Geosciences 2019

Annual Conference of the Geoscience Society of New Zealand

Field Trip 1

Geochemistry of Waipuna Cave

28th November 2019

Leaders: Adam Hartland & Jackson White

School of Science, University of Waikato, Private Bag 3105, Hamilton 3240

Citation:

Hartland, A., White, J. 2019. Geochemistry of Waipuna Cave. In: Lowe, D.J., Pittari, A. (editors), Field Trip Guides. Geosciences 2019 Conference, Hamilton, New Zealand (24-29 November). *Geoscience Society of New Zealand Miscellaneous Publication* 155B, pp. 1–7

Note: Cover photo shows karst landscape on limestone west of Waitomo (from Edbrooke 2005).

Geoscience Society of New Zealand Miscellaneous Publication 155B

ISBN (online): 978-0-473-49901-3

ISSN (online): 2230-4495

GEOCHEMISTRY OF WAIPUNA CAVE

Introduction to Waipuna Cave

Fig. 1. Elemental and isotopic sample collection at Waipuna Cave (Blogs 2019).

Waipuna Cave is the subject of a multi-year cave monitoring programme, which focusses on the development of novel quantitative proxies for palaeoclimatology. The parameters measured in the cave are the elemental and isotopic composition of drips, electrical conductivity, drip rate and temperature (Fig. 1). These results are compared to the meteorological records in order to calibrate proxies for quantitative climate reconstruction. The larger purpose of this data collection is to understand the dynamics of the El Niño-Southern Oscillation with the southern westerlies and the local response to changes in their interplay (Blogs 2019).

Waipuna Cave is a non-commercial cave jointly managed between landowners and the Department of Conservation. This cave is 3560 m long (New Zealand Speleological Society 2018) and 20 m deep from the entrance point. Waipuna is subject to a temperate climate because of its geographical location at latitude 38° 15S' and longitude 175° 06'E. The cave is 214 km south of Auckland (Fig. 2) and the annual mean air temperature in the Waitomo region varies between 12–13 C° with a minimum of 4–5 C° during winter and a maxima between 22–23 C° during summer months (Chappell 2013). The mean annual rainfall at Waitomo is between the 1,600 and 1,800 mm, but the ranges to the west receive over 2,000 mm since most of the rainfall is carried by westerly winds (Chappell 2013). The oldest records found in this cave date to 35,000 BP (B. Ward, personal communication, November 7, 2019) although there is undoubtedly older material, and speleothems are still actively growing.

Geological context

Waipuna Cave is located on an unnamed northeast trending fault west of the southern end of the Hikurangi Fault (Nelson 1973, 1978; Edbrooke 2005). Faults are permeable pathways to focus water flow into karstic landscapes, with these widening over time. To the west of the karst landscape is the Herangi Range, a thrusted block of greywacke basement corresponding to the Murihiku Terrane. This range protrudes 180–240 m above sea level (Nelson 1973).

Fig. 2. Google Earth satellite image of study sites in relation to Auckland and Hamilton (White 2019).

Most of the Waipuna Cave bedrock is composed of Otorohanga Limestone. This limestone formed between 37.8 and 28.1 million years ago in subtidal seaways at 40 to 60 m depth in <20˚C waters. The Otorohanga Limestone is composed of erect robust and delicate branching bryozoans, echinoderm fragments and large benthic foraminifers (Anastas et al. 2006). However, further upstream in Waipuna cave, the bedrock changes to a yellow-brown very fine grained sandstone, which Nelson (1973) has described as the Aotea Sandstone.

Principles of karst geochemistry

Plants expire large quantities of CO_2 from their roots and soil microorganisms also respire CO_2 into the soil pore space. Thus, biological processes act to raise the $_{P}CO_2$ of the soil atmosphere to several percent of an atmosphere. Water passing down through the soil will dissolve this CO_2

$$H_2O + CO_2 = HCO_3^- + H^+$$

When this solution comes into contact with the limestone, the hydrogen ions attack the carbonates

$$H^+ + CaCO_3 = Ca^{2+} + HCO_3^-$$

which results in solution of calcium ions and a disturbance of the chain of equilibria:

$$\begin{aligned} H_2O + CO_2 &= HCO_3^- + H^+ \\ HCO_3^- &= CO_3^- + H^+ \\ CO_3^{2-} + Ca^{2+} &= CaCO_3 \end{aligned}$$

If the soils are shallow, as CO_2 is removed from solution through attack on $CaCO_3$, more CO_2 is replaced from the soil atmosphere (OPEN SYSTEM). However, if the soils are deep and plant roots are isolated from the limestone, the $_{P}CO_2$ will drop substantially, and the pH will rise as the water passes into the limestone (CLOSED SYSTEM).

When the solution reemerges in a cave the $_{P}CO_2$ will readjust to achieve equilibrium with the cave air. If it is higher than the cave air, CO_2 will be lost from solution, forcing carbonates to be precipitated.

$$Ca^{2+} + 2HCO_3^- = CaCO_{3(\text{calcite})} + H_2O + CO_2$$

But if it is lower than the cave atmosphere the reverse will occur and further solution of calcium carbonate will take place. Where calcium carbonate is precipitated formations known as “speleothems” will be deposited. These include stalactites, stalagmites and flowstone. You can find both of these effects in Waipuna Cave. A special problem can arise when large numbers of people occupy small or poorly ventilated caves. As people respire CO_2 the partial pressure rises in the cave atmosphere and can exceed that of the drip waters causing speleothems to redissolve (Figure 3). Other deposits can also occur as a result of the loss of CO_2 (and rise in pH). Look for deposits of black MnO_2 (pyrolusite) in the form of cave varnish on stones, and “cave leather”. These are precipitated by:-

$$Mn^{2+} + H_2O + {}^{1}/{}_{2}O_2 + MnO_{2(\text{pyrolusite})} + 2H^+$$

as the pH rises and oxygen is readily available. Evaporation also causes precipitation of carbonates and sulphates.

$$Ca^{2+} + SO_4^{2-} = CaSO_4.2H_2O_{(\text{gypsum})}$$

Measure the pH of the solutions and decide the extent of the access of soil CO_2 to the limestone in various cave and karst waters.

A supplementary diagram of cave processes in provided in Fig. 3.

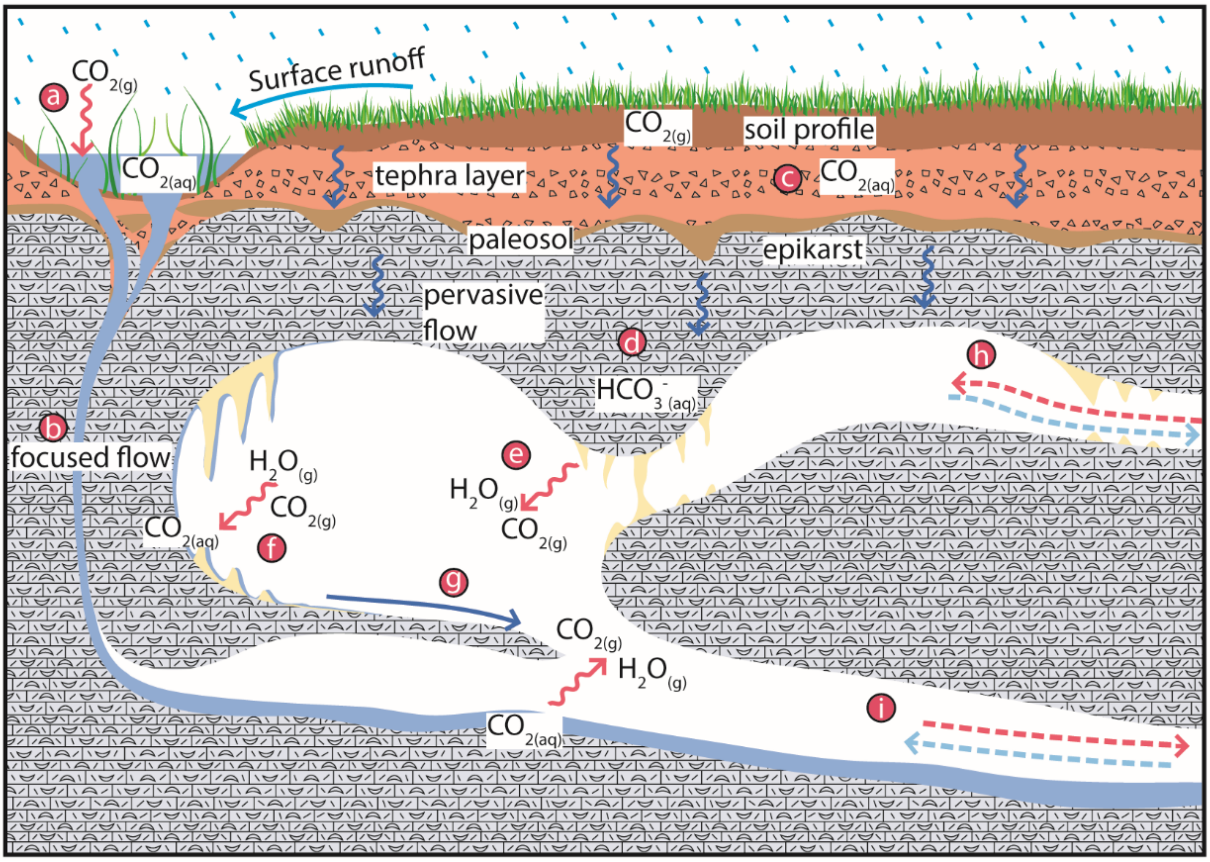


Fig. 3. Summary of cave processes in the Waitomo region with relevance to condensation corrosion. (a) Diffusion of atmospheric CO_2(g) into surface water. (b) Focused (channelized) flow catch surface and groundwater flow into open spaces (Ague 2014), which flow through karst. (c) Diffusion of CO_2(g)¬ from soil respiration (microbial and plant contributions) into percolating water due to the partial pressure gradient between reservoirs (Ford and Williams 2007). The partial pressure of CO_2(g) in percolating water is atmospheric (≈405 ppm, NOAA 2018) while the contribution from soil respiration is in the range between 1,000 ppm and 60,000 ppm this temperate region (Ford and Williams 2007). (d) Once percolation waters pass through the soil horizon, they become more corrosive with the additional dissolved CO_2 contributed by soil respiration. These corrosive groundwaters flow through tephra and reach limestone where calcium carbonate is dissolved between the shell-derived grains (pervasive flow, Ague 2014) and can later find preferential flow paths in fractures. (e) As pervasive flows enter the cave, the groundwater releases CO_2(g) due to the partial pressure difference between cave atmospheric CO_2(g) and the groundwater. This release results in calcite precipitation and the formation of speleothems. (f) Condensation films form on speleothems and cave walls depending on the cave atmospheric conditions. CO_2(g) in the cave atmosphere diffuses into and out of theses condensate films which dissolve or precipitate calcite, respectively. (g) When condensation forms a film thick enough, it will flow, transporting dissolved Ca^{2+}(aq) and CO_3^{2-}(aq) ions with it. (h) The red dashed arrow indicates the direction of air flow during summer in a dual entrance cave. Air enters from the top entrance as the cave air is cooler and therefore denser. (i) In contrast, the blue dashed arrows indicate the airflow direction in winter; when the cave air is warmer (less dense) than the air outside. Figure taken from White (2019).

Monitoring of Waipuna Cave dripwaters for climate signals

Cave microclimatic and geochemical monitoring is essential for correct interpretations of proxy time series from speleothems with regard to past climatic and environmental dynamics. A complex cave monitoring programme has been undertaken in Waipuna Cave over the last three years. The caves' location in the North Island of New Zealand provides the opportunity to study the past expression of the southern westerlies and the El Niño-Southern Oscillation (ENSO). Our work aims to characterize the hydrological response of Waipuna Cave to atmospheric circulation dynamics in the southwestern Pacific region in order to improve the interpretation of palaeo-environmental reconstructions from this cave.

Cave air temperature and CO_2, water isotopes ($\delta^{18}O$, δD, D-$_{excess}$, $^{17}O_{excess}$) and trace elements (Mg/Ca, Sr/Ca), drip rates, and water temperatures are collected continuously and at monthly intervals from 10 drip sites inside Waipuna Cave. Based on the drip response dynamics to rainfall and other characteristics we identify three hydrological pathways in Waipuna Cave: diffuse flow, combined flow, and fracture flow. Water isotopes do not reveal seasonal variability, but show higher values during severe drought. Dripwater $\delta^{18}O$ values are very narrow and reflect the mean isotopic signature of precipitation (Fig. 4), testifying to rapid and thorough buffering in the epikarst. Mg/Ca and Sr/Ca in dripwaters are predominantly controlled by prior calcite precipitation (PCP): PCP is strongest during austral summer (December-February), reflecting drier conditions and lack of effective infiltration; and is weakest during the wet austral winter (July-September). These elemental ratios are particularly sensitive to ENSO conditions because of the interplay of congruent/incongruent host-rock dissolution, becoming manifest in lower Sr/Ca in above-average warmer and wetter (La Niña-like) conditions. Our microclimatic observations at Waipuna Cave therefore provide valuable baseline data for the interpretation of speleothem proxy records with a view to the past expression of Pacific climate modes.

Unpublished data from dripwater monitoring in Waipuna Cave are provided in Figs. 4 and 5. The hydrological significance of these data will be discussed during the field trip.

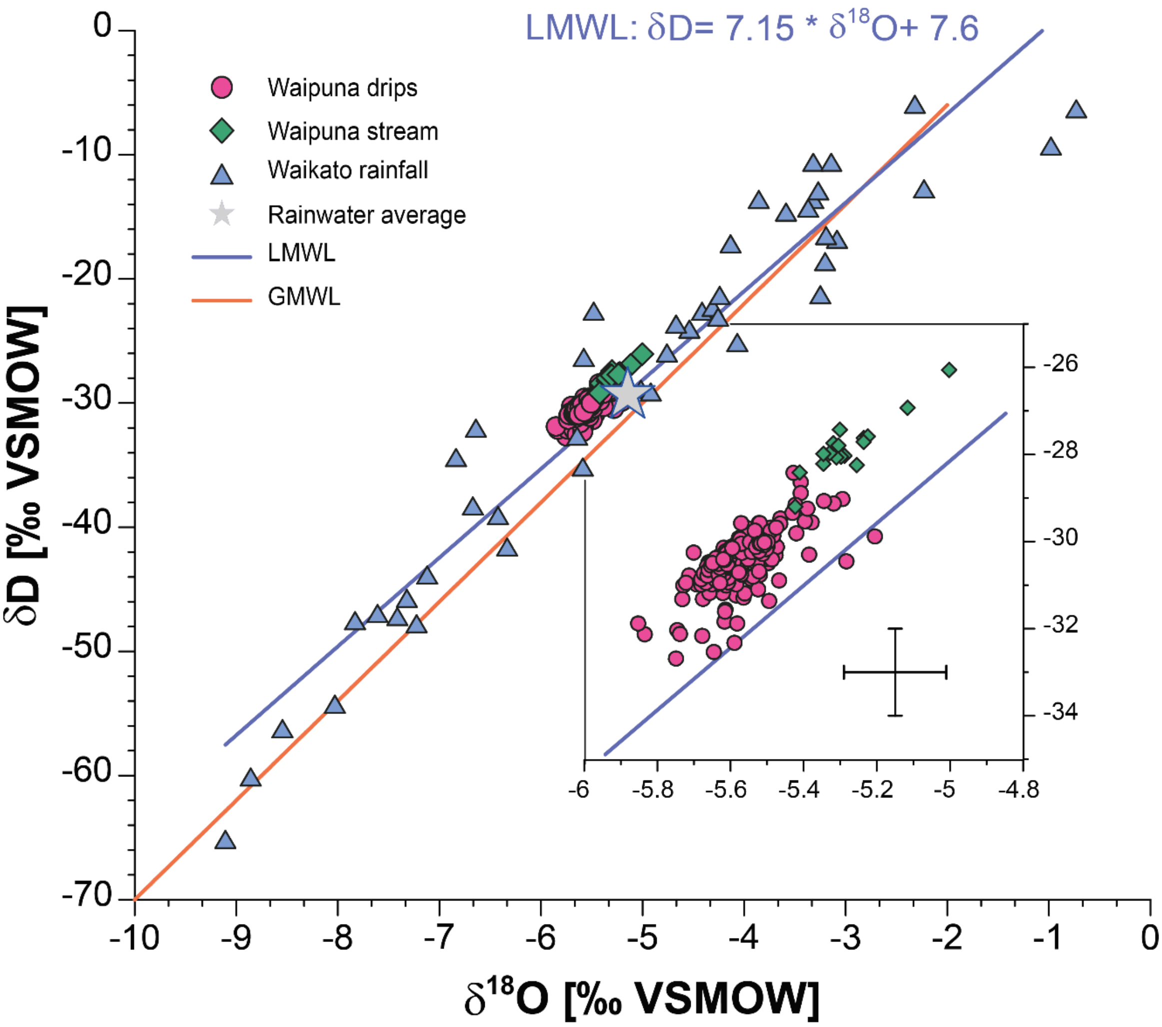


Fig. 4. Cross-plot of δD versus δ18O in dripwater (pink circles), the Waikato region precipitation (blue triangles), and Waipuna stream (green diamonds). All cave waters fall in a very narrow range (inset) on the Local Meteoric Water Line (blue line). The cross in the inset shows the 2σ uncertainties for δ18O and δD.

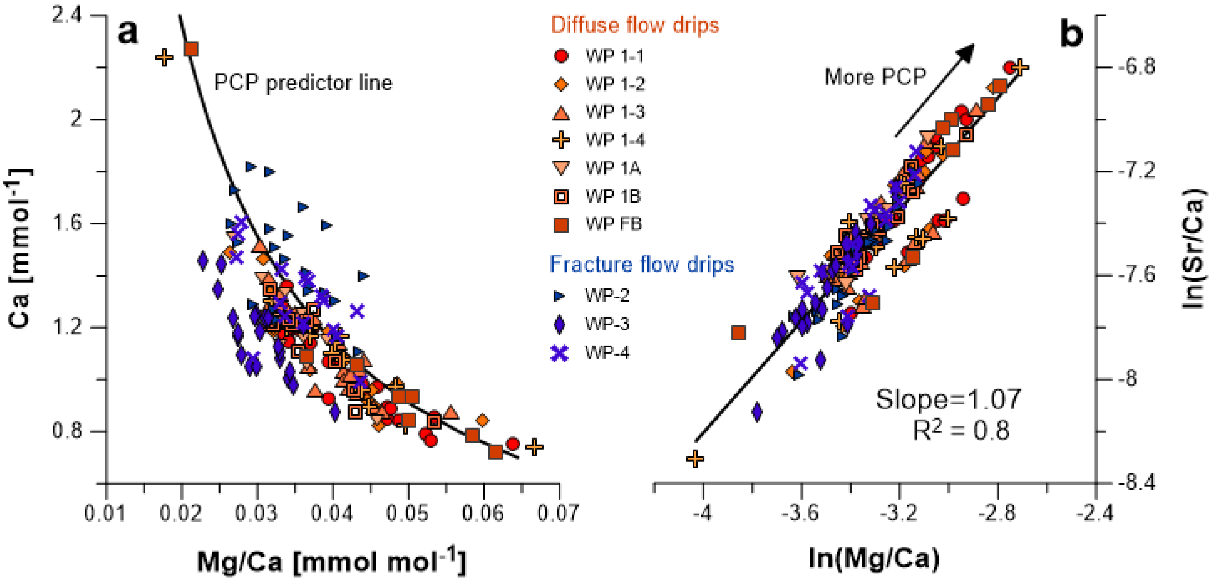


Fig. 5. (a) Ca concentration vs. Mg/Ca, and (b) Sr/Ca vs. Mg/Ca ratios for all Waipuna Cave waters sampled during the monitoring period October 2016 to January 2019. The orange symbols correspond to diffuse flow drip sites and blue symbols signify fracture flow drip sites.

References

Ague, J.J. 2014. Fluid flow in the Deep Crust. In: Holland, H.D., Turekian, K.K. (editors), Treatise on Geochemistry, Second ed. Elsevier, Amsterdam, pp. 203-247.

Anastas, A.S., Dalrymple, R.W., James, N.P., Nelson, C.S. 2006. Lithofacies and dynamics of a cool-water carbonate seaway: mid-Tertiary, Te Kuiti Group, New Zealand. Geological Society, London, Special Publications 255(1), 245-268.

Blogs, E. 2019. Imaggeo on Mondays: Our QUEST for innovative tools to understand changing environments and climates. https://blogs.egu.eu/geolog/2019/06/10/imaggeo-on-mondays-our-quest-for-innovative-tools-to-understand-changing-environments-and-climates/

Chappell, P.R. 2013. The climate and weather of Waikato. NIWA Science and Technology Series 61, 40 pp.

Edbrooke, S.W. (compiler) 2005. Geology of the Waikato area. Institute of Geological and Nuclear Sciences 1: 250,000 map 4. Institute of Geological and Nuclear Sciences, Lower Hutt. 1 sheet + 68 pp.

Ford, D., Williams, P. 2007. Karst and Geomorphology, Revised ed. Wiley, Chichester, England.

Nelson, C.S. 1973. Stratigraphy and sedimentology of the Te Kuiti Group in Waitomo County, South Auckland. Unpublished PhD thesis, University of Auckland, Auckland.

Nelson, C.S. 1978. Stratigraphy and paleontology of the Oligocene Te Kuiti group, Waitomo County, South Auckland, New Zealand. New Zealand Journal of Geology and Geophysics 21, 553-594.

New Zealand Speleological Society 2018. Cave Statistics. http://caves.org.nz/cave-statistics/ (retrieved 26 September, 2018).

NOAA 2018. Trends in atmospheric carbon dioxide. https://www.esrl.noaa.gov/gmd/ccgg/trends/ (retrieved 20th of September, 2018).

White, J. 2019. Quantifying condensation corrosion in the Glowworm Cave, Waitomo. BSc (hons) thesis, The University of Waikato.

Geosciences 2019

Annual Conference of the Geoscience Society of New Zealand

Field Trip 2

Hamilton Basin Faults

28th November 2019

Leaders: Vicki Moon and Francesca Spinardi

School of Science, University of Waikato, Private Bag 3105, Hamilton 3240

Citation:

Moon, V.G., Spinardi, F. 2019. Hamilton Basin faults. In: Lowe, D.J., Pittari, A. (editors), Field Trip Guides. Geosciences 2019 Conference, Hamilton, New Zealand (24-29 November). *Geoscience Society of New Zealand Miscellaneous Publication* 155B, pp. 1–15.

Geoscience Society of New Zealand Miscellaneous Publication 155B

ISBN (online): 978-0-473-49901-3

ISSN (online): 2230-4495

HAMILTON BASIN FAULTS

Itinerary and route

8.30 am – Depart university

8.35–9.00 am – **STOP 1**: Edinburgh Road

9.20–9.45 am – **STOP 2**: Rototuna

9.55–10.45 am – **STOP 3:** Day's Park (includes toilet stop, Swarbrick Landing)

11.00–11.30 am – **STOP 4:** Osborne Road

11.45 am–12.30 pm – **STOP 5:** Kay Road

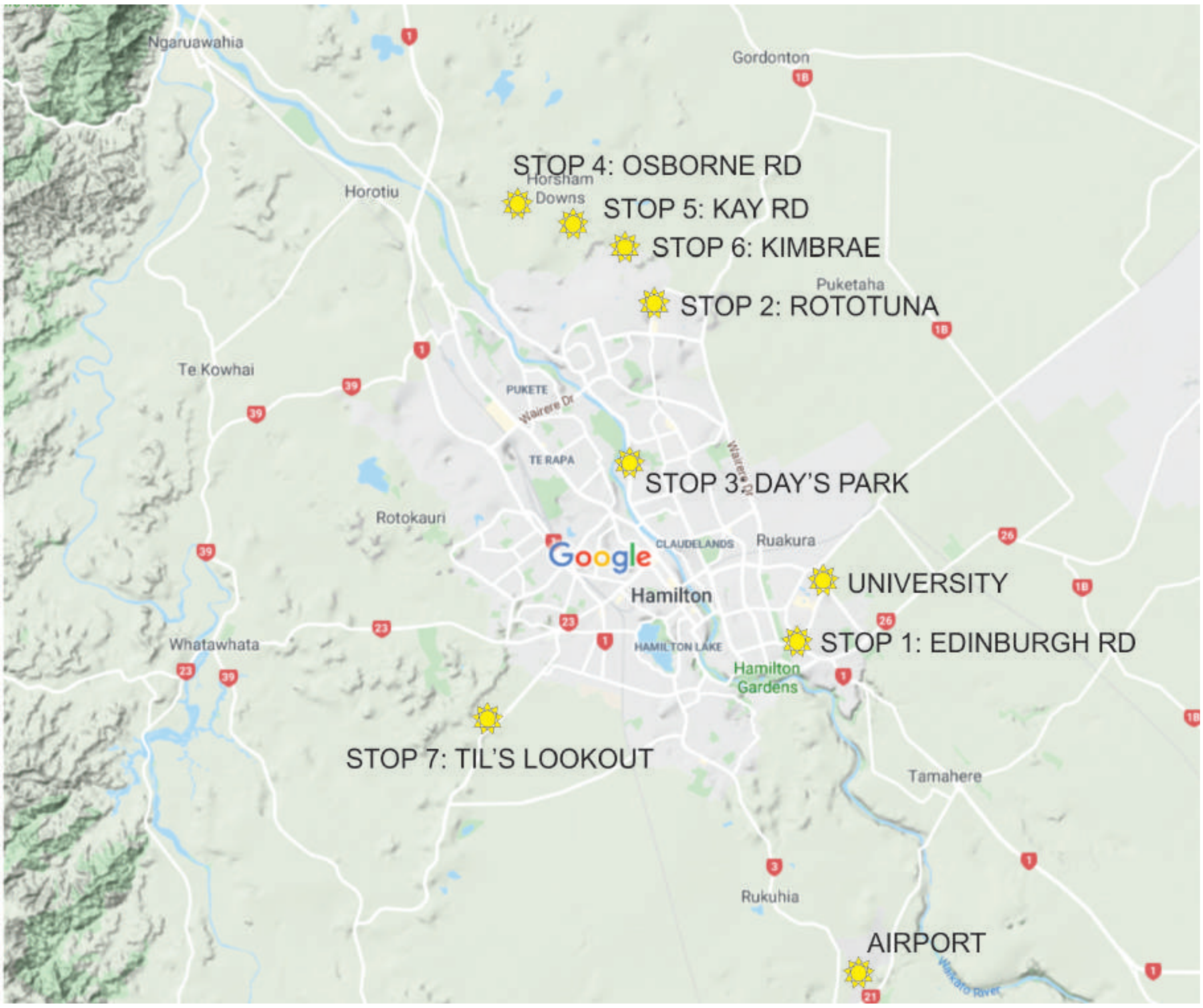
12.45–1.15 pm – **LUNCH:** Rototuna shops/Grosvenor Park (toilets available)

1.30–2.00 pm – **STOP 6:** Kimbrae

2.30–3.00 pm – **STOP 7**: Til's Lookout

3.30 – Hamilton Airport

4.00 pm – Return to university



Introduction

Prior to 2015, our conventional wisdom said that there were no exposed faults within the Hamilton Basin, the assumption being that any faults were covered by the extensive Pleistocene–Holocene sedimentary basin infill materials. A local consultant phoned in April 2015 and said “I think we’ve found a fault”. We visited and logged the site and tried every explanation for it to not be a fault (this was changing our paradigm for the relatively recent development of the basin) but, by elimination, we eventually decided that faulting was the best explanation.

Having identified a fault exposure, we “looked up” (examined the LiDAR), and could see a distinct ridge running southwest-northeast through central/north Hamilton City that was so blindingly obvious it was hard to credit that we had not seen it before. This feature, when linked with (1) a known geothermal system, and (2) a dog-leg offset in the Waikato River, made us pretty confident that we were looking at a fault trace. Since then we have mapped the river floor and walls using shallow seismics and geological mapping, pored over the LiDAR to look for geomorphic signals of faulting, reinterpreted oil prospecting seismic data from the 1970s, undertaken a few electrical resistivity soundings, and, most importantly, mapped and analysed several stunning cuttings prepared as part of the Hamilton Bypass section of the Waikato Expressway development. We are now confident that a complex network of faults occurs throughout the basin.

During this trip we will visit some of our key sites and outline where we are at in terms of understanding the nature and pattern of faulting in the basin, and where we are not confident in terms of the timing of the movements. We will also highlight some of the difficulties of working in an area smothered in young sediments and tephra deposits, both from the point of view of exposure, and the effects of the deposits on fault development and expression, together with the difficulties of working in an urban environment. Unfortunately, relying on development sites means that cuttings are open for short periods then quickly topsoiled and planted. We will therefore end up visiting a number of grassy slopes.

STOP 1: EDINBURGH RD

This is a current development site just down the road from the university. We are pretty certain that there is a fault in the site, but are still in the process of collecting as much data as we can. Interpretation will come later.

At time of writing (31 October 2019), the slope was still open with the sequence well exposed. However, topsoiling has now been completed. The sequence consists of disturbed soils at the top, overlying Hamilton Ash beds that have a distinctive grey/white layer (bed H1) at their base. This layer is the Rangitawa Tephra, aged ~ 340,000 years (Pillans et al. 1996; Lowe et al. 2001) and is a key marker bed for our work. The Hamilton Ash beds comprise weathered, clayey tephra deposits >c. 50,000 years old (on the basis of overlying c. 50-ka Rotoehu Ash) and ≤c. 340,000 years (e.g. Lowe 2019 and references therein).

Below the Rangitawa Tephra is the Walton Subgroup (Kear and Schofield 1978) that consists of:

1. a sequence of older and weathered, clay-rich tephras, the Kauroa Ash beds, which have a very strongly developed paleosol on top aged >c. 0.78 Ma on the basis of its reversed magnetic polarity (Horrocks 2000; Lowe et al. 2001); elsewhere in western Waikato the the Kauroa Ash beds date back to 2.3 Ma (Briggs et al. 1989);
2. sequence of volcanogenic alluvial sediments, often stained red or pink, sometimes pumiceous, and often containing layers of very slippery white/cream clays;
3. ignimbrite – various ignimbrites are identified within the basin including Ongatiti (c. 1.23 Ma), Kidnappers (c. 1.01 Ma), and Rocky Hill (c. 1.0 Ma) ignimbrites; the distribution of ignimbrites in the basin is complex, and there are clearly locally reworked pyroclastic materials interbedded with them and other deposits.

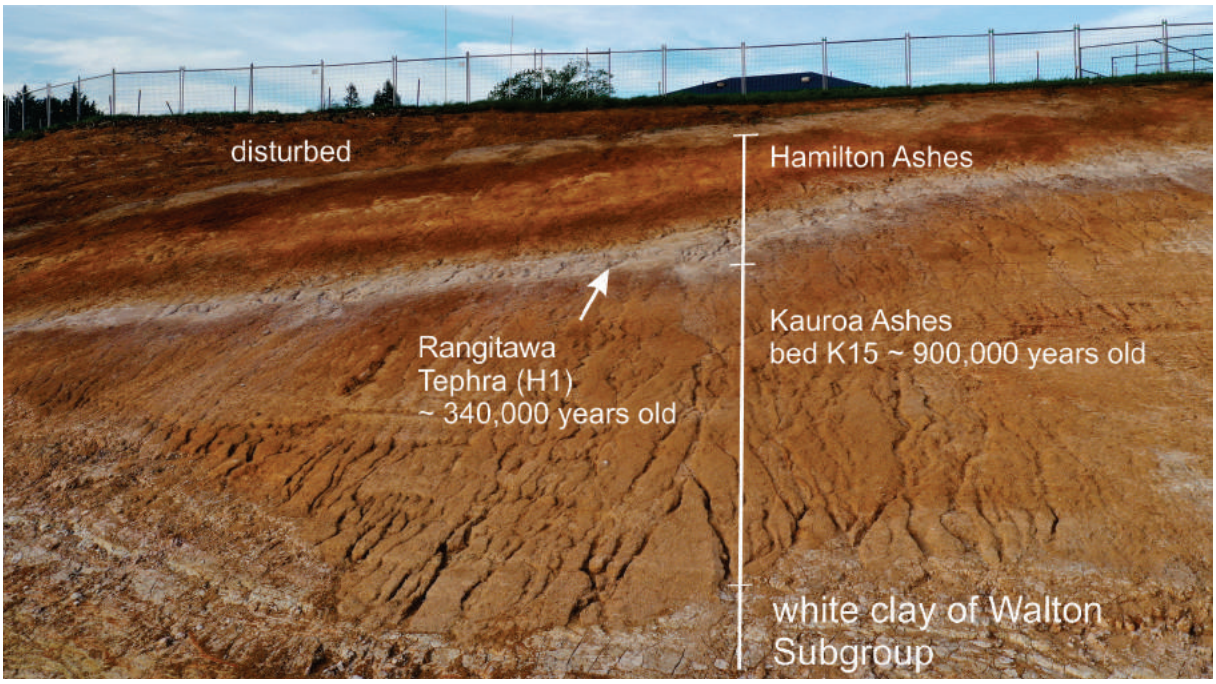


Figure 1: Drone image of the slope behind Edinburgh Road. The base of the Hamilton Ash sequence is marked by a very distinctive pale grey layer, the Rangitawa Tephra (c. 0.34 Ma). This is an important chronostratigraphic marker bed for our work.

STOP 2: ROTOTUNA

This is where we began following a phone call in 2015: an unassuming small cutting in a new subdivision.

The zone is approximately 4 m wide, comprises four main strands of a fault trace, with several smaller strands linking between them, and has a measurable vertical offset across the zone of approximately 0.5 m. Unfortunately, the top layers of the sequence were removed before the vertical exposure was cut and hence limited stratigraphic information is available to date the movement of this fault. The white layers at the top of the cutting, which are clearly displaced by the fault movement, are tentatively identified as beds K12/K13 of the Kauroa Ash sequence (correlated with Ongatiti Ignimbrite: Horrocks 2000; Lowe et al. 2001) and aged c. 1.23 Ma. Soil infilling down the fault traces is identified as part of the upper (younger) Hamilton Ash sequence because of the soil's dark reddish brown colouration; the lower, older Hamilton Ash beds are pale (yellowish-brown) coloured (Lowe 2019). This relationship suggests that the fault movement is <250,000 years, but is not definitive.

From the exposure, a component of normal (extensional) movement can be identified based on the vertical offset. The four apparent main strands have an average dip direction of 089° (strike 359°), while the two measurable minor strands have a dip direction of 351° (strike 081°). All measured strands have steep dips ranging from 51° to 84°. Stereonet analysis indicates dominantly strike-slip movement. Note that splintering, splitting, and spreading are expected as faults develop through weak cover deposits (and we have virtually nothing "strong" exposed in the basin).

This site does not lie immediately along the line of the ridge of the main fault system, but suggests some form of splinter from the main lineament.

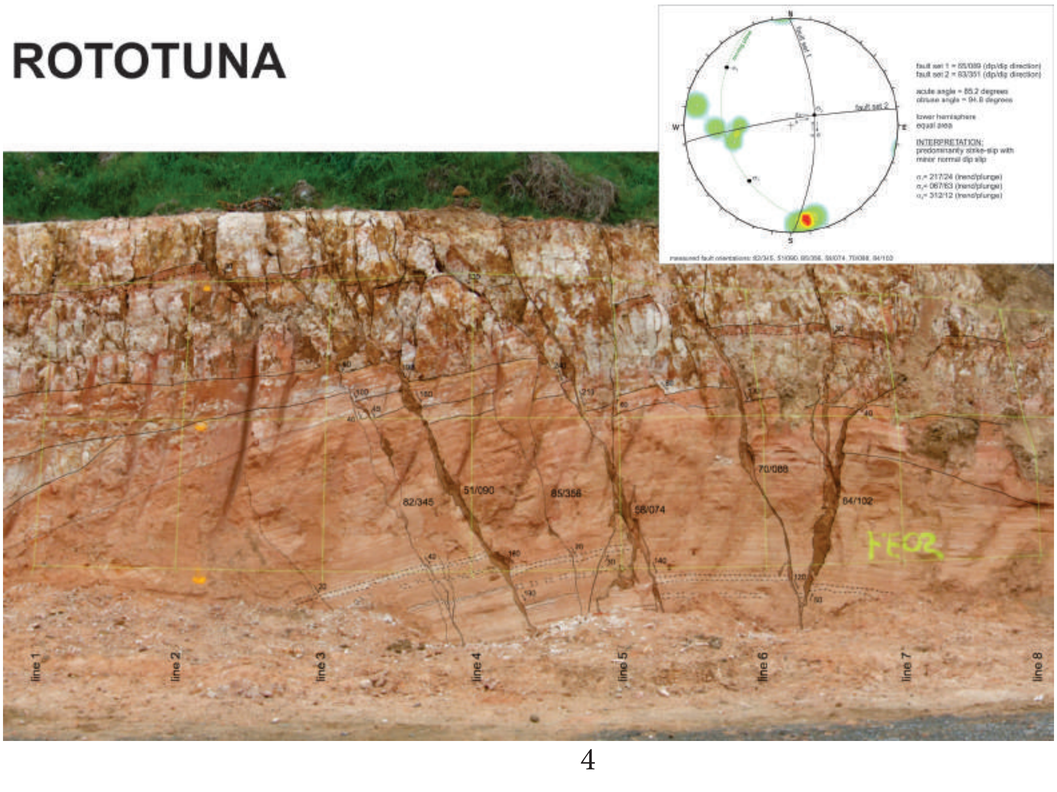


Figure 2: Image and stereonet analysis of initial fault zone identified at Rototuna.

STOP 3: DAY'S PARK

Geomorphic evidence has been critical in extending the known fault positions to lineations that may reflect the main fault traces. The Waikato River and its tributaries in particular provide pathways through many of the young sediments that display a number of interesting geomorphic features such as knickpoints, offsets, and gully beheadment. Unfortunately, none of these lines of evidence give unequivocal support for faulting, as geomorphic features can usually have multiple potential explanations. Putting together as many lines of geomorphic evidence as possible, however, suggests that the river has been affected by fault movement since (or during) entrenchment over the last c. 18,000 calendar (cal.) years.

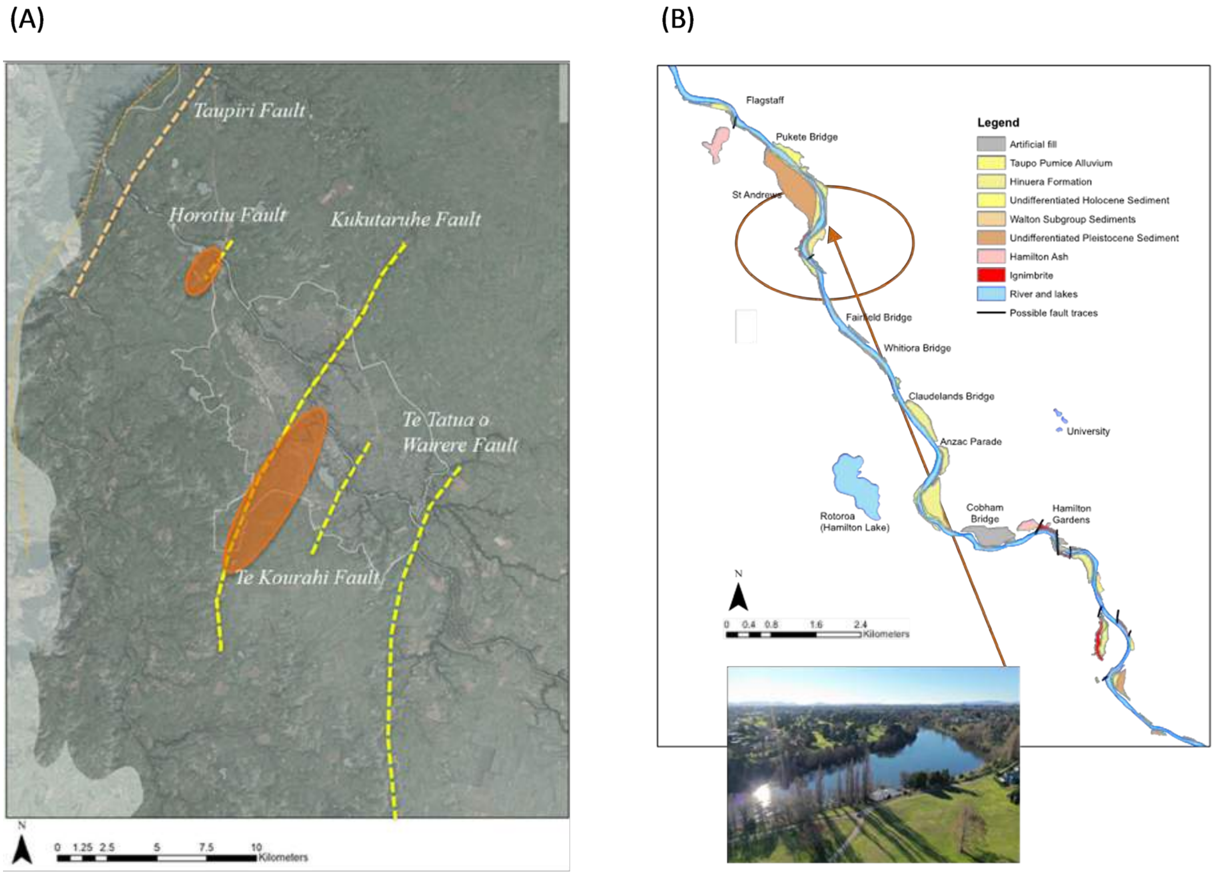


Figure 3: (A) Kukutaruhe Fault zone identified based on LiDAR information. (B) A "dog-leg" in the Waikato River at Day's Park provides geomorphic and geological evidence of this fault trace.

Day's Park provided an "ah-ha" moment at the start when we examined the LiDAR initially. This area is located on a sharp "dog-leg" in the river. The river at this point is quite deeply entrenched into the Hinuera Surface. Day's Park itself lies on volcanogenic sediments of the Hinuera Formation (Hume et al. 1975) aged c. 22,000 to 18,000 cal. years BP (Hogg et al. 1987; Manville and Wilson 2004), which were formerly mined as a gravel source for construction in Hamilton; the immediate geomorphology in the park area is thus highly modified.
On the eastern side of the river (true right bank) immediately south of Day's Park are fluvial

sediments, whilst on the western side (true left bank) is a steep bank of ignimbrite. The river takes two sharp turns at this point – to the east just south of the park, and back towards the west at the northern end. Our interpretation of this dog-leg is not strike-slip offset since the entrenchment of the river (that would be scary), but that the harder ignimbrite has been uplifted along the fault strike in the past, and the river has encountered this as it entrenched into the surface. It has been forced to migrate around the upstanding block of more resistant material.

Supporting data

At this point we (1) searched existing geophysical data, and (2) undertook CHIRP shallow seismic survey along the river, together with mapping riverbank geology.

From Cambridge to Taupiri, we identified 26 "targets" in our seismic traces that represented some discontinuity in the riverbed sediments that may represent faults. Fortunately, we had pre-existing multibeam and side scan sonar images of the riverbed to help interpret these traces.

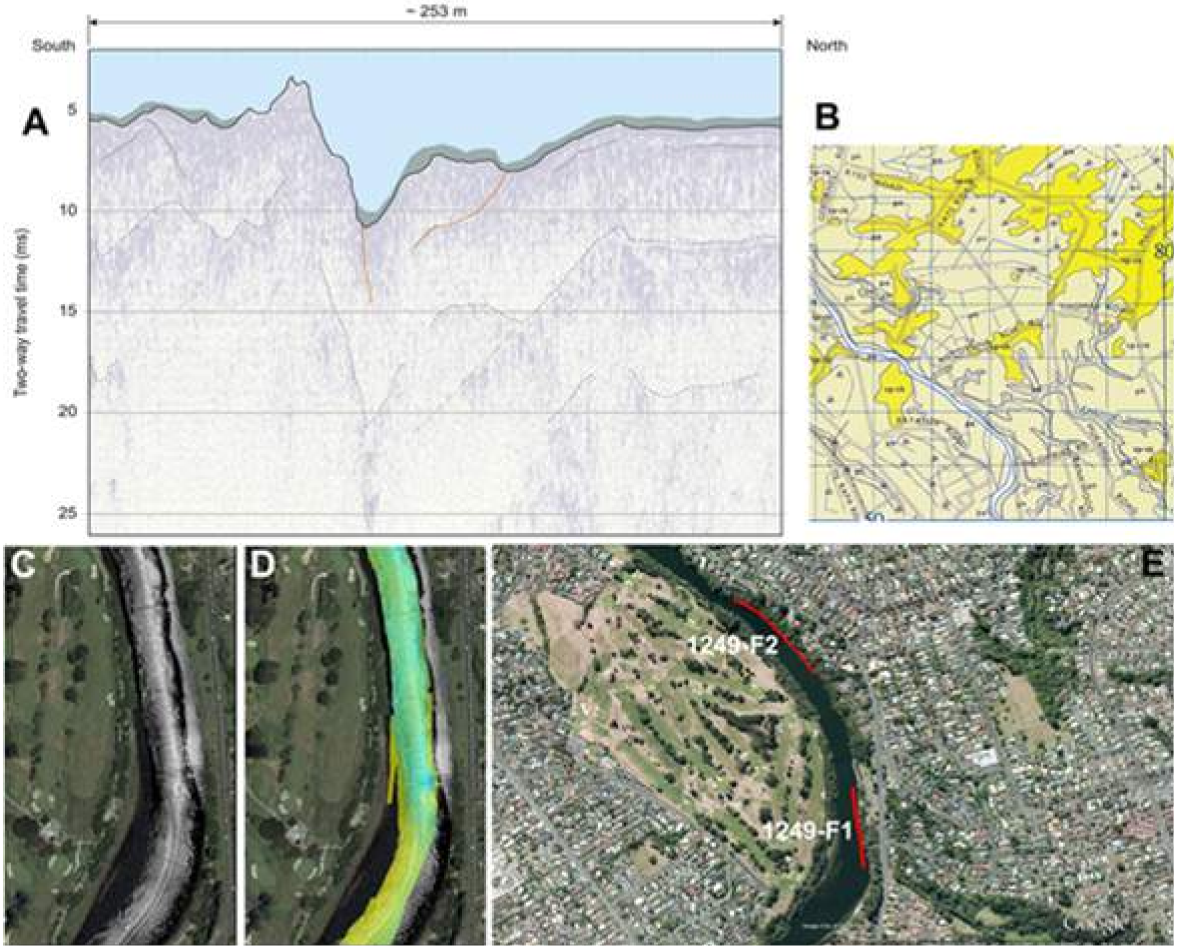


Figure 4: Kukutaruhe fault zone. (A) Seismic section showing multiple discontinuities below the riverbed near Swarbrick Landing in section 1249-F1 – the low-angle trace may reflect the fact that the river is running parallel to the fault for part of this section, (B) N56 surficial geology, (C) sidescan image, (D) multibeam image, and (E) Google Earth locations.

A series of deep seismic surveys was undertaken in the northern part of the basin in the 1970s as part of oil exploration; these surveys were accompanied by two deep boreholes. Unfortunately, only scanned copies of unprocessed traces exist, and so the interpretation of the old seismic data is sketchy at the best, but from looking at the two long traces running roughly north-south we can recognise features underlying all of the hills.

