclastic dikes (light cream colour). The dikes are filled with lumps of pumice, fine ash and pieces of the surrounding conglomerate. These dikes are inferred to have been formed by a nearby erupting volcanic neck. The immense forces of the eruption injected pumice along fractures through the surrounding rock. The cave was eroded by the sea a few thousand years ago, along the weaker rocks of the dikes and fractures.

Piha and Whatipu's Ninepin Rock are the eroded remains of funnel-shaped vents, filled with collapsed lava, scoria and volcanic bombs (*6.31*). Karekare Beach is in the eroded centre of a former crater, and The Watchman and Paratahi Island are the eroded remains of domes of viscous dacite lava, which were extruded into it like thick toothpaste (*6.29, 6.30*). The youngest-known eruptions of Waitakere Volcano occurred 15 Myr ago.

Box 25. WORLD'S OLDEST FOSSIL RAM'S HORN SHELL

Small white spiral shells, known as ram's horn shells, are commonly washed up on exposed beaches around northern New Zealand. A broken piece of fossil ram's horn shell (*Spirula spirula*) collected from Early Miocene (18 Myr old) sedimentary rocks on Hukatere Peninsula, Kaipara, is the oldest specimen known of this globally distributed and highly distinctive species of squid (Mollusca, Cephalopoda). The 12 mm-long fossil consists of the internal cast of six of the last chambers of the shell. The shell was buried in the ancient sediment and filled with mud, which then hardened. Sometime later, ground water passing through the rock has dissolved away the original calcareous shell material and left behind the cast made of mudstone. Clearly present and distinctive are the locations of the concave septa that separated chambers and were pierced by a marginal siphonal tube.

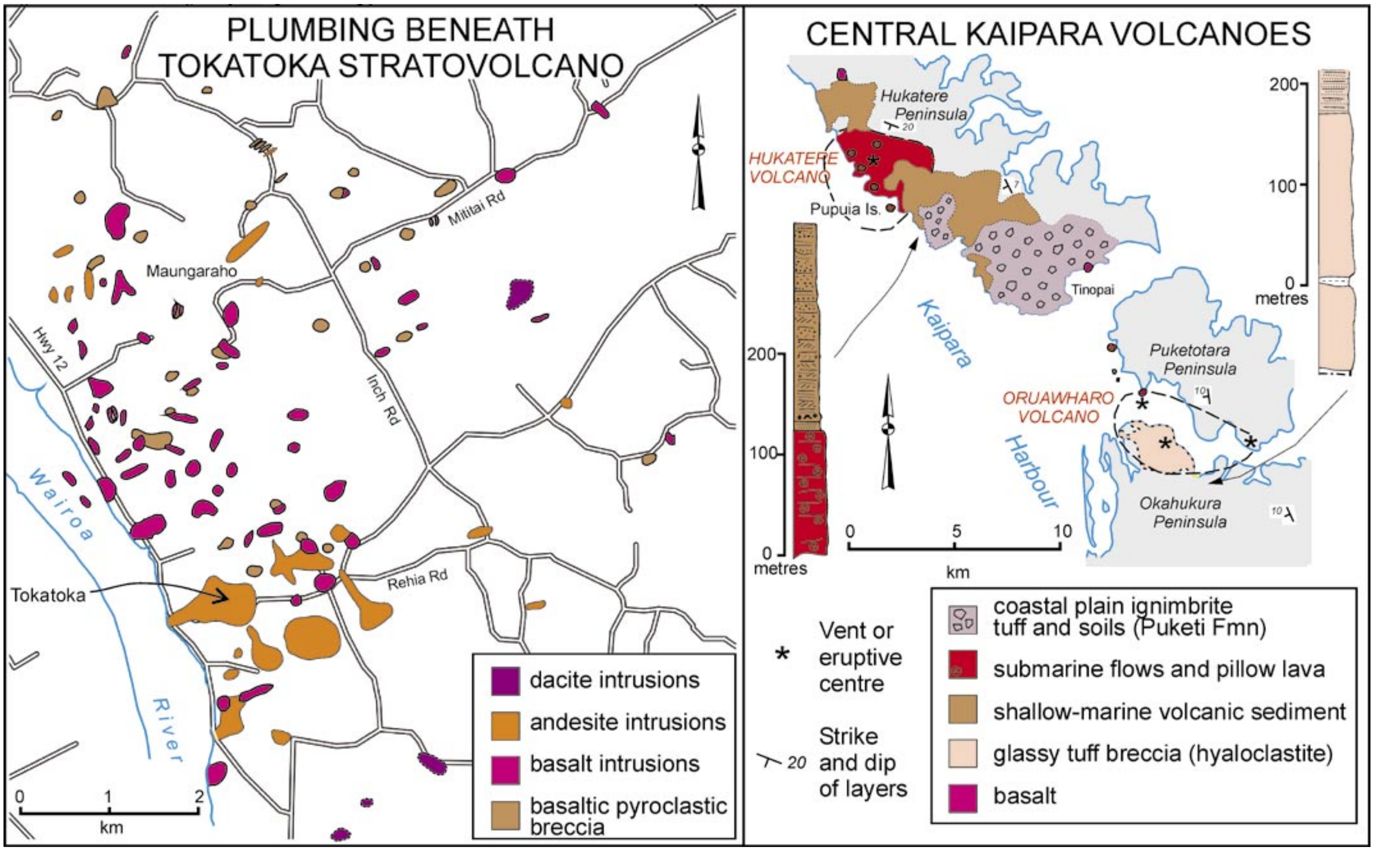
Spiral ram's horn shells are the internal skeleton of a small kind of squid, which lives today in tropical to subtropical waters, at depths of 300-1000 m. When the squid dies and decays, the buoyant shell floats and may be transported around by winds and currents before sinking or washing ashore on beaches. The shell is used for buoyancy and helps the live animal orient itself vertically with its head downwards in the water. The amount of gas in the chambers can be varied to allow the animal to ascend through the water column at night and descend during daylight hours.

6.33 Ram's horn shells are the internal skeleton near the tail end of a small squid. Drawing by Margaret Morley.

6.34 Far left: Front and side views of the broken fossil piece of the ram's horn shell found in the Early Miocene volcanic sedimentary rocks of western Hukatere Peninsula, near Tinopai, Kaipara. Length of fossil cast is 1 cm.

6.35 Left centre: Modern ram's horn shells are commonly washed ashore on Northland and Auckland's west coast beaches. Photo width 12 cm.

KAIPARA AND NEARBY VOLCANOES



6.36 Simplified geological maps showing the distribution of remnants of the small Early Miocene satellite volcanoes that erupted east of the giant Kaipara Volcano.

The eroded stump of the 40 x 30 km Early Miocene Kaipara Volcano has been mapped by remote sensing methods lying beneath the north Kaipara Peninsula and the sea floor off the entrance to the Kaipara Harbour. There are no outcrops of this volcano on land to be seen, but maybe some of the volcaniclastic deposits or ignimbrites seen on Hukatere Peninsula within the harbour could have been sourced from it. There are at least ten much smaller volcanoes that have been identified by similar remote sensing methods lying beneath the sea floor to the west and north of the Kaipara Volcano (*6.1*). Northeast of Kaipara Volcano and outcropping on land in west Northland are the remains of at least three more smaller volcanoes (Tokatoka, Hukatere and Oruawharo) that erupted at the same time as the Kaipara Volcano (19-16 Myrs ago).

Tokatoka stratovolcano

At Tokatoka there is inferred to have been a stratovolcano because of the composition of the lavas that have cooled in the shallow plumbing system now exposed at the surface. Tokatoka Volcano erupted through Northland Allochthon rocks that had been uplifted to form dry land in this vicinity by the time it started erupting, about 19 Myrs ago. All trace of its erupted volcanic cone has eroded away revealing at least 80 intrusive dikes, plugs, volcanic necks and small magma

6.37 The conical peak of Tokatoka is the eroded portion of an Early Miocene andesite plug that solidified in the throat of a volcanic conduit that fed magma to the surface, where it erupted to form part of a 10 km-diameter stratovolcano.

6.38 Maungaraho is a 220 m-high blade of andesite that is the eroded remains of a large vertical sheet of magma (dike) that fed eruptions to part of the Tokatoka stratovolcano above (now eroded away), between 19 and 17 Myr ago. The Wairoa River estuary, south of Dargaville, is in the background. Photographer Alastair Jamieson.

chambers scattered through a 60 km^2 area between Ruawai and Dargaville, in the north Kaipara area. The composition of the solidified magma in these intrusions varies considerably from basalt, through andesite to dacite. This indicates that numerous eruptions occurred from many vents over a 2 Myr-long interval of periodic activity. The erupted magma was derived from shallow magma chambers, where the initial mantle-derived basalt magma stewed and changed in composition by partial crystallisation and possibly some melting of the surrounding crust. The hot magma that passed through or sat in direct contact with the surrounding limestone rock metamorphosed a zone up to several metres thick forming a number of rare high temperature calcium-rich minerals. These thermally metamorphosed zones are called skarn.

The feeder pipes and intrusions are all now filled with solidified magma which is considerably harder than the surrounding soft Northland Allochthon muddy limestones and other sedimentary rocks. Thus each of these intrusions now forms a small hill or rocky knoll, rising 10-200 m above the background paddock level. The most iconic of these hills is the conical peak of Tokatoka (*6.37, 13.23*) and the blade-like protrusion of Maungaraho dike (*6.38*). There are public walking/climbing tracks to the top of both these prominent landforms.

Hukatere volcanism

Three peninsulas protrude into the eastern side of the Kaipara Harbour. The northernmost, Hukatere, is due south of Matakohe. On the northwest of Hukatere Peninsula is the eroded remains of a relatively small, 4 km-diameter, pillow-lava shield volcano, which was erupted into shallow sea water, 18-16 Myr ago. A succession of lava flows, many of them pillowed, built up a shield that was at least 150 m high. The best place to see these flows is along the Kaipara Harbour foreshore, especially around Pupuia Island (*6.39*), but there is no public road access.

Further south, around the southern shores of Hukatere Peninsula, both east and west of Tinopai at the end of the road, there is evidence of further Early Miocene volcanism. Most of the coastal sections in this vicinity are composed of 2-4 m-thick ignimbrite flows and cross-bedded, sandy andesitic and pumice tuff interspersed with lignite seams (Puketi Formation). These all appear to have been deposited in a coastal plain setting, possibly in a small delta on the edge of the Waitemata Basin. Ignimbrite flows are searing hot clouds of ash and pumice that sped across the ground away from the vent before coming to a standstill. Each killed and charred the vegetation it engulfed. Some logs were plucked up by the flow and buried in the deposit when it stopped (*6.40*). East of Tinopai some of these large logs have been petrified with silica and can be seen on the shoreline today (*6.41*). In quiet times, between ignimbrite flows, forest was re-established and humus accumulated, forming black lignite layers (*6.42*). The river feeding the delta possibly originated on the eastern slopes of the large Kaipara Volcano out to the west, which probably erupted the ignimbrites and tuffs. Some

6.39 A 10 m-thick pillow lava flow exposed in sea cliffs near Pupuia Island, on the west side of Hukatere Peninsula. This is part of the Early Miocene Hukatere pillow-lava shield volcano.

6.40 Left. Three log moulds in the base of a pumice ignimbrite deposit that accumulated on a coastal plain east of Kaipara Volcano about 18 Myr ago. The ignimbrite was deposited by a pyroclastic flow of hot gas, ash and pumice that swept down the volcano's slopes, flattening and carrying along the forest trees it flowed through. Sandy Beach, Tinopai.

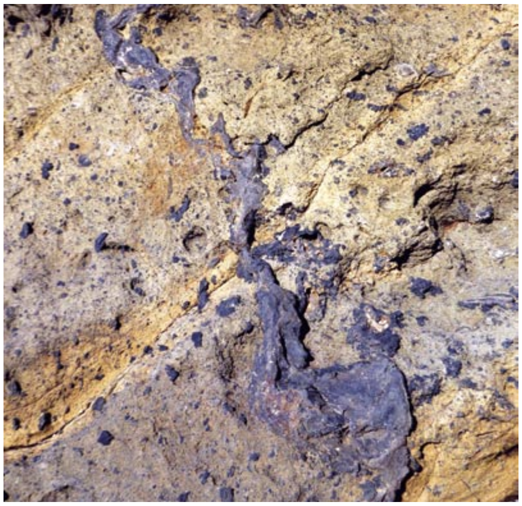
folding, faulting and intraformational sliding within the Puketi Formation sequence was probably produced by continued gravity-driven southwards movement within the underlying Allochthon.

6.41 Above. Silicified logs, encrusted by modern oysters, within the Early Miocene sequence of ignimbrites, tuffs, lignites and soils that was deposited on a coastal plain near Tinopai, east of Kaipara Volcano, about 18 Myr ago. Width of photo 2 m.

Oruawharo submarine volcano

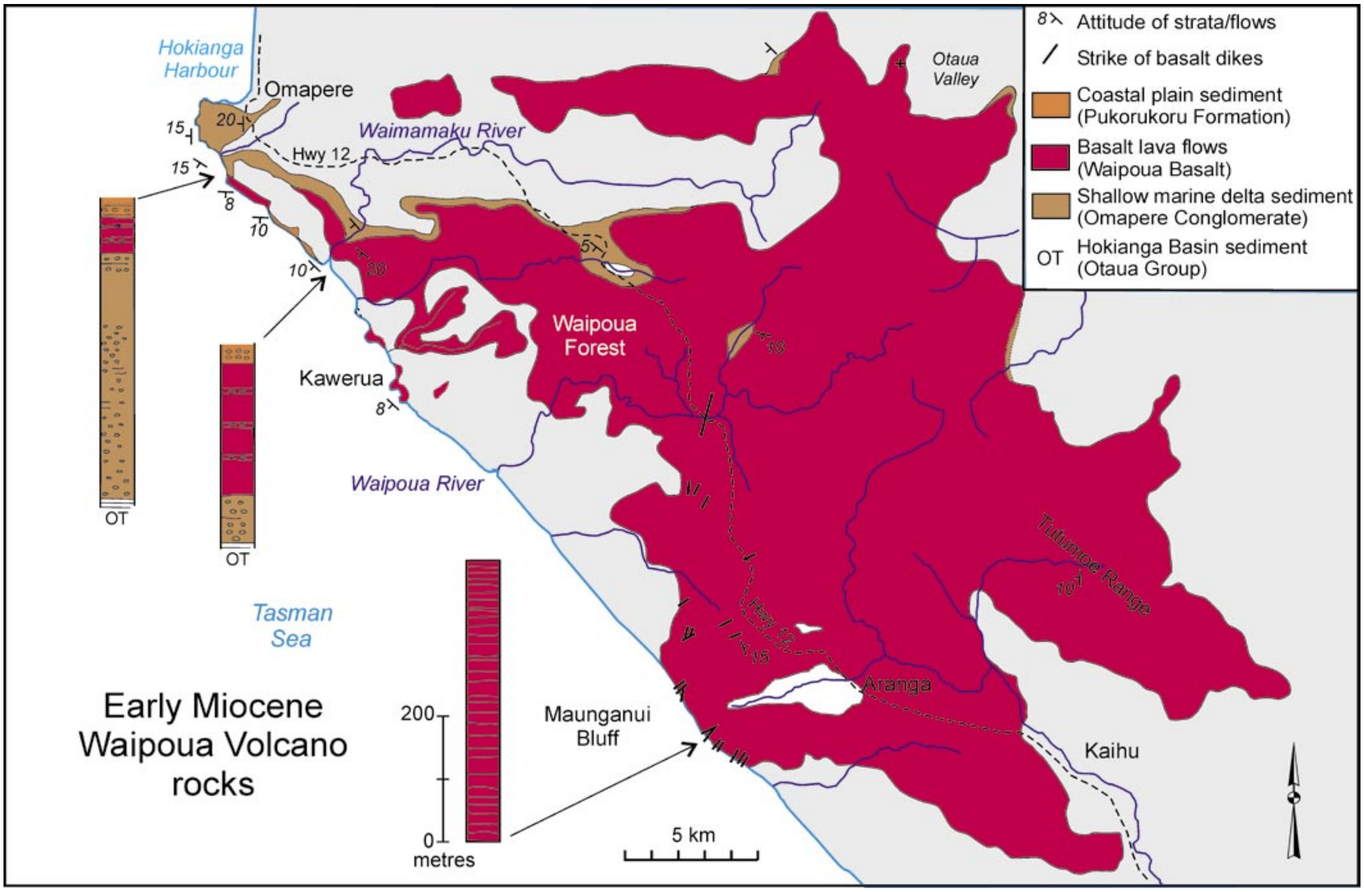
Remains of another small, 5 km-diameter volcano, known as Oruawharo Volcano, occur near the tips of the two southeastern peninsulas in the Kaipara Harbour – Puketotara and Okahukura. Where seen on the coast, its volcanic products consist of a 150 m-thick heap of glassy volcanic breccia, known as hyaloclastite (*6.43*). This is formed when hot lava is extruded into cold sea water and instantaneously freezes to glass, which shatters into many shards and lumps, as quickly as it forms. In places, there are a few basalt pillow-lava lobes fed by small intrusive dikes and the whole lot is overlain by a thick mantle of bedded volcanic ash. Radiometric dating suggests it erupted around 18.5 Myr ago.

6.42 Sequence of ignimbrites, tuff breccias and cross-bedded sandstone (Puketi Formation) in cliffs east of Tinopai. Four thin black layers visible within the sequence are soil horizons with tree stumps in-situ that mark former quiet periods, when vegetation grew on the coastal plain between the periodic arrivals of volcanic debris from Kaipara Volcano.



6.43 A thin, irregular dike of basalt lava intrudes massive glassy volcanic breccia (hyaloclastite). It is part of the remains of the shallow-marine Oruawharo Volcano, Kaipara. Width of photo 1 m. North coast of Okahukura Peninsula.

NEW ZEALAND'S LARGEST SHIELD VOLCANO – WAIPOUA



6.44 Simplified geological map of the Waipoua area, south of Hokianga Harbour mouth, showing the distribution on land today of Waipoua basalt lava flows and radial dikes, as well as deltaic sediments that underlie (*Omapere Conglomerate*) *and coastal plain sediments that overlie* (*Pukorukoru Formation*) *the youngest flows in the north.*

Most of the Waipoua Forest area and Maunganui Bluff, on the west coast of Northland, is underlain by a thick sequence of Early Miocene basalt lava flows (Waipoua Basalt) that have radiometric K/Ar ages of eruption of 19-17.5 Myr ago. Remote sensing techniques show that they are the eroded eastern third of a 50 km-wide basalt shield volcano, which was centred 10 km west of Maunganui Bluff. For comparison, the Miocene Banks Peninsula and Dunedin "shield" volcanoes were each 20-30 km in diameter.

The cliffs of 450 m-high Maunganui Bluff are entirely composed of a pile of 2-10 m-thick basalt flows separated from each other by thin beds of rubbly basalt breccia and red baked and oxidised volcanic ash (*6.45*). In the cliffs of the bluff, and in road cuts and quarries to the east, there are many near-vertical dikes that cut through the lava flow sequence. These dikes were sheets of basalt lava

6.45 A Waipoua Volcano basalt lava flow (*dark grey*) *overlying red-oxidised volcanic ash and breccia in the coastal cliffs at the south side of Maunganui Bluff. The geologist is standing on a vertical, 50 cm-thick basalt dike that cuts through the sequence.*

6.46 450 m-high Maunganui Bluff, on Northland's west coast, is composed of a thick sequence of Early Miocene basalt lava flows from the Waipoua Volcano. The centre of the shield was offshore. The wide valley on the left is the beheaded remains of one of the original radiating valleys that drained the volcano. Photographer Alastair Jamieson.

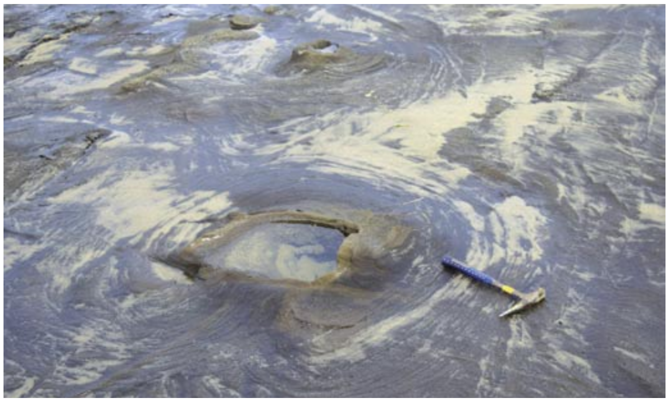
that intruded up vertical fractures in the growing Waipoua shield volcano. In basalt shields, the dikes of molten lava commonly intruded fractures that radiate outwards from the central conduit. This seems to be the case at Waipoua also (*6.44*), where the dike orientations indicate the centre was just offshore from Maunganui Bluff. Some of these dikes could have fed young lava flows that were erupted on the upper slopes of the shield volcano.

As the centre and highest point of the shield volcano was offshore to the west, all the lava flows that are now visible on land would have originally flowed down the northern and eastern slopes and had a slope in these directions of about 10-15°. Today, however, the flows north and east of Maunganui Bluff dip at 10° to the southwest and west (*6.44*), indicating that sometime after the shield stopped erupting, there has been uplift in the northeast and a tilt of about 20° down to the southwest. On the east side of Maunganui Bluff itself, there is a small, underfit stream flowing east down a wide valley through Aranga (*6.44, 6.46*). Clearly this valley could not have been eroded by this small stream and undoubtedly it is a remnant of one of the radial valleys that flowed down the original Waipoua Volcano, but now all its higher headwaters have been eroded away by the Tasman Sea.

A lot of the coastal belt of the Waipoua Volcano is hidden beneath Pleistocene sand dunes and modern beach sand, except near its northern limits, where 3-4 of the youngest flows (18-17 Myr old) can be traced from the gorge at the mouth of the Waimamaku River (*5.73*) to where they form intertidal reefs 5 km to the north (*6.47*). Here we see the flows interfingering with the top of the Omapere Conglomerate, which was deposited in a shallow marine delta.

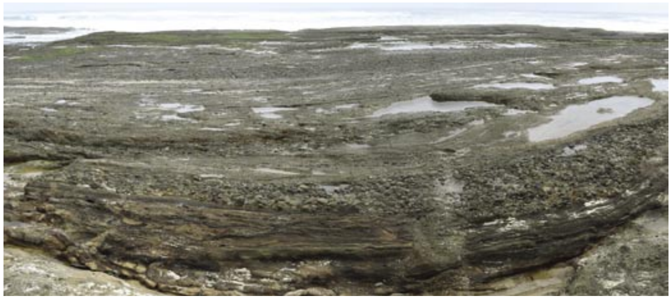
The arrival in the Hokianga-Waimamaku area of basalt lava flows, from the Waipoua Volcano to the south, coincided with a change in setting from shallow marine to a coastal plain. Fluvial (stream-carried) sediment (Pukorukoru Formation), deposited between and on top of the flows can be seen along the coast, north

6.47 View south, down the west coast of Northland, south of Hokianga Harbour. The three most prominent linear reefs in the right foreground are the youngest and northernmost basalt lava flows from Waipoua Shield Volcano, which erupted 19-17.5 Myr ago. The centre of the volcano was 25 km to the south just offshore from Maunganui Bluff (*skyline*). *The flows overlie bedded Omapere Conglomerate* (*forming along-strike reefs in the foreground*), *which accumulated in the shallow marine part of a delta.*



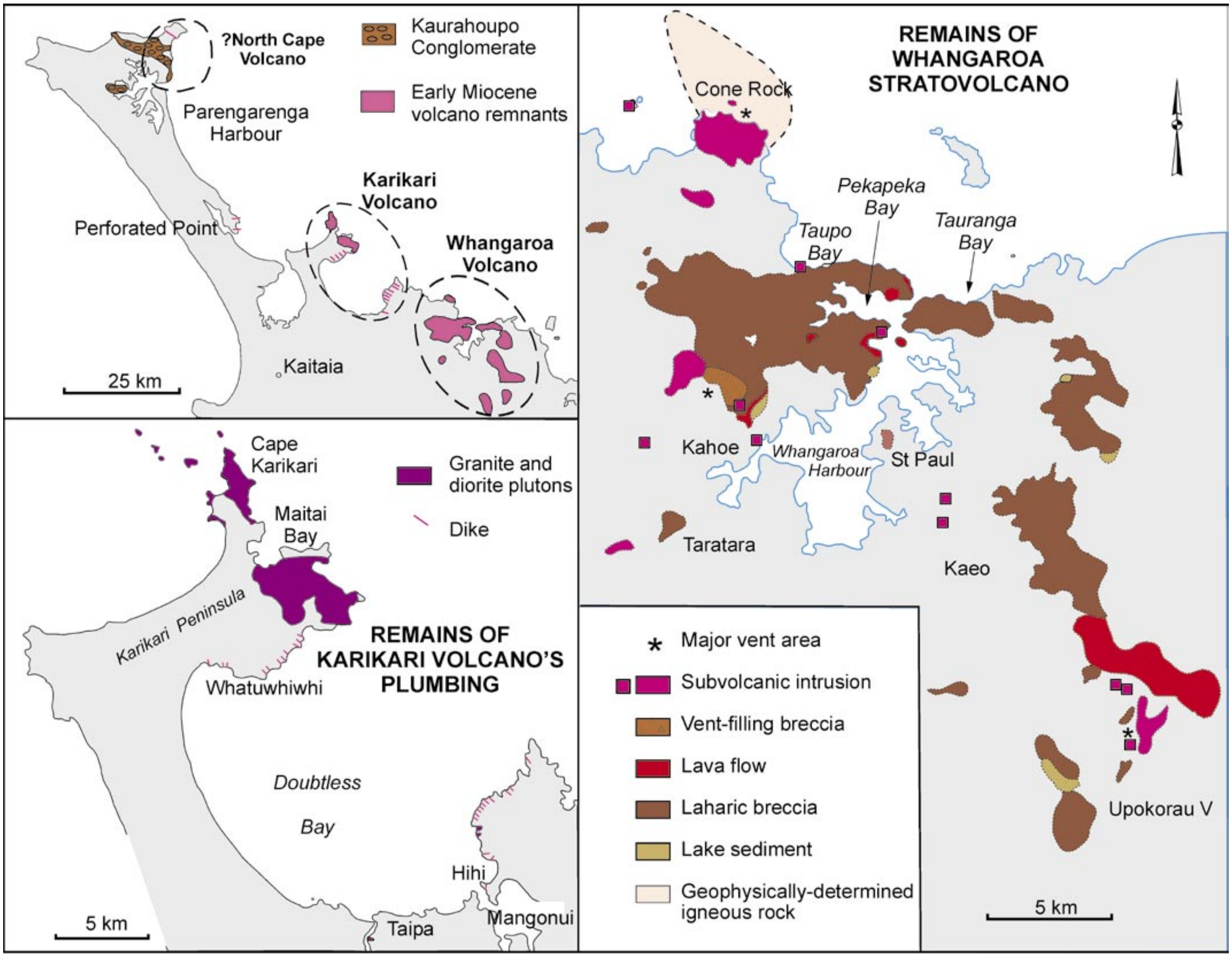
6.48 The hollow centres of these two small mounds mark the former locations of trees that were growing on an alluvial flood plain that had developed on top of the Hokianga Basin sedimentary infill during the latter part of the Early Miocene (*18-17 Myr ago*). *Lines in the shore platform are made by sand that swirled around the trees, killing and burying them as a major flood or perhaps a volcanic lahar swept across the valley floor. Pukorukoru Formation, Waimamaku coast.*

of the Waimamaku River mouth (*6.49*). They contain basalt-derived cobbles and pebbles that had washed down streams off the newly erupted Waipoua Volcano. The coastal plain sequence includes evidence for flood deposits of gravels and sand that killed and buried growing forests (*6.48*) and lenses of peat and mudstone that accumulated in swamps and ponds.



6.49 Exposures of river-deposited conglomerate and thin lignites of the Early Miocene (*18-17 Myr old*) *Pukorukoru Formation, on the coast north of the Waimamaku River mouth, south Hokianga.*

WHANGAROA, KARIKARI AND NORTH CAPE STRATOVOLCANOES



6.50 Simplified geological maps of the remnants of the Early Miocene Whangaroa and Karikari stratovolcanoes.

Whangaroa stratovolcano

Most of the higher hills, bluffs and coastal cliffs around Whangaroa, and for 10-15 km inland, are composed of the much eroded remnants of the ring plain of the Early Miocene Whangaroa stratovolcano, which erupted between 21 and 18 Myr ago. The ring plain is composed of weakly layered andesite breccia deposited by passing lahars as they swept down off the steep slopes of the central cone. Examples of these laharic breccias are easily seen in the coastal cliffs between Tauranga Bay and Taupo Bay (*6.51*), on either side of the entrance to Whangaroa Harbour. Within the laharic breccias, there are several lava flows (e.g. west of Tauranga Bay, *13.8*) that have flowed down shallow gullies that cut across the plain. In these gullies the pebbles are often somewhat rounded from tumbling along in the streams that eroded

6.51 Laharic breccia at Taupo Bay contains rounded to subangular cobbles and pebbles of many different compositions that were picked up by a volcanic lahar during its journey down a stream valley on the slopes of the Whangaroa Stratovolcano. Width of photo 2 m.

6.52 300 m-high Taratara, inland Whangaroa, is one of the best examples of a butte in New Zealand. A butte is a small flat-topped hill with vertical sides. The flat top is produced by the horizontal layering in the laharic breccia it is composed of. This is an isolated erosional remnant of the ring plain of Early Miocene Whangaroa Stratovolcano. View from the top of St Paul, above Whangaroa.

6.53 Intertidal exposure of mudstone and sandstone that was deposited in a freshwater lake, created by the earliest eruptions of Whangaroa Stratovolcano. The two tightly folded horizons are inferred to be a result of downslope sliding of the lake-floor strata, within a few thousand years of their deposition about 20 Myr ago. Photo 4 m across.

them. In several places there are leaf and wood-bearing mudstones and sandstones that accumulated in freshwater lakes, possibly formed in small valleys that were dammed by some of the earliest lava flows and lahars erupted from the volcano (*6.53*). In one area at least, some of the buried logs have been petrified by later silica-rich waters passing through the sedimentary rocks.

At lower levels, often seen where erosion has cut right through the former ring plain and down into the underlying Northland Allochthon rocks, there are a number of sheet-like dikes and other less regular intrusions of andesite. These mark the location of some of the plumbing that fed the stratovolcano above. These dikes are where molten magma stopped moving upwards and then cooled and solidified into solid rock inside the sheet-like conduits. One large (3-5 km diameter) andesite intrusion, centred on Cone Rock (10 km north of Whangaroa), might have been a shallow magma chamber beneath a central cone of Whangaroa Volcano.

6.54 Much of the outer part of Whangaroa Harbour is surrounded by high bluffs and cliffs composed of andesite breccia, deposited by passing lahars from the Whangaroa Stratovolcano cone. The vertical faces on the bluffs are a result of blocks breaking off along vertical joint planes and rolling off down slope. Dukes Nose, Pekapeka Bay, Whangaroa Harbour.

6.55 Rounded coastal boulders of massive speckled diorite on the southern shore of Maitai Bay. These rocks are inferred to be from an exhumed magma chamber from beneath the Karikari Stratovolcano, which has been eroded away since it erupted about 20 Myr ago.

Karikari stratovolcano

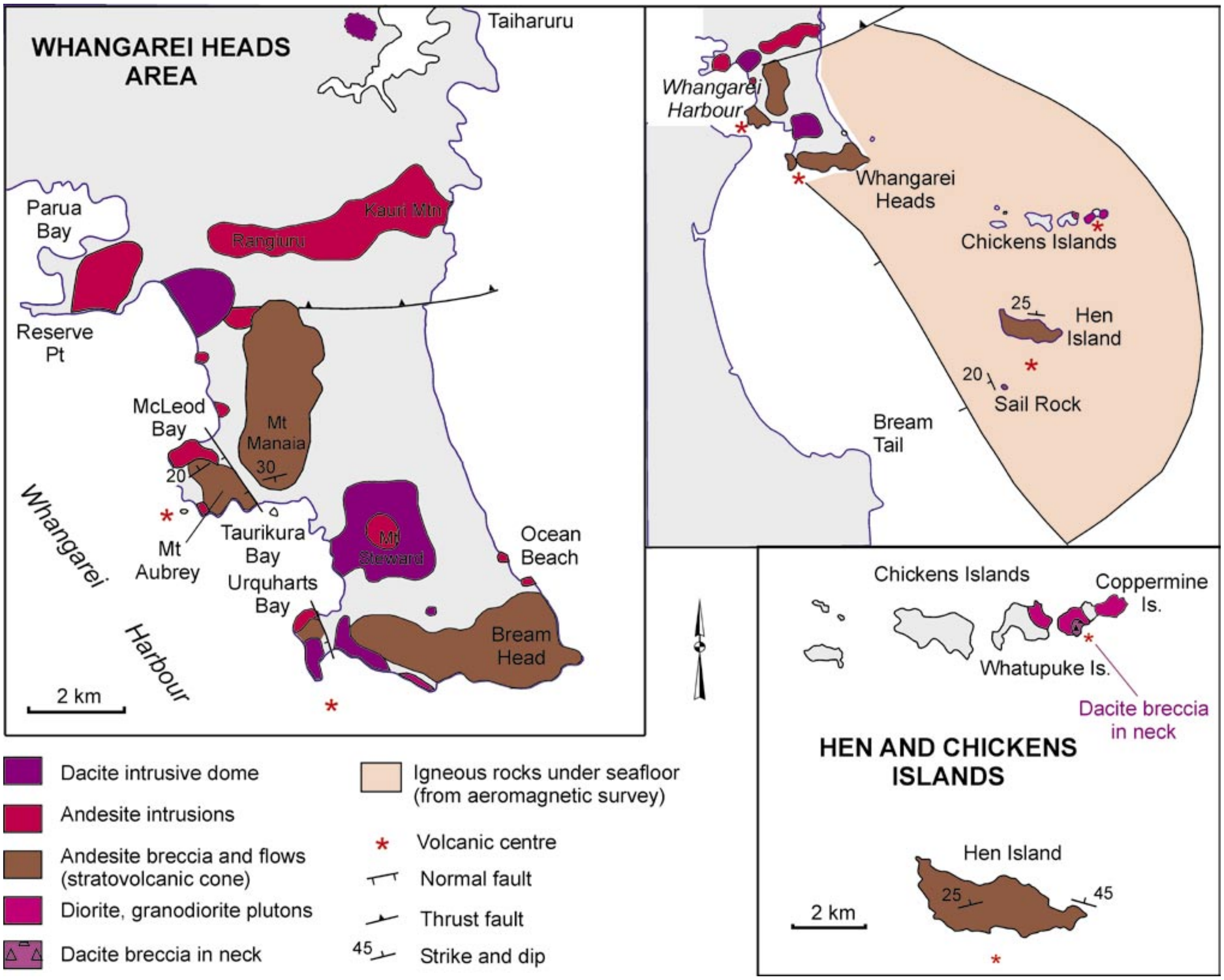
A large body of coarsely crystalline, speckled black and white diorite rock (most easily seen at Maitai Bay, *6.55*) forms much of the northern tip of Karikari Peninsula, 30 km northeast of Whangaroa. This diorite is inferred to be the exhumed magma chamber from beneath another Early Miocene stratovolcano. Radiometric dating indicates that it was active between 22 and 17.5 Myr ago. Associated with it, and intruding the older rocks beneath, is a series of northwest-southeast aligned andesite and diorite dikes that can be seen along both the northern and southern shores of Doubtless Bay. Karikari Volcano appears to have been uplifted higher, and to have suffered much greater erosion, than Whangaroa Volcano, as there are no remaining remnants of any of the erupted stratovolcano around Karikari Peninsula.

6.56 Historic photo from the early 1900s of a mushroom rock of andesite breccia in Pekapeka Bay, Whangaroa Harbour. It was formed by faster erosion at around the high tide level as a result of daily wetting and drying of the rock at this level. Unfortunately the rock has now naturally collapsed.

North Cape Volcano

Seventy kilometres northeast of Whangaroa, and along the same trend as Whangaroa and Karikari stratovolcanoes, there is evidence of the former existence of perhaps another completely eroded away volcano near North Cape (*6.50*). The evidence consists of a diorite intrusion – inferred to be subvolcanic plumbing of an andesite volcano and huge volumes of andesite-derived conglomerate (Kaurahaupo Conglomerate) within the Parengarenga Basin sequence (chapter 5). The well-rounded cobbles and pebbles in the conglomerate indicate that they have been transported some distance, probably down a river, from an eroding volcano source. This could have been Karikari and Whangaroa stratovolcanoes to the southeast or a closer volcano that may have existed near North Cape. The conglomerate was deposited in deltaic and shallow marine environments around 22-20 Myr ago.

WHANGAREI HEADS AND HEN ISLAND STRATOVOLCANOES



6.57 Simplified geological map of the Whangarei and Hen and Chickens Islands areas, showing the distribution of the eroded remains of Early Miocene stratovolcanoes.

In the Early Miocene a line of relatively small stratovolcanoes erupted on land between Whangarei Heads and the Hen and Chickens Islands (*6.57*). They erupted through and over greywacke basement and Northland Allochthon rocks, which had slid into the area about 23-21 Myr ago. Some eruptions in this vicinity might have occurred prior to the incoming of the Allochthon, but there is no direct evidence either for or against this hypothesis.

Around Whangarei Heads there are three rock-capped highland areas with pinnacles on their crests (*6.59*), forming Mt Manaia (420 m), Mt Aubrey (216 m) and Bream Head (476 m). These are all composed of massive to weakly-bedded rubbly breccia with angular cobbles and pebbles of andesite and rare lava flows that are the eroded remnants of the steep composite cone of one or

6.58 This 30 m-long natural jetty at Taurikura Bay, Whangarei Heads, is an andesite dike that has intruded into Northland Allochthon muddy limestone (Motatau Complex) and baked some of it to a black skarn (middle right). The dike is part of the subvolcanic plumbing of the Early Miocene Whangarei Heads Stratovolcano.

6.59 View northwest over the three highland areas around Whangarei Heads, each of which is composed of the eroded remains of one or more, small, Early Miocene stratovolcanoes. The highest, Bream Head (476 m), is in the left foreground, with forest-covered Mt Manaia (420 m) in the right distance and smaller Mt Aubrey (216 m) beyond, projecting south into Whangarei Harbour. Photographer Alastair Jamieson.

more andesite stratovolcanoes. These areas are the lower parts of the volcanic cone as the flat-lying land surface (of uplifted Northland Allochthon rocks) over which they erupted, is at about 100 m above sea level today.

In the same area, but usually at a lower elevation, erosion has exposed at least five large intrusions of andesite and dacite that have been squeezed up into the Allochthon and greywacke. These are inferred to be shallow level intrusive magma chambers that lay beneath the stratovolcano. Other evidence of the subvolcanic plumbing that fed the stratovolcanoes are numerous andesite dikes (*6.58*), best seen along the coast, where sometimes they have baked the allochthonous limestone to a hard black skarn. Numerous K/Ar radiometric dates indicate that Whangarei Heads Volcano erupted between 20 and 17 Myr ago.

The rocks at the Hen and Chickens Islands (*6.63*), 10-15 km to the southeast, tell a similar story. Hen Island and Sail Rock are the eroded remnants of a 5-10 km diameter stratovolcano with numerous andesite flows interspersed with rubbly breccia (*6.62*). Some of this weakly-layered cobble breccia forms the pinnacles on

6.60 Volcanic breccia, like this, forms most of the higher hills around Whangarei Heads. It is from the eroding composite cone of the 20-17 Myr-old Whangarei Heads Stratovolcano. It differs from laharic breccia (6.51) by having most clasts of one composition and the clasts are usually quite angular, as they have not been transported far. South of Ocean Beach, Whangarei Heads. Photo width 1.5 m.

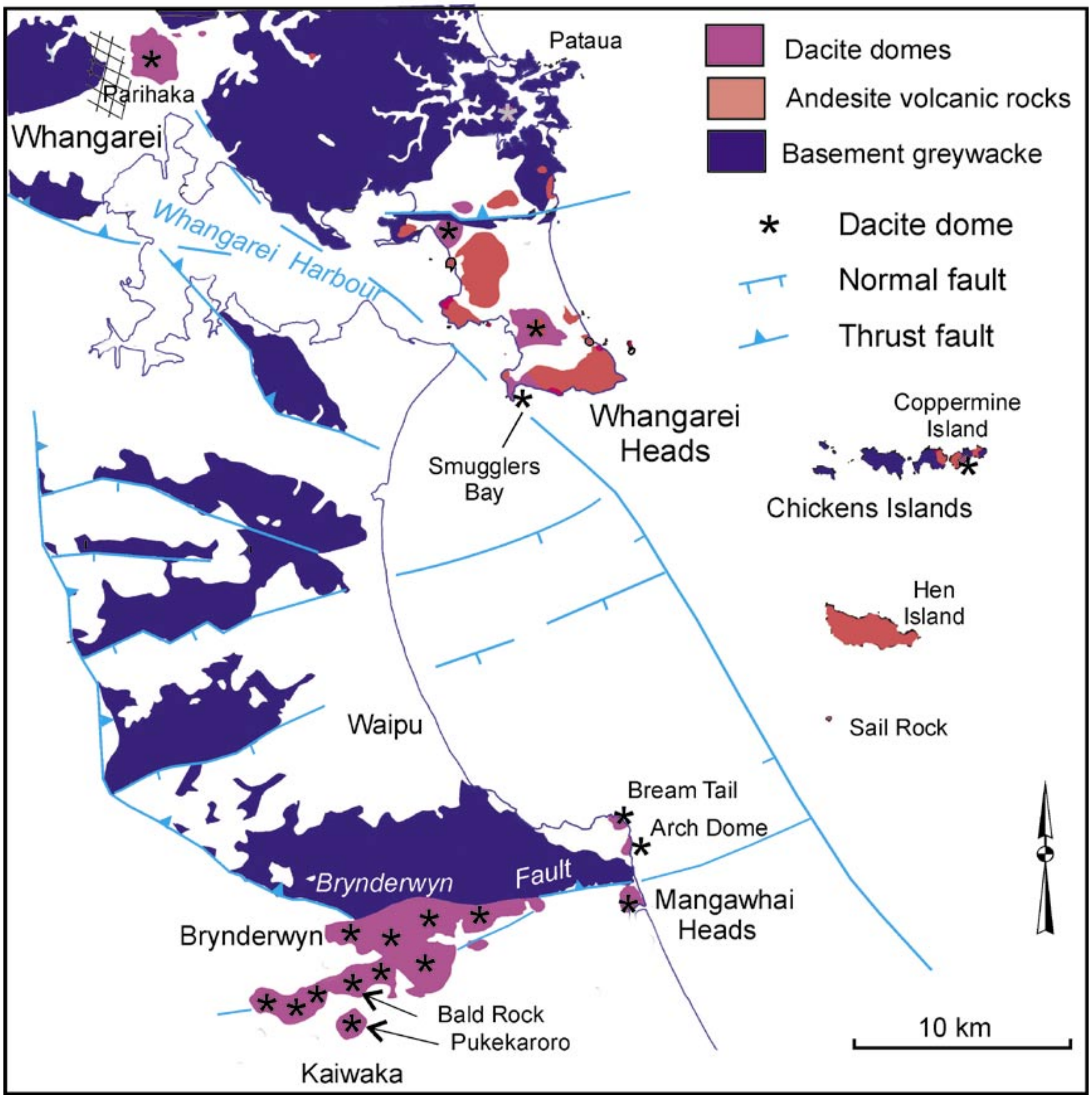
6.61 The pinnacled top of Mt Manaia, Whangarei Heads, is the eroded remnant of an Early Miocene stratovolcanic cone. The vertical cliff faces and pinnacles have been created when blocks of massive volcanic breccia broke off the mountain along weak joint plains and rolled downhill, sometimes reaching the shoreline below.

the highest point of Hen Island. The Chickens Islands have been uplifted compared to the Hen. The western Chickens Islands are composed of basement greywacke intruded by andesite dikes. The two easternmost islands are made of a mass of coarsely crystalline diorite and granodiorite that is inferred to have been a small magma chamber at shallow depths beneath perhaps another stratovolcano. There is also a small associated volcanic neck on Coppermine Island. Copper mining on the widely dispersed mineralisation associated with the hydrothermally-altered diorite occurred in 1849 and 1899, but was not a commercial success (box 5). Radiometric dating indicates that volcanic activity at the Hen and Chickens Islands occurred between 19 and 16 Myr ago, at the same time as activity at Whangarei Heads.

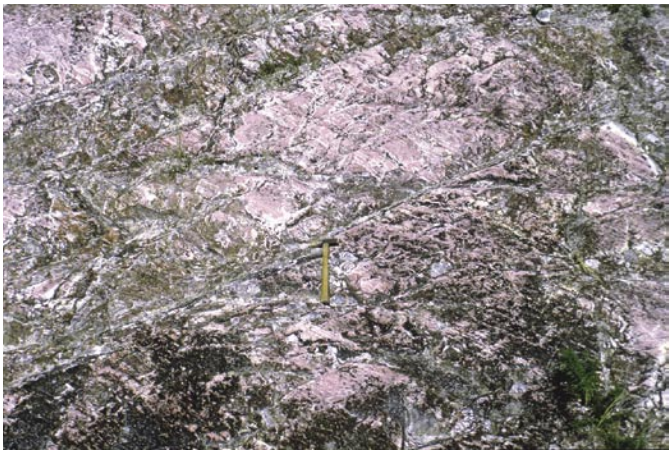
6.62 Angular blocky breccia on the north side of Hen Island is part of the eroded cone of the small Hen Island Stratovolcano, which erupted 19-16 Myr ago. Bream Head in the distance is the eroded remnant of another similar volcanic cone of the same age.

6.63 View of Hen and Chickens Islands from Langs Beach, Waipu. Hen Island (centre) and Sail Rock (right) are the remnants of a 5-10 km stratovolcano. The Chickens Islands (left) are basement greywacke intruded by the subvolcanic plumbing and small magma chambers of another volcano that has been eroded completely away from on top of them.

DACITE DOMES OF WHANGAREI AND KAIWAKA



6.64 Simplified geological map showing the distribution of Early Miocene dacite domes between Whangarei and Kaiwaka, on the east side of central Northland.



6.65 Flow-banded, pink and white rock, in a road cutting at Whangarei Heads, is a weathered portion of a shallow intrusive dacite dome of Early Miocene age.

Associated with the Whangarei Heads andesite stratovolcano are the eroded remains of four, 1-2 km-diameter domes of viscous dacite lava, which were extruded onto the stratovolcano's slopes at the same time as the erupting andesite. Outcrops of this lighter-coloured, grey-pink rock (*6.65*) can be seen in road cuts on the Whangarei Heads road and on either side of Smugglers Bay (*13.22*). Another dome forms a small hill just south of Pataua to the north (*6.64*). A volcanic neck full of dacite breccia on Coppermine Island is the only remains today of a similar dome associated with the Chickens andesite volcanic centre.

15 km northwest of the Whangarei Heads Volcano, an even larger dacite dome (3-4 km in diameter) was extruded out over the land during the Early Miocene (20-19 Myr ago). Softer rocks have been eroded from

6.66 Columnar-jointed dacite on the southern side of Arch Dome forms sea cliffs and intertidal reefs on the Mangawhai Heads coastal walkway. The near-horizontal lines behind the person are flow-banding of the dacite, produced as the viscous lava was extruded out of the feeder conduit.

around it and the hard dacite now forms the imposing Mount Parihaka, which overshadows much of downtown Whangarei. (The spelling of Mt Parihaka was corrected from Parahaki in 2005).

20-25 km south of Whangarei Heads Volcano there is another group of Early Miocene dacite domes (Pukekaroro Dacite). These have been dated as erupting between 19.5 and 18 Myr ago. Here there are three deeply-eroded domes on the coast between Mangawhai Heads and Bream Tail. All that is left are the subvolcanic feeders, where the dacite intruded basement greywacke and overlying Waitemata Sandstone sedimentary rocks. Where the Mangawhai Coastal Walkway goes along the coast, it passes over intertidal rocks and cliffs of two of these deeply eroded domes.

Inland, between Kaiwaka and the Brynderwyn road junction, there are the slightly eroded remains of about ten dacite domes, each 1-2 km across and most reaching 250-300 m in elevation. The most iconic is Pukekaroro Dome (*6.69*) with its dense cover of young kauri forest rising up next to Highway 1, north of Kaiwaka township. North and west of Pukekaroro, there is an 8 km-long (E-W oriented), bush-covered range of domes of similar height

6.67 This white hillock beside the Mangawhai Heads beach carpark is made of halloysite clay, produced by the intense weathering of part of the Early Miocene Mangawhai Heads Dacite Dome that forms the adjacent headland and rocky stack offshore.

6.68 View down on the south side of Bald Rock Dacite Dome, Kaiwaka. This rock is a prominent feature above the east side of Highway 1. The lines through the dacite are strong flow-banding, produced within the lava as it was being extruded. Photographer Alastair Jamieson.

(*6.64, 6.69*). In this area, it appears that the dacite magma that fed these domes intruded up from the depths, along several fault planes, before being squeezed out onto the surface like heaps of coalescing, molten toothpaste. The domes we see today appear to be little altered from their original landform shapes. If they had remained at the surface, however, they would have been largely eroded away in the 18 Myr since their eruption. Maybe the lower parts of these domes intruded soft allochthonous sedimentary rocks and their upper parts might have been buried by soft volcanic ash or ignimbrite. They were probably pushed up, along with the Brynderwyn Hills, by block faulting within the last few million years and the soft rocks that buried them have been eroded away, thereby exhuming their former dome shapes. The more vigorous marine processes along the Mangawhai coast have resulted in the much greater erosion of the domes over there.

6.69 View east along the alignment of Early Miocene dacite domes between Brynderwyn (left) and Kaiwaka (right). Pukekaroro Dome is the conical cone in the mid distance. Photographer Alastair Jamieson.

6.70 View north, from near Kaiwaka, of some of the cluster of Early Miocene dacite domes that form an east-west alignment above the fault, which the magma was extruded up. The prominent conical dome on the right is Pukekaroro Dome next to Highway 1.

Box 26. FOSSIL PALMS AND FERNS

Mudstone and fine sandstone (Pukorukoru Formation) that accumulated in freshwater ponds and swamps on the coastal plain on the northern fringes of the Waipoua Volcano, about 18-17 Myr ago, contain some well-preserved remains of the leaves and fronds of trees, palms and ferns that grew around the coast of subtropical ancestral Northland at that time. Fossil evidence of similar vegetation can be found in freshwater sedimentary rocks associated with the Early Miocene North Cape, Whangaroa and Hukatere volcanoes.

6.71 Above. Part of a palm frond, similar to modern nikau palm, found preserved in fine sandstone within an Early Miocene (about 20 Myr old) deltaic conglomerate sequence (Kaurahaupo Conglomerate), at the entrance to Parengarenga Harbour. Other Early Miocene occurrences of palm fronds have been found in the fluvial Pukorukoru Formation sequence on the South Hokianga coast. Photo 40 cm wide. University of Auckland fossil collection.

6.72 Top right: Rare fossilised Blechnum *fern frond, found in Pukorukoru Formation, Hokianga coast. Photo 15 cm wide.*

6.73 Lower right: Parts of several fossilised fronds of an Asplenium-like *fern. Pukorukoru Formation, Early Miocene, South Hokianga coast. Photo 10 cm across.*

6.74 Bottom left: Fossil bracken fern in Pukorukoru Formation siltstone that was deposited in a pond on the gravelly coastal plain of the Waipoua Volcano. South Hokianga coast. Photo 10 cm across.

Chapter 7. COROMANDEL VOLCANIC ZONE (18-2 Myr old)

Chapter Summary

Subduction-related volcanic activity in the eastern belt of the Northland Volcanic Zone started migrating southeastwards about 18 Myr ago, beginning at what is now Great Barrier Island and the northern Coromandel Peninsula. Between 16 and 5 Myr ago (Middle-Late Miocene) volcanism migrated progressively southwards, down the Coromandel Peninsula. By ~9 Myr ago, intermittent volcanic activity stretched for 250 km along the NNW-trending Coromandel Volcanic Zone, from the Poor Knights Islands in the north to Thames in the south. By 5-2 Myr ago (Pliocene-Early Pleistocene), active volcanism was confined to the Waihi-Kaimai Ranges area south to Papamoa. Between 1.9 and 1.6 Myr ago, volcanism jumped across to the present NE-trending Taupo Volcanic Zone.

The early phase of Coromandel Zone volcanism was almost entirely andesitic (Coromandel Group), producing numerous overlapping stratovolcanoes with surrounding laharic ring plains. Rhyolite magma (Whitianga Group) started erupting 12 Myr ago and continued throughout the rest of the Coromandel Zone's history. At most centres, initial rhyolitic eruptions were explosive - producing hot ignimbrite flows and high clouds of ash. Some of the ash was blown far away and mantled the floor of the Pacific Ocean, where there is a near-complete record of all the large rhyolitic eruptions from the Coromandel. Huge explosive eruptions resulted in the creation of at least six large caldera craters, each 5-15 km across and 1.5-3 km deep, now filled with ignimbrite and rhyolite and partly eroded away. Dozens of lava domes, composed of viscous rhyolite lava, were extruded into and around the rims of these calderas. Many other rhyolite domes exist outside the recognised collapsed craters, which might indicate the former existence of more, now unrecognisable, caldera volcano centres. About 10-5 Myr ago (Late Miocene), during an interval of sporadic rhyolite caldera eruptions, there were also eruptions of small basalt scoria cones and shield volcanoes in the vicinity of Kuaotunu Peninsula and the Mercury Islands, and of more voluminous andesite lava flows from inland Thames southwards. Table Mountain was formed at this time as a crater lake of andesite lava, surrounded by softer ignimbrite rock that has since been eroded away.

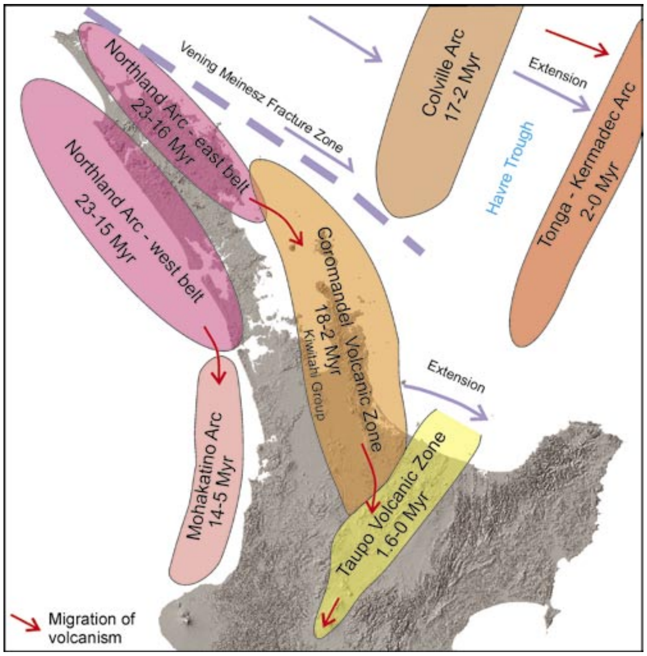
Meteoric waters were heated by shallow magma chambers beneath the Coromandel Volcanic Zone. The resultant hydrothermal fluids dissolved silicon and metals from the rocks they passed up through and deposited quartz and calcite veins and reefs in major fractures. Rare intermittent pulses of hot fluids were also released from the magma chambers and contributed to the base metal sulfide minerals and electrum (silver-gold alloy) in some of the reefs - the target of the Coromandel gold rushes. Prior to the 1990s, almost all gold and silver was obtained by underground mining of the quartz reefs from the Coromandel, Thames and Ohinemuri (Waitekauri, Karangahake, Waihi) goldfields.

Volcanic arcs of northern New Zealand

The present-day collisional boundary between the Australian and Pacific tectonic plates has run through New Zealand for at least the last 45 Myr. Since the start of the Miocene, about 23 Myr ago, there has been evidence of this plate boundary in the form of an actively erupting, subduction-related volcanic arc in the northern half of the North Island. This volcanic arc has not remained stationary, but through time has migrated south-eastwards in several jumps (*7.1*) that undoubtedly relate to changes in what was happening along the plate tectonic boundary.

Subduction-related volcanic rocks (generated above oceanic crust being pushed down beneath the edge of continental crust) can be recognised by the composition of the erupted lava. These rocks are characterised by the eruption of andesite, usually in association with rhyolite and dacite and sometimes basalt as well. The earliest subduction-related arc was oriented northwest-southeast and erupted in two belts on either side of the Northland-Auckland peninsula during the Early Miocene, 23-15 Myr ago (chapter 6). About 15 Myr ago, volcanic activity on the western belt jumped southwards on the same arcuate trend, to erupt as a belt of submarine andesite volcanoes (Mohakatino Volcanic Arc) that were intermittently active 14-5 Myr ago (Middle-Late Miocene). All these volcanoes are now buried beneath the seafloor and only known from remote sensing and a few oil exploration drill holes.

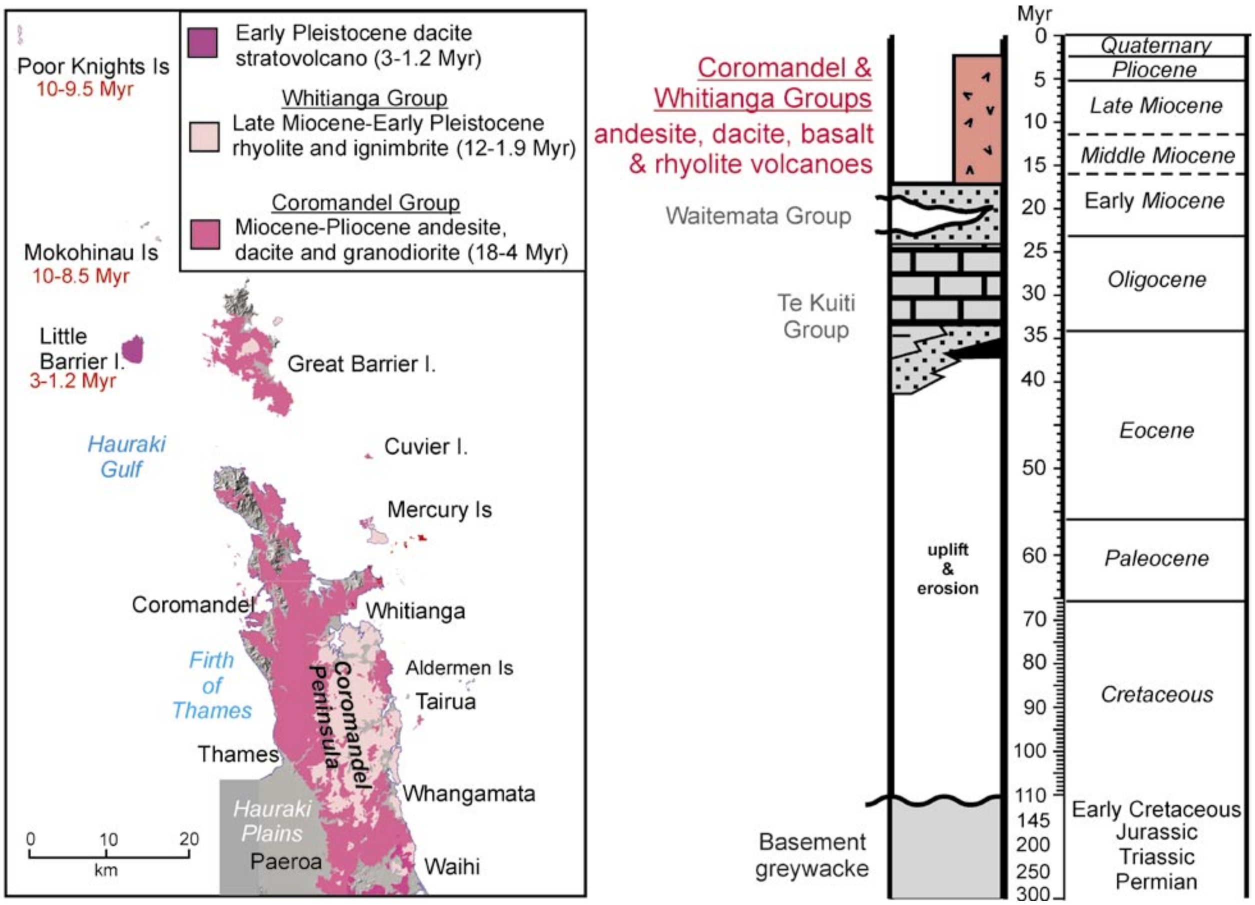
Southeastward migration of the eastern belt of the Northland Volcanic Arc was more gradual, starting about 18 Myr ago (Early Miocene) with the outbreak of andesitic volcanism on what is now Great Barrier Island and the northern Coromandel Peninsula. Through the Middle and Late Miocene (16-5 Myr ago), andesite



7.1 Above. Northland Volcanic Arc (*Early Miocene*) *migrated via the Coromandel Volcanic Zone* (*Miocene-Early Pleistocene*)*, to its present NE-oriented location* (*Taupo Volcanic Zone, Early Pleistocene-present*) *at the southern end of the Havre Trough and Tonga-Kermadec Volcanic Arc.*

volcanism progressively advanced southwards, down the Coromandel Peninsula (*7.4*). By 9 Myr ago, intermittent rhyolitic and andesitic activity extended from the Poor Knights and Mokohinau islands in the north to Thames in the south. The southern extent of the Coromandel Volcanic Zone continued to migrate southwards, extending into the Kaimai Ranges by 5 Myr ago. By the Pliocene-Early Pleistocene (5.5-2 Myr ago) all volcanism along the Coromandel Zone was in the south, in the Waihi-Kaimai Range area and southeast as far as Papamoa. The shift of volcanism to the present-day northeast-oriented Taupo Volcanic Zone at the southern end of the Tonga-Kermadec Volcanic Arc and Havre Trough occurred between 1.9 and 1.6 Myr ago. Since then, the Havre Trough has extended southwards and started opening up the Bay of Plenty down to Ruapehu. This southwards migration has been accompanied by the clockwise rotation of the northeastern North Island (East Cape-Hawkes Bay crustal block) with widespread

7.2 Below. Distribution of andesitic (*Coromandel Group*) *and rhyolitic* (*Whitianga Group*) *volcanic rocks of the Coromandel Volcanic Zone with rock column showing their age relationship to older rocks of the area.*



extension and voluminous eruption of rhyolite caldera volcanoes in the Taupo Volcanic Zone.

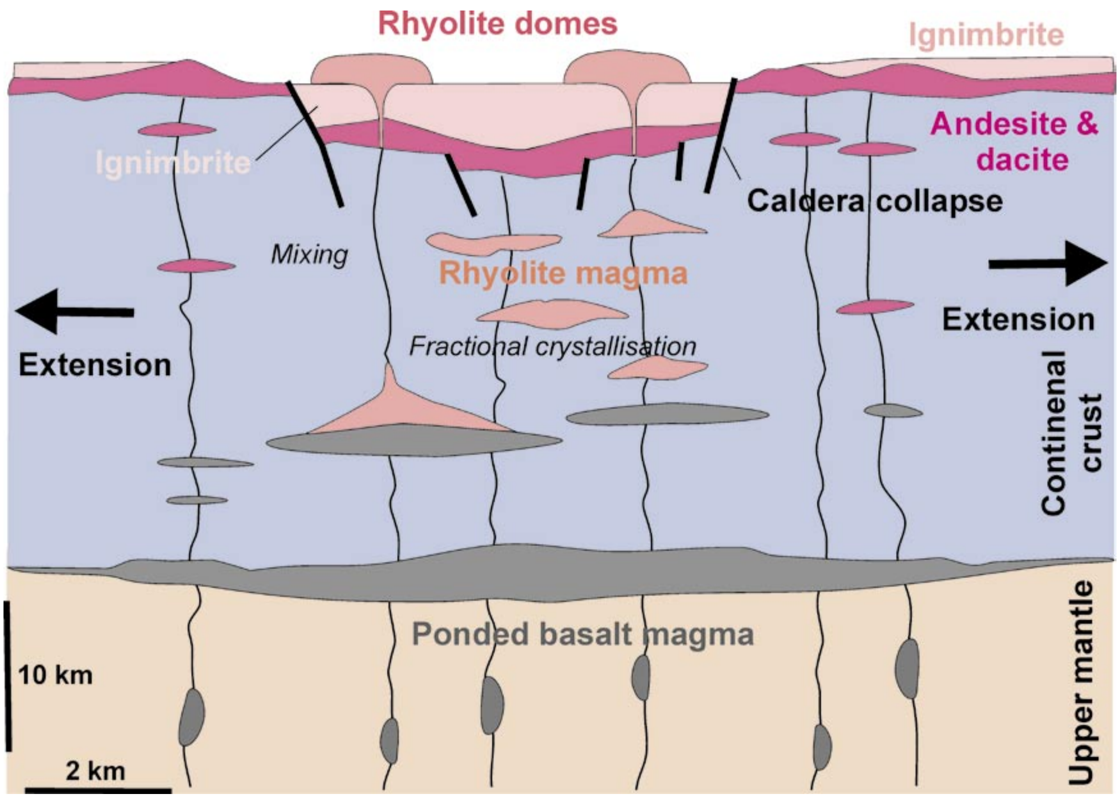
An additional narrow line of subduction-related andesite volcanoes (Kiwitahi Group; *7.4*) runs parallel to the Coromandel Peninsula along the west side of the Hauraki Rift (Firth of Thames, Hauraki Plains). It too exhibits southward migration of activity, starting 15 Myr ago on Waiheke Island and finishing about 6 Myr ago west of Matamata. This line is inferred to mark the western edge of the Coromandel Volcanic Zone, which has subsequently been separated from it by foundering of the Hauraki Rift. This implies that Coromandel Volcanic Zone rocks are likely deeply buried beneath younger sediment under the Firth of Thames and Hauraki Plains. Seismic profiles and rock samples dredged from a number of submerged rocky shoals indicate that the Coromandel Volcanic Zone also extended many kms east of Great Barrier Island and the Coromandel Peninsula. These eastern volcanoes have eroded down and their remains lie beneath the sea.

Some geoscientists hypothesise that there was no northnorthwest-oriented Coromandel Volcanic Zone. Instead, they envisage the volcanism on the Coromandel as being part of a southern extension of the northeast-trending Colville Volcanic Arc (*7.1*) that continued southwest as the Mohakatino Arc.

Generation of subduction-related magmas of the Coromandel Volcanic Zone

All the lava that erupted in the Coromandel Volcanic Zone is inferred to have been derived from, or at least strongly influenced by, mantle-sourced basalt magma. Water driven off from the subducted Pacific Ocean crust and accompanying ocean-floor sediment is thought to have caused the melting and hydrothermal alteration of part of the overlying upper mantle (peridotite), as it reached depths of about 100 km below the surface. The resulting basalt magma started rising towards the surface. Most of it was probably ponded as magma chambers at the base of, or within, the cooler solid continental crust (*7.3*) and there it sat slowly cooling for thousands to hundreds of thousands of years. As the basalt magma cooled, high-temperature minerals (olivine, clinopyroxene) crystallised out (fractional crystallisation) and as a result, the composition of the remaining liquid became more silica-rich and andesitic in composition. This andesite was erupted throughout the length, and most of the life, of the Coromandel Volcanic Zone.

Somewhat later in the Coromandel Zone, even more silica-rich rhyolite magma was generated in shallow magma chambers in the continental crust (*7.3*). Geochemists debate exactly how much of this was produced by more advanced fractional crystallisation,



7.3 Diagrammatic cross-section through the central part of the Coromandel Volcanic Zone. It shows the envisioned magma plumbing in the upper mantle and continental crust that fed the andesite stratovolcanoes, then in the Late Miocene (after 8 Myr) produced large rhyolitic caldera volcanoes and smaller rhyolite domes with interspersed small basalt volcanoes.

