GeoSciences 2015

Annual Conference of the
Geoscience Society of New Zealand

Victoria University of Wellington
25th-27th November 2015

Field Trip Guides

ZEALANDIA IN SPACE AND TIME

GEOSCIENCES 2015

GEOSCIENCE SOCIETY OF NEW ZEALAND

25th-27th November Wellington

Field Guides

Conference Convenor

Mike Hannah (Victoria University)

Organising Committee

Brent Alloway, Cliff Atkins, Katie Collins, Monika Hanson, Huw Horgan, Robert McKay, Kevin Norton, Martha Savage, Miranda Voke, Colin Wilson (Victoria University), James Crampton (Victoria University / GNS Science), Christian Timm (GNS Science)

Administration

Janet George (Absolutely Organised Ltd.)

Field Trip Leaders

Kevin Norton, Cliff Atkins, Dene Carroll, Tim Little, Dee Ninis, Ben Hines (Victoria University), Russ Van Dissen, Nicola Litchfield (GNS Science)

Geoscience Society of New Zealand

The bibliographic reference for field guide is:

Author, A.N. (2015). Title of Field Trip. In: Atkins, C., (ed) Field Guides Geosciences 2015, Wellington, Geoscience Society of New Zealand Miscellaneous Publication 143b.

ISBN 978-1-877480-50-8
Geoscience Society of New Zealand Miscellaneous Publication number 143b
Print ISSN 2230-4487
Online ISSN 2230-4495

FIELD TRIP 4

Paleogene Stratigraphy and Paleoenvironment of the Tora Coast

Ben Hines[1,2]

[1]Victoria University of Wellington
[2]GNS Science, Lower Hutt

Frontispiece: Aerial view looking southwards down the Tora coastline. Lloyd Homer/GNS Science.

Trip Summary

This field trip showcases the stratigraphy of the wild and rocky coast at Tora, southeast Wairarapa. The Paleocene-Eocene (65–40 Ma) stratigraphy of the Tora area is substantially different from the remainder of the largely homogenous siliclastic sediments of the East Coast Basin. The extensively deformed stratigraphy of the Tora and Coastal Blocks in the eastern Wairarapa Coast effectively represents the onshore expression of the accretionary wedge associated with subduction of the Pacific Plate beneath the Australian Plate (Figure 1). At our first stop, we examine the Late Cretaceous Glenburn Formation, working our way up the stratigraphic sequence in Pukemuri Stream to the K/Pg Boundary and the Earliest Paleocene Awhea Formation, before moving to our second locality at Manurewa Point. At Manurewa Point, we pick up again at the K/Pg Boundary, highlighting the lateral variability in lithofacies at this horizon, before continuing up the sequence to the Mungaroa Limestone, and a potential correlative of the Waipawa Formation, a late Paleocene source rock of substantial interest in the East Coast and Pegasus basins. The third stop (tide dependant) is at Stingray Bay, near Hungaroa Stream, where the faulted contact between the late Eocene Wanstead Formation and the mid-Cretaceous Mangapokia Formation can be observed. Finally, a fourth stop examines the Mangapokia Formation near the Oterei River Mouth.
In summary, we aim to demonstrate and understand some of the complexities in the late Cretaceous to Late Eocene stratigraphy of the Tora Block, and correlations with the wider East Coast Basin.

Introduction

This guide provides notes on the Upper Cretaceous-Paleogene stratigraphy and structure of coastal southeast Wairarapa. The Upper Cretaceous and Paleogene stratigraphy of the Tora-White Rock area has general similarities with the rest of the East Coast Basin (Field et al., 1997) but also has some significant differences. We will view a general fining upwards trend of marine sediments from Upper Cretaceous Glenburn Formation (alternating sandstone and mudstone) to Cretaceous-Paleocene Whangai Formation (siliciclastic mudstone) to Eocene Wanstead Formation (calcareous mudstone). These units are found throughout the East Coast Basin, however, between the Whangai and Wanstead formations, we find five units that are restricted to the Tora area: Manurewa, Awhea, Mungaroa Limestone, Awheaiti and Pukemuri Siltstone formations. These formations exhibit considerable variation in thickness and lithologic character and suggest a dynamic depositional environment within or adjacent to a submarine fan system in a deep water setting (Hines et al., 2013). This sequence may be the closest onshore analogue for the sediments deposited in the offshore Pegasus Basin (Uruski & Bland, 2011). The aim of this trip is to give a taste of East Coast Cretaceous-Paleogene stratigraphy and to highlight this variation of sedimentary facies within a 5 km stretch of coastline.

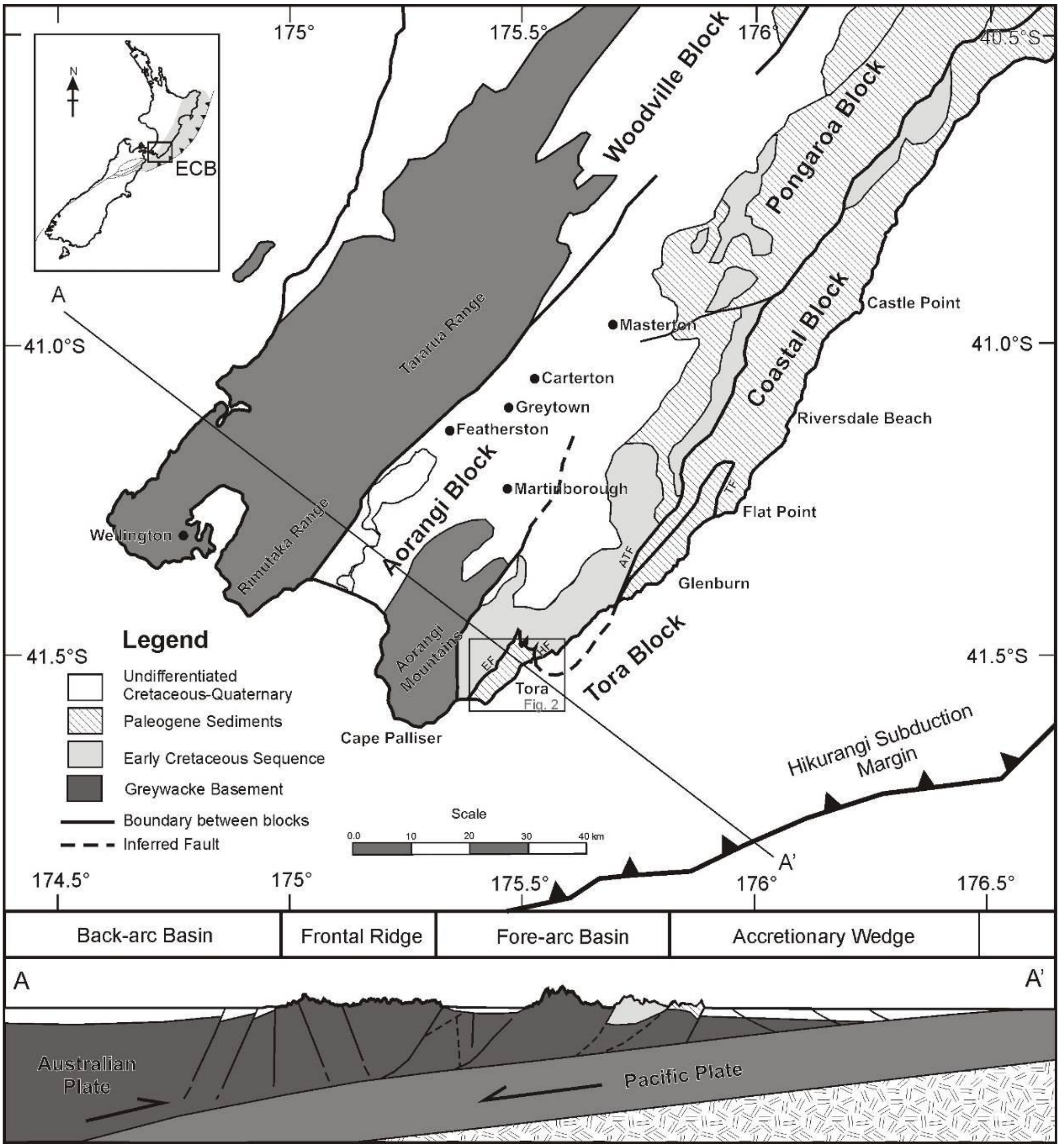

Figure 1: Simplified geological map and structural setting of the southern North Island, New Zealand, and schematic cross-section (From Hines et al., 2013; *after* Moore, 1988a; Little *et al*., 2009). Key to acronyms: ECB = East Coast Basin, EF = Ewe Fault, HF = Hungaroa Fault, ATF = Adams-Tinui Fault, TF = Tutu Fault.

Regional Stratigraphy

Passive margin thermal subsidence following the Late Cretaceous Rangitata Orogeny resulted in an overall fining-upwards succession from Cretaceous sandstone to Paleocene–Eocene mudstone and muddy limestone in the East Coast Basin (Field et al., 1997). Distinct contrasts in the stratigraphy and structure were recognised and utilised by Moore (1986, 1988a) to propose the division of the East Coast Basin into structural blocks. These blocks are grouped into the Western Sub-belt and the Eastern Sub-belt.

In the southern North Island, the Western Sub-belt consists of the Aorangi, Woodville and Pongaroa Blocks (Figure 1). The Eastern Sub-belt is subdivided into the Coastal and Tora Blocks, which are approximately analogous to the narrow (≤10 km wide) onshore expression of an accretionary wedge (Figure 1). Post-Oligocene east–west orientated compression associated with the Kaikoura Orogeny, in conjunction with westward-dipping thrust faulting, has resulted in complex folding and faulting relationships in the Tora and Coastal Blocks (Moore, 1988a; Berryman et al., 2011). The onshore exposure of the Tora Block is separated from the Pongaroa and Coastal Blocks by the Ewe, Hungaroa, Tutu and Adams-Tinui Fault systems (Figures 1 & 2). The eastern and southern extent of the Tora Block is undetermined, but seismic mapping and modelling (Barnes et al., 2010; Berryman et al., 2011) suggest that a significant thrust system lies close to the Tora-Glenburn coast. The upper Cretaceous strata of the Tora Block are considered laterally continuous with the Coastal Block to the north (Crampton, 1997; after Moore et al., 1986), with the Tora Block distinguished primarily by facies differences in the Paleogene sediments.

