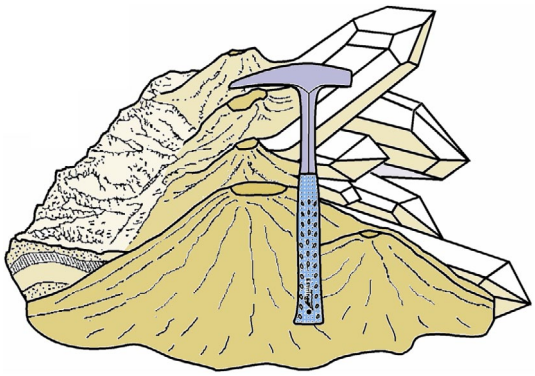


Geocene

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Geocene is a periodic publication of Auckland Geology Club, a section of the Geoscience Society of New Zealand's Auckland Branch.

Contributions about the geology of New Zealand (particularly northern New Zealand) from members are welcome. Articles are lightly edited but not refereed.

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GABBRO KARST AT LA PROMENADE DES GABBROS, RAIATEA ISLAND, FRENCH POLYNESIA

Bruce W. Hayward

"La Promenade des Gabbros
The Gabbros Walk, located on the island of Raʻiātea, is a unique trail that crosses an area characterized by outcrops of gabbros, igneous rocks formed deep within the Earth's crust. This route, accessible via a marked path, offers visitors immersion in the heart of a unique mineral landscape, where the dark hues of the gabbros contrast with the surrounding lush vegetation. This natural setting invites geological discovery and contemplation, attracting both geology enthusiasts and simple walkers.

Beyond its scenic appeal, the Gabbros Walk represents a true testimony to the geological history of Raʻiātea and the Society Islands. Gabbros, rich in minerals such as pyroxene and olivine, are the result of slow crystallization of magma at depth, before being exposed by erosion processes. This trail thus allows visitors to understand the evolution of the island, while raising awareness among visitors of the importance of preserving this exceptional geological heritage.

Designed to welcome the public, the promenade features well-marked trails, explanatory panels, and observation points offering panoramic views of the surrounding area. Families, hikers, and natural science enthusiasts will find it a space conducive to exploration and learning. Between wonder and transmission, the Gabbros promenade embodies a place where nature and knowledge harmoniously meet." (Translated from French from Service du Tourisme de la Polynésie Française: https://www.service-public.pf/sdt/st-gabbros/)

We were self-driving (on the right) around Raiatea Island in French Polynesia during a one day stop there in September 2025. The French tour map suggested taking the cross-island road and stopping at two viewing points (Belvederes). After stopping at the first, we contemplated skipping the second, but I happened to notice its name included the geological term "gabbro".

We pulled into the carpark in front of an information board to see how long the walk would be if we took it, and my wife exclaimed – "*You have to stop here. Look at the boulder forms in the photographs.*" What an absolute surprise. We had no inkling that here was an area of amazing gabbro karst boulders – indeed the first I had ever heard of. In all my on-line research since then, I have not actually found the term "gabbro karst" and karst or solution are not mentioned in any explanation of how these boulders were shaped. On site, the English information says:
"The alteration of these rocks by characteristic "gutter" erosion patterns is remarkable and has produced these vertical slabs that emerge from the 'mamu' (ferralitic soil) and their amazing shapes".



Fig. 1. Map of Raiatea Island and the location of the La Promenade des Gabbros (red circled) on the cross-island road.

Similar karst (formed dominantly by dissolution) developed on basalt has been documented from northern New Zealand, Norfolk Island and Oahu, Hawaii (e.g. Palmer 1927, Bartrum & Mason 1948, Hayward & Kenny 2011, Hayward 2012 2015 2017, Thomson & Hayward 2024) and on dolerite in Northern Ireland (Reynolds 1961).

Raiatea Setting
The island of Raiatea (Fig. 1) in French Polynesia is a partly eroded intra-plate basalt shield volcano (Blais *et al*. 1997). It erupted in the Late Pliocene–Early Pleistocene (2.75–2.44 Ma) from the Society hot spot before being moved away by plate motion. The elongate island consists of two overlapping edifices. The southern shield consists of 1000 m of pahoehoe basalt flows. The centre of the shield is a collapsed caldera (Faaroa Caldera) that opens out to the east (Blais *et al*. 1997) (Fig. 2), possibly as a result of sector collapse or deeper erosion along the main radial stream valley that once flowed out from a caldera lake (cf. Lyttleton, Akaroa and Dunedin shield volcanoes). Several areas of shallow magma chambers (cf. Onawe Peninsula in Akaroa Volcano) are exposed inside the centre of the eroded-out caldera and one of these forms an 80 m high knoll crest where the gabbro boulders (Fig. 3) are found.

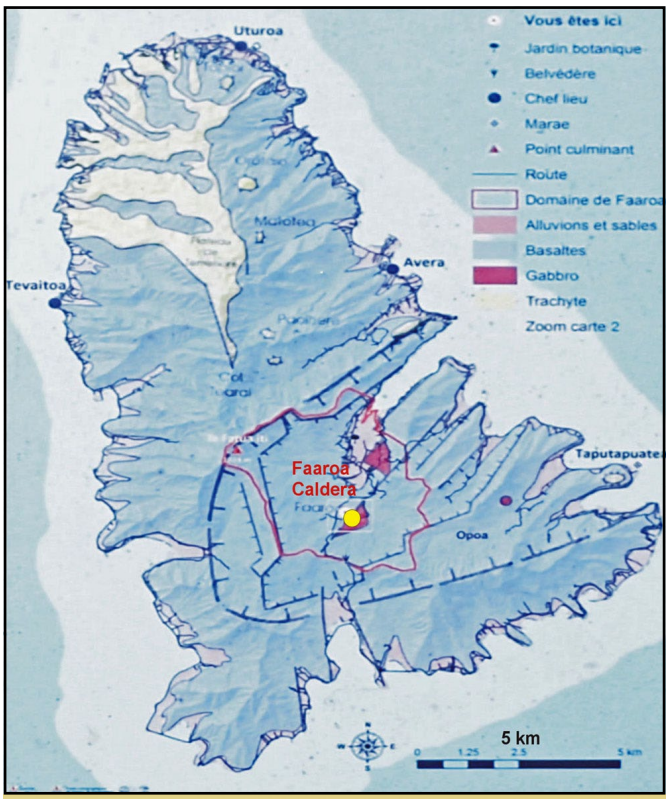


Fig. 2. Geological map of Raiatea (from Service du Tourisme de la Polynésie Française website) showing the subject gabbro (yellow) inside the eroded-out caldera.

The narrow knoll rises about 20 m above the cross-island road. It is covered in regrowth vegetation including introduced wilding fruit plants. A stepped path leads up to a viewing point with two wooden platforms on the top (Fig. 4). In this area, most of the forest cover has been removed and the grass between and around the scattered gabbro boulders is regularly mown (Fig. 4). Thus, the original prehuman forest setting in which the karst landforms were made is no longer present.

Raiatea Gabbro Karst

The boulders on the ridge crest are up to 4 m across but mostly 1–2 m, and up to 2 m high above the ground but often only just visible above soil level. Low-lying boulders and flatter lower portions of higher boulders are often smooth (Figs 5–7) and are inferred to have been largely covered by leaf litter humus or soil beneath the forest until anthropogenic fires and recent forest clearance have exposed them. A number of the boulders have fluted steep faces in the higher parts but smooth flat surfaces parallel to the sloping ground around their base (e.g. Figs 5–8). The 2D-outline of these flat surfaces is rounded and seems to be the pre-solution shape of the lower parts of each boulder. One boulder (Figs 7–8) has a smooth undercut, about 30 cm high, above the smooth gently sloping surface along the base of a vertical blade (Fig. 7). This suggests that there was a 30 cm-thick zone of leaf litter and soil that was acidic and wet enough to dissolve the rock as the vertical blade was being dissolved back towards the original centre of the boulder.



Fig. 3. Close up of coarsely crystalline gabbro boulder. Photo 30 cm across.



Fig. 4. Viewing platform among karst gabbro boulders.



Fig. 5. Low ground cover, roots, soil and moss on top of the smooth surface of a low boulder. Width of photo 1 m.



Fig. 6. Boulder on slope with smooth surface (above left) and foreground (right). The fluting on this boulder is inferred to have occurred when the upper and foreground surfaces were shallowly buried by soil with a steep face of rock exposed on the downhill side where the fluting has developed by seepage of acidic water. Width of photo 1.2 m.



Fig. 7. Original subspherical boulder has been reduced to a narrow vertical blade (1.2 m high) surrounded on two sides by a smooth horizontal base. The base is the size and outline shape of the original boulder. The upper 70% of the vertical blade has fluted sides but the lower 30% has been dissolved to form a smooth undercut on both sides.

A number of boulders have a mix of fluted steep faces and smoother flatter faces (e.g. Figs 9–10). The fluting likely formed by solution in runnels carrying humic acid seepage from humus formed around roots of lithophytes growing on top of the boulders. The smoother, flatter surfaces presumably formed by humic acid solution beneath and around the humus and leaf litter itself. Smooth but irregular surfaces, especially higher on the boulders (Figs 9–10), is inferred to have formed between ridges beneath irregular clumps of lithophytes. Occasionally, shallow basins have



Fig.8. Another view of the boulder in Fig. 7 showing the smooth, flat portions of the original boulder on the uphill and downhill sides that support the remaining fluted vertical blade. Note the smooth surfaces slope downhill parallel to the ground and are likely to have been formed beneath soil and leaf litter beneath a forest cover. Width of photo 3 m.



Fig. 9. Moderately low boulder with a mixture of vertical/subvertical flutes formed on steeper faces (right) and smoother surfaces that probably formed beneath acidic leaf litter and soil. Width of photo 2 m.



Fig. 10. Another boulder with a mix of fluted, subvertical blades/ridges and smoother flatter surfaces in between. Width of photo 1.5 m.

been dissolved in these surfaces (Fig. 11). Like New Zealand basalt karst, some boulders have deeply dissolved basins on top with equally deep overflow flutes creating “armchair” basins (Figs 12–13).

A few of the boulders, some sitting as feature boulders in the mown grass, have deep vertical or subvertical fluting on one or more sides (Figs 14–16). These are probably the most striking features noticed by general visitors.

These gabbro karst boulders are, in terms of showing stages in their development, on a par with the best basalt karst in Northland. They share many features in common: their location as stable boulders or in-situ rocks on the crest of a ridge or top of a slope; presence of smooth flatter surfaces and fluted steeper slopes; lack of solution beneath the originally round core stone boulders; combination of deeply dissolved basins and flutes creating “armchair” basins.