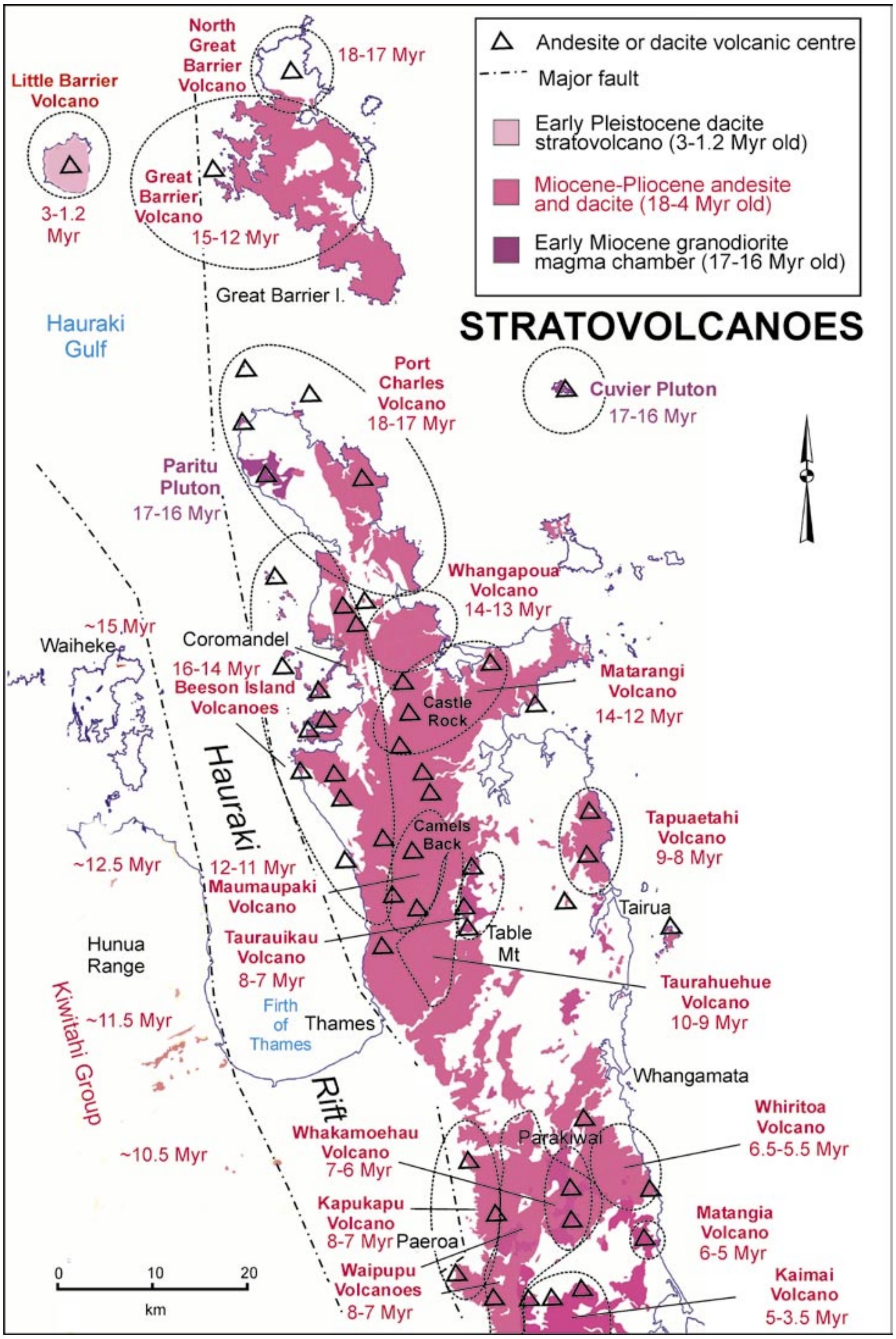
and how much by melting of the continental crust (of silica-rich granite) from the heat of the adjacent magma chamber. The onset of rhyolitic volcanism 12 Myr ago, and its sudden increase 8 Myr ago, has been linked to episodes of increased crustal extension (pulling apart) in the Coromandel Zone at these times. This might have resulted in a significant increase in the amount of basaltic magma rising up from the mantle and induced upwards-mobilisation of stalled magma bodies. A small amount of this relatively unmodified basalt magma (Mercury Basalt) reached the surface and erupted alongside the voluminous rhyolite. The crustal extension has been attributed to the increasing rotation of the East Cape crustal block away from the Northland-Coromandel area, leading to the eventual opening of the Taupo Volcanic Zone (Bay of Plenty) and the Hauraki Rift.

ANDESITE STRATOVOLCANOES

Most andesite and some of the dacite volcanism in the Coromandel Volcanic Zone is believed to have produced stratovolcanoes - steep central cones made of lava flows, broken-up blocks of andesite lava (breccia) and volcanic ash surrounded by a more gently sloping apron (ring plain) of lahar breccias and rare lava flows (Box 22) - similar in character to Mt Ruapehu or Mt Taranaki today.

Great Barrier Island stratovolcanoes

On the northern tip of Great Barrier Island, basement greywacke is intruded by numerous diorite, dacite and andesite dikes dated at 18-17 Myr old (*7.5*). Some are hydrothermally altered with copper mineralisation. As with Coppermine Island, mining was attempted at Miners Head in the 19th century on the copper mineralisation, which extended into adjacent greywacke, but was abandoned as uneconomic. The dikes are believed to be the shallow plumbing or conduits that fed magma to the land surface above, where a small North Great



7.4 Map showing the eruption age ranges and inferred location of andesitic and dacitic stratovolcanoes and vents in the Coromandel Volcanic Zone and its western extremities (west of the Hauraki Rift). Ellipses show inferred extent of volcanoes.

7.5 Top left. A 4 m-thick dacite dike (cream-coloured) intruding basement greywacke on the east side of northern Great Barrier Island. The numerous dikes in this area are inferred to be part of the subvolcanic plumbing of a small, Early Miocene, North Great Barrier Stratovolcano that erupted above, but has since been removed by erosion.

7.6 Top right. Layers of andesite tuff breccia can be seen in road cuts above Port Fitzroy on Great Barrier Island and around much of the island's coast. They were left behind by passing lahars that swept down the slopes of the Great Barrier Stratovolcano in the Middle Miocene (15-12 Myr ago).

7.7 Bottom. Layers of andesite lahar breccia and tuff breccia (lighter colour) that accumulated on the ring plain of the Great Barrier Volcano form the cliffs on the southeast side of Great Barrier Island. Originally the layers would have been near horizontal, but have subsequently been uplifted and tilted to the southwest.

Barrier Volcano was probably produced. All traces of this inferred cone have been eroded off.

A larger andesite stratovolcano, possibly centred west of present-day Great Barrier Island, is inferred to have erupted between 15 and 12 Myr ago, building a sizeable cone and surrounding ring plain. Although much of this volcano has subsequently sunk as the Hauraki Gulf subsided, the eroded eastern flanks form the bulk of central and southern Great Barrier Island today (*7.4*). Here there are typical rock associations that accumulated in central cone and ring plain settings - lava flows, small intrusions, rubbly breccia, laharic breccia and interbedded tuff (ash) beds (*7.6, 7.7*). In several places there are fine-grained lake sediments containing fossil leaves (*7.8*), freshwater mussel impressions or silicified

7.8 Middle Miocene leaf fossil preserved in mudstone deposited in a small lake on the lower flanks of Great Barrier Volcano, Medlands Stream. Length of leaf 10 cm. University of Auckland collections.

logs, which all support the inference that Great Barrier Volcano erupted on land, with intervening quiet periods when forest was able to colonise its slopes.

Coromandel Peninsula stratovolcanoes

On Cuvier Island and northern Coromandel Peninsula, 17-16 Myr old plutons (Cuvier and Paritu Plutons) of diorite and granodiorite, and associated andesite and dacite dikes, intrude the basement greywacke. Mineralogy of the thermally metamorphosed rocks around their edges indicate that these were magma chambers, which cooled at depths about 1 km below the surface. Thus both are inferred to be the exhumed shallow plumbing of two stratovolcanoes. If a small volcano did exist above Cuvier Island it has been completely removed by erosion long ago.

The eastern coastline of northern Coromandel Peninsula, from Fletchers Bay down to Kennedy Bay, is composed of the eroded parts of a medium-sized, andesitic Port Charles Volcano that erupted on land between 18 and 16 Myr ago (*7.9, 7.12*). The coarsely crystalline Paritu Pluton of northwestern Coromandel Peninsula was probably a magma chamber that fed the Port Charles Volcano above.

7.9 Platy-jointed andesite lava flow overlying red-baked tuff and breccia, east of Fletchers Bay. This flow is inferred to have come to rest near the base of the growing cone of Port Charles stratovolcano, about 18 Myr ago. Photo width 10 m.

Most of the northern and western half of the Coromandel Peninsula - north of Whitianga and south,

Box 27. COROMANDEL “GRANITE” BUILDING STONE

Coromandel “Granite” is the common name used by the building industry for a coarse, black- and white-speckled, plutonic rock (*7.10*) that was taken from the west coast of the northernmost Coromandel Peninsula. It was used as a strong, durable building stone between about 1900 and the 1970s. Slabs were also polished and widely used as facing stones and headstones. Strictly speaking, Coromandel Granite is tonalite as it lacks the orangy-pink potassium feldspar of true granites. It crystallised around the margins of the Paritu Pluton - a magma reservoir for the Early Miocene Port Charles Stratovolcano. The tonalite is composed of crystals up to 6 mm across, predominantly of white plagioclase and black hornblende, with a few flakes of black biotite mica and crystals of colourless quartz. The rock often contains scattered, rounded xenoliths (up to 10 cm or more across) of darker plutonic rock, which had crystallised out earlier in the magma chamber and were incorporated into the tonalite magma before it cooled and solidified.

7.10 Coromandel “Granite” was widely used as a building stone all around New Zealand.

7.11 During the 1900s to 1950s most Coromandel “granite” was taken from boulders on the hillside above Paritu and lifted onto scows and barges alongside a wharf built specially for the purpose.

7.12 View east over Fletchers Bay at the northern tip of Coromandel Peninsula, showing basement greywacke forming the nearest point, overlain by a deep-marine sequence of Early Miocene Waitemata Group sedimentary rocks (*Colville Formation, ~20 Myr old*) *in the bay beyond* (*5.36*)*. The Waitemata sedimentary rocks pass upward into younger andesite tuff and terrestrial laharic breccia and lava flows erupted from the 18-16 Myr-old Port Charles Volcano, which form the impressive Sugar Loaf and Pinnacles* (*background high point and rock to its left*)*.*

down the west side to Thames - is underlain by andesite and minor dacite lava and breccia that was erupted from stratovolcanoes (Whangapoua, Matarangi, Beesons Island, Maumaupaki volcanoes) between 16 and 11 Myr ago (Middle Miocene). The andesite rocks further east and south, down to Paeroa, Waihi and beyond - erupted slightly later, between 10 and 5 Myr ago (Late Miocene). At least nine, small, Late Miocene stratovolcanoes or compound stratovolcanoes have been mapped and named. Some (e.g. Matangia) were only 2-3 km in diameter, whereas others (e.g. Waipupu) consisted of several overlapping cones and ring plains extending over 20 km in distance. Likely there were more out to the east of the Coromandel Peninsula that have been eroded down and are now submerged beneath the sea.

All the original landforms of these 800-1500 m-high, Miocene andesite volcanoes have long since been removed by erosion, and what is left forming the countryside are sequences of lava flows and rubbly breccias and less commonly, tuff horizons. In some places the highest hills and most prominent headlands are formed of more massive, coarsely crystalline andesite or dacite rock, which may have been some of the near-surface plumbing that fed lava to the volcano vents. Spectacular examples of former vent-filling plugs, which can be seen as high points on the skyline profile of the Coromandel Range main divide, include Castle Rock (Matarangi Volcano; *7.13*), between Coromandel and Whitianga, and Camels Back (Maumaupaki Volcano), near the Tapu-Coroglen road. Throughout this area there are many eroded volcanic vents and feeder dikes (plumbing), which indicate that there were a number of overlapping volcanic cones, some with smaller vents on their lower slopes.

Away from the coastline, it is a challenge to locate andesite volcanic vents and the extent of individual stratovolcanoes. Rock exposure is often poor, because of the extensive forest cover and the deep chemical weathering or hydrothermal alteration of the rocks. This hydrothermal alteration was caused by underground circulation of hot water (heated by shallow magma chambers), which changed the mineral composition

7.13 A jagged pinnacle of the 520 m-high Castle Rock, on the main divide between Coromandel and Whitianga townships, is made of vertical intrusive dikes (*with horizontal columnar joints*) *thought to be the compound plug of a large dacite stratovolcano that was active about 12 Myr ago.*

of the rocks to chlorite, illite clays, calcite and pyrite. Later weathering of the altered rocks produced a variety of colours. Red, brown and yellow shades indicate the presence of iron oxides, whereas black and purple colours are derived from the presence of manganese oxides. Not only did the hydrothermal fluids alter the rocks, but those fluids also formed quartz veins with gold and silver mineralisation (Box 31).

For the first six million years of volcanic eruptions in the Coromandel Volcanic Zone (18-12 Myr ago), eruptions were entirely andesitic or dacitic, largely producing stratovolcanoes. For the next 10 Myr (Late Miocene-Early Pleistocene), however, andesite and dacitic eruptions were interspersed with caldera volcano eruptions of ignimbrites, extrusion of rhyolite domes and even small eruptions of basalt scoria and lava cones.

Table Mountain and other young Coromandel andesite volcanoes

The best known landform on Coromandel Peninsula is the 800 m-high plateau of Table Mountain, located on the main divide inland from Thames (*7.14, 7.15*). Table Mountain is almost completely surrounded by 150 m-high, vertical bluffs of columnar-jointed andesite that is oriented at various angles, which indicate that a large mass of lava cooled from the sides inwards and from the top down. Thus it would appear that Table Mountain is a cooled and solidified lava lake that was erupted into a 1 km-diameter elongate crater about 8 Myr ago. The flat top is probably close to the original surface of the lava lake, which has not eroded away because it is composed of much harder rock than the surrounding softer ignimbrite that once formed the crater walls. Some of the Table Mountain andesite appears to have spilled from the crater lake, as lava flows over the surrounding land to the north and east. Due north of Table Mountain, a prominent, 7 km-long ridge dividing the Waiwawa and Rangihau valleys, consists of the skeletal remains of elongate andesite fissure vents and a surrounding pedestal of lava flows that had erupted from them, at about the same time as Table Mountain (Taurauikau Volcano) was active. The fissure appears to have been near the western margin of the 15 km-diameter Kapowai Caldera crater (see later).

The eroded remains of Tapuaetahi stratovolcano, which erupted between 10 and 8 Myr ago, forms the land on the east coast between Hot Water Beach and Tairua. Four coastal exposures of vent-filling andesite plugs or eruption breccias mark the location of small eruption centres intruding sequences of lava flows and cone breccias in this volcano.

South of Thames and Whangamata are the eroded and overlapping remains of at least four andesitic and dacitic stratovolcanoes (Waipupu, Kapukapuka, Whiritoa, Whakamoehau). They all erupted in the latter part of the Late Miocene, between 8 and 6 Myr ago. They form the bulk of the hills in the southern Coromandel Ranges. A dominance of plugs and lava flows indicate the position of the former steep cones, with tuff breccia the main deposits left by passing lahars that flowed down the sides of the cones. The youngest of these andesite volcanoes in the Coromandel Peninsula is the remains of the 15-20 km diameter Kaimai Volcano, which erupted 6-4 Myr ago (7.4). Being the youngest of these conical

7.14 Flat-topped Table Mountain is one of the highest parts of the Coromandel Peninsula. Its distinctive flat top is easily recognised on the main divide skyline, inland from Thames.

7.15 View southeast over flat-topped Table Mountain with The Pinnacles eroded rhyolite domes in the centre distance. Table Mountain is a former andesite lava lake that solidified about 8 Myr ago inside a volcanic crater. It overlies and intrudes softer rhyolitic sediment and ignimbrite that has been eroded away from around the uplifted plateau - the surface of which was once the surface of the lava lake. Photographer Alastair Jamieson.

7.16 Inland from Whangamata at Parakiwai, this beautiful columnar-jointed dacite is an eroded plug that solidified in the throat of a young dacite dome. These beautiful columns are protected within Parakiwai Geological Reserve. Photo 3 m across.

volcanoes, it overlies and buries older ones, forming much of the landscape between Paeroa, Te Aroha and Katikati. The Kaimai stratovolcano has an eroded central cone area of andesite plugs and lava flows (Ananui Andesite Formation) surrounded by laharic breccia and tuff breccia of the ring plain (Uretara Formation). A number of small dacite domes were also extruded on the stratovolcano's slopes.

Little Barrier stratovolcano

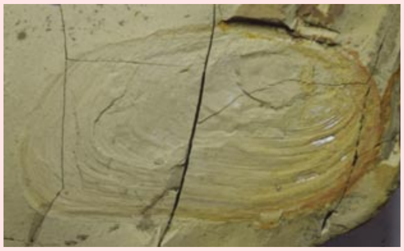
Located west of Great Barrier Island, in the middle of the northern sector of the Hauraki Rift, is Little Barrier Island. This is a partly-eroded stratovolcano with a diameter of 8 km, rising to a 700 m-high craggy peak. The rugged central part of the island is the eroded steep-sided stratovolcanic cone, composed of dacite lava flows and intervening breccias, intruded by near-vertical sheets of lava (dikes). This is surrounded by the eroded remnants of an outwardly-sloping ring plain composed of laharic

7.17 Little Barrier Island is a partly-eroded dacite stratovolcano that erupted in two phases, 3 and 1.2 Myr ago. It still retains its characteristic stratovolcano profile, with a steep-sided central cone surrounded by a gently sloping ring plain. The east side of the island is viewed here from Great Barrier Island, with Port Fitzroy in the middle foreground.

breccia, at elevations of 100-200 m (*7.17*). This volcano has been dated as erupting 1.6-1.2 Myr ago. On its northern side it overlies the eroded remnant of an earlier small 3 Myr-old dacite dome.

Little Barrier Volcano is a geological puzzle. The chemical composition of its rocks links them to a plate subduction zone like that beneath the Coromandel Volcanic Zone, but millions of years earlier the subduction zone had shifted, and by 3-1 Myr ago was located near its present position, 200 km to the southeast. Little Barrier Volcano's chemistry is very similar to that of Parakiore and Hikurangi dacite domes, of similar age within the Whangarei Basalt Field (chapter 9), and it has been suggested that all three might be related.

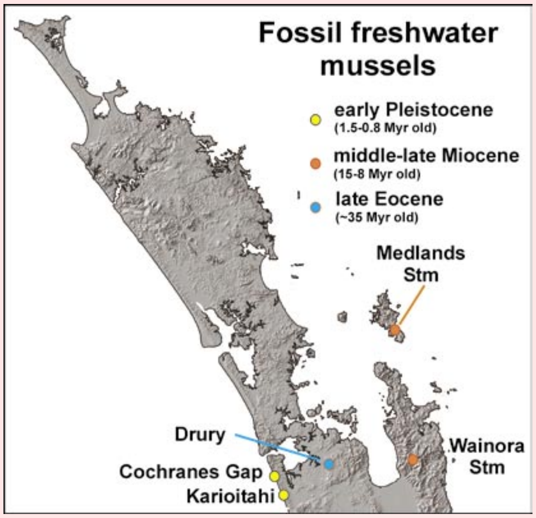
Box 28. FRESHWATER MUSSEL FOSSILS



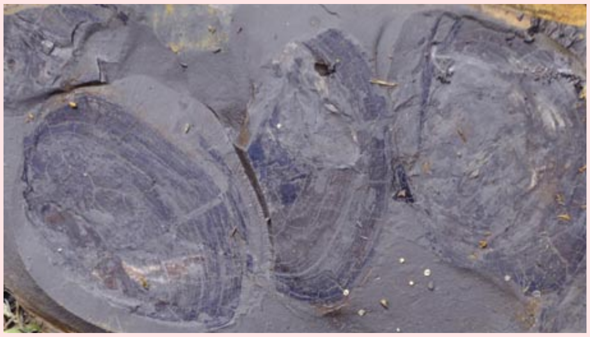
7.18 A 5 cm-long impression of a Middle Miocene (15-12 Myr old) freshwater mussel (Echyridella) from freshwater lake mudstone, Medlands Stream, Great Barrier Island. Auckland University collections.

Freshwater mussels are thin-shelled bivalves that live in the surface sediment on the floors of freshwater lakes, ponds and sometimes streams. Occasionally their shells, or the shape of their shells, are found preserved in mudstones that accumulated in these freshwater environments. Often they are accompanied by numerous fossil leaves. Fossil freshwater mussels are found in sedimentary rocks in New Zealand extending back in age as far as the Late Cretaceous (about 70 Myr ago). Three endemic species of freshwater mussels (genus *Echyridella*) live in New Zealand today. The modern species can grow up to 10 cm long and in perfect conditions live for at least 35 years. They filter-feed on detrital matter suspended in the water. There has been speculation over whether the ancestors of these modern freshwater mussels needed to have somehow been transported over the ocean from Australia, or whether they are all derived from Cretaceous species that were part of the original cargo carried by the ancient Zealandia landmass as it split away from the supercontinent of Gondwana.

In northern New Zealand, fossil freshwater mussels have been found in Late Eocene (35 Myr old) Drury coalfield mudstone (*7.20*), in sediment that accumulated in several Miocene volcanic lakes in the Coromandel Volcanic Zone (Great Barrier Island, (*7.18*); Wainora Stream, Kauaeranga Valley), and in Pleistocene dune-lake peaty sediment on Awhitu Peninsula (Cochranes Gap and Karioitahi).



7.19 Freshwater mussel fossil localities in northern New Zealand.



7.20 Three Late Eocene (35 Myr old), freshwater mussel fossils from the Waikato Coal Measures, east of Drury. The thin-shelled mussels have been flattened and much of their shell has subsequently dissolved away. The two shells on the right are an open pair that are still joined together along their hinge. Width of photo 30 cm.

Box 29. CALDERA VOLCANOES AND IGNIMBRITE ERUPTIONS

7.21 Cross-section through an idealised eruption of a caldera volcano showing an enormous cloud of ash and pumice, up to 30-50 km high, with the finer parts blowing away and the denser parts collapsing and blasting out sideways as hot pyroclastic clouds that sped across the land and left behind a sheet of ignimbrite rock. Drawing modified from Geoff Cox.

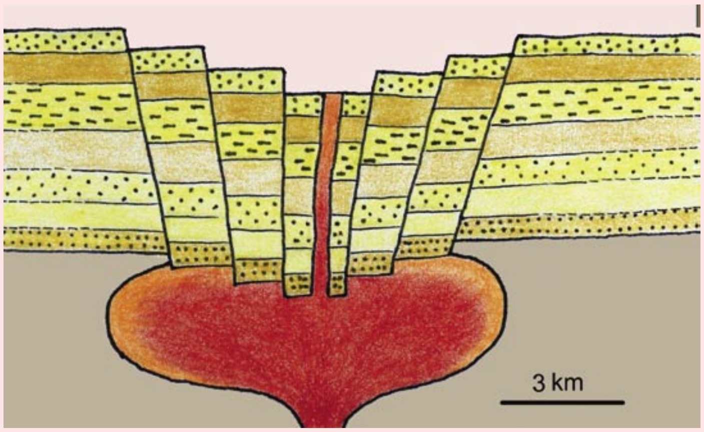
The rhyolite volcanoes of the Coromandel Volcanic Zone were fed from shallow magma chambers within the continental crust. They erupted at the surface in one of two styles. The rhyolite magma contained a great deal of dissolved gas, primarily carbon dioxide. As magma rose to the surface, the confining pressure decreased and the gas came out of solution. Its release powered an enormous fountaining of hot frothy lava rising up to 50 km or more into the air (*7.21*). The lighter, smaller fragments of volcanic ash were blown by the wind and mantled a wide area of land and sea in a layer of light-coloured glassy particles. Often the denser parts of the eruption column of frothy lava, hot gas and glass collapsed back towards the ground. As it hit the ground, the energy of the collapsing column blasted it out sideways as a searing hot, pyroclastic flow (or ignimbrite flow) that travelled across the ground at speeds up to 500 km/h. It would have incinerated or buried any forests it engulfed.

The largest such eruptions came out from the Taupo Volcanic Zone in the last 1.5 Myr with at least four super-eruptions, each erupting more than 450 km^3 of magma. The eruptions and ignimbrite flows, produced by caldera volcanoes in the Coromandel Volcanic Zone between 12 and 2 Myr ago, were probably smaller, but many ash layers from these have been found in deep-sea cores taken 600 km east of Gisborne. Ignimbrite flows from Coromandel sources are mostly known from the Coromandel Peninsula itself, but at least one 4 m-thick Pliocene ignimbrite from the Coromandel Volcanic Zone is known from Mangatangi, 40 km west of the nearest caldera volcano vent.

If the pyroclastic flow was still extremely hot as it came to a stop, the deposit of pumice, glass, crystals and a few rock fragments would be welded together into a hard ignimbrite rock as it solidified (*7.23*). If the flow had cooled sufficiently during its journey, then the resulting ignimbrite deposit was unwelded and relatively soft or even a friable pumice breccia deposit.

The rapid emptying of the shallow rhyolite magma chambers during these huge explosive eruptions occurred over a matter of hours to a few days. The land overlying the emptying magma chamber collapsed into the hole, creating a huge crater known as a caldera (*7.22*). Recognised ancient calderas on the Coromandel Peninsula are 5-15 km in diameter (*7.24*) - significantly smaller than the 30 km-diameter Taupo Caldera.

The second style of eruption of Coromandel rhyolite volcanoes was of gas-poor, highly viscous magma that was extruded up through the surface rocks and out onto the surface as a rugged rhyolite dome (Box 22). Often these were extruded in and around a collapsed caldera, after the gas-rich part of the rhyolite magma had been erupted as ignimbrite flows and ash. The domes usually flared outwards and had an intrusive neck-filling portion and extrusive portion above ground, which often had thick toothpaste-like flows that spread out over the ground away from the vent. Domes could



7.22 Idealised cross-section through a caldera volcano after a large eruption of frothy ash and ignimbrite. The rapid emptying of the upper part of the magma chamber, in a matter of days, resulted in the inwards collapse of the chamber's roof, creating a large, roughly circular collapse crater known as a caldera. Typical width 5-15 km. Drawing by Margaret Morley.

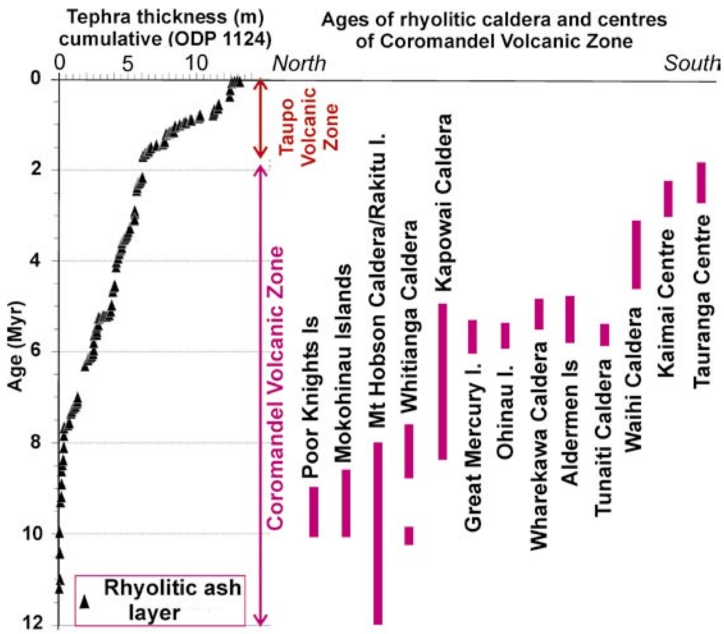
Box 29 continued

be tens to hundreds of metres high and hundreds of metres to several kilometres across. In the Coromandel Volcanic Zone, some rhyolite domes were single, subcircular landforms, but many others had a number of vents and the domes joined together and overlapped to form quite complex features.

7.23 Sometimes the residual heat in an ignimbrite deposit was so great that the near-molten pumice fragments were flattened before the rock solidified, forming a texture of lenticular blebs (called fiamme) in a fine-grained ashy matrix. These rocks were so distinctive and different that early 20th century geologist, Les Grange, gave them the new rock name owharoaite, from the type locality in the southern Coromandel Range, but this name is no longer used and the term lenticular ignimbrite is used instead. Photo: Whiritoa, south eastern Coromandel Peninsula.

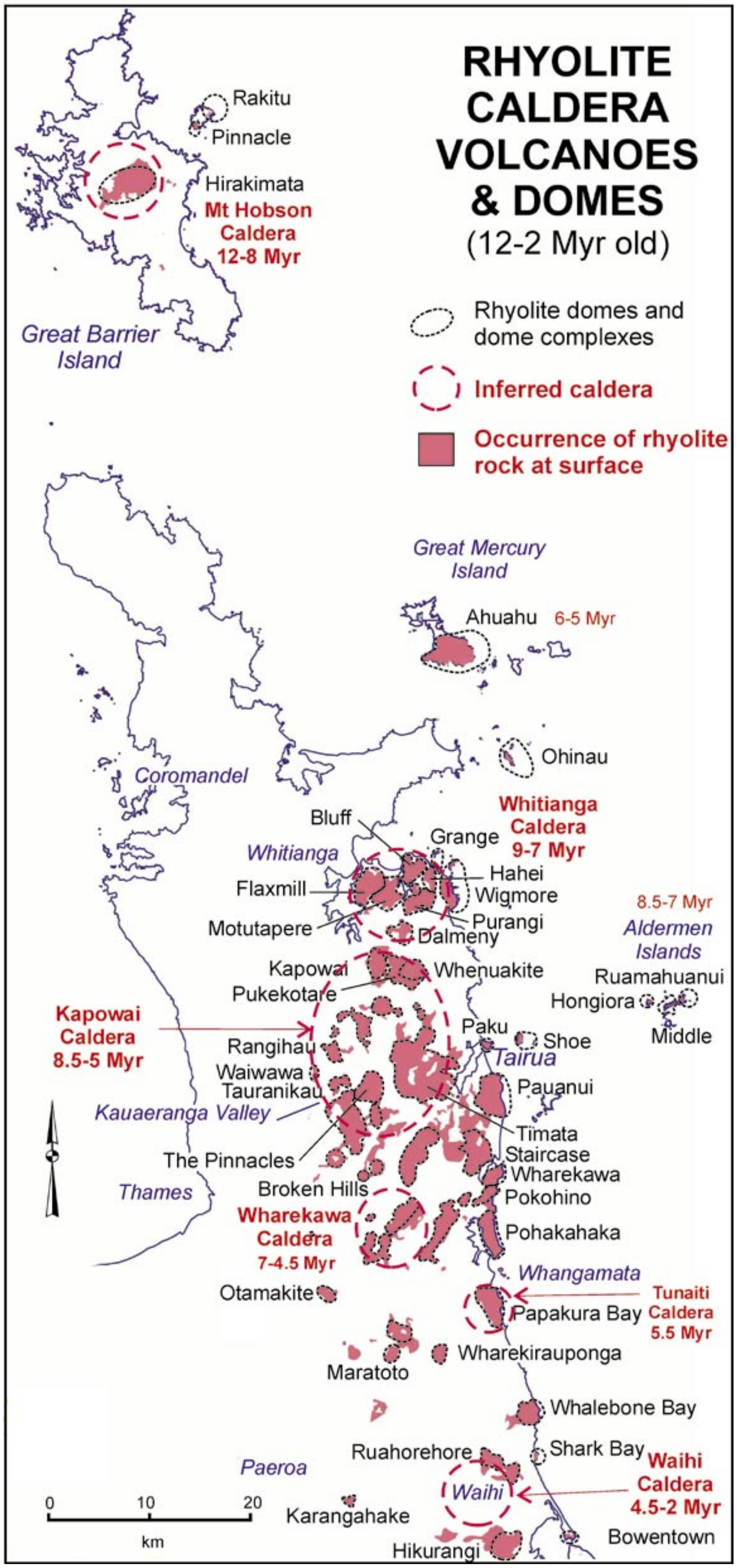
RHYOLITE CALDERA VOLCANOES AND DOMES

The locations of at least six caldera volcanoes have been identified in the Coromandel Volcanic Zone (7.24). The Coromandel calderas are near-circular collapse structures, each 5-15 km in diameter, and recognised by their concentration of rhyolite and ignimbrite rocks and by remote sensing using gravity measurements. The calderas are filled with low-density lake sediment, ignimbrite and rhyolite, whereas the surrounding areas have denser andesite and greywacke at similar shallow depths. It has been calculated that Whitianga, Kapowai and Wharekawa calderas are filled with erupted ignimbrite and rhyolite to depths of 1.5-1.8 km below sea level and Waihi Caldera, further south, is close to 3 km deep. About 50-250 km^3 of magma has been estimated to have been erupted from each caldera, maybe in only a few eruptive episodes each. Scattered throughout the andesitic and particularly rhyolitic volcanic rocks of the Coromandel Peninsula are numerous occurrences of plant-rich, freshwater lake sediments. These show that not only were the volcanoes quickly colonised by forest, but that there were many small volcanic lakes, rather like the Rotorua lakes area today. In addition to the six recognised caldera volcanoes, there are other areas where rhyolite domes are present (e.g. Poor Knights, Mokohinau, Rakitu, Great Mercury, Ohinau, Shoe and Aldermen islands), which might or might not be linked to further, as yet unrecognised, calderas.



7.24 Age and thickness of rhyolitic ash layers obtained in a deep-sea core (ODP 1124, 3967 m water depth) located 750 km east of the Coromandel Volcanic Zone, compared to the known eruption age ranges of the rhyolitic caldera and other major rhyolite centres in the Coromandel Zone. Modified from Briggs (2004) and Carter et al. (2004).

As with the andesite volcanism in the Coromandel Volcanic Zone, the oldest rhyolite volcanoes (12-10 Myr old) erupted in the north and activity migrated southwards, with the youngest (5-2 Myr old) volcanism located between Waihi, Kaimai and Tauranga. Interestingly, the start of rhyolite volcanism lagged behind initial andesite eruptions by 5-6 Myr at Great Barrier and in the Whitianga



7.25 Location of inferred calderas and associated rhyolite domes and dome complexes on Coromandel Peninsula and Great Barrier Island. Dome complexes are composed of a number of overlapping extruded domes.

area, but was only 2-3 Myr behind in the south, at Wharekawa and Waihi calderas.

The best record of the continuity and frequency of major rhyolite volcanism in the Coromandel Volcanic Zone comes from a deep-sea drillhole record taken 750 km away to the east, in 4000 m of water off the East Coast of the North Island (*7.24*). In this core, there are 82 layers of rhyolitic ash that are inferred to have been erupted from the Coromandel Volcanic Zone between 12 and 2 Myr ago. These ash layers must have been ejected tens of kilometres into the air by large ignimbrite-related caldera eruptions and been transported hundreds of kilometres in the air by the predominant westerly winds. The average thickness of these ash layers in this core is 7 cm, but the largest, which erupted approximately 5 Myr ago, is close to 50 cm thick. The average frequency of these large eruptions was at least one every 140,000 yr in the Late Miocene (12-5 Myr ago) and one every 80,000 yr during the Pliocene-Early Pleistocene (5-2 Myr ago). Of course, not all ash would have been blown eastwards, so this core provides an incomplete record of Coromandel rhyolitic ash eruptions.

Rhyolitic volcanism in the northern Coromandel Volcanic Zone

The oldest-known rhyolitic eruptions in the Coromandel Volcanic Zone occurred in the northern part of the zone. Furthest north are the Poor Knights Islands, which are largely composed of silicified ignimbrite and rhyolite breccia that has been dated at 10 Myr old. The flat top of the northern island, Tawhiti Rahi (190 m above sea level), is formed of erosion-resistant sinter that possibly retains the original land surface from when it was formed. Ten million years of erosion has removed most of this volcano, which the ignimbrite presence suggests might have been a small caldera volcano. The seafloor west of the Poor Knights is no deeper than 100 m, which suggests the islands were probably joined to mainland Northland as recently as 18,000 yr ago, when sea level was 120-130 m lower than present.

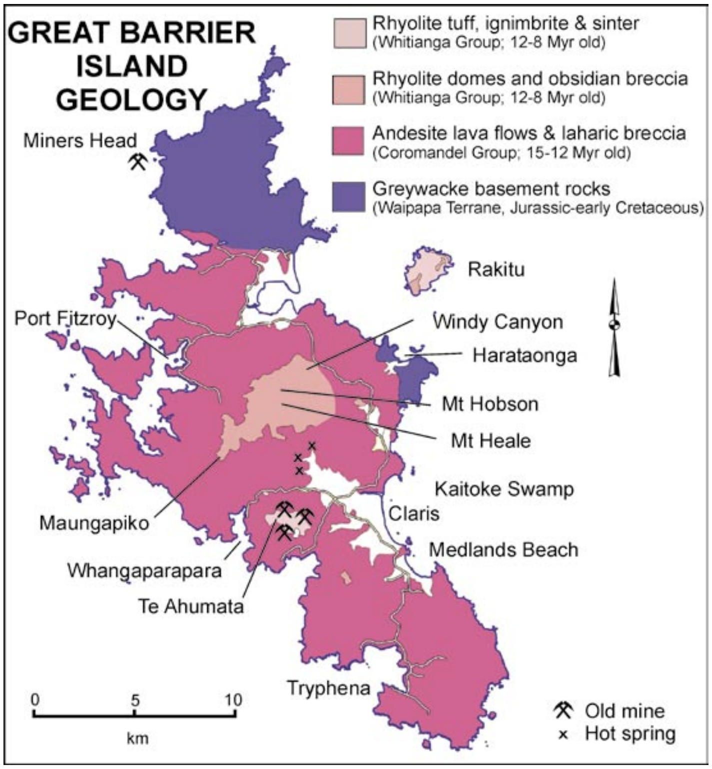
Eighty kilometres south of the Poor Knights are the similarly remote Mokohinau Islands (*7.2*). The majority of the islands are composed of rhyolite overlain by rhyolitic tuff and breccia. These are the deeply-eroded remnants of a much larger rhyolite

7.26 *The Poor Knights Islands are made of silicified rhyolite breccia and ignimbrite - eroded remnants of a much larger 10 Myr-old caldera volcano. Looking south from Tawhiti Rahi to north western Aorangi Island.*

7.27 *Rakitu Island, off the east coast of Great Barrier Island, is composed of the eroded remains of two Late Miocene rhyolite domes and ignimbrite flows. Photographer Alastair Jamieson.*

dome complex that has been dated as erupting 10-8.5 Myr ago.

There are two areas of Late Miocene rhyolitic rocks on Great Barrier Island (*7.28*) that erupted 11.5-8 Myr ago. The 600 m-high Mt Hobson area, in the centre of the island, is composed of the eroded remains of a complex of rhyolite domes surrounded by shattered glassy obsidian breccia and perlite. In places, such as Mt Heale and Maungapiko, there are prominent pinnacled hills and bluffs of flow-banded rhyolite. The eroded domes and possibly deeper ignimbrite fill the 3 km-diameter Mt Hobson Caldera, which has been estimated from remote sensing measurements of gravity to be approximately 2 km deep. Initial highly explosive eruptions from this caldera volcano possibly produced hot ignimbrite flows, which might have deeply buried all the area now occupied by Great Barrier Island and well beyond, and resulted in the collapse of the caldera crater.



7.28 *Simplified geological map of Great Barrier Island showing the present-day distribution of the eroded remains of its Middle-Late Miocene andesite and rhyolite volcanoes. Modified after Moore (2001).*

All trace of these ignimbrites has been removed by erosion, except for a small remnant located 6 km to the south. These prominent bluffs are on the north side of Te Ahumata, a 400 m-high plateau composed of altered older andesite overlain by ignimbrite, rhyolitic tuff and sinter. This was the site of an extinct geothermal field. Silica-rich hot water that discharged at the surface deposited the sinter over an area at least the size of the present plateau. As this hot water passed through the underlying rocks, it also silicified the ignimbrite and tuff, and formed quartz veins with silver and gold mineralisation (*7.48*). The flat top of Te Ahumata Plateau appears to be a remnant of the land surface formed about 9 Myr ago, left upstanding as the softer surrounding rocks were eroded away from around the hard, erosion-resistant sinter.

Just off the northeast coast of Great Barrier Island is Rakitu (Arid Island) (*7.27*), which is the eroded remnant of yet another rhyolite centre, possibly a small caldera volcano that erupted about 12-11 Myr ago. The rocks consist of remnants of two domes, separated by a columnar-jointed ignimbrite flow, rhyolitic breccia, tuff and a small basalt lava flow. This is the only known basalt in the northern Coromandel Volcanic Zone.

7.29 Left: The Windy Canyon Track on Great Barrier Island passes through a deeply eroded landscape of gullies, rocky pinnacles and rounded knolls. This unusual rock, composed of glassy obsidian and rhyolite fragments, was formed by shattering of lava as it rapidly chilled along the margin of a rhyolite dome erupted from the Mt Hobson caldera, about 10 Myr ago (*Late Miocene*).

7.30 Right: Ahuahu Rhyolite Dome (*6-5 Myr old*) *forms the southern half of Great Mercury Island, off the east coast of northern Coromandel Peninsula. More vigorous erosion on its northern side has created its distinctive, 200 m-high white cliffs. Red Mercury Island is in the left distance. Photographer David Towns.*

Rhyolitic volcanism in the central Coromandel Volcanic Zone

Two 12-15 km-diameter calderas (Whitianga and Kapowai), filled with low density rocks, have been identified by gravity studies in the central part of the Coromandel Volcanic Zone. There are also many rhyolite domes outside of these that might have been associated with additional smaller caldera volcanoes that are not identifiable by density contrasts of the near-surface rocks.

The northernmost rhyolite vent on Coromandel Peninsula or its adjacent islands is Ahuahu Dome Complex, which forms the southern half of Great Mercury Island (*7.30*). This complex of two coalescing domes was preceded by the eruption of rhyolitic breccia, tuff and ignimbrite that presumably came out of the same vent. Rhyolite eruptions from the Ahuahu centre have been dated at 6-5 Myr old and occurred between eruptions of basalt on the nearby smaller Mercury Islands (Mercury Basalt).

Ten kilometres south of Great Mercury, the slightly smaller Ohinau Rhyolite centre appears to be of a similar age to Ahuahu and also interfingers with Mercury Basalt. The spectacular cliffs of Ohinau Island expose eroded sections through both intrusive and extrusive portions of small rhyolite domes.

As with all caldera volcanoes, the Whitianga and Kapowai calderas probably began with explosive eruptions of frothy pumice, tuff and ignimbrite flows. Thick deposits of these pyroclastic rocks presumably fill most of the 1.5-2 km deep collapsed calderas. Most of the deposits that accumulated beyond the walls of the caldera have been eroded away, especially on their more uplifted, western sides. Near Whitianga, the oldest ignimbrite (Carina Rock, west of the caldera) has been dated as having erupted 11 Myr ago, about 3 Myr before the oldest-dated rhyolite domes that fill the upper part of the Whitianga Caldera today. The most widespread ignimbrite and associated rhyolitic pumice and tuff deposits is Wharepapa Ignimbrite (*7.31*), which erupted around 8.5 Myr ago from Kapowai Caldera. This unit unconformably overlies an eroded and weathered surface of older andesite that has been gently tilted down to the east. Prior to 8 Myr ago, the number and thickness of rhyolitic ash layers in the distant deep sea core was small, but the size and frequency increased dramatically after 8 Myr ago, with the onset of eruptions from the Whitianga and Kapowai calderas.

Early eruptions from the Kapowai Caldera created several freshwater lakes by damming valleys or by partial collapse of the giant crater, 9-8.5 Myr ago.

7.31 Eroded and fluted bluffs of ignimbrite that was erupted around 8.5 Myr ago from Kapowai Caldera. Wharepapa Ignimbrite, Kapowai Valley.

7.32 Coastal cliffs made of thick ignimbrite erupted from Whitianga Caldera about 8 Myr ago (Late Miocene). Stingray Bay, north of Hahei, Coromandel Peninsula.

Mixed andesite and rhyolite gravel, tuffaceous and carbonaceous mud and sand (Wainora Formation) accumulated in these lakes and outcrop in the beds of a number of remote streams in the middle of Coromandel Forest Park (e.g., Waiwawa and Rangihau streams). Some of these lake sediments (e.g., exposed in Wainora Stream) contain freshwater mussels, leaves, branches and logs. Percolating silica-rich ground water later petrified some of the logs and branches, creating various colours of silicified wood, chalcedony and common opal (Box 30). Studies of the leaves and fossil pollen and spores in Wainora Formation show that the dominant forest growing over and around the Coromandel volcanoes about 9 Myr ago (Late Miocene) was of large-leaved southern beech (*Nothofagus brassospora* type, *7.54*), similar to that which grows in high altitudes in New Caledonia and Papua New Guinea today.

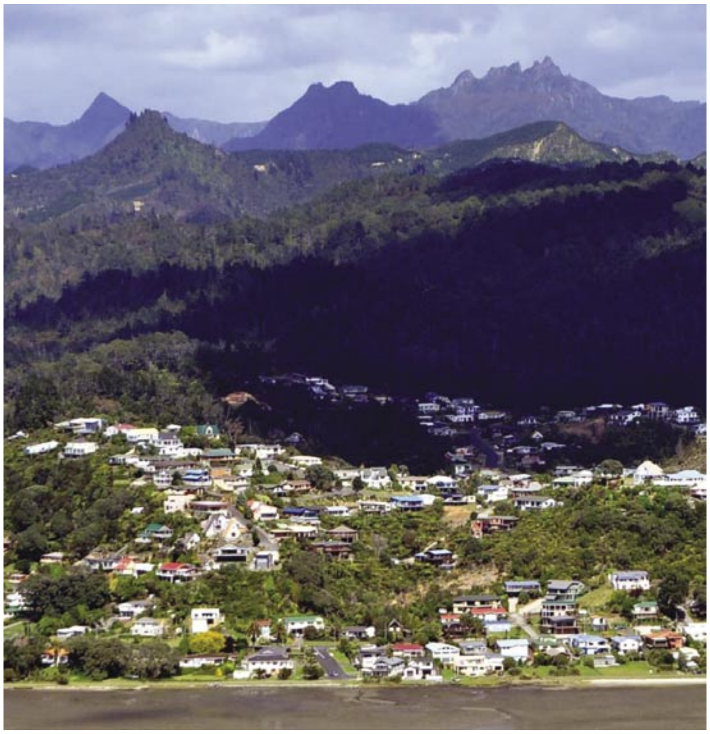
7.33 Large spherical accretionary lapilli (Box 44) within an 8 Myr-old ignimbrite deposit from the Whitianga Caldera. Stingray Bay, north of Hahei, Coromandel Peninsula. Photo 15 cm across.

7.34 View southeast over Whenuakite Dome, which has a crater and a small vent-filling tholoid (plug). A lava flow breached the collapsed crater wall and has flowed out at the bottom right. Dated at about 5.5 Myr old, it is the youngest and best preserved rhyolite dome in the Whitianga and Kapowai caldera centres. Photographer Lloyd Homer, GNS Science.

7.35 Top left. This coastal stack of flow-banded rhyolite is an eroded part of the 8 Myr-old Wigmore Dome. Te Pupuha Pt, south of Hahei, Coromandel Peninsula. Photographer Alastair Jamieson.

7.36 Top right. Viscous rhyolite magma extruded out of a vent to form a rhyolite dome often is finely flow-banded like this example in Paku Island Dome, Tairua.

7.37 Bottom. Paku Island, Tairua, is the eroded central portion of a Late Miocene rhyolite dome. Photographer Alastair Jamieson.



7.38 View west from the top of Paku Island, Tairua, showing the eroded rhyolite tops of The Pinnacles dome (*right skyline*) *and Timata Dome complex* (*middle ground left*) *that were erupted from the Kapowai Caldera between 8 and 5 Myr ago* (*Late Miocene*).

Wharepapa Ignimbrite is intruded and overlain by numerous rhyolite domes that were mostly extruded inside or around the edges of the Whitianga and Kapowai calderas over the succeeding 2-3 Myr (*7.34*). In the Kapowai Caldera, the ignimbrite is also intruded and overlain by andesite lavas of the Taurauikau Volcano, which erupted during the same time period as the rhyolite domes.

Lying outside and east of the Kapowai Caldera are a number of rhyolite domes of highly varied size (e.g., Paku, Shoe, Pauanui, and at the Aldermen Islands). Paku Dome, at the entrance to Tairua Harbour, has been deeply eroded, such that Paku Island of today (*7.36*) is composed of the remaining solidified intrusive throat of a two phase dome. Pauanui Dome is 5 km from north to south and consists of coalescing domes extruded from several vents. Located 20 km off the Coromandel's east coast, the Aldermen Islands are composed of the eroded remains of at least five small rhyolite domes and associated slightly older ignimbrite and rhyolitic breccia. Out here, remote sensing gravity methods suggest that there is no caldera present, but instead dense rock, probably andesite or basement greywacke, is close to the surface beneath the Aldermen Islands.

Rhyolitic volcanism in the southern Coromandel Volcanic Zone

South of the Kopu-Hikuai road there are many more rhyolite domes and large areas composed of eroding ignimbrite and tuff. Some of these were erupted from the Wharekawa, Tunaiti and Waihi caldera volcanoes, but many others are not associated with these three identified calderas and there are probably others yet to be recognised, especially between Whangamata and Tairua and in the main range between Wharekawa and Waihi calderas.

The best-exposed of the identified calderas is Tunaiti, located on the coast between Whiritoa and Whangamata. In the eroding coastal cliffs behind Papakura Bay (end of Waimama coastal walkway) one can see the Papakura Bay Dome complex (*7.39*) filling most of the caldera, and separated from the caldera's faulted southern wall by several hundred metres of rubbly scree of collapsed rhyolite breccia and ash. This rhyolite dome appears to have been squeezed out over the floor of a small freshwater lake that had formed inside the collapsed caldera. This resulted in wedges of dark, plant-rich mud that have been bulldozed along and incorporated into the base of the extruded rhyolite (*7.40*). A similar lake appears to have been present within Wharekawa Caldera.

7.39 Intricately-folded flow-banding in the base of the Papakura Bay Dome complex, which fills most of Tunaiti Caldera between Whangamata and Whiritoa, on the east coast of Coromandel Peninsula. The rock here is dark-coloured, glassy perlite, probably formed by rapid chilling as the lava oozed into a freshwater lake that filled the caldera, about 5.5 Myr ago. The thick, treacle-like lava flowed out in short pulses producing the intricate folding. Photo 1.5 m wide.

7.40 The base of the Papakura Bay Dome complex contains wedges of carbonaceous mud that was rucked up and incorporated into the base of the viscous rhyolite lava, as it flowed across the floor of a freshwater lake that had formed inside the Tunaiti Caldera.

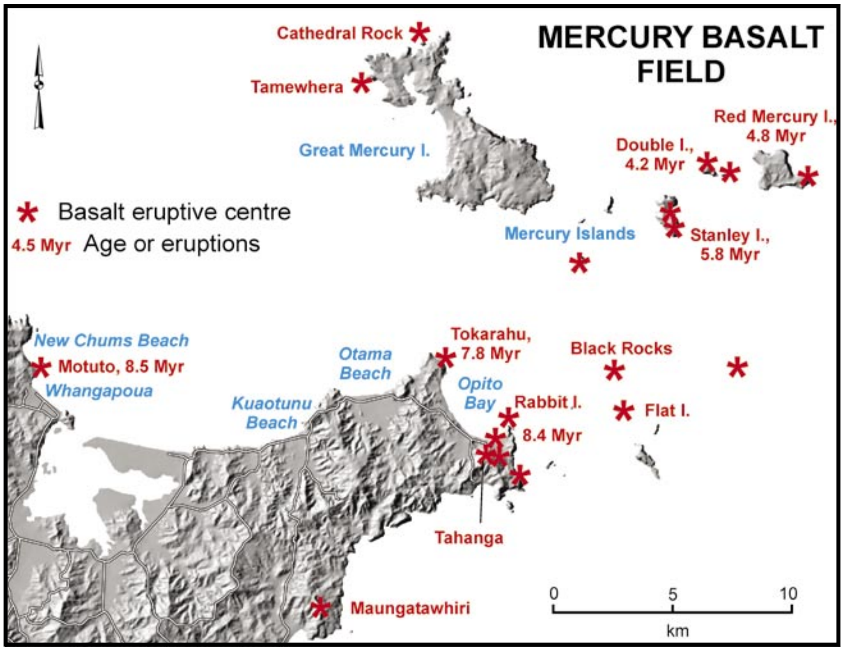
Around Neavesville, black mud and rhyolitic ash accumulated within the lake, but these have later been silicified into hard flint-like rocks by percolating hydrothermal waters. As in the central Coromandel Zone, these rhyolite eruptions were interspersed with andesitic volcanism, which produced a number of small stratovolcanoes, sometimes with associated small dacite domes.

The youngest Coromandel volcanism in this area (3.5-2 Myr ago) was entirely rhyolitic and associated with the Waihi Caldera (*7.24*). Remote sensing gravity surveys show Waihi Caldera to be a 7 km-wide, 2-3 km-deep depression. Existing faults on the northern and western sides have controlled the location of subsidence, which resulted from initial ignimbrite eruptions emptying a shallow magma chamber beneath. Waihi Caldera is filled with low-density lake sediment and at least three major ignimbrite deposits (Ohinemuri Subgroup). The oldest of the ignimbrite sheets preserved within the Waihi Caldera is an unwelded pumice deposit (Corbett Ignimbrite) that was not erupted from Waihi, and probably is a cooled, more distal ignimbrite sheet thrown out from the Bowentown centre about 2.5 Myr ago. Overlying this and filling the upper part of the Waihi Caldera, are two welded ignimbrite sheets that were obviously much hotter when they were emplaced, and probably erupted from vents within the caldera. The older welded ignimbrite (Owharoa) is characterised by numerous flattened pumice clasts that produced a distinctive lenticular ignimbrite. The upper surface of the younger ignimbrite (Waikino), erupted about 2 Myr ago and forms the present day floor of the central part of the Waihi Basin.

7.41 View southeast over Red Mercury I., off the east coast of northern Coromandel Peninsula. The island is an eroded remnant of a small scoria cone and surrounding apron of basalt lava flows. At 4 Myr old, it is one of the youngest volcanoes in the Mercury Basalt Field. Photographer Lloyd Homer, GNS Science.

Small basalt eruptions (Mercury Basalt)

A number of small basalt volcanoes (Mercury Basalt) erupted during the Late Miocene in the northeast of Coromandel Peninsula (*7.42*). These erupted during the period when caldera volcanoes and rhyolite domes were also active in the same area. The basalt magma is believed to have formed by melting and hydrothermal alteration of upper mantle peridotite above the plate subduction zone, and therefore differs from the intraplate basalts of Northland and Auckland (chapter 9). Most of the subduction-generated basalt magma stalled in the continental crust as it rose towards the surface. While stalled in magma chambers, most of the basalt was transformed by fractional crystallisation and mixing with crustal rocks, to form more silica-rich andesite, dacite and rhyolite magma (*7.3*).



7.42 Distribution and age of small basalt volcanoes (*Mercury Basalt*) *of the Mercury Islands and Kuaotunu Peninsula areas, northeast Coromandel Peninsula.*

In the Late Miocene, during the interval of accelerated magma rise from the mantle, small amounts of virtually unaltered basalt managed to rise and erupt at the surface. Eroded remnants of at least seven basalt volcanoes (9-8 Myr old) occur around Kuaotunu Peninsula and at Whangapoua (*7.44*) and Maungatawhiri, just north of Whitianga. To the northeast, the eroded remains of at least ten younger scoria cones or small shield volcanoes (6-4 Myr old) form many of the islands in the Mercury Group (*7.41*). Elsewhere in the Coromandel Volcanic Zone there are a number of more isolated basalt dikes,

7.43 Conical Woody Hill, inland from Tairua on the Coromandel Peninsula, is the eroded plug of a small, 5 Myr-old basalt volcano - an isolated occurrence of Mercury Basalt in the central part of the Coromandel Peninsula. Photographer Lloyd Homer, GNS Science.

small volcanoes (*7.43*) and flows, where small amounts of basalt magma have reached the surface relatively unmodified. One small flow of basalt is exposed on Rakitu Island, east of Great Barrier Island, and has been dated at 12 Myr - the oldest known basalt in northern New Zealand.

7.44 Left. Columnar-jointed basalt forming Motuto Point, east end of New Chums Beach, Whangapoua, Coromandel Peninsula, is the eroded remnant of a basalt volcano (Mercury Basalt) that erupted here 9 Myr ago.

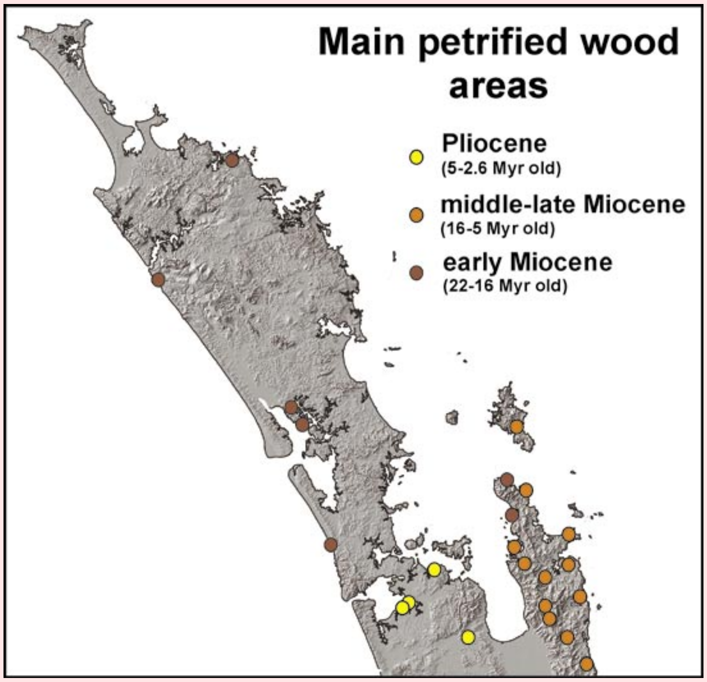
Box 30. PETRIFIED WOOD

Petrified wood is fossilised wood that has been "turned to stone", usually through its progressive replacement by silica, SiO_2. Petrified wood is commonly found associated with volcanic rocks that erupted on land, such as those in the Coromandel Range. The petrified wood often occurs in lahar deposits, ignimbrite flows, volcanic lake sediment or ash layers. Volcanic glass, formed by rapid cooling of lava, is abundant in these deposits, and is chemically unstable and readily degrades in circulating ground water, releasing dissolved silica. Wood cellulose attracts this dissolved silica, which crystallises within each cell and may perfectly preserve the wood's cellular structure (*7.45*). When dissolved silica continues to circulate, it may eventually fill all remaining spaces and destroy the cellular structure (*7.46*), producing chert, chalcedony or opal.

7.46 A piece of petrified branch where the texture of the bark has been captured, but advanced replacement by silica has lost all the internal wood structure. Late Miocene (~9 Myr old), Wainora Formation, Kauaeranga Valley, Coromandel Peninsula.

Petrified wood is harder and more resistant to weathering than most other rocks and is therefore often found reworked in stream and beach gravels and sometimes even on hillsides. Petrified wood comes in many colours and is targeted by rockhounds, who cut and polish it or turn it into jewellery. The most common wood that is found petrified in the Coromandel volcanic sequence is southern beech and casuarina, with less common pukatea, kamahi, kauri and tanekaha.

7.45 Petrified wood with well-preserved growth rings from, tuff-rich lake sediments, Wainora Formation, Kauaeranga Valley, Coromandel Peninsula. Photo width 15 cm.



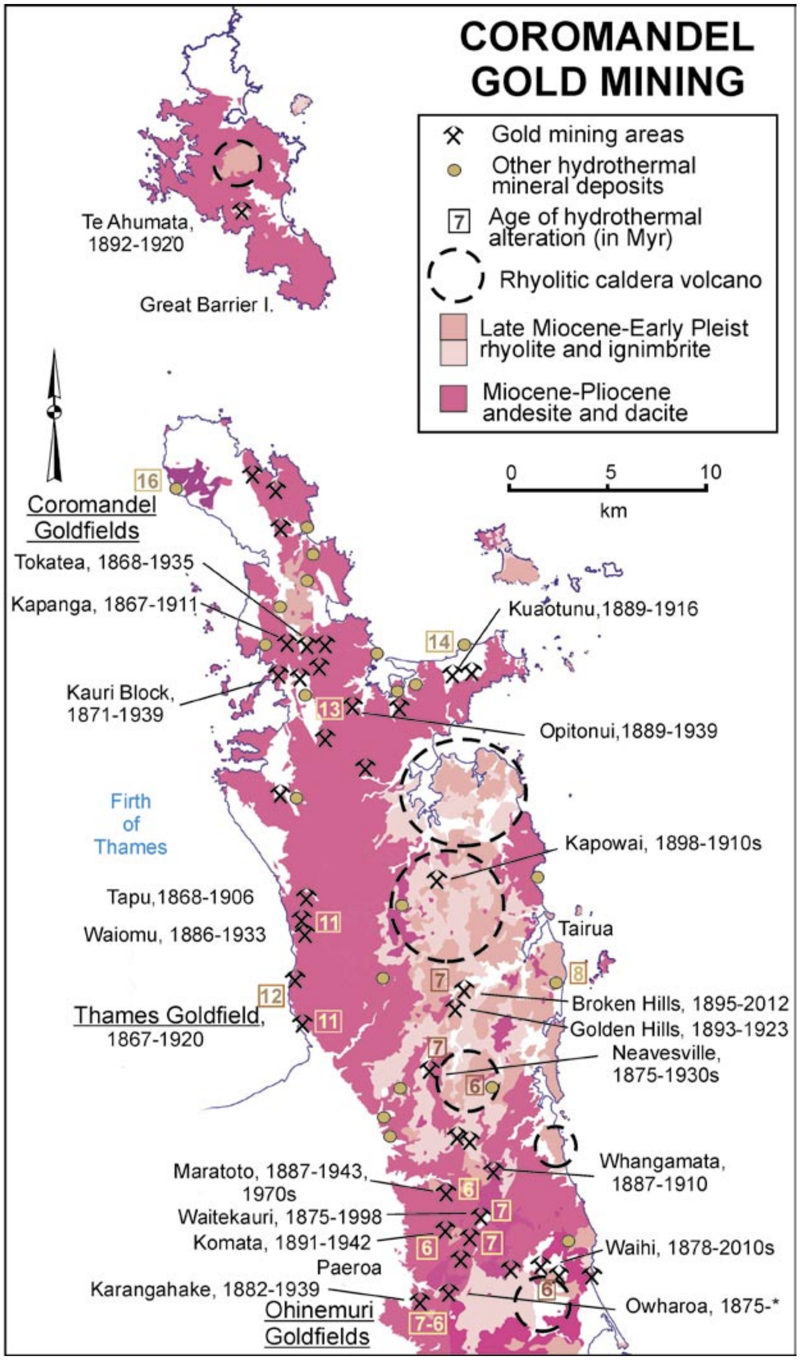
7.47 Locations in northern New Zealand where petrified wood commonly occurs.

COROMANDEL GOLD AND HYDROTHERMAL ALTERATION

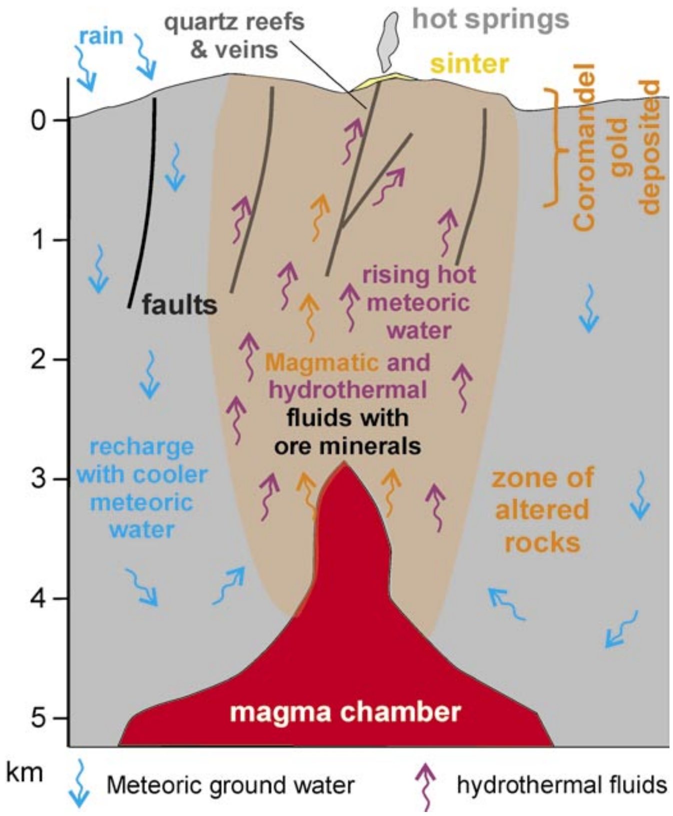
A characteristic feature of subduction-related volcanic regions is the presence of numerous bodies of molten magma (hundreds to thousands of metres across) lying within the underlying crust. These magma chambers might take hundreds of thousands, or even millions of years, to cool and solidify. If the hot magma chamber was within 5-10 km of the surface, it would heat the meteoric water in the surrounding rocks (*7.49*). Being less dense than cold water, the hot (hydrothermal) water rose. In addition to heat, various chemicals were released as fluids and gas (e.g. carbon dioxide, CO_2; hydrogen sulphide, H_2S; chlorine, Cl) into the surrounding rocks from the molten magma, and became dissolved in the rising hydrothermal waters. The hot water, at temperatures up to 400°C, often dissolved silicon, calcium and metals from the rocks it flowed through. Studies by Auckland University's mineral geologists, Jeff Mauk and Stuart Simmons, indicate that the metals that form ore bodies in the Coromandel goldfields, came from both these hydrothermal fluids and from intermittent pulses of fluids from the magma, which carried enriched concentrations of gold, silver, lead and zinc. Gold and silver were transported predominantly as bisulphide complexes, whereas copper, lead and zinc were transported as chloride complexes.

As the hot, mineral-rich fluids migrated upwards, they cooled, and the pressure reduced, resulting in the deposition of quartz, calcite and other minerals on the walls of the fluid conduits, such as fractures and fault zones. Over time, steeply-dipping reefs (large veins) made dominantly of quartz (silica, SiO_2), but often with associated calcite ($CaCO_3$), were produced (*7.50*). Within the reefs, lesser amounts of other minerals were precipitated, depending on the pressure and temperature. At higher pressures (deeper than 200 m) and temperatures (200-300°C), sulfides of iron (pyrite and marcasite, both FeS_2), lead (galena, PbS), copper (chalcopyrite, $CuFeS_2$), zinc (sphalerite, (Zn,Fe)S), silver (acanthite, Ag_2S) and some native gold were sometimes deposited.

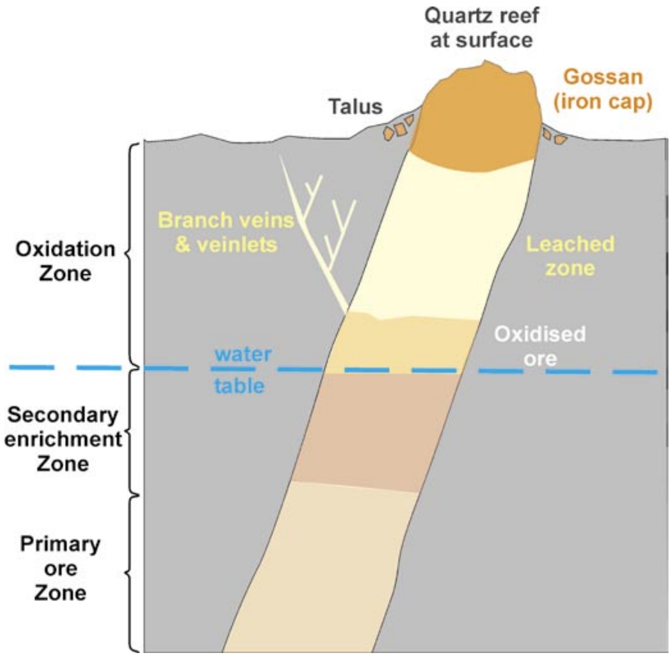
Nearer the surface where the fluids were slightly cooler (100-200°C), sulfides of mercury (cinnabar, HgS) and antimony (stibnite, Sb_2S_3), together with silver and gold, were formed. Bonanza reefs rich in gold and silver, were usually deposited in places where there was a sudden pressure drop and vigorous boiling of the hot



7.48 Location of gold-mining areas and other known areas of significant hydrothermal mineralisation and alteration in the Coromandel Volcanic Zone. Where known, the age of hydrothermal activity is shown in boxes, and can be seen to get younger southwards, like the volcanic activity from which it was derived.