The Cretaceous to Eocene stratigraphic succession exposed at Tora has been divided into nine formations (Figures 2, 3 & 4). The late Cretaceous–Paleogene stratigraphy is divided into eight lithostratigraphic units overlying early to mid-Cretaceous Torlesse Supergroup basement (primarily the Mangapokia Formation).

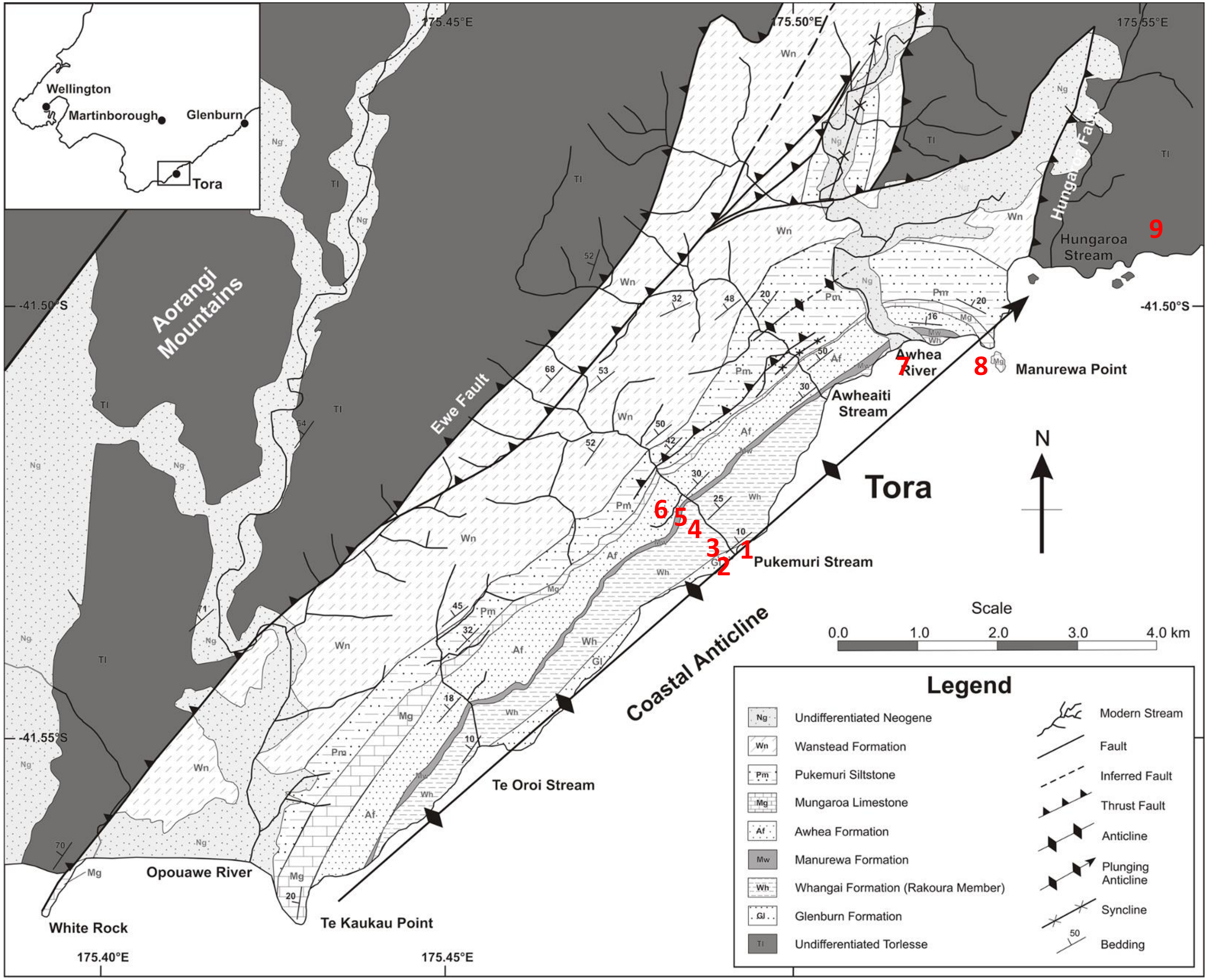

Figure 2: Geological map of the Tora area (Hines et al. 2013). Fieldtrip stops indicated by red numerals.

The **Mangapokia Formation** of the Pahaoa Group represents the youngest component of the Mesozoic accretionary complex, and is an extensively sheared, indurated sequence of flysch, sandstones, argillites and conglomerates.
The **Glenburn Formation** consists of alternating conglomerate, sandstone and mudstone deposited in a submarine fan setting. Only the upper part of the formation is exposed at Tora.
This is overlain by the Rakauroa Member of the **Whangai Formation**. It consists of siliceous non-calcareous mudstone with sparse calcareous concretions. Foraminifera indicate deposition at shelf depths and dinoflagellates indicate a Late Cretaceous age (Laird et al. 2003).

The **Manurewa Formation** represents renewed fan progradation and includes an interesting record of the K/T boundary that can be seen at Pukemuri Stream and Manurewa Point.
The **Awhea Formation** is relatively thick unit of a fining upwards alternating sandstone and mudstone succession that represents mid-fan turbidite deposition in the Early Paleocene, and contains extensive bioturbation.

The **Mungaroa Limestone** is a calcareous mudstone to micritic limestone that resembles the Mead Hill Formation in Marlborough. In places the formation displays extensive soft sediment deformation and frequent greensand dikes and sills. Towards the top of the unit there is a potential correlative of the Waipawa Formation, an important petroleum source rock in the East Coast Basin. Here, as at Mead Stream in Marlborough, the unit lies within a micritic limestone succession. This is quite different from the typical East Coast facies association, which more commonly lies between siliciclastic units such as the Whangai and Wanstead Formations. The Mungaroa Limestone is Middle to Late Paleocene in age.
The Late Paleocene **Awheati Formation** is a variable unit that unconformably overlies the Mungaroa Limestone in Te Oroi and Pukemuri Streams but is absent in Awheati Stream (Figure 4). It varies from cross-bedded sandstone to thin-bedded mudstone and is interpreted to be a submarine channel-fill deposit.

The **Pukemuri Siltstone** is a pebbly mudstone that unconformably overlies the Aheaiti Formation and Mungaroa Limestone (Figure 4). Many of the pebbles appear to be derived from underlying Cretaceous and Paleocene lithologies (hard mudstone, chert and micrite). Pebbles are most common at the base of the unit, which grades up into a weakly bedded calcareous mudstone. The lower part of the unit is inferred to be a debris flow deposit, potentially situated within a broad submarine channel. The upper calcareous mudstone may represents bathyal background deposition at the margin of the channel/fan system. The Mangaorapan (late Early Eocene) age of the Pukemuri Siltstone makes it of particular interest for paleoclimate research. The Mangaorapan is correlated with a prolonged episode of global warmth termed the Early Eocene Climatic Optimum (EECO, ~53–49 Ma). South Island studies have found the New Zealand sea surface temperatures (SSTs) rose to close to 30°C at this time. Mg/Ca ratios from foraminifera in the Pukemuri Siltstone indicate SSTs in Tora area during the EECO reached ~27°C and water at the bathyal sea floor (~1000 m water depth) reached ~16°C (Hines et al. *in prep*). These values are equivalent to those previously recorded for Canterbury Basin (Hollis et al., 2012) and the SSTs are ~15°C warmer than present day.

The **Wanstead Formation** unconformably overlies the Pukemuri Siltstone and also has a pebbly base that may represent a submarine debris flow. This unit grades up into more typical Wanstead Formation, which is a smectite-rich calcareous mudstone. Elsewhere the Wanstead Formation ranges from Paleocene to Late Eocene age; although here it is exclusively Middle to Late Eocene age (Bortonian to Kaiatan).

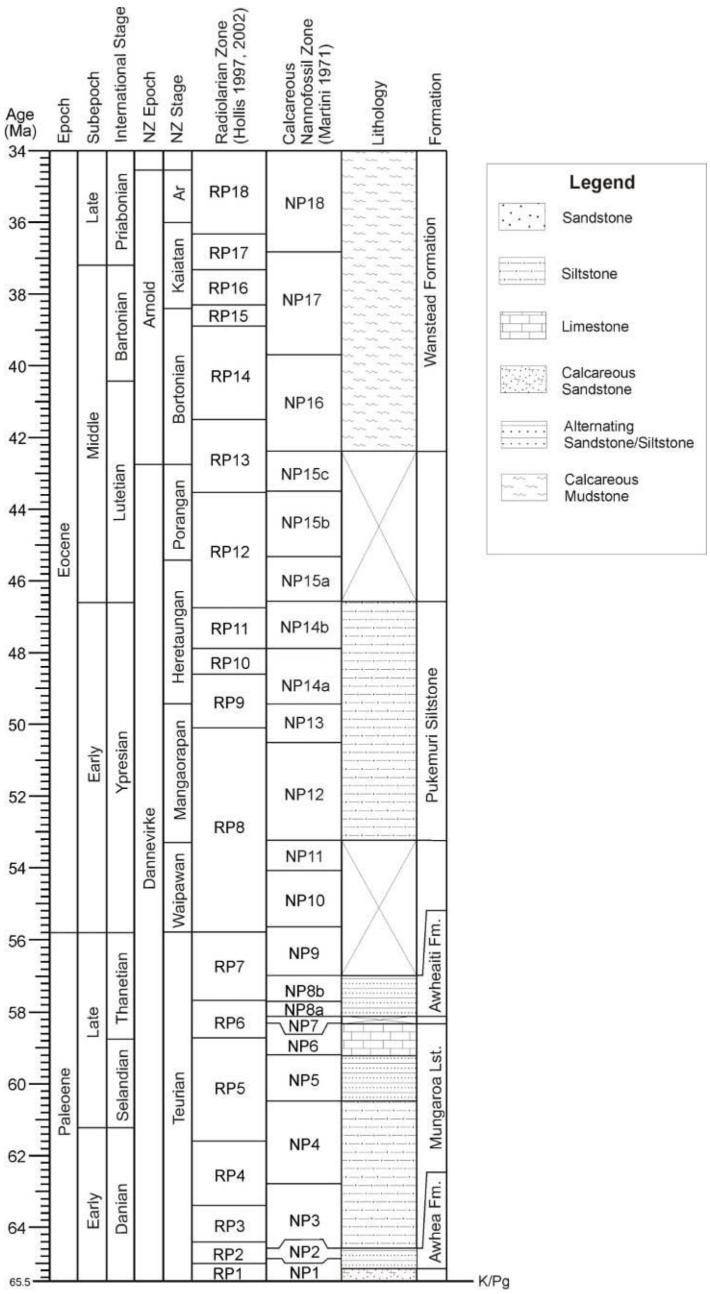

Figure 3: Revised formation ages for the Paleogene stratigraphy at Tora from Hines et al. (2013). ‘Ar’ denotes the Runangan Stage in the New Zealand Geological timescale. Timescale based on Hollis *et al*. (2010). Note radiolarians only used for age control on the upper limestone member of the Mungaroa Limestone. No nannofossil assemblages were studied from the Awhea Formation.

