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Title **Biostratigraphy, Sr isotope chronology and chronostratigraphy of the Late Eocene – earliest Miocene Te Kuiti Group, Waikato – King Country Basin, New Zealand**

Operator

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Summary This report reviews and synthesises the biostratigraphy of the Te Kuiti Group based on existing sample data archived in the Fossil Record Electronic Database (FRED). Based on these faunal and floral data, New Zealand biostratigraphic stages for the Late Eocene to Early Miocene are assigned to the formations and members within the group. Analytical strontium (Sr) data and resulting numerical ages are reported here for 26 new macrofossil samples from the Te Kuiti Group, but they do not improve the accuracy of the biostratigraphy and the age information that can be derived from it. The identification of unconformity-bound sequences, the boundaries of which align with the formation contacts within the group, provide an important set of time planes within the group. The integration of the biostratigraphy and sequence stratigraphy produces a robust chronostratigraphy for the Te Kuiti Group.

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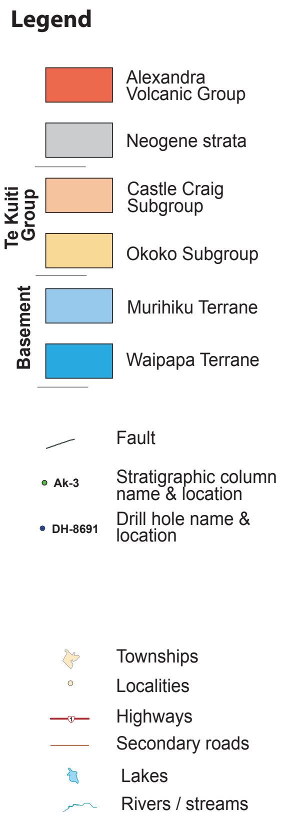
Introduction

The Te Kuiti Group is a Late Eocene to earliest Miocene mixed siliciclastic-carbonate fluvial (including coal measures) to shelf to upper bathyal succession that accumulated in the Waikato – King Country Basin east of northern Taranaki Basin (Fig. 1). This succession marks regional marine inundation about the same time similar successions accumulated in many other parts of New Zealand (Northland, Westland, Canterbury, Southland). This report reviews the



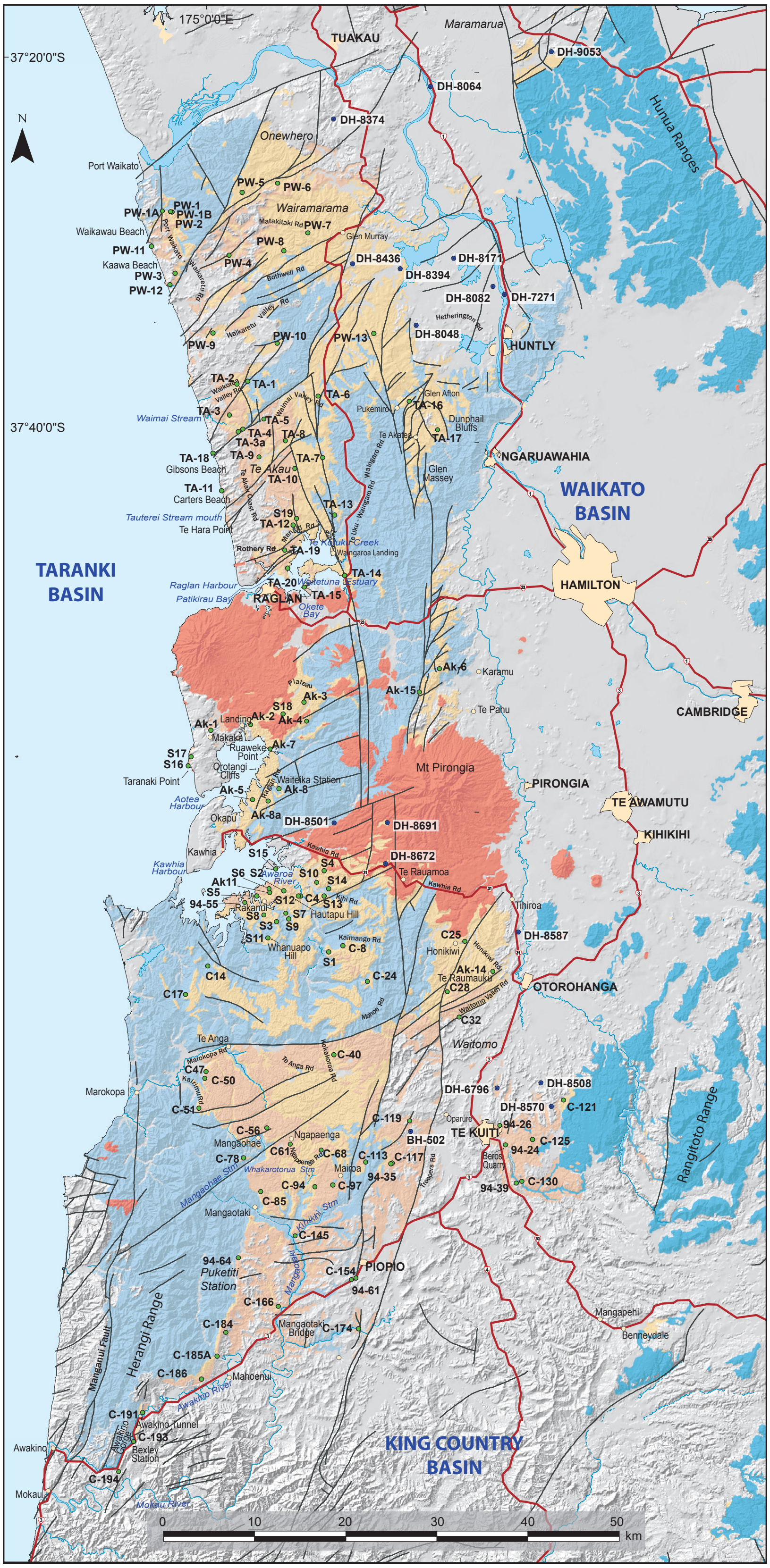


Fig. 1: Map of central-western North Island showing the distribution of the Te Kuiti Group and other units. Note the location of key stratigraphic columns.

biostratigraphy of the Te Kuiti Group based mainly upon previously reported microfossil data, and presents and interprets new geochronological data (strontium (Sr) ages) for macrofossils collected from the group. The Te Kuiti Group succession has been extensively sampled for its floral and faunal content for more than 100 years. The resulting microfossil and macrofossil collections are held at the New Zealand Institute of Geological and Nuclear Sciences, as well as in the Geology Department at Auckland University, data for all of them accessible via the New Zealand Fossil Record Electronic Database (FRED).

The biostratigraphy of the Te Kuiti Group was developed principally from Kear & Schofield's (1959) fossil collections from formations and members of the group cropping out between Papakura (southern Auckland) and Taumarunui (King Country). The formations within the group were assigned New Zealand biostratigraphic stages based mainly upon N. Hornibrook's foraminiferal identifications (Hornibrook et al. 1989). Significant gaps in fossil collections from the Te Akau and Waitomo areas were filled by Kear (1963) and Nelson (1978). Waterhouse & White (1994) made important additional fossil collections in the Raglan-Kawhia area and reported their interpretation.

Despite the advances made in prior investigations, understanding about the biostratigraphy of the Te Kuiti Group has remained problematic because of a combination of few biostratigraphic events during the Oligocene and the difficulty of separating foraminifera from tightly cemented limestone and barren sandstone facies. Our interest in reviewing the biostratigraphy for the Te Kuiti Group and obtaining numerical Sr ages from macrofossils follows the development of a revised lithostratigraphic framework for the group (Tripathi et al. 2008) and our wish to develop a robust chronostratigraphic template to help interpret the paleogeographic development of the region (Kamp et al. 2014). No new microfossil determinations have been made here, but a key element of the review has been reconstruction of the correct stratigraphic unit, in terms of our revised lithostratigraphy, from which the fossil samples were originally collected.

Constraints on determination of Te Kuiti Group biostratigraphy

The lithostratigraphy of the Te Kuiti Group between Port Waikato and Awakino has recently been rationalised and reported in Tripathi et al. (2008). This has resulted in the definition and correlation of seven formations, each containing mulitple members. They have been grouped into six (TK1 -TK6) unconformity bound sequences (Fig 2).

No single fossil group is ubiquitous within all of the stratigraphic units within the group. In non-marine sequences, such as the Waikato Coal Measures, spores and pollens are the most useful fossil groups. In the overlying marginal marine to shallow marine Mangakotuku Formation, a combination of spores and pollen, ostracods, molluscs, and occasionally foraminifera have proved to be useful. As the water depth increased upward in the group to shelfal depths, foraminifera, dinoflagellates and calcareous nannofossils are the most widely used fossil groups for stage determination, especially in the calcareous sequences of the Te Kuiti Group. Although molluscs are common in the group, they are mainly fragmental and are of lower utility than most microfossils due to: (i) the paucity of age diagnostic macrofauna; (ii) their common aragonitic composition, which has led to dissolution; and (iii) the physical limitation of working with fragmented taxa cemented in rocks and the difficulty of separating macrofossil (and microfossil) specimens for identification. Consequently, the majority of the useful biostratigraphic datums within the group are derived from planktic foraminiferal bio-events, the samples having been sourced from the more muddy lithologies. Molluscs are however useful for the assignment of biostratigraphic age in the Orahiri Formation and Otorohanga Limestone. These limestone formations contain large calcite bivalves (oysters, pectinids), brachiopods and the epitoniid gastropod *Cirsotrema*, all reasonably well preserved. Foraminiferal identifications are hard to make within these tightly cemented limestone units as they contain few larger foraminifera, and planktic species are usually rare and difficult to extract (Hornibrook et al. 1989).

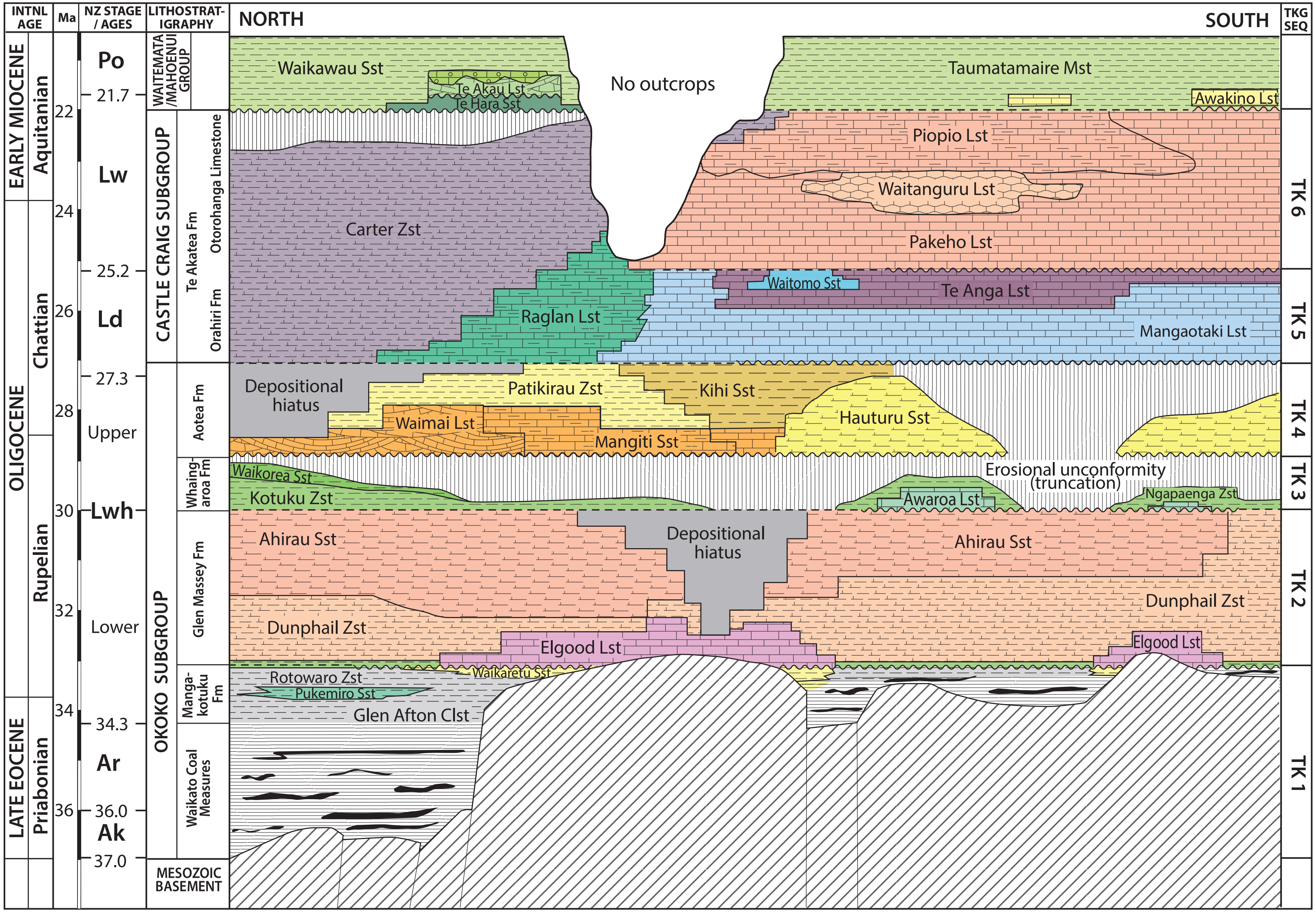


Fig. 2: A new chronostratigraphic scheme for the Te Kuiti Group and the transition to the Waitemata and Mahoenui Groups, Note the occurrence of six unconformity-bound sequences (TK 1 – TK6).

Planktic foraminifera are extremely important taxa for the biostratigraphy of the Te Kuiti Group, especially for samples derived from calcareous siltstone facies. Benthic foraminifera are taxonomically and morphologically more diverse than planktic species, but are facies dependent. Benthic foraminifera have limited use in biostratigraphy because of the occurrence of fewer bio-events compared with planktic bio-events that mark the (lower and upper) Whaingaroan Stage and Duntroonian Stage boundaries (Cooper et al. 2004).

New Zealand Late Eocene-Oligocene-Early Miocene biostratigraphic stages

The basis for defining the New Zealand biostratigraphic stages within the Late Eocene to Early Miocene, when the Te Kuiti Group accumulated, is summarised in Figs 3 & 4. Type and reference sections for these stages, all of them outside the Te Kuiti Group, except for the Whaingaroan-Duntroonian boundary (Fig. 3), have been laid out and described by Cooper et al. (2004), to which readers are referred for details. The fossil samples used here for the assignment of biostratigraphic stages to Te Kuiti Group formations and members are depicted on the composite stratigraphic columns in Fig. 5. Because of our revisions in the correlations and nomenclature for lithostratigraphic units following the collection of all of the fossil samples and their processing onto the fossil record database, a critical part of this review has been establishing the correct stratigraphic units for the samples (collected by many other people) and the plotting of them on the stratigraphic columns in Fig. 5. Although we are confident that the fossil samples are associated with the correct units, there is some uncertainty in the height we have plotted them within those members in representative columns in Fig. 5. This leads to a level of uncertainty in the assignment of biostratigraphic stage to some members.

