

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.



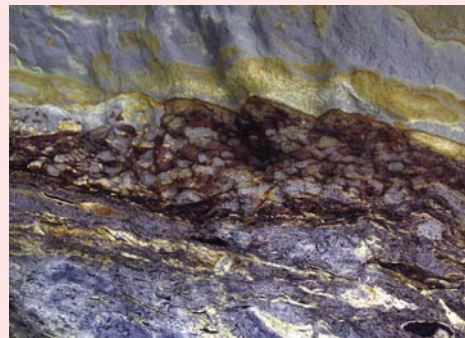
5.27 Trace fossil burrows may be large or small. These are 1-2 mm in diameter and were probably made by marine polychaete worms. ~18 Myr old, Okahukura Peninsula, Kaipara Harbour.



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.*

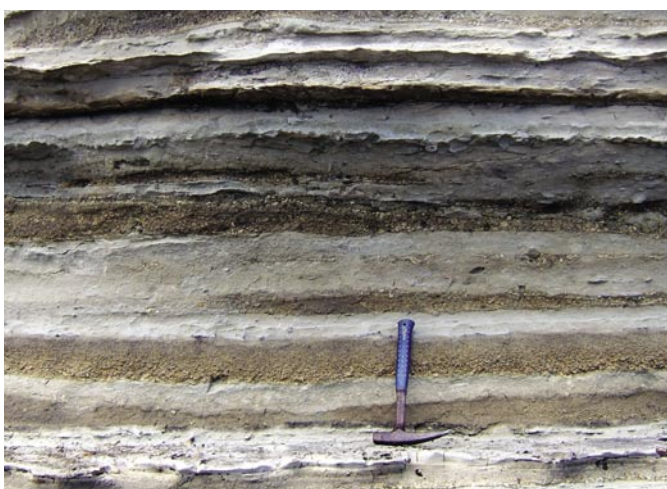
Auckland City (south of Waiwera) are composed of sand grains derived predominantly from the erosion of Northland Allochthon sedimentary and igneous rocks in ancient Northland. In this area the sandstones are volcanic-poor and the rocks are formally known as East Coast Bays Formation. Studies of past 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.

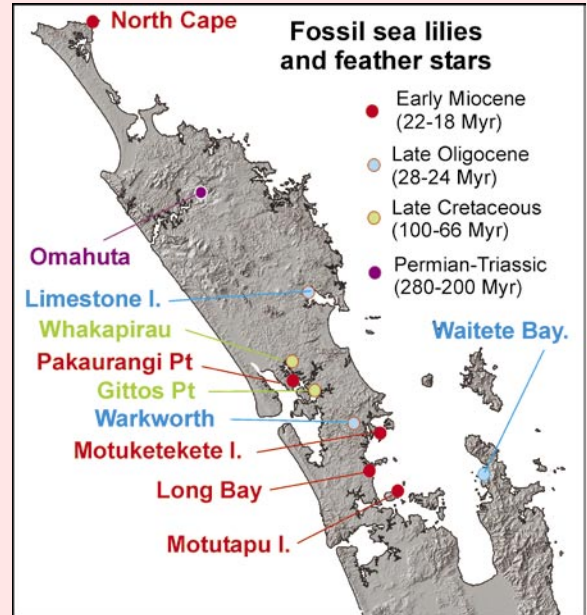


5.36 The easternmost outcrop of Early Miocene sediments that were deposited in the Waitemata Basin occurs at Fletcher's Bay, northern tip of Coromandel Peninsula. Here the eroded and east-tilted strata form an extensive shore platform. The oldest rocks (left) are shallow marine basal Waitemata Group 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 permanently attached to the seafloor by a cemented holdfast or by a multi-carried 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.



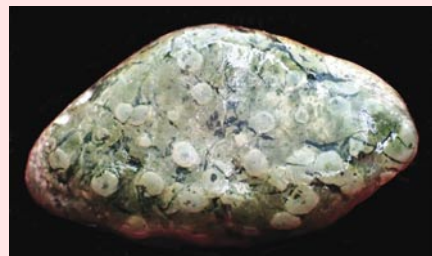
5.38 A living sea lily.



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.

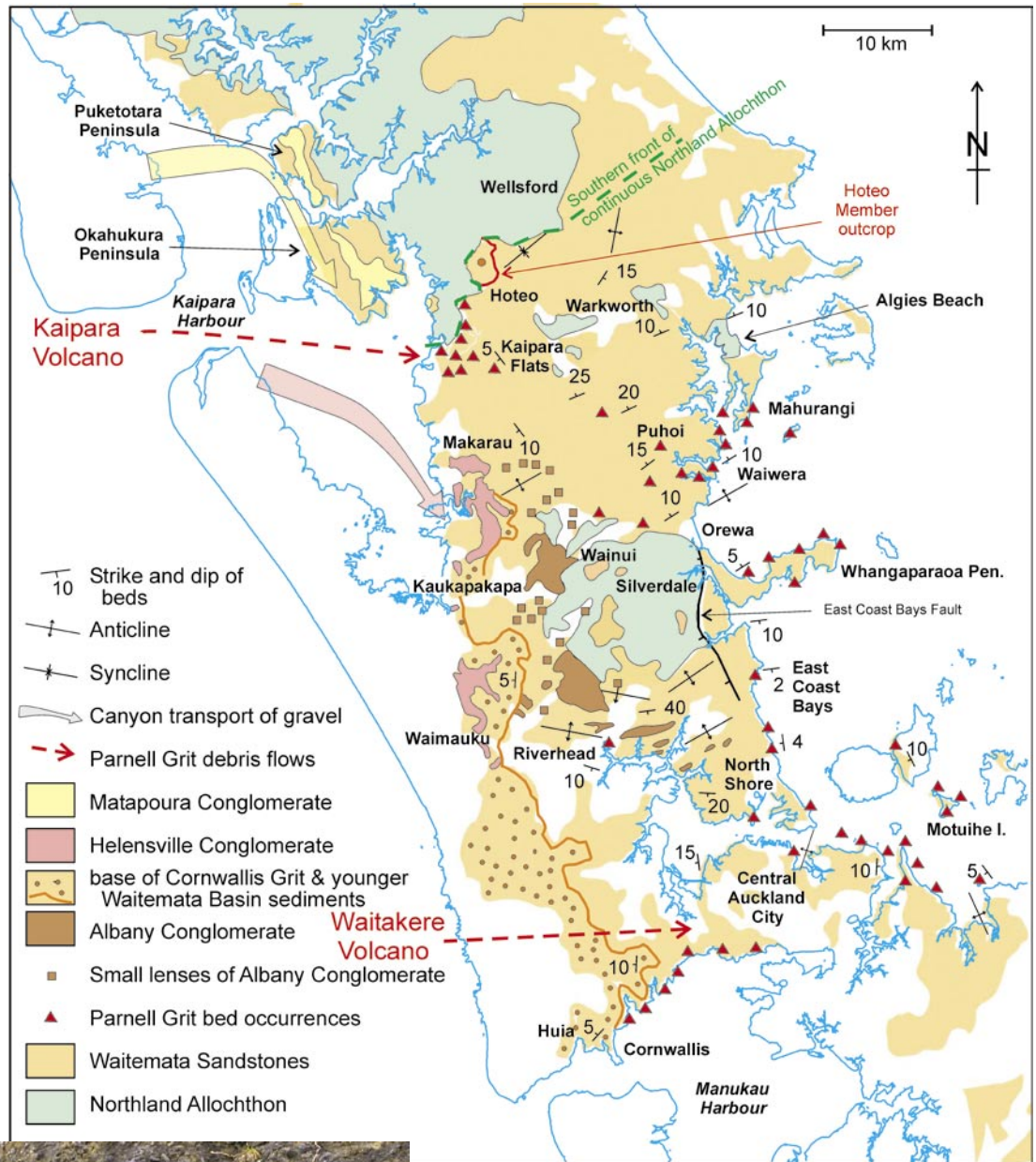


5.43 Close-up photo of part of a volcanic debris flow deposit (Parnell Grit) that occurs within the Waitemata Sandstone sequence at Castor Bay, North Shore, Auckland. Parnell Grits are characterised by coarse sediment containing both fresh (grey) and oxidised (red) volcanic (andesite and basalt) pebbles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



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.

turbidity currents flowed as they transported gravel, sand and mud from the shelf down into the depths of the basin to the southeast.

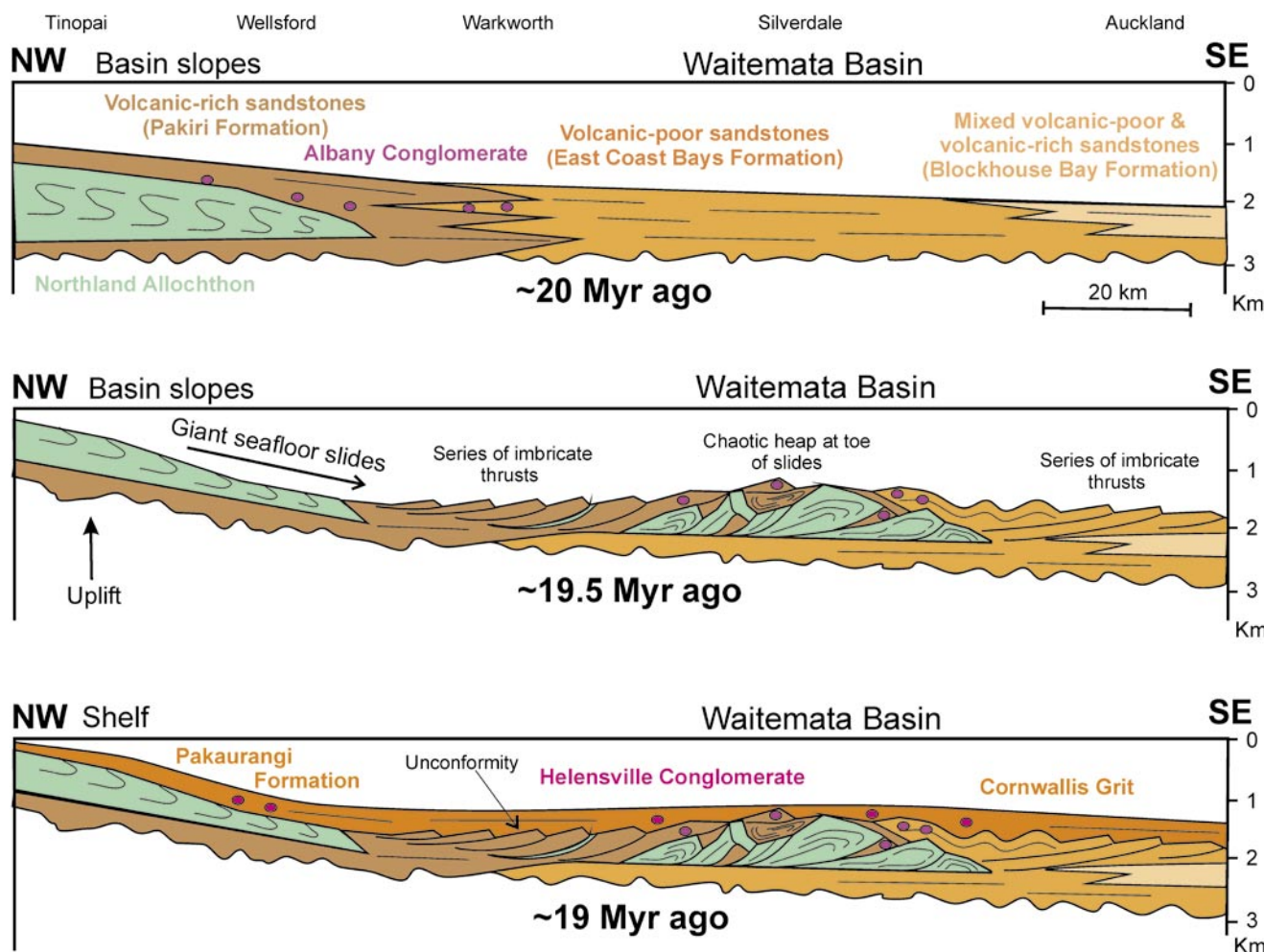
Giant seafloor landslides on the northern slopes

A jumbled heap of fault blocks of Northland Allochthon rocks and Waitemata Sandstone, covering an area of about 200 km², 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 km³.

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



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.

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.

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.

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



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.

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).

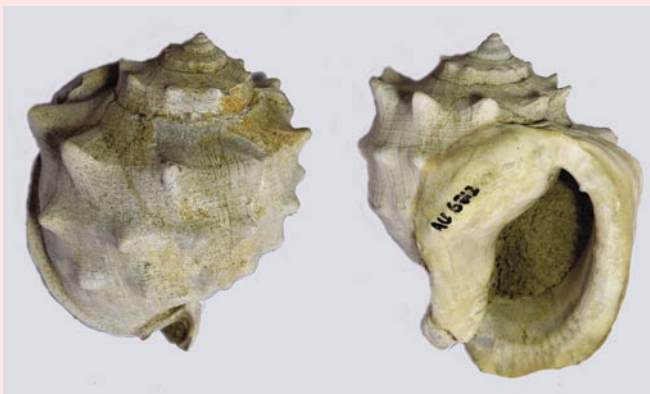
Box 21. EARLY MIOCENE SUBTROPICAL FOSSILS

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.



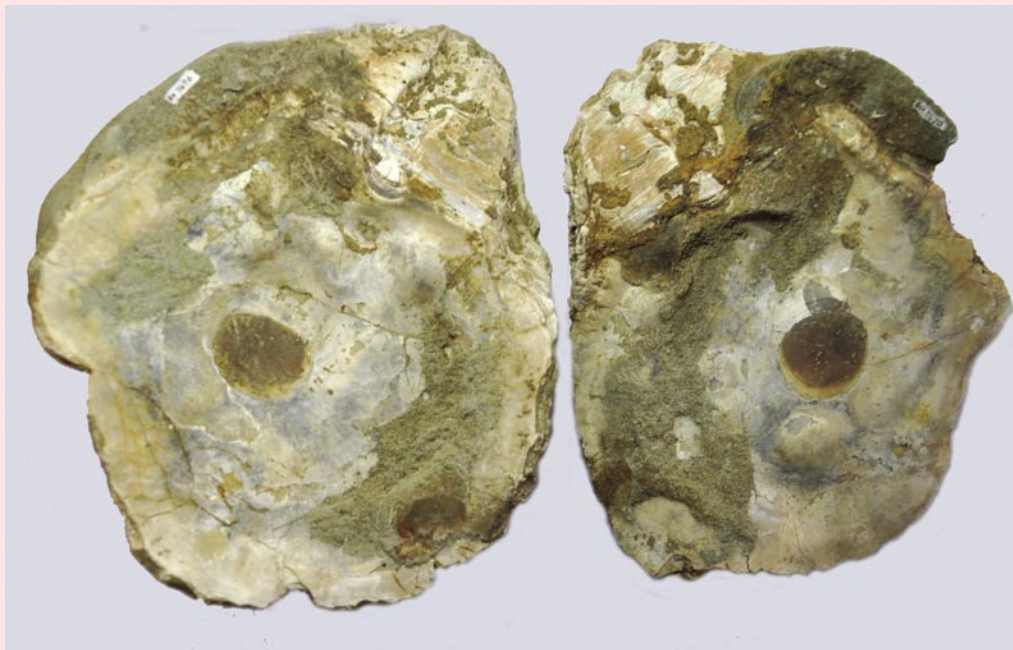
5.60 Two beautifully ornamented, subtropical, Early Miocene (18 Myr old) helmet shells (*Echinophoria hectori*) from the Parengarenga Basin, Te Pokere cliffs. Helmet snails live in seafloor sand at inner-mid shelf depths (0-100 m) and prey on heart urchins. Width of photo 10 cm. University of Auckland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



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.