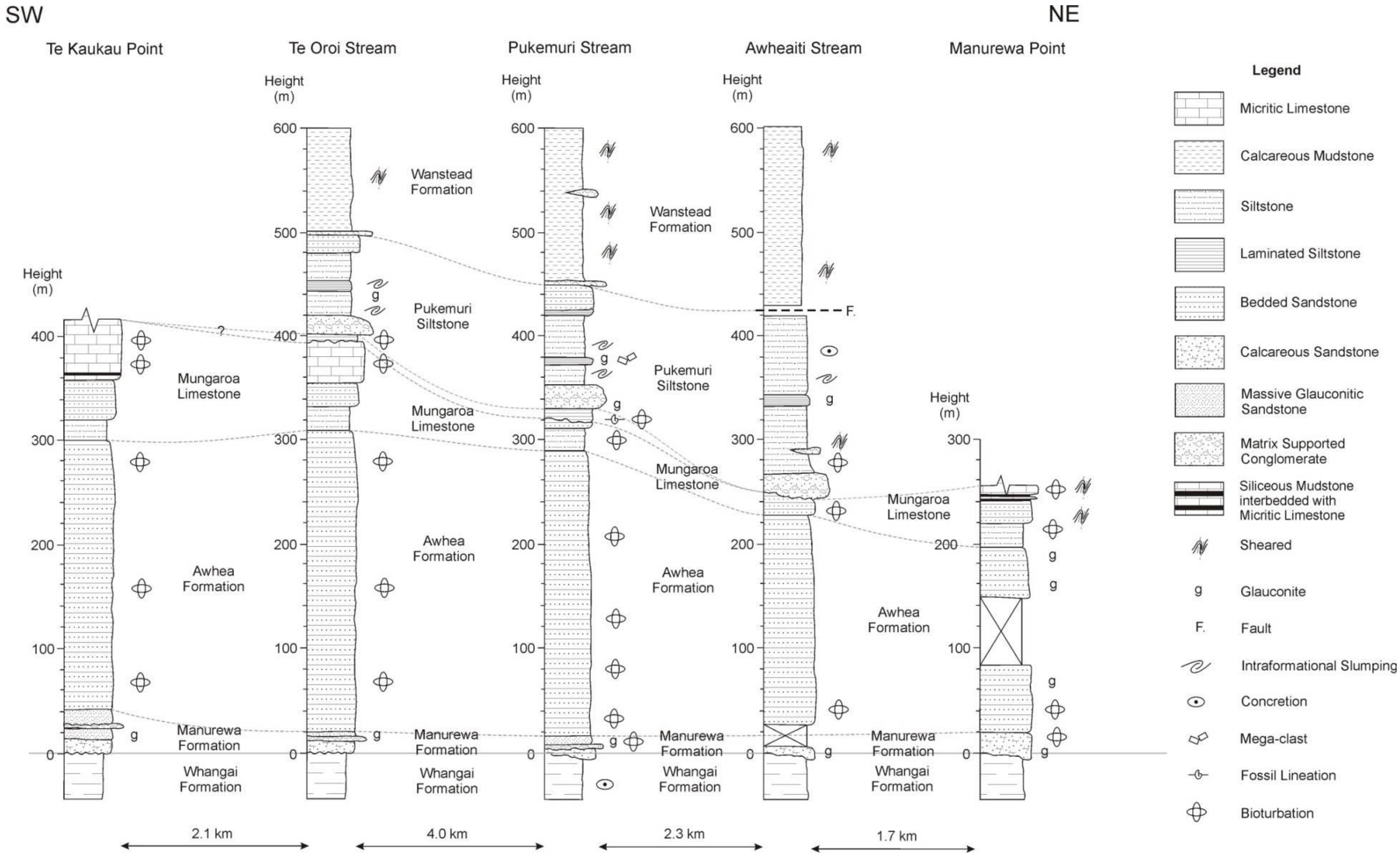

Figure 4: Correlation between sections, from Te Kaukau Point in the southeast, to Manurewa Point in the northwest of the Tora area. Figure sourced from Hines et al. (2013).

Stop 1: Beach Terraces, Pukemuri Stream

As we travel along the coast Pukemuri Stream and Manurewa Point we can see a series of seven preserved Holocene storm ridges (Figures 5 & 6a). These can be correlated to the more famous ridges at Turakirae Head, and records sequential uplift events along the Wairarapa coast (Berryman et al. 2011). During periods of stable sea level, a wave-cut intertidal platform, such as that seen on the modern shoreline is formed, and a storm ridge is formed above the tide line (Figure 6b). Following an uplift event, the tidal platform and storm ridge is uplifted beyond the reach of tides and storms, resulting in the development of a new storm ridge and tidal platform. Meanwhile, impeded drainage caused by the new and old storm ridges results in the development of a swamp (e.g. Figures 5 & 6b). This cycle of event continues through multiple Holocene uplift events, resulting in the formation of seven distinct beach ridge and terrace couplets at the Mouth of Pukemuri Stream (Figure 6a, 6c, 6d). On top of several of these ridges are parallel rows of stones (Figure 5). These are a common feature of Maori habitation in the coastal Wairarapa region, and their purpose is not fully understood (McFadgen, 2003). The prevailing though is these were originally walls that most likely divided Maori kumara gardens, or retained heat for the cultivation of kumara.

Figure 5: Raised beach ridges (outlined by swamps) and Maori gardens (arrowed) at the entrance to Pukemuri Stream, with late Cretaceous Whangai Formation in the foreground.

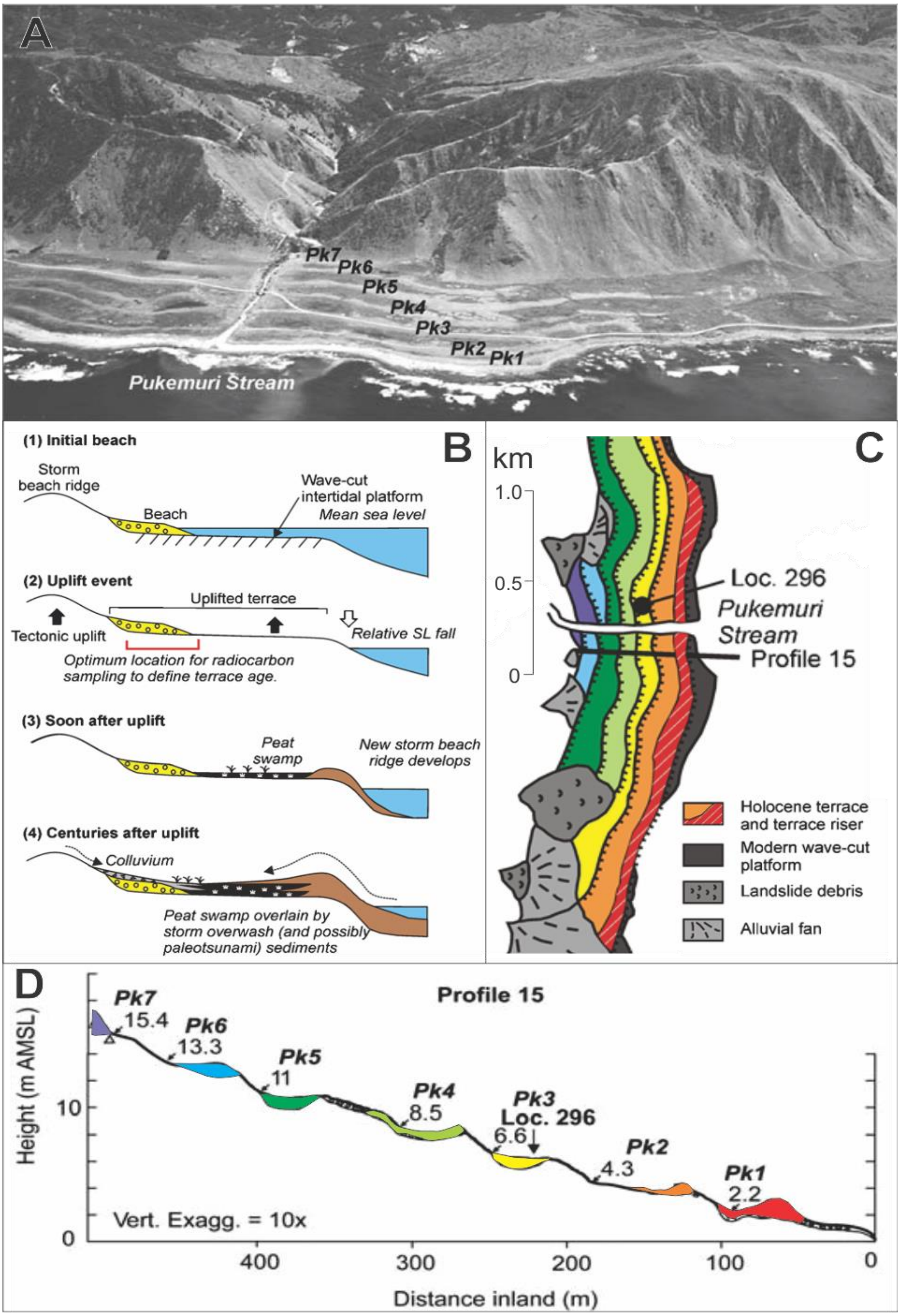

Figure 6: Raised terraces at the entrance to Pukemuri Stream. Figures modified from Berryman et al. (2011). **A**) Aerial photograph of the mouth of Pukemuri Stream, showing seven distinct terraces. **B**) Process of sequential development of successive beach ridges on the Wairarapa coast. **C**) Mapped of terraces along the coast near Pukemuri Stream. **D**) Transect across the successive terraces at Pukemuri Stream.

Stop 2: Glenburn Formation, Pukemuri Stream

At the entrance of Pukemuri Stream, the late Cretaceous flysch sequence of the Glenburn Formation is observed (Figure 7). At this point, the coastline is situated on the hinge-line of the Coastal anticline (Figure 8), the dominant structural control over late Cretaceous-Paleogene sediments at Tora. The Glenburn Formation is a thick succession of well-bedded, non-calcareous alternating sandstone-mudstone. Beds are decimetre to metre thick, with many beds containing fine pebbles to cobble sized clasts (Figure 9). Beds are often carbonaceous, in many instances containing a high amount of organic matter. Sedimentary structures include ripples, cross-bedding and convolute bedding.