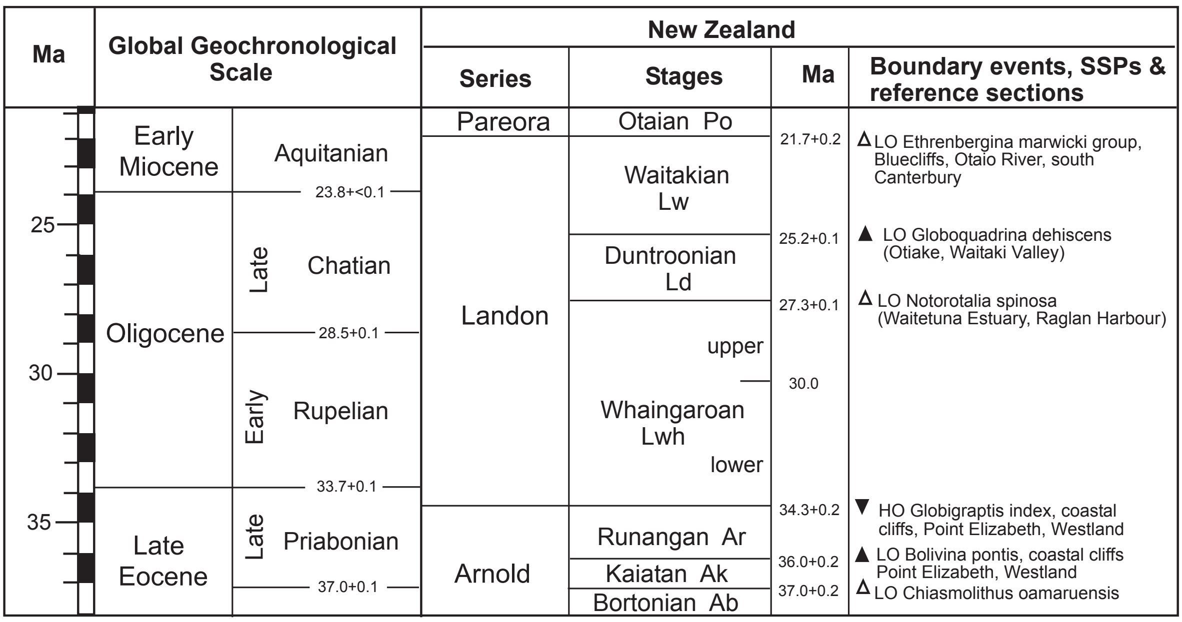
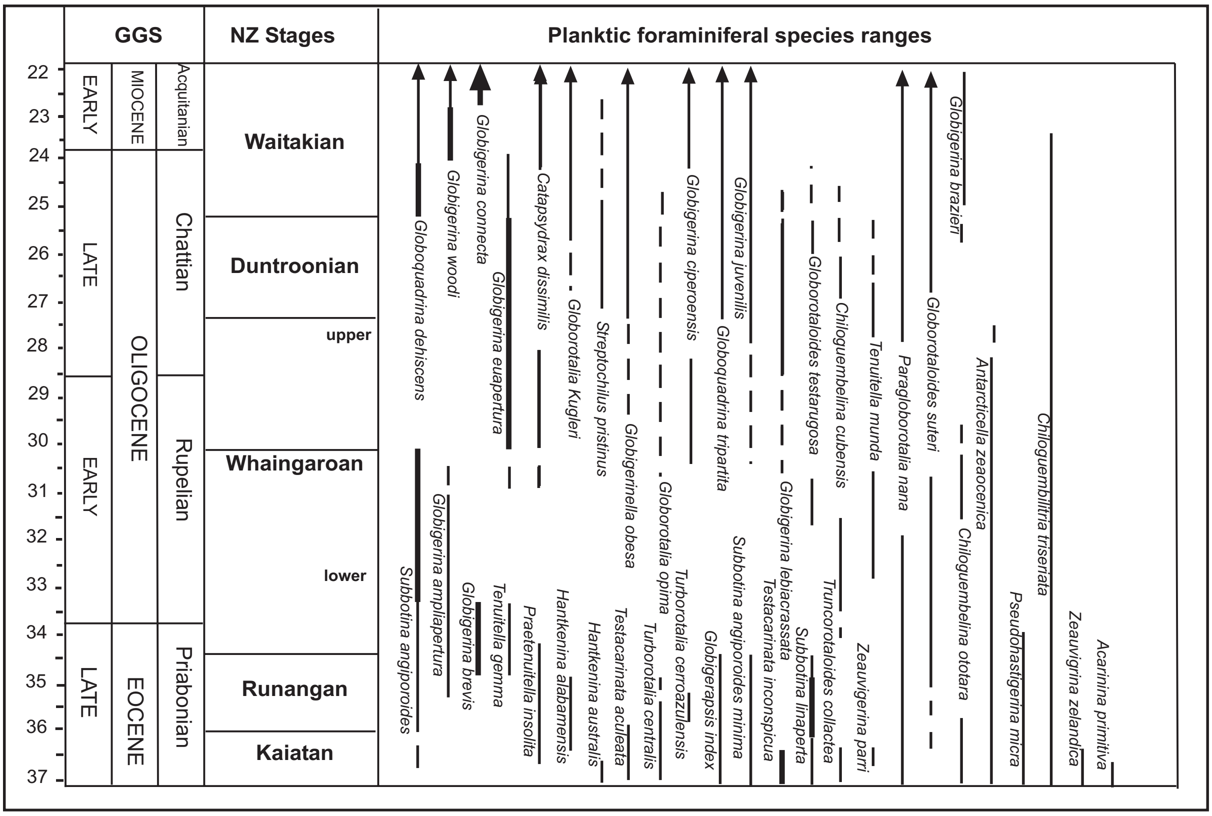


Fig. 3: Late Eocene to Early Miocene New Zealand Series and Stages correlated with the Global Geochronological Scale (Berggren et al. 1995). The boundary-defining event for each stage is shown and the boundary stratotype section and point (SSP), or a reference section in brackets, are indicated. Formal SSPs are indicated by solid triangles and informal SSPs by open triangles. From Cooper et al. (2004).

(a)



(b)

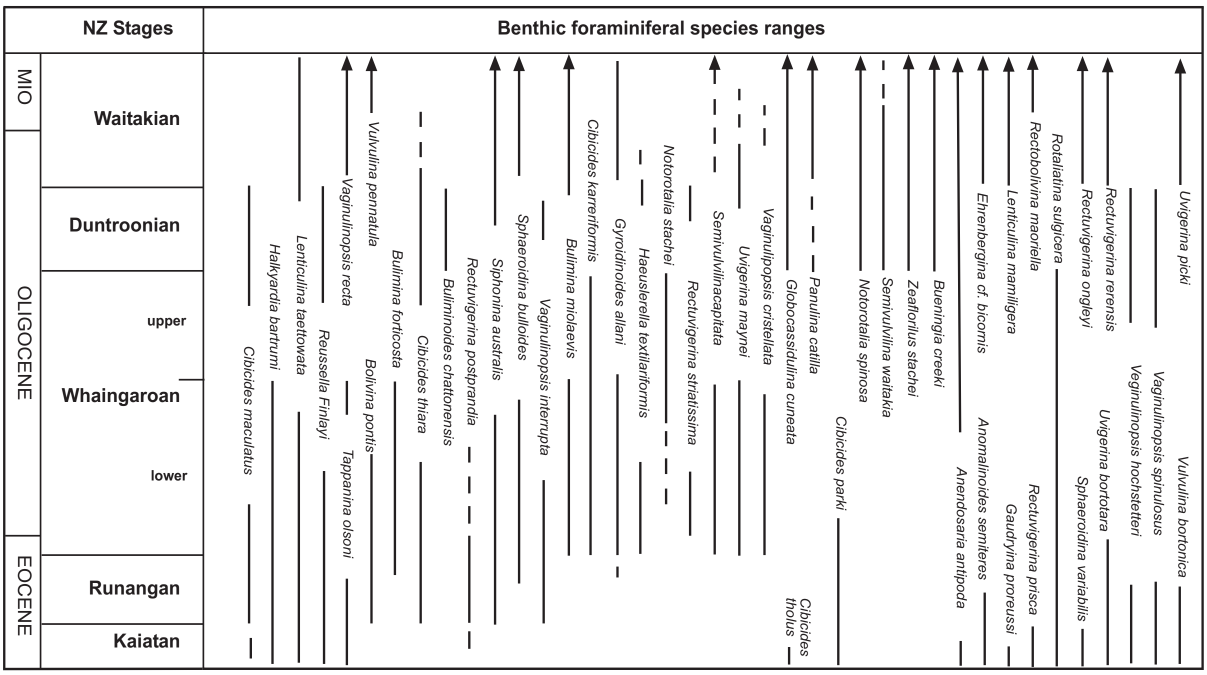
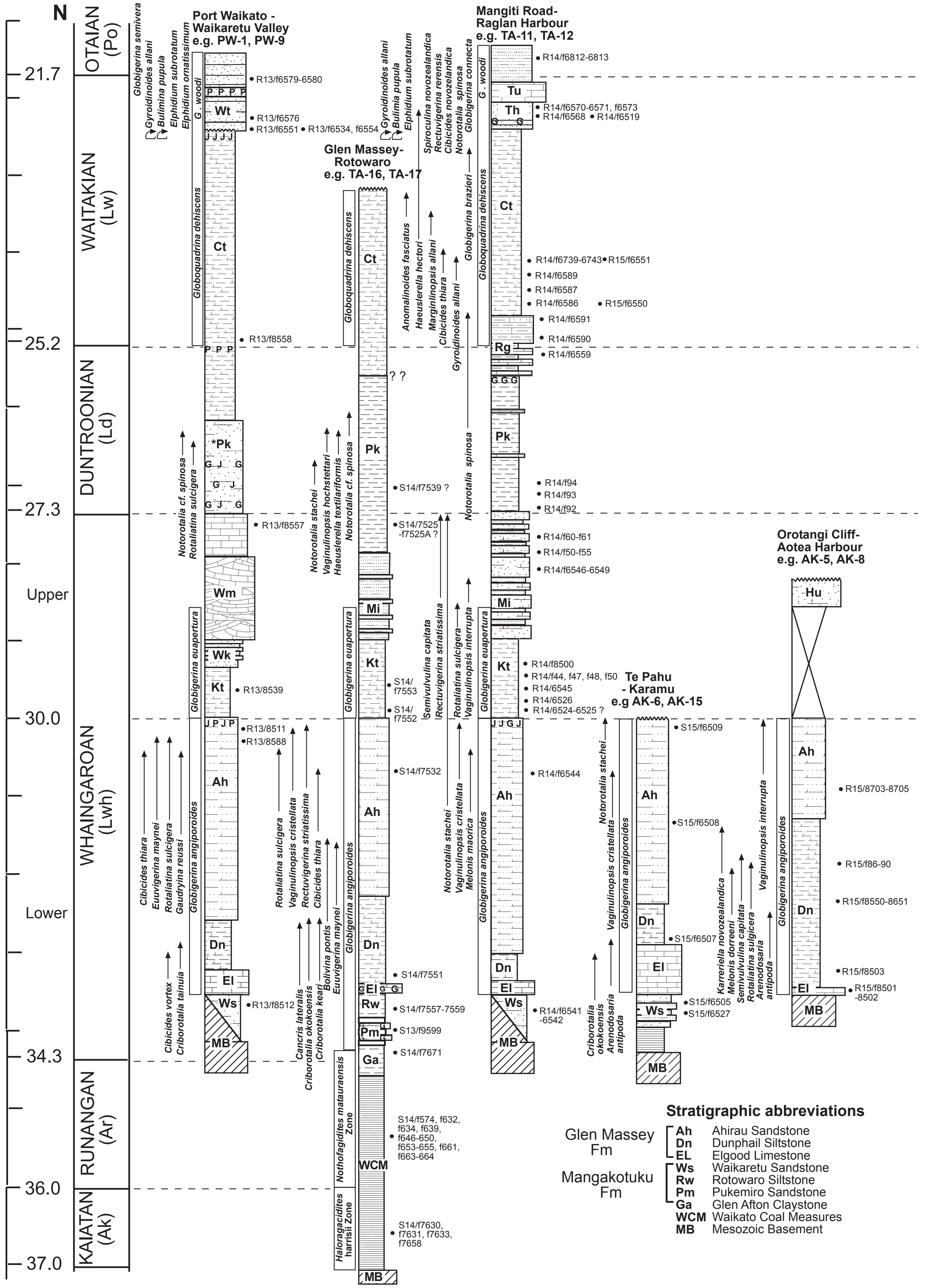
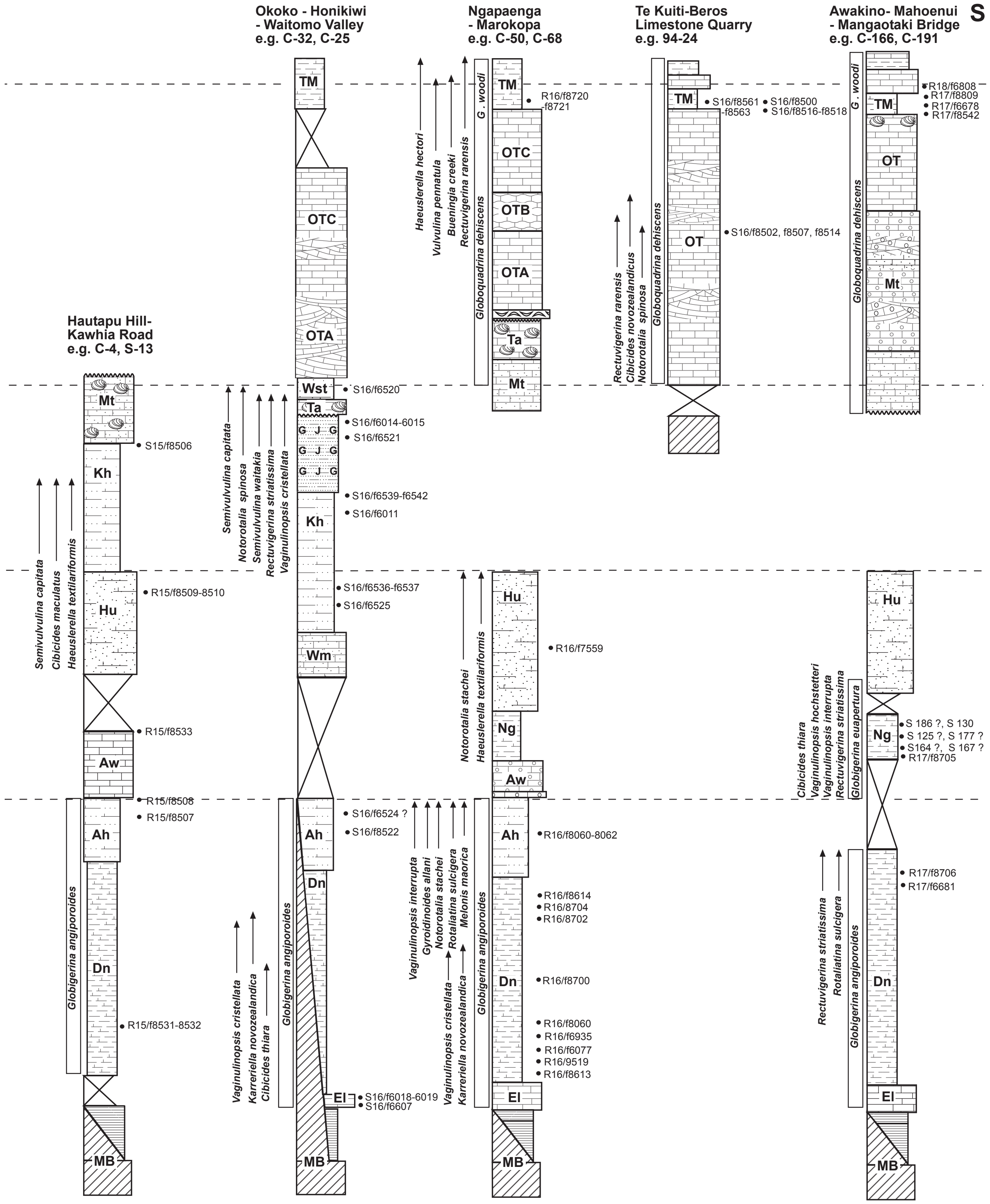


Fig. 4: Stratigraphic ranges of selected biostratigraphically useful planktic (a) and benthic (b) foraminifera. From Cooper et al. (2004).