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.

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.



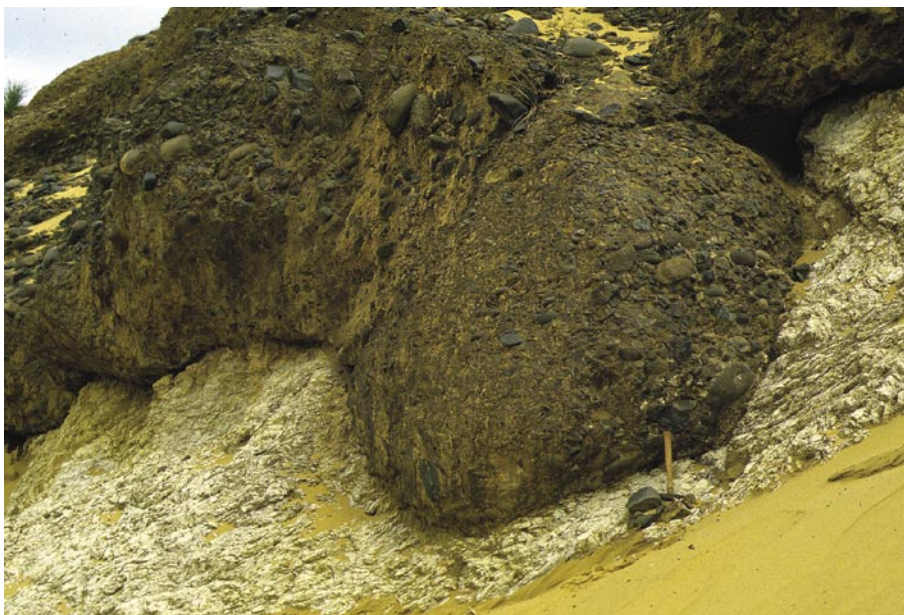
5.69 These rounded hills at the east end of Spirits Bay, are composed of eroded andesite conglomerate (Kaurahaupo Conglomerate) that was deposited in shallow marine and deltaic settings in the Parengarenga Basin, during the Early Miocene. The strata are tilted down to the west (right) forming the gentler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

Hokianga Basin

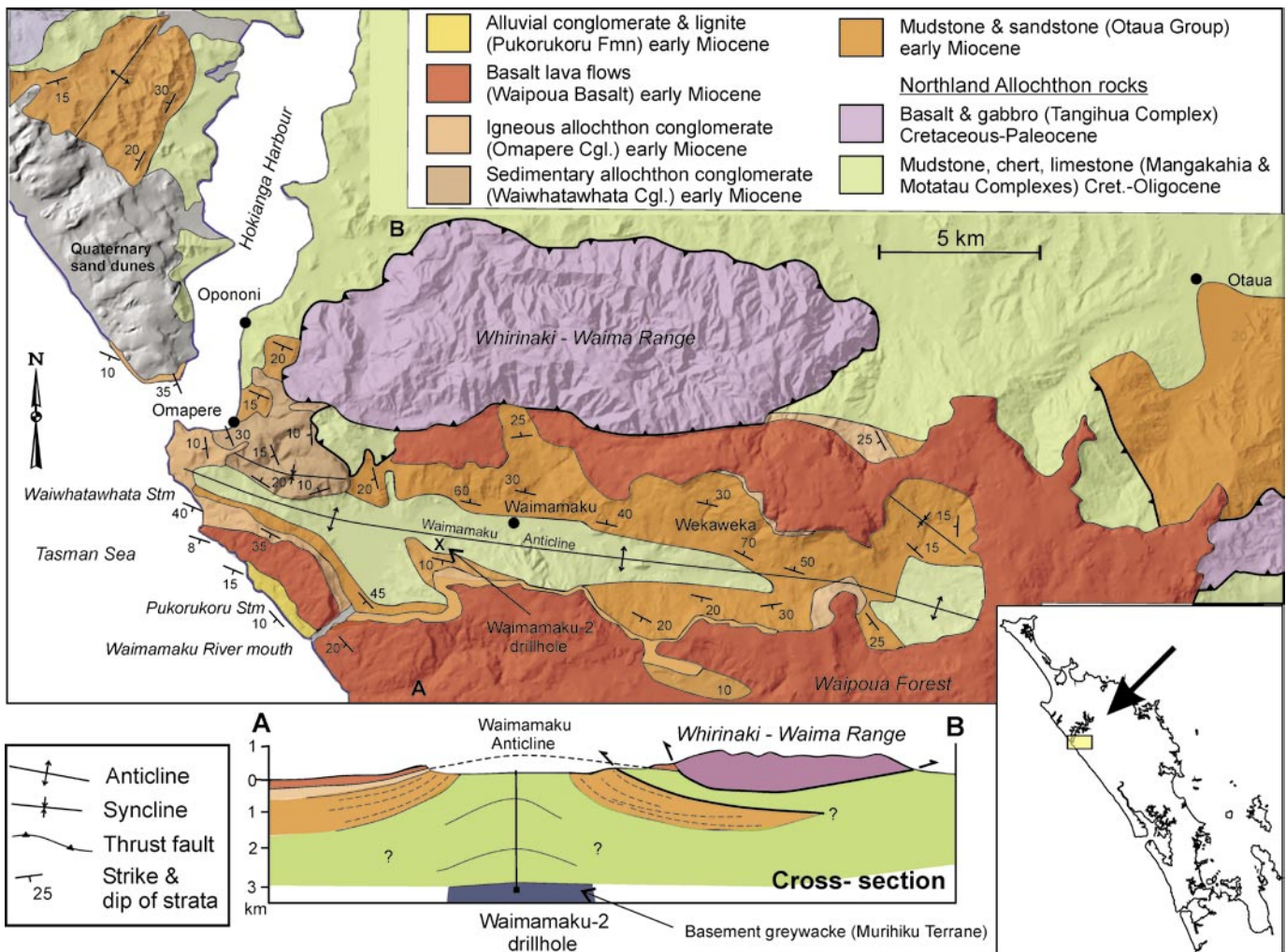
Early Miocene sedimentary rocks (23-18 Myr old) can be seen in the area on either side of the mouth of the Hokianga Harbour and extend 30 km to the east up the Waimamaku Valley. They were deposited unconformably on top of various blocks of Northland Allochthon. The oldest of these strata consist of 300-1000 m of mudstone and shell-bearing fine sandstone (Otatau 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.

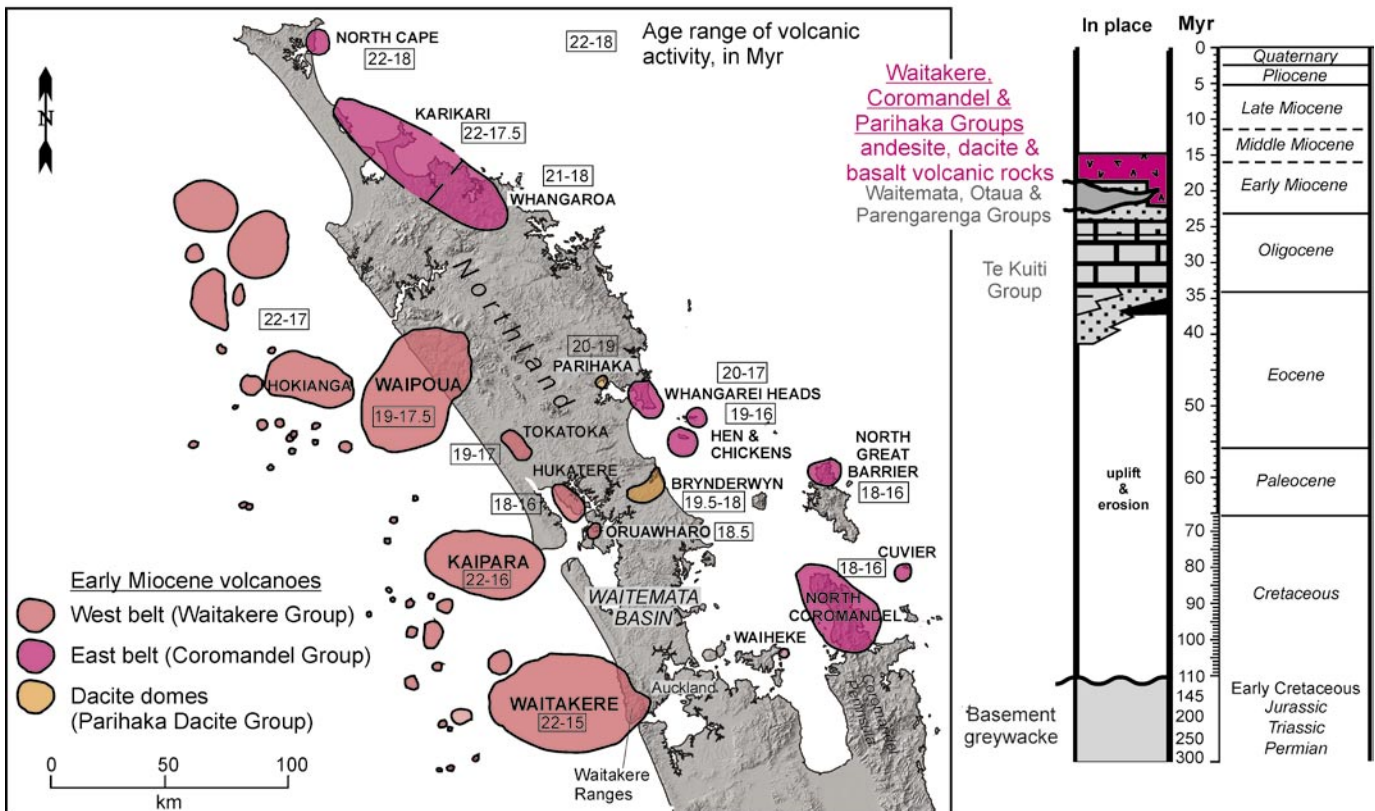


5.73 The bluffs on the south side of the Waimamaku River mouth gorge, south Hokianga, expose some of the youngest rocks (20-19 Myr old) that accumulated in the Hokianga Basin. The grass slope at the foot of the bluffs on the left is composed of sandstone and mudstone that accumulated at 500-50 m water 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).

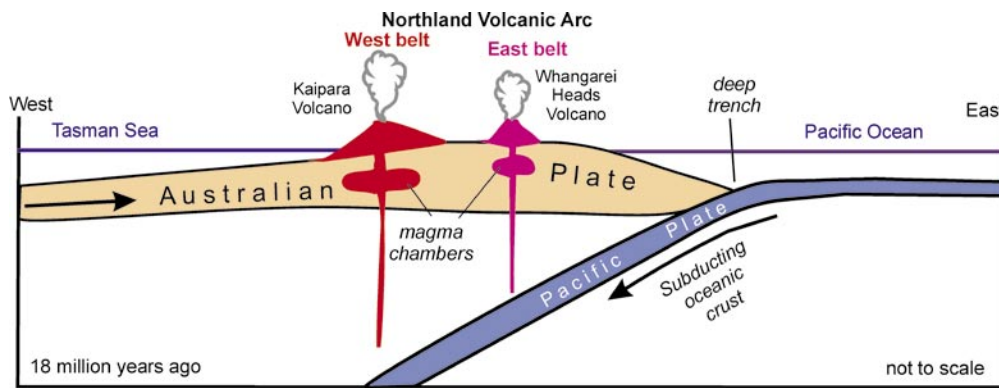
Chapter 6. NORTHLAND VOLCANIC ARC (23-15 Myr ago)

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.

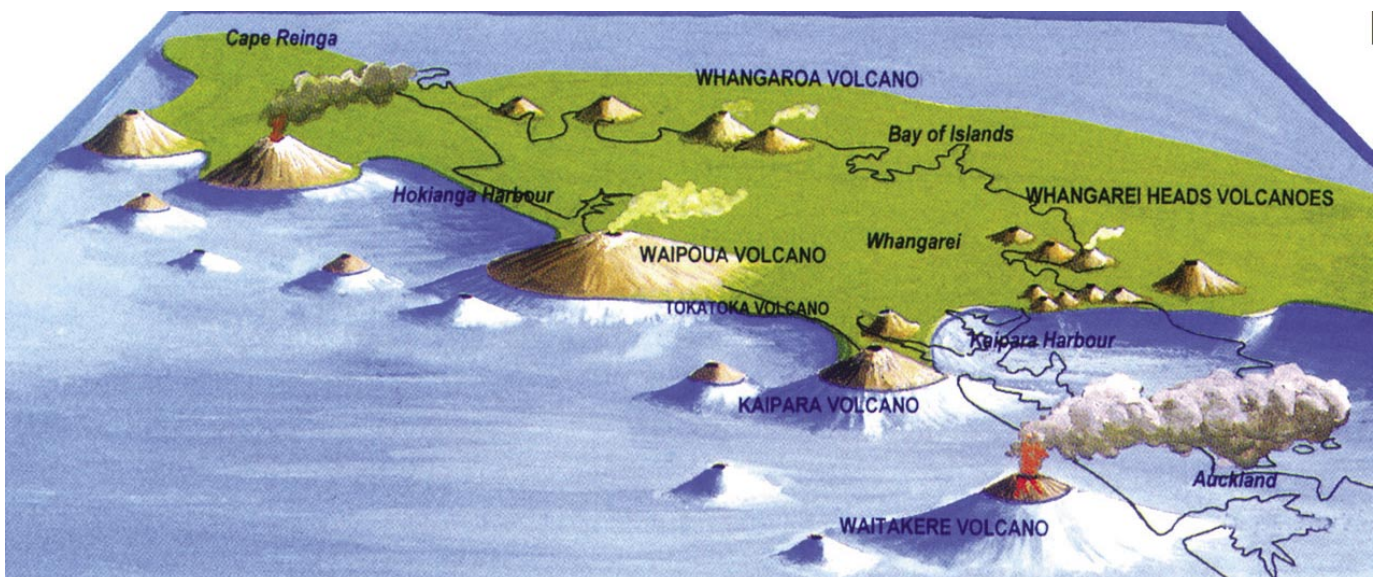


6.2 East-west cross-section through southern Northland showing the oceanic Pacific Plate being subducted westwards beneath the edge of the continental crust of the Australian Plate, resulting in the generation of magma bodies and an arc of volcanoes above the subduction zone.

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.

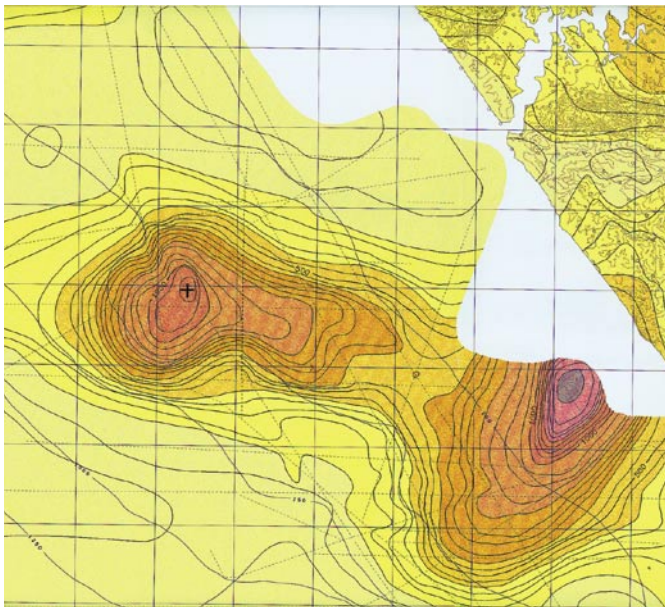
The volcanoes of the western belt are placed in the Waitakere Group. Eruption along this line ceased about 15 Myr ago, although activity shifted southwards along the same line offshore and parallel to the North Island's west coast as far south as Taranaki during the subsequent 10 Myr (Middle-Late Miocene). 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).