The Glenburn Formation has a minimum thickness of 62 m (Laird et al., 2003), and is inferred to unconformably overlie Mangapokia Formation. A late Piripauan (Santonian) age is inferred from inoceramids and dinoflagellates (Crampton, 1996; Laird et al., 2003). Much of the Glenburn Formation was deposited in a submarine fan environment at bathyal depths (Crampton, 1997). However, only the uppermost part of the unit is exposed at Tora and sedimentary structures suggest a shallow marine setting (Laird et al., 2003).

Figure 7: Alternating sandstone-mudstone of the Glenburn Formation exposed on the coastline near the mouth of Pukemuri Stream.

Figure 8: Looking north-northwest down the axis of the Coastal Anticline near the mouth of Pukemuri Stream. Note strata of the Glenburn Formation dipping to the east on the right-hand side, and to the west on the left-hand side of the image**.**

Figure 9: Cross-bedded sandstones and conglomerates within the Glenburn Formation on the Tora coast.

Stop 3: Whangai Formation, Pukemuri Stream

The Glenburn Formation is overlain by the Rakauroa Member of the Whangai Formation, with a faulted contact. The Rakauroa Member is a widespread, and generally massive, siliceous mudstone. The Rakauroa Member of the Whangai Formation occurs throughout the East Coast Basin, and is the only member of the Whangai Formation formally identified at Tora (Moore, 1988b). The formation consists of hard, non-calcareous, micaceous siltstone with sparse beds of calcareous, glauconitic sandstone. The formation has a measured thickness of 300 m. The basal contact with the Glenburn Formation is faulted at Tora (Moore, 1988b).

Foraminifera from lower in the formation indicate deposition at shelf depths, possibly with reduced oxygen levels (Moore, 1988b). Dinoflagellate assemblages give an early Campanian (early Haumurian) age for the base of the section at Pukemuri Stream and a late Haumurian (late Campanian–Maastrichtian) age for the uppermost Whangai Formation at Manurewa Point (Laird et al., 2003).

Stop 4: Manurewa Formation, Pukemuri Stream

The Manurewa Formation overlies the Whangai Formation with a sharp, channelised lower contact (Moore, 1988b; Laird et al., 2003) and exhibits significant variability along strike (Waterhouse & Bradley, 1957; Wasmuth, 1996). The formation comprises two informal members; a lower limestone member and an upper greensand member. The 4 m-thick lower member consists of thin, interbedded glauconitic mud and calcareous beds which grade upwards from coarse pebbly sandstones and glauconitic mudstone into pure limestone (Waterhouse & Bradley, 1957). The upper member is a *ca*. 15 m-thick laminated greensand that contains abundant pyrite nodules. The basal contact of the upper member is channelised into underlying strata and in some sections the lower member is absent (Figure 10).

Dinoflagellate and foraminiferal assemblages indicate a late Haumurian to Teurian (Maastrichtian to Paleocene) age, with an environment of deposition at middle to lower bathyal depths (Wasmuth, 1996; Wilson, 1998). Several studies have identified the Cretaceous–Paleogene boundary at the base of the upper member (Figure 10; Wasmuth, 1996; Laird et al., 2003; Vellekoop, 2010). Dinoflagellate assemblages from the lower member of the Manurewa Formation are assigned to the latest Cretaceous *Manumiella druggii* Zone, whereas the upper member contains an assemblage that is correlated to the Early Paleocene *Trithyrodinium evitii* Zone (Figure 10; Laird et al., 2003).

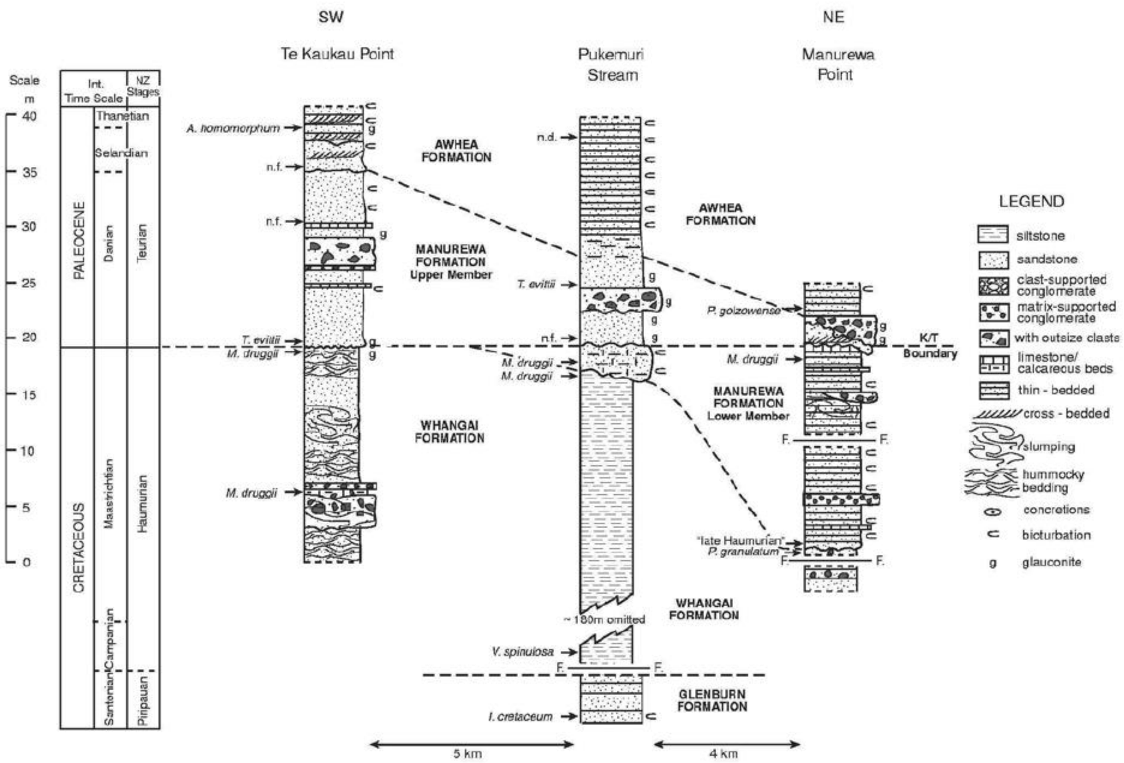

Figure 10: Identification of K/Pg (K/T) boundary section in the Manurewa Formation at Manurewa Point, Pukemuri Steam and Te Kaukau Point. Image sourced from Laird et al. (2003).

The Manurewa Formation is interpreted as a nested channel complex, with cross-bedding, scours, channels, and conglomeratic intervals indicative of periods of high energy erosion and deposition. Laird et al. (2003) interpreted the Manurewa Formation as a shallow marine channel complex based on the presence of marginal marine acritarchs and fungal material. However, these indicators are possibly reworked, as the benthic foraminiferal assemblages suggest a bathyal paleodepth which is supported by trace fossil assemblages associated with the *Nereites* ichnofacies (*Nereites*, *Chondrites*, *Zoophycos*) (Figure 11), and observations of *Helminthoida* and c.f. *Paleodictyon* recorded by Wasmuth (1996).

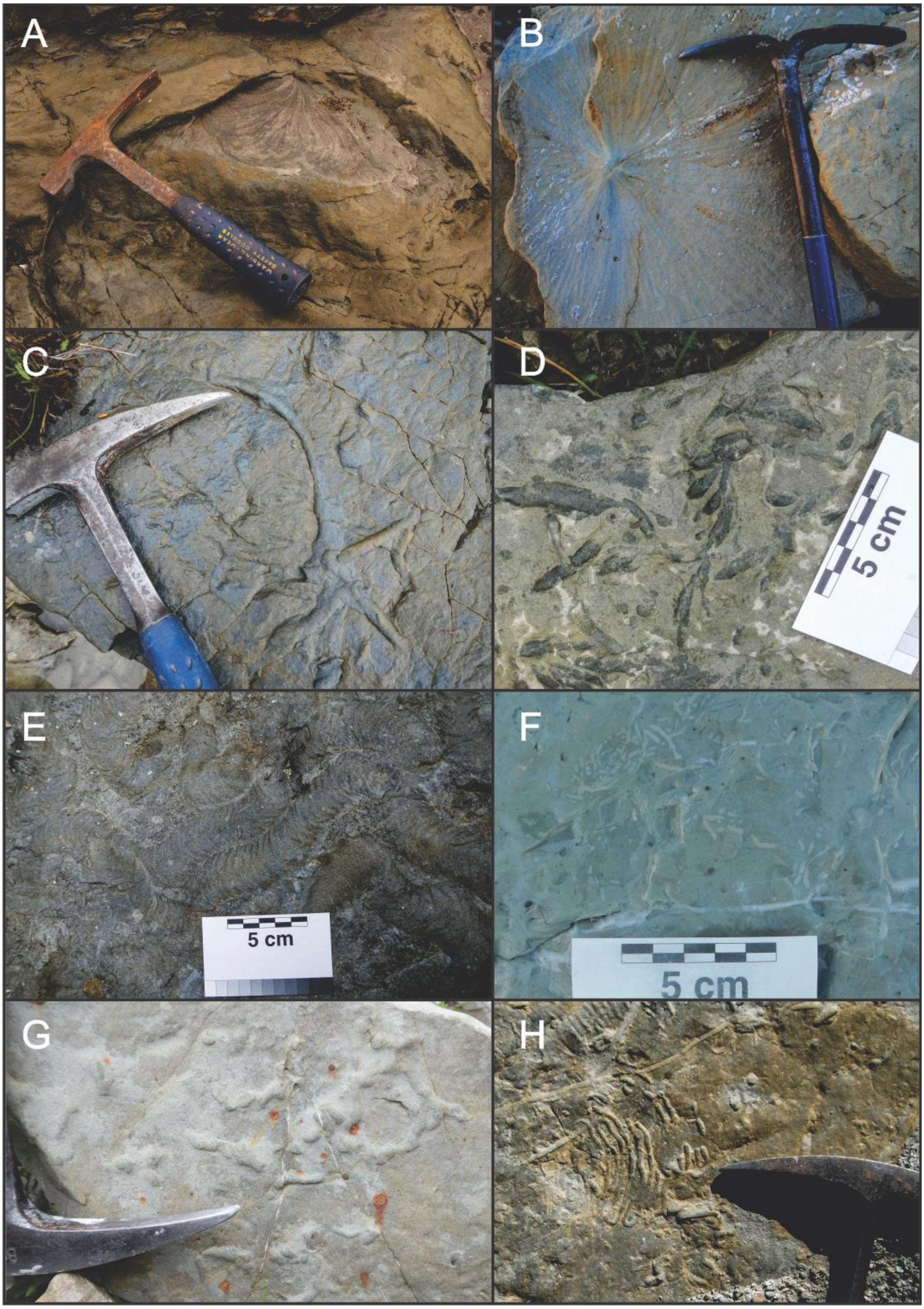

Figure 11: Bioturbation observed in various units at Tora. **A**) *Zoophycos*, Glenburn Formation. **B**) *Zoophycos*, Mungaroa Limestone. **C, D**) *Ophiomorpha* spp., Awhea Formation. **E**) *Scolicia*, Mungaroa Limestone. **F**) *Chondrites*, Mungaroa Limestone. **G**) *Paleodictyon*, Mungaroa Limestone. **H**) *Nereites*, Manurewa Formation.

