Annual Conference of the Geoscience Society of New Zealand
Field Trip 1
Sunday 25th–Tuesday 27th November 2018

Subduction to subduction:
100 million years on the eastern margin of Zealandia

Image: NASA, International Space Station, image iss042e178671_lrg

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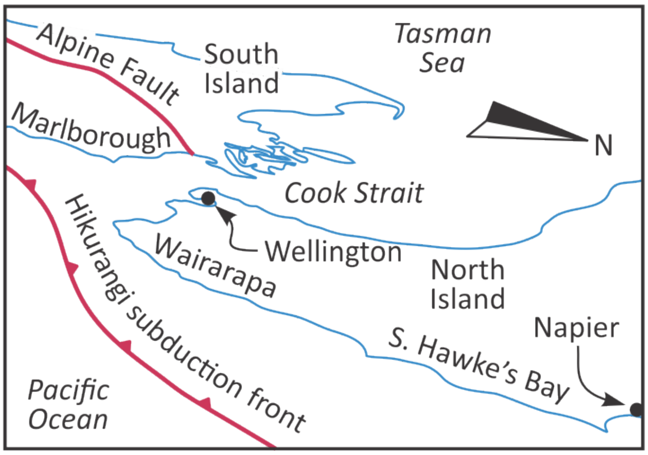
The image on the cover shows an oblique view of central New Zealand outlined in sunglint, viewed from the east and as seen from the International Space Station on January 24th, 2014. The view spans approximately 450 km south to north (left to right). The eastern margin of the North Island, closest to the viewer, was the site of prolonged, Permian to Cretaceous accretion above a subduction zone along the margin of Gondwana. Following opening of the Tasman Sea at ~83 Ma and the separation of Zealandia from Gondwana, the area developed as a passive margin until the propagation of the modern Pacific–Australia plate boundary through Zealandia, by Oligocene times. Since then, eastern North Island has been uplifted by accretion along the modern, active, Hikurangi subduction zone.



CONTENTS

1. IMPORTANT HEALTH AND SAFETY INFORMATION

There are several potential hazards that will be encountered during the course of this field trip. In particular, please note the following.

- Participants must heed and observe the **warnings** and time limitations imposed at certain stops by the trip leaders. The leaders will point out comparatively safe outcrops to inspect: please keep to these. Due to the changing nature of the coastal sections, we cannot guarantee that conditions will be exactly as expected. Circumstances on the day may dictate what is appropriate in terms of access and health and safety considerations.
- **Cliffs** and road cuttings can be **unstable**, and portions may collapse or shed debris without prior warning. Caution should therefore be exercised when examining rocks at the base of natural or man-made cliffs, and please do not linger at cliff exposures.
- **Water** can be dangerous! Wave, river, and tidal conditions can be unpredictable; large waves can appear unexpectedly, and you should watch for wave run-up. The coastal sections in eastern North Island are often subject to strong undertows. There is to be no swimming at fieldtrip stops.
- Caution must be exercised when crossing public **roads**, standing on the road reserve, or farm track locations where vehicles or **machinery** may be in use. At certain stops we will be on privately owned farmland, and we request that you respect property, animals and facilities. When we visit stops on farms or quarries the party is requested to stay together and stay well clear of machinery and trucks. Please leave all gates as you found them, and avoid entering paddocks with stock in.
- An average level of **fitness** and mobility is required for this trip; there will be some clambering over rocks and some moderate walks (up to 7 km on day 3).
- A number of **uneven**, rocky and **slippery** surfaces will be encountered—please ensure that you wear adequate, supportive footwear. Lightweight boots are recommended. Be aware that visits to the coastal and stream sections may involve getting wet feet.
- Participants should carry any personal **medications**, including those for **allergic reactions** (e.g., insect stings, pollen, food allergies). Please make the field trip leader aware of any **medical issues** (including allergies) you may have that could affect your participation in the field trip.
- The **weather** in this area can be variable, although we hope for dry conditions! Participants need to be prepared for warm, cold, wet, and/or dry conditions. The expectation is that temperatures would be in the range 10–20 °C. A sunhat, sun cream, sunglasses, waterproof and windproof raincoat, and warm clothing (layers) are essential. The UV strength of the sun in New Zealand is much higher than other parts of the world. It is very easy to get **sunburnt**, even on cool, cloudy days. Make sure you are well protected from the sun and that you use sunscreen. Please don't underestimate the climatic variations that are possible or the potential to get sunburnt.
- **Seals** will be present on several coastal outcrops. Please do not venture within 5 m of seals or get between a seal and the water's edge, or a seal and her pup. Seals can become aggressive.
- The field area is currently experiencing increased seismic activity, and aftershocks are likely to be felt. In the event of an **earthquake**, ensure you drop to the ground, place yourself under some cover (or, if outside, cover your head), and hold on to something. Remember: DROP–COVER–HOLD. There is a real but very low frequency risk of **tsunami**. These might be generated from around the Pacific Ocean (in which case we should get forewarning) or locally, in which case we might get no warning except a rapid fall in sea level. A tsunami generated by submarine slope failure need not be associated with a felt earthquake. Please keep in mind what high ground (at least 10–20 m above sea level) is readily accessible.

2. INTRODUCTION

New Zealand represents the subaerial ~6% of the largely submerged continent of Zealandia (Fig. 1; Mortimer *et al.*, 2017), and the present land area reflects Neogene deformation and uplift related to propagation of the Pacific–Australia plate boundary through the region. The east coast of the North Island is the site of active accretion above the modern, west-dipping, Hikurangi subduction zone. It was also the site of Cretaceous accretion during the final stages of Mesozoic convergence along the paleo-Pacific margin of Gondwana. This field trip will examine a geological record that spans 100 million years, from the final stages of Cretaceous subduction through to processes that can be observed in the modern accretionary wedge. Sequences examined all lie within the East Coast Basin, which extends from the northeastern part of the South Island in the south, to Raukumara Peninsula in the North Island, and offshore to the modern plate boundary (Fig. 1).

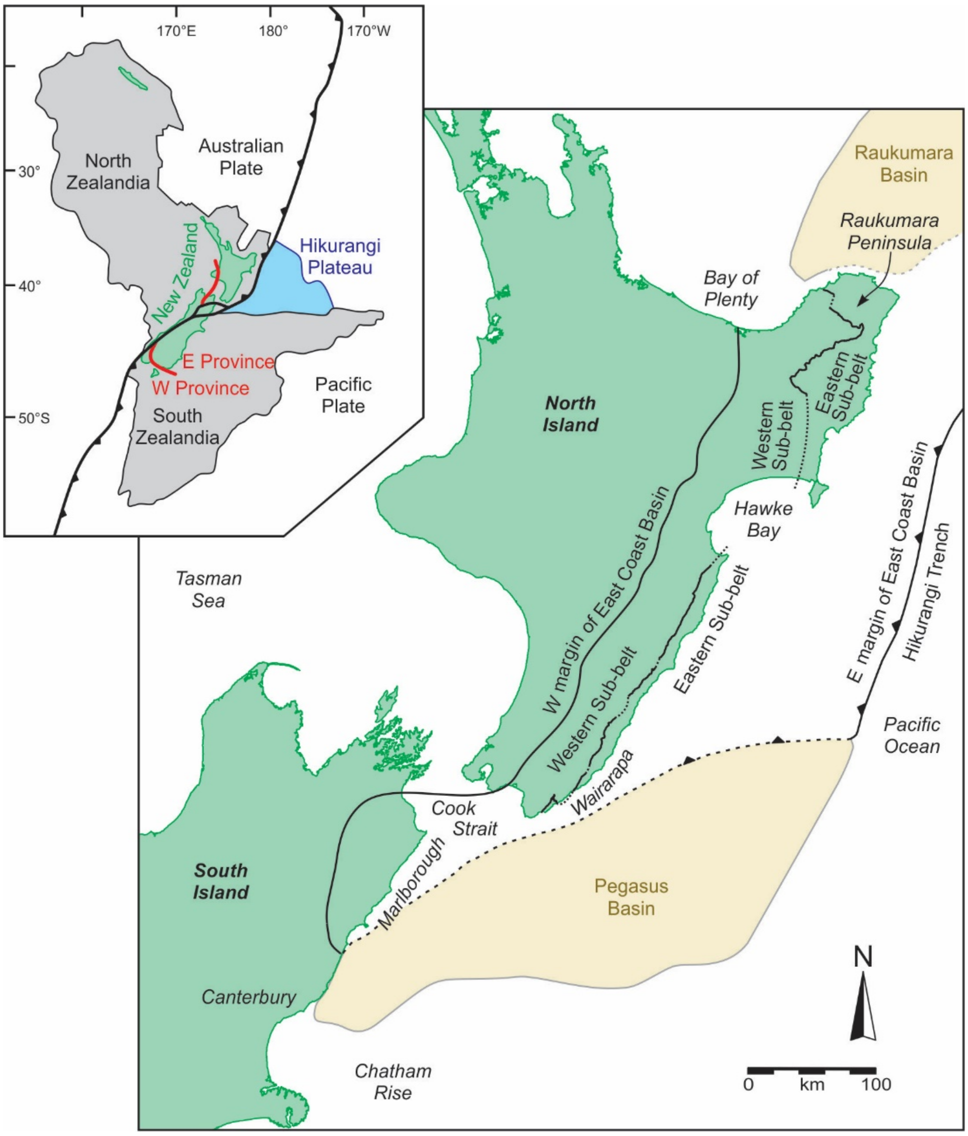


***Fig. 1.** Map of central New Zealand, showing location of the East Coast Basin and other key features and places mentioned in the text. Inset shows the continent of Zealandia, the Hikurangi Plateau, and major geological divisions of Zealandia. Figure modified from Crampton* et al. *(submitted).*

2.1 The foundations of Zealandia

Zealandia comprises a "basement" of Cambrian–Early Cretaceous terranes and plutons that occupied a position on, intruded, or were accreted to, the margin of Gondwana; these units are assigned to the Austral Superprovince *sensu* Mortimer *et al.* (2014) (Fig. 2). Within this, terranes that record early Paleozoic accretion are referred to the Western Province, whereas terranes to the east that record latest Paleozoic–Early Cretaceous accretion or deposition are grouped within the Eastern Province. The boundary between these provinces is defined by the eastern margin of the Median Batholith, which comprises Paleozoic–Early Cretaceous plutons and forms a conspicuous basement marker within Zealandia (Figs 1, 2).

Overlying these basement rocks of the Austral Superprovince is a "cover" of Cretaceous–Recent sedimentary basins that are assigned to the Zealandia Megasequence of Mortimer *et al.* (2014) (Fig. 2). These basins record the rifting of Zealandia from Gondwana (Momotu Supergroup), Late Cretaceous–Eocene continent-wide subsidence (Haerenga Supergroup), maximum flooding in the Oligocene (Waka Supergroup), and Miocene–Recent uplift related to development of the modern convergent margin (Māui Supergroup).

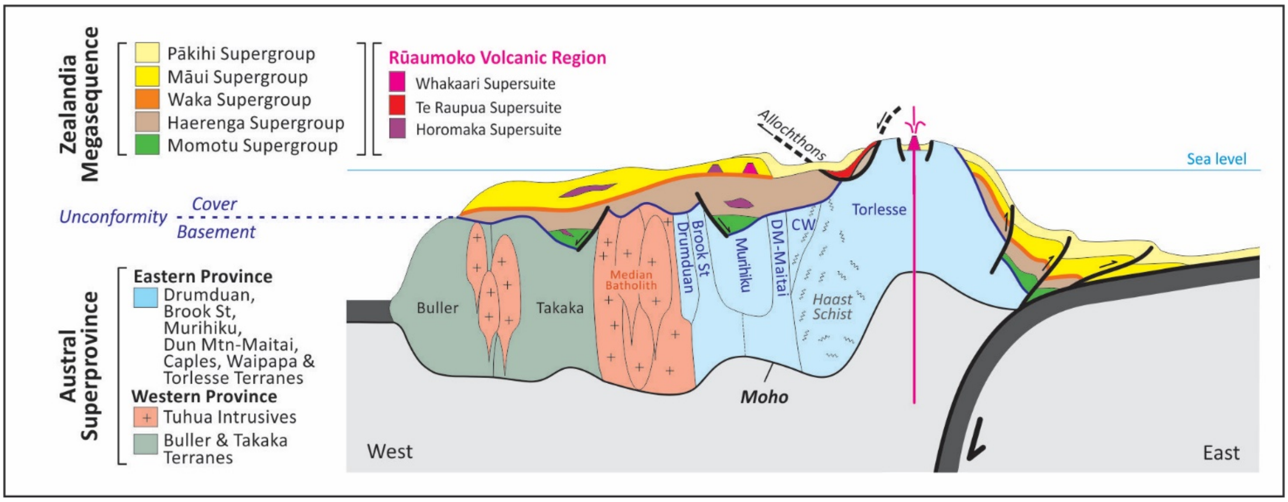


Fig. 2. *Schematic crustal cross-section of New Zealand showing the major litho-tectono-stratigraphic units. Reproduced from Mortimer* et al. *(2014, fig. 1).*

2.2 The East Coast Basin

Prior to development of the modern plate boundary, the East Coast Basin is assumed to have been contiguous with the Raukumara Basin in the north and the Pegasus Basin in the south (Fig. 1), and all three basins are assumed to record similar pre-Neogene geological histories. The East Coast Basin has experienced four major phases of development that reflect the high-level subdivision of the Zealandia Megasequence outlined above:

1. Mesozoic subduction along the Gondwana margin (Austral Superprovince).
2. Subduction termination (Momotu Supergroup).
3. Passive margin subsidence (Haerenga to Waka supergroups).
4. Development of the modern plate boundary (Māui Supergroup).

These phases of development are outlined in more detail below.

Within the East Coast Basin, spatial contrasts in Cretaceous to Paleogene tectonostratigraphic patterns were used by Moore (1988a) to delineate a number of structural divisions. Although several subordinate structural blocks or domains were identified (Moore, 1988a; and see also Mazengarb and Harris, 1994), here we focus on the highest level, two-fold division of the East Coast Basin into Eastern and Western sub-belts (Fig. 1) that are characterised by distinctive Cretaceous and Paleogene, mostly marine, stratigraphic successions (e.g., Moore, 1988a; Field *et al.*, 1997).

In general, the Western Sub-belt is typified by comparatively little complex deformation, deposition on Torlesse basement, a virtual absence of igneous rocks, and relatively common, local, polychronous unconformities and/or condensed sections (Moore *et al.*, 1986; Moore, 1988a; Field *et al.*, 1997; Crampton *et al.*, 2006). In contrast, the Eastern Sub-belt is typified by comparatively intense deformation, no exposure of a basal contact, and relatively common igneous rocks (Moore *et al.*, 1986; Moore, 1988a; Crampton, 1997; Field *et al.*, 1997). In the north of the basin, the Eastern Sub-belt is allochthonous (the East Coast Allochthon), and parts may have been obducted and transported from the northeast by up to many tens of kilometres during the early Miocene (Rait *et al.*, 1991).

The position and geometry of the East Coast Basin prior to the inception of the modern plate boundary between the Australian and Pacific plates continues to be a contentious issue in paleogeographic and tectonic reconstructions of Zealandia and the Southwest Pacific region. It is fair to say that in many studies, the East Coast Basin has been employed, in effect, as a sponge to soak up large uncertainties in regional tectonic models. Discussion and resolution of this problem is beyond the scope of this field trip guide, but the interested reader is directed to a recent study on this topic by Hines (2018).

2.3. Mesozoic subduction in the East Coast Basin

Permian to Cretaceous subduction along the Zealandian segment of the paleo-Pacific margin of Gondwana resulted in the accretion of several terranes that are grouped within the Eastern Province of the Austral Superprovince (see above). Of relevance here is the eastern-most of these terranes, the Pahau Terrane of the Torlesse Composite Terrane (Fig. 2; see Mortimer *et al.*, 2014). Pahau Terrane forms basement to the Western Sub-belt of the East Coast Basin, and comprises Triassic to Early Cretaceous, mainly terrigenous clastic rocks that were accreted by the end of the Early Cretaceous. Pahau Terrane is typically highly indurated, strongly deformed, poorly fossiliferous, and is dominated by thinly to very thickly interbedded sandstone and mudstone turbidites, with subordinate conglomerate (e.g., Barnes, 1988). Basement is not observed in the Eastern Sub-belt.