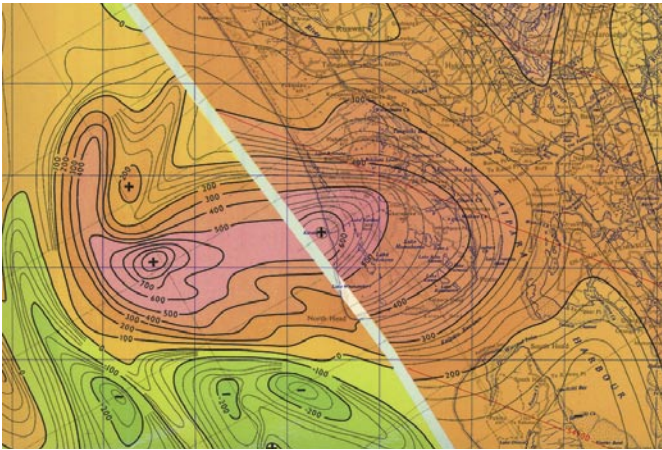
6.4 Part of a gravity anomaly map offshore south of Hokianga Harbour mouth, showing two large ovoid bodies of dense rocks producing strongly positive anomalies. The southeastern body passes northeastwards into the land at Maunganui Bluff and clearly appears to be the buried remains of the Early Miocene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

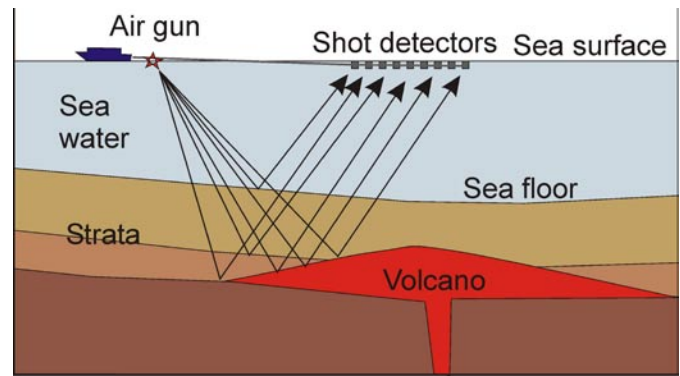
Aeromagnetic surveys measure variations in the strength of the geomagnetic field and identify differences in the magnetic properties of the subsurface rocks beneath the flight path. Effectively, this method recognises bodies of rock containing magnetic minerals – primarily iron-titanium oxide and iron 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.

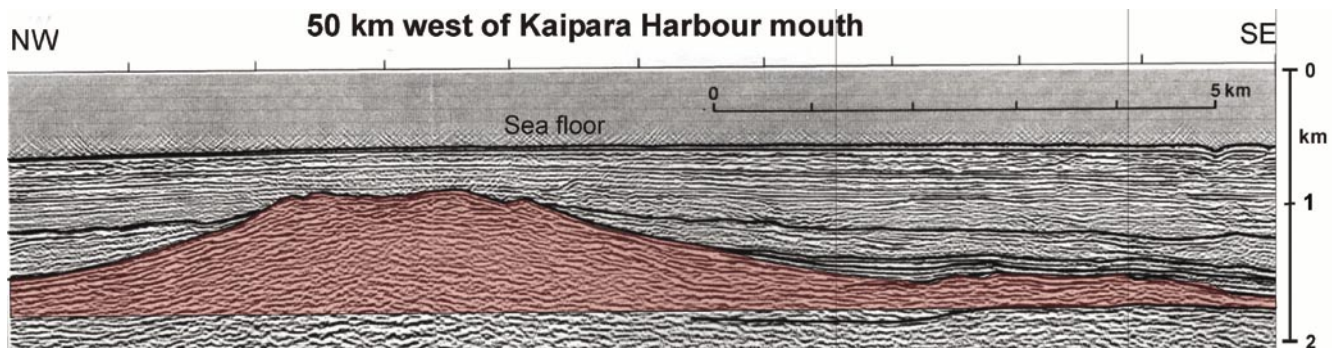
that they were igneous in origin and not basement greywacke blocks.

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



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).

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.

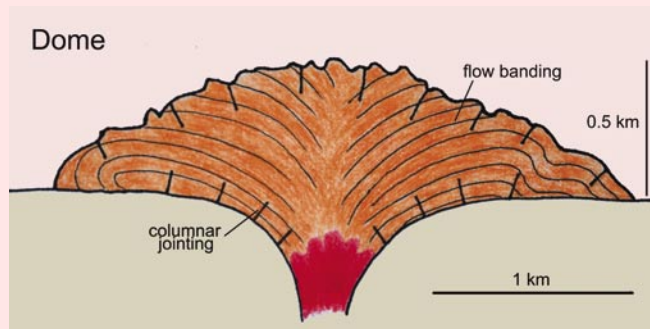
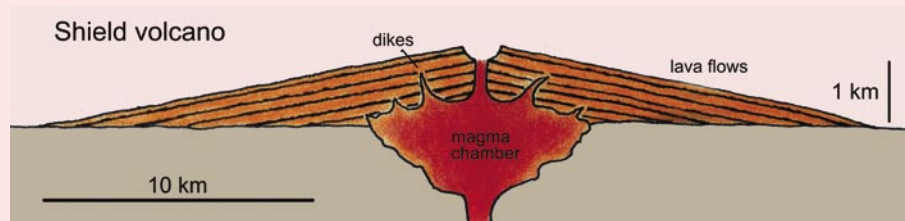


6.7 Seismic reflection profile showing the structure of rocks beneath the Tasman Sea floor west of Northland. Highlighted in red is a medium-sized (10 km diameter) Early Miocene volcano buried by younger seafloor sediment. Modified from Herzer (1995).

Box 22. VOLCANIC SHIELDS, DOMES AND STRATOVOLCANOES

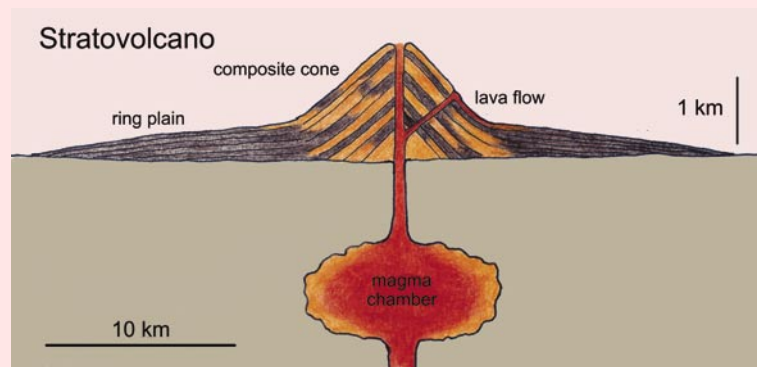
Most of the subduction-related volcanoes of the Early Miocene Northland Volcanic Arc were andesite stratovolcanoes, but there were a number of dacite domes and one huge shield volcano (see Waipoua Volcano). The simple explanation for the different kinds of volcanoes that were formed, is that the magma 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 ($5\text{-}10^\circ$) 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 ($5\text{-}10^\circ$ 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.

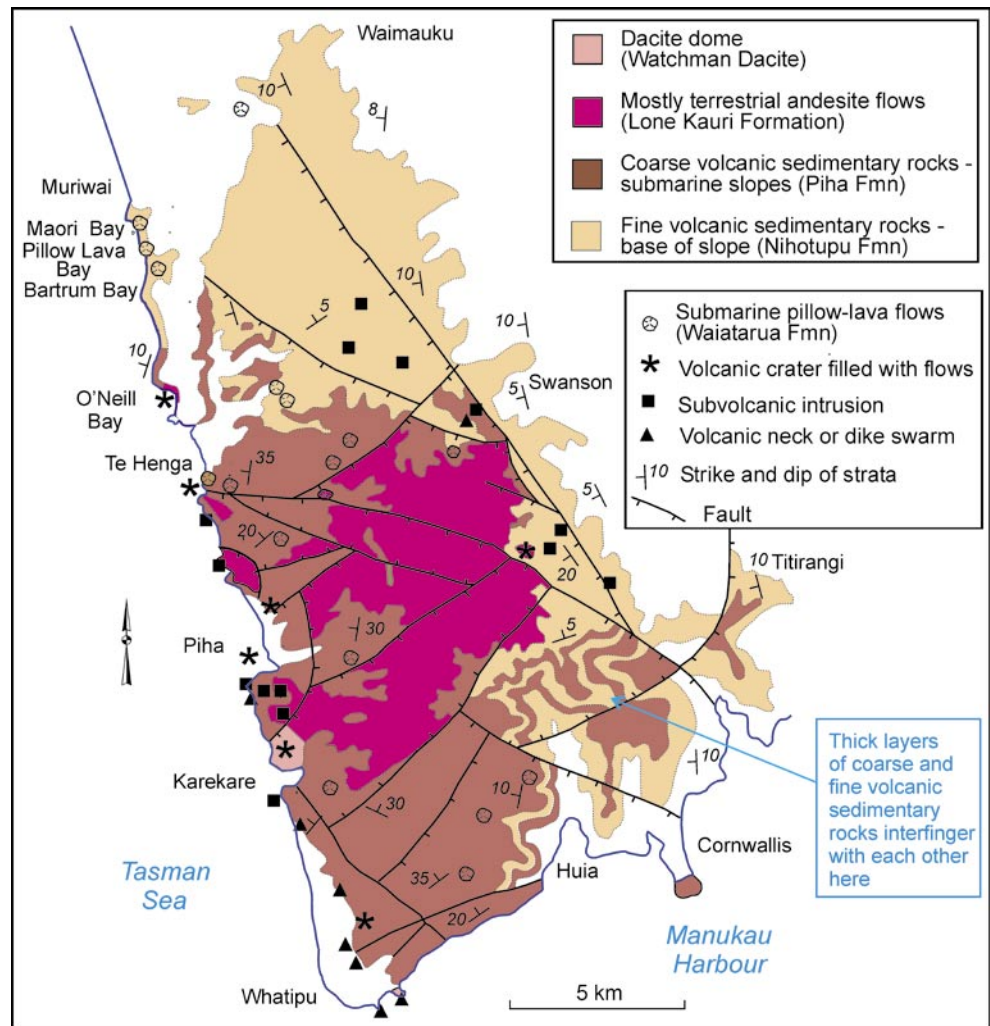
6.10 Right. Cross-section through an idealised stratovolcano composed of a central, steep-sided volcanic cone surrounded by a gently-sloping ring plain. The cone (sometimes called a composite cone) consists of a mix of lava flows and volcanic breccias and ash. The ring plain has been built up of volcanic 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.



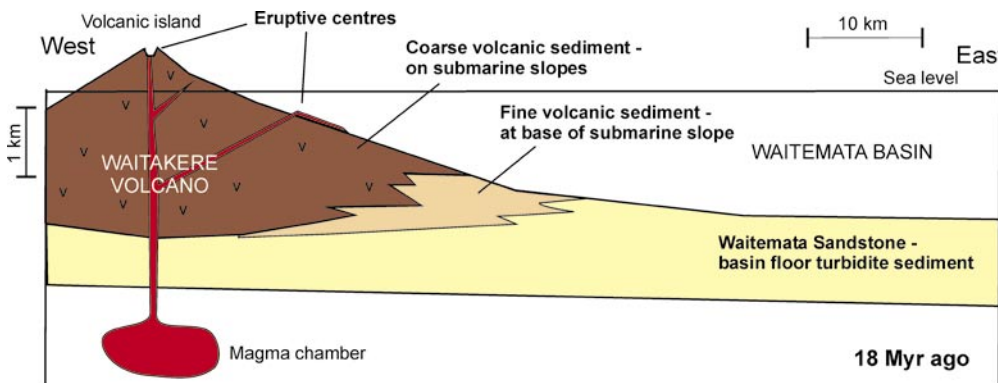
WAITAKERE GIANT STRATOVOLCANO

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.

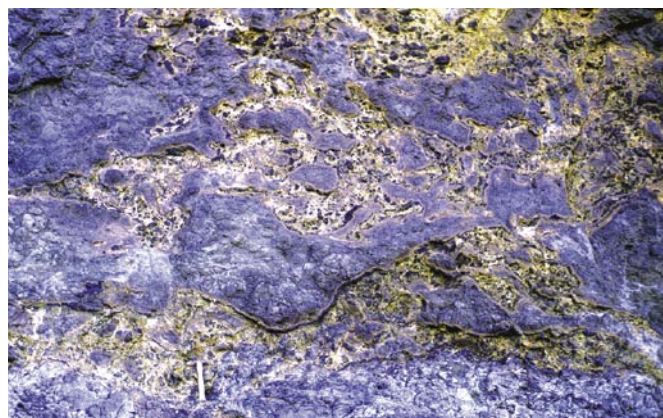
Undersea lava flows

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



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.



6.13 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 selvages) 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.

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.

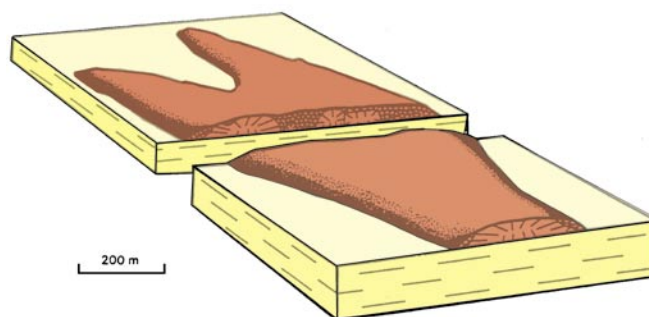
In two places in the coastal cliffs south of Muriwai, we can see sheet-like feeder dikes of solid andesite rock,



6.15 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.



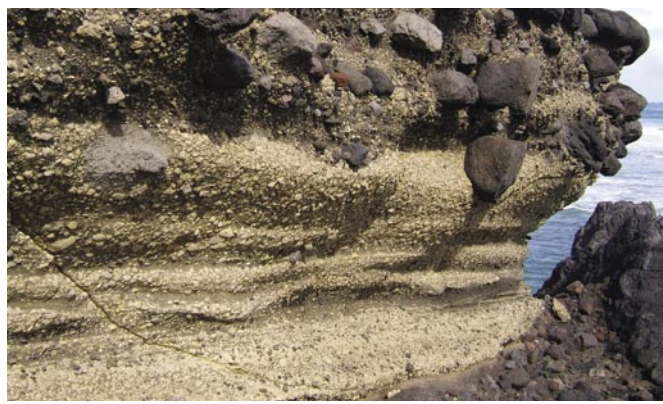
6.16 View east of cut-away block diagrams illustrating the inferred shape of the Maori Bay pillow lava flow seen in cross-section high in the cliffs (middle of diagram). The giant internal fans of cooling joints are solidified andesite lava that once flowed along as large feeder tubes inside the moving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

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.

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.