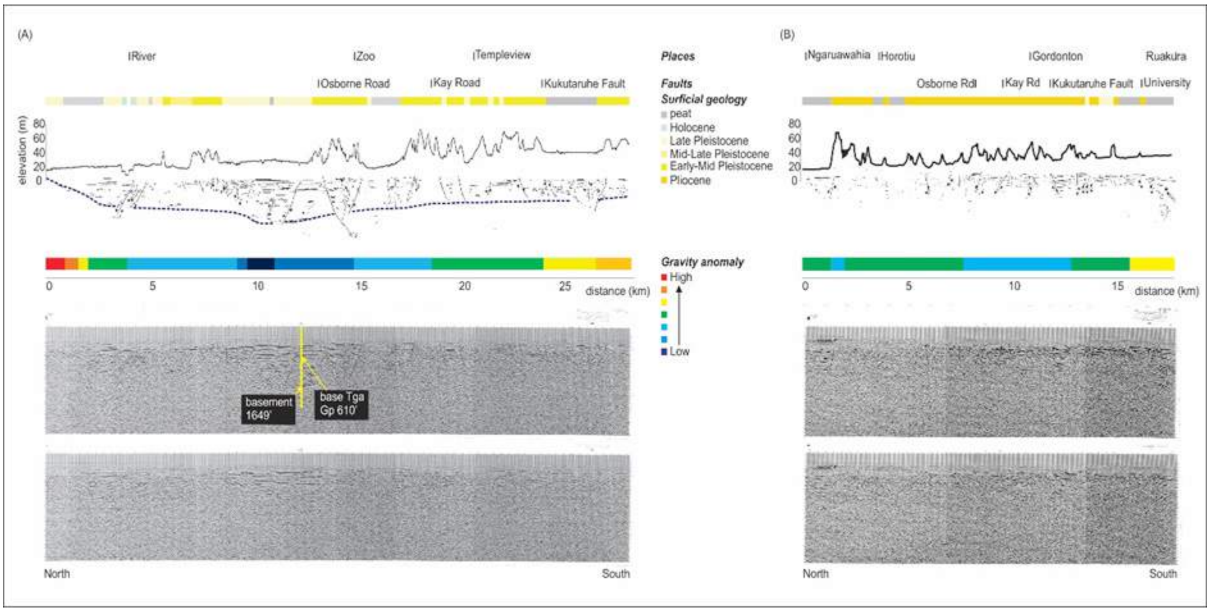


Figure 5: Interpretation seismic reflection lines from PR569 (Liles 1971). (A) Line PR569-2 running along the western margin of Hamilton City (B) Line PR569-16 running to the east of Hamilton City. Original and interpreted images are shown at the base of the diagrams, with key stratigraphic horizons identified from borehole Te Rapa-1 (Liles 1971) marked on (A). Indicative gravity anomaly strips are shown with colours derived from FrOGTech (2011). Interpreted sections, including depth to basement for (A) marked with a dashed blue line are overlain with geomorphology (vertical exaggeration ~ 30x), and surficial geology is marked with a coloured strip. Fault traces identified on land are indicated, and several geographic locations are projected onto the line and marked for reference.

Airborne gravity data (FrOGtech 2011) shows that the depth to basement is deep in the northern portion, shallowing to the south. This gradient in depth is supported by seismic tests recently undertaken by our engineering colleagues. From the LiDAR, distinctive features at the southwest end of the Kukutaruhe Fault zone appear to be volcanic structures (maars). These were originally mapped by Kear and Schofield (1966), but removed from more recent geological maps (Edbrooke 2005). Aeromagnetics suggest that there is magnetic material below them, but our drilling so far has not confirmed a volcanic origin.

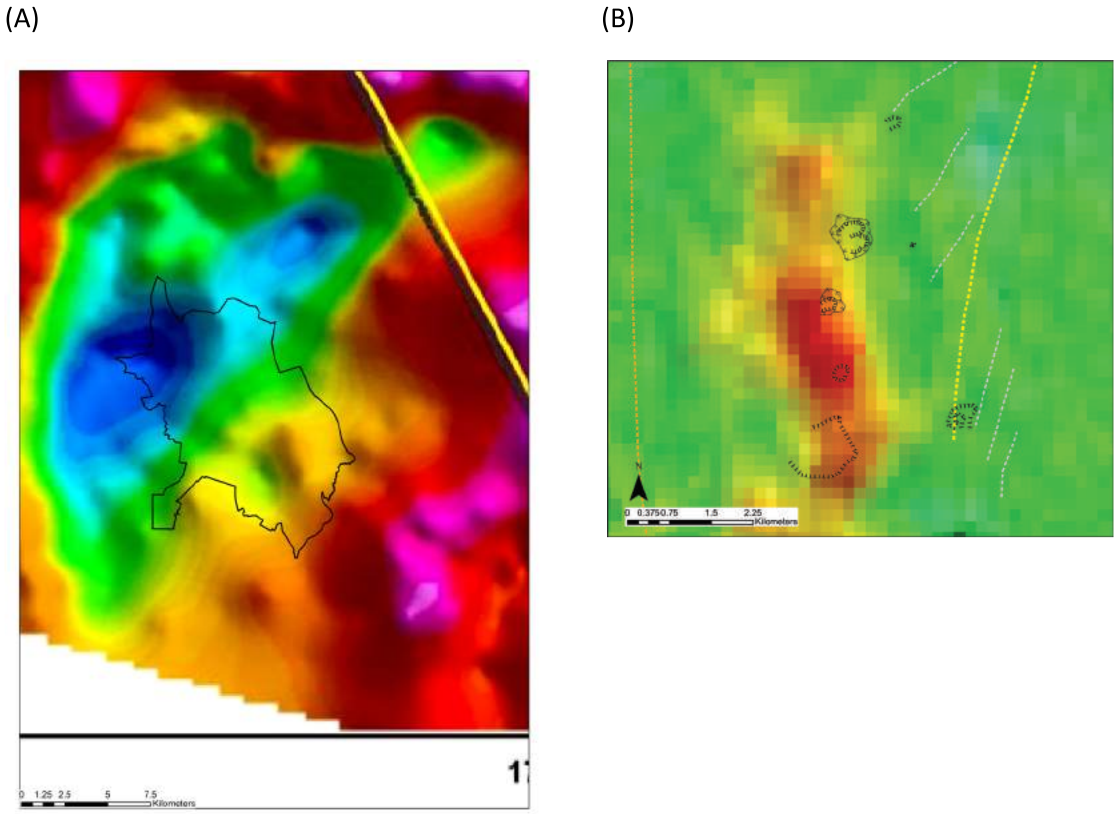


Figure 6: (A) Gravity anomaly for the Hamilton Basin (Hamilton City boundary shown in outline). (B) Georectified aeromagnetics map at Koromatua with the geomorphological map interpretation superimposed.

STOP 4: OSBORNE RD

The cutting at Osborne Road showed two sub-parallel faults that run at very shallow angles to the cutting face. Displaced materials suggest normal displacement; no evidence exists to determine any strike-slip movement.

Between the two faults is a stretch of highly deformed materials (including vertical tilting of large blocks) overlying a distinctive zone of bedded alluvial sediments (red/pink discolouration makes these clay-rich beds stand out very clearly and identify them as Walton Subgroup sediments). Orientation measurements on the bedding surface at the top of the alluvial sediments suggests gentle folding. Our interpretation is of a relay between two developing, almost parallel, faults, with folding and ductile deformation in this transfer zone.

The upper tephra layers are partially removed by the earthworks so it is not immediately clear whether the tephras are displaced by movement along the faults, or whether they are simply mantling a paleotopography. We think they are displaced, but we cannot put an age on them.

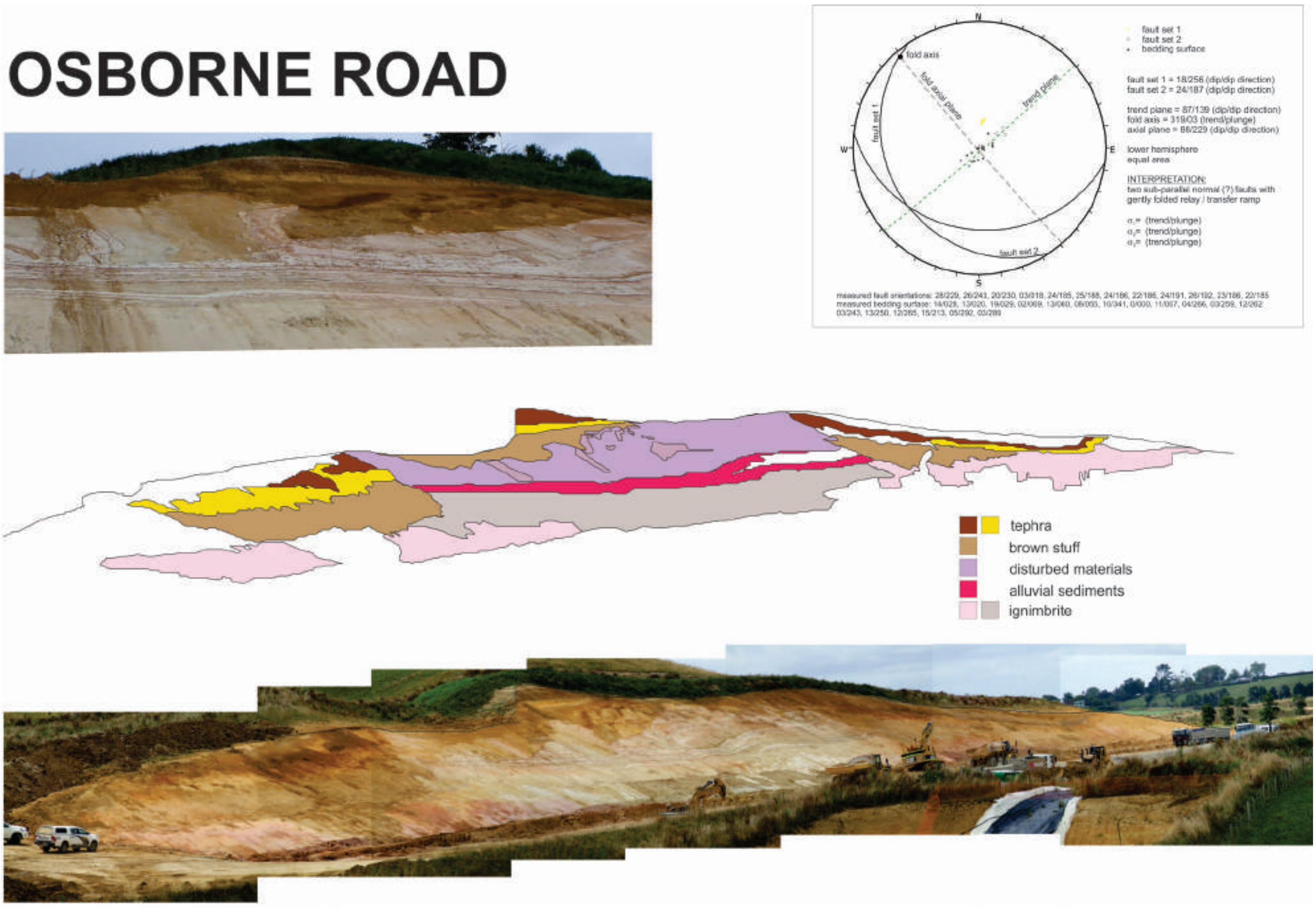


Figure 7: Osborne Road Expressway cutting site.

STOP 5: KAY ROAD

Kay Road overbridge site was the first of the Expressway cuttings available. The site showed a series of normal faults, forming horst and graben structures that extended across the site. Although the overall graben structure appeared quite simple, there was very complex deformation of the materials within the graben.

Faults extended through the full thickness of the Kauroa Ash beds. Within the weathered ash materials the faults were frequent and odd shapes. Many faults could also be recognised deeper into the underlying Walton Subgroup alluvial materials. These faults were more distinct, and their offset was marked by well defined displacement of recognisable sedimentary layers.

When examining this sequence we were unable to identify any offset in the distinctive Rangitawa Tephra (H1) at the base of the Hamilton Ash sequence. This pale grey layer clearly sagged into the graben, but no brittle-type fractures could be identified extending across the Rangitawa Tephra nor into the overlying Hamilton Ash beds.

A clear graben structure on the western face showed conjugate jointing with almost pure normal dip-slip movement; the eastern wall proved more difficult to interpret due to a lack of suitable measurement sites. The western wall suggests a major principal stress from the northeast, steeply dipping, and almost horizontal minor principal stress.

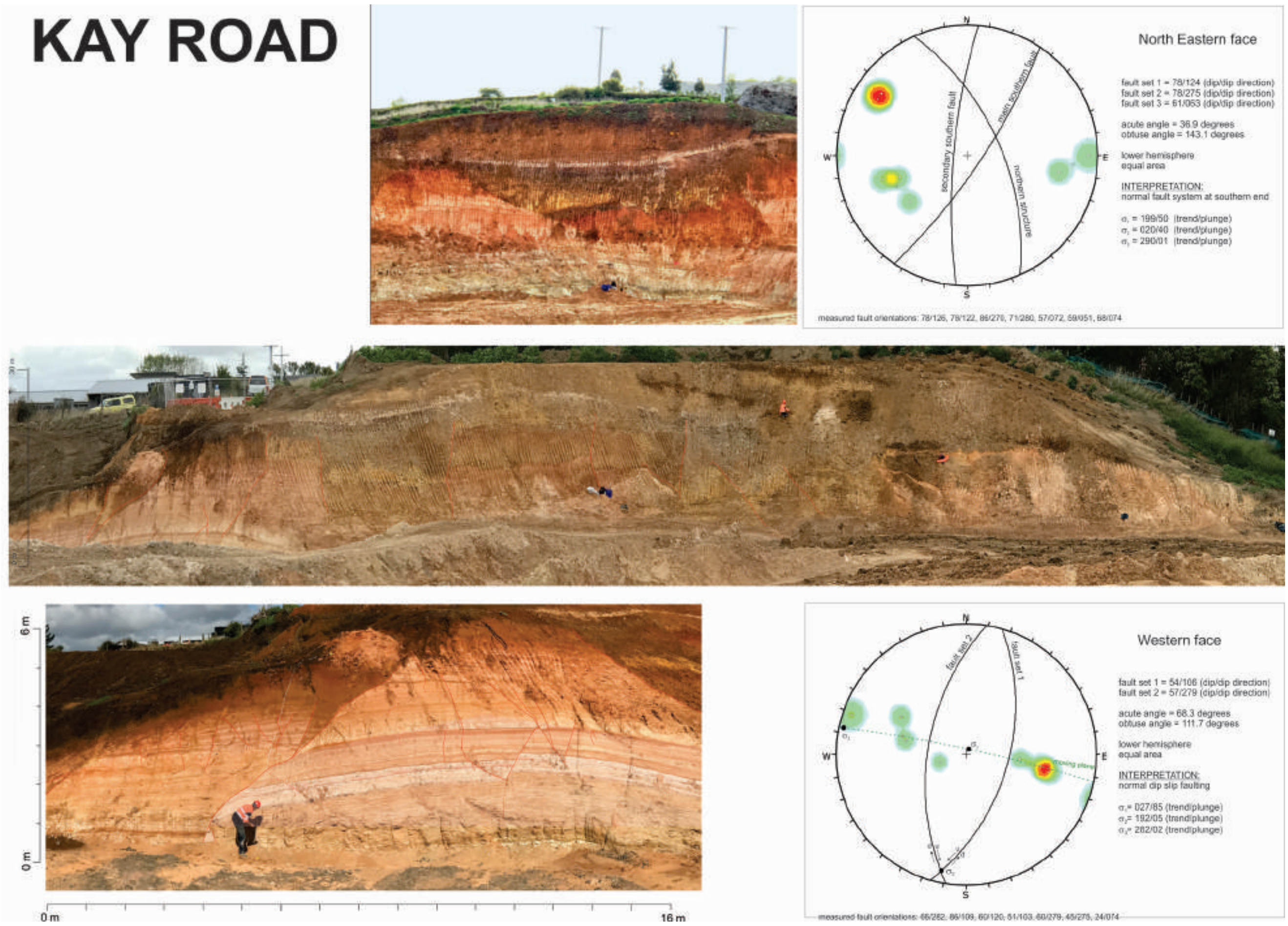


Figure 8: Kay Road Expressway cutting site.

STOP 6: KIMBRAE

Kimbrae is a complex site that will be described when we reach the stop.

STOP 7: TIL'S LANDING - OVERVIEW

What we think we do know now:

We are convinced of a complex network of faults in the basin. They generally run SW–NE, with some curvature. Most of the faults show at least a component of normal displacement in cutting faces. However, we believe that in a number of instances there is evidence of strike-slip movement. It is unclear whether strike-slip is dominant.

Principal stresses generally show σ_1 to be steeply plunging from the NE direction, with σ_3 sub-horizontal. These stresses indicate an extensional environment, but are only measurable for the simplest fault exposures (the ones that show most normal displacement).

Below is our latest map, with indications of confidence of our identifications. Two key systems are clear: one along the ridge we are standing on at Til's Lookout; the other that we can see to the southeast which runs through the Hamilton Gardens and University of Waikato. There are likely a number of splinters associated with them.

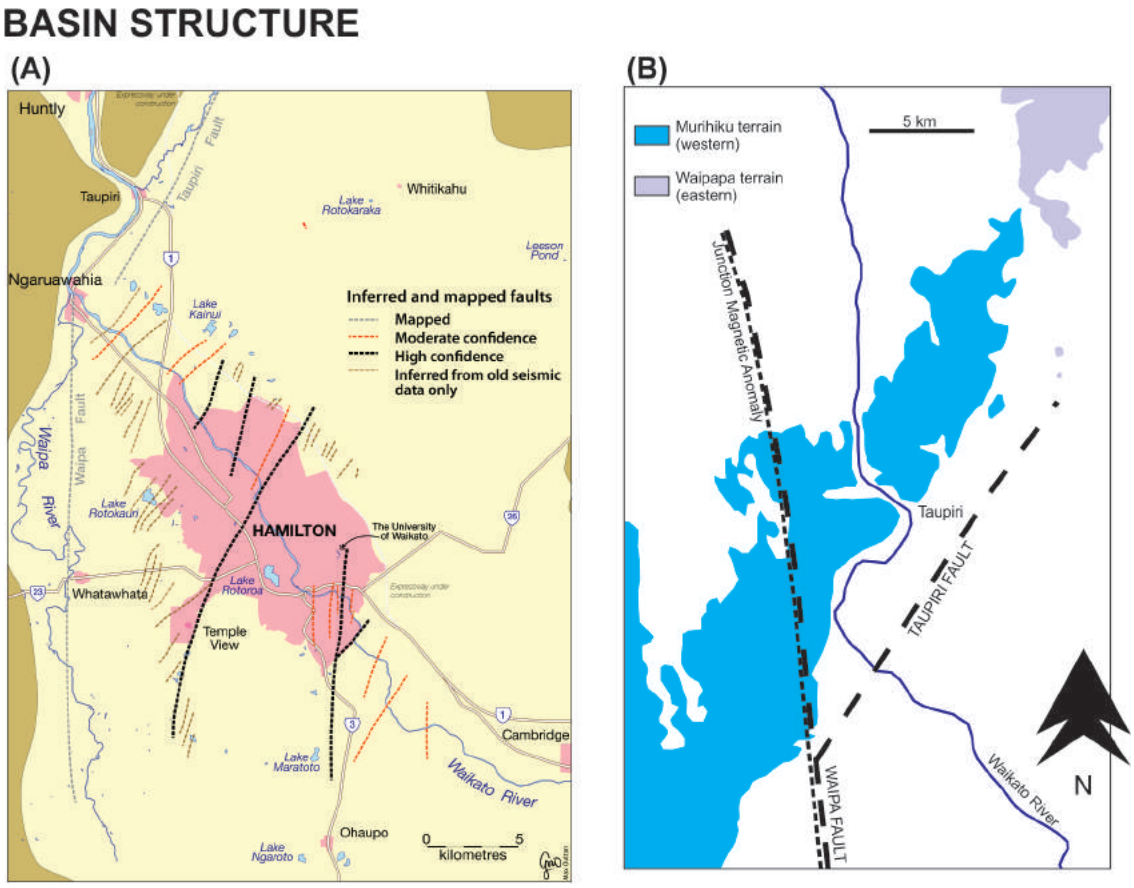


Figure 9: (A) Our most recent map of inferred faults. Reality is almost certainly much more complex. (B) Waipa Fault, Junction Magnetic Anomaly, and basement terranes at the northern boundary of the Hamilton Basin.

What we don't yet know (but we have some new avenues to explore…):

1. We cannot yet put the faults into a model of the overall basin structure.
    a. The Waipa Fault, bounding the western margin of the Hamilton Basin, follows the Junction Magnetic Anomaly (JMA) beneath the eastern rim of Pirongia. To the south there is serpentine recognised along the JMA at PioPio, but there is no, to limited, vertical displacement along the Waipa Fault at this point.

Only in the Hamilton Basin area does the Waipa Fault show significant vertical offset.

   b. The Hakarimata Range, which separates the Hamilton Basin from Huntly in the north, is comprised of Murihiku terrane rocks on the “wrong” (eastern) side of the JMA. Kirk (1991) has proposed that these rocks are rotated across the JMA in some way.

   c. The Taupiri Fault is postulated along the southern margin of the Hakarimata Range, but little real evidence for it exists.

2. Timing – geomorphic evidence suggests displacement of Hinuera Formation sediments (which also show some evidence of paleoliquefaction: Kleyburg et al. 2016). However, we have not yet found a site we are willing to pour money into for trenching that may give a history of recent movement.

3. However, liquefied tephra layers and ash-grade injectites, projected downwards, occur systematically within undeformed organic sediments in c. 20,000 cal. year-old lakes in the Hamilton Basin (Fig. 10). We suggest that the liquefied tephras reflect (palaeo) liquefaction arising from severe shaking from earthquakes generated on faults proximal to the lakes in which the tephras occur, forming ‘tephra seismites’ (Loam et al. 2018; Lowe et al. 2018). The lakes are found scattered amidst the faults (see Fig. 9A). Our preliminary works shows that the same ash layer is not necessarily liquefied in every lake, suggesting that the effect of an earthquake relies on proximity to a nearby fault. The tephra seismites are unlikely to represent shaking induced by movement on the distant Kerepehi Fault system in the neighbouring Hauraki Basin (Persaud et al. 2016). The University of Waikato has just been granted Endeavour and Marsden funding to work on these liquefied lacustrine tephra layers in the Hamilton Basin over the next three years.

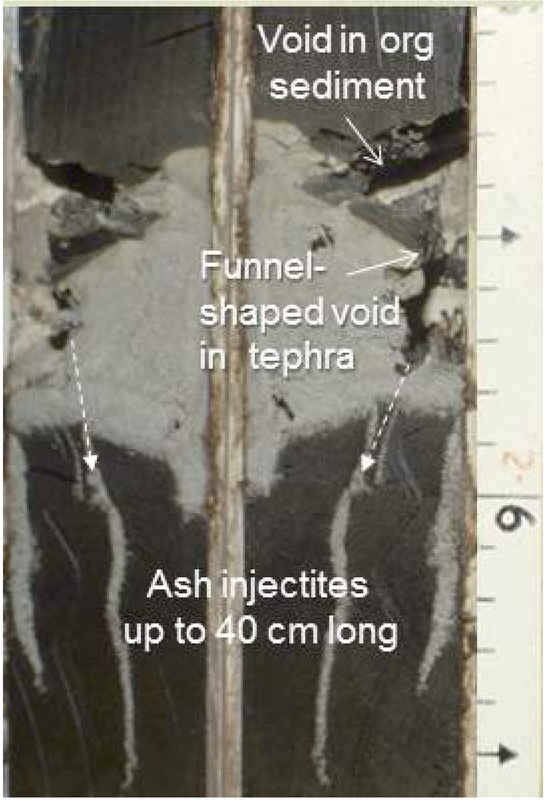


Figure 10 (A)

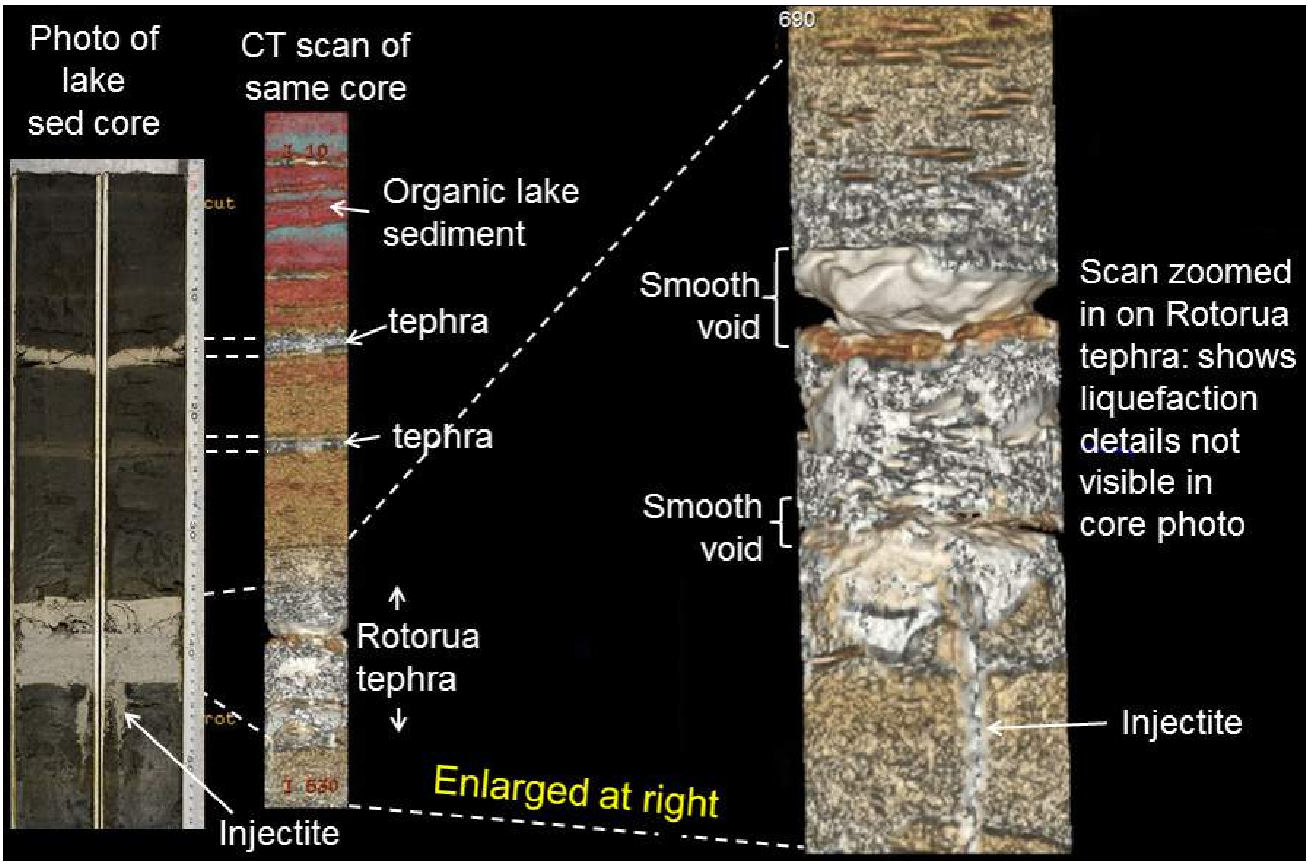


Figure 10: (A) Photo of liquefied Rotorua Tephra (c. 15,600 cal. years old) in a core taken from Lake Kainui in the early 1980s (Lowe 1988, p. 134). The image shows that fine ash has 'flowed' downward from the centre of the 5-cm-thick layer leaving a funnel-shaped void later infilled with organic sediment from above; a downward-propagated injectite underlies the layer. Originally, Lowe (1988) suggested, in the absence of known faults at the time, that these features may have been the result of bioturbation and methane gas pocket formation. (B) These images include (left) a photo of part of a new core (0.6 m long) extracted in 2016 containing Rotorua Tephra near the base. To the right are CT images including a close-up of voids (far right). Photos by David Lowe and CT images by Nic Ross.

Acknowledgements

Funding support:

EQC Biennial Grant 16/717

EQC Postgraduate Grant 15/U713

Waikato Regional Council

University of Waikato

Marsden Fund 19-UOW-001

MBIE Endeavour Fund Smart Ideas PROP-61840-ENDSI-UOW

Site access:

CityEdge Consortium

Jessica McLennan, Dave Sullivan, Susan Tilsley, Mark Argent, Ross Winter, Islay Laird, Raj Ramgobin

Phoenix Civil

Craig McCabe, Inniss Anderson

Students:

Francesca Spinardi, Ben Campbell, Vittoria Gibbons, Michael Cummings, Ben Roche, Tom Robertson, Aleesha McKay, Remedy Loame

X-ray computed tomography (CT imaging):

Nic Ross (radiographer) and Philip Hassall (CEO), Hamilton Radiology

REFERENCES

Briggs, R.M., Itaya, T., Lowe, D.J., Keane, A.J. 1989. Ages of the Pliocene-Pleistocene Alexandra and Ngatutura Volcanics, western North Island, New Zealand, and some geological implications. New Zealand Journal of Geology and Geophysics 32, 417-427.

Edbrooke, S.W. (compiler) 2005. Geology of the Waikato area. Institute of Geological and Nuclear Sciences 1: 250,000 map 4. Institute of Geological and Nuclear Sciences, Lower Hutt. 1 sheet + 68 pp.

FrOG Tech 2011. Waikato structural GIS and SEEBASETM Project: Phase 1 November 2010, FrOG Tech Project Code CWE701 and Phase 2 November 2011, FrOG Tech Project Code CWE703. Ministry of Economic Development New Zealand Unpublished Petroleum Report PR 4432.

Hogg, A.G., Lowe, D.J., Hendy, C.H. 1987. University of Waikato radiocarbon dates I. Radiocarbon 29, 263-301.

Horrocks, J.L. 2000. Stratigraphy, chronology and correlation of the Plio-Pleistocene (c. 2.2–0.8 Ma) Kauroa Ash sequence, western North Island, New Zealand. Unpublished PhD thesis, University of Waikato, Hamilton.

Hume, T.M., Sherwood, A.M., Nelson, C.S. 1975. Alluvial sedimentology of the Upper Pleistocene Hinuera Formation, Hamilton Basin, New Zealand. Journal of the Royal Society of New Zealand 5, 421-462.

Kear, D., Schofield, J.C. 1966. N56 – Ngaruawahia. Geological Map of New Zealand 1: 63,360. Department of Scientific and Industrial Research, Lower Hutt.

Kear, D., Schofield, J.C. 1978. Geology of the Ngaruawahia Subdivision. New Zealand Geological Survey Bulletin 88. 168 pp.

Kirk, P.A. 1991. Waipa Fault and the tectonic rotation of the Hakarimata-Taupiri Block. New Zealand Geological Survey Record 43, 81-84.

Kleyburg, M.A., Moon, V.G., Lowe, D.J., Nelson, C.S. 2015. Paleoliquefaction in Late Pleistocene alluvial sediments in Hauraki and Hamilton basins, and implications for paleoseismicity. Proceedings, 12th Australia New Zealand Conference on Geomechanics (ANZ 2015), 22-25 February, 2015, Wellington, pp. 524-531.

Liles, V.E. 1971. Seismic survey, Waikato Basin 1970-71. Ministry of Economic Development New Zealand. Unpulished Petroleum Report PR569.

Loame, R.C., Lowe, D.J, Johnston, R.E., Evans, E., Pittari, A., Moon, V.G., de Lange, W.P., Davies, S.M., Magill, C.R., Vandergoes, M.J., Rees, A.B.H., Ross, N. 2018. CT and micro-CT scanning of liquefied tephra deposits in ~22,000-yr-old lake sediments, central Waikato region, New Zealand, and implications. In: Hambach, U., Veres, D. (editors), Book of Abstracts, Crossing New Frontiers: INTAV International Field Conference on Tephrochronology, 'Tephra Hunt in Transylvania', Moieciu de Sus, Romania, 24 June-1 July, p. 93.

Lowe, D.J. 1988. Stratigraphy, age, composition, and correlation of late Quaternary tephras interbedded with organic sediments in Waikato lakes, North Island, New Zealand. New Zealand Journal of Geology and Geophysics 31, 125-165.

Lowe, D.J. 2019. Using soil stratigraphy and tephrochronology to understand the origin, age, and classification of a unique Late Quaternary tephra-derived Ultisol in Aotearoa New Zealand. Quaternary 2 (1), 9 (https://doi.org/10.3390/quat2010009).

Lowe, D.J., Tippett, J.M., Kamp, P.J.J., Liddell, I.J., Briggs, R.M., Horrocks, J.L. 2001. Ages on weathered Plio-Pleistocene tephra sequences, western North Island, New Zealand. Les Dossiers de l'Archeo-Logis 1, 45-60.

Lowe, D.J., Loame, R.C., Moon, V.G., Johnston, R.E., Kluger, M.O., Villamor, P., Orense, R., de Lange, W.P., Davies, S.M., Ross, N., Vandergoes, M.J., Rees, A.B.H. 2018. Earth-shaking insight from liquefied tephra layers in lakes in central Waikato region, New Zealand: a new tool to evaluate and date palaeoseismicity? In: Hambach, U., Veres, D. (editors), Book of Abstracts, Crossing New Frontiers: INTAV International Field Conference on Tephrochronology, 'Tephra Hunt in Transylvania', Moieciu de Sus, Romania, 24 June-1 July, pp. 38-39.

Manville, V., Wilson, C.J.N. 2004. The 26.5 ka Oruanui eruption, New Zealand: a review of the roles of volcanism and climate in the post-eruptive sedimentary response. New Zealand Journal of Geology and Geophysics 47, 525-547.

Persaud, M., Villamor, P., Berryman, K.R., Ries, W., Cousins, W.J., Litchfield, N., Alloway, B.V. 2016. The Kerepehi Fault, Hauraki Rift, North Island, New Zealand: active fault characterisation and hazard. New Zealand Journal of Geology and Geophysics 59, 117-135.

Pillans, B.J., Kohn, B.P., Berger, G.W., Froggatt, P.C., Duller, G., Alloway, B.V., Hesse, P. 1996. Multi-method dating comparison for mid-Pleistocene Rangitawa Tephra, New Zealand. Quaternary Science Reviews 15, 1-14.

Geosciences 2019

Annual Conference of the Geoscience Society of New Zealand

Field Trip 3

Mount Pirongia – North Island's largest basaltic volcano

28th November 2019

Leaders: Oliver McLeod & Adrian Pittari

School of Science, University of Waikato, Private Bag 3105, Hamilton 3240

Citation:

McLeod, O.E., Pittari, A. 2019. Mount Pirongia – North Island's largest basaltic volcano. In: Lowe, D.J., Pittari, A. (editors), Field Trip Guides. Geosciences 2019 Conference, Hamilton, New Zealand (24-29 November). *Geoscience Society of New Zealand Miscellaneous Publication* 155B, pp. 1–18.

Geoscience Society of New Zealand Miscellaneous Publication 155B

ISBN (online): 978-0-473-49901-3

ISSN (online): 2230-4495

MOUNT PIRONGIA – NORTH ISLAND’S LARGEST BASALTIC VOLCANO

Itinerary and route

This is an all-day scenic geological excursion to investigate the newly discovered (and mapped) volcanic history of Mt Pirongia, North Island’s largest basaltic volcano. The morning will involve an uphill tramp to Ruapane Trig which requires moderate fitness. We will have lunch in Pirongia township. The afternoon involves a drive to investigate deposits on the southwestern side of Pirongia.

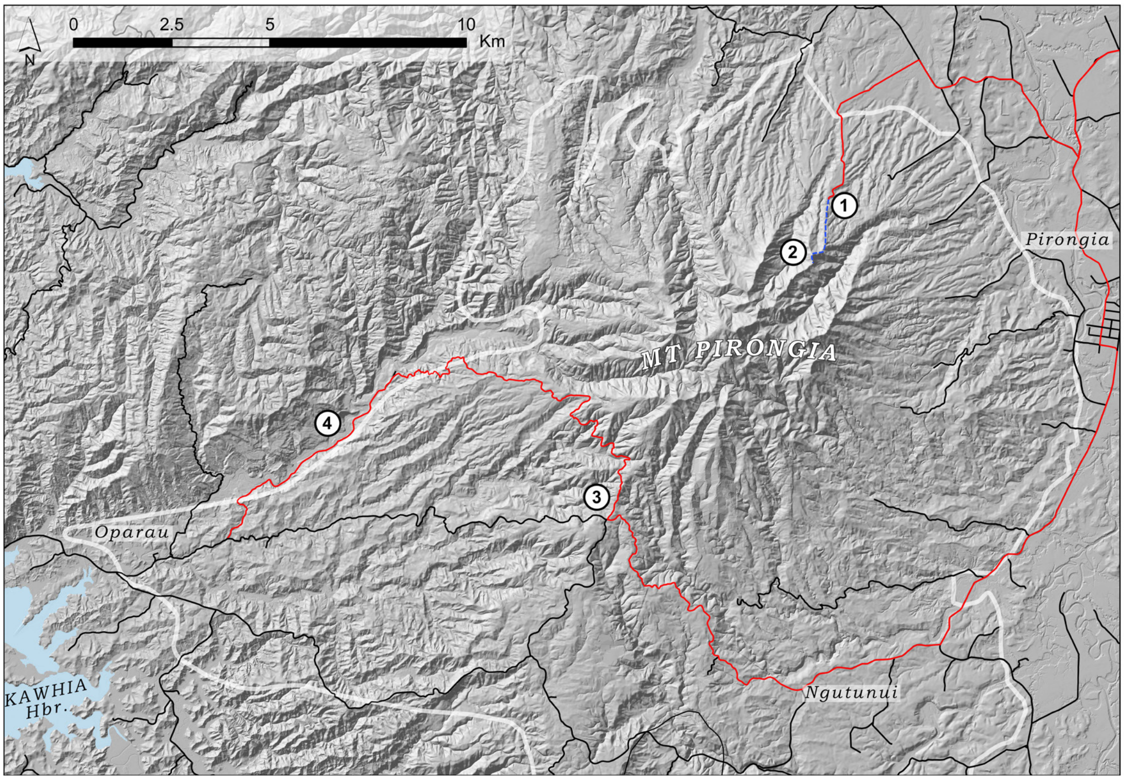


Figure 1. Field trip route map on hill-shaded base map. Symbols: numbered circles = field stops; red line = driving route; blue dashed line = walking track to Ruapane Peak; thick white line = approximate extent of Pirongia volcanics.

8:30 am – Depart Hamilton

Drive to STOP 1

9:30 am Stop 1 – Corcoran Rd car park: brief introduction (*basic DoC toilet available*)

Walk to STOP 2 – approx. 1-hour tramp upslope to Ruapane Trig. The tramp involves sections of steep and rocky ground, and large tree roots; take care with your footing.

10:50 am Stop 2 – Ruapane Trig: extended discussion, landscape views and outcrop examination. Walk back to Corcoran Rd car park (*basic DoC toilet available*) by 12:45 pm; drive to Pirongia township

1:00 pm Lunch – Pirongia township *(30 mins, toilets available)*

Drive to STOP 3

2:00 pm Stop 3 – Intersection Pirongia West and Okupata roads: brief discussion, landscape views

Drive to STOP 4

3:00 pm Stop 4 – Pirongia West Rd (lower):

extended discussion and outcrop examination

Return (via Kawhia Rd/Hwy 31; Ngutunui Rd; Ormsby Rd/Hwy 39 via Pirongia – *toilet stop if needed*) via Hamilton Airport

5:00 pm – Return to Hamilton

Introduction

Mount Pirongia is the eroded landform of the largest basaltic volcano in North Island, New Zealand (Fig. 2) and is the most prominent landmark in the Waikato region. The mountain is a broad cone (13 km wide, 175 km^2 area) that rises from a piedmont to several jagged summit peaks, the highest at 959 m above sea level (asl). The edifice lies east of the Kawhia Harbour, where it mantles the Kapamahunga Range and prevails over the skylines of Hamilton city (30 km northeast) and Te Awamutu (20 km east). The Waipa River, which is the largest tributary of the Waikato River, flows around the volcano's northern slopes. Pirongia formed initially around 2.5 Ma, during a flare-up of regional basaltic volcanism across the wider Alexandra Group, which was associated with the rapidly transitioning Hikurangi subduction front and back-arc spreading in western North Island. The last eruptions of Pirongia, around 1.6 Ma, were contemporaneous with the first super eruptions of the Mangakino caldera in the early development of the Taupo Volcanic Zone (TVZ).

Geological setting

The Alexandra Volcanic Group (AVG, Kear 1960) is a Quaternary volcanic field in western North Island that produced ~55 km^3 of mainly basaltic eruptive material over a total area of 1100 km^2. It includes an extinct chain of subduction-related volcanoes (Fig. 2), comprising two large stratovolcanoes (Pirongia and Karioi) and two smaller cones (Kakepuku and Te

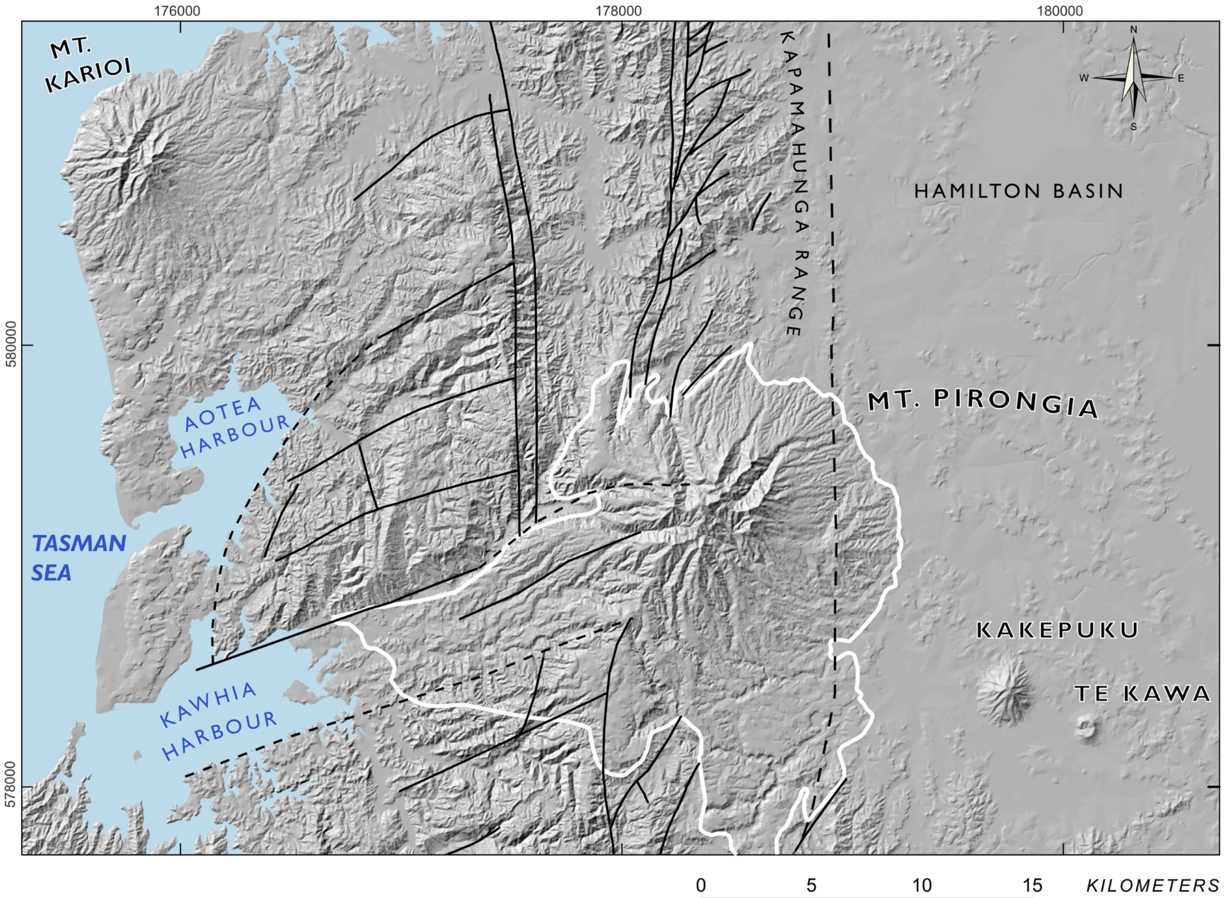


Figure 2. Location map for the Alexandra Volcanic Group, Waikato. The main physiographic features are the extinct volcanic cones of Mts Pirongia, Karioi, Kakepuku and Te Kawa. The Hamilton Basin is separated from the coastal harbours of Aotea and Kawhia by the Kapamahunga Range. Local faults are shown in black solid (outcropping) or dashed (concealed) lines.

Kawa), termed the 'convergent margin' group (Briggs & McDonough 1990), that were active between 2.74 and 1.60 Ma (Briggs et al. 1989). Interspersed with the larger volcanoes is the intraplate monogenetic Okete volcanic field (2.69 to 1.80 Ma), a group of alkaline basaltic scoria cones, lava flows and tuff rings (Briggs 1983, 1986; Briggs and Goles 1984). The convergent margin volcanoes form a volcanic lineament oriented (NW-SE, 120°; Henderson and Grange 1926; Kear 1964; Briggs 1983, 1986) perpendicular to the modern TVZ, located 70–120 km to its east. Most eruptions within the AVG were subaerial except for several coastal vents near Raglan Harbour and Mt Karioi. The AVG produced large volumes of ankaramite, an extremely clinopyroxene porphyritic basalt.