Fig. 5: (following pages) Biostratigraphic correlations for the Te Kuiti Group, and lowermost parts of the Mahoenui and Waitemata Groups in the field area. Formations and members are rescaled to show the distribution of time within them based on assignment of faunal and floral sample data (FRED sample numbers) to the New Zealand stages within the Late Eocene to Late Oligocene. The biostratigraphically most important taxa only are shown. The position of the samples against the composite stratigraphic columns is approximate as most are not serial samples and rather have been correlated onto the composite columns from diverse locations in their vicinity.


N
OTAIAN (Po)
WAITAKIAN (Lw)
DUNTROONIAN (Ld)
WHAINGAROAN (Lwh)
Upper
Lower
RUNANGAN (Ar)
KAIATAN (Ak)
21.7
25.2
27.3
30.0
34.3
36.0
37.0
Port Waikato - Waikaretu Valley e.g. PW-1, PW-9
Glen Massey- Rotowaro e.g. TA-16, TA-17
Mangiti Road- Raglan Harbour e.g. TA-11, TA-12
Te Pahu - Karamu e.g AK-6, AK-15
Orotangi Cliff- Aotea Harbour e.g. AK-5, AK-8
Globigerina semivera
Gyroidinoides allani
Bulimina pupula
Elphidium subrotatum
Elphidium ornatissimum
G. woodi
Globoquadrina dehiscens
Globigerina euapertura
Globigerina angiporoides
Globigerina brazieri
Globigerina connecta
Nothofagidites matauraensis Zone
Haloragacidites harrisii Zone
Stratigraphic abbreviations
Glen Massey Fm
Ah Ahirau Sandstone
Dn Dunphail Siltstone
EL Elgood Limestone
Mangakotuku Fm
Ws Waikaretu Sandstone
Rw Rotowaro Siltstone
Pm Pukemiro Sandstone
Ga Glen Afton Claystone
WCM Waikato Coal Measures
MB Mesozoic Basement



Orahiri Fm	Wst	Waitomo Sandstone
	Ta	Te Anga Limestone
	Mt	Mangaotaki Limestone
Aotea Fm	Pk	Patikirau Siltstone
	Kh	Kihi Sandstone
	Hu	Hauturu Sandstone
	Mi	Mangiti Sandstone
	Wm	Waimai Limestone
Whaingaroa Fm	Ng	Ngapaenga Siltstone
	Aw	Awaroa Limestone
	Wk	Waikorea Sandstone
	Kt	Kotuku Siltstone

Mahoenui Gp	TM	Taumatamaire Siltstone
Waitemata Gp	Wt	Waikawau Sandstone
	Tu	Te Akau Limestone
	Th	Te Hara Sandstone
Otorohanga Limestone (OT)	OTC	Piopio Limestone
	OTB	Waitanguru Limestone
	OTA	Pakeho Limestone
Te Akatea Fm	Ct	Carter Siltstone
	Rg	Raglan Limestone

P Phosphate
G Glaucony
J Burrows
Reworked fauna
Interval missing / no outcrops
Prominent erosional contact
Top eroded

Assignment of biostratigraphic stages to Te Kuiti Group formations and members

In the following section, under subheadings of the successive Late Eocene and Oligocene biostratigraphic stages, relevant microfossil samples are assigned to formations and members, emphasising the key taxa within samples and the related age (stage) determination. This section is highly descriptive but deserving given the need to extract as much information as possible from existing processed samples. Most of the samples we refer to here (FRED numbers on Fig. 5) carry diagnostic biostratigraphic information, but many of the entries in FRED for the Te Kuiti Group do not and are not referred to in this report.

Kaiatan Stage (Ak)

Hornibrook et al. (1989) summarised the foraminiferal basis for the Kaiatan Stage. The base of the stage is primarily recognised by the disappearance of *Nuttallides truempyi*, *Bulimina subbortonica*, and *Cibicides tholus*. *Sphaeroidina variabilis* ranges through the Kaiatan. No planktic events mark either the base or top of the Kaiatan. The best defined planktic event is the highest occurrence of *Acarinina primitiva*. No nannofossil event coincides with the base of the stage, although the lowest occurrence of *Reticulofenestra bisecta* lies near, and above, the base of the Kaiatian. The lowest occurrence of *Ismolithus recurvus*, an event dated at 36.0 Ma (Berggren et al. 1995), is extremely useful for correlating the upper Kaiatan with the international time scale.

Most of the rocks of Kaiatan age in the study area (i.e. lower parts of the Waikato Coal Measures) are inferred to be of non-marine (alluvial to coastal plain) origin (Edbrooke et al. 1994), and any age diagnostic microfossils are uncommon. Pocknall (1991) investigated and proposed the type of vegetation that grew during Waikato Coal Measures accumulation, and its subdivision into biozones, based on abundance levels of the major palynomorphs. The lowermost spore and pollen zone of the Waikato Coal Measures is his *Haloragacidites harrisii* Zone, which corresponds to the upper part of the Kaiatan (Pocknall 1991). Palynofloras of the *H. harrisii* Zone are restricted to basal Waikato Coal Measures in the Rotowaro Coalfield and in the northeastern part of Huntly Coalfield (Edbrooke et al. 1994). Four samples (S14/f7630, f7631, f7633 and f7658) containing palynofloras of Arnold (Ab-Ak) age were reported by Kear & Schofield (1978) from the Rotowaro area (Fig. 5). Although these samples derive from unmeasured sections, the collections are significant as the oldest in the study area.

Runangan Stage (Ar)

The lowest occurrence of *Bolivina pontis*, *Sphaeroidina bulloides* replacing *S. variabilis*, and the lowest occurrence of *Rectuvigerina postprandia*, replacing *R. prisca*, are all used as primary criteria for identifying the base of the Runangan Stage (Pocknall 1991). *B. pontis* is now routinely adopted for defining the base of this stage (Morgans et al. 2004). The lowest occurrence of *Reticulofenstra reticulata*, an event dated at 36.1 Ma (Berggren et al. 1995), is a useful planktic proxy for the base of the Runangan.

The *Nothofagidites matauraensis* Assemblage Zone in the Waikato region spans the Runangan and the lower part of the Whaingaroan. This assemblage, dominated by *Nothofagus*, is subdivided into a lower *Myrtaceidites* Subzone predominantly of Runangan age, and an upper *Araucariacites australis* Subzone of upper Runangan to lower Whaingaroan age (Pocknall & Mildenhall 1984; Pocknall 1991). These age assignments are based on microfaunal assemblages reported from marine strata overlying the coal measures in the Ngaruawahia Subdivision (Hornibrook in Kear & Schofield 1978). Palynoflora characteristic of the *Myrtaceidites* Subzone have been identified in samples from the Drury, Maramarua, Huntly, and Rotowaro coalfields.

Whaingaroan Stage (Lwh)

The Whaingaroan has a duration of 7 m.y. and is informally subdivided into lower and upper divisions (Hornibrook et al. 1989; Morgans et al. 1996; Cooper et al. 2004). The base of the Whaingaroan has previously been regarded as equivalent to the base of the Oligocene. Recent correlations indicate that the base may be about 0.5 to 1.1 m.y. older than the base of the Oligocene (Morgans et al. 1996; Nelson et al. 2004). Cooper et al. (2004) have the base of the Whaingaroan at 34.3 Ma, some 0.6 m.y. older than the base of the Oligocene. Finlay (1939) proposed the Whaingaroan Stage for the interval associated with accumulation of the Kotuku Siltstone at Raglan Harbour (Whaingaroa Harbour). The original faunal definition used by Finlay (1939) and Finlay & Marwick (1940) to define the base of the Whaingaroan Stage has changed and this is currently defined by the highest occurrence of the planktic foraminifera *Globigerapsis index* (Morgans et al. 2004). The highest occurrence of *G. index* is given an age of 34.3 Ma (Berggren et al. 1995). The molluscs within the Whaingaroan Stage are of low diversity, dominated by calcitic taxa such as oysters and pectinidids, and are of little use for biostratigraphy. *Nothofagidites matauraensis* dominated palynoflora of the *N. matauraensis* Assemblage continue into the Whaingaroan. The top of this zone is defined by the lowest occurrence of *Rubipollis oblatus* (Morgans et al. 2004). Hornibrook et al. (1989) proposed an informal subdivision of the Whaingaroan into lower and upper divisions.

Lower Whaingaroan (lower Lwh)

The lower Whaingaroan is defined as those beds lacking *G. index* and containing *Subbotina angiporoides* and *Globigerina ampliapertura*. This substage was established by Jenkins (1966, 1971) based on the upper part of the *Globigerina brevis* zone together with the *Globigerina angiporoides* Zone, the top of which defines the lower - upper Whaingaroan boundary. Shallow water assemblages, lacking planktic foraminifera, are difficult to differentiate from Runangan assemblages.

In the Huntly Coalfield the Waikato Coal Measures are overlain by members of the Mangakotuku Formation (Fig. 2). Glen Afton Claystone contains the brachiopod *Lingula*, but no foraminifera (Penseler 1930). The upper deeper-water parts of Pukemiro Sandstone contain *Cyclammina, Flabellammina, Semivulvulina, Gaudryina, Arenodosaria, Quinqueloculina, Lenticulina, Polymorphinids, Operculina, Trifarina, Reussella finlayi, Criborotalia keari, Melonis, Amphistegina, Anomalinoides fasciatus, Cibicides vortex* and rare planktics (Hornibrook et al. 1989). The scarcity of planktics makes it difficult to assign an age to the Pukemiro Sandstone; however the microfauna that are there favour a basal Whaingaroan age. Only *Criborotalia keari* indicates a more precise upper Kaiatan - lower Whaingaroan age range. Sample S14/f7671, reported in Kear & Schofield (1978), was collected above the top of Glen Afton Claystone near the type Pukemiro locality (Fig. 5), and it contains abundant *Ammobaculites*, suggesting a Runangan - lowermost Whaingaroan age range. Sample S13/f9599 collected from Pukemiro Sandstone in DH 1768, about 21 m above the coal measures, contains *Haplophragmoides, Elphidium*, and *Cancris lateralis*, indicating a lowermost Whaingaroan age (Fig. 5).

The Rotowaro Siltstone contains plentiful foraminifera in places and assemblages are typically dominated by an abundance of *Arenodosaria, Elphidium, Criborotalia keari*, *C. okokoensis, Asterigerina cyclops*, and *Cancris lateralis minima* (Hornibrook et al. 1989), indicating a lowermost Whaingaroan age. Samples S14/f7557-7559 collected from the Dunphail Bluff type locality (TA-17) for Rotowaro Siltstone (Fig. 5), yielded lowermost Whaingaroan age microfauna, however samples S14/f7558 and S14/f7559 contain a macrofaunal assemblage indicating a lowermost Whaingaroan - Duntroonian age range, which seems too young. The abundance of *Criborotalia keari* and *C. okokoensis* favours an upper Ak - lower Whaingaroan age. Sample S12/f9566 collected from drill cuttings (DH4996) near Mercer provides microfauna of no definite age range. Samples S12/f9554 and S12/f9555 collected from a drill hole in Lake Whangape west of Rangiriri, yielded microfaunas containing *Notorotalia stachei* and rare *Criborotalia keari*, indicating a Whaingaroan age range, but there is a strong probability of contamination from the upper parts of the hole, and a lowermost Whaingaroan age is favoured.

The Waikaretu Sandstone is a variably muddy fine to coarse sandstone usually overlying Mesozoic basement. Sample R13/f8512 collected from its type locality (TA-9) on Waikaretu Valley Road (Fig. 5) contains a microfaunal assemblage including *Cibicides vortex* and *Criborotalia* *tainuia* of lowermost Whaingaroan age. Samples R13/8514 and 8515 collected from Waikorea Road contain *Notorotalia stachei, Rotaliatina sulcigera* and *Vaginulinopsis hochstetteri*, suggesting a Whaingaroan age. Samples R14/6541-6542 collected from north of Waingaro Landing (Fig. 5) contain a microfaunal assemblage including *Melonis maorica, Asterigerina cyclops, Elphidium ingressans*, and *Cibicides vortex* of lowermost Whaingaroan age. Sample S15/6527, reported in Kear & Schofield (1978) from the lowest exposed parts of Waikaretu Sandstone in the Te Pahu Mine (Fig. 5), contains *Ammobaculites, Haplophragmoides*, and *Elphidium* suggesting a lowermost Whaingaroan age. Another sample (S15/f6505) collected about 17 m above the previous sample contains *Arenodosaria antipoda*, *Arenodosaria*, *Operculina*, and *Criborotalia okokoensis*, giving a lowermost Whaingaroan age. Sample R16/8701 (C-51), collected from Kairimu Road south of Awamarino, is inferred to be of Whaingaroan age.

Foraminifera are difficult to extract from the well-cemented lithology of Glen Massey Formation, however the microfaunal assemblage indicates deepening from shelfal to upper bathyal water depths. The common microfauna within Glen Massey Formation include *Arenodosaria antipoda, Gaudryina reussi, Melonis maorica, Vaginulinopsis cristellata, Rectuvigerina striatissima, Uvigerina maynei, Melonis dorreeni, Bolivina reticulata, Globocassidulina subglobosa, Rotaliatina sulcigera, Notorotalia stachei* (abundant), *Cibicides pronovozelandicus, Semivulvulina capitata, Karreriella novozealandica* and *Cibicides thiara*. Planktics are moderately common, especially *Globigerina angiporoides* and *G. ampliapertura,* indicating a lower Whaingaroan age (Hornibrook et al. 1989).

The sample (S14/f7551) collected from Dunphail Siltstone (3 m above Elgood Limestone) at its type locality of Dunphail Bluffs (Fig. 5), yielded *Gaudryina reussi, Notorotalia stachei, Uvigerina maynei, Gyroidinoides allani, Bolivina pontis, Cibicides thiara, Cancris compressus, Globocassidulina subglobosa* and *Globigerina angiporoides*, suggesting a lower Whaingaroan age and a deeper water, more open marine depositional setting than that of the underlying Mangakotuku Formation (Fig. 5). Sample S14/f7532 collected from Ahirau Sandstone exposures along Waingaro Road and north of Glen Massey village (Fig. 5), include the microfauna *Cibicides pronovozelandicus, Karreriella novozealandica, Cibicides thiara, Vaginulinopsis cristellata, Gaudryina reussi, Rotaliatina sulcigera, Notorotalia stachei, Rectuvigerina striatissima, Globocassidulina subglobosa* and *Globigerina reticulata*, indicating a Whaingaroan age. Sample R13/f8511 collected from Ahirau Sandstone exposed along the Waikaretu Valley Road (Fig. 5) contains *Cibicides thiara, Gaudryina reussi* and *Rotaliatina sulcigera.* Another sample (R13/f8558) collected from Kokonga East Road (Fig. 5) contains *Gaudryina reussi, Rotaliatina sulcigera* and *Uvigerina maynei*, indicating a Whaingaroan age. Sample R14/f6544 collected from Mangiti Road (Fig. 5) includes fauna common in Glen Massey Formation (e.g., *Arenodosaria antipoda*, *Melonis maorica*, *Vaginulinopsis cristellata, Gaudryina reussi, Notorotalia stachei* and *Gyroidinoides allani*), indicating a Whaingaroan age.