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

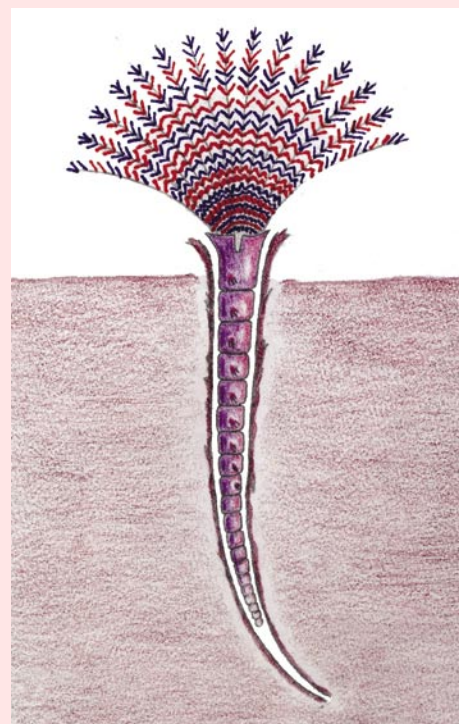
Interspersed with the conglomerate are chaotic deposits of contorted and twisted blocks of volcanic strata that have slumped down the volcano's side (6.20).

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



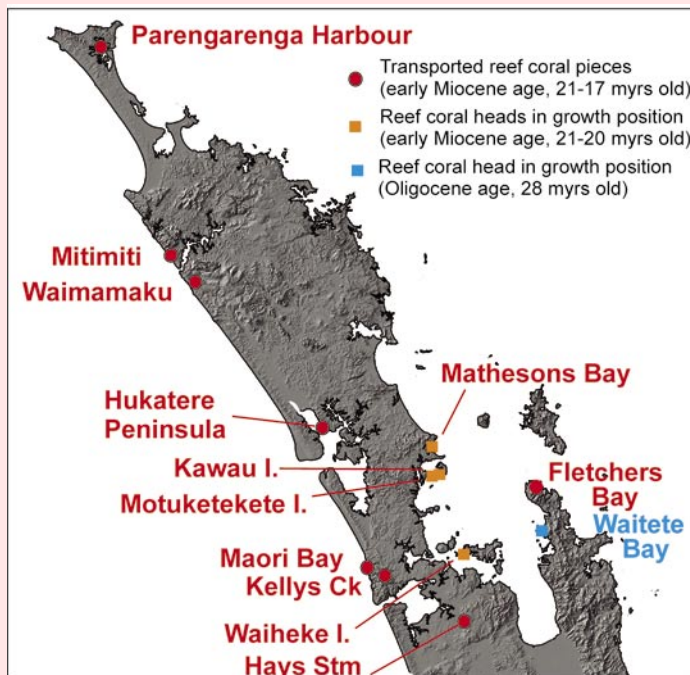
Box 24. FOSSIL REEF CORALS

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.

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.



6.26 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.



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.



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.

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.

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.



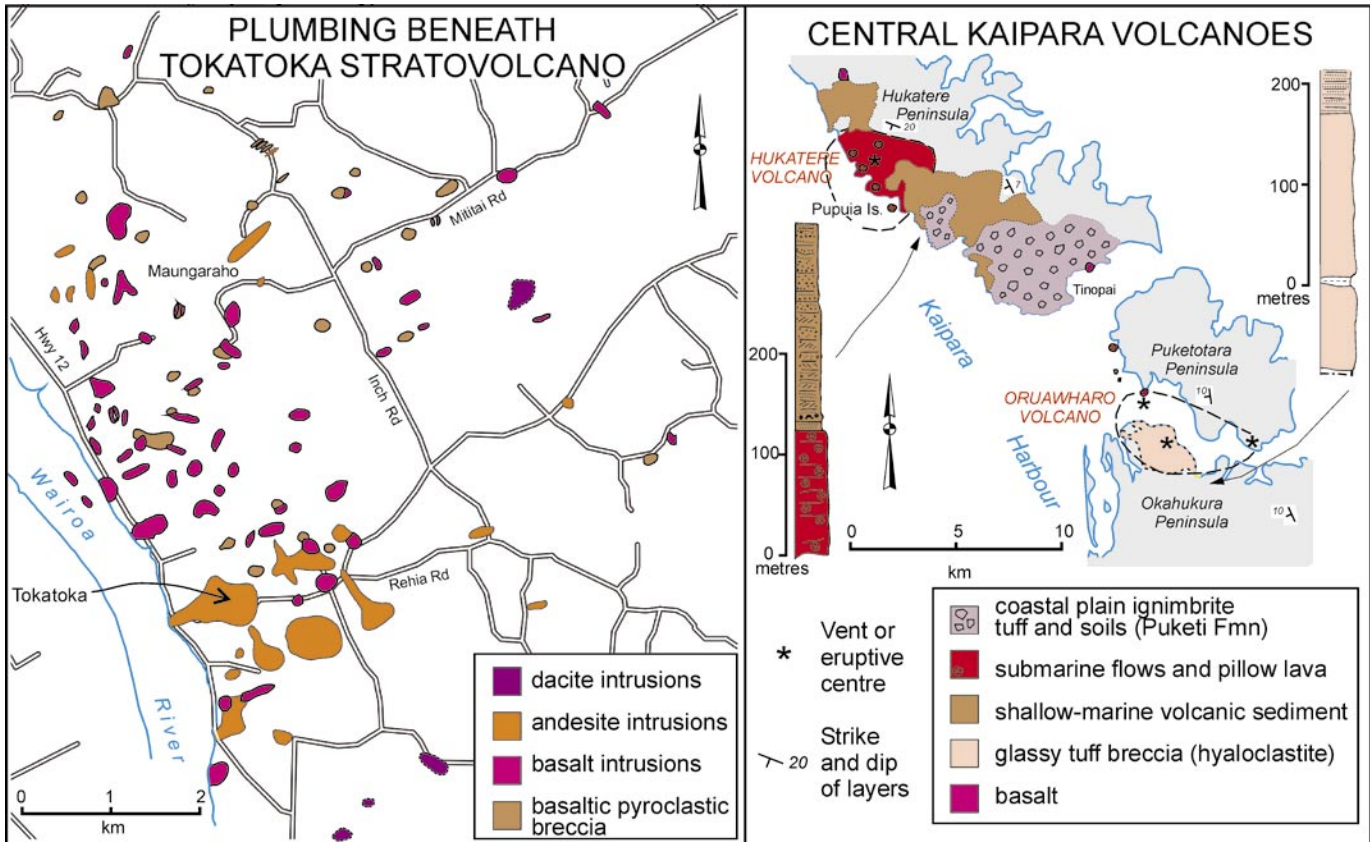
6.33 Ram's horn shells are the internal skeleton near the tail end of a small squid. Drawing by Margaret Morley.



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 volcanoclastic 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 Oruawhoro) 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 km² 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 Matakoho. 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 Pupua 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 Pupua 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.



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.

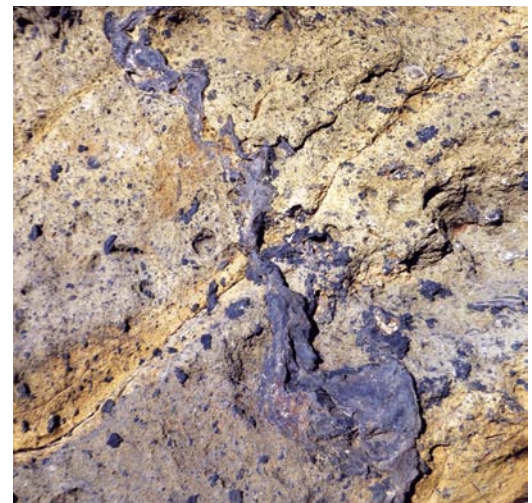


6.42 Sequence of ignimbrites, tuff breccias and cross-bedded sandstone (Puketi Formation) in cliffs east of Tinopai. Four thin black layers visible within the sequence are soil horizons with tree stumps in-situ that mark former quiet periods, when vegetation grew on the coastal plain between the periodic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

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

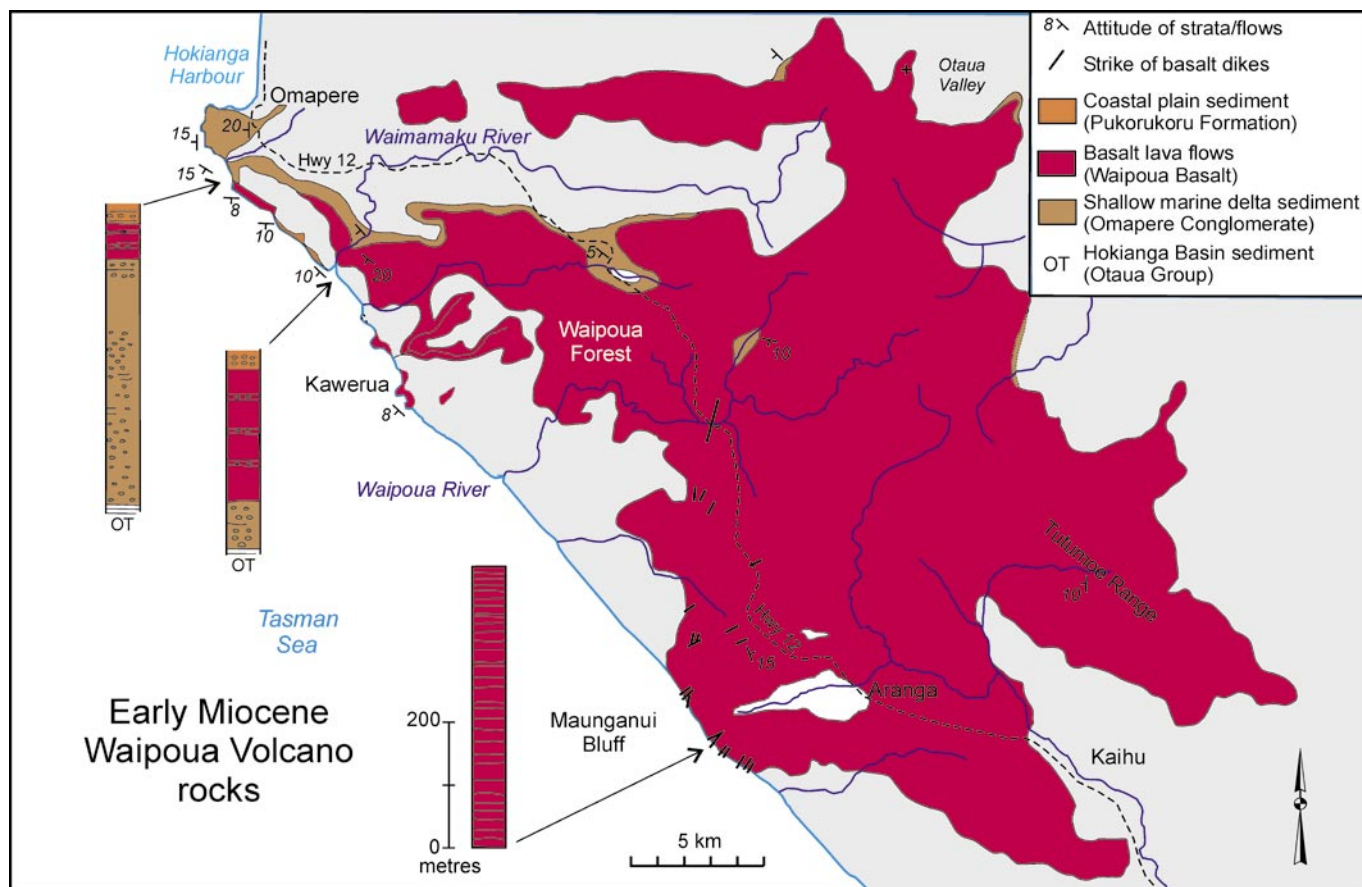
Oruawharo submarine volcano

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.



6.43 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.



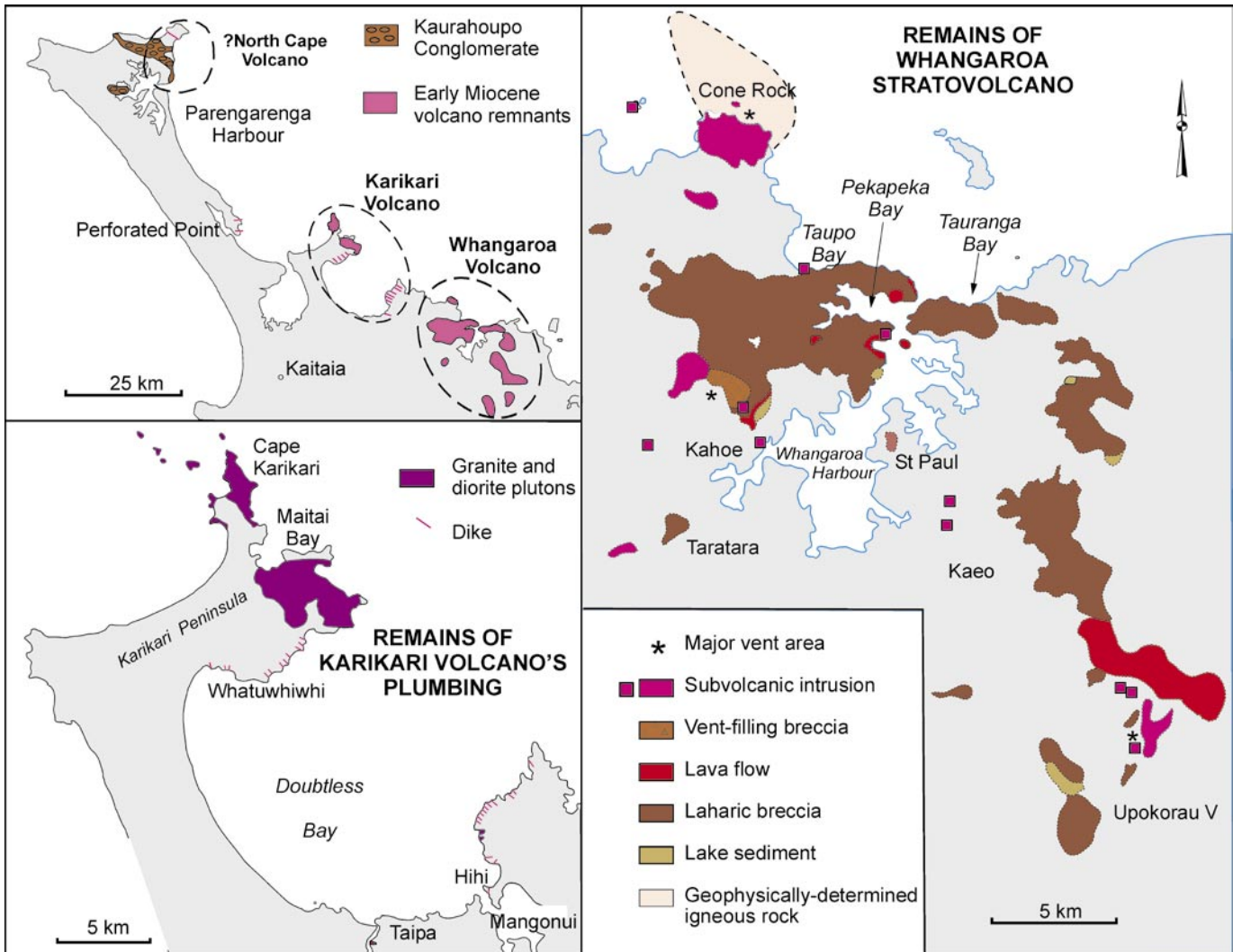
6.48 The hollow centres of these two small mounds mark the former locations of trees that were growing on an alluvial flood plain that had developed on top of the Hokianga Basin sedimentary infill during the latter part of the Early Miocene (18-17 Myr ago). Lines in the shore platform are made by sand 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.