The biggest difference between Raiatea’s gabbro karst and Northland’s basalt karst is that in French Polynesia, the solution of some boulders is far more advanced than in Northland. At Raiatea, several boulders only have a single remaining vertical blade of rock from the original boulder (Fig. 8). There are several possible reasons for the greater solution: the boulders were more stable and exposed for much longer at Raiatea; gabbro is more susceptible to solution than basalt; the humus at Raiatea produced lower pH (more acidic) seepage; solution processes are faster in the higher temperatures. The reason could be a combination of several of these factors.



Fig. 11. Solution of the gabbro in this depression, presumably beneath humus, has created this shallow basin in an enlarged seepage-derived flute. Width of photo 60 cm.



Fig. 12. Deeply eroded flutes and armchair basins in a gabbro boulder. Width of photo 1 m.



Fig. 13. Deeply dissolved armchair basin and flute with a sharp bend. Width of photo 80 cm.



Fig. 14. Deep flute under canopy with mosses and ferns. Width of photo 60 cm.



Fig. 15. Feature gabbro boulder with deeply incised flutes. Boulder 1 m high.



Fig. 16. Largest boulder, with deep vertical flutes, is inferred to have been dissolved by humic acid seepage from above. Note that the rounded base of this boulder (especially on right) is probably the original outer surface of the core stone before karst started to form. The elevation of the right-hand end of the boulder suggests that up to a metre of soil has slumped and eroded away in recent centuries.

Because the solution process probably takes 10s to 100s of thousands of years, it is difficult to design experiments that might test which of these options are most significant.

My recommendation is that French Polynesian Tourism could provide additional signage that explained how these highly unusual gabbro boulders were formed, but more significantly should celebrate and promote them for their international significance as probably the best example of gabbro karst in the world.

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VERTICAL TO HORIZONTAL – FIRST LIGHTBULB MOMENT – DÉCOLLEMENT SLICES AT IHUNGIA, EAST CAPE

Jill Kenny

Setting the Scene

This paper is from my MSc thesis (Kenny 1980) and from an article based on that thesis (Kenny 1984a). It is an historical account, reflecting unmodified concepts from that time. It is not intended to be an update of those concepts.

The 75 km^2 Ihungia catchment is located halfway between Gisborne and East Cape, west of State Highway 35, on the Raukumara Peninsula near Ruatoria, in the extreme east of the North Island of New Zealand (Fig. 1). The region is within the northern part of a northeast-trending, complex belt of Cretaceous and Tertiary strata occupying central and eastern Raukumara Peninsula, often affected by tectonic forces during its geological history (Kingma 1965, Mazengarb *et al*. 1991, Mazengarb & Speden 2000).

When I set out on this mapping exercise in 1978, I was already aware that lithologies of Cretaceous age could be found in the northern part of the Ihungia valley, 'papa'-like Miocene strata occupied the lower half of the catchment, and they were separated from each other by a complicated mix of Lower Tertiary lithologies.

For this article, I have tried to avoid use of lithology names because, in the decades since this thesis was written, some names have changed, or been incorporated into larger units, or called 'undifferentiated'. The names are irrelevant to this story anyway. I will now attempt to describe the stratigraphy in simple terms.

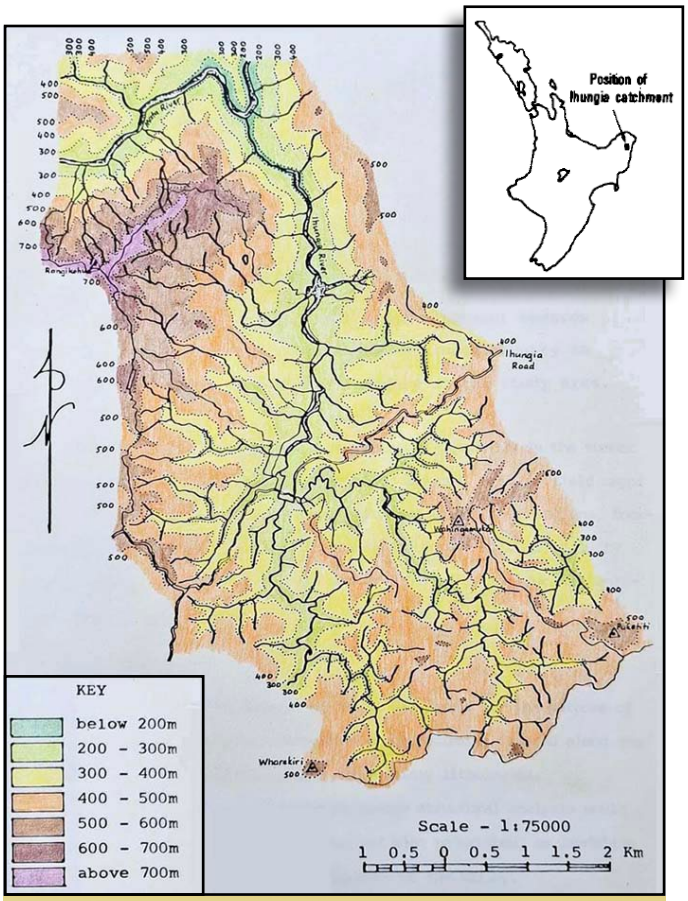


Fig. 1. Topography of the Ihungia valley. Slightly modified from Kenny (1980, fig. 1-4)

The Upper Cretaceous rocks in the north were indurated, isoclinally folded, sandstone-dominated flysch sequences of Ngaterian age (c. 99–95 Ma) (Kenny 1980 1984a 1984b) and could be traced further to the north and west out of the Ihungia catchment towards the Raukumara Ranges (IG Speden, pers. comm. 1980) (see also the following article in Geocene 43, Kenny 2026).

The southern half of the Ihungia catchment was dominated by massive, shattered, slightly to very calcareous, grey to blue-grey, very fine sandy mudstone ('papa') with occasional thin-bedded flysch sequences. I knew these rocks as Ihungia Formation – the 'Ihungia beds' of McKay (1887) and given formation status by Lillie (1953) and Kingma (1971) – but since my time there, this formation has been combined with other Miocene lithologies into the Tolaga Group (Moore *et al*. 1989) that extends southwards to Gisborne. In the Ihungia valley, the 'papa' was late Otaian to early Lillburnian in age (Early to Middle Miocene, c. 20–13 Ma).

Separating the Upper Cretaceous rocks in the north from the Upper Tertiary 'papa' in the south was an east–west zone of jumbled lithologies of Middle Cretaceous to Miocene age, always with sheared contacts to the north and south and with each other. The largest chunk was a crushed, dark blue-grey to black, noncalcareous, highly indurated siltstone, with occasional flysch sequences, of Motuan age (Middle Cretaceous, c. 103–100 Ma) that had been considerably folded and faulted. I knew it as Mokoiwi Formation (Speden 1976, after Bremner 1934). It was the oldest lithology in the valley, but it rested with a sheared contact upon the northern Upper Cretaceous lithologies (older over younger). This sheared contact was down-faulted in the Ihungia valley, therefore it was not visible here, but it was visible and traceable further west (Kenny 1986).

Between this large, down-faulted chunk and the Ihungia Formation 'papa' above it was a sliver of diverse lithologies of Middle Cretaceous to Oligocene age, bound together in what could only be described as a mélange of disintegrated blocks in a lubricant of finely sheared, pale cream-grey coloured gouge material. It oozed down slopes, forming a veneer, accompanied by small, sheared blocks of the diverse lithologies.

Decades ago, we called the oozy lubricant "bentonite" (Kenny 1980 1984a 1984b). Until a detailed analysis of smectite mudstones from East Cape to Marlborough was undertaken by Fergusson (1985), everyone called this stuff "bentonite". But it wasn't bentonite. By definition, bentonites were commonly regarded as originating from in

situ submarine alteration of volcanic ash or tuff (Grim & Guven 1978), and there was no volcanic ash or tuff at this locality. Pettinga (1980) concluded that the "bentonitic mudstones" in his PhD thesis area in coastal southern Hawkes Bay were merely montmorillonite-rich clays introduced to the environment by normal turbidite and hemipelagic sedimentation. Montmorillonite is swelling clay; it is magnesium-rich smectite.

Fergusson (1985) thought that East Coast "bentonites" should be termed "smectite mudstones". As with true bentonite, it swelled and became very sticky when wet, like 'quick mud', and when dry, displayed the cobweb-type deep jointing pattern typical of bentonite. Its pale cream-grey colour was often discoloured by weathering inclusions of lithologies incorporated into the smectite during movement along the shear zones (Kenny 1980). Most common discolouration was a red mudstone that often accompanied the smectite mudstone (Fig. 2).

Within the smectite-rich gouge veneer were diverse clasts of crushed uppermost Cretaceous to Oligocene lithologies including:

- siliceous, noncalcareous, hard, brittle and flaky, light creamy grey–medium grey clay shales;
- pale mudstones that were usually calcareous;
- chalky limestone;
- alternating glauconitic greensand and mudstone;
- bottle green, fine-medium grained, noncalcareous greensand; and
- hard, red-brown, calcareous argillite.



Fig. 2. Oozy smectite clay "bentonite" (top) and dried out cobweb-style jointing pattern (lower) in the Ihungia valley. Photos from Kenny (1980).

The role of oil companies

In the mid-Ihungia valley, where the mélange of lithologies crossed east–west, oil seepages (which discoloured the smectite-rich gouge) and gas smells were often encountered during field work. It was clear to me, and explained in my thesis, that small amounts of oil were trapped in host rocks at depth, and was squeezed out as a result of stresses, but it was very doubtful whether any actual reservoirs still existed in these highly fractured and faulted lithologies.

Oil and gas seepages were recorded at many sites in the East Coast region and attracted a host of petroleum geologists to the area since before the turn of the 20th century in the hopes of finding exploitable hydrocarbon deposits. After 1928, many geologists worked in the area for the New Zealand Geological Survey (as it was then called) and for petroleum companies. Their explorations for hydrocarbons never amounted to anything, but the maps their geologists drew were useful to me in the initial stages of my thesis work.

All workers in the district before my time recognised that a discordance of some kind existed between the base of the Ihungia Formation 'papa' and the underlying sliver of mélange material, but they all explained the phenomenon by carefully positioned, sub-vertical faults. In the mid Ihungia valley, where most of the seeps and smells were found, their maps all looked similar. On the eastern side of the valley, just north of the access road, they had mapped curious vertical faults, offsetting the interface between the Miocene 'papa' mudstone above and the complex Lower Tertiary lithologies beneath. Unfortunately, my copies of their unpublished petroleum company reports have long since been thrown out, but they are referenced at the end of this paper. My best recollections of the stubby little faults they had drawn are sketched in Fig. 3.