Samples R15/f8501-8502 collected from the "basal facies" of Glen Massey Formation exposed along the Mangaora Stream in Kawhia (Fig. 5), contain *Arenodosaria antipoda, Rotaliatina sulcigera, Notorotalia stachei, Melonis dorreeni, Semivulvulina capitata* and the key planktic *Globigerina angiporoides*, indicating a lower Whaingaroan age. Sample R15/f8503 collected from the formation farther to the north along the Raglan-Kawhia Road (Fig. 5) contains *Melonis dorreeni* and *Vaginulinopsis interrupta*, with an uncertain age. Another set of three samples (R15/f8703-8705) collected from the Glen Massey Formation exposed along the Raglan-Kawhia Road (Fig. 5) contain the middle to outer shelf species *Semivulvulina capitata* and other inferred mid-Whaingaroan microfauna. Samples R15/8650 and 8651 collected from Dunphail Siltstone exposed in the lower part of Orotangi Cliff at Aotea Harbour (Fig. 5) contain the planktics *Globigerina ampliapertura* (f8650-651) and *G. angiporoides*, inferred to be of lower Whaingaroan age, whereas samples R15/8652 and 8653 contain mid-Whaingaroan microfaunas. Another set of five samples (R15/f86-90) reported by Waterhouse & White

(1994) from Glen Massey Formation exposed at Orotangi cliff (Fig. 5) contain *Nodosaria longiscata*, *Sigmoilina tenuis*, and the deeper water species *Semivulvulina capitata, Karreriella novozealandica* and *Globigerina angiporoides*, indicating a lower Whaingaroan age. Samples R15/f8531 and 8532 collected from massive calcareous siltstone at 20 and 6 m, respectively, above basement exposed along Kihi Road (R15/813428) (Fig. 5), contain *Globigerina angiporoides* and other lower Whaingaroan microfauna. Sample R15/8507 collected from near the top of Glen Massey Formation exposed at the lower level of Hautapu Hill (C-4) (Fig. 5) also contains *Globigerina angiporoides* and is inferred to be of lower Whaingaroan age.

Sample S16/f8503 collected from 6 m above the base of the Dunphail Siltstone in the Okoko Coalmine area (Fig. 5) contains *Globigerina angiporoides* and is inferred to be of lower Whaingaroan age. Samples S16/f6018-6019 reported from near basal facies of Glen Massey Formation overlying basement exposed along Tapuae Road near Honikiwi (Fig. 5) contains *Cibicides thiara, Vaginulinopsis cristellata, Karreriella novozealandica*, and abundant *Globigerina angiporoides* (f6018), indicating a lower Whaingaroan age.

Samples R16/f8061-8062 collected from Glen Massey Formation exposed near the bridge on Mangapohue Stream on Te Anga Road (Fig. 5) contains *Melonis maorica, Rotaliatina sulcigera* and *Notorotalia stachei*. Sample f8060 contains *Globigerina angiporoides* of lower Whaingaroan age, whereas samples (f8061-8062) have no age diagnostic faunas. Sample R16/f8700 collected from Dunphail Siltstone exposed along the Kairimu Stream south of Awamarino (C-51) (Fig. 5) contains *Rotaliatina sulcigera,* and the deep-water species *Karreriella novozealandica*, *Vaginulinopsis cristellata*, and *Globigerina angiporoides* indicating a lower Whaingaroan age. Another set of samples R16/8613-8614 (Fig. 5) collected 2.5 m above Elgood Limestone in Dunphail Siltstone and in the base of Ahirau Sandstone contain *Notorotalia stachei, Gyroidinoides allani* and *Globigerina angiporoides* (f8613), indicating a lower Whaingaroan age range. Sample R16/f8702 from Dunphail Siltstone west of Mairoa (Fig. 5) contains mainly shelfal fauna (e.g. *Notorotalia stachei, Rectuvigerina striatissima*) and is inferred to be of Whaingaroan age. Sample R16/f8704 collected from Mangaohae Stream exposure (C-56, Fig. 5) contains *Semivulvulina capitata* and *Vaginulinopsis interrupta,* indicating a Whaingaroan to possibly Duntroonian age range, which seems too young. Sample R16/9519 collected from the lowermost exposed calcareous siltstone (Dunphail Siltstone) along the Mairoa-Te Kuiti Road near Pakeho (Fig. 5) contains *Globigerina angiporoides* and is inferred to be of lower Whaingaroan age. Sample R16/f6077 (Fig. 5) collected from probably the basal facies near Waitere and Taharoa Road intersection (R16/677316) contains abundant *Globigerina angiporoides* and another sample R16/f6935 collected from the same area contains *Globigerina* sp. and is of lower Whaingaroan age. Sample R17/ 8706 collected from the same unit exposed in Mangaorongo Road (Fig. 5), contains *Rotaliatina sulcigera, Rectuvigerina striatissima* and *Globigerina angiporoides* indicating a lower Whaingaroan age. Sample R17/f6681 collected from Puketiti Station (Fig. 5), south of Mangaotaki, contains *Globigerina angiporoides* and is inferred to be of lower Whaingaroan age. Three samples (R17/f656-658) collected from Dunphail Siltstone exposed along SH3 near Bexley Station (C-193) contain lower Whaingaroan foraminifera. From these data the whole of the Glen Massey Formation is inferred to be of lower Whaingaroan age.

Upper Whaingaroan (upper Lwh)

The fauna described by Stache (1864) from Waitetuna Estuary (Raglan Harbour) are representative of upper Whaingaroan fauna. The sub-stage is defined as strata lacking *Subbotina angiporoides* and containing *Notorotalia stachei*. In Taranaki Basin, the uppermost Whaingaroan is defined on the highest occurrence of the benthic foraminifera *Rotaliatina sulcigera*, a useful and ubiquitous event. The co-occurrence of *Globigerina euapertura* and *R. sulcigera* is usually a reliable guide to the upper Whaingaroan in deeper water settings, while in shallow water and restricted environments *Notorotalia stachei* is a key taxon (Morgans et al. 2004). Jenkins (1966, 1971) correlated the upper Whaingaroan with the lower part of the *Globigerina euapertura* zone. The highest occurrence of the planktic foraminifer *Subbotina angiporoides* defines the base of the upper Whaingaroan and has been given an age of 30.0 Ma by Berggren et al. (1995) and Cooper et al. (2004).

Sample R14/f6545 reported by Kear (1963) from 8.5 m above the base of Kotuku Siltstone of Whaingaroa Formation in Tawatahi River Valley (Fig. 5) in the northern inland part of Raglan Harbour, contains typical upper Whaingaroan fauna including *Cibicides thiara, Notorotalia stachei, Rectuvigerina striatissima, Rotaliatina sulcigera*, and *Vaginulinopsis interrupta* as identified by Hornibrook. Samples R14/f44, f47, f49, f50 reported by Waterhouse & White (1994) from the type area of Whaingaroa Formation in Raglan Harbour (Column TA-14, Kamp et al. 2008) contain most of the typical upper Whaingaroan fauna and lack *Globigerina angiporoides* (Fig. 5). Sample R14/f8500 reported from Te Uku Landing (Waterhouse & White 1994) includes *Gaudryina reussi*, the deeper water species *Semivulvulina capitata,* and the planktic *Globigerina euapertura,* indicating a Whaingaroan-Duntroonian age range (Fig. 5). These samples are reported from Glen Massey Formation, but are likely to have been collected from Kotuku Siltstone of the Whaingaroa Formation, as the Glen Massey Formation is a highly condensed unit and poorly exposed at this locality (Tripathi et al. 2008). Similarly, samples R14/f6524-6525 reported from Ahirau Sandstone north of Ohautira (Fig. 5) contain *Rotaliatina sulcigera* and *Notorotalia stachei,* indicating an upper Whaingaroan age, and are more likely to have been collected from Kotuku Siltstone. Sample R14/f6526 collected 10 m above the base of the Whaingaroa Formation at Ohautira contains a faunal assemblage typical of Whaingaroan age (Fig. 5). Samples S14/f7552-7553 reported from 8.5 and 42.5 m above the Ahirau Sandstone (Fig. 5), north of Dunphail Bluff (TA-17), contain *Globigerina euapertura* and are inferred to be of upper Whaingaroan age. Sample R13/f8539 is reported by Kear (1963) to have been collected from 7 m above the base of the Whaingaroa Formation in Waikaretu Valley and contains *Cibicides thiara* and *Rotaliatina sulcigera* and is inferred to be of Whaingaroan age (Fig. 5).

Sample R15/f8508 was reported from the "bored contact" between the Glen Massey Formation and Awaroa Limestone at Kihi Road (Fig. 5) and contains rare *Globigerina angiporoides* and other fauna of lower Whaingaroan age. Another sample R15/f8533 reported from immediately above the Awaroa Limestone (Fig. 5) contains Whaingaroan fauna. Samples S125 and S177 reported by Stainton (1966) from massive calcareous siltstone (tentatively identified here as the equivalent of Ngapaenga Siltstone Member) in the Mangaorongo Road section (Section C-183, Kamp et al. 2008) (Fig. 5) is inferred to be of upper Whaingaroan age on the basis of *Rectuvigerina striatissima* and the key planktic fauna *Globigerina euapertura*. Sample S186 reported from probably the equivalent facies in the Puketiti section (C -139) is inferred to contain Whaingaroan-Duntroonian transition fauna (Fig. 5), which are a bit young. Samples S164 and S167 reported from the lowermost exposed massive calcareous mudstone near Ototohu Stream, Mahoenui, are inferred to contain Whaingaroan-Duntroonian transition fauna; however S164 is more likely to be upper Whaingaroan as it contains *Globigerina euapertura.* Sample S130 reported from the stratigraphically equivalent facies exposed at Bexley Station (Section C-193) contains rare *Globigerina euapertura* and is inferred to indicate a mid or upper Whaingaroan age. Sample R17/f8705 collected from the calcareous siltstone exposed along Gibbon Road (R17/697919) near Mahoenui (Fig. 5) contains *Vaginulinopsis interrupta*, *Vaginulinopsis hochstettari, Globocassidulina subglobosa,* and *Cibicides thiara,* indicating a Whaingaroan-Duntroonian age range.

Samples R15/f8509-8510 collected from Hauturu Sandstone and Kihi Sandstone of Aotea Formation exposed at Hautapu Hill (Section C-4, Kamp et al. 2008) (Fig. 5) are inferred to contain Whaingaroan-Duntroonian fauna. Sample R16/f7559 collected from Hauturu Sandstone 12 m above basement (R16/879274) is inferred to be of Whaingaroan age at Ngapaenga (Fig. 5). Samples S16/f6536-6537 collected from Aotea Formation (tentatively identified as Kihi Sandstone) exposed along SH31 (north of Otorohanga) (S16/025388) have an upper Whaingaroan fauna but S16/f6536 contains *Semivulvulina waitakia* and is possibly of Duntroonian age (Fig. 5). Sample S182 reported by Stainton (1966) from Kihi Sandstone exposed along SH3 near Mangaotaki Bridge (C-166) and R17/f8507 collected 12 m above the basement are inferred to be of Whaingaroan-Duntroonian age. Sample S16/f6524 collected from the base of the Kihi Sandstone in Waitomo Valley is inferred to have a lower Whaingaroan age, whereas another sample S16/f6523 higher up in Kihi Sandstone is inferred to be of upper Whaingaroan age. Samples R14/f6546-6549 reported by Kear (1963) from the type locality of Mangiti Sandstone in Aotea Formation exposed to the east of Te Kotuku Trig (Mangiti Road, TA-12) (Fig. 5) are inferred to have consistent Whaingaroan ages. Samples R14/f0050 and f0055 reported by Waterhouse & White (1994) from the Mangiti Sandstone exposed at Haroto Bay, Raglan Harbour (R14/827771), and samples R14/f0060-61 from Paritata Peninsula, contain *Rectuvigerina striatissima and Notorotalia stachei,* indicating an upper Whaingaroan age (Fig. 5). Sample R14/f0092 collected 1 m above the contact between Mangiti Sandstone and Patikirau Siltstone (Aotea Formation) at the type locality of Patikirau Siltstone at Patikirau Bay (TA-20) is inferred to contain Whaingaroan-Duntroonian transition fauna (Fig. 5). Sample R13/f8557 reported by Kear (1963) from the seams within Waimai Limestone (Aotea Formation) exposed near Kokanga East Road (Fig. 5) contains *Rotaliatina sulcigera* and *Notorotalia* cf. *spinosa* and is inferred to be of Whaingaroan-Duntroonian age.

Duntroonian Stage (Ld)

The Duntroonian stage is identified from the occurrence of diverse molluscan fauna. The large shallow-water bivalve *Athlopecten athleta* occurs in rocks of Duntroonian age. The Orahiri Formation contains closely packed banks of enormously thick-shelled *Flemingostrea wollastoni* (Nelson, 1973, 1978; Morgans et al. 2004). The base of the Duntroonian Stage is defined by the lowest occurrence of the benthic foraminifer *Notorotalia spinosa*, which replaces the Whaingaroan index *N. stachei*. Planktic foraminifera or calcareous nannofossil events are not known at the base of the Duntroonian (Morgans et al. 2004).

The lowermost stratigraphic level within the Te Kuiti Group having Duntroonian age occurs within the Kihi Sandstone Member of Aotea Formation. Sample S16/6521 collected and reported by Nelson (1978) from the top of the Kihi Sandstone exposed at Waitomo Valley Road (Section C-32) (Fig. 5) contains *Vaginulinopsis cristellata* and *Notorotalia spinosa*. Samples S16/6539-6542, all collected from Kihi Sandstone near Te Raumauku (S16/998346) (Fig. 5), contain *Rectuvigerina striatissima, Notorotalia spinosa,* and *Semivulvulina waitakia* (S16/6541) of Duntroonian age. Samples S16/f6011, 6014-6015 collected from the Kihi Sandstone in the vicinity of Te Raumauku contain Duntroonian fauna, and sample S16/6014 may possibly contain Duntroonian-Waitakian transition fauna (Fig. 5). Sample S15/f8506 collected from the Kihi Sandstone on Kawhia Road near the intersection with Okoko Road (S15/917439) is inferred to contain Duntroonian fauna (Fig. 5).

Samples R14/f0093-0094 reported by Waterhouse & White (1994) from 12 m and 20 m, respectively, above the base of the Patikirau Siltstone at Patikirau Bay (Fig. 5), contain *Notorotalia spinosa*. Sample S14/f7539, reported to have been collected from the uppermost part of the Ahirau Sandstone north of Te Akatea and along the Glen Massey-Waingaro Road (S14/909937), contains *Notorotalia* cf. *spinosa* and probably came from the Patikirau Siltstone (Fig. 5). Sample S14/f7525-7525A reported by Kear & Schofield (1978) from north of Te Akatea (S14/916951), apparently from the Carter Siltstone, yielded an upper Whaingaroan to Duntroonian fauna including *Haeuslerella textilariformis*, *Vaginulinopsis hochstetteri,* and *Notorotalia stachei*. These samples are likely to have been collected from the Patikirau Siltstone (Fig. 5).