7.49 Schematic cross-section showing magma heating the meteoric waters that rise, altering and dissolving silicon,calcite and metals from the permeable rocks they pass through, and depositing quartz veins and reefs in major fault conduits. If these hydrothermal fluids discharge at the surface, they produce hot springs and sinter deposits. The whole system is recharged by rain that percolates down into the ground water. The ore minerals, such as gold, silver, copper, zinc and lead, are thought to be precipitated not only from the hydrothermal fluids but also out of intermittent pulses of hot fluids released from the magma chambers themselves.



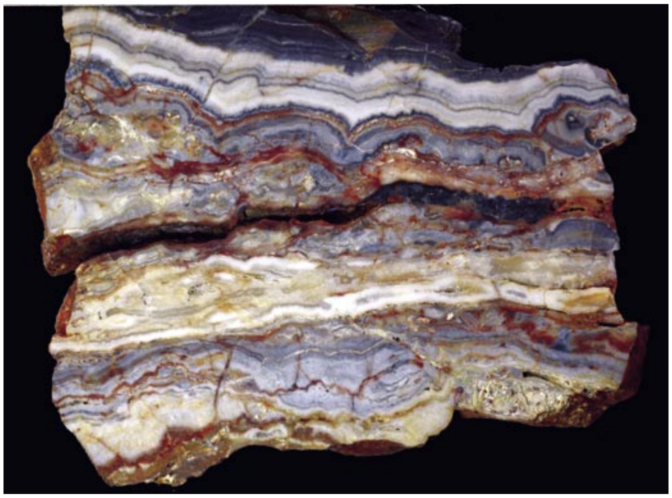
7.50 Schematic cross-section of the effects of weathering on minersalised quartz reefs. Oxidation might produce an iron-oxide-rich gossan cap at the surface. Below this, some minerals are leached out of the reef and deposited below the ground water level, forming a secondary enrichment zone. Here copper, silver and gold might occur in much higher concentrations than in the primary ore zone of the original reef.

fluid occurred. Seldom is pure gold or silver present - mostly it occurs as electrum (gold-silver alloy). In the Coromandel goldfields, the electrum usually occurs as fine particles throughout the quartz reefs, or sometimes within some of the sulfide minerals, which created great difficulty during processing to release the precious metals. An average of four times as much silver than gold was present in Coromandel reefs, but this varied a great deal from place to place. Hydrothermal fluid reaching the surface flowed out as hot springs, forming siliceous sinter deposits (*7.54*).

In the Coromandel Volcanic Zone, the rising hydrothermal fluids also altered wide zones of rocks

7.51 Intense hydrothermal alteration of the original andesite rocks in the Kauri Block, close to Coromandel Wharf, has produced this veined and multi-coloured rock. The black is from manganese and orange and yellow from oxidised iron sulphides.

beyond the reefs through which they percolated more slowly, particularly the andesitic volcanic rocks. This alteration can be so intense that it is hard to recognise the original rock composition (*7.51, 13.40*) and they are sometimes given a different rock name - propylite.



7.52 A slice through a mineralised quartz vein from a Coromandel gold deposit. The layers crystallised out of the hydrothermal fluids passing through a fracture and grew from the walls (top and bottom) inwards. Width of photo 20 cm. University of Auckland collection.

7.53 Amethyst is a purple variety of quartz resulting from slight impurities in the silica. This example is from a hydrothermal vein in the Tokatea Goldfield, Coromandel. Photo 10 cm across. University of Auckland collection.

Propylitic alteration produces minerals such as quartz, feldspar, pyrite (fool's gold), calcite, chlorite, epidote and clays (illite, smectite, kaolinite), and the resulting rocks can have a wide variety of colours, although dominantly green from the chlorite. Characteristic stains of lemon yellow come from jarosite (iron potassium sulfate) and orange from limonite (iron oxide) formed by oxidative weathering of iron sulfide minerals, particularly pyrite.

A similar process of alteration and weathering occurs after the magma chamber has cooled and the hydrothermal fluids stop rising. Weathering advances from the surface downwards, altering the host rocks to clay minerals and iron oxides, and leaching out the ore minerals, which are reprecipitated in different forms near the ground water table. This often resulted in quartz reefs with an enriched zone of secondary sulfides tens of metres down, leaving the upper part of the quartz reef with a concentration of relatively immobile gold (*7.50*). Most of the gold and silver mined in the Coromandel Goldfields was obtained from quartz reefs (or lodes).

The rocks and hydrothermal fields in the northwest and west have mostly been uplifted further and eroded more deeply than the younger ones to the south and east. Thus deeper parts of the extinct hydrothermal fields are exposed in the north and west, with resulting differences in their alteration mineral assemblages and quartz reef sulfide and precious metal compositions. Most of the extinct hydrothermal fields in the Coromandel occur in altered andesite rocks (*7.48*), but some are in rhyolite (e.g. Broken Hills, Golden Hills, Kapowai), and several have been sufficiently eroded to expose basement greywacke host rocks (e.g. Kuaotunu, Tokatea).

A question often asked is why are gold, silver and base metal (sulfides) minerals so widespread in the Coromandel Volcanic Zone, but not in the rocks of the Northland Volcanic Arc? The magmas for both were generated above the subducting edge of an oceanic plate and produced volcanoes with characteristic volcanic arc signatures. The main difference is the widespread

7.54 These large leaves of an extinct species of southern beech (Nothofagus brassi *type*) *have fallen onto the surface of an active hydrothermal sinter terrace about 6-7 Myr ago. They have then been petrified* (*turned to stone*) *by the deposition of further silica from the hot water flowing over them. Width of photo 15 cm. Parakau River, Whenuakite, south of Whitianga. University of Auckland fossil collection.*

presence of rhyolite volcanism in the Coromandel and its almost complete absence from the Northland Arc. This reflects different structural settings, with the Coromandel Volcanic Zone erupting in a region of long-lived structural rifting and extension of the crust. This appears to be a requirement for the generation of voluminous rhyolite magmas, and also to create open fractures and pathways for hydrothermal fluids.

Dating of vein minerals from the Coromandel goldfield deposits indicates that mineralisation began in the north and migrated southwards through time, like the volcanicism (*7.48*). The oldest dated gold mineralisation (14-11 Myr old) occurs in the andesite-hosted northern Coromandel goldfields, between Kuaotunu and Thames. The quartz reefs and veins in these more northern goldfields mostly strike north and northwest, and indicate extension perpendicular to this. In the eastern and southern goldfields, between Tairua and Ohinemuri, mineralisation occurred between 8 and 6 Myr ago, with the new reefs and veins oriented nearly perpendicular (east-west) to those in the earlier northern goldfields. Evidence of increased structural extension after 10 Myr ago, in the southern Coromandel Volcanic Zone, includes a marked increase in rhyolitic magma production and increased hydrothermal activity. More than 80% of the gold taken from the Coromandel Goldfields came from the younger (7-6 Myr old), southern Ohinemuri Goldfields area at Waitekauri, Karangahake, and Waihi.

Box 31. GOLD MINING ON COROMANDEL PENINSULA

Gold was first discovered in New Zealand in 1852 by Charles Ring at Driving Creek, Kapanga, near Coromandel township. There was a brief gold rush to this small patch of alluvial gold, but only a small amount of gold was recovered and the alluvial miners migrated away to the rich placer fields of the South Island. Prospecting activity around Coromandel declined until 1861, when a rich gold-bearing quartz reef was found in the same area, setting off a new more sustained Coromandel gold rush. Crushing of ore began at Kapanga in 1863, and mining spread to nearby Tokatea and the Kauri Block (*7.48*; adjacent to the present Coromandel wharf).

The first big gold strike on the Coromandel Peninsula occurred in 1867, with the discovery of gold-rich quartz reefs inland from Thames. Several more rich strikes in the ensuing months resulted in a huge influx of miners and by the end of 1868, Thames township had a population of 18,000. Initially the gold rush attracted individuals seeking a quick fortune, similar to that made in the alluvial goldfields of Otago and the West Coast in the early-mid 1860s. Coromandel gold was different, however, as it mainly occurred in the solid quartz reefs and not in the more easily-worked alluvial gravels of the South Island fields. To mine the reefs required capital investment to put in the underground workings, to keep them pumped dry, to establish transport systems to bring out the ore, to erect stamper batteries to crush the ore (*7.56*), and to build a variety of equipment to separate the gold and silver out from the quartz and sulphides. Thus from 1870 onwards, most of the more successful gold extraction from the Coromandel goldfields was undertaken by companies with rich financial backers, many of them overseas. The richest reef in the Thames field - the Caledonian bonanza - was discovered in 1870, but within a few years this was exhausted and the Thames field went into a steady decline.

In the mid-late 1870s the Ohinemuri River catchment between Waihi and Paeroa, in the southern Coromandel Ranges, was

7.55 The huge Martha Mine (260 m deep) at Waihi, following major slips on the north wall in 2015 and 2016 that suspended mining operations. Prior to 1989, all gold mining at Martha had been by underground methods. Since then, this opencast mine has opened up the main reef and original workings and recovered significant amounts of additional gold and silver.

Box 31 continued

7.56 Left: A large, water-wheel-powered stamper battery, typical of those used in the Coromandel Peninsula goldfields for crushing quartz ore, as part of the process of extracting gold and silver. Russell's Battery, Tararu Valley, Thames goldfield, 1870s. Photo: Alexander Turnbull Library.

7.57 Right: This old gold-mining adit (tunnel entrance) is one of dozens that were dug into the hillsides of the Coromandel Peninsula in the hope of finding a rich bonanza of gold-bearing ore. Wharf Rd, Coromandel township.

opened up as a goldfield. Quartz reefs were found and gold workings established at Waitekauri Valley, Owharoa, Waihi, and a little later on at Karangahake Mt. It was during this period that the massive Martha Reef at Waihi was discovered. Coromandel, Thames, and Ohinemuri were the major goldfield areas in the Coromandel Ranges, but smaller enterprises were established on other quartz reefs and hydrothermal deposits scattered around the peninsula and even on Great Barrier Island (*7.48*). The rich bonanzas of secondarily-concentrated electrum near the surface in the quartz reefs were quickly worked out, and by the 1890s all the big gold rushes on the Coromandel were over.

There was still lots of gold-bearing quartz that could be mined, but the concentration of the gold was not high enough to be economic using the available extraction methods. Releasing gold and silver from the veins in the Ohinemuri fields was particularly inefficient, often with less than 50% of the gold and even less of the silver being recovered. To make lower grade ore profitable to work, a greater proportion of the gold and silver needed to be extracted. The breakthrough came in 1889 with the introduction of a cyanide process at Karangahake. Gold and silver particles in the crushed sulphides and quartz were able to be dissolved in the cyanide solution (sodium, potassium or calcium cyanide) and then removed from the solution by other chemical processes, resulting in recovery rates of about 90% for gold and 50% for silver. The process was adopted in many of the other goldfields around the Coromandel and attracted new investment money that saw the lifespans of many of the marginally-profitable fields extended into the early 1920s, with a brief flurry of new activity during the 1930s depression.

After 1900, two of the three major goldfields (Coromandel and Thames) declined rapidly as many companies struggled to survive, because their easily recoverable ore reserves were worked out. Things were different in the Ohinemuri fields, however, as London-based companies poured money into exploration, mine development and expensive machinery, which resulted in rich returns from enterprises at Waitekauri, Karangahake and Waihi. The Martha Mine, operated by the Waihi Gold Mining Company, became one of the largest gold mines in the world in the 1910s. Around that time, its production reached £1 million-worth of bullion annually. Through the 1920s and 1930s, the Martha was a steady producer, but by the 1940s it was struggling and finally closed down as the last operating gold mine on the peninsula in 1952. During its lifetime, the Martha Mine had yielded an astonishing 5.6 million ounces of gold and 38 million ounces of silver.

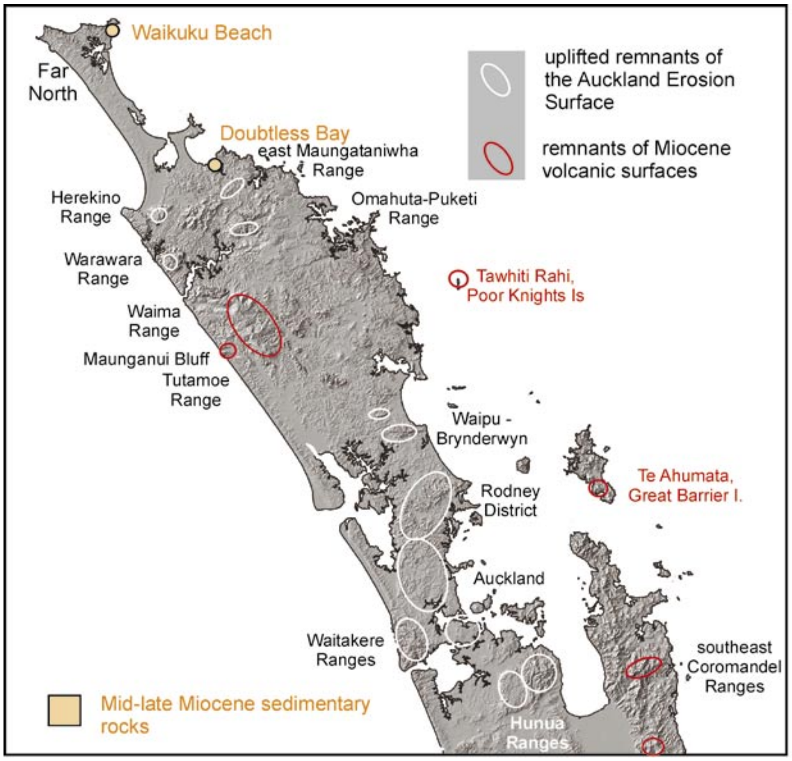
The sky-rocketing global price of gold in the 1970s led to a renewed search for gold and silver in the Coromandel Peninsula, especially around former mine workings. No new fields were discovered, but additional ore zones were located at the old Martha and Golden Cross (Waitekauri) mines. These were re-opened as large-scale opencast and underground operations in 1988 and 1991 respectively. The Golden Cross mine closed in 1998 and the site in the ranges was rehabilitated. The Martha open pit was dug deeper and deeper, and mining continued until operations were suspended by large slips in 2015 and 2016 (*7.55*). In the meantime, new prospects had been found nearby, and modern underground gold mines opened by the same company at Favona (2004), Trio (2010-2014) and Correnso (2015). In 2016, it was estimated that there were still 300,000 ounces of gold and 1.1 million ounces of silver left to be recovered in these Waihi mines (about 3 years of mining).

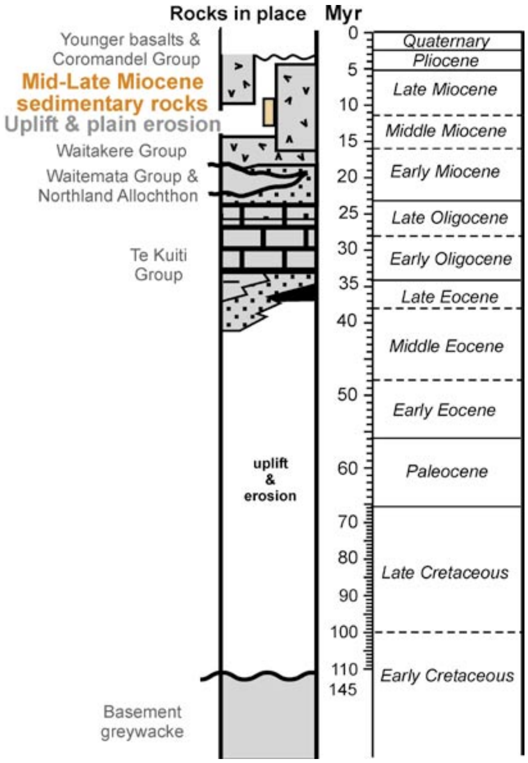
A detailed account of the mining history of the Coromandel goldfields, and a guide to seeing some of the remains, can be found in the excellent book "Coromandel Gold" by Moore and Ritchie (1996).

Chapter 8. ERODING DOWN THE LAND (15-4 Myr ago)

Chapter Summary

By about 15 Myr ago (Middle Miocene), all of northern New Zealand was again entirely land. The eastern side had been uplifted higher than the west and many rivers drained westward, carrying eroded sediment to the Tasman Sea. The land was relatively stable for the next 10 Myr or so and erosive forces removed many of the hills. Much of Northland and Auckland became an extensive shallow-marine shelf. Stream gravels and swamp lignites that accumulated on top of the surface as it was eroding can now be seen at Doubtless Bay, where small fossil coconuts erode out of the sequence. Starting about 5 Myr ago, parts of Northland, Auckland and Coromandel regions once again began to rise – a slow process that continues today. As land areas rose, erosion bit deeply into them. The flat tops now seen on many of the ranges (e.g. Waitakere, Hunua, southern Coromandel ranges, Rodney area) are mostly the remains of this Auckland Erosion Surface on the ridge crests, now separated by valleys. Some of the flat-topped highland blocks of hard igneous rocks in west Northland, may be the uplifted, partly-eroded original surfaces of the allochthonous Tangihua slabs (e.g. Warawara, Herekino ranges) or the uplifted gentle slopes of the Waipoua Shield Volcano (e.g. Waima, Tutamoe ranges).





8.1 Location of Middle to Late Miocene sedimentary rocks and of some of the eroding, uplifted remnants of flat-topped surfaces in northern New Zealand. Rock column shows relationship with older rock types.

8.2 Reconstructed paleogeographic map for northern New Zealand during the Late Miocene, about 10-8 Myr ago.

By 18-16 Myr ago (late Early Miocene), all of the deep marine basin that had formed over Northland a few million years earlier, had been filled by the displaced rocks of the Northland Allochthon and uplifted out of the sea to become land (*8.2*). The Early Miocene marine sedimentary rocks of Parengarenga, Hokianga and Kaipara areas had been deposited in actively deforming piggyback basins that had formed on top of the Allochthon, but by the Early Miocene (19-18 Myr ago) the continued movement of the underlying Allochthon had essentially stopped. The youngest sediments in these piggyback basins filled up the remaining marine depressions. At Hokianga and Kaipara there is clear evidence for these areas having become land with actively erupting volcanoes in the vicinity by 18 million years ago.

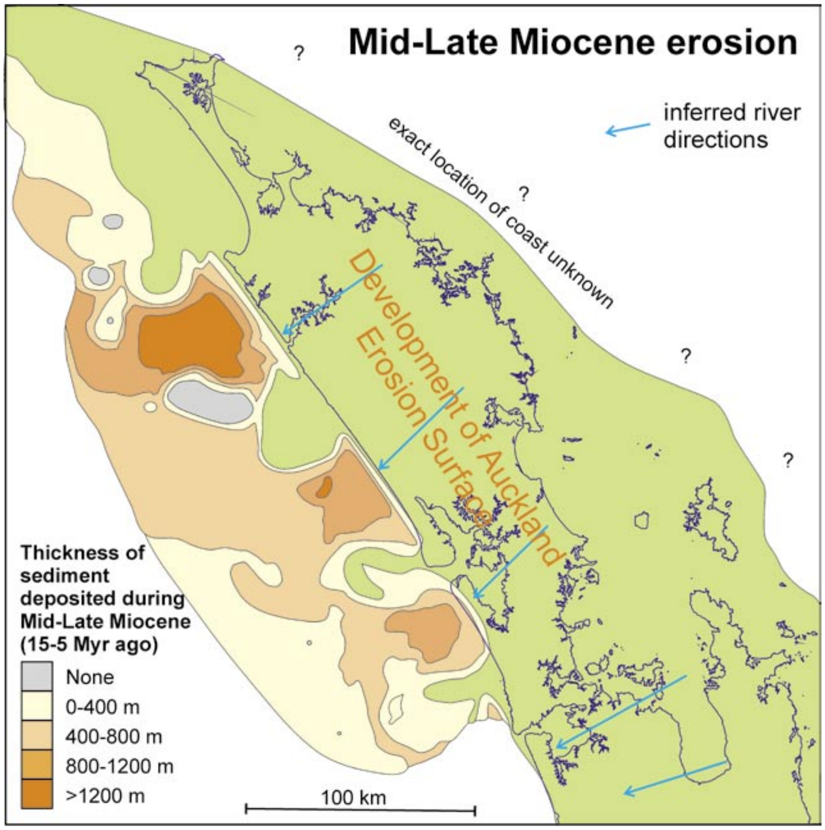
Uplift of the Waitemata Basin

Further south over Auckland, there is no direct evidence in the rocks of the demise of the Waitemata Basin, as all of its younger strata have been uplifted and eroded away. The youngest Waitemata Sandstone beds left between Warkworth and the Waikato region are about 19 Myr old and were deposited at deep bathyal depths (1000-2000 m). To get an idea of what happened to the Waitemata Basin we have to go west to the younger rock record preserved on the eastern flanks of the Waitakere Volcano (in the Waitakere Ranges), which formed the western margin of the Basin. Here, as we have seen in chapter 6, deep bathyal sediments were being deposited up until about 17 Myr ago, and soon after that there was considerable uplift and all subsequent deposits and eruptions were on land. This uplift in the Waitakeres is inferred to be a continuation of the southward moving uplift that passed from north to south through Northland-Auckland after emplacement of the Northland Allochthon (*4.64, 4.69*). Thus it is logical to assume that the uplift seen in the Waitakere Ranges rock record also occurred at around the same time further east, and that the Waitemata Basin was uplifted from bathyal depths out of the sea towards the end of the Early Miocene, about 18-16 Myr ago.

Apart from two stacks near North Cape, there are no Middle to Late Miocene (15-5 Myr old) marine sedimentary rocks in Northland, Auckland or Coromandel. There are, however, many volcanic rocks on Coromandel Peninsula, Great Barrier Island and in eastern Auckland and Northland (chapters 7, 9) that spewed out over the land at this time. There are two other lines of evidence that suggest that much of northern New Zealand (especially the eastern parts) was eroding land throughout most of this period and not submerged beneath the sea (*8.2*).

Accumulation of eroded sediment

The first line of evidence is from remote sensing (seismic profiles) techniques that show large thicknesses, up to 1500 m thick, of eroded sediment that was deposited off the west coast of the Northland-Auckland region, during the Mid-Late Miocene period (8.3). This sand and mud filled up the deep marine holes between many of the major western arc volcanoes (Waitakere, Kaipara, Waipoua, Hokianga), creating a wide western continental shelf. There is no remote sensing evidence for the accumulation of similar thick piles of sediment of this age off the east coast at this time, although there could be some present. The much greater thickness of accumulated sediment off the west coast implies that most of the rivers draining Northland and Auckland flowed westwards, as they still do today, and that this was likely to be a result of greater uplift of eastern Northland and Auckland with tilting down towards the west (*8.4*).

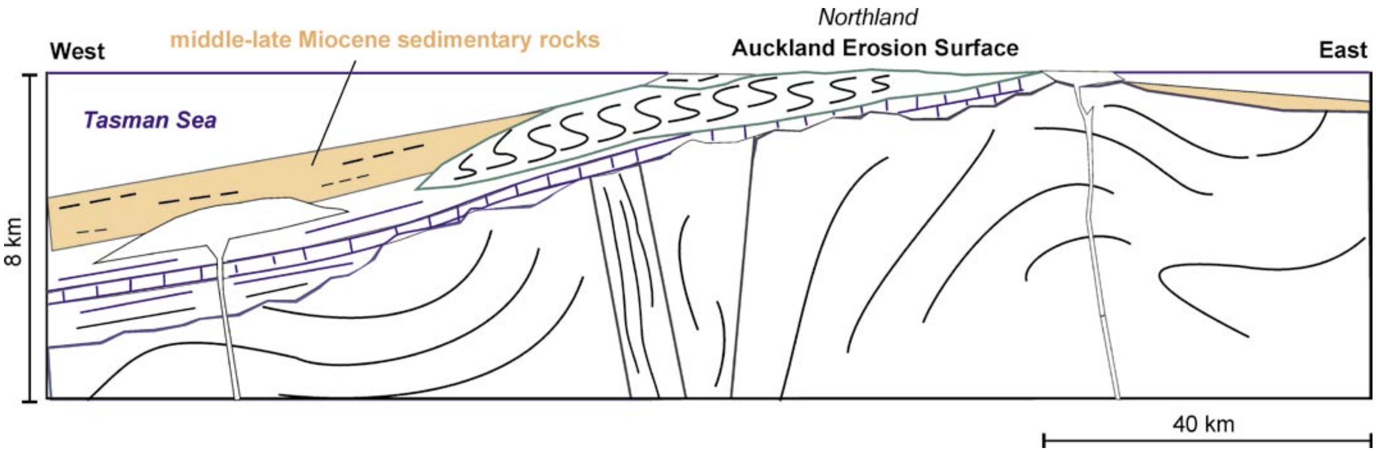


8.3 Contoured thickness of sediment that was eroded off northern New Zealand and deposited off the west coast, between 15 and 5 Myr ago (Middle-Late Miocene).

Formation of flat erosion surfaces

The second line of evidence comes in the form of uplifted remnants of a widespread surface, which must have been formed by marine erosion, primarily during the Middle to Late Miocene (15-5 Myr ago), but maybe even in the Early Pliocene (up to 3 Myr ago). This erosion surface was named the Auckland Peneplain, way back in 1929, by Professor Bartrum of Auckland University, but is now more correctly referred to as an erosion surface. This Auckland Erosion Surface can be seen today as the horizontal, or sometimes slightly-tilted, flat tops on higher land areas in southern Northland, Auckland and maybe parts of the southern half of the Coromandel Ranges. Some of the most easily appreciated examples can be seen forming the flat tops of the Waitakere (*8.5*) and Hunua ranges, and even some of the lower-lying country, such as the Auckland Isthmus and land stretching north towards Wellsford (Rodney District) (*8.7*). Further north there are relatively flat crests to some uplifted blocks of basement greywacke rocks forming the Brynderwyn and Omahuta-Puketi ranges that may also be relics of the Auckland Erosion Surface. In northwestern Northland, some of the highland blocks made of allochthonous Tangihua Complex rocks, such as the Herekino, Maungataniwha and Warawara (*8.6*) ranges, have flat topped ridge crests. These could be inherited flattish tops from the slabs that slid onto Northland, 20 plus Myr ago, or they could be a northern version of the Auckland Erosion Surface that was cut across the top of the slabs in the Mid-Late Miocene (15-5 Myr ago).

Today the remnants of the Auckland Erosion Surface



8.4 Simplified cross-section through Northland about 8 Myr ago showing transgression of the sea over the land with coastal erosion progressively forming the Auckland Erosion Surface. Much of the eroded soil and rock was deposited as sediment off the west coast.

8.5 Looking north to the Waitakere Ranges, west Auckland, from the southern shores of the Manukau Harbour. The smooth, relatively flat crest is considered to be remnants of the Late Miocene Auckland Erosion Surface that was eroded right across the Auckland area during a 10 Myr-long period, with little tectonic movement and relatively stable sea levels. A fault-line running along the Huia Valley through the middle of the Waitakere Ranges appears to have displaced the surface upwards on the west side (left). The erosion surface on the western half is tilted down to the west.

8.6 Above: View north over the flat-lying crest of part of the Warawara Range, northwest Northland. This may be an uplifted remnant of the Auckland Erosion Surface or the original surface of the hard Tangihua Complex slab that slid in as the last phase of Northland Allochthon emplacement, 23-21 Myr ago.

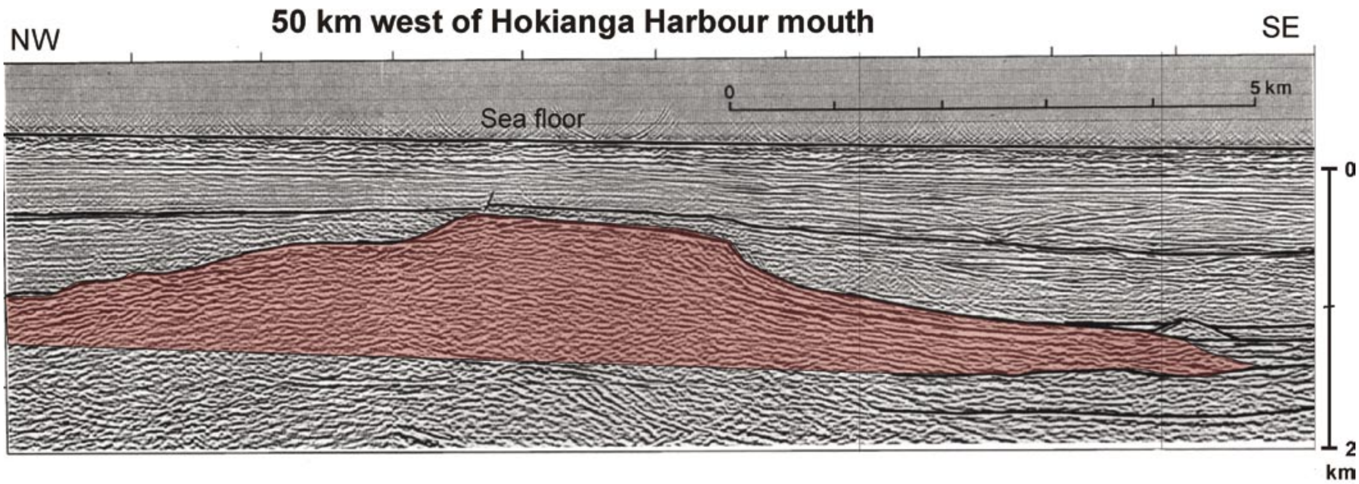
8.7 Below: View north from Mt Wellington showing an example of the flat-topped ridge crests of the Auckland Isthmus (inland Orakei) in the middle ground and north of the city (Rodney District) in the distance. These are the dissected remnants of the Auckland Erosion Surface eroded during the Late Miocene or even Early Pliocene (10-4 Myr ago).

have very little young sediment underlying them, which would seem to rule out the possibility that they were built up as large alluvial plains on land. The main process where extensive flat-lying surfaces can be eroded into existing rocks is coastal erosion, intertidally or subtidally down to wave base, where sea level and land remain relatively stable for millions of years. This was likely the situation in northern New Zealand during this time, as the effects of plate boundary forces had largely migrated eastwards to the Coromandel and beyond. Thus the Auckland Erosion Surface presumably eroded progressively inland over millions of years as the sea transgressed (especially from the west) over the relatively stable land.

We can see the effects of just 7000 years of erosion around the coast today (*8.8*) since sea level more or

8.8 This 150 m-wide shore platform at Musick Pt, east Auckland, has been eroded by the sea into Waitemata Sandstone rocks in the 7000 yr since sea level reached its present height after the end of the Last Glacial period. This gives an erosion rate of about 2 cm per year. At this rate the erosion surface, eroded across much of northern New Zealand during the Middle and Late Miocene, would have taken 5-10 Myr to form.

less stabilised after the end of the Last Glacial interval (chapter 11). Intertidal shore platforms of various widths have been eroded around the shorelines – their widths depend upon the softness of the rock being eroded and the degree of exposure to the forces of the sea. Average erosional rates on exposed coasts are in the order of 2 cm per year for softer rocks, like Waitemata Sandstone, and 0.2-0.5 cm per year for harder rocks, like basement greywacke or igneous varieties. At these rates a coastal plain could have been eroded 50-100 km right across most of Northland and Auckland in 5-10 Myr. So, although there are virtually no marine



8.9 Seismic reflection profile of structure beneath the sea floor west of Hokianga Harbour mouth, showing the top of an Early Miocene volcano (coloured red) that has been eroded flat at sea level (Auckland Erosion Surface) before it was tilted and buried by 500 m of sediment. The black line just above the flat top marks strata that were deposited 5 Myr ago and shows that erosion here occurred prior to that. The terrace on the left side of the volcano is inferred to have been eroded by the sea earlier than the flat top, before the volcano began to subside greatly. Modified from Herzer (1995).

8.10 View south from the Camels Back peak near the Tapu-Coroglen Rd showing the eastward-tilted remnants of a Late Miocene erosion surface (*about 5 Myr old*) *that forms the concordant ridge crests that cap the southern Coromandel Range. The top of 800 m-high Table Mt is at the western end* (*right*).

sediments of this age in Northland and Auckland, when the erosion surface was nearing its maximum size late in the Miocene, most of the region may have been submerged by an extensive shallow sea.

Although the Auckland Erosion Surface remnants look remarkably flat when viewed from a distance, close-up they are anything but flat. This is because the erosion surface has subsequently broken up into numerous large blocks and these have been uplifted to various heights and often tilted. As these blocks were rising they were already starting to erode further, forming incised valleys with intervening ridges. In many instances the ridge crests have hardly eroded down and these retain the original flat-lying outline of the Auckland Erosion Surface when viewed from afar. A few parts of Northland, such as Whirinaki amd Maungataniwha ranges and some of the east coast basement greywacke ranges, have no remnants of the erosion surface. They may have been land throughout this period and not eroded flat.

In the southern Coromandel Ranges there are several places with unusually flat, high ridge crests (e.g. from Table Mountain eastwards – *8.10*, and east of Paeroa) that could also be remnants of a coastal erosion surface from the Late Miocene to Early Pliocene or even younger (about 5-3 Myr ago), or maybe they represent flat surfaces formed by gently sloping lava-flows? Possible examples of uplifted, flat-lying original volcanic land surfaces are Te Ahumata Plateau on Great Barrier Island and the northern half of Tawhiti Rahi in the Poor Knights Islands. Both these latter plateaux are underlain by hard silicified sinter areas that might have slowed erosion sufficiently to have survived uneroded since they were formed in the Late Miocene.

Ridge crests of the Waima and Tutamoe ranges in west Northland are underlain by Waipoua Basalt lava flows that originally would have been sloping gently to the east on the lower eastern slopes of Waipoua shield volcano. These ridge crests are probably remnants of the original slopes of the volcano that have subsequently been uplifted 700 m or so in the east and tilted down towards the west (*8.11*). Approaching Maunganui Bluff the surface flattens and then rises up towards the centre of the shield situated west of the bluff, indicating that there has been little or no uplift or tilting in the vicinity of Maunganui Bluff.

8.11 The flat-topped crest of the Tutamoe Range is inferred to be the remnants of the eastern flanks of the 19-18 Myr-old Waipoua shield volcano, which have been uplifted 750 m in the east and tilted down to 250 m above sea level in the west, and eroded into by many valleys.

MIDDLE TO LATE MIOCENE SEDIMENTARY ROCKS

The two eroded stacks of limestone, which are the only known marine sedimentary rocks exposed in northern New Zealand deposited between 17 and 5 Myr ago, poke out from the sandy fore dunes of Waikuku Beach, near North Cape. These limestones are primarily composed of the shelly remains of marine organisms such as molluscs and bryozoa and accumulated as a shell bank at inner shelf depths (0-50 m) sometime between 14 and 11 Myr ago.

The other Middle to Late Miocene sedimentary rocks in Northland occur at the southeast end of Doubtless Bay around Mangonui. These are freshwater deposits that filled small ancient valleys and swamps during the Late Miocene period, about 12-8 Myr ago. They consist of conglomerate, pebbly sandstone, carbonaceous mudstone, and lignite that can be seen in the low bank at the back of Coopers Beach and periodically protrude from beneath the beach sand at low tide. In 2015, sand was swept from the western half of the beach, exposing three levels of ancient fossil forest with stumps still in growth position (*8.12*). These Coopers Beach rocks are well known for the small fossil coconuts that erode out of them, but many other kinds of fossil fruits and seeds also erode out and are periodically found washed up on the beach. Another outcrop of these sedimentary rocks occurs in the cliffs at the west end of Hihi Beach, where they are valley-filling cobble and pebble conglomerate with occasional fossil logs and carbonaceous sandstone lenses (*8.14*).

8.12 Approximately 10 Myr-old tree stump in-situ in a sequence of lignites and mudstones exposed in Coopers Beach, Doubtless Bay in 2015 when sand was temporarily washed off part of the beach.

Box 32. SIDERITE “FLOWERS”

One of the best examples of rock flowers found in New Zealand comes from Coopers Beach, Northland, where they are occasionally exposed when sand is washed off the beach by storms. The name “flowers” suggests that they are fossilised plant material, but in fact they are not. The “petals” of these “flowers” are actually crystals of the mineral siderite (composed of iron carbonate, $FeCO_3$), that appear to have grown within a shallow evaporating pond of mineral-rich water during the warmer climate of the Middle Miocene period, about 12 Myr ago. They occur within the same sequence of lignites and freshwater sediment that preserved the miniature fossil coconuts.

These siderite flowers are usually black or rusty brown on the outside, produced by oxidation of the thin surface layer to the iron oxide minerals haematite or limonite, when it came in contact with oxygen from the air. The siderite flowers are similar, but not identical in shape, size and mode of growth, to the famous desert or barite roses from Oklahoma, USA. Both barite (barium sulphate) and siderite are characterised by their high specific gravities (4.48 and 3.96 respectively), which makes them feel unusually heavy when picked up.

8.13 Siderite flowers (6-10 cm across) from Coopers Beach. Photographer Heather Smith.

8.14 This 20 m-high cliff at Hihi Beach, Doubtless Bay, is composed of layers of orange-weathered conglomerate containing rare fossil logs that fill a 10 Myr-old (Late Miocene) valley eroded into the underlying Tangihua Complex rocks.

Box 33. MINIATURE FOSSIL COCONUTS

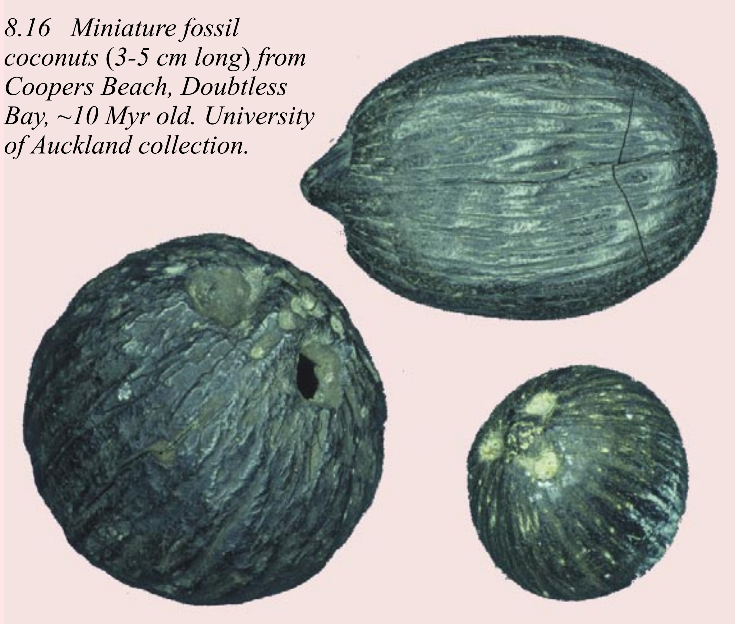
The most famous fossil coconuts in New Zealand are periodically found washed up on Coopers Beach, Northland. They are not the full-size coconuts that grow on coconut palms on tropical islands that we try to knock down in coconut shies at fairs. These are miniature coconuts, 3-5 cm long, with the characteristic three eyes at one end. We now know that they are the nuts of a relative of the South American "mountain coconut" (*Parajubaea cocoides*), known as cococumbe in Ecuador where the nuts are a popular food. Today this palm grows close to the equator in South America, but at high altitudes, where the temperatures are not too dissimilar to present-day Northland. The mountain coconut palm tree is of similar size and appearance to the classic coconut palm.

The miniature fossil coconuts at Coopers Beach are generally flattened as a result of burial beneath a thick sequence of sediment. They erode out of freshwater sedimentary rocks at the back of the beach or from shallow subtidal reefs just offshore. Occasionally small fossil coconuts are also washed up at Taipa Beach a few kilometres to the west.

Much older, but similar small coconuts have been found at Waikiekie Quarry in southern Northland. These fossils occur in 28 million year old (Late Oligocene period) muddy limestone that accumulated on the floor of the ocean well offshore from land. The coconuts must have floated out to sea and become waterlogged before sinking to the seafloor. They are not usually as flattened as those from Coopers Beach.

8.15 Mature mountain coconut palm growing in Ecuador, similar to the one that produced the small coconuts found in Northland.

8.16 Miniature fossil coconuts (3-5 cm long) from Coopers Beach, Doubtless Bay, ~10 Myr old. University of Auckland collection.



8.17 Small fossil coconut from Waikiekie Quarry, north Kaipara, ~28 Myr old. Coconut 5 cm-long. Found by Shirley Gates.

Chapter 9. INTRA-PLATE BASALT VOLCANIC FIELDS

(last 10 Myr)

Chapter Summary

The young basalt volcanoes of northern New Zealand erupted magma sourced from the partially molten upper mantle, 60-90 km beneath our feet. They were mostly unrelated to the subducting plate boundary that had migrated away to the east by this time, and are called intra-plate basalt volcanoes. At least 200 small basalt volcanoes have erupted in the last 10 Myr in seven volcanic fields. The older Kaikohe-Bay of Islands (*10-1 Myr old*) *and Puhipuhi* (*10-4 Myr old*) *volcanic fields in Northland erupted voluminous lava flows, some of which still form distinctive, gently sloping plateaux. More isolated and eroded basalt volcanoes, erupted on Waiheke Island and around Leigh* (*Ti Point Basalt, 10-7 Myr ago*)*, are inferred to be related to the subduction and eruption of the Coromandel Volcanic Zone to the east.*

The younger (*last 0.3 Myr*) *Kaikohe-Bay of Islands Volcanic Field contains one explosion crater and twelve scoria cone volcanoes, many of which form prominent hills around the town of Kaikohe. The Whangarei Volcanic Field consists of a number of older* (*4-1 Myr old*) *eroded and weathered volcanoes, a miniature shield volcano* (*Whatitiri*) *and ten prominent, younger scoria cones* (*less than 0.5 Myr old*) *scattered around the fringes of Whangarei. The young Auckland Volcanic Field* (*less than 0.2 Myr*) *has 53 small volcanoes, mostly scoria cones and explosion craters, but also the iconic 600 yr-old Rangitoto shield volcano. The South Auckland Volcanic Field is slightly older* (*1.6-0.5 Myr old*) *and has over 80 recognised volcanoes - mostly explosion craters and small shields* (*e.g. Pukekohe Hill*)*, but with a few prominent scoria cones in the south.*

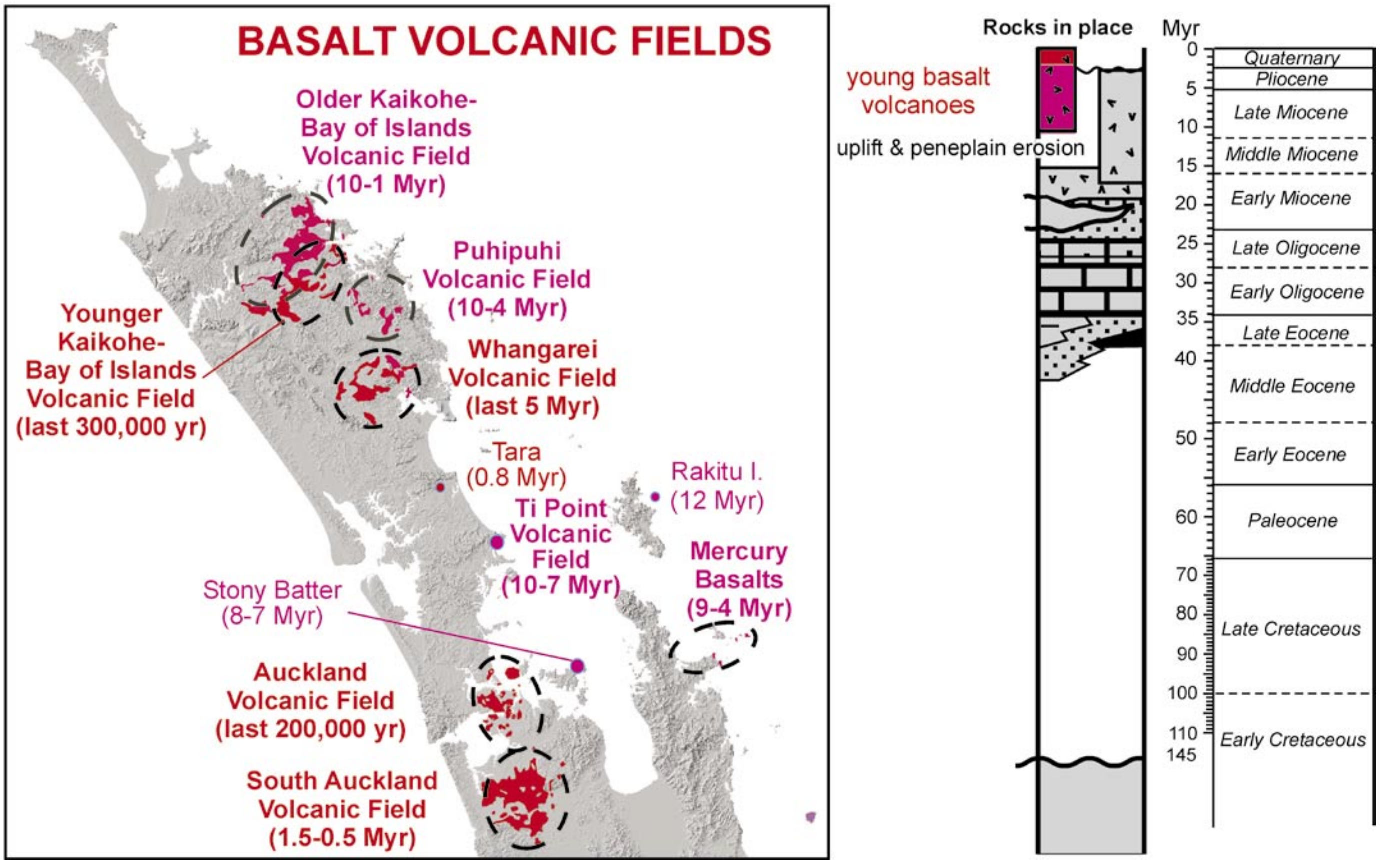
The style of eruption and kind of volcanic landforms produced by these small basalt volcanoes depended on a number of factors. If erupting through wet ground, the initial eruption was explosive and produced a large explosion crater and surrounding ring of hardened ash, called a tuff ring. Dry eruptions of gas-rich lava produced episodic or continuous fire-fountaining of frothy lava that built steep-sided scoria cones. Dry eruptions of gas-poor lava produced lava flows, which if voluminous, built gently-sloping shield volcanoes or extensive lava flow fields. Auckland, Whangarei and Kaikohe-Bay of Islands fields are considered to be dormant and will probably erupt again in the future, forming new volcanoes.

Lava caves and the remains of forests preserved in erupted ash or lava occur in the Auckland Field. Basalt from the younger lava flows in the Auckland and Northland fields has been widely used in drystone walls, a few prominent buildings and as kerb stones. Many of the young scoria cones in Auckland and Northland fields were used as defensive forts (*pa*) *by pre-European Maori.*

Beneath the Northland basalt fields, some rising basalt magma is thought to have stalled in chambers within the crust. There it partially crystallised and the remaining molten magma, which was more silica-rich, was extruded as small rhyolite and dacite domes among the basalt volcanoes. Older rhyolite domes near Kerikeri have been altered to the whitest halloysite clay in the world, which is mined for the overseas manufacture of ceramic ware. Near Kaikohe, present-day Ngawha Geothermal Field (*used for electricity production*) *is believed to be heated by a remaining hot rhyolite magma chamber beneath it.*

The majority of northern New Zealand's basalt volcanic fields erupted magma sourced directly from the asthenosphere (upper mantle) some 60-90 km below the surface. They are called intra-plate volcanoes as they had nothing to do with the plate boundary, which by the time of their eruption, had migrated well away to the east. Only the Late Miocene Mercury Basalt (chapter 7) and Ti Pt Basalt fields appear to have been influenced by subduction plate boundary processes, which were producing the Coromandel volcanoes at that time.

In all but one of these basalt fields, the magma erupted from many widely-spaced vents over a period of millions to hundreds of thousands of years. In the Kaikohe-Bay of Islands and Puhipuhi fields, basalt has been erupted in far greater quantities, off and on, for much longer (last 10 Myr). In most cases, each vent erupted only once over a period of weeks to several years in a single episode of eruptions (possibly with a number of phases). Each episode usually erupted in a new place, producing a new small volcanic crater and/or cone. Volcanic fields with numerous small centres that each erupted once, are called monogenetic.



9.1 Distribution and age of the basalt volcanic fields in northern New Zealand.

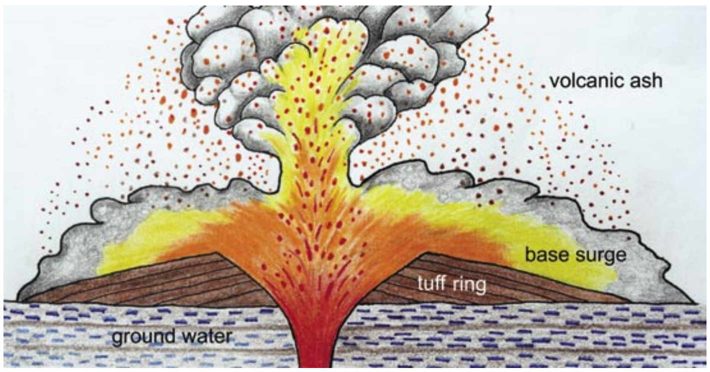
STYLES OF BASALT ERUPTION, ROCK TYPE AND LANDFORM

Eruption style	Scientific term	Rock produced	Landform
Wet explosive	Phreatomagmatic, Surtseyan	Tuff (hardened volcanic ash)	Explosion crater (maar), tuff cone or tuff ring
Fire-fountaining & fiery explosive	Hawaiian & Strombolian	Scoria (lapilli, cinders), spatter, volcanic bombs	Scoria cone (cinder cone)
Lava outpouring	Strombolian & Hawaiian	Basalt lava	Lava flow, lava field, or lava shield

The shape of a Northland or Auckland basalt volcano depends on the styles of eruption that formed it. Its size depends on the volume of magma expelled and duration of the eruptions. These volcanoes erupted in three basic styles resulting in the production of three different types of volcanic rock and three different kinds of landform.

Wet explosive eruptions

When many of Auckland and South Auckland's basalt volcanoes first erupted, the rising magma came in contact with near-surface water in aquifers or swampy ground. As this hot magma (about 1200˚C) encountered cold water, its surface chilled instantly, solidified, and explosively fragmented. The water flashed to steam, resulting in a violent explosion.



9.2 Cartoon of a wet explosive eruption from a small basalt volcano. These typically form an explosion crater surrounded by a tuff ring or cone composed of hardened layers of volcanic ash. Drawing by Margaret Morley.

9.3 View from the west across Pukaki explosion crater and surrounding tuff ring/tuff cone, Auckland. The flat floor of the crater is filled up with lake and marine sediment.

A rapidly expanding cloud of steam, magmatic gas, fragmented lava and other pieces of rock from the vent walls was erupted upwards and outwards.

The solid particles that were blasted into the air and fell back to the ground are called tephra. Tephra is divided on the basis of particle size into ash (fragments smaller than 2 mm), lapilli (2-64 mm across), and blocks and bombs (greater than 64 mm). Wet explosive eruption columns rise to heights of several kilometres and the volcanic ash and lapilli within them might be blown some distance away by the wind. Fallout tephra accumulates on the ground downwind of the volcano. Blocks of solid rock ripped from the walls of the volcano's throat might be thrown out of the vent on ballistic trajectories, to land nearby (*9.4*).

Around the denser base of the eruption column, base surges of superheated steam, gas, ash and lapilli can be blasted out sideways (*9.2*) at speeds up to hundreds of kilometres per hour. These turbulent ground-hugging surges (*9.14*) might devastate and partly bury areas within 3-5 km of the vent and are the most dangerous style of eruption produced by these small basalt volcanoes. As these surges pass, they commonly leave behind wavy beds of fine ash, sometimes with cross-bedded dune forms.

Wet explosive eruptions usually come in a series of pulsating episodes interspersed by short periods of inactivity. Typically these eruptions produced a relatively shallow (50-100 m deep), wide (200-1000 m), circular explosion crater surrounded by a low ring of bedded volcanic ash and lapilli. The ash and lapilli were erupted wet, and as the layers dried out they hardened into a

9.4 A sea cliff exposure of bedded tuff on Motukorea/ Browns Island, Auckland. This tuff accumulated as wet ash around the explosion crater. Each layer represents an explosive eruption pulse. Rock fragments include smaller grey basalt from the chilled surface of the rising magma and a large, rounded, brown block from the underlying country rock (Parnell Grit). Wavy and cross-bedded layers of ash in the middle of the section were left behind by fast-moving base surges of searing gas, steam and ash.

creamy-brown rock called tuff. Thus the raised ring of rock around the explosion crater is called a tuff ring. A tuff ring usually has its circular crest forming the rim of the crater, with relatively steep slopes back into the crater and gentler slopes (c. 5-10˚) on the outside (*9.3*). The steeper inner slopes are often formed by a series of slump scarps as a result of sections of the tuff ring slipping back into the crater after being deposited. A larger tuff ring may be called a tuff cone.

If magma supply ceased before all the groundwater was used up, then the only landforms produced by the volcano would have been an explosion crater surrounded by a tuff ring. There is one explosion crater with surrounding tuff ring in the Kaikohe-Bay of Islands Field, 19 in Auckland and dozens of eroded tuff ring segments in the South Auckland Field.

After eruptions finished, most explosion craters filled with rainwater, creating crater lakes (*9.70*). Many of these lakes subsequently filled with sediment and in Auckland are now tidal lagoons, swamps or reclaimed wetlands. Those that became tidal lagoons were formerly lakes that were breached by rising sea level about 8000 years ago, as a result of the melting of the northern hemisphere ice sheets after the end of the Last Glacial period.

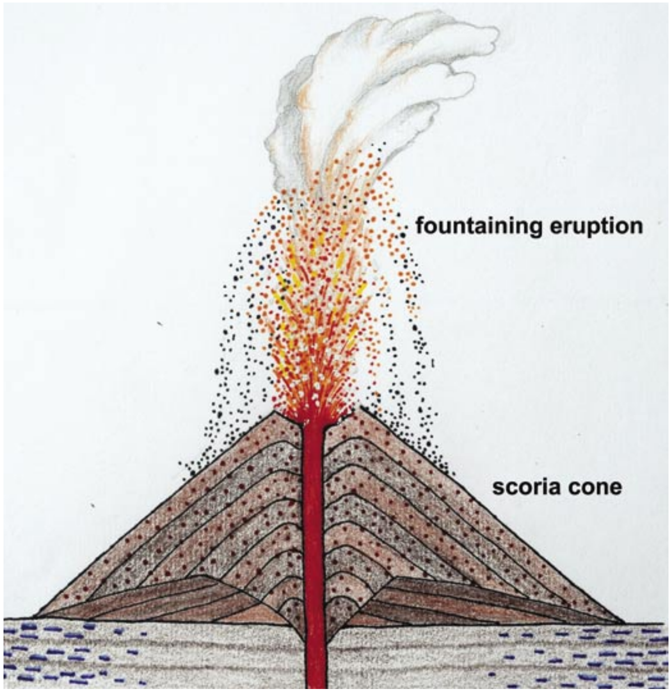
Fire-fountaining and fiery explosive eruptions

If the wet explosive eruptions used up all the water in the vent, then volcanic activity switched to a dry style of fiery eruptions or fountaining. These built scoria cones that partly or completely filled the explosion crater and might have buried all trace of the tuff ring.

The basalt magma was molten rock containing dissolved gas (mostly water vapour and carbon dioxide) under pressure. As the rising magma neared the surface, pressure reduced and the releasing gas drove a fountaining of frothy liquid from the vent, called fire-fountaining. As the fountaining magma flew through the air, it cooled and solidified, forming the frothy rock known as scoria. This rock is initially black, but oxidation (reaction with oxygen) of iron in the still-hot scoria deposits from fire-fountaining, turned much of it to its characteristic red colour (*9.6*). Scoria that remained black was cooler when it landed and did not remain hot for long enough to become oxidised red.

The erupted scoria built up a steep-sided scoria cone with a deep crater (*9.7*). Scoria cones consist of layers of scoria of various sizes. Larger and denser fragments landed closer to the vent and the smallest lapilli and scoriaceous ash could be blown many kilometres away. A 30 m-high scoria cone can be thrown up in a day, and a 100 m cone in little more than a week. If a strong wind was blowing during fire-fountaining, much of the scoria landed on the downwind side of the vent, building up a higher peak on one side of the scoria cone. Northland and Auckland's scoria cones were mostly built by steady fire-fountaining eruptions of rapidly rising, rather fluid magma containing multitudes of small gas bubbles.

Within some of the scoria cones there are layers of larger, ragged chunks of coarsely vesicular or more dense basalt, which were thrown out of the vent by discrete fiery explosive eruptions (called Strombolian style) of more pasty magma. These incandescent lumps often landed in a sticky molten form and welded together into hard layers. The rate of magma ascent usually determines the style of eruption and the character of the ejected lava. The discrete fiery explosive outbursts occurred at



9.5 Cartoon of a fire-fountaining eruption that produced a scoria cone capped with a central crater. Drawing by Margaret Morley.

9.6 Typical well-sorted red scoria produced by fire-fountaining. The lumps of scoria are honeycombed with small holes (called vesicles) that were once bubbles in the erupting frothy magma.

9.7 A steep-sided scoria cone built by fire-fountaining and fiery explosive eruptions of frothy magma (scoria) from the central crater. Maungaturoto, Kaikohe. Photographer Alastair Jamieson.

fairly regular intervals minutes apart and indicate more slowly rising, less fluid magma. Some of the small gas bubbles coalesced and grew extremely large as they rose through the magma column, each bursting at the surface to produce a separate explosive blast, throwing lumps of fiery magma tens to hundreds of metres into the air.

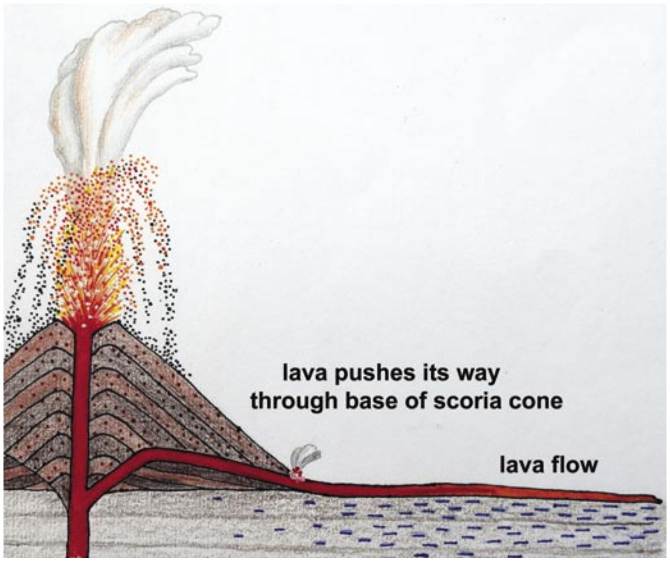
These discrete fiery explosive eruptions often occurred towards the end of the fire-fountaining as the rate of magma ascent slowed and it became thicker and less gaseous. As a result, a number of the scoria cones are capped by partly welded deposits of large, ragged lumps of scoriaceous basalt and aerodynamically-shaped volcanic bombs.

Lava outpouring eruptions

During the fire-fountaining and fiery explosive phase of eruption of Auckland and Northland's scoria cones, the molten magma often became less gaseous and rose up inside the throat of the volcano. If it reached the height of the base of the cone, this magma would often push a way through the loose scoria and emerge as a flow of lava from near the base of the cone. Sometimes the loose scoria collapsed and the side of the scoria cone was rafted away by the outflowing lava. This created a horseshoe-shaped or breached crater (*9.78*). Any scoria that landed on the lava flowing through the breach was also rafted away.

Gas in the fluid magma was released in the volcano's throat and powered the fountaining eruptions from the vent directly above; whereas the lava that flowed out the side had lost most of its dissolved gas and when it cooled and solidified, it became a relatively dense, dark grey basalt rock. Small amounts of gas that were still trapped in the lava often rose towards the surface of the flow as it cooled. This sometimes resulted in a zone of more vesicular or holey basalt near the top of the flow.

As molten basalt lava cooled and solidified, it contracted and cooling cracks formed. These cracks often formed fairly regular hexagonal-shaped columns (called columnar joints) that were vertical (or more accurately, perpendicular to the cooling surfaces at the top and bottom of the flow, (*9.9*). Near-horizontal cooling joints sometimes formed near the top or bottom of a flow (e.g. seen in Whangarei Falls, *9.43*).



9.8 Cartoon cross-section of the plumbing and eruption style that resulted in the outpouring of lava flows from the base of a scoria cone. Drawing by Margaret Morley.

9.9 As lava cools and solidifies it contracts, often forming vertical columnar fractures within the lava flow, as seen here at Black Rocks, Bay of Islands. Photographer Egon Eberle.

The size of the lava flow, or field of coalescing lava flows, depended on the supply of lava. Some of Northland and Auckland's cones produced just one small flow, whereas others produced sizeable lava flow fields that completely surrounded them (*9.74*).

The speed and distance travelled by individual flows were controlled by the eruption rate and the temperature of the erupted lava and hence its viscosity. The hotter, more liquid lava flowed downhill at running pace. Its surface quickly chilled to a thin, elastic, black crust but the fluid lava beneath continued to flow and deform the surface skin into curved ropey rolls, rather like the skin on a pot of cooling jam (*9.10*). Flows with such a smooth surface texture are known by their Hawaiian name as pahoehoe flows. As the flows moved downhill they cooled and became more sticky, eventually stopping and solidifying into basalt rock.

Cooler, more viscous lava flows formed thicker, more solid surface crusts that behaved brittly not elastically. This thick crust was broken up into sharp blocks of rotating basalt by the continued movement of the fluid lava within the flow. These slow-moving flows that look like a moving pile of rocky rubble are known by their Hawaiian name as a'a flows (*9.11*).

Where the volume of outpouring lava was not great, the shape of the land over which it erupted influenced the resulting form of the lava flow field. Flows that erupted onto the relatively flat South Auckland and Manukau lowlands generally spread out as a wide apron around the central vent or cone. Northland and Auckland isthmus were more dissected, with incised streams draining rolling hill country. In these areas, outpouring lava flowed as viscous rivers down stream-valleys, and cooled to form solid ribbons of basalt filling the valley. The streams were displaced and now flow along the side of the basalt flows, eroding new courses into the softer sandstone banks.

In two of the volcanic fields (Kaikohe-Bay of Islands and South Auckland), vast quantities of gas-poor magma were erupted as numerous lava flows from one vent, over periods of one or more years. These flows cooled and solidified on top of each other to build up roughly

9.10 Typical ropey pahoehoe lava flows can be seen exposed adjacent to Kiwi Esplanade, Mangere Bridge, Auckland. They were erupted from nearby Mangere Mt.

9.11 Typical rubbly surface of an a'a lava flow on Rangitoto Island, Auckland.

9.12 The gentle slopes of Bombay shield volcano, South Auckland (seen from the west) produced by voluminous outpouring of lava flows.

circular shield volcanoes with gentle slopes of about 10 degrees (*9.12*). In the Auckland and Whangarei fields, just three and one volcano respectively, erupted sufficient fluid lava to form shield volcanoes. Some of the shield volcanoes in Northland and Auckland are capped by scoria cones above the main vent (e.g. Pukekawa, South Auckland; and Rangitoto). Others do not seem to have had much dissolved gas at all in the magma and no scoria cone was formed (e.g. Pukekohe Hill, South Auckland; Whatitiri, Whangarei Field).

MAGMA SOURCES

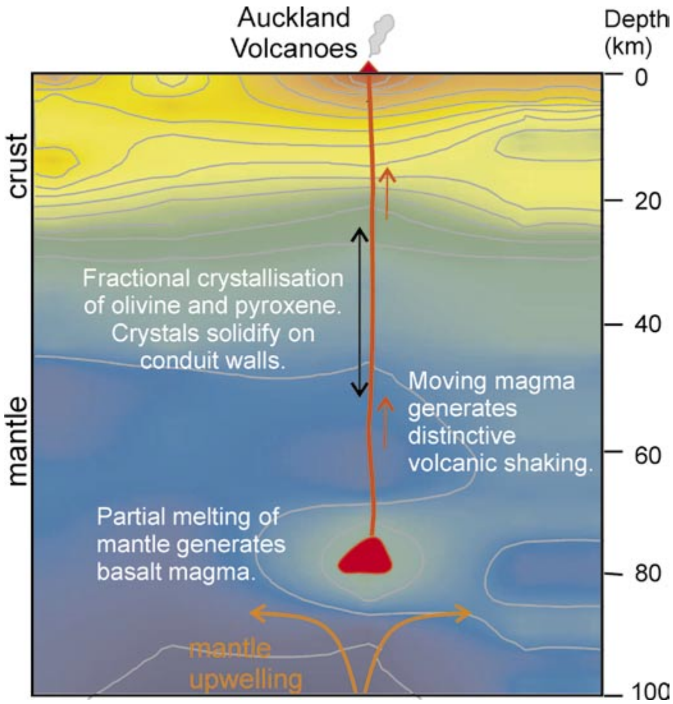
Basalt magma beneath Northland and Auckland comes from partially melted mantle rock at about 60-90 kilometres depth. This magma rises to the surface in small batches that usually erupt in a different place each time to form a new volcano.

Specialised geologists called petrologists cut thin slices of rock and study the composition of the basalt rocks with a transmitted-light microscope. Through the microscope they see a closely knit mix of small and very small crystals of several minerals - plagioclase, olivine, clinopyroxene and iron-titanium oxides. The larger crystals formed within the magma as it started to cool while slowly rising towards the surface. The smaller crystals grew quickly as the basalt lava cooled and solidified after it was erupted. The margins of flows and frothy scoria cool so rapidly that there is no time for even small crystals to grow, and as a result, dense, black glass is formed.

Geochemists use expensive modern equipment to study in detail the chemical composition of small samples or crystals in these volcanic rocks. They have found that there is a considerable amount of variation in their composition, with their silica composition ranging between 38 and 50 per cent, which defines them as basalts. Determination of the chemistry of these rocks provides considerable insight into the temperature and pressure, and therefore depth, at which the original magmas were formed, and also information on how the chemistry changed during the magma's slow or fast ascent, and how magma from multiple sources might have mixed together in some instances.

Some magma batches have risen more slowly and cooled during their ascent to temperatures low enough for crystals of some minerals (olivine, clinopyroxene) to start growing inside the melt. The growth of these minerals and their separation from the remaining melt is called fractional crystallisation. This process preferentially removes elements (magnesium and iron particularly) from the magma, which changes the chemistry of the remaining melt. Often these crystals grow on the walls of the conduit at depth and are not erupted. Other times, some crystals, 1-10 mm across, are erupted with the molten lava and captured in the basalt as it solidifies. Yellow-green crystals of olivine may be visible within the solid basalt or scoria deposits.

Studies show that the primitive parent magmas were formed by partial melting of solid mantle rock called peridotite. Almost all of the volcanoes in the Kaikohe-Bay of Islands and Auckland volcanic fields erupted alkali basalt. This has 45-49 % silica and formed at about 1450˚C by partial melting of about 1-4 % of the parent mantle peridotite at depths of about 70-90 km. The volcanoes in the Puhipuhi, Whangarei and Ti Pt volcanic fields, as well as the main phase of Rangitoto, erupted sub-alkalic to tholeiitic basalt containing 49-50 % silica. This is



9.13 Magma beneath Auckland is formed by partial melting of solid mantle rock. During its ascent to the surface, the chemistry of the primitive magma might evolve by the growth within the magma of olivine and pyroxene minerals. These crystallise at higher temperatures and preferentially remove some elements from the remaining molten mix. Background is the coloured seismic shear-wave velocity profile provided by geophysicist, Nick Horspool. Similar magma sources are inferred for the other basalt volcanic fields in Northland and Auckland.

known to be formed at the slightly lower temperature of about 1400˚C by partial melting of around 5 % of the peridotite at a shallower depth near 65 kilometres.

These geochemical studies have shown that the basalt magma originates in the upper mantle, which is quite different from normal hot-spot mantle plume volcanoes, like Hawaii, where the basalt magma originates from much deeper in the mantle. The questions now being asked are: why is this partial melting present beneath discrete areas of Northland and Auckland and why do small batches sometimes rise to the surface to erupt as volcanoes? While there is no obvious direct connection between these volcanoes and the boundary between the Australian and Pacific tectonic plates, their close proximity to that boundary might not entirely be a coincidence. One hypothesis is that these areas are under tension, being slowly pulled apart at depth and that maybe there is some upwelling of hotter mobile mantle from beneath, which slightly increases the temperature and reduces the pressure in this zone of partial melting and magma generation.