Fig. 3. Illustration of what I can remember of the stubby little faults drawn in the unpublished petroleum reports. The background map is the middle section of Fig.1. The stylised faults are superimposed in red with a tiny tick on the downthrown side of each fault.

Lightbulb moment – vertical to horizontal
On wet days, it was normal for the pale grey smectite-rich gouge to ooze down the slopes like a veneer, much to the chagrin of the farmers because it ruined their pastures. On one such wet day, I had trudged halfway up the western slopes of the mid Ihungia valley, from which position I could miserably try to visualise the confusing eastern side of the valley. I had taken cover under a tree to have lunch and was at just the right elevation to look straight across the valley at the vertical faults area, described above (Fig. 3) and couldn't believe my eyes. The oozing pale material formed a subhorizontal line, nearly following the contours around the small spurs and imperfections. The demarcation between the lush green grass covering the 'papa' hills and the ooze beneath it was sharp and profound. I estimated a dip of 10˚S (Fig. 4).

What had I done? Everything had changed. Vertical had become horizontal. Previously mapped, weird, stubby, vertical faults could be replaced by one contour-hugging feature – a single subhorizontal plane dipping about 10˚S.

If this estimation was true, the pale grey material should also be visible in a deep valley to the southeast, beyond the access road along a ridge (Fig. 5). I didn't expect to find it, mainly because I was aware of a well-known caution relating to some parts of the east coast of the North Island, used here from members of the former Gisborne office of the old New Zealand Geological Survey, 1985 – "*Thought for the day: The most significant geological quandaries strike towards, and culminate at, the area of poorest outcrop, and then re-emerge on the other side with a different solution*" (GSNZ Newsletter 68, cited in Kenny 2013).

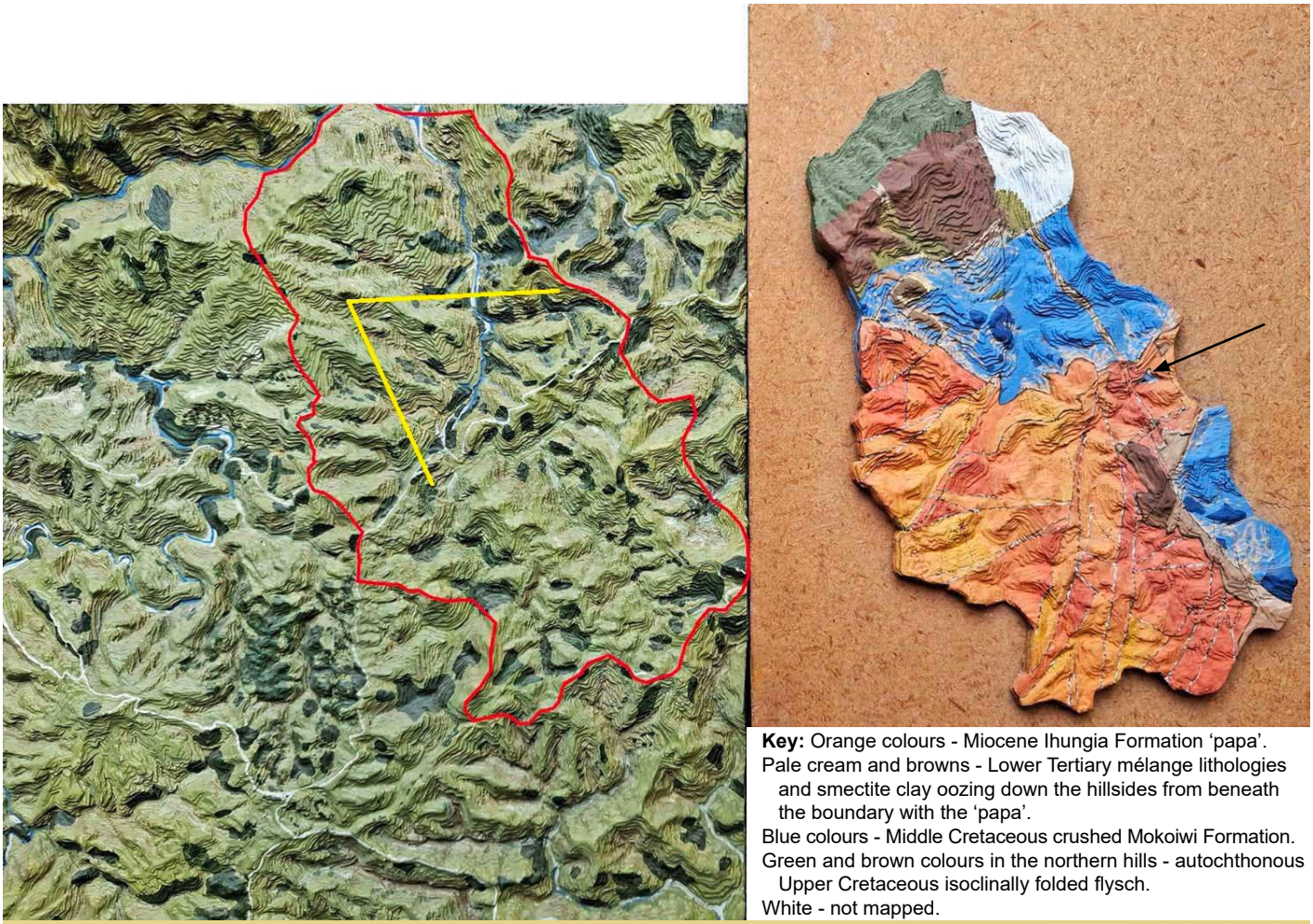
With this caution in mind, I tested my hunch the next day, which didn't start off well – thick fog meant I had to inch my way along fence lines to get into the valley, so that I could find my way out again later from a place I had not explored before, if the fog persisted. It didn't, and as the valley sides became visible, there was the oozy material clearly displayed, and even some Cretaceous Mokoiwi Formation beneath it as well. An exciting find, a turning point in my thesis mapping and a whole new understanding of what this area was all about. And, in this rare instance, the perverse outcrop caution did not impose itself.

Fitting this into the big picture
The various workers who had studied the geology of the Ihungia area had all reached the conclusion that it was structurally very complex. They envisaged that an unconformity of some kind existed between the base of the Miocene Ihungia Formation 'papa' and the underlying, Cretaceous sheared Mokoiwi Formation, but as mentioned above, all had explained the gap by carefully positioned vertical faults. The outcrop pattern that I mapped revealed that this could not be valid.

Initially during mapping, I thought that the boundary between the Ihunga Formation 'papa' and the Mokoiwi Formation to the north was, with some reservation, an onlap feature because of the subhorizontal trace. Misgivings about the contact, however, were enhanced by the amounts of ooze flowing from it, and by the absence of basal conglomerate pebbles that usually mark such an onlap. Following my mapping of the Ihungia Formation using biostratigraphic microfossil interpretations, it became obvious for a number of reasons that onlap was not a possible interpretation.



Fig. 4. Panorama from my MSc thesis (Kenny 1980) of the subhorizontal thrust plane meandering around the hillsides on the far side of the Ihungia valley and on the near side of the valley towards the right of the photo. The pale smectite clay (part of the Lower Tertiary mélange) does not appear to ooze from the plane in this photo because it was taken during summer drought. It was taken from a high-standing limestone knoll caught up within the mélange (low gradient hills in the foreground. My lightbulb moment happened when I was sheltering from the rain under trees on another, much smaller knoll in the middle distance, at the end of the mélange ridge, and much closer to the thrust plane on the far side of the valley. The thrust plane dips about 10˚S (south is beyond the right side of the photo). Puketiti, the highest knoll on the skyline, is southeast of my position. Refer to Fig. 5 for the yellow-lined photo angle.



Key: Orange colours - Miocene Ihungia Formation 'papa'.
Pale cream and browns - Lower Tertiary mélange lithologies and smectite clay oozing down the hillsides from beneath the boundary with the 'papa'.
Blue colours - Middle Cretaceous crushed Mokoiwi Formation.
Green and brown colours in the northern hills - autochthonous Upper Cretaceous isoclinally folded flysch.
White - not mapped.

Fig. 5. Two models of the Ihungia catchment, juxtaposed. The left-hand model was painted to depict vegetation, rivers and roads. It has been cropped for this figure from a much larger model of my PhD thesis area (Kenny 1986) and my MSc thesis area (Kenny 1980) contained within the red boundary. It also shows the camera angle used in Fig. 4 as two joined yellow lines. The right-hand model is just the Ihungia catchment and was painted with my MSc geological interpretation (Kenny 1980). North is towards the top of the page. Puketiti knoll on the skyline of Fig. 4 is the darker blue blob at the southeast corner of the model. The ooze and Mokoiwi Formation that I found on a foggy day is the tiny speck of blue, deep in a valley half way up the right-hand side of the model (black arrow), surrounded by orange colouring. Both models were made in the 1980s using thin layers of cardboard, traced from topography maps, and painstakingly cut out and pasted, layer upon layer. I used 3x vertical exaggeration, which gave them a realistic geomorphological appearance.

Could the sub-horizontal plane be a fault? A literature search confirmed that such phenomena had been mapped 40 km to the southwest, in the Maungahaumia region (near State Highway 2 between Opotiki and Gisborne) by Stoneley (1968). He had mapped a number of thrust complexes (he called them décollement slices) that had advanced individually from their sites of deposition and overridden earlier ones.

I envisaged my subhorizontal plane as one such décollement slice. A NNW–SSE tensional regime in the Ihungia area at the time of emplacement of the 'papa' décollement was indicated by faulting patterns (Kenny 1980 1984a). Tension may have been caused by dragging within the thrust sheet on the underlying material. A northwestern source for this thrust sheet was apparent from my fault analyses, but no Miocene 'papa' lithologies of this age were known in the Raukumara Range to the northwest.

Could multiple décollement slices explain other problematic configurations in the Ihungia valley? Stoneley (1968) had discovered many slices. Recall from 'Setting the Scene' (above) that, in the northern Ihungia valley, the Motuan age (Middle Cretaceous) Mokoiwi Formation rested with a sheared contact upon the Ngaterian (Upper Cretaceous) lithologies (Fig. 5). Although this sheared contact was down-faulted here, it was inferred to be a thrust slice as well, which had been emplaced from the NNW (Kenny 1980).