2.4. Termination of Cretaceous subduction in the East Coast Basin

There has been widespread consensus that subduction along the New Zealand sector of the Zealandian margin ceased by the end of the Early Cretaceous, by about 105–100 Ma, and was followed by Late Cretaceous extension and rifting (e.g., Bradshaw, 1989; Field *et al.*, 1997; and references therein). The end of subduction has been linked to collision of the Hikurangi Plateau large igneous province into the New Zealand sector of the margin at ~110–105 Ma, and consequent jamming of the subduction zone (Davy *et al.*, 2008; Davy, 2014). Indirect evidence for the timing of this jamming comes from the 101 Ma age for cessation of spreading in the Osbourn Trough northeast of New Zealand (Zhang and Li, 2016).

In contrast, based on diverse lines of evidence, some authors have inferred that subduction persisted through part or much of the Late Cretaceous, until at least 85 Ma and perhaps as late as 70 Ma (e.g., Spörli and Ballance, 1989; Mazengarb and Harris, 1994; Kamp, 1999, 2000; Vry *et al.*, 2004; Cooper and Ireland, 2015). A few previous studies have adopted an intermediate position, and inferred that subduction continued until ~92 Ma (e.g., Ballance, 1993). These alternatives need not be mutually exclusive: subduction may have terminated along one segment of the margin and continued elsewhere (e.g., Jabaloy *et al.*, 2003; Marsaglia, 2012).

Debate regarding the nature of this basement–cover tectonic transition in Zealandia has been on-going, in one form or another, for many decades (e.g., Macpherson, 1948; Wellman, 1959; Suggate, 1978; and references therein). The age at which subduction ceased on this margin remains unresolved but is important for tectonic and paleogeographic reconstructions of Zealandia and the wider southwest Pacific during the Late Cretaceous, for understanding plate boundary processes (Luyendyk, 1995; Reyners *et al.*, 2017), and in relation to global plate-tectonic models (Matthews *et al.*, 2012). Importantly, the East Coast Basin lay on the outboard margin of Zealandia during the Cretaceous, on top of the accretionary prism, adjacent to and possibly superimposed on the Cretaceous subduction trench; it should, therefore, preserve direct structural and stratigraphic evidence for or against Late Cretaceous subduction.

A recent synthesis of data from the East Coast Basin and from elsewhere in Zealandia has concluded that subduction apparently terminated along this segment of the margin at 100 Ma, and that youngest Pahau Terrane strata are the youngest accreted rocks (Crampton *et al.*, submitted); we will see some of these rocks at STOPS 5 and 6. That said, there is clear evidence from the East Coast Basin for on-going compressional deformation until about 85 Ma. This might relate to gravitational collapse of the over-thickened Median Batholith crust and east-directed compression at the margin, following the removal of external bounding forces or because of dynamic topography (Tulloch, 1990; Waight *et al.*, 1998; Rey and Müller, 2010; Schwartz *et al.*, 2016). A modern analogue for this model is seen in the western United States, where gravitational potential energy differences over a distance of ~1000 km in part drive extension in the Basin and Range and compression at the coast (Flesch *et al.*, 2000). Alternatively, Late Cretaceous compression might reflect deformation at restraining structures within a strike-slip regime. Late Cretaceous strike-slip deformation through Zealandia has been discussed widely (e.g., Lamb *et al.*, 2016; van der Meer *et al.*, 2016; Mortimer, 2018), but remains unproven.

On the Western Sub-belt of the East Coast Basin, strata unconformably overlying undoubted accretionary rocks of Pahau Terrane comprise substantial thicknesses (1000–2500 m) of relatively undeformed, fossiliferous, marine mudstone-dominated Momotu Supergroup that was probably deposited largely at slope to outer shelf depths. Notably, in many places the lowest part of these successions comprises thick (up to ~700 m) muddy olistostromes, mass-transport deposits, and other mélanges that may be partially tectonic and partially sedimentary in origin (Crampton et al., submitted). Similar units are only a very minor component of younger Late Cretaceous successions. The maximum age of strata overlying Pahau Terrane varies from about 115 to 100 Ma, and the age of the unconformity separating Pahau Terrane from cover is clearly diachronous and youngs eastwards. Conformably overlying the mélange units or resting directly on Pahau Terrane are mudstone-dominated successions that contain numerous local unconformities and complex stratigraphic patterns; these successions seems to record alternating uplift and subsidence in adjacent, small, “reciprocating” sub-basins.

In contrast, on the Eastern Sub-belt, basement is not observed, and the oldest cover beds are ~100 Ma. Momotu Supergroup on the Eastern Sub-belt comprises thick (1000–2000 m), monotonous and essentially continuous successions of turbidites that were deposited between ~100 and ~80 Ma. These strata were probably deposited largely on basin-floor fans, although they probably record shallowing up-section.

2.5. *Passive margin subsidence phase in the East Coast Basin*

Between cessation of subduction along the southern East Coast–Pegasus–Chatham Rise sector of the Gondwana margin and initiation of subduction at the modern Hikurangi subduction margin, a period of around 80 million years, the East Coast Basin occupied a position on a passively subsiding continental margin (Fig. 3). As the surrounding land areas decreased, the clastic sediment supply waned.

Folding, faulting, uplift, and erosion in the East Coast Basin during the Late Cretaceous was followed by marine transgression. By the latest Cretaceous, slow accumulation of fine-grained clastic sediment and limestone was occurring over much the East Coast region (Field *et al.,* 1997), strata assigned to the Haerenga Supergroup (Fig. 2). The Whangai Formation, a 300–500 m-thick non-calcareous to calcareous mudstone to fine sandstone, was deposited over virtually the entire East Coast region

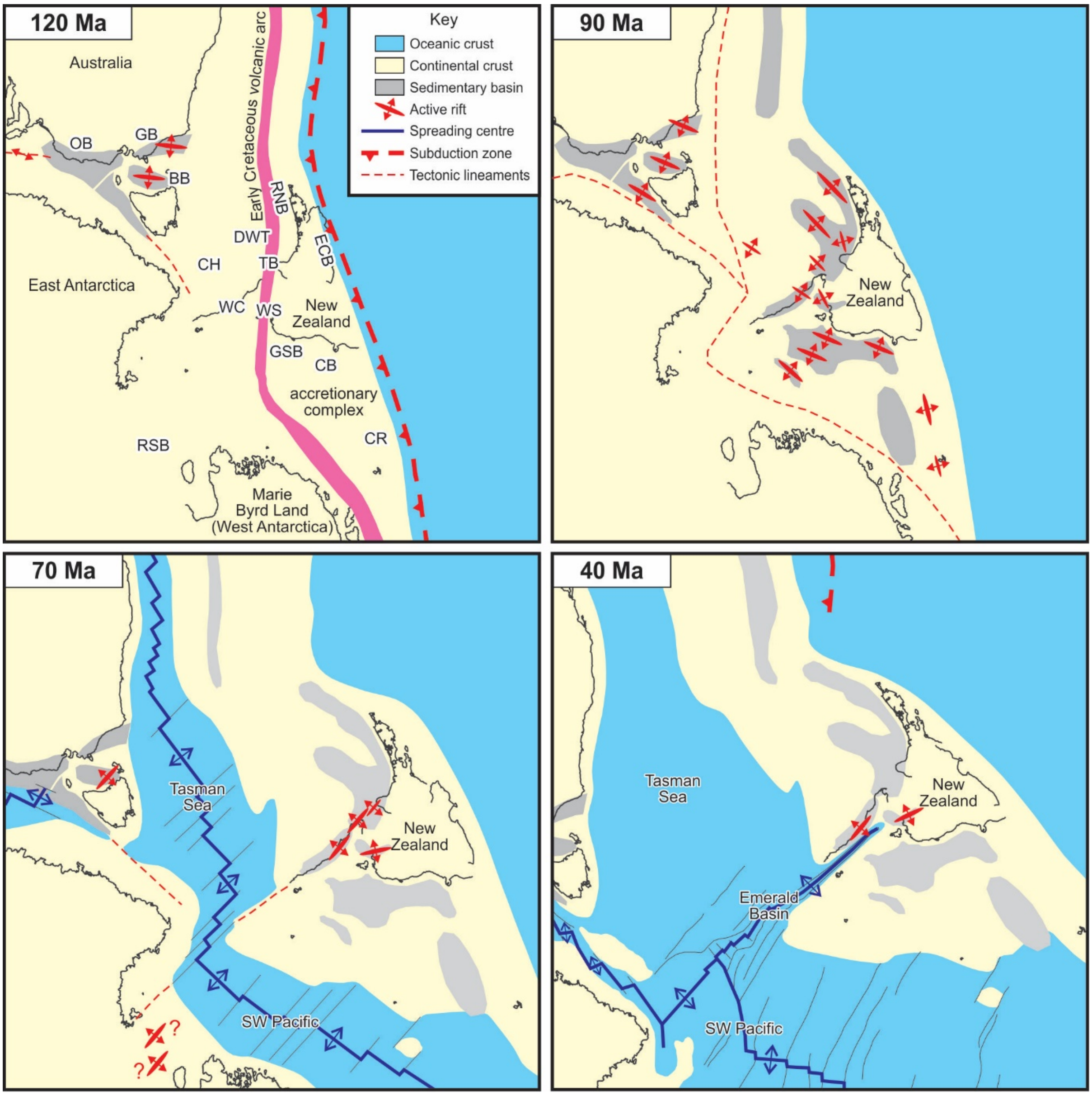


Fig. 3. *Plate reconstruction of the Zealandia–Australia–Antarctic region for the Late Cretaceous to middle Eocene. Adapted from Sutherland* et al. *(2001).*

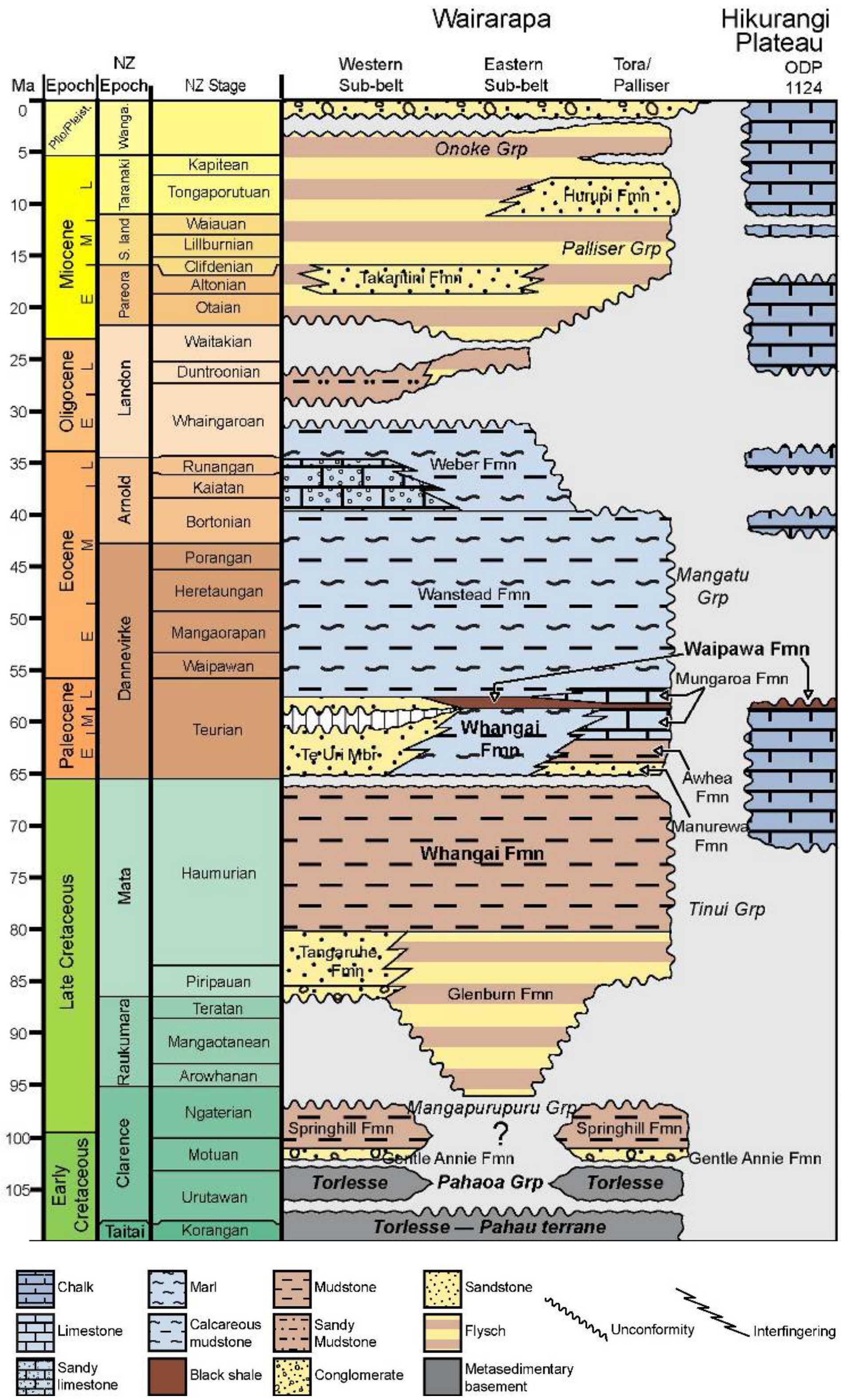


Fig. 4. *Generalised chronostratigraphic panel of the Wairarapa–Marlborough region illustrating the main stratigraphic groups and general lithofacies distribution. Modified from Bland et al. (2015).*

during the Late Cretaceous to middle Paleocene (Fig. 4; Moore, 1988b). In most places it is overlain conformably by late Paleocene (~58 Ma), organic-rich Waipawa Formation. Rocks of latest Paleocene to Eocene age are dominated by (slumped) smectitic mudstones of the Wanstead Formation, a general term for all fine-grained bentonitic (smectite-rich) sediments of Paleocene to Eocene age in eastern North Island (Moore and Morgans, 1987). Other lithofacies include greensand, breccia, conglomerate, poorly to well-bedded glauconitic sandstone and mudstone, flysch, and siliceous units. The Wanstead Formation (Fig. 4) is generally considered to represent the deepest-water depositional paleoenvironment of the Late Cretaceous–Paleogene in the East Coast region, with average middle bathyal paleodepths, although lower bathyal–abyssal depths are recorded in some parts (Field *et al.*, 1997; Hines *et al.*, 2013).

Whereas there is some evidence for minor tectonism during the Paleogene, the pattern of passive margin sedimentation continued through this time and lasted in most areas until the late Oligocene, the time of maximum flooding of Zealandia and deposition of condensed sequences assigned to the Waka Supergroup (Mortimer *et al.*, 2014). Rocks of Oligocene age throughout eastern North Island are dominated by white-weathering marls and micritic mudstones, with minor flysch, of the Weber Formation (Field *et al.*, 1997). Weber Formation conformably overlies Wanstead Formation in most places (Lee and Begg, 2002; Morgans, 2016).

2.6. Development of the modern plate boundary in the East Coast Basin

The current phase of subduction on the eastern margin of Zealandia commenced in the Early Miocene (e.g., Ballance, 1993). All of the North Island forms part of the upper (Australian) of the two plates involved with the modern subduction plate boundary (Fig. 1). Active tectonics within North Island are dominated by subduction at the Hikurangi Trough, strike-slip faulting in the North Island Shear Belt, and back-arc rifting in the Taupō Volcanic Zone (TVZ) (Wallace *et al.*, 2004). The plate boundary zone accommodates oblique subduction of the Pacific plate beneath the Australia plate. The relative plate motion vector trends at ~40–70° to the general strike of the subduction margin with a slip-rate of 38–50 mm/yr. Relative Australia–Pacific plate motion decreases in rate and takes on a greater margin-parallel component southward along the New Zealand margin (DeMets *et al.*, 1990, 1994). Margin-parallel motion in the East Coast Basin is minor in relation to the overall relative motion and appears to be accommodated by strike-slip faults bounding the eastern side of the axial ranges. Margin-normal motion is accommodated on the subduction thrust and on reverse faults predominantly east of the axial ranges and within the subduction prism.

