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Title **Stratigraphic columns and correlations for the Late Eocene - Oligocene Te Kuiti Group, central-western North Island, New Zealand**

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Stratigraphic columns and correlations for the Late Eocene-Oligocene Te Kuiti Group, central-western North Island, New Zealand

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Executive Summary

This report presents a compilation of stratigraphic columns for geological sections and outcrops of Late Eocene – Oligocene Te Kuiti Group units in central-western parts of North Island, New Zealand, between Port Waikato and Awakino. The columns have been prepared as part of a basin analysis investigation undertaken by the Sedimentary and Petroleum Geology Research Group in the Department of Earth and Ocean Sciences at the University of Waikato, and have been compiled into a common format from recent MSc and PhD theses to make the information more readily available, principally to assist hydrocarbon exploration activities in the region. The columns represent a level of detail underpinning a rationalised lithostratigraphy of the Te Kuiti Group presented in a companion report (Tripathi et al. 2008). This report contains two enclosures, one showing the location of columns in relation to the distribution of the two subgroups (Okoko Subgroup, Castle Craig Subgroup) of the Te Kuiti Group, and the other shows a series of north-south and west-east column correlation panels.

Introduction

Numerous naturally exposed geological sections and outcrops of Te Kuiti Group strata in central-western North Island (Fig. 1.1, Enclosure 1), some associated with road cuts, have been described in detail as part of a basin analysis investigation undertaken by University of Waikato researchers. This report brings together in a common format the stratigraphic columns for this investigation, most of which appeared initially in an MSc thesis (Fergusson 1986) and three PhD theses (Nelson 1973, Anastas 1997, Tripathi 2008). Nelson (1977) reported numerous stratigraphic columns for the area covered by the former Waitomo County and key columns/sites from that report have been revisited, described and redrafted for incorporation in this report.

The report is a companion to another Petroleum Report entitled: "Late Eocene-Oligocene (Te Kuiti Group) lithostratigraphy east of Taranaki Basin in central-western North Island, New Zealand" by Tripathi, Kamp and Nelson (2008), which comprehensively describes the lithostratigraphy for much of the basin. The stratigraphic logs reproduced here form an important level of detail underpinning the revised lithostratigraphy. Enclosure 2 gives a series of lithostratigraphic correlation panels drawn through key columns to form north-south and west-east transects. These panels provide a useful level of generalisation of the lithostratigraphy and help show the thickness distribution of the formations and members. The panels are flattened on the base of the Aotea Formation or the equivalent stratigraphic horizon, and show the location and extent of conformable and unconformable contacts between the various units.

Stratigraphic Nomenclature

The Te Kuiti Group is subdivided into two subgroups, a lower Okoko Subgroup and an upper Castle Craig Subgroup. The revised stratigraphic scheme for the Te Kuiti Group has seven formations and 24 members of Kaiatian to Waitakian (Late Oligocene to earliest Miocene) age (Fig. 1.2).

The Okoko Subgroup comprises the Waikato Coal Measures, Mangakotuku Formation, Glen Massey Formation and Whaingaroa Formation. The Castle Craig Subgroup comprises the Te Akatea Formation, Orahiri Formation and Otorohanga Limestone. The Orahiri Formation and Otorohanga Limestone can be difficult to distinguish from each another over extensive areas of the outcrop belt, especially in the vicinity of Kawhia Harbour, Te Kuiti and Awakino Gorge, and hence is referred to as undifferentiated Orahiri Formation/Otorohanga Limestone. In areas north of Raglan Harbour, units mapped by Kear (1963) and Waterhouse and White (1994) as Waitomo Sandstone and Otorohanga Limestone above Carter Siltstone are now included as basal units within the Waitemata Group.