Mazengarb (1982) investigated Stoneley's area a couple of years after I had mapped Ihungia. I continued mapping west of Ihungia for my PhD thesis (Kenny 1986), linking up with fieldwork being undertaken at the time even further west by a geologist working for the New Zealand Forest Service (Phillips 1985). Moore & Speden (NZ Geological Survey, pers. comm. 1982), published since my time in the region by Mazengarb & Speden (2000), mapped a series of décollement sheets north of the Tapuaeroa River – the next major catchment north of the Ihungia area. We all found more thrust slices, and the story got quite complicated.

I will not delve into those complications in this article, but suffice to say, the Upper Cretaceous flysch sequences in the northern Ihungia valley, and further north and west, were autochthonous basement – that is, they were in situ. The décollement sheets were thought to have overridden this relatively stable autochthonous material. I inferred gravity sliding from the north or west, and therefore the Middle Cretaceous Mokoiwi Formation and Lower Tertiary diverse lithologies in the smectite-rich mélange, exposed in the mid Ihungia valley, were allochthonous – that is, they were out of place.

Mapping west of the Ihungia catchment (Kenny 1986), I established that there was much evidence of décollement movement. Allochthonous material included packets of the Middle Cretaceous Mokoiwi Formation and Upper Cretaceous indurated flysch sequences, both of which were also found in areas of the autochthonous "basement". There were many smaller sheets of sandstone, siltstone, mudstone, greensand and limestone caught up in the overlying Lower Tertiary mélange material, all emplaced from the northwest.

It was envisaged that the sheets toppled sideways, like a pile of books (Fig 6) or stack of cards, where simple low-angle shear was involved. This was not true thrusting (i.e. low-angle reverse faulting) and it was not related to a compressional regime usually associated with thrusting. These gravity slides involved low-angle extensional tectonics. The date of emplacement was determined to be no later than earliest Miocene (roughly 22 Ma) (Kenny 1986).

The boundary between the autochthon and the allochthon ran ENE-WSW, right through the Ihungia valley. I later traced it west of Ihungia (Kenny 1986) and it was recognised subsequently as a major feature of the geology of East Cape (Moore *et al*. 1989, Mazengarb & Speden 2000, Ballance 2017).

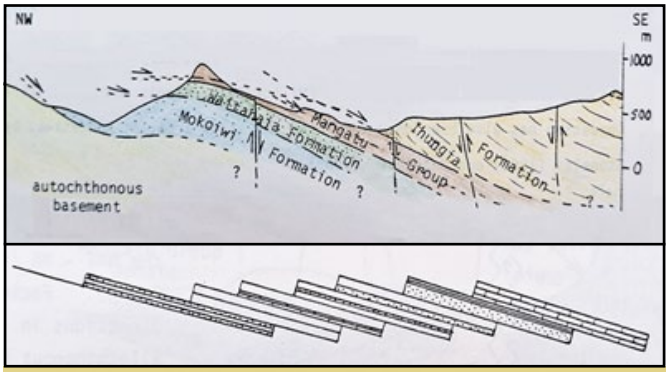


Fig. 6. Simplified cross-section through the study area from NW to SE, modified from Kenny (1986, fig. 12.1), illustrating a series of imbricate thrust sheets inferred to have toppled sideways like a pile of books (fig. 12.4). Disregard the unfamiliar names. Colours are similar to those in Fig. 5, with pale green indicating autochthonous Upper Cretaceous basement, blue and darker green representing crushed allochthonous Middle and Upper Cretaceous sediments, brown being a mixture of Lower Tertiary lithologies, and 'papa' the highest level.

How did the Ihungia Formation's oozy demarcation with mélange material beneath – the boundary that I had been so excited about – fit with this big picture?

As I extended my mapping to the west (Kenny 1986), it became apparent that the Ihungia Formation 'papa' terrain was extensive, reaching beyond Gisborne. This could not possibly be one of the décollement sheets, and there was no place in the Ihungia region, nor further south, where allochthonous Ihungia Formation could become autochthonous, either suddenly or gradually.

I proposed that the Ihungia Formation 'papa' had been emplaced 'piggy-back' upon the Lower Tertiary material (Kenny 1986). This potential method of emplacement appeared to be unique in New Zealand, at the level of knowledge back then, however, the concept of one allochthonous sheet riding 'piggy-back' on another was not unusual overseas (Butler 1982a, b).

If only there had been boreholes and geophysical data to assist with 3D interpretation of the autochthon, the allochthon, and how the Ihungia Formation 'papa' related to them. There was no useful geophysics and the only borehole, Te Puia-1, located about 5 km beyond the eastern boundary of the mid-Ihunga catchment, showed the Mokoiwi Formation to be a rootless mass 'floating' on Lower Tertiary 'bentonite' (Laing 1972). Miocene Ihungia Formation 'papa' was not present in the borehole, so it did not show the relationship between the 'papa' and underlying material.

An even bigger picture

The Northland Allochthon, covering most of Northland, had been proposed and mapped in detail by Ballance & Spörli (1979) and they suggested that a similar geological situation at Raukumara Peninsula might be related to it. When I was mapping at East Cape at that same time, I had no appreciation that the Ihunga area might be part of an allochthon. I have not kept up to date with current thinking on the East Coast Allochthon, but thanks to books that the general public can comprehend, written by authors such as Ballance (2017) and Hayward (2017 2023), we are now aware of a very big picture. The East Coast Allochthon came from much further away, from the same place as the Northland Allochthon. About 25–20 Ma, huge slabs of uplifted rocks slid from somewhere to the north of New Zealand, southwards over the subsided seafloor basins in the proto-Northland and East Cape areas. The two regions were adjacent back then and have subsequently moved apart with the opening of the Bay of Plenty and the pervasive dextral slip throughout the eastern North Island. One group of slabs became the Northland Allochthon; the other group became the East Coast Allochthon.

My suggestion (Kenny 1986), that the Ihungia Formation 'papa' might have been deposited in a piggy-back basin upon the East Coast Allochthon as it moved southwards, was endorsed by Mazengarb & Speden (2000). It also supported studies in Northland, described by Hayward (2017), where Early Miocene marine sediments from the Parengarenga, Hokianga and Kaipara areas filled actively deforming piggy-back basins created on the sub-marine surface of the Northland Allochthon as it crept slowly southwards. But these were small basins. The Ihungia Formation covered a much larger area, so I was not totally convinced about this hypothesis either.

East Cape geology is complicated. Northland geology is complicated. I was *au fait* with the components of the East Coast Allochthon, and now that I am living in Northland, the lithologies and deformation styles are satisfyingly familiar. Back in the late 1970s, I was an inexperienced student grappling with mapping the difficult terrain in the Ihungia valley for an MSc thesis (Kenny 1980). Previous geologists had mapped the strange lithologic boundary configurations by adding vertical faults. My lightbulb moment on a hillside in the rain changed all that. So, with assistance from my follow-up PhD study west of Ihungia (Kenny 1986) and many articles written by others on the Northland and East Coast allochthons, I hope I have demonstrated how some lithological boundaries, mapped as vertical faults, should be horizontal.

But now they are invisible. Sadly, all the geology has been hidden beneath a ubiquitous green carpet of pine trees that have smothered almost the entire Ihungia valley for the last 40 years.

Acknowledgements

In my MSc thesis, I acknowledged many people, including my University of Auckland supervisors – Peter Ballance, Bernhard Spörli and Graham Gibson, and to 'Geological Survey' staff in Lower Hutt – Ian Speden, Phil Moore, Ian Raine, Richard Cook, Ian Keyes, George Scott and Percy Strong. I also thanked the farmers of the region, especially the Williams Family of Ruangarehu Station, with whom I lived during my weeks of fieldwork, and who offered their home as accommodation to various Auckland University and Geological Survey staff, field assistants and my family, who sometimes accompanied me. I was grateful to Adrian Williams for allowing me the use of his tractor, farm bike and horses on occasions.

For this current article, as Geocene Editor, I thought it was inappropriate to proofread my own paper, so I called upon the expert skills of Bruce Hayward, and for this, I thank him.

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VERTICAL TO HORIZONTAL – SECOND LIGHTBULB MOMENT – ACCRETIONARY WEDGE DIACHRONEITY AT PUKETORO, EAST CAPE

Jill Kenny

Setting the Scene

This article is from my PhD thesis (Kenny 1986). It is an historical account, reflecting unmodified concepts from that time. It is not intended to be an update of those concepts. Reference citations were the most up-to-date at that time and, no doubt, have been superceded many times since then.

The Puketoro area is directly west of the Ihungia catchment (Kenny 1980 1984 2026), halfway between Gisborne and East Cape, west of State Highway 35, on the Raukumara Peninsula near Ruatoria, in the extreme east of the North Island of New Zealand. It is drained mostly by the Mata and Waitahaia rivers and their many tributaries (Fig.1). As with Ihungia, the northern part of my new study area contained autochthonous Cretaceous lithologies, and it is the configuration of these lithologies that is the focus of this article.

Although extremely dire for the local farmers, for one year's summer field season (probably the summer of 1982/83), the region had a drought, more extreme and long-lasting than usual. In the north of my area, the often uncrossable Mata and Waitahaia rivers stopped flowing and became a series of stagnant pools. There was 100% outcrop along at least one bank of the rivers and often the riverbeds as well, so I had excellent opportunities to examine the Cretaceous lithologies for many kilometres and even through usually inaccessible gorges.

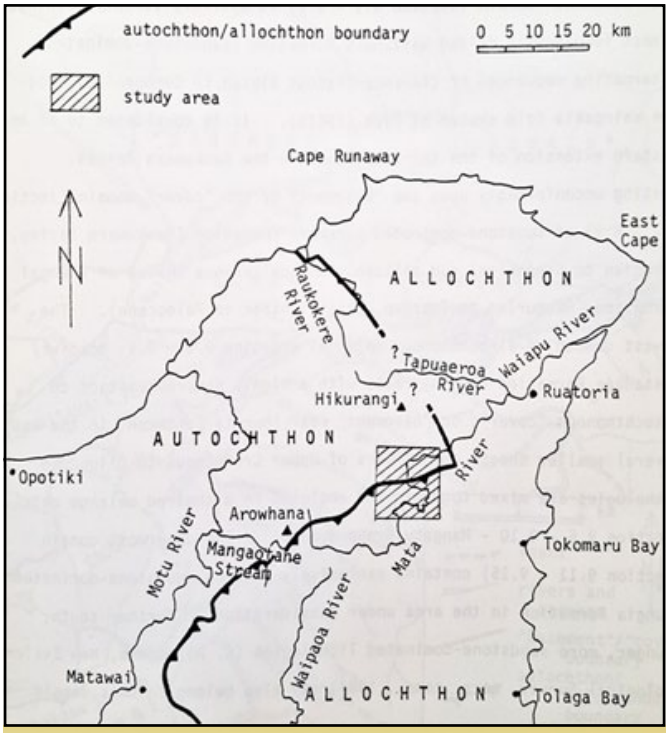


Fig. 1. Locality map of the Raukumara Peninsula from my PhD thesis (Kenny 1986) showing the approximate boundary between the autochthonous region and the area covered by the East Coast Allochthon, although the interpretation has now changed in the southern part. The thesis area is within the box and the Mata River flows through it from south to north. The Waitahaia River is not shown, but it flows west to east from the top left corner of the box and joins the Mata top centre at the sharp bend.