The presence of *Athlopecten athleta* in sample R16/f9552 from near Pakeho (R16/888131) and the abundance of closely packed banks of thick shelled oysters (*Flemingostrea wollastoni*) from the Te Anga Limestone Member (Orahiri Formation), indicates a Duntroonian age (Nelson 1978). Sample S16/f6520 collected from Waitomo Sandstone exposed near Te Raumauku Caves (Section C-29) (Fig. 5) contains *Haeuslerella textilariformis*, *Semivulvulina capitata* and *Notorotalia spinosa,* indicating a Duntroonian to possibly Waitakian age (Nelson 1978). Macrofossils reported from Raglan Limestone exposed in an inland section north of Carters Beach (R14/707884) include *Cirsotrema lyratum, Lentipecten huttoni (hochstetteri), Chlamys williamsoni* and *Terebratulina suessi* (R14/f6011), indicating a Duntroonian to possibly Waitakian age (Kear 1978; Waterhouse & White 1994).

Waitakian Stage (Lw)

The lowest occurrence of the planktic foraminifera *Globoquadrina dehiscens* has become the most widely accepted criterion for defining the base of the Waitakian Stage (Hornibrook 1974). Another useful criterion is the disappearance of the large ribbed *Vaginulinopsis* at the top of the Duntroonian. The highest occurrence of the planktic foraminifera *Globigerina euapertura* is an important intra-Waitakian event used informally to subdivide the upper and lower Waitakian (Morgans et al. 2004). Berggren et al. (1995) dated this event at 23.8 Ma and it serves as a proxy for the Oligocene-Miocene boundary. In deeper water facies the highest occurrence of *Cibicides thiara* is an important intra-Waitakian event, especially in Taranaki Basin. Molluscan species last recorded from Waitakian rocks include *Athlopecten athleta, Lentipecten huttoni (hochstetteri), Flemingostrea wollastoni* and *Cirsotrema lyratum* (Morgans et al. 2004).

Not many microfauna are known from the Orahiri Formation - Otorohanga Limestone due to extraction difficulties from well lithified limestone. Samples S16/f8502, f8507, f8514 from Beros Limestone Quarry near Te Kuiti (Column 94-24) (Fig. 5) contain the common Waitakian fauna *Notorotalia spinosa, Cibicides novozelandicus, Rectuvigerina rerensis* and the planktic *Globoquadrina dehiscens* (Nelson 1978). *Athlopecten athleta,* a large pectinid, has been reported as widespread within Otorohanga Limestone and has been the basis to assign a Waitakian age to this unit (Nelson 1978). This large pectinid is however no longer regarded as restricted to the Waitakian and its lowest occurrence is now known to extend into the Duntroonian (Morgans et al. 2004).

Samples R14/f6590-91 reported by Kear (1963) from the top of the 8.5 m-thick Raglan Limestone of Te Akatea Formation exposed near Te Akau (Fig. 5.) contain Waitakian fauna such as *Notorotalia* cf. *spinosa* and *Globoquadrina dehiscens.* Another sample R14/f6559 from the Raglan Limestone exposed near Te Kotuku Trig. (Mangiti Road) contains *Gyroidinoides allani* and is inferred to be of Duntroonian-Waitakian age. Samples R14/f6586-6588 collected 5 m, 24 m and 32 m, respectively, above the Raglan Limestone near Te Kotuku Trig (Column TA-12) are all inferred to be of Waitakian age (Fig. 5). Samples R14/f6739-6743 reported by Waterhouse & White (1994) from the Carter Siltstone of Te Akatea Formation near Te Kotuku Trig contain *Cibicides thiara* and the planktics *Globoquadrina dehiscens* and *Globigerina brazieri* and are inferred to be of Waitakian age (Hornibrook 1974). Another set of samples R14/f6550-6551 collected 1.7 m and 17 m, respectively, above the Raglan Limestone at Te Kotuku Trig contains *Marginulinopsis allani*, *Anomalinoides fasciatus*, *Haeuslerella hectori* and *Globoquadrina subdehiscens* and is inferred to be of Waitakian age. Sample R13/f8558 reported by Kear (1963) from basal Carter Siltstone beds 5 m above the Waimai Limestone near Ohuka Creek in Kokonga East Road (R13/687017) yields Waitakian fauna.

Sample R14/f6568 reported by Kear (1978) from Te Hara Sandstone (a basal unit of the Waitemata Group) at the southern end of Te Hara Point (Fig. 5), contains Waitakian to Otaian (?) fauna (*Haeuslerella* aff. *hectori* and *Notorotalia spinosa*). Samples R14/f6570-6571 and 6573 (R14/747847) collected from the same unit exposed along Te Akau South Road are inferred to contain Waitakian fauna. Samples R14/f6527-6528 collected from Te Hara Sandstone exposed in a cliff along the coast 3.8 km south of Waimai Stream mouth have been inferred to be of Duntroonian-Waitakian age. Sample R14/f6519 reported from the Te Hara Sandstone exposed to the east of Carters Beach contains Otaian fauna (e.g. *Cibicides novozelandicus, Rectuvigerina rerensis*, *Spiroloculina novozealandica*). Large oysters, pectinids and brachiopods (*Crenostrea wuellerstorfi, Athlopecten athleta* and *Rhizothyris curta*) occur in the Te Akau Limestone exposed at Carters and Gibson Beach, indicating a Waitakian age (Kear 1978). Sample R14/f6812-6813 reported in Waterhouse & White (1994) from Gibson Siltstone (Waitemata Group) exposed in the cliff section immediately south of Te Hara Point (R14/711826) contains the key upper Waitakian to Otaian planktics *Globigerina woodi* and *Globigerina connecta*.

A few important microfaunal samples from the basal Waitemata Group lithologies exposed at Waikawau and Waiwiri Beach coastal sections south of Port Waikato were collected and reported in Hornibrook & Schofield (1963). Sample R13/f6551 collected 30 cm above Carter Siltstone in the base of the Waitemata Group at Waikawau Stream mouth (Fig. 5) yielded mixed fauna consisting of large specimens of *Elphidium ornatissimum* and *E. subrotatum*. Other species, inferred to have been reworked from the underlying Carter Siltstone, include *Sigmoidella kagaensis, Bulimina pupula,* and *Gyroidinoides allani*. Similar microfauna dominated by *Elphidium* were also recorded in samples R13/f6534 and f6554 from immediately above the bored zone exposed at Waiwiri Beach. Another sample R13/f6576 collected about 1.7 m above the base of the Waitemata Group also yielded *Elphidium subrotatum* and plentiful ostrocods. Samples R13/6579-6580 collected a few metres above the top of Carter Siltstone and at the top of the "Cardita Beds" (basal Waitemata Group, Hornibrook & Schofield 1963) at Waiwiri Beach are dominated by large specimens of *Elphidium* that also occur in a *Venericardia* bed. The planktics include *Globoquadrina dehiscens* and *Globigerina semivera*. The sudden entry and dominance of large species of *Elphidium* in the above samples collected from the basal facies of the Waitemata Group is evidence of an abrupt shallowing.

Taken together, the microfaunal assemblages from the basal Waitemata Group beds indicate an uppermost Waitakian age (Hornibrook & Schofield 1963). *Elphidium subrotatum* along with *Bulimina pupula* and *Gyroidinoides allani* also occur in samples R14/f6570-6571 and f7673 collected from the Te Hara Sandstone described earlier, and are the basis for its correlation with the basal Waitemata Group.

The common presence of the planktic foraminifera *Globoquadrina dehiscens* in samples from the base of the Mahoenui Group immediately above the Otorohanga Limestone indicates a Waitakian age (Nelson 1973). Sample R16/f8720 from Mahoenui Group mudstone immediately above Otorohanga Limestone at Mangaohae River contains *Globoquadrina dehiscens* and abundant *Globigerina woodi* and is inferred to be of Waitakian age. Sample R16/f8721 from Mahoenui Group mudstone in the vicinity of Waitanguru is also inferred to contain Waitakian fauna. Samples S16/f8561, f8563 and f8500 collected from calcareous mudstone exposed immediately above Otorohanga Limestone in the vicinity of Te Kuiti (Fig. 5) are inferred to contain Waitakian fauna. Samples S16/f8516-f8518 collected 0.15 m, 0.3 m and 2 m, respectively, above Otorohanga Limestone at Troopers Road (S16/926123) contain *Globoquadrina dehiscens* and are inferred to be of Waitakian age. Sample R17/f6678 reported from Mahoenui Group mudstone exposed 0.3 m above Otorohanga Limestone at Mangaotaki Road west of Piopio contains *Globoquadrina dehiscens* and abundant *Globigerina* sp. Sample R17/f8542 collected from Mahoenui Group mudstone exposed along SH3 2.8 km south of Mangaotaki Bridge (R17/753942) contains *Globigerina woodi* and *Globoquadrina dehiscens* of Waitakian age.

Discussion

Comment on assignment of biostratigraphic stages to Te Kuiti Group formations and members

It has been possible to confidently assign biostratigraphic stage boundaries to formations and members of the Te Kuiti Group. Within particular stages, the fossil samples for which data have been reported necessarily float within the stages, which will always be the case given the nature of biozones, but the uncertainty is exaggerated because the samples in many cases come from dispersed outcrop sites (and have been assembled into composite sections in Fig. 5). Given the synthesis presented here (Fig. 5) there is room for serial sampling at multiple sections through some members to better tie their tops and bottoms to stage boundaries. To this end, detailed stratigraphic columns and correlations are available for the Te Kuiti Group (Kamp et al. 2008). An issue that has confounded this objective to date has been the paucity of planktic foraminifera in the predominantly shelf sediments and the cemented nature of limestone members, especially in the upper parts of the group.

There is good certainty around the Kaiatan and Runangan Stage designations for the northern occurrences of the Waikato Coal Measures. The Mangakotuku Formation may be as old as the upper part of the Runangan Stage in the Glen Massey-Rotowaro area, although this formation is mainly lower Whaingaroan in age.

The Glen Massey Formation is exclusively lower Whaingaroan in age and the lower to upper Whaingaroan Stage boundary lies at or near the boundary between the Glen Massey Formation – Whaingaroa Formation boundary, which is unconformable in the south and conformable in the north.

The Whaingaroa Formation is upper Whaingaroan in age, as well as most of the Aotea Formation, although this formation does extend into the Duntroonian Stage. The greatest uncertainty in the stage designations for the Te Kuiti Group lies in the location of the upper Whaingaroan – Duntroonian boundary within the Aotea Formation. In the southern part of central-western North Island there has been marked erosion of the top of the Aotea Formation and we regard the Hauturu Sandstone Member as being wholly of upper Whaingaroan age. In the northern part of central-western North Island the top of the Aotea Formation is highly condensed (glauconitic and phosphate nodules occur in firm carbonate mudstone) and the stage boundary probably lies within this condensed interval. In central parts of the Te Kuiti Group outcrop area, the upper Whaingaroan – Duntroonian boundary probably lies within the Patikirau Siltstone, possibly its lower part, or within the upper part of the Kihi Sandstone Member (Fig. 5).

The Duntroonian – Waitakian boundary in the southern part of the Te Kuiti Group outcrop area is assigned to the boundary between the Orahiri Formation and Otorohanga Limestone. Outside of the Waitomo area, and in particular to the south (Mangaotaki and Awakino) and east (Piopio - Aria), there is considerable difficulty in distinguishing these two formations and along with that any certainty about the location of the Duntroonian – Waitakian boundary. Historically, the distinction between the Orahiri Formation and Otorohanga Limestone has been mapped on the basis of the occurrence of large oysters, but regional correlations do not hold up on this basis (Tripathi et al. 2008) and it has to be acknowledged that oyster occurrence is a facies/environmental characteristic and unlikely to be a robust basis for correlation.

Our synthesis based on existing sample data affirms previous work that the base of the Waitemata Group lies within the upper part of the Waitakian Stage. The top of the Te Kuiti Group also lies within the Waitakian Stage. North of Raglan Harbour the top of the Carter Siltstone Member is wave-planed and hence an erosional unconformity separates the Te Kuiti Group from the Waitemata Group. We are firmly of the view that previous mapping of Orahiri Formation and Otorohanga Limestone north of Raglan Harbour (Kear 1966; Waterhouse and White 1994) is not correct and limestone and sandstone units above the Carter Siltstone Member are diversified basal members of the Waitemata Group.

To help confirm or further constrain the assignment of biostratigraphic stages to the Te Kuiti Group formations and members, we have applied strontium isotope geochronology to macrofossils in the hope of reducing the uncertainties outlined above and to help develop an absolute chronology for the group. We detail the results of this undertaking below.

Comment on the age of the Whaingaroan Stage at Waitetuna Estuary, Raglan/Whaingaroa Harbour, versus the age of Whaingaroa Formation south of Raglan

Siltstone members of the Te Kuiti Group between Raglan Harbour and Waitomo – Kawhia areas have been miscorrelated in the past. The 30 - 40 m of massive calcareous siltstone exposed in Waitetuna Estuary, Raglan Harbour ("Whaingaroa Siltstone" in the original work by Kear & Schofield (1959)), was nominated by Findlay (1939) as the stratotype for the Whaingaroan

Stage. Subsequently, Hornibrook et al. (1989) identified the planktic fauna from this unit as being characteristic of Jenkins (1966) *Globigerina euapertura* Zone, assigned to the upper Whaingaroan. However, the planktic fauna identified from "Whaingaroa Siltstone" south of Raglan in the Aotea – Kawhia areas are characteristic of Jenkins (1966) *Globigerina brevis* and *Subbotina angiporoides* Zones assigned to the lower Whaingaroan (Hornibrook et al. 1989). The two siltstone units cannot therefore be correlatives and this is recognised in the rationalised lithostratigraphy of Tripathi et al. (2008): the siltstone exposed at Waitetuna Estuary is now mapped as Kotuku Siltstone of the Whaingaroa Formation, whereas the siltstone in the Aotea – Kawhia region is now mapped as Dunphail Siltstone Member of Glen Massey Formation (Tripathi et al. 2008).

Strontium isotope dating results

Strontium isotope ratios are an increasingly common means of determining the numerical age of fossiliferous marine successions of Cenozoic age (McArthur 1994; Veizer et al. 1999). The approach is based on the following assumptions:

1. At any point in time, the $^{87}Sr/^{86}Sr$ ratio of seawater is homogenous throughout the world's oceans because the residence time of Sr (2 - 4 m.y.) in sea water is longer than the mixing time of the oceans (about 1000 years).

2. The influx of Sr to the oceans from various sources, each with its own characteristic $^{87}Sr/^{86}Sr$ ratio, varies over geological time. The $^{87}Sr/^{86}Sr$ ratio of incoming strontium is counterbalanced by its removal from seawater mainly via co-precipitation in biogenic carbonate.

3. The $^{87}Sr/^{86}Sr$ ratio in fossil skeletons is identical to that of the seawater in which the fossil organisms lived; that is, there is no biological fractionation between the ocean water and contemporary skeletal material.

The rate of change of the $^{87}Sr/^{86}Sr$ ratio in marine biogenic carbonate forming from ocean waters was especially high during the Oligocene to Early Miocene (36-16 Ma), enabling determination of numerical ages to within 0.5 m.y. resolution during this interval (Fig. 6). Although planktic foraminifera are preferred for the calibration of ocean water curves, there is no convincing evidence that marine macrofossils have significantly different $^{87}Sr/^{86}Sr$ values from contemporary planktic taxa, provided the fossils are well preserved and diagenetic effects are minimal (Oslick et al. 1994).