The term “Hikurangi Margin” describes all elements of the modern subduction zone of eastern North Island and northeastern South Island from the subduction interface in the east to the modern volcanic arc in the west (Figs 5, 6). The Hikurangi Margin corresponds to the southern termination of the Tonga–Kermadec subduction zone, and has evolved over the last ~45 million years as the Australian plate moved northwards relative to the Pacific plate, with the effect that Zealandia was sheared through the middle. The apparent dextral displacement along the central part of the plate boundary through South Island totals about 480 km.

Morphostructural elements of the Hikurangi Margin comprise, from east to west (Figs 5, 6):

1. The Hikurangi Trough, which is the bathymetric depression that marks the modern subduction interface.

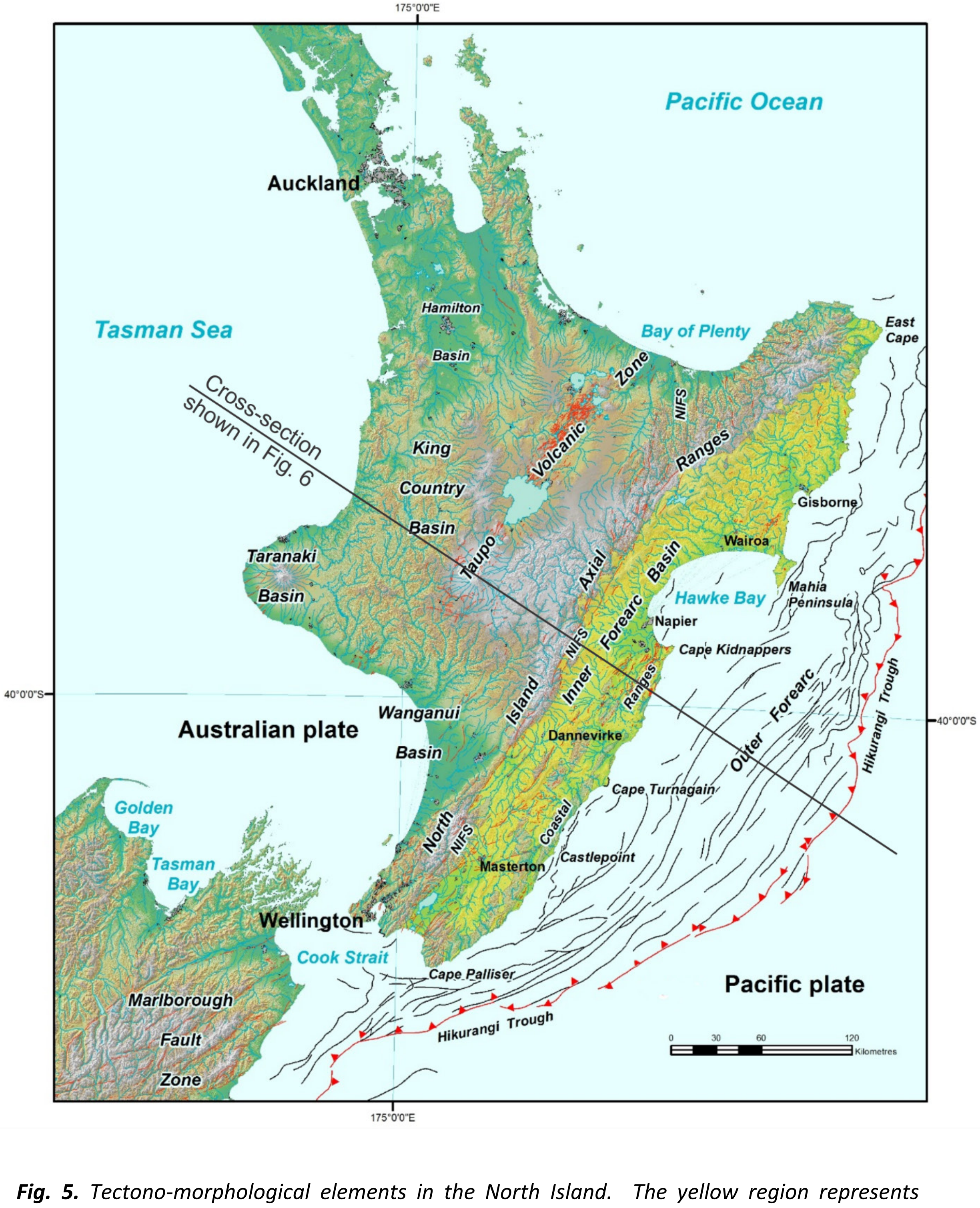


Fig. 5. *Tectono-morphological elements in the North Island. The yellow region represents exposed, onshore parts of the East Coast Basin; black lines denote offshore faults. Line of the cross-section shown in Fig. 6 indicated. "NIFS" = North Island Fault System. Map modified from Bland (2018).*

2. The outer forearc region, which comprises the thrust fault-controlled, imbricate accretionary wedge, and many small Neogene trench-slope basins; this zone is largely offshore but encroaches on land around Mahia Peninsula and Cape Kidnappers (Beanland, 1995) (Fig. 5).
3. The inner forearc region, which comprises the topographic and structural depression of eastern North Island, the forearc basin. About half of the basin is presently above sea-level and most of this only emerged since ~1.6 Ma (Beanland, 1995).
4. The frontal ridge and the axial ranges, which define the western margin of the East Coast Basin. The frontal ridge is separated from the forearc basin by major, active, dextral, oblique-slip faults of the North Island Shear Belt, which accommodates some of the modern plate motion through the North Island (Cashman *et al.*, 1992; Beanland *et al.*, 1998; Nicol and Van Dissen, 2002; Wallace *et al.*, 2004).

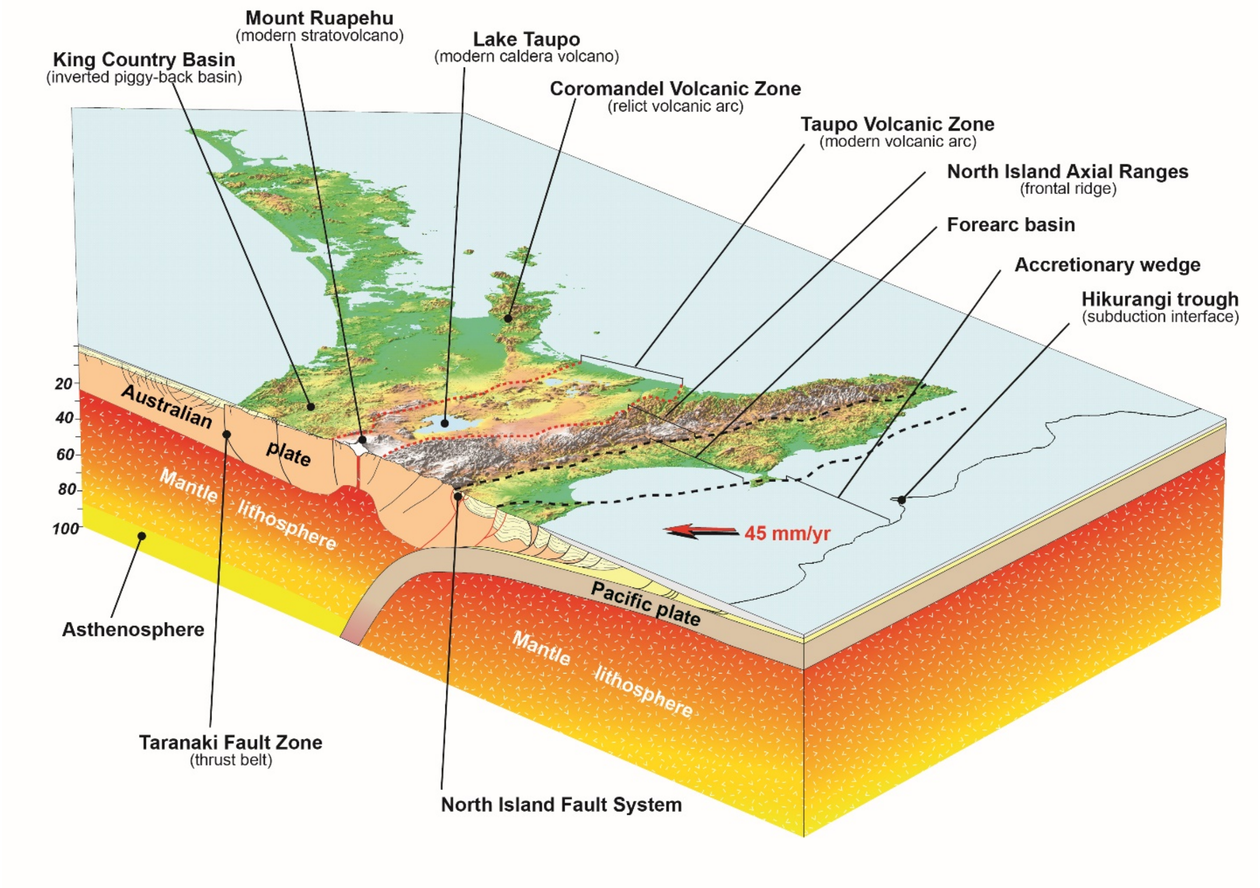


Fig. 6. *Illustration of the tectonic setting of eastern North Island, New Zealand. From Bland (2006); data used in the figure were derived from Beanland (1995), Field* et al. *(1997), Barnes and Nicol (2002), and Barnes* et al. *(2002). Location of the cross-section shown on Fig. 5.*

3. OVERVIEW OF THE FIELD TRIP

On this field trip we will view features that relate to the cessation of Cretaceous subduction on the margin of Gondwana, to the Late Cretaceous to Paleogene passive margin phase of development, and a range of features associated with the modern subduction zone and plate boundary. In order, we will visit the following (and see Fig. 7):

DAY 1, Sunday 25th November

- Depart Wellington; pickup for all field trip participants in front of Wellington Railway Station, 8.45 am.
- STOPS 1–3. 1855 rupture trace of the Wairarapa Fault in the Pigeon Bush area, southern Wairarapa. The Wairarapa Fault forms part of the modern Hikurangi Margin and is interpreted to have initiated in the Pliocene as a reverse fault and subsequently to have been reactivated as a strike-slip fault at ~1–2 Ma.
- Lunch at Lake Ferry Hotel.
- STOPS 4–6. Early Cretaceous rocks in the vicinity of Cape Palliser, southern Wairarapa. These rocks record the final stages of Cretaceous subduction along the Pacific-facing margin of Zealandia, and have furnished debated but important constraints on the timing of subduction cessation.
- STOP 7. (Time permitting.) Miocene strata at Kupe's Sail, southern Wairarapa, which record local Neogene subsidence.
- Drive to Martinborough; accommodation at Martinborough Hotel (ph. 06 3069350) and Martinborough Top 10 Holiday Park (ph. 0800 780909); dinner reservation at Martinborough Hotel, 7:00 pm.

DAY 2, Monday 26th November

- Depart Martinborough 8.30 am. Purchase lunch en route.
- STOP 8. Castlepoint reef, to view Pleistocene submarine canyon fill that was deposited within the accretionary prism. Lunch.
- STOPS 9–10. Early Miocene olistostrome and turbidites that were deposited within a trench-slope basin shortly after the inception of subduction on the Hikurangi Margin.
- Drive to Dannevirke; accommodation at Gateway Motor Lodge (ph. 0800 666 716); dinner venue to be confirmed.

DAY 3, Tuesday 27th November

- Depart Dannevirke 8.00 am. Drive to Waimarama where we will join with Field Trip 5, led by Jarg Pettinga and Carolyn Boulton. Refer to that field trip guide for further information.
- Drive to Napier to arrive by 6.30 pm at the latest.

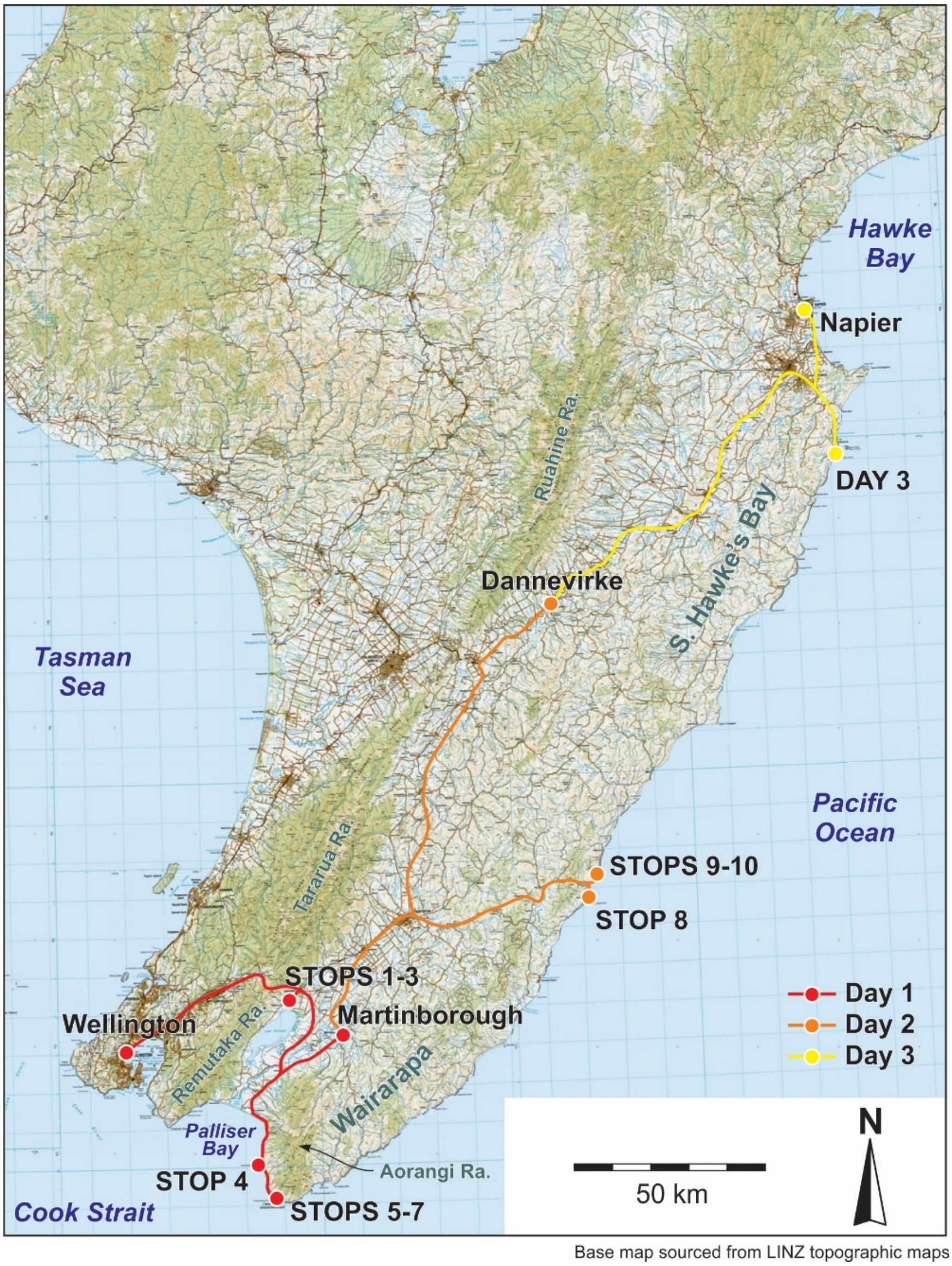


Fig. 7. *Overview of the field trip, showing locations of geological stops, route taken, overnight stays, and key place names mentioned in the text. Detailed maps of the stops are given at relevant places in the text.*

4. THE WAIRARAPA FAULT AT PIGEON BUSH: STOPS 1–3

4.1. Introduction

The Pacific–Australia plate boundary in the North Island of New Zealand accommodates oblique subduction of oceanic crust along the Hikurangi Margin of the North Island, and oblique continental collision in the South Island (Fig. 8). In the southernmost North Island, the contemporary oblique plate convergence of ~42 mm/yr can be broken down into ~30 mm/yr of margin-orthogonal motion and ~28 mm/yr of margin-parallel motion (Beavan *et al.*, 2002). Active faults in the upper plate of the Hikurangi Margin of New Zealand form a complex array of strike-slip, oblique-slip, and reverse faults (Fig. 8a). Most of New Zealand's largest historical earthquakes have occurred on these faults, including in 1855 (Wairarapa, M_w 8.2), 1931 (Napier, M_w 7.8), and 1934 (Pahiatua, M_w 7.6). The Wairarapa Fault (Fig. 8) is one of the major faults in the North Island, and plays an important role in accommodating upper plate deformation (e.g., Beanland and Haines, 1998). The 1855 Wairarapa earthquake, was observed to produce surface rupture along the southern part of the Wairapapa Fault (Ongley, 1943; Grapes and Wellman, 1988; Grapes and Downes, 1997). It resulted in up to 6.4 m of coastal uplift (McSaveney *et al.*, 2006), and up to ~18.5 m of dextral slip—making it the largest coseismic displacement so far documented for a strike-slip earthquake worldwide (Rodgers and Little, 2006).