Many renowned geologists had mapped the area previously (e.g. Ongley & Macpherson 1928, Wellman 1959, Kingma 1965, Speden 1976 1977, but not in as much detail as was required for a PhD thesis (Kenny 1986). I have just described a small section of the complicated autochthon/allochthon boundary as it traversed the Ihungia catchment (Kenny 2026) and this boundary continues west-south-westwards through the Puketoro area and beyond. North of this boundary, the indurated Cretaceous rocks are not as easily eroded as the Cenozoic mélanges and papa terrain to the south. Hence the hills are higher and steeper (Fig. 2), and merge further north and west, out of the study area, into the forested foothills of the Raukumara Ranges. It took hours each day to walk in and out, although sometimes I could edge my car along farm tracks, and from there I would offload my tiny Honda Chaly motorbike from the trailer and continue on two wheels for quite some distances. For a city bike, it did remarkably well (Fig. 3).

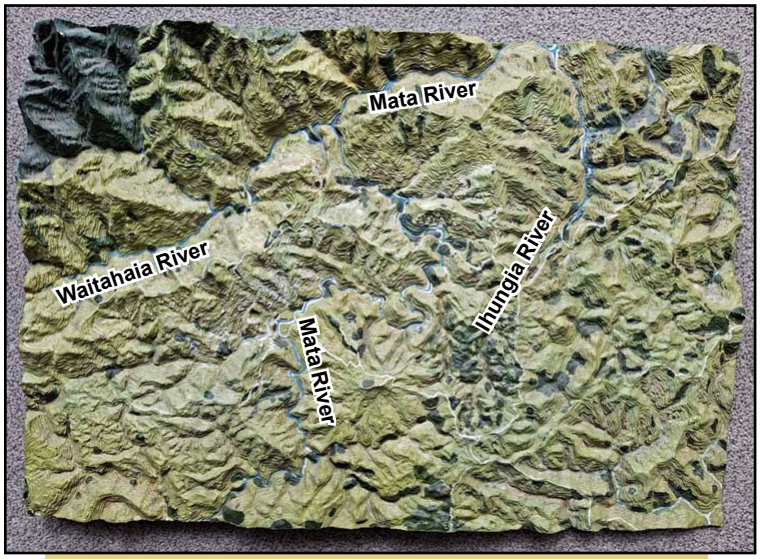


Fig. 2. A model of my PhD and MSc theses areas, north to top, painted according to the vegetation. The Ihungia catchment takes up the eastern two fifths, and is shown in Fig. 5 of Kenny (2026 - article prior to this). The area of indurated Cretaceous rocks is clearly visible north of the Waitahaia River in the north. Miocene 'papa country' is roughly south of a line from the southwest corner to the northeast corner of the model. These two areas are separated by the autochthon/allochthon boundary and rocks either side of it. The model is 41 cm across = 24 km.

Isoclinally folded Cretaceous lithologies

The oldest **autochthonous** lithologies in the study area were Cretaceous, alternating, fine grained sandstone and sheared mudstone sequences, sometimes interrupted by very thick, fine grained sandstone units. I knew these lithologies as Waitahaia Formation (Moore 1986) (Fig. 4). They outcropped across the northern third of the study area (Fig. 5). **Allochthonous** equivalents of the Waitahaia Formation outcropped in the west of the area, further west beyond the area, and in the Ihungia catchment to the east - part of the blue colour in Fig. 5. The **autochthonous** lithologies extended an unknown distance westwards and northwestwards into the Raukumara Ranges. I often referred to these lithologies as "basement".



Fig. 3. A Honda Chaly from the internet - too clean to have been mine!

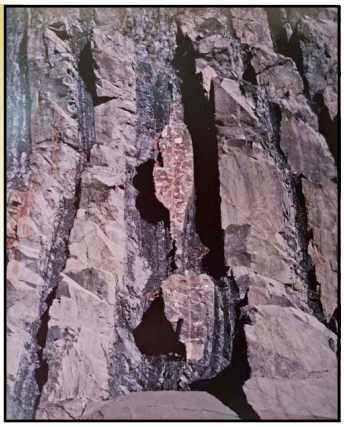


Fig. 4. Typical alternating fine grained sandstone and sheared mudstone of the Waitahaia Formation along the Mata River. This photo, from Kenny (1986, figure 3.11), also includes a lovely example of pulled-apart boudinage structure. For scale, the sandstone to the left of the boudins is c. 20 cm thick.

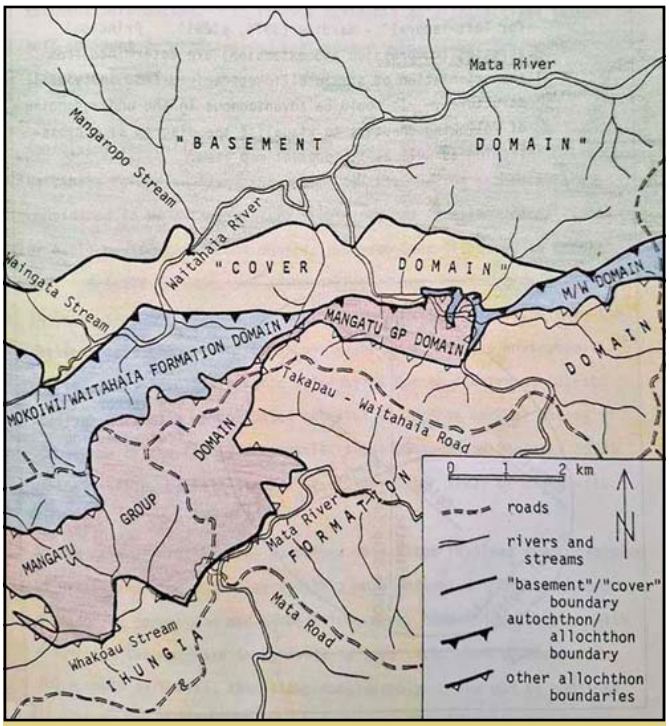
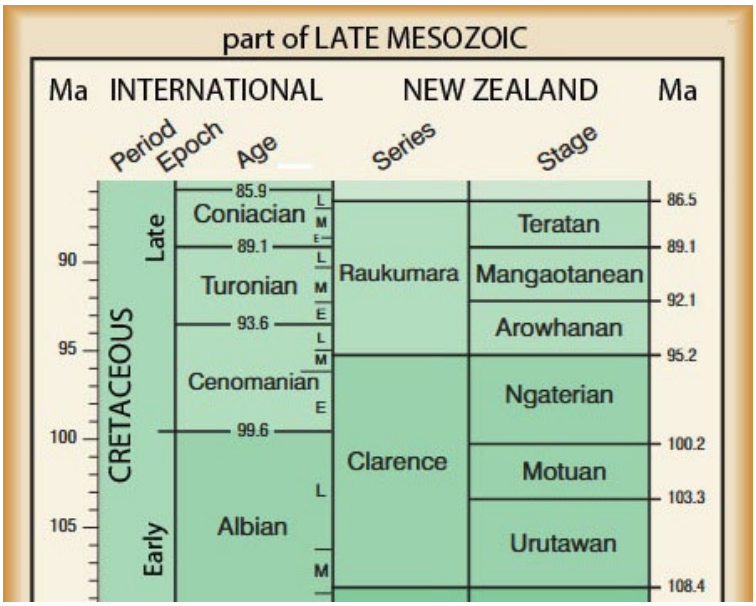


Fig. 5. Simplified map of the PhD area from Kenny (1986, figure 7.2), showing Waitahaia Formation as the "basement domain" - one of the various structural domains within the study area. It is coloured green across the northern part of the map.

Fossil *Inoceramus hakarius* Wellman or *I. hakarius-fyfei* species group and fossil palynomorphs (microscopic organic remains) from a carbonaceous sandstone all indicated a Ngaterian age (c. 99–95 Ma) (Table 1) (Kenny 1980 1984 2026). A few kilometres northwest of the study area, *I. hakarius-fyfei* was again present, but further upstream (northwards) similar lithologies preserved *Aucellina euglypha* Woods (the Motuan index fossil) and *Inoceramus* sp. cf. *ipuanus-kapuus* Wellman, suggesting an Urutawan-Motuan or younger age (Moore *et al*. 1984). A similar situation occurred further west, where a geologist working for the New Zealand Forest Service (Phillips 1985) considered the formation to be of Urutawan to Ngaterian age. Therefore, I thought it was likely that the majority of the Waitahaia Formation was Ngaterian in age, but became older towards the northwest.

The entire Waitahaia Formation was involved in a N–S-trending, isoclinal fold system with near-vertical axial planes. *[Isoclinal folds are folds that have been compressed to such extent that their limbs are so tightly folded, they are nearly parallel - cf. part of a paper clip]*. East–west compression was indicated. The material was displaced along megascopic, steep reverse faults, with consistent displacement down to the east. The geometric relationship between the N–S-trending faults and the close-to-isoclinal megascopic folds, also trending N–S, suggested that both sets of structures were formed at the same time.

Table 1. Small, modified portion of the New Zealand Geological Timescale, poster version, showing just part of the Cretaceous. It is highly simplified from Cooper (2004).