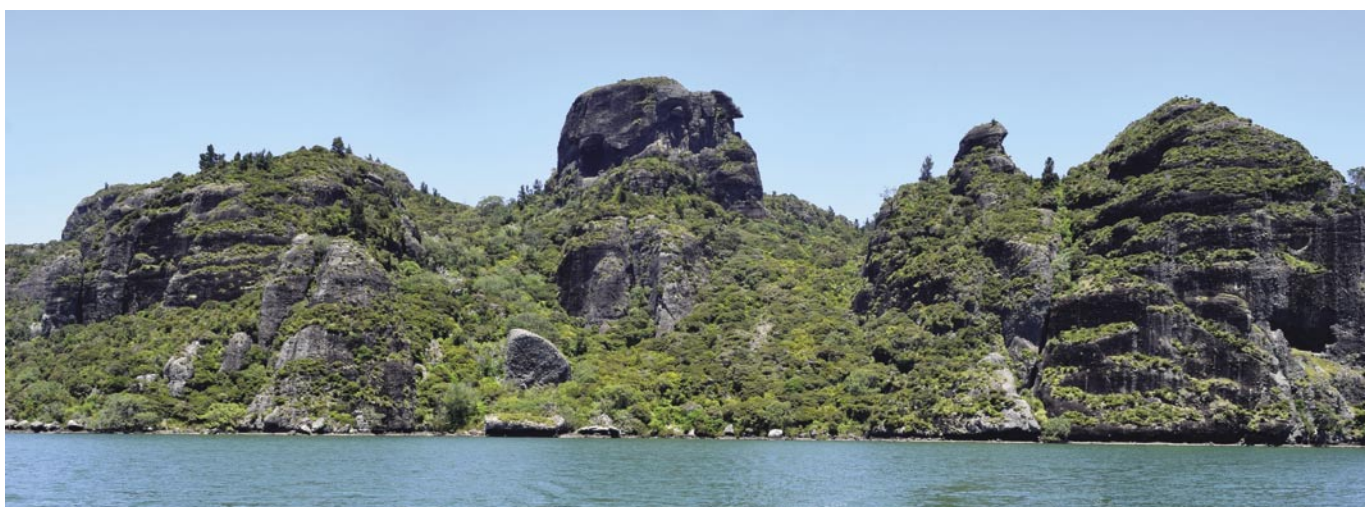


6.53 Intertidal exposure of mudstone and sandstone that was deposited in a freshwater lake, created by the earliest eruptions of Whangaroa Stratovolcano. The two tightly folded horizons are inferred to be a result of downslope sliding of the lake-floor strata, within a few thousand years of their deposition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

North Cape Volcano

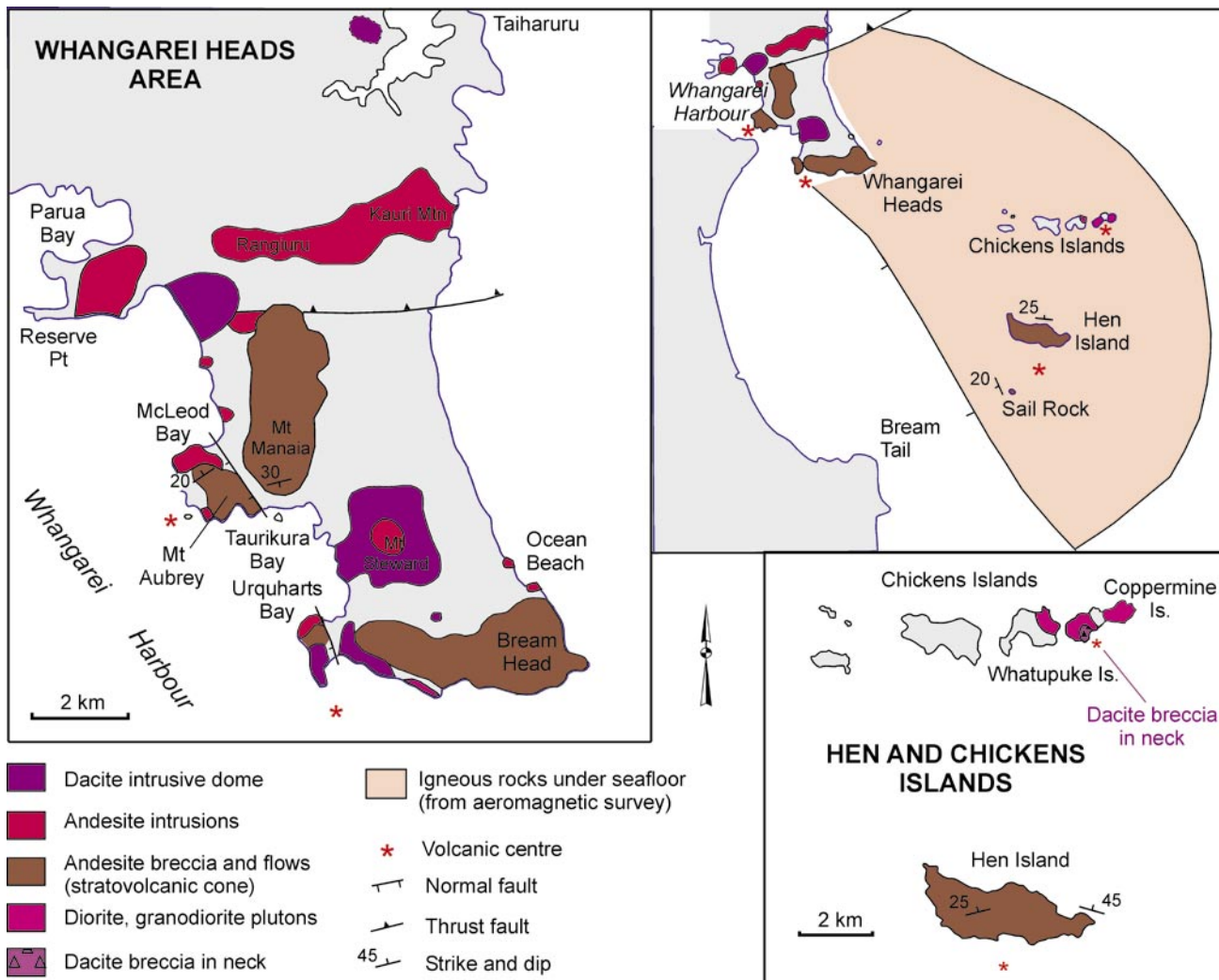
Seventy kilometres northeast of Whangaroa, and along the same trend as Whangaroa and Karikari stratovolcanoes, there is evidence of the former existence of perhaps another completely eroded away volcano near North Cape (6.50). The evidence consists of a diorite intrusion – inferred to be subvolcanic 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,



6.56 Historic photo from the early 1900s of a mushroom rock of andesite breccia in Pekaheka 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.

probably downriver, 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.

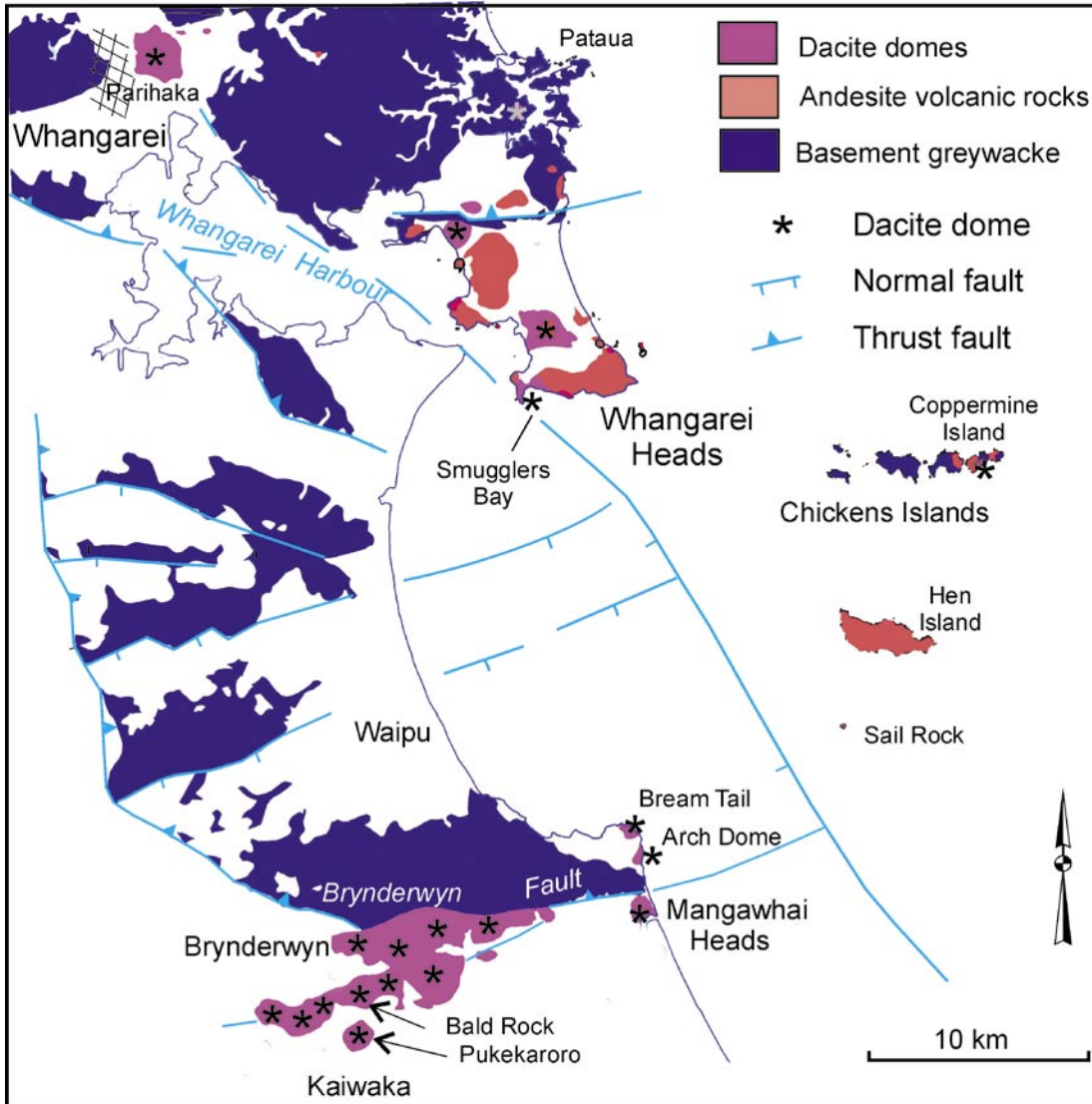


6.62 *Angular blocky breccia on the north side of Hen Island is part of the eroded cone of the small Hen Island Stratovolcano, which erupted 19-16 Myr ago. Bream Head in the distance is the eroded remnant of another similar volcanic cone of the same age.*

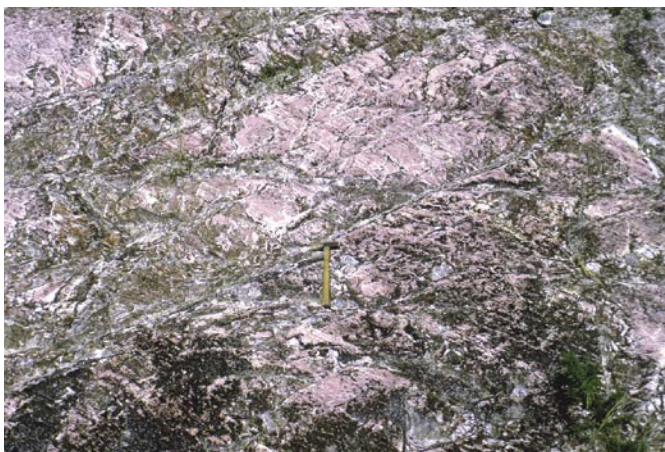


6.63 *View of Hen and Chickens Islands from Langs Beach, Waipu. Hen Island (centre) and Sail Rock (right) are the remnants of a 5-10 km stratovolcano. The Chickens Islands (left) are basement greywacke intruded by the subvolcanic plumbing and small magma chambers of another volcano that has been eroded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

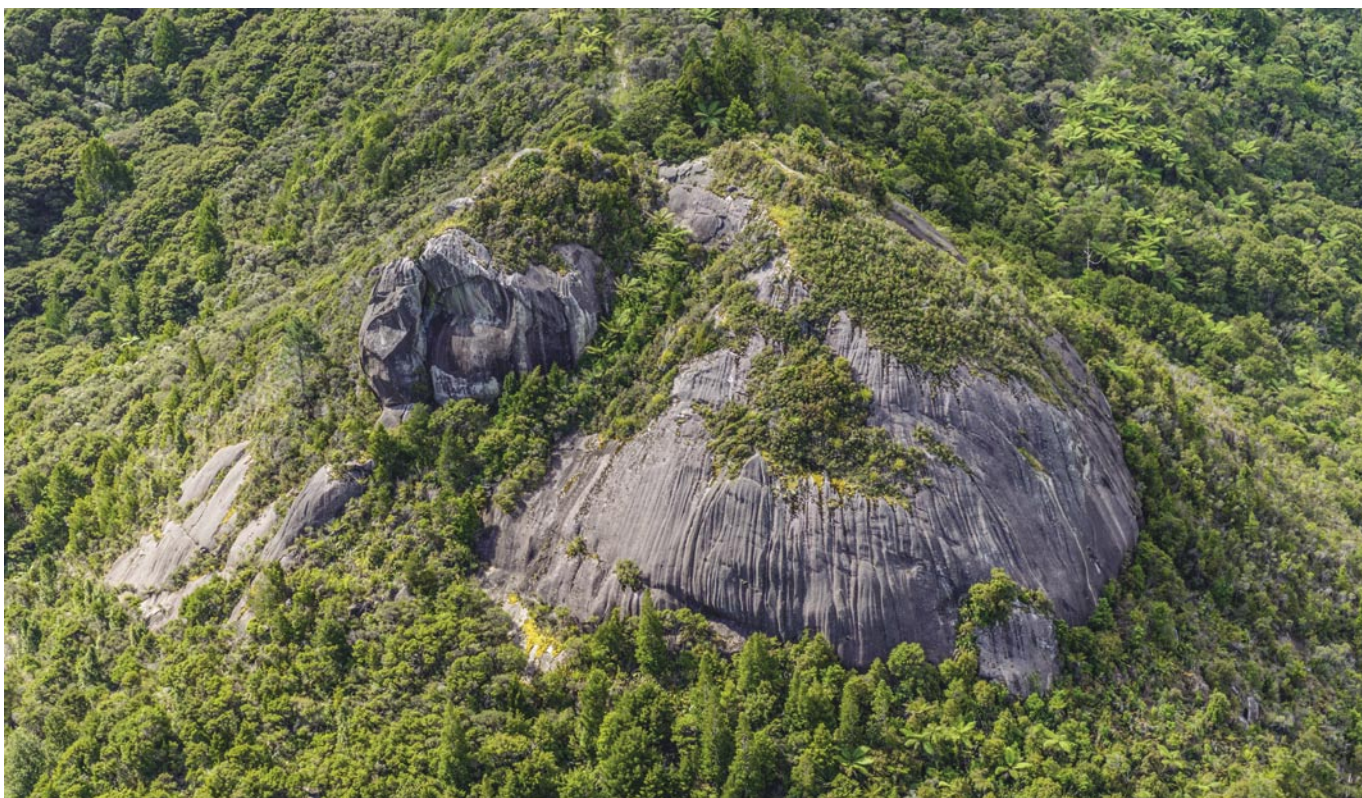
around it and the hard dacite now forms the imposing Mount Parihaka, which overshadows much of downtown Whangarei. (The spelling of Mt Parihaka was corrected from Parahaki in 2005).

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.

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.

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





6.68 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.