Fingerprinting Auckland volcanoes

Geochemical studies show that each batch of basalt magma that rose to the surface and erupted in the Auckland Volcanic Field had a slightly different composition, and sometimes that composition has changed (as crystals grew within it) during the time it was erupting - a period of weeks to months. In many instances the chemical differences as measured by the proportion of elements, such as magnesium, potassium, strontium and rubidium, are sufficient to be able to 'fingerprint' the rocks erupted from different centres, so that lava flows and sometimes volcanic ash can be traced back to their source volcano.

Origin of rhyolites and dacites in Northland volcanic fields

In the Kaikohe-Bay of Islands fields, a number of the solidified lavas contain large crystals or clumps of crystals that clearly crystallised at depth before being erupted. These seem to suggest that, in contrast to the other northern New Zealand fields, the rising basalt might have stalled during its ascent towards the surface to form a magma chamber, maybe near the base of the crust. This would have allowed time for crystals to grow and the composition of the remaining molten magma to change as a result of fractional crystallisation, but also perhaps from recharge, with the addition of more basaltic magma from the mantle, and maybe at times some melting and assimilation of the more silica-rich crust. Unlike Auckland and the other intra-plate fields, maybe one or more magma chambers existed at considerable depth beneath the Kaikohe-Bay of Islands field for most of its life with periodic eruptions sourced from them.

If the process of fractional crystallisation continues for quite some time in a magma chamber, then it is possible to dramatically change the composition of the magma that remains molten in the upper parts of the reservoir into a much more silica-rich magma, such as dacite or even rhyolite. Auckland University geochemist, Ian Smith, who has worked extensively on the chemistry of the Northland and Auckland basalt fields, believes that this is the most probable explanation for the origin of the rhyolite and dacite magmas that erupted as viscous domes within the Kaikohe-Bay of Islands, Puhipuhi and Whangarei fields. Some additional mixing in of continental crust melted by the heat of the magma chamber might also have occurred.

VOLCANIC HAZARDS

The Kaikohe-Bay of Islands, Whangarei and Auckland volcanic fields are considered to be dormant and could erupt again some time. The Auckland field has been the most active in recent geological times (20+ eruptions in last 35,000 years or so) and is considered to provide more risk of the next eruption than the two Northland fields.

As rising magma approaches the surface and an eruption is imminent, the intensity of earthquake shaking will increase and buildings close to the pending eruption centre could be damaged. In the hours, perhaps days, before the eruption commences, the ground directly above the magma might start to bulge upwards and crack. By then everybody should have evacuated the immediate area as it is the initial phases of a basalt eruption in an Auckland or Northland volcanic field that are potentially the most dangerous and destructive.

If the rising magma encounters ground or surface water, the initial eruptions will likely be of the explosive style. In these, the entire land surface will be destroyed in the area surrounding the eruption. The explosion craters usually have a diameter of 200-2000 m. Surrounding the crater, the build-up of volcanic ash forming a tuff ring will likely destroy and bury everything for a further 1 km or so beyond the crater edge. Beyond this, the most dangerous and damaging parts of explosive eruptions are the base surges of searing gas and ash. They explode out in all directions from the vent and might devastate an area 1-5 km from the eruption's centre. These explosive surges are usually preceded by powerful shock waves strong enough to knock down trees and break windows and these impacts might extend beyond those of the base surge itself. The rapidly-travelling superheated blast arrives a few seconds later and would kill all humans and animals in its path and destroy all vegetation and houses. Only the skeletons of the more strongly constructed buildings would remain. Base surges will travel further over flat land or sea than over more hilly suburbs.

The explosive style of eruption also blasts volcanic ash a few km into the air. The height, volume and duration of these ash eruptions, as well as the strength and direction of the wind, will determine the extent of the damage and disruption they will cause. The majority of the ash will fall back to the ground and build up a tuff ring close to the crater, but wind might blow a blanket of ash a few cm to tens of cm thick over 10 km or more from the vent, into areas not evacuated. In areas of thick ash fall, darkness might descend and people without respirators will experience breathing difficulties. Ash is abrasive and if it gets into motors it can cause damage to machinery and vehicles. Auckland or Whangarei airports might be closed as a precaution against ash damage to aircraft. Ash will build up on roads, causing further major traffic congestion.

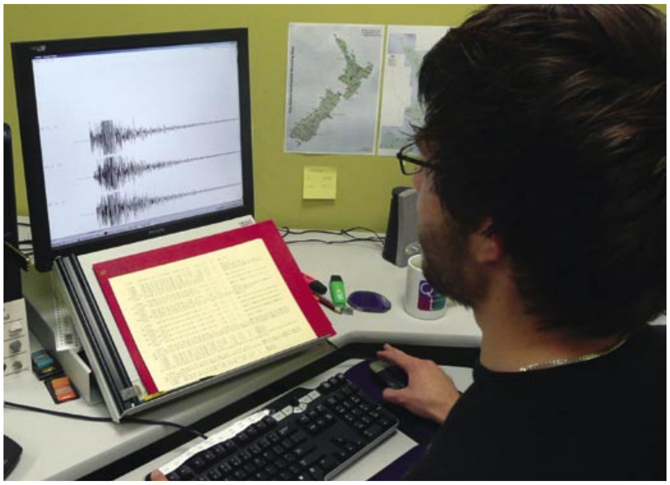
9.14 The most dangerous phase of the next eruption in Auckland or Northland is likely to be an explosive pyroclastic surge of searing-hot gas and ash, which might smother and kill anything in its path for up to 5 km from the vent. This photo, from Mt Pinatubo eruption in 1991, illustrates a pyroclastic base surge style of eruption. Photo courtesy of US Geological Survey.

Ash will accumulate on house roofs and if it is wet or many tens of cm thick, its weight could cause many to collapse. If heavy rain accompanies or follows the ash eruptions, there is a likelihood that many stormwater drains will become blocked and widespread flooding would occur. Wet ash, erupted wet or falling with rain, might stick to trees, telephone and electricity lines and insulators, causing branches to fall, potential electricity flashovers with power outages and communications disruption. Ash fall will contaminate water, merely making it less palatable rather than toxic, and given the right wind direction could temporarily close freshwater supplies to Auckland, Whangarei or Kaikohe. In some areas, power outages could impact on essential services such as pumping stations for freshwater supply and sewerage reticulation.

After the explosive eruptions are replaced by dry eruption styles of fire-fountaining, fiery explosions and lava flows, the hazards to life and property will be less, and more predictable. The hazards will mostly be limited to within the area that has already been devastated by the explosive eruptions and base surges. During fire-fountaining, scoria lands close to the vent and builds up a scoria cone, and fine scoriaceous ash might be blown a few km away. Hot wind-blown scoria can start fires, and

9.15 Basalt fire-fountaining style of eruption of Heimaey Volcano, Iceland, 1973. Any future eruption in Auckland, Whangarei or Kaikohe-Bay of Islands is likely to include several weeks or longer of fire-fountaining, producing mounds of scoria that might bury and set on fire any buildings and trees still standing near the vent. Photo courtesy of US Geological Survey.

9.16 In the latter phases of the next eruption in Auckland or Northland, molten lava is likely to flow down valleys and streets, slowly burning and destroying everything in its path, as here in Hawaii. Photo courtesy of US Geological Survey.



9.17 A GNS seismologist examines the seismometer record of an earthquake. A network of eleven seismometers is permanently focussed on the crust beneath the Auckland Volcanic Field to detect any signs of volcanic tremor at depth that might signal rising magma. It is believed that these seismometers will give Civil Defence authorities a minimum of several days to evacuate the part of Auckland where the magma is likely to erupt. As of 2016, there is no similar early warning system for the Kaikohe-Bay of Islands or Whangarei volcanic fields. Photo by New Zealand Geonet Project.

boarding up windows might reduce this risk to houses. Periodically, volcanic bombs, up to a metre across, might be blasted high into the air and land within a km of the vent, but these would usually only be a threat to scientists who may be allowed this close to take samples for monitoring and predicting the course of further eruptions.

If the supply of magma is sufficient, lava flows might pour from around the base of the rising scoria cone and spread out over low-lying land or flow down valleys. The speed of these flows would usually allow all animals and many moveable possessions to be evacuated, but any vegetation or buildings in the way are likely to be set on fire and demolished and consumed by a lava flow. In some instances the speed of flows can be slowed or the lava halted by hosing cold water on them. Bulldozers can build barriers that might divert the flows but this could be difficult in built-up suburban areas.

In summary, the next eruption in Auckland or Northland will cause considerable economic and social disruption and physical destruction. If people evacuate the target zone when instructed to do so by Civil Defence, then they, most of their pets and a few of their most treasured belongings will survive the volcanic activity. During the eruption, life in surrounding areas (especially if the eruption is in Auckland) will likely be disrupted by traffic congestion, power outages, and the impacts of ash fall. At present, scientists have no idea when or where the next eruption in Auckland or either of the two Northland volcanic fields might occur. There is no discernible pattern of the timing or location of eruptions in the past. Thus we rely on the earthquake monitoring to give us sufficient warning and to define which areas civil defence will order to be evacuated once moving magma is detected at depth. This could be next week or not for another 10,000 yr.

OLDER KAIKOHE-BAY OF ISLANDS AND PUHIPUHI VOLCANIC FIELDS

Subduction-related volcanism ended in Northland-Auckland about 15 Myr ago and this activity became largely restricted to Coromandel Peninsula and off the west coast of Waikato and Taranaki. After a period without volcanism, a new phase of volcanic activity began with the outbreak of basaltic eruptions about 10 Myr ago (Late Miocene) in Northland and to a limited extent in east Auckland. These are called intra-plate basalt volcanic fields. They differ from the classic intra-plate hot spot basalt volcanoes, like Hawaii, in which the magma originates from much deeper within the mantle beneath the moving crustal plates.

The northernmost basalt field, called the older Kaikohe-Bay of Islands Field, erupted large volumes of basaltic lava between 10 and 2 Myr ago. These lava flows, now somewhat weathered and eroded, form much of the high plateau between Okaihau, Kerikeri and Whangaroa (*9.19*). Deep, subtropical weathering of these has produced the rich volcanic soils that nurture Kerikeri's orchards and crops. Presumably some of the vents that erupted the extensive, overlapping sequence of basalt flows also produced scoria cones by fire-fountaining of gas-rich lava, but these cones have subsequently eroded away. More recently, volcanism has moved slightly southward and produced the younger and better-preserved small basalt volcanoes of the younger Kaikohe-Bay of Islands Field.

9.18 Haruru Falls on the Waitangi River flows over the eroding lip of a 2 Myr-old basalt flow of the Kaikohe-Bay of Islands Volcanic Field.

The Puhipuhi Volcanic Field erupted between 10 and 4 Myr ago. It consists of basalt lava flow sequences with intervening soil horizons, that form extensive plateaux (*9.20*). Further east, in the hills south of Russell and inland from Whangaruru Harbour, erosional remnants of basalt lava form ridge crests sitting directly on top of weathered basement greywacke rocks. Many of these are recognised by the scattering of basalt boulders on the surface, often with fluted forms resulting from thousands of years of exposure to acid-rich seepage beneath native forest cover (Box 34). These ridge-crest lava flow remnants still retain the original flat surface of the basalt plateau they formed, although it has possibly been uplifted somewhat since it was erupted.

9.19 Top: View south across the eroding flat surface of the Okaihau basalt plateau formed by the voluminous outpouring of basalt flows in the Kaikohe-Bay of Islands Volcanic Field during the Pliocene, 4-3 Myr ago.

9.20 Bottom: In eastern Northland, the west-tilted Puhipuhi Plateau is held up by 5 Myr-old basalt flows that overlie the slightly dissected Auckland Erosion Surface. It would seem that these flood basalt flows spread out over about 200 km² of this relatively flat coastal plain before being uplifted 200-400 m along with the greywacke ranges that extend from Whangarei Harbour to the Bay of Islands. View northwest from Stoney Knowe, above Helena Bay.

TI POINT VOLCANIC FIELD

Further south, in the Auckland region, scattered eruptions of basalt (Ti Point Basalts) occurred in three places between 10 and 7 Myr ago. The most prolific was around Leigh, where basalt plugs, intrusions and dikes are present on Goat Island, forming Ti Point (*9.21*), and in four other inland localities (*9.22*). These are the plumbing systems beneath basalt volcanoes that have been unearthed by deep erosion. A similar 10 Myr-old basalt intrusive dike occurs intruding greywacke in a quarry at Brynderwyn. Also belonging to this group of Late Miocene basalt volcanoes is Stony Batter (*9.23*) at the east of Waiheke Island, in the inner Hauraki Gulf. The basalt boulders covering the hilltops are the eroded remnants of basalt lava flows or a small shield volcano that erupted here 8-7 Myr ago. Many of these basalt boulders are also fluted from solution by acidic seepage down their sides over a long period (*9.26, 9.28*).

Chemical analyses of these Ti Point Basalts shows that they are intermediate in composition between basalt and andesite. They have chemical signatures that suggest they are related to the deeper part of the subduction zone that generated volcanism, including the closely similar Mercury Basalts, in the Coromandel Zone at this time (chapter 7). In this respect they are best referred to as back-arc basalts distinct from the other intra-plate basalts of Northland and Auckland described in this chapter.

9.21 Above. Ti Point at the mouth of the Whangateau Harbour, just north of Omaha, exists because it is composed of intrusive bodies of hard basalt. This basalt solidified in the plumbing beneath a basalt volcano that erupted here about 10 Myr ago.

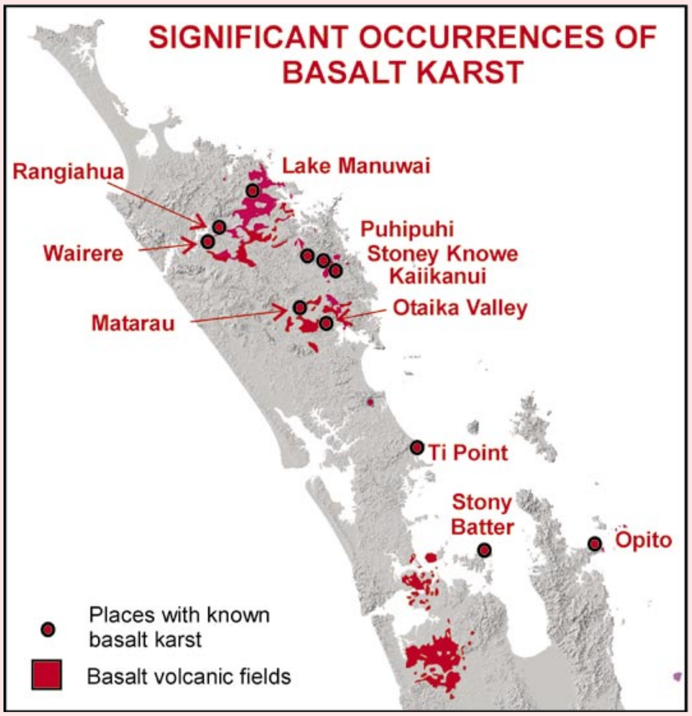
9.22 Left. Around Leigh, north of Auckland, there are at least four Late Miocene basalt centres that erupted between 10 and 8 Myr ago. All erupted products have since been eroded away to expose the basalt that solidified in the plumbing beneath. The conical peak of Pukematekeo (Sugar Loaf, seen here), on the ridge crest 2 km north of Matakana, is a plug of basalt that solidified in the throat of one of these volcanoes.

9.23 The basalt boulders that dot the hills around Stony Batter, on the east end of Waiheke Island, are the eroded remnants of a once more extensive basalt volcano that erupted here 7-8 Myr ago in the Late Miocene.

Box 34. BASALT KARST

Basalt karst is rare world-wide and in New Zealand is only known in a few, small patches of surface boulders in the older Kaikohe-Bay of Islands, Puhipuhi, Whangarei and Ti Point (including Waiheke Island) volcanic fields. Some of the most fluted and attractive boulders have been removed from a number of localities and sold as ornamental garden stones. Two large examples can be seen in the Town Basin tourist area in Whangarei.

The basalt solution features appear to have formed when the boulders were sitting above ground. The solution runnels (fluting, karren, lapiez) occur on the boulder sides (*9.27)* and may be up to 100 cm deep and 100 cm across, but are mostly smaller. Solution basins (mostly 10-60 cm diameter and depth) occur on the tops of the boulders, some with overflow solution runnels down the sides (*9.25*). The basins and fluting mimic the solution features on limestone or marble outcrops, although undoubtedly they were formed more slowly on the basalt. In carbonate rocks, surface fluting is attributed to the slightly acidic nature of rain, or rainwater that has percolated down through a forest cover.



9.24 Known areas with basalt karst in northern New Zealand.

To dissolve basalt, the water would have to be more acidic than plain rainwater that dribbles down through a forest canopy. In places where a forest canopy still exists, the majority of the underlying basalt boulders have a dense growth of plants growing on top, particularly kauri grass, perching lilies, spiderwood and broadleaf puka (*9.26*). In and around the root bases of these plants, leaf litter and soil builds up on top of the rocks. Rainwater sits around in this moist "soil" for weeks becoming more and more acidic with the humic acid formed from the breakdown of the plant debris. It is this acidic water that appears to have slowly dissolved the basins on the tops of the boulders and has dribbled down the sides, gradually etching out the flutings. This process has undoubtedly taken many thousands of years as no such solution features are known in the young Auckland Volcanic Field.

9.25 Left: Basalt boulder with 60 cm-deep basin and overflow fluting, for sale on side of the road, Waro. The basin was dissolved by humic acid around the roots of plants that were growing in humus on the top of the boulder.

9.26 Right: Fluted basalt boulder with natural cap of wharawhara (Astelia banksii) beneath taraire forest, Stony Batter, Waiheke Island. The acid nature of the leaf litter and soil around the base of these plants is inferred to have been imparted to seeping rainwater that dissolved the surface basins and flutes in the basalt.

Box 34 continued

9.27 The northern end of Lake Manuwai, Kerikeri's irrigation water storage lake, is bordered by the best-developed fluted basalt karst in New Zealand. Unfortunately the only access is by kayak.

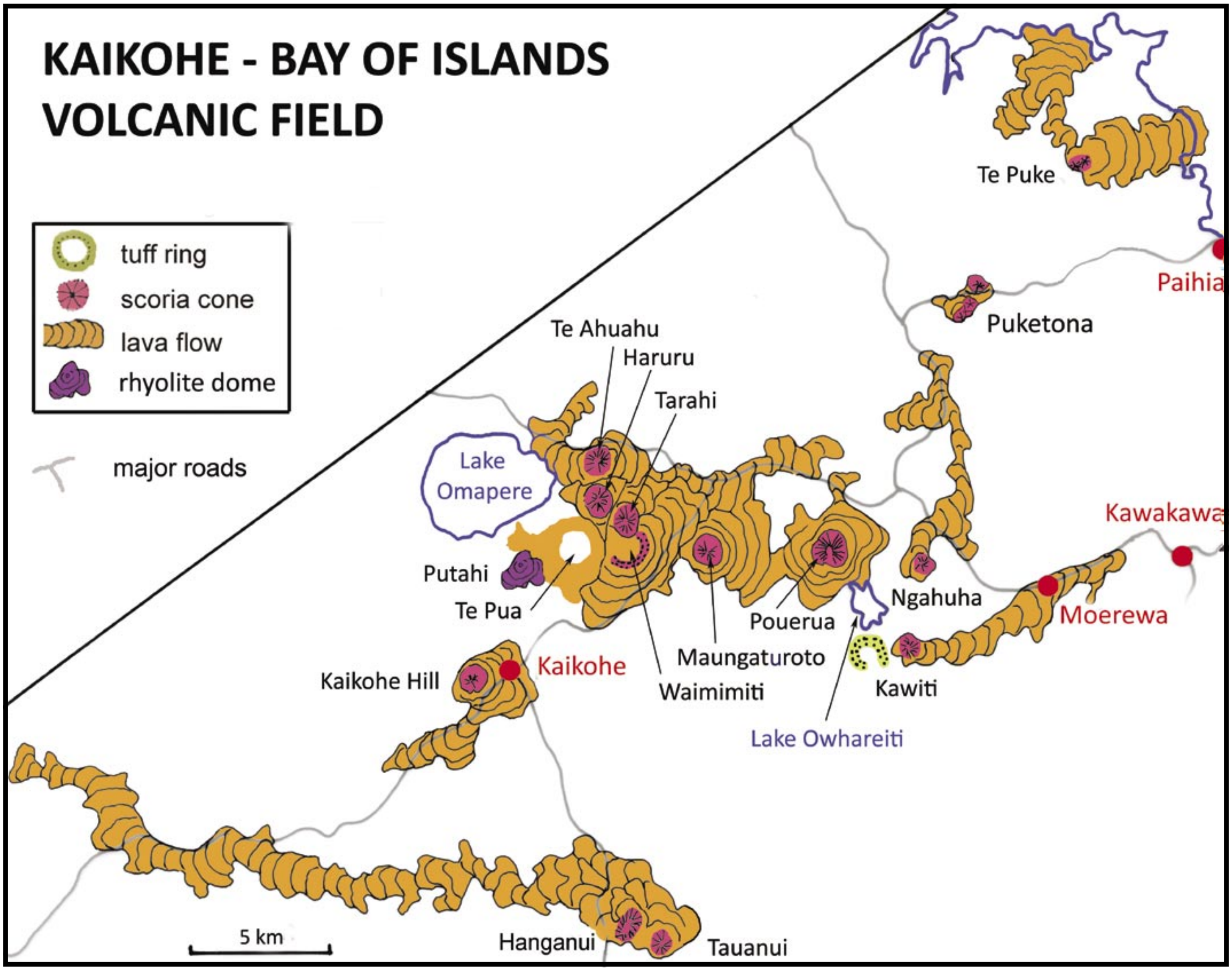
9.28 Left: Three spectacularly fluted basalt boulders, Stony Batter, Waiheke Island.

9.29 Right: Wairere Boulders is a privately-run tourist attraction in the upper Hokianga. Boardwalks lead through a huge heap of giant basalt boulders that have slid down into the valley from the bluffs above. Humic acid-rich water running over the boulders has dissolved their surface into large flutes. This large flower-shaped boulder has rolled over (top to the left) and the originally vertical fluting has been tilted to near-horizontal. Photographer Egon Eberle.

YOUNGER KAIKOHE-BAY OF ISLANDS VOLCANIC FIELD

The younger part of the Kaikohe-Bay of Islands Volcanic Field erupted in the last 300,000 years and retains most of its volcanic landforms. The majority of these volcanic centres are clustered around the central Northland town of Kaikohe, but there are also two centres further east towards Waitangi in the Bay of Islands. Most eruptions were dry and produced scoria cones, often with associated lava flows that spilled down adjacent stream valleys. Around Kaikohe there are eleven, mostly prominent, conical scoria cones (*9.30*) and an explosion crater with surrounding tuff ring. A lava flow from Te Ahuahu dammed a small valley forming the shallow Lake Omapere between Kaikohe and Okaihau about 80,000 years ago. The longest lava flow in the young Kaikohe-Bay of Islands Volcanic Field flowed

9.30 Te Ahuahu is one of the highest scoria cones in the Kaikohe-Bay of Islands Volcanic Field.



9.31 *Map of the younger Kaikohe-Bay of Islands Volcanic Field.*

9.32 Right. Te Puke Volcano, inland from Waitangi, consists of four small, cratered-scoria cones in a northeast-southwest line. In this photo from the west, the top of the three southern cones are clearly visible as grassed circles, but the northernmost is camouflaged by planted pine forest (left). The Bay of Islands is in the distance. Photographer Alastair Jamieson.

9.33 Pouerua Volcano near Kaikohe, is surrounded by about 10 km² of lava flows. Some of the flows are covered in mounds of scoria that were rafted away from the cone on top of the flows. Lava flow-dammed Lake Owhareiti is in the foreground. Viewed from the south. Photographer Alastair Jamieson.

19 km down the Taheke Valley towards Hokianga Harbour from one of the youngest volcanoes, Tauanui, located 10 km south of Kaikohe (*9.36*). Another of the youngest volcanic centres was Te Puke, which erupted a northeast-southwest line of four small cratered scoria cones in the hills behind Waitangi (*9.32*). Lava poured out to the north and east, forming rocky lava flow fields with tongues of lava extending out into Kerikeri Inlet (*9.33*). Six kilometres southwest of the Te Puke cones, and on the same fault line, is another line of six small scoria cones at Puketona. Several of these have been quarried away.

The Kaikohe-Bay of Islands Field is considered to be dormant, and not extinct. It is likely that all erupted within the last 300,000 years and that many are likely younger than 100,000 years. Ages of 300,000-60,000 years have been determined for volcanoes in this field using the K-Ar radiometric dating method, but this method is not considered to be terribly accurate for rocks this young. From the freshness of their lava flows and

9.34 Pouerua is one of the youngest volcanoes in the Kaikohe-Bay of Islands Volcanic Field. It consists of a high elongate scoria cone with two craters breached to the south (right). Lava flows to the south have dammed two small valleys, creating lakes and wetlands. Photographer Alastair Jamieson.

cones, Te Puke and Tauanui volcanoes appear to be among the youngest centres in this field with dates of 75,000 and 45,000 yr respectively, recently obtained by Phil Shane (University of Auckland) using the more accurate Ar-Ar radiometric dating technique. Further dates using more refined modern methods are needed.

9.35 Right. View south over Te Pua crater, which is surrounded by lava flows. Kaikohe can be seen beyond, 4 km to the south. Remuera Settlement Rd runs through the northern side of the crater. The amount of erosion suggests that this might be one of the older volcanoes in the Kaikohe-Bay of Islands Volcanic Field. Photographer Alastair Jamieson.

9.36 Left. Tauanui scoria cone, 10 km south of Kaikohe, erupted about 45,000 yr ago. It sits on the north side of Lake Tauanui which was formed by a small valley being dammed by lava flows from the volcano. Photographer Alastair Jamieson.

9.37 Left. This lobate shoreline on the south side of Kerikeri Inlet, Bay of Islands, is the partially-drowned crest of a branching lava flow from the 75,000 yr old Te Puke Volcano. Photographer Alastair Jamieson.

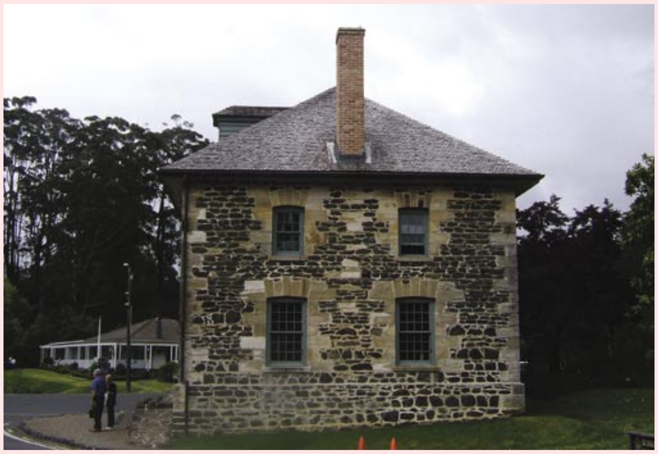
Box 35. BASALT STONE BUILDINGS

British colonists, who settled in Northland and Auckland in the 19th century, came from a heritage of stone buildings with slate roofs. Attempts to recreate the stone building styles they were familiar with back home were hampered by the lack of suitable local building stones. The hard greywacke rocks were too intensely fractured and the sedimentary rocks generally too soft. This left the basalt from Auckland and Northland's lava flows as the only handy rock that might be utilised, but in many places it too was closely fractured and it was a hard stone to work for intricate and precise facing stones. Mortar, to cement the stone blocks together, was derived from lime burning of cockle shell deposits from the foreshore or, where available, local limestone.

The oldest stone building, indeed the oldest surviving building in New Zealand, is the stone store at Kerikeri (*9.38*), built in 1832 from the local basalt lava flow from the older Kaikohe-Bay of Islands Field. Basalt was more widely used for building in Auckland, with over 20 surviving basalt buildings. Many were major churches, such as St Pauls, Symonds St, often made with basalt walls, but the more intricate facing stones carved from Oamaru Limestone blocks.

One of the earliest sources of basalt to be used in Auckland came from Rangitoto Island, where small cobbles were collected from the foreshore and used for rubble walls. Larger blocks prized from the lava flows were worked by skilled stone masons like Benjamin Strange. Rangitoto basalt can be seen in a number of 1850s and 1860s Auckland buildings (e.g. The Deanery and Strange's House, Parnell and the Mission House in Mission Bay).

Basalt from Lake Pupuke, Mt Victoria, Mangere Mountain, Mt Hobson and Hampton Park lava flows was also used in the construction of stone buildings near to each quarry. The most prominent source of basalt for building, especially after the 1880s when the prison quarry opened, has been the thick lava flows from Mt Eden. In addition to stone for buildings, the prisoners prepared hundreds of thousands of squared rectangular basalt blocks for use as kerb stones, many of which are still in use around Auckland's streets.

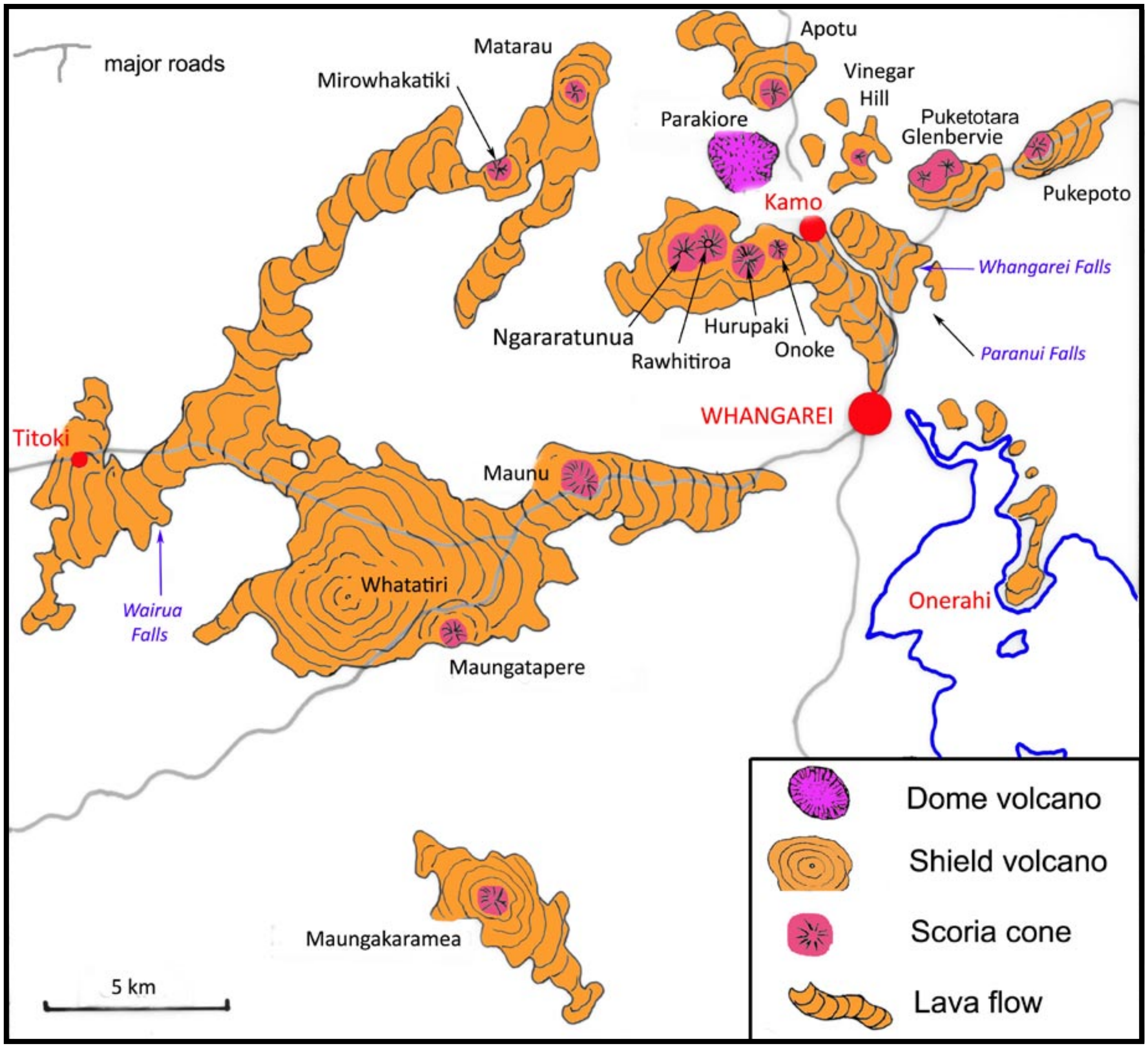


9.38 Top left: St Pauls Anglican Church, Paihia (1925) was built from basalt sourced from a basalt lava flow near Kawakawa in the younger Kaikohe-Bay of Islands Field. It was built as a memorial to the pioneering missionaries Henry and William Williams.

9.39 Top right: Kerikeri stone store (1832-36) is made from locally-collected dark grey basalt rock from an ancient basalt lava flow that flowed down the adjacent Kerikeri Valley about 4 million years ago. The lighter-coloured facing stones are Sydney Sandstone shipped in from Australia.

9.40 Left: Kinder House (1856-57), Parnell, is one of Auckland's best known historic stone homes. It was designed by Frederick Thatcher and built by Benjamin Strange for Dr John Kinder. The walls are made of random rubble held together with mortar and the facings are of large squared blocks of basalt. The source of the rock is unknown.

WHANGAREI VOLCANIC FIELD



9.41 Map of Whangarei Volcanic Field.

The Whangarei Volcanic Field appears to have had entirely dry eruptions with no evidence of any explosive phases resulting from the interaction of magma with water. Fire-fountaining built scoria cones and large volumes of fluid lava flowed out from around their bases and down existing valleys. The field erupted in two distinct periods. The first, between 4 and 1 Myr ago, saw a number of volcanoes erupt north and west of Kamo and north of Onerahi. The eroded and weathered remnants of some of these older scoria cones still form higher land at Apotu, Matarau and Mirowhakatiki (*9.41*). Their more-resistant older lava flows still underlie parts of the Whangarei district, sometimes with inverted topography. This means that while they originally formed by flowing down valleys, subsequent erosion has been faster in the softer rocks of the original valley sides and now the harder basalt flows form

9.42 Bush-capped Hurupaki forms a prominent 350 m-high scoria cone on the skyline of Kamo in the Whangarei Volcanic Field. Radiometric dating suggests that it erupted about 300,000 yr ago.

9.43 Top: Whangarei Falls cascade over a basalt lava flow that erupted from the Vinegar Hill area during the first period of volcanicity in the Whangarei Volcanic Field, about 2.5 Myr ago.

9.44 Bottom left: Titoki Natural Bridge is the only natural bridge in a basalt flow in New Zealand. It is eroded, possibly along a former lava cave, into a 1 Myr-old lava flow from Mirowhakatiki Volcano.

9.45 Bottom right: As molten lava cools and solidifies, it contracts, forming cooling joints that are often pentagonal or hexagonal columns, like these in a 2.5 Myr-old flow at the bottom of Whangarei Falls.

ridges, such as the crest of Onerahi Peninsula and much of the suburb of Tikipunga, southeast of Kamo. These older flows have deeply weathered red soils with fresh rock seen in incised stream beds, such as Whangarei Falls (*9.43*). The longest flow in the Whangarei Field erupted from Mirowhakatiki scoria cone, about 1 Myr ago, and flowed about 12 km down the Wairua River valley.

The second period of eruptions, within the last 500,000 years, produced ten scoria cones with associated lava flows. These younger lava flows are not as deeply weathered as the older ones and their surfaces are frequently covered in scattered basalt rocks. These rocks have often been gathered up by farmers and used to construct drystone walls between paddocks on the outskirts of Whangarei City (box 40). They show the location of the flows beneath. Three relatively large scoria cones (Maunu, Maungatapere, Maungakaramea) form prominent landmarks southwest of Whangarei (*9.46, 9.47, 9.52*). The other seven younger scoria cones form an east-west line through Kamo. Three of these (Pukepoto, Glenbervie two cones, *9.49*) lie north of the road to Ngunguru, whereas the others (Onoke, Hurupaki, Rawhitiroa, Ngararatuna, *13.18, 9.42, 9.50, 9.51*) are lined up west of Kamo. Their alignment suggests that the magma that erupted to form these seven

9.46 Top left: View south over the tall scoria cone of Maunu Volcano, with Maungatapere Volcano beyond. A private road leads to telecommunication masts on the summit. Photographer Alastair Jamieson.

9.47 Top right: 359 m-high Maungatapere is the tallest scoria cone in northern New Zealand. It is clothed in regenerating taraire-dominated broadleaf forest, with swamp maire forest growing in the damp crater floor. Photographer Alastair Jamieson.

9.48 Lower: View west across Whatitiri Volcano, the most perfectly-formed shield volcano in New Zealand. It is circular in plan, 4 km in diameter and rises 230 m above the surrounding land. The shield is made entirely of lava flows. It is located 15 km southwest of Whangarei and has been dated at 500,000 yr old. Photographer Alastair Jamieson.

scoria cones, rose-up along the same deeply-buried fault line through the basement rocks, although not all at the same time.

Intact craters can still be recognised on the top of Maungatapere and Rawhitiroa scoria cones - the latter crater is occupied by a swampy lake (*9.51*). Five of these younger scoria cones (Pukepoto, Glenbervie east, Hurupaki, Ngararatuna, Maungakaramea) are U-shaped in plan view and have their craters “breached” by outpouring lava flows. South-west of Whangarei there is a gently sloping, symmetrical, conical shield volcano called Whatitiri (*9.48*). The rising basalt magma contained unusually low amounts of dissolved gas, insufficient for any fire-fountaining to build a scoria cone above the central vent.

Almost all the dates on Whangarei Field volcanoes have been obtained by the K-Ar radiometric method, which is best suited for older rocks and less reliable

9.49 View east to the two scoria cones at Glenbervie, 3 km northeast of Kamo in the Whangarei Volcanic Field. The western (nearest) Puketotara Volcano is a high scoria cone with no obvious crater, whereas the eastern cone (Glenbervie) is horseshoe-shaped with a crater breached to the south (right).

9.50 View west from Rotomate Rd, across lava flows from Ngararatunua Volcano, west of Kamo. Half of the scoria cone (on right) has been carried away to the south by the lava flows and can be seen as rounded mounds on top of the flows.

9.51 Right. View south over Rawhitiroa scoria cone, one of four volcanoes on an east-west line running west from Kamo. The summit crater is filled with a swampy pond. Because scoria cones are made of loosely packed scoria, the crater does not normally hold water. In this instance it has either been lined with impermeable volcanic ash, or more likely the volcano is sufficiently old that leaf litter and soil development have, over time, created an impermeable lining. Photographer Alastair Jamieson.

9.52 View south over Maungakaramea scoria cone (in foreground), the southernmost volcano in the Whangarei Volcanic Field. The summit and its crater have been subdivided into private lifestyle blocks with the access road running up through the crater breach. Lava flows extend north and south. Tangihua Range beyond. Photographer Alastair Jamieson.

and precise for those younger than 500,000 years old. The youngest dates obtained by this method from this field are about 300,000 years old. A single more recent age obtained by Phil Shane of the University of Auckland, using the Ar-Ar method, gave a similar age of 300,000 years to that determined by the K-Ar method, for a lava flow from Hurupaki. It is possible that some of the better preserved cones erupted more recently than this. The field is considered to be dormant with the potential for further eruptions some time.

Box 36. PRE-EUROPEAN MAORI USE OF THE VOLCANIC FIELDS

Gardening

Traditional and archaeological evidence indicates that the rich volcanic soils and cones of the Auckland, Kaikohe-Bay of Islands and Whangarei volcanic fields were highly attractive to early Maori colonisers and were widely occupied by about 600 years ago, and remained so up until the arrival of Europeans in the 19th century. The soils of the basalt fields were the fundamental reason for these areas' attraction. The volcanic ash-mantled land and lava flow 'stonefields' were more fertile than the surrounding clay soils derived from older sedimentary rocks, and were friable and relatively easy to cultivate using hand-held wooden implements. They were also warmer throughout the year because of their stony nature, providing a longer growing season for the subtropical plants introduced by Maori from the Pacific - kumara, taro, yam, and gourds. The earliest Maori arrivals might have been able to survive as hunters and gatherers of the natural resources, but as the population built up, larger prey species such as seals and moa disappeared and cultivations became an increasingly important part of their food source.

On lava-flow "stonefield gardens" a large amount of surface rock had to be cleared and heaped up (*9.54, 9.55*). The heaps were often used as raised rock and earth garden mounds, which increased soil moisture and temperature, providing a longer growing season for frost-tender crops. The cleared rocks were also used to form low boundary walls that often extended out from the cones like the spokes of a wheel between gardens of different family groups. These areas were subdivided by smaller stone walls and stone alignments for different crops. Some stone alignments also formed the base of brush wind breaks that sheltered the gardens, while others demarcated pathways. Rectangular and C-shaped stone alignments also indicate the sites of cooking shelters and houses.

Many of the pre-European stonefield garden features have been destroyed by urban sprawl in Auckland or cleared and highly modified by European pastural farming practices in the more northern fields. In Auckland, small areas of less-modified stonefield garden are protected within Otuataua Stonefields Historic Reserve (*9.55*) and at Matukuturua, Wiri. An extensive area of pre-European stonefield remains on the lava flow field of Pouerua Volcano near Kaikohe.

9.53 Top left: Pre-European Maori gardens and settlements on the Matukuturua lava flow fields on the south side of Matukutureia/McLaughlin Mt, Wiri. Painting by Chris Gaskin.

9.54 Top right: These circular heaps of basalt rocks are remains of a pre-European Maori garden area. The rocks were collected up into heaps from the stony surface of young lava flows from Puketona Volcano on the south side of Waitangi River. Both the cleared areas and the heaps were planted in kumara and gourd. The stones in the heaps heated up in the sun, warming the soil and assisting growth of these subtropical crops. Photographer Alastair Jamieson.

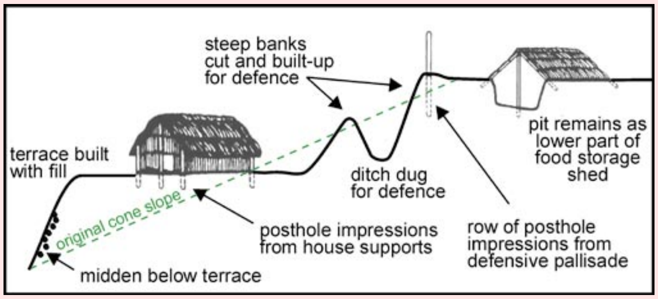
9.55 Bottom right: Stone walls that were part of an extensive pre-European gardening system established on the lava flows from Otuataua Volcano, Mangere, Auckland.

Box 36 continued

Settlement and defence

Maori, who were attracted to the rich volcanic soils of the lava flow fields, initially used the associated scoria cones for settlements. The smaller cones were occupied by as many as several hundred people living in scattered hamlets located on the cone's slopes. The largest cones were sprawling settlements occupied by much larger groups of related families. The main archaeological modifications of the cones are the hand-dug terraces on the slopes, crater rims and high points. The terraces provided flat areas for the construction of houses, cooking shelters and kumara pits (*9.57, 9.58*). These food storage pits are usually rectangular in plan and several metres deep. They were covered by steeply pitched roofs made from tree fern trunks covered with dirt. These "underground" buildings were surrounded by drains, secure from pests and could be entered through small tightly-closing wooden doors. They were dry, warm and of uniform humidity - well-suited for the long-term storage of kumara and other delicate subtropical food crops.

Fortification of the cones, creating defensive pa sites, was not really needed until the 16th century, when population pressure and increasing tribal separation led to feuds and local warfare. The rich volcanic soils were prizes sought after by those who did not have them, and the harvested kumara in their storehouses needed protection from marauding thieves. More intensive earthwork fortifications emerged in the 17th century when inter-regional conflict intensified. To fortify the cones, the slopes were artificially steepened, particularly at the front and back of terraces, wooden stockades were erected along the edges of some of the terraces, and ditch and bank defences constructed across ridges and spurs that otherwise created easier routes for attack (*9.56, 9.57*). Although the wooden portions of these pa and buildings have long since disappeared, the earthworks associated with them still remain on almost all of the scoria cones in northern New Zealand (*9.57, 9.78, 9.79*) – reminding us of their central role in this period of the human history of our country.

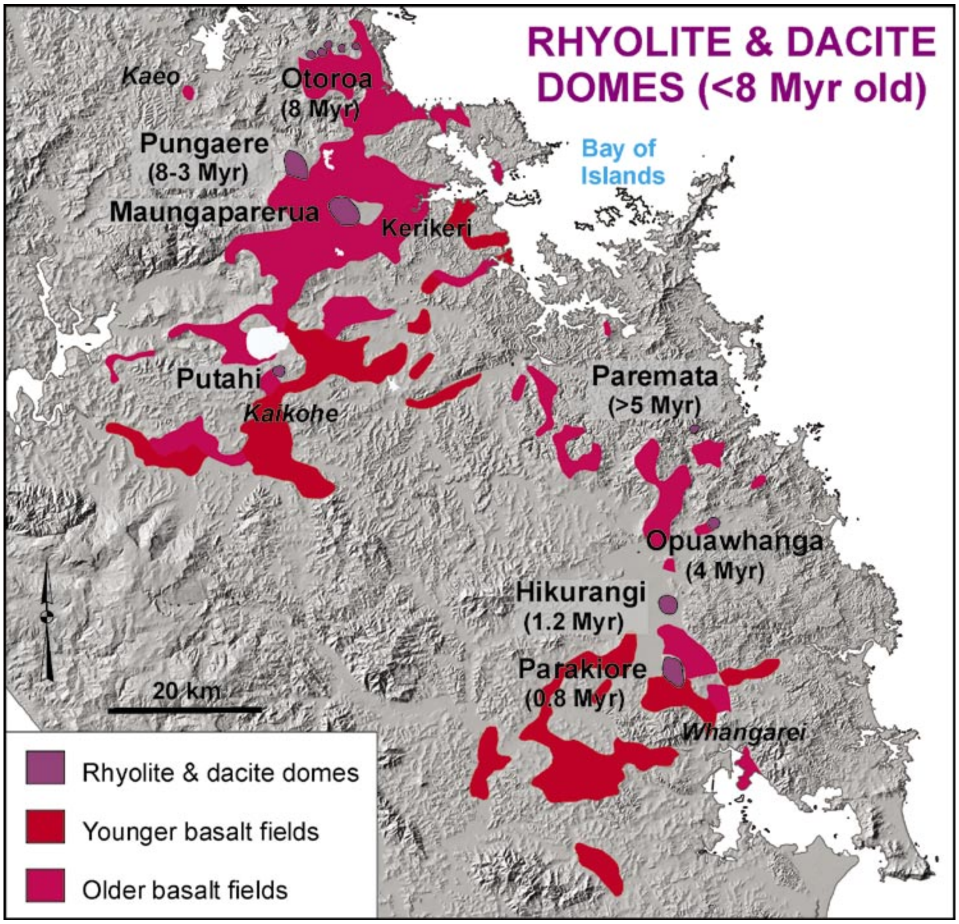


9.56 Top left: Sketched cross-section showing how the pre-European archaeological features on the scoria cone pa were created out of the original slopes, with the wooden structures that once sat above them.

9.57 Above: Maungakiekie is the most extensively terraced of all of Auckland's volcanic cones and one of the largest pre-European archaeological site complexes in New Zealand. It includes dozens of house site and garden terraces, and numerous groups of food storage pits. The mountain lay at the centre of Nga Mara o Tahuri – the expansive cultivations of Tahuri, a Waiohua ancestress. This scoria cone pa is one of the largest pre-iron-age forts in the world. Its four summits were all heavily defended by ditches and wooden palisades. On its peak was the 'tihi', the most sacred and heavily-defended part of the complex.

9.58 Bottom left: Most of the scoria cones in the Auckland, Whangarei and Kaikohe-Bay of Islands volcanic fields were used as defensive pa by the pre-European Maori. Roof-covered pits were used for storing kumara. Ditches, banks and wooden stockades were used for defence. Mangere Mt. Painting by Chris Gaskin.

RHYOLITE AND DACITE DOMES IN NORTHLAND'S BASALT FIELDS



Rhyolite or dacite domes occur within all the basalt fields of central Northland and, as discussed above, their original magma source was probably the basalt melt that had evolved over a considerable period of time through fractional crystallisation into silica-rich magma in the upper part of the reservoir within the continental crust. This felsic lava would have been thick and viscous as it was extruded out to form steep-sided domes on the surface of ancestral Northland (Box 22).

The oldest domes (10-3 Myr old) are rhyolitic and occur in the north, associated with the older Kaikohe-Bay of Islands and Puhipuhi volcanic fields. Some of these (e.g. Pungaere,

9.59 Left. Map of central Northland showing the location of rhyolite and dacite domes associated with the basalt volcanic fields.

9.60 View north over the 800,000 yr-old Parakiore complex dacite dome, located on the northwest outskirts of Whangarei City. Hikurangi dome is 5 km further north (top right). Photographer Alastair Jamieson.

Mahimahi, Paremata) contain small areas of glassy obsidian that was formed by rapid cooling along the dome margins. Eight relatively small (200-800 m across) rhyolite domes occur in an east-west belt at Otoroa, southeast of Kaeo. They have been intensely weathered to white halloysite clay, with two of the weathered domes (Te Pene, Mahimahi) mined for the manufacture of ceramics. Inland from Kerikeri, the large Pungaere rhyolite centre consists of a deeply weathered dome, flows and tuff. Further south in the Puhipuhi Volcanic Field, the remnants of a less weathered, flow-banded rhyolite dome (older than 5 Myr old) forms the 400 m peak of Paremata. These older, Late Miocene-Pliocene domes are all somewhat weathered and eroded and no longer form prominent hills like the younger domes. There is one rhyolite dome associated with the younger Kaikohe-Bay of Islands Volcanic Field. It is the undated Putahi dome that rises 100 m above the surrounding land, on the south shore of Lake Omapere (*9.63*).

The silica content and chemistry of the domes associated with the more southern Puhipuhi and Whangarei fields is somewhat different and the three young domes here have dacite compositions. The 4 Myr-old, 800 m-diameter, Opuawhanga dome (*9.62*) rises 160 m above the level of the surrounding valley. A little further south, the two youngest and most prominent dacite domes form the prominent hills of Hikurangi and Parakiore on the northern outskirts of Whangarei City. Both these domes are believed to have been extruded to the surface up the same North-South-oriented fault through the underlying crustal rocks. The 1.2 Myr-old Hikurangi dome rises to an impressive 260 m above the surrounding Hikurangi Swamp and is composed of a single main dome with several lower protuberances on its eastern side (*9.61*). The slightly younger (800,000 yr old) Parakiore dacite dome is even larger, rising 300 m above Hikurangi Swamp and northern Kamo, and having a 2.5 km-diameter footprint. It appears to be a complex dome with five extruded mounds (*9.60*). The chemistry of these dacite domes is similar to that of Little Barrier Island and there is some suggestion that their magmas might have been sitting dormant deep in the crust since the Miocene and have been formed above the former subduction zone of that time.

9.61 Hikurangi dacite dome (1.2 Myr old) rises 260 m above the Hikurangi Swamp. It has a small secondary dome on its eastern side (right).

9.62 Opuawhanga dacite dome was extruded 4 Myr ago within the Puhipuhi Volcanic Field, 10 km north of Hikurangi township.

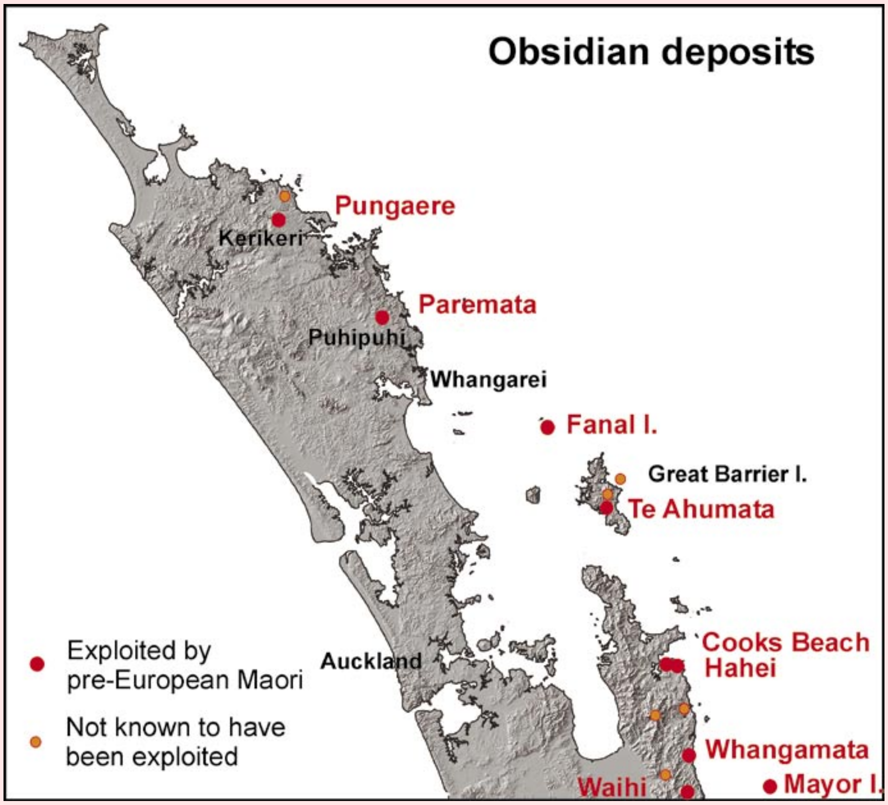
9.63 Putahi rhyolite dome in the young Kaikohe-Bay of Islands Volcanic Field, viewed from the north (Hwy 1) across Lake Omapere. Lake Omapere is a shallow lake formed by the damming of a valley by a basalt lava flow.

Box 37. OBSIDIAN AND ITS PRE-EUROPEAN USE IN NORTHERN NEW ZEALAND

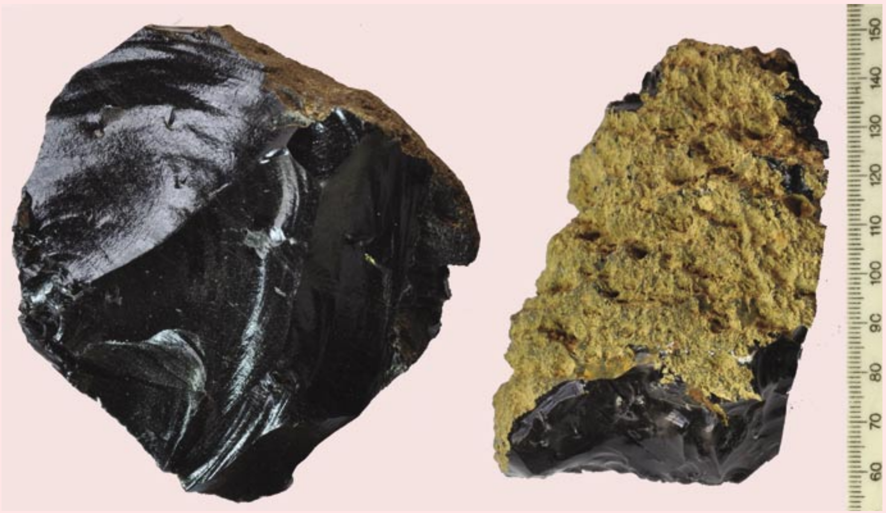
Obsidian is volcanic glass of felsic composition (usually rhyolite) that chilled and solidified rapidly without the formation of any crystals. This rapid cooling occurs around the margins of lava flows or domes and forms obsidian rinds a few cm to a few metres thick. Obsidian is hard and brittle and breaks leaving a sharp edge. In stone-age cultures, like the pre-European New Zealand Maori, the sharp obsidian edges were used for a variety of purposes, such as cutting flax and flesh, scraping wood or drilling holes. The relative rarity of obsidian in New Zealand made it highly prized by pre-European Maori.

By far the major source was Mayor Island in the centre of the Bay of Plenty. Mayor Island obsidian occurs in pre-European archaeological sites throughout New Zealand and even as far away as Norfolk Island, and attests to the fact that it was widely traded between tribes. Smaller deposits were also found and utilised in Northland, Coromandel Peninsula and the Taupo Volcanic Zone. In Northland, two small obsidian deposits in the older Kaikohe-Bay of Islands and Puhipuhi volcanic fields were used and traded locally. This obsidian mostly occurs in ancient or more modern stream deposits and appears to have been derived from the rhyolite domes of Pungaere and Paremata.

Nine obsidian sources are known from the Coromandel Volcanic Zone, with at least six having been utilised by pre-European Maori. All sources are from the rapidly-chilled glassy margins of Late Miocene-Pliocene rhyolite domes and flows (Whitianga Group). One locality is on Fanal Island (Mokohinau group), two on Great Barrier Island, and the other six on Coromandel Peninsula, between Whitianga and Waihi.



9.64 Places in northern New Zealand where obsidian deposits occur naturally. Sites named are those that are known to have been utilised by pre-European Maori for production of cutting tools. Source of information Moore (2012, 2013).



9.65 Lumps of obsidian from Pungaere rhyolite dome area, Kerikeri. University of Auckland collection.

Box 38. WORLD'S WHITEST CERAMIC CLAY

Hydrothermal alteration and weathering of some of the Miocene and Pliocene rhyolite and dacite domes in Northland soon after they were erupted, has created commercially-valuable kaolinite and halloysite deposits. Of most interest is the exceptionally pure halloysite clay currently being extracted from two adjacent domes (Te Pene/Matauri Bay and Mahimahi) at Otoroa, southeast of Kaeo. It is marketed as the whitest and brightest ceramic clay in the world, because of its low levels of impurities, such as iron and titanium oxides. Subtropical weathering, in the presence of abundant groundwater, of the upper 10-30 m of the lava domes produced halloysite clay. The quarried material contains about 50% halloysite clay and 50% silica (quartz). In the processing plant, the silica is removed and the halloysite further purified and dried. In the 1970s, the clay was used as a filler in the manufacture of paper. Today it is mostly exported for use in the production of high-quality ceramic tableware (primarily translucent white porcelain and fine bone china) and technical ceramics (predominantly zeolite-based molecular sieves).

9.66 Halloysite clay pit in hydrothermally-altered Te Pene/ Matauri Bay rhyolite dome, Otoroa, Kaeo. The halloysite is exported for use in the manufacture of the whitest ceramic tableware in the world.

Halloysite and kaolinite clays, produced by weathering and hydrothermal alteration of volcanic rocks, occur in Northland, Coromandel and the Taupo Volcanic Zone. The four best quality halloysite deposits occur in Northland – three at Otoroa, near Matauri Bay, and one at Maungaparerua, west of Kerikeri. Smaller or less pure deposits of halloysite clay are present in association with other rhyolite and dacite domes at Kaikohe, Whangarei Heads and Kaiwaka in Northland and hydrothermal kaolinite occurs in a number of places on Coromandel Peninsula (e.g. Cooks Beach and Hahei).

9.67 Looking west over Imerys Ceramics NZ's two halloysite clay pits inland from Matauri Bay, near Kerikeri. The nearer pit (beyond the buildings) works Te Pene Dome and the distant pit works Mahimahi Dome. Photo by Pete McGhee, Imerys Ceramics NZ.

Box 39. GEOTHERMAL POWER AND RELATED MINERALISATION IN NORTHLAND

Within the Puhipuhi and Kaikohe-Bay of Islands fields there is evidence of hydrothermal activity as a result of hot waters percolating up through the overlying rocks. The Puhipuhi activity is now dead, but that near Kaikohe is still on-going. At Puhipuhi, there are ancient silver-bearing sinters and sulphide deposits that have been subject to extensive prospecting and small-scale mining. Also present is silicified lake sediment, hydrothermal breccia and chert. This system is believed to have been active during the Pliocene (~4-2 Myr ago).

9.68 One of the two Ngawha geothermal power stations (Ngawha 2) currently in operation. The two lakes fill the craters created by small hydrothermal eruptions. Photographer Alastair Jamieson.

The one active geothermal field in Northland is located 5 km east of Kaikohe, at Ngawha. It is famous for its small mineral deposits of cinnabar (mercury) and muddy geothermal baths, which have high cultural and therapeutic values. There are about 20 natural hot springs, areas of steaming ground and hydrothermally-altered clay. The Ngawha Geothermal Field is believed to be heated by a partially cooled rhyolitic magma body or intrusion within the upper crust (3-8 km depth). It produces heated water at temperatures of 200-300 ºC at depths of 600-1000 m below the ground. Many deep exploratory wells were drilled in the 1970s-80s. They passed through about 600 m-thickness of Northland Allochthon sedimentary rocks and into greywacke basement beneath. Hot water and steam accumulates in fractures within the greywacke and beneath the near impermeable cap of allochthonous clay-rich rocks. This hot water resource is extracted from the underground reservoir via three production wells and is currently used to produce 25 MW of power from the two Ngawha power stations. Heat exchangers at the surface extract some of the heat, which is used to drive the electricity-generating turbines. The cooled water is reinjected down five wells back into the reservoir at depth. There are plans to more than double the output of electricity from Ngawha within the next decade, thereby producing much of Northland's electricity requirements.

9.69 Ngawha geothermal area is the only active geothermal field on the Northland Peninsula. It occurs as three northeast alignments of small hydrothermal crater lakes and minor steaming ground. The most active area is adjacent to Ngawha Village, which is also the area of historic mercury mining in the early 20th century. There are two hot mineral bath areas – one beside the loop in the road (centre) and the other next to Lake Tuwhakino (top left). Photographer Alastair Jamieson.

AUCKLAND VOLCANIC FIELD

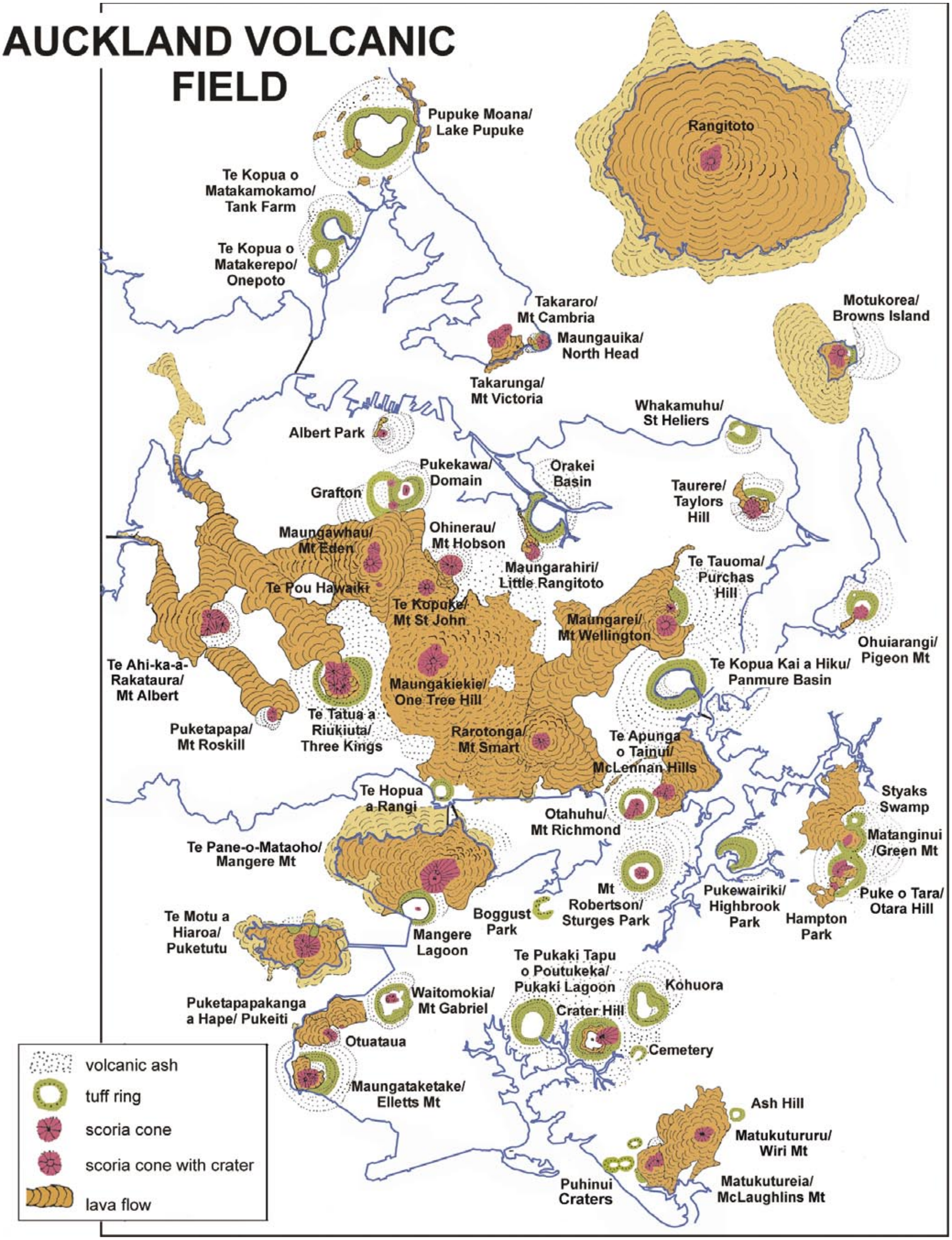
The Auckland Volcanic Field is the youngest basalt field in the country, with about 53 volcanic centres (*9.71*), each erupting within the last 200,000 years. While the field is currently dormant, the last eruption, Rangitoto, was just 600 years ago. The field is considered to be still alive and likely to erupt again. Auckland's volcanoes did not erupt in an evenly spaced procession. The majority have erupted in the last 40,000 yr, with only widely-spaced eruptions prior to that. There was a peak of eruptions within a few thousand years of 30,000 yr ago, with possibly six (Puketutu, Crater Hill, Mt Richmond, Taylors Hill, Wiri, Ash Hill) erupting within a space of a few hundred years and possibly all at the same time. While Rangitoto erupted just 600 yr ago, the eruption before that was Mt Wellington and its neighbour Purchas Hill at 10,000 yr ago.

The Auckland Volcanic Field is oval-shaped and extends from Lake Pupuke and Rangitoto in the north to McLaughlin Mt and Wiri Mt in the south, and from Mt Albert in the west to Pigeon Mt in the east. All of Auckland's volcanoes, except Rangitoto and perhaps North Head, seem to have erupted during the cooler climate of the Ice Ages, when sea level was lower and the Waitemata and Manukau Harbours were forested valleys.

The majority of centres appear to have begun with wet eruptions producing explosion craters surrounded by tuff rings. In some, the magma supply was exhausted before all the ground water was used up and eruptions stopped at this stage. There are 13 explosion craters/tuff ring volcanoes in Auckland that have no evidence of any fire-fountaining or lava flow eruptions (e.g. Onepoto (*9.70*), Orakei Basin, St Heliers, Te Hopua, Pukewairiki (*9.73*), Kohuora). A further 10 volcanoes had a short period of fire-fountaining after the wet explosive phase, which threw up one or more small scoria cones that sat over the vent inside the tuff ring. These are often referred to as "castle and moat" volcanoes and include Grafton, Auckland Domain, Panmure Basin, Hampton Park, Mangere Lagoon, Waitomokia, Mt Richmond, Mt Robertson and Crater Hill (*title pages*).

After the above volcanoes stopped erupting, their explosion craters filled with rainwater to become lakes, and over tens of thousands of years they began slowly filling with sediment. This sediment was a mixture of the silica skeletons of freshwater diatoms (phytoplankton), mud and plant material washed in from the sides of the crater, and volcanic ash from sporadic eruptions as far away as Rotorua, Taupo, Ruapehu and Taranaki (*10.29*). Some filled completely to become swamps that have subsequently been drained, such as at Auckland Domain, St Heliers (Glover Park) and Kohuora. A few have not yet filled with sediment and remain as lakes or ponds, as in Lake Pupuke, Crater Hill and Puhinui Pond (*9.72*). Another group of 7 explosion craters were still freshwater lakes as sea level rose up to its present level about 7300 years ago, after the end of the Last Ice Age (*11.27*). Those

9.70 The magma supply to these three aligned North Shore explosion craters seems to have reached the surface up the same straight fault line. Onepoto (foreground) and Lake Pupuke (distance) are the two oldest-dated volcanoes in Auckland at about 200,000 yr old. In between is Tank Farm explosion crater and tuff ring that has not been dated, but might be of similar age. Indeed it is possible that all three erupted together. Photographer Alastair Jamieson.