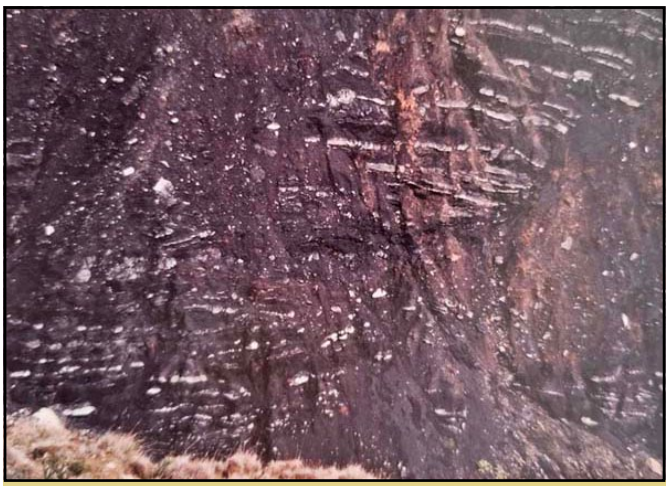


Fig. 6. Isoclinal folds of the Mokoiwi Formation were oriented vertically before the rocks were deformed within the allochthon and fold axes were rotated to subhorizontal orientations, as seen here on the side of a gully. The view is about 20 m across (Kenny 1986, figure 9.5).

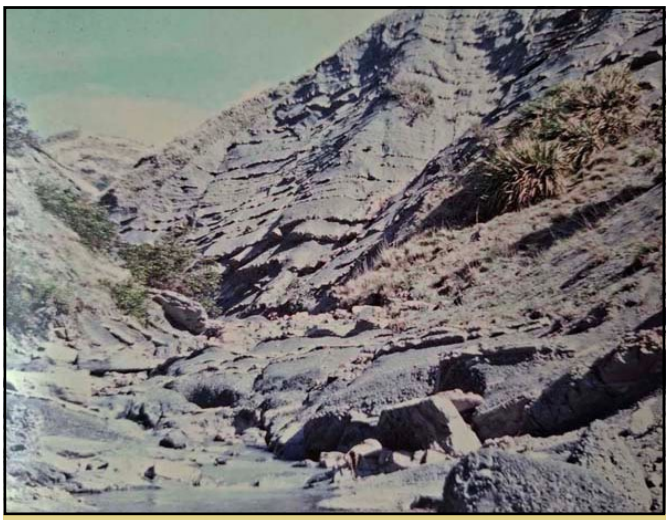


Fig. 7. Typical Karekare Formation alternating sequence in lower Puketoro Stream - a reference section for the Raukumara Series of the Late Cretaceous (Kenny 1986, figure 3.16). Bedding is gently dipping upstream.

A lower contact with older material was never seen in the **autochthonous** part of the study area. A contact with slightly older **allochthonous** material in the west and in the mid-Ihungia Valley was probably sheared. This slightly older material (Motuan, Table 1) was subjected to the same isoclinal folding, but was additionally rotated and intensely deformed within the allochthon. It was a dark blue-grey to black, noncalcareous, highly indurated siltstone, with occasional flysch sequences. I knew it as Mokoiwi Formation (Speden 1976, after Bremner 1934) (Fig. 6 and blue colouring in Fig. 5). The same Motuan-age lithology, with vertical isoclinal folds, occurred *in situ* just west of the study area (Phillips 1985). Both autochthonous and allochthonous versions of the Mokoiwi Formation contained the distinctive inoceramid shell, *Inoceramus warakius* Wellman, the species indicative of the Motuan Stage (Wellman 1959, Speden 1976 1977).

Minimally folded Cretaceous lithologies

Then I discovered autochthonous lithologies that were horizontal - or would have been originally, before they were tilted about 30° SSE, and this is where the title "Vertical to horizontal" comes into play. The sudden change in orientation of strata had not been expected because nothing of this nature had been encountered in my MSc area to the east (Kenny 1980 1984 2026).

This was Karekare Formation (Speden 1975, after Gair 1967). I had seen it before, in the Matawai area of the Raukumara Ranges, in the vicinity of State Highway 2 through the Waioeka Gorge, on a reconnaissance trip in 1981 with East Coast geology specialists Ian Speden, Mike Isaac, Phil Moore and many others. It was typically a silty mudstone-dominated, thinning and fining upwards, alternating sequence (Speden 1975, Isaac 1977, Moore 1978, Kenny 1986) (Fig. 7). *Inoceramus* shells, fragments and prisms were common. In the Raukumara Ranges, and largely based on index *Inoceramus* fossils, it was of Urutawan–Mangaotanean age at Te Whaka Stream (Isaac 1977) and Ngaterian–Teratan age further east at Mangaotane (IG Speden, New Zealand Geological Survey, pers. comm. 1982). Further east (just west of my Puketoro study area), it was also Ngaterian–Arowhanan age (Phillips 1985).

At Puketoro, I had been mapping Puketoro Stream, and I knew it was a reference section for *Inoceramus* species of the Arowhanan, Mangaotanean and Teratan stages of the Late Cretaceous Raukumara Series (Table 1). As with the Ihungia valley (Kenny 2026), this valuable reference section has also been hidden since the mid 1980s beneath pine trees that have compromised all useful fossil localities. But back in the 1980s I was able to trace Karekare Formation over ridges and into other streams, and from this mapping it seemed to be unconformably onlapping upon Waitahaia Formation, sometimes with a basal conglomerate, and with an undulating contact that dipped gently south (Fig. 8). Ongley & Macpherson (1928) and Wellman (1959) had also visited Puketoro Stream and had concluded that the contact was an angular unconformity.

The immediate source of Karekare Formation sandstones was from variable directions (measured from flute casts, load casts and ripple foreset beds), and indications were that they could not have travelled far (e.g. still-plastic mudstones and recognisable fossil fragments in the sandstones). Sandstone clasts closely resembled sandstones from the underlying Waitahaia Formation, and it was thought conceivable that all the lithologies of the Karekare Formation were in fact derived from adjacent slightly older Waitahaia Formation (Kenny 1986).

I was puzzled. This Karekare Formation was on average slightly younger than the Karekare Formation further west. I had found beautiful specimens of *Inoceramus rangatira* Wellman (Arowhanan Stage), *I. bicorrugatus* Marwick

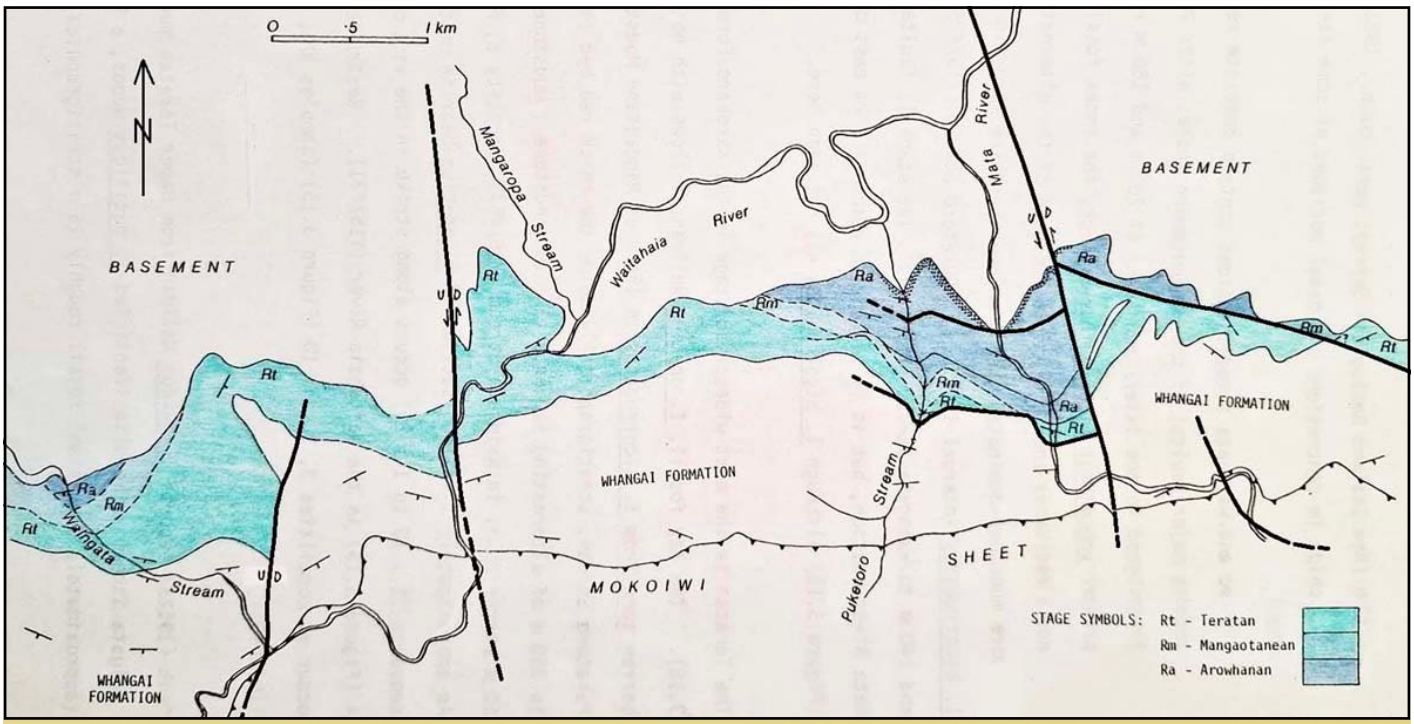


Fig. 8. Karekare Formation biostratigraphy from Kenny (1986, figure 3.18) has been coloured in shades of greeny-blue. Left uncoloured are underlying "basement", other "cover" lithologies, and an allochthonous sheet of Mokoiwi Formation (boundary shown by meandering toothed line). Faults (thick black lines) and bedding dip and strike symbols are also shown.

(Mangaotanean Stage) and *I. opetius* Wellman (Teratan Stage), all within the zones indicated by variously shaded areas in Fig 8.

I often referred to these rocks, and younger, overlying, autochthonous lithologies, as "cover". In the Puketoro area, there were vertical, isoclinally folded "basement" rocks overlain by younger, relatively undeformed "cover" lithologies. And, in another complication, vertical "basement" rocks at Puketoro were the same ages as relatively undeformed "cover" sediments further west in the ranges. This information had not been available to me during my MSc study (Kenny 1980) because Karekare Formation was not present in the Ihungia catchment.

Lightbulb moment – vertical to horizontal

"Vertical to horizontal" occurred as an unconformable contact at outcrop scale at Puketoro and at a regional scale from Puketoro westwards towards the ranges.

In the Cretaceous of the Wairarapa, Moore & Speden (1979 1984) proposed that similar unconformable contacts could be attributed to classic fault-angle depressions in an extensional (rifting) regime. In Kenny (1986), I discussed the pros and cons of this extension model to explain basin development and infilling of horizontal sediments in fault angle depressions at Puketoro. The model would assume that the major Waitahaia Formation N–S-trending, near-vertical faults, along which material was down-thrown to the east, would be steep normal faults, formed in an extensional regime (Fig. 9). For many reasons, outlined in depth in Kenny (1986), this model was discarded.