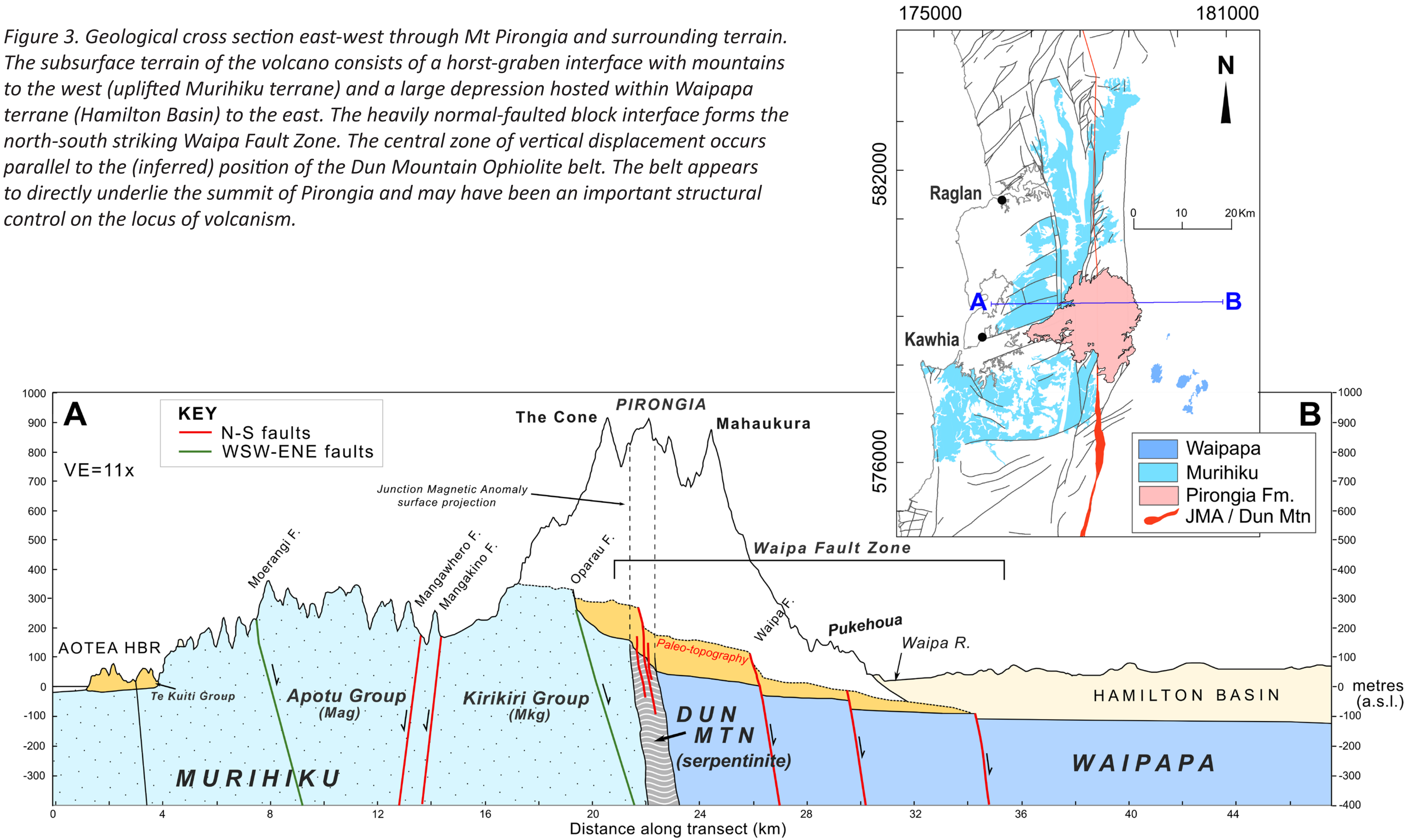
The eruptive history of the AVG (2.7–1.6 Ma) overlaps with the termination of activity of the Coromandel Volcanic Zone (CVZ, 2.69–1.95 Ma rhyolites and dacites at Tauranga; Briggs et al. 2005) and initiation of major caldera-forming eruptions centred east along strike of the Alexandra volcanic lineament at Mangakino caldera (1.68–1.53 Ma; Houghton et al. 1995; Wilson et al. 2009). Activity of the AVG was also coeval with that of other small, predominantly andesitic stratovolcanoes west of the arc front, including Maungatautari (1.8 Ma; Robertson, 1983; Prentice et al. 2019), Pureora and Titiraupenga (1.89 Ma; Stipp 1968). It is, therefore, proposed that the subduction-related AVG represents an arc-perpendicular chain of basaltic stratovolcanoes situated within the back-arc zone of the CVZ-TVZ transitional arc.

Mt Pirongia is the largest volcano of the AVG (Figs. 2, 3). The volcanic edifice lies above the uplifted Triassic to Jurassic Murihuku, Dun Mountain and Waipapa basement terranes, and the overlying Late Eocene to Oligocene Te Kuiti Group siltstones, sandstones and limestones, including the lowermost Waikato Coal Measures (Henderson and Grange 1926; Kear and Schofield 1959; Nelson 1978; Tripathi et al. 2008). Highly magnetic serpentinites of the Dun Mountain Terrane form a linear (mostly <10 km wide) belt, inferred in the subsurface as the Junction Magnetic Anomaly through the western North Island (e.g. Spöorli et al. 1989) that projects into field area beneath the summit of Mt Pirongia (Fig. 3).

Pirongia Volcano was constructed over a period of approximately one million years. Growth of the edifice occurred from numerous central and flank vents and was characterised by sporadic flare ups in activity separated by long periods of repose (up to 500,000 years). Fluctuations between active and repose periods were probably controlled by the regional tectonic environment, where heightened vent activity corresponded with periods of extension in the western Waikato. The volcanic history of Pirongia has been subdivided into six main stages of growth and collapse (Fig. 4). Each stage is separated temporally by an unconformity and is associated with a shift in the main vent centre on the volcano.

The volcanic lithologies of Pirongia and the AVG are dominated by basalts, subordinate volumes of basaltic-andesite, and rare andesites (Fig. 5). The most characteristic rock type of Mt Pirongia and the wider AVG is ankaramite, a highly porphyritic variety of basalt abundant in clinopyroxene and olivine (mega-) phenocrysts. Elsewhere in Zealandia and the wider southwest Pacific area, ankaramites are rare– Patrick Marshall commented that ‘the rocks differ markedly from all other volcanic material of the North Island’ (Marshall 1907, p.96). Ankaramites found across the AVG are melanocratic rocks with large, euhedral phenocrysts of clinopyroxene. On Pirongia, clinopyroxene is typically dull black, although some crystals have a dark greenish tinge. Olivine is typically subordinate in abundance to clinopyroxene and has been altered to orange “iddingsite” (likely made up of nanocrystalline forms of smectites and iron oxides ± silica: Churchman and Lowe 2012). The groundmass ranges from dark purple and very-fine grained to paler-grey with abundant, tabular plagioclase. Rarely, the phenocryst content is so high that the rocks display an apparent doleritic texture. Most ankaramites are weakly to non-vesicular, except for scoria, which are also glassy, and near-vent lavas.

Figure 3. Geological cross section east-west through Mt Pirongia and surrounding terrain. The subsurface terrain of the volcano consists of a horst-graben interface with mountains to the west (uplifted Murihiku terrane) and a large depression hosted within Waipapa terrane (Hamilton Basin) to the east. The heavily normal-faulted block interface forms the north-south striking Waipa Fault Zone. The central zone of vertical displacement occurs parallel to the (inferred) position of the Dun Mountain Ophiolite belt. The belt appears to directly underlie the summit of Pirongia and may have been an important structural control on the locus of volcanism.



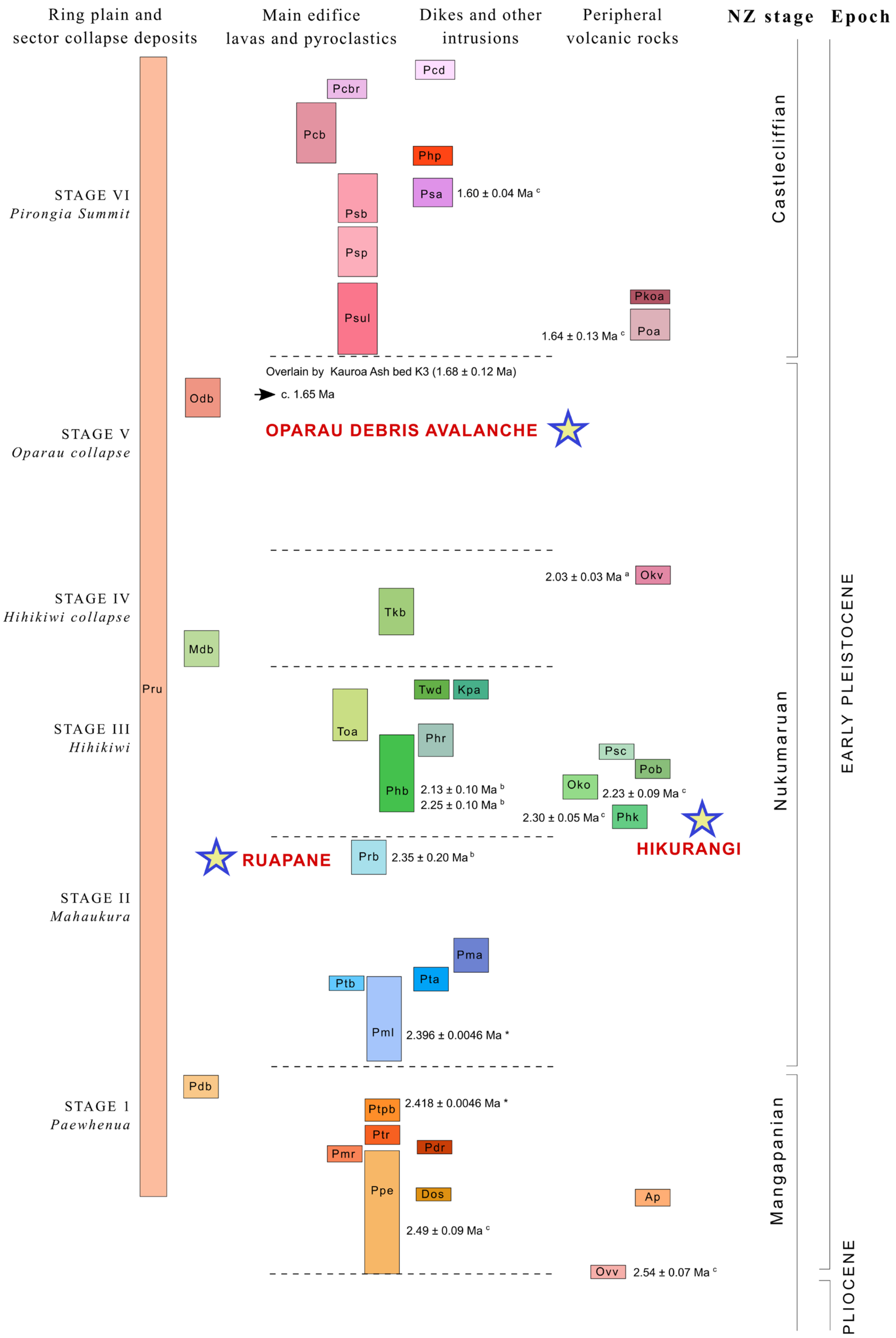


Figure 4. Stratigraphic correlation chart for Pirongia Volcano, based on the Pirongia Geological Map. The volcano is subdivided into six main constructional/destructive stages (I-VI) spanning c. 1 million years. Volcanic units corresponding to field trip stops are marked by star symbols.

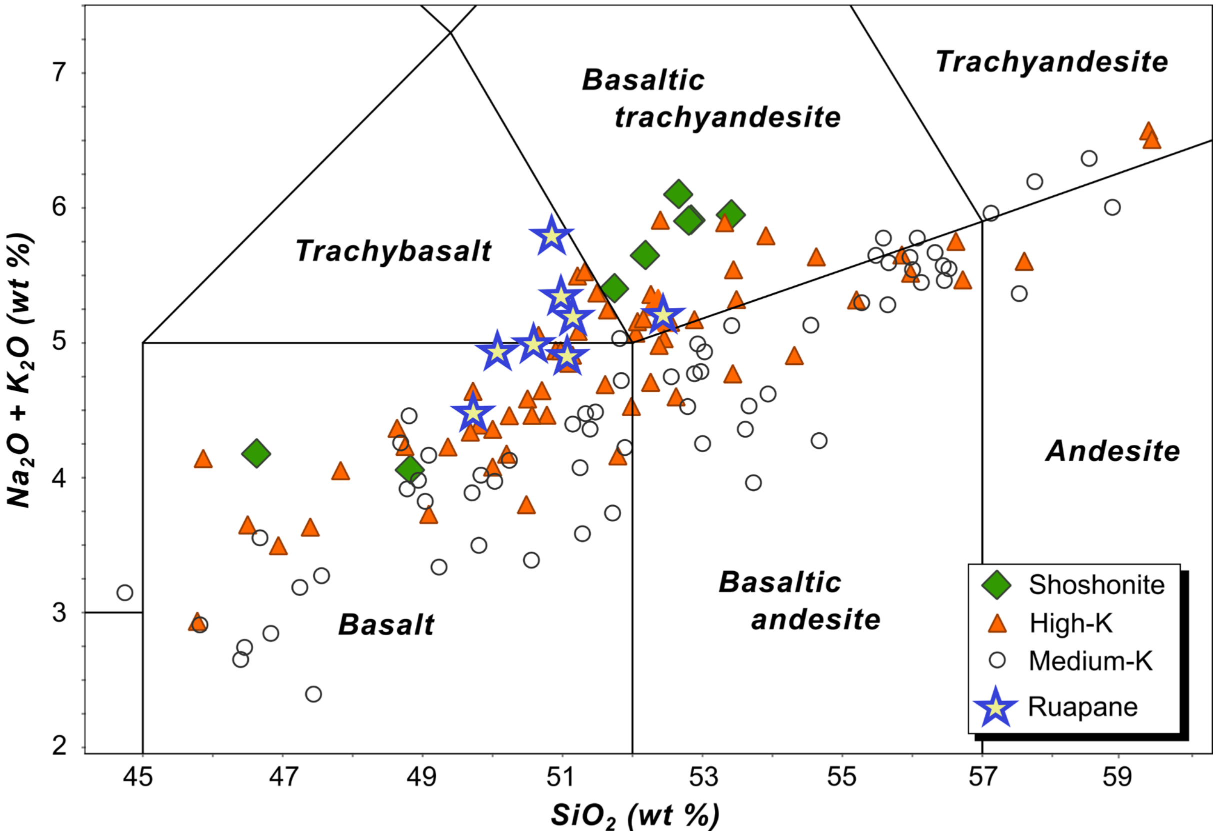


Figure 5. Total alkali (Na_2O + K_2O)–SiO_2 classification diagram (Le Bas et al. 1986) for Pirongia volcanics. Rock compositions are relatively alkalic and range from basalt and trachybasalt to andesite and trachyandesite. Symbols show sub-classification according to the SiO_2–K_2O diagram (Le Maitre 1989). Ruapane rocks (Stop 2) are highlighted with star symbols.

STOP 1 – Corcoran Rd car park

The drive from the university to Pirongia crosses the Hamilton Basin, a large extensional graben that has accumulated volcaniclastic sediment and primary pyroclastic deposits mainly from the TVZ (Kear and Schofield 1978; Edbrooke 2005). The basin is bordered by two ranges of uplifted basement rocks, the Western Ranges (Hakarimata) and Eastern Ranges. The Pirongia ring plain is buried by basin deposits and extends at least 10 km northeast of the mountain. The exposed surface of the ring plain appears south of the Waipa River, near Pirongia township. The Corcoran Rd car park is located on the outer ring plain. Here we will stop at the look out that provides a brief overview of Pirongia Volcano and its surrounds.

The car park marks the beginning of the one-hour hike to a peak at Ruapane Trig through dense native forest.

STOP 2 – Ruapane Trig

The Ruapane Trig is a surveying mark centred on the highest of three basaltic peaks of the Ruapane dyke swarm (Figs. 6a-c). The swarm marks a prominent flank vent on the northern side of the volcano. From this view point, there are panoramic views:

- to the northwest, of Mt Karioi, the sister volcano of Pirongia;
- to the north, of the Kapamahunga-Hakarimata ranges; and
- to the east, of the Hamilton Basin, the Kiwitahi volcanoes (6.2–5.8 Ma), the Eastern Ranges, and Maungatautari Volcano (1.8 Ma).

The immediate views of the nearby peaks and ridges of Pirongia are part of the Stage 2 edifice (Mahaukura Member) erupted between 2.4 and 2.35 Ma. The pinnacle just south of Ruapane is Tirohanga Peak, an andesitic dyke complex (Fig. 7) that marks the central vent of Stage 2 activity. Observe the radial valleys, up to 300 m deep, of Mangakara and Rangitukia streams. These valleys incise the oldest shield of Pirongia (Paewhenua Member). Across the valley is the most prominent outcrop succession: the 'Mahaukura Bluffs' (Fig. 8). These bluffs consist of another andesitic dyke swarm, oriented radially to Mahaukura Peak that marks the location of a Stage 2 flank vent. Associated with these dykes are domes at Mahaukura (Fig. 8) and Wharauroa (Fig. 9) Peaks. The dykes cross cut basaltic-andesite lavas of similar age. The southernmost dyke is the most silicic volcanic rock of the Alexandra Group. A spectacular monolith (called here as Mangamauku Peak) below Wharauroa Peak appears to be an andesitic plug with a truncated face.

Ruapane Peak (723 m asl) is satellite vent of Stage II fed by two dyke swarms and includes remnants of spatter cones represented by agglomerates and lavas (Fig. 6a). The best exposures of ankaramite on the mountain occur at Ruapane Peak (Figs. 6b,c; Table 1).

As we approach the peak, we will walk across lapilli-tuff deposits that form the basal succession. Outcrops north and east of Ruapane Peak are matrix-supported deposits with coarse angular lapilli of vesicular ankaramite and finer-grained red scoria (7-10% clasts) set within a reddish-brown matrix of clay and loose clinopyroxene and plagioclase crystals. These deposits are intercalated with red crystal-rich tuffs containing clinopyroxene.

The ankaramite dykes intrude and mantle older Paewhenua flank lavas, and are typically 1 to 1.5 m wide with undulating, brecciated margins, and display platy jointing. They comprise abundant clinopyroxene (glomero-) phenocrysts (1–3 mm; 6–13% of the rock) and plagioclase (mostly 1 mm), and subordinate olivine set within dark-grey (or purple) groundmass, with similar minerals. Some dykes are moderately vesicular, and the southernmost dyke is a finer-grained basaltic andesite.

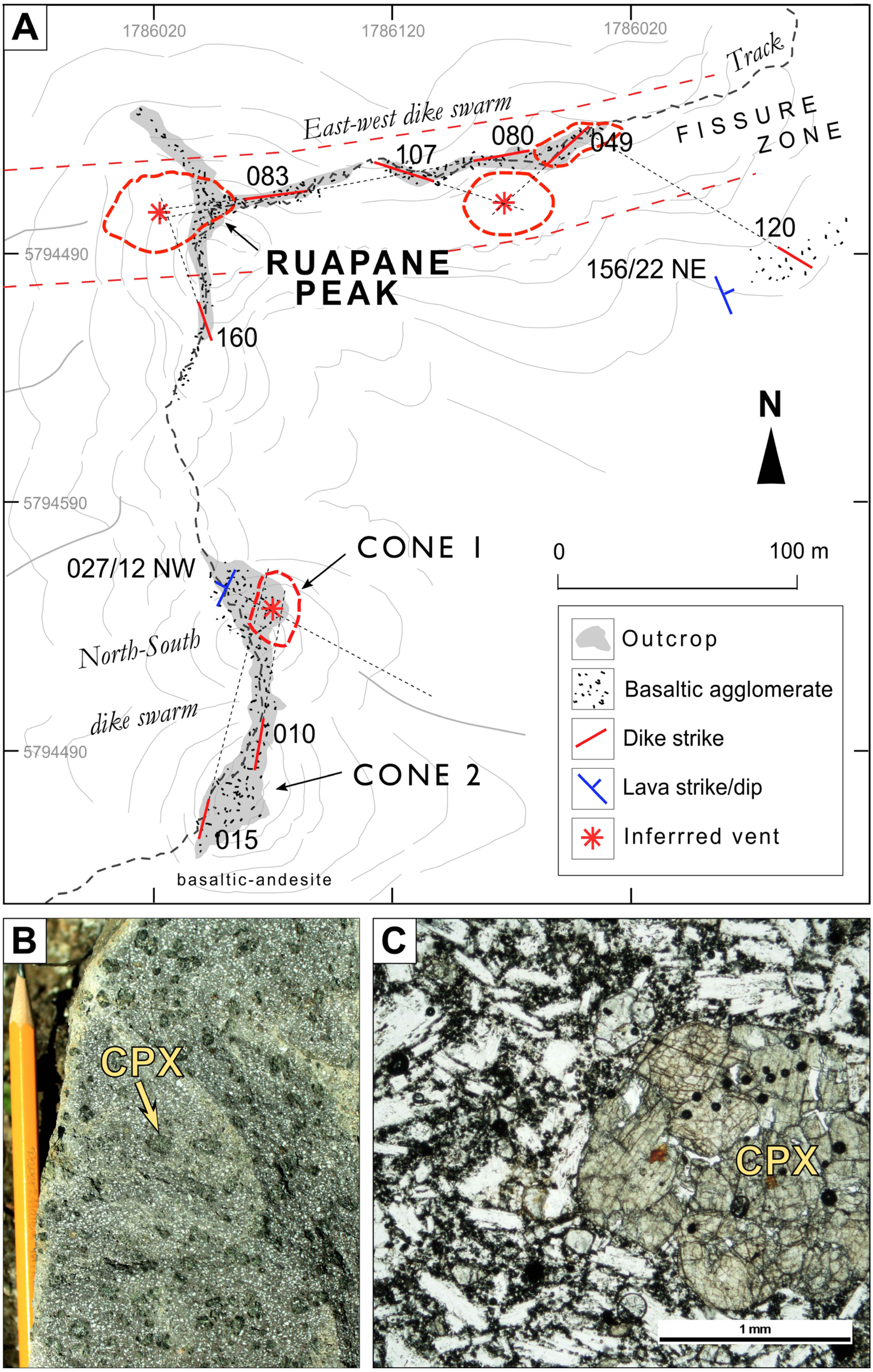


Figure 6. Ruapane Peak (Stop 2). (A) Ridge map showing the location of key volcanic outcrops and dyke orientations. The peak lies within a cluster of dykes that once formed a fissure zone on the flank of Pirongia. (B) Ankaramite-type basalt characteristic of Ruapane. The rock contains large phenocrysts of diopside and abundant microphenocrysts of plagioclase (for composition, see analysis #1, Table 1). (C) Photomicrograph of Ruapane ankaramite, showing the same texture as in photo B.

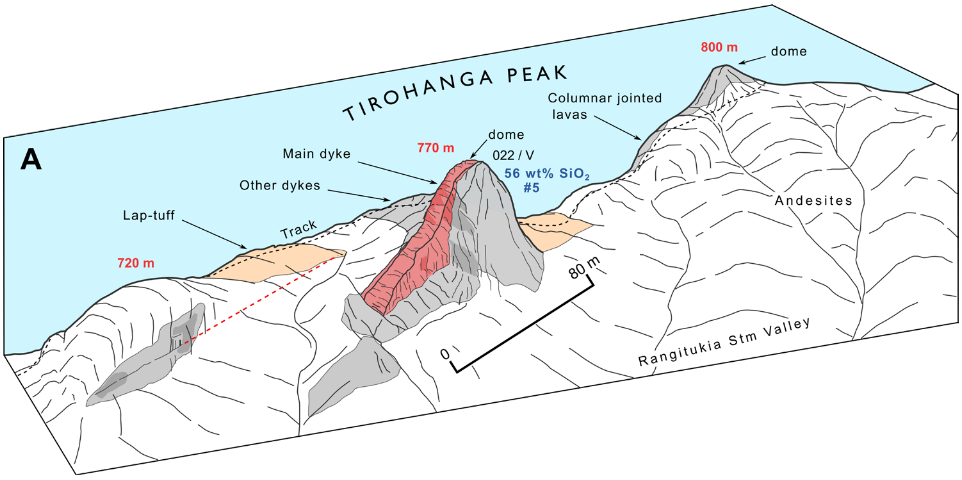


Figure 7. Sketch of Tirohanga Peak, located 800 m southwest of Ruapane. Tirohanga consists of an andesitic dyke swarm cross cutting lavas of similar composition (~56 wt% SiO_2, see analysis #5, Table 1). The main dyke (in red) feeds a small dome at the peak.

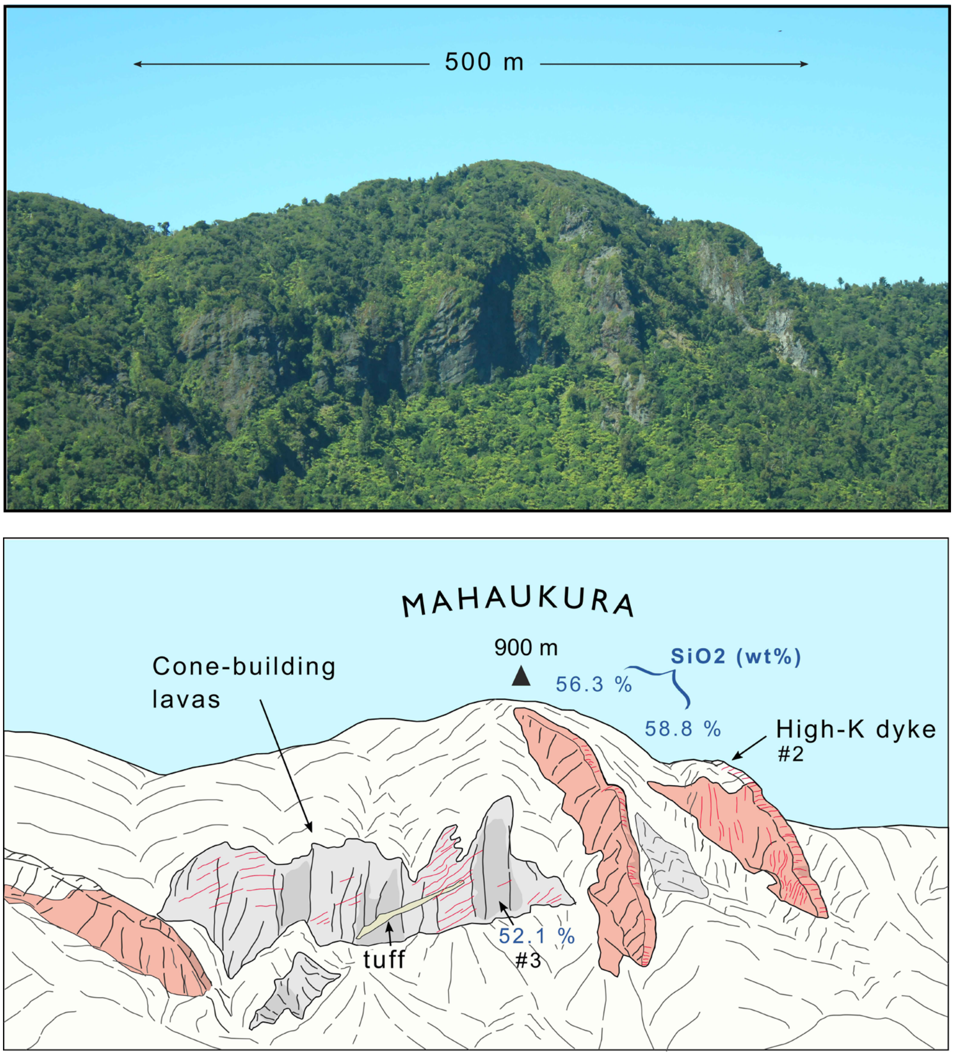


Figure 8. Panoramic photo (top) and geological sketch (bottom) of the 'Mahaukura bluffs'. The bluffs are situated 2 km south of Ruapane, across Mangakara valley. They consist of three prominent dykes that cross cut autobrecciated lava flows (analysis #3, Table 1) and tuff. The southernmost dyke is the most silicic (58.76 wt %; see analysis #2, Table 1) rock on Pirongia Volcano and has a high-K composition. The dykes and lavas relate to Stage II activity and represent flank eruptions of the Tirohanga Volcano (centred on Tirohanga Peak).

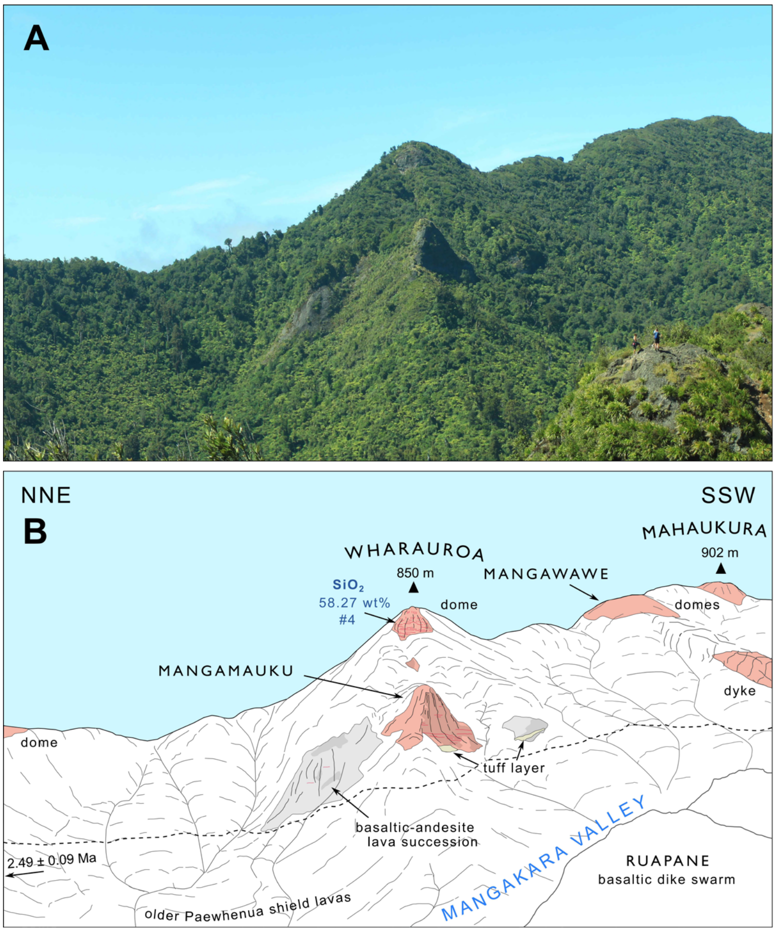


Figure 9. Wharauroa Peak, (A) as viewed from Ruapane Peak, and (B) geological sketch of the same view. The peak (see analysis #4, Table 1, for composition) and surrounding ridges consist of andesitic dykes and domes belonging to volcanic Stage II. In the foreground is the Mangamauku monolith, an andesitic body that cross cuts and overlies lavas and tuffs. The contact between Stage II lavas and older Stage I shield lavas is shown by the dashed line.

Table 1. Major element analyses of selected lavas and dykes of Pirongia Volcano.

	1	2	3	4	5	6
Wt% oxide	**Ruapane**	**Mahaukura Dyke**	**Mahaukura Lava**	**Wharauroa Dome**	**Tirohanga**	**Hikurangi**
	High-K basalt	High-K trachyandesite	High-K basaltic trachyandesite	Med-K trachyandesite	Med-K basaltic andesite	Shoshonitic bas-trachyandesite
SiO_2	49.38	58.76	52.39	58.27	56	52.48
Al_2O_3	16.12	18.47	18.5	17.24	17.49	16.55
TiO_2	1.33	0.58	1.03	0.76	0.83	1.13
MnO	0.19	0.10	0.15	0.13	0.16	0.18
Fe_2O_3	10.88	6.58	9.55	6.72	8.22	9.18
MgO	6.61	1.63	3.62	2.42	3.49	4.53
CaO	9.74	5.64	9.18	7.13	7.12	8.88
Na_2O	2.99	4.07	3.45	4.47	3.89	3.54
K_2O	1.53	2.45	1.85	1.90	1.80	2.38
P_2O_5	0.39	0.38	0.36	0.27	0.25	0.35
LOI	1.19	1.29	0.41	0.45	0.85	0.62
Total	100.52	100.17	100.64	100.01	100.28	99.98

Ankaramitic agglomerates consist of dense, sub-rounded blocks or scoriaceous to non-vesicular bombs. At Ruapane peak, the clasts are strongly vesicular with mineral assemblages and textures similar to those of the dyke rocks. At cone 1 (Fig. 6a), the observed succession consists of (1) relatively thick (>5 m) agglomerate, overlain by (2) a thin (<1 m thick), northwest-dipping lava flow that is further overlain by another more coarsely porphyritic lava flow towards the top of cone 1. The lavas are mantled by (3) agglomerate containing weakly vesicular, finer-grained clasts.

Lunch

We will descend Ruapane Peak and return to the Corcoran Rd car park, then drive to Pirongia township for lunch.

STOP 3 – Intersection Pirongia West and Okupata roads

From Pirongia township we will drive around the southern ring plain, passing by Pukehoua flank vent, today marked by a low hill on grassy farmland. The rolling hills around Ngutunui School, at the beginning of Pekanui Rd, are in the middle of the Mangakiekie Breccia, one of the mapped debris avalanche deposits of the Pirongia ring plain. After turning into Pekanui Rd, we ascend along a fluvially-dissected plateau. Road cuttings on the left-hand side show examples of similar breccias that are stratigraphically older. Stop 3 is at the end of Pekanui Rd at the intersection with Pirongia West Rd.

The view from Stop 3 includes Pirongia Peak to the northeast, and Karioi volcano on the horizon to the northwest. The immediately adjacent hill at Stop 3, to the south, is the Hikurangi Dome (Fig. 10a,b), a flank vent of Pirongia that erupted lava to the west across the Pekanui Breccia (Fig. 10b). The lavas have a shoshonitic composition (Table 1) with characteristic phlogopite phenocrysts (Fig. 10c).

The lowlands in the foreground form the Oparau Graben (Figs. 11, 12) bound on the far side by the Oparau Fault and uplifted Jurassic basement hills of the Murihiku Terrane. Infilling the graben from the base of Pirongia Peak through to Kawhia Harbour is the Oparau Breccia, on which we will focus at Stop 4.

STOP 4 – Pirongia West Rd (lower)

From Stop 3, along the Pirongia West Rd, we will drive across the Pekanui ring plain, across a lava flow, then onto the Oparau Breccia, which we will follow downslope to Stop 4 (Fig. 12).

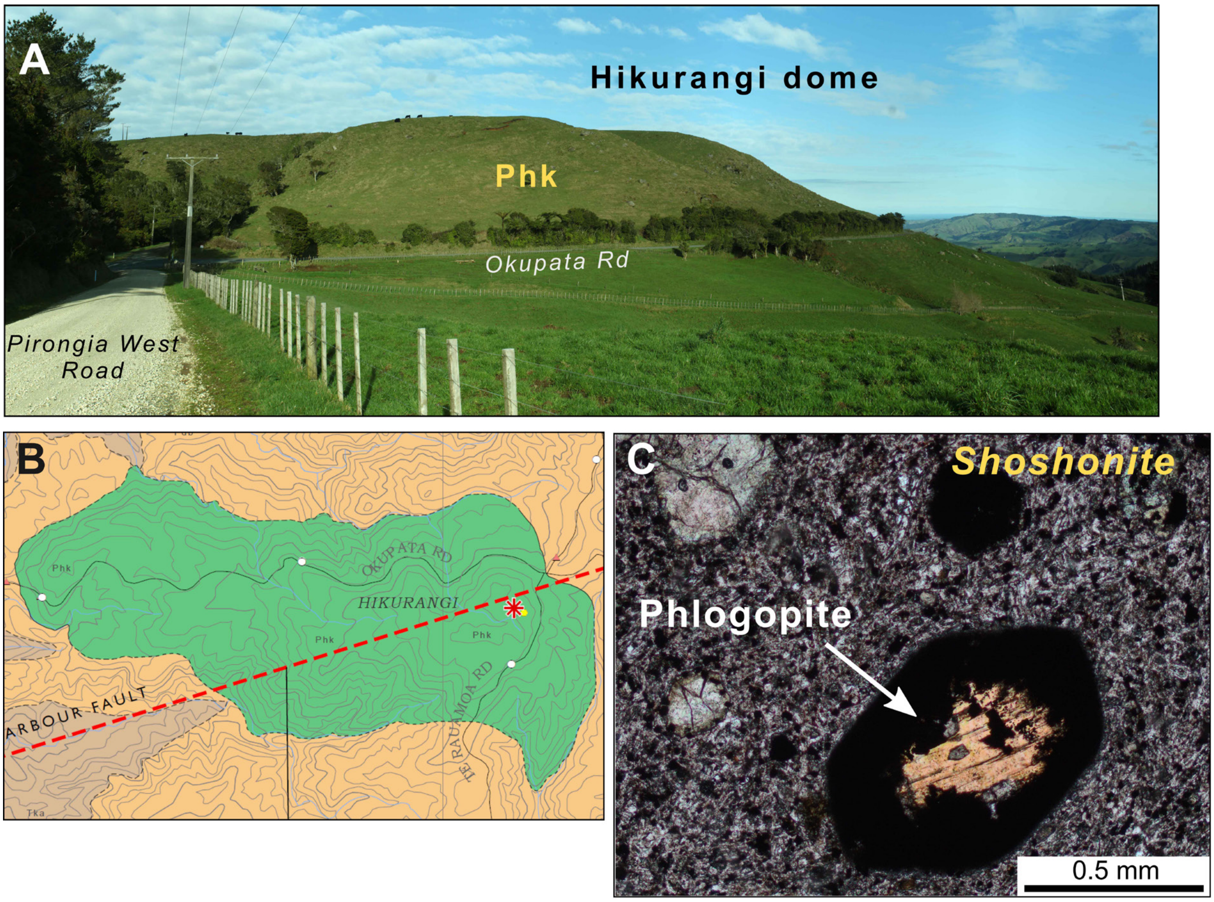


Figure 10. Hikurangi dome, southern Pirongia. (A) Photo of the dome from Pirongia West Road, at Stop 3. (B) Westward distribution of lavas from Hikurangi, taken from the Pirongia Geological Map. (C) The dome is a peripheral vent of Pirongia Volcano and erupted unusual shoshonitic basaltic-trachyandesite (see analysis #6, Table 1). The rock is weakly porphyritic but with relatively abundant phlogopite that occurs within resorbed phenocrysts of hornblende. Phlogopite is rare in Pirongia lavas and always associated with resorbed hornblende.

Undifferentiated volcaniclastic breccia (Odb, Fig. 4) covers the southwestern flanks of Pirongia. The voluminous Oparau breccia, which covers an area of at least 31 km^2, is interpreted as a debris avalanche deposit derived from collapse of the western flank. Deposits of the unit extend ~20 km southeast of the volcano to Kawhia Harbour, where volcanic breccia crops out at Kaiwaka Point (Tiritirimatangi Peninsula). The Oparau breccia is confined to the Oparau Graben, where it partially overlies Murihiku basement rocks, Te Kuiti Group sedimentary rocks and older Pirongia Formation breccias. The breccia is overlain in the northeast by younger lavas of Pūāwhe/The Cone.

The composition of proximal deposits is known from limited outcrops on the upper planeze surface of the Oparau breccia, which consist of large (1–2 m) blocks of basalt and basaltic-andesite weathered from the underlying breccia. Hydrothermal alteration (clay-altered plagioclase) is evident in some boulders. Two radiometric dates for boulders from this area

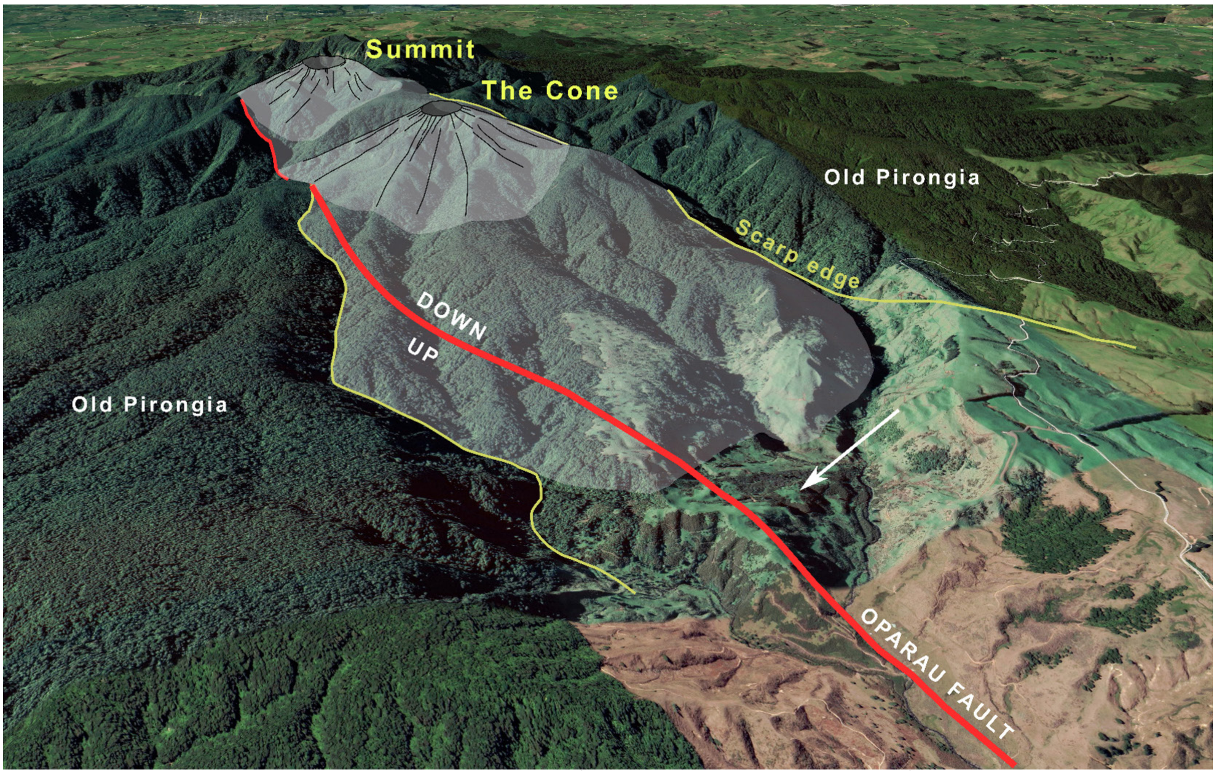


Figure 11. View to the western flank of Pirongia (imagery from Google Earth) showing the location of a large sector collapse scarp (yellow line) associated with the Oparau debris avalanche. The scarp edges mark a major unconformity between older shield lavas (~2.5 Ma, 'Old Pirongia') and younger (1.6 Ma) lavas of The Cone and Pirongia Summit that subsequently infilled the scarp. The northern edge of the scarp coincides with the projected trace of the Oparau Fault (heavy red line). The summit vents are aligned roughly parallel to the Oparau Fault.

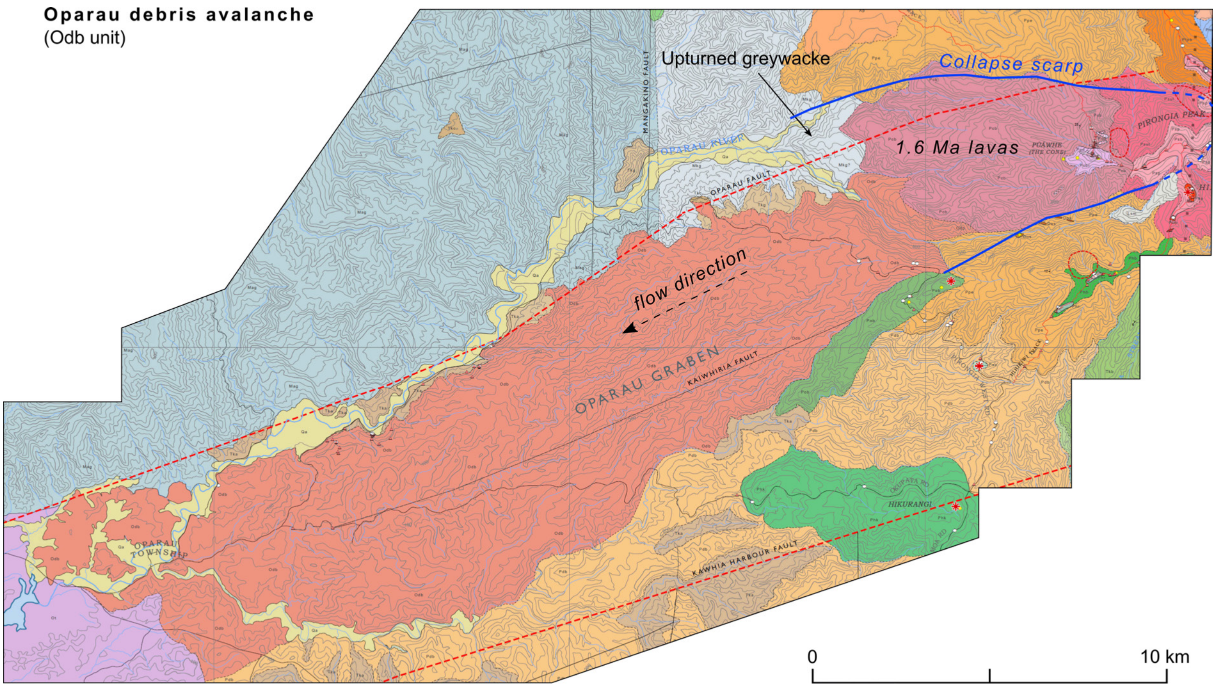


Figure 12. Geological map of the Oparau Breccia (Odb, Fig. 4) debris avalanche deposit (shown in red). The approximate boundary of the collapse scarp is shown by the blue line. Also labelled are the 1.6 Ma lavas that infilled the scarp, and a large block of greywacke at the foot of the scarp that was rotated during the collapse event.

yield ages of 2.13 ± 0.10 Ma and 2.25 ± 0.10 Ma (Robertson 1976). The boulders are correlated stratigraphically to lavas from the Hihikiwi volcanic centre, 2.6 km east and upslope. Finer-grained basanites are found as clasts in the breccia, indicating that intraplate basalt exists in the lower edifice succession of Pirongia.

Distal portions of the Oparau breccia (Fig. 13a-f) form prominent crags (below 70 m asl) along the Oparau River valley where the unit overlies Aotea Formation sandstone (Fig. 13a,c). At the best exposed bluff (base height ~38 m asl), the breccia is vertically continuous over 42 m (Fig. 13b) and forms scattered outcrops to the top of the ridge line (~95 m asl). Deposits in this area consist of poorly sorted, matrix supported diamictons of volcanic rock (Fig. 13d). Clasts range from angular, coarse lapilli up to large, metre-sized, blocks. Many of the blocks show jigsaw fracturing (Fig. 13e) infilled by matrix material. The clastic component is polymict and dominantly basaltic in composition. Lithologies range from ankaramite to finer-grained basaltic-andesite. Andesite is relatively uncommon and occurs mainly as lapilli, including pale-coloured pumice. Hydrothermal alteration is prevalent in many clasts (e.g. zeolite amygdales). Deformed blocks of Te Kuiti Group sandstone and angular basement (metasedimentary) clasts are relatively common in the breccia (Fig. 13f).

Concluding Remarks

On this field trip we have shown a selection of key landforms and deposit types that capture the main characteristics of Pirongia Volcano. In the morning, we focussed on proximal vent systems (e.g. dykes, vent structures and deposits) and the volcanic cone reconstruction, and highlighted the characteristic ankaramites of Pirongia. In the afternoon, we focussed on aspects of the volcanic ring plain (e.g. flank vents and debris avalanche breccias). A new Geological Map of Pirongia Volcano and its associated bulletin, soon to be published, will provide a more comprehensive overview of the volcanic structure and stratigraphy.

Acknowledgements

The following are acknowledged for their contribution to this field guide: representatives of Tainui for allowing scientific access to the peaks of Pirongia, in particular Tom Roa (Ngāti Maniapoto, University of Waikato) for providing geographic information on Pirongia; Department of Conservation for a research and collection permit; landowners of the Pirongia and Oparau areas for access to field sites; and colleagues Roger Briggs and Marco Brenna. The research was supported by a University of Waikato Doctoral Scholarship and internal University of Waikato funds.