Stop 5: Awhea Formation, Pukemuri Stream

The Awhea Formation conformably overlies Manurewa Formation with 275 m of hard, cm- to dm-bedded, glauconitic sandstone beds with sharp basal contacts, separated by thin, calcareous, micaceous mudstone. The lower Awhea Formation consists of well-bedded, green-grey, glauconitic sandstone beds divided by thin layers of mudstone, and often outcrops as prominent, steeply inclined dip slopes (Figure 12). Bedding surfaces are extensively bioturbated, including traces of *Nereites*, *Paleodictyon*, *Ophiomorpha*, *Scolicia* and *Planolites*. Vertically and horizontally oriented burrows are commonly infilled with pyrite and carbonaceous material is occasionally found in sandstone beds. The formation becomes progressively finer-grained thinner bedded up-section and bioturbation becomes significantly less extensive towards the top of the formation.

The lower Awhea Formation contains a long-ranging agglutinated foraminiferal assemblage that extends from the Haumurian to Teurian. Identification of the K/Pg boundary in the underlying Manurewa Formation, and the presence of distinctly Teurian (Paleocene) foraminiferal assemblages from the middle and upper Awhea Formation, constrains the age (Figure 3; Hines et al., 2013). Benthic foraminiferal assemblages from the Awhea Formation suggest a middle to lower bathyal depositional depth, which is consistent with trace fossil assemblages containing *Paleodictyon*, *Ophiomorpha*, *Scolicia* and *Planolites* place the Awhea Formation within the *Nereites* ichnofacies.

Figure 12: Steeply inclined dip-slopes of the Awhea Formation exposed in Pukemuri Stream.

Stop 6: Mungaroa Limestone, Pukemuri Stream

The Mungaroa Limestone outcrops in a 20 m high waterfall (Figure 13) 1500 m from the mouth of Pukemuri Stream, where it conformably overlies the Awhea Formation. The lower 20 m of Mungaroa Limestone is pale grey, calcareous, decimetre-bedded, fine sandstone and mudstone. Conformably overlying this interval is a 10 m-thick green-grey, centimetre to decimetre-bedded glauconitic sandstone. The formation is extensively bioturbated on some bedding planes, including traces of *Scolicia* and *Zoophycos*.

Foraminiferal assemblages from the Mungaroa Limestone give a Teurian (Paleocene) age. Calcareous nannofossil assemblages from the middle member of the Mungaroa Limestone in Pukemuri Stream are correlated with Nannofossil Zone NP5 (middle Paleocene, late Teurian). The lower member of the Mungaroa Limestone exposed in Pukemuri Stream was deposited in a middle to lower bathyal environment (600-800 m) based on benthic foraminiferal assemblages (Hines et al., 2013). The reduced thickness of the Mungaroa Limestone in the Pukemuri and Awheaiti Stream sections is attributed to paleo-channel erosion, corresponding with the removal of much of the upper two members of the Mungaroa Limestone in these sections (Figure 4).

Figure 13: Outcrop of the lower two members of the Mungaroa Limestone in Pukemuri Stream.

Stop 7: Manurewa Formation, Manurewa Point

A second K/Pg boundary is clearly exposed on the coastline near Manurewa Point (Figure 10), and provides a good example of the rapid lateral facies changes observed within the latest Cretaceous-Paleogene succession at Tora. Here, the uppermost Whangai Formation displays evidence of syn-sedimentary disturbance, containing olistostromes of various lithologies (Figure 14a). The contact between the Whangai Formation is abrupt (Figure 14b), as at Pukemuri Stream, though the sedimentary characteristics of the Manurewa Formation differ here. Normal faulting occurs near the crest of the anticline in the Mungaroa and Awhea Formations (Figure 15), likely associated with folding of the anticline.

Figure 14: A) The uppermost Whangai Formation is quite disturbed at Manurewa Point, containing olistostromes and demonstrating a high degree of shearing. **B**) Abrupt lower contact between the Rakauroa Member of the Whangai Formation and the base of the Manurewa Formation.

Figure 15: The location of the K/Pg boundary in the Manurewa Point section lies at the contact immediately above the hammer head. The Manurewa and Awhea Formations in this location are displaced by a number of normal faults (an example on the right-hand side of the image) caused by extension associated with the development of the Coastal Anticline.

Stop 8: Mungaroa Limestone, Manurewa Point

Here, we observe the abrupt transition from a dominantly siliciclastic turbidite sequence into the beginning of a micritic limestone which bears distinct similarities to the Mead Hill Formation and Amuri Limestone of Marlborough. Also associated with this horizon are paired layers of dark, organic-rich mudstone (Figure 16a), which correlate well with confirmed outcrop observations of the Waipawa Formation in Mead Stream, Marlborough (Figure 16b). The Mungaroa Limestone divided into four informal units on the basis of lithology; the lower member, middle member, "Waipawa facies" and the upper limestone member. White, faintly bedded, calcareous mudstone of the lower member conformably overlies the Awhea Formation, and the basal contact is gradational, distinguished by a change in colour and an increase in bedding thickness, carbonate and degree of cementation. The lower member grades into a well-bedded sequence of grey-green sandstones and mudstones of the middle member. The middle member is abruptly overlain by the upper member which contains the "Waipawa facies"; a pair of 50 cm-thick, glauconitic black mudstone intervals separated by 1.5 m of decimetre-bedded white, porcellaneous limestone and white-grey sandstone. The "Waipawa facies" is sharply overlain by well-bedded, white micritic limestone of the upper limestone member. The formation is extensively bioturbated on some bedding planes, including traces of *Scolicia* and *Zoophycos*. *Zoophycos* trace fossils occur throughout the formation, becoming extensive in the upper micritic limestone member.

The Mungaroa Limestone varies significantly in stratigraphic thickness laterally, thinning dramatically from south to north. This is displayed by its physical morphology in the landscape; in Te Oroi Stream to the south, all three members of the formation outcrop with a stratigraphic thickness of 85 m; in Pukemuri Stream, 4 km to the north, the lower two members outcrop with a thickness of 30 m; further north, only the lowermost member is expressed as a small gorge in Awheaiti Stream (Figure 4). Exposure of the upper members of the formation resumes at Manurewa Point (Figure 4). The greatest outcrop representation of the upper micritic limestone member is in coastal exposures at Te Kaukau Point (Figure 4 & 18).

The foraminiferal assemblages from the base of the Mungaroa Limestone give a Teurian (Paleocene) age. This is further refined using calcareous nannofossil assemblages, indicating deposition during Nannofossil Zone NP3–4 (Figure 3). Calcareous nannofossil assemblages place the middle member in zone NP5, and the upper micritic limestone member and the incorporated 'Waipawa facies' mudstone are placed in Radiolarian Zone RP5 (61-59 Ma; Hollis, 2002) based on sampling at Te Kaukau Point (Figure 3).

Deformation structures within the formation (slump folding and sedimentary dykes) and the apparent absence of brittle shearing suggest that the formation was semi-lithified, but still plastic, at the time of deformation, consistent with the observations of Waterhouse & Bradley (1957), Kirk (1966) and Browne (1987). These slump structures indicate paleoslope movements and syn-sedimentary deformation of sediments.

Figure 16: A) ‘Waipawa’ facies at Manurewa Point. Paired, dark, organic rich horizons (Arrowed). Worm borings. Image courtesy of C. Atkins. **B**) Waipawa Formation in Mead Stream overlying the Mead Hill Formation, showing the characteristic ‘double pulse’ (Arrowed).

Figure 17: Deformed sediments of the Mungaroa Limestone at Manurewa Point.

Figure 18: Syn-sedimentary slumping is readily apparent in the upper micritic limestone member of the Mungaroa Limestone, which outcrops extensively at Te Kaukau Point, south of Tora.

Pukemuri Siltstone

The Pukemuri Siltstone unconformably overlies the Awheaiti Formation with an angular discordance of 20°. The base of the formation is represented by 20–40 m of pebbly-mudstone with well-rounded pebbles of mixed lithologies, mostly indurated sandstone and occasional chert. This interval also contains megaclasts of indurated, clast-supported conglomerate and well-rounded boulders of hard, cemented sandstone (Figures 19 & 20). This grades into ~100 m of blue-grey, faintly centimetre-bedded mudstone.

The Pukemuri Siltstone ranges from Mangaorapan (Early Eocene) at the base to Heretaungan (early Middle Eocene) at the uppermost extent of the formation based on calcareous nannofossil and foraminifera assemblages (Figure 3). The presence of the calcareous nannofossil *Discoaster lodoensis* throughout the formation, indicates correlation with Nannofossil Zones NP12–14 (late Early to early Middle Eocene), consistent with foraminiferal biostratigraphy. The upper Pukemuri Siltstone contains the key foraminifera index species *Morozovella crater* and *Elphidium hampdenense*, indicating a Heretaungan age (latest Early Eocene to early Middle Eocene).

The pebbly-mudstone of the lower Pukemuri Siltstone is interpreted as a marine debris flow deposit, with supporting evidence including intraformational slump structures, convolute bedding and rafted blocks of conglomerate and sandstone. Micritic limestone and chert clasts observed in the lowermost Pukemuri Siltstone probably originated from the upper member of the Mungaroa Limestone, which was reworked as a result of the erosion of the Mungaroa-Pukemuri unconformity.