The margin-orthogonal component of plate motion in the southern North Island is accommodated by thrust faulting and related folding in the onshore and offshore parts of the Hikurangi Margin's upper plate, including in an offshore accretionary wedge consisting of NE-striking reverse faults and folds, and by contractional slip on the subduction megathrust beneath these faults, which is thought to be strongly "coupled" in the southern part of the North Island (Barnes and Mercier de Lépinay, 1997; Barnes *et al.*, 1998; Nicol *et al.*, 2007; Wallace *et al.*, 2004, 2012). The margin-parallel component of plate motion is accommodated by dextral-slip on the NNE-striking faults of the North Island Dextral fault belt (NIDFB), including the Wellington and Wairarapa faults (e.g., Beanland, 1995; Van Dissen and Berryman, 1996; Mouslopoulou *et al.*, 2007), by clockwise vertical-axis rotation of eastern parts of the North Island (e.g., Wallace *et al.*, 2004; Nicol *et al.*, 2007; Rowen and Roberts, 2008; Lamb, 2011), by strike-slip on active ENE-striking structures in Cook Strait (such as the Boo Boo Fault, Barnes *et al.*, 2008), and by oblique- or reverse-slip on NE-striking onshore and offshore faults, including the subduction megathrust (Nicol *et al.*, 2007).

Seismicity data suggest that faults of the NIDFB, including the Wairarapa Fault, intersect the subduction megathrust at depths of 20–30 km beneath the southernmost part of the North Island (e.g., Reyners, 1998; Henrys et al, 2013—see Fig. 8b). GPS geodetic data suggest that this segment of the subduction interface is currently "locked" and is accumulating elastic strain (Wallace *et al.*, 2004, 2012).

The Wairarapa Fault is interpreted to have been initiated in the Pliocene as a reverse fault and reactivated as a strike-slip fault at ~1–2 Ma in response to a clockwise vertical-axis rotation of the forearc relative to the Pacific Plate (Beanland, 1995; Beanland and Haines, 1998). Dipping steeply to the northwest, the Wairarapa Fault bounds the eastern side of the Remutaka Range (spelt "Rimutaka" on many maps), marked by a topographic step between the ranges and the subdued alluvial plain of the Wairarapa basin to the east. The central section of the fault is typically complex at the surface, including 250–500 m wide zone of mostly left-stepping *en echelon* traces and/or deformational bulges that have been active in the late Quaternary (Grapes and Wellman, 1988; Rodgers and Little, 2006;

Carne and Little, 2012). The northern section of the fault is marked by a series of dextral-slip splays (e.g., Carterton Fault) that bifurcate eastward away from the main trace of the Wairarapa Fault farther to the west (Fig. 8a).

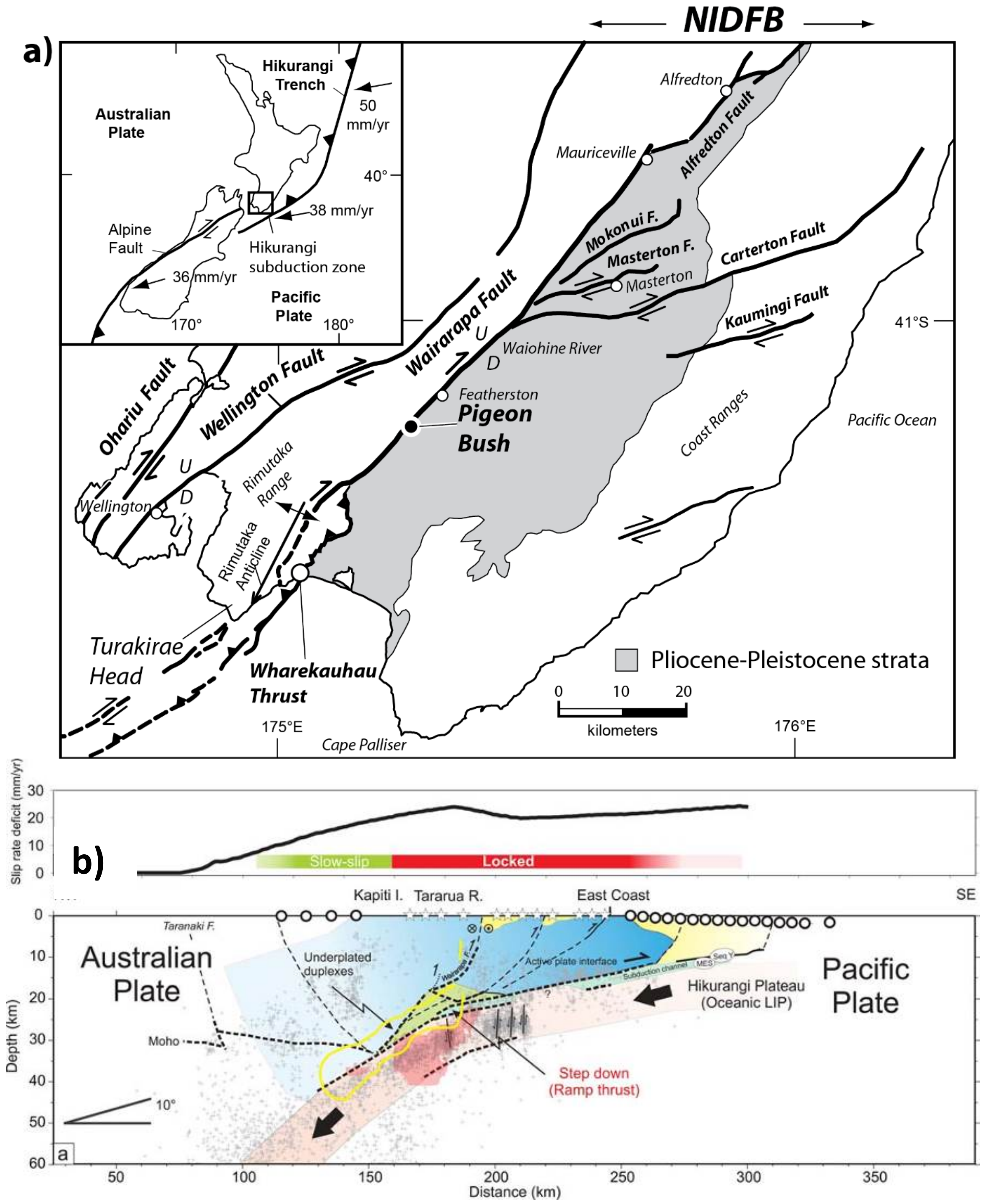


Fig. 8. ***a)*** *Tectonic map showing major active faults and other structures of the southern North Island (largely after Begg and Johnston, 2000; Lee and Begg, 2002; and Barnes et al., 2008), and location of field trip stop at Pigeon Bush Station. Inset: contemporary plate tectonic setting of New Zealand (plate motions from Beavan* et al.*, 2002).* ***b)*** *Composite section along the SAHKE seismic transect, which crosses the North Island approximately at the level of Pigeon Bush, showing interpreted boundaries and faults, including the Wairarapa Fault (Henrys et al., 2013).*

Near its southern end, the fault zone becomes complex near the south coast, where it includes a thrust structure (now mostly inactive) called the Wharekauhau Fault (Schermer *et al.*, 2009).

The Wairarapa and Wharekauhau faults dip to the NW and have a reverse component of dip-slip. They separate uplifted Mesozoic greywacke on the northwest from Quaternary strata of the Wairarapa basin on the southeast. Along the western margin of Lake Wairarapa, Quaternary strata in the footwall of the Wairarapa fault chiefly consist of last interglacial marine deposits and alluvial fan gravels derived from erosion of the rising the Rimutaka Range. Post-Last Glacial Maximum gravels mapped as "Q2a" by Begg and Johnston (2000), have informally been termed the "Waiohine gravels" by others in the Wairarapa Valley. The top surface of this abandoned fan complex (the "Waiohine surface") dips gently eastward beneath the surface of Lake Wairarapa (Begg and Johnston, 2000; Lee and Begg, 2002). On the western margin of the lake, at Cross Creek just south of Pigeon Bush, the age of this surface has been bracketed by ^{14}C dating of trench samples collected on both sides of its gravel tread. These results (Little *et al.*, 2009) constrain fan abandonment to have taken place soon after 12.4 ka. Based on the stratigraphic context of the samples collected in gravel close below the terrace tread, these authors infer an abandonment age of 12–10 ka for the surface at that locality. This age, together with reported lateral offsets of 99–130 m relative to that terrace surface (in particular at Waiohine River, Fig. 8a), suggests a Late Quaternary dextral-slip rate for the Wairarapa Fault of 11.9 ± 2.9 mm/yr (Carne *et al.*, 2011).

4.2. The 1855 earthquake

The Wairarapa Fault east of Wellington, New Zealand ruptured on January 23, 1855, resulting in ground shaking, landsliding (especially in the Rimutaka Range), regional uplift, tsunamis, and >120 km of ground rupturing (Grapes, 1999; Grapes and Downes, 1997). Historic accounts indicate that the 1855 earthquake ruptured the Wairarapa Fault. Fresh scarps attributed by Grapes (1999) to the 1855 rupture are preserved in the landscape from near the coast to Mauriceville, as much as ~88 km northward (Fig. 8). More recent work suggests that slip in 1855 may also have ruptured a northward continuation of the Wairarapa Fault, the Alfredton Fault: scarps along that fault were rejuvenated sometime after 250–330 years BP, implying that the 1855 rupture may have extended to Alfredton, as much as 30 km beyond Mauriceville (Schermer *et al.*, 2004). These data suggest that the onshore part of the 1855 rupture could have been as long as ~120 km. Modern estimates of magnitude based on dislocation modelling of the observed distribution of vertical uplift, and on the felt extent of ground shaking suggest a moment magnitude (M_w) of 7.9 to 8.2 (Darby and Beanland, 1992; Dowrick, 1992), whereas revised measurements of surface offset and inferred rupture size suggest an M_w of at least 8.2 to 8.3 (Rodgers and Little, 2006). This makes the 1855 earthquake by far the largest seismic event in modern New Zealand history (Van Dissen and Berryman, 1996).

The large co-seismic uplift (up to a maximum of 6.4 m at the crest of the Rimutaka anticline, Fig. 8) has been inferred from the height of a fossil beach ridge near Turakirae Head. Dating of this beach ridge and the three other beach ridges, above it, led McSaveney *et al.* (2006) to infer the timing the last four earthquakes on the Wairarapa Fault, and to infer a mean recurrence interval of ~2200 years for Wairarapa Fault earthquakes. More recently, Little *et al.* (2009) undertook paleoseismic trenching to determine the chronology of paleoearthquakes on this fault, and to compare this record of fault rupturing with the geomorphic record of coastal uplifts near Turakirae Head. They recognised five surface-rupturing earthquakes since ~5.2 ka. This is one more event than was inferred for the same time period using uplifted beach ridges, and revises the mean earthquake recurrence interval for the southern Wairarapa Fault to 1230 ± 190 years (Little *et al.*, 2009).

4.3. The Wairarapa Fault Zone south of Featherston

Heading South from Featherston on Western Lake Road, you note the scarp of the Wairarapa fault off your right. Typically, it is located near the upper edge of the grazed paddock land at the foot of the heavily bushed foothills of the Remutaka Range.

Although within a few decades of 1855 the land was largely deforested and converted to grazing land, and despite the passage of 160 years, many of the scarps in the Featherson–Lake Wairarapa region are still remarkably fresh-looking and are likely to be of 1855 age. These scarps locally retain slopes of 30–70°—steep enough to expose planar outcrops of the terrace alluvium. Other probable 1855 scarps lack such steep faces, but demonstrably cut and displace small landforms, such as shallow rills. Scarps higher than ~20 m occur on the limbs of the anticlinal bulges. These are typically mantled by landslides. Where the fault is expressed by multiple overlapping segments at the surface, each not necessarily experiencing slip at the same time, recognition of the 1855 increment of slip becomes difficult or impossible.

4.4. 1855 Rupture Trace in the Pigeon Bush Area

4.4.1. Pigeon Bush: STOP 1

41°08’24.66” S; 175°16’47.71” E.

Pigeon Bush STOP 1 (Figs 9, 10) is justifiably the most famous geological site on the Wairarapa Fault. There, Grapes and Wellman (1988) interpreted two well-preserved, beheaded streams as evidence of dextral offset of a small stream gully cross-cutting the Wairarapa Fault during two sequential earthquake events, most recently in 1855. The fault is marked by a SE-facing scarp cut into Waiohine gravel that is ~6 m high. On the northern side of this scarp, the uplifted “Waiohine” terrace is tilted SW, whereas on its southern side it is partly buried beneath a ~1 m-thick layer of silt (and by younger swamp deposits). The silt was incised by the two channels. Wang and Grapes (2008) dated two samples of the silt by OSL methods, obtaining ages of 7.0 ± 0.5 ka and 4.3 ± 0.5 ka.

Fig. 9. *Google Earth Image of the Pigeon Bush STOPS 1–3.*

On the uplifted (NW) side of the fault, the "Waiohine" gravels have been back-tilted to the southwest by ~5° on the limb of an anticlinal bulge that crests to the NE of this site. This tilting has diverted some of the stream's headwaters southward into an adjacent stream. Thus, the gorge on the up-thrown side of the scarp now seems disproportionately deep with respect to the small, low-discharge stream that currently flows within it. This is important because the stream flows through an entrenched gorge that is, in a sense, partially abandoned and thus little modified since its displacement along the fault.

As recognized by Grapes and Wellman (1988), the well-preserved geomorphology of the beheaded streams supports the idea that this younger increment of slip accrued during a single event, rather than as a composite displacement involving one or more intermediate stages. Both beheaded channels on the downstream side of the fault retain a linear morphology all the way up to the fault, where they are orthogonally truncated against the scarp. Similarly, the source gorge on the upstream side does not widen significantly at the fault, but remains narrow, linear, and fault-transverse all the way to the scarp. There is no evidence for a paleo-channel having run along the fault scarp between the modern stream and either of the abandoned channels, as might reflect an intermediate phase of stream dog-legging induced by shutter ridge damming.