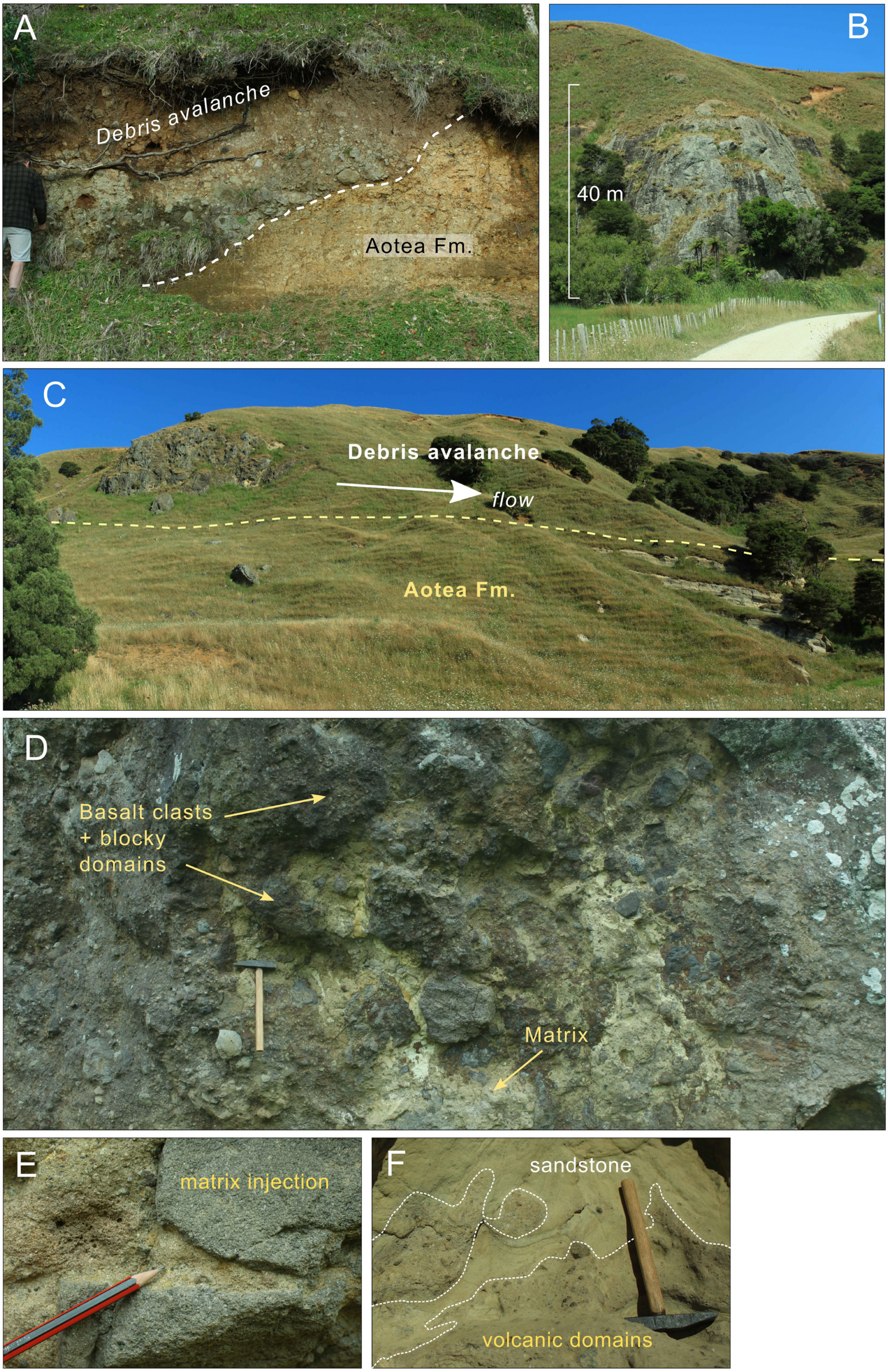

A
Debris avalanche
Aotea Fm.
B
40 m
C
Debris avalanche
flow
Aotea Fm.
D
Basalt clasts
+ blocky
domains
Matrix
E
matrix injection
F
sandstone
volcanic domains

Figure 13 (facing page). Clastic features of the Oparau Breccia. (A) Outcrop at Stop 4, where the debris avalanche overlies Aotea Formation (dashed line is contact, person for scale). (B) Prominent outcrop of breccia on Pirongia West Road, near to Stop 4. (C) Panoramic view of the contact (dashed line) between the breccia and Aotea Formation sandstone near stop 4. (D) Clastic texture of the deposit, with hammer for scale. (E) Matrix injection into jigsaw fractured clast within the deposit. (F) Plastically deformed sandstone clast with volcaniclastic matrix domain of the breccia.

References

Briggs, R.M. 1983. Distribution, form and structural control of the Alexandra Volcanic Group, North Island, New Zealand. New Zealand Journal of Geology and Geophysics 26, 47-55.

Briggs, R.M. 1986. Volcanic rocks of the Waikato Region, western North Island, and some possible petrologic and tectonic constraints on their origin. In: Smith, I.E.M. (editor), Late Cenozoic Volcanism in New Zealand. Royal Society of New Zealand Bulletin 23, 76-91.

Briggs, R.M., McDonough, W.F. 1990. Contemporaneous convergent margin and intraplate magmatism, North Island, New Zealand. Journal of Petrology 31, 813-851.

Briggs, R.M., Goles, G.G. 1984. Petrological and trace element geochemical features of the Okete Volcanics, western North Island, New Zealand. Contributions to Mineralogy and Petrology 86, 77-88.

Briggs, R.M., Houghton, B.F., McWilliams, M., Wilson, C.J.N. 2005. ^{40}Ar/^{39}Ar ages of silicic volcanic rocks in the Tauranga-Kaimai area, New Zealand: dating the transition between volcanism in the Coromandel Arc and the Taupo Volcanic Zone. New Zealand Journal of Geology and Geophysics 48, 459-469.

Briggs, R.M., Itaya, T., Lowe, D.J., Keane, A.J. 1989. Ages of the Pliocene-Pleistocene Alexandra and Ngatutura Volcanics, western North Island, New Zealand, and some geological implication. New Zealand Journal of Geology and Geophysics 32, 417-427.

Churchman, G.J., Lowe, D.J. 2012. Alteration, formation, and occurrence of minerals in soils. In: Huang, P.M., Li, Y., Sumner, M.E. (editors), Handbook of Soil Sciences. 2nd edition. Vol. 1: Properties and Processes. CRC Press, Boca Raton, FL, pp.20.1-20.72.

Edbrooke, S.W. (compiler) 2005. Geology of the Waikato area. Institute of Geological and Nuclear Sciences 1: 250,000 map 4. Institute of Geological and Nuclear Sciences, Lower Hutt. 1 sheet + 68 pp.

Henderson, J., Grange, L.I. 1926. The geology of the Huntly-Kawhia Subdivision. New Zealand Geological Survey Bulletin 28, 112.

Houghton, B.F., Wilson, C.J.N., McWilliams, M.O., Lanphere, M.A., Weaver, S.D., Briggs, R.M., Pringle, M.S. 1995. Chronology and dynamics of a large silicic magmatic system: central Taupo Volcanic Zone, New Zealand. Geology 23, 13-16.

Kear, D. 1960. Sheet 4 Hamilton. Geological Map of New Zealand 1:250 000. N.Z. Department of Scientific and Industrial Research, Wellington.

Kear, D. 1964. Volcanic alignments north and west of New Zealand's Central Volcanic Region. New Zealand Journal of Geology and Geophysics 7, 24-44.

Kear, D., Schofield, J.C. 1959. Te Kuiti Group. New Zealand Journal of Geology and Geophysics 4, 685-717.

Kear, D., Schofield, J.C. 1978. Geology of the Ngaruawahia Subdivision. New Zealand Geological Survey Bulletin 88.

Le Bas, M.J., Le Maitre, R.W., Streckeisen, A., Zanettin, B. 1986. A chemical classification of volcanic rocks based on the total alkali-silica diagram. Journal of Petrology 27, 745-750.

Le Maitre, R.W. (editor) 1989. A Classification of Igneous Rocks and Glossary of Terms. Blackwell, Oxford, 193 pp.

Marshall, P. 1907. Geology of centre and north of North Island. Read before the Otago Institute, 10th September, 1907.

Nelson, C.S. 1978. Stratigraphy and paleontology of the Oligocene Te Kuiti group, Waitomo County, South Auckland, New Zealand. New Zealand Journal of Geology and Geophysics 21, 553-594.

Prentice, M.L., Pittari, A., Barker, S.L.L., Moon, V.G 2019. Volcanogenic processes and petrogenesis of the early Pleistocene andesitic-dacitic Maungatautari composite cone, central Waikato, New Zealand. New Zealand Journal of Geology and Geophysics (in press) https://doi.org/10.1080/00288306.2019.1656259

Robertson, D.J. 1983. Paleomagnetism and geochronology of volcanics in the northern North Island. Unpublished PhD thesis, University of Auckland.

Spöorli, K.B. 1989. Tectonic framework of Northland, New Zealand. In: Spöorli, K.B., Kear, D. (editors), Geology of Northland – Accretion, Allocthons and Arcs at the Edge of the New Zealand Micro-continent. Royal Society of New Zealand Bulletin 26, 3-14.

Stipp, J.J. 1968. The geochronology and petrogenesis of the Cenozoic Volcanics of the North Island, New Zealand. Unpublished Ph.D thesis, Australian National University.

Tripathi, A.R.P., Kamp, P.J.J., Nelson, C.S. 2008. Te Kuiti Group (Late Eocene-Oligocene) lithostratigraphy east of Taranaki Basin in central-western North Island, New Zealand. Ministry of Economic Development, New Zealand, unpublished Petroleum Report PR3900, 70 pp.

Wilson, C.J.N., Gravley, D.M., Leonard, G.S., Rowland, J.V. 2009. Volcanism in the central Taupo Volcanic Zone, New Zealand: tempo, styles and controls. In: Thordarson, T., Self, S., Larsen, G., Rowland, S.K., Hoskuldsson, A. (editors), Studies in Volcanology: The Legacy of George Walker. Special Publications of IAVCEI (Geological Society, London) 2, 225-247.

Geosciences 2019

Annual Conference of the Geoscience Society of New Zealand

Field Trip 4

King Country Basin: Oligocene and Miocene Structure, Stratigraphy and Depositional Systems

28th & 29th November 2019

Leader: Peter J.J. Kamp

School of Science, University of Waikato, Hamilton
(p.kamp@waikato.ac.nz)

Bibliographic reference:

Kamp, P. J. J. 2019: King Country Basin: Oligocene and Miocene Structure, Stratigraphy and Depositional Systems. In: Lowe, D. J., Pittari, A. (eds). Field Trip Guides: Geosciences 2019, Hamilton, New Zealand. Geoscience Society of New Zealand Miscellaneous Publication 155B, pp. 1 - 80.

Geoscience Society of New Zealand Miscellaneous Publication 155B

ISBN (online): 978-0-473-49901-3

ISSN (online): 2230-4495

TABLE OF CONTENTS

1.0 RATIONALE FOR THIS FIELD TRIP GUIDE 3

- 1.1 Health and Safety 4
- 1.2 Accommodation 5

Part A - BACKGROUND INFORMATION

2.0 GEOLOGICAL SETTING 5

- 2.1 Outcrop patterns 5
- 2.2 Uplift and erosion of central North Island 6
- 2.3 Stratigraphic units removed 7

3.0 STRATIGRAPHIC ARCHITECTURE OF THE BASIN FILLS 7

- 3.1 Wanganui Basin - King Country Basin: Parakino-1 to Ararimu-1 transect 7
- 3.2 Wanganui Basin - eastern Taranaki Basin: Santoft-1A to Tuhua-1 transect 11 .. 9

4.0 TWO PHASES OF NEOGENE CONTINENTAL MARGIN PROGRADATION 10

5.0 STRATIGRAPHIC ARCHITECTURE ACROSS THE BOUNDARY BETWEEN TARANAKI AND KING COUNTRY BASINS 11

- 5.1 Late-Early Miocene to Middle Miocene subsidence of eastern Taranaki Basin margin 12

6.0 FIFTH AND 6TH ORDER SEQUENCES WITHIN WHANGAMOMOANA AND RANGITIKEI SEQUENCES 15

7.0 ACKNOWLEDGEMENTS 15

8.0 REFERENCES 16

King Country field trip route map 36

PART B – ITINERY AND FIELD SITE NOTES 37

Day 1: *Structural and Stratigraphic expression onshore of Late Oligocene – Early Miocene units and their relationship to tectonics along the eastern margin of Taranaki Basin.*

- STOP 1. SH3, Pukenui Road, south of Te Kuiti (S16-981116) 37
- STOP 2. SH3, Piopio Quarry, immediately south of Piopio. (R17-855003) 38
- STOP 3. SH3, Mangaotaki Bridge section (R17-761957) 39
- STOP 4. Totoro Road, Mahoenui (R17-729924). Over-view of northern part of King Country Basin. 43

STOP 5. Oligocene – Early Miocene geology at Awakino Tunnel (R17-618853) 43

Awakino Tunnel - Orahiri Limestone lithoclasts and their significance (R17- 615854)49

STOP 6. SSH3, Bexley Tunnel section (R17- 609827) 52

STOP 7. Western end of Awakino Gorge on SH3 (R17-559800) 52

STOP 8. Rest Area off SH3, eastern end of Ladies Mile (R17-547806) 53

STOP 9. Bexley Sandstone to Manganui Formation transition (R17-525818) 55

STOP 10. Awakino Heads section (R17- 511808) 57
....

DAY 2 Theme: *Stratigraphic architecture and depositional systems of a middle Miocene retrogradational continental margin, eastern Taranaki Basin.* 62

STOP 11. Pahaoa Hill Section (R18-513799) 64

STOP 12. Mt Messenger Fmn sandstone, Mohakatino River bridge (R18-505736) .. 66

STOP 13. Tongaporutu River Mouth, Rest Area (R18 – 484642).....................
66

STOP 14. Mt Messenger & Mohakatino formations Okau Road, SH40
(R18 – 515578) ....
69

STOP 15. Okau Road – Otunui, Mohakatino and Mt Messenger formations
exposed in close proximity (R18-587564) ....
70

STOP 16. Tongaporutu-Ohura Road, east of Kotare Stream, Moki – Otunui Fmn
contact (R18 – 651596) ....

STOP 17. N.G. Tucker Scenic Reserve. Tongaporutu-Ohura Road SH40, south of
Huhatahi Valley, Waingarara Sandstone Member (Tangarakau Formation 73
– Mokau Group) (R18-771593) ....

STOP 18. Tongaporutu-Ohura Road SH40, south of Huhatahi Valley, Maryville 74
Coal Measures (R18-774597) ....

STOP 19. Tongaporutu-Ohura Road SH40, south of Huhatahi Valley, Mahoenui 74
Gp – Bexley Sandstone contact. (R18-785617) 77

STOP 20. River Road, Nevins Lookout (R18-814520) ....
77

STOP 21. Stratigraphic transition from Otunui Formation to Mt Messenger
Formation, Mangatarata Road. (R18-826522.) 79

STOP 22. River Road, Aukopae Saddle (S18-913509) ....

STOP 23. Mahoenui Group, Taumarunui Formation at Herlihy's Bluff, River Road 79
(S18-033516) ....

1.0 RATIONALE FOR FIELD GUIDE

For many years there has been ambiguity about the relationship between the Cenozoic successions exposed on land east of the northern Taranaki coastline in the King Country Region and the fill of Taranaki Basin in the offshore realm. The suites of data for Taranaki Basin have been much more comprehensive than for King Country Basin, where the stratigraphy has not even been properly described or mapped. The exception has been the development of the concept that the Mt Messenger Formation is a useful outcrop analogue as a basin floor fan for offshore parts of the same formation (e.g. King et al. 1993). The proximity of the Patea-Tongaporutu-Herangi structural high to the modern coastline has also contributed to the view that the eastern margin of Taranaki Basin has lain near the coastline, and that the bulk of the sediments exposed farther inland accumulated in a different basin (e.g. King & Thrasher 1996).

Our recent research on the Cenozoic succession exposed on land in the King Country Region, eastern Taranaki Peninsula and northern Wanganui has clarified the stratigraphic relationships between Taranaki Basin, King Country Basin and Whanganui Basin. A key realisation has been the degree, extent and timing (Pliocene-Pleistocene) of significant uplift and erosion of central-western North Island and its determination, which amongst other things has produced the westerly, southwest and southward shallow dips of different parts of the Neogene succession. We have now mapped the whole of the region north-south between Te Kuiti township and Whanganui City and east-west between Mt Ruapehu and Mt Taranaki (Egmont) at a 1:50,000 scale. Expressed another way, in a Hamilton – Wellington flight, half its duration is above this area of mixed forest and farmland. Although our research is not fully written up, it is timely to present a field guide to the northern part of the King Country Basin to enable those interested to examine in outcrop Neogene marine formations, correlatives being buried offshore in northern Taranaki Basin and Taranaki Peninsula.

The methods we have used in coming to a better understanding of the character of the successions on land, and the geological signals they contains, have in many ways been the traditional ones of developing a lithostratigraphy (including 1:50 000 geological mapping), a chronostratigraphy through biostratigraphy, facies analysis for paleoenvironmental interpretation, sequence stratigraphy, and petrography. In Taranaki Peninsula we have found wireline logs to be very useful in correlating individual Vail-type sequences that can be mapped in outcrop (Matemateaonga Formation) with correlative occurrences in the sub-crop of Taranaki Peninsula and southern parts of Taranaki Basin. Concurrently, we have been undertaking seismic mapping and wireline log analysis of the Neogene succession in northern Taranaki Basin, so as to better understand the development of the Northern Graben and associated structural inversion of the eastern margin of Taranaki Basin (e.g. Hansen & Kamp 2004, 2006). We have also undertaken new basin analysis work in Whanganui Basin to better understand the evolution of two continental margin wedges that have prograded from Whanganui Basin into the King Country region and northern Taranaki Basin.

The field guide has been designed to start and end in Hamilton. Our analysis of the fill of King Country Basin reveals the occurrence of five 2nd order sequences of essentially tectonic origin. These include the Late Eocene-Oligocene Te Kuiti Sequence, the early-Early Miocene (Otaian) Mahoenui Group/Sequence, the late-Early to Mid-Miocene (Altonian - mid-Lillburnian) Mokau Group/Sequence, the Middle Miocene to Early Pliocene Whangamomona Group/ Sequence, and the mid -Pliocene - Pleistocene Rangitikei Supergroup/Sequence. Higher order sequences are evident in the Whangamomona and Rangitikei sequences, with those of 5th (100 ka) and 6th (41 ka) order being especially common in those sequences.

Several themes emerging from the stratigraphic architecture of the basin sequences will recur during the field guide: (1) The stratigraphy and structure of the Te Kuiti Group, Mahoenui Group and Mokau Group around the southern end of the Herangi Range suggest that Taranaki and Manganui faults were active, involving basement overthrusting and foreshortening of Taranaki Basin margin during the Late Oligocene and the early-Early Miocene (Otaian Stage). (2) During the late-Early Miocene and into the Middle Miocene, the eastern margin of Taranaki Basin subsided and the contemporary continental slope retrograded into the King Country Region. (3) The late Middle Miocene –Pliocene units (Whangamomona and Rangitikei Sequences) each comprise erosionally truncated shelf-slope-basin depositional systems that prograded northward through Wanganui and King Country Basin into eastern Taranaki Basin. (4) There has been a very significant Pliocene-Pleistocene tectonically driven uplift and erosion episode centred on central North Island including King Country Basin and extending out into Wanganui Basin and eastern parts of Taranaki Basin.

In the following text (**PART A**) we outline the general geology of the eastern margin of Taranaki Basin (onshore), and in (**PART B**) an itinerary and field STOP notes for the trip.

1.1 Health and Safety

In terms of health and safety issues, please be aware of the inherent hazards of working along roads and adjacent areas. Some stops are on State Highway 3 which frequently carries heavy traffic, and importantly, heavy trucks; at other times we will be on provincial roads, which are narrow and sometimes unsealed. Some of the traffic may be of foreign tourists unfamiliar with driving on the left hand side; at other times it may involve local farm traffic, including machinery, where drivers are not expecting a group of people on the side of the road. Many of the sites will be at cliff faces over-steepened by road construction. Cliffs may be unstable and collapse or shed debris at any time without warning. Caution should therefore be exercised when assessing exposures and examining rocks at the base of cliffs or road cuttings. The west coast has a high-energy wave climate, and wave, river and tidal conditions can combine to produce extreme hazards in walking and working along this coast, including the sudden collapse of sea cliffs.

1.2 Accommodation

Awakino Hotel: Ph 06-752-9815; fax: 06-752-9829

PART A - Background Information

2.0 GEOLOGICAL SETTING

A simplified geological map of central-western North Island is shown in Fig. 1. Fig. 2 is a structure map of the same region. Fig. 3 shows schematically the occurrence of major Neogene stratigraphic units in each of the three basins. The eastern margin of Taranaki Basin has traditionally been defined by the Taranaki Fault (e.g. King & Thrasher 1996). Note, however, in Fig. 1, how the boundaries of the Late Miocene and Pliocene stratigraphic units cross the projected trace of the Taranaki Fault. This highlights the common geological history the basins have had during the late Neogene.

The King Country Basin lies to the east of the northern part of Taranaki Basin (Fig. 2). Its southern and common boundary with Whanganui Basin is poorly defined with no obvious structure between them. It broadly lies within a southward dipping monocline (Whanganui Monocline, Fig. 2) that reflects progressive southward onlap on to basement, which has been modified by later uplift and tilting to the south and southwest. For the purposes of defining the boundary between these basins, the base of the Matemateaonga Formation has been adopted. This marks the stratigraphic point at which substantial subsidence of basement in the northern part of Wanganui Basin started, with marked southward migration of the shoreline. The eastern margin of Wanganui Basin is marked by the axial ranges, and the western margin is marked by the offshore continuation of the Patea-Tongaporutu High and by the D'Urville High (Fig. 2).

2.1 Outcrop patterns

Much of the Neogene tectonic development of the region can be read from geology and structure maps (Figs 1 & 2). A striking feature of the outcrop pattern in the northern part of Whanganui Basin and the southern part of King Country Basin is the west-east strike of the formations (Fig. 1). This involves the Mount Messenger Formation through to Nukumaruan strata (Late Pliocene - Early Pleistocene) (Fig. 3). These units are structurally conformable and dip 2-4° S or SW. The strike of these beds is normal to the orientation of the plate boundary zone, and therefore the origin of the bedding attitude is not simply related to upper crustal shortening driven by plate convergence. Significantly, the distribution of Castlecliffian (Middle to Late Pleistocene; Fig. 1, 3) strata only are influenced by the occurrence of the axial ranges (Tararua-Ruahine Range), suggesting that the uplift of these ranges occurred mainly during the Castlecliffian to Holocene interval.

In the central and northern parts of King Country Basin the stratigraphic units are Oligocene (Te Kuiti Group) and Early Miocene (Mahoenui and Mokau Groups) in age and have shallow to negligible dip, being influenced more locally by tilting about the Herangi Range (Nelson et al. 1994), and faults (e.g. Ohura Fault) having northeast-southwest strikes sympathetic to those defining the Northern Graben in Taranaki Basin and the Taupo Volcanic Zone (Fig. 2). In central and western parts of Taranaki Peninsula, the Urenui Formation through to Tangahoe Mudstone successions are overlain by Mount Taranaki Quaternary volcanics and volcaniclastic sediments of the ring-plain (Fig. 1).

2.2 Uplift and erosion of central North Island

The outcrop pattern of central-western North Island reflects long wavelength up-doming of central North Island and associated erosion of weakly lithified mudstone and associated lithologies. Fig. 4 is a map showing the magnitude and pattern of erosion calculated by kriging of estimates of the amount of erosion determined chiefly from analysis of the bulk density of mudstone cores (Kamp et al. 2004). There are two sets of bulk density data underpinning the map, including a DSIR dataset obtained during the 1960s for regional gravity mapping (Reilly 1965) and made available by the Institute of Geological & Nuclear Sciences Ltd, and a second data set collected as part of our University of Waikato work, which concentrated on high density sampling in the main river valleys of Wanganui Basin and more sparsely in King Country Basin (Fig. 4).

Fig. 4 is essentially an erosion map as the data underpinning it reflect the amount of exhumation of the mudstone horizons sampled. The magnitude of erosion varies systematically, increasing northward from Wanganui Basin into King Country Basin, and eastward from eastern Taranaki Basin into the King Country region (Fig. 4). The maximum amount of erosion is probably about 2000 m. The zero erosion line offshore is presumed to have formed chiefly by wave planation and cliff retreat during successive Pleistocene marine transgressions and sea-level highstands, which also formed the uplifted flights of Middle and Late Pleistocene terraces in the vicinity of Taranaki Peninsula. Inland of the coastal zone, fluvial and slope processes acting on weakly lithified mudstone and sandstone are likely to have produced the erosion at rates that will have nearly approximated the rock uplift rates. In the Kaimanawa Range and northern Ruahine Range the Neogene cover rock succession has been almost completely removed and the exhumed basement surface, which is still evident in places, has been finely dissected (Fig. 4). The material eroded was dispersed to the surrounding basins, including northern Taranaki Basin (Giant Foresets Formation), Wanganui Basin (Rangitikei Supergroup), and Hawke's Bay Basin (Maungahururu Formation and Petane Group).

2.3 Stratigraphic units removed

The magnitude of erosion leads to the question of what stratigraphic units were removed. We consider that these included mainly the Mokau and Mahoenui Groups and the Middle Miocene through Pliocene stratigraphic units involved in the Wanganui Monocline. The former occurrence of these units as evidenced by the results of analyses of the bulk density of exhumed mudstone beds, indicates that the King Country Basin was a long-lived marine sedimentary depocentre, and points to its probable former depositional continuity with northern parts of Wanganui Basin, and possibly the East Coast Basin during the Early Miocene. This has implications for understanding of the Neogene paleogeographic development of central North Island.

3.0 STRATIGRAPHIC ARCHITECTURE OF THE BASIN FILLS

We illustrate the stratigraphic architecture of the fills of the three basins in central-western North Island by reference to two cross-sections and related time-stratigraphic panels (Kamp et al. 2004). Fig. 5 shows the lines of these cross-sections in relation to the distribution of the major stratigraphic units.

3.1 Whanganui Basin - King Country Basin: Parakino-1 to Ararimu-1 transect

Fig. 6 illustrates a cross-section through the axis of the Wanganui and King Country Basins. It shows the stratigraphic and structural concordance of the formations and how the slope on the basement surface is similar to the dip on the formation contacts. The Whanganui Monocline, defined from the dip of Neogene sediments (Fig. 2), is a reflection of the subsurface structure on basement. The cross-section also shows the persistent southward onlap of successive formations on to basement, suggestive of a north-facing paleoslope prior to later uplift and tilting to the south.

The time-stratigraphic section (Fig. 6) highlights particularly the occurrence of four major Neogene unconformity-bounded sequences (excluding the late Paleogene Te Kuiti Sequence). The first two are of early Miocene age. The Mahoenui Group comprises massive mudstone (Taumatamaire Formation) and flysch (Taumarunui Formation) facies (Hay 1967; Nelson & Hume 1977; Topping 1978; Cartwright 2003). The initial subsidence of the basin containing this succession occurred during the Oligocene (Te Kuiti Sequence) and is marked in the south by thin (up to 30 m) coaly incised valley fill deposits, thin transgressive (onlap) shellbeds, and overlying marine neritic sandstone and mudstone beds (Pungpunga Formation (new) of the Te Kuiti Group (2nd order) sequence; Cartwright 2003). A glauconitic mudstone a few dm thick locally at the base of the Mahoenui Sequence marks a prominent flooding surface. It reflects initial terrigenous sediment starvation associated with rapid subsidence and flooding of the basin, marked onlap of basement around the margins, and the establishment of deep-water conditions. This was followed locally by the accumulation of about 100 m of massive shelf mudstone and then by about 1000 m of redeposited sediments (turbidites) that accumulated at bathyal depths. The Mahoenui Group is predominantly of Otaian age (Topping 1978). Surprisingly, no regressive slope or shelf facies have been identified at the top of the Mahoenui Group. Presumably, if they were originally present, they were abridged and eroded during a short-lived and marked phase of uplift and erosion that affected the whole of the Mahoenui depocentre. The Herangi-Tongaporutu High separated the Mahoenui depocentre from Taranaki Basin. This depocentre was a piggy-back basin being transported westward during basement overthrusting on the Taranaki and Manganui Faults. The Taimana Formation and lower parts of the Manganui Formation are stratigraphic equivalents in Taranaki Basin of the Mahoenui Group in the King Country region.

The inversion of the Mahoenui depocentre was previously associated with reverse movement on the Ohura Fault. However, the depositional edge of the Mokau Group actually lies a few km east of Ohura Fault, as shown by Mokau Group succession in Tatau-1, and therefore it is doubtful that displacement on Ohura Fault occurred during the Early or Middle Mioceme. Nevertheless, generally east of the trace of Ohura Fault, Mahoenui Group strata were exposed at the surface during the Altonian - mid-Lillburnian. This “high-standing” block partly sourced sediments to the Mokau Group/Sequence (Fig. 6). The Mokau Sequence comprises lower transgressive sandstone (Bexley Sandstone), a coal measure and fluvial succession (Maryville Coal Measures), and an upper, regressive, shoreface sandstone (Tangarakau Sandstone) (e.g., Vonk 1999). The upper surface of the Tangarakau Formation appears to be conformable, especially in the southern part of the basin, with overlying Otunui Formation. The Manganui and Moki Formations exposed along the eastern margin of Taranaki basin are correlatives of the Mokau Group inland, the uppermost parts being of lower Lillburnian age.

The third Neogene megasequence is represented by the Whangamomona Group and this unit is common to parts of Wanganui, King Country, and Taranaki basins (Fig. 6, 7). During the middle Miocene the whole of the King Country region subsided. This resulted in the accumulation of a transgressive shelf succession represented by the upper Lillburnian-Waiauan Otunui Formation (Mohakatino Formation of Hay 1967). It overlies the Mahoenui Group east of the Ohura Fault, and Mokau Group west of this fault (Fig. 1). The basal facies of the Otunui Formation are heterolithic, commonly characterised by an onlap shellbed known as the Mangarara Formation (Henderson & Ongley 1923). The Otunui Formation is 100-200 m thick and comprises crudely bedded silty fine sandstone and sandy siltstone, with occasional conglomeratic channels. The Otunui Formation passes conformably upwards into the Mount Messenger Formation, which comprises a slightly calcareous siltstone containing very well sorted massive micaceous sandstone beds (sandy debris flow deposits). The transition to Mount Messenger Formation reflects rapid lower Tongaporutuan subsidence of the basin to bathyal depths.

The Whangamomona Group comprises an asymmetric transgressive-regressive sequence. Soon after bathyal conditions were achieved in the King Country Basin (upper Waiauan - lower Tongaporutuan) the depositional sequence became regressive with the aggradation of bottom-sets (including basin floor – lower slope fan deposits) and the northward progradation of slope (Urenui and Kiore Formations) and shelf (Matemateaonga Formation, upper Tongaporutuan – lower Opoitian) deposits. Concurrently, the regressive units, and notably the Matemateaonga Formation, onlapped basement to the south. This geometry required there to be a persistent increase in sediment flux delivered to the continental margin, particularly from about 11 m.y. ago, after which most of the thickness of the megasequence accumulated.

The last megasequence comprises the upper Opoitian - upper Castlecliffian Rangitikei Supergroup. In the northern parts of Wanganui Basin the Tangahoe Mudstone is the basal unit of the Rangitikei Sequence and has also a major flooding surface at its base. It is marked by a 20-30 cm thick condensed horizon of glauconitic mudstone, which lies a few metres above inner shelf deposits. Within the condensed horizon the paleobathymetry changed from neritic to upper bathyal water depths and the condensed unit contains some 600 k.y. of time across the lower to upper Opoitian boundary. This is followed upwards, within a few tens of metres, by packets of redeposited sandstone beds that accumulated in broad submarine channels on a continental slope. The upper bathyal deposits (slope-sets) shallow upwards into shelf deposits as a result of shelf and slope progradation during the Waipipian. Mangapanian and younger units make up aggradational shelf deposits (top-sets) (e.g., Fleming 1953; Beu & Edwards 1984; Kamp & Turner 1990; Abbott & Carter 1994; Naish & Kamp 1995, 1997; McIntyre & Kamp 1998; Kamp & McIntyre 1998).

3.2 Whanganui Basin - eastern Taranaki Basin: Santoft-1A to Tuhua-1 transect

The cross-section from Santoft–1A to Tuhua-1 starts near the modern depocentre of Whanganui Basin, passes north to Parakino-1 in the Whanganui River valley, east across the Patea-Tongaporutu High to Manutahi-1, north along the eastern margin of Taranaki Basin, and crosses the Taranaki Fault between Rotokare-1 and Wingrove-1 (Fig. 7). It shows the consistent and shallow south to southwesterly dip of the beds irrespective of the basin containing them. The steeper dip of the beds between Parakino-1 and Whangaehu-1 reflects the marked subsidence in Whanganui Basin associated with deposition of the Tangahoe Mudstone.

Fig. 7 also shows the chronostratigraphic distribution of the units along the cross-section line. The striking feature is the southward onlap on to basement of the Middle Miocene to Pleistocene sedimentary succession, also evident in Fig. 6. This onlap followed the end of substantial displacement on Taranaki Fault in the peninsula area. The rate of onlap increased markedly during the latest Miocene and earliest Pliocene. The southward onlap implies a north-facing paleoslope. This pattern was clearly reversed after deposition of the Tangahoe Mudstone, with southward tilting involving both the basement and cover succession and occurring without much differential movement on the Taranaki Fault.

In the Santoft-1A to Tuhua-1 cross-section the base of the Middle to Late Miocene Whangamomona Group/Sequence is placed at the base of a limestone succession lying unconformably on basement near the base of Rotokare-1. This limestone has a Clifdenian to Lillburnian age and probably corresponds to the Mangarara Formation. It is also known in other places on the Tongaporutu-Herangi High (Uruti-1 & 2). During accumulation of the Mount Messenger, Urenui, and Kiore Formations there must have been a very narrow shelf along the cross-section line between Rotokare-1 and Manutahi-1, which widened substantially during accumulation of the Matemateaonga Formation.

4.0 TWO PHASES OF NEOGENE CONTINENTAL MARGIN PROGRADATION

Fig. 8 is a block diagram that shows schematically the depositional and stratigraphic architecture of the two 2nd order sequences comprising the Middle Miocene to Pleistocene sedimentary succession in the Wanganui, King Country, and Taranaki Basins. Both the Whangamomona and Rangitikei Sequences formed as northward prograding continental margin wedges, and had similar top-set, slope-set, and bottom-set stratal architecture. Unusually, the onlap margin of the Whangamomona Sequence is the preserved component, the deeper-water more oceanward part of the sequence having been uplifted and truncated by erosion in the King Country region.

The Whangamomona Sequence can be mapped along the eastern margin of Taranaki Basin, upon, and to the west of the Tongaporutu-Herangi High, part of it being exposed in the northern Taranaki coastal section (Mount Messenger and Urenui Formations) (King et al. 1994; Browne & Slatt 2002). The Kiore and Matemateaonga Formations crop out to the south in the hill country of eastern Taranaki Peninsula (Vonk et al. 2002).

The Whangamomona Sequence accumulated mainly in the Wanganui and King Country Basins, which reflected the main sedimentary fairway and depositional axis, but the sequence also extended into eastern parts of Taranaki Basin, as outlined above. Correlative beds of the Whangamomona Sequence in Taranaki Basin (Manganui Formation) accumulated in bathyal environments and will be identified on the basis of age. The continental margin comprising the Rangitikei Sequence advanced northward on two fronts, one directly northward from the Southern Alps source through Whanganui Basin and into southern parts of King Country Basin, while the other was directed west of the Patea-Tongaporutu High through the Toru Trough and into the Central and Northern Grabens of Taranaki Basin and ultimately on to the Western Stable Platform (Hansen & Kamp 2002, 2004). This sequence forms the thick and extensive deposits underlying the modern shelf and slope in the offshore parts of Taranaki Basin, where it is known as the Giant Foresets Formation. The equivalent sediments have been uplifted and totally removed from the King Country Basin and erosionally truncated in the northern parts of Whanganui Basin and over Taranaki Peninsula. The Pliocene-Pleistocene erosion of the Whangamomona, Mokau, and Mahoenui Groups in the King Country Basin will have contributed to the sediments making up the Giant Foresets Formation.

5.0 STRATIGRAPHIC ARCHITECTURE ACROSS THE BOUNDARY BETWEEN TARANAKI AND KING COUNTRY BASINS

In the vicinity of eastern Taranaki Peninsula and Whanganui Basin the major stratigraphic units, as described above, accumulated across the boundaries between all three basins (Figs. 1, 2, 9), reflecting contemporary broad crustal downwarping and associated sedimentation. Farther to the north where these units have been eroded, the stratigraphic and structural relationships between eastern Taranaki Basin and King Country Basin are much less clear, but are of particular interest as they relate to the timing of basement overthrusting on Taranaki Fault, movement on other faults, and the change from Early Miocene crustal shortening to Middle Miocene broad crustal downwarping. Fig. 9 is a chronostratigraphic panel drawn for a cross-section between Awakino Heads in eastern Taranaki Basin and Waitui Saddle on the Hauhungaroa Range along the eastern margin of King Country Basin. This panel is based on various sources including Happy (1971), Cochrane (1988), King et al. (1993), Nelson et al. (1994), Wilson (1994), King & Thrasher (1996), Vonk (1999), Vonk et al. (2002), Cartwright (2003), Evans (2003), and our unpublished work. In this section we outline the Late Oligocene through Middle Miocene stratigraphic and structural development of this eastern Taranaki - King Country margin and its implications.

During most of the Oligocene a structural high (Herangi High) persisted as a semi-continuous paleogeographic feature from south of Awakino to Port Waikato (Nelson 1978). Nelson et al. (1994) have described a distinctive Te Kuiti Group succession at Awakino Tunnel on the eastern side of the Herangi Range where it is generally thick (300 m), has strong dips (40-30^o), exhibits an upsection decrease in the amount of dip, and the capping Orahiri Limestone includes several thick (up to 3 m) mass-emplaced units containing a variety of 1-10 cm-sized lithoclasts of older Te Kuiti Group rocks. Tilting of the southern part of the high began during the upper Whaingaroan around 30 Ma, concomitant with the onset of rapid subsidence along eastern Taranaki Basin, and continued through to the end of the Waitakian Stage (22 Ma, earliest Miocene), when erosion expanded on to the shelf at Awakino Tunnel, stripping out the Otorohanga Limestone in places.

In eastern Taranaki Basin the latest Oligocene (lower Waitakian) Tikorangi Formation is offset by the Taranaki Fault (Fig. 9), which has its present reverse character in this region as a result of overthrusting of basement into the eastern margin of Taranaki Basin (e.g., King & Thrasher 1996). The oldest sediments overlying the overthrust basement block are upper Otaian, and more regionally, Altonian in age (King & Thrasher 1996). This brackets the final emplacement of the overthrust basement into Taranaki Basin as lying between 23.8 (mid-Waitakian; Oligocene-Miocene boundary) and 19.0 Ma (Otaian-Altonian Stage boundary). Taranaki Fault as a pre-existing structure appears to have accommodated part of the compressive regional strain that developed across North Island at that time associated with the development of the Australia-Pacific plate boundary to the east (e.g., Kamp 1986).

On the southeastern flank of Herangi Range near Awakino Tunnel, the Te Kuiti Group is onlapped and overlapped on to basement by early Miocene siliciclastic mudstone and sandstone of the Mahoenui and Mokau Groups, respectively (Fig. 9). The Mahoenui Group is Otaian in age (22-19 Ma) and throughout the King Country region is either a bathyal massive mudstone facies (Taumatamaire Formation) or a flysch facies (Taumarunui Formation). Near Awakino Tunnel, mapping shows that the Taumatamaire Formation clearly onlaps an unconformity cut across the Te Kuiti Group, which it oversteps to onlap basement (Cochrane 1988). The onlap shows that the basin margin subsided differentially during accumulation of Taumatamaire Formation, as indicated by the fanning of dips from 20-5^{o} (Cochrane 1988). The Manganui Fault (Campbell & Raine 1989) lies 3 km to the west of the eroded onlap margin and has the appropriate strike to have acted as the structure controlling the rotation of the block carrying the differentially tilted Taumatamaire Formation. We infer that the Manganui Fault was a high-angle reverse fault at this time, upthrown to the east, with several hundred to 1250 m of displacement.

5.1 Late-Early Miocene to Middle Miocene subsidence of eastern Taranaki Basin margin

The youngest parts of the Mahoenui Group in King Country Basin are late Otaian to possibly earliest Altonian in age (Topping 1978). No regressive deposits are associated with this predominantly bathyal succession, even though its unconformable contact with the overlying Mokau Group and Otunui Formation formed through subaerial erosion. This emphasises the regional nature of an initial uplift phase that seems to have involved inversion of the whole of the Mahoenui depocentre (Fig. 9). During the Altonian – mid-Lillburnian Mahoenui Group southeast of Ohura Fault was eroding and supplying sediment to the Mokau Group depocentre to the west and to North Taranaki Basin. East of Pungapunga Fault, Mahoenui Group was completely eroded (Fig. 9).

Mokau Group accumulated during the Altonian – mid-Lillburnian to a thickness of about 260 m mainly northwest of Ohura Fault (Crosdale 1993; Vonk 1999) (Fig. 9). This group comprises three main units: (i) a 60 m-thick lower transgressive shoreface sandstone (Bexley Sandstone); (ii) a 120 m-thick middle unit of coal measures and fluvial conglomerate (Maryville Coal Measures); and (iii), an upper 80 m-thick unit of regressive shoreface to innermost shelf sandstone (Tangarakau Sandstone) (Vonk 1999). Concurrently, to the west of the Herangi High, transgressive shoreface facies (Bexley Sandstone) onlapped the basement east of Taranaki Fault (Fig. 9). This was followed by the accumulation of Manganui Formation mudstone, initially as a shelfal deposit, but by the middle Altonian as a mid-bathyal succession (King et al. 1993). Moki Formation accumulated as submarine channel and fan deposits on a lower slope to basin floor west of the modern coastline (King & Thrasher 1996) and as channel complexes and associated continental slope facies east of the North Taranaki coastline (Kamp et al. 2004). Hence a complete coastal plain-shoreface-shelf-slope-basin floor linked depositional system developed across the margin between Taranaki and King Country basins during the Altonian and into the mid-Lillburnian. This depositional system formed over a narrow belt some 35 km wide. We show in Fig. 9 the approximate positions of the shelf-slope break during the Altonian – lower Lillburnian and infer that this break migrated slowly inland (retrogressed). The system had a strong aggradational component during the Altonian - lower Lillburnian and a surprisingly narrow shelf, which will have been controlled by the balance between the rate of subsidence of the underlying basement block and by the rate of sediment flux.

The Altonian marked the start of marked subsidence of the Kawhia Harbour to Taranaki Peninsula sector of the eastern margin of Taranaki Basin. This subsidence accelerated during the early-Middle Miocene, leading at the end of the Middle Miocene to the development of a bathyal environment over the eastern Taranaki Basin margin and the King Country Region. During the upper Lillburnian, the King Country region underwent marine flooding, possibly in response to emplacement of the subducted slab of Pacific plate beneath the region (Kamp 1999). The basal stratigraphic unit is the Mangarara Formation, which over most of the King Country is a transgressive shellbed. The Otunui Formation is a 100-200 m-thick sandstone to calcareous sandy siltstone, containing a variety of facies typical of an onlapping shoreline through shelf and upper slope succession, including glauconite-rich units (Gerritsen 1994; Cartwright 2003; Evans 2003). It passes gradationally upwards into massive siltstone facies of the Mt Messenger Formation (Kohu Member) or sandstone facies of the Tongaporutu Member. Channelised redeposited sandstone deposits occur within the upper parts of the Otunui Formation (Fig. 11).

The Mangarara Formation in the Awakino area comprises a Clifdenian (16-15 Ma), variably calcareous (slightly calcareous to limestone composition) glauconitic sandstone, which in all of the western river catchments accumulated as mass-emplaced beds on a continental slope. It is closely associated with, well sorted very fine grained sandstone beds that accumulated as turbidites, which we assign to Moki Formation, as described from other parts of Taranaki Basin by de Bock (1994), and King & Thrasher (1996). The mechanism(s) of emplacement and the continental slope environment of deposition of the Mangarara Formation are common to the Moki Formation, which differ only in carbonate content. The Mangarara Formation facies, which are rich in *Amphistegina* and rhodoliths (calcareous red algal balls), were sourced from areas of carbonate accumulation on the contemporary shelf to the east in the King Country region (Tangarakau Formation, Fig. 11), whereas the sandstone facies of the Moki Formation were transported across the shelf and upper slope from a shoreface in the southeast, where the sandstone had been well sorted by wave action. The Moki Formation turbidite deposits persist through the Middle Miocene section. The Moki and Manganui facies pass upwards into Mohakatino Formation or Mount Messenger Formation.

The Mohakatino Formation comprises richly volcaniclastic sandstone sourced from andesitic volcanoes of Middle to Late Miocene age in northern Taranaki Basin. This formation occurs onshore but strongly volcaniclastic facies are restricted to coastal sections (Nodder et al. 1990a, b; King et al. 1993) or within 10 km east of the modern coastline. These sediments occur as either airfall units, or dominantly as channelised mass-emplaced beds.

Between about 14 Ma (upper Lillburnian) and 11 Ma (lower Tongaporutuan) there was marked subsidence to bathyal (1000 m) basin floor environments of what had previously been land along the eastern margin of Taranaki Basin and in the King Country region (Fig. 9). This subsidence, in the absence of an oversupply of sediment, led to southeastward retrogradation of the continental margin that previously (in the Otaian) had been pinned to the Taranaki Fault. At about 11 Ma, when higher rates of uplift and erosion developed along the Alpine Fault, reflected in high rates of sediment flux, a continental margin wedge comprising Mt Messenger, Urenui, Kiore, and Matemateaonga formations started to prograde northward into this basin as the progradational part of the Whangamomona Sequence (Fig. 6 - 9). There are no indications that any paleogeographic barriers separated the Taranaki Basin from the King Country Basin north of Taranaki Peninsula. We illustrate in Fig. 9 the Altonian-Lillburnian retrogradation of the continental margin and its subsequent (Tongaporutuan - lower Opoitian) progradation via red markings representing successive positions of the shelf-slope break. During the early Pliocene the Wanganui Basin subsided rapidly in response to the southward migration of the depocentre.

6.0 FIFTH AND 6TH ORDER SEQUENCES WIHTIN WHANGAMOMOANA AND RANGITIKEI SEQUENCES *(but we will not visit this part of the section on this excursion)*

Fourth, 5th, and 6th order sequences are considered to be of 100 ka, and 41 ka duration, the latter two being related to Milankovitch orbital parameters, widely considered to have modulated Earth's climatic and sea level history during the late Cenozoic. The 100 ka cyclicity characterises the last 900 k.y. of Earth history, whereas 41 ka cyclicity appears to have been the dominant climatic signal during the late Miocene, Pliocene, and early Pleistocene.

Fourth, 5th, and 6th order sequences are evident to various degrees within the Whangamomona and Rangitikei Sequences. These lower orders of cyclicity are reflected in the lithofacies character and stratal geometry of the formations and units occurring within the megasequences. Excluding the 5th order Castlecliffian sequences (Turner & Kamp 1990; Abbott & Carter 1994), 6th order sequences are most prevalent in upper parts of the Whangamomona and in Rangitikei Sequences. They are well developed in shelf top-sets of the Matemateaonga Formation (Kamp et al. 2002; Vonk et al. 2002, Hendy & Kamp 2004), the Whenuakura Subgroup (Naish et al. in press), the Okiwa Subgroup (Kamp & McIntyre 1998), the Paparangi Subgroup (Kamp et al. 1998), and in Nukumaruan strata (Naish & Kamp 1995, 1997). This arises because of a very characteristic repetitive succession of shellbed-siltstone-sandstone lithofacies, typically of 25-70 m thickness.