9.71 Map of cones, lava flows and explosion craters in the Auckland Volcanic Field.

9.72 Puhinui Pond Crater is one of the smallest explosion craters and surrounding tuff rings in Auckland Volcanic Field. It is one of three small tuff rings and craters in Puhinui Reserve that were not recognised as volcanic in origin until 2011.

with the overflow lips of their crater lakes at or below present sea level were breached by the rising salt water. They quickly filled up with mud carried in by the tides and were intertidal lagoons when Europeans arrived. Some of these have been reclaimed and their mudflats are now grassed playing fields (Onepoto, *9.70*), motorways (Te Hopua), or farmland (Pukaki Lagoon). Tank Farm (Northcote, *9.70*), Orakei Basin, Panmure Basin and Mangere Lagoon are still tidal lagoons, although Orakei Basin is maintained as a high tide lake by gates for most of the time. Two of the older explosion craters (Boggust Park, Pukewairiki; *9.73*) are believed to have erupted prior to 130,000 years ago and to have been breached by high sea levels during the Last Interglacial warm period at that time.

Thirty-seven of Auckland's volcanoes had a

9.73 View south over Pukewairiki explosion crater and tuff cone, Highbrook, Auckland. This is one of the oldest volcanoes in Auckland and is believed to have been breached by the sea during the Last Interglacial period (125,000 yr ago) when sea level was about 6 m higher than present.

9.74 View looking west over Mangere Mt scoria cone (centre), which erupted about 60,000 yr ago. It has two craters. Lava flows that poured out from around the base of the scoria cone have spread out as a large lava-flow field that underlies all the surrounding flat land in the photo.

9.75 The main crater of Mangere Mt scoria cone has a central dome-shaped tholoid of solid basalt that was pushed out of the vent by gas pressure from beneath, in the last phase of eruption. Once the dome had been extruded, the volcanic gas escaped from around the sides, forming three small explosion craters.

fire-fountaining phase that produced one or more scoria cones from single or multiple vents. In all, a total of about 57 scoria cones were produced by these volcanoes, although many more small scoria mounds were also produced, either by short periods of unidirectional fountaining or by rafting of scoria away from the main cone by lava flows (e.g. Duders Hill, Devonport). Lava pouring out from around the base of some of these cones rafted away scoria from 8 of them, creating breached, horseshoe-shaped craters, as on Mt Victoria, Mt Hobson, Green Mt, Otara Hill, McLaughlin Mt and One Tree Hill (*9.78*).

Many of the scoria cones also produced lava flows. On the Auckland Isthmus these flows often flowed down stream valleys, cooling to form long tongues of lava - the longest of which extended from Mt St John all the way to Meola Reef in the Waitemata Harbour (*9.76*). On the flat land of the Manukau lowlands, the lava flows spread out to form a wide apron of lava flow fields partly or completely encircling the source scoria cone, as at Otuataua, McLaughlin Mt, Mangere Mt (*9.74*) and Puketutu Island. In three instances, the outpouring of lava in all directions from around the central scoria cones built up a whole pile of lava flows to create gently-sloping shield volcanoes. The smallest was McLennan Hills at Otahuhu, where the Southern Motorway rises up and over it between the Mt Wellington and Otahuhu interchanges. One Tree Hill is a much larger shield, with its lava flows extending from Onehunga to Newmarket and east to Penrose and Ellerslie. By far the largest and best known shield volcano, with its profile often used as a symbol of Auckland, is Rangitoto in the middle of the Waitemata Harbour entrance (*9.84, 13.38*).

9.76 View south over Meola Reef/Te Tokaroa, which stretches most of the way across the Waitemata Harbour from Westmere towards Birkenhead. It is the partly drowned end of the longest lava flow (10 km) in the Auckland Volcanic Field. It was erupted from Mt St John about 75,000 yrs ago and flowed down a narrow valley, prior to the eruption of Mt Eden and at a time when the Waitemata Harbour was a forest-clothed river valley.

Of all the rocks and landforms in New Zealand, the Auckland Volcanic Field has been the most damaged by quarrying. This is because of its proximity to the country's largest and fastest growing city, Auckland. From early European times the scoria cones were seen to be easy sources for obtaining loose scoria for use on roads and as aggregate. Later it was realised that the basalt of the lava flows was much stronger and better for use on roads and for aggregate, but the scoria continued to be quarried for use as a cheap fill material and for quick draining requirements. As a result, quarries have been opened up on all but two of Auckland's scoria

9.77 Above: View north over Motukorea/Browns Island, in the Waitemata Harbour. This is one of the least modified volcanoes in the Auckland Volcanic Field. It contains landforms produced by the three styles of eruption - a tuff ring remnant arc (right) partly encircles the original explosion crater, which now has the main scoria cone in its centre. The main cone is surrounded by scoria mounds that have been rafted away from the cone on top of lava that poured out from around the cone's base. Some of the lava flows form the flat land in the foreground and on the left.

9.78 Below: Maungakiekie/One Tree Hill scoria cone, with its one intact and two breached craters, viewed from the southwest. This is the second-largest volcano in the Auckland Volcanic Field with 20 sq kms of rubbly lava-flow fields surrounding a large, complex scoria cone. Recent studies indicate that it erupted about 68,000 yrs ago.

9.79 Maungawhau/ Mt Eden, one of the most visited volcanoes in Auckland, erupted around 28,000 yr ago. Its cone is an elongate mound of two overlapping scoria cones. The deep basin-shaped fire-fountaining crater of the younger cone can be seen at the southern (left) end.

cones and at least 25 of the 57 cones have been largely quarried away, and many of the others badly damaged. Fortunately some far-sighted administrators, such as Sir George Grey, and benevolent landowners, like Sir John Logan Campbell, Alfred Sturges, George Winstone and Sir Ernest Davis, ensured that some of the volcanoes were placed in public reserves to protect them as iconic features for future Aucklanders.

9.80 Rangitoto's fiery display, about 600 years ago, was the only volcanic eruption in northern New Zealand that has been witnessed by humans. The remains of a small Maori fishing village has been excavated from beneath about 1 m of Rangitoto ash, on the shore of neighbouring Motutapu Island. Human and dog footprints in the soft wet ash, show that the local people were still present during or between some of the eruptions. Research results that suggest that Rangitoto may have had a number of small earlier eruptions are controversial and not widely accepted. Drawing by Chris Gaskin.

Box 40. DRYSTONE WALLS

Drystone walls are a characteristic heritage feature of the lava flow fields of the three youngest basalt fields in northern New Zealand – Auckland, Whangarei and Kaikohe-Bay of Islands. In these areas the rolling hills were naturally covered in fresh rocks, whereas the lava flows of the older volcanic fields are more weathered and ash-covered and the hills less stony. The other place in New Zealand with numerous drystone walls between paddocks is on lava flows on Otago Peninsula, Dunedin.

In many instances the earliest attempts to clear the stones from these hillsides and use them for cultivation was by pre-European Maori. After European colonisers arrived, these lava-flow fields were converted to grassy pasture for grazing stock. The loose stones were cleared by farmers and used for the construction of drystone walls between paddocks. These walls were built by immigrants using the techniques and styles developed back home in stony places like Wales and Cornwall. In the early 20th century many lava flow areas in Northland had their stones cleared and used in the construction of basalt walls by government-sponsored work teams.

Drystone walls are not cemented together with mortar but are held in place by the weight of the rocks and their careful interlocking construction. Although there are a number of distinctive styles, the basic construction of these walls is essentially the same. They are usually 1.2-1.5 m high, and twice as wide at the bottom as the top. Close-fitting stones are used for the inward-sloping sides and the internal cavity between is filled with smaller stones and a few longer stones that pass right through and hold both sides together. The largest stones are usually used in the base course with progressively decreasing size upwards. The better made walls have capping stones that may be laid horizontally or edgewise.

9.81 Top left: A drystone wall built from basalt rocks on the surface of lava flows from Pukepoto Volcano, Whangarei Volcanic Field.

9.82 Top right: Remnants of older, lichen-festooned basalt walls, which once bordered 19th century paddocks, can still be recognised in many parts of suburban Auckland, such as here in Onehunga. These areas are underlain by lava flows from the local volcano.

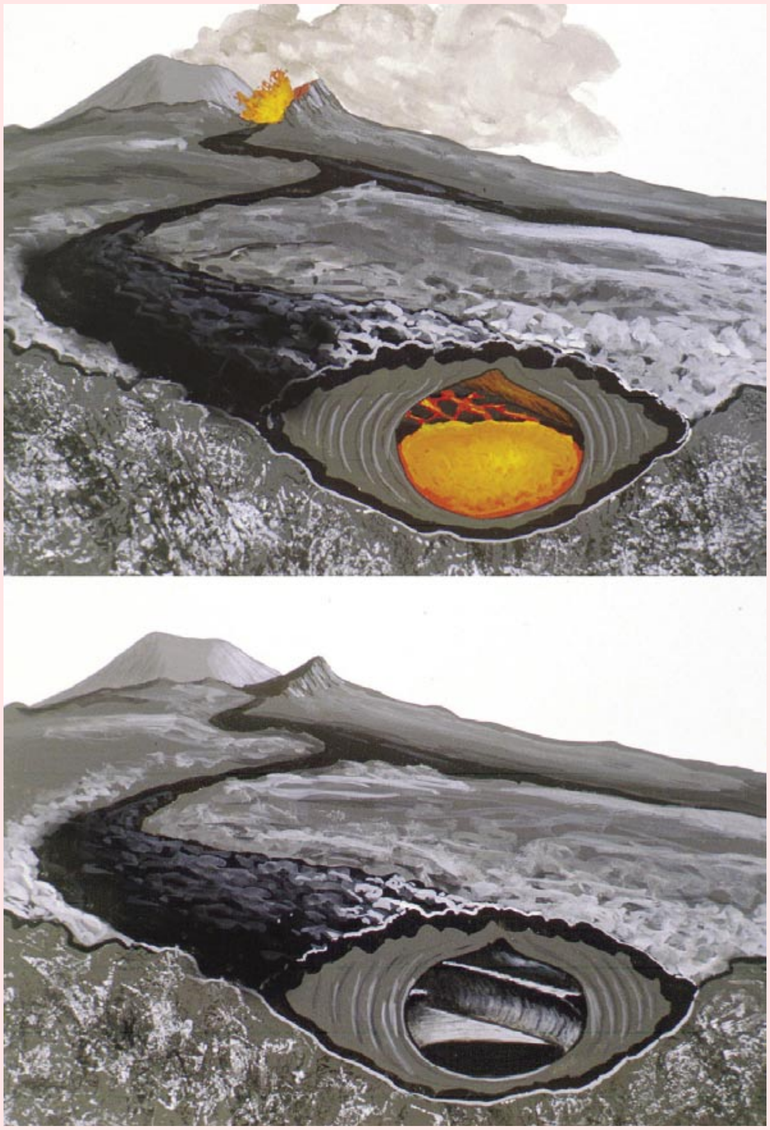
9.83 Bottom: A drystone basalt wall built from rocky rubble collected from the surface of young lava flows from Ngahuha Volcano in the Kaikohe-Bay of Islands Volcanic Field.

9.84 Profile of Rangitoto from Auckland, showing the gentle lower slopes of the lava-flow shield surmounted by the steeper main scoria cones. The youngest scoria cone forms the summit peak and has a substantial, 60 m-deep crater. Rangitoto is perfectly circular in plan view and has a 5 km diameter. It is by far the largest of Auckland's volcanoes, having erupted more lava than all the other volcanoes in the field combined.

Box 41. LAVA CAVES

In New Zealand, lava caves are only known in the Auckland Volcanic Field. About thirty substantial lava caves have been found, but many of these have now been sealed off by buildings or streets, filled with rubbish or quarried away. The most easily visited lava caves are on Rangitoto Island (*9.87*), signposted from the main walking track up to the summit. Other small lava caves occur within Ambury Regional Park and Otuataua Stonefields Reserve. Several privately-owned lava caves within a flow from Three Kings Volcano are occasionally open to visitors in guided groups.

Almost all lava caves form inside lava flows. As the molten lava flows away from the vent, it rapidly cools on the outside of the flow to form a solid crust of surrounding grey basalt. As the supply of molten lava ebbs, it drains from inside the flow, leaving an empty tube, or lava cave. The roofs of these caves have collapsed in a number of places, forming 'skylights', and access can be gained through these. Because of the roof collapses, most caves are not very long, with few exceeding 50 m.



9.85 Two cross-sections showing lava cave formation: Most lava caves form inside lava flows. The outside of the flow cools and solidifies, forming a crust of basalt around an internal tube filled with flowing hot lava. When the supply of lava stops, the molten liquid drains out leaving an empty tube or cave. Illustrations by Geoff Cox.

Box 41 continued

9.86 Inside Wiri Lava Cave, Auckland, with its unusual Gothic arch cross-section and surge benches on the walls. The ropey pahoehoe floor is the remnant of lava that did not manage to drain completely out of the lava flow feeder tube. Wiri is the longest (290 m) and best example of a lava cave in New Zealand. As a result it is protected within a scientific reserve and requires a permit for entry. Cave floor 2 m wide. Photographer Peter Crossley.

9.87 The most accessible lava caves for the public are those on Rangitoto Island. The main one is a narrow, straight, trench-shaped cave with several sections of collapsed roof that provide welcome light for those who come without a torch.

9.88 Some lava caves have short lava stalactites hanging from their roof, as seen here in Selwyn Rd Lava Cave, Onehunga. These were formed when extremely hot gas was trapped between the top of the flowing lava and the cave ceiling. The heat from the gas partially re-melted the basalt lining, giving it a glazed appearance. Photo 80 cm across.

Box 42. FOSSIL FORESTS BENEATH AUCKLAND'S VOLCANOES

All of Auckland's volcanoes, except Rangitoto and maybe North Head, erupted on land. Their eruptions would have devastated the native forest in the vicinity, setting it on fire or burying it with scoria and wet ash. The fossilised remains of some of these forests can be seen at Takapuna and near Auckland International Airport, Mangere.

Between Takapuna Beach and Thornes Bay on Auckland's North Shore, we see the moulds of the stumps of numerous small trees and a few large kauri that were engulfed by lava flows from Lake Pupuke Volcano, about 200,000 yr ago. Lava flowed through the forest to a depth of 1-2 m, cooling and solidifying around the trees' lower trunks, forming cylindrical moulds of 0.3-0.6 m-thick basalt. As the tree moulds formed, the surface of the flow also crusted over with solid basalt and in some places this is preserved as arches between stumps that are close together. Most of the fluid lava between the moulds and beneath the basalt roof subsequently drained away. Much of the solid basalt roof on top of the flow has disappeared, probably broken up and carried away by continued lava movement.

Elsewhere on Takapuna Reef and along the coastal track between Takapuna Beach and Thorne Bay we can also see hollow moulds of horizontal branches and trunks within the basalt lava flows. These were trees that collapsed into the moving lava and were rafted along within the upper parts of the flows. Their shape was captured in the rapidly cooling basalt lava, before the wood slowly incinerated away. A little later, the Takapuna lava flows and tree moulds were buried by 3-5 m of orange-brown volcanic ash. They remained buried, and therefore protected from weathering, until the last few thousand years. Since then they have been exhumed by coastal erosion, which has removed the soft ash but not the harder basalt.

On the coast of the Manukau Harbour near Auckland International Airport (at the end of Renton Rd) are the fossilised remains of two ancient forests (see also *12.27*). Both grew during cooler times in the ice ages, when sea level was lower than at present and the Manukau Harbour was a broad, forested valley draining out past Whatipu to the coast. The remains of the younger forest can be seen in the coastal cliffs. They consist of scattered tree stumps and lower trunks still in growth position, and broken-off branches that are buried and preserved by volcanic ash from nearby Maungataketake Volcano (Elletts Mountain) that erupted about 90,000 yr ago. Wood in the lower layers of volcanic ash, has remained waterlogged since burial and consequently has not rotted away. Ground water levels have obviously dropped below the level of some of the branches buried closer to the surface within the layered tuff, as their wood is now badly rotted or gone, leaving hollow moulds behind.

9.89 Above: Lava flowing through a forest created these cylindrical, basalt moulds of the lower trunks of many small trees. The passing lava cooled and solidified rapidly around the cold tree trunks and the remaining, still-molten lava flowed on, leaving the moulds upstanding. The moulds have hollow insides where the original wood slowly burned away. Over 200 of these tree moulds form most of Takapuna Reef beside the boat ramp car park. This is New Zealand's best example of a fossilised forest preserved in lava.

9.90 Right: This is the fossil mould of a kauri tree trunk at Takapuna Reef. The tree must have fallen into the molten lava flow and its shape captured by the cooling and solidifying basalt before the wood had time to burn away. The forest was growing here around 200,000 yr ago, at a time when sea level was considerably lower than at present.

Box 42 continued

9.91 Left: This tree was partly pushed over and lost its top during early base-surge blasts of volcanic ash and gas from nearby Maungataketake Volcano, Mangere. It was subsequently buried by layers of ash. In recent decades, coastal erosion of the cliffs of tuff (hardened ash) has uncovered this in-situ tree trunk near the steps down to the beach at the end of Renton Rd, Ihumatao.

9.92 Right: Fossil leaves of rimu trees that were growing at Ihumatao when Maungataketake Volcano erupted about 80,000 yr ago. The initial explosive blasts stripped the leaves from the branches. They fell to the ground and were buried and fossilised in the lower layers of volcanic tuff. Photo width 6 cm.

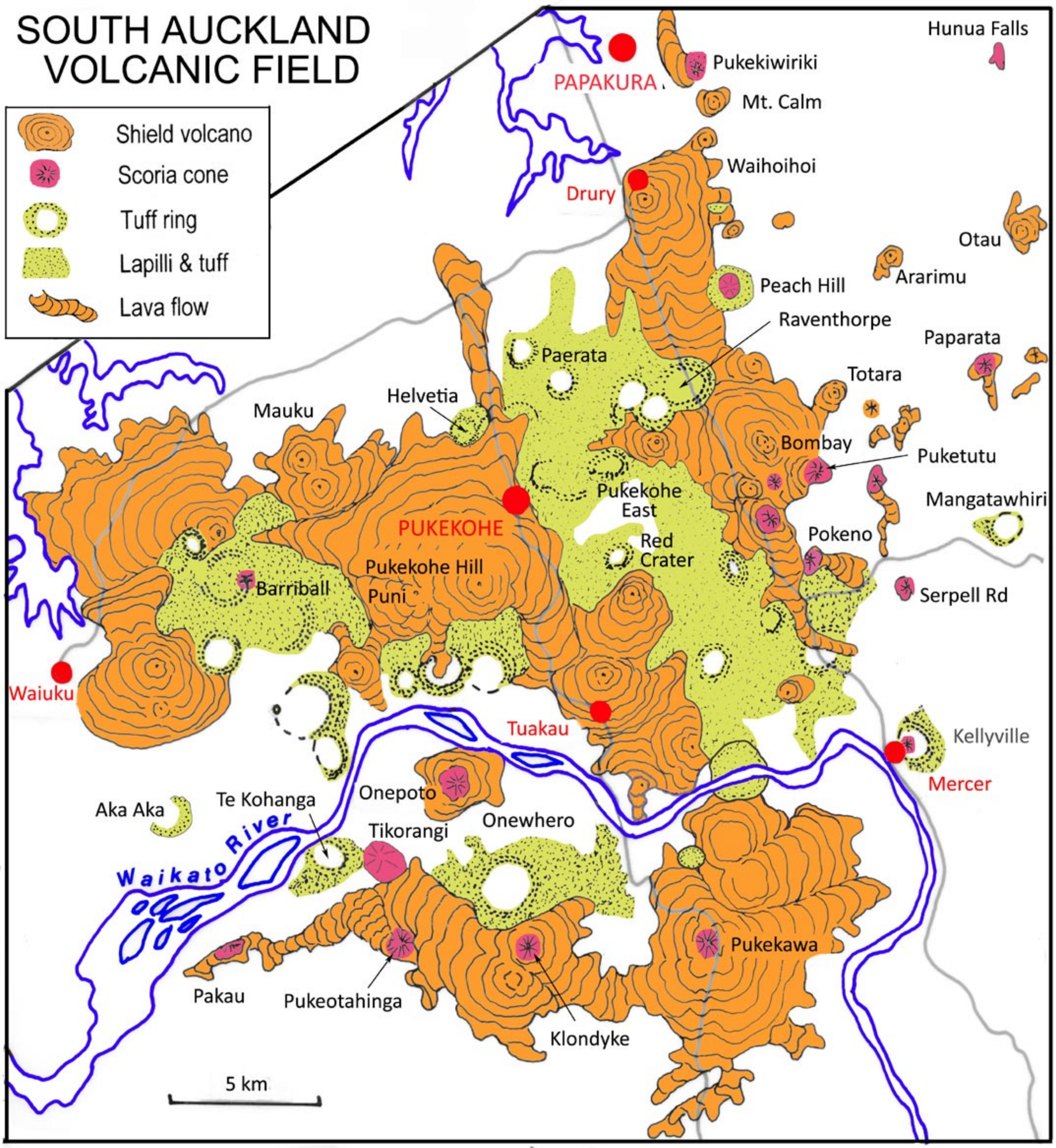
SOUTH AUCKLAND VOLCANIC FIELD

The South Auckland (sometimes called Franklin) Volcanic Field contains at least 82 volcanoes that erupted over a span of about a million years, between 1.6 and 0.5 Myr ago. This field stretches from Papakura in the north to Pukekawa in the south, on the south side of the Waikato River, and from the Hunua Falls in the east almost to Waiuku in the west - an area of nearly 300 km^2. Some geologists speculate that whatever caused the partial melting of the upper mantle beneath the South Auckland Volcanic Field, migrated northwards between 0.5 and 0.2 Myr ago to then erupt as the Auckland Volcanic Field.

Because the South Auckland volcanoes are older than those erupted in Auckland and the later phases of the Whangarei and Kaikohe-Bay of Islands fields, they are more eroded and weathered and a little more difficult to recognise. There is no basalt scattered over the surface of the lava fields and thus drystone walls, so typical of the other basalt lava fields, are absent. The scoria of the cones is deeply weathered and the cones themselves more rounded than those further north and their craters are generally partly filled and less distinct. The explosion craters have been filled with sediment (*9.95*) and none remain as lakes and in many instances their surrounding tuff rings have been partly removed by erosion. This is particularly true on the lowland areas around the Waikato River, where the meandering river has left only partial tuff-ring arcs from the original circular tuff rings.

Many of the volcanoes in the eastern part of the South Auckland Field, erupted along fault lines (e.g. Wairoa and Drury faults) through the greywacke uplands of the western Hunua Ranges (*9.93, 9.99*). Being at a higher elevation, these flows and scoria cones have been subjected to more erosion than those that form the low divide between the Manukau and Waikato lowlands. The largest, and perhaps

9.93 Looking south along the Drury Fault, which forms the boundary between the Manukau lowlands to the west and the uplifted basement greywacke rocks of the Hunua Ranges to the east. This North-South-oriented fault line appears to have acted as a conduit for the rise of some of the basalt magma of the South Auckland Volcanic Field. As many as ten volcanoes erupted along the Drury Fault (mostly between 1.3 and 1 Myr ago) from Red Hills at Papakura in the north to Pokeno scoria cone in the south.



9.94 Map of the South Auckland Volcanic Field. Adapted from Briggs et al. (1994) and Nemeth et al. (2012).

youngest (600,000 yr old) of these volcanoes in the east, is the Bombay shield volcano that forms the Bombay Hills, traversed by all who travel between Auckland and Hamilton. The effusive centres of this shield volcano, from where most of the lava flows were sourced, are the small twin conical peaks clearly seen to the east of Collison Crossroads motorway interchange.

Most of the volcanoes in the Hunua Ranges are older than 1 Myr, whereas all those to the west and south in the Manukau lowlands and around the Waikato River are less than 1 Myr old. The one exception is the large Kellyville Explosion Crater at Mercer, which has been

9.95 Top left: Kellyville is the oldest explosion crater (1.5 Myr old) in the South Auckland Field. Deposits of cream diatomite can be seen in road cuttings near the centre of the crater. The diatomite (composed of the silica skeletons of microscopic alga called diatoms) accumulated on the floor of the freshwater crater lake, before the surrounding tuff ring was breached and eroded away on its western side by the Waikato River at Mercer.

9.96 Top right: Note the piece of fossil leaf (left) in the close-up photo of this 10 cm piece of diatomite.

9.97 Pukekohe East explosion crater, beside the road from the Bombay Hills to Pukekohe, is the deepest and best-preserved volcanic crater in the South Auckland Volcanic Field.

dated at about 1.5 Myr old.

Explosion craters and tuff rings are more common in the South Auckland Field than in the other northern basalt fields. Many of them occur in the Manukau lowlands area, which is underlain at shallow depth (100-150 m below the surface) by a major near-horizontal aquifer - the Kaawa Shellbeds. It is inferred that it was the rising magma interacting with water in this aquifer, which was responsible for the many explosive eruptions. Of the 38 recognised explosion craters, the widest is Onewhero Crater (2.7 km across, *9.103*), located south of the Waikato River. The deepest and most obvious is East Pukekohe Crater (70 m deep, *9.97*), which blasted its way through lava flows from the Rutherford Rd shield volcano.

The South Auckland Volcanic Field has more shield volcanoes than all the other northern basalt fields combined. Of the forty lava shields identified, the largest are Pukekohe Hill (*9.102*), Waiuku, Mauku, Bombay and the three Pukekawa shield volcanoes. Many of the shield volcanoes might have had low levels of dissolved gas and had no fire-fountaining eruptive phase, but some in the south did and are capped by scoria cones. The most prominent scoria cones include Pukekawa (*9.98*), Klondyke Rd, Pukeotahinga (*9.101*), Tikorangi and Onepoto (*9.100*) - all located south of the Waikato River.

9.98 Pukekawa Hill, on the south side of the Waikato River, is the best-preserved and one of the youngest (500,000 yr old) scoria cones in the South Auckland Volcanic Field.

9.99 The Hunua Falls cascade over the edge of a hard basalt plug that fills the original throat of a 1.3 Myr-old volcano. Most of the erupted scoria cone above has since been eroded away. The magma rose to the surface along the Wairoa Fault – the only known active fault in the Auckland region.

9.100 Onepoto Volcano, located on the south bank of the Waikato River, is a prominent, 650,000 yr-old shield volcano, capped by a scoria cone.

9.101 850,000 yr-old Pukeotahinga scoria cone forms one of the highest points on the ridge to the south of the lower Waikato River, within the South Auckland Volcanic Field.

9.102 Pukekohe Hill shield volcano is the largest and most prominent of the forty identified shield volcanoes in the South Auckland Volcanic Field. It erupted about 550,000 yr ago.

9.103 Onewhero, south of the Waikato River, is the largest explosion crater (2.7 km across) in the South Auckland Volcanic Field. It is surrounded by a low tuff ring and the crater floor is flat, having been a lake that has filled up with sediment. It has been dated at about 900,000 yr old.

10. BLOCK FAULTING, OLD RIVERS AND VOLCANIC ASH
(last 5 Myr)

Chapter Summary

Northern New Zealand exists today because the region has experienced a further period of tectonic deformation in the last 5 Myr, mainly during the Pliocene (5.3-2.6 Myr), but extending into the Pleistocene (last 2.6 Myr). This has uplifted most of the areas that are now eroding land. Fault-bounded tectonic blocks of various sizes have moved up and down. The elevation and angle of the partly eroded Auckland Erosion Surface that can still be seen on top of many blocks, indicates how much each has been uplifted. The west-tilted Hunua and east-tilted Coromandel blocks might have been uplifted by a narrow bulge on the top of the mantle before deep-seated extension that created the Hauraki Rift, which has subsided up to 2.5 km in the last 3 Myr. Some of the faults around Auckland and the Hauraki Rift (e.g. Kerepehi, Wairoa, Drury, Port Waikato, Firth of Thames faults) are considered to be still active and their ruptures are a possible source of infrequent earthquakes. Hot springs in this southern region (e.g. Parakai, Waiwera, Miranda, Te Aroha) are fed by warm water that flows rapidly up to the surface through fractured rock along the block-related faults. Soda springs, some with travertine deposits, occur sporadically in Northland.

Prior to subsidence of the Hauraki Rift, rivers flowed west from the Coromandel volcanoes through down-faulted corridors in the uplifted Hunua greywacke block, depositing sediment in estuaries and a shallow embayment, now occupied by the Manukau Harbour and Lowlands. These sediments contain fossilised bracket fungi and dozens of different kinds of fossil fruit and seeds, many from plants now extinct in New Zealand.

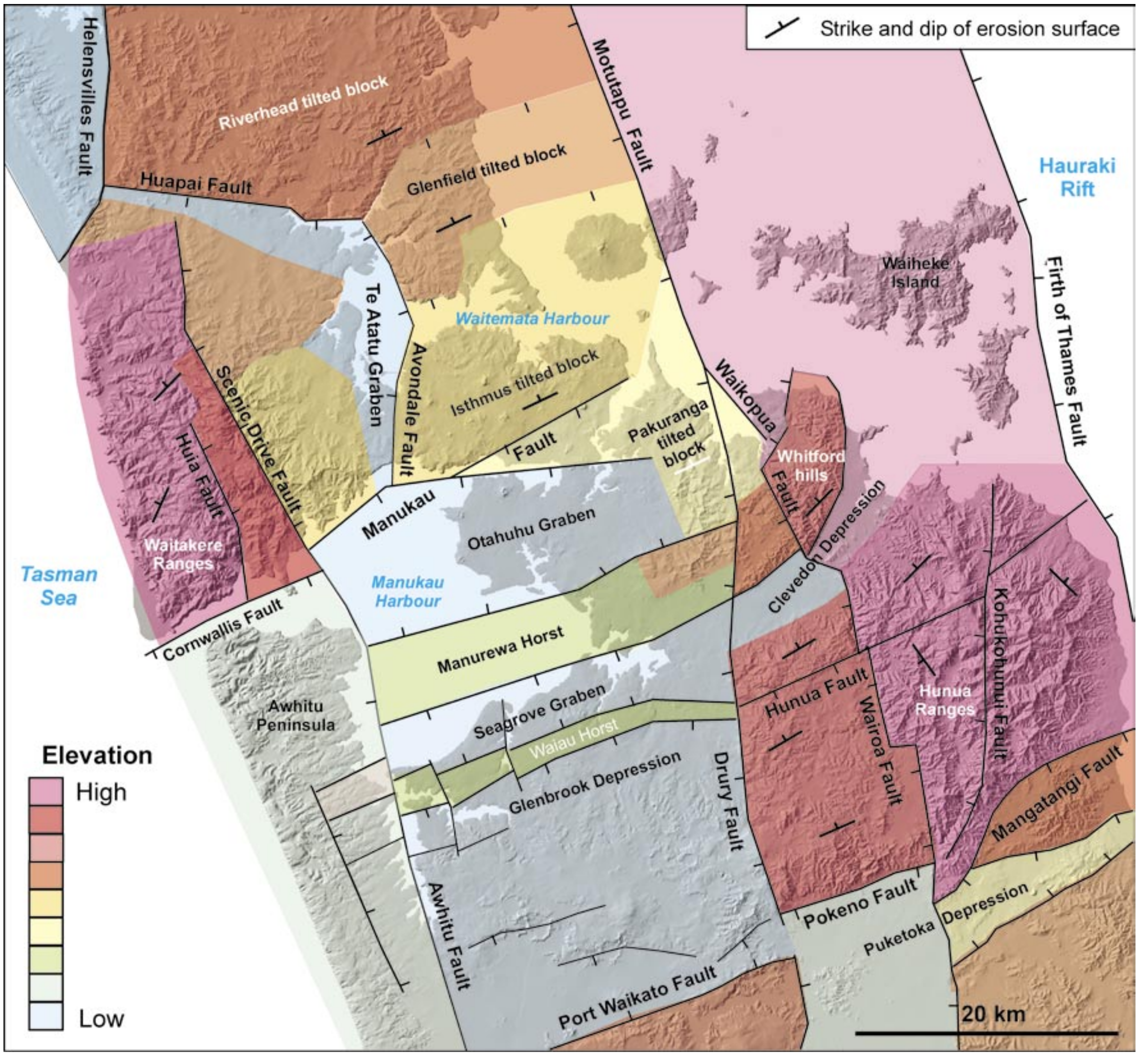
On numerous occasions in the last 1.5 Myr, the southern part of the study region has been mantled by rhyolitic and andesitic volcanic ash blown north from eruptions in the Taupo Volcanic Zone and from Mt Taranaki. The thickest ash deposits and several huge ignimbrite flows that reached Auckland and Coromandel regions were erupted from large caldera volcanoes, the oldest of which are now buried by more recent eruptions from Taupo and Okataina calderas. Fossil forests killed and buried by the largest eruptions, about 1 Myr ago, can be seen around Auckland.

The existence of Northland, Auckland and Coromandel Peninsula as land today is primarily a result of tectonic uplift that has occurred in the last 5 Myr or so, since formation of the extensive Auckland Erosion Surface during the stable Middle-Late Miocene interval (15-5 Myr ago, described in chapter 8). This interval of uplift has often been called block faulting, because a number of large, fault-bounded blocks (tens of kilometres across) were uplifted or downthrown to different levels in the Auckland region.

Auckland

The pattern of block faulting around Auckland City (*10.1*) is quite complex, but is dominated by two sets of faults more or less at right angles to each other – one set is oriented north-north-west parallel to the Northland Peninsula and the other set is oriented east-north-east. The main NNW-trending faults are (from west to east):
1. the Scenic Drive-Awhitu Fault with uplift of the Waitakere Ranges and Awhitu Peninsula on the west side and downthrow of the Auckland isthmus and Manukau lowlands on the east side;
2. the Drury-Motutapu Fault with uplift of the basement greywacke on the east side (Motutapu, Whitford hills, Hunua Ranges) and the lower level Auckland isthmus and Manukau lowlands on the west side;
3. the Firth of Thames Fault as the western boundary of the Hauraki Rift, with the Rift downthrown on the east side and Hunua Ranges greywacke uplifted on the west;
4. a secondary Avondale Fault has a similar alignment and has downthrown the small Te Atatu Graben on its western side. This 30-60 m deep basin filled with rhyolitic lake sediment and peat during the Pleistocene about 1 Myr ago.

The main ENE-trending faults are (from south to north):
1. the Port Waikato Fault that uplifts the greywacke basement (Murihiku Terrane) and Tertiary cover rocks on the south side and downthrows the Manukau lowlands on the north. The Waikato River makes an abrupt change in its course to follow this fault line westwards out to the Tasman Sea;
2. the Pokeno Fault is parallel to the Port Waikato Fault but has the opposite throw across it, with greywacke basement (Waipapa Terrane) upfaulted on its northern side to form the Hunua Ranges;



10.1 Map of greater Auckland showing how it has been cut by numerous, mostly NNW- and ENE-trending faults during the Pliocene and Pleistocene (last 5 Myr) with blocks being uplifted or sometimes downthrown to various elevations. The formerly flat erosion surface on top of each block has been tilted in various directions, often to the northwest (modified after Kenny 2013a, b).

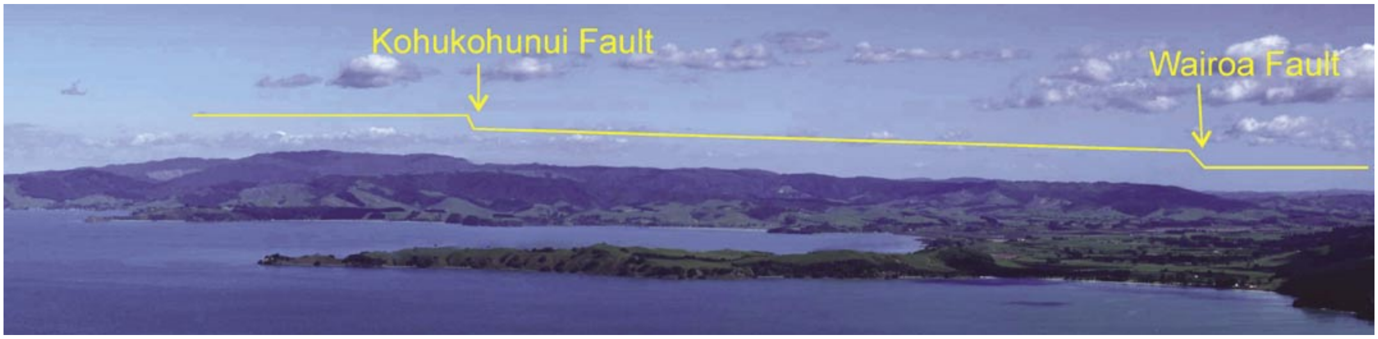
3. a series of ENE-trending secondary faults that cut the Manukau lowlands into ENE-trending slices – the higher ones are the Manurewa and Waiau horsts separated by downfaulted grabens. These horsts and grabens are all now buried below sea level and have been recognised under the ground by drilling and remote-sensing techniques;
4. the Manukau and Cornwallis faults with the Waitakere Ranges and Auckland isthmus uplifted on the north side and Manukau lowlands downthrown on the south side;
5. four northwest-tilted, uplifted blocks of Waitemata Sandstone (Pakuranga, Isthmus, Glenfield, Riverhead) can be recognised through east and central Auckland by the elevation of the near flat-lying erosion surface on top of them. Each block is uplifted higher along its southern edge and dips down to the northwest with most streams flowing northwards towards the next fault-angle depression.

Uplifted Waitakere Ranges

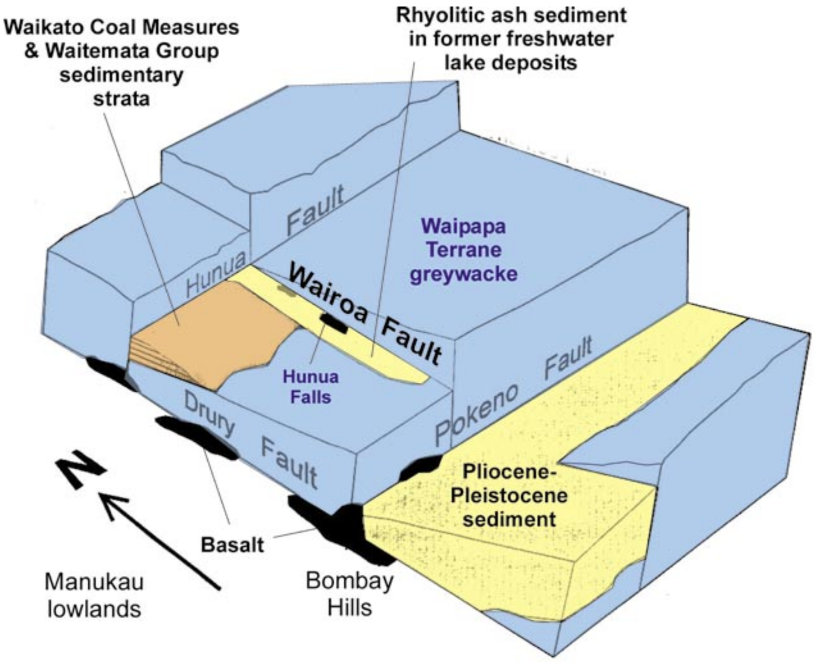
The highest part of the uplifted erosion surface in the Waitakere Ranges is Te Toi-o-Kawharu, at 474 m above sea level. From here the flat surface on the ridge crests tilts down to the west and northwest. It is also down-faulted 100 m to the east along a secondary NNW-trending fault that runs along the Huia Valley (*8.5*). The steep eastern slopes of the Waitakere Ranges between the Scenic Drive and Henderson are the eroded scarp of the Scenic Drive Fault. The ranges also have steep slopes along the eroded Cornwallis Fault scarp in the south, but with the tilt to the northwest there is no obvious fault forming a topographic scarp in the north.

Uplifted Hunua Ranges

The west-tilted erosion surface on the ridge crests of the uplifted Hunua Ranges rises to an elevation of 688 m (Kohukohunui) (*10.2*) and is underlain by basement greywacke exposed by erosion of up to 800 m



10.2 Oblique aerial view southwards over the Hunua Ranges showing its smooth, skyline crest that is inferred to be the remnants of the Auckland Erosion Surface that has been uplifted and tilted by block faulting in the last ~5 Myr. Note how the surface is dropped down to the west (right) in two steps by NNW-trending faults. Up to 800 m of Waitemata Sandstone was removed from on top of the Hunua basement greywackes as the erosion surface was being cut between about 17 and 5 Myr ago. Duders Peninsula is in the foreground.



10.3 Schematic diagram, viewed from the southwest, of the main fault blocks that comprise the Hunua Ranges today, showing how they have been uplifted and tilted relative to each other. Note that the Drury, Wairoa and Pokeno faults have been pathways for rising basalt magma within the South Auckland Volcanic Field, when it was active 1.5-0.5 Myr ago (chapter 9). Young sediment (yellow) has been deposited in the fault-angle depressions of some tilted blocks.

of soft Waitemata Sandstone. The surface may, in part, be approximately the exhumed erosion surface that predated deposition of the Waitemata rocks in the Early Miocene. The NNW-trending Wairoa Fault cuts through the Hunua block and Whitford hills with approximately 100 m more uplift of the greywacke on the east side (*10.3*). West of the Wairoa Fault, there are two significant smaller blocks separated by the ENE-trending Hunua Fault. Both these blocks are uplifted more in the southeast and tilt down towards the north and west. Some of the Tertiary cover rocks (Drury Coal Measures and Waitemata Sandstones) are preserved on top of these north-tilted blocks in the vicinity of the Hunua Gorge and Ardmore hills. A thick sequence of rhyolitic ash deposits has accumulated in former freshwater lakes in the fault-angle depression along the west side of the Wairoa Fault, south of Hunua township. Volcanic vents occur at the surface on the Drury, Wairoa and Pokeno faults (*9.93, 9.99, 10.3*) where basalt magma of the 1.5-0.5 Myr old South Auckland Volcanic Field has risen to the surface up these planar zones of crushed rock.

Coromandel Peninsula

The Coromandel Range and Great Barrier Island form an elongate uplifted block or blocks that include the three highest peaks in northern New Zealand – Mt Moehau (892 m), Table Mt (846 m) and the Camels Back (822 m). The most obvious question is how much of the elevation has resulted from tectonic uplift and how much remains from the volcanic cones that were erupted here?

10.4 On a clear day, Mt Moehau (892 m) on the northern tip of Coromandel Peninsula is easily seen on Auckland city's eastern skyline. It is the highest point in northern New Zealand and was mostly uplifted to this elevation in the last 5 Myr or so. All the volcanic rocks that were erupted on top of it have been eroded off.

The northern tip of the peninsula has been elevated the most, at least 1000 m on the western side, and tilted steeply down to the east. The top of the Moehau Range (*10.4*) is made of basement greywacke with almost all of the overlying Early Miocene volcanic rocks stripped off from above, although they are present at sea level downslope on the east coast. Table Mt and the Camels Back are formed from 12-7 Myr old volcanic rocks, but their original elevation is unknown and therefore so is the amount of uplift. Between Thames and Coromandel, basement greywacke occurs above sea level and the volcanic sequence has a general tilt down to the east, as does the topography east of the main divide (*8.10*). This suggests that the central part of the Coromandel Range was also pushed up 500 or more metres on its western side and tilted eastwards maybe with some subsidence out east of the peninsula.

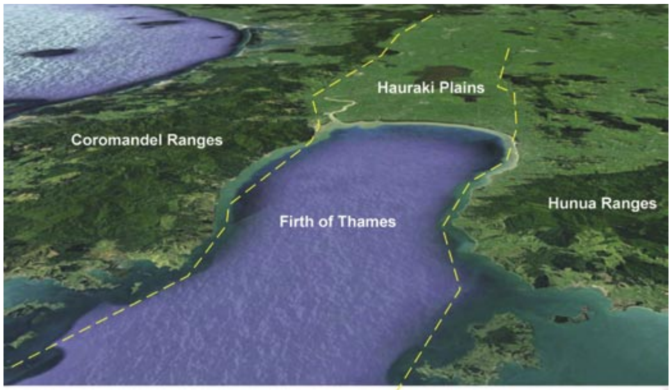
There are several near-flat ridges on the crest of the southern Coromandel Ranges between Paeroa and Waihi that might be coastal or fluvial erosion surfaces that were cut into the 8-7 Myr old volcanic rocks near sea level. These too suggest that the eastern side of this part of the range was also uplifted, perhaps by 400-500 m and down-tilted slightly to the east. While evidence for eastwards tilt of Coromandel Peninsula is widespread it is not universally true. On Kuaotunu Peninsula on the northeast side of the peninsula, a block of basement greywacke has been upfaulted to over 200 m above sea level and most of the overlying volcanic rocks eroded off.

On Great Barrier Island, the northern end has been uplifted by more than 500 m as greywacke has been moved up to at least this height. Most of the rest of the island is made of volcanic rock and has presumably experienced far less uplift. The 350-m-high, flat-topped Te Ahumata Plateau is thought to be the remnant surface of a Late Miocene ignimbrite flow and sinter terrace, but how much it has been uplifted, if at all, is not clear.

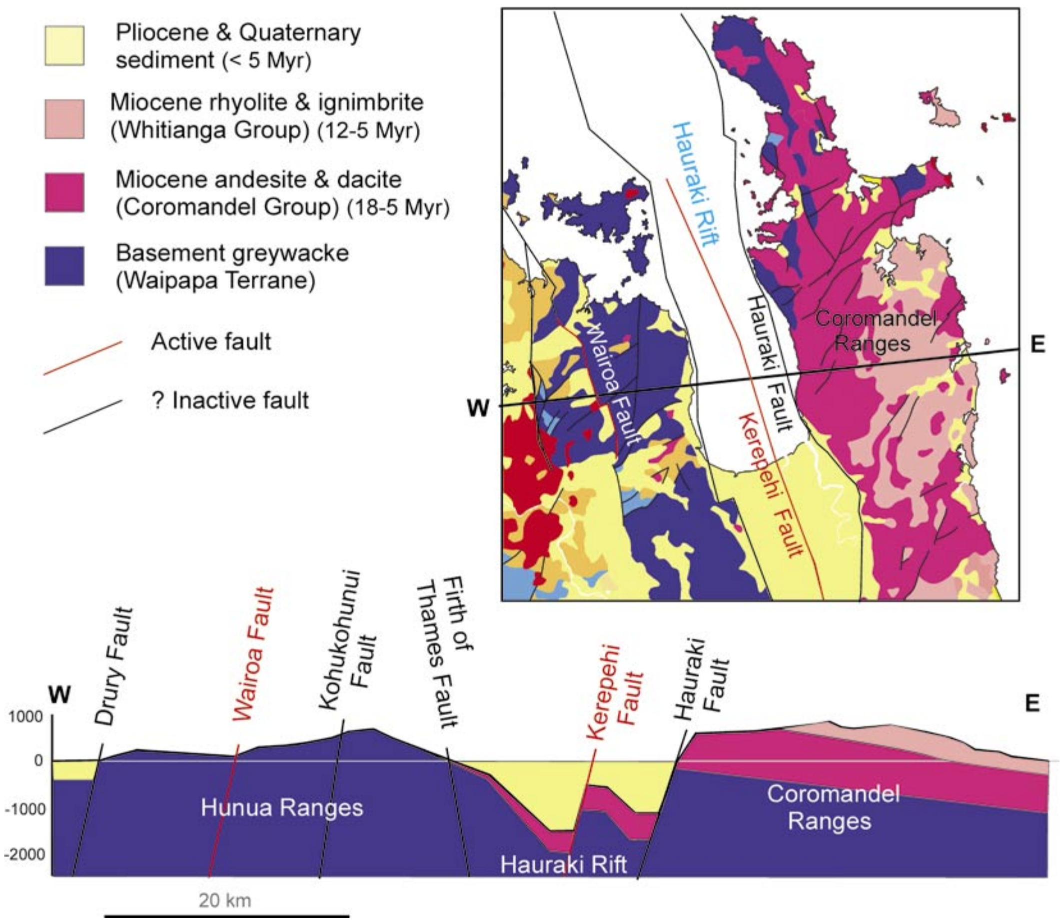
Hauraki Rift

The Hauraki Rift is a 250 km-long elongate depression comprising the Hauraki Gulf, Firth of Thames and Hauraki Plains, located between the uplifted Coromandel Ranges and Hunua Ranges (*10.5*) and extending north as far as Whangarei. It is bounded to the east by the Hauraki Fault and to the west by the Firth of Thames Fault. One, and in some places two, normal faults run up the middle of the rift and divide it into 2 or 3 subsided half grabens, each tilted to the east (*10.6*). These grabens have subsided to varying depths, with a maximum depth of 2.5 km under the eastern Firth of Thames.

The Rift is believed to have formed as a result of deep-seated, east-west extension, which is slowly pulling the two sides apart. As a result, the rift's floor is subsiding along several normal faults. A driver for the Hauraki rifting could be the oblique angle of subduction of the Pacific Plate beneath the Australian Plate, which is also causing the rifting apart of the Taupo Volcanic Zone.



10.5 View southeast down the central and southern parts of the Hauraki Rift (flanking faults shown dashed) from above Waiheke Island. These parts of the rift are currently occupied by the shallow Firth of Thames (centre) and Hauraki Plains (distance). Photo from GoogleEarth.



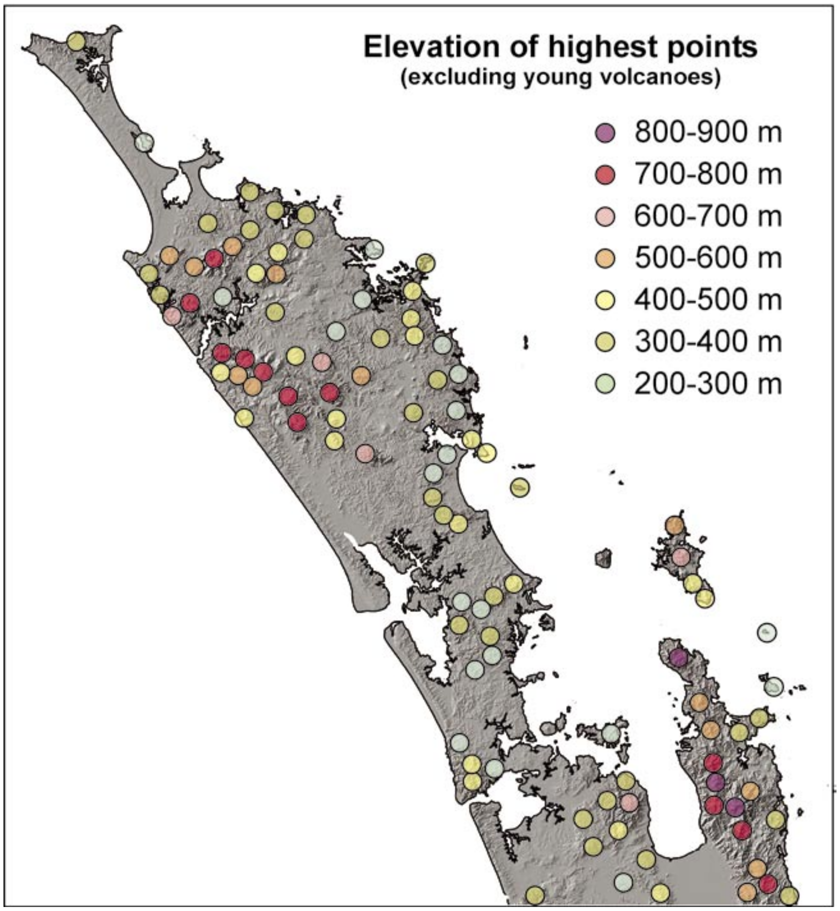
10.6 West to east cross-section (W-E) through the uplifted Hunua Ranges, subsided Hauraki Rift and uplifted Coromandel Range. The depth and structure in the Hauraki Rift has been determined by remote sensing techniques. Modified from Hochstein and Ballance (1993).

Onset of the Hauraki rifting about 3 Myr ago was preceded by upward arching of the crust along the same north-south-oriented belt (back-arc zone), parallel to, and west of the Coromandel Volcanic Zone. The rocks that underlie the Rift today are anomalously hot compared with surrounding areas, and support the inference that an elongate bulge of hot mantle may have pushed up the crust prior to the start of rifting. Maybe the enigmatic dacite eruptions of Little Barrier, 3 and 1 Myr ago, in the middle of the Rift, were related to crustal melting above such a mantle bulge. Evidence of the crustal arch can be seen on either side of the Rift in the Hunua and Coromandel Ranges, which have been uplifted and tilted away from the crest of the bulge prior to the rifting.

As the rift foundered it was progressively filled up with ignimbrite sheets and sediment that mostly flowed in from the southern end, as they do today. Vast amounts of sediment derived from the huge rhyolitic eruptions in the Taupo Volcanic Zone were carried into the head of the rift, especially prior to 22,000 yr ago, when the Waikato River course flowed into it via the Hinuera Valley. After that, the Waikato switched to its present course through Hamilton and out to the west coast at Port Waikato.

Northland

In Northland, there are numerous high-standing blocks reaching elevations of 300-800 m above sea level (*10.7*). All of these are composed of the harder, more erosion-resistant rocks (basement greywackes of the Caples and Waipapa terranes, Tangihua Complex and Waipoua Basalt). Most of the surrounding mosaic of low-lying land is composed of softer sedimentary rocks, mostly of the Northland Allochthon, but also the Otaua Group. The tops of some of the highest ranges retain remnants of former flat surfaces. Some of these may have been original flat tops on the giant slabs of Tangihua rocks, as they slid into Northland as the last phase of the Northland Allochthon, 23-21 Myr ago. The flat top of the Waima-Tutamoe Range is probably remnants of the gentle eastern slopes of the Waipoua shield volcano, which erupted 19-17.5 Myr old, whereas other flat tops in the east (e.g. on greywacke) may be remnants of the younger Auckland Erosion Surface, which had formed by about 5 Myr ago.



10.7 Elevation of the highest points of ranges throughout northern New Zealand, excluding the heights of young volcanic landforms. Most of these heights record how high the erosion surface has been uplifted in each area.

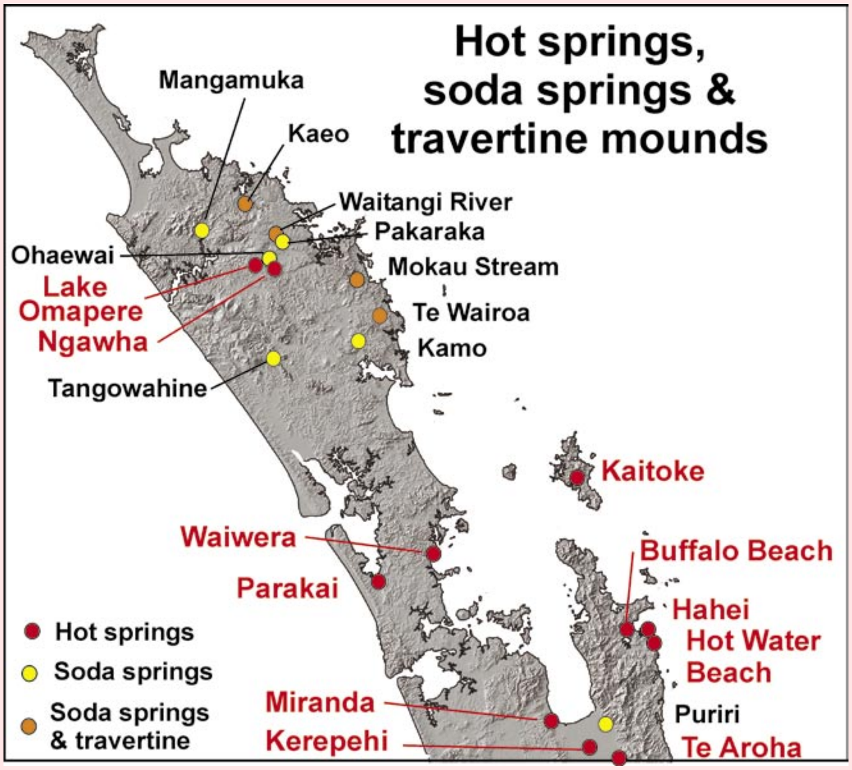
Remnants of the erosion surfaces are only seen on the tops of the higher blocks. This pattern suggests that pretty much all of Northland has been pushed up by tectonic forces since the surfaces were formed and that the softer rocks have lost 100-700 m off the top by erosion. Erosion has cut steep streams and gorges into the harder rocks of the higher blocks with the erosion surface remnants only remaining on ridge crests.

The elevation of the top of the basement greywacke rocks (*5.1*), suggests that the east side of Northland has been uplifted by 2000-3000 m more than the west, since the emplacement of the Northland Allochthon, 23-20 Myr ago. Today, however, the highest parts of Northland are in the northwest (*10.7*). The Tutamoe and Mangakahia ranges northwards through the Waima (*10.8*), Whirinaki and Warawara ranges to the Maungataniwha Range are the highest areas (700-800 m). Further east, the Omahuta-Puketi and Maungataniwha ranges reach elevations today of 500-600 m. Most of the basement greywacke belt forming a strip down the east side of Northland has been uplifted to elevations between 250 and 450 m, with highest points in the Russell forest, Bream Head and Brynderwyn Hills.

An explanation for this might be that most of the eastern uplift and westward tilting of Northland took place in the Early Miocene, prior to 16 Myr ago. As a result, a far greater thickness of softer cover rocks were eroded off the uplifted east side than the west during the Miocene. In the last 5 Myr or so, the whole of Northland may have been further uplifted by another 250-500 m, and the reason why the northwestern ranges are now the highest, would be because they are composed of more erosion-resistant igneous rocks. The dominance today of west-draining river catchments in Northland and northern Auckland (e.g. Hokianga, Wairoa, Kaipara), is probably inherited from the Early Miocene phase of regional tilting.

10.8 Viewed from the east from the Kaikohe to Opononi Rd, the 600-700 m-high, flat top of the Waima Range is clearly evident. The range has been uplifted and tilted gently to the southwest. The flat top is probably the partly-dissected, lower eastern slopes of the Waipoua shield volcano, that originally sloped in the opposite direction.

Box 43. HOT SPRINGS AND SODA SPRINGS



10.9 Location of all the hot springs and significant soda springs, some with travertine deposits, in northern New Zealand.

The Earth gets hotter the deeper one goes into it. Where the crust is not influenced by shallow magma, the temperature of the rock, and groundwater, riseshot at about 30°C for every km down. Most of the water discharged from hot springs in northern New Zealand, except Ngawha and Kerepehi, is probably background hot water from several kms down. It has rapidly risen to the surface up relatively open pathways of fractured rock (major fault planes), without having time to cool significantly on its way up. Hot water, being less dense than cold, will slowly rise to the surface, but in the case of these hot springs the hot water is probably at least partly artesian. This means the water is in a confined aquifer and is forced upwards by the pressure of cold water flowing down through the rocks from higher elevations some distance away.

Some of the hot springs are on well-known faults, such as those that bound the Hauraki Rift. Te Aroha Hot Springs are located above the Hauraki Fault and Miranda above the Firth of Thames Fault. Parakai Hot Springs at Helensville sit directly above the buried top of the Helensville Fault, which upthrows the land east of the Kaipara Harbour. The presumed faults that the hot water rises up to form hot springs at Waiwera, Hot Water Beach (*10.11*) and Kaitoke, Great Barrier Island (*10.10*), have not been recognised at the surface. In these instances the hot water is probably flowing up through older faults that cut the greywacke basement but may not have moved since the rocks on top of them were formed.

Ngawha, in central Northland, is different, as the hot water discharged there is heated by a shallow magma chamber, inferred to be a few kilometres below the surface (Box 38). Kerepehi Hot Springs, in the middle of the Hauraki Rift, are not located directly above the active Kerepehi Fault and may come up a lesser buried fault. Studies have shown that the Earth's crust is unusually hot beneath the Hauraki Rift, possibly because of an elongate dome of hotter mantle running along beneath it. This extra heat beneath the Rift probably explains the existence of the Kerepehi Hot Springs and may also be a heat source contributing to the temperature of the Miranda and Te Aroha springs on its flanks and be responsible for a number of other hot springs at the southern end of the Rift, around Matamata.

Because of the high subsurface pressures, the boiling point of groundwater at depth may be

10.10 Kaitoke Hot Springs, Great Barrier Island, are one of two hot springs in northern New Zealand that have not been commercialised. They are fed by hot water from depth that rises quickly to the surface probably up a buried fault in the basement greywacke.

Box 43 continued

raised so the water can reach temperatures higher than 100°C. At these elevated temperatures the groundwater may react more readily with the rocks through which it is flowing, dissolving minerals before it ascends to the surface. When the amount of dissolved mineral in a spring is sufficient to give the water a definite taste, it is classified as a mineral spring. Many of these springs also dissolve gas, often carbon dioxide, which is released as rising bubbles when the pressure reduces as the water approaches the ground surface.

There are thousands of cold freshwater springs that discharge clean fresh water to the surface. The exception in northern New Zealand are cold soda springs, named because they contain carbon dioxide gas producing "soda water". Soda springs usually discharge cold, mineral-rich, alkaline water rich in dissolved sodium carbonate. As the water is discharged carbon dioxide is released from solution resulting in an increase in pH. Carbonate solubility decreases with increased pH and thus carbonate in the form of travertine often precipitates around the soda spring vents (*10.12*). Four of the easternmost springs in Northland have built substantial travertine mounds (up to 4 m high; *10.13*) or terraces (up to 20 m across), where the water flows away from their discharge points. Travertine is a slowly-formed calcium carbonate ($CaCO_3$) or limestone rock deposited by mineral springs. It may have a fibrous texture and is usually white, cream or tan-coloured. The soda springs mostly occur in the eastern half of central Northland and therefore presumably have acquired their similar properties deep down within the greywacke basement rocks.

10.11 At low tide, visitors flock to Hot Water Beach, east Coromandel Peninsula, to dig shallow pools in the beach to immerse themselves in the thermal waters.

10.12 Travertine terracettes on the surface of a 4 m–high mound that has precipitated out of mineral waters discharged from Mokau Stream soda spring, inland Helena Bay, east Northland. Width of photo 50 cm.

10.13 3 m-high travertine mound that has built up over thousands of years around the Te Wairoa soda spring, inland Matapouri Bay, east Northland.

10.14 View east of the Karangahake Gorge, which was carved out of the rising Coromandel Range by the Ohinemuri River. Its west-flowing course has been inherited from a time 3-4 Myr ago when this part of the range was low lying and the river drained the lake filling the recently formed Waihi Caldera on the east side of the peninsula. Photo by Lloyd Homer, GNS Science.

Antecedent rivers

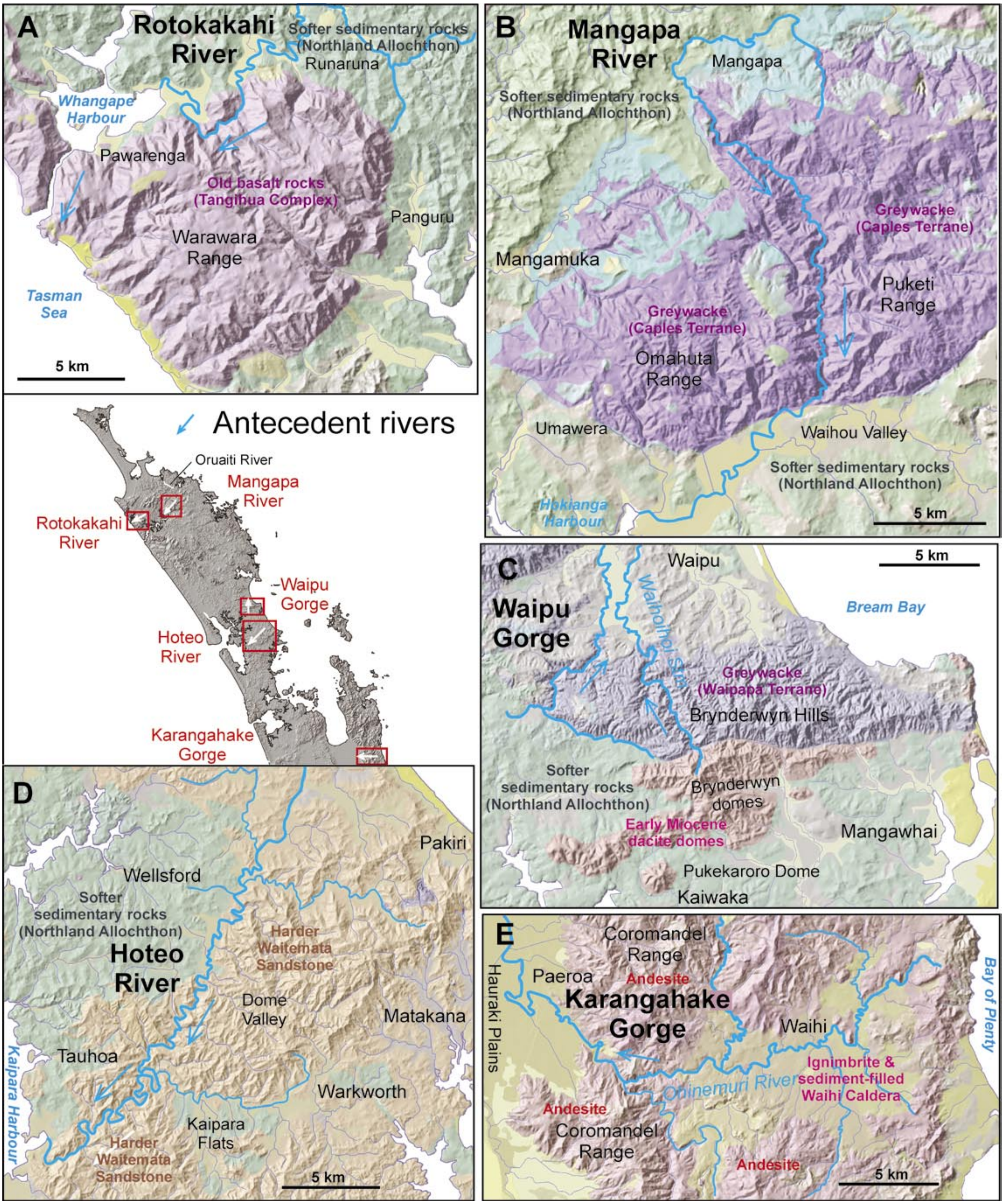
Antecedent rivers are those that retain their original course even though the topography around them has changed. For example, a river might erode into a slowly-rising ridge or mountain range, creating a deeply incised gorge rather than eroding a new course, in softer rock, flowing away from the rising ridge. Several antecedent rivers have carved deep gorges passing right through more recently uplifted blocks of hard rocks in Northland (*10.15*). The flow directions of these rivers are inherited from the topography that existed prior to the uplift.

For example, the Rotokakahi River has carved two 300 m-deep gorges from east to west through the hard Tangihua basalts of the uplifted Warawara Range (*10.16*). The eastern one is sinuous and retains this pattern from the time when the surface was a gently-sloping, near-flat surface with a meandering river flowing westward across it. The second gorge is now the flooded narrow entrance to Whangape Harbour (*11.45*).

Further east, the Mangapa River has eroded a 300-400 m-deep gorge from north to south right through the uplifted basement greywacke of the Omahuta-Puketi Range to flow into the head of Hokianga Harbour. The nearby Oruaiti River flows northward right through the eastern end of the uplifted Tangihua rocks of the Mangataniwha Range and into the Mangonui Harbour.

Another classic example of antecedent rivers is on the east side of Northland, south of Whangarei, where the Waipu River and Waihoihoi Stream have eroded 150-200 m-deep gorges from south to north right through the basement greywacke of the Brynderwyn Hills. Prior to uplift, these waterways must have flowed northwards across the gently sloping Auckland Erosion Surface that extended from at least Kaiwaka to Waipu.

10.15 Page opposite. Examples of antecedent rivers (highlighted in white) in northern New Zealand. These are rivers that have eroded gorges right through ranges of harder rock as they were rising. The rivers have inherited their flow directions from before the uplift. A. Rotokakahi River cut through Warawara Range; B. Mangapa River cut through Omahuta-Puketi block; C. Waipu River and Waihoihoi Stm cut through Brynderwyn Hills; D. Hoteo River cut through Kaipara hills; E. Ohinemuri River cut through southern Coromandel Range. Background colours show outcrop of different rock types as labelled.