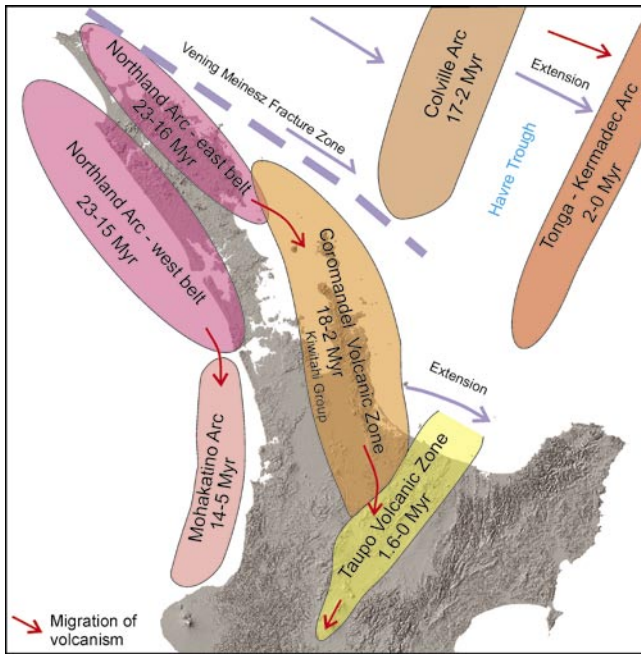
Volcanic arcs of northern New Zealand

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.

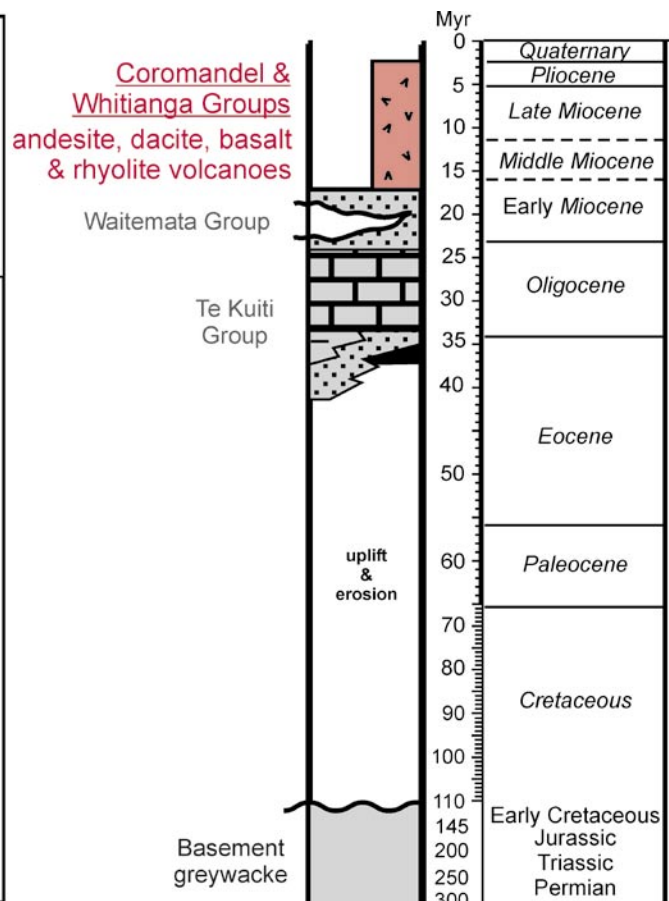
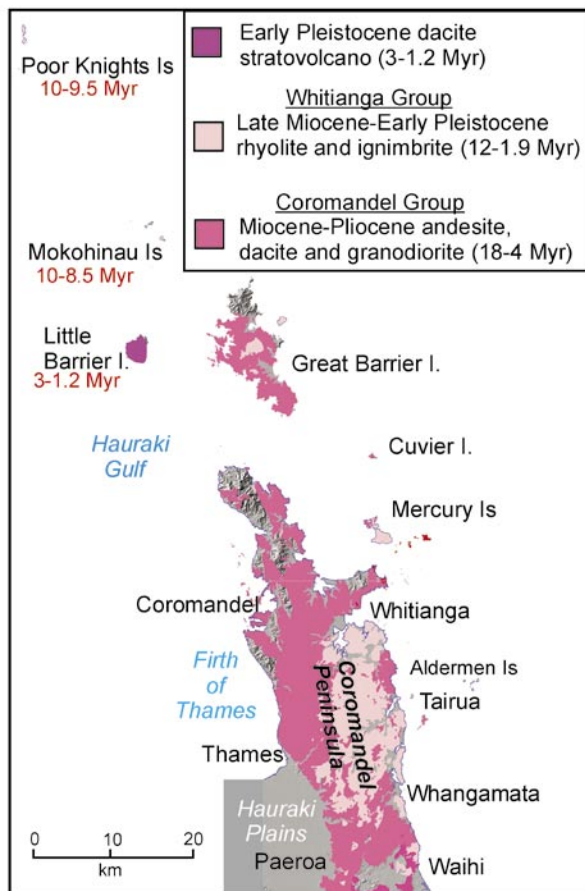
Southeastward migration of the eastern belt of the Northland Volcanic Arc was more gradual, starting about 18 Myr ago (Early Miocene) with the outbreak of andesitic volcanism on what is now Great Barrier Island and the northern Coromandel Peninsula. Through the Middle and Late Miocene (16-5 Myr ago),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

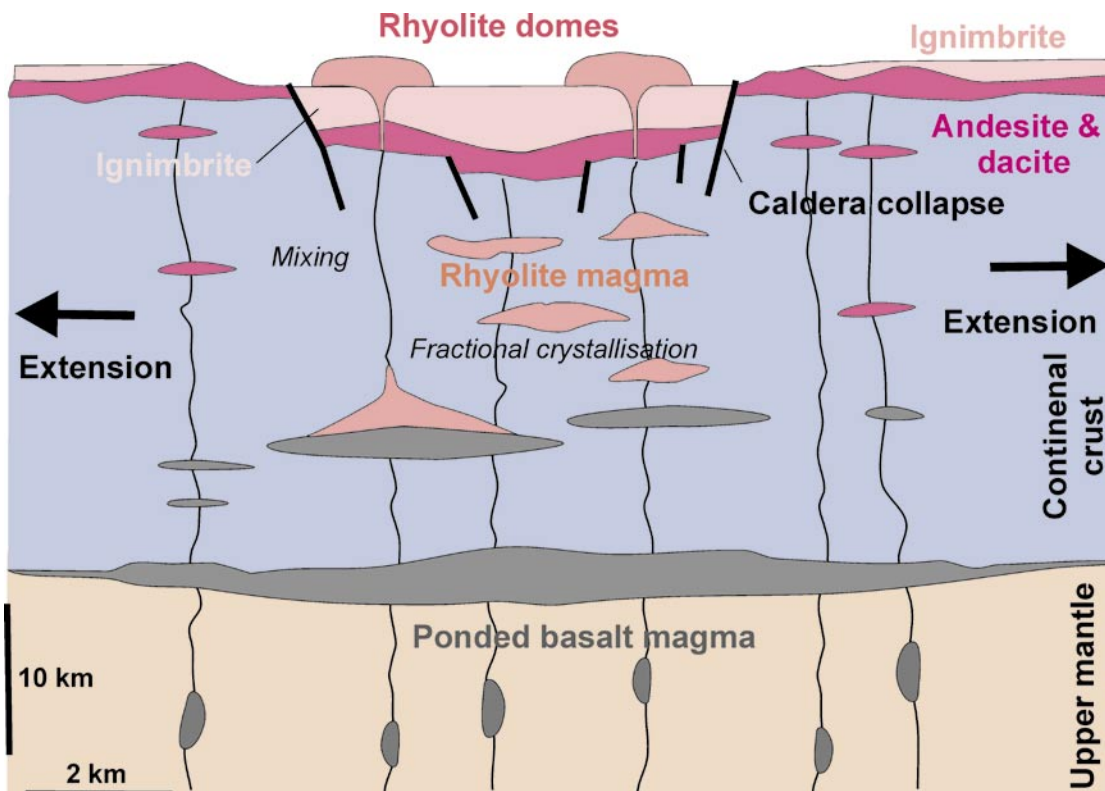
An additional narrow line of subduction-related andesite volcanoes (Kiwitahi Group; 7.4) runs parallel to the Coromandel Peninsula along the west side of the Hauraki Rift (Firth of Thames, Hauraki Plains). It too exhibits southward migration of activity, starting 15 Myr ago on Waiheke Island and finishing 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 north-northwest-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.

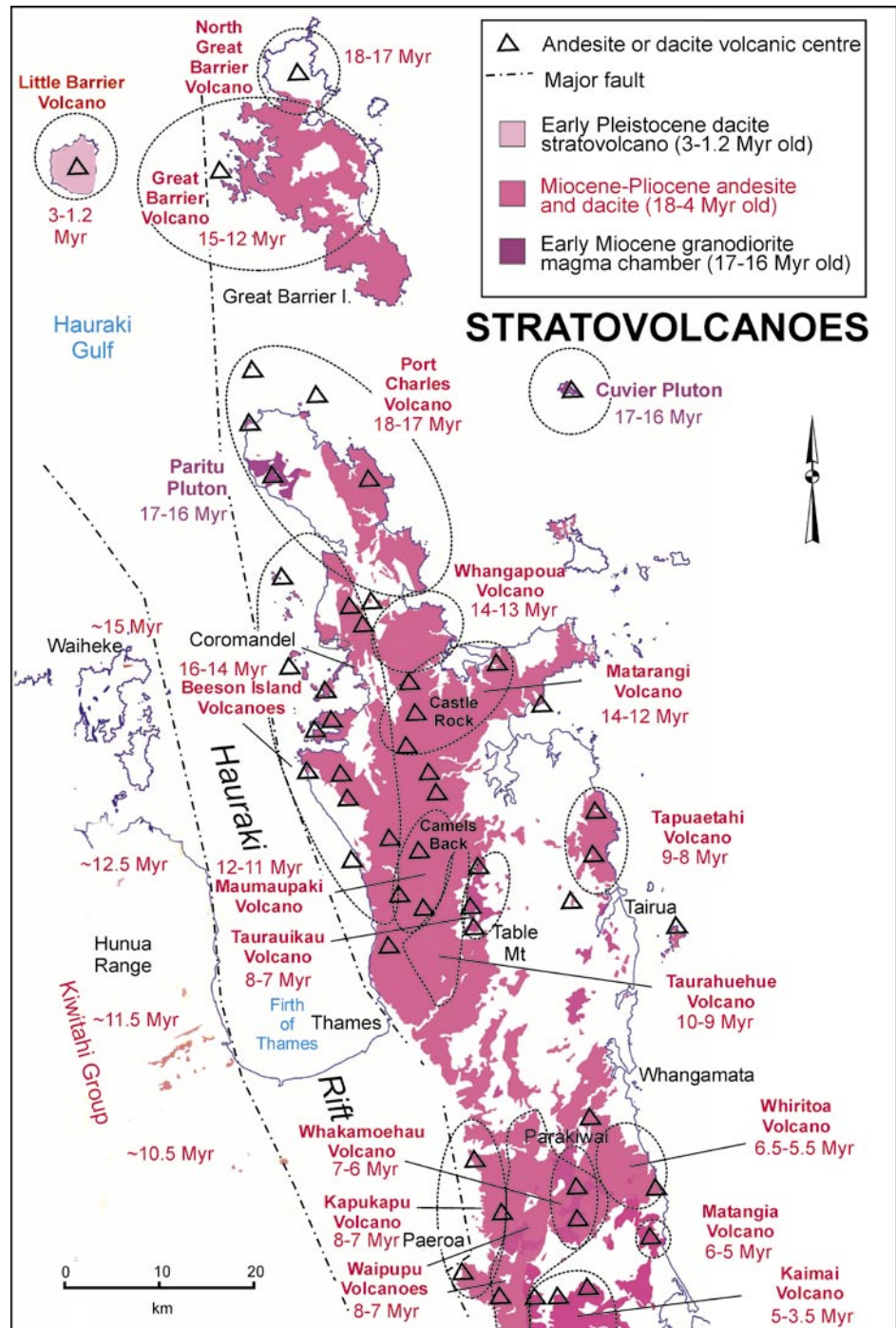
ANDESITE STRATOVOLCANOES

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



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.*

Peninsula was probably a magma chamber that fed the Port Charles Volcano above.

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.

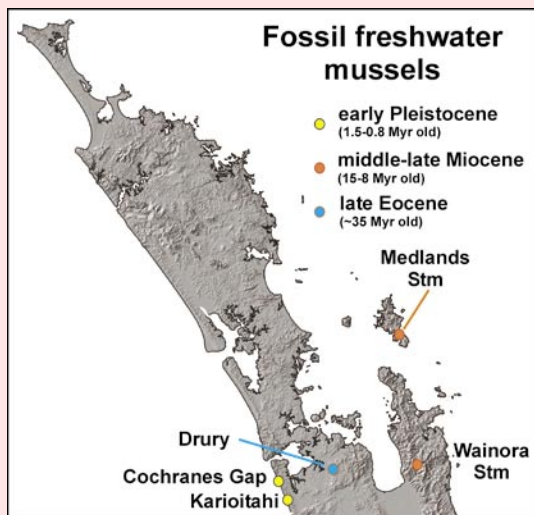
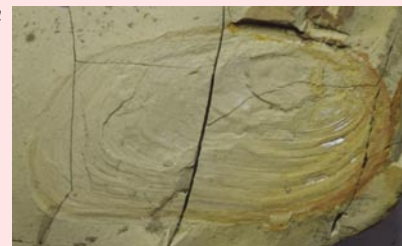
Box 28. FRESHWATER MUSSEL FOSSILS

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).

7.18 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.



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

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 km³ 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.

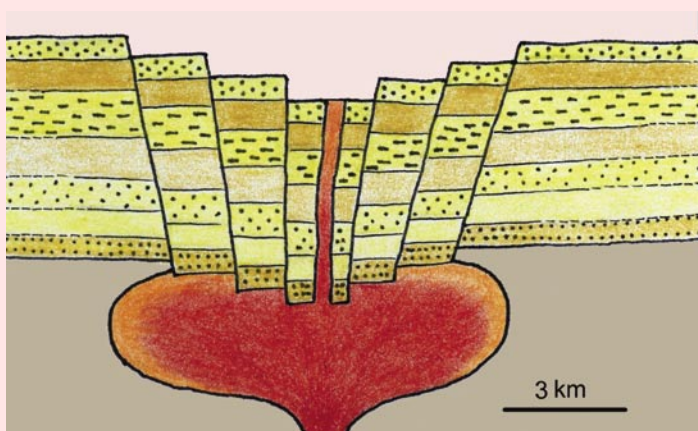
The rapid emptying of the shallow rhyolite magma chambers during these huge explosive eruptions occurred over a matter of hours to a few days. The land overlying the emptying magma chamber collapsed into the hole, creating a huge crater known as a caldera (7.22). Recognised ancient calderas on the Coromandel 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



7.21 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.