Figure 19: View north form Manurewa Point showing outcrop of Pukemuri Siltstone (middle distance), Hungaroa Fault trace and mid-Cretaceous sediments of the Mangapokia Formation (background).

Figure 20: The lower Pukemuri Siltstone containing reworked clasts and olistostromes of various sizes exposed in an outcrop above Stoney Bay.

Wanstead Formation & Hungaroa Fault

Outcrops of the Wanstead Formation are typically slumped and poorly exposed (Figure 21). The Wanstead Formation unconformably overlies the Pukemuri Siltstone, with a basal 1 m-thick poorly-sorted, clast-supported conglomerate comprised of a broad assortment of pebble-sized, moderately to well-rounded, chert, greywacke and sandstone clasts. The remainder of the formation is *ca*. 200 m-thick, intensely sheared and deformed green-grey calcareous mudstone (Figure 22). Undeformed mudstones display a mottled, bioturbated texture and little or no primary sedimentary structures. The formation exhibits a high degree of tectonic shearing and folding makes it difficult to determine true stratigraphic thickness. In addition, the Wanstead Formation at Tora is truncated by the Ewe and Hungaroa Faults.

A late Middle Eocene (Bortonian) age applied to the base of the Wanstead Formation (Figure 3). Further up the section, the formation produces a somewhat younger assemblage indicating a correlation with upper Zone NP17 giving a Kaiatan to Runangan age (latest Middle to earliest Late Eocene).

Foraminferal assemblages include *Abyssamina poagi*, an abyssal dwelling formainifera in the middle Eocene (Morkhoven *et al*., 1986) that implies a paleodepth of >3500 m, consistent other species suggesting deposition occurred in water depths between 2000 and 4000 m (Hines et al., 2013). This indicates that the basin deepened rapidly during the Middle Eocene from mid-bathyal depths in the Early Eocene Pukemuri Siltstone to lower bathyal-abyssal depths in the Wanstead Formation.

Figure 21: **A**) Outcrop of coherent green mudstone of the Wanstead Formation exposed in Pukemuri Stream. **B**) Typical slumped, sheared and deformed outcrop of the Wanstead Formation at Tora.

The Hungaroa Fault juxtaposes Early Cretaceous sediments of the Mangapokia Formation with Late Eocene sediments of the Wanstead Formation. The fault itself represents an over-steepened thrust fault (Figure 22a). The shear zone associated with the Hungaroa Fault is 20 metres wide, with a well-developed shear fabric exposed on a wave cut section near the mouth of Hungaroa Stream (Figure 22b).

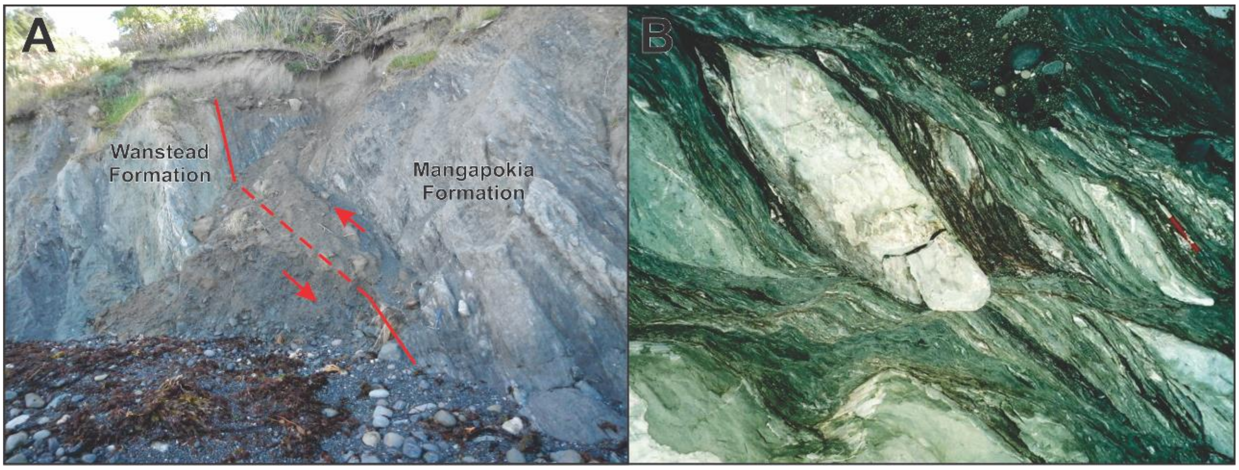

Figure 22: **A**) Hungaroa Fault zone outcropping on the shore platform, with lower Cretaceous Mangapokia Formation thrust over middle to late Eocene Wanstead Formation. **B**) Well-defined C/S shear fabric exposed in the shear zone adjacent to the Hungaroa Fault, exposed on the shore platform at Stoney Bay, Tora. Image courtesy of T. Little.

Stop 10: Mangapokia Formation, Oterei River Mouth

The Pahaoa Group sediments are generally considered the basement rocks of southern Wairarapa. In the Tora area, this is largely represented by the Mangapokia Formation. The mid-Cretaceous (Motuan) Mangapokia Formation represents the youngest part of the Torlesse accretionary wedge and predominantly consists of sandstone, argillite and conglomerate along with minor pebbly-mudstone (Figure 23), scattered spilitic igneous rocks and associated volcanogenic sediments (Moore & Speden, 1984; Barnes & Korsch, 1991). The accreted submarine fan turbidite sequence is weakly metamorphosed and complexly deformed (Barnes, 1988; Barnes & Korsch, 1991).

Figure 23: Sheared clasts within the Mangapokia Formation at Te Awaite.

Depositional History

The basal conglomerate of the Manurewa Formation likely represents a phase of down-cutting and channel incision into the underlying Whangai Formation, associated with the initial stages of the development of a submarine fan or the expansion of a new lobe of an existing fan. The massive sandstone of the upper member which is channelised into the lower member of the Manurewa Formation (Wasmuth, 1996; Laird et al., 2003) is also consistent with the interpretation of channel incision, deposition and lobe development. Furthermore, the Manurewa Formation is a localised unit restricted to the Tora area (Laird et al., 2003), consistent with the interpretation of restricted early stage fan development (Figure 24).

The Manurewa Formation grades into the bedded sandstones of the lower Awhea Formation which is interpreted as the deposition of proximal turbidite sequences within the main body of a submarine fan (Figure 24). Higher in the formation, the shift to normal-graded, well-bedded turbidites is interpreted to represent 'smooth' fan environments towards the outer extent of the supra-fan lobes (Walker, 1978). The Awhea Formation displays a thinning upwards sequence of turbidites which is indicative of gradual lobe shifting (Walker & James, 1992). The stratigraphic thickness of the Awhea Formation thins northwards, from 290 m at Te Oroi Stream to 47 m near the Pahoa River mouth at Glenburn (Tayler, 2011), consistent with the interpretation of a fan environment which had its source to the southeast and the depositional centre located near the Tora area, extending and thinning to the north during deposition of the Awhea Formation (Figure 24). The gradational contact from the Awhea Formation upwards into the lower member of the Mungaroa Limestone, as well as the transition from the thin, fine-grained turbidites of the upper Awhea Formation to the thicker sandstone beds separated by thin mudstones in the lower members of the Mungaroa Limestone, suggests a return to a more proximal position in the lower fan (Walker, 1978). The abrupt transition to the upper limestone member, suggests a rapid, regional reduction in the deposition of clastic sediment during NP5 (mid-Paleocene) and potentially a northwards extension of the calcareous, biogenic Mead Hill-Amuri Limestone sedimentary sequence of the southern East Coast Basin (Figure 24). Like the Awhea Formation, the Mungaroa Limestone thins northwards, where is has a thickness of 28 m at Glenburn (Tayler, 2011). The upper micritic member of the Mungaroa Limestone reflects pelagic deposition with minor terrigenous input, although the inclusion of the 'Waipawa facies' at the base of the member suggests an influx of terrestrial organic matter and a possible fall in eustatic sea level (Hollis et al., 2014).

The Pukemuri Siltstone likely represents a slope-influenced end member equivalent of the Wanstead Formation (Figure 24). Benthic foraminiferal assemblages indicate a mid-bathyal depositional depths greater than 800 m, deepening during deposition to lower bathyal depths in the upper Pukemuri Siltstone. Benthic foraminiferal assemblages indicate that the Wanstead Formation at Tora was deposited in lower bathyal water depths through to the Late Eocene. The calcareous mudstones of the Wanstead Formation at Tora display little variation and a pervasive bioturbated texture common to basin plain deposits, reflecting a deeper and more distal facies than the underlying units.