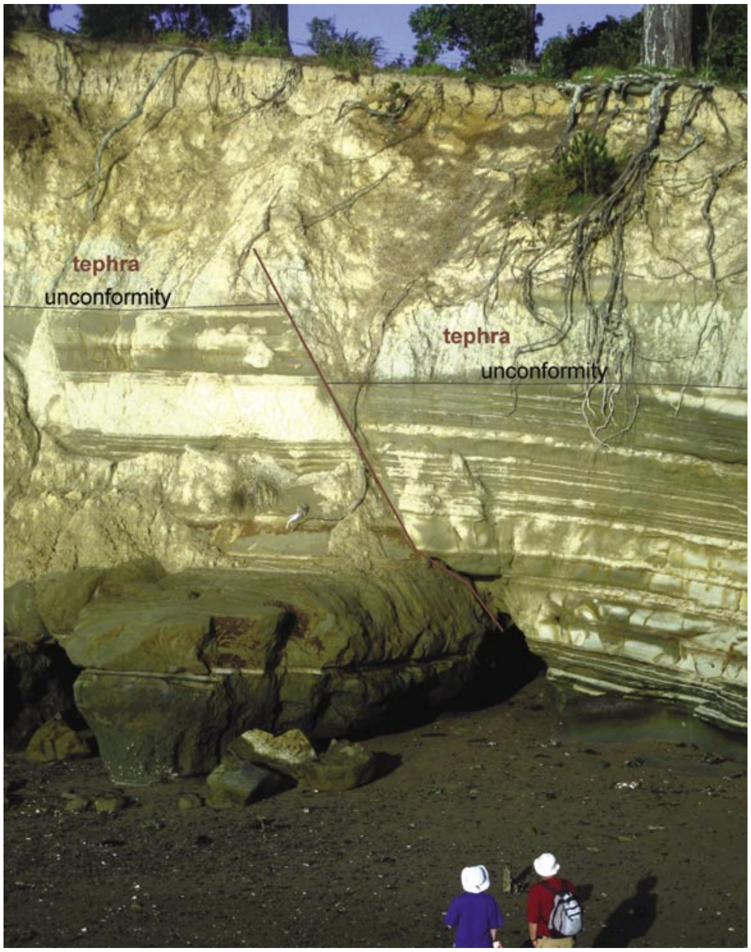

A
Rotokakahi River
Softer sedimentary rocks (Northland Allochthon)
Runaruna
Whangape Harbour
Pawarenga
Old basalt rocks (Tangihua Complex)
Panguru
Warawara Range
Tasman Sea
5 km
B
Mangapa River
Mangapa
Softer sedimentary rocks (Northland Allochthon)
Greywacke (Caples Terrane)
Mangamuka
Puketi Range
Greywacke (Caples Terrane)
Omahuta Range
Umawera
Waihou Valley
Softer sedimentary rocks (Northland Allochthon)
Hokianga Harbour
5 km
Antecedent rivers
Oruaiti River
Mangapa River
Rotokakahi River
Waipu Gorge
Hoteo River
Karangahake Gorge
C
Waipu
5 km
Waipu Gorge
Waihoihoi Stm
Bream Bay
Greywacke (Waipapa Terrane)
Brynderwyn Hills
Softer sedimentary rocks (Northland Allochthon)
Brynderwyn domes
Early Miocene dacite domes
Mangawhai
Pukekaroro Dome
Kaiwaka
D
Pakiri
Wellsford
Softer sedimentary rocks (Northland Allochthon)
Hoteo River
Harder Waitemata Sandstone
Dome Valley
Matakana
Tauhoa
Warkworth
Kaipara Harbour
Kaipara Flats
Harder Waitemata Sandstone
5 km
E
Coromandel Range
Paeroa
Andesite
Karangahake Gorge
Hauraki Plains
Waihi
Bay of Plenty
Ohinemuri River
Ignimbrite & sediment-filled Waihi Caldera
Andesite
Coromandel Range
Andesite
5 km

10.16 View southeast from the head of Whangape Harbour, northwest Northland. Here the Rotokakahi River flows through a sinuous gorge (on right) sliced deeply into the uplifted Tangihua basalt rocks of the Warawara Range, rather than through the soft rocks that form the low saddle on left. This course is said to be antecedent because it is inherited from a time before the Warawara Range was pushed up.

The Brynderwyn Hills and the previously buried Pukekaroro-Brynderwyn dacite domes to the south (*6.69, 6.70*) have been uplifted similar amounts (300-400 m above sea level). Erosion has occurred as this area was slowly rising and afterwards, removing much of the soft allochthon sedimentary rocks and volcanic ash, exhuming the buried domes and leaving the harder rocks of the Brynderwyn Hills fault block upstanding (*10.15*).

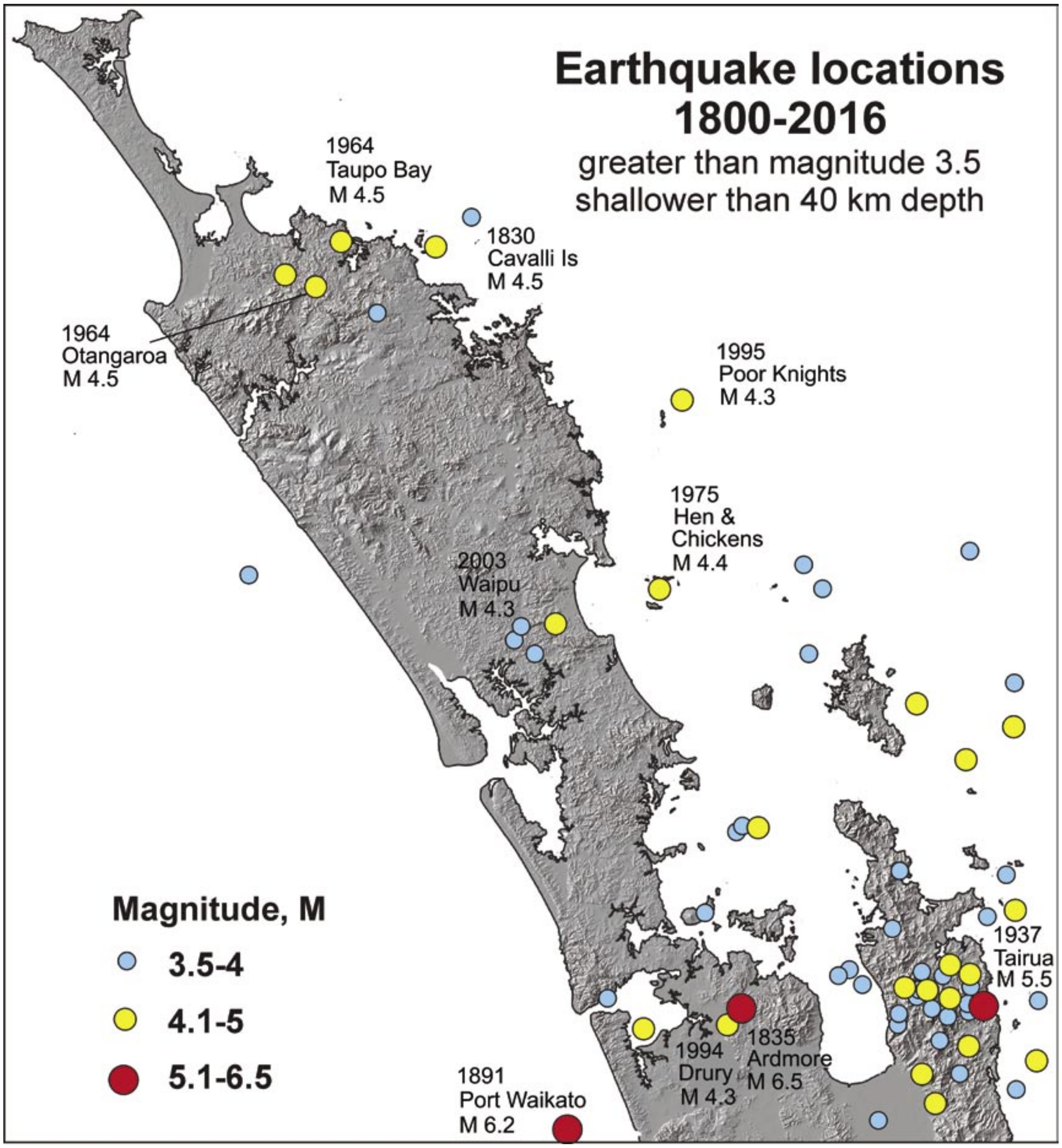
Further south, the Hoteo River (between Wellsford and Warkworth) flows southwest from its low elevation headwaters in soft allochthon sedimentary rocks between Wellsford and Pakiri Beach, through a 200 m-deep sinuous gorge eroded into Early Miocene Waitemata Sandstone to empty into the Kaipara Harbour. Once again, this antecedent river has inherited its meandering course from a time when the area was a low-lying, gently west-tilted plain. As the area was slowly uplifted, the river has incised vertically down into the sandstones, creating this sinuous gorge.

Another prominent antecedent river flows right through the southern Coromandel Ranges. Here the Ohinemuri River flows westwards from Waihi via the 300-500 m-deep Karangahake Gorge to the Hauraki Plains near Paeroa (*10.14*). The river drains the flat-floored Waihi Basin at an elevation of 100 m above sea level. Its logical drainage direction would be eastward over a 120 m-high saddle behind Waihi Beach, but instead it flows westward through the 400-500 m-high Coromandel Range. The course of the Ohinemuri



10.17 The Beachlands Fault is the best exposed example of a relatively young fault in the Auckland area. In the cliffs adjacent to Beachlands wharf it can be seen to displace an unconformity cut into the Waitemata Sandstones and a pre-Ongatiti rhyolitic tephra (slightly older than 1.2 Myr) by about 1.5 m (downthrown to the west – right side).

10.18 Location of historic earthquakes (since 1800) greater than magnitude M = 3.5, shallower than 40 km depth, in northern New Zealand. Data from Geonet, Dec 2016.



River is clearly inherited from a time when a large lake filled the Waihi Basin caldera and the older volcanoes to the west were lower than the slightly younger volcanic barrier to the east. The river provides compelling evidence that the Coromandel Range in this vicinity has been uplifted 300-500 m in the west and tilted down to the east in the last 4 Myr, since the Waihi Caldera was formed.

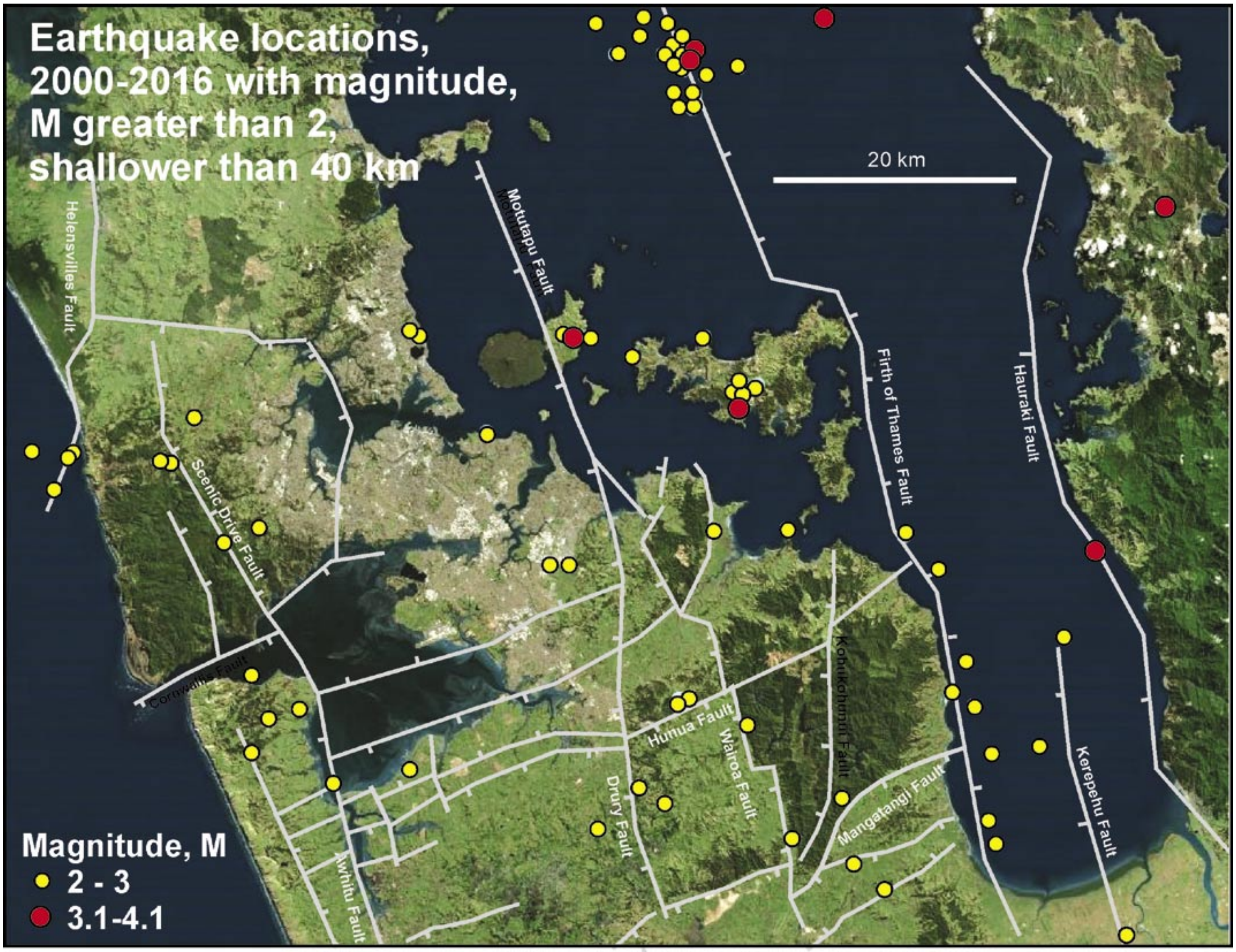
Timing of block faulting and tilting

The block faulting around Auckland appears to have started during the Pliocene and has probably continued through to the present-day. The ENE-trending grabens beneath the Manukau lowlands (*10.1*) were forming at the same time as they were being filled with 4-3 Myr old shallow marine and estuarine sediment. Some of the sediment was sourced from the Coromandel Volcanic Zone and transported by rivers through the Clevedon and Puketoka depressions (*10.1*). Thus the faults around the Hunua Block were already active before the Hauraki Rift started subsiding about 3 Myr ago. Other smaller depressions in the Tamaki Estuary valley, Shoal Bay and the Te Atatu Depression are filled with 2-1 Myr old (Early Pleistocene) lake sediments that suggest they also might not have been formed until after 3 Myr ago. The Wairoa Fault through the Hunua Block retains a fault scarp along part of its length that indicates that it moved not too many thousands of years ago and is potentially active. Also potentially active are the Motutapu, Drury, Firth of Thames and Port Waikato faults that have been the locus of earthquakes in recent times (*10.18, 10.19*).

The uplifted Coromandel Range and adjacent Hauraki Rift are possibly the youngest significant tectonic landforms in northern New Zealand. The northern end of both may have started moving in the Pliocene (or even Late Miocene), whereas uplift of the southern sector of the Coromandel Range and subsidence of the Hauraki Plains and Firth of Thames appear to have all occurred in the last 3-2 Myr. The Waiteariki Ignimbrite that forms part of the Kaimai Ranges next to the southern end of the Hauraki Rift has been displaced 1 km vertically across the Hauraki and Kerepehi faults in the last 2 Myr since it was erupted.

The Kerepehi Fault that runs through the centre of the Hauraki Plains is considered to be the most active fault in northern New Zealand, having last ruptured in a large earthquake about 5000 yr ago, with a lesser event about 600 yr ago. The other faults on the east and west sides of the Hauraki Rift are also potentially active. Recent high-resolution GPS studies of crustal movement on either side of the Hauraki Rift, by Auckland University graduate student Robert Pickle, shows that it is currently being pulled apart in an east-west direction at a rate of about 1 km per 1 Myr. Movement on faults in the Hauraki Rift is considered to be the source of the most potent earthquake hazard for Auckland and surrounding areas.

In Northland there are fewer clues to the precise timing of this Pliocene and possibly younger faulting, uplift and tilting. Remote sensing offshore to the west of Northland shows that subsided marine erosion surfaces on top of several Early Miocene volcanoes are directly overlain by 6-5 Myr old marine sedimentary rocks that indicate westward down-tilting began about that time.



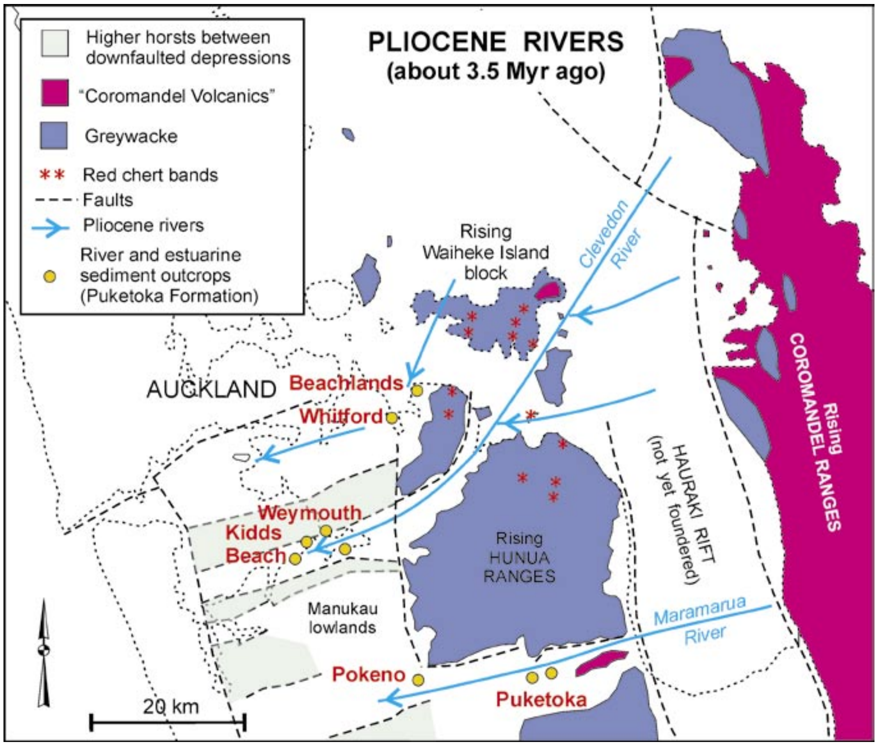
10.19 Location of all earthquakes greater than magnitude M = 2, shallower than 40 km depth, that have been recorded accurately by Geonet in the Auckland area in the period 2000-2016. Note that many occurred on known fault lines, especially the Firth of Thames Fault. Data from Geonet, Dec 2016.

PLIOCENE RIVERS AND SEDIMENTARY ROCKS

The pattern and timing of movement on the block faulting determined Auckland's geography of today. By about 4-3 Myr ago (Pliocene), the Hunua and Whitford greywacke blocks had already started to rise with north-east trending fault-bounded depressions running through Clevedon and Maramarua (*10.20*). The northern and central parts of the Coromandel Range had also started rising, whereas the Hauraki Rift, between the Hunuas and Coromandels, had not started subsiding.

In the west, a series of north-east-trending faults were actively offsetting the floor of the Manukau lowlands (*10.1*), creating a set of elongate west-tilted depressions separated by elongate high ridges (horsts). The top of the horsts remained at around sea level, whereas the depressions slowly subsided down to a maximum depth of 250 m in the southwest. As they subsided the depressions were continuously filled with sand (Kaawa Formation) deposited on the floor of shallow marine bays and inlets. Early on, when the supply of sand was limited, a mollusc shell bed (Kaawa Shellbeds; *10.21*), up to 10 m thick in some places, accumulated intertidally or in the shallows just offshore. In the deeper depressions there are several separate shell beds, whereas only one shell bed is preserved on top of the horsts. Although the shell bed is not exposed at the surface in the Mangere-Papatoetoe area of the northern Manukau lowlands, it is known to occur in this area at depths shallower than 30 m. A rich and diverse fauna containing a number of extinct mollusc species was described from Kaawa Shellbed material dug out of a water well on the site of the Dominion Brewery at Otahuhu in the 1940s. The highly permeable Kaawa Shellbeds form the main underground aquifers in the Manukau Lowlands today, and provide much of the water used by horticulturists around Pukekohe and Waiuku, in South Auckland.

In several places in the southeastern Manukau Lowlands (Weymouth, Kidds Beach, Karaka) and at



10.20 Map of Auckland area showing inferred river courses that carried distinctive gravel from the Coromandel Range and red chert from the Waiheke-northern Hunua Ranges area southwestwards through gaps in the rising ranges to where it was deposited during the Pliocene (about 4-3 Myr ago) around Puketoka, Beachlands and the Manukau lowlands. At this time, faults were actively offsetting the floor of the Manukau lowlands with the elongate depressions progressively filling with shallow marine and estuarine sediment.

10.21 All the shells in the Pliocene (4-3 Myr old) shellbed at Karaka Pt, southern Manukau Harbour, have been dissolved away leaving a sandy mudstone full of moulds. Most of the shell moulds seen here are shallow marine bivalves, but also present is the internal cast of a turret shell. Photo 15 cm across.

Beachlands, there is Pliocene-aged conglomerate, sandy peat and wood- and leaf-bearing mudstone and sandstone (Puketoka Formation; *10.22-10.28*). These beds interfinger with the shallow marine Kaawa Formation and are inferred to have been deposited in the heads of sheltered estuaries. In the narrow Maramarua depression at the south end of the Hunua Ranges (Puketoka, Pokeno), there are similar-aged deposits of cobble and pebble conglomerate that appear to have been deposited by a river. Also present is ignimbrite presumably erupted from a caldera at the southern end of the Coromandel Volcanic Zone. The cobbles and pebbles in the river and estuary conglomerates are rich in rock-types that can only have come from the Coromandel Volcanic Zone (rhyolite, vein quartz, silicified wood) and provide strong evidence that the Hauraki Rift had not yet started to founder. The conglomerates on the southern shores of the Manukau Harbour (especially Kidds Beach) are also full of small rounded pebbles of red chert derived from the Waiheke Island-northern Hunua Ranges area (*10.23*). These support the inference that they were transported by a Pliocene Clevedon River that flowed southwestards from near Coromandel township past Waiheke Island and through the narrow Clevedon depression to the estuarine coastline of the Manukau Lowlands, about 4-3 Myr ago.

10.22 These layers of Pliocene sedimentary rock (Puketoka Formation) were deposited in the upper parts of a tidal estuary, 4-3 Myr ago. Here they consist of a layer of angular blocks (breccia) of Waitemata Sandstone, eroded from the side of a tidal channel, overlain by thin laminae of sandy peat (black) and carbonaceous leaf-bearing sandstone. The leaves and twigs were carried down streams into the estuary. Some of the rippled laminae (flaser bedding) below the hammer indicate that they were deposited by reversing intertidal currents that would have transported sand grains back and forth in the estuary. Coastal cliffs, Beachlands, South Auckland. Photo 50 cm across.

10.23 These pebbles on the beach at Kidds Beach (southern Manukau Harbour) have eroded out of Pliocene (4-3 Myr old) estuarine conglomerate (Puketoka Formation). The red-brown pebbles are chert from the Waiheke-northern Hunua Ranges area and the harder, more rounded, white pebbles are vein quartz from hydrothermal fields of the Coromandel Volcanic Zone. These provide the best evidence for the inferred Pliocene Clevedon River, sourced from near Coromandel township and flowing southwest through the narrow Clevedon depression to the Manukau lowlands.

10.24 The mooring stone believed to have been used by the Tainui Canoe in Early Maori history, lies on the foreshore of Turanga Creek, near Whitford, South Auckland. It is made of hydrothermally-altered silicified breccia that can only have come from the Coromandel Volcanic Zone and was most probably transported here by flash floods down a Pliocene river before the Hauraki Rift subsided.

Box 44. FOSSIL FRUIT, BRACKET FUNGI AND SEA GRASS

Sand, sandy peat and mud (Puketoka Formation), which was deposited in estuaries in the South Auckland area about 4-3 Myr ago (Pliocene), contain abundant fossilised plant remains. These include logs, twigs, leaves and fruit, all of which were washed down rivers, became waterlogged and accumulated in the upper parts of estuaries. Some horizons are full of fossilised eel grass, which would have grown in the estuary. Recently, an Otago graduate student, Ian Geary, has collected and studied in great detail numerous fossil fruits (stones, nuts, seeds and cones) from Beachlands and Weymouth. He has recognised about 50 different kinds of fruit, many of which come from subtropical plants that no longer grow in New Zealand.

10.25 Otago University paleobotany student, Ian Geary, with a large fossil bracket fungus he found in 4-3 Myr-old estuarine sediment at Beachlands, East Auckland. These fungi are the second known occurrence of fossil bracket fungi from New Zealand – a group rarely found fossil anywhere in the world.

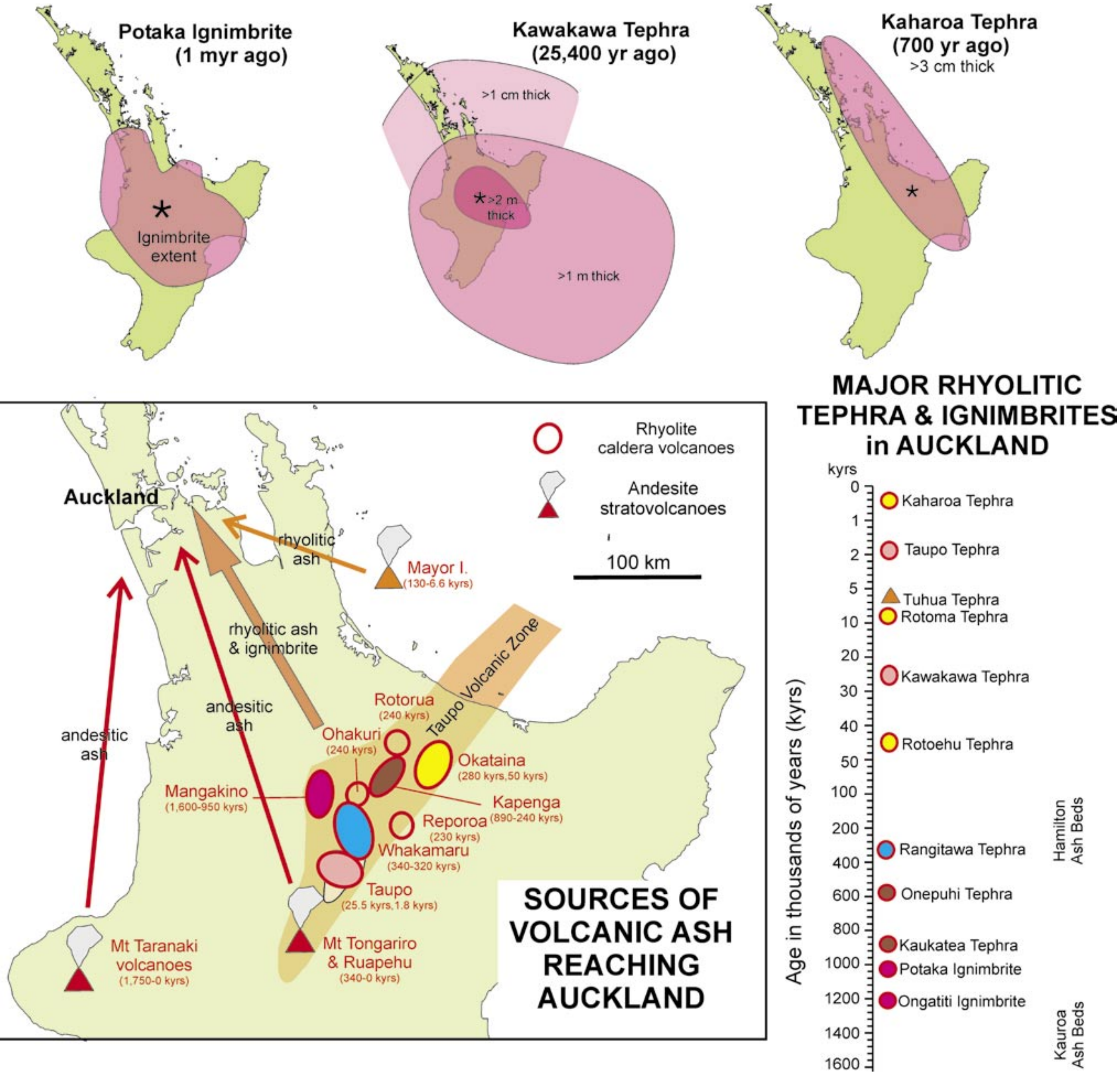
10.26 Two fossil cones, like those of the she-oak (Casuarina) *(arrowed), and one other fruit, in woody mudstone at Weymouth, South Auckland. The wide occurrence of* Casuarina *pollen indicates that she-oak forests grew in New Zealand between 60 and 3 Myr ago, but they disappeared here with the onset of the Ice Ages. She-oak forests still grow in much of Australia and in other subtropical-tropical areas. Photo 8 cm across.*

10.27 Four carbonised (black), fossil fruits in Pliocene sandstone (about 4 Myr old) at Weymouth, South Auckland. Photo 12 cm across.

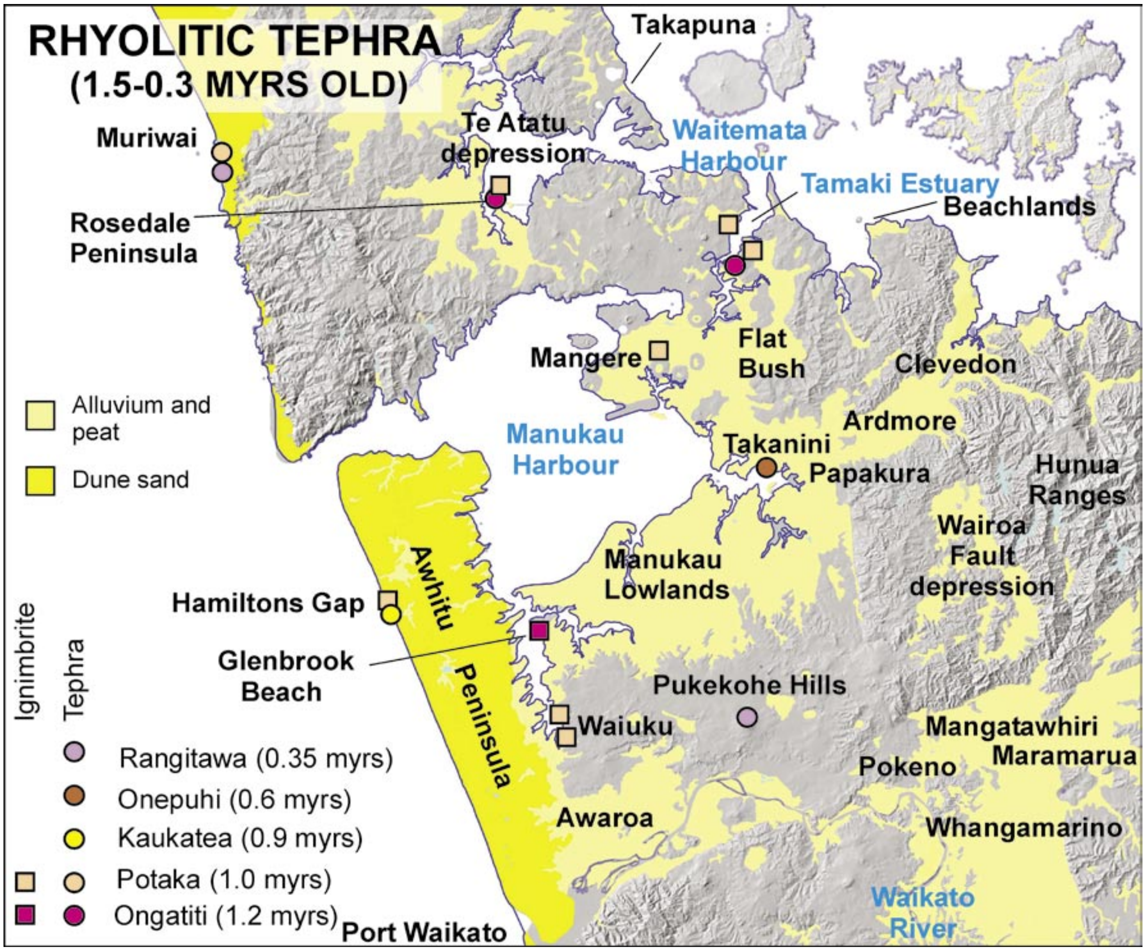
10.28 Fossil eel grass blades (Zostera) *that have been preserved in sandstone that was deposited around the head of a tidal estuary 4-3 Myr ago. Fossil sea grass like this has only been recognised here and in one other locality in New Zealand. Weymouth, South Auckland. Photo 10 cm across.*

VOLCANIC ASH AND IGNIMBRITE FROM AFAR

In the last 1.5 Myr, the southern part of northern New Zealand has been mantled on numerous occasions by volcanic ash that has been blown from its source volcanoes hundreds of kilometres to the south (*10.29*). The source volcanoes were mainly in the Taupo Volcanic Zone, which began erupting about 1.8 Myr ago. Eight large caldera volcanoes have erupted during this period in the region between Rotorua and Taupo. The older ones, like Mangakino (active 1.6-0.95 Myr ago), Kapenga (890-240 kyr), Whakamaru (340-320 kyr) and Ohakuri (240 kyr), are no longer visible as they have been buried by huge thicknesses of ignimbrite and ash that have been erupted more recently from other nearby calderas, such as Rotorua, Okataina and Taupo.



10.29 Map showing the main sources of volcanic ash (tephra) and ignimbrite that have periodically reached the southern part of northern New Zealand (especially Auckland and Manukau Lowlands) in the last 1.5 Myr. The column on right shows the ages of the largest rhyolitic ash and ignimbrite eruptions that mantled the Auckland region over that period (colour coded to source caldera). The upper maps show the extent of ignimbrite cover, the thickness of ash, and source caldera locations for three of the largest or most recent eruptions. (Modified from A Continent on the Move, 2015).



10.30 Locations where some of the thicker Early and Middle Pleistocene rhyolitic ash layers and ignimbrites (1.5-0.3 Myr old) occur around Auckland.

Caldera volcanoes can produce some of the largest and most violent eruptions on Earth (chapter 7), with vast quantities of pumice-rich glassy ash and ignimbrite erupted in a matter of hours to days. Areas in northern New Zealand that were most severely impacted by these ash and ignimbrite eruptions are around Auckland (*10.30*), particularly the lower lying Pukekohe hills, Manukau Lowlands, Tamaki valley and upper parts of the Waitemata Harbour, as well as the western Hunua Ranges, much of the southern Coromandel Peninsula and of course the Hauraki Rift.

Often you will see these volcanic ash deposits and ignimbrite flow deposits referred to as tephra and indeed many of them are given formal names, such as Kawakawa Tephra. Tephra comes from the Greek word meaning ashes. The formal names, that have been given to each major tephra, do not usually come from the name of the volcano that erupted them, but from a place where they were first recognised and described. Thus many of the caldera volcanoes erupted more than one tephra and each may have been given a different name. In some instances, the same tephra has been given different names in different regions, before it was shown that they were from the same eruption (e.g. Potaka, Kidnappers, Rocky Hill and Waiuku Tephras are all from the same eruption).

The thickness of ash that mantled various places depended upon the size of the eruption, the height of the ash cloud, the direction of the wind and the distance from the volcanic vent. Much of the ash that landed on the forested hillsides was either incorporated into the leaf litter and soil or washed off during rain storms and accumulated in thick deposits in stream valleys, lakes and estuaries. Only the very thickest ash deposits appear to have remained mantling much of the land, especially where the slopes are not too steep. For example, Waikato University's tephrochronologist, David Lowe, has shown that 1-3.5 m of Hamilton Ash beds still cover a great deal of the basalt lava flow fields of the older South Auckland Volcanic Field around Pukekohe (*10.31*), Waiuku, Ramarama, Bombay and Pokeno. These ash beds were erupted from the Taupo Volcanic Zone in a series of huge eruptions from 350-100 kyr ago.

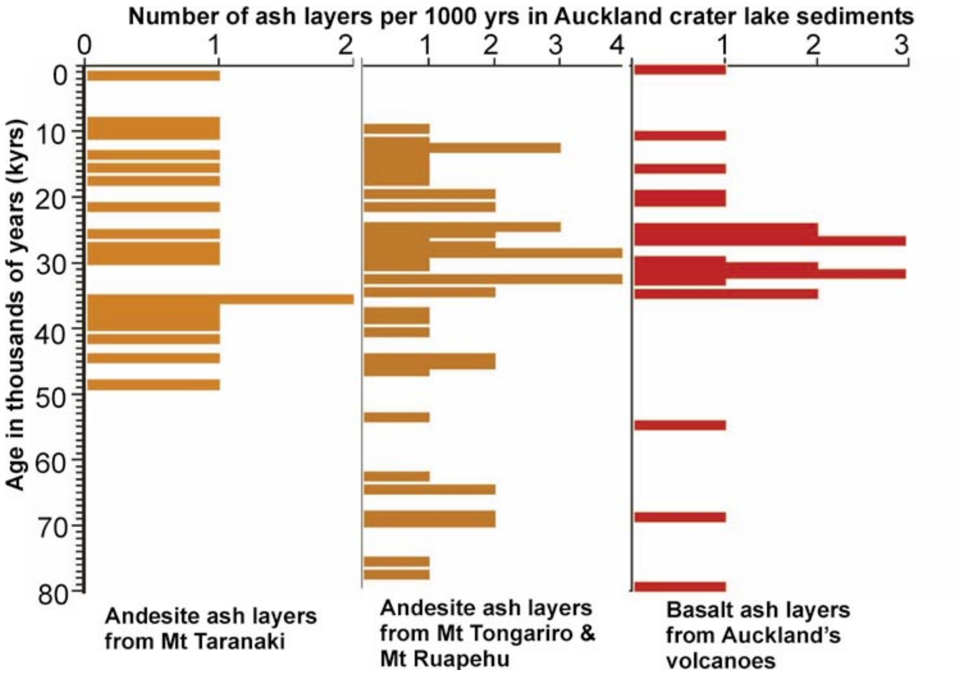
10.31 The rich volcanic soils that overlie many of the shield volcanoes of the Bombay-Pukekohe area of the South Auckland Basalt Field are derived from the 1-3.5 m thick mantle of rhyolitic Hamilton Ash beds, which are air fall deposits erupted from caldera volcanoes in the centre of the North Island, 350-100 kyr ago. Northern slopes of Pukekohe Hill.

Ash layers in lakes

The best records of the history of volcanic ash fall are found in the sediment sequences that have accumulated undisturbed on the quiet floors of small lakes that lack any significant streams flowing into them. Thus in the last 20 yr, geologists have cored the sedimentary fill of several 100 m-deep explosion craters in the Auckland Volcanic Field, such as Onepoto, Pukaki, Lake Pupuke and Orakei Basin. Main targets of this coring have been to investigate the eruption history of the local basalt volcanoes, whose volcanic ashes were not erupted very high nor blown very far (*9.71*). Another goal of these cores has been to study the past climate of Auckland, back through the Last Ice Age cycle. A by-product of these studies has been the record of deposition of volcanic ashes blown in from afar (*10.32*). For example, in the combined sedimentary record from several cored Auckland craters there are at least 21 readily identifiable cream-coloured rhyolitic ash fall deposits (*10.32*). Geochemical studies by tephrochronologist Phil Shane, and his Auckland University group, have recognised that ~13 of these came from the Okataina Caldera and ~8 from Taupo Caldera. Many of these ashes can be recognised as named tephra by their geochemistry and their order in the sequence. The age of these named tephra has been determined elsewhere by fission-track or radiocarbon dating (chapter 1).

The thickest ash to mantle Auckland in the last 80,000 years came from a large eruption out of Okataina Caldera about 45,000 yr ago (Rotoehu Tephra), which deposited a 7-60 cm thick layer on the floors of Auckland's crater lakes. It is also known to have mantled most of Northland, but by the time it reached as far north as Lake Omapere near Kaikohe, it only deposited a layer 10 cm thick. Other large, more recent eruptions have been Kawakawa Tephra, erupted during the formation of Taupo Caldera, 25,400 yr ago, which deposited a layer 3-6 cm thick in Auckland lakes. The most recent large ignimbrite eruption from the centre of the North Island was the Taupo Tephra, just 1800 yr ago (~ 232 AD), which deposited a 3 mm-thick ash layer in Lake Pupuke, Auckland. Presumably there was little wind blowing towards the northwest at the time.

Tuhua Tephra is a highly distinctive rhyolitic ash, because of the presence of the mineral aegerine. It is found on Coromandel Peninsula and around Auckland and was erupted from Mayor Island in the Bay of Plenty,



10.32 Bar histograms showing the number of various ash layers that have been deposited in Auckland's crater lakes over the last 80,000 years (from Molloy et al., 2009).

about 6500 yr ago. Also found within the lake-floor sediments of Auckland's volcanic craters are a number of thin, darker-coloured andesitic ash layers. Geochemistry can distinguish those erupted from Mt Taranaki from those erupted from Mts Tongariro and Ruapehu. In the last 80,000 yr, at least 52 andesite ash layers from Mt Taranaki and 7 from Tongariro-Ruapehu have been blown north and mantled Auckland. Southerly and southeasterly winds that would have blown these ashes over Auckland are not particularly common in this region today. Maybe they were more common during the colder glacial times that predominated between 80,000 and 12,000 yr ago.

Ash layers in sand dunes and on coastal terraces

In addition to their preservation on the quiet floors of small lakes, some of the thicker rhyolitic air fall tephras have been preserved intact in depressions between actively accumulating sand dunes (*10.33*) and on flat-lying coastal terraces that are not river flood plains. This is particularly true in more southern areas, such as the Awhitu sand-dune barrier/strand plain, and coastal terraces, such as those on the east coast of the Hunua Ranges and at Beachlands. Further north, the number and thickness of these distinctive white ash layers decreases, so that none are known from the Aupouri Peninsula in the Far North.

The most recent large rhyolitic ash eruption from the Taupo Volcanic Zone was the Kaharoa Tephra, which blasted out from Mt Tarawera in the Okataina Caldera. It was erupted 700 yr ago (~1314 AD) just after the first significant Maori colonisation of Aotearoa/New Zealand. Wind spread this ash right up the east side of Coromandel Peninsula and Northland, depositing 3 cm in sand dune hollows at Mangawhai Heads (*10.34*) and 1 cm in Lake Omapere, near Kaikohe.

*10.34 Eroding 3 cm-thick layer of fine white rhyolitic ash (*Kaharoa Tephra*) erupted 700 yr ago from Mt Tarawera, and preserved within the sand dunes at Mangawhai Heads, east coast Northland.*

*10.33 This 20 cm-thick layer of air-fall rhyolitic ash (*Kaukatea Tephra*) was deposited in an inter-dune hollow in the actively growing sand-dune barrier/strand plain of Awhitu Peninsula, about 900 kyr ago. Near Hamiltons Gap.*

Ash layers in swamps and alluvial valleys

Older Pleistocene sequences of light-coloured rhyolitic ash interbedded with peat deposits infilled many of the low-lying valleys and depressions in the Auckland region (*10.30*). In some places these sequences include the fossilised stumps and fallen branches of ancient forests (*10.35*). These valley-filling, young sedimentary sequences often form flat-lying plains now covered in pasture or suburbia, like the Pokeno-Mangatawhiri-Maramarua-Whangamarino swamplands, the Awaroa floodplain south of Waiuku, the Wairoa fault-angle depression in the Hunua Ranges, the Clevedon-Ardmore-Papakura swampy lowlands, and the Flat Bush-Otahuhu-Mangere lowlands. The deposits that underlie these swamps and plains might be tens of metres thick and were deposited over the last 1.5 Myr or so. We only know of their presence through bore holes and the occasional temporary excavations made into them.

Some of these ash and peat sequences can be seen in the eroding low cliffs around the fringes of the Waitemata Harbour, at places like the head of Shoal Bay and under the sands in the middle of Takapuna Beach (*10.35*). In the upper Waitemata Harbour, the down-faulted 30-60 m deep, Te Atatu depression is filled with peat and rhyolitic ash, much of which was probably washed in from off the surrounding hillsides. The sequence was cored at the end of Rosedale Peninsula (near Pollen Island). Studies by Auckland-based tephrochronologist Brent Alloway, and colleagues, showed that it accumulated in a swampy environment over a few hundred thousand years, around 1 Myr ago. It contains recognisable Ongatiti Tephra (1.23 Myr old), separated from younger Potaka Tephra

10.35 Lower areas around the fringes of the Waitemata Harbour, Auckland, are often filled with black peat and light-coloured sediment composed of rhyolitic ash that has been washed in, from off the surrounding hillsides. In 2014, sand was washed off the middle of Takapuna Beach, exposing the in-situ remains of fossilised tree stumps killed and buried by rhyolitic sediment that was probably deposited around 1 Myr ago.

(1.0 Myr old) by 15 m of black peat and thinner tephra layers.

Similar, light-coloured rhyolitic ash and black peat can be seen in many places around the shores of the Manukau Harbour, sometimes outcropping beneath overlying basalt lava flows and basaltic tuff, such as at Ihumatao, Puhinui, Waiuku Inlet and Pakuranga. Between 1.2 and 0.9 Myr ago there were a number of large pyroclastic flow (ignimbrite) and ash eruptions in the centre of the North Island. A lot of reworked rhyolitic ash from these eruptions appears to have got over the divide to the west and into the Waipa River valley and Hamilton Basin, possibly via a much earlier version of the present Waikato River's course through the Maungatautari Gap. This voluminous sediment was transported northwards down the Waipa valley (along the route of the present Waikato River, north of Ngaruawahia) and into the ancestral Manukau River flats on the west coast (currently partly drowned by the Manukau Harbour). This rhyolitic sediment filled up many of the remaining depressions in the Manukau Lowlands and spilled over into the ancestral Waitemata and Tamaki river valleys.

In addition to the airfall tephra, two large, ground-hugging ignimbrite flows (Ongatiti, Potaka), erupted from Mangakino Caldera, swept north into the Manukau and Waitemata lowlands around 1.2-1 Myr ago. In cliffs at Glenbrook Beach, near Waiuku, the Ongatiti Ignimbrite and associated air-fall ash (1.23 Myr old) is 4 m thick. The slightly younger (1.0 Myr) Potaka Ignimbrite was possibly the most voluminous ignimbrite to have erupted from the Taupo Volcanic Zone (*10.29*). At Waiuku Inlet and Hamiltons Gap (Awhitu Peninsula), it has a basal surge-like unit, up to 1.5 m thick that indicates it was still a hot, gas-supported flow as it arrived in the Manukau Lowlands. This is 200 km from source and the ignimbrite flow probably took less than an hour to travel that distance. Potaka Ignimbrite cooled, slowed and picked up water as it moved north over Auckland, where deposits are dominated by wet mass-flow features, such as accretionary lapilli and associated air-fall ash. These white deposits are 3 m thick at Farm Cove (*10.36*) and slightly thinner at Pt England on the other side of the Tamaki Estuary. Further north on the west coast, south of Muriwai, there is 3 m of airfall, and possibly reworked, Potaka Tephra preserved in inter-dune hollows.

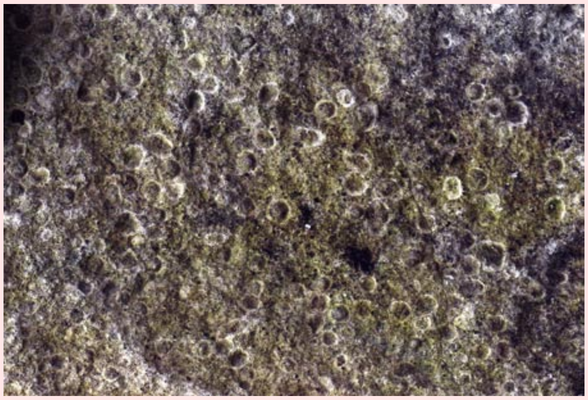
After 900 kyr ago, far less rhyolitic volcanic debris reached the Manukau and Waitemata harbours. There are several likely reasons for this. Firstly, the younger caldera eruptions from the Taupo Volcanic Zone were not as large as those that occurred around 1 Myr ago. Secondly, the Waikato River does not appear to have flowed from the Taupo Volcano Zone through to the west coast between 900 and 22 kyr ago, flowing instead out to the east coast via the Hauraki Rift. Thirdly, several basalt shield volcanoes of the South Auckland Volcanic Field (*9.94*) erupted between 900 and 600 kyr ago, creating a barrier between the lower Waipa River and the Manukau Harbour. From that time on, the Waipa, and later the modern Waikato River, would have flowed out to the west coast around the southern end of the Awhitu sand-dune barrier/strand plain, in the vicinity of the present-day Port Waikato.

10.36 This 3 m-thick bank of white ash was deposited by the Potaka Ignimbrite eruption 1 Myr ago in the Tamaki Valley, Auckland, as it was slowing down and cooling. It underlies Farm Cove in the suburb of Pakuranga.

10.37 The lower part of St Kentigern's cliff on the Tamaki Estuary, Pakuranga, consists of black peat, brown mud and light-coloured volcanic ash beds that accumulated in a swampy environment between 1.2 and 1 Myr ago. In-situ stumps of small trees are buried and fossilised at the bottom of the cliff. On top of the peat (at level of orange-shirt person's head) is a bright white layer of Potaka Ignimbrite. This has been partly eroded away and overlain by ash-rich sediment that fills a small former stream channel.

Box 45. ACCRETIONARY LAPILLI or VOLCANIC HAILSTONES

Accretionary lapilli (sometimes called volcanic hailstones) are fine volcanic ash balls that form by ash sticking together (accreting) inside hot, steamy, pyroclastic flows or base surges. Ash layers full of these accretionary lapilli, 5-25 mm in diameter, occasionally occur within the light-coloured rhyolitic ash deposits around Auckland and the Coromandel Peninsula at places like Point England (Tamaki Estuary), Hamiltons Gap (Awhitu Peninsula) and Stingray Bay (Hahei, Coromandel Peninsula). The occurrence of these accretionary lapilli within the basal surge part of the ignimbrite deposits, suggests that the ash particles became stuck together as the turbulent surge front of the ignimbrite flows passed over swampy lowlands or estuaries. Brown accretionary lapilli occur in scattered layers within the tuff rings of some of Auckland's young basalt volcanoes. These also accreted together in the steamy base surge clouds that sped across the ground away from the wet explosive vents.



10.38 Top left: Small accretionary lapilli are common within the base surge deposits of the Maungataketake basalt volcano tuff ring. Note the two phases of formation with lighter-coloured lithic ash (pulverised Pleistocene rhyolitic sediment) added on around the outside of each ball. In coastal cliffs, Ihumatao. Photo width 10 cm.

10.39 Lower left: Small basaltic accretionary lapilli (3-5 mm diameter) occur in several horizons within the base surge deposits from Three Kings basalt volcano. Liverpool St road cutting, Epsom (13.34). Photo width 5 cm.

10.40 Top right: Rhyolitic accretionary lapilli occur within 1 Myr-old Potaka Ignimbrite south of Hamiltons Gap, Awhitu Peninsula. Photo width 10 cm.

Chapter 11. CRAFTING THE COAST (last 1-2 Myr)

Chapter Summary

The coastal diversity of northern New Zealand has been crafted by an interplay between coastal land building, drowning and eroding processes over the past 1-2 Myr, especially during the last 10,000 yr (Holocene period). During the Ice Ages of the last 2.6 Myr, the climate and sea level have alternated back and forth in cycles of 40,000 and 100,000 yr length. For 90% of this time, sea level has been lower than present. During the coldest glacial peaks, sea level was 60-130 m below present, with its lowest recorded level during the peak of the Last Glacial Period, just 18,000 yr ago. During the short (5000-10,000 yr long), warm, interglacial periods, sea level was within 10 m of present level, with its highest peaks around 10 m, 6 m and 1-2 m above present at 400,000, 120,000 and 7000-3000 yr ago.

Since the start of the Ice Ages, two large bays on the west coast have been transformed into New Zealand's largest harbours – the Kaipara and Manukau – by the building of sand-dune barrier/strand plains across their mouths. The growth of these barriers was a result of greatly increased sand supply to the west coast from large volcanic eruptions in the central North Island, particularly around 1 Myr, 300,000 yr, and since the Waikato River switched its course 22,000 yr ago, to flow out on the west coast instead of through the Hauraki Rift. In the Far North, large sand-dune tombolos were constructed during the same period, linking islands at North Cape, Mt Camel and Cape Karikari to the main part of Northland.

Valleys that had been eroded across the forested coastal plain during lower sea level, were drowned by the rising sea after the end of the Last Glacial Period, about 10,000-7500 yr ago. Where sediment supply was limited, these drowned valleys became the indented harbours and estuaries of the east coast and the branching inner reaches of Hokianga, Kaipara and Manukau harbours. With sea level rise, ridge and hill crests have become peninsulas and islands. Where sand supply was more plentiful, sand spits were thrown up across the mouths of estuaries, and beaches accumulated in bays. In the last 3000 yr, as sea level has dropped from 1-2 m higher than present, a series of sand dune belts have been deposited behind sandy shorelines on both coasts. At the same time, the 2 km-wide Miranda chenier plain, consisting of a sequence of shell banks, has accreted onto the west coast of the Firth of Thames.

Where sand supply has been low, degraded coastal cliffs from previous high sea-level stands, have been exhumed and eroded back at rates of 0.1-0.3 m per 100 yr for hard greywacke and volcanic rocks, and 0.6-3 m per 100 yr for softer Waitemata Sandstone. Marine erosion has been fastest where the rocks alternate between wet and dry during the tidal cycles, creating mid-tidal platforms in more porous sandstone and high tidal platforms and notches on harder rocks or on more exposed coasts. Intertidal guts, caves, tunnels and sea stacks mostly result from erosion along fault and joint planes that cut through the rocks.

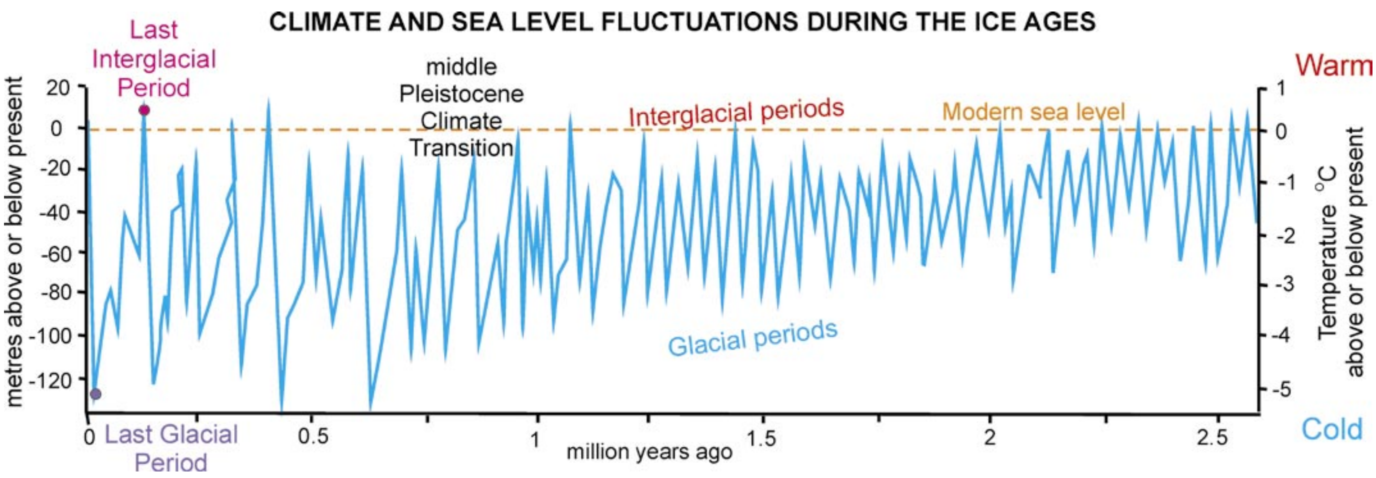
North-moving longshore drift, abrasion and weathering have sorted out the components of the volcanic sediment supply to the west coast. Dense black titanomagnetite grains have been left behind and concentrated in the south, where old deposits are mined and used in making steel. White sand, composed of almost pure quartz, has been concentrated further north and is used for glass manufacture.

Fossil bird and reptile bones occur in young sand dune, cave, swamp and midden deposits and provide evidence of the vertebrates that have been lost since the arrival of humans. Most noteworthy are the bones of a number of large, extinct flightless birds including four species of moa, and New Zealand's largest skink (also extinct).

ICE AGE CLIMATE AND SEA-LEVEL CYCLES (last 2.6 Myr)

The Earth has experienced periods of extensive polar glaciation on a number of occasions back through deep time, with the most recent period in the last 2.6 Myr often referred to as the Ice Ages. Astronomically-driven cycles of warm and cold climate can be recognised throughout most of Earth's history, but in the last 2.6 Myr their amplitude increased markedly and resulted in the cold glacial periods developing polar ice. Initially, up until about 1 Myr ago, the peaks and troughs (interglacial and glacial periods) of the climate cycles were 40,000 yr apart but this changed during the Middle Pleistocene Climate Transition (1.2-0.7 Myr ago) when the cycles lengthened to 100,000 yr. Thus, since 2.6 Myr ago, there have been about forty-two ice age cycles and nine of these were 100,000 yr cycles (*11.1*).

Not only did the climate cycles start getting longer

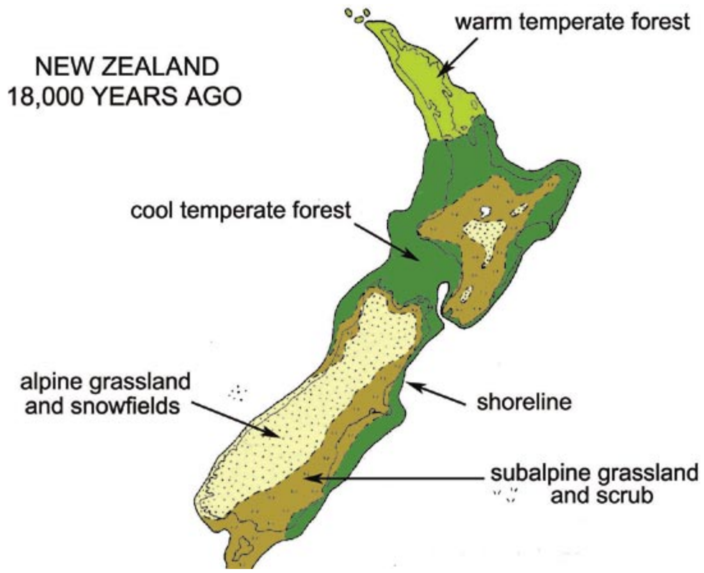


11.1 Global climate and sea-level curve for the past 2.6 Myr (*Ice Ages*).

during the Middle Pleistocene, but the cold glacials got increasingly severe, with development of extensive polar ice caps, particularly on land in the northern hemisphere. Although the cycles had become 100,000 yr long, the peaks of cold glacials and warm interglacials each lasted only a few thousand years. In the more recent cycles, the Earth's climate slowly declined in a saw-tooth-like series of oscillations over a period of 80,000 yr after the peak warmth. After each glacial low, the Earth's climate warmed up much faster, often in less than 10,000 yr (*11.1*).

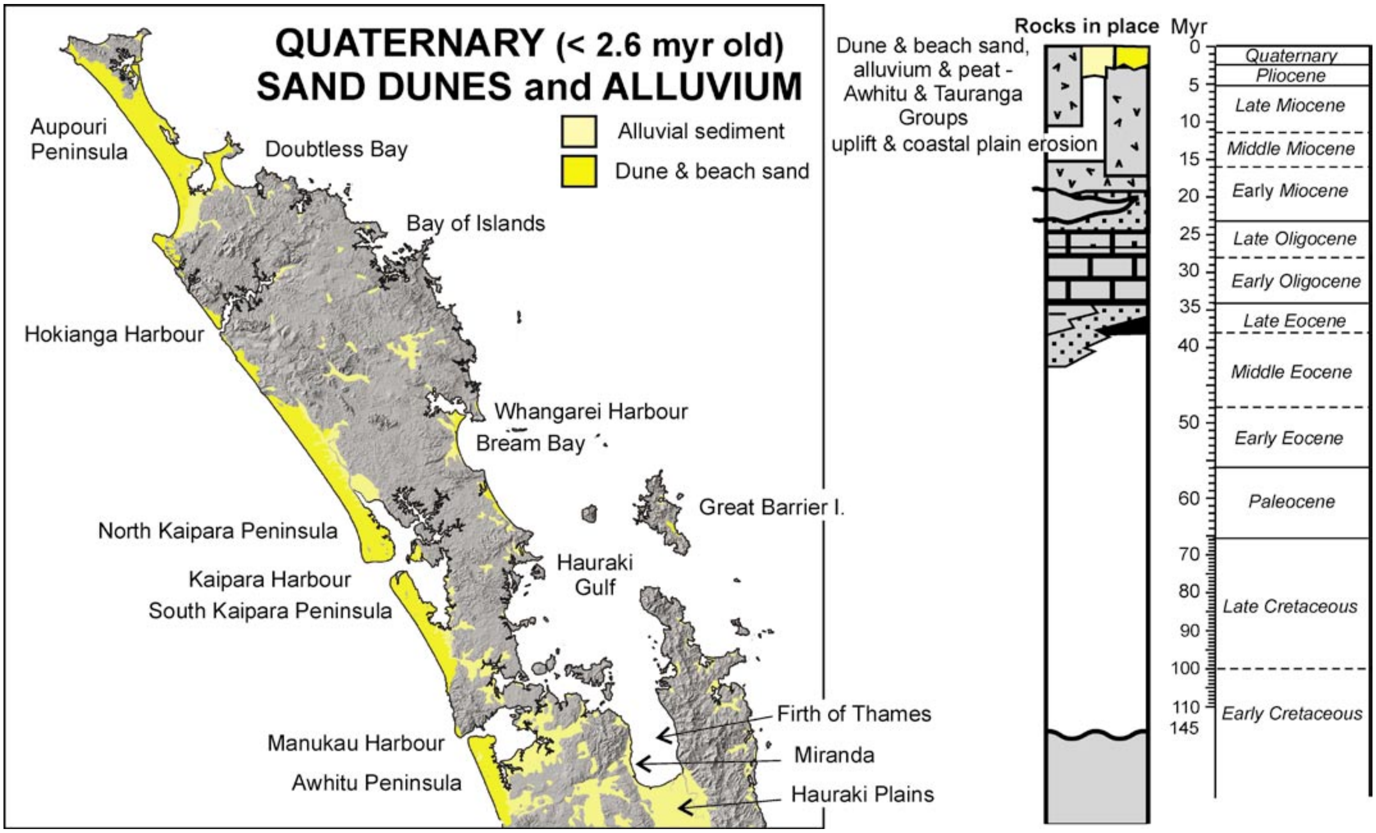
During the intense cold of all the glacial intervals since the Middle Pleistocene, almost all the forest of New Zealand's South Island and southern North Island disappeared and was replaced by subalpine grassland and scrub, with snow fields and glaciers developing in the more mountainous areas (*11.2*). In the northern North Island, forest persisted over all but the highest peaks through the glacial periods. Studies of the pollen record captured in lake and swamp sediments indicate that the composition of our northern forests changed through the climate cycles. During the warmer interglacial times, the forests were dominantly mixed podocarp-broadleaf in composition, much like they are today. During colder times, the forest, particularly in higher and more inland locations, became dominated by southern beech and shrublands of temperate climates, rather like the South Island vegetation today.

A direct result of the climate cycles, and mimicking them in periodicity and amplitude, were sea-level cycles (*11.1*). During the more recent, severe glacial peaks, a large amount of the Earth's water was captured on land in polar ice caps, especially in Eurasia and North America. This ice was sourced, via evaporation and snow fall, from the oceans and as a consequence sea level fell. During the most severe glacials, such as the Last Glacial peak just 18,000 yr ago, sea level fell to as low as ~130 m below present, but for most of the Ice Ages sea level was fluctuating between 100 and 30 m lower than present. Sea level has only been high and close to the present for about 10% of the time in the last 1 Myr. These sea-level cycles have had a greater impact on the shape of northern New Zealand than the fluctuating climate cycles, as will become clear later in this chapter.



11.2 Map of New Zealand during the peak of the Last Glacial Period just 18,000 yr ago, when sea level was ~130 m below present. Because of the cold, the latitudinal vegetation zones were much further north than today. New Zealand would have looked very similar to this during each of the last seven major glacial periods in the last 700,000 yr, since the Middle Pleistocene Climate Transition.

WEST COAST SAND-DUNE BARRIERS (last 2 Myr)



11.3 Distribution of Quaternary (last 2.6 Myr) sedimentary rocks and sediments in northern New Zealand and stratigraphic column showing their relationship with the underlying rocks.

By the beginning of the Ice Ages (2.6 Myr ago), most of northern New Zealand had been uplifted above sea level with some areas, especially in the northwest, many hundreds of metres high. The Hauraki Rift had probably started to subside by this time as well. The west coast was not long and straight as it is today, but had two large embayments – the Manukau and Kaipara bays (*11.4*). In the Far North, erosion of the uplifted blocks had created a series of islands around the Three Kings, North Cape, Mt Camel and Cape Karikari, which were separated from most of Northland by shallow seas.

Since the start of the Ice Ages, major sand-dune barriers have grown across the mouths of the large west coast embayments creating the Awhitu and South and North Kaipara peninsulas and the 100 km-long Aupouri Peninsula in the Far North (*11.3, 11.5-11.7*). The explanation for the sudden growth of west coast sand-dune barriers was the vast increase in sand supply to the coastal system during that period.

11.4 Reconstructed paleogeographic map for northern New Zealand at the start of the Quaternary period (Pliocene-Pleistocene boundary), about 2.5 Myr ago.

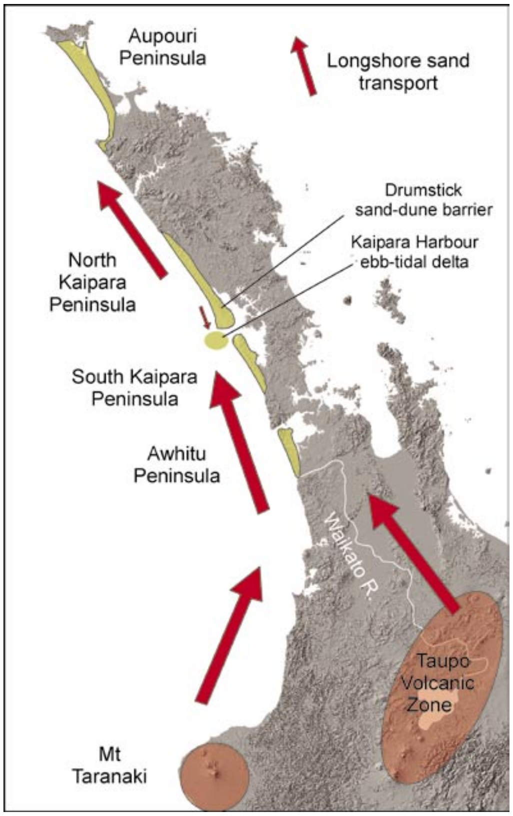
11.5 View south from the southern Waitakere Ranges to the eroding, 285 m-high north end of the Awhitu Peninsula sand-dune barrier that was built across the mouth of the Manukau Bay in the last 2 Myr.

Sand supply

A little after 2 Myr ago, an ancestor of Mt Taranaki started erupting in the vicinity of New Plymouth and volcanic activity broke out in the Taupo Volcanic Zone in the centre of the North Island. Both volcanic areas have been erupting large volumes of lava and ash, off and on, ever since. Coastal and terrestrial erosion of the andesitic ash and lahar deposits around Mt Taranaki and its ancestor volcanoes has provided a considerable quantity of sand to the west coast continental shelf sand budget. Similarly, terrestrial erosion of the voluminous rhyolitic ash layers and ignimbrites, erupted from the centre of the North Island, resulted in huge quantities of pumice and sand being carried down the Waipa River and delivered to the sea at or near Port Waikato. After 22,000 yr ago, the Waipa River was joined by the Waikato River, which brought with it increased quantities of ignimbrite-derived sediment.