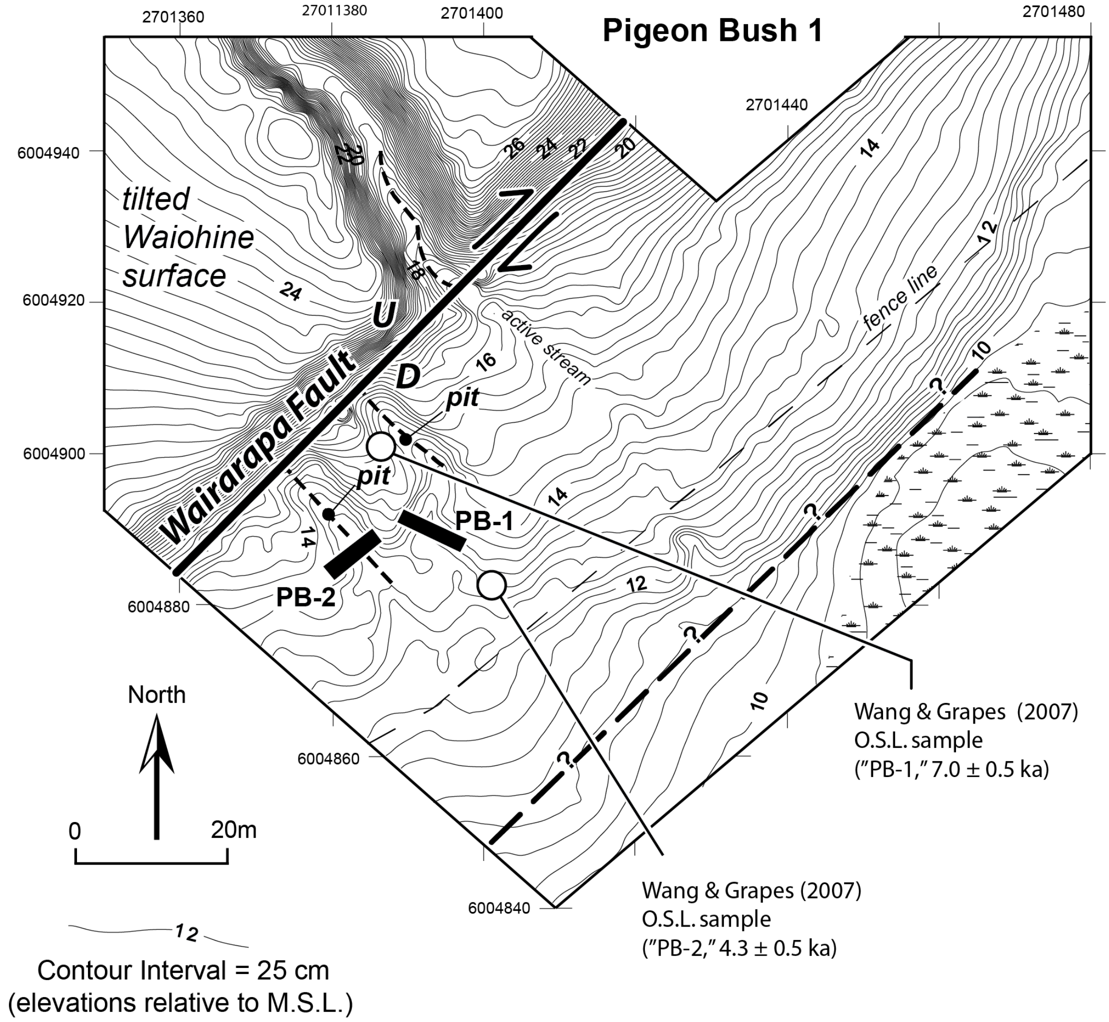


Fig. 10. *Topographic map of the Pigeon Bush 1 site. Map is based on a survey data set consisting of >10,000 points (Rodgers and Little, 2006). Logs of the PB-1 and PB-2 trench sites are presented in Little et al. (2009).*

According to Rodgers and Little 2006, the proximal beheaded channel has been displaced 18.7 ± 1.0 m dextrally and ≥1.25 ± 0.5 m vertically relative to the deeply entrenched active channel on the upstream side of the fault. The other channel is displaced 32.7 ± 1.0 m dextrally and ≥2.25 ± 0.5 m vertically from its source. This larger offset suggests that the older, distal channel had previously been displaced by 14.0 ± 1.0 m of dextral-slip and ~1.0 m of vertical-slip prior to incision of the proximal abandoned channel. The vertical-slip estimates do not account for post-slip incision of the upstream channel and so are minima. The ~18.5 m dextral-slip of the proximal channel is the largest coseismic displacement documented for any strike-slip earthquake globally. The next-largest is 14.6 m of strike-slip during the 1931 earthquake on the Keketuohai-Ertai fault in Mongolia (Baljinnyam, 1993).

Each of the last two earthquakes on the Wairarapa Fault at this site resulted in abandonment of a stream channel immediately downstream of the narrow headwater gully and incision of a new channel in downstream continuity with that gully. Hoping to date the last two earthquakes, Little *et al.* (2009) excavated trenches PB-1 and PB-2 (Fig. 10) at right angles to each of the two channels to date their incision and abandonment. The only fluvially deposited organic material that was found in either channel (charcoal) occurs as coarse detrital particles of charcoal within the fluvial deposits that infill the incisional scour beneath the younger of the two beheaded channels. This channel was cut immediately after the penultimate earthquake. The age of charcoal-producing "burn event" (~546–497 cal. yr BP) provides a minimum age constraint for the penultimate (next to last, i.e., pre-1855) earthquake at this site. Historical data indicates that the youngest earthquake here took place in 1855.

4.4.2. Pigeon Bush: STOP 2

41°08'15.28" S; 175°16'59.97" E.

This region is located <1 km northeast of Pigeon Bush 1 (Fig. 9). Here the fault is characterized by a scarp that coincides with an abrupt southeast-facing topographic step and two elongate topographic depressions. A second strand marked by a small, southeast-facing topographic step may occur to the southeast of the main one, and a third may be present ~100 m to the northwest, but neither of these coincides with any fresh scarps or has revealed any evidence of recent slip.

Two small streams are incised 1.0 to 4.5 m into the older terrace alluvium and are dextrally displaced across the fault (Fig. 11). Where the streams cross the fault trace they deflect abruptly to the southwest to flow parallel to the fault before deflecting back to the southeast again on the downthrown side of the fault. Linear axes were defined along these incised channels and their dextral offset was restored with the aid of a detailed topographic map. A narrow fluvial terrace remnant is preserved on the NW side of the western of the two streams (Stream B). Its 0.75 ± 0.25 m of incision by the modern stream on the NW side of the fault, and the 1.25 ± 0.25 m of vertical-offset of stream channel B across the fault together suggest ~2 m of vertical-slip (interpreted as a minimum, as this sum does not account for any post-1855 deposition that may have partially infilled the channel on the on SE side).

Dog-legging (offset) of this southwestern stream implies 13.0 ± 1.5 m of dextral-slip, whereas dog-legging of the other active stream to the NE records 27.4 ± 1.5 of dextral-slip. Following Grapes and Wellman (1988), we interpret the smaller stream offset to have accumulated in 1855 and the larger one to record a summation of slip during both 1855 and the next-older (penultimate) earthquake. This two-increment model of slip accumulation is strongly supported by our discovery of a subtle abandoned stream channel on the downthrown side of the fault to the southwest of the SW active stream (labelled as "H2" in Fig. 11). The beheaded stream channel is dextrally offset by 26.3 ± 5.0 m from its incised source, thus, both of the small streams preserve evidence for a ~26–27 m horizontal slip, and one of the streams, similar to the nearby Pigeon Bush 1 site, also preserves evidence for a younger and smaller increment of offset.

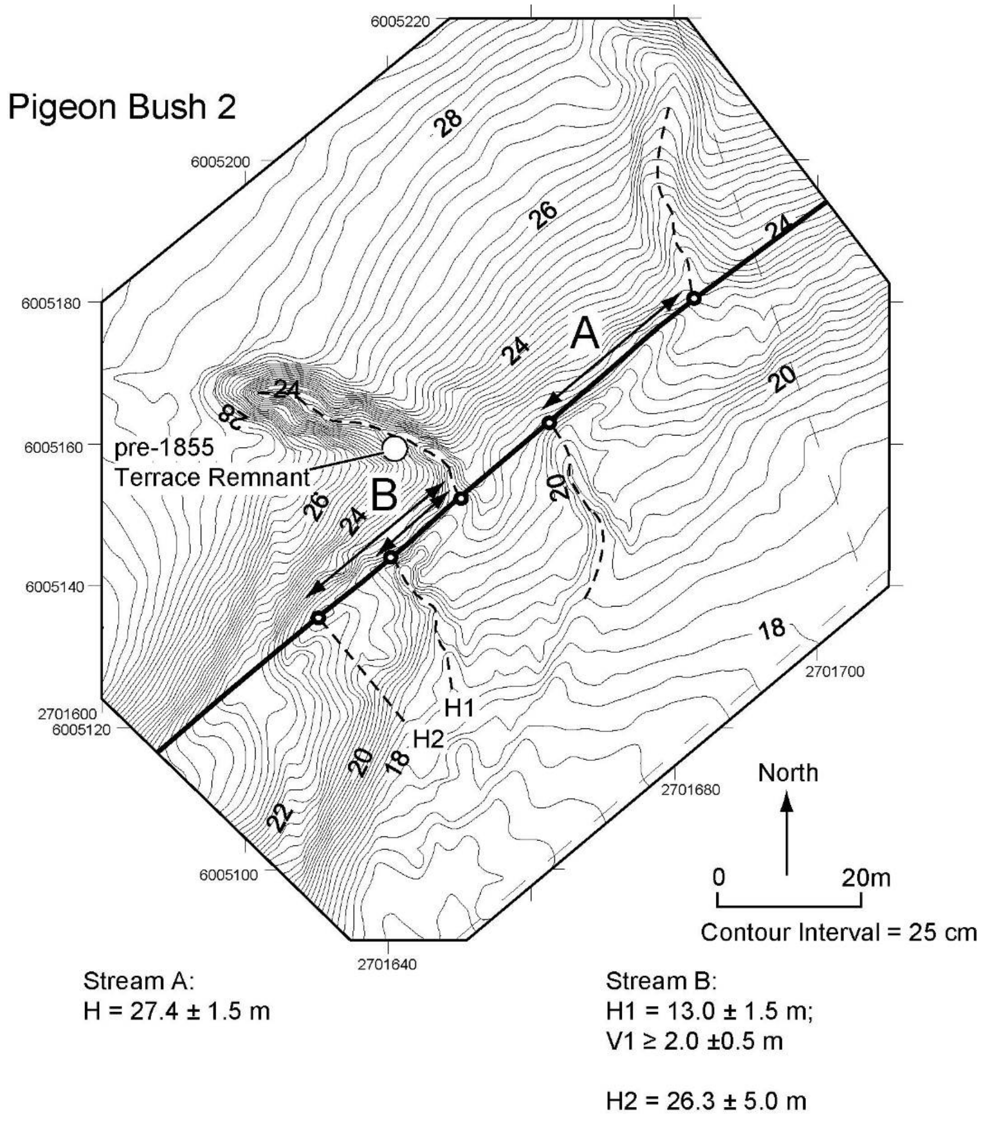


Fig. 11. *Topographic map of the Pigeon Bush 2 site, showing channels displaced (and in one case beheaded, channel H2) by slip on the Wairarapa Fault (from Rodgers and Little, 2006). See Fig. 9 for location.*

4.4.3. Pigeon Bush: STOP 3

41°08’28.35” S; 175°16’42.67” E.

Located about 300 m southwest of Pigeon Bush 1 (see Fig. 9) is site that Rodgers and Little (2006) described featuring a beheaded channel on the southeast side of the fault that has been dextrally offset relative to an active channel segment on the upstream side. At this locality (Pigeon Bush 3), the

Wairarapa Fault zone is ~50 m wide, comprising a 2-m-high, southeast-facing fault scarp to the southeast and a 2-m-high, northwest-facing fault scarp to the northwest (Fig. 12). The southeast strand is characterised by a linear, southeast-facing topographic step, though it is unclear whether this segment slipped in 1855. The northwestern strand is continuous with the main scarp at Pigeon Bush 1, is similarly fresh-looking, and crosses a small stream, and displaces a small river terrace. This stream is now partly dammed by a dextrally displaced shutter ridge.

The small stream that flows across the northwestern fault strand has been diverted northeastward around the shutter ridge. Southwest of this fault strand, a 0.75 to 2.0 m deep wind gap (abandoned channel) is incised into the shutter ridge at an elevation ~2 m higher than the current level of the stream. Restoration of the western edge of this inactive, beheaded channel segment on the southeast side of the fault with the (also inactive) terrace riser on the northwest side of the fault indicates a dextral-slip of 15.1 ± 1.0 m and vertical-slip of −1.8 ± 0.5 m (up to southeast) across this strand. Recent incision of the terrace remnant on the upstream part of the fault suggests that despite its downthrown sense of local relative motion, this northwest fault block was uplifted relative to sea level in 1855, similar to other sites on that side of the Wairarapa Fault.

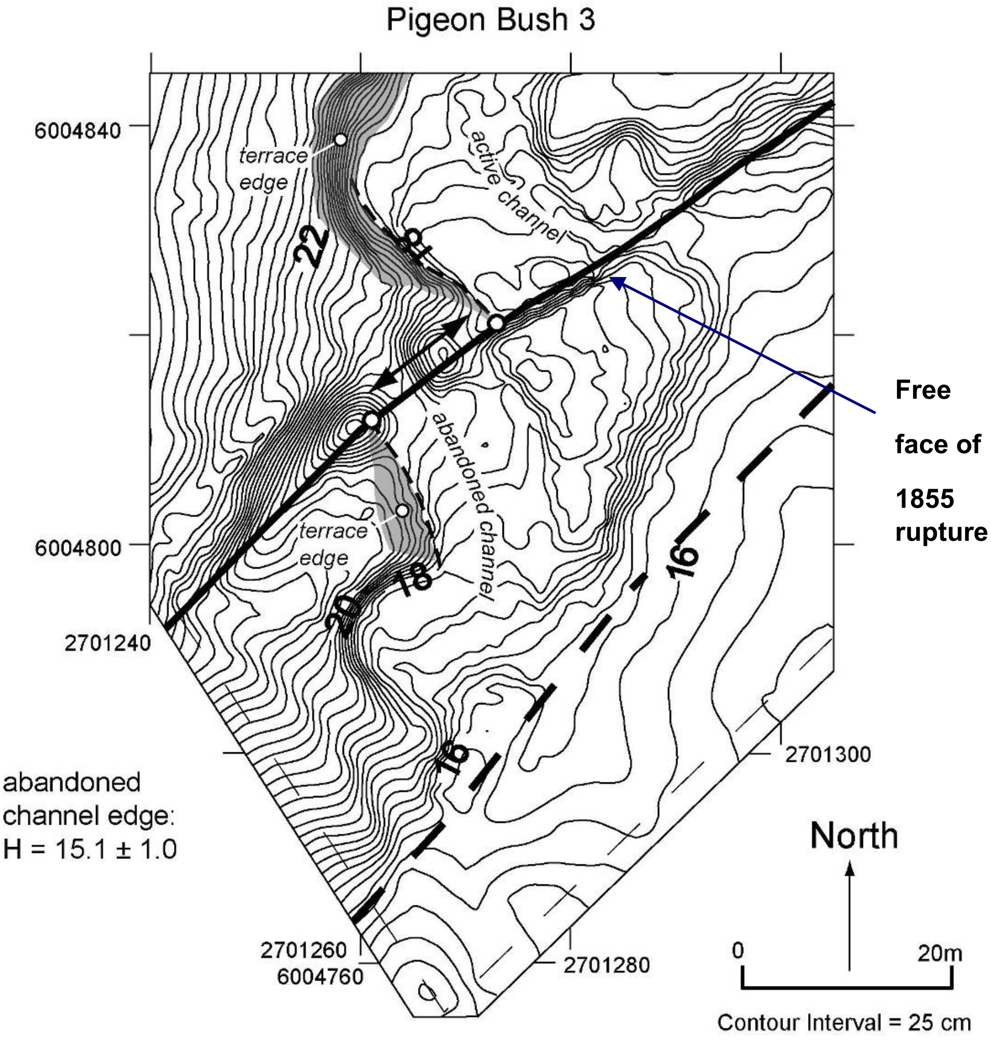


Fig. 12. *Topographic map of the Pigeon Bush 3 site, showing channels displaced by slip on the Wairarapa Fault. See Fig. 9 for location. From Rodgers and Little (2006).*

Between the offset (abandoned) channel and the active stream, an uphill-facing free face formed by the 1855 rupture plane is still remarkably well preserved. This near-vertical plane is only locally obscured beneath small fans of colluvial debris derived by the gravitational collapse of that free face during the past ~160 years.

5. THE DRIVE FROM LAKE FERRY TO CAPE PALLISER

Following lunch at the village of Lake Ferry, we travel east and south towards Cape Palliser or, to use the Māori name, Matakitaki-a-kupe (Fig. 13).