The identification of 5th, and 6th order sequences in the slope-sets and bottom-sets of the Whangamomona Sequence is more difficult to achieve and to date than for the top-sets. King et al. (1994) have described sequences in the Urenui Formation and Mount Messenger Formation in the northern Taranaki coastal section, which are probably of 5th order cyclicity. The combination of the inclined depositional surface in slope environments, the more random depositional and mass movement processes that occur off the shelf, and the accidental position of outcrop sections and drill hole locations with respect to the depositional lobes, conspire to make it difficult to reconstruct a comprehensive record of higher order sequences in off-shelf settings, and so to establish their periodicity.

7.0 ACKNOWLEDGEMENTS

We acknowledge the Foundation for Research Science and Technology for research funding (contracts: UOW608 and UOWX0301). This field trip guide draws upon Petroleum Report PR3463 by Kamp & Vonk (2006).

8.0 REFERENCES

Abbott, S. T.; Carter, R. M. 1994: The sequence architecture of mid-Pleistocene (c. 1.1-0.4 Ma) cyclothems from New Zealand: facies development during a period of orbital control on sea level cyclicity. *In*: de Boer, P. L.; Smith, D. G. *ed*., Orbital forcing and cyclic sequences. *Special Publication of the International Association of Sedimentologists 19*: 367-394.

Beu A. G.; Edwards, A. R. 1984: New Zealand Pleistocene and late-Pliocene glacio-eustatic cycles. *Palaeogeography, Palaeoclimatology, Palaeoecology 46*: 119-142.

Browne, G. H.; Slatt, R. M. 2002: Outcrop and behind outcrop characterization of a late Miocene slope fan system, Mt. Messenger Formation, New Zealand. American Association of Petroleum Geologists Bulletin 86: 841-862.

Campbell, H. J.; Raine, J. I. 1989: Biostratigraphic evidence for the Manganui Fault, near Awakino, southwest Auckland. *Journal of the Royal Society of New Zealand 19*: 43-53.

Cartwright, S. J. 2003: Cenozoic geological evolution of the central-eastern King Country Basin, North Island. Unpublished MSc Thesis, University of Waikato, Hamilton, New Zealand.

Cochrane, P. R. 1988: The stratigraphy and structure of the early Miocene Mahoenui Group, northern Awakino Gorge: controls on cyclic carbonate-terrigenous sedimentation. Unpublished MSc Thesis, University of Waikato, Hamilton, New Zealand.

Crosdale, P. J. 1993: Regression-related coal-bearing sequences in the Neogene of New Zealand: relation to the developing Alpine fault transform. *In:* Ballance, P. F. ed. South Pacific sedimentary basins. Sedimentary Basins of the World 2. Amsterdam, Elsevier. Pp.279-293.

Cooper, R.A.(ed.) 2004: The New Zealand Geological Timescale. Institute of Geological and Nuclear Sciences Monograph 22, 284pp.

de Bock, J. F. 1994: Moki Formation, a Miocene reservoir sequence, its facies distribution and source in offshore southern Taranaki Basin. 1994 New Zealand Petroleum Conference Proceedings, The Publicity Unit, Crown Minerals Operations Group, Energy and Resources Division, Ministry of Commerce. Pp. 155-167.

Fleming, C. A. 1953: The geology of Wanganui Subdivision. *New Zealand Geological Survey Bulletin 52*. 362 p.

Edbrooke, S.W. (compiler) 2005: Geology of the Waikato area. Institute of Geological and Nuclear Sciences 1:250 000 geological map 4. I sheet +68p. Lower Hutt, New Zealand.

Evans, T. P. H. 2003: Stratigraphy and sedimentology of early to middle Miocene strata, western Taumarunui region, King Country Basin. Unpublished MSc thesis, University of Waikato, Hamilton, New Zealand.

Gerritsen, S. W. 1994: The regional stratigraphy and sedimentology of the Miocene sequence in the Ohura-Taumarunui region. Unpublished MSc thesis, University of Waikato, Hamilton, New Zealand.

Glaessner, M. F. 1960: The fossil decapod crustacea of New Zealand and the evolution of the order decapoda. New Zealand Geological Survey Paleontological bulletin v. 31, Dept of Scientific and Industrial Research, Wellington, 63 pp.

Hansen, R. J.; Kamp, P. J. J. 2002: Evolution of the Giant Foresets Formation, northern Taranaki Basin, New Zealand. *Proceedings 2002 New Zealand Petroleum Conference, Auckland 24-27 February, 2002*. Ministry of Economic Development, Wellington. Pp. 419-435.

Hansen, R. J.; Kamp, P. J. J. 2004: Late Miocene - early Pliocene stratigraphic record in northern Taranaki Basin: Prelude to Northern Graben extension and progradation of the modern continental margin. *New Zealand Journal of Geology and Geophysics, 47(4), 645-662.*

Hansen, R.J. and Kamp, P.J.J., 2006: An integrated biostratigraphy and seismic stratigraphy of the late Neogene continental margin succession in northern Taranaki Basin, New Zealand. *New Zealand Journal of Geology and Geophysics. 49*: 39-46.

Happy, A. J. 1971: Tertiary geology of the Awakino area, North Taranaki. Unpublished MSc Thesis, University of Auckland, New Zealand.

Hay, R. F. 1967: Geological map of New Zealand, Sheet 7, Taranaki. 1:250,000. Wellington, Department of Scientific and Industrial Research.\

Nelson, C.S., Kamp, P.J.J. and Young, H.R. 1994: Sedimentology and petrography of mass-emplaced limestone (Orahiri Limestone) on a late Oligocene shelf, western North Island, and tectonic implications for eastern margin development of Taranaki Basin. *New Zealand Journal of Geology and Geophysics, 37, 269-285.*

Henderson, J.; Ongley, M. 1923: The geology of the Mokau Subdivision. *New Zealand Geological Survey Bulletin 24*.

Hendy, A. J. W.; Kamp, P. J. J. 2004: Late Miocene-early Pliocene biofacies of Wanganui and Taranaki Basins, New Zealand: applications to paleoenvironmental and sequence stratigraphic analysis. *New Zealand Journal of Geology and Geophysics 47(4):769-785.*

Hendy, A.J.W. Kamp, P.J.J. and Vonk, A.J. 2006: Cool-water shell bed taphofacies from the Miocene-Pliocene shelf sequences in New Zealand: utility of taphofacies in sequence stratigraphic analysis. *In:* Pedley, H.M. & Carannante, G. (eds) *Cool-Water Carbonates: Depositional Systems and Palaeoenvironmental Controls*. Geological. Society, London, Special Publications, 255: 283-305.

Kamp, P. J. J. 1986: The mid-Cenozoic Challenger Rift System of western New Zealand and its implications for the age of Alpine Fault inception. *Geological Society of America Bulletin 97*: 255-281.

Kamp, P. J. J. 1999: Tracking crustal processes by FT thermochronology in a forearc high (Hikurangi margin, New Zealand) involving Cretaceous subduction termination and mid-Cenozoic subduction initiation. *Tectonophysics 307*: 313-343.

Kamp, P. J. J.; McIntyre, A. P. 1998: The stratigraphic architecture of late Pliocene (2.8-2.4 Ma) asymmetrical shelf sequences, western Wanganui Basin, New Zealand. *Sedimentary Geology 122*: 53-67.

Kamp, P. J. J.; Turner, G. 1990: Pleistocene unconformity bounded sequences (Wanganui Basin, New Zealand) correlated with global isotope record. *Sedimentary Geology 68*: 155-161.

Kamp, P. J. J.; Journeaux, T. D.; Morgans, H. E. G. 1998: Cyclostratigraphy of middle Pliocene mid-shelf to upper slope strata, eastern Wanganui Basin (New Zealand): correlations to the deep sea isotope record. *Sedimentary Geology 117*: 165-192.

Kamp, P. J. J. and Vonk, A. J. 2006: Eastern Taranaki field guide. Ministry of Economic Development, New Zealand. Petroleum Report PR3463. 97 p.

Kamp, P. J. J., Tripathi, A. and Nelson, C. S. 2008: Stratigraphic columns and correlations for the Late Eocene – Oligocene Te Kuiti Group, central-western North Island, New Zealand. Ministry of Economic Development New Zealand. Unpublished Petroleum Report PR3901. 257 p.

Kamp, P. J. J., Tripathi, A. and Nelson, C. S. 2014: Paleogeography of Late Eocene to earliest Miocene Te Kuiti Group, central-western North Island, New Zealand. *New Zealand Journal of Geology and Geophysics* v.57 (2) 128-148.

Kamp, P. J. J.; Vonk, A. J.; Bland, K. J. et al. 2002: Megasequence architecture of Taranaki-Wanganui-King Country Basins and Neogene progradation of two continental margin wedges across western New Zealand. *Proceedings 2002 New Zealand Petroleum Conference, Auckland 24-27 February, 2002.* Ministry of Economic Development, Wellington. Pp. 464-481.

Kamp, P.J.J., Vonk, A.J., Bland, K.J. Hansen, R.J., Hendy, A.J.W., McIntyre, A.P., Ngatai, M., Cartwright, S.J., Hayton, S., and Nelson, C.S. 2004: Neogene Stratigraphic architecture and tectonic evolution of Wanganui, King Country, and eastern Taranaki Basins, New Zealand. *New Zealand Journal of Geology and Geophysics* v.47 (4) 625-644.

King, P. R.; Browne, G. H.; Slatt, R. M. 1994: Sequence architecture of exposed late Miocene basin floor fan and channel-levee complexes (Mount Messenger Formation), Taranaki Basin, New Zealand. *In*: Weimer, P.; Bouma, A. H.; Perkins, B. F. *ed*. Submarine fans and turbidite systems. *Gulf Coast Section, Society of Economic Paleontologists and Mineralogists Foundation, 15th Annual Research Conference*. Pp. 172-192.

King, P. R.; Scott, G. H.; Robinson, P. H. 1993: Description, correlation and depositional history of Miocene Sediments outcropping along the North Taranaki coast. *Institute of Geological and Nuclear Sciences Monograph 5*. 199 p. Lower Hutt, Institute of Geological and Nuclear Sciences Ltd.

King, P. R.; Thrasher, G. P. 1996: Cretaceous – Cenozoic geology and petroleum systems of the Taranaki Basin, New Zealand. *Institute of Geological and Nuclear Sciences Monograph 13*. 243 p.

McIntyre, A. P.; Kamp, P. J. J. 1998: Late Pliocene (2.8-2.4 Ma) cyclothemic shelf deposits, Parikino, Wanganui Basin, New Zealand: lithostratigraphy and correlation of cycles. *New Zealand Journal of Geology and Geophysics 41*: 69-84.

Naish, T. R.; Kamp, P. J. J. 1995: Late Pliocene marine cyclothems, Wanganui Basin, New Zealand. *New Zealand Journal of Geology and Geophysics 38*: 223-243.

Naish, T. R.; Kamp, P. J. J. 1997: Sequence stratigraphy of 6th order (41 k.y.) Pliocene-Pleistocene cyclothems, Wanganui Basin, New Zealand: a case for the regressive systems tract. *Geological Society of America Bulletin 109*: 978-999.

Naish, T. R.; Wehland, F.; Wilson, G. S.; Browne, G. H.; Cook, R.; Morgans, H.; Rosenburg, M.; King, P. R.; Smale, D.; Nelson, C. S.; Kamp, P. J. J.; Ricketts, B. in review: An integrated sequence stratigraphic, paleoenvironmental and chronostratigraphic analysis of the mid-Pliocene (c. 3.4-3.0 Ma) Tangahoe Formation, southern Taranaki Coast: implications for glacio-eustatic sea-level changes. *Journal of the Royal Society of New Zealand,* V. *35 Numbers 1&2, 151-196.*

New Zealand Geological Survey 1972: North Island (1st Ed.) Geological map of New Zealand 1: 1,000,000. Wellington, Department of Scientific and Industrial Research.

Nelson, C. S. 1973: Stratigraphy and sedimentology of the Te Kuiti Group in Waitomo County, South Auckland. Unpublished PhD Thesis, University of Auckland, New Zealand.

Nelson, C. S. 1978: Stratigraphy and paleontology of the Te Kuiti Group, Waitomo County, South Auckland, New Zealand. *New Zealand Journal of Geology and Geophysics 21*: 223-243.

Nelson, C. S.; Hume, T. M. 1977: Relative intensity of tectonic events revealed by the Tertiary sedimentary record in the North Wanganui Basin and adjacent areas, New Zealand. *New Zealand Journal of Geology and Geophysics 20*: 369-392.

Nelson, C. S.; Kamp, P. J. J.; Young, H. R. 1994: Sedimentology and petrography of mass-emplaced limestone (Orahiri Limestone) on a late Oligocene shelf, western North Island, and tectonic implications for eastern margin development of Taranaki Basin. *New Zealand Journal of Geology and Geophysics 37*: 269-285

Nodder, S. D.; Nelson, C. S.; Kamp, P. J. J. 1990a: Middle Miocene formational stratigraphy (Mokau-Mohakatino Groups) at Waikawau, northeastern Taranaki Basin margin, New Zealand. *New Zealand Journal of Geology and Geophysics 33*: 585-598.

Nodder, S. D.; Nelson, C. S.; Kamp, P. J. J. 1990b: Mass-emplaced siliciclastic - volcaniclastic - carbonate sediments in middle Miocene shelf-to-slope environments at Waikawau, northern Taranaki and some implications for Taranaki Basin development. *New Zealand Journal of Geology and Geophysics 33*: 599-615.

Puga-Bernabéu, A., Vonk, A. J., Nelson, C. S. and Kamp, P. J. J. 2009: Mangarara Formation: exhumed remnants of a middle Miocene, temperate carbonate, submarine channel-fan system on the eastern margin of Taranaki Basin, New Zealand. *New Zealand Journal of Geology and Geophysics 52: 73-93.*

Reilly, W. I. 1965: Gravity map of New Zealand 1:4,000,000. Bouger and Isostatic Anomalies (1st ed.). Wellington, Department of Scientific and Industrial Research.

Topping, R. M. 1978: Foraminifera from the Mahoenui Group, North Wanganui Basin. Unpublished PhD Thesis, University of Auckland, New Zealand.

Turner, G. M.; Kamp, P. J. J. 1990: Paleomagnetic location of the Jaramillo subchron and Brunhes - Matuyama transition in the Castlecliffian Stratotype section, Wanganui Basin, New Zealand. *Earth and Planetary Science Letters* 100: 42-50.

Vail, P.R., 1987: Seismic stratigraphy interpretation using sequence stratigraphy Part I: Seismic stratigraphy interpretation procedure. In Bally, A.W. (ed) AAPG Atlas of Seismic Stratigraphy, volume 1. *American Association of Petroleum Geologists studies in geology no. 27: 1-10.* American Association of Petroleum Geologists, Tulsa.

Vonk, A. J. 1999: Stratigraphic architecture and sedimentology of the early Miocene Mokau Group, North Wanganui Basin, western North Island, New Zealand. Unpublished MSc thesis, University of Waikato, Hamilton, New Zealand.

Vonk, A. J.; Kamp, P. J. J.; Hendy, A. W. 2002: Outcrop to subcrop correlations of late Miocene-Pliocene strata, Taranaki Peninsula. *Proceedings 2002 New Zealand Petroleum Conference, Auckland 24-27 February, 2002.* Wellington, Ministry of Economic Development. Pp. 234-255.

Wilson, B. T. 1994: Sedimentology of the Miocene succession (coastal section), eastern Taranaki Basin margin: sequence stratigraphic interpretation. Unpublished MSc thesis, University of Waikato, Hamilton, New Zealand.

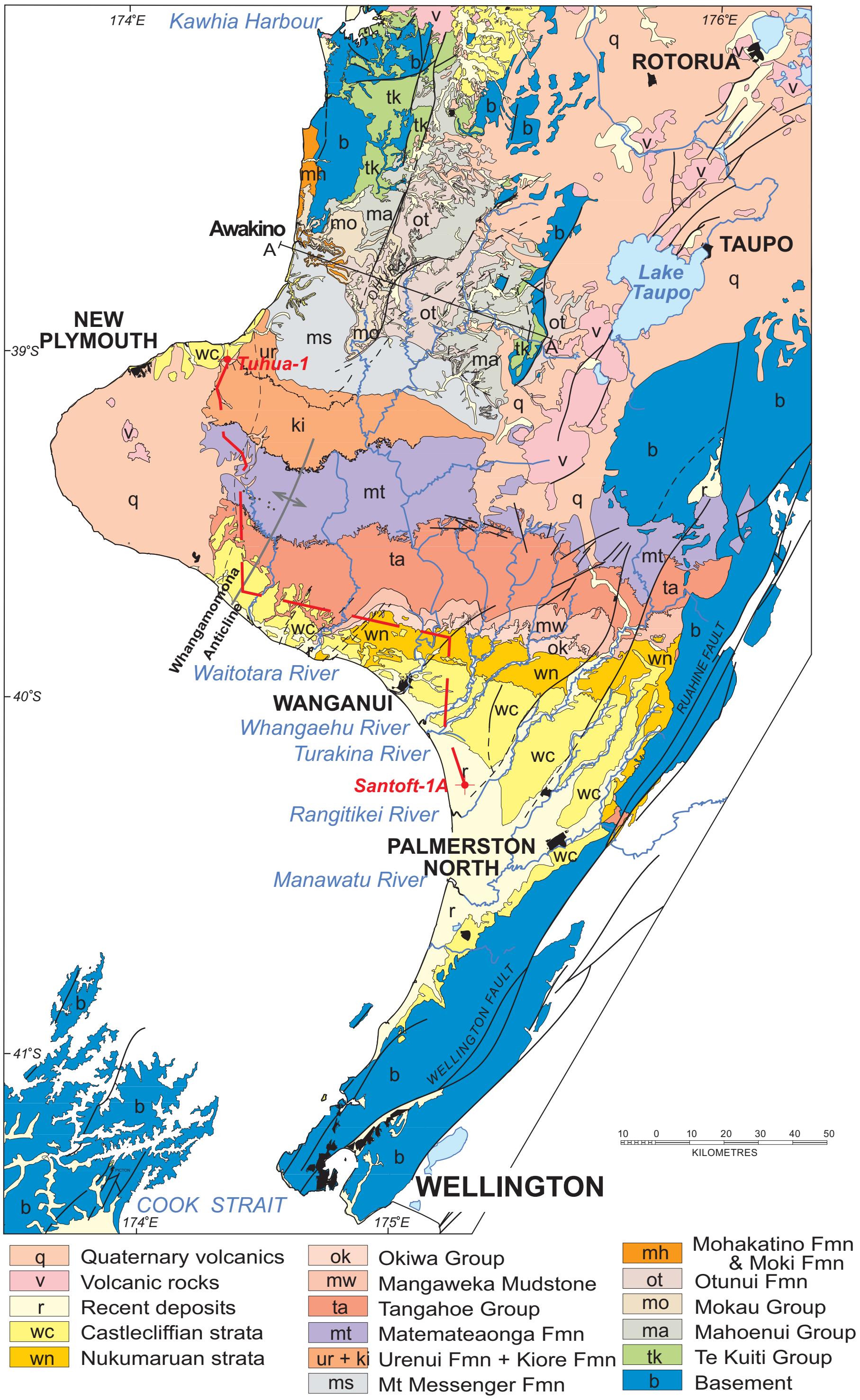


Fig. 1. Simplified geological map of western North Island (modified from New Zealand Geological Survey 1972), showing the main stratigraphic units in the eastern Taranaki, King Country, and Wanganui Basins (see Fig. 2). Cross-section line A-A' is the basis for the chronostratigraphic panel in Fig. 9. From Kamp et al. 2004 (Fig.1).

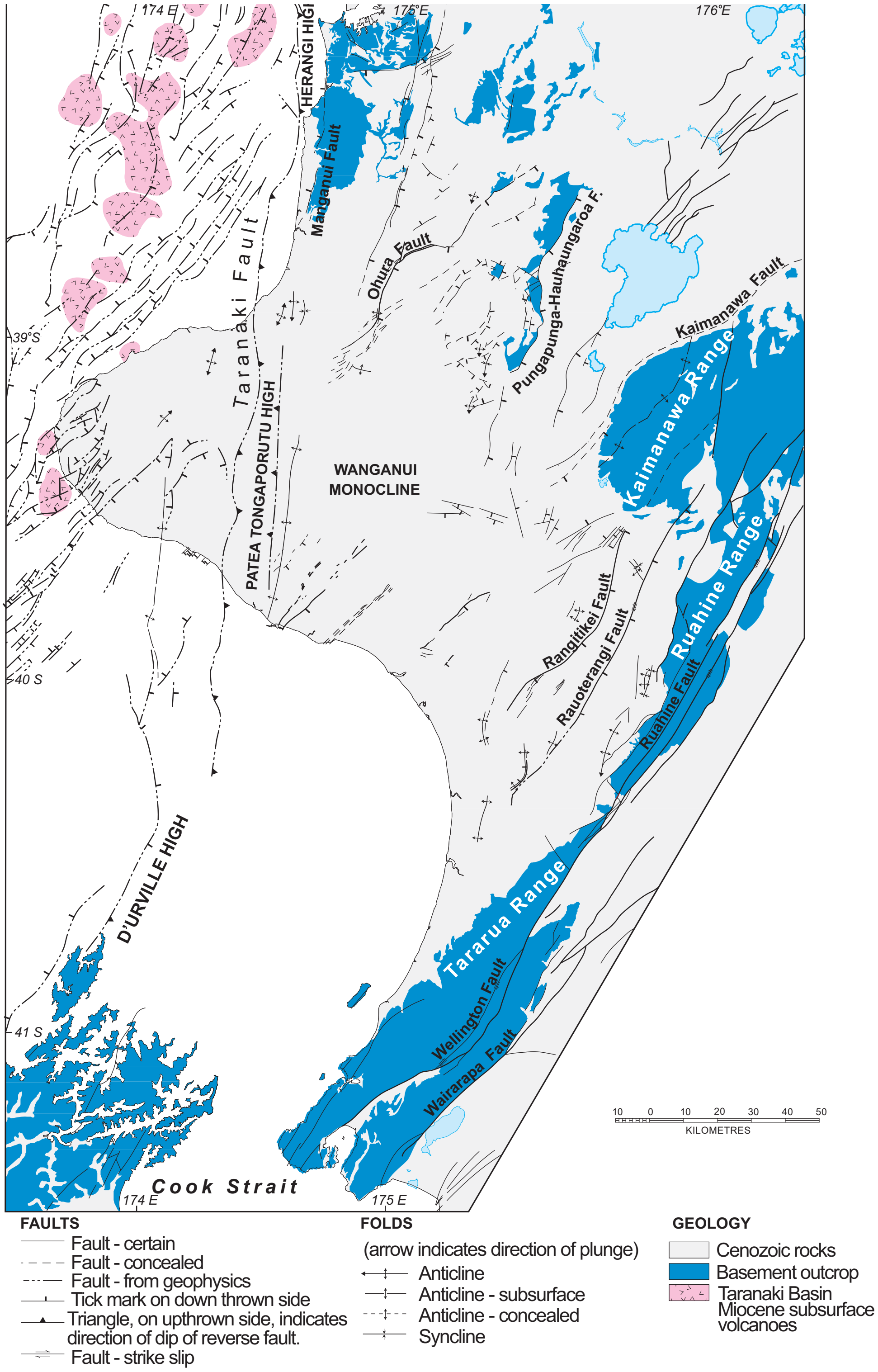


Fig. 2. Map of western North Island showing the major geological structures and the distribution of basement. While many of the structures are of Pliocene-Pleistocene age, some date back to the early Miocene and may not be currently active. From Kamp et al. 2004 (Fig. 2).

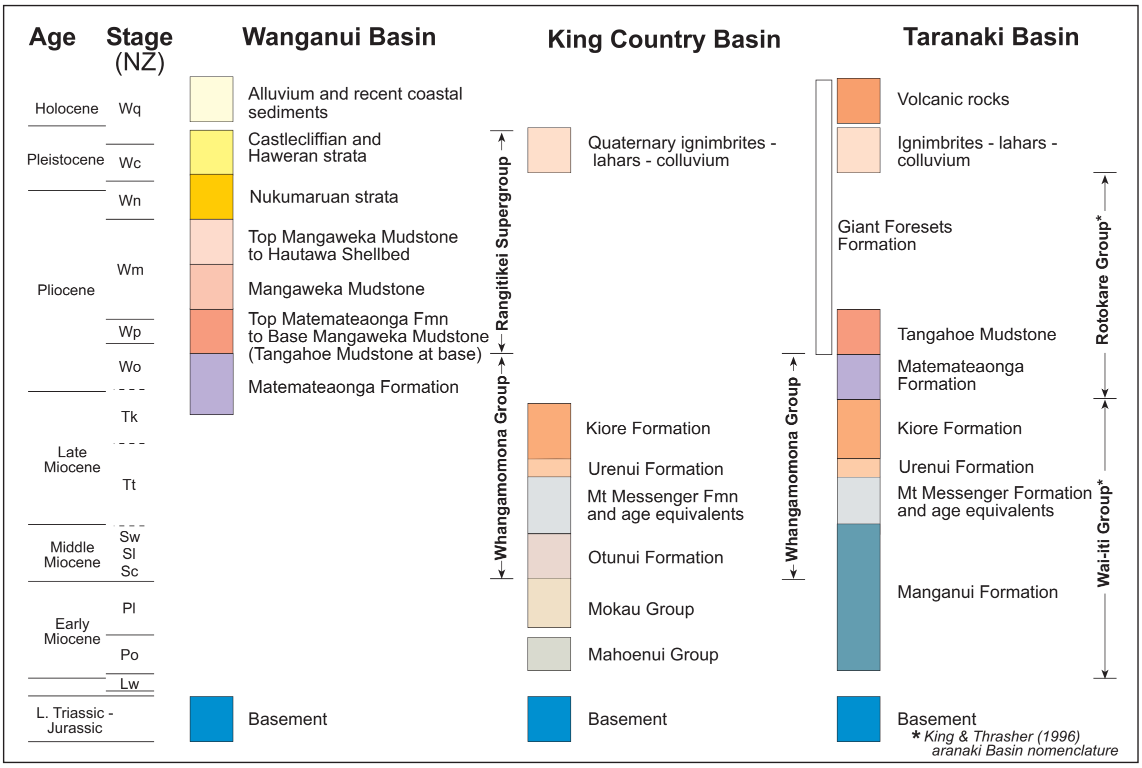


Fig. 3. The major Neogene stratigraphic units in each of Taranaki, King Country, and Whanganui Basins, and their age. The Moki and Mohakatino Formations, which occur within Manganui Formation in Taranaki Basin, are not shown. From Kamp et al. 2004 (Fig. 3).

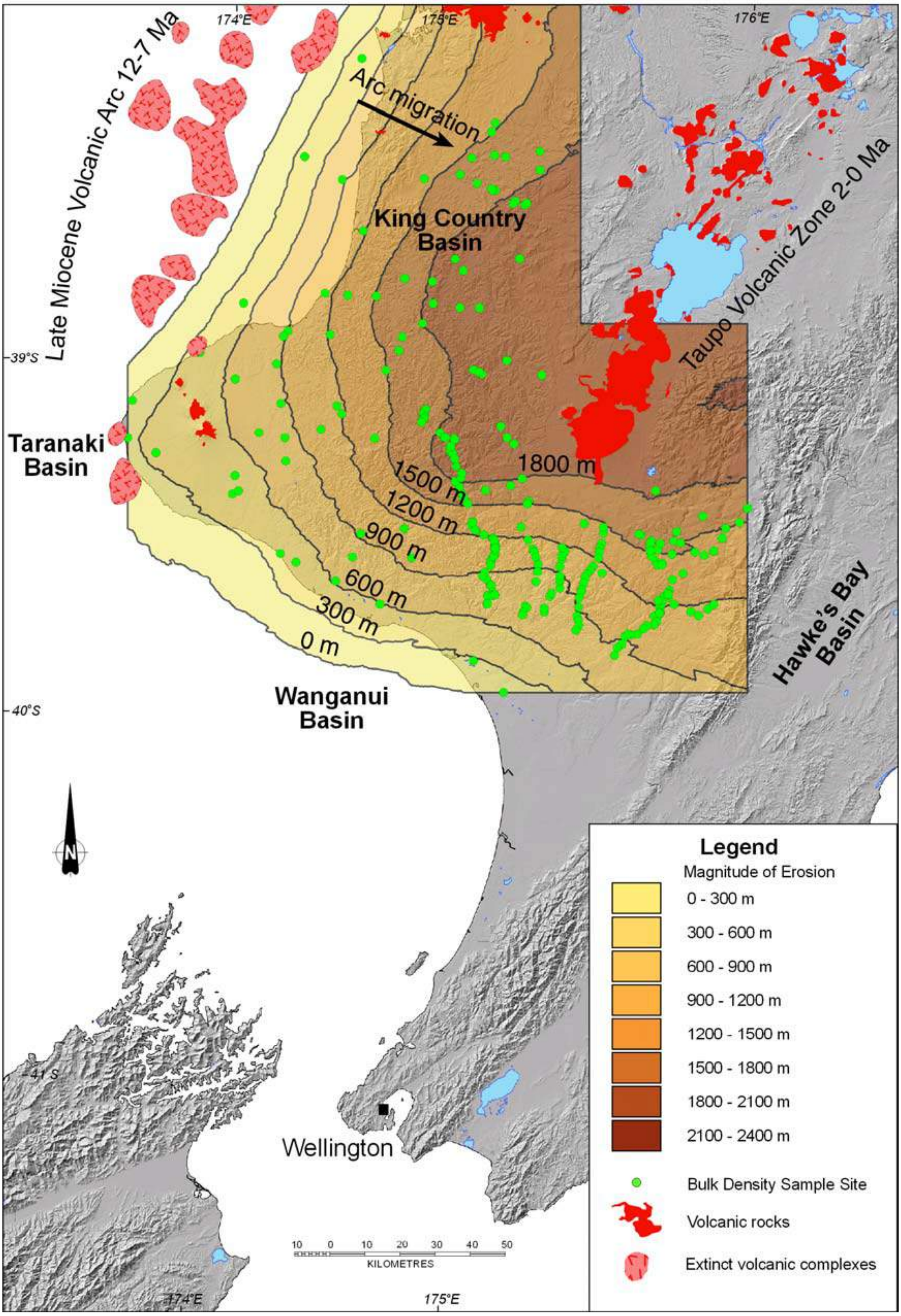


Fig. 4. Map showing the magnitude in 300 m contours and pattern of Pliocene-Pleistocene erosion over central North Island derived from mudstone bulk density data. See text for discussion. From Kamp et al. 2004 (Fig. 4).

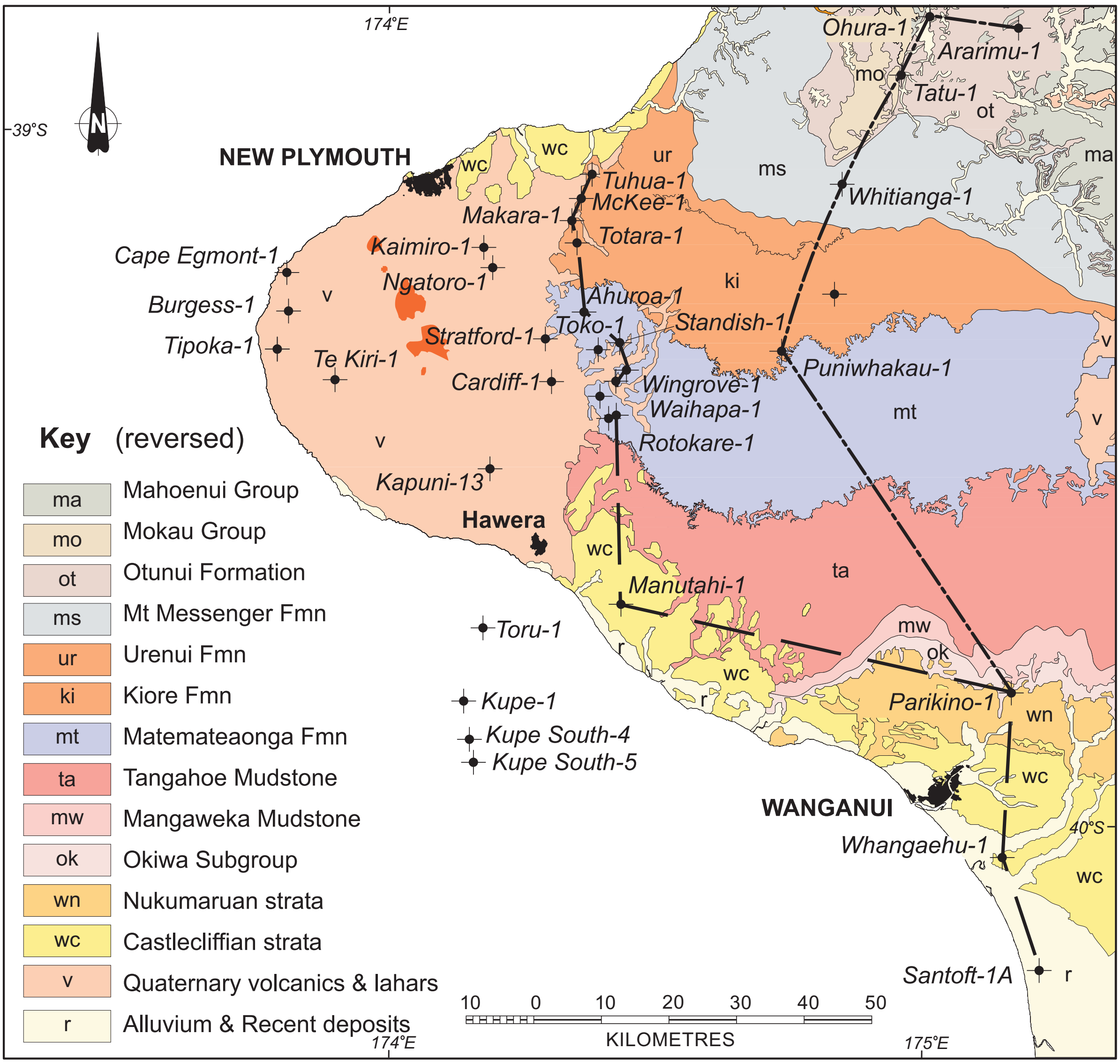


Fig. 5. Geological map of central-western North Island, including Taranaki Peninsula, showing the location of key hydrocarbon exploration holes and the line of two cross-sections illustrated in Fig. 6 & 7. Modified from Kamp et al. 2004 (Fig. 5).

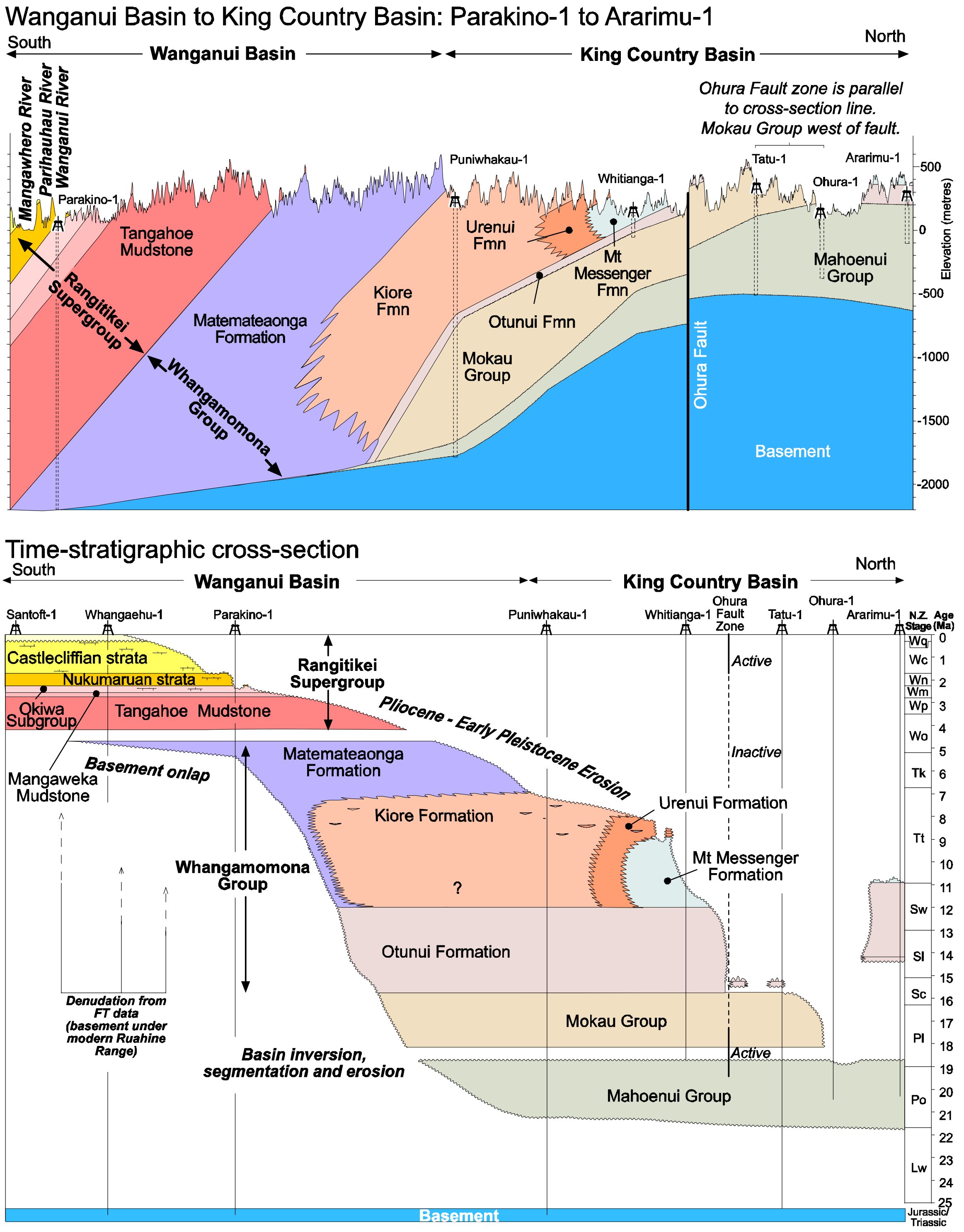
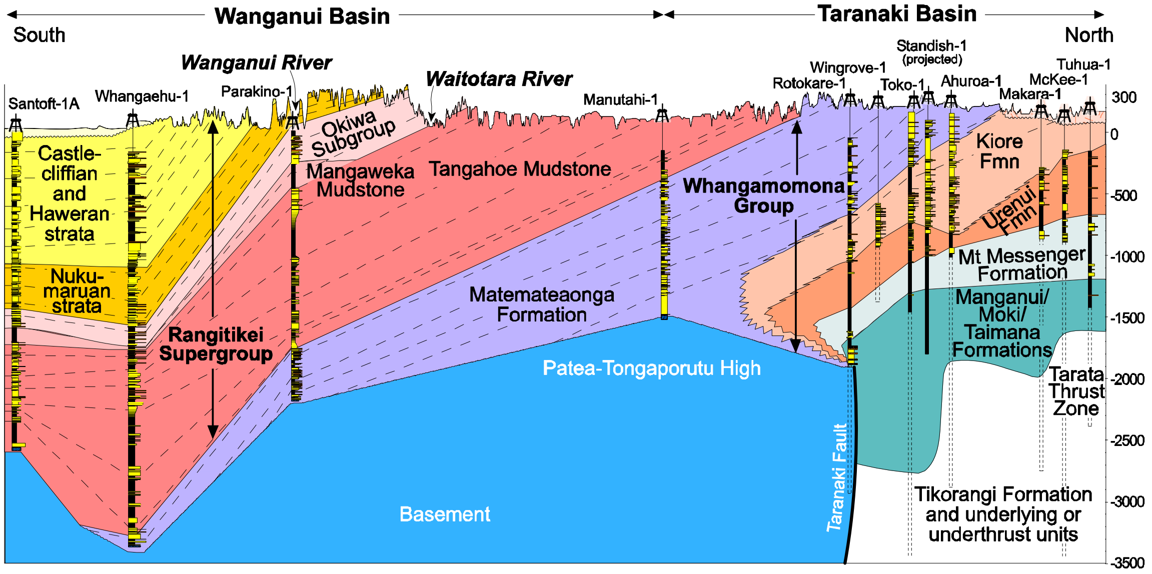


Fig. 6. Whanganui Basin to King Country Basin (Parakino-1 to Ararimu-1) stratigraphic panel built up from well-to-well correlations, and related time- stratigraphic cross-section. The timing of denudation of basement underlying the present Ruahine Range, determined from apatite fission track analysis, is also shown. From Kamp et al. 2004 (Fig. 6).

Wanganui Basin to Taranaki Basin: Santoft-1A to Tuhua-1



Time-stratigraphic cross-section

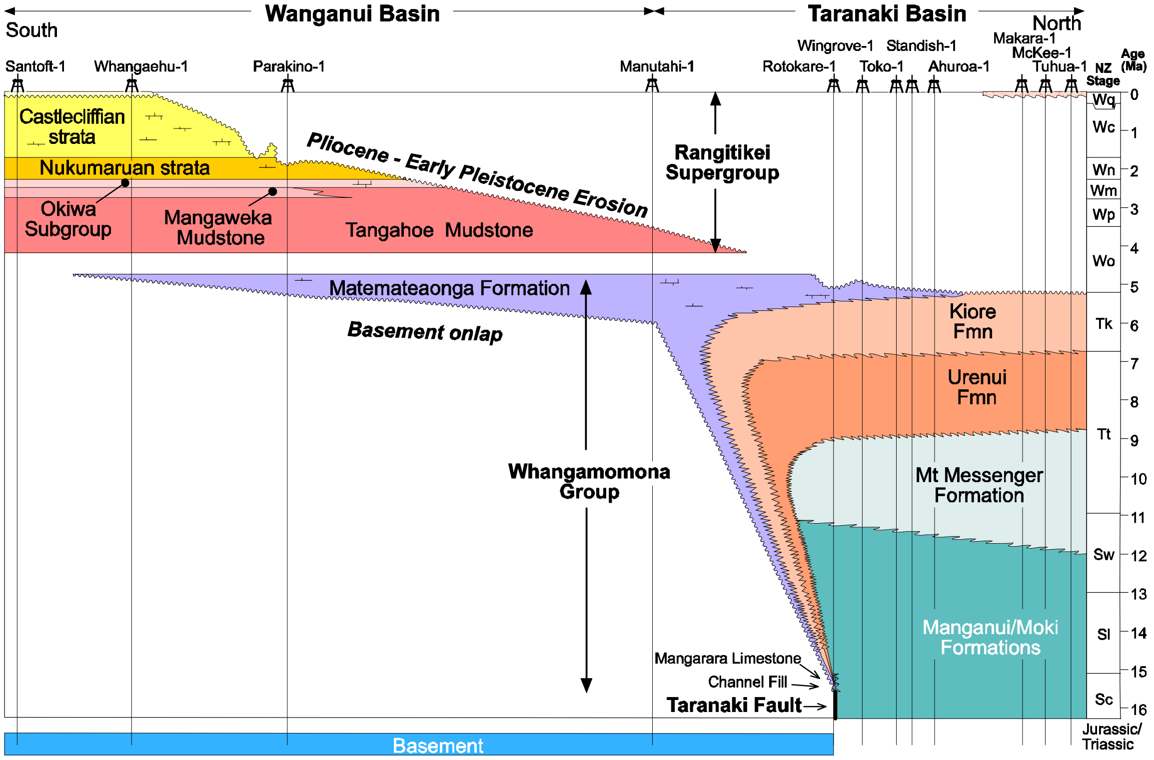


Fig. 7. Wanganui Basin to Taranaki Basin (Santoft-1A to Tuhua-1) stratigraphic panel built up from well-to-well correlations, and related time-stratigraphic cross-section. From Kamp et al. 2004 (Fig. 7).

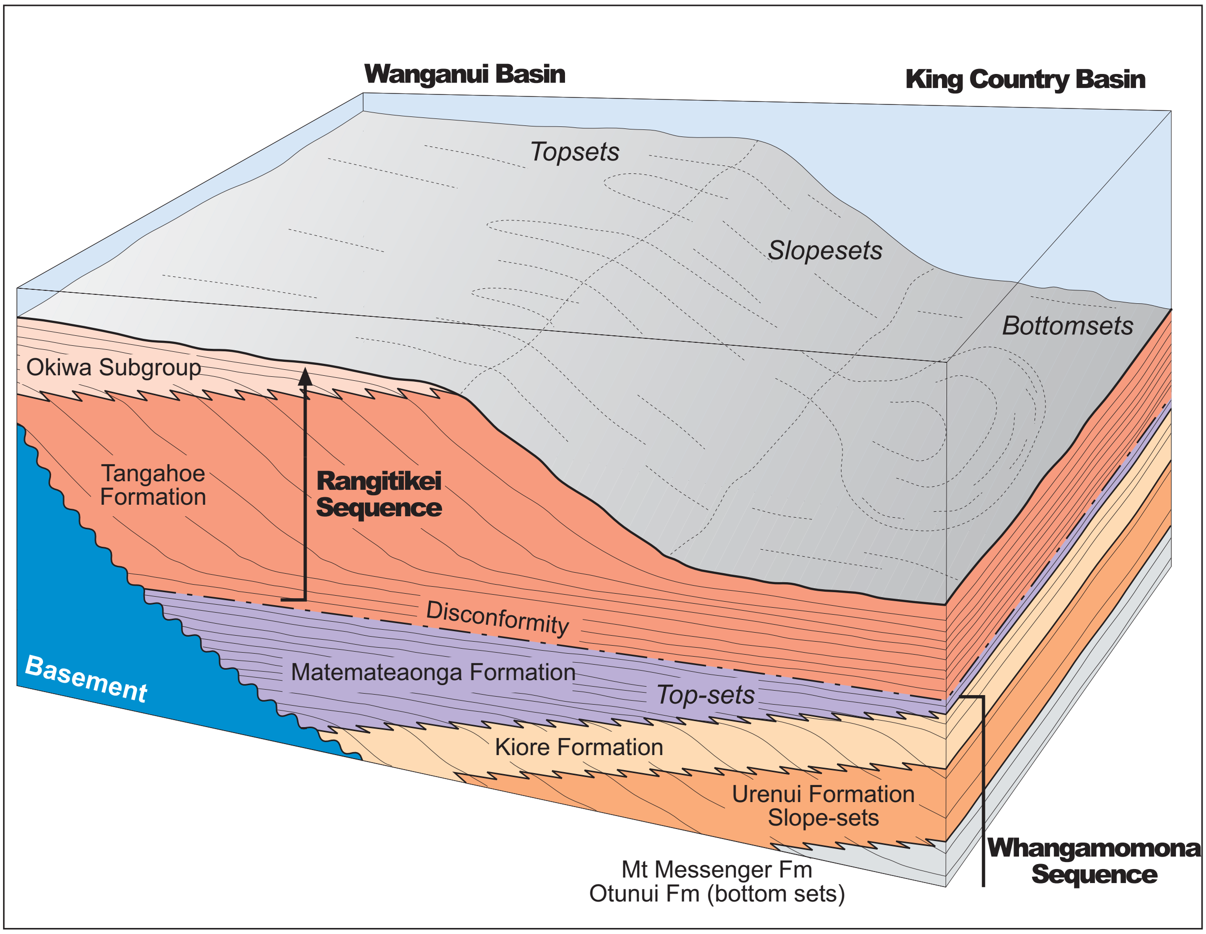


Fig. 8. Block diagram showing schematically the occurrence of two continental margin wedges representing the Whangamomona and Rangitikei Sequences, each having prograded northward through central-western North Island during the late Neogene. North is to the right. From Kamp et al. 2004 (Fig. 10).