Early Miocene Waitemata Group strata unconformably overlie the Te Kuiti Group in the north, reflecting basin inversion and erosion driven by uplift focused in the northeast. Early Miocene Mahoenui Group strata conformably overlie the Te Kuiti Group over much of the southern parts of the basin, with unconformable relationships along southeastern parts the Herangi Range (Nelson et al. 1994).

Readers are referred to the companion volume (Tripathi et al. 2008) for a full description of the lithostratigraphy of the Te Kuiti Group and its relationship to overlying units. The lithostratigraphy is underpinned by the numerous stratigraphic column descriptions contained in this report.

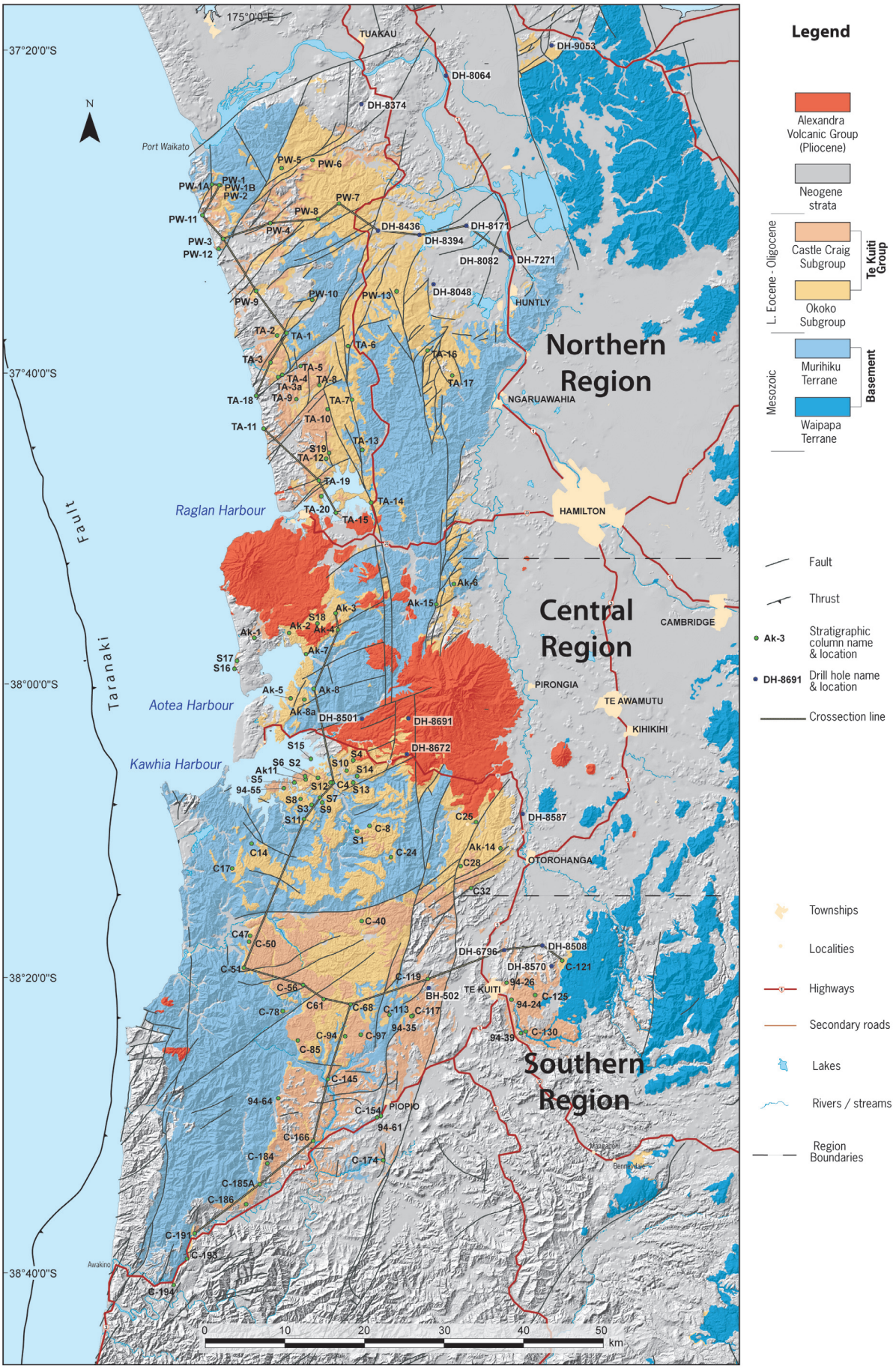

Fig. 1.1: Simplified map of the outcrop geology of the Waikato and King Country regions showing the distribution of Pliocene-Pleistocene volcanics, mid-Cenozoic Te Kuiti Group (Okoko and Castle Craig Subgroups) and Mesozoic basement rocks in central-western North Island. Also shown are the major structural features. Map compiled from Edbrooke 2001 and 2005 .

Waikato (north)				King Country (south)			
White & Waterhouse (1993)		This study		White & Waterhouse (1993)		This study	
Waitemata Group				Mahoenui Group			
Castle Craig Subgroup				Castle Craig Subgroup			
Otorohanga Lst		Regarded as Waitemata Group basal units		Otorohanga Lst	Piopio Lst Waitanguru Lst Pakeho Lst	Otorohanga Lst	Piopio Lst Waitanguru Lst Pakeho Lst
Waitomo Sst				Waitomo Sst			
Te Akatea Fm	Carter Zst Raglan Lst	Te Akatea Fm	Carter Zst Raglan Lst	Orahiri Lst	Te Anga Lst Mangaotaki Lst	Orahiri Fm	Waitomo Sst Te Anga Lst Mangaotaki Lst
Okoko Subgroup				Okoko Subgroup			
Aotea Fm	Patikirau Zst Mangiti Sst Waimai Lst	Aotea Fm	Patikirau Zst Waimai Lst / Mangiti Sst	Aotea Fm	Kihi Sst Hauturu Sst Waimai Lst	Aotea Fm	Kihi Sst Hauturu Sst / Waimai Lst