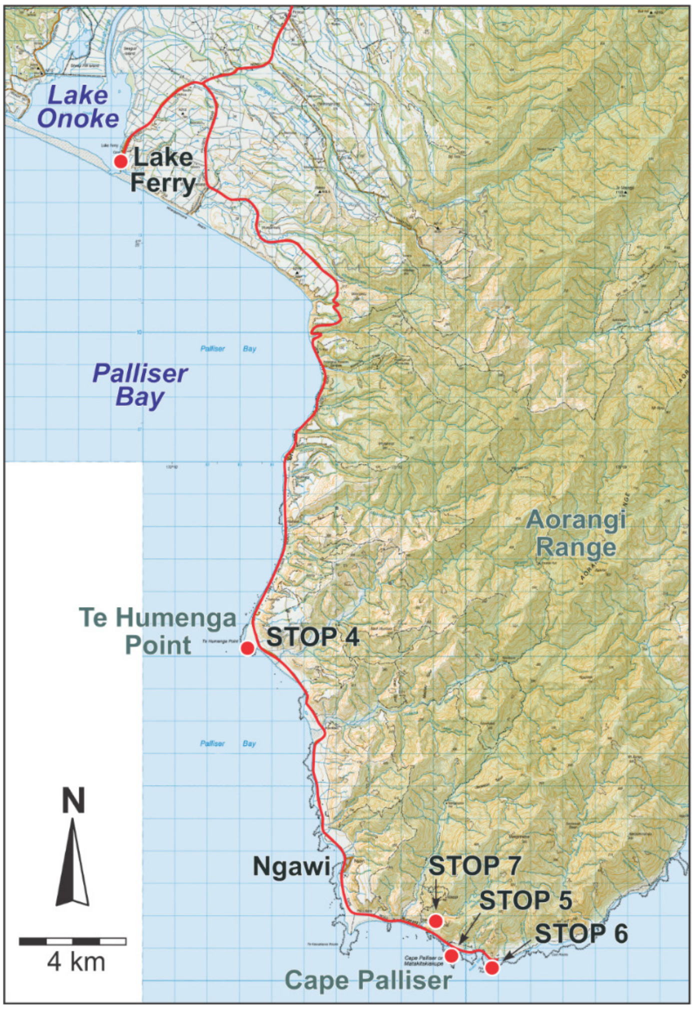


Fig. 13. *Locations of STOPS 4–7 on the southern Wairarapa coastline, and the route taken.*

On the drive southeast from Lake Ferry, the road rises up on a conspicuous, tilted terrace surface. This is the Marine Isotope Stage 5c wave-cut surface, dated to ~96 ka, that has been uplifted and tilted by ongoing deformation of the accretionary prism overlying the Hikurangi subduction zone. It is one of several such terraces in the region that have been dated and correlated in a recent study by Ninis (2018; Fig. 14). Each terrace comprises an ancient shore platform, overlain by thin marine deposits and thicker non-marine coverbeds, and bounded on the inland side by an ancient sea cliff. Based on data from these terraces, the highest uplift rate of 1.7 ± 0.1 mm/yr and maximum westwards tilting of 2.9° are observed in the east, close to Cape Palliser, and are inferred to indicate coseismic uplift resulting from megathrust earthquakes (Fig. 14; Ninis, 2018). In places, from this terrace and if visibility is clear, we catch views to the southwest of the Seaward and Inland Kaikōura ranges in the South Island. Mt Tapuae-o-Uenuku crowns the Inland Kaikoura Range, 140 km distant and 2885 m high, and comprises 100–94 Ma alkaline plutonic rocks.

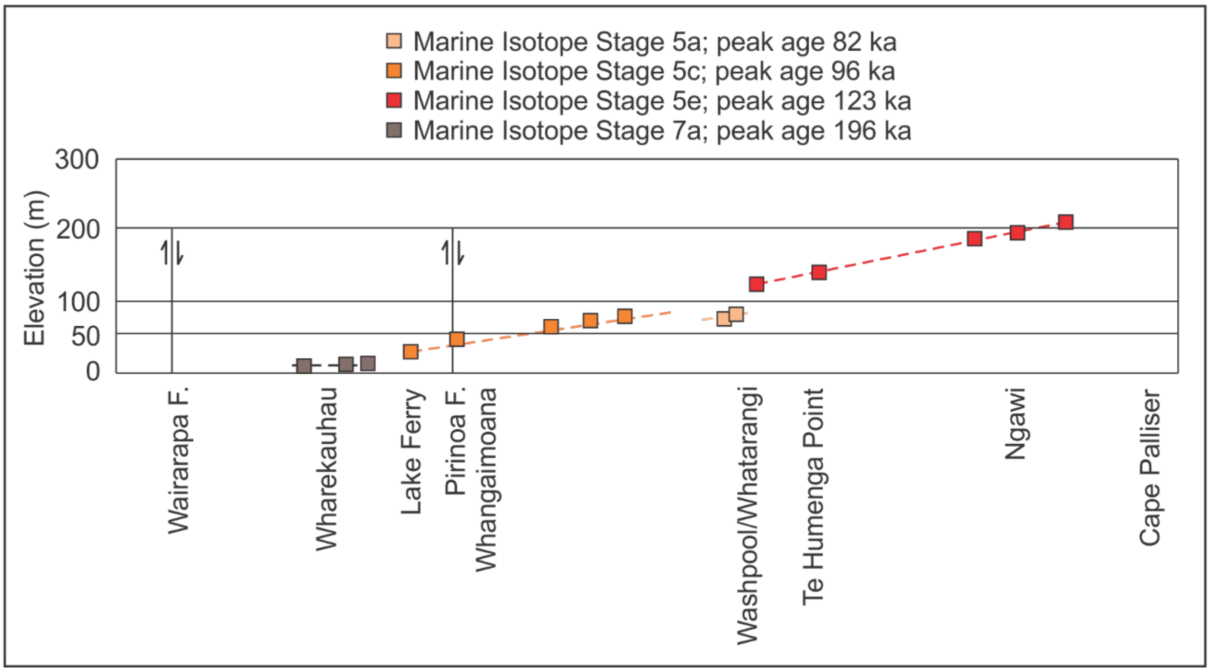


Fig. 14. *Elevation of uplifted and tilted wave-cut terraces between the Wairarapa Fault in the northwest and Cape Palliser in the southeast, adapted from Ninis (2018, fig. 3.11). The road east of our lunch stop at Lake Ferry rises up the Marine Isotope Stage 5c terrace.*

Fig. 15. *Tinky Winky on the beach at Ngawi. (Photo: J. S. Crampton.)*

On route to Cape Palliser, we pass through the fishing village of Ngawi, which hosts the highest ratio of tracked bulldozers to humans of any settlement on Earth (Fig. 15). This village is only the most recent of many along this coastline. Māori are believed to have settled here by about 1300 AD, but they apparently largely abandoned the area around 1600 AD, either due to a cooling climate, environmental degradation, the catastrophic effect of tsunami, or some combination thereof (McFadgen, 2007). The human population between Cape Palliser and Lake Ferry prior to 1600 AD is thought to have been small, perhaps on the order of 300 (McFadgen, 2003). Former occupation by Māori is marked today in many places by stone rows and storage pits. The stone rows are typically up to 2 m wide and 20–30 cm high; their function is unclear although they are certainly related to gardening in some way (McFadgen, 2003).

6. THE CAPE PALLISER AREA—DATING THE END OF CRETACEOUS SUBDUCTION: STOPS 4–7

6.1. Introduction

Cape Palliser lies at the southern end of the Aorangi Range and forms the southernmost point of the North Island (Fig. 13). Here, the Pahau Terrane includes pillow basalts and dikes that have been described by Challis (1960), George (1990, 1993), Grapes *et al.* (1992), and Kamp (2000). These rocks are important because they lie close to the eastern-most outcrops of undoubted Cretaceous accretionary prism, and they provide important evidence for the timing of cessation of Cretaceous subduction along the margin of Zealandia. Based mainly on revision of radiolarian determinations from George (1993) and modelling of zircon fission track ages, Kamp (2000) inferred a Late Cretaceous age for these rocks and that Cretaceous subduction in what is now southeastern North Island terminated within the interval 89–78 Ma. Recently and in contrast, available paleontological, detrital zircon, and geochronological data have been reassessed by Crampton *et al.* (submitted), who suggest that the youngest Pahau Terrane rocks in the southeastern North Island are ~100 Ma. Crampton *et al.* go on to infer that the weight of evidence does not support Late Cretaceous subduction along this sector of the Zealandian margin (see discussion in Introduction and below). We will view these rocks at STOPS 5 and 6.

Before we get to Cape Palliser, however, at STOP 4 we will view outcrops of Whatarangi Formation, which is inferred to represent fill of a trench slope basin that was deposited on top of the Pahau Terrane accretionary wedge.

6.2. Whatarangi Formation at Te Humenga Point: STOP 4

41°31’39” S; 175°11’44” E.

Note: low tide is at approximately 13:18.

On the western side of the Aorangi Range is a geographically-restricted, fault-bounded belt of moderately indurated and deformed, conglomerate, sandstone and mudstone that has been assigned to the Whatarangi Formation (Bates, 1969; George, 1992). Mollusc fossils suggest an age in the range of ~108–100 Ma (Speden, 1969). These rocks are regarded as distinct from the adjacent, more highly indurated and deformed Pahau Terrane, and are interpreted as the fill of a trench slope basin that formed on the Pahau accretionary wedge during the final stages of Cretaceous subduction (George, 1992; and see interpretation of STOPS 4–6, below). The basin is inferred to have lain between ridges of the actively deforming accretionary wedge, with sediment delivered via submarine canyons, and sediment flow both across and along the elongate basin (Fig. 16).

We will visit an outcrop of Whatarangi Formation that is exposed in the shore platform at Te Humenga Point (Fig. 13). Here, the formation comprises decimetre–metre interbedded sandstone and mudstone, with sole structures and partial Bouma sequences preserved in places.

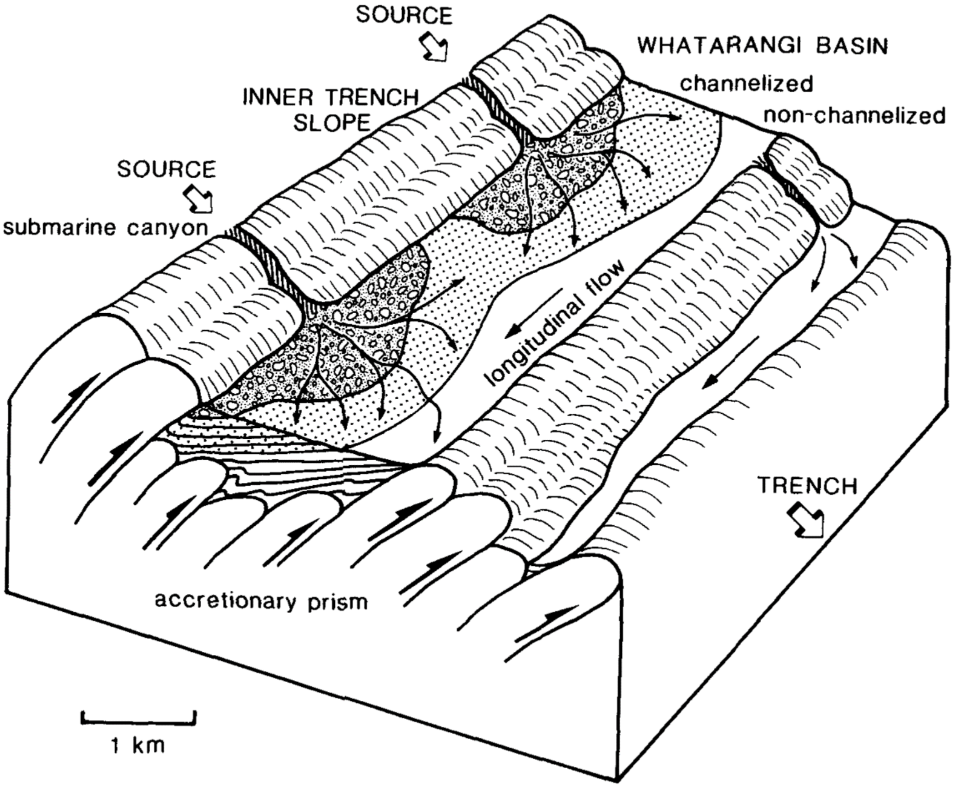


Fig. 16. *Schematic model for the deposition of the Whatarangi Formation, reproduced from George (1992, fig. 6).*

6.3. Cape Palliser Pillow Basalts: STOP 5

41°36’43” S; 175°16’25” E.

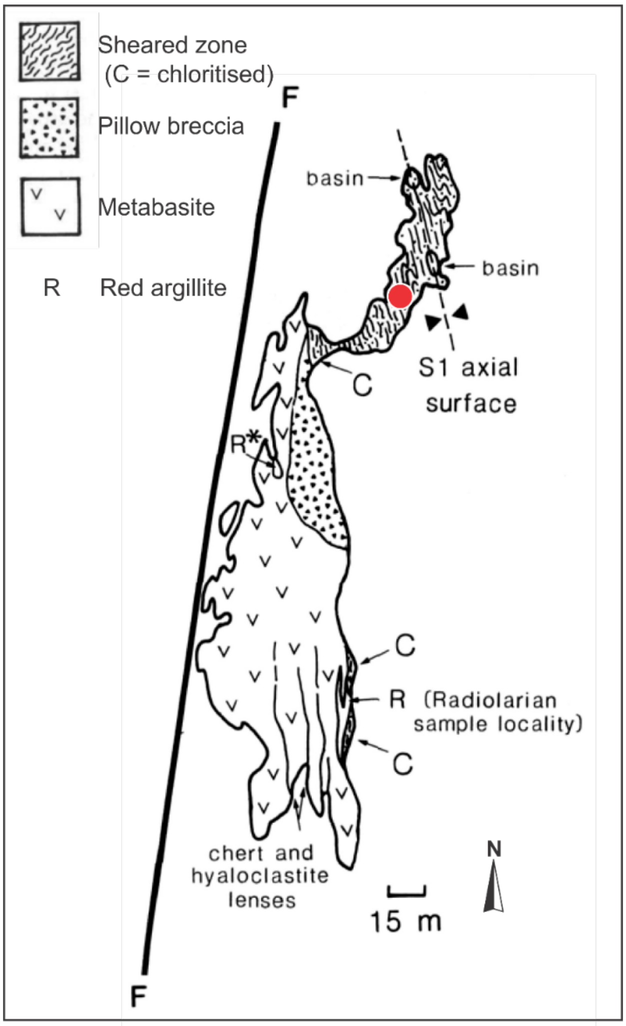
Note: low tide is at approximately 13:18.

WARNING: New Zealand fur seals (kekeno, *Arctocephalus forsteri*) are abundant at both STOPS 5 and 6, and there are many seal pups present. FUR SEALS BITE (and you *really* don’t want to be bitten by a fur seal)! Please stay close to your tour guides and do not approach any seals closer than 5 m. In addition, during a reconnaissance visit in mid-October, we observed a very large elephant seal at this locality. You will almost certainly NOT be able to actually touch the pillow basalts at STOP 5 because of the seals.

The headland ~1.4 km west of Cape Palliser preserves a succession of sheared sandstone and argillite, pillow breccia, and pillowed metabasite (Figs 17–19). Here, at the locality known to the local Māori tribe (iwi) of Ngāti Kahungunu as Matakitaki-a-Kupe, legend has it that Kupe, the great explorer, looked through a hole in the rocks and spied his daughter being carried off by a gigantic octopus (wheke) named Muturangi. At STOP 5, white rocks are said to symbolize Kupe’s tears, red rocks to represent blood spilt by mourners cutting themselves, and green rocks to symbolize snot that accompanies great mourning. The wheke was eventually chased into the Marlborough Sounds in the South Island where, following a great battle, Kupe succeeded in killing the monster.