Strontium ($^{87}Sr/^{86}Sr$) isotope-derived numerical ages for the Te Kuiti Group

The strontium isotope method has previously been applied to molluscan and brachiopod shell samples from the Te Kuiti Group and from the Alma/Otekaike Group in South Island (Nelson et al. 2004). The $^{87}Sr/^{86}Sr$ ratio data reported for 77 macrofossil samples by Nelson et al. (2004) have helped to constrain the age of several mid-Cenozoic stage boundaries. Of the 77 samples, 43 samples derived from the Te Kuiti Group and

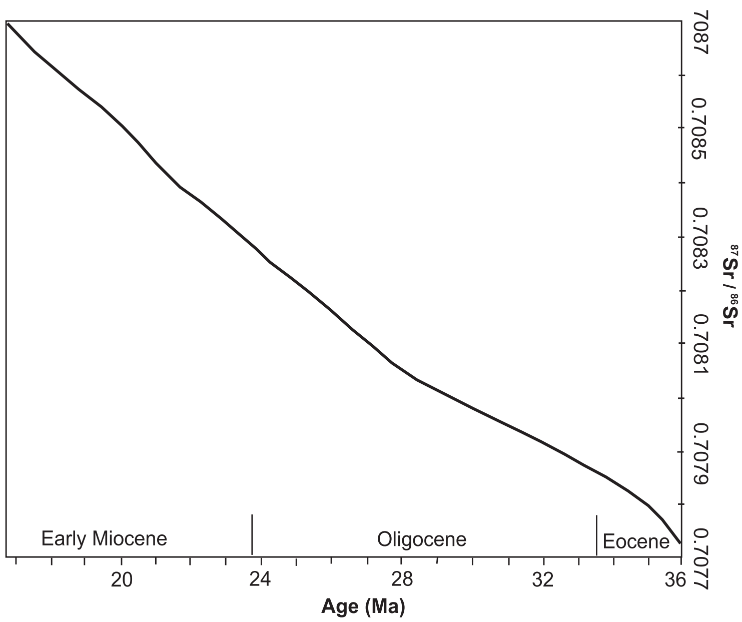


Fig. 6: Calibration curve relating $^{87}Sr/^{86}Sr$ isotope ratio in marine fossil shells to numerical age for the Late Eocene to Early Miocene (after Oslick et al. 1994).

are incorporated here with seven new samples sourced from the group in the Aotea Harbour area previously reported by Carter (2003), and with 26 new samples collected during this investigation (Appendix I).

Methods

Twenty six samples of unweathered shell material, mainly from pectinids, brachiopods and oysters, were collected from multiple localities within the study area. In all cases the lithostratigraphic units bearing the fossil samples were ascertained by careful field correlation and have assigned to them a New Zealand biostratigraphic stage based on microfossil content at correlative sites. Close microscope examination of the shell material was undertaken to check for any visible signs of weathering or diagenetic alteration. After extensive and careful cleaning to remove surficial impurities or rock matrix, the shell material was extracted by a scraper.

All Sr measurements were undertaken on small aliquots containing 2000-10000 ng Sr, using an automated Finnegan MAT262 mass spectrometer at the University of Melbourne. Data were normalised to $^{88}Sr/^{86}Sr$ = 8.375209 using exponential law. Normalised data were adjusted to the SRM standard, which has the value: SRM987 = 0.710230. Four runs of a laboratory standard (EN-1, a recent coral from the Pacific) established the composition of modern seawater ranged from 0.709154-0.709184, averaging 0.709168 $\pm$ 26 (2 SD). Age assignments were made for each sample analysis after adjusting $^{87}Sr/^{86}Sr$ ratios by +0.000029 to be consistent with the SRM987 value of 0.710248 (Hmc = 0.709175) used in the Howarth & McArthur (1997) calibration. The $^{87}Sr/^{86}Sr$ ages were derived using the detailed look-up tables available from Howarth & McArthur (1997).

Analytical results

The $^{87}Sr/^{86}Sr$ results are presented in Appendix I. The absolute ages derived from the $^{87}Sr/^{86}Sr$ isotope ratios are plotted in Fig. 7 in relation to the New Zealand time scale (Cooper et al. 2004). The sample data show a broad trend of decreasing age from the Bortonian to Otaian Stages. The few discrepant ages (e.g. AU2045 53.36 Ma; sample 39) falling outside the general trend could result from either undetected shell alteration or the sample host having grown in marginal marine conditions (Nelson et al. 2004). Figure 8 shows the ages plotted for each of the Te Kuiti Group formations.

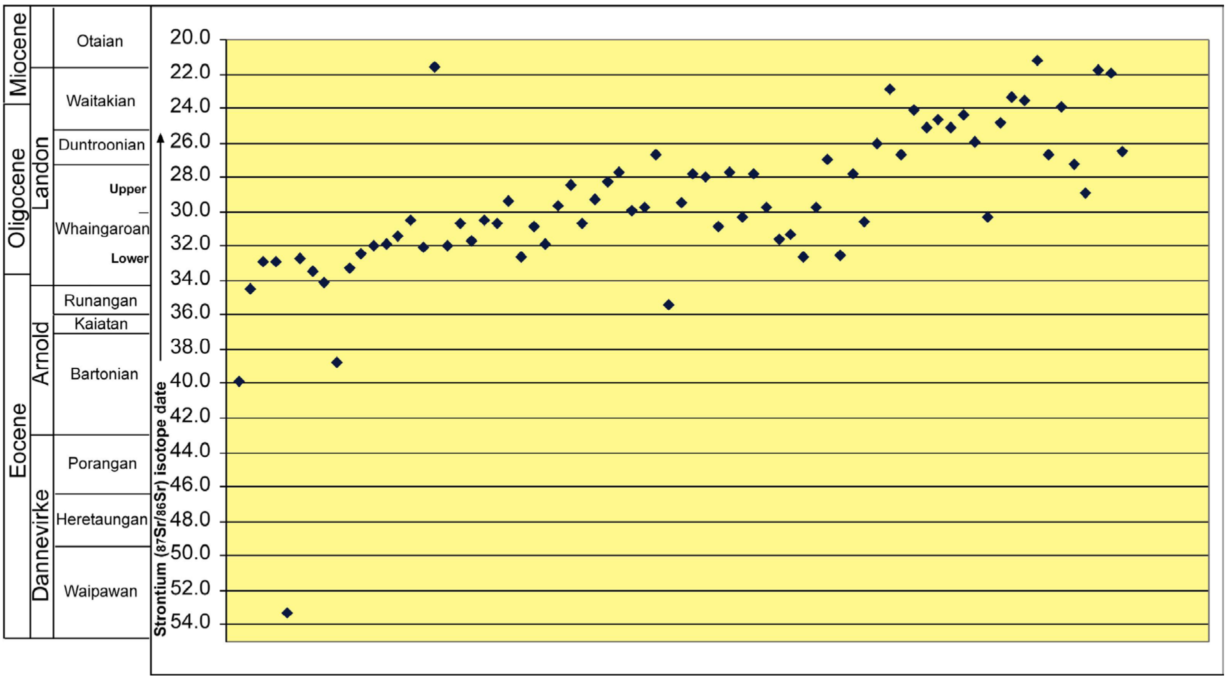


Fig. 7: Plot of $^{87}Sr/^{86}Sr$ isotope age versus stratigraphic position of macrofossil samples from within the Te Kuiti Group and basal units of the Waitemata Group.

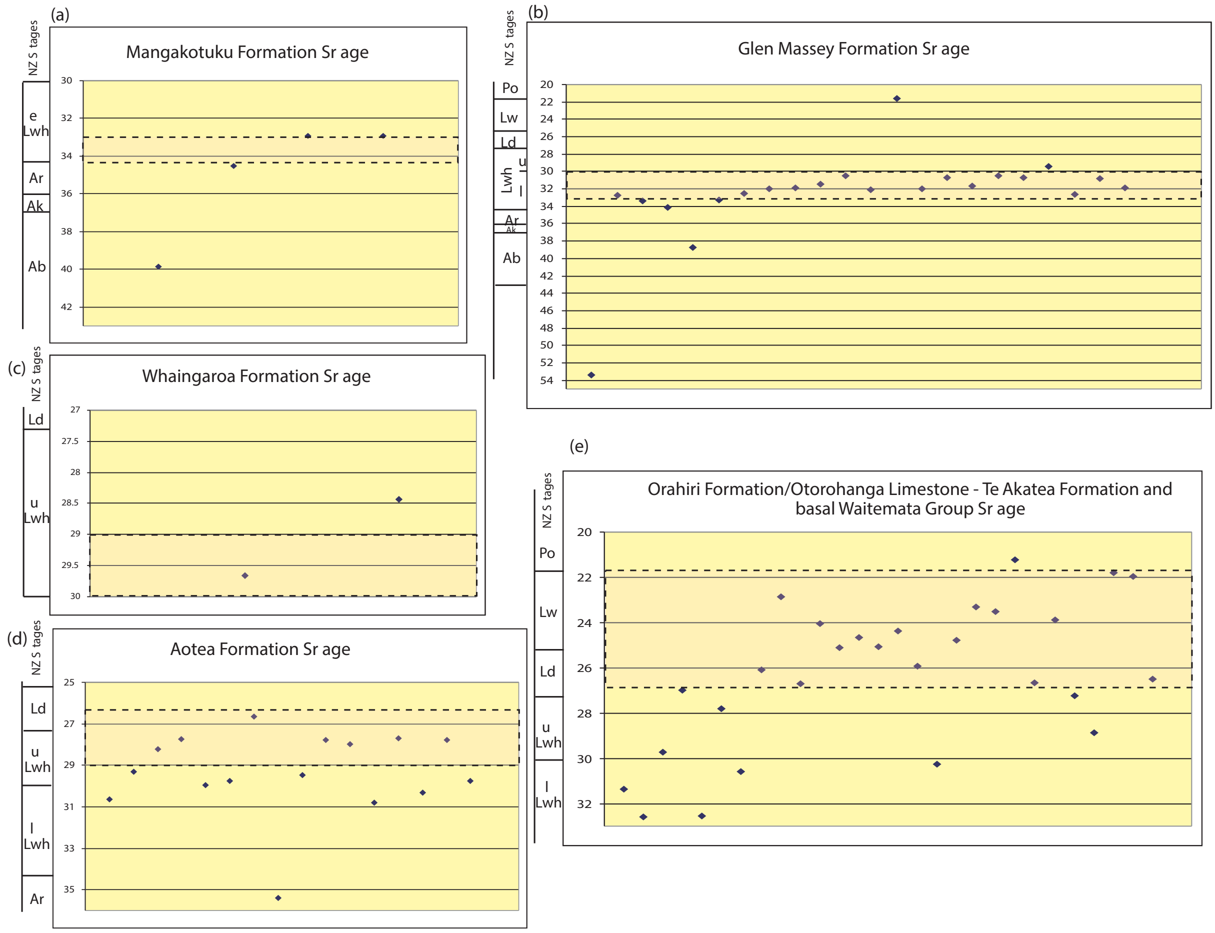


Fig. 8: Strontium ($^{87}Sr/^{86}Sr$) isotope ages of macrofossil samples from various individual Te Kuiti Group and Waitemata Group formations plotted against the New Zealand biostratigraphic stages assigned to them (between dashed lines). See text for discussion.

Stable oxygen and carbon isotope analysis

To test whether or not the host shell material analysed for $^{87}Sr/^{86}Sr$ had been affected by significant diagenetic alteration, including weathering, the oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotope compositions of subsamples of the fossil shell material were also determined using standard methods for stable oxygen and carbon isotope analysis (Cooke et al. 2008). The samples were reacted in the Europa CAPS system in the Department of Earth and Ocean Sciences (The University of Waikato) using the individual acid dosing method. After the reactions were completed, the sample CO_2 was introduced to the Europa Geo 20-20 mass spectrometer. The isotope ratios are expressed relative to Vienna PeeDee Belemnite (VPDB), and have an external precision better than 0.05 ‰ for both carbon and oxygen.

Stable oxygen and carbon isotope results

All $\delta^{18}O$ and $\delta^{13}C$ values of the shell samples are presented in Appendix I. The $\delta^{13}C$ values range between -10.36 and 2.91, and $\delta^{18}O$ values range between -2.52 and 1.09. A cross-plot of the stable oxygen versus carbon isotope data is presented in Fig. 9. According to criteria established by Nelson & Smith (1996), the values plotting to the left (AU2014, WU023) of the dashed line may have been diagenetically altered. The more negative $\delta^{13}C$ of a few samples (AU2438, AU12890, WU01 and WU021) suggests growth in a marginal marine environment.

Sr dating results for formations

Mangakotuku Formation

The numerical ages of four shell samples from the Mangakotuku Formation range between 39.85 - 32.91 Ma (Fig. 8a). Three of these ages conform

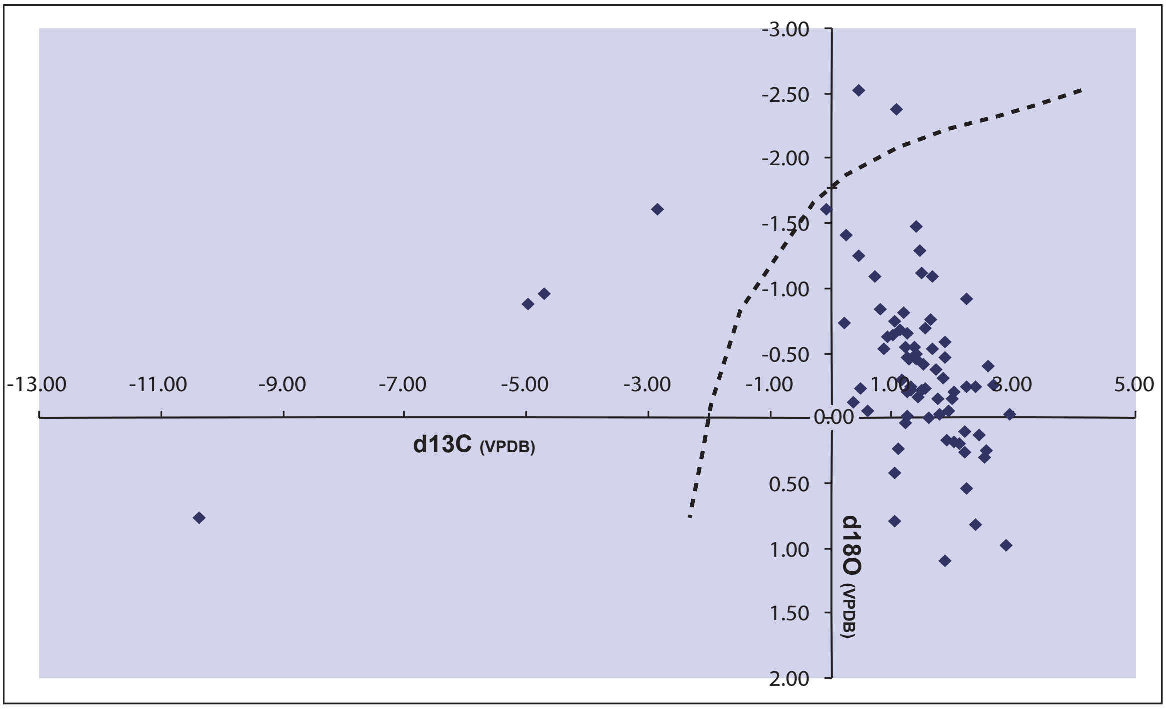


Fig. 9: Cross-plot of stable oxygen isotope versus carbon isotope values (‰) for macrofossil samples from the Te Kuiti Group and basal units of the Waitemata Group for which Sr isotope ratios were also determined. Dashed line separates the parts of the isotope field regarded as not having undergone post-depositional alteration (majority of data points) versus likely post-depositional re-equilibration of the isotope systems, probably during diagenesis.

to the upper Runangan to lower Whaingaroan age of this formation. However the oldest data point (39.85 Ma) is from an oyster shell (AU12890) collected from the Kopuku Coalmine at Maramarua and it is much older than the expected stratigraphic age. Based on its $\delta^{13}C$ value (-4.96%) (Appendix I) this sample could have a marginal marine origin and therefore not have a Sr ratio that reflected a well mixed contemporary seawater Sr composition. On the other hand, sample WU01 collected from Waikaretu Sandstone Member near Waikoha Road, yielded a -10.36 $\delta^{13}C$ value and may also be of marginal marine origin, but surprisingly, shows a predictable stratigraphic age of 32.91 Ma.