Whaingaroa Fm	Kotuku Zst	Whaingaroa Fm	Waikorea Sst Kotuku Zst	Whaingaroa Fm	Orotangi Sst Kotuku Zst Awamarino Lst	Whaingaroa Fm	Ngapaenga Zst Awaroa Lst
Glen Massey Fm	Ahirau Sst Dunphail Zst Elgood Lst	Glen Massey Fm	Ahirau Sst Dunphail Zst Elgood Lst	Glen Massey Fm	Ahirau Sst Elgood Lst	Glen Massey Fm	Ahirau Sst Dunphail Zst Elgood Lst
Mangakotuku Fm	Rotowaro Zst Pukemiro Sst Glen Afton Cst	Mangakotuku Fm	Waikaretu Sst Rotowaro Zst Pukemiro Sst Glen Afton Cst	Mangakotuku Fm	Undifferentiated	Mangakotuku Fm	Waikaretu Sst Rotowaro Zst
Waikato Coal Measures		Waikato Coal Measures		Waikato Coal Measures		Waikato Coal Measures	

Fig. 1.2: Comparisons between White & Waterhouse's (1993) lithostratigraphy for the Te Kuiti Group in northern and southern areas of central-western North Island versus the rationalised lithostratigraphy developed in this study.

Age and Timescale

The stratigraphic columns show age expressed in terms of New Zealand stage names. The stage designations have been chiefly determined from microfossil content, and for selected units from their macrofossil content. Historically, the biostratigraphy of the Te Kuiti Group was developed principally from Kear & Schofield's (1959) fossil collections of units cropping out between Papakura (southern Auckland) and Taumarunui (King Country). More recently, the formations and members within the group have been assigned stage designations based mainly upon foraminiferal identifications (Hornibrook et al. 1989). Significant gaps in fossil collections in the Te Akau and Waitomo areas were filled by collections made by Kear (1963) and Nelson (1978a), respectively. Waterhouse & White (1994) made important additional fossil collections in the Raglan-Kawhia area. The majority of the biostratigraphic data used in this study are open file in the New Zealand Fossil Record Database (FRED).