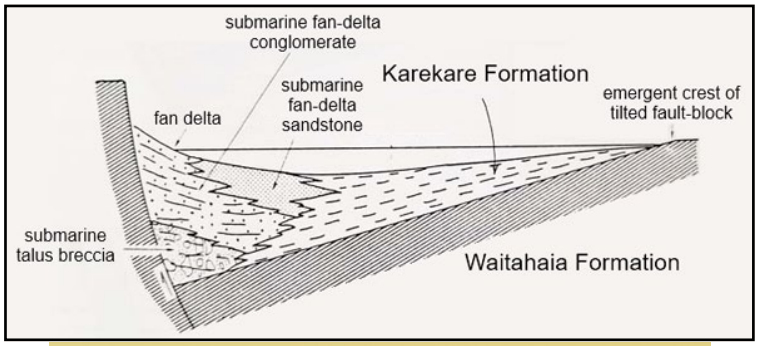


Fig. 9. Typical fault-angle depression model in an extensional (rifting) regime, as used by Moore & Speden (1979) and modified by Kenny (1986, figure 11.3).

I suddenly realised that the Puketoro area was **not** related to a fault-angle depression (extensional regime), but rather to an accretionary wedge configuration (compression regime) (Fig. 10). I came to this lightbulb moment during the write-up of my PhD (Kenny 1986). Waitahaia Formation (and its older equivalent, the Mokoiwi Formation, although Mokoiwi was only seen within the allochthon) was envisaged to be material accreted to an over-riding plate that produced highly deformed strata. Karekare Formation was then postulated to be the sedimentary basin material deposited in the depressions between high-standing pressure ridges formed on the surface of the accretionary wedge (Fig. 10).

The following points were favourable for this scenario:-

1) complex deformation within presumed accreted sediments (Waitahaia and Mokoiwi formations);

2) steep reverse faults trending N–S, approximately parallel to the predicted subducting trench, active from pre-Urutawan times until the Teratan (Table 1), and moving in the same direction as the subducting slab;
3) basin sediments (Karekare Formation) resting unconformably upon the accreted sediments;
4) evidence of several small basins, a factor that is inherent in the accretionary wedge model but unnecessary in a rifting scenario;
5) provenance of basin sediments from local Waitahaia Formation structural highs on both the landward and trench side of the basins;
6) slight buckling of basin sediments in response to continued compressive forces within the accretionary wedge.

Relative topography of the Waitahaia Formation surface between structural highs and depressions was judged to have been small because of the paucity of conglomerates (e.g. in Fig. 10, the stippled pattern in the lowest Arowhanan zone in lower Puketoro Stream, on the adjacent ridge and east into the Mata River) and the high proportion of mudstone within the Karekare Formation. Mudstone became more dominant up the sequence in response to burial of the highs that provided the coarser detritus, and because of regional subsidence related to eventual cessation of the Cretaceous subduction zone (Kenny 1986).

Although I have deliberately not researched modern studies related to this area, it is important to note that my PhD findings correlate well with the cessation of long-lived, Permian–Cretaceous convergence along a southwest-dipping subduction zone on the Pacific-facing margin of Gondwana (Crampton *et al*. 2019). These authors acknowledge that in some parts of the subduction zone, subduction might have even continued until almost the end of the Cretaceous.

The lightbulb got brighter - diachronism

Spörli & Ballance (1985) constructed a terrane map in which Torlesse rocks were restricted to a region west of a line from Whakatane to western Wairarapa and were considered to be the remains of an older accretionary complex added to the existing New Zealand area from the east, perhaps as one entity. East of this line, they reclassified the "basement" as Mata River Terrane, which they thought was an eastward-younging, accretionary wedge of imbricated packets, extending eastwards from a tectonic contact with Torlesse rocks, roughly 100 million years old. In this hypothesis, continental margin sediments were trapped in supra-accretionary wedge basins.

Note that the ideas of Spörli & Ballance were being mooted at the same time as I was writing up my PhD. I was not aware of their work, and until then, as far as I knew, subduction-related compression had not been considered by others working in the Raukumara Ranges. Oblivious of the Spörli and Ballance model, I realised that the Mokoiwi and Waitahaia formations formed parts of an eastward-

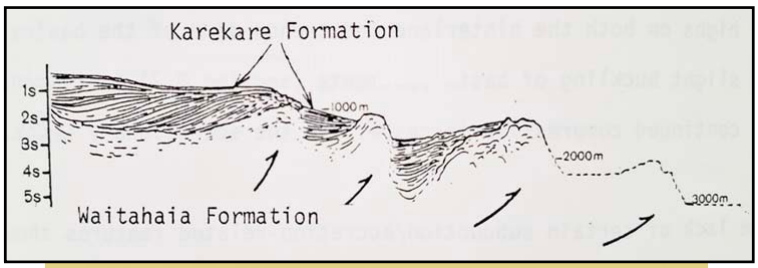


Fig. 10. Tracing of seismic profile 72-124 from the present continental shelf and slope off the eastern North Island of New Zealand (Lewis 1980, figure 5) showing accretionary wedge deformation, with structural highs separating depressions that are partially or totally infilled with basin sediments. Lewis' figure was modified by Kenny (1986, figure 11.5) with Waitahaia and Karekare formations superimposed in their postulated positions. Although not seen in the autochthonous part of the study area, Mokoiwi Formation could be postulated to exist beneath Waitahaia Formation in this diagram.

younging, diachronistic sequence within their new Mata River Terrane. Both formations received detritus shed from older Mata River Terrane and from Torlesse rocks further to the west. The diachronism was also evident in the "basement"/"cover" angular unconformity and in the ages of the Karekare Formation deposited in basins upon it.

In the Puketoro area, "basement" Waitahaia Formation was of Ngaterian age (c. 99–95 Ma). Oldest basin sediments (Karekare Formation), unconformably overlying Waitahaia Formation, were of early Arowhanan age at Puketoro Stream (c. 95–94 Ma). Therefore, the unconformity represented a remarkably brief hiatus in deposition for major accretion-related deformation to occur and irregular erosion surfaces to develop at end of the Ngaterian (c. 95 Ma).

Less than 10 km to the west, Phillips (1985) mapped Waitahaia Formation which, at Urutawan to Early Ngaterian age (c. 108–98 Ma), was mostly older than Waitahaia Formation in my area, but equivalent to my allochthonous Mokoiwi Formation. It was overlain unconformably by Karekare Formation of Late Ngaterian to Teratan age (c. 96–85 Ma). Therefore, in his area, the hiatus was probably Middle Ngaterian in age (c. 97 Ma) and also short-lived.

Further southwest, the equivalent unconformity between highly deformed and relatively undeformed strata in the Mangaotane and Matawai areas (central Raukumara Peninsula) represented a brief intra-Motuan tectonic event (c. 101 Ma). In central Raukumara, an intra-Urutawan unconformity at Motu Falls (c. 105 Ma) and a Korangan to Urutawan unconformity at Koranga (c. 108 Ma) (Speden 1975, Isaac 1977, Moore 1978a) were similar in character.

I drew cartoons (Kenny 1986) to display a simplified Cretaceous history of the middle Raukumara Peninsula, to demonstrate the apparent diachroneity in the area, using the subduction/accretion model (Fig. 11 a–c).

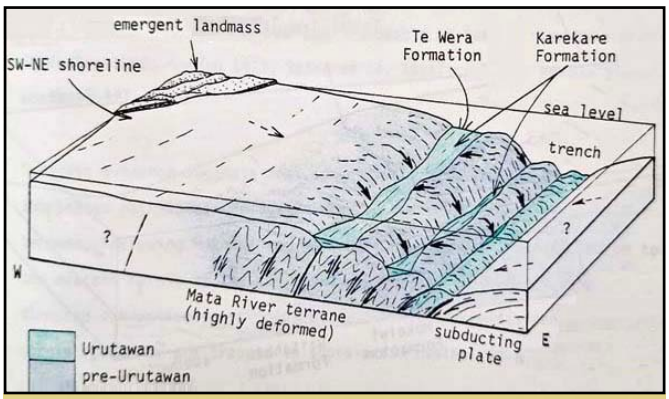


Fig. 11a. Cartoon from Kenny (1986, figure 11.8A) depicting Urutawan age accretion and deformation of sediments in the vicinity of a subduction zone. It shows accumulation of sediments derived from the continental shelf and from local structural highs. An eroding landmass to the west supplied detritus to the more proximal basins.

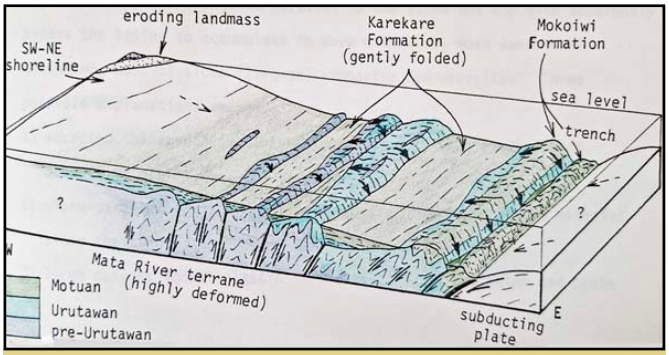


Fig. 11b. Cartoon from Kenny (1986, figure 11.8B) depicting continuing subduction and accretion in the Motuan. Successively younger material is accreted. Some highs are buried by basin sediments.

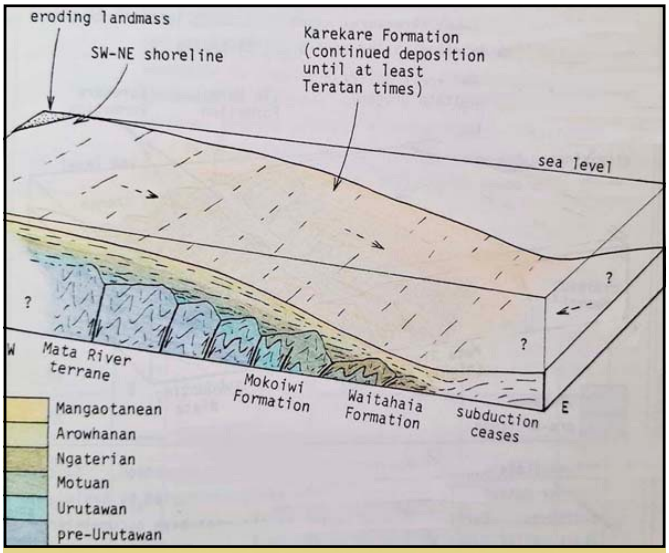


Fig. 11c. Cartoon from Kenny (1986, figure 11.8C) shows the termination of subduction in approximately the Arowhanan with consequent gradual subsidence of the whole region. There was burial of the basement by a fining-upwards sequence, and influence of the eroding landmass became negligible.