Glen Massey Formation

The numerical ages for 22 samples from the Glen Massey Formation fall within the range 53.36 - 21.59 Ma. Eighteen of these ages conform to the expected stratigraphic age (lower Whaingaroan) (Fig. 8b). One brachiopod shell (AU2045) collected from south of Kawhia yielded an age of 53.36 Ma and another brachiopod shell (AU9529) collected from the north end of Huriwai Beach south of Port Waikato yielded an age of 38.77 Ma, both ages being much older than expected. These samples both came from basal facies of Glen Massey Formation where it rests on Mesozoic basement, and both samples may have therefore incorporated “old strontium” into their shells (Nelson et al. 2004). Sample WU04, with an age of 21.59 Ma is well outside the biostratigraphic age of the formation, whereas sample AU4173, with an age of 34.13 Ma, and sample AHR04, with an age of 29.42 Ma, are just outside the expected age range.

Whaingaroa Formation

The numerical ages for two samples from the Whaingaroa Formation are in the range 29.66 - 28.44 Ma (Fig. 8c). Sample WU010, with an age of 28.43 Ma, is younger than the upper Whaingaroan age assigned to the Whaingaroa Formation.

Aotea Formation

The numerical ages for 16 samples from the Aotea Formation lie in the range 35.4 - 26.67 Ma (Fig. 8d). Eight sample ages conform to the expected stratigraphic age range of the formation (upper Whaingaroan to Duntroonian) given the biostratigraphic assignments made above. Seven samples (AU1330, AU1087, AU1536, WU011, WU013, WU018 & WU019) are marginally older than the upper Whaingaroan age (~30 Ma) inferred for the formation. One sample (M8) from the upper part of Kihi Sandstone Member in the Mangaotaki Bridge section is markedly older (35.4 Ma) than expected.

Orahiri Formation, Otorohanga Limestone and Te Akatea Formation

The numerical ages for 28 samples from the Orahiri Formation, Otorohanga Limestone and Te Akatea Formation fall in the range 32.37 - 21.24 Ma (Fig. 8e). Of the 28 sample ages, nine lie outside the age range of biostratigraphic stages assigned to these formations (i.e. Duntroonian to upper Waitakian). Eight of them show lower to upper Whaingaroan ages, which seem unreasonably old. One age, the youngest at 21.24 Ma, relates to fossil shell (WU017) from the "Coquinite Beds" in the Orahiri Formation at Bexley Station tunnel (Nelson 1978) and this age is clearly too young, possibly affected by the porous nature of the host facies.

Te Hara Sandstone

An oyster sample (WU021) collected from the lower part of Te Hara Sandstone has stable carbon and oxygen values of -2.84 $\delta^{13}C$ and -1.61 $\delta^{18}O$, suggesting it may have been affected by diagenetic alteration, and its numerical age (23.88 Ma) is 2 m.y. older than expected.

Discussion of Sr dating results

The intention of undertaking Sr geochronology of macrofossil material from the Te Kuiti Group was to help develop an improved chronology for the group. Having outlined and interpreted the Sr results, the key question is to what extent they have actually improved the chronology for the Group beyond that determined by biostratigraphic means?

We have shown all of the Sr data obtained in this study in Appendix I and in Figs. 7 and 8. While most of these data, analytically, are of high quality, the difficulty we have faced is that a proportion of them lie outside the reasonably expected age range of the biostratigraphic stages for the respective sample host formations and members, and neither do the data on their own make sense at face value because of clear overlaps in age range between adjacent formations. A few of the samples, as described above, are clearly outliers and can be eliminated as useful data. About a third of the data points lie just outside the expected biostratigraphic age ranges, especially for the Aotea Formation and Orahiri Formation, Otorohanga Limestone and Te Akatea Formation, although they seem to be analytically good data. Given this situation (Fig. 9), it is difficult to give full credibility to the Sr age results that do lie within the expected age range for each formation. The main pattern is that the measured Sr ages are too old for the biostratigraphic stage(s) of each formation and there is no basis to independently determine the lower age boundary of acceptable ages. Consequently the Sr age data set reported here can only be regarded as broadly confirming the biostratigraphic results derived from the faunal and floral content within the formations.

Chronostratigraphy for the Te Kuiti Group

The intention for our review and synthesis of biostratigraphic data for the Te Kuiti Group and the determination of Sr ages for macrofossils from its various formations and members has been to establish a robust chronostratigraphy for the group. A stratigraphic feature that integrates well with the biostratigraphy and carries useful time value is the occurrence of unconformities between formations in the group. In Fig. 5, the formations and members have been rescaled from a thickness to a time-stratigraphic scale for a series of composite stratigraphic columns based on the available biostratigraphic data. In Fig. 2 this approach has been extended to the development of a north – south time-stratigraphic panel for the group using the occurrence of unconformities and estimating the amount of time missing on them between subjacent formations where this is substantial. What falls out of this exercise is the occurrence of six unconformity-bound formations that have many of the characteristics of unconformity-bound sequences. We have named these sequences TK 1 to TK 6 (Fig. 2).

Waikato Coal Measures and Mangakotuku Formation: TK1

The Waikato Coal Measures is a fluvial succession that started to onlap basement in the northern part of the field area during the Kaiatan and became more extensive during the Runangan (Fig. 2). This deposition was driven by the start of regional subsidence of the underlying lithosphere and led to gradual marine incursion into the Waikato Basin. The marine facies overstepped the non-marine deposits onto basement as shown for example by the distribution of the Waikaretu Sandstone Member (Tripathi et al. 2008) (Fig. 5).

Glen Massey Formation: TK2

The Glen Massey Formation accumulated during the *Globigerina angiporoides* Zone and hence it lies within the lower Whaingaroan Stage (Fig. 5). The base of this formation throughout much of its extent is an unconformity. This is marked by a wave-planed surface of erosion (transgressive surface of erosion, TSE) across Waikato Coal Measures (in the south) or basement. In northern parts of the basin the contact is conformable over Waikato Coal Measures (Fig. 2). The formation shows many of the classic features of a sequence, with transgressive (TST), highstand (HST) and falling stage (FSST) systems tracts.

Whaingaroa Formation: TK3

The Whaingaroa Formation in our lithostratigraphic framework (Tripathi et al. 2008) comprises basal TST limestone facies in places (Awaroa Limestone Member), HST deposits (Kotuku Siltstone Member) and FSST deposits (Waikorea Sandstone Member) and hence conforms to a typical mixed carbonate – siliciclastic sequence. Its lower boundary is unconformable and wave-planed in the southern part of the field area, but conformable in the north. This sequence accumulated during the upper Whaingaroan, the boundary with the lower Whaingaroan lying in the contact with the Glen Massey Formation. The Whaingaroa Formation is extensively eroded and in some areas is completely missing such that Aotea Formation rests upon Glen Massey Formation (Fig. 2).

Aotea Formation: TK4

The base of the Aotea Formation is marked by a significant erosional unconformity, which probably formed initially through subaerial erosion but was subsequently modified by wave planation that gave rise to the sharp planar surface observed in most areas (Tripathi et al. 2008). Aotea Formation spans the upper Whaingaroan - Duntroonian boundary (Fig. 5). The lower part of the formation lies within the upper part of the Whaingaroan Stage but this is difficult to demonstrate, as planktic foraminfera are difficult to recover from the inner shelf facies of the Hauturu Sandstone Member and the Waimai Limestone Member. The upper Whaingaroan is identified by the occurrence of *Rectuvigerina striatissima* and occurs in the Mangiti Sandstone Member near its type locality north of Raglan Harbour. Kihi Sandstone in the Waitomo-Honikiwi area records the first appearance of *Notorotalia spinosa* and *Semivulvulina waitakia*, which are good indicators of Duntroonian age. Good Duntroonian fauna also occur in the Patikirau Siltstone Member in Raglan Harbour sections, and possible Duntroonian faunas have been reported from the condensed facies of Patikirau Siltstone overlying Waimai Limestone and Mangiti Sandstone in the northern region.

Aotea Formation shows many of the characteristics of a mixed carbonate-siliciclastic sequence (Fig. 2). As noted above, it has an unconformable lower sequence boundary, which is overlain by transgressive (TST) facies (Hauturu Sandstone; Wamai Limestone), which pass upward into HST deposits (Mangiti Sandstone; Kihi Sandstone; Patikirau Sandstone). In central and northern parts of the field area the upper part of the HST deposits are very condensed and marked by a pronounced greensand horizon (e.g. Kihi Sandstone in Waitomo Valley) and phosphate nodules within glauconitic calcareous mudstone (Patikirau Siltstone near Port Waikato).

Orahiri Formation and Te Akatea Formation: TK5

Orahiri Formation is regarded as having accumulated within the upper part of the Dntroonian Stage (Figs 2 & 5). This is based upon macrofossil content as planktic foraminifera are difficult to extract from the limestone facies. There is an abundance of *Flemingostrea wollastoni* in the Te Anga Limestone Member in the Waitomo-Te Anga area, taken as an indicator of Duntroonian age. Duntroonian molluscan fauna such as *Cirsotrema lyratum* and *Lentipecten huttoni (hochstetteri)* are also reported from the Raglan Limestone Member in exposures north of Raglan Harbour.

The base of Orahiri Formation is a sharp planar unconformity in southern parts of the field area (e.g. Mangaotaki, Awakino Tunnel) formed through subaerial and subsequent wave erosion of the Hauturu Sandstone and Kihi Sandstone members (Tripathi et al. 2008). This erosion affected mid-shelf deposits (Kihi Sandstone Member) indicating substantial sea level lowering preceding accumulation of lower parts of the Orahiri Formation. In northern parts of the field area, particularly where the upper part of the underlying Aotea Formation has condensed facies, the lower boundary of Te Akatea Formation (Carter Siltstone Member) is conformable. Orahiri Formation is dominated by carbonate sediments and within them the expression of systems tracts is rather subtle. The Mangaotaki Limestone Member is too thick to be regarded as a TST, but its yellow sandstone content, probably sourced from erosion of the Hauturu Sandstone, indicates contemporary wave erosion in the south concurrent with (re)deposition on the adjacent shelf. These sandy carbonate shelf deposits pass upward in the sequence into more pure and macrofossiliferous limestone facies (Te Anga Limestone Member). The mixed micritic-skeletal limestone facies within Raglan Limestone Member indicates the development of a ramp sourcing carbonate skeletons and mud into deeper (upper bathyal) water to the north where lower parts of the Carter Siltstone Member accumulated as marl comprised of micrite derived from the breakdown of skeletons on the carbonate shelf to the south, admixed with planktic foraminifera (Fig. 2).

Otorohanga Limestone and Te Akatea Formation: TK6

Otorohanga Limestone is regarded as having accumulated during the Waitakian Stage as Waitakian microfauna have been reported from the siliciclastic interflags within limestone at Beros Quarry near Te Kuiti, including *Notorotalia spinosa, Cibicides novozelandicus, Rectuvigerina rerensis* and the planktic species *Globoquadrina dehiscens* (Fig. 5). The lower boundary of Otorohanga Limestone is locally unconformable south of Kawhia and along the eastern margin of the Herangi Range (Nelson 1973, 1978). This boundary passes northward into a correlative conformity in Carter Siltstone Member (Fig. 2). In the carbonate shelf facies characterising Otorohanga Limestone it is difficult to distinguish TST from HST divisions. An important observation is that in outcrops in the Kawhia area the upper part of the formation becomes micritic, suggestive of deepening of the depositional paleoenvironment. This implies a retrogradation stratal pattern signaling and heralding the subsequent marked deepening (shelf to bathyal) across the conformable boundary from Otorohanga Limestone into Taumatamaire Formation (Mahoenui Group) (Fig. 2). North of Raglan Harbour Waitemata Group overlies Carter Siltstone Member, and this contact is marked by a sharp planar erosion surface caused by wave planation. Hence accumulation of Te Kuiti Group in the north was brought to an end by uplift of upper bathyal facies into shoreface environments, which contrasts with the marked subsidence in the south where Mahoenui Group overlies Otorohanga Limestone (Fig. 2), both features indicating more pronounced and rapid impact of plate boundary tectonics on the sedimentation patterns.

Discussion

Figure 10 illustrates a new and robust chronostratigraphy for the Te Kuiti Group. The identification of unconformity-bound sequences within the group throughout its central-western North Island extent follows from the rationalised lithostratigraphic framework for the group, which reasonably correlates the various formations and members throughout the basin (Tripathi et al. 2008). It is noted that the sequence boundaries coincide with formation contacts, reflecting marked changes in lithofacies resulting from changes in base level and hence paleogeography. These basin-wide sequence boundaries provide

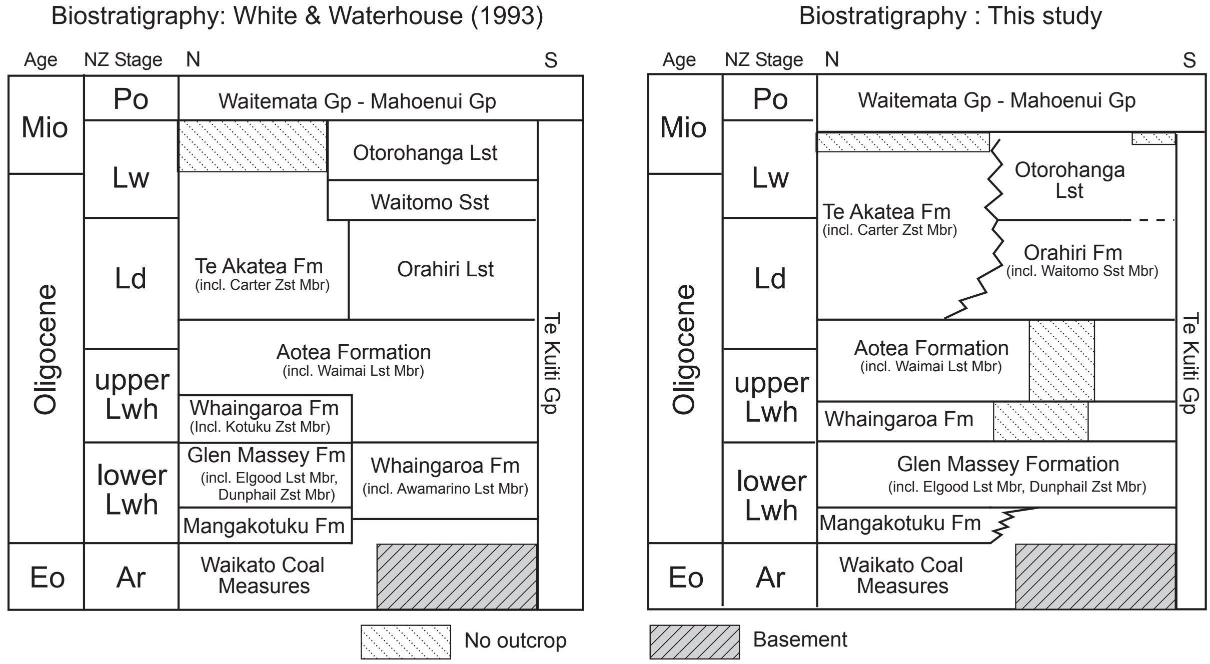


Fig. 10: Two biostratigraphic models for the Te Kuiti Group, one by White & Waterhouse (1993) and the other proposed here.

time-planes useful for partitioning the group into six time intervals, TK1 to TK6 (Fig. 2). We note that the foraminiferal and macrofossil biozones and the associated biostratigraphic stages independently align with these sequences in some cases and parallel them in others, thus calibrating the TK sequences to the mid-Cenozoic timeframe. The resulting chronostratigraphy (Fig. 2) provides a sound basis to interpret the paleogeographic development of the basin for time horizons within and between sequences (Kamp et al. 2014).