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

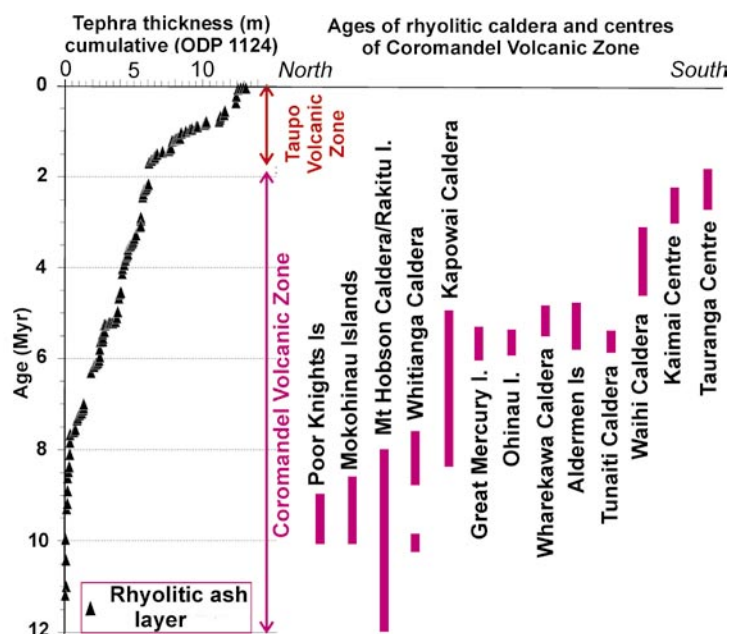
be tens to hundreds of metres high and hundreds of metres to several kilometres across. In the Coromandel Volcanic Zone, some rhyolite domes were single, subcircular landforms, but many others had a number of vents and the domes joined together and overlapped to form quite complex features.

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 *owharaite*, 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 km³ 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).

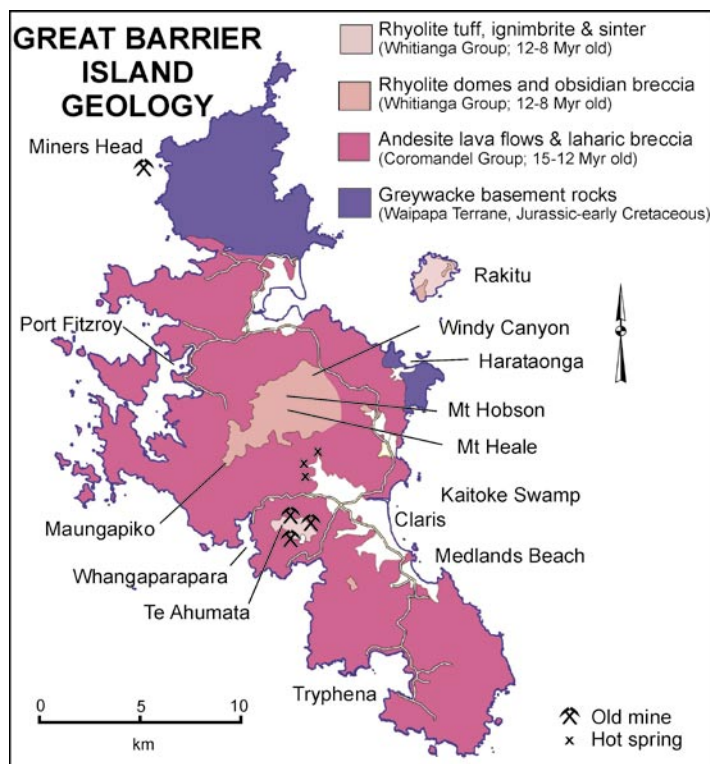
As with the andesite volcanism in the Coromandel Volcanic Zone, the oldest rhyolite volcanoes (12-10 Myr old) erupted in the north and activity migrated southwards, with the youngest (5-2 Myr old) volcanism located between Waihi, Kaimai and Tauranga. Interestingly, the start of rhyolite volcanism lagged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



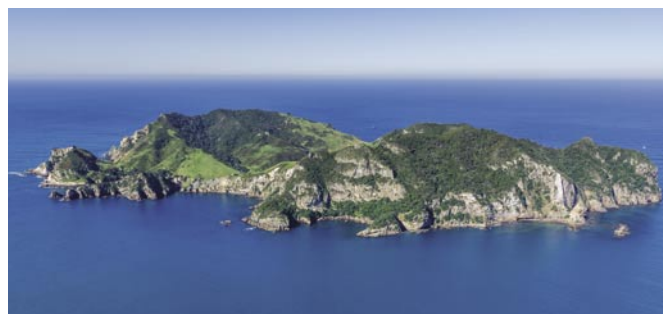
7.26 The Poor Knights Islands are made of silicified rhyolite breccia and ignimbrite - eroded remnants of a much larger 10 Myr-old caldera volcano. Looking south from Tawhiti Rahi to north western Aorangi Island.

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



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).



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.

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.

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-Hikua 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 the 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.

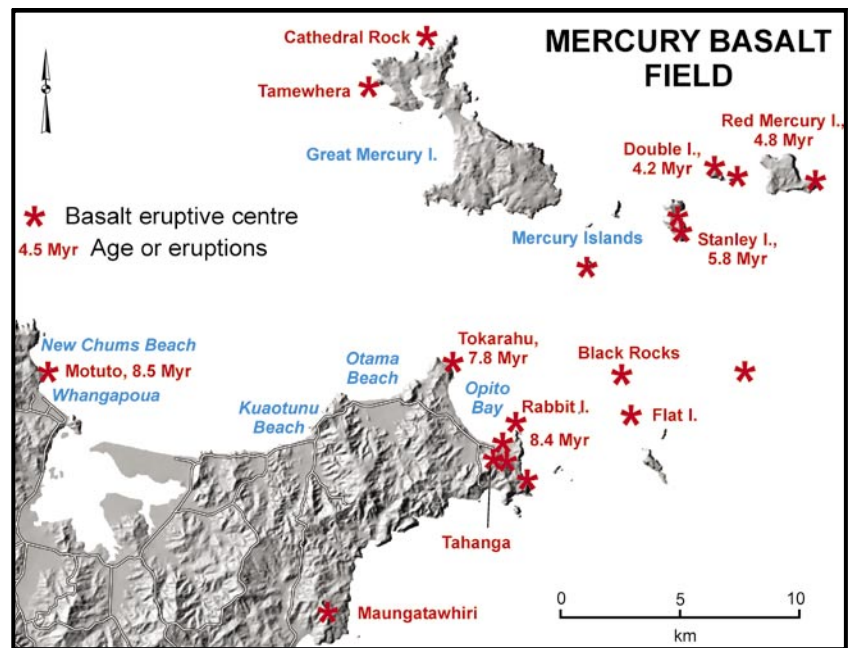


7.41 View southeast over Red Mercury I., off the east coast of northern Coromandel Peninsula. The island is an eroded remnant of a small scoria cone and surrounding apron of basalt lava flows. At 4 Myr old, it is one of the youngest volcanoes in the Mercury Basalt Field. Photographer Lloyd Homer, GNS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

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



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

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.

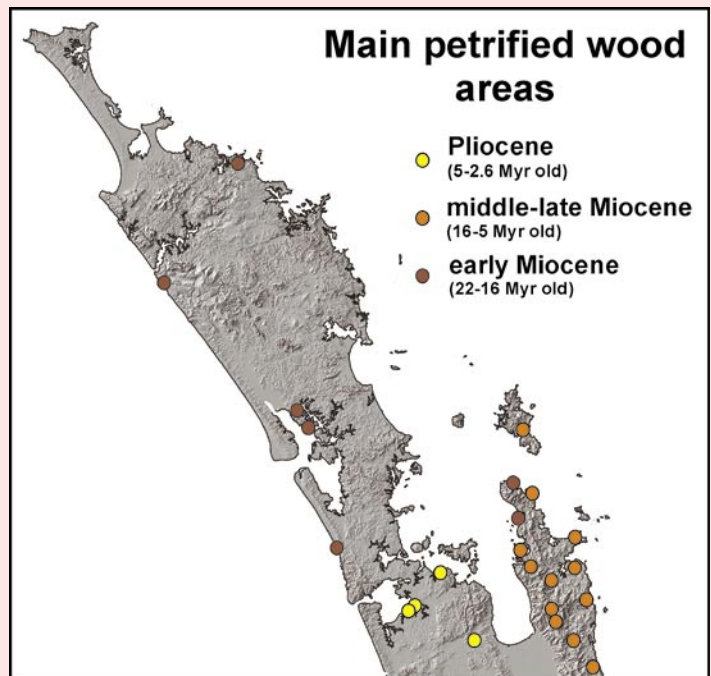
Petrified wood is harder and more resistant to weathering than most other rocks and is therefore often found reworked in stream and beach gravels and sometimes even on hillsides. Petrified wood comes in many colours and is targeted by rockhounds, who cut and polish it or turn it into jewellery. The most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



7.46 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.



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



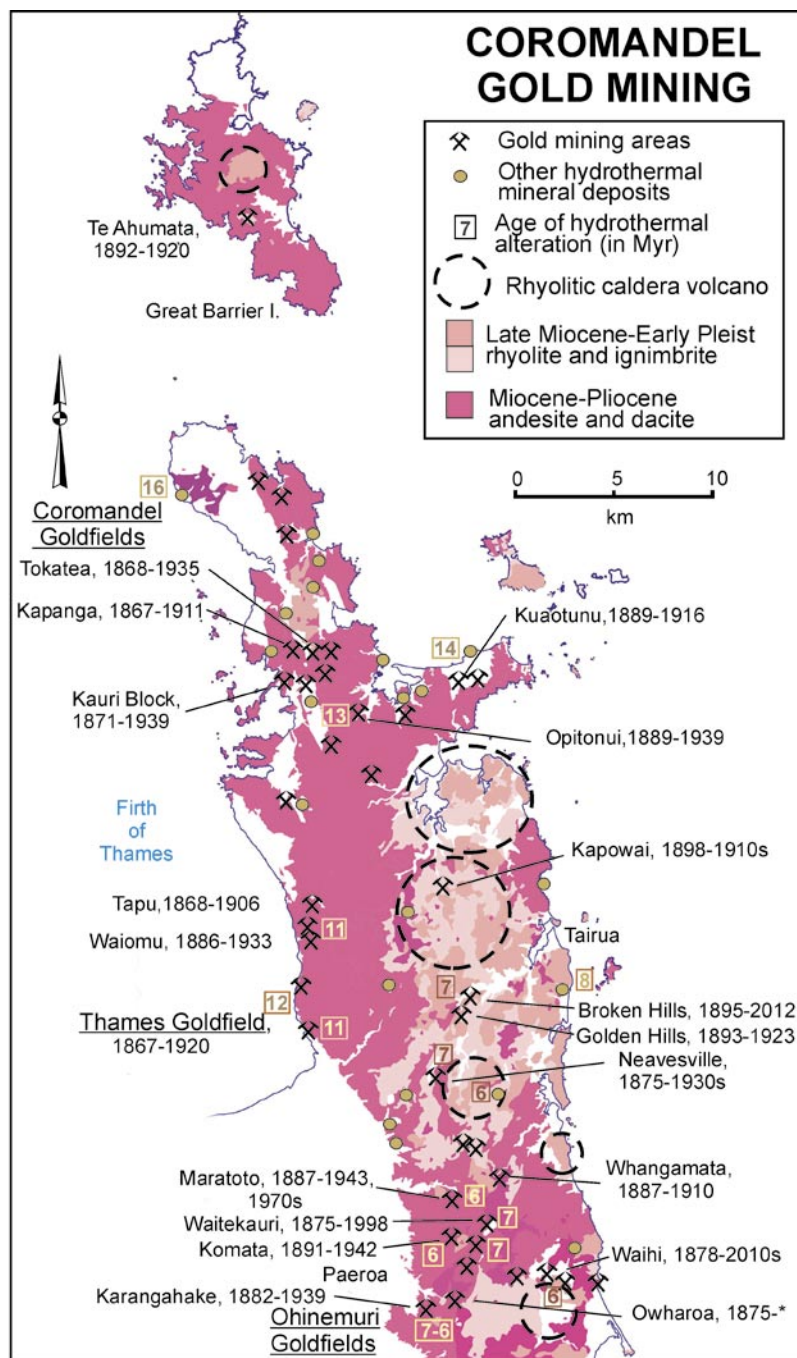
7.47 Locations in northern New Zealand where petrified wood commonly occurs.

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.

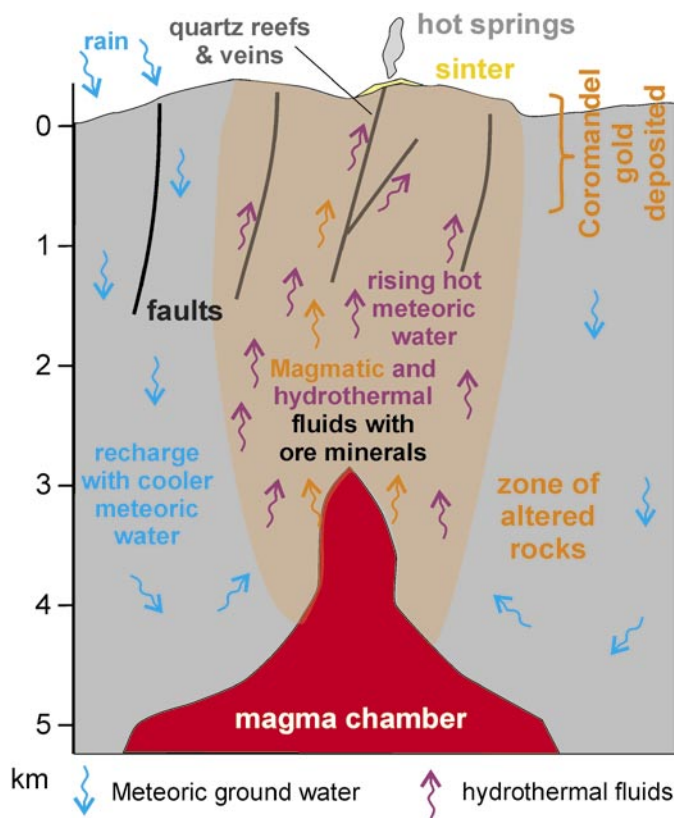
As the hot, mineral-rich fluids migrated upwards, they cooled, and the pressure reduced, resulting in the deposition of quartz, calcite and other minerals on the walls of the fluid conduits, such as fractures and fault zones. Over time, steeply-dipping reefs (large veins) made dominantly of quartz (silica, 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 ($200\text{-}300^\circ\text{C}$), sulfides of iron (pyrite and marcasite, both FeS_2), lead (galena, PbS), copper (chalcopyrite, CuFeS_2), zinc (sphalerite, $(\text{Zn,Fe})\text{S}$), silver (acanthite, Ag_2S) and some native gold were sometimes deposited.

Nearer the surface where the fluids were slightly cooler ($100\text{-}200^\circ\text{C}$), sulfides of mercury (cinnabar,



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.

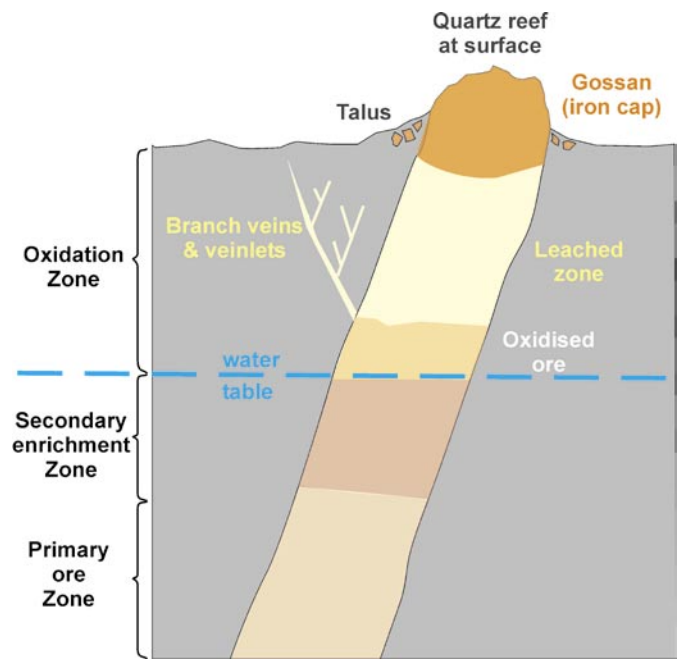
HgS) and antimony (stibnite, Sb_2S_3), together with silver and gold, were formed. Bonanza reefs rich in gold and silver, were usually deposited in places where there was a sudden pressure drop and vigorous boiling of the hot



7.49 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.