Fig. 17. *Aerial oblique photograph of Cape Palliser, viewed from the west, showing STOPS 5–7. (Photo: S. N. Beatus, GNS Science, image 8941, taken in 1970.)*

At STOP 5, the eastern contact of the volcanic succession is irregular and concordant and is inferred to be the top contact; apparently overlying sandstone and argillite adjacent to the volcanic sequence are highly chloritized and deformed (George, 1993). The western contact is inferred to be faulted (ibid.). The bulk of the visible outcrop comprises green and red pillow metabasite; the following description is from George (1993, p. 188): "*The red metabasites generally display variolitic textures, which comprise elongate laths of albitised plagioclase feldspar … or plagioclase and acicular titaniferous augite in an altered groundmass of chlorite, hematite, and titanite …. The green metabasites display porphyritic textures with large, multiply-twinned plagioclase laths, relict titanomagnetite and ilmenite, and rare interstitial titaniferous augite …. Thin (1–2 m) layers and lenses of sedimentary rock (chert, argillite, and marble) occur throughout the metabasite. … Some of the pillows display well-developed chilled margins and radial cracks infilled with a green, calcareous interpillow material.*" Major and trace element compositions indicate that these volcanic rocks are likely to represent fragments of intra-plate seamounts that were incorporated into Pahau Terrane during accretion (George, 1993). Structural analysis of faults and folds in the Cape Palliser area led George (1993) to infer that the volcanic rocks were emplaced as a gravitational slide mass, rather than as a result of thrust faulting.



Age control for the rocks at STOP 5 comes from radiolarians that were extracted from a red argillite close to the eastern margin of the sequence (George, 1993) (Fig. 18). As noted elsewhere, the ages of these radiolarians have been subject to some uncertainty (cf. George, 1993; Kamp, 2000). Recent re-examination of these fossils now suggests that they are almost certainly Aptian in age (i.e., 125–113 Ma). In particular, figs 7.7, 7.8 and 8.12 of George (1993) are, respectively, reidentified here as *Campanomitra conica* (Nakaseko and Nishimura, 1981), *Parvimitrella communis* (Squinabol, 1903), and *Trimulus parmatus* O'Dogherty, 1994 (Luis O'Dogherty pers. comm. 2017; see Crampton *et al.*, submitted).

Further interpretation of the rocks at STOP 5, in the context of STOPS 4 and 6, is given below.

Fig. 18. *Geological map of STOP 5, adapted from George (1993, fig. 2.3). The red spot marks the approximate viewing position that we will visit.*

Fig. 19. *Pillow metabasite and pillow breccia at STOP 5. Photograph looking southwest and taken from location of red spot on Fig. 18. Figure stands on pillow breccia that is red-weathering in places; behind the figure, the most distant outcrops comprise pillow metabasite. Although not obvious, there are many fur seal pups in this field of view! (Photo: J. S. Crampton.)*

6.4. Cape Palliser dikes and sills: STOP 6

41°36’49” S; 175°17’26” E

Note: low tide is at approximately 13:18.

Thin dolerite and camptonite dikes and sills intrude Pahau Terrane in a number of places in the Cape Palliser area, and we will view some of these in the shore platform immediately below the Cape Palliser lighthouse (Fig. 17). At STOP 6, dolerite sills are highly deformed, disturbed, and associated with intraformational breccia, and in places they are broken into stringers and fragments that are incorporated into the breccia (Fig. 20). Challis (1960) inferred that this deformation reflected submarine slumping that resulted from intrusion of magma into relatively unlithified sediments close to the sea floor (and see interpretation of STOPS 4–6, below).

These dolerites are fine- to medium-grained, contain phenocrysts of altered oligoclase–andesine ($An_{30–32}$) and zoned pyroxene, in a matrix of chlorite, albite, calcite, minor quartz, and accessory epidote, ilmenite, magnetite, pyrite, apatite and biotite (Challis, 1960).

Fig. 20. *Dolerite sill at STOP 6. This sill is associated with intraformational breccia and is folded, boudinaged, and incorporated into enclosing breccia as stringers and fragments (right hand half of view). (Photo: J. S. Crampton.)*

In addition to the deformed sills described above, there are also compositionally similar dolerite dikes as well as camptonite dikes exposed on both the shore platform at Cape Palliser and in nearby streams that clearly post-date lithification and deformation of the enclosing sedimentary rocks (Challis, 1960; George, 1993). We will not get to view these dikes. One of these dikes has a whole-rock K–Ar age of 98.9 ± 3.2 Ma (George, 1993). In general, these undeformed dikes are considered to be mineralogically and chemically similar to, and genetically related to, intrusive alkaline igneous rocks exposed in Marlborough (e.g., the Tapuaenuku Igneous Complex, centred on the geographic feature Mt Tapuae-o-Uenuku mentioned above), which are dated to the interval between 100 and 94 Ma (Challis, 1960; George, 1993; and see Reay, 1993, and Baker *et al.*, 1994, for a description of the Tapuaenuku Igneous Complex and associated volcanics).

6.5. Interpretation of Cretaceous magmatic, depositional and tectonic events in the Cape Palliser area (STOPS 4–6)

Based on available evidence and previous studies summarized above, we suggest the following chronology for Cretaceous magmatic, depositional and tectonic events recorded in the Cape Palliser area.

1. 125–113 Ma: Seamounts were erupted onto the Hikurangi Plateau, and radiolarian-bearing argillites were deposited on and between pillow basalts. These rocks are now represented by pillow metabasite, pillow breccia, and argillite seen at STOP 5.
2. 125–100 Ma: Terrigenous clastic sediments of Pahau Terrane were deposited on submarine fans close to the convergent plate boundary at the margin of Gondwana, and subsequently accreted to the margin during subduction (George, 1990). Parts of the Pahau Terrane assigned to Pahaoa Group, which crops out to the north of Cape Palliser, apparently record contemporaneous sedimentation and accretion at the base of the inner trench slope (Barnes, 1988). The youngest detrital zircon populations within these accreted Pahau Terrane strata in the southeastern North Island are dated as ~100 Ma, (Crampton *et al.*, submitted, and references therein). During subduction, fragments of seamounts (STOP 5) on the margin of the Hikurangi Plateau were incorporated into the accretionary prism, possibly by gravitational sliding.
3. 108–~100 Ma: Strata of the Whatarangi Formation (STOP 4) were deposited within a trench-slope basin formed within the Pahau Terrane accretionary prism.
4. 100 Ma: Subduction along the Zealandian segment of the Gondwana margin ceased, probably following collision of the Hikurangi Plateau and consequent jamming of the subduction zone (Davy *et al.*, 2008; Davy, 2014; discussion in Crampton *et al.*, submitted).
5. ~100 Ma: Dolerite sills were intruded at shallow structural levels into the accretionary complex, causing slumping of unstable, poorly lithified sediments close to the sea floor (STOP 6).
6. 100–~94 Ma: Dolerite and camptonite dikes, which are inferred to be genetically related to compositionally similar igneous bodies in Marlborough, were intruded into deformed Pahau Terrane in what is now the Cape Palliser area.

7. KUPE'S SAIL BEDS IN LITTLE MANGATOETOE STREAM—MIOCENE SUBSIDENCE: STOP 7

41° 36′ 12″ S; 175° 15′ 57″ E

Time permitting, we will take a short walk up Little Mangatoetoe Stream (Fig. 17) to view the angular unconformity at the base of the Kupe's Sail Beds (Figs 21, 22). Here, Early Cretaceous Pahau Terrane is overlain with ~90° angular unconformity by late Miocene Kupe's Sail Beds (Begg and Johnston, 2000). Kupe's Sail itself, Nga-ra-o-Kupe, is a spectacular bedding plane exposure of the Miocene strata that are preserved as a small wedge between a fault in the west and the angular unconformity that strikes southeast, out to sea. Māori history records that Kupe and his companion Ngake were camped in the area and had a competition to see who could produce a sail ("ra") in the shortest time. Kupe won, and the sails were hung against the cliffs, where they can be seen to this day in the rock formation.

The Kupe's Sail Beds comprise mostly fossiliferous, concretionary, coarse to fine sandstone that was deposited about 11–7 Ma. There is conglomerate and breccia at the base, which infills several metres of erosional topography and contains large boulders of Pahau Terrane (Fig. 22). The total preserved section is 130 m thick, and the uppermost 10 m comprises impure bioclastic limestone. Fossils are mostly fragmentary and include barnacles, echinoids, bryozoans and brachiopods. These strata were deposited in shallow water, close to the paleo-shoreline.

The Kupe's Sail Beds record late Miocene subsidence and marine transgression across southern Wairarapa that resulted in eventual drowning of "Aorangi Island" by ~5 Ma (Bertaud-Gandar *et al.*, 2018). This paleo-island, comprising approximately what is now the Aorangi Range (see Fig. 7), was separated from mainland proto-New Zealand to the west by a precursor of the Pliocene, deep-water, "Ruataniwha Strait" that extended from Wairarapa northwards to Hawke Bay (Beu, 1995; see also Trewick and Bland, 2012).

Fig. 21. *Kupe's Sail viewed edge-on from the southeast, with rocks of Pahau Terrane in the foreground. Little Mangatoetoe Stream (STOP 7) is on the far side of Kupe's Sail. (Photo: B. Hines.)*

Fig. 22. *Angular unconformity at the base of the Kupe's Sail Beds in Little Mangatoetoe Stream (STOP 7). Kupe's Sail Beds on the left comprise Late Miocene, fossiliferous basal conglomerate and concretionary sandstone, and dip southwest (left) at 40°. Underlying Early Cretaceous Pahau Terrane dips northeast. (Photo: B. Hines.)*

8. CASTLEPOINT REEF—UPLIFTED CANYON FILL ON THE ACCRETIONARY PRISM: STOP 8

40°54'08" S; 176°13'46" E

Note: low tide is at approximately 14:31.

WARNING: This stop is located on top of a rocky reef that commonly experiences high wave energy and strong winds. Keep a watch for wave run-up and, if the rock is wet from waves, do not proceed. Move quickly to high ground if the sea suddenly recedes. Stay clear of the cliff edge.

Note also that Castlepoint is a reserve and fossil collecting is not permitted; please do not take your rock hammers onto the outcrop.

Shelly sandstones and coquina limestones are characteristic of the early Pleistocene (Nukumaruan Stage) succession in the Wairarapa and Hawke's Bay. These limestones are widespread and form prominent landforms, arguably the most famous of which are the Castle and Reef at Castlepoint (Figs 23, 24). The Maori name for Castlepoint is Rangi-Whakaoma, which means "where the sky runs".

Maori legend records that the gigantic wheke (octopus) Muturangi, mentioned above in relation to STOP 5, was initially startled by Kupe and his crew in the cave beneath Castlepoint lighthouse.

During the Plio-Pleistocene the paleogeography of the Wairarapa–Hawke's Bay was dominated by a shallow seaway, termed the Ruataniwha Strait (Fig. 25), bounded on the west by the early stages of the uplifting axial ranges. Parts of the Ruahine Ranges have Pleistocene limestones on their tops, indicating that the majority of uplift has occurred since ~2.4 Ma (Nicol *et al.*, 2007). East of the Ruataniwha Strait, the coastal ranges were largely submerged, with the highest emergent points forming an archipelago of small islands and outcroppings.

At first glance, the Castlepoint Formation appears to be a typical, early Pleistocene shallow marine coquina limestone. However, detailed analysis of molluscan faunas indicate that the Castlepoint Formation is comprised of mixed cool- and warm-water taxa, and outer shelf and shallow water taxa (Buckeridge *et al.*, 2018). Additionally, sedimentological evidence includes fluid release structures, displaced blocks, soft sediment folding, large load casts and steep original dips, and suggest that the formation was remobilized from a shallow marine setting and deposited in a shelf-edge submarine canyon head (Buckeridge *et al.*, 2018). Therefore, the Castlepoint Formation effectively represents *in situ* canyon fill.

The geology of Castlepoint has been described in detail by Johnston (1973, 1980) and van der Lingen *et al.* (1985) (and see Homer and Moore, 1989). The Reef and The Castle consist of interbedded coquina limestone and shelly sandstone (Castlepoint Formation, basal Nukumaruan (earliest Pleistocene); Figs 10, 11) resting unconformably, across an incised and channelized contact, on poorly-bedded grey sandstone and siltstone of the Opoitian (early Pliocene) Rangiwhakaoma Formation (Fig. 24). The unconformity is exposed at beach level on the embayment side of the reef at low tide.

Fig. 23. *Locations of STOPS 8–10 on the Wairarapa coastline.*

Fig. 24. *Aerial view of Castlepoint, looking south across The Reef towards The Castle (high point in middle distance), both of which consist primarily of early Pleistocene Castlepoint Formation coquina, limestone, and calcareous sandstone. The mudstone-dominated early Pliocene Rangiwhakaoma Formation, into which the Castlepoint Formation has been incised, is exposed around the lower slopes of The Castle (grey exposures). The western (right-hand-side) face of The Castle represents a faulted contact, which separates the Castlepoint and Rangiwhakaoma formations from early Miocene Whakataki Formation turbidites. (Photo: D. L. Homer, GNS Science, image 4979.)*

The Castlepoint Formation consists primarily of barnacle plates, bryozoans, larger shells and pebbles, and some distinct shellbeds (Fig. 26). Large sedimentary clasts, some boulder-sized, are bored. These, the channeling, intraformational slumps, and large load structures indicating significant fluidisation, suggest some of the limestone was deposited by mass flows (Fig. 27). Deep-water macrofossils at this locality suggest the limestones are deep-water mass flow deposits. It is thought that the Castlepoint Formation was deposited at the head of a submarine canyon that was similar in character to those presently incising the modern continental shelf just offshore of this site.

One mollusc of note within the formation is scallop *Zygochalmys delicatula* (Fig. 26). This species is extant and lives in 400 m water depth off the Otago coast. However, temperature, rather than water depth is the controlling factor in the distribution of this pecten. An influx of this pecten marks the base Nukumaruan (base Pleistocene) throughout the Hawke's Bay–Wairarapa, signaling a ~4 °C drop in annual sea temperature, marking the onset of significant Pleistocene glaciation (Beu, 1995).