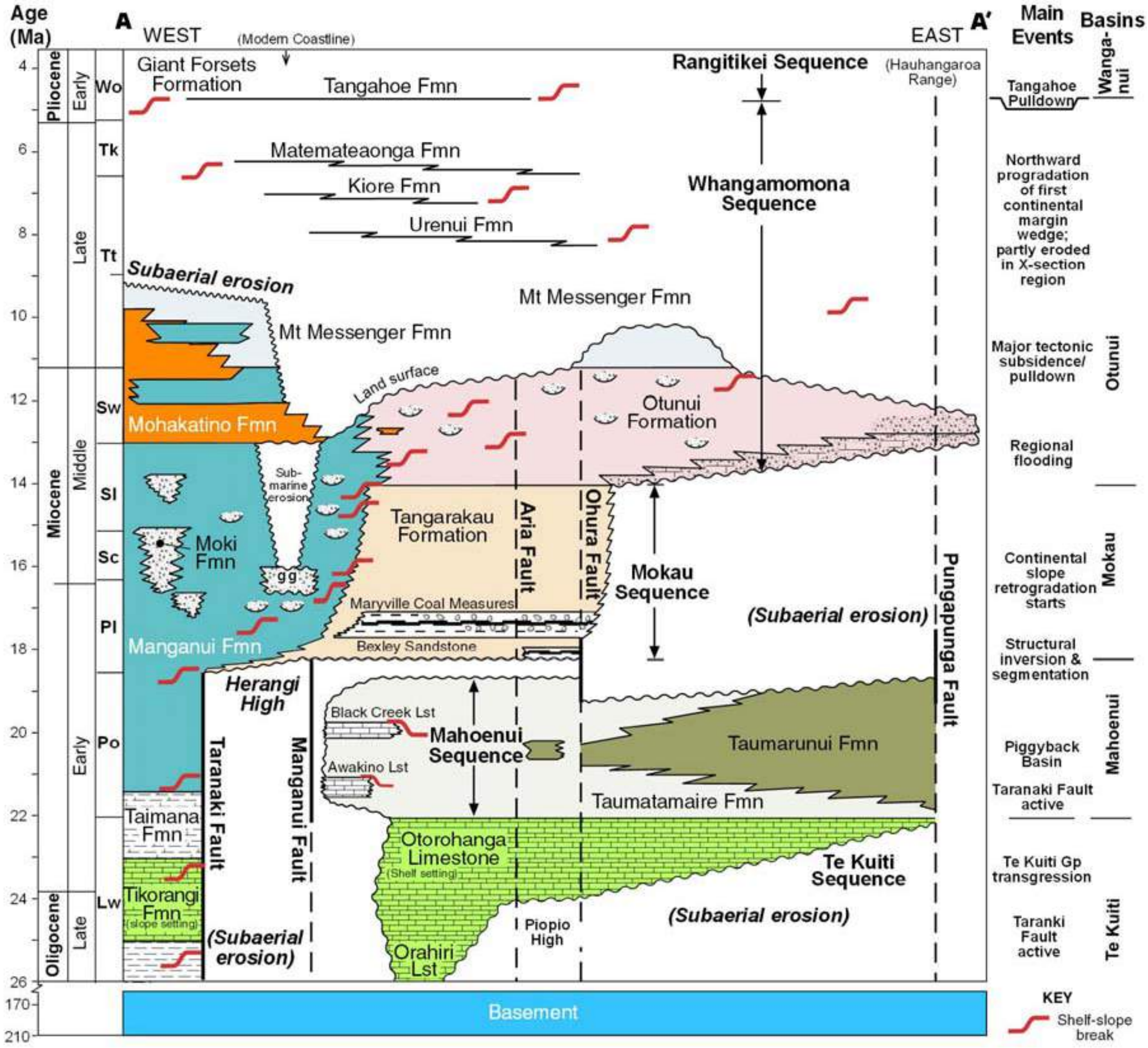


Fig. 9. Chronostratigraphic panel representing the relationship between formations and 2nd order sequences of Cenozoic age cropping out in a cross-section between Awakino Heads in eastern Taranaki Basin and Waitui Saddle on the Hauhungaroa Range along the eastern margin of the King Country region (line of section A-A'on Fig. 1). "g" represents occurrence of glauconite. Depocentres within the King Country and Wanganui Basins are noted on the right. Modified from Kamp et al. 2004 (Fig. 11).

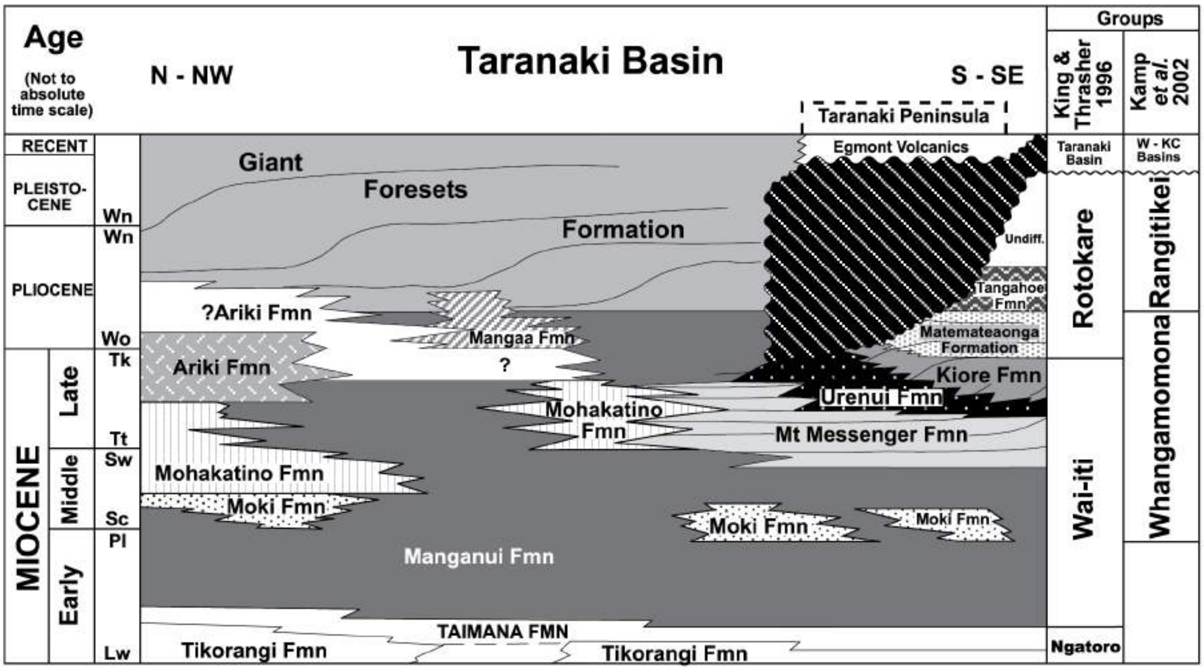
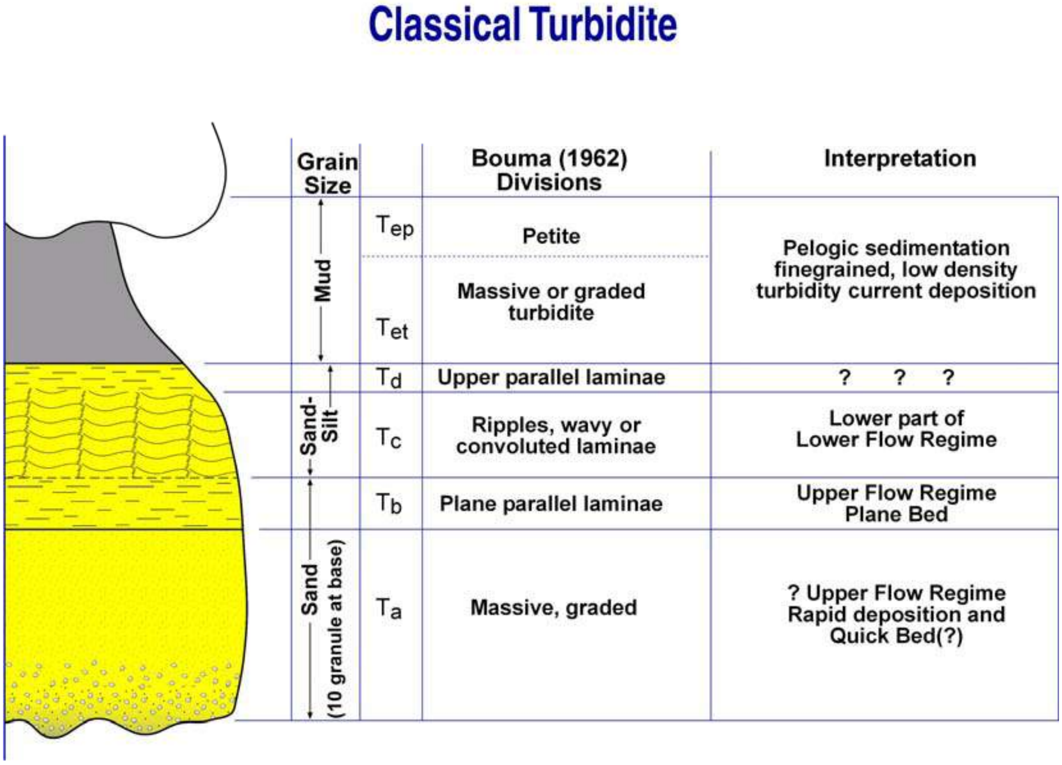


Fig. 10. Simplified Neogene stratigraphic nomenclature for Taranaki basin modified from King & Thrasher (1996) in Hansen & Kamp (2004, Fig. 2)). The Whangamomona Group is a name for a unit in the King Country region; its base is shown approximately.


Classical Turbidite

Grain Size		Bouma (1962) Divisions	Interpretation
Mud	T_{ep}	Petite	Pelogic sedimentation finegrained, low density turbidity current deposition
	T_{et}	Massive or graded turbidite	
Sand-Silt	T_d	Upper parallel laminae	? ? ?
	T_c	Ripples, wavy or convoluted laminae	Lower part of Lower Flow Regime
	T_b	Plane parallel laminae	Upper Flow Regime Plane Bed
Sand (10 granule at base)	T_a	Massive, graded	? Upper Flow Regime Rapid deposition and Quick Bed(?)

Fig. 11. Sketch of the features of a classical turbidite.

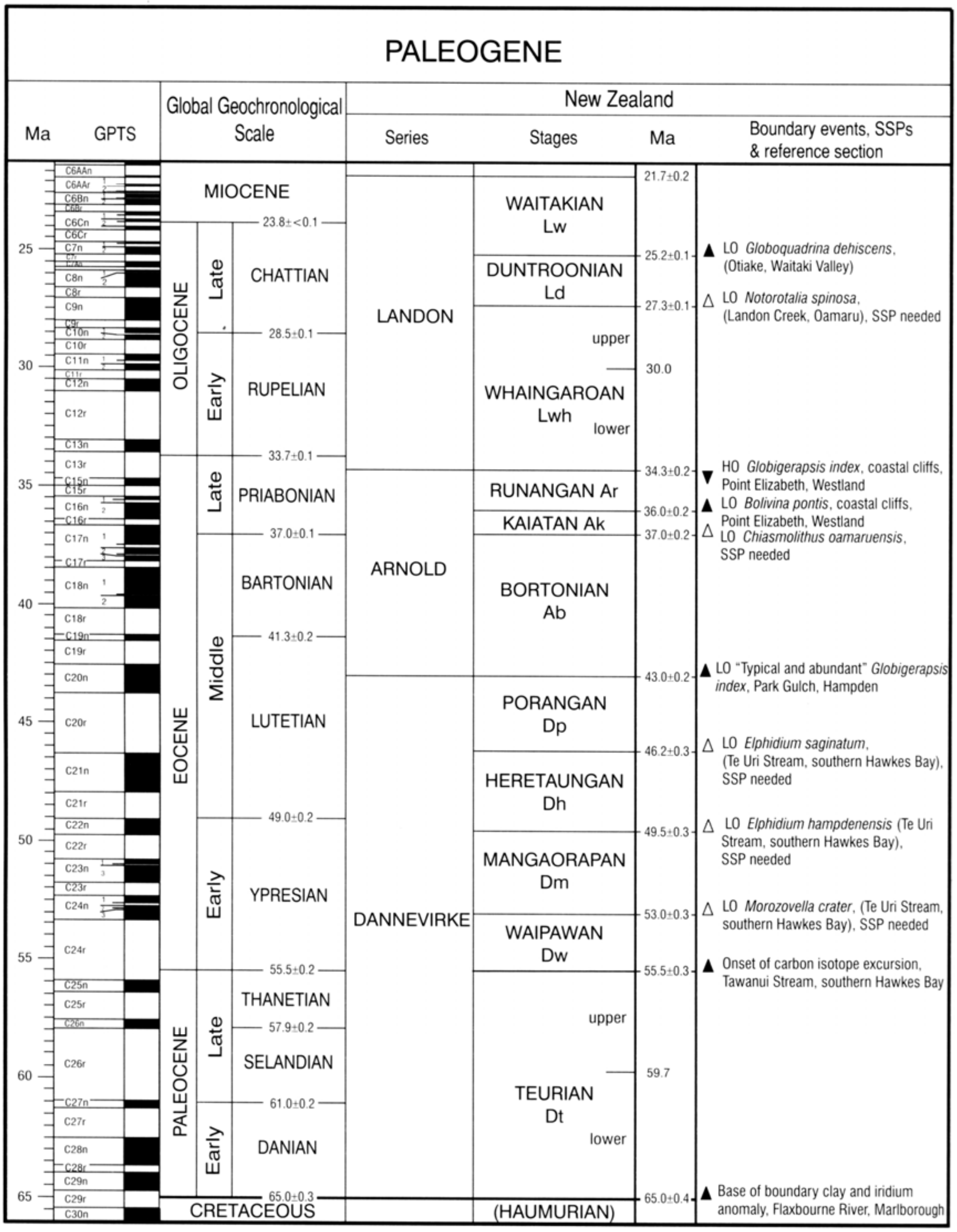


Fig.12a. Paleogene Time Scale showing the age of New Zealand Stages. From H.E. Morgans et al. (Fig. 11.1) in Cooper (ed.) (2004).

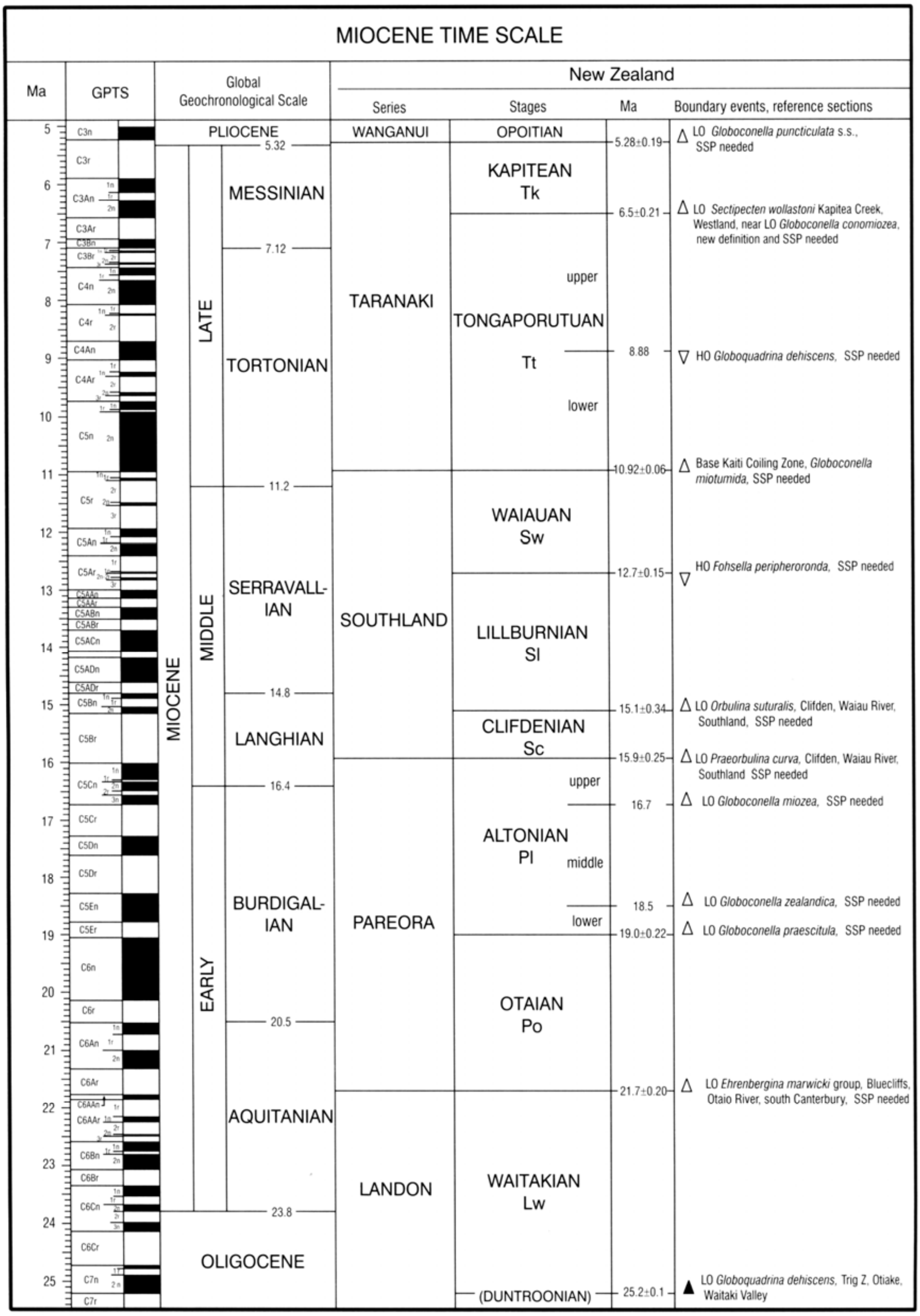


Fig.12b. Neogene Time Scale showing the age of New Zealand Stages. From M.P. Crundwell et al. (Fig. 12.1) in Cooper (ed.) (2004).

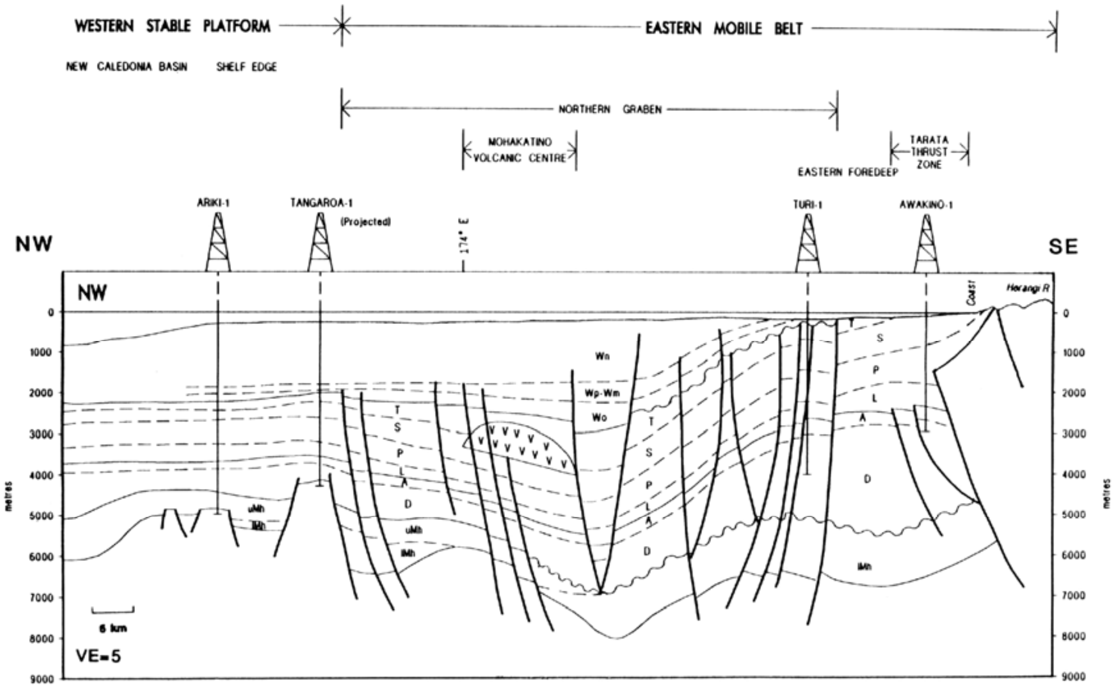


Fig 13. NW-SE structural cross-section intersecting the coastline 8 km north of Awakino, and extending across the Northern Graben to the edge of the continental shelf. Note the upward flexure of the Cenozoic succession, which continues onshore, where it is progressively beveled by Pliocene-Pleistocene erosion. From King et al. 1993 (Fig. 8).

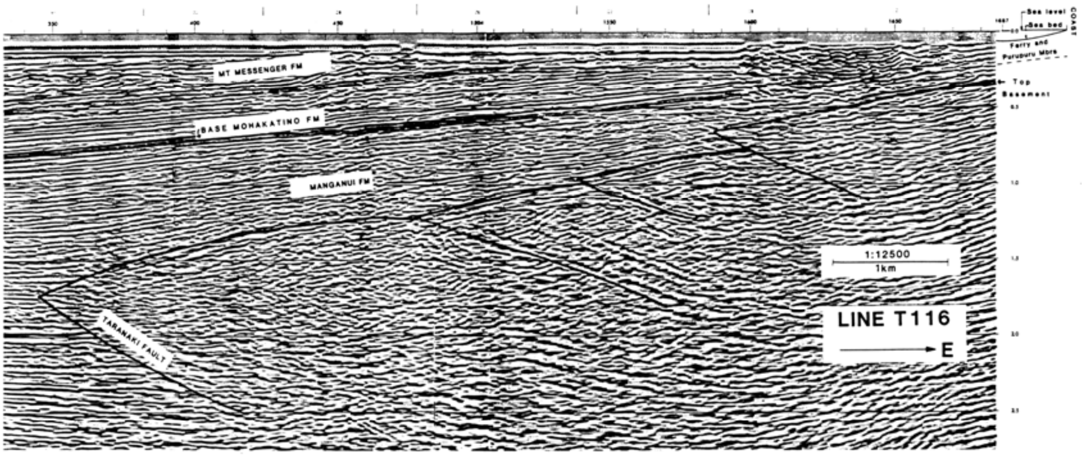
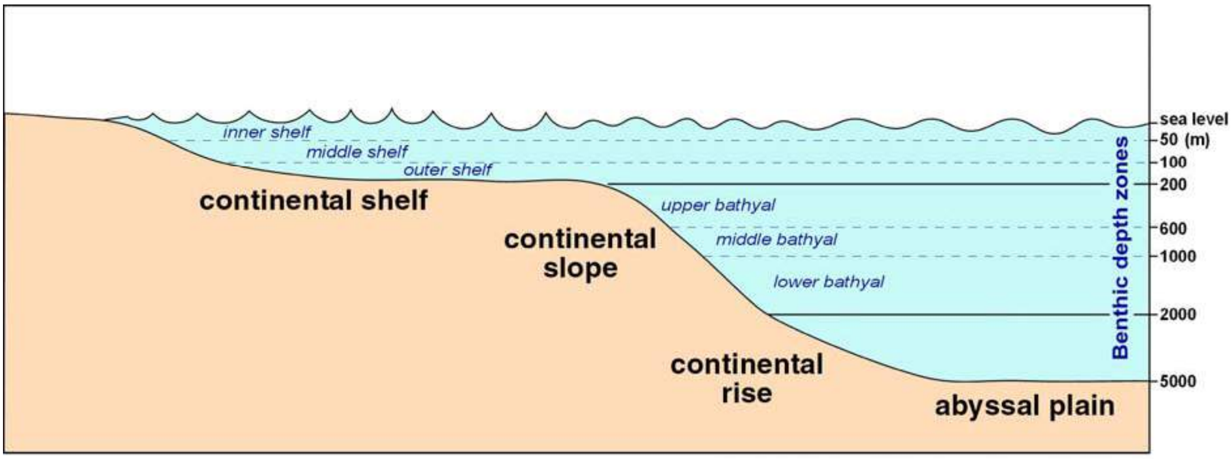
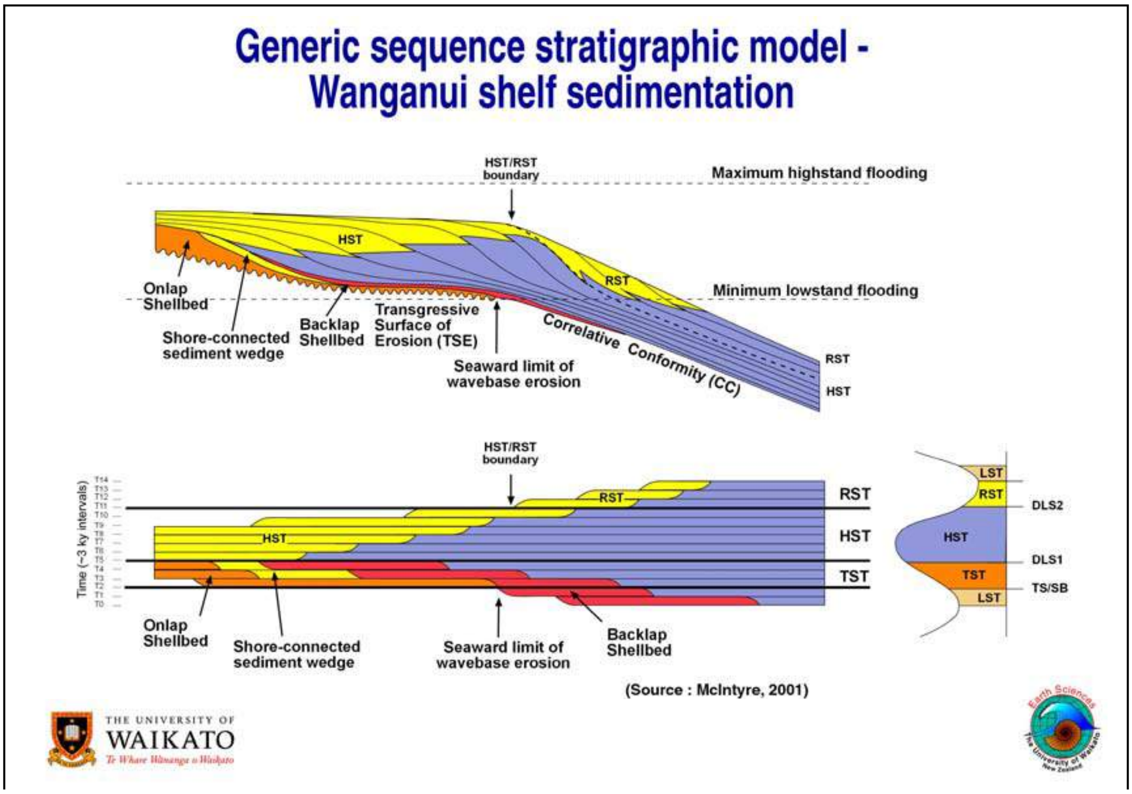


Fig. 14. E-W seismic reflection line T116. The eastern end lies just offshore between the Mohakatino and Tongaporutu River mouths. Vertical axis in seconds TWT. The Manganui, Mohakatino and Mt Messenger Fmns successively overlie the overthrust block east of the Taranaki Fault, representing onlap and foundering of the block during the Miocene. The sediments exposed in the coastal cliffs, and inland, project westward and southwestward into the offshore succession. From King et al. 1993 (Fig. 9)



Depth Zones after Hayward *et al* (1999)

Fig.15. Sketch showing exaggerated "typical" morphology of a passive continental margin, and associated water depth zones of Hayward et al (1999).



Generic sequence stratigraphic model - Wanganui shelf sedimentation

(Source : McIntyre, 2001)

Fig. 16. Sequence stratigraphic model developed from Wanganui Basin shelf sequences showing the distribution of systems tracts in thickness and time.

Order of Sea-level Changes

Order	Duration	Origin	Amplitude
1st	c. 100 million	Ocean basin volume changes	100 - 300m
2nd	5 - 30 million	Tectonic subsidence megacycles	50 - 100m
3rd	1 - 5 million	Tectonic subsidence cycles	50 - 100m
4th	200 - 600 k.y.	Tectonic subsidence cycles	50 -100m
5th	c. 100 k.y.	Milankovich eccentricity	50 - 135m
6th	41 k.y.	Milankovitch tilt/obliquity	50 - 100m
7th	21 k.y.	Milankovitch precession	0 - 20m

Milankovitch Frequencies

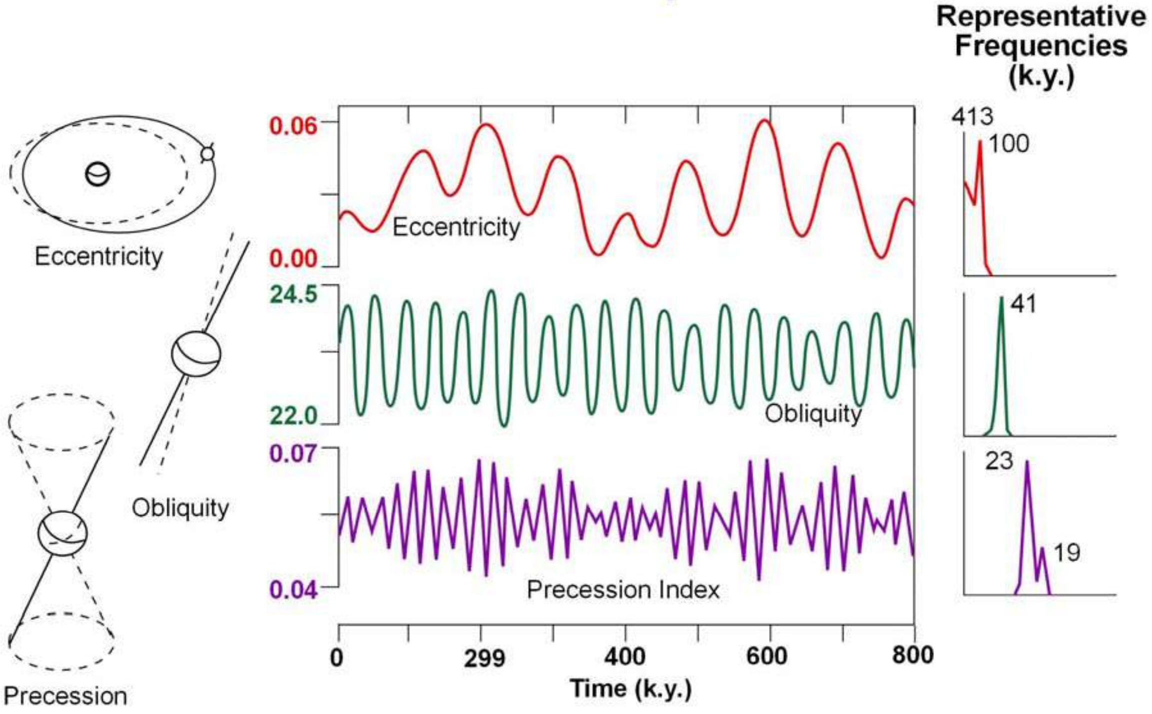
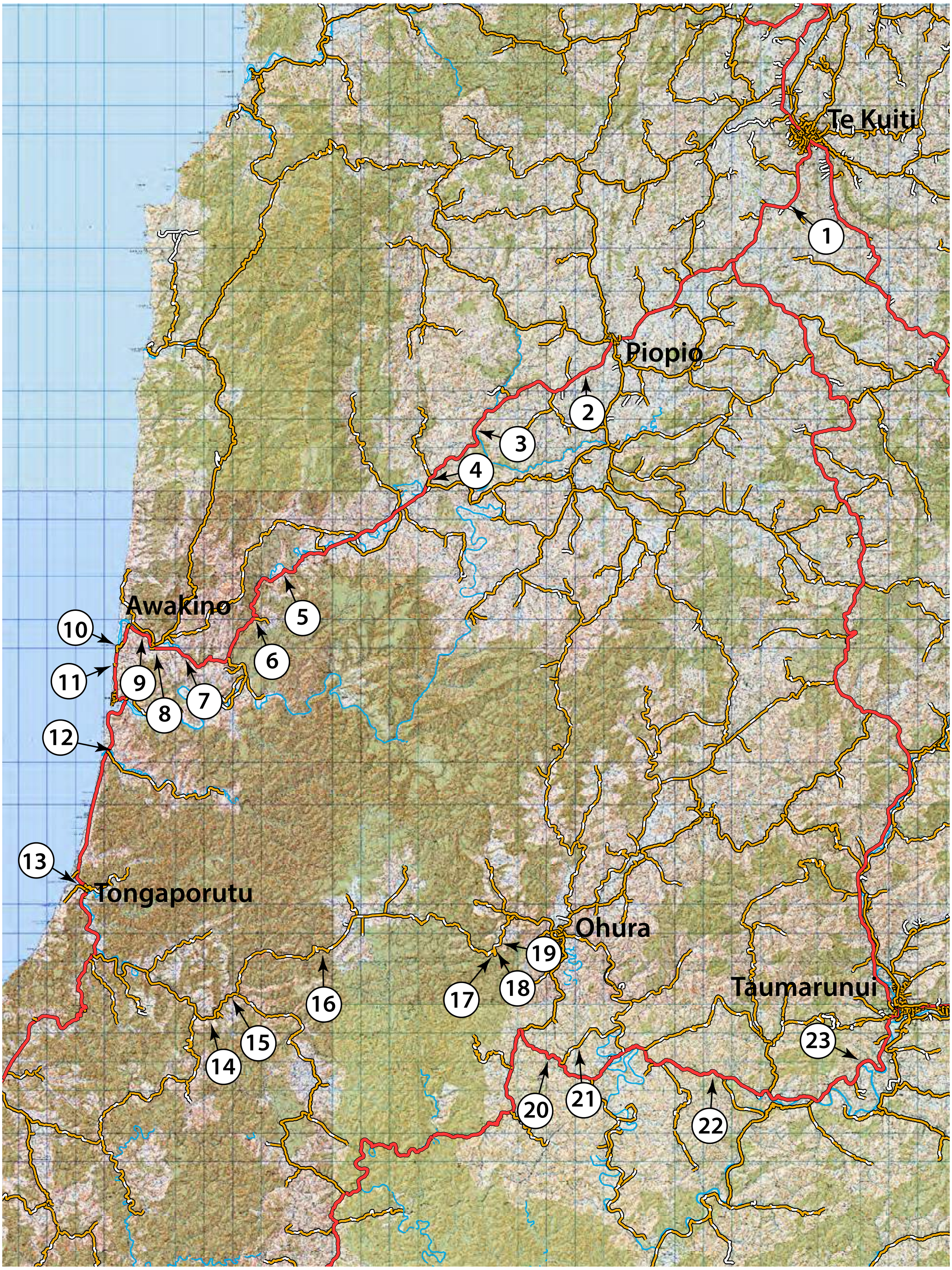


Fig. 17. Orders of sea level change, duration, origin and magnitude, and Milankovitch frequencies and inferred astronomical origins.

King Country field trip route map



PART B - NOTES FOR FIELD SITES

The field guide is written for it to start in Hamilton and to end in Hamilton via Hamilton Airport. See the field trip route map on the facing page for the location of each of the 23 stops.

THEMES FOR EACH DAY

Day 1: *Structural and Stratigraphic expression onshore of late Oligocene – early Miocene units and their relationship to tectonics along the eastern margin of Taranaki Basin.*

Stops: 1-10. Accommodation at Awakino Hotel on evening of 28th November.

Day 2: *Stratigraphic architecture and depositional systems of a middle Miocene retrogradational continental margin, eastern Taranaki and King Country basins.*

Stops 11-21. Last stop south of Taumarunui

DAY 1: Depart from Hamilton and drive to Te Kuiti and Awakino via State Highway 3.

STOP 1. SH3, Pukenui Road, south of Te Kuiti (S16-981116)

At this stop, note the distribution of Mahoenui Group (Taumatamaire Formation calcareous mudstone facies), which forms low angle and landslide prone slopes that are engineering issues for roading, and bluff forming Mokau Group sediments. Mokau Group comprises Bexley Sandstone, including conglomerate and cross-bedded sandstone that accumulated in shoreface environments and thin occurrences of coal measure facies. The top of the Mokau Group is unconformably overlain by Pakaumanu Group Pleistocene ignimbrite derived from Taupo Volcanic Zone, including Ongatiti Formation (Ignimbrite), Mangaokewa Formation (Ahuroa Ignimbrite) and Raepahu Formation (Rocky Hill Ignimbrite). Middle Miocene formations we will encounter farther south were probably deposited in the unconformity between Mokau Group and Pakaumanu Group, but eroded during the Pliocene (Edbrooke 2005).

STOP 2. SH3, Piopio Quarry, immediately south of Piopio. (R17-855003)

(*Park on driveway on LHS looking SW and group will stay on this side of the road to take a view into the far side of the quarry workings.)*

Recent quarry workings have created good exposure of steeply west-dipping, well-bedded Late Triassic sandstone (Warepan Stage, Bw) unconformably overlain by 2 m of Waitakian (Late Oligocene – Early Miocene) Otorohanga Limestone (a bryozoan biosparite or grainstone), in turn conformably overlain by Taumatamaire Formation calcareous mudstone (Fig. 18). We are standing on what has been termed the Piopio Threshold (High) in early petroleum reports – a north-south trending ridge of basement that is probably a paleorelief feature built upon indurated Late Triassic sandstone along the eastern margin of the Kawkia Syncline (Triassic- E. Cretaceous forearc basin). These rocks have probably been buried 10 km, based on the aggregated thickness of Jurassic and Late Triassic section in the Kawhia Syncline. The eastern margin of this syncline lies a few km to the east of this site and is defined by the trace of the Waipa-Aria Fault, where, at the Wairere quarry (R17/859932), serpentinite has been intruded along the fault, being a local expression of the Dun Mountain-Maitai Terrane between the Murihiku Terrane (Kawhia Syncline) and the Waipapa Terrane (Late Jurassic-E. Cretaceous accretionary wedge) (Edbrooke 2005).

Fig.18. View into Piopio Quarry, SH3, showing steeply west dipping Late Triassic sandstone beds on the eastern limb of the Kawhia Syncline, and onlapping, thin latest Oligocene or earliest Miocene (Waitakian) Otorahanga Limestone, conformably overlain by Mahoenui Group mudstone.

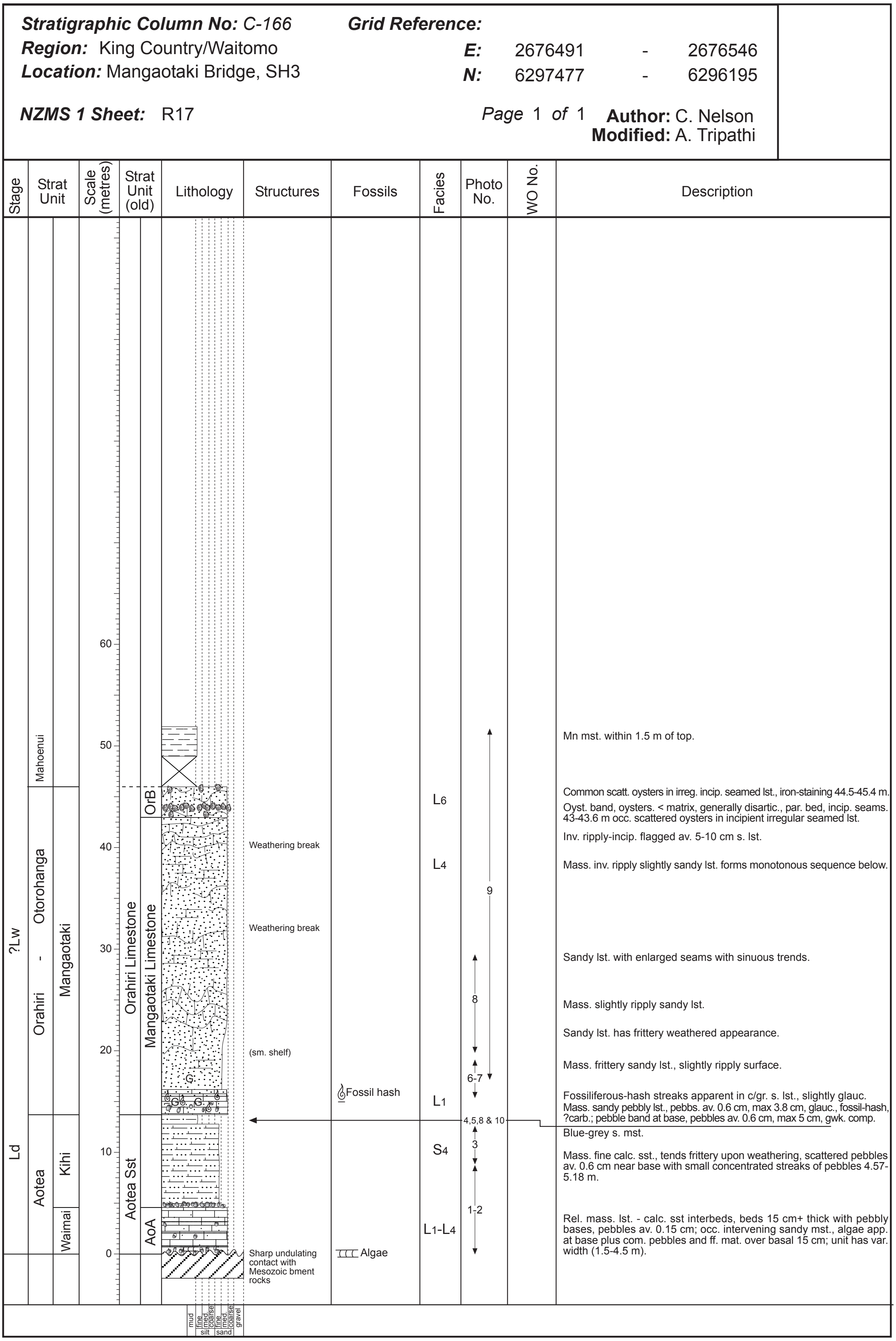
West of this site, and within the axis of the Kawhia Syncline, Oligocene Te Kuiti Group is formed in all its glory, amounting to several hundred m in thickness. Here however, shelf marine carbonate facies could only onlap basement at the end of the period of accumulation of Te Kuiti Group. A few hundred metres west of this site Otorohanga Limestone does not occur at all and Taumatamaire Formation accumulated on basement. The contact between limestone and mudstone is indisputably conformable: limestone passes over 10s of cm into calcareous mudstone with a few interbeds of fine-grained muddy carbonate. The sudden appearance of mudstone in the succession marks very rapid basin subsidence developing a bathyal environment in which mudstone started to accumulate, probably initially as an under-filled basin. It is most likely that the Waitakian onlap of Otorohanga Limestone in this area was driven by the start of tectonically-driven subsidence that accelerated into the Otaian, rather than simply being part of the peak of the New Zealand-wide Early Cenozoic marine transgression. The Taumatamaire Formation mudstone facies is analogous to Manganui Formation in northern Taranaki Basin.

STOP 3. SH3, Mangaotaki Bridge section (R17-761957)

(Park on left in driveway just north of Mangaotaki Bridge)

This section (Figs 19 & 20) gives the best outcrop of Oligocene Te Kuiti Group on SH3, but regular rock falls have resulted in cliff protection works that now restrict stratigraphic details to an extent.

In this area, Aotea Formation onlaps Jurassic basement as a bioclastic limestone (Waimai Limestone Member, upper Whaingaroan substage) (Fig. 21), a transgressive systems tract, followed by Kihi Sandstone Member, which is considered a highstand systems tract (Fig.16). A pronounced planar surface cut across the top of the Kihi Sandstone Mb (Fig. 20) is of regional extent (Fig. 21). In this outcrop it is a good example of a sequence boundary. Its regional extent suggests a period of uplift and erosion, followed by wave planation prior to accumulation of Orahiri Limestone (Duntroonian Stage). At its base, Orahiri Limestone comprises pebbles with phosphatic coating, glauconitic sandstone and macrofossils in a calcareous sandstone matrix, passing upward into yellow sandy limestone. Large fossil oysters, considered diagnostic of the Orahiri Limestone (Nelson et al. 1983), occur in beds up to a few m thick at the top of these 30 m high cliffs. Flaggy limestone, typical of the Otorohanga Limestone elsewhere in the basin, is not expressed here, but correlative beds are considered to be present, passing conformably into Taumatamaire Formation (Mahoenui Group), expressed as rounded topography above the limestone cliffs.



Stratigraphic Column No: *C-166*
Region: King Country/Waitomo
Location: Mangaotaki Bridge, SH3

NZMS 1 Sheet: R17

Grid Reference:
E: 2676491 - 2676546
N: 6297477 - 6296195

Page 1 *of* 1
Author: C. Nelson
Modified: A. Tripathi

Mn mst. within 1.5 m of top.

Common scatt. oysters in irreg. incip. seamed lst., iron-staining 44.5-45.4 m.

Oyst. band, oysters. < matrix, generally disartic., par. bed, incip. seams. 43-43.6 m occ. scattered oysters in incipient irregular seamed lst.

Inv. ripply-incip. flagged av. 5-10 cm s. lst.

Mass. inv. ripply slightly sandy lst. forms monotonous sequence below.

Sandy lst. with enlarged seams with sinuous trends.

Mass. slightly ripply sandy lst.

Sandy lst. has frittery weathered appearance.

Mass. frittery sandy lst., slightly ripply surface.

Fossiliferous-hash streaks apparent in c/gr. s. lst., slightly glauc.

Mass. sandy pebbly lst., pebbs. av. 0.6 cm, max 3.8 cm, glauc., fossil-hash, ?carb.; pebble band at base, pebbles av. 0.6 cm, max 5 cm, gwk. comp.

Blue-grey s. mst.

Mass. fine calc. sst., tends frittery upon weathering, scattered pebbles av. 0.6 cm near base with small concentrated streaks of pebbles 4.57-5.18 m.

Rel. mass. lst. - calc. sst interbeds, beds 15 cm+ thick with pebbly bases, pebbles av. 0.15 cm; occ. intervening sandy mst., algae app. at base plus com. pebbles and ff. mat. over basal 15 cm; unit has var. width (1.5-4.5 m).

Fig. 19 Stratigraphic log at Mangaotaki Bridge section.