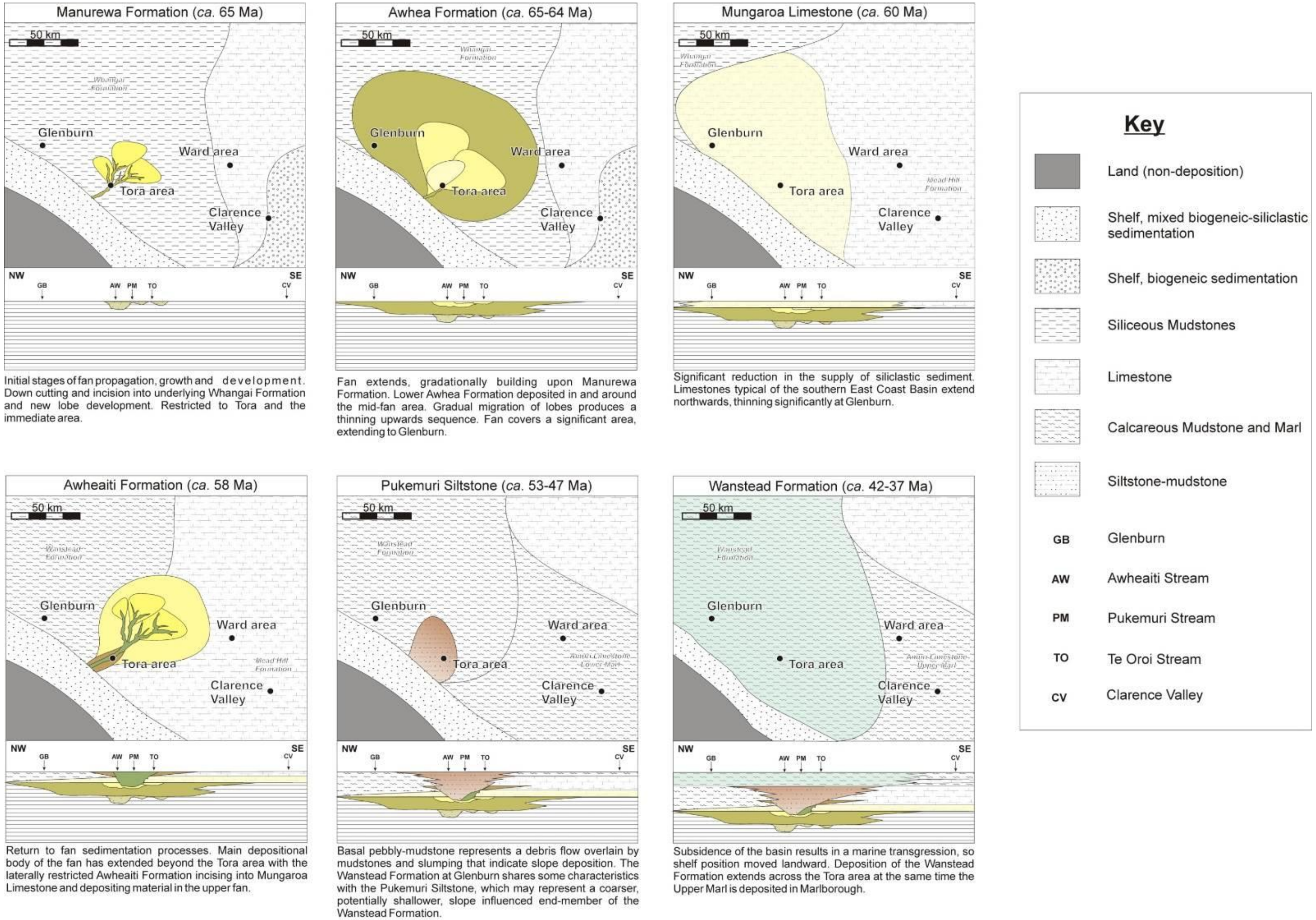

Figure 24: Schematic paleoenvironmental maps and cross-sections at different times in the central East Coast Basin. Base map adapted from Crampton et al. (2003) to accommodate the bathyal marine interpretation of Tora. No relative scale has been applied to cross-sections in order to exaggerate stratigraphic relationships. Figure sourced from Hines (2012).

Correlation with Other East Coast Sections

The sedimentary succession exposed at Tora can be correlated to other slope-basin sediments deposited elsewhere in the East Coast Basin. The Paleogene succession at Tora broadly fits the typical fining upwards sequence that is observed throughout the East Coast Basin (Moore, 1986; Ballance, 1993).

The Upper Cretaceous to Lower Paleocene strata at Glenburn, north of Tora, display no obvious unconformities that can be correlated with the basal Manurewa, intra-Haumurian unconformity at Tora (Lee, 1995; Laird et al., 2003), consistent with the localised extent of the Manurewa Formation submarine channel system (Figure 24). Field et al. (1997) suggest that the Manurewa Formation is a lateral correlative of the Upper Calcareous or Porongahau Members of the Whangai Formation. However, this seems unlikely due to the localised and incised nature of the lower Manurewa Formation as documented by Wasmuth (1996) and Laird et al. (2003).

The Awhea Formation is coarser than typical early Paleocene facies observed elsewhere in the East Coast Basin (Field et al., 1997), but share sedimentary characteristics with the Porangahau Member of the Whangai Formation and occupies the same stratigraphic position, overlying the Rakauroa Member. Collectively the Manurewa and Awhea Formations at Tora may represent a southern extension of the Poranaghau Member described elsewhere in the East Coast Basin (Figure 25). The upper Mungaroa Limestone is recognised as a lateral correlative of the Kaiwhata Limestone, mapped in the Glenburn-Flat Point area, in terms of both age and environment (van de Hueval, 1966; Webby, 1969; Field et al., 1997), thereby placing an upper limit on the application of the Whangai Formation nomenclature at Tora. The upper member of the Mungaroa Limestone is a likely correlative or northern extension of the Mead Hill Formation in Marlborough (van de Hueval, 1966; Browne, 1987; Field et al., 1997; Hines et al., 2013).

Siliceous, dark-grey mudstones of the ‘Waipawa facies’ within the Mungaroa Limestone at Tora probably represent the siliceous, deep marine end member of the Waipawa Formation, similar to that observed in Mead Stream overlying the Mead Hill Formation in the southern East Coast Basin at Marlborough (Strong et al., 1995; Hollis et al., 2014). The paired dark mudstone bands of the ‘Waipawa facies’ identified at Tora correlate well with outcrop observations at Mead Stream.

Deposition of Wanstead Formation at Tora occurred at lower bathyal to abyssal depths during the early Middle to Late Eocene (Heretaungan to Kaiatan), which may reflect regional deepening of the area. The Wanstead Formation represents the deepest depositional environment of the Cretaceous-Paleogene East Coast Basin, with average paleodepths of mid-bathyal and lower bathyal to abyssal (Field et al., 1997). The Wanstead Formation at Tora is younger than typically expressed in many other East Coast sections (typically Paleocene to middle Eocene; Field et al., 1997). The transition from Wanstead to Weber Formation, which usually occurs during the Bortonian (Figure 25), may represent a facies change to shallower, more calcareous sediments within the basin that is not represented at Tora because this portion of the basin was significantly deeper. The deposition of the Wanstead Formation at Tora is coeval with the deposition of the 'upper marl' member of the Amuri Limestone in the Marlborough area (Figure 24; Crampton et al., 2003).

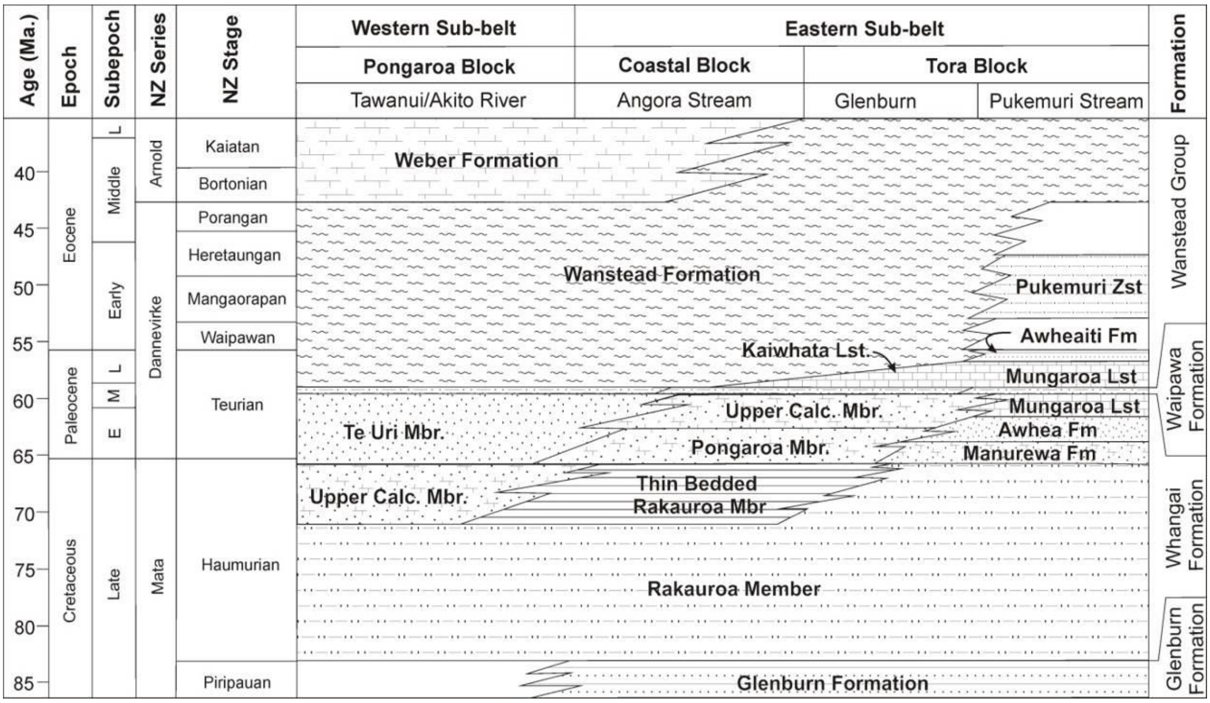

Figure 25: Generalised regional stratigraphic framework of the southern East Coast Basin, North Island, displaying the revised, distinctly different sedimentary trends of the late Cretaceous to early Paleogene present at Tora in comparison to the typical East Coast succession. Blank areas depict unconformities.

Summary

The Paleogene stratigraphy of the Tora area is divided into six distinct lithostratigraphic units, representing a finer stratigraphic division than the typical lithostratigraphic succession observed in other areas of the East Coast Basin. The diversity of facies at Tora reflects sedimentation within a submarine fan and channel complex at middle to lower bathyal depths within the context of a regional transgression from the late Cretaceous to the late Eocene.

The Awhea Formation is inferred to have been deposited as a turbidite succession within the main body of a fan complex during the early Paleocene. The Mungaroa Limestone consists of a lower part that represents the distal or lateral margin of a fan complex and an upper part that is dominated by deposition of pelagic carbonate during the middle and late Paleocene.

The Awheaiti Formation was likely deposited in a channel incised into the Mungaroa Limestone during the late Paleocene. The lower Pukemuri Siltstone was most likely deposited in a slope setting, with a basal debris flow overlain by siliclastic sediments. The Middle to Late Eocene Wanstead Formation was deposited in a deep bathyal basin floor setting.

References

Barnes, P. M. (1988). Submarine fan sedimentation at a convergent margin: the Cretaceous Mangapokia Formation, New Zealand. Sedimentary Geology. Vol. 59, pp. 155-178.

Barnes, P. M. & Korsch, R. J. (1991). Melange and related structures in Torlesse accretionary wedge, Wairarapa, New Zealand. New Zealand Journal of Geology and Geophysics. Vol. 34 (4), pp. 517-532.

Berryman, K., Ota, Y. & Hull, A. (1989). Holocene paleoseismicity in the fold and thrust belt of the Hikurangi subduction zone, eastern North Island, New Zealand. Tectonophysics. vol. 163, pp. 185-195.

Berryman, K., Ota, Y., Miauchi, T., Hull, A., Clark, K., Ishibashi, K., Iso, N. & Litchfield, N. (2011). Holocene Paleoseismic History of Upper-Plate Faults in the Southern Hikurangi Subduction Margin, New Zealand, Deduced from Marine Terrace Records. Bulletin of the Seismological Society of America, Vol. 101, No. 5, pp. 2064–2087.