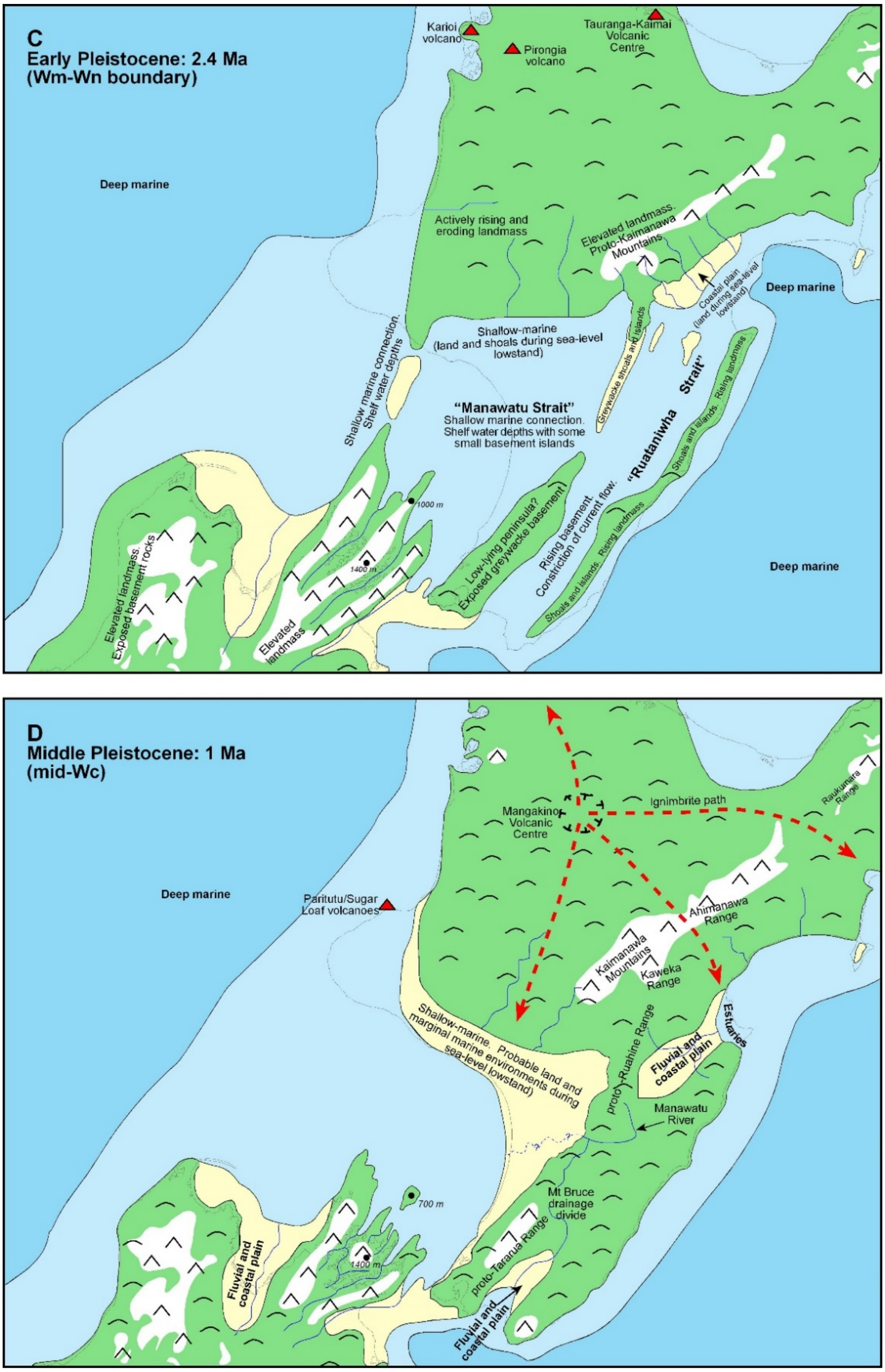


Fig. 25. *Simplified paleogeographic maps of central New Zealand from Trewick and Bland (2012: top, 2.4 Ma; bottom, 1 Ma) illustrating inferred land area (green), areas potentially >1000 m (white), coastal land (light yellow), shelfal water depths (0–200 m; light blue) and deep marine environments (>200 m; dark blue), relative to the modern New Zealand coastline. Inverted "Vs" indicate potential mountains, lower symbols indicate hills. Red dashed arrows indicate general ignimbrite paths from the Mangakino volcanic centre. Wm, Mangapanian (3.0–2.4 Ma); Wn, Nukumaruan (2.4–1.63 Ma); Wc, Castlecliffian (1.63–0.34 Ma).*

Fig. 26. *Shelly early Pleistocene (~2.4 Ma) limestone of the Castlepoint Formation, exposed at The Reef, here containing abundant fossils of the scallop* Zygochlamys delicatula*, with a few specimens visible of* Phialopecten triphooki *and the oyster* Ostrea chilensis*, and fragmented infaunal bivalves, barnacles, etc. (Photo: J. S. Crampton.)*

Fig. 27*. Slump-bedded and deformed fossiliferous limestone and sandstone beds within the Castlepoint Formation. (Photo: J. S. Crampton.)*

9. WHAKATAKI FORMATION—MIOCENE SLOPE BASIN FORMED AT THE INITIATION OF SUBDUCTION: STOPS 9–10

WARNING: STOPS 9 and 10 are tide-dependant stops along a shore platform that can experience high wave energy. Keep a close watch for wave run-up. Move quickly to high ground if the sea suddenly recedes. Take care on the slippery and uneven shore platform.

9.1. Introduction

Just to the north of Castlepoint (Fig. 23) we will view two shore platform exposures of Whakataki Formation, first described by Johnston (1973) from the Castlepoint area. This is an early Miocene unit that crops out extensively in eastern and central parts of Wairarapa (e.g., Lee and Begg, 2002), and in places is up to 1000 m thick. It comprises interbedded sandstone and mudstone (STOP 9) and, particularly towards the base, pebbly mudstone, chaotic conglomerate, and olistostrome deposits (STOP 10). At the two sites visited here, the unit was deposited in a bathyal environment based on foraminifera (Hugh Morgans, 1995, unpublished data). Precise biostratigraphic age control is difficult to establish as faunas appear to have been winnowed and to contain older, reworked elements.

Based on structural and stratigraphic mapping both onshore and offshore, Bailleul *et al.* (2007, 2013) inferred that the exposures of Whakataki Formation in the coastal strip north of Castlepoint were deposited on submarine fans within a trench-slope basin that was formed on the lower part of the accretionary prism at the same time as, or shortly after, the onset of rapid subduction on the modern Hikurangi subduction zone (Fig. 28; Bailleul *et al.*, 2007, 2013). Olistostromes low in the formation represent submarine reworking along the eastern margin of structural highs produced by active thrusting on the Whakataki Fault that runs parallel to the coast and just inland (west) of the outcrops visited. Geographically separated occurrences of Whakataki Formation further inland and to the north are inferred to have been deposited in separate trench-slope basins located between other active thrust faults (Fig. 28). From consideration of early Miocene to Pliocene formations across the region, Bailleul *et al.* (2013) suggested that the subduction wedge evolved in a discontinuous manner, with four discrete tectonic episodes: early Miocene seaward-directed thrust sheet emplacement; early to middle Miocene east–west contraction; middle to late Miocene tectonic erosion that resulted in upslope subsidence; and finally latest Miocene to Recent pulses of east–west to northwest–southeast shortening and overall uplift of the coastal ranges.

9.2. Te Wharepouri Mark: STOP 9

40°51’27” S; 176°14’30” E

Note: low tide is at approximately 14:31.

At this stop we examine a spectacular shore platform exposure of Whakataki Formation (Figs 29, 30). Here it consists almost entirely of alternating sandstone and mudstone turbidites that display good Bouma sequences dominated by intervals T_b and T_c (Fig. 31). On average, the formation comprises between ~70 and 80% sandstone. Features at Te Wharepouri Mark locality include well-developed climbing ripples (Fig. 31), suggesting a high rate of sediment supply during deposition, lateral continuity of beds that can be traced along strike for up to 500 m (Figs 29, 30; Edbrooke and Browne, 1996), and apparent cyclicity of bed thickness in packets ~1 m and perhaps 14 m thick (Field, 2005).

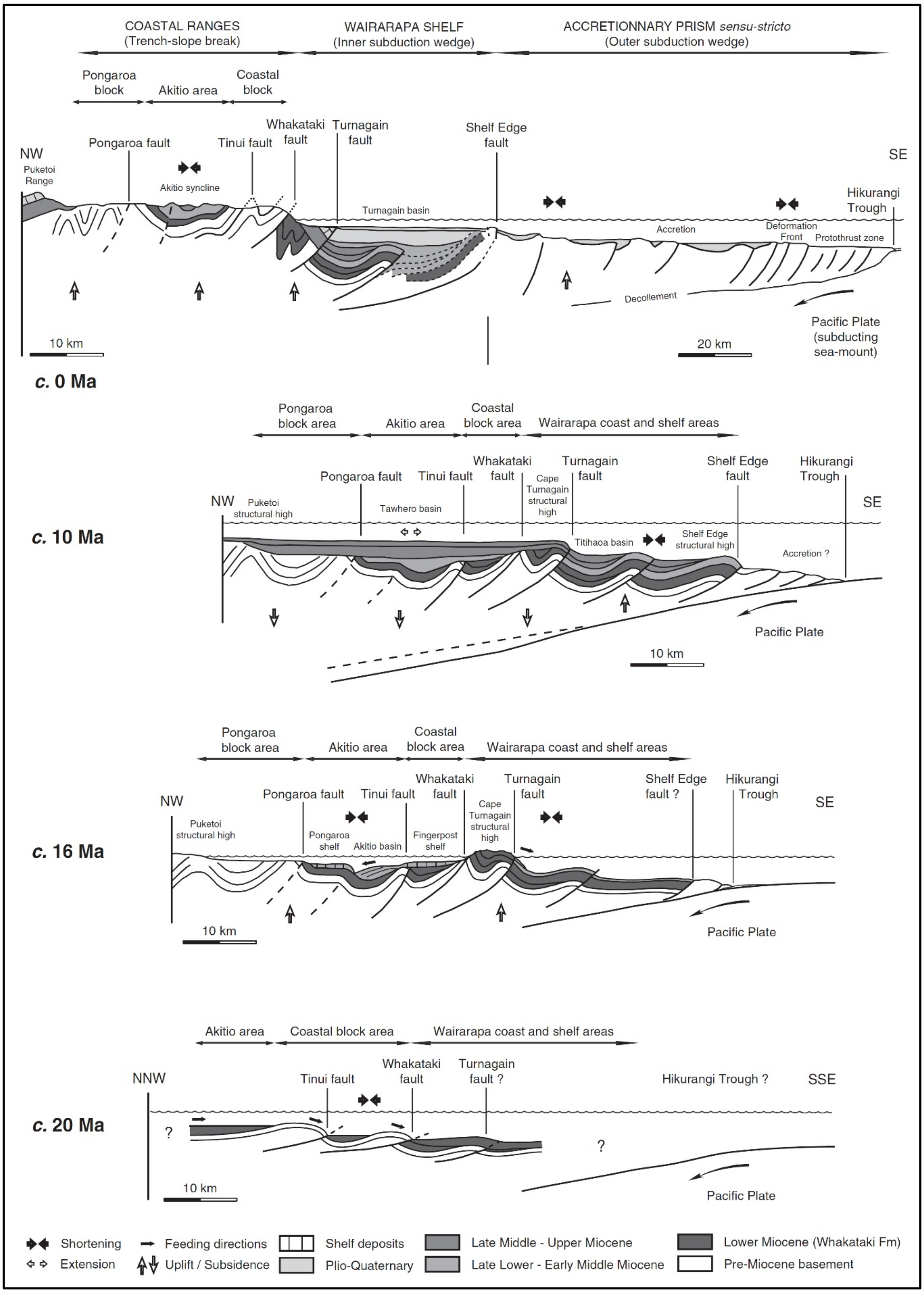


Fig. 28. *Schematic cross-sections through the Hikurangi Margin at about the latitude of modern-day Castlepoint, illustrating the Neogene tectonic evolution of the margin since onset of subduction. Outcrops examined here—STOPS 9 and 10—lie immediately to the east of the Whakataki Fault. Reproduced from Bailleul et al. (2013, fig. 13).*

Whakataki Formation at this locality has been subject to several sedimentological studies because of the wonderful exposure and because it forms one of the most widespread and promising hydrocarbon reservoirs in the East Coast Basin. The formation provides an analogue for gas-bearing thin beds at the Titihaoa-1 well site, drilled a few kilometres offshore from here, and also for the fill of the many similar accretionary slope basins in this region. At Te Wharepouri Mark, Whakataki Formation is inferred to have been deposited in a medial to distal levee-overbank setting (Field, 2005).

Fig. 29. *Aerial photograph, taken with a drone, of the shore platform at Te Wharepouri Mark, showing the spectacular exposure of early Miocene Whakataki Formation. Three figures in centre of view give scale. (Photo: N. Neiminski.)*

Fig. 30. *Thin-bedded turbidites exposed in the shore platform at Te Wharepouri Mark. The Reef and The Castle are visible on the horizon. (Photo: K. J. Bland.)*

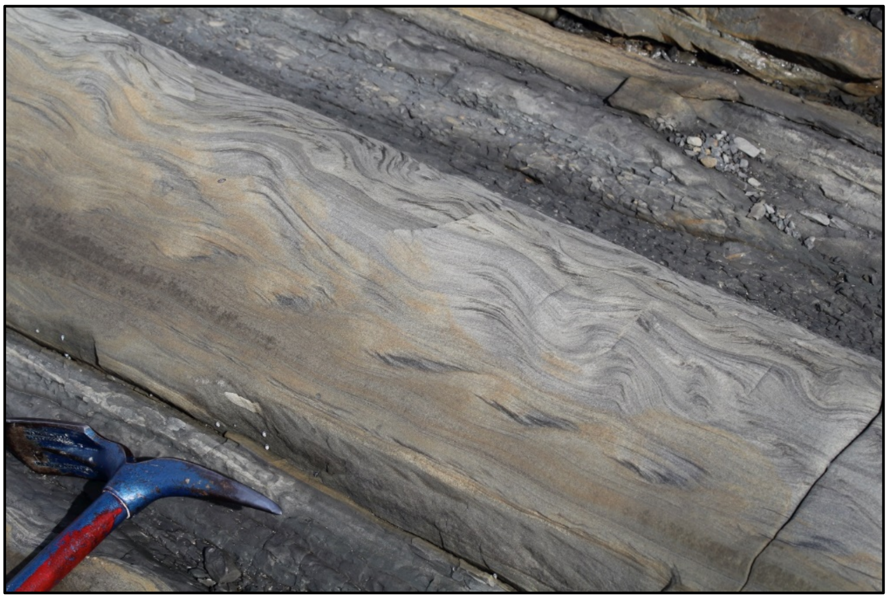


Fig. 31. *Decimetre-thick sandstone bed, interbedded with mudstone facies. The sandstone displays well-developed Bouma-style structures, including prominent ripple laminated and climbing-ripple sedimentary structures. (Photo: K. J. Bland.)*

9.3. Suicide Point: STOP 10

40°48’42” S; 176°15’30” E

Note: low tide is at approximately 14:31.

This section, located on the coast 5 km north of Te Wharepouri Mark (Figs 23, 32), comprises a shore platform that exposes a chaotic mixture of lithofacies and lithologies of different ages sitting within a sheared mudstone matrix (Fig. 33). The exposure is interpreted to be an olistostrome deposit. Lithologies characteristic of the Whangai, Waipawa, Wanstead, Weber, and Whakataki formations can all be viewed at this site. However, it is often difficult to determine which rocks are stratigraphically *in situ*, and which are part of the olistostrome (e.g., Fig. 34). Similar packages of multiple lithologies, such as this one, are common along coastal parts of the East Coast region (e.g., Delteil *et al.*, 2006), and are likely to be present in many parts of the offshore East Coast Basin. Their formation and emplacement at Suicide Point and elsewhere may relate to collapse of hangingwall blocks associated with thrust-faulted ridges in a growing accretionary prism (see Section 9.1).

There has been debate as to the age of emplacement of this olistostrome, with some believing it to be late Eocene to early Oligocene in age, and others interpreting it as earliest Miocene, and marking the onset of Neogene subduction on the Hikurangi Margin. Foraminifera faunas extracted from the olistostrome provide a late Eocene (Bortonian; ~40 Ma) age, although these are likely reworked (Morgans, pers. comm.). The overlying early Miocene age (18.7–15.9 Ma) Whakataki Formation provides an upper constraint for olistostrome emplacement. Delteil *et al.* (2006) have demonstrated that the olistostrome interfingers with the Whakataki Formation near Mataikona, supporting an early Miocene age for deposition, and the olistostome is now generally regarded as part of the Whakataki Formation and to have been shed from the adjacent Whakataki Fault scarp lying just to the west (see interpretation in Bailleul *et al.*, 2013).

At Suicide Point, the Whakataki Fault approximately follows the road, parallel to the coast. Formations exposed on the western side of the fault span the Late Cretaceous to Oligocene, passive margin succession, comprised of the Glenburn Formation, the Rakauroa and Upper Calcareous members of the Whangai Formation, Waipawa Formation, Wanstead Formation and Weber Formation.

Fig. 32. *View across the shore platform and olistostrome succession at Suicide Point, looking north towards Mataikona. (Photo: K. J. Bland.)*

Fig. 33. *Folded and chaotic beds and clasts within the olistostrome exposed in the shore platform at Suicide Point. (Photo: K. J. Bland.)*

Fig. 34. *Whangai Formation cropping out at Suicide Point. It is uncertain whether this interval of Whangai Formation is in situ, whether it is a megaclast within the olistostrome, or if it is part of the coastal fault zone. (Photo: K. J. Bland.)*

10. DAY 3

On DAY 3 of the field trip, we will combine with Field Trip 5, led by Jarg Pettinga and Carolyn Boulton, and entitled "*Structural Styles and Deformation Fabrics of an Emergent Accretionary Ridge, Hikurangi Margin, Southern Hawke's Bay: from broken formation and dismembered units to tectonic mélange*". We will travel to the Waimarama area, southern Hawke's Bay, and examine features along the coastline. For information, refer to the Field Trip 5 guide.

11. ACKNOWLEDGMENTS

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