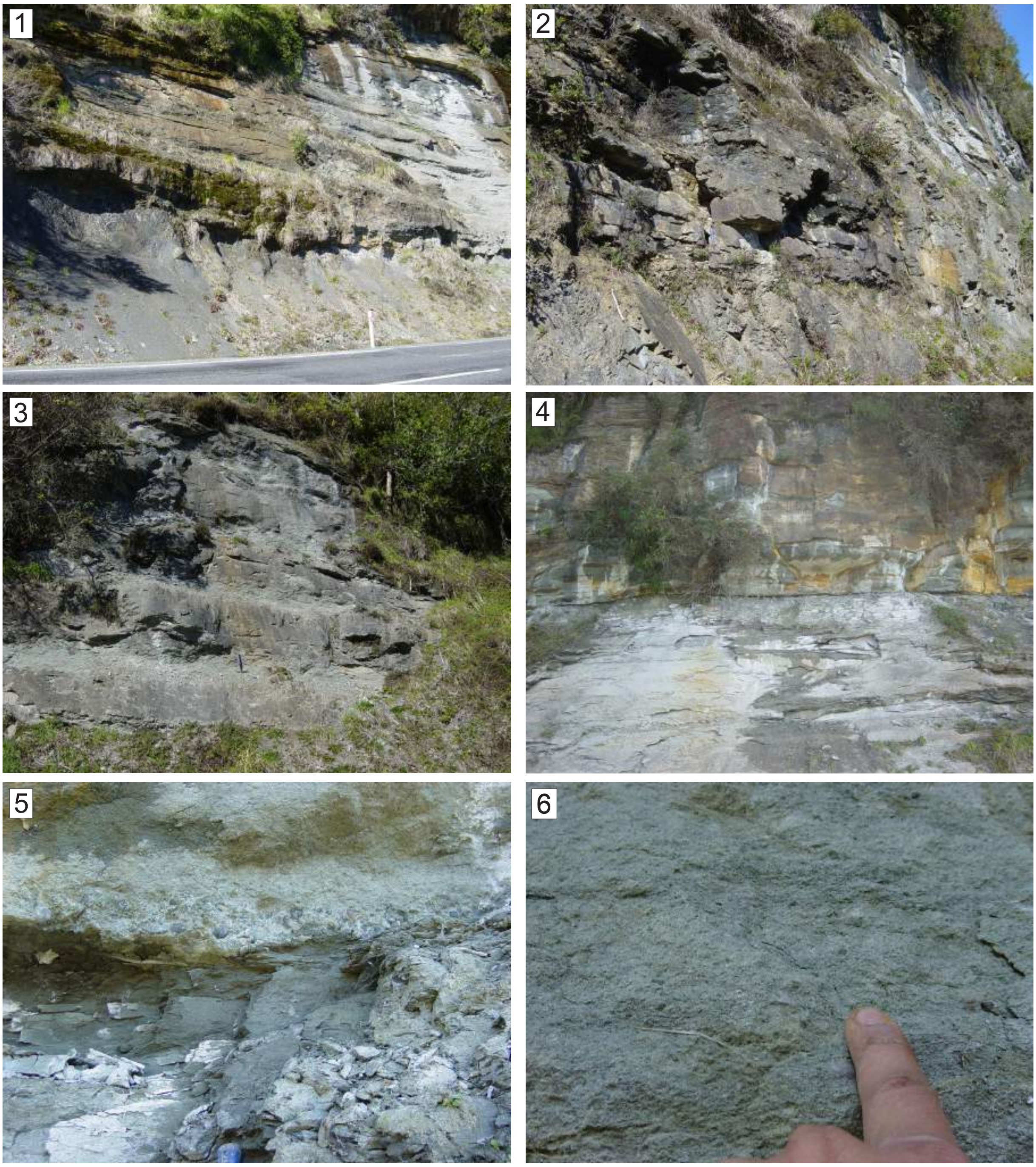


Fig. 20 Photos associated with stratigraphic log (Fig. 19).

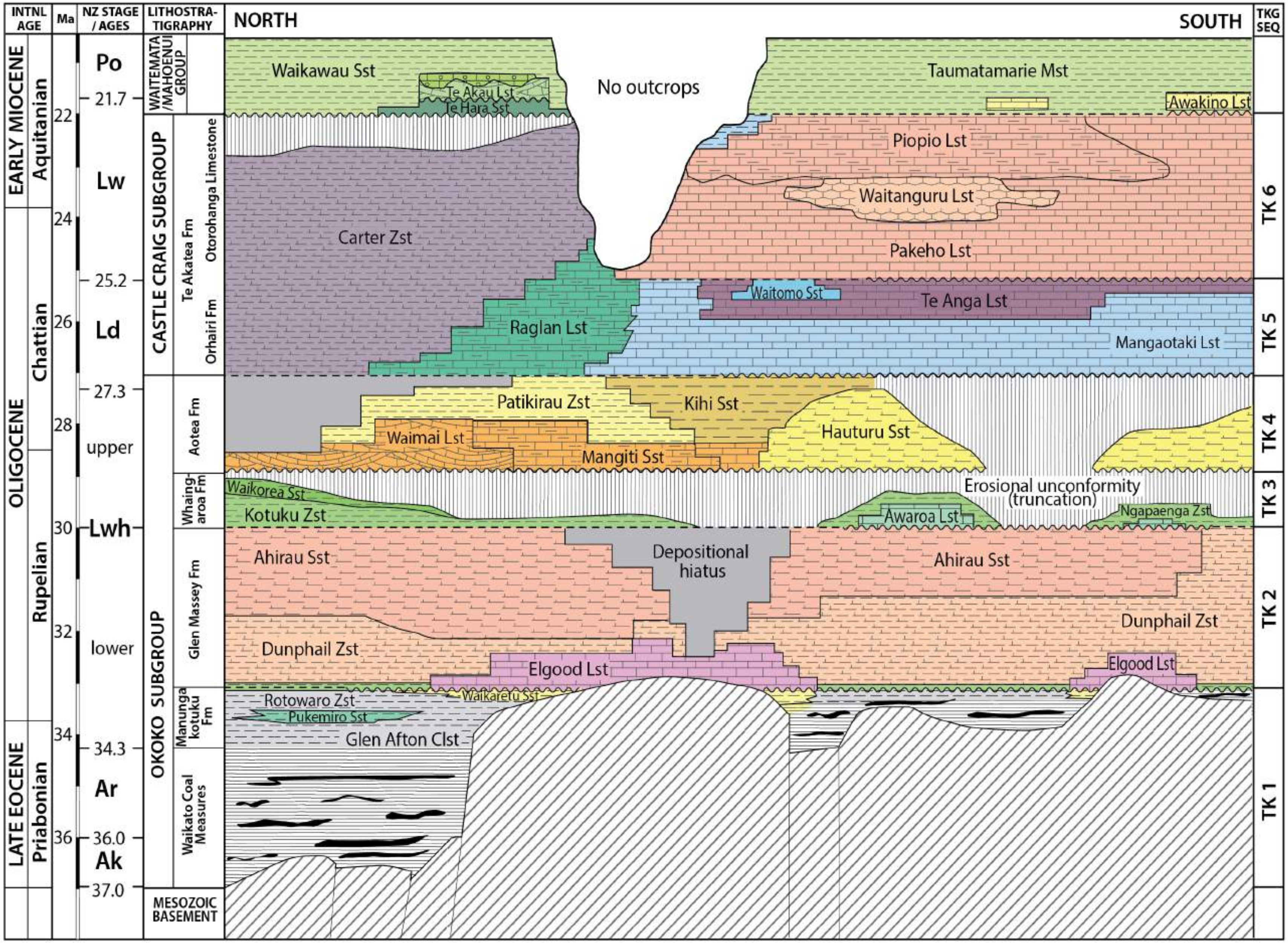


Fig. 21. Chronostratigraphic panel showing for a N-S orientation through central-western North Island the distribution in time of subgroups, formations and members of the Oligocene and earliest Miocene Te Kuiti Group.

STOP 4. Totoro Road, Mahoenui (R17-729924). Over-view of northern part of King Country Basin.

Turn off SH3 into Totoro Rd and park on gravel area.

From here we can view the main geological units and their relationship to the landscape (new 1:50 000 geological maps for BG31 & 32; Kamp et al. in prep.). Murhiku Terrane basement forms the Herangi Range on the skyline to the west. The elevation of this basement decreases to the south, where it last crops out in Awakino Gorge, but the structural high persists in the subsurface farther south. Oligocene Orahiri Limestone (plus thin Otorohanga Limestone) onlaps basement forming the intermediate slopes dipping southeast towards us. The underlying Aotea Formation and Glen Massey Formation are only exposed in Awakino Gorge and are overstepped by Orahiri Limestone onto the basement high. Mahoenui Group (Taumatamaire Fmn) forms the lower slopes facing us, the material beneath our feet and the hill country immediately to the south. The Papakauri Plateau forming the skyline to the southwest is constructed on Early Miocene (Altonian – mid-Lillburnian) Mokau Group (Bexley Sandstone, Maryville Coal Measures and Tangarakau Sandstone). Highly dissected Mahoenui Group mudstone forming tent-ridges are sharply overlain by bluff-forming Bexley Sandstone. Distant views to the east show heavily bush-clad hill country typical of much of the King Country Region, underlain by variably eroded Mokau Group, Otunui Formation and, out of view, Mount Messenger Formation.

As we continue south on SH3, note good road cutting exposures of Taumatamaire Formation mudstone with concretions.

STOP 5. Oligocene – Early Miocene geology at Awakino Tunnel (R17-618853)

(*Park on gravel area on LHS of SH3)*

At this stop we view the dip-slope on the top of the Orahiri Limestone/Otorohanga Limestone, which dips at 31^{o}E east towards us (Figs 22 and 23). The Awakino Tunnel just beyond this stop is cut through these limestone units, but currently engineering work is being undertaken to re-route the road north of the tunnel across Awakino River.

Figure 23 illustrates the stratigraphy and structure of three groups (Te Kuiti, Mahoenui and Mokau) in relation to basement at Awakino Tunnel on its southern side. The lowermost unit in the Te Kuiti Group here is Glen Massey Formation, based on biostratigraphy, the lowermost unit within it being Elgood Limestone Mbr that has a dip of about 40^{o}E and onlaps basement, which itself has a dip of 45^{o}E. Calcareous mudstone (45-55% CaCO3) above this basal limestone passes upward into Whaingaroa Formation having the same facies, here of Early Whaingaroan age (34.3 – 30.0 Ma, Cooper et al., 2004). This succession is c.200 m thick from the contact with basement. A significant unconformity separates the Whaingaroa

Fig. 22. Photo composite of the section exposed on the southern side of the Awakino Tunnel, eastern end of Awakino Gorge. Fig 23 shows the wider geological setting of this photo, and inset, its extent and stratigraphic nomenclature of units exposed in this section. From Kamp et al. 2004, (Fig. 11).

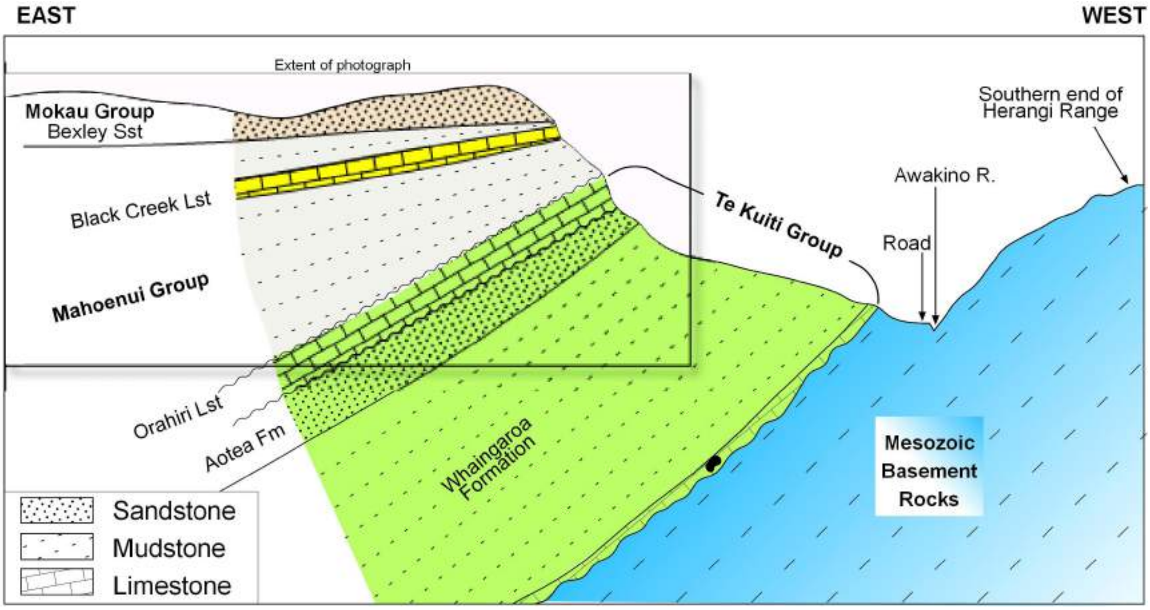


Fig. 23. Sketch illustrating the stratigraphy and structure of the Te Kuiti, Mahoenui and Mokau groups in relation to basement for the eastern end of Awakino Gorge. The inset box shows the approximate extent of the photo composite illustrated in Fig. 22. From Kamp et al. 2004, (Fig. 12). R17- 595840.

and Aotea formations. It is a sharp burrowed contact, overlain by a bioturbated, glauconitic pebbly sandstone for 0.5 m. The Aotea Fmn is c.30 m thick, upper Whaingaroan-Duntroonian in age, concretionary, massif to bedded, calcareous fine to medium sandstone, mapped as Hauturu Sandstone Member from here northward along the eastern side of the Herangi Range. Its quartzofeldspathic composition reflects the appearance of sediment provenance exotic to the Murihiku Terrane, which otherwise sourced terrigenous components to all other members of the Te Kuiti Group. It contains a component of E. Cretaceous zircon crystals sourced from the Separation Point Suite (Hopcroft 2008). Dips within the Whaingaroa and Aotea formations are difficult to measure precisely, but probably lie in the range 40-30^{o}E. Aotea Formation is unconformably overlain by Orahiri Limestone, this contact having a dip of 31^{o}E. The internal fabric of Orahiri Limestone is described below.

The contact between Orahiri/Otorohanga Limestone and overlying Taumatamaire Formation is an angular unconformity of about 10^o, being the only locality about which we are aware that has this character; in all other parts of the King Country, this contact is conformable. There is a marked shallowing of dip upward within Taumatamaire Formation mudstone in the range 20 to 8^o ESE. Several thin (<m) discontinuous limestone beds are developed within the mudstone in the shrub above the western end of the dipslope above the Orahiri Limestone, which transition eastward into calcareous sandstone and then into muddy sandstone within 100s m east of the tunnel entrance. A 10 m-thick limestone (Black Creek Limestone Member) (Figs 22 & 23), lies within the upper part of Taumatamaire Formation. It forms a prominent apron of limestone east of the Herangi Range to the north of where we are standing (right), but it had limited down-dip extent into the basin. Note the last occurrence of it in the hills south of where we are standing. There is a 10 m section of Taumatamaire Formation mudstone above Black Creek Limestone south of the tunnel. An angular unconformity of a few degrees separates Taumatamaire Formation from bluff-forming Bexley Sandstone of the Mokau Group (Figs 22 & 23).

From geological mapping north of Awakino Tunnel (Cochrane 1988), the extent of Awakino Limestone Mamber has been established. This unit does not occur south of the tunnel within Taumatamaire Formation, but it is present within this formation north of the tunnel (Fig 24). Awakino Limestone is a well-cemented bioclastic conglomeratic limestone with angular greywacke pebbles and a marked content of calcareous red algae, mostly as broken fragments but sometimes as rhodoliths. This limestone can be distinguished from Te Kuiti Group limestone facies by a consistently higher content of calcareous red algal and (larger) benthic foraminiferal (e.g. *Amphistegina*) grains (Cochrane 1988). These carbonate components are transported from the places where they formed, possibly a rocky shoreline a few hundred metres to the west and on the basement high.

Black Creek Limestone formed a larger carbonate apron than Awakino Limestone (Fig. 24). The photo in Fig. 25 is taken from the flanks of the Herangi Range to the ESE, down dip, as well as down the Early Miocene (Otaian) paleoslope. Black Creek Limestone forms a prominent dipslope facing away to the east into King Country Basin. Note the much thicker section (c.120 m) of Taumatamaire Formation mudstone below Black Creek Limestone in the valley wall in Fig. 25 compared with the section thickness up-dip in Fig. 22 (20 m). Note also that Taumatamaire Mudstone that would have accumulated above Black Creek Limestone was eroded prior to accumulation of Bexley Sandstone in the area of the ridge shown in Fig. 25.

Sediment accommodation and structural significance.

The stratigraphic and structural relationships shown in Figs 23 and 25 enable one to appreciate the style and degree of sediment accommodation formed along this part of the western

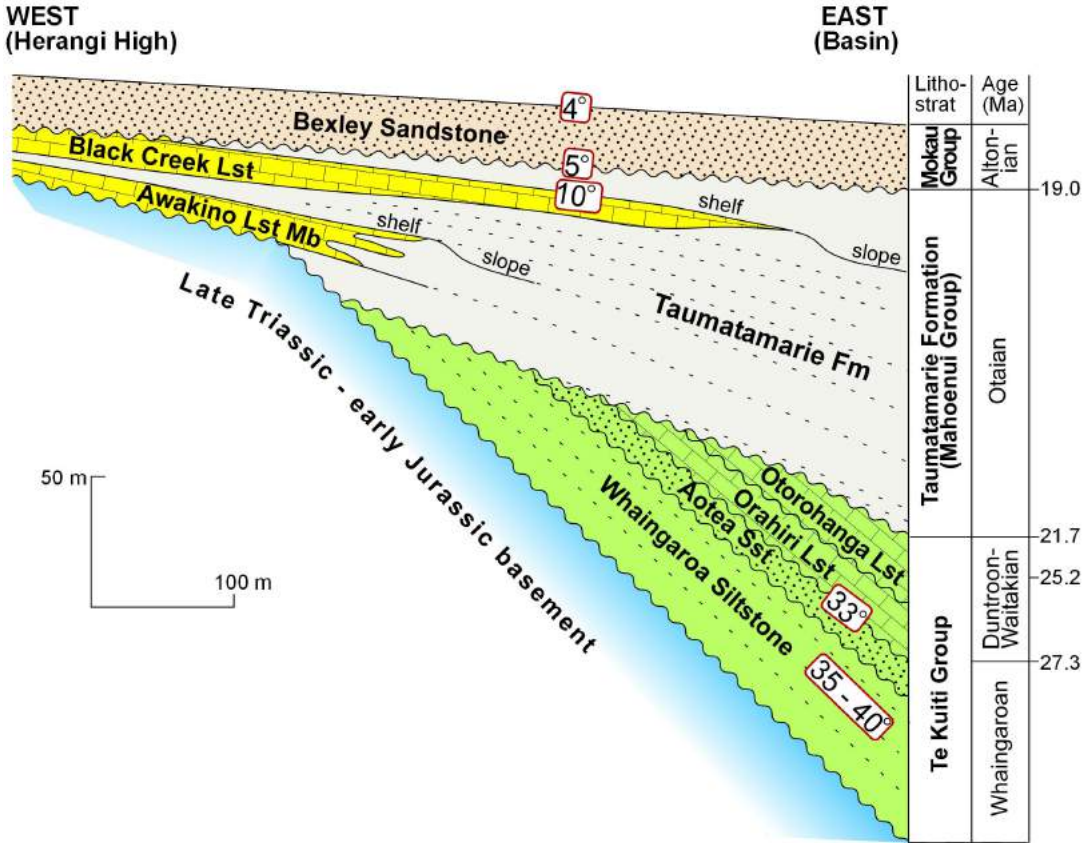


Fig. 24. Sketch illustrating the stratigraphy and structure of the Te Kuiti Group, Mahoenui Group, and Mokau Group in relation to basement for the area in the view in Fig 22. From Kamp et al. 2004, (Fig. 13).

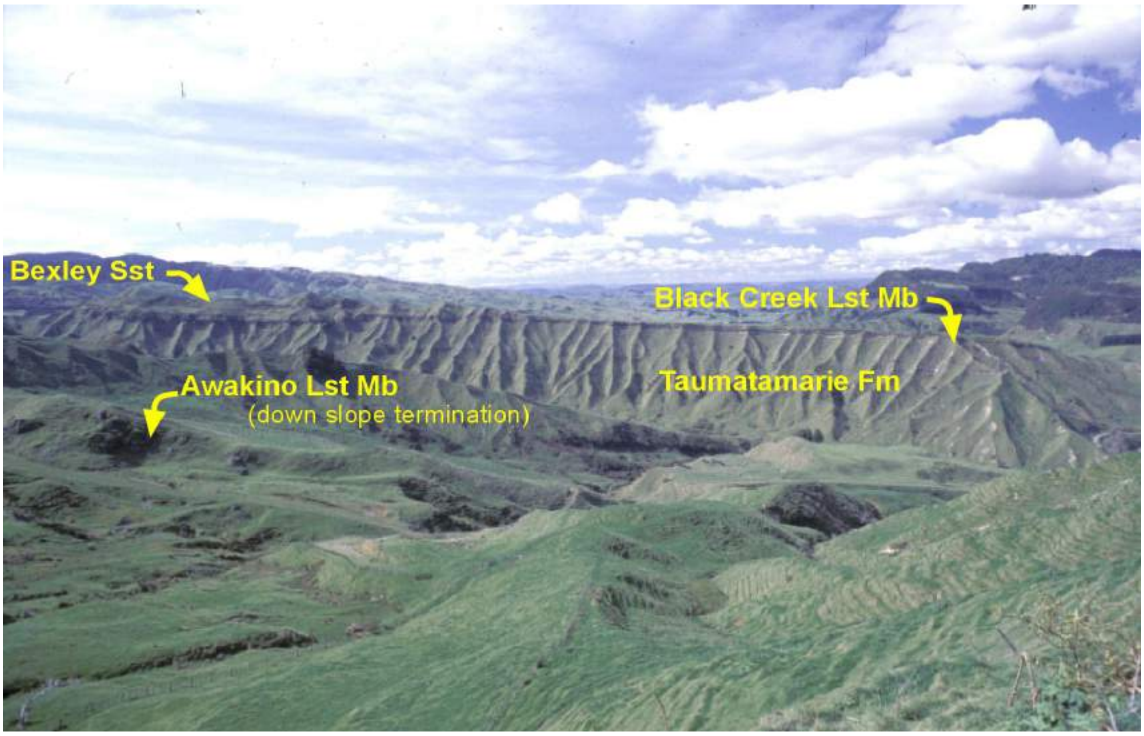


Fig. 25. Photo view from the ridge east of southern Herangi Range looking towards the southeast inland to northern King Country, prior to this area being planted in pine trees. Fig. 24 illustrates the stratigraphy and structure. From Kamp et al. 2004, (Fig. 14).

margin of northern King Country Basin during the Late Oligocene and Early Miocene. The mechanism we have proposed for sediment accommodation was rotation of basement due to reverse displacement on Manganui Fault (Fig. 26). Difficulty in measuring dips in the Glen Massey and Whaingaroa formations make one weary to conclude that reverse displacement occurred on Manganui Fault during the Early Whaingaroan. Another relevant point is that there was onlap onto basement and subsidence to at least outershelf and possibly upper bathyal conditions during the lower Whaingaroan to allow accumulation of calcareous siltstone facies (Glen Massey and Whaingaroa formations) in the Awakino Gorge area, which argue against active faulting at that time. The marked unconformity between Whaingaroa and Aotea formations in the Awakino Tunnel section, which is a common feature along the western margin of northern King Country Basin (Fig. 20 Mangaotaki Bridge STOP 3), probably marks the Late Oligocene (27 Ma, Duntroonian) start of reverse displacement on Manganui Fault (Kamp et al. 2014). Accumulation of Aotea Formation (Hauturu Sandstone Mbr) quartz-ofeldspathic sandstone required a shoreline to have developed along the eastern side of the Herangi High. Also, within Orahiri Limestone at the tunnel there are a series of redeposited carbonate beds that required a tilting shelf for their formation and accumulation (see next section below). Hence we infer a lower Duntroonian (27 Ma) start (or restart) to reverse displacement on Manganui Fault. The rate of displacement and associated rotation accelerated during the Early Miocene (Otaian) as shown by the marked extent of fanning of dip with the Taumatamaire Formation and associated sediment accumulation along the basin margin. An interesting observation is that despite the tilting, Taumatamaire Formation overstepped the Te Kuiti Group to onlap basement towards the Manganui Fault, probably as far as the hinge line of the rotation. Fault displacement continued into the lower Altonian at least as Bexley Sandstone in the tunnel area unconformably overlies underlying formations, in places comprising channelized conglomerate that cut into them. Also, there are significant differences near Awakino in the thickness of Bexley Sandstone west of the fault (c.100m) versus east of the fault trace (c.20 m). Another interesting feature is that from the distribution of outliers, Bexley Sandstone towards the end of its accumulation overtopped and buried the southern part of the Herangi High, indicating a rapid end to reverse displacement on Manganui Fault and uplift of its hanging wall. The history of displacement we have inferred from the stratigraphy and structure of the Awakino Tunnel area and in particular the timing of reverse displacement on the Manganui Fault, is probably representative of the history of displacement on Taranaki Fault in the northern Taranaki Basin area as both faults were part of crustal shortening of central North Island driven from the developing plate boundary to the east.

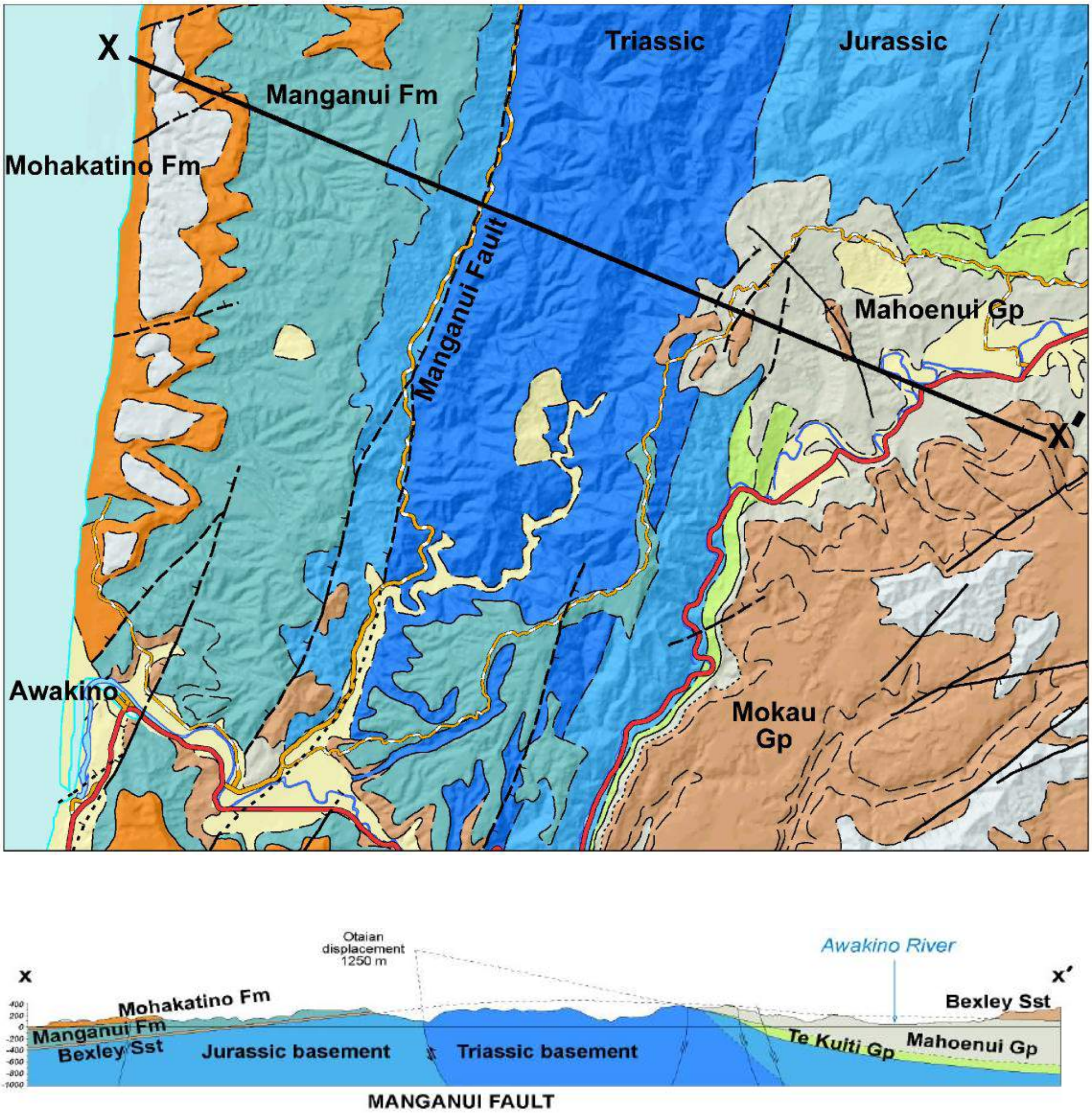


Fig. 26. Geological map and cross-section of the southern end of the Herangi Range. Source of map: S. Edbrooke (compiler) Institute of Geological and Nuclear Sciences, 1:250 000 Waikato Sheet, 2004.

Awakino Tunnel - Orahiri Limestone lithoclasts and their significance (R17-615854)

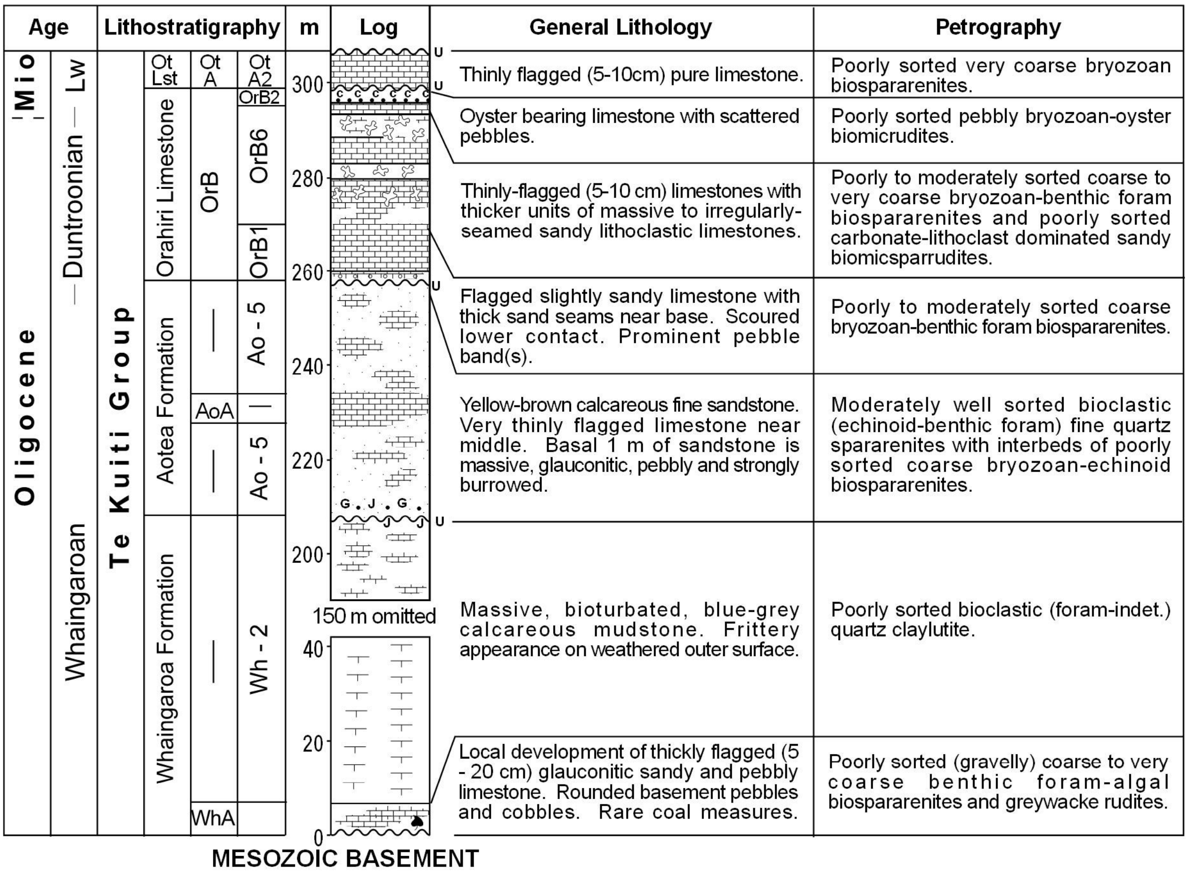
We can no longer stop safely at Awakino Tunnel as in the past, but in the future with the re-routing of the road, this may be possible and hence we include notes and figures of substantial significance for the Duntroonian timing of early seafloor tilting of the flanks of the Herangi High.

Figure 27 is a photo of the western end of Awakino Tunnel taken during the late 1960s by C.S. Nelson. Figure 28 is a stratigraphic column for the Te Kuiti Group section from basement to the top of the prominent dip-slope (Nelson et al. 1994, Fig.4) above the tunnel.

The Orahiri Limestone at the tunnel comprises three facies. 1. Flaggy limestone beds – sandy, bryozoan-benthic, foraminiferal-echinoid skeletal limestone, comprising the lower 8 m in the lower portion of the formation. 2. Oyster beds – large oysters of the tribe *Flemingostreini Stenzel* in a pebbly, micritic, very coarse, bryozoan-bivalve-benthic foraminiferal limestone. This facies dominates in the upper few metres of the formation. The oysters formed as low relief banks in a fully marine tide-swept seaway, probably at inner to mid-shelf depths. 3. limestone-in-limestone beds – interbedded flaggy and "conglomeratic" limestone, the individual beds ranging from 0.5-3.0 m thick, occurring in the bulk of the thickness of the formation in the vicinity of the tunnel (Figs 27, 28). There are six such beds, interpreted to have been mass-emplaced as debris flows. This facies has a variably micritic matrix, containing highly irregular clasts of dark grey calcareous sandstone and limestone, 1-10 cm in size (Figs. 29 & 30), and some well-rounded greywacke and igneous clasts derived from basement. The calcareous lithoclasts are commonly bored, possibly by intertidal pholad bivalves; calcareous red algae encrust some clasts.

Nelson et al. (1994) inferred that the limestone lithoclasts and the enclosing mass-emplaced beds represent sedimentological evidence for deposition on an actively tilting shelf on the flanks of a Herangi High that was starting to become mobile as a result of initial Late Oligocene crustal shortening along eastern Taranaki Basin margin driven from the plate boundary to the east. The situation is more complicated in that the lithoclasts probably represent cannibalization of older (Whaingaroan) Glen Massey Formation basal limestone, which had undergone prior burial and cementation, those beds having been inverted during the Late Oligocene. These exhumed beds must have been located more proximal to the Herangi High than the Awakino Tunnel location, possibly in and around the Manganui Valley prior to the start of reverse faulting during the Late Oligocene (Duntroonian).

Fig. 27. Photo of Orahiri Limestone exposed above Awakino Tunnel (western entrance). The recessive beds in the cliff above the tunnel entrance are a succession of redeposited beds containing lithoclasts. (R17-615854)



General Lithology	Petrography
Thinly flagged (5-10cm) pure limestone.	Poorly sorted very coarse bryozoan biospararenites.
Oyster bearing limestone with scattered pebbles.	Poorly sorted pebbly bryozoan-oyster biomicrudites.
Thinly-flagged (5-10 cm) limestones with thicker units of massive to irregularly-seamed sandy lithoclastic limestones.	Poorly to moderately sorted coarse to very coarse bryozoan-benthic foram biospararenites and poorly sorted carbonate-lithoclast dominated sandy biomicsparrudites.
Flagged slightly sandy limestone with thick sand seams near base. Scoured lower contact. Prominent pebble band(s).	Poorly to moderately sorted coarse bryozoan-benthic foram biospararenites.
Yellow-brown calcareous fine sandstone. Very thinly flagged limestone near middle. Basal 1 m of sandstone is massive, glauconitic, pebbly and strongly burrowed.	Moderately well sorted bioclastic (echinoid-benthic foram) fine quartz spararenites with interbeds of poorly sorted coarse bryozoan-echinoid biospararenites.
Massive, bioturbated, blue-grey calcareous mudstone. Frittery appearance on weathered outer surface.	Poorly sorted bioclastic (foram-indet.) quartz claylutite.
Local development of thickly flagged (5 - 20 cm) glauconitic sandy and pebbly limestone. Rounded basement pebbles and cobbles. Rare coal measures.	Poorly sorted (gravelly) coarse to very coarse benthic foram-algal biospararenites and greywacke rudites.

Fig. 28. Stratigraphic column for Te Kuiti Group exposed in the Awakino Tunnel and vicinity. From Nelson et al. 1994 (Fig. 4).

Fig. 29. Close-up photo of a fresh outcrop of a redeposited bed within Orahiri Limestone at Awakino Tunnel. The dark parts are pholad-bored lithoclasts (Fig. 30). From Nelson et al. 1994 (Fig. 5A).

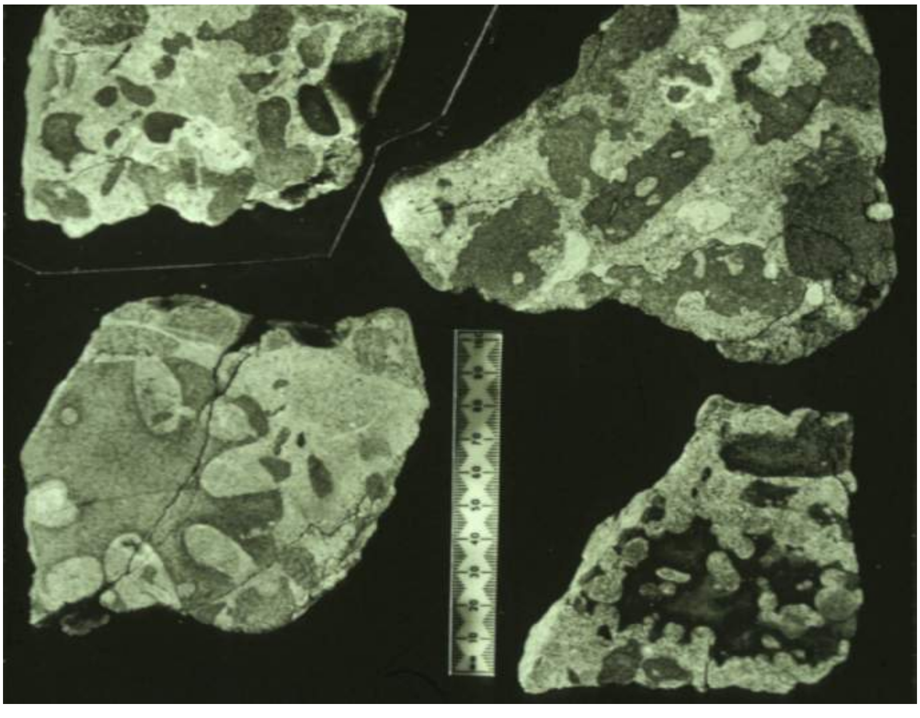


Fig. 30. Photo of cut slabs of samples from a redeposited bed within Orahiri Limestone at Awakino Tunnel, showing pholad-bored lithoclasts. From Nelson et al. 1994 (Fig. 6).

STOP 6. SH3, Bexley Tunnel section (R17- 609827)

(Park on the turn-around gravel surface opposite the entrance to Bexley Tunnel where we will leave the van and as a group cross SH3 and walk up the track to Bexley Tunnel.)

Te Kuiti Group is mapped on the south side of Awakino Gorge between Awakino Tunnel and Awakau Road to the west. The formations dip at about 30° SE away from highstanding topography on the opposite side of Awakino River underlain by basement. Whaingaroa Formation, expressed as bedded calcateous mudstone, is exposed at road level 10s of metres east of the start of the track to Bexley Station, and together with overlying Aotea Formation (concretionary and very well-sorted quartzofeldspathic sandstone) underlies the slope up to the base of Orahiri Limestone, which forms the steep bluff through which Bexley Tunnel passes. Thin-bedded Otorohanga Limestone forms a bluff high up in the bush some distance to the right (west) of the tunnel entrance.

Through the tunnel, note the steep dip-slope developed on Otorohanga Limestone above the tunnel. Otorohanga Limestone is overlain by about 20 m of massive mudstone (Taumatamaire Formation) followed by 2-3 m of Awakino Limestone, and then three cycles of mudstone (10m thick) alternating with flaggy limestone (between 4 and 7 m thick). The last limestone unit is overlain by 10 m of mudstone (Taumatamaire Formation), which in turn is overlain by c.60 m of Bexley Sandstone.

Return as a group to SH3 and cross the road as a group.

STOP 7. Western end of Awakino Gorge on SH3 (R17-559800)

(Park on the wide verge 100 m past the outcrop and carefully cross the road as a group and walk back in the direction from which we came.)

Here, Bexley Sandstone (Mokau Group) rests unconformably on steeply dipping Murihiku Terrane of Late Triassic age, (Warepan Stage, *Monotis richmondiana*). Bexley Sandstone is a transgressive shoreface deposit comprised of well-sorted fine sandstone with weakly developed low-angle cross-bedding and fossil casts (Fig. 31). It represents eastward-directed marine onlap of basement during the late-Early Miocene (Altonian Stage), during a late stage in reverse displacement on the Taranaki and Manganui faults. Note also the degree (c.8 m) of paleorelief on the top of the basement rocks, indicating that this site was part of a coastal headland that was being inundated by the sea and being buried by coastal sandstone facies due to regional subsidence. The stratigraphic features of this outcrop are probably representative of basement onlap (buried in the subsurface) between this site and the tip of the Taranaki Fault to the west and offshore.

Fig. 31. Photo of Bexley Sandstone on Late Triassic Murihiku Terrane basement (contact marked) at the western end of Awakino Gorge taken soon after road works when the outcrop was less vegetated than at present. Photo from King et al. (1993, Plate 2).

STOP 8. Rest Area off SH3, eastern end of Ladies Mile (R17-547806)

The long straight road west of STOP 7 is known as Ladies Mile. We stop at the rest area at the end of Ladies Mile to view the geological units exposed in the valley sides (Fig 32).

On our RHS at the rest area, as shown in Fig. 32 (upper panel), note SW dipping Manganui Formation, Mohakatino Formation and Mount Messenger Formation. Manganui Formation overlies Bexley Sandstone and comprises massive slightly calcareous mudstone with thin sandstone beds. Mohakatino Formation is a brown volcaniclastic sandstone forming a prominent buttress high up on the far slope. Mt Messenger Formation underlies the uppermost part of the cliff, rounded hills and a dip-slope. These formations drop in elevation to the block immediately opposite the rest area.

The trace of the Manganui Fault crosses the valley floor passing through the saddle to the south and in the opposite direction passes beneath the rest area. The fault is upthrown on the west side, bringing Bexley Sandstone to the surface and exposing a full section of Manganui Formation (Fig. 32 lower panel). Manganui Formation is overlain by Mangarara Formation, Mohakatino Formation and the lowermost part of Mt Messenger Formation. Mangarara Formation only occurs west of Manganui Fault in this section and comprises calcareous sandstone and limestone beds as submarine channel complexes (Puga-Bernabéu et al., 2009).

Fig. 32. Photo panorama split into two panels, the upper one being a view to the east and the other to the west in lower Awakino Valley.

The Manganui Fault as observed in the Ladies Mile section has normal throw and is of Pliocene-Pleistocene age, which is the opposite sense of throw of this fault in the Late Oligocene and Early Miocene. West of the fault in the upper part of the cliff, the Mangarara Formation clearly thickens into the fault. This suggests that during its accumulation, redeposited calcareous sandstone and limestone beds were channeled along the downthrown side of the fault due to sea floor topography. Hence the last reverse displacement on the Manganui Fault may have occurred during the middle to possibly late-Middle Miocene.

The prominent bush-covered hill on the RHS of the reset area at the end of the old road comprises Bexley Sandstone. There has been some hundreds of m of erosion of the Manganui Fault scarp between the rest area and the end of the old road. The full thickness of Bexley Sandstone is not evident in that section, but it is on the opposite side of the river, where it is at least 120 m. This thickness west of Manganui Fault needs to be contrasted with a thickness of c.20 m at previous STOP 7. This indicates that reverse faulting of basement on Manganui Fault and loading of its western down-thrown side created a fault-angle depression within which thick Bexley Sandstone could accumulate, compared with much lesser accommodation being formed on the hanging wall side of this fault.

STOP 9. Bexley Sandstone to Manganui Formation transition (R17-525818)

(Park on the RHS of the road on a wide tar sealed section adjacent to a crash barrier. Remain on this side of the road.)

Continue towards Awakino and about one km west of the petrol station, park on the river side of SH3. Road works a few years ago created a nice exposure across the transition from Bexley Sandstone into lower Manganui Formation. Firstly, appreciate that Bexley Sandstone is the only formation west of Awakino Gorge expressed in the Mokau Group. Manganui Formation is the lateral correlative of the Maryville Coal Measures and Tangarakau Sandstone that overlie Bexley Sandstone south and east of the latitude of the gorge. This requires there to have been a narrow continental shelf during the Altonian to mid-Lillburnian, a point we will talk more about on Day 2 of this excursion.

On the opposite side of the road we see the section illustrated in Fig. 33. Bexley Sandstone transitions from very-well sorted sandstone into a bioturbated muddy sandstone. There is a sharp boundary (marked at chest level of the person in Fig. 33) to grey massive fossiliferous mudstone, which is overlain by two concretionary shellbeds that contain solitary coral fossils (Truncatoflabellum sp.), reflecting a degree of sediment starvation. The mudstone for about 6 m above the shellbeds probably accumulated on a paleoshelf. Above that level (high up in the section illustrated in Fig. 33 and better exposed in road cuts to the west) very fine to fine sand turbidites occur in the succession 5 to 50 cm thick. This marks a transition to an upper

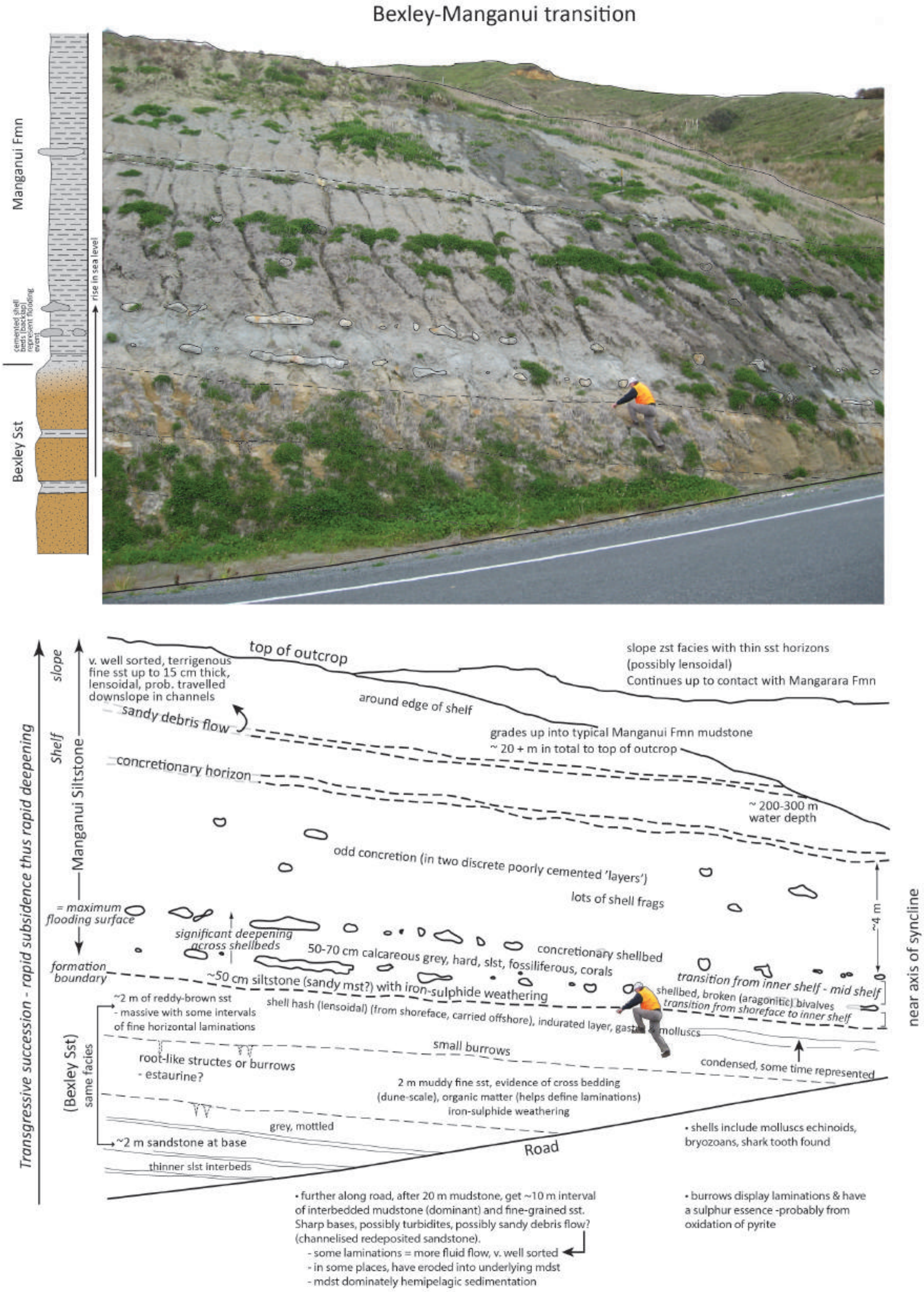


Fig. 33 Photo and sketch describing the sharp transition between Bexley Sandstone and Manganui Formation in a road cutting a kilometre east of Awakino. Photograph and sketch prepared by Rochelle Hansen, University of Waikato.

bathyal environment of deposition and retrogradation of the shelf-slope system to the east as a consequence of the end of crustal shortening and subsidence of the block of basement carrying the hanging wall of Taranaki Fault.