The need for submarine canyons

I argued (Kenny 1986) that there seemed to be a discrepancy between the sedimentary and tectonic evidence, in that at any given time, clastic sediments were trapped in supra-accretionary-wedge basins elongated parallel to the slope, but might also have apparently bypassed the basins to accumulate in more extensive, more sandstone-dominated, base-of-slope (?trench) submarine fan deposits.

The most likely option to comply with the evidence was that large canyons funnelled clastic sediments past the accretion and basin system to the base-of-slope (?trench) area. Clastic shelf sediments could have been channelled via submarine canyons to the actively accreting zone along the trench, thus bypassing the continental slope/accretionary wedge region (Fig. 12) (e.g. Taitai Sandstone Member within the Mokoiwi Formation). In the inter-canyon areas, small basins on the accretionary wedge accumulated detritus from local structural highs, and from the continental shelf to a lesser extent.

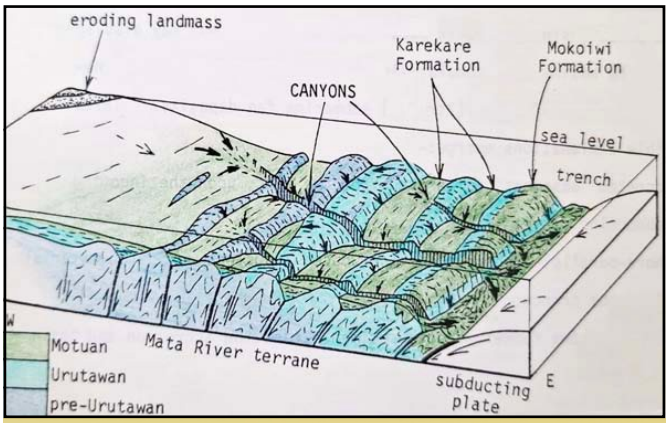


Fig. 12. Addition of submarine canyons to the Fig. 11b cartoon (Kenny 1986, figure 11.9), which could have enabled shelf sediments to bypass the accretion zones.

Using recently written articles at the time, I compared Miocene to Recent subduction along the Hikurangi Trough (e.g. Lewis 1980), which provided an excellent analogue to the proposed Middle Cretaceous subduction/accretion model. Onland Miocene sediments (e.g. Makara Flysch of southern Hawkes Bay – van der Lingen & Pettinga 1980, Pettinga 1982) and present continental shelf and slope sediments (Lewis & Bennett 1985) accumulated in thrust-controlled basins elongated perpendicular to the present subduction direction, formed on highly deformed accreted material.

Conclusion

The sudden change from vertical to horizontal - i.e. from vertical, isoclinally folded Waitahaia Formation “basement” to horizontal, relatively undeformed Karekare Formation “cover” - was unexpected because that association had not occurred in my MSc thesis area in the adjacent Ihungia catchment to the east.

In a lightbulb moment, I realised that this basement/cover association was an accumulation of subduction zone

accretionary wedge sediments that had formed vertical, isoclinal folds and steep reverse faults, with supra-wedge depressions filled with younger sediments. Similar situations had been mapped inland to the southwest, but they were older, and a link to subduction zone compression was only just being recognised.

In a second lightbulb moment, I realised that both the basement and cover sediments were older in the southwest because they were diachronous. They were progressively younger eastwards because the whole accretionary wedge developed eastwards as material was scraped off the subducting plate. My study area was the furthest east and youngest association before subduction ceased.

Acknowledgements

In my PhD thesis, I acknowledged many people, including my family and friends and the Williams family of Ruangarehu Station, for their encouragement and support throughout the project. I thanked my supervisors – Peter Ballance and Bernhard Spörli – from the University of Auckland, other University staff, and 'Geological Survey' staff including Fred Brook, Ian Speden, Phil Moore, Colin Mazengarb and Dave Francis. I also thanked Chris Phillips from the New Zealand Forest Service and many land-owners and station managers.

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For this current article, as Geocene Editor, I thought it was inappropriate to proofread my own paper, so I called upon the expert skills of Bruce Hayward, and for this, I thank him.

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EARLY MIOCENE LOG EATEN OUT BY SHIPWORMS, TOROA POINT, LONG BAY, AUCKLAND

Bruce W. Hayward

On a sunny afternoon in March 2025, 26 Geoclubbers sauntered around the intertidal rocks and cliffs south of Long Bay, North Shore, Auckland. We wandered 1.5 km, stopping periodically to discuss features we saw in the alternating turbiditic sandstone and mudstone of the Early Miocene Waitematā Group (Ballance 1974).

We reached Toroa Pt (Fig. 1) and there was a slight step to climb down to carry on. About half the group decided to turn around and return the easy way back to the start, probably put off from continuing by the description of the challenge of climbing out of Ladder Bay, 200 m further on. I stayed till last at the step to assist some down over the obstacle. I rounded the corner, and everyone was huddled around an object in the high-tide sandstone platform (Fig. 2). Upon arrival, I asked what they were all looking at and I was met with blank looks – it was something different from what anyone had seen before (Fig. 3). I immediately recognised what it was because I have seen more rocks and fossils than anyone else and had figured out the origin of something very similar in my thesis area at Muriwai, 50 years ago.

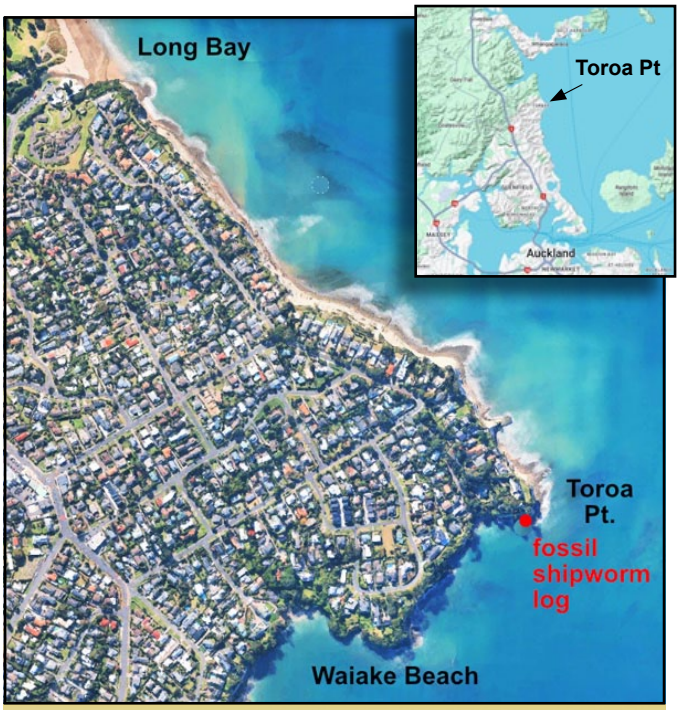


Fig. 1. Google map showing the location of the fossil log just southwest of Toroa Pt, between Long Bay and Waiake Beach/Tor Bay.



Fig. 2. White circle shows location of shipworm eaten-out fossil log within sandstone bed, Toroa Pt. Width of the white circle 50 cm.



Fig. 3. The eaten-out fossil log in the upper part of a thick sandstone bed, Toroa Pt, Long Bay. Width of photo 60 cm.

The object of interest was a large fossil (~ 25 cm x 60 cm) in the shape of a piece of log, but with almost no obvious remaining wood (black and carbonised). It is an example of a piece of wood that had been completely "eaten-out" by shipworm and virtually all that remained were the intertwined casts of the sediment-filled borehole tubes with a little of their white calcite lining remaining (Fig. 4). Around the edge of the wood, the tubes were primarily oriented perpendicular to the wood's outer surface but deeper in they became more random (Figs 4–5).

Most of the group had seen pieces of carbonised wood in the Waitematā Group sequence around Auckland that in some instances contained the preserved, sparse, calcite-lined, irregular tubes of shipworm (see fig. 5.32 in Hayward 2017) – but an example where there was no obvious wood remaining was deceiving. Shipworm refers to the worm-like borings of bivalve molluscs of the Family Teredinidae. The common shipworm living around New Zealand today is *Bankia australis* (=Teredo). The tubular boreholes preserved in wood are the parts most commonly found fossil, but occasionally the small double valves at one end of each tube are found and these are the main feature

used in recognising fossil species. Fossil shipworm tubes inside wood are known from marine sedimentary rocks of New Zealand from at least the Cretaceous onwards (e.g. McKoy 1978). Five species of fossil teredinid have been described and named from New Zealand, but four of these are considered *nomen dubia* because only the undiagnostic tubes are known. One large species from the early Miocene basal Waitematā Group of Oneroa, Waiheke (*Bankia turneri*), is currently recognised because it also has fossilised valves (McKoy 1978).



Fig. 4. Subparallel, partly calcite-lined shipworm tubes perpendicular to the outside surface of the original log (top). Width of photo 20 cm.



Fig. 5. Randomly oriented shipworm tubes in the deeper parts (top right) of the original log. Width of photo 25 cm.

Fossilised pieces of wood, up to log size, occur widely throughout the Waitematā Group, Auckland (Hayward 2017). The sedimentary rocks are recognised as consisting of sandstone beds that were transported as sand turbidity currents that had flowed down into the depths of the Waitematā Basin (1000–2000 m depth) from coastal shallows. The wood occurs either within the upper part or at the top of some sandstone beds. This suggests that most of the wood may have been water-logged on the shallow seafloor and was carried down into the depths within the turbidity currents, but maybe some became water-logged while floating in the ocean and sank through the water column to the deep ocean floor.

Shipworms usually invade floating wood (and wooden ships) at shallow depths (0–20 m), but occasionally live within it at depths up to 200 m. Thus, our Toroa Pt log was likely completely eaten out and held together by the cemented shipworm tubes as it was transported down in the turbidity current. In a few instances within a few kilometres of Toroa Pt, there are examples of pieces of wood that, unlike the present example, were clearly sitting exposed on the ocean floor for some time. This is because fossil shells of wood-eating limpets and small wood-associated grazing skeneimorph snails have been found in association with the wood now buried within mudstone (Marshall 1985, Hayward & Marshall 2022).

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