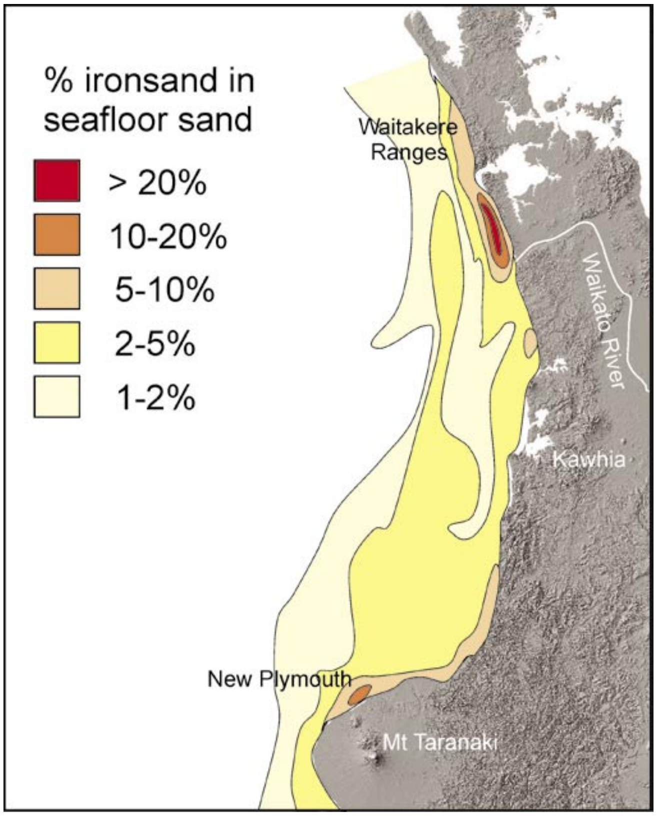
Longshore sand transport

Throughout most of the last 2 Myr there has been net longshore drift and sediment movement from south to north up the west coast from Cape Egmont to the Kaipara Harbour and beyond (*11.6*). The dominant southwest swells hit the coast obliquely with the surging waves sweeping sand diagonally up the beach. The returning wave surge flows straight back down the sloping beach. As a result much of the voluminous volcanic-derived sediment supply to the west coast has been carried progressively northwards. This northerly longshore transport of sand is a long-term process, driven by dominant southwest swells, imposed on top of much shorter seasonal and storm-induced transport of sand back and forth on and off the beaches. Where there was excess sand, often during falling sea level, it was thrown up at the back of beaches. Here the dry sand was blown inland to create sand-dunes.



11.6 Large volcanic eruptions over the last 1.8 Myr, in Taranaki and the centre of the North Island, provided much of the extra sand to the west coast that resulted in the construction of the dune barriers that enclosed the Manukau and Kaipara harbours, and the Aupouri Peninsula tombolo in the Far North.

The orientation of the present-day North Kaipara sand-dune barrier appears to be anomalous and suggestive of south-directed growth. Indeed its southern end probably has grown southwards at times of high sea level, like today. A local reversal in sand transport direction on the coastline has probably been caused by the large ebb-tide delta of sand banks, which have built



11.7 Above left. View south down the currently eroding exposed coast of the North Kaipara sand-dune barrier from above Omamari. The North and South Kaipara sand barriers grew across the mouth of the large Kaipara bay as a result of the greatly increased sand supply to the west coast in the last 2 Myrs. Photographer Alastair Jamieson.

11.8 Above right. The concentration of titanomagnetite (iron sand) in the sand on the modern sea floor west of the North Island, shows that it is coming from erosion of the volcanic deposits of Taranaki and the centre of the North Island. In the latter instance it has been transported down the Waikato River over the last 22,000 years since the river switched its course from flowing down the Hauraki Rift to flowing via the Hamilton Basin and out to the west coast. From Carter (1980).

up off the mouth of the large Kaipara Harbour. The delta alters the direction of the dominant southwest swells and waves so that they approach from the west and the sand on the southern end of the barrier is moved southwards rather than northwards, resulting in a drumstick-shaped barrier with a wide southern end (*11.6, 11.30*).

South to north changes in sand composition

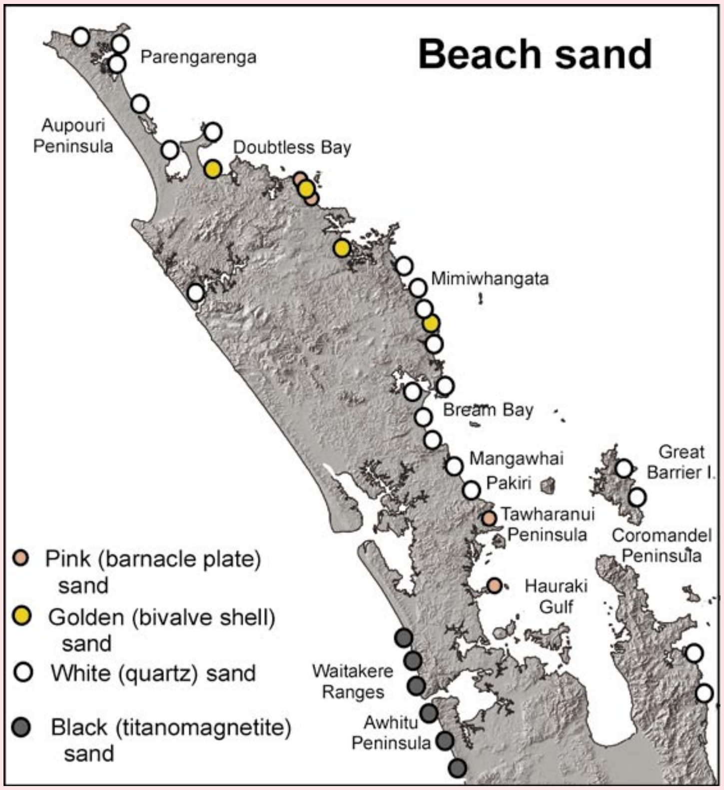
As the sand along the west coast has been transported northwards over thousands of years it has changed composition. Initially at source it was dominated by grains of quartz, feldspar, pumice, rock fragments and minor iron sand (titanomagnetite). The rock fragments and pumice were the first to break up or weather to clays, while the sand-sized mineral grains are sorted during transport by their different densities. The lighter grains of feldspar and quartz (specific gravity, SG = 2.6-2.7) moved northwards much faster than the dense titanomagnetite (SG = 5). The iron sand was left behind and was concentrated nearer source on the coast of Awhitu Peninsula, the Waitakere Ranges and South Kaipara Peninsula. On modern beaches the black sand is often concentrated in drifts up near high tide mark because the strength of the incoming wave surging up the beach is stronger than that of the outgoing water.

The beach and dune sands further north are primarily composed of a mix of feldspar and quartz. Quartz, being much harder than feldspar, survived a lot longer in the battering coastal environment. Quartz is chemically inert and so it does not weather to clay whereas feldspar will when thrown up on land in dunes. Thus the older sand deposits on the beaches and in the dunes tend to be the richest in quartz and whitest, such as those at Parengarenga in the Far North.

Box 46. BEACH SAND

The colour of the sand on the beaches around northern New Zealand (*11.9*) is highly variable and depends on a number of factors, such as the proximity to the mouths of sediment-carrying rivers and streams; whether or not the local cliffs are made of soft, rapidly eroding material; and whether there are rich offshore shell beds. The main source of the beach sand has been from the Waikato River, which in the last 22,000 years has flowed out to the west coast as it does today. For hundreds of thousands of years prior to that it flowed out into the Hauraki Gulf on the east coast, carrying vast quantities of volcanic ash- and ignimbrite-derived sediment.

A small proportion of the Waikato River sediment (about 5%) was heavy black grains of titanomagnetite, which moves far more slowly northwards up the west coast by longshore drift than the much lighter quartz, feldspar and volcanic glass grains. Hence the beaches just north of the Waikato River mouth, along the Tasman coast of Awhitu Peninsula and the Waitakere Ranges, are rich in black sand (*11.10*). Small patches of black sand can be found around the inner Hauraki Gulf beaches – reminders of the time when the Waikato flowed out on the east coast.

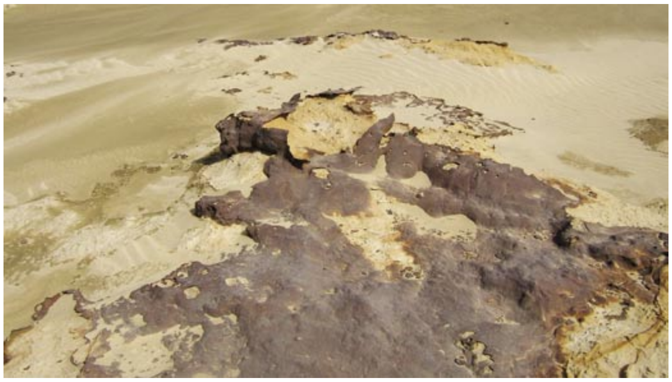


11.9 Map showing locations of examples of different coloured beach sand around northern New Zealand.

As the lighter grains have progressively moved northwards up the east and west coasts of Northland, the volcanic glass and feldspar have been destroyed and mainly quartz (silica) has reached the Far North, creating the white sands of the Aupouri Peninsula tombolo (*11.11*) and especially Parengarenga Harbour. On the east coast the same mix of volcanic-derived sand has poured into the Bay of Plenty as well and over the last few climate cycles been moved northwards along the coast, providing the brilliant white silica sands of the eastern Coromandel Peninsula, Great Barrier Island, Pakiri, Mangawhai, Bream Bay and Mimiwhangata.

In some east coast bays north of Auckland, there is very little mineral sand being washed up on the shore, because there is no major river discharging sediment onto this coast. In these places, the locally-derived, broken-up shells of subtidal shellfish and other organisms with shelly hard parts, have accumulated. If the shells are dominantly bivalve, especially tuatua, the beach appears golden orange as at Cable Bay, Doubtless Bay (*11.12*). If the shells are dominantly broken barnacle plates, the beach appears pink, as on the north side of Tawharanui Peninsula (*11.13*). Inside the harbours and around the shores of the inner Hauraki Gulf, the sand is various hues of buff-brown (*11.14*) derived from the eroding and partly weathered greywacke basement and Early Miocene sedimentary rocks.

Clockwise from top left.
11.10 Black sand at Anawhata, Waitakere Ranges coast.
11.11 White sand, Ngakengo Bay, North Cape.
11.12 Golden sand at Cable Bay, Doubtless Bay.
11.13 Pink sand, east of Omaha, Tawharanui Peninsula.
11.14 Buff-brown sand at Takapuna Beach.



11.15 This undulating iron pan at Te Paki, Far North, formed by advanced podzolisation, has been exhumed from within the sand-dune sequence by wind deflation.

11.16 A large piece of mammillary limonite (*hydrous iron-oxide*) *that was part of an iron pan formed by mature podzolisation, within the South Kaipara sand-dune barrier sequence.*

11.17 Large-scale cross-bedded sand, like this 1 Myr-old, iron-stained example south of Muriwai, is characteristic of ancient sand dunes. The cross beds were deposited at an angle of about 30° on the lee slope of the dune as the sand advanced (*from right to left*). *Flat-lying top set beds that accumulated on top of the dune are preserved in the upper right of the photo.*

Podzolisation

Podzolisation is an extreme and complex soil-forming process under acid conditions that often occurs beneath podocarp forests, such as the kauri of northern New Zealand. Organic acids pass down through the substrate leaching out aluminium and iron (together with magnesium and silicon) and redepositing them at lower levels in the soil profile. Over time, strongly podzolised soils develop with successive cemented horizons of silica, humus and iron-rich pans in downward order to depths of 1 to 2 m below the surface. The abundance of contorted, rusty-orange iron pans (*11.15, 11.16*) within the sand deposits along the west coast, provides evidence of a number of periods of sand-dune stabilisation and forest establishment during construction of the strand plain-barriers. Alternatively, the iron pans may form diagenetically, that is simply by the precipitation of iron, dissolved from the weathering of iron-bearing titanomagnetite sand grains, from a reduced to oxidised form. Such changes in oxidation state occur typically where grain-size changes (and hence changes in porosity) occur in the sand deposits. Whatever their origin, these iron pans are often referred to as coffee rock.

Dune stabilisation and deflation

As wind-blown sand dunes advance across the land they leave behind thick sand deposits with sloping layering (called cross-bedding; *11.17*), which marks the progressive growth of the sloping front of each dune. Intercalated with these cross-bedded sand-dune deposits that built the west coast sand-dune barriers are flat-lying lenses of lignite (*11.18*) and laminated sand that accumulated in freshwater ponds, swamps, lakes and small valleys in hollows within the dunes.

Gently undulating flat surfaces occur on ridge crests on top of some of these older sand-dune deposits in places like Awhitu Peninsula, south of Muriwai and on the Kaipara barriers. These are inferred to be remnants of wind deflation surfaces (Stokes surfaces) that periodically develop within sand-dune areas. Strong winds can blow dry sand grains along, which may erode the surface down (deflate) to local ground water level, where the damp sand is immobile. Wind erosion may also erode an area of sand down to erosion-resistant iron pans (*11.15*). If sand supply from the back of the beach has been cut off, then extensive flat deflation areas may develop in the sand dunes before the dunes are stabilised by vegetation growth.

Since they started forming, the west coast sand-dune barrier/strand plains and the Aupouri Peninsula

11.18 A lens of woody, black lignite, up to 5 m thick, within the North Kaipara sand-dune barrier sequence at Baylys Beach. Lignite lenses like these are commonly exposed along this piece of coastline. They accumulated as peat in small valley-bottom swamps within stabilised and forested sand dunes, probably about 300,000 yr ago.

tombolo have suffered repeated periods of modification. Sometimes, especially during periods of rising sea level, coastal erosion or wind deflation have removed significant chunks of land. At other times, especially during sea-level stability or fall, foredunes have been added along their coasts and wind-blown sand has advanced inland over the forested hills. The main controlling factors influencing barrier growth or erosion were sea level, coastal sand supply and storm frequency.

Influence of sea-level changes

The sand-dune barriers/strand plains were built-up along the west coast during the Ice Ages, when sea level was fluctuating in regular cycles (*11.1*). Given sufficient sediment supply, the inshore coastal sand system will develop an equilibrium between the sand on the beaches and that on the seafloor offshore down to storm wave base at a depth of ~60-70 m. If extra sand is added into the system, from say the Waikato River, then much of the excess will be thrown up at the back of the beaches and blown inland as sand dunes. If lots of sand is dredged from offshore at depths shallower than 60-70 m, then beach erosion can be expected. Similarly, if sea level falls, some of this seafloor sand will be eroded by the lowered storm wave base and will be added to the beaches. If sea level rises then net beach erosion can be expected. These are longer term processes that will be overprinted by short term events such as storms and the seasonality of storms and wave climate.

Thus coastal sand dunes presumably built up along the west coast each time sea level fell as the Earth's climate moved into a cold glacial period. The dunes would have created wide strand plains over what is, today, the continental shelf below sea level. Every time sea level rose again during warming intervals, the strand-plain dunes would have been eroded away and the sand redistributed over the resubmerged inshore seafloor. During each low sea-level stand, there may have been a small proportion of the onshore sand that was blown inland and added dunes onto the seaward side or on top of the existing sand dune barriers above present sea level. When sea level was high like today and there was excess sand in the system, sand dunes built up across the mouths of the Manukau and Kaipara bays, creating the large Awhitu and Kaipara sand-dune barriers enclosing large harbours.

Influence of coastal sand supply

Over the last 1.5 Myr the total amount of sand in the inshore west coast system probably remained about the same from one climate cycle to the next, except for three known periods when the Waipa or Waikato Rivers carried voluminous sediment from the Taupo Volcanic Zone and discharged it into the west coast sand system. The first period, between 1.2 and 0.9 Myr ago, probably

11.19 The north eastern portion of the South Kaipara dune barrier is underlain by water-deposited cross-bedded sandstone that accumulated in a flood-tide delta, inside the northward-migrating entrance to the Kaipara Harbour. These beds can be seen forming the lower 5-10 m of the harbour-side cliffs north of Te Rau Puriri Regional Park.

Box 47. WHITE SAND TO GLASS

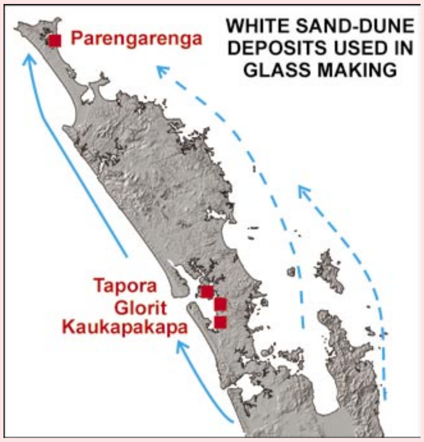
White sand from dunes north of Auckland has been used for many decades, and still is in a small way, in the manufacture of glass for local use. The white sand is near pure quartz (silica, SiO2), derived originally from the huge rhyolite eruptions in the centre of the North Island, which have been erupting on and off for the last 1.8 Myr. Pumice, quartz, feldspar and other minor components in these giant ash eruptions washed down rivers into the sea and, over thousands of years, have been transported northwards by longshore drift, particularly up the west coast of Auckland and Northland. During this northwards transport, the pumice and feldspar have broken up or weathered away and dense grains of iron sand have been left behind. Thus the quartz-sand component has been naturally concentrated and purified.

11.20 Heaps of white quartz sand at the Glorit purification plant.

Some of this quartz sand was carried by tidal currents into the Kaipara Harbour and thrown up to form beaches on its eastern shore at Tapora, Glorit and other places south towards Helensville. Westerly winds blew the white beach sand inland forming sand dunes like those at Tapora today, and in places blew the sand up into the surrounding hills, where it accumulated in thick drifts at elevations of 50-75 m above present sea level. These deposits are currently being quarried at Tapora and Glorit, and have in the past been worked near Kaukapakapa. Impurities are removed from the ancient dune sand (*11.20*) and then it is transported to Auckland for glass manufacture.

The largest silica sand deposit in New Zealand is the spectacular white dunes that form Kokota Spit that encloses Parengarenga Harbour near North Cape (*11.21*). For many decades this sand was sucked from here onto barges offshore that then took it south to Auckland. The original source of the Parengarenga sand is also believed to be the huge rhyolite eruptions around Taupo. This sand was probably transported north by longshore drift up the west coast, but some could have come up the east coast at times of lower sea level during the Ice Ages (*11.22*).

11.21 Kokota Spit at Parengarenga, near North Cape, is made of exceptionally pure white quartz sand, which has been used in the manufacture of glass in Auckland.



11.22 Location of white quartz sand deposits that have been used for glass manufacture in northern New Zealand.

11.23 Other silica-rich white sand beach and dune deposits, which have not been mined for glass manufacture, occur up the east coast of northern New Zealand, especially on the east coast of Great Barrier Island and between Pakiri and Mangawhai Heads, as seen in this photo.

Box 48. BLACK SAND TO STEEL

The black sand of the North Island's west coast beaches and coastal dunes contains vast quantities of the iron-oxide mineral, titanomagnetite, which is used in the production of steel both in New Zealand and overseas. New Zealand Steel's mill at Glenbrook (*below right, 11.25*), near Waiuku in South Auckland, produces about 90% of the country's steel requirements. The raw material for the Glenbrook mill comes from their large iron-sand mine at the south end of the Awhitu sand barrier on the north side of the Waikato River mouth (*below left, 11.24*).

The mine is located in sand-dune deposits that were blown inland from the back of the beach at the mouth of the Waikato River during two time periods – one during the last interglacial, about 120,000 yrs ago and the other in the Holocene in the last 7,000 or so years. The loose dune sand consists of a mix of light feldspar and quartz grains and denser titanomagnetite. The titanomagnetite component averages 20-40% of the sand deposit with some rich lenses up to 70%. More than 150 million tonnes of iron sand have been shown to be present in the area with about 1.2 million tonnes being mined annually to produce 650,000 tonnes of steel. Mill construction began in 1966 and it has been producing steel since 1968. Making steel from titanomagnetite sand in New Zealand in the 1960s was a global first. New Zealand engineers and scientists pioneered new smelting techniques to remove most of the titanium from the iron in the titanomagnetite sand, which up until that time had largely prevented its use for steel making.

The iron sand is mined by bucket wheel excavators and transported by moveable conveyor belts to the concentrating mill. Here the titanomagnetite sand grains are separated from non-magnetic minerals and clay in a wet magnetic separator followed by final upgrading by gravity separation. The concentrate is mixed with water and pumped as a slurry through a buried pipe 18 km north to Glenbrook steel mill. This pipeline was another New Zealand innovation and a world first. A similar slurry pipeline is used today to transport iron sand from the coastal mine at Taharoa, west Waikato, to ships offshore.

Glenbrook's steel mill contains four multiple hearth furnaces, four rotary kilns, and two smelters. At the mill, the iron-sand concentrate, together with coal from Huntly and a small amount of limestone, are fed into the four multi-hearth furnaces, where it is dried and heated to 650°C. The coal is converted to char through the liberation of volatiles and the resulting material is then suitable for feeding into the kilns. The rotary kilns reduce the iron-oxide ore to metallic iron. This is unusual, as most mills use blast furnaces for this reduction process. The steel produced has been used to build modern New Zealand.

11.24 The Waiuku sand mine on the north side of the Waikato River mouth quarries 1.2 million tonnes of iron sand every year from the sand-dune deposits. Photographer Alastair Jamieson.

11.25 The Glenbrook Steel Mill in South Auckland makes ~90% of New Zealand's steel requirements from iron sand mined from sand-dune deposits nearby. Photographer Alastair Jamieson.

resulted in the building of much of the older, cemented sand dunes that form the backbones of the west coast barriers. At this time the Mangakino Caldera Volcano in the centre of the North Island was at its peak, erupting huge quantitis of ash and ignimbrite (especially the Ongatiti and Potaka, *10.29*). There is ample evidence that voluminous rhyolitic sediment was carried down the Waipa River through the Hamilton Basin and out to the west coast at this time. During this period the Awhitu sand dune barrier/strand plain appears to have grown northwards from Port Waikato, and the mouth of the Waipa River may have been diverted around it, perhaps almost as far north as the present Manukau Harbour mouth. After about 0.6 Myr ago, the Waipa River route into the Manukau Harbour was likely blocked by eruptions of the South Auckland basalt field (chapter 9), after which it would have discharged directly onto the west coast via the present Port Waikato river mouth.

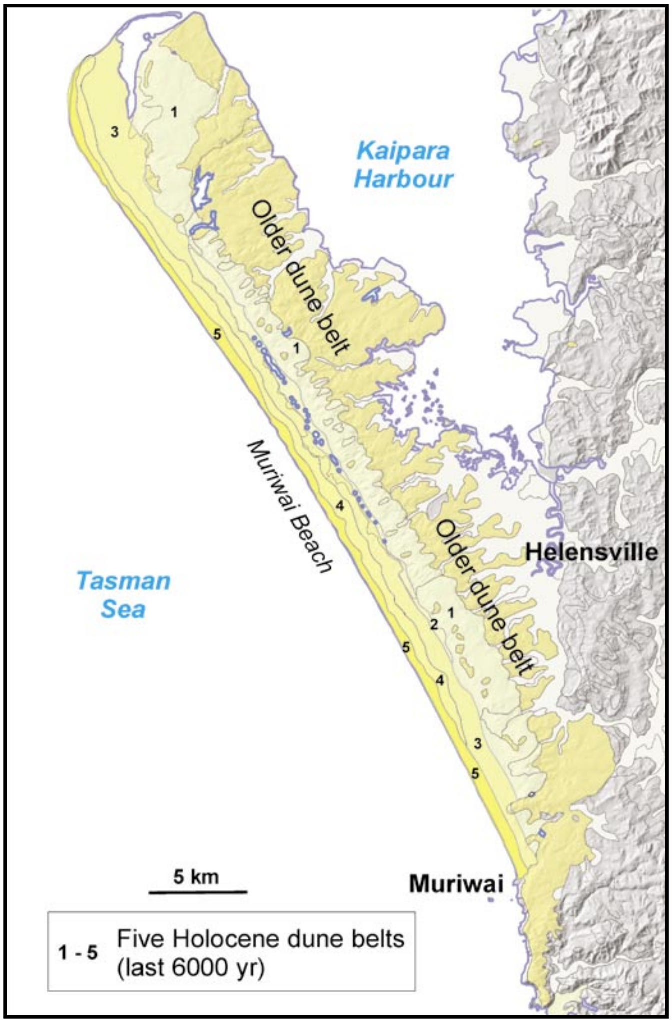
The precise time of growth of the older parts of the west coast sand dune systems is unknown, except where there are identified volcanic ash beds within the sequence (chapter 10). Little ash was blown as far as Northland, but tephra layers from the large eruptions 1.2-0.9 Myr ago, show that at least some of the sequence that forms Awhitu Peninsula and the south Muriwai dune lands was deposited at this time. It seems likely therefore, that the excess sand supply around 1 Myr ago, may have also created the older backbones of the other three major sand-dune barriers in northern New Zealand – South Kaipara, North Kaipara and Aupouri (Ahipara to Cape Reinga) peninsulas (*11.26, 11.30, 11.53*). Today these can be seen as high-standing, eroded remnants of partly-cemented, often weathered, iron-stained sand-dune deposits. Similar deposits occur today mantling older rocks on the coast of the northern Waitakere Ranges (Te Henga-Muriwai).

A second period of enhanced sediment input into the west coast sand system occurred during the period of large eruptions from the Whakamaru and other caldera volcanoes, 0.35-0.1 Myr ago (loosely called Hamilton Ash beds). At that time, however, the Waikato River was probably flowing directly into the Firth of Thames on the east coast, but there is plenty of evidence that extensive ignimbrite and rhyolitic ash came over the catchment divide and into the Hamilton Basin and a good deal of this was probably washed down the Waipa River and out to the west coast at Port Waikato. It appears that a large amount of ash blew northwest during this period as 1-3.5 m thickness of Hamilton Ash beds mantle the South Auckland basalt volcanoes and several thin ash beds of this age occur in the eroding sand dune sequence near Baylys Beach on the North Kaipara barrier. It appears that sand-dune belts, several kilometres wide, were added at this time along the Tasman Sea sides of most of the west coast barriers, especially Awhitu Peninsula and from the North Kaipara barrier northwards (*11.26*).

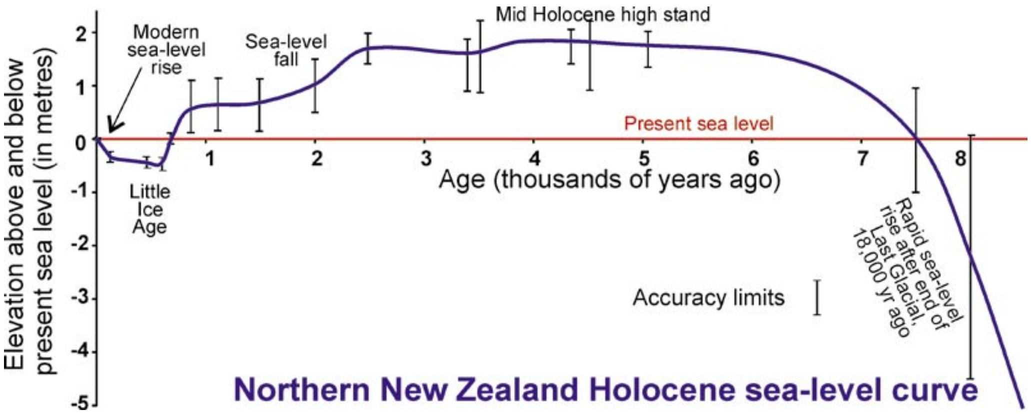
The third, much shorter and more recent period of barrier building, has been in the last 22,000 yr and this coincided with another major, and better dated, phase of sand-dune barrier accretion. The huge Oruanui eruption from Lake Taupo 25,000 yr ago over-filled the Waikato River valley down to the Hauraki Rift with volcanic sediment and resulted in its deviation west into its present course, about 22,000 yr ago. Since that time, vast quantities of sediment derived from the Oruanui and more recent Taupo eruption (AD232), have been transported from the central North Island down the Waikato and into the west coast sand system.

Holocene sand-dune belts

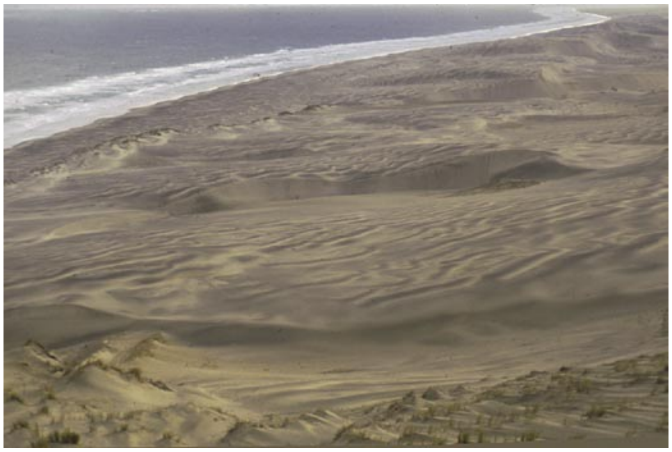
For most of the recent period since the Waikato River began flowing out to the west coast, sea level has been lower than present, but rising (18,000-7500 yr ago). Sea level rose to 1-2 m above its present level by about 7000 yr ago (*11.27*), but because of the extra Waikato River sediment input, the west coast sand budget was probably already close to equilibrium or even with excess sand. Between 3000 and 600 yr ago sea level around New Zealand fell by about 2 m (*11.27*) and



11.26 Map of the South Kaipara sand-dune barrier showing the distribution of the older, weakly-cemented, partly eroded sand-dune belt, which forms the high backbone of the barrier. During the latest sea-level high stand, five linear sand-dune belts have been added along the west side of the barrier, each possibly thrown up during a period of slight sea-level fall, since a peak 1-2 m above present 7000-3000 yr ago. A line of narrow lakes or swamps occurs in the boundary depressions between dune belts 2 and 3. Map modified after Schofield (1975).



11.27 Graph showing a generalised Holocene sea-level curve for northern New Zealand over the past 8500 yr. Modified from Hayward et al. (2015) and Clements et al. (2016).

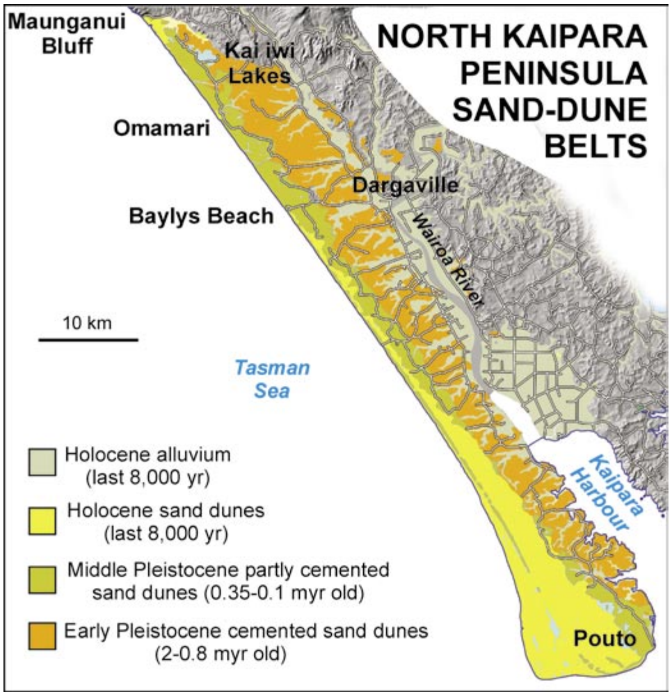


11.28 Young sand dunes that have been added to the seaward side of the southern tip of the North Kaipara sand-dune barrier within the last 1000 yr, west of Pouto.

11.29 A small section of Ninety Mile Beach, north of Kaitaia, showing the youngest of a number of sand-dune belts that have been accreted along the west coast of the Aupouri sand-dune tombolo during the last 7000 yr (Holocene). The foredune has ponded a linear belt of small lakes behind it. The older sand dunes behind have been planted in exotic pine forest like many parts of Northland and Auckland's west coast dune barriers.

during this time the Kaipara, Aupouri and Cape Karikari barriers doubled in width through the seaward accretion of a number of shore-parallel belts of sand dunes (*11.26, 11.28-11.30, 11.53*).

The growth of these young coastal dune belts was a result of the excess sand thrown up on the beaches in front of them as a result of the sea level fall. Sea level fall probably occurred in several steps, each of which may have resulted in an episode of sand-dune building. In many places there are elongate hollows between the



11.30 The North Kaipara sand-dune barrier appears to have been built by coast-parallel sand-dune belts that accumulated during three periods of enhanced sand supply to the west coast system from large eruptions in the centre of the North Island. Map derived from Edbrooke and Brook (2009).

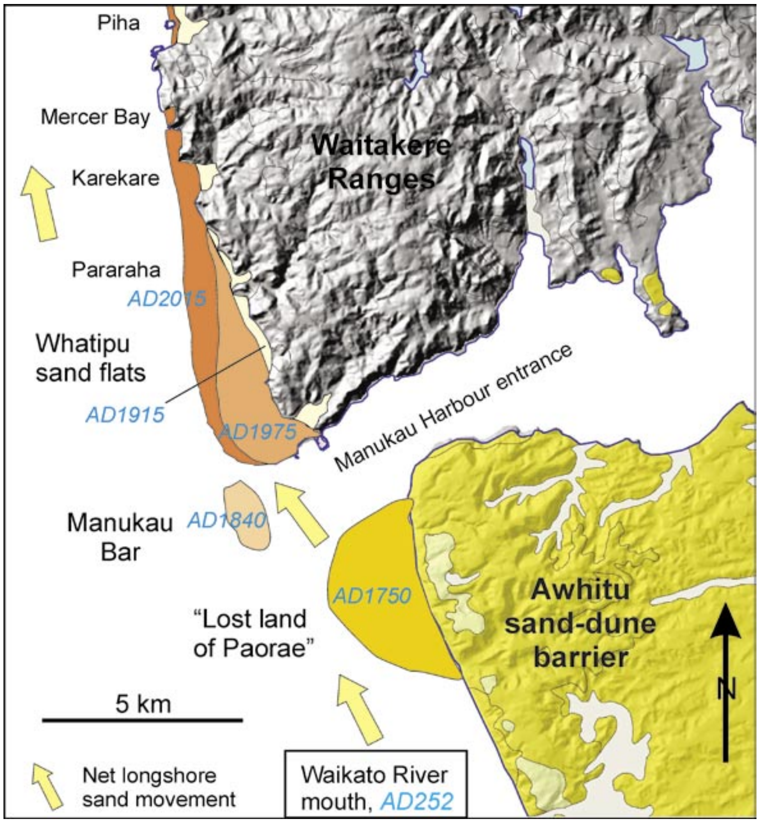
11.31 Kai-iwi lakes, north of Dargaville, fill hollows within the North Kaipara sand-dune barrier on Northland's west coast. They occur in a depression between the older barrier and a belt of younger dunes that was added about 300,000 yrs ago. Photographer Alastair Jamieson.

different dune belts, which are now occupied by lines of linear dune lakes or swamps (*11.26, 11.29*). In some places excess sand accumulated at the bottom of a cliff or steep slope (e.g. Awhitu Peninsula) and strong winds blew the sand up steep valleys or guts to build small dune fields on the cliff tops and beyond.

Whatipu sand flats

Sea level is currently rising (0.3 m since the 1880s) and now most of New Zealand's beaches and foredunes are eroding slowly as nature tries to restore the equilibrium between sand on the beach and the inshore seafloor. An exception to this occurs along the coast of the southern Waitakere Ranges, where the Whatipu sand flats and sand dunes have built out 1 km from the rocky cliffs since the 1920s (*11.32, 11.33*). This is one of the few areas of sand accretion on the coast of New Zealand at the present time and it is a result of a unique situation. Maori traditional histories document that a similar large sand flat and dunes ("the lost land of Paorae") existed offshore from the north end of the Awhitu sand-dune barrier in the 18th century and was eroded away by the sea over a number of decades around AD1800. In the first half of the 19th century large sand islands were present outside the entrance to the Manukau Harbour. It would appear that a large slug of excess sand has been moving northwards in this area. Observations in the last 50 years show that this northwards longshore drift of sand continues today and in the last decade it has all but filled up Karekare Bay and its front is advancing into Piha. A likely cause of this pulse of excess sand is

11.32 This 1 km-wide sand flat with low dunes at Whatipu, southern Waitakere Ranges, built out from the cliffs in the early 20th century and currently is moving slowly northwards as a result of longshore drift, driven by dominant southwest swells. This photo was taken in the 1990s and the flat is now covered in more vegetation. The northern tip of the Awhitu Peninsula sand-dune barrier can be seen across the Manukau Harbour entrance. Photographer Alastair Jamieson.



11.33 Right. In the last 250 yr, sand that once formed an extensive coastal flat, attached to Awhitu Peninsula, has moved northwards across the mouth of the Manukau Harbour and built the Whatipu sand flats. At present the sand is continuing its gradual journey northwards up the west coast of the Waitakere Ranges. This appears to be a pulse of excess sand that was discharged onto the west coast by the Waikato River, soon after the AD232 Taupo eruption. This excess sand has been slowly moving up the coast since then.

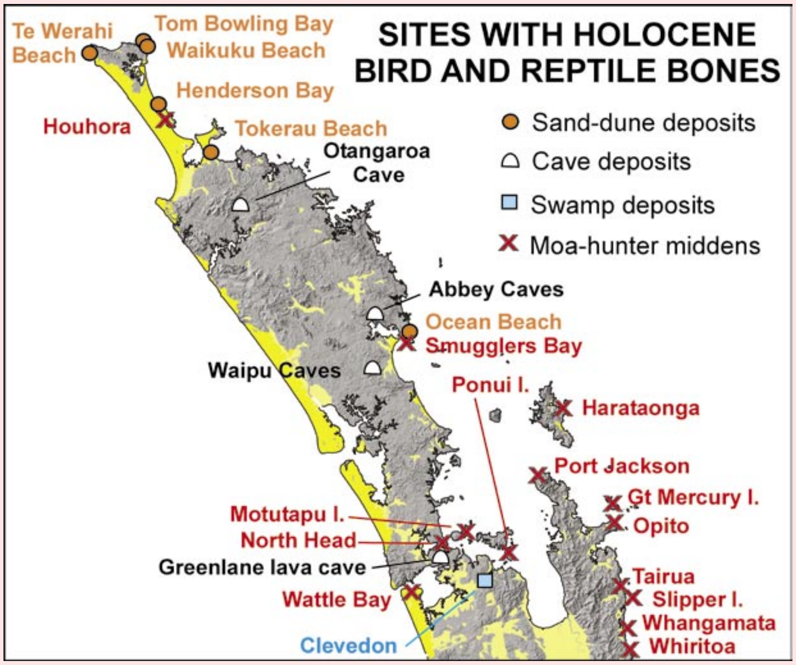
the AD232 Taupo eruption and break-out flood from Lake Taupo, which would have resulted in a large quantity of ignimbrite-derived sand being carried down the Waikato River into the west coast sand system over just a few decades after the eruption. Since then, the sand has moved northwards at a net rate of about 2.5 km per century – a rate compatible with the recent record of movement. Although the excess sand is progressing northwards there have been local pulses of sand build-up and sand erosion that have lasted a few months to a few decades.

Now that this pulse of extra sand has moved north past the coast of Awhitu Peninsula, this sand-dune barrier is starting to erode on its western side particularly at the northern end. Not helping this situation is the fact that the natural sediment supply coming down the Waikato River has been greatly reduced in the last century by the construction of hydroelectric dams upstream and sand dredging in its lower reaches.

Box 49. FOSSIL EVIDENCE OF MOA AND OTHER VERTEBRATES

No fossilised bones of land vertebrates older than Holocene (last ~10,000 yr) have been found so far in northern New Zealand. Preserved bones of birds, and sometimes reptiles and amphibians, have been found in Holocene sand-dune, swamp and cave deposits (mostly younger than 6000 yr) and also in the midden (rubbish heaps) of early Maori (younger than 800 yr).

The only significant find of bones preserved in a peat swamp has been a large collection of bones from three species of moa, including two complete skeletons, which were excavated from a swamp near Clevedon in the early 19th century. Bones are often found preserved buried in sediment or even in the open on the



11.34 Locations where rich deposits of bones from moa and other birds and reptiles have been found in northern New Zealand. All are younger than 10,000 yr (Holocene).

Box 49. Fossil moa and other vertebrates .. continued

floors of limestone caves and fissures. Since there are few good limestone karst areas in northern New Zealand, the number of bone finds in these situations have been small. The two richest deposits have been in the extensive Waipu Caves network and in a small, seldom-visited cave at Otangaroa, in northern Northland. Moa bones have also been found in a small fissure near Abbey Caves, Whangarei. The bones of a number of smaller birds have been recovered from the Waipu and Otangaroa caves, as have bones of four species of the native New Zealand frog, *Leiopelma*, including two of the three known extinct species. Also found in these cave deposits are bones of the only known extinct New Zealand skink (*Oligosoma northlandica*). There are probably a number of other extinct species, but they cannot easily be recognised from their skeletal remains. The bones of the extinct Northland skink are recognised because they are larger than any living New Zealand species, with the original animal probably being up to 25 cm long. Moa bones were found in a lava cave on a building site at Greenlane Hospital in Auckland in 1957.

The richest record of the pre-European bird fauna of northern New Zealand comes from bones that have been buried in sand dunes in the Far North – mostly behind Te Werahi Beach (Cape Reinga), Tom Bowling Bay and Waikuku Beach (North Cape) and Tokerau Beach (Doubtless Bay). In the latter half of the Holocene (last 4000 yr), all these sand-dune systems have gone through cycles of active sand-dune building and stable periods of forest establishment across them. As with the Kaipara sand-dune barriers, the episodes of sand-dune building probably occurred during times of minor sea-level fall, such as 1000-600 yr ago. The bones now found eroding out of the dune deposits are from birds that probably died on the dunes and were buried by their advance. In the Far North, at Tom Bowling Bay, Te Werahi and Waikuku beaches, the bones eroding out of the sand dunes occur together with multitudes of the large bleached shells of the flax snail (*Placostylus*; *11.35*).

The bird bones present include a mix of land species from forest, open shrubby country and wetland, together with sea birds. Many of the larger, more robust bones came from species that are now extinct and include the New Zealand crow, pelican, adzebill, raven, laughing owl, and North Island takahe, as well as smaller extinct birds such as the huia, North Island snipe and stout-legged wren. The New Zealand pelican was our country's heaviest flying bird, with some individuals weighing up to 12 kg – very close to the world's heaviest flying bird. Also present in the dunes are bones of species that were once widespread around New Zealand, but no longer live on the mainland North Island, such as kakapo and the ancient reptilian tuatara.

The most robust bones in the sand dunes are those of the extinct, flightless moa. Four of the nine known species lived in the North Island and bones of all four have been found in the sand-dune deposits in the Far North. These were the Little Bush Moa (*Anomalopteryx didiformis*), Mappin's Moa (*Pachyornis geranoides*), the Stout-legged Moa (*Euryapteryx curtus*) and the North Island Giant Moa (*Dinornis novaezealandiae*). The Giant Moa (weighing up to an estimated 240 kg) was the tallest bird in the world (up to 3 m tall with neck outstretched), but not the heaviest. The most common moa in northern New Zealand appear to have been the Stout-legged and Mappin's moa (*11.36, 11.38*), both of which are inferred to have lived in the mosaic of grassland, shrubland and forest habitats around the northern coasts and dunes. The other two moa are inferred to have preferred the high rainfall forest of inland northern New Zealand, though they periodically ventured out onto coastal dunes.

Bones of all four North Island moa species occur in middens from the early periods of Maori occupation

11.35 Parts of the fossilised skeleton of a Mappin's moa (Pachyornis geranoides) *and two flax snail shells* (Placostylus ambagiosus) *unearthed by moving wind-blown sand in the 2000-3000 yr old sand dunes behind Tom Bowling Bay, North Cape. Width of photo 50 cm. Photograph by Phil Millener.*

11.36 Bones from the stout-legged moa, Euryapteryx curtus, *that were buried by blowing sand behind Tokerau Beach in Northland about 1000 yr ago (Late Holocene) and recently exhumed by wind erosion. In collections of Auckland Museum. Photograph 60 cm across. Photo coutesy of Auckland Museum.*

Box 49. continued

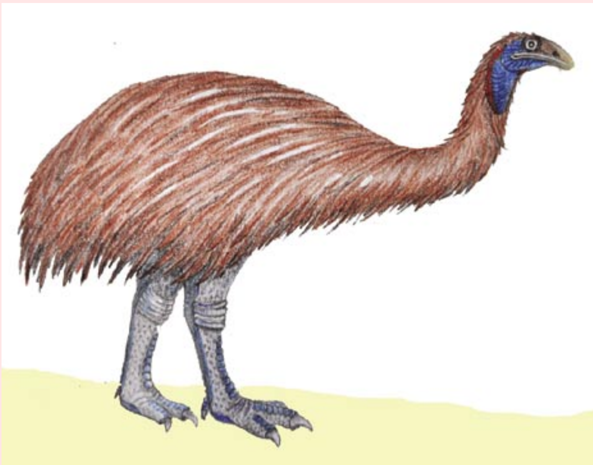
(800-400 yr ago). There is no convincing evidence that any moa survived beyond AD1600. The arrival of humans in New Zealand, around 800 yr ago, resulted in the extinction of the moa and other bird species mentioned above. The larger bird species were hunted for food, but other human-facilitated impacts came from predation by feral dogs and kiore (Polynesian rats), and forest clearance. Moa were clearly a much prized resource in those early days as a source of food, feathers and skins for clothing, and bones for fish hooks and pendants. In northern New Zealand, older middens containing butchered moa remains include those found at Houhora in Northland; North Head and Motutapu Island in Auckland; and Port Jackson, Opito, Tairua, Whangamata and Whiritoa on the Coromandel Peninsula.

Other evidence of the former presence of moa comes from fragments of moa egg shells and rare intact eggs found in the Far North sand dunes. The most widespread sign of the former presence of moa are their polished gizzard stones that occur in soil layers throughout northern New Zealand. Gizzard stones are also found in eroding sand dunes, including the older sand-dune barriers that may have been deposited as far back as 1.5 Myr or more. Moa fed on a range of fibrous twigs and leaves taken from low trees and shrubs and they needed stones in their gizzard to help masticate the plant material, as they lacked teeth to do this job.

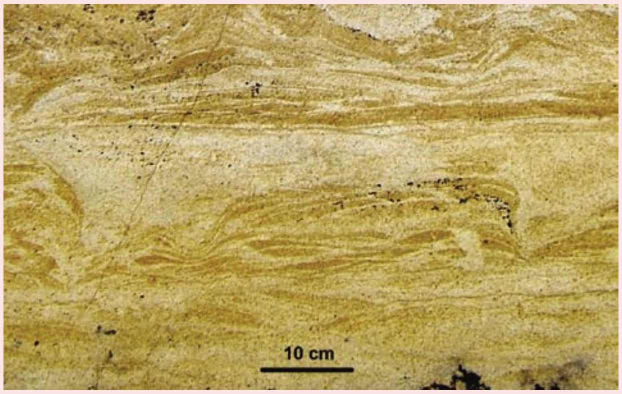
Most gizzard stones (gastroliths) are 1-2 cm in size (*11.37*) but they can be smaller or larger, up to 6 cm across. The most common rock types for gizzard stones were various kinds of abrasion-resistant quartz, such as chert, jasper and even common opal. The moa may have preferentially picked up and swallowed the harder rock types, possibly attracted by their glinting appearance, but undoubtedly softer rocks they may have picked up soon ground down in their gizzard and the more resistant quartz ones became dominant. Sometimes a concentration or heap of moa stones are found representing the contents of one moa gizzard left behind when all the rest of the moa remains had decayed away. The most distinctive moa gizzard stones are those that have a polished concave side that can only have been formed by another stone grinding against it inside a gizzard.

The rarest preserved evidence of the former presence of moa is their footprints. In New Zealand, there are ten recorded sites where moa footprints have been recognised in plan view by their distinctive three-toed impressions preserved in weakly consolidated mudstone or ash. One of these sites is in northern New Zealand, at Henderson Bay in the Far North. There is also one probable footprint site in west Auckland, where the impressions of moa footprints can be seen in vertical cross-section in 1 Myr-old sandstone layers deposited within the South Kaipara sand-dune barrier sequence near Muriwai (*11.39*).

11.37 A selection of moa gizzard stones from sand-dune deposits at Mitimiti, west coast of Northland. Note that all are rounded and polished white or cream chert that would have been more resistant to abrasion in the moa gizzards than the local basalt rocks. Width of photo 12 cm. University of Auckland collection.

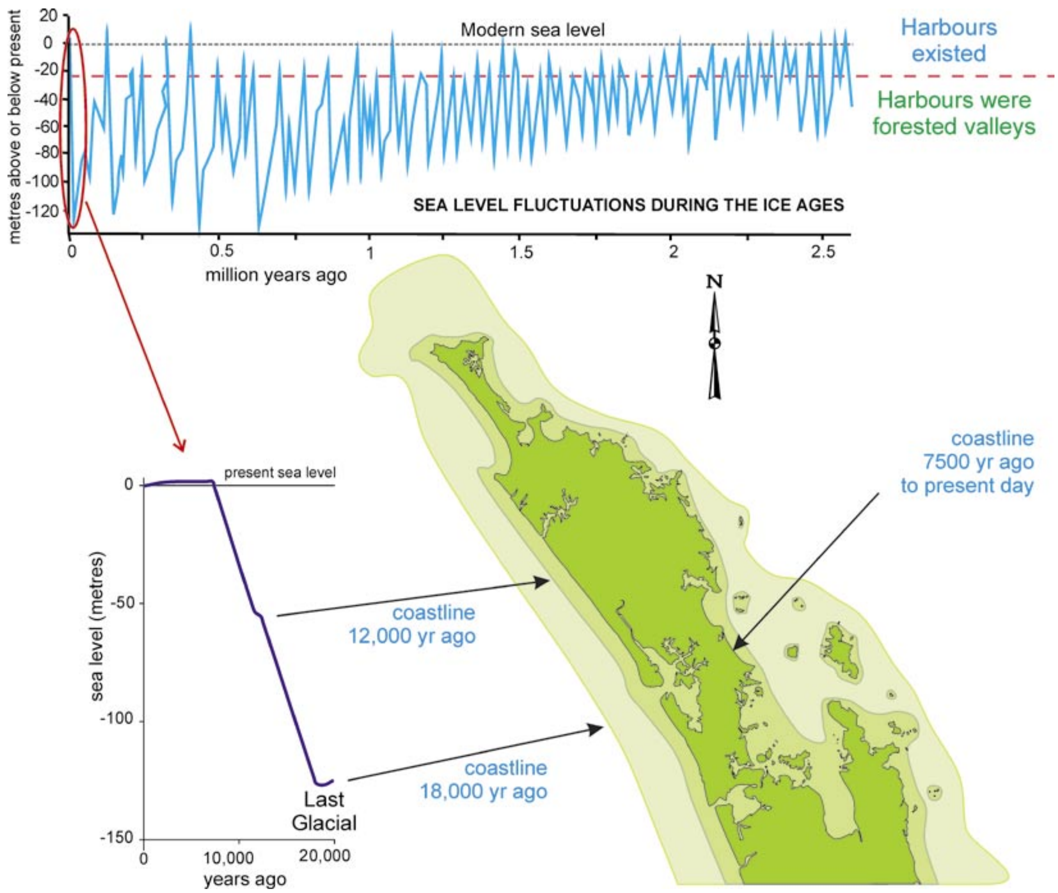


11.38 A stout-legged moa like this may have left the footprints in wet sand on the edge of a dune lake near Muriwai, about 1 Myr ago. Drawing by Margaret S. Morley.



11.39 Vertical cross-section through layers of sand that were deposited on the damp edge of a dune lake near Muriwai about 1 Myr ago. The two depressions pushed into the iron-stained sand layers and filled with lighter-coloured sand are inferred to be the fossil footprints of extinct moa.

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.

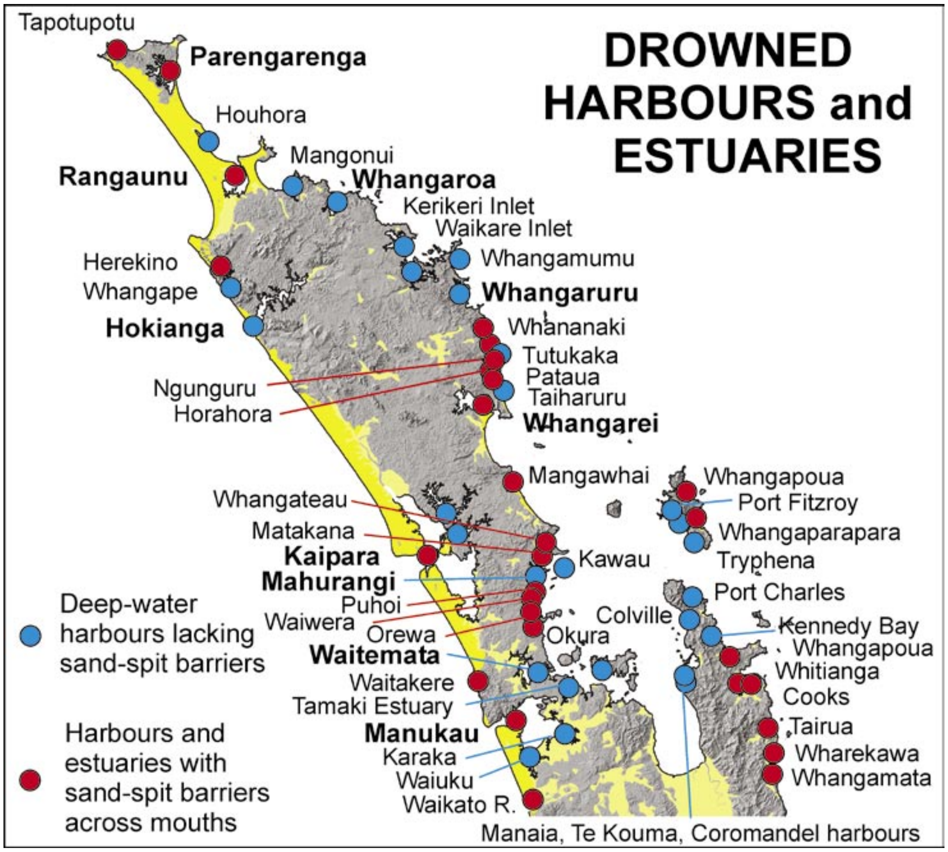
COASTAL LANDFORMS FORMED BY DROWNING

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

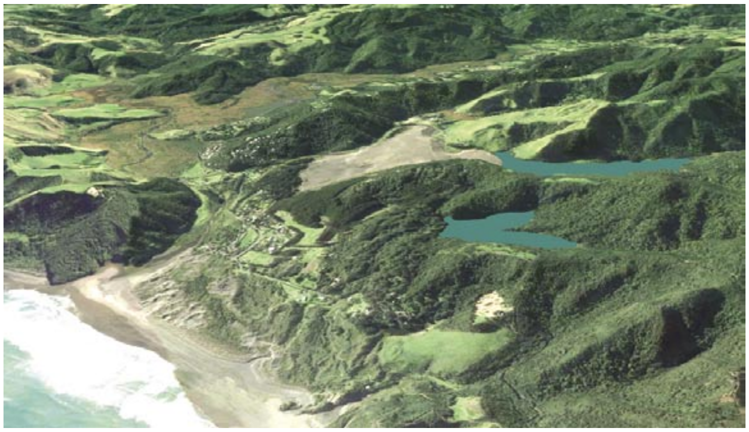
Where there was a more plentiful supply of coastal sand, it filled all the eroded valleys in the drowned coastal plain as sea level rose. The excess sand started accumulating as sand-dune spits just inside the sheltered mouths of drowned valleys. In some instances, like at Parengarenga, the young sand-dune 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.*

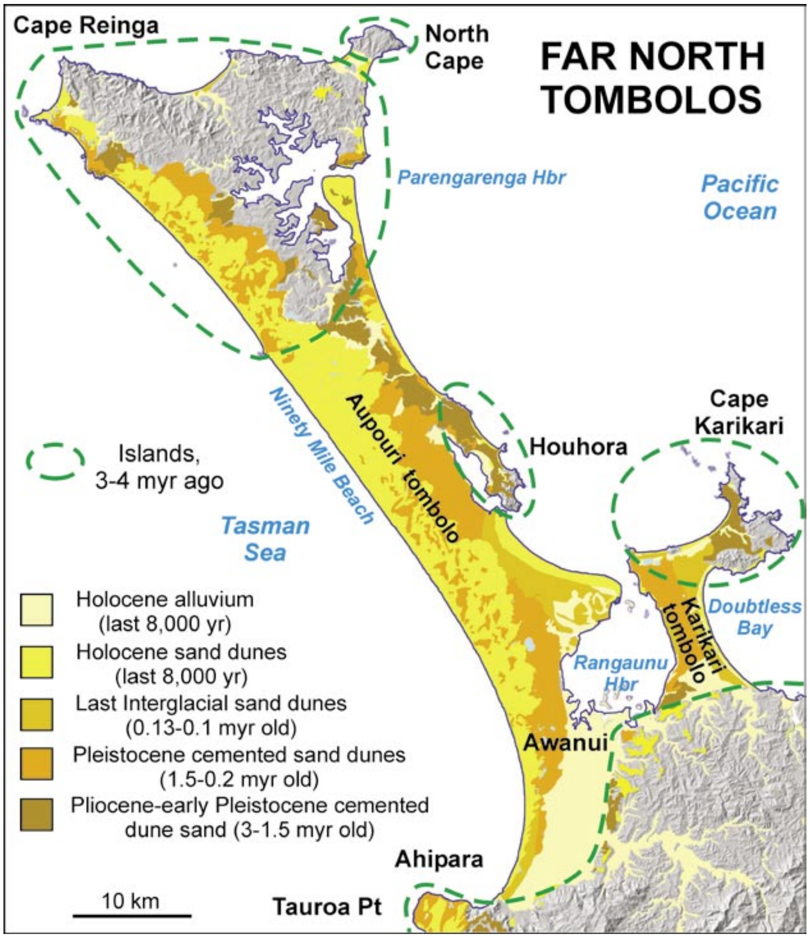
11.49 ***Sand spit:*** *View south over the Pauanui sand-dune spit, eastern Coromandel Peninsula, that built up across the mouth of the flooded Tairua Valley in the last 7500 yr, creating the sand- and mud-filled tidal estuary behind.*

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 tombolos, over the last 2-3 Myr. Base map from GNS Science's QMAP.

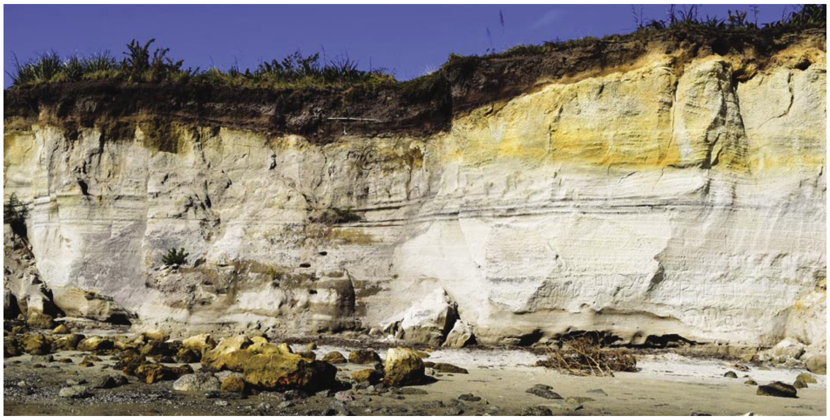
sand-dune spit or barrier across the mouth of a large embayment, enclosing a wide tidal harbour in behind, such as Parengarenga, Rangaunu, Whangarei, Mangawhai, Omaha, Orewa, Whangapoua (Great Barrier) and Whangapoua (Coromandel Peninsula). The shape of these sand-dune spits indicates how they grew and 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:*** *Motukiore 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 cuspate 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 cuspate (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.*

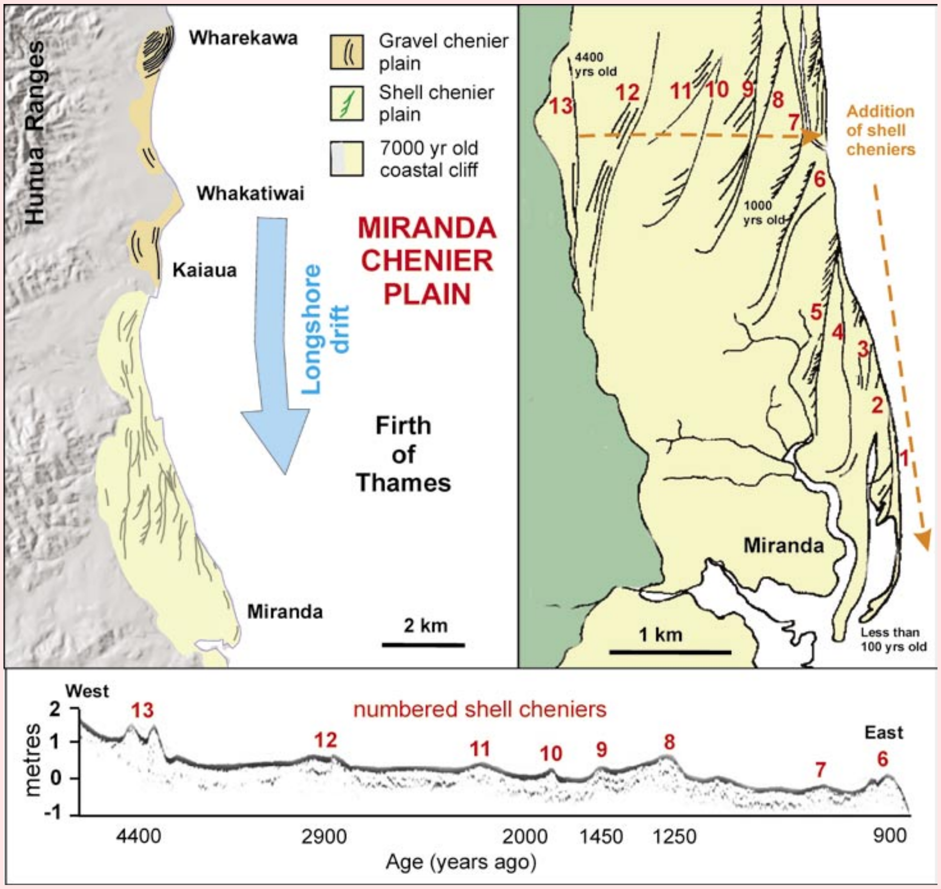
Box 50. MIRANDA CHENIER PLAIN

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 Kaiaua.

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 Kaiaua. 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.

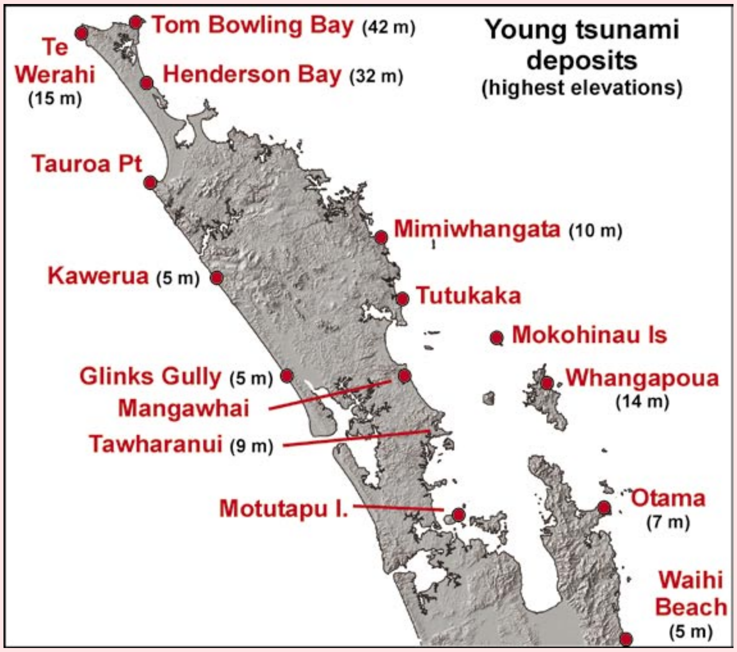
11.69 This recently formed shell chenier had just formed and attached to the Miranda chenier plain when photographed in 1980. Within ten years, it had migrated landward to form a new shore-parallel, south-migrating beach ridge.

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).

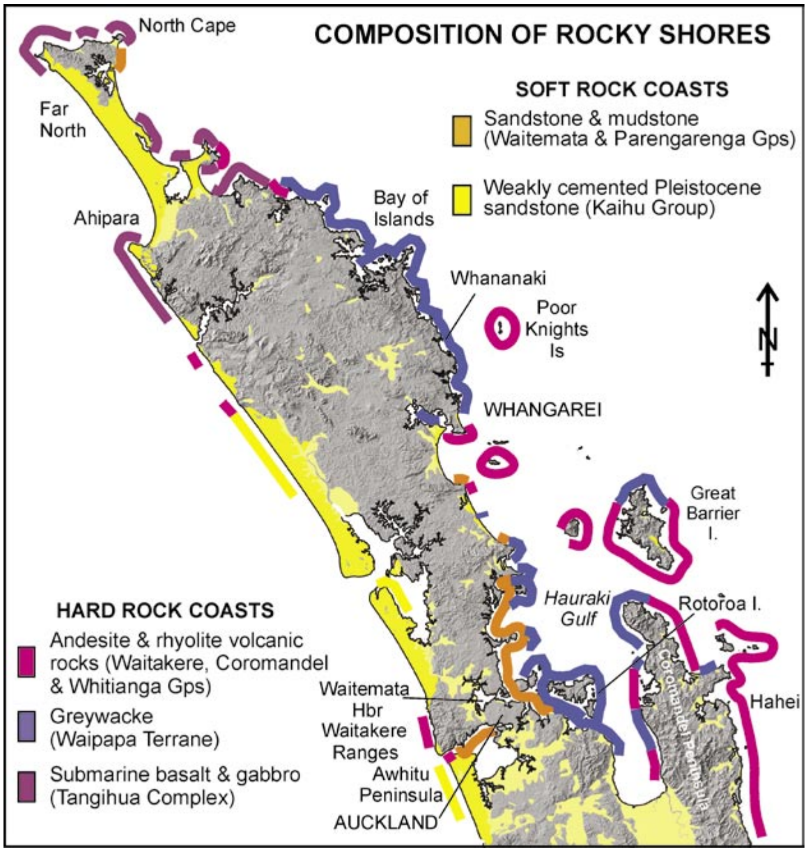
11.71 Deposit of rounded pebbles and thick shells located up to 14 m above MSL in the sand dunes behind Whangapoua Beach, northeast Great Barrier Island. They are inferred to have been picked up from the 20 m-deep sea floor, between Rakitu Island (left) and Haratounga (right), by a large tsunami about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



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

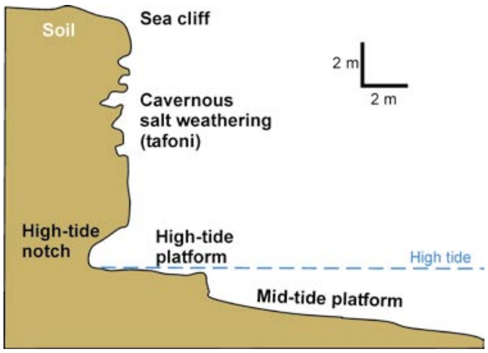
How far hard-rock cliffs have retreated since sea level uncovered them most recently (about 8000 yr ago) can often be estimated by the width of the shore platform at their feet. These platforms are often 5-20 m wide on the harder volcanic rock shores right around northern New Zealand (*11.72*). Eroding 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.

11.73 ***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.*

11.74 ***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 Kaitaia. 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 plaftorm - 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 level 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.*

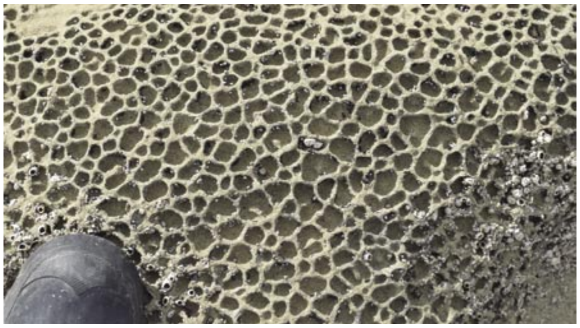
and mudstones of the Waitemata Sandstones around Auckland can influence the local shape of the rocky shoreline. The sandstone layers are always more resistant to erosion than the thinner mudstone beds between. Thus the sandstone layers project out slightly from the face of the cliff and above the surface 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.