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

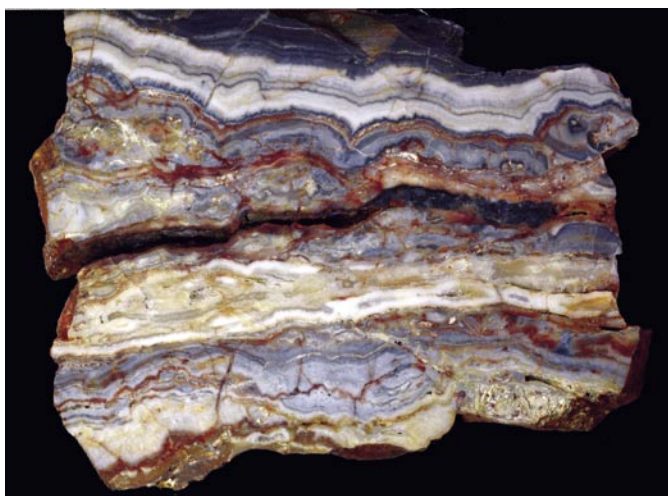


7.50 Schematic cross-section of the effects of weathering on mineralised quartz reefs. Oxidation might produce an iron-oxide-rich gossan cap at the surface. Below this, some minerals are leached out of the reef and deposited below the ground water level, forming a secondary enrichment zone. Here copper, silver and gold might occur in much higher concentrations than in the primary ore zone of the original reef.



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 volcanism (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, Owharua, 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.

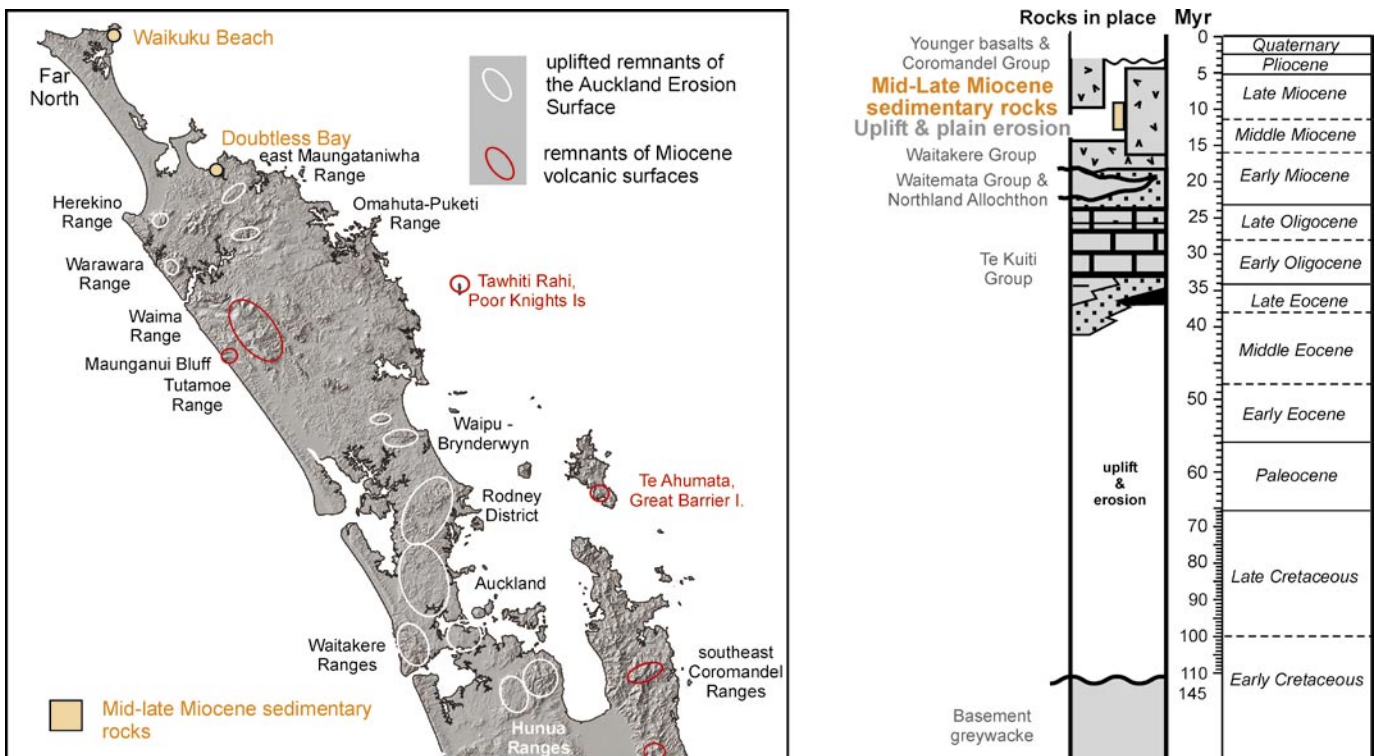
The sky-rocketing global price of gold in the 1970s led to a renewed search for gold and silver in the Coromandel Peninsula, especially around former mine workings. No new fields were discovered, but additional ore zones were located at the old Martha and Golden Cross (Waitekauri) mines. These were re-opened 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).

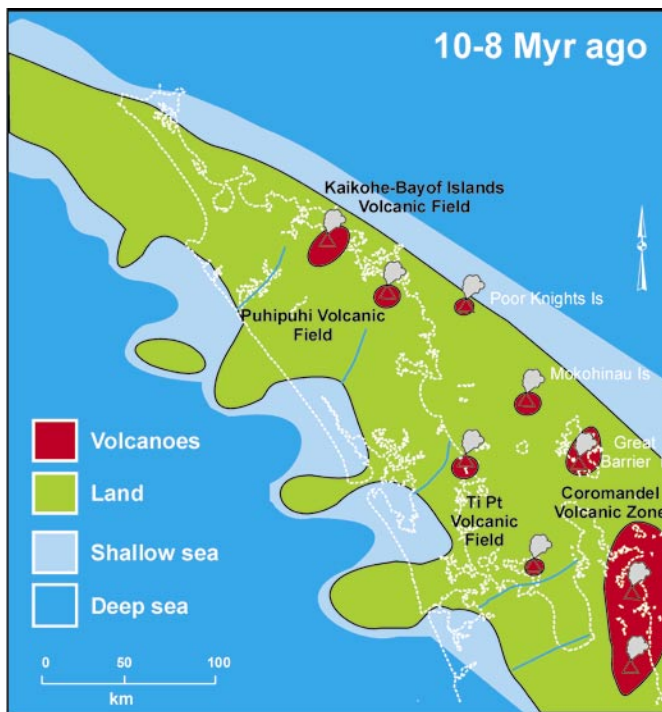
Chapter 8. ERODING DOWN THE LAND (15-4 Myr ago)

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

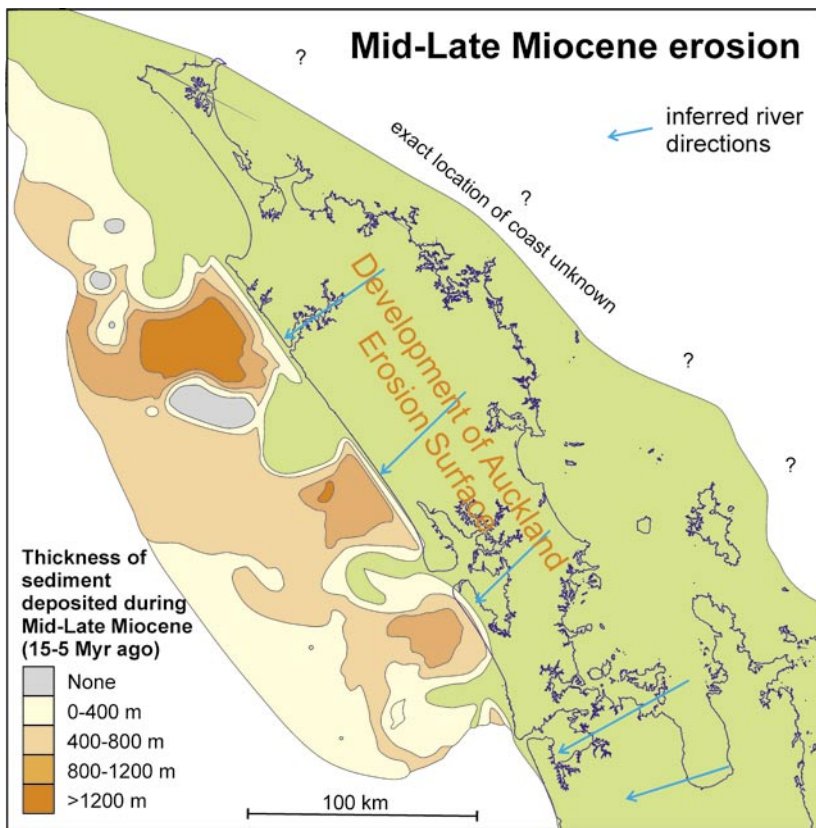
Further south over Auckland, there is no direct evidence in the rocks of the demise of the Waitemata Basin, as all of its younger strata have been uplifted and eroded away. The youngest Waitemata Sandstone beds left between Warkworth and the Waikato region are about 19 Myr old and were deposited at deep

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).

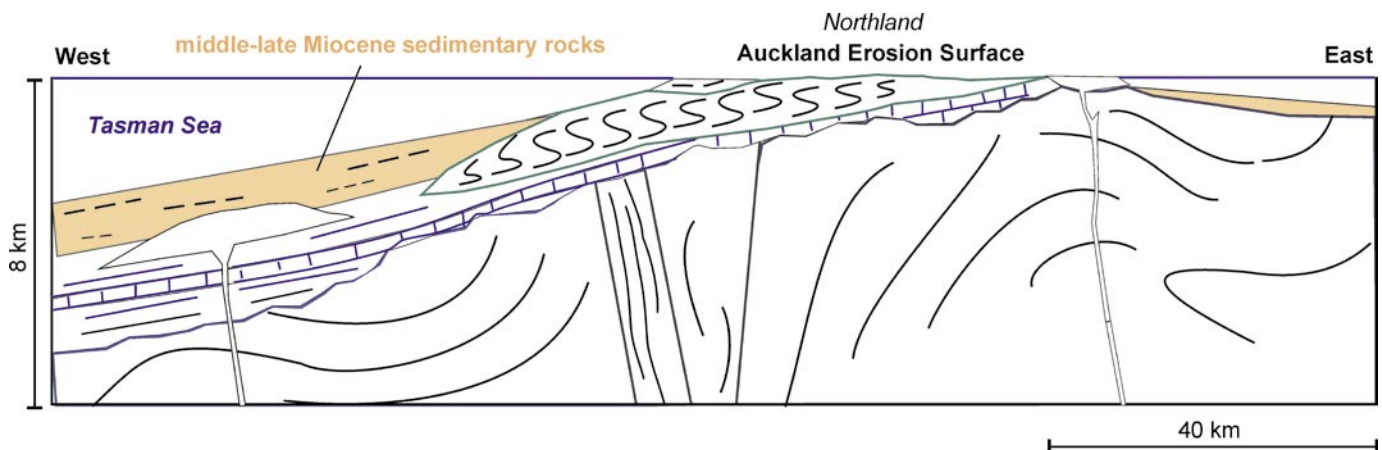
Formation of flat erosion surfaces

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.



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

8.6 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).

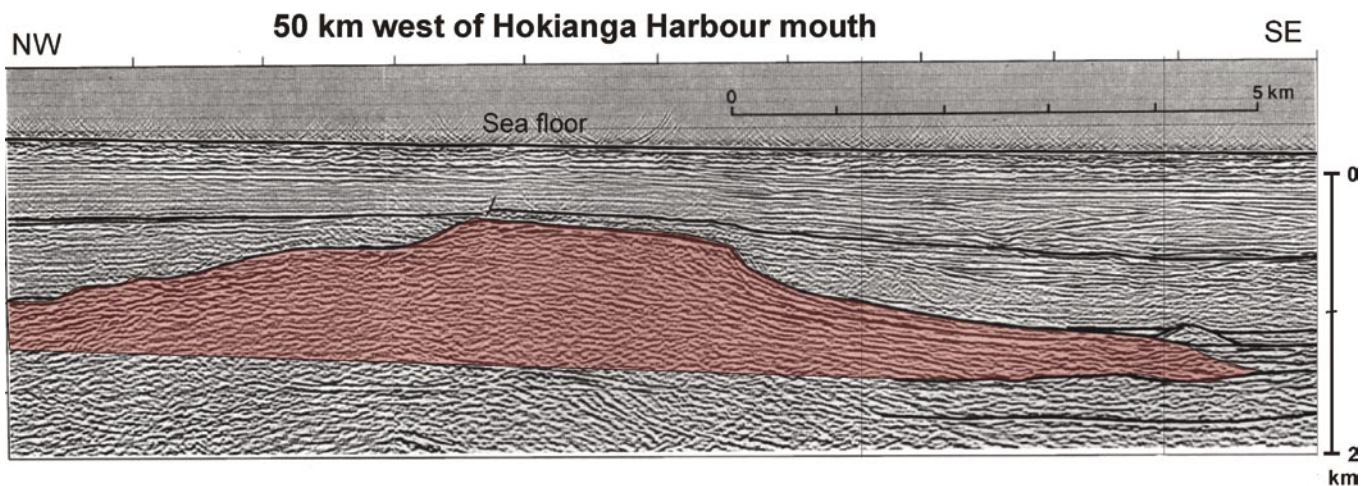




8.8 This 150 m-wide shore platform at Musick Pt, east Auckland, has been eroded by the sea into Waitemata Sandstone rocks in the 7000 yr since sea level reached its present height after the end of the Last Glacial period. This gives an erosion rate of about 2 cm per year. At this rate the erosion surface, 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 and 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 cocumbe 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.

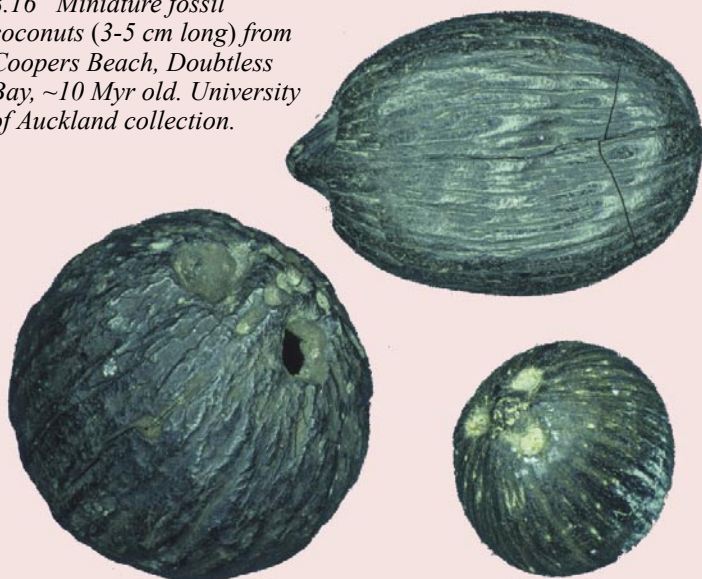
The miniature fossil coconuts at Coopers Beach are generally flattened as a result of burial beneath a thick sequence of sediment. They erode out of freshwater sedimentary rocks at the back of the beach or from shallow subtidal reefs just offshore. Occasionally small fossil coconuts are also washed up 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.