A 200m-thick section of Manganui Formation occurs above the beds exposed in this outcrop, all of Altonian age (King et al. 1993), confirming that this formation and the underlying Bexley Sandstone are correlative of the Mokau Group inland in King Country Basin. Manganui Formation is of course a Taranaki Basin formation, so in the Awakino area the relationship between the stratigraphy of both basins can be resolved for Altonian – mid Lillburnian strata. The top of the Manganui Formation is exposed at Awakino Heads.

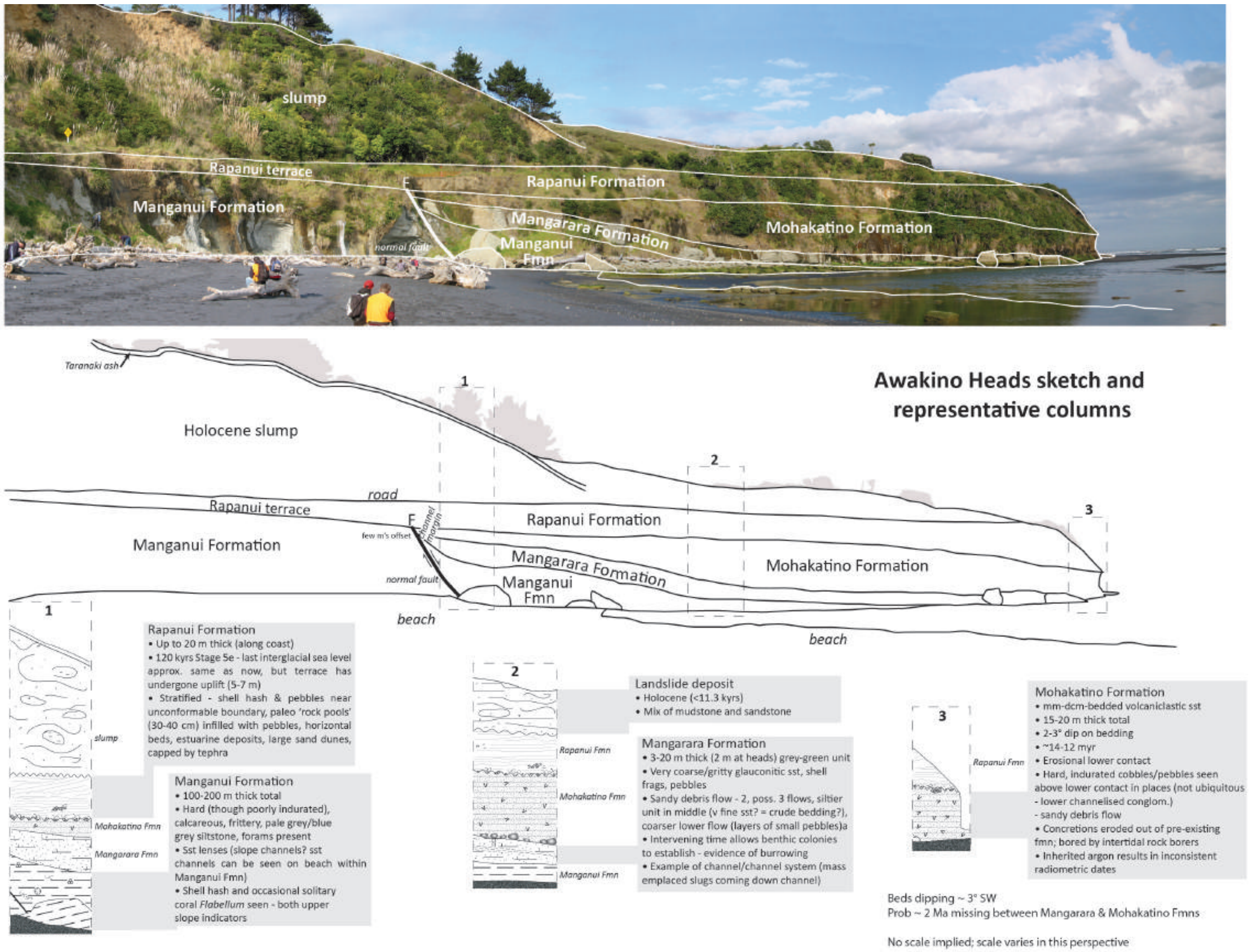
STOP 10. Awakino Heads (R17- 511808)

Last stop for Day 1. (Toilets here).

Awakino Heads is an important section as a 10 m-thick succession is well exposed on the southern side of the Awakino River mouth, including the upper part of the Manganui Fmn, Mangarara Sandstone and Purupuru Tuff (Mohakatino Fmn), covering the late-Early to Middle Miocene stratigraphy common to Taranaki and King Country Basins, depending on how their margins are defined. This section has been down-faulted on Blacks Fault, here running more-or-less along SH3, and is comparable to the section exposed in the bluff 100 m above the road. Differences are that the Mangarara Sandstone is not present there and the Mohakatino Formation is overlain by Mt Messenger Formation.

Figures 34A & B illustrate the section, and Fig. 35 gives a simplified stratigraphic log from King et al. (1993). The upper part of Manganui Fmn is (dangerously) well exposed in a cave/ bluff at the inland end of the coastal section. This is overlain by Mangarara Sandstone, which is up to 3 m thick and channelized into the top of Manganui Formation. The base of Mohakatino Formation along much of the outcrop comprises a 20-50 cm-thick conglomerate (concretions) bed with a volcaniclastic matrix. The majority of 8 m-thick Mohakatino Formation (Purupuru Tuff) comprises thin to medium bedded volcaniclastic sandstone beds. An angular unconformity formed by wave planation marks the base of the Late Pleistocene Rapanui Formation, which is a terrace deposit considered to have accumulated during the highstand and early regressive phases of sea level during Marine Oxygen Isotope Stage 5e (Last Interglacial).

The Manganui Formation is a pale grey massive mudstone facies, with sticks of solitary coral (*Truncatoflabellum* sp.) scattered within it, jarasite and occasional phosphate nodules and concoidal fractures. The part of the formation exposed is of upper Altonian age, and the sediments accumulated at mid-bathyal depths (c.1500 m) (King et al. 1993). The Manganui Formation is well exposed in the hill country to the east of SH3 where it is about 200 m thick, and includes a variety of facies, including thin turbidite facies, channelised beds of mass-em-



Awakino Heads sketch and representative columns

Rapanui Formation
- Up to 20 m thick (along coast)
- 120 kyrs Stage 5e - last interglacial sea level approx. same as now, but terrace has undergone uplift (5-7 m)
- Stratified - shell hash & pebbles near unconformable boundary, paleo 'rock pools' (30-40 cm) infilled with pebbles, horizontal beds, estuarine deposits, large sand dunes, capped by tephra

Manganui Formation
- 100-200 m thick total
- Hard (though poorly indurated), calcareous, frittery, pale grey/blue grey siltstone, forams present
- Sst lenses (slope channels? sst channels can be seen on beach within Manganui Fmn)
- Shell hash and occasional solitary coral *Flabellum* seen - both upper slope indicators

Landslide deposit
- Holocene (<11.3 kyrs)
- Mix of mudstone and sandstone

Mangarara Formation
- 3-20 m thick (2 m at heads) grey-green unit
- Very coarse/gritty glauconitic sst, shell frags, pebbles
- Sandy debris flow - 2, poss. 3 flows, siltier unit in middle (v fine sst? = crude bedding?), coarser lower flow (layers of small pebbles)a
- Intervening time allows benthic colonies to establish - evidence of burrowing
- Example of channel/channel system (mass emplaced slugs coming down channel)

Mohakatino Formation
- mm-dcm-bedded volcaniclastic sst
- 15-20 m thick total
- 2-3° dip on bedding
- ~14-12 myr
- Erosional lower contact
- Hard, indurated cobbles/pebbles seen above lower contact in places (not ubiquitous - lower channelised conglom.) - sandy debris flow
- Concretions eroded out of pre-existing fmn; bored by intertidal rock borers
- Inherited argon results in inconsistent radiometric dates

Beds dipping ~ 3° SW
Prob ~ 2 Ma missing between Mangarara & Mohakatino Fmns

No scale implied; scale varies in this perspective

Fig. 34A. Photo of Awakino Heads section and associated sketch showing the extent of Manganui Formation Mangarara Sandstone, Mohakatino Formation and Rapanui Formation and overlying slump deposit. R17- 511808. Photograph and sketch prepared by Rochelle Hansen, University of Waikato.

Fig. 34B. Close-up photo of the eastern end of the Awakino Heads section with the formation names and ages annotated. Note the 10 cm thick redeposited carbonate bed below the Mangarara Sandstone channel. The 1.5 m-thick mudstone bed below this thin carbonate bed is loaded with glauconite pellets and angular glauconite coated mudstone clasts. R17- 511808. Pl, Altonian; Sc, Clifdenian; Tt, Tongaporutuan; Wc, Castlecliffian (Fig. 12B for ages of Stage boundaries).

placed siliciclastic very fine sandstone, and large wavelength (50 m) wavy concretionary siltstone channel facies high in the succession. The channelised sandstone facies would be regarded as Moki Formation in eastern Taranaki Basin well records. This would include the Mangarara Sandstone channel at Awakino Heads and the more carbonate rich (i.e. limestone facies) beds in the section above Ladies Mile. At low tide, examples of these channelised beds are exposed in the river bed at Awakino Heads.

Fig 34B illustrates the upper part of the Manganui Fmn and the transition to Mangarara Sandstone. A subtle normal fault with more than 4 m of throw offsets the Manganui Formation, down-faulting the uppermost part to the west. In this block we can observe the transition from Manganui Fmn into Mangarara Sandstone. The lower part comprises 1.5 m of very glauconitic siltstone. The glauconite occurs mainly as rounded pellets and angular coated siltstone grains. This is overlain by a 10 cm-thick calcareous redeposited bed, followed by 2 m of laminated siltstone, which is cut into by a 2.5 m-thick channelised deposit of Mangarara Sandstone. Further along the outcrop the Mangarara Sandstone comprises two or three sedimentation units. Mangarara Sandstone at Awakino Heads is glauconitic, gritty, shelly muddy sandstone with abundant foraminifera. In the steep section at the western end of Ladies Mile there are channelised beds of calcareous sandstone that grade upwards into limestone. Puga-Bernabéu et al. (2009) have described and interpreted the Mangarara Sandstone (formation) in the Awakino-Mohakatino Valley area.

We interpret the upper Manganui – Mangarara succession as having accumulated on a retrogradational paleo continental slope. The mudstone facies represent background hemipelagic

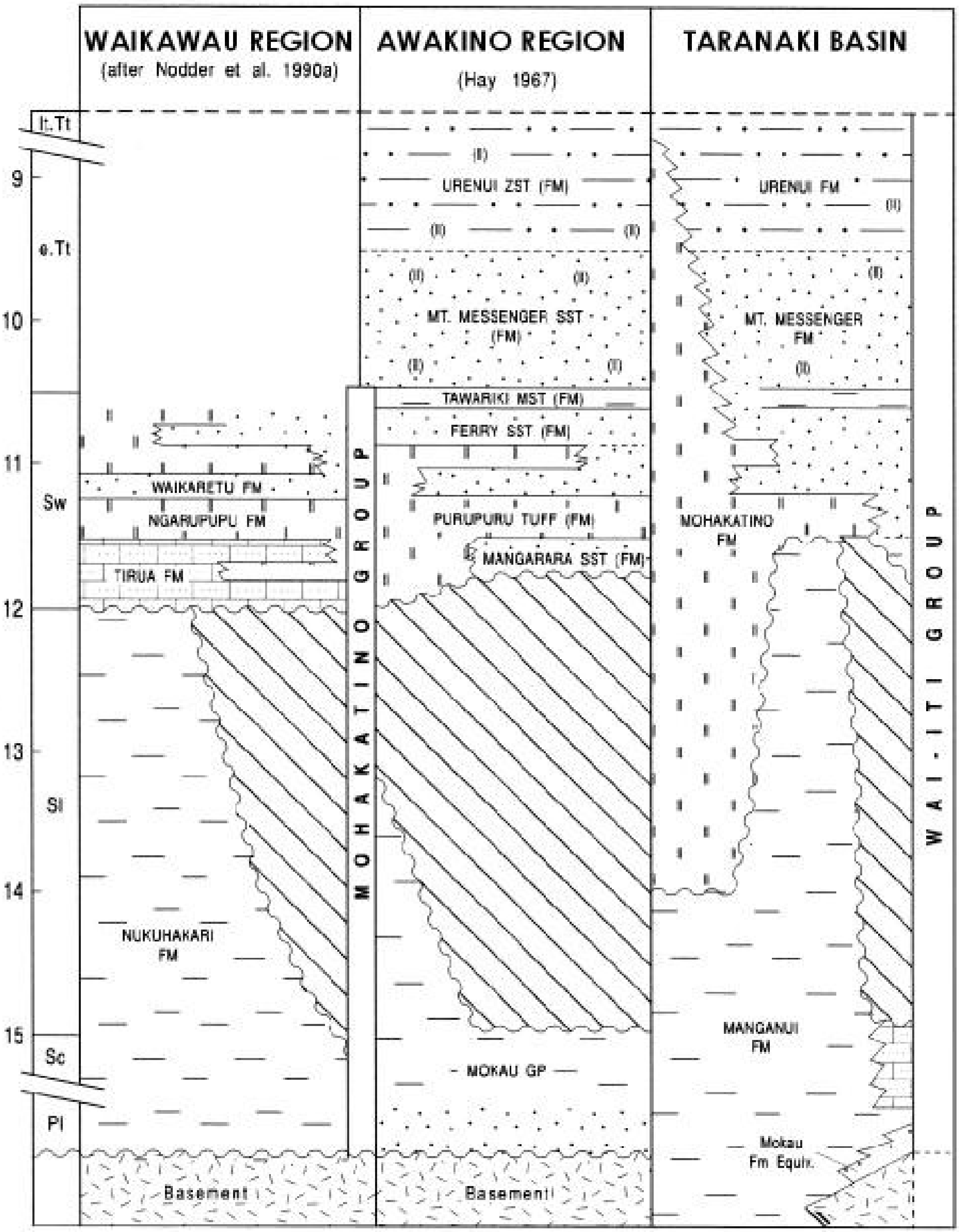


Fig. 35. Time-stratigraphic logs for the Waikawau and Awakino areas and for northern Taranaki Basin. Waikawau is north of Awakino Heads along the Taranaki Coast. Mangarara Sandstone is shown for Awakino area as being of Waiauan age, but it contains Clifdenian microfauna (King et al. 1993). From King & Thrasher 1996 (Fig. 4.7).

slope sedimentation and the calcareous sandstone and limestone facies represent submarine channel fill and upper fan facies. The carbonate material, chiefly large benthic foraminifera and algal fragments, will have been sourced from a narrow shelf to the east, or from the south along submarine portions of the Patea-Tongaporutu High. The glauconite would have been sourced from near the shelf-slope break and incorporated into the debris flows as they passed over the shelf edge and down the paleo slope channels. The unconformity at the top of the Mangarara Sandstone at Awakino Heads represents the base of another submarine channel, where submarine erosion at slope depths has removed sedimentary section of upper Clifdenian through to Waiauan age, some three million years of time (Figs 9 & 35). The Mohakatino Formation accumulated at lower slope depths, and the beds accumulated as sedimentation from tephra fallout and as mass-emplaced debris flows sourced from the collapse and erosion of the contemporary Mohakatino volcanoes in northern Taranaki Basin. The conglomerate at the base of the Mohakatino Formation contains concretions, some pholad-bored (having passed through an intertidal zone), that were probably sourced out of older Neogene beds (e.g. Mahoenui Gp) exposed at the time to the east, and deposited as a submarine channel fill. The clast-supported conglomerate may have been infiltrated by andesitic volcaniclastic sand soon after deposition. The unconformity between the Rapanui Formation and older beds formed a few metres above present sea level by wave erosion during the end of the last interglacial sea-level rise. The degree of tectonically-driven uplift, if any at all, has still to be resolved.

Figure 36 attempts to place the structure and stratigraphy of Altonian – Tongaporutuan formations examined at STOPs 7-10 into the wider basin fill and structure of northern Taranaki Basin. The Bexley Sandstone – Manganui Formation section above Murihiku basement comprises a retrogradational stratal pattern and it is comparatively thin (c.300 m maximum). This pattern results from the end of crustal shortening across central-northern North Island during the Altonian and hence cessation of reverse displacement on Taranaki and Manganui faults, which resulted in subsidence of those basement blocks below sea level. Mangarara Formation and the parts of Mohakatino Formation in the on land section accumulated during the late phase of retrogradation. This is followed by a progradational phase, which remains ongoing, from the base of Mt Messenger Formation. The sketch places the various formations within this progradational phase into the shelf-slope-basin depositional system.

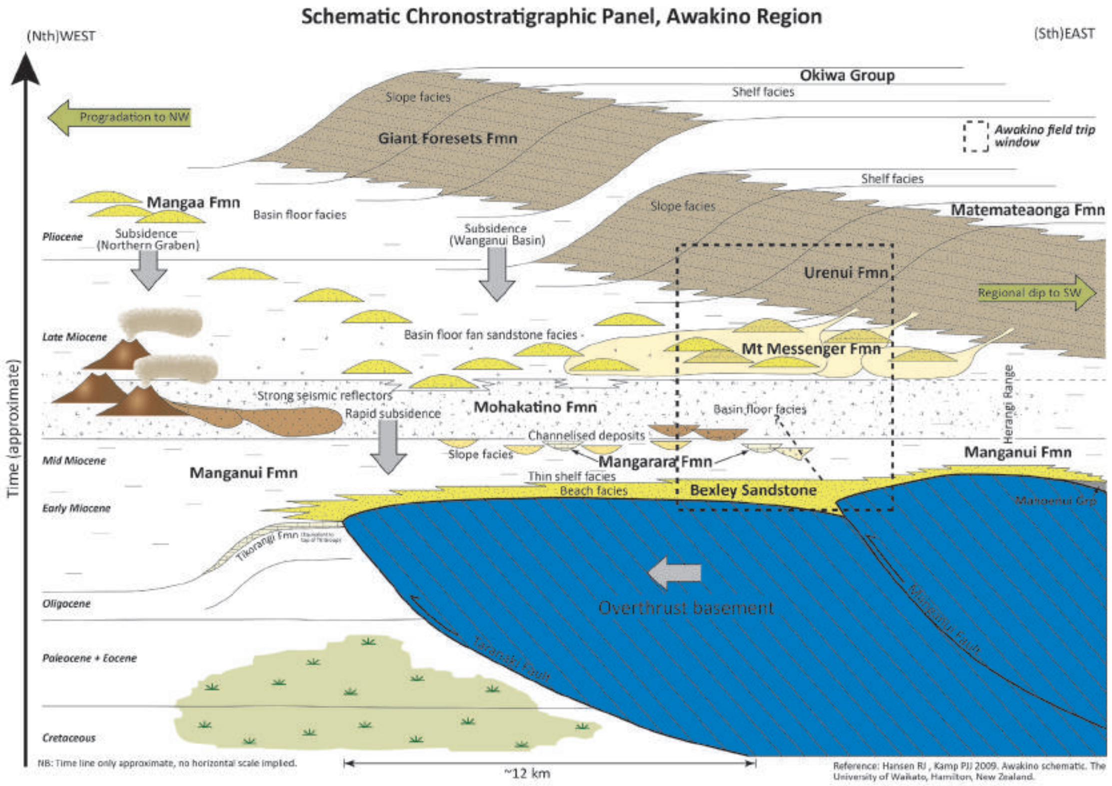


Fig.36. Sketch with elements of both a conventional cross-section and chronostratigraphic chart that seeks to place the formations observed at STOPs 7-10 in the Awakino area into the wider structure and basin fill of northern Taranaki Basin.

DAY 2

Depart Awakino Hotel at 8.30 a.m. and drive south via SH3 to Ye Old Mill Road.

STOP 11. Pahaoa Hill Section (R18-513799)

Stop briefly at Ye Old Mill Road off SH3 to view Mt Messenger Formation exposed in the high slope above Rapanui Terrace. However, there is good exposure in cuttings adjacent to the farm track (David Black, owner) past the Mokau township water works to the top of the hill. The Mt Messenger Formation is of lower Tongaporutuan age (King et al. 1993; M.P. Crundwell, personal communication, 2003). The lower part of Mt Messenger Formation here at Awakino, in the section on the south side of the Mokau River Mouth and in exposures north to Waikawau is sandstone-dominated (and was previously known as Ferry Sandstone Formation), in contrast with a mudstone lower part of the formation inland to the southeast around Tahora (Kohu Member).

Amalgamated yellow-brown siliciclastic sandstone beds form a prominent unit at the base of the hill section, which is probably a basin floor fan deposit (Fig. 37). The beds are well-sorted

Fig. 37. Photo of Pahaoa Hill, showing exposures of Mt Messenger Formation. Note the amalgamated sandstone beds in the lower part of the section, which are interpreted as a basin floor fan deposit. Siliciclastic sandstone and mudstone beds are intercalated with andesitic tuff beds in the cuttings along the upper part of the farm track (Fig. 38), R18- 513 799.

Fig. 38. Photo of intercalated siliciclastic sandstone and mudstone beds with andesitic tuff beds in the farm track shown in Fig. 37. The tuffs were sourced from Late Miocene andesitic volcanoes in northern Taranaki Basin much like modern day Mt Taranaki seen here in the background. R18-513799.

fine sandstone and probably accumulated as a succession of sandy debris flows as part of a lowstand systems tract. Overlying beds are hemipelagic siliciclastic mudstone and single or amalgamated sandstone beds. Higher up in the section in the road cutting (Fig. 38) the bedding comprises interbedded sandstone and mudstone and thin (5-10 cm) andesitic tuff beds. This bimodality in the composition of the sediments reflects the concurrent activity of the andesitic volcanoes in northern Taranaki Basin, supplying sediments semi-radially into the basin from the volcanic centres, and the bottom sets (Mt Messenger Formation) of the continental margin prograding into the basin from the south, being sourced from erosion of the Southern Alps developing at that time in South Island.

STOP 12. Mt Messenger Formation sandstone, Mohakatino River bridge (R18-505736)

(Park in the rest area on LHS of SH3 just north of Mohakatino River mouth and cross the road as a group when traffic is clear onto the new bridge over the small stream north of the main Mohakatino River bridge.)

Continue south and stop in the rest area on the LHS of SH3 on the north side of the Mohakatino River Bridge. Across the road in the lower part of Mt Messenger Formation is a 25 m-thick package of amalgamated sandstone beds typical of those at several horizons in the Tongarorutu Member of the Mt Messenger Formation (Fig. 39). The individual sandstone beds are thick-bedded (up to a few m), fine-grained sandstone with subtle gently wavy internal stratification (Fig. 40). Flame structures in mudstone occur at the base of some thick beds. These sandstone beds are interpreted as sandy debrites deposited as a basin floor fan, but some may regard these beds as turbidites, albeit that they do not display Bouma Divisions. These thick-bedded sandstone beds are equivalent to those in subsurface lower Mt Messenger Formation beneath Taranaki Peninsula (Kaimiro and Ngatoro fields).

At this site the 25 m-thick sandstone package rests on hemipelagic grey mudstone, which includes dark thinly bedded tuff beds. The occurrence of tuff in mudstone but typically not in amalgamated sandstone packets highlights the much slower sedimentation rates associated with the mudstone (and hence the probability of preservation of the products of random volcanic eruptions) compared with the basin floor fan sandstone beds, which accumulated quickly. We would place the sequence boundary at the top of the basin floor fan succession, being the last phase of a regressive systems tract, rather than at the base of the sandstone packet as per the Vail sequence stratigraphic model.

Fig. 39. Exposure of 25 m-thick amalgamated sandstone succession within Mt Messenger Formation on SH3 immediately north of Mohakatino River mouth.

Fig. 40. Close-up photograph of thick bedded sandstone units at the base of the succession illustrated in Fig. 39. Note the sharp boundary between depositional units and subtle wavy laminations within well-sorted fine sandstone, Mt Messenger Formation, redeposited units.

STOP 13. Tongaporutu River Mouth, Rest Area (R18-484642)

Turn into Clifton Road on the southern side of the Tongaporutu Bridge and drive past the iconic baches to the rest area and the public toilets.

Fig. 41. Photo of the Tongaporutu River mouth and estuary taken from the Rest Area adjacent to SH3 north of the road bridge.

STOP 14. Mt Messenger & Mohakatino formations, Okau Road, SH40 (R18-515578)

South of Tongaporutu we turn off SH3 onto Okau Road (SH40). In driving to STOP 14, we pass several high road cuttings of Mt Messenger Formation on the LHS that are becoming degraded. Fig. 42 is a photograph of one of these cuttings soon after road works on it. It shows well-exposed medium to thinly-bedded sandstone beds and associated mudstone. The more prominent and thicker sandstone beds are examples of sandy debris flow deposits, as distinct from classical turbidites, which are deposited out of a more fluid medium. The beds in this exposure lie in a transition between the lower part of the Mt Messenger Formation viewed at STOPs 11 & 12 and as far up-section as Tongaporutu River mouth (STOP 13, Fig. 41), characterised by thick (10-40 m) amalgamated sandstone beds (basin floor fan deposits), and the upper part of the formation, characterised by thin bedding and muddy turbidites, which accumulated as parts of slope fans (Browne & Slatt 2003), as exposed at Mt Messenger tunnel cuttings and along the coastal Whitecliffs section.

At STOP 14 we examine Otunui Formation overlain by a 4 m-thick interval of Mohakatino Formation andesitic volcaniclastic sandstone facies (Fig. 43). The Mohakatino Formation beds are compositionally similar to the Purupuru Tuff of the Mohakatino Formation at Awakino Heads, albeit that they are thicker-bedded and mass-emplaced, the flows having ridden part way up the contemporary slope from the northwest.

This outcrop of Otunui Formation is the uppermost part of this formation and the most western occurrence of it. Otunui Formation is widespread at the surface to the east (to north of Mt Ruapehu) and southeast (to Tahora) of this locality. Otunui Formation comprises muddy very fine sandstone and sandy mudstone. Decimetre scale bedding is common, but bed surfaces are ill-defined, probably due to profuse burrowing/bioturbation, expressed as mottling. Otunui Formation in Tongaporutu Valley is inferred to have accumulated in an upper bathyal environment upon an upper to mid continental slope setting (Fig.9).

Fig. 42. Photo of medium to thin-bedded Mt Messenger Fmn exposed on Okau Road. R18 – 515 578.

Fig. 43. Photo of Otunui Fmn at Okau Road with a thin overlying succession of Mohakatino Formation. R18-574 547.

Otunui Formation does not occur in the lower Mohakatino Valley or in the Awakino area. In Mohakatino Valley, correlative beds of Otunui Formation are Moki Formation, comprised of slope channel complexes with hemipelagic mudstone (Figs 44 & 45), and in the Awakino area are correlative of Mangarara Formation.

Fig. 44. Photo of hills at the eastern end of Mohakatino Valley Road, which are underlain by Moki Formation. R18-590698.

Fig. 45. Photo of part of Moki Formation exposed adjacent to the woolshed at the end of Mohakatino Valley Road. It shows redeposited siliciclastic very fine sandstone beds forming the fill of a slope channel to upper submarine fan deposit. R18-590698.

STOP 15. Okau Road – Otunui, Mohakatino and Mt Messenger formations exposed in close proximity (R18-587564)

Drive farther east along Okau Road and we will make a brief stop to appreciate in surrounding cliffs of the lower Tongaporutu Valley a near complete thickness of Otunui Formation, overlying Mohakatino Formation, which in turn is overlain by Mt Messenger Formation, the lowermost beds being mudstone (Kohu Member) (Fig. 46). Dip-slopes develop in the lower part of the Mt Messenger Formation about 10 metres above the contact where it overlies Mohakatino Formation. They have proved to be useful in geological mapping these formations.

Fig. 46. View of the middle to upper part of Otunui Formation, overlain by brown bedded sandstone of the Mohakatino Formation. The upper 8 – 10 m of mudstone at the top of the section is Mt Messenger Formation

Crudely defined sedimentary cycles are expressed in the Otunui Formation, reflecting sandy mudstone versus muddy sandstone sections of the order of 10s of metres. This is also evident in the the part of Otunui Formation exposed at Dampier Falls (Okau Road). Otunui Formation accumulated between the mid-Lillburnian (14 Ma) and upper Waiauan (11-12 Ma). This corresponds to the interval when ocean climate deteriorated and widespread ice-sheets started to develop in Antarctica. Marked sea-level changes are therefore anticipated. Otunui Formation could usefully be a mid-latitude archive of sea-level change to be investigated by a drilling project to obtain a high-resolution stratigraphic record.

STOP 16. Tongaporutu-Ohura Road, east of Kotare Stream, Moki – Otunui Formation contact (R18-651596)

Turn off Okau Road onto Tongaporutu-Ohura Road. At the start of a steep hill climb, exposures of Moki Formation occur on the RHS. Moki Formation is identified, and distinguished from Otunui Formation, by the occurrence of 10s of m-thick outcrops of sharp-based turbidites, reflecting slope fan deposition. Moki Formation has been mapped extensively in the surrounding valleys. Moki Formation is known principally in Taranaki Basin as sandstone intervals within Manganui Formation. We drive to the top of the hill/scarp of the 400-500 m-high Waitaanga Plateau where we will stop. Partway up the slope, the road crosses Kotare Fault, which is up-thrown on its eastern side.

Stop to examine the upper part of the Moki Formation where it is sharply overlain by Otunui Formation (Fig. 47). Moki Formation comprises turbidites and associated frittery siltstone, which we infer to have accumulated on a slope fan. The sandstone beds have a fine to very fine sandstone texture. There is up to 140 m thickness of Moki Formation variably exposed in the Mangatawa Valley to the west of this site. The upper part of the formation is of lower Lillburnian age. The overlying Otunui Formation is massive to very thick-bedded, indurated, bioturbated silty sandstone to sandy siltstone. Regionally the Otunui Formation has an upper Lillburnian to Waiauan age. As this unit overlies the Tangarakau Formation to the east, it is likely that the Moki beds exposed in this outcrop are correlative of the upper part of the neritic Tangarakau Formation (Mokau Group). This will be emphasized by comparing the stratigraphy at this stop versus STOP 17. It means that there must have been a very narrow shelf between this stop and STOP 17 during the early-Middle Miocene.

Let’s consider the stratal patterns within this and surrounding outcrops? It is likely that Bexley Sandstone is present at depth beneath this outcrop, overlain by a transition to shelfal and then upper bathyal (upper slope) Manganui Formation (STOP 9). Moki Formation at this site accumulated as a fan at mid-slope depths, possibly indicating the deepest water conditions upwards to this point in the stratigraphy. During the mid-Lillburnian the eastern part of King Country Basin subsided, leading to marine onlap at least as far as the western margin of what

Fig. 47. Photo of section on the Tongaporutu-Ohura Road, east of Kotare Stream, showing the Moki – Otunui Formation stratigraphic contact. R18-651596.

is now the Taupo Volcanic Zone. This indicates that the depositional system continued to be retrogradational into the late-Middle Miocene.

How then do we interpret the stratal patterns in Otunui Formation in this outcrop, those farther down in the lower Tongaporutu Valley and offshore in northern Taranaki Basin? Overall retrogradation clearly continued, but there was concurrent downlap in a westerly and northwesterly direction as well. This pattern occurs when there is an increase in sediment supply and insufficient accommodation is developed on the shelf, leading to downlap on the slope, which we consider to be the case at this site.

Farther up the road, we encounter overlying parts of the Otunui Formation in road cuttings, which are degrading from their condition when they were formed (Fig. 48). There, the formation is massive silty sandstone. During road reconstruction, fantastic specimens of *Tumidocarcinus giganteus* (Glaessner, 1960), a deep water crab fossil, were exposed in the lower part the outcrop commonly associated with concretions (Fig. 49). There seems to be a widespread zone in the lower part of the Otunui Fmn containing this fossil, forming a useful basis for intrabasinal correlation. In the dry-run for this excursion we could not locate any of these fossils in the outcrop shown in Figs. 48 & 49. Also at this location there have been exposed examples of paramoudra concretions oriented semi-vertically in the outcrop. They may be diagenetic expressions of cold methane seeps.

Fig. 48. Photo of a long road cutting on the Tongaporutu-Ohura Road east of Kotare Stream, showing the lower part of Otunui Formation. R18-661597.

Fig. 49. Photo of Tumidocarcinus giganteus *(Glaessner, 1960) within Otunui Formation. R18-661 597.*

From STOP 16 we drive across the Waitaanga Plateau to the scarp above Ohura. The photograph in Fig. 50 is a view of the western part of the Waitiaanga Plateau and its geology. The hills are underlain by Otunui Fmn, with Recent alluvium/swamp deposits in the bottom of the valley. This part of the plateau is drained to the south by the Tangarakau River, the watershed with the Tongaporutu River lying more-or-less at the western end (right hand side) of the grassland. During the winter of 2019 this area was planted in *Pinus radiata*.

Fig. 50. Photo of view to south from the Tongaporutu-Ohura Road SH40, west of Waitaanga cross roads. R18-671607.

STOP 17. N.G. Tucker Scenic Reserve. Tongaporutu-Ohura Road SH40, south of Huhatahi Valley, Waingarara Sandstone Member (Tangarakau Fmn – Mokau Group) (R18-771 593)

Stop to examine part of the Waingarara Sandstone Member of the Tangarakau Formation exposed in what was a new road cutting when the photo in Fig. 51 was taken during 2005. The outcrop is partitioned by thin shell beds (0.1-0.2 m-thick) into 3-5 m-thick packets of well-sorted fine sandstone, which accumulated in shoreface environments. There are very large siderite concretions in this section at multiple horizons that were red wine coloured during road reconstruction activity.

This formation is very extensive in the Ohura-Tangarakau Coalfield, varying from 30-200 m thick. Its age is very poorly known, the upper limit being constrained by the age of the base of the overlying Otunui Formation as mid-Lillburnian (c.14 Ma). It probably ranges in age between upper Altonian and mid-Lillburnian. The Waingarara Sandstone Member is characterised by a very uniform and well-sorted sandstone texture, reflecting the development of extensive shoreface deposits, which aggraded in a situation where there was persistence of a fine balance for several million years between subsidence and sedimentation. The well-sorted texture of the sandstone reflects the physical processes on the contemporary foreshore and shoreface environments. This is possibly the siliciclastic sandstone that was captured by shelf channels and feed down slope channels to source Moki Formation occurrences between Kotare (STOP 16) and northern Taranaki Basin.

By walking a short distance down the road, one can appreciate the stratigraphy shown in Fig. 52. The observer is standing on a dip-slope developed in the top of the Maryville Coal Measures (Fig. 52). These dip-slopes occur throughout the Ohura area, north to Awakino Gorge and south to Tangarakau Gorge. The light bush-covered bluff immediately above the dip-slope is underlain by Tangarakau Formation, as observed earlier at this stop (Fig. 51). Sharply and conformably overlying Tangarakau Formation (Mokau Group) is Otunui Formation. This contact represents marine flooding of the eastern King Country region during the mid-Lillburnian (Fig. 11). The Ohura Fault trace lies a short distance to the east of this site, and a bit beyond it Otunui Formation lies upon Mahoenui Group.

STOP 18. Tongaporutu-Ohura Road SH40, south of Huhatahi Valley, Maryville Coal Measures (R18-774 597)

Brief stop to examine part of the Maryville Coal Measures exposed in a road cutting (Fig. 53). Note the intense weathering of the sediments promoted by acid leaching below the coal measures. This formation is about 10-20 m thick.

STOP 19. Tongaporutu-Ohura Road SH40, south of Huhatahi Valley, Mahoenui Gp – Bexley Sandstone contact. (R18-785617)

Where the road drops below the level of the dip-slope, Bexley Sandstone crops out having a thickness of 40-50 m. We will stop at a road cutting where the contact of Mahoenui Group and Bexley Sandstone is exposed. This is one of few accessible exposures of this contact and it is partially vegetated. The contact is very sharp (Fig. 54) and probably planar (wave-planned) and considered to be a slight angular unconformity from geological mapping in this area. The underlying Mahoenui Group strata are weathered in this outcrop and bedding is not obvious, but from drill hole records near Ohura and other outcrop observations in the Ohura area, the specific formation is Taumarunui Formation, which is typically comprised of turbidites. Wherever we have observed this contact, facies belts are cutout at this stratigraphic contact; that is, bathyal facies are overlain by transgressive shore face deposits (Bexley Sandstone). From this we interpret uppermost Otaian and/or lowermost Altonian inversion of the Mahoenui Group depocentre, due to a climax in crustal shortening driven from the contemporary plate boundary in the east. Uplift and erosion associated with this inversion removed the stratigraphic section of regressive upper slope – neritic facies that must have developed to an extent during the infilling or shallowing of the depocentre prior to, or as it was uplifted above sea level.

Fig. 51. Photo of Waingarara Sandstone Member (Tangarakau Formation, Mokau Group) on the Tongaporutu-Ohura Road SH40, south of Huhatahi Valley. R18-771593.

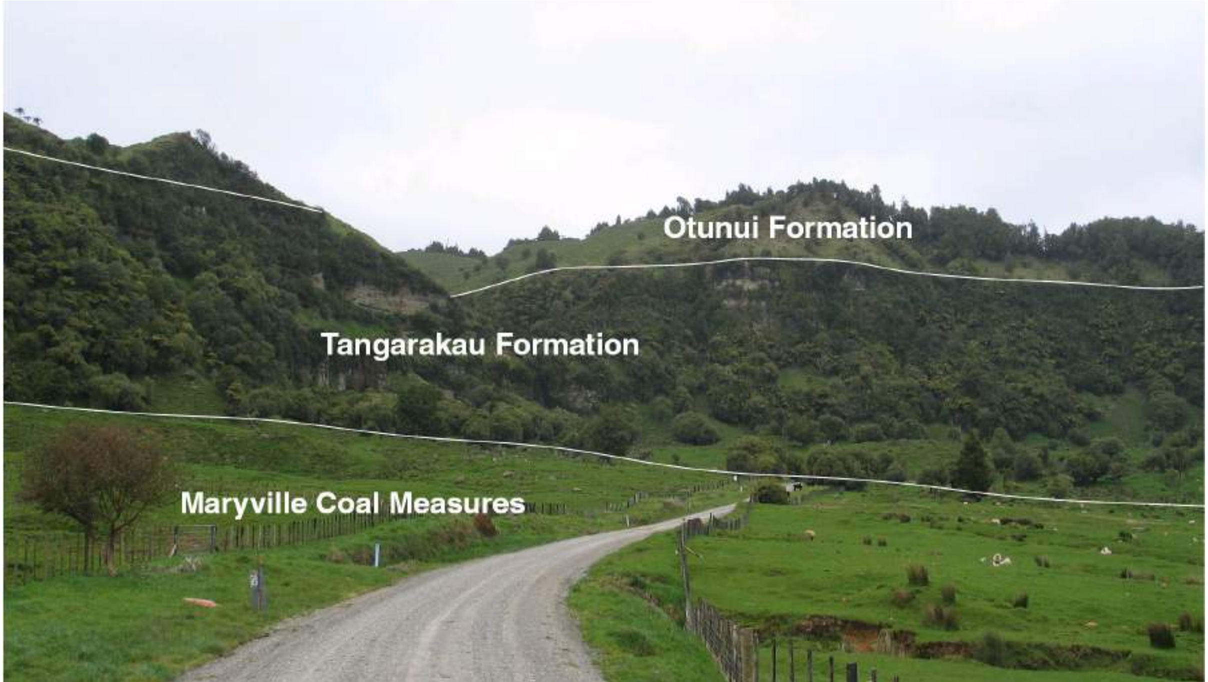


Fig. 52. Photo of the dip-slope developed on the Maryville Coal Measures on the Tongaporutu-Ohura Road SH40, overlying Tangarakau and Otunui formations. R18- 781608.

Fig. 53. Photo of Maryville Coal Measures on the Tongaporutu-Ohura Road SH40, south of Huhatahi Valley. R18-774597.

Fig. 54. Photograph of the sharp, planar contact between Mahoenui Group and overlying Bexley Sandstone exposed in a cutting on the Tongaporutu-Ohura Road.

STOP 20. River Road, Nevins Lookout (R18-814520)

View to the south of the high topography of Harvey Trig hill, all underlain by Mt Messenger Formation. Note the sandstone beds at the top of the hill, which are either faulted or more probably comprise stacked channel complexes with margins at different levels. The Ararimu Fault passes just to the west of where we are standing and has a northeast-southwest strike, with about 170 m throw down to the southeast. The Waiaraia Range to the west comprises Mokau Group upthrown to the west on Ohura Fault, which strikes roughly north-south to the west of where we stand.

STOP 21. Stratigraphic transition from Otunui Formation to Mt Messenger Formation, Mangatarata Road. R18-826522.

There are few good outcrops of the contact between Otunui Formation and Mt Messenger Formation. This arises because in southern King Country the basal facies of Mt Messenger Formation is a mudstone (Kohu Member) and hence the transition with Otunui Formation is a fining in grain size, which is not conducive to forming natural outcrops.

An outcrop on the side of Mangatarata Road, due to recent (2017) slope failure next to the road, currently gives a good exposure of the uppermost part of Otunui Formation (Fig. 55). The actual contact with Mt Messenger Formation is poorly exposed a short distance up the road at higher elevation than the Otunui Formation exposure (Fig. 56).

Samples have been collected for biostratigraphic examination and the results are not yet available, but there is interesting development of pale-coloured calcareous mudstone loaded with what look to be foraminifera at several horizons through the uppermost 10 m of Otunui Formation (Fig. 55). If so, this is symptomatic of condensation and possibly of depositional cyclicity. Condensation could have been caused by deepening of the contemporary bathymetry, trapping sediment in areas more proximal to the terrigenous sediment source, leaving more basinward locations, such as this site, sediment starved, accentuating pelagic sedimentation.

The actual contact between Otunui Formation and Mt Messenger Formation is marked by a very sharp change from calcareous muddy sandstone to terrigenous mudstone. At this contact the rate of hemipelagic (terrigenous) sediment supply increased dramatically. It accumulated in bathyal conditions. It is possible that the bathyal conditions developed during the late phase of accumulation of Otunui Formation, consistent with the observed sediment starvation and condensation, as described above, due to tectonic pulldown of the basin at 11 Ma as the leading edge of the subducted Pacific plate was emplaced beneath the Australia plate lithosphere in southern King Country.

Fig. 55. *Photograph with stratigraphic column of an outcrop of uppermost Otunui Formation exposed adjacent to Mangatarata Road.*

Fig. 56. *Photograph of the poorly exposed contact between Otunui Formation and overlying Mt Messenger Formation adjacent to Mangatarata Road.*

STOP 22. River Road, Aukopae Saddle (S18-913509)

The drive up River Road to Aukopae Saddle is a climb up-section of the Otunui Formation. The saddle is also the watershed between the Ohura and Whanganui rivers. The rocks exposed at the saddle and on the western side comprise bioturbated m-scale bedded sandy siltstone and muddy sandstone (Fig. 57). The mega-bedding is suggestive of cyclicity that may have an origin in sea-level change as discussed in the text associated with STOP 15. In this area Otunui Formation accumulated upon the inundated land surface cut across the Mahoenui Group. A fossiliferous transgressive (onlap) inner shelf succession is exposed in Whanganui River at Paparoa Rapids to the southeast of this locality. It is tempting to consider the Otunui Formation at this stop as shelfal, but these sediments probably accumulated at upper bathyal depths, although the basin was rather flat lying and it would be inappropriate to think in morphological terms. Note the normal fault in this section.

Fig. 57. Road cutting in the upper part of Otunui Formation, River Road, Aukopae Saddle (S18-913509).

STOP 23. Mahoenui Group, Taumarunui Formation at Herlihy's Bluff, River Road (S18-033 516)

Mahoenui Group and specifically Taumarunui Formation is extensively exposed in eastern parts of the King Country Basin where Pliocene-Pleistocene uplift and erosion of central North Island has been most marked (Fig. 4), thereby removing what had been the overlying Neogene succession still present to the west and south. Hence Mahoenui Group is exposed between Hangatiki near the SH3 turnoff to Waitomo (north of Te Kuiti) as far south as the Kaitieke Valley west of Raurimu (north of National Park).

Herlihy’s Bluff is a well-known exposure on the Whanganui River south of Taumarunui, mainly because of engineering challenges in maintaining road safety due to falling rocks (Fig. 58). It is relatively safe at either end of this outcrop and we will pick the safest spot on the day to examine fallen blocks.

This outcrop shows spectacular turbidite development in the Taumarunui Formation (Fig. 58). From fallen blocks note the following features. Erosional flute marks at the base of sandstone beds. Bouma Divisions including at least B-E divisions with the associated sequence of sedimentary structures resulting from the progressive decrease in flow regime and related decreasing density of the turbidity current forming the couplet. The occurrence of organic matter (plant leaf fragments) forming parting surfaces within the Bouma B Division (planar laminated sandstone) is especialy common.

From a study of the Taumarunui Formation south of Taumarunui, we were unable to convincingly determine the size of the submarine fan(s) to which this stack of turbidites, and others, contributed. There is little evidence of thinning of packages that can be discerned from the scale of natural outcrop, of which Herlihy’s Bluff is one of the largest.

Fig.58. Taumarunui Formation, Herlihy’s Bluff, River Road.