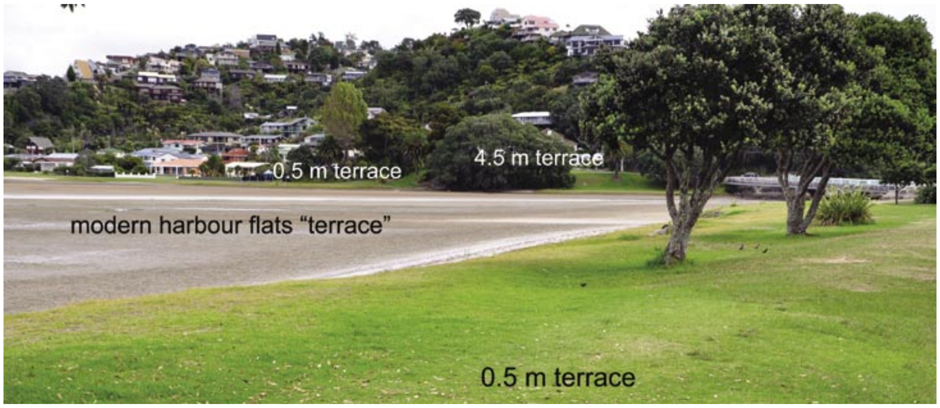
Coastal terraces are recognised on land at levels above the influence of present-day sea level processes. Thus these terraces were either deposited when sea level was higher than it is now, or there has been uplift of the land since the terrace was formed. In chapter 8 the extensive Late Miocene erosion 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 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

11.95 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.



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 Patauoa 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.

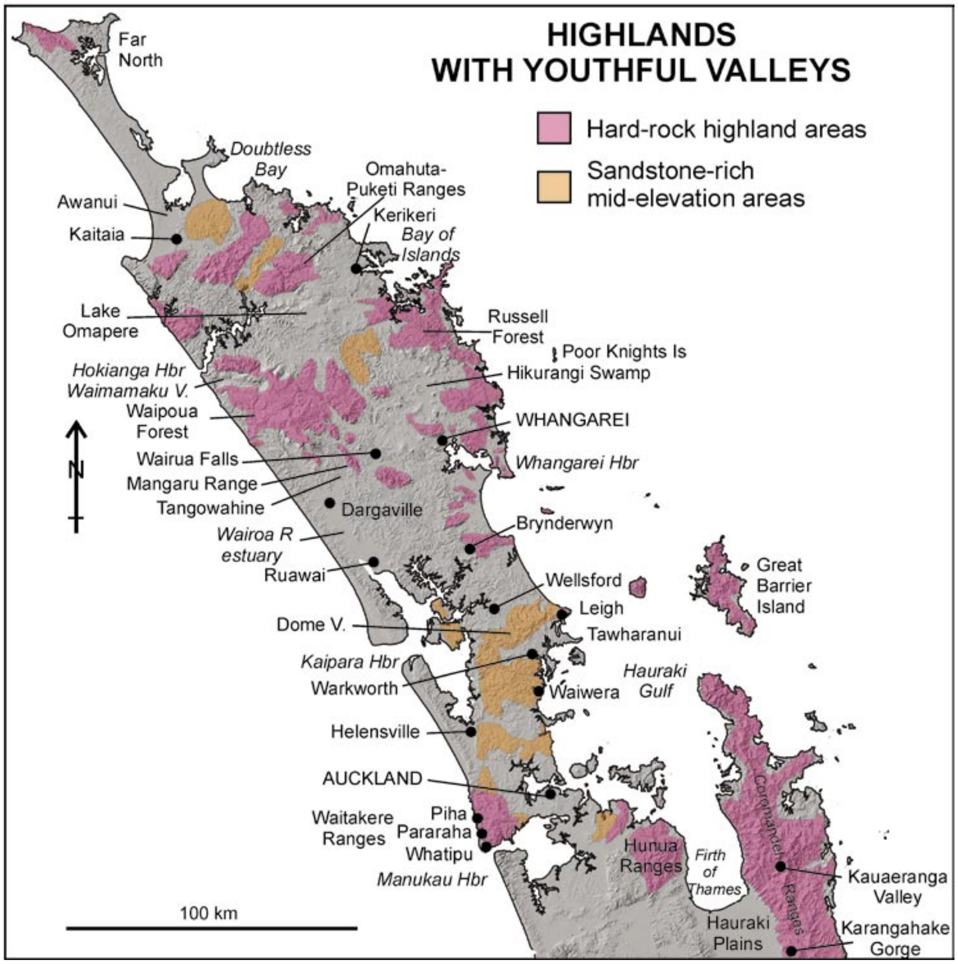
12.1 The 5-20 m-thick orange clay that overlies fresh blue-grey greywacke in the Glenbervie Quarry, Whangarei, indicates the extent of deep weathering that has occurred in northern New Zealand.

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 Otaua 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.

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 allochthon 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, 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.

12.5 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 Stm, 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. Owharoa 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, Otaua 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.

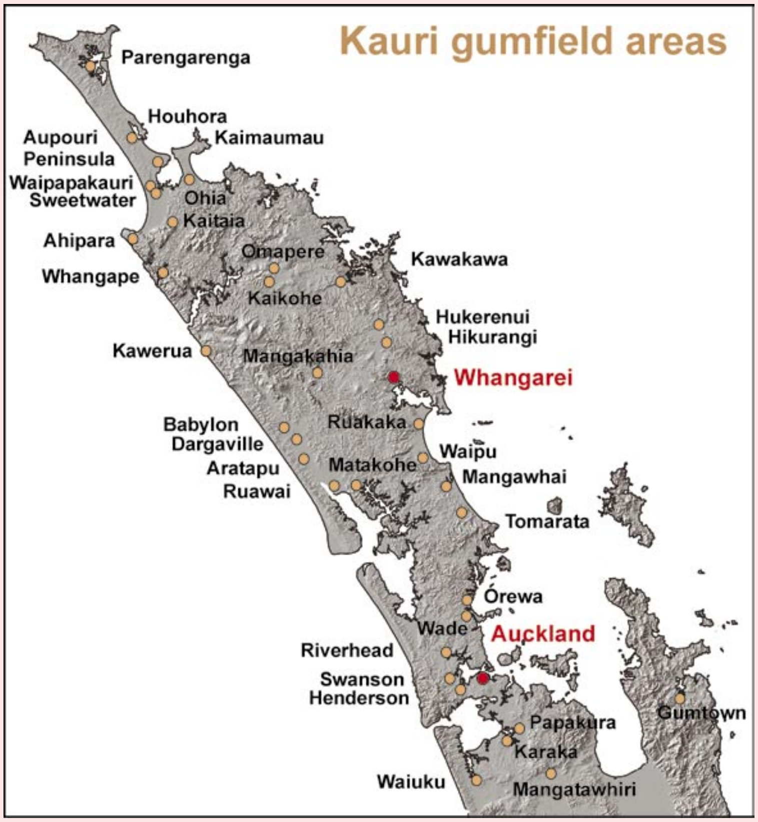
12.14 4 m-high Oakley Creek waterfall in Waterview is the largest waterfall on the Auckland Isthmus. It is held up by several thick Waitemata Sandstone beds and could be the upstream-migrating nickpoint (former base level) from the Last Interglacial high sea level, 120,000 yr ago.

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 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



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

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

12.17 A large piece of high quality kauri gum.

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.

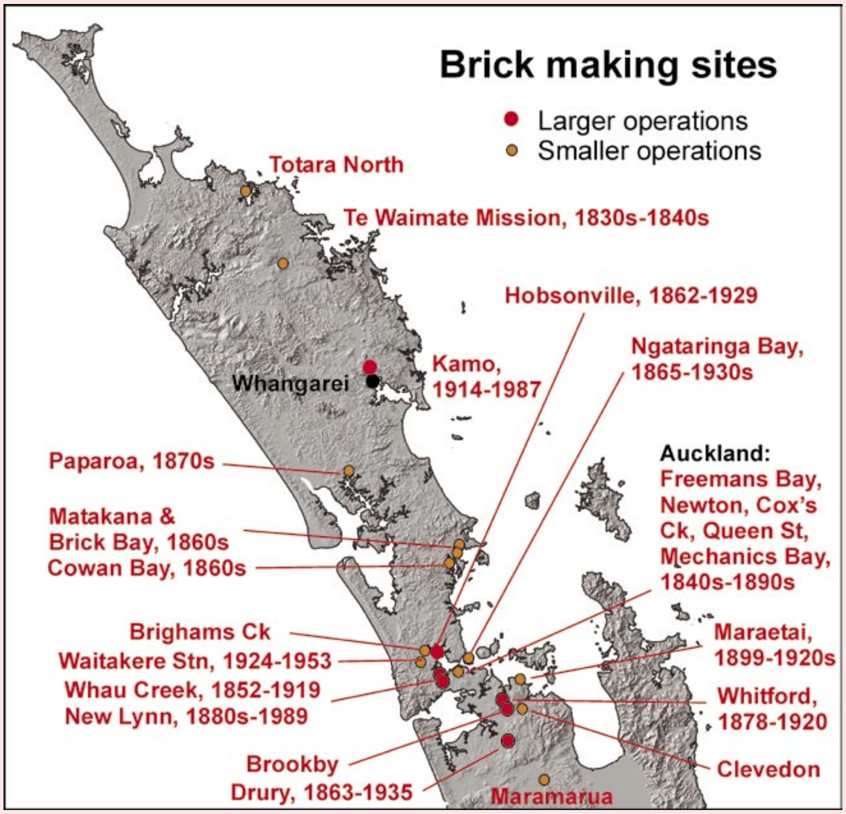
Lava, erupted from a number of Northland and Auckland's younger basalt volcanoes, flowed down valleys before stopping, cooling and leaving a ribbon of solid basalt rock filling the former stream course. If the water flow in the lava-filled valley was relatively small, it took to flowing underground through 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 Islands Field, and Whangarei (*9.43*) and Paranui falls in the Whangarei Field.

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

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.

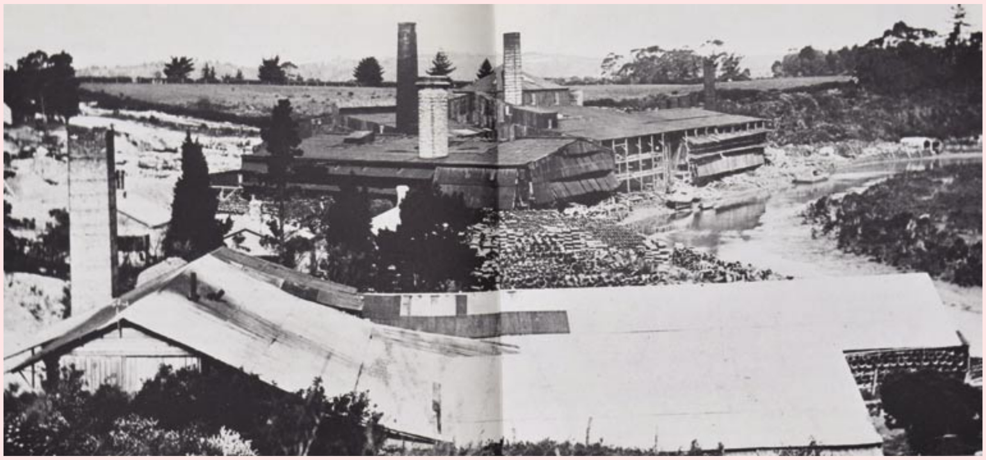
Box 53. CLAY AND BRICK MAKING

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).



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

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 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.

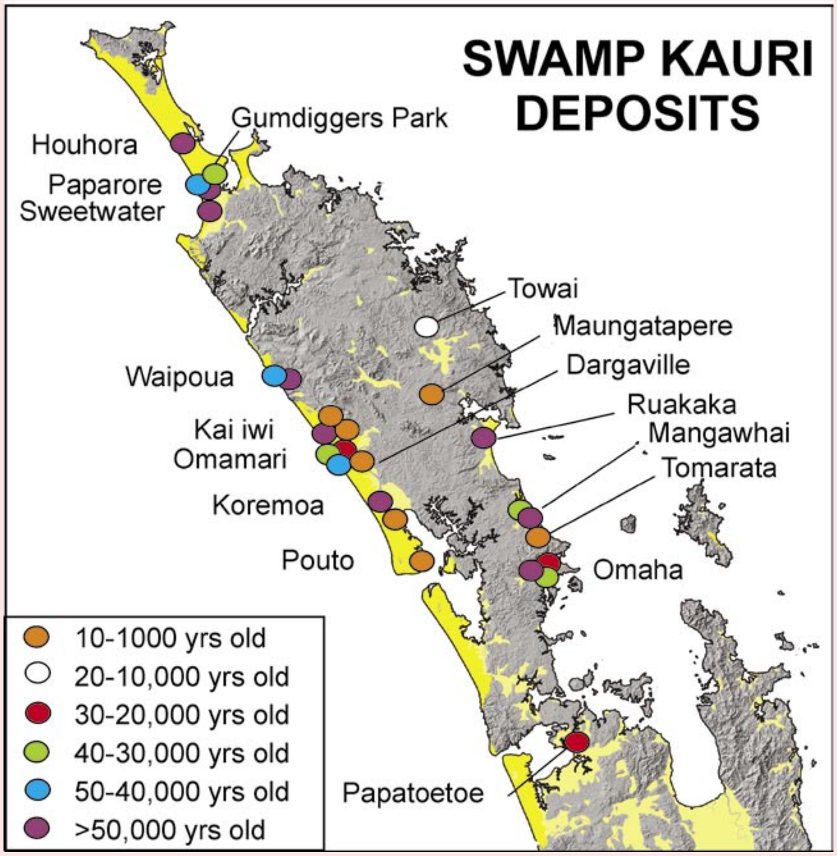
In forests there is a natural procession of old trees dying, falling over and rotting away, and being replaced by new trees. Only in special conditions is the wood of fallen trees preserved, usually by being submerged in water, often in a peat swamp, where all oxygen is excluded and decay does not occur. 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.

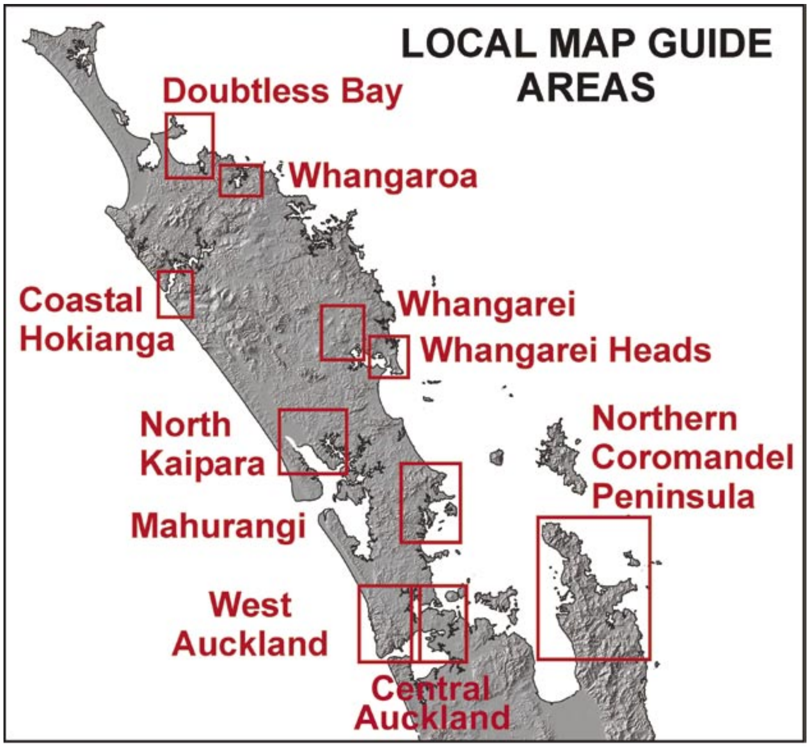


12.26 Distribution of swamps containing kauri logs that have been radiocarbon dated. Data from Turney et al. (2007), Boswijk et al. (2014).

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. 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.

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.

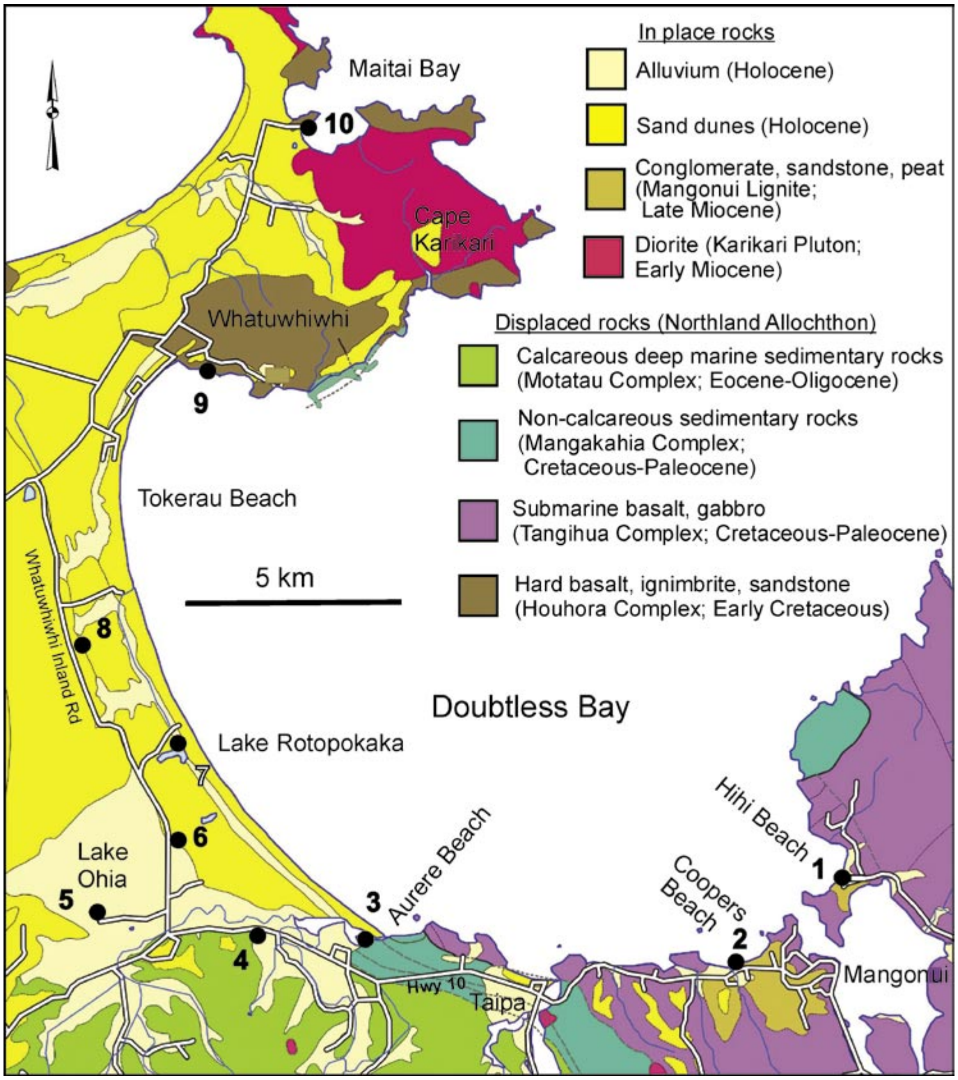
Chapter 13. LOCAL MAP GUIDES TO FEATURES OF INTEREST



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 Whatuwhiwhi 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. Hihi Beach Late Miocene fluvial valley fill (*8.14*)
In cliffs and shore platform at low tide behind southern end of Hihi 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 Puketu 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.

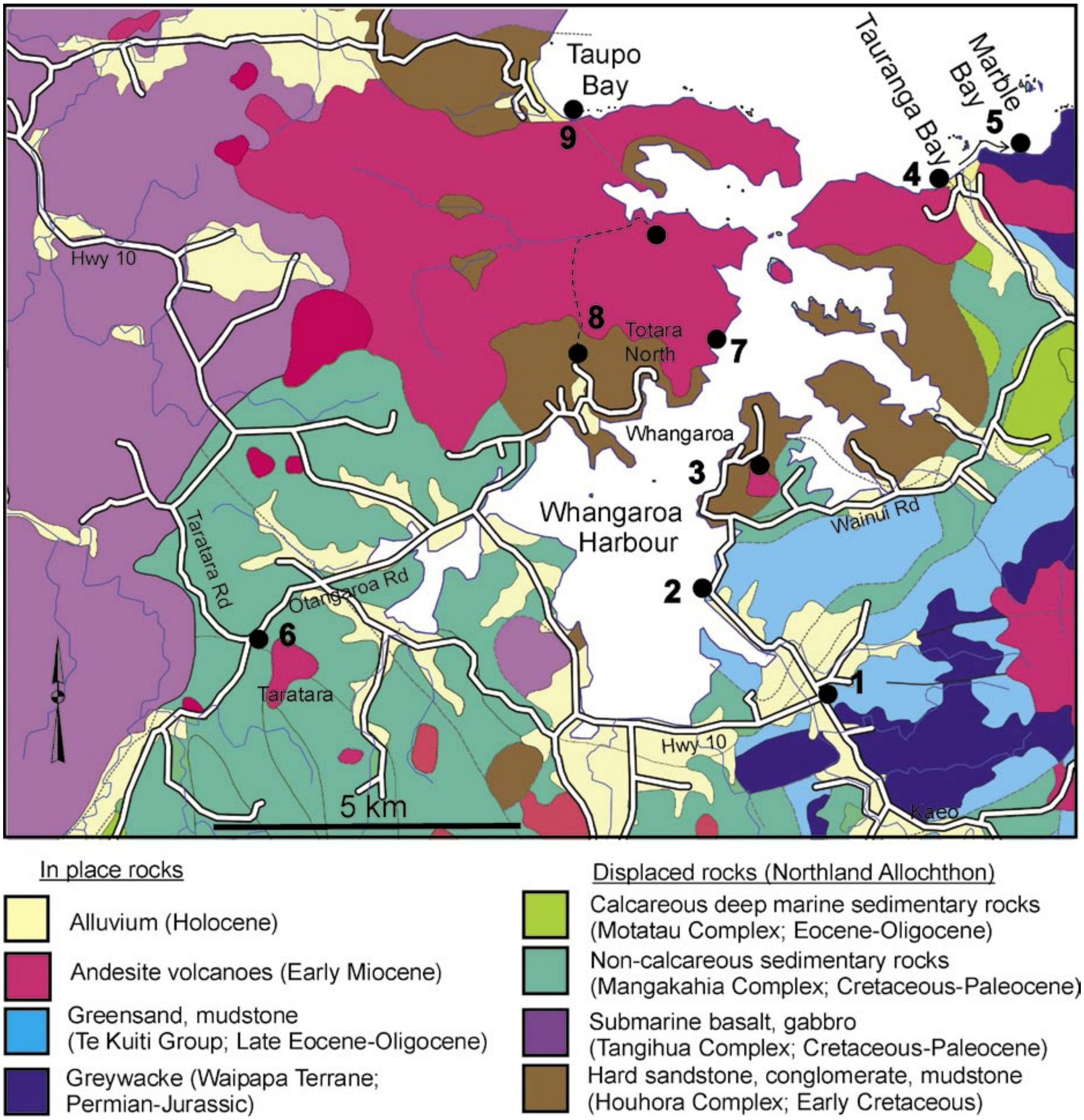
8. Karikari tombolo and sand dunes (*11.53*)
View as you drive along Whatuwhiwhi Inland Rd. The tombolo is a composite of sand dunes that has been built during stands of higher sea level over many Ice Age climate cycles. The oldest part of the tombolo, built more than 200,000 yr ago, is on the west side 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



1, 2. Greensand near Kaeo (*13.6*)
In road cutting opposite east end of Kaeo 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 Kaeo.

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.

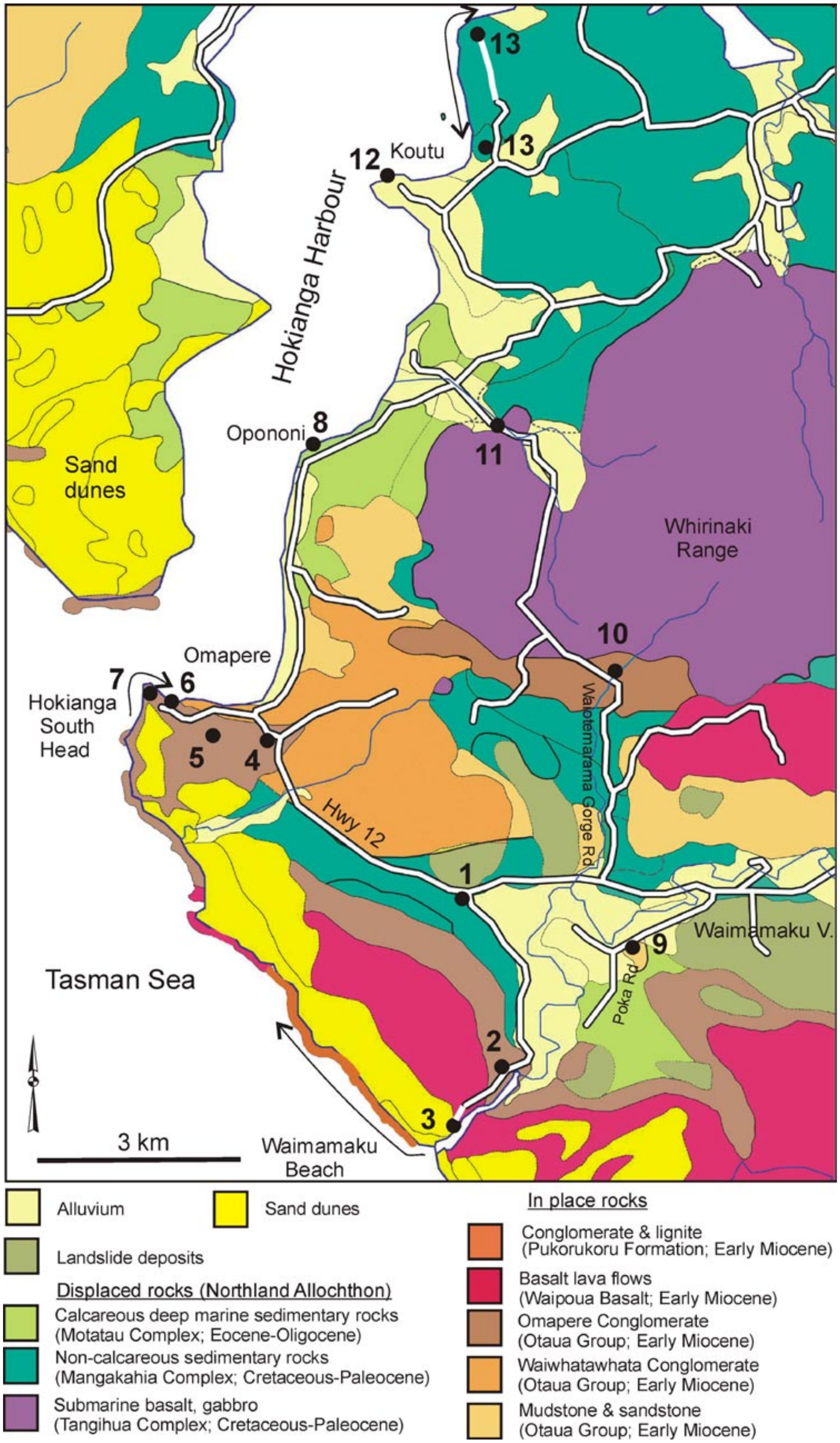
7. Whangaroa Harbour lake beds (*6.53*)
Access by boat at low tide. Bedded lake sediments with tightly-folded slumped bed, deposited in a small lake early in the history of eruption of Whangaroa Volcano (20 Myr ago).

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



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.

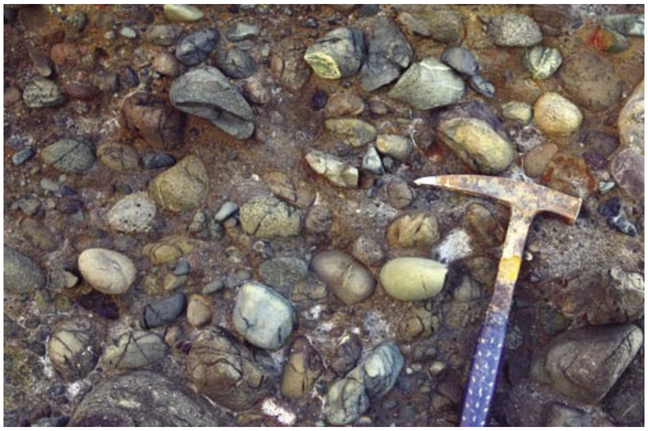
4. Omapere Hill view of sand dunes and Warawara Range (*8.6, 13.9*)
High sand dunes on the north side of Hokianga Harbour mouth have been thrown up by the sea and wind in the last 7000 yr. Beyond is the uplifted Warawara Range composed of Tangihua Complex (Northland Allochthon). The flat topped portion 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. Waiotemarama Waterfall (*13.14*)
10 min walk each way from carpark on Waiotemarama 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*)

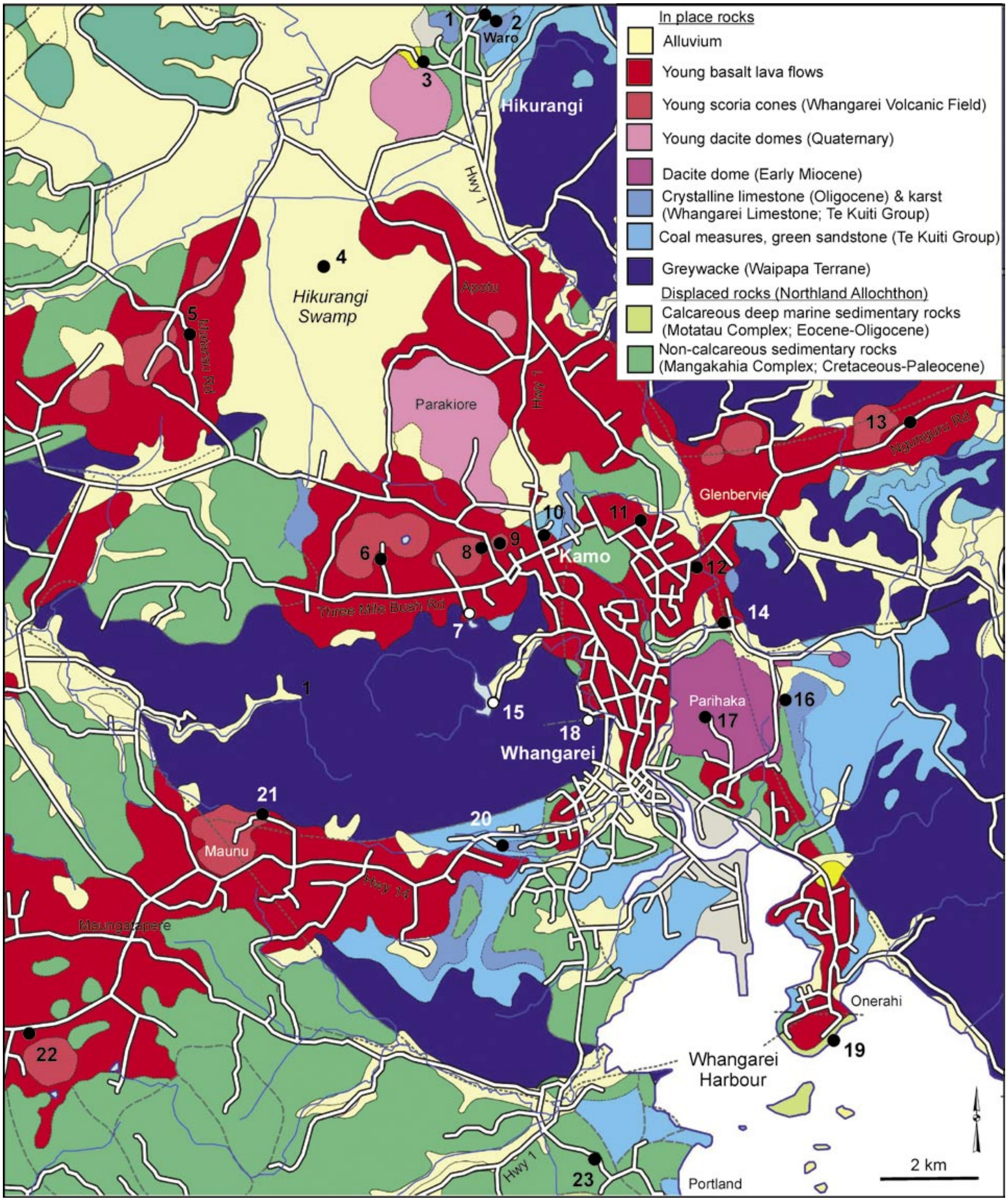
Access to the coast at mid-low tide via boat ramp at end of Koutu Pt Rd. Intertidal reefs of steeply-dipping Oligocene muddy limestone (Motatau Complex).

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.

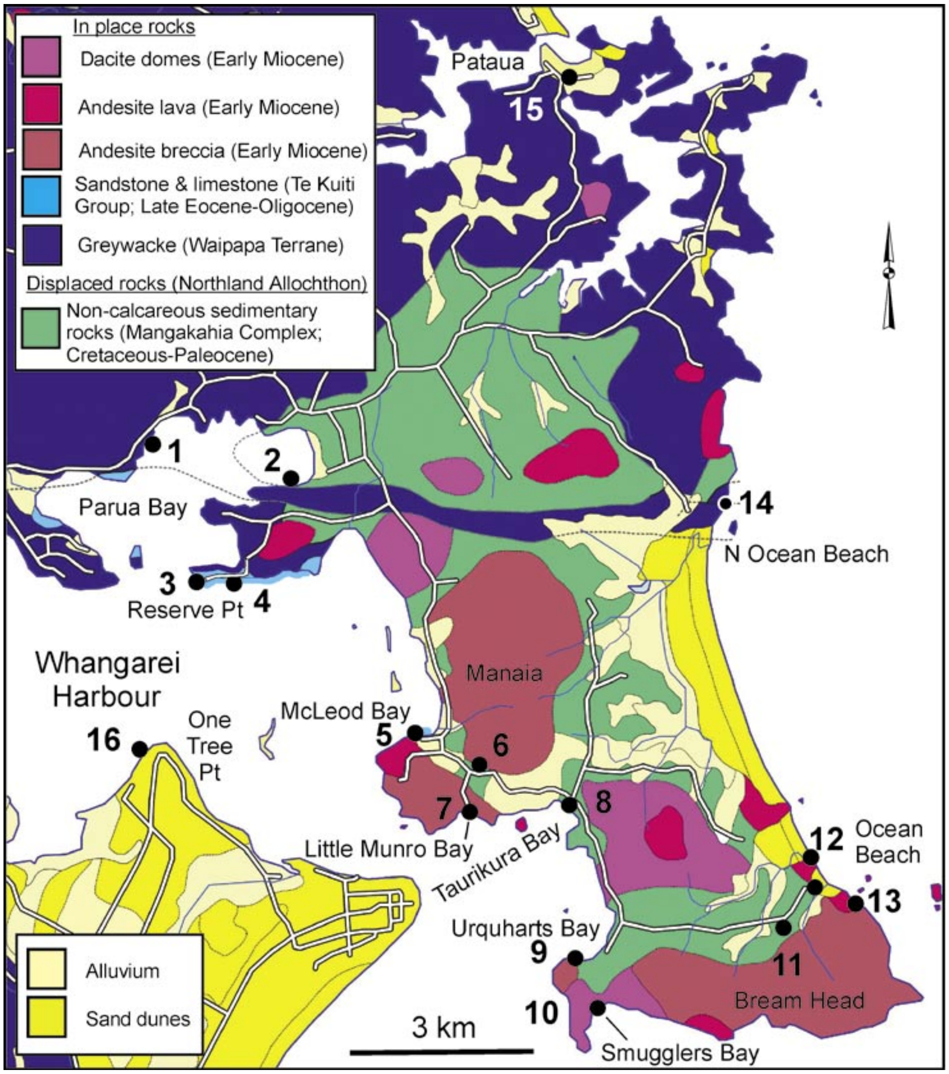
20. Ngahere Drive limestone karst
Beautifully fluted Whangarei Limestone blocks and pinnacles occur in middle of Ngahere Drive and in small reserve at No. 47, Horahora, Whangarei.

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 taraire 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 nephelenite. 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.

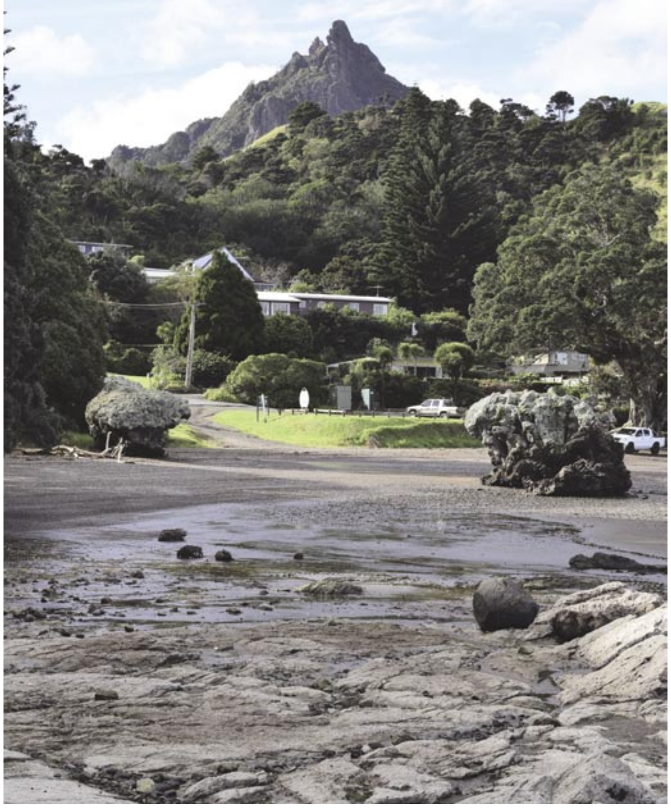
7. Little Munro Bay (*13.21*)
Park at end of Bay View Rd. At mid-tide level on west (right) side of beach, grey andesite (magma plumbing beneath the volcano) intrudes and partly bakes light-coloured, allochthonous muddy limestone (Oligocene). Large boulders on beach are composed of massive andesite breccia 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.

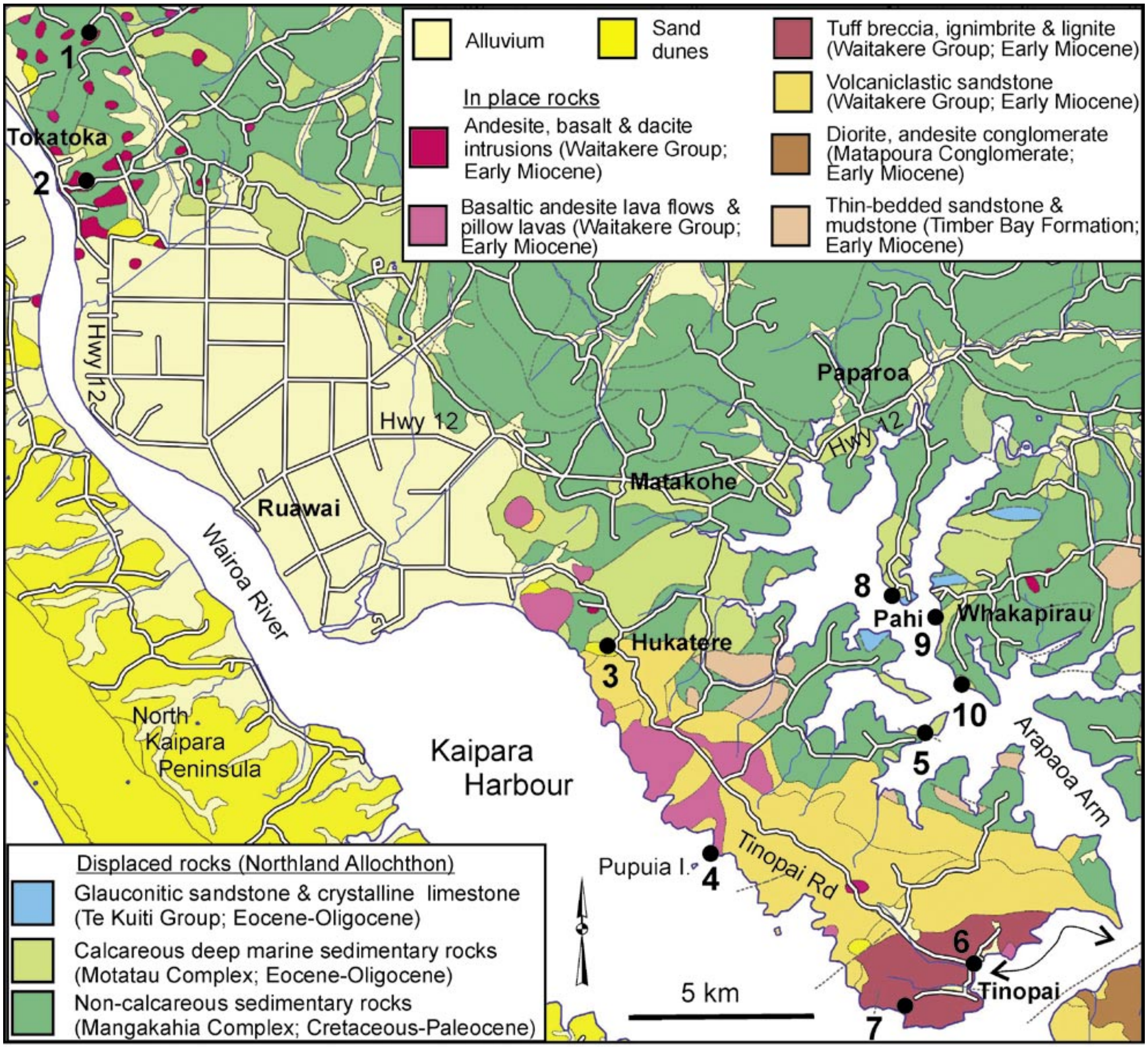
14. North Ocean Beach (*4.37*)
Park at end of Kauri Mt Rd, off Taiharuru Rd, off Pataua Sth Rd from Parua Bay. Take public access track to rocks at north end of Ocean Beach. Disrupted contacts of sheared Northland Allochthon overlying in-situ Waipapa greywacke.

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, Hukatere (*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 Hukatere 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.

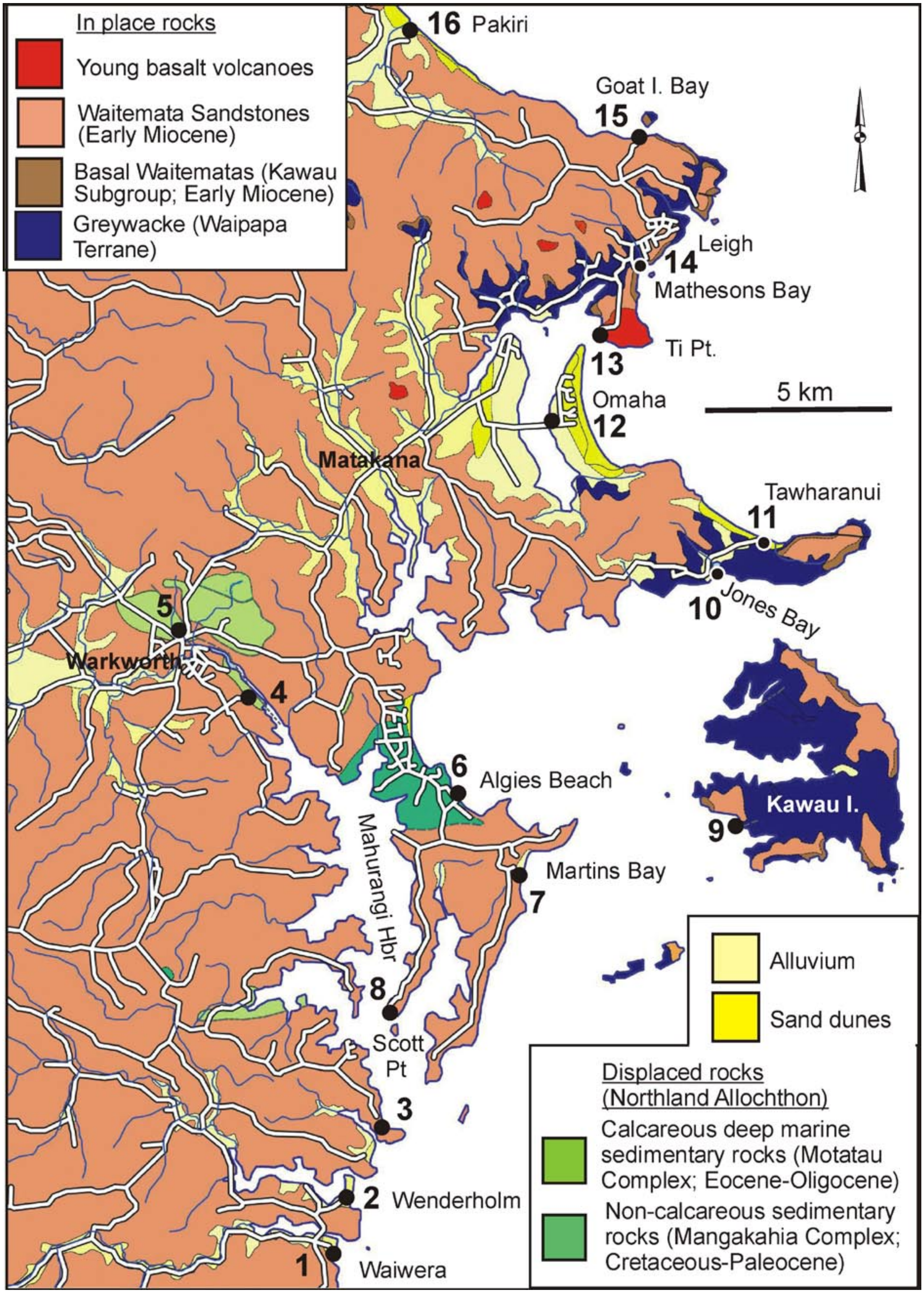
8. Pahi greensand and limestone sequences (*4.55*)
Park at end of Dem St, 500 m before campground. At mid-low tide, walk south (left) to see 35 Myr-old (Late Eocene) massive greensand with occasional shallow-water fossil shells. Walk north, up to 1 km, passing 30-25 Myr-old (Oligocene) muddy and sandy 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


In place rocks
Young basalt volcanoes
Waitemata Sandstones (Early Miocene)
Basal Waitematas (Kawau Subgroup; Early Miocene)
Greywacke (Waipapa Terrane)
16 Pakiri
Goat I. Bay
15
Leigh
14
Mathesons Bay
Ti Pt.
13
5 km
Omaha
12
Matakana
Tawharanui
11
10
Jones Bay
5
Warkworth
4
6
Algies Beach
Kawau I.
9
Mahurangi Hbr
Martins Bay
7
8
Scott Pt
3
2 Wenderholm
1
Waiwera
Alluvium
Sand dunes
Displaced rocks (Northland Allochthon)
Calcareous deep marine sedimentary rocks (Motatau Complex; Eocene-Oligocene)
Non-calcareous sedimentary rocks (Mangakahia Complex; Cretaceous-Paleocene)

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.

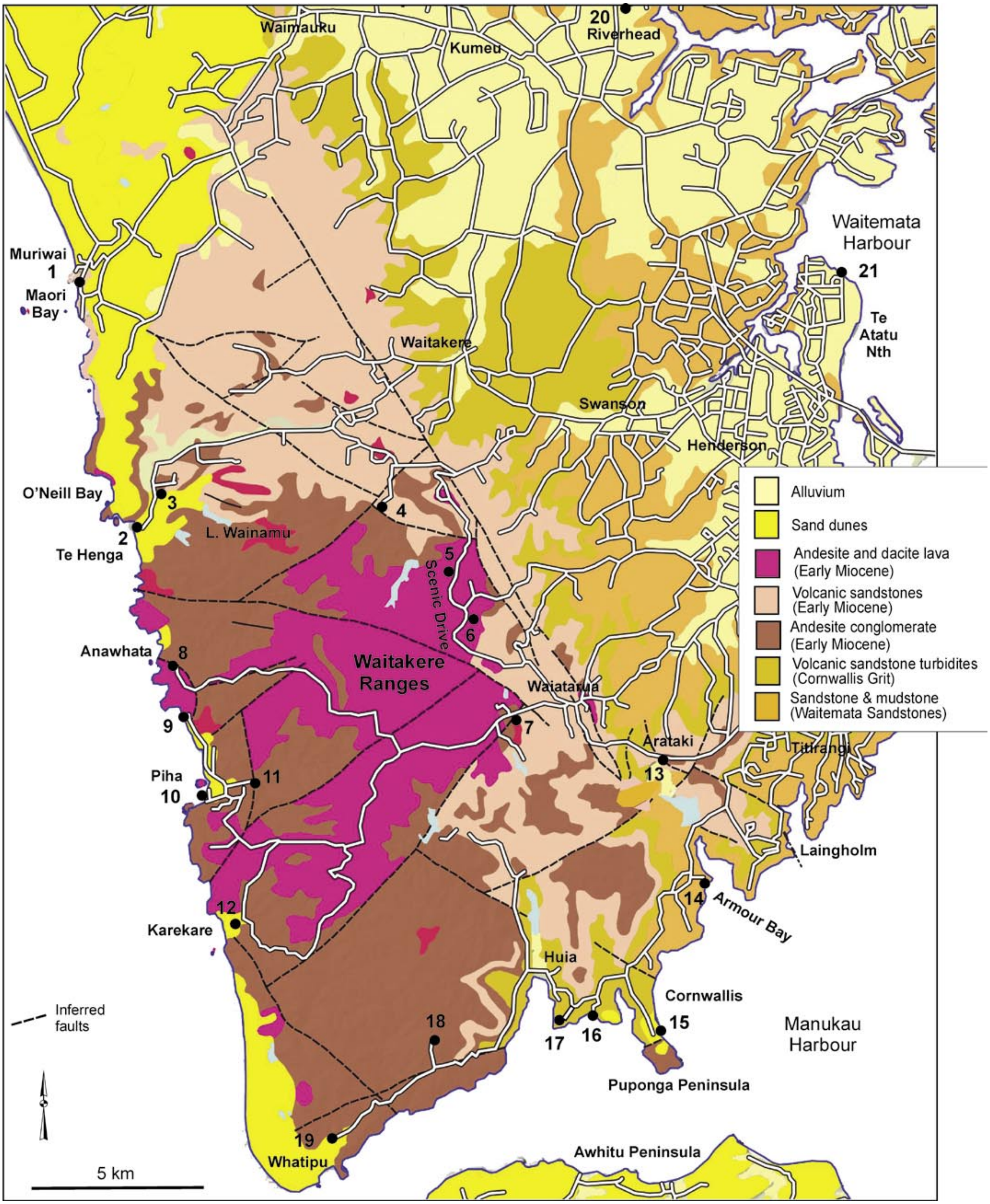
13. Ti Pt basalt volcano (*9.21, 13.26*)
Park by Ti Pt wharf, at end of Ti Pt Rd. Take walking track around end of Ti Pt to reserve on southeast corner. Basalt boulders line the foreshore. Cliffs are made of intrusive basalt, the exhumed plumbing from beneath a 10-7 Myr-old volcano. 1-2 hrs return.

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.

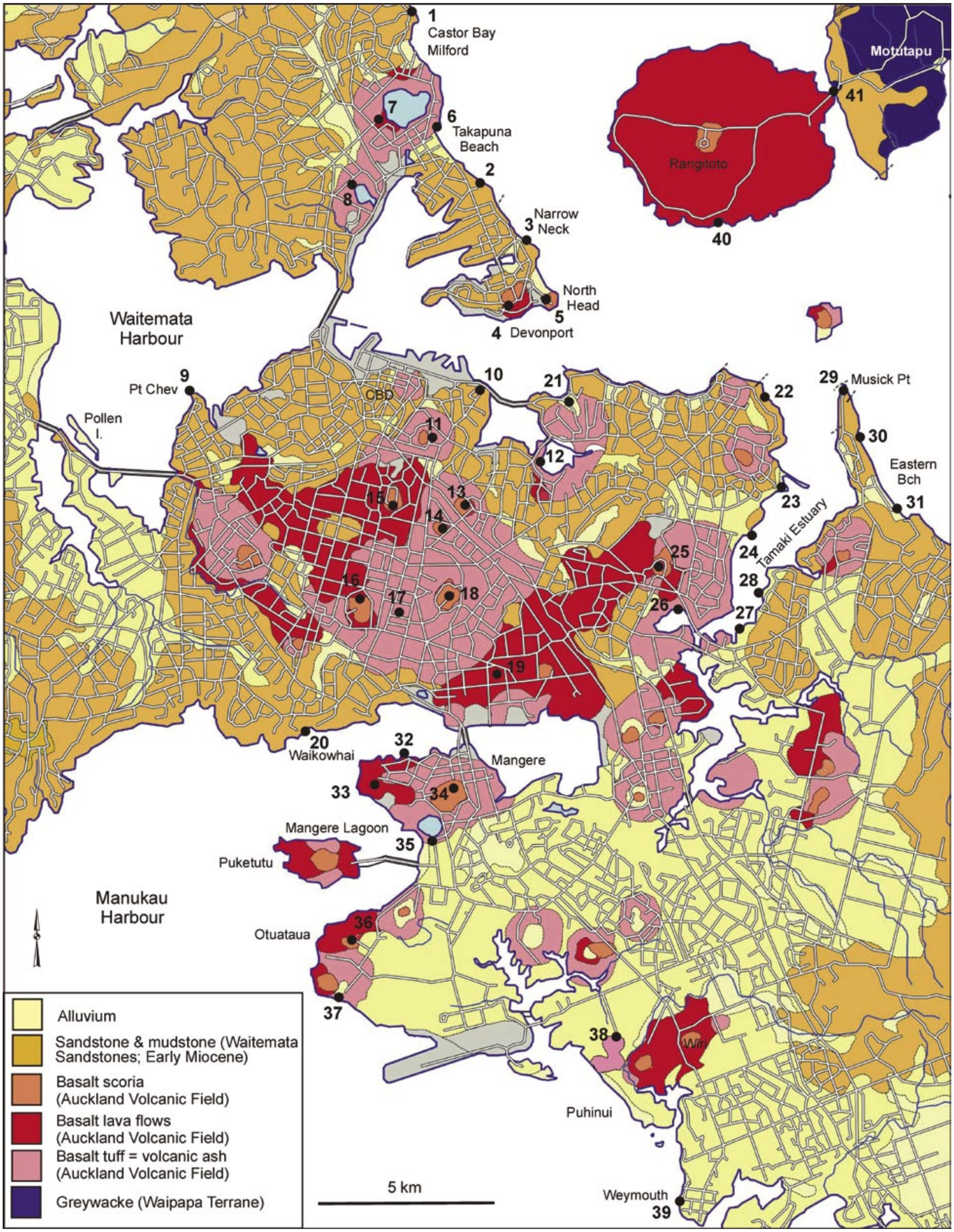
21. Te Atatu fossil forest

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 cuspate 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 cuspate (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.

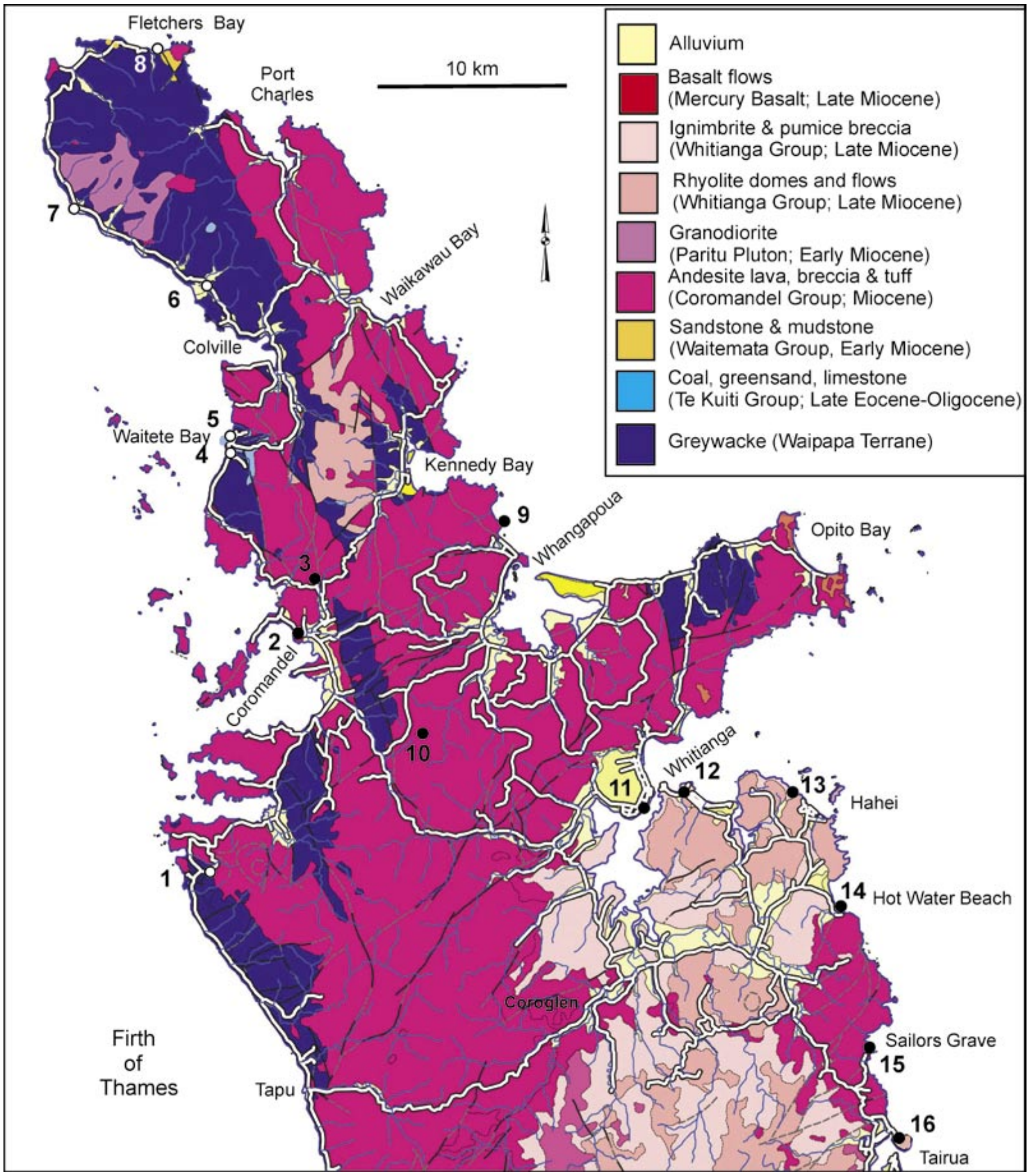
40. Rangitoto shield volcano, scoria cones and lava caves (*9.11, 9.80, 9.84, 9.87, 11.76, 13.38*)
Usual public access is by ferry to Rangitoto Wharf. Auckland's youngest (550-600 yr old) and largest volcano. Take walking track or tractor ride to top of high scoria cone with deep crater. Most of circular 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.

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.

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.

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*).

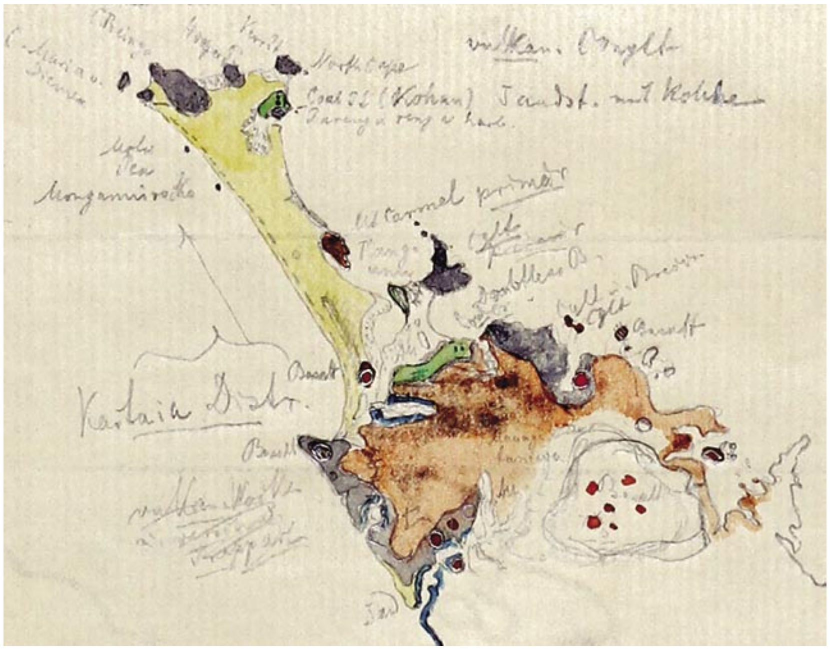
Ernst Dieffenbach was the next geologist on the scene, as part of a 2-year survey (1839-1841) of the colony by a group employed by the New Zealand Company to find and purchase land for the establishment of British settlements. Dieffenbach travelled widely throughout the north, describing the volcanic 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, carneleon, 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. Kaiaraara 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.



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.

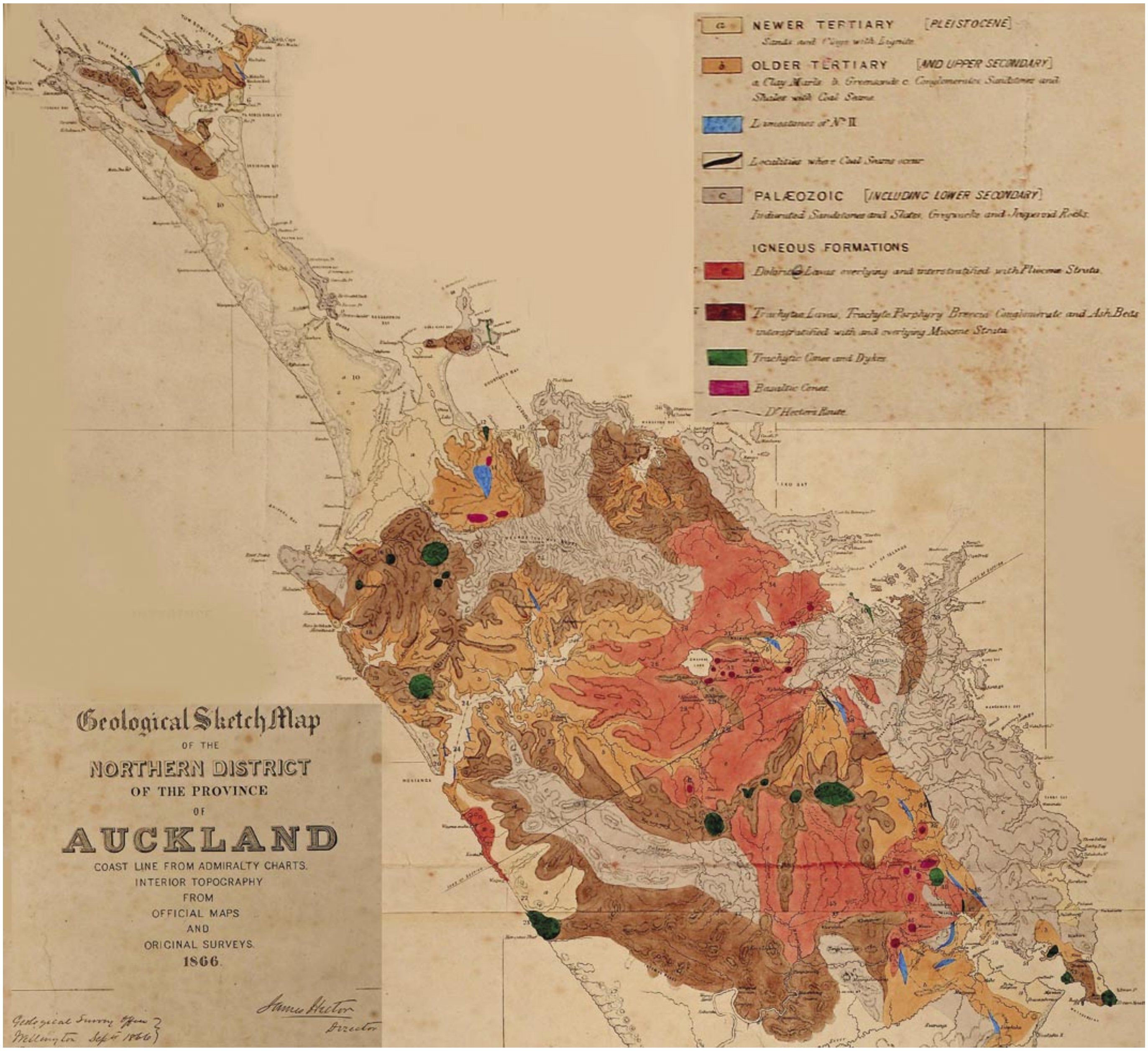
Thus the first extensive geological map of Auckland was produced by Hochstetter (1863) and of Northland by Hector (unpublished 1866). Apart from the 1850s visits to the Coromandel goldfield by Heaphy and Hochstetter, and small surveys of the goldfield areas in 1867 by Hector and Frederick Hutton (on 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, 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



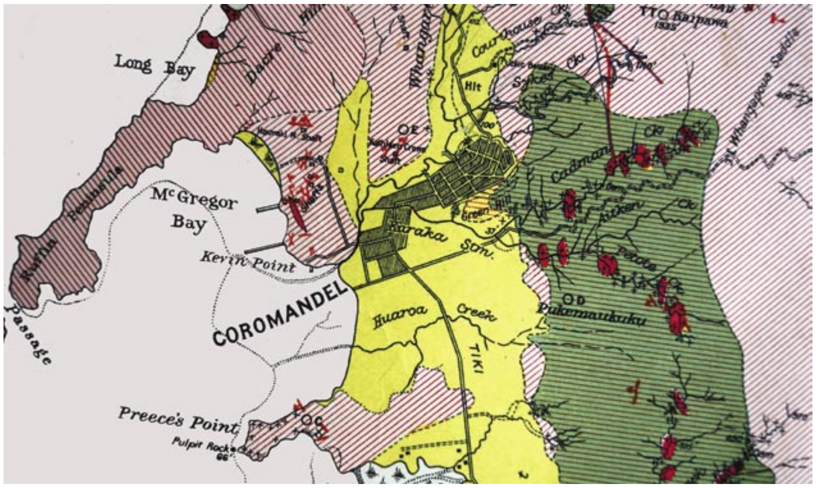
14.3 Most of the unpublished geological map of northern Northland, prepared in 1866 by James Hector and John Buchanan, following a 4-month geological field trip to the north. Image courtesy of Simon Nathan.

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 Otara 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 Otara 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 Otara-based Fred Brook and Waitakere by Bruce Hayward.



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.

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 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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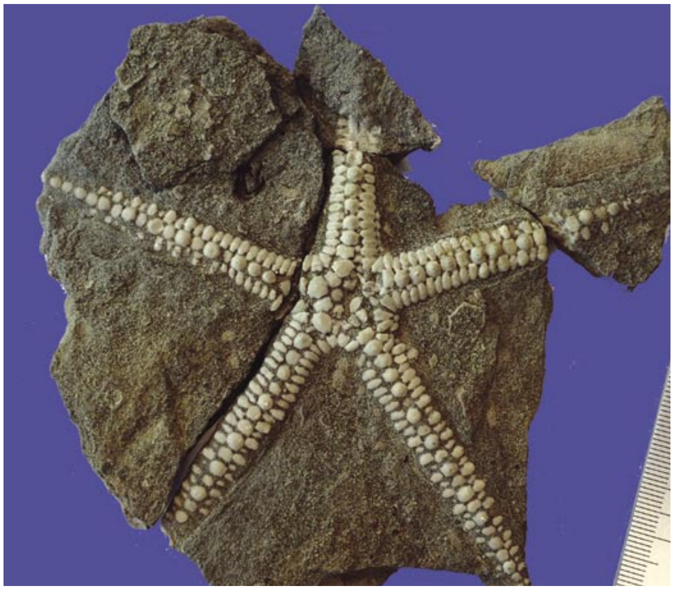

14.6 A 35 Myr-old (*late Eocene*) *fossil starfish* (Zoroaster whangareiensis) *from Reserve Pt, Whangarei Harbour. Width of photo 10 cm.*

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, $CaCO_3$ (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 ^{14}C 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 (SiO_2)
chlorite – a green mineral with soapy feel formed by metamorphism or hydrothermal alteration
clast, clastic sedimentary rocks – particles up to boulder side 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 **fel**spar and **si**lica (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 – arock 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% SiO_2
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, SiO_2
radiolaria – microscopic, single-celled plankton having an intricate skeleton of SiO_2, 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, SiO_2
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, Puhipuhi 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
terrigeneous – 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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