Begg, J. G. & Johnston, M. R. (compilers) (2000). Geology of the Wellington area. Institute of Geological & Nuclear Sciences 1:250 000 geological map 10. 1 sheet + 64p. Lower Hutt, New Zealand: Institute of Geological and Nuclear Sciences Limited. ISBN: 0-478-09685-2.

Browne, G.H. (1987). In situ and intrusive sandstone in Amuri facies limestone at Te Kau Kau Point, southeast Wairarapa, New Zealand. New Zealand Journal of Geology and Geophysics. Vol. 30, pp. 363-374.

Collen, J. D. (1978). Biogenic collapse structures from Paleocene limestones, New Zealand. Search. Vol. 9 (11), pp. 410-411.

Crampton, J. S. (1996). Inoceramid bivalves from the Late Cretaceous of New Zealand. Institute of Geologicaland Nuclear Sciences Monograph 14.

Crampton, J.S. (1997). The Cretaceous stratigraphy of the Southern Hawke's Bay – Wairarapa region. Institute of Geological and Nuclear Sciences Report 97/08. 92p.

Crampton, J., Laird, M., Nicol, A., Townsend, D. & van Dissen, R. (2003). Palinspastic reconstructions of southeastern Marlborough, New Zealand, for mid-Cretaceous – Eocene times. New Zealand Journal of Geology and Geophysics. Vol. 46, pp. 153-175.

Edwards, A.R., 1971. A calcareous nannoplankton zonation of the New Zealand Paleogene. In: Farinacci, A., (Ed.), Proceedings of the II Planktonic Conference, Roma, 1970. Edizioni Tecnoscienza, Rome, pp. 381-419.

Field, B. D., Uruski, C. I., Beu, A., Browne, G., Crampton, J., Funnell, R., Killops, S., Laird, M., Mazengarb, C., Morgans, H., Rait, G., Smale, D. & Strong, P. (1997). Cretaceous-Cenozoic geology and petroleum systems of the East Coast Region, New Zealand. Institute of Geological and Nuclear Sciences monograph 19. 301p, 7 enclosures. Lower Hutt, New Zealand: Institute of Geological & Nuclear Sciences Limited. ISBN: 0-478-09610-0.

Furlong, K.P. & Kamp, P.J.J. (2009). The lithospheric geodynamics of plate boundary transpression in New Zealand: Initiating and emplacing subduction along the Hikurangi margin, and the tectonic evolution of the Alpine Fault system. Tectonophysics. Vol. 474, pp. 499-462.

Grapes, R. H., Little, T.A., Browne, G.H., Rait, G.J. 1997. Ngapotiki Thrust, White Rock and Te Kaukau Point, southeast Wairarapa: Active and inactive structures of the Hikurangi forarc. Geological Society of New Zealand Annual Conference, November 1997 Field trip Guide.

Hayward, B. W. (1986). A guide to paleoenvironmental assessment using New Zealand Cenozoic foraminiferal faunas. New Zealand Geological Survey Report PAL 109.

Hayward, B. W., Grenfell, H. R., Sabaa, A. T., Neil, H. L. & Buzas, M. A. (2010). Recent New Zealand deep-water benthic foraminifera: Taxonomy, ecologic distribution, biogeography, and use in paleoenvironmental assessment. GNS Science Monograph 26. 363 pp. Lower Hutt, New Zealand. ISBN: 978-0-478-19777-8.

Hines, B.R., 2012. The early Paleogene succession at Tora, New Zealand: Stratigraphy and paleoclimate. Victoria University of Wellington, p. 220.

Hines, B. R., Kulhanek, D. D., Hollis, C. J., Atkins, C. B. & Morgans, H. E. G. (2013). The Paleogene stratigraphy and paleoenvironment of the Tora area, southeast Wairarapa, New Zealand. New Zealand Journal of Geology and Geophysics.

Hollis, C. J. (1997). Field Trip Guide: Tora-Te Kaukau Point, southeast Wairarapa. Unpublished document.

Hollis, C.J. (1998). Stratigraphic summary of the Te Kau Kau Point-Manurewa Point area, SE Wairarapa. Unpublished document.

Hollis, C.J., Taylor, K.W.T., Handley, L., Pancost, R.D., Huber, M., Creech, J., Hines, B., Crouch, E.M., Morgans, H.E.G., Crampton, J.S., Gibbs, S., Pearson, P., Zachos, J.C., 2012. Early Paleogene temperature history of the Southwest Pacific Ocean: reconciling proxies and models. Earth and Planetary Science Letters 349-350, 53-66.

Hollis, C. J., Tayler, M. J., Andrew, B., Taylor, K. W., Lurcock, P., Bijl, P. K., Kulhanek, D. K., Crouch, E. M., Nelson, C. S., Pancost, R. D., Huber, M., Wilson, G. S., Ventura, G. T., Crampton, J. S., Schioler, P. & Phillips, A. (2014). Organic-rich sedimentation in the South Pacific Ocean associated with Late Paleocene climatic cooling. Earth Science Reviews, 134: 81–97.

Laird, M.G., Bassett, K. N., Schiøler, P., Morgans, H E. G., Bradshaw, J. D., Weaver, S. D. (2003). Paleoenvironmental and tectonic changes across the Cretaceous/Tertiary Boundary at Tora, southeast Wairarapa, New Zealand: a link between Marlborough and Hawkes Bay. New Zealand Journal of Geology and Geophysics. Vol. 46, 275-293.

Lee, J.M. (1995). A stratigraphic, biostratigraphic and structural analysis of the geology at Huatokitoki Stream, Glenburn, southern Wairarapa, New Zealand. Unpublished MSc thesis lodged at Victoria University of Wellington.

Lee, J.M. & Begg, J.G. (Compilers). (2002). Geology of the Wairarapa Area. Institute of Geological and Nuclear Sciences 1:250 000 geological map 11. 1 sheet + 66 p. Lower Hutt, New Zealand. Institute of Geological and Nuclear Sciences Limited. ISBN: 0-478-09750-6.

Little, T. A., Van Dissen, R., Schermer, E., & Carne, R. (2009). Late Holocene surface ruptures on the southern Wairarapa fault, New Zealand: Link between earthquakes and the uplifting of beach ridges on a rocky coast. Lithosphere, 1(1), 4–28.

McFadgen, B. (2003). Archaeology of the Wellington Conservancy: Wairarapa A study in tectonic archaeology. Department of Conservation, New Zealand. ISBN 0.478.22401.X

Moore, P.R. (1980). Late Cretaceous-Tertiary stratigraphy, structure, and tectonic history of the area between Whareama and Ngahape, eastern Wairarapa, New Zealand. New Zealand Journal of Geology and Geophysics. Vol. 23, 167-177.

Moore, P.R. & Speden, I.G. (1984). The Early Cretaceous (Albian) sequence of eastern Wairarapa, New Zealand. New Zealand Geological Survey Bulletin 97. pp. 98. ISSN: 0077-9628.

Moore, P. R. (1986). A revised Cretaceous-Early Tertiary stratigraphic nomenclature for Eastern North Island, New Zealand. New Zealand Geological Survey Report G104. ISSN: 0111-6991.

Moore, P.R. (1988a). Structural divisions of eastern North Island. New Zealand Geological Survey Record. Vol. 30, 24p. ISSN: 0112-465x.

Moore, P. R. (1988b). Stratigraphy, composition and environment of deposition of the Whangai Formation and associated Late Cretaceous-Paleocene rocks, eastern North Island, New Zealand. New Zealand Geological Survey Bulletin 100. ISSN 0077-9628.

Morgans, H.E.G. (1990). East Coast CCP (Late Cretaceous-Paleogene). Section 16 (EC-16), Section 17 (EC-17), Section 18 (EC-18). Unpublished data. GNS Science, Lower Hutt.

Morkhoven, P. C. M., Berggren, W. A. and Edwards, A. S. (1986). Cenozoic cosmopolitan deep-water benthic foraminifera. Bull. Centres Rech. Explor.-Prod. Elf-Aquitaine, Mem. 11; Pau. ISBN: 2-901026-20-6. 421 pp.

Pettinga, J.R. (1982). Upper Cenozoic structural history, coastal Southern Hawke's Bay, New Zealand. New Zealand Journal of Geology and Geophysics. Vol. 25, pp. 149-191.

Strong, C. P., Hollis, C. J. & Wilson, G. J. (1995). Foraminiferal, radiolarian, and dinoflagellate biostratigraphy of Late Cretaceous to middle Eocene pelagic sediments (Muzzle Group), Mead Stream, Marlborough, New Zealand. New Zealand Journal of Geology and Geophysics. Vol. 38 (2), pp. 171– 209.

Tayler, M.J.S. (2011). Investigating Stratigraphic Evidence for Antarctic glaciation in the Greenhouse World of the Paleocene, Eastern North Island, New Zealand, MSc Thesis, Earth and Ocean Sciences. University of Waikato, Hamilton p. 292.

Uruski, C.I; Bland, K.J. (2011). Pegasus Basin and the Prospects for Oil and Gas. GNS Science Consultancy Report 2010/291 van de Heuval, H. B. (1960). The geology of the Flat Point area, eastern Wairarapa. New Zealand Journal of Geology and Geophysics. Vol. 3 (2), pp. 309-320.

Vellekoop, J. (2010). Unravelling Paleoenvironmental Changes Across the Cretaceous-Paleogene Boundary in New Zealand. Unpublished MSc Research Project, Utrecht University, the Netherlands. pp. 1-35.

Waterhouse, J.B. (1955). Geology of the White Rock-Tora Area, South East Wairarapa. Unpublished MSc Thesis lodged at Victoria University of Wellington.

Waterhouse, J.B. & Bradley, J. (1957). Redeposition and Slumping in the Cretaceo-Tertiary Strata of S.E Wellington. Transactions of the Royal Society of New Zealand. Vol. 84, pp. 519-548

Wasmuth, C. (1996). Biological and Lithological Changes in the Late Haumurian-Teurian Strata (Cretaceous-Tertiary Boundary, at Tora, Southern Wairarapa, New Zealand. Thesis. Victoria University of Wellington. 103 pp.

Webby, B. D. (1969). Trace fossils Zoophycos and Chondrites from the Tertiary of New Zealand. New Zealand Journal of Geology and Geophysics. Vol. 12 (1), pp. 208-214.

Wilson, G. J. (1998). Dinoflagellate biostratigraphy around the K/T boundary at Pukemuri Stream, Wairarapa (S28). Unpublished report. GJW 303/98.