Summary

This report reviews and synthesises the biostratigraphy of the Te Kuiti Group based on existing sample data archived in the Fossil Record Electronic Database (FRED) and presents the results of new Sr ages for macrofossil samples. A rationalised lithostratigraphy for the group provides the framework to relate faunal and flora data for samples from a great diversity of locations of mainly outcrop occurrences of the Te Kuiti Group. It has proved useful to plot the faunal and floral samples onto composite stratigraphic columns for different areas, which has required some judgment to be made about the relative order of samples within formations and members. This exercise has enabled the distribution of time within the various stratigraphic units to be plotted, which essentially involves assignment of the Late Eocene to earliest Miocene New Zealand biostratigraphic stages to the formations and members.

Analytical Sr data and resulting numerical ages are reported here for 26 new macrofossil samples from the Te Kuiti Group. While the Sr ages are in broad agreement with the ages inferred for the Te Kuiti Group formations from the boundaries of the biostratigraphic stages, a proportion of the Sr ages lie outside the expected age range of the formations implied by the biostratigraphy. There is also significant overlap in the Sr ages for sub-jacent formations. Hence not a lot of confidence can be taken from the Sr ages and they mainly do not improve the accuracy of the biostratigraphy and the age information that can be derived from it.

The identification of unconformity-bound sequences, the boundaries of which align with the formation contacts within the group, provide an important set of time planes from which intervals can be derived and compared soundly with the boundaries of the assigned biostratigraphic stages. The integration of the biostratigraphy and sequence stratigraphy produces a robust chrono-stratigraphy for the Te Kuiti Group. The utility of this chronostratigraphy lies in the confidence with which the Late Eocene – earliest Miocene paleogeographic development of the Waikato – King Country Basin can be inferred for multiple intervals during accumulation of the Te Kuiti Group (Kamp et al. 2014).

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Appendix I : $\delta^{18}O$ and $\delta^{13}C$ isotope data and $^{87}Sr/^{86}Sr$ isotope ratio derived ages for macrofossil samples from the Te Kuiti Group and basal units of the Waitemata Group.

* No.	Sample	Locality	Formation	NZ Stage	Shell type	Strat. order	$\delta^{13}C$	$\delta^{18}O$	$^{87/86}Sr$ lab	$^{87/86}Sr$ adj lab+16	Age (Ma) H & McA (1997)	Average (Ma) H & McA (1997)
Total Samples : 76												
35	AU2438	Pt Waikato	Mangakotuku Zst	Lwh	Oyster	Bottom	-4.707	-0.960	0.707597	0.707613		
36	AU12890	S12/Q08 (0)	Mangakotuku Zst	Lwh	Oyster		-4.961	-0.876	0.707706	0.707722	39.85	
37	AU6472	R13 (3)	Mangakotuku Zst	Lwh	*Eumarcia*		0.234	-0.733	0.707578	0.707594		
38	AU7842b	S15 (19)	Mangakotuku Zst	Lwh	*Eumarcia*		1.244	-0.656	0.707772	0.707788	34.52	
39	AU2045	N73/803	Whaingaroa Zst	Lwh	Brachiopod		1.545	-0.224	0.707693	0.707709	53.36	
40	AU2000	N82/689	Whaingaroa Zst	Lwh	Pectinid		1.210	-0.549	0.707851	0.707867	32.72	
41	AU1090	N91/745	Whaingaroa Zst	Lwh	Pectinid		1.994	-0.148	0.707814	0.707830	33.43	
42	AU1092	N91/747	Whaingaroa Zst	Lwh	Bivalve		2.111	0.190	0.707660	0.707676		
43	AU4173	R13 (10)	Sub Elgood Lst	Lwh	Pectinid		1.240	-0.469	0.707784	0.707800	34.13	
44	AU9529	R13 (7)	Elgood Lst	Lwh	Pectinid		0.799	-0.832	0.707719	0.707735	38.77	
45	AU2468	R13 (13)	Elgood Lst	Lwh	Pectinid		1.456	-1.286	0.707824	0.707840	33.23	
46	AU8998	N51/675	Dunphail Zst	Lwh	Pectinid		1.877	-0.465	0.707865	0.707881	32.48	
47	AU2460	S14 (17)	Dunphail Zst	Lwh	Pectinid		1.226	0.035	0.707890	0.707906	31.96	
48	AU1331	R13 (7)	Glen Massey Sst	Lwh	Brachiopod		2.237	0.538	0.707893	0.707909	31.89	
49	AU8003	S15 (19b)	Glen Massey	Lwh	Pectinid		0.881	-0.527	0.707912	0.707928	31.46	
50	AU1330	R13 (6)	Waimai Lst	Lwh	Pectinid		2.385	0.822	0.707943	0.707959	30.65	
51	AU3037	N64/558	Aotea Sst	Lwh	Pectinid		1.285	-0.447	0.707949	0.707965	30.49	
52	AU1974(a)	N73/936	Aotea Sst	Lwh-(?)	Pectinid		2.931	-0.025	0.707885	0.707901	32.07	
53	AU1978	N74/609	Aotea Sst (Ao-2)	Lwh	Pectinid		1.712	-0.374	0.707995	0.708011	29.32	
54	AU1979	N74/610	Aotea Sst	Lwh+	Pectinid		1.621	-0.005	0.708038	0.708054	28.22	
55	AU1991	N74/613	Aotea Sst	Lwh	Pectinid		1.129	-0.680	0.708058	0.708074	27.72	
56	AU1087	N91/741	Aotea Sst	Ld	Brachiopod		2.007	-0.202	0.707969	0.707985	29.96	
57	AU1536	R13 (4)	Aotea Sst	Ld	Pectinid		0.710	-1.088	0.707978	0.707994	29.74	
58	AU2441	R15 (6)	TeAk-Waimai bdy	Ld	Brachiopod		1.769	-0.031	0.708094	0.708110	26.67	
59	M8	Mangaotaki	Aotea Sst	Lwh-Ld	Pectinid		1.634	-0.764	0.707755	0.707771	35.4	
60	M7	Mangaotaki	Orahiri Lst	Ld	Pectinid		1.184	-0.809	0.707916	0.707932	31.37	
61	M5	Mangaotaki	Orahiri Lst	Ld	Pectinid		1.413	-1.478	0.707858	0.707874	32.61	

62	M1	Mangaotaki	Orahiri Lst	Ld	Pectinid		1.501	-1.114	0.707979	0.707995	29.71	
63	AU2053	N74/566	Orahiri Lst	Ld-w	Oyster		1.099	0.239	0.708083	0.708099	26.99	
64	AU2007	N82/708	Orahiri Lst	Ld	Oyster		1.882	1.099	0.707862	0.707878	32.54	
65	AU2008	N82/709	Orahiri Lst	Ld	Oyster		1.042	0.790	0.708054	0.708070	27.82	
66	AU2014	N82/715	Orahiri Lst	Ld	Pectinid		1.067	-2.380	0.707946	0.707962	30.57	
67	AU1088	N91/743	Orahiri Lst	Ld	Brachiopod		1.049	-0.740	0.708120	0.708136	26.08	
68	AU1298a	R14 (5)	Carter Zst	Ld	Oyster		1.484	-0.218	0.708298	0.708314	22.86	
69	AU4184	N51/678	Te Akatea Zst	Ld-Lw	Brachiopod		1.911	0.173	0.708093	0.708109	26.70	
70	AU4179	N51/1096	Te Akatea Zst	Lw	Echinoderm		0.478	-0.230	0.708238	0.708254	24.05	
71	AU6387	R13 (2)	Te Akatea Zst	Lw	Echinoderm		0.354	-0.123	0.708170	0.708186	25.10	
72	AU7995	R15 (6)	Waitomo Sst	Lw	Brachiopod		2.594	-0.404	0.708197	0.708213	24.68	
73	AU2050	N74/563	Otorohanga Lst	Lw	Brachiopod		2.511	0.304	0.708172	0.708188	25.06	
74	AU2028	N83/557	Otorohanga Lst	Lw	Pectinid		2.541	0.252	0.708218	0.708234	24.38	
75	AU2029	N83/558	Otorohanga Lst	Lw	Pectinid		2.216	-0.913	0.708128	0.708144	25.91	
76	AU2026	N83/555	Otorohanga Lst	Ld-w	Brachiopod		-0.067	-1.613	0.707957	0.707973	30.27	
77	AU2039	N91/807	Otorohanga Lst	Lw	Pectinid	Top	2.368	-0.247	0.708189	0.708205	24.80	
1	WU01	S14/ Waikoha Road	Waikaretu Sst	early Lwh	Oyster	Approx middle	-10.36	0.77	0.707820	0.707856	32.91	
2	WU02	R13/ Waikaretu	Waikaretu Sst	early Lwh	Bivalve	Near top	1.85	-0.31	0.707818	0.707854	32.94	
3	WU03	S16/ Waitomo Valley	Kihi Sst	Lwh-Ld	Pectinid	Approx middle	1.24	-0.01	0.707969	0.708005	29.47	
3 repeat	WU03								0.707969	0.708005	29.47	29.47
4	WU04	R13/ Port Waikato	Ahirau Sst	early Lwh	Pectinid	Approx middle	1.93	-0.05	0.708339	0.708375	21.36	
4 repeat	WU04								0.708325	0.708354	21.82	21.59
5	WU05	R15/ Harbour Road	Kihi Sst	Lwh-Ld	Pectinid	Lower-middle	2.44	0.13	0.708035	0.708071	27.79	
6	WU06	R15/ Kawhia Road	Kihi Sst	Lwh-Ld	Pectinid	Approx middle	2.87	0.98	0.708016	0.708052	28.27	
6 repeat	WU06								0.708038	0.708074	27.72	27.99
7	WU07	S14/ Elgood Road	Elgood Lst	early Lwh	Pectinid	Near base	1.67	-0.53	0.707868	0.707904	32.00	
8	WU08	R14/ Waitetuna	Ahirau Sst	early Lwh	Pectinid	Approx middle	1.75	-0.15	0.707922	0.707958	30.68	
9	WU09	R16/ Ngapaenga	Awaroa Lst	upper Lwh	Pectinid	Near base	1.40	-0.49	0.707982	0.708018	29.14	
Repeat #1	WU09								0.707960	0.707984	29.99	

* No.	Sample	Locality	Formation	NZ Stage	Shell type	Strat. order	$\delta^{13}C$	$\delta^{18}O$	$^{87/86}Sr$ lab	$^{87/86}Sr$ adj lab+16	Age (Ma) H & McA (1997)	Average (Ma) H & McA (1997)
Repeat #2	WU09								0.707955	0.707989	29.86	29.66
10	WU010	R17/ Mangaotaki	Ngapaenga Zst	upper Lwh	Pectinid	Near top	1.54	-0.69	0.708010	0.708046	28.43	
11	WU011	R13/ Kaawa Stream	Patikirau Zst	Ld	Pectinid		1.43	-0.16	0.707917	0.707953	30.82	
12	WU012	S16/ Waitomo Valley	Aotea-Orahiri U/C	Ld	Bivalve		1.51	-0.42	0.708039	0.708075	27.69	
13	WU013	R15/ Kihi Road	Hauturu Sst	mid Lwh	Pectinid	Lower	0.45	-1.25	0.707964	0.708000	29.59	
Repeat #1	WU013								0.707938	0.707962	30.57	
Repeat #2	WU013								0.707930	0.707964	30.51	
Repeat #3	WU013								0.707929	0.707963	30.54	30.3
14	WU014	R13/ Waikaretu	Waimai Lst	Lwh-Ld	Pectinid		1.37	-0.55	0.708042	0.708071	27.79	
15	WU015	R14/ Raglan Harbour	Raglan Lst	Ld	Pectinid	Upper	1.39	-0.46	0.708271	0.708300	23.18	
Repeat #1	WU015								0.708263	0.708287	23.44	23.31
16	WU016	R14/ Carters Beach	Raglan Lst	Ld	Pectinid	Approx middle	2.66	-0.26	0.708288	0.708317	22.79	
Repeat #1	WU016								0.708240	0.708264	23.88	
Repeat #2	WU016								0.708230	0.708264	23.88	23.51
17	WU017	R17/ Bexley Station	Orahiri Lst	Ld	Oyster		1.88	-0.58	0.708352	0.708381	21.24	
18	WU018	R15/ Makaka	Waimai Lst	Lwh-Ld	Pectinid	Upper-middle	1.05	0.42	0.707954	0.707983	30.01	
18 Repeat	WU018								0.707987	0.708016	29.19	
18 Repeat	WU018								0.707994	0.708023	29.01	
Repeat #1	WU018								0.707971	0.707995	30.82	29.75
19	WU019	R15/ Waimaori Road	Waimai Lst	Lwh-Ld	Pectinid		2.23	-0.24	0.707894	0.707923	31.58	
20	WU020	R15/ Rakanui Peninsula	Waitomo Sst	Ld-Lw	Pectinid	Near base	1.68	-1.09	0.708066	0.708095	27.11	
20 Repeat	WU020								0.708099	0.708128	26.25	26.68

21	WU021	R14/ Carters Beach	Te Hara Sandstone			Near base	-2.84	-1.61	0.708235	0.708264	23.88	
22	WU022	R15/ Waimaori Station	Otorohanga Lst	Lw	Brachiopod	Near top	2.19	0.26	0.708062	0.708091	27.23	
23	WU023	R14/ Gibson Beach	Te Akau Lst	Lw-Po	Oyster	Near top	0.47	-2.52	0.707998	0.708027	28.91	
Repeat #1	WU023								0.708006	0.708030	28.84	28.87
24	WU024	R14/ Gibson Beach	Te Akau Lst	Lw-Po	Brachiopod	Near base	1.17	-0.3	0.708326	0.708355	21.80	
25	WU025	R14/ Gibson Beach	Te Akau Lst/ Conglomerate	Lw-Po	Brachiopod	Near base	0.25	-1.41	0.708318	0.708347	21.98	
26	WU026	R15/ Rakanui Peninsula	Orahiri Lst	Ld	Pectinid	Near top	2.01	0.18	0.708087	0.708116	26.52	
M1	AHR01	R15/ Shea Road	Elgood Lst	early Lwh		Approx middle	0.93	-0.62	0.707893	0.707919	31.67	
M2	AHR02	R15/ Shea Road	Dunphail Zst	early Lwh		Near top	1.24	-0.2	0.707939	0.707965	30.49	
M3	AHR03	R15/ Shea Road	Ahirau Sst	early Lwh		Lower	1.02	-0.64	0.707932	0.707958	30.68	
M4	AHR04	R15/ Shea Road	Ahirau Sst	early Lwh		Upper	1.32	-0.22	0.707981	0.708007	29.42	
M5	AHR05	R15/ Kawhia Harbour	Dunphail Zst	early Lwh		Approx middle	0.59	-0.06	0.707848	0.707874	32.61	
M6	AHR06	R14/ Waitetuna Estuary	Ahirau Sst	early Lwh			2.19	0.1	0.707926	0.707952	30.85	
M7	AHR07	R15/ Palteaue Road	Dunphail Zst	early Lwh		Lower	1.32	-0.24	0.707884	0.707910	31.87	

* For sample numbers 36 – 77, see Nelson et al. (2004)

* For sample number M1 – M7, see Carter (2003)