Despite the advances of prior investigations, understanding about the biostratigraphy of the Te Kuiti Group remains problematic, due to a combination of few biostratigraphic events during the Oligocene, and the difficulty of separating from tightly cemented limestone facies the foraminiferal species upon which the stages are based. The unconformities between formations and their correlative conformities provide important constraints on the interpretation of ages for various parts of the Te Kuiti Group.

The current biostratigraphic basis for defining the Late Eocene to Early Miocene stages in New Zealand, covering the age range of the Te Kuiti Group, are summarised in Figs 1.3 and 1.4. Type and reference sections for these stages, all of them outside the Te Kuiti Group except for the Whaingaroan-Duntroonian boundary (Fig. 1.3), are described by Cooper et al. (2004), and are not elaborated upon here.

Stratigraphic Columns

The stratigraphic columns originate from various MSc and PhD theses, but have been imported into a common template and redrafted, with key information about the location of the various sections and outcrops standardised. Clearly indicated on each column is the author of the original column description. In addition to the descriptive text included on the columns, facies codes are listed for the various depositional units. The facies codes have been standardised in

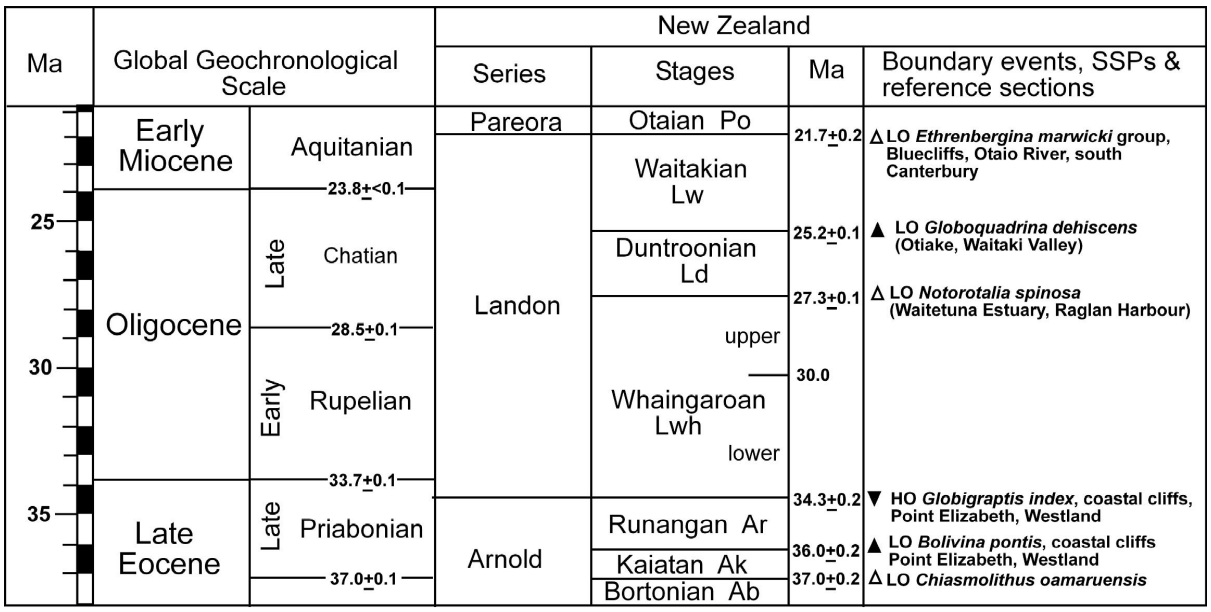

Fig. 1.3: Late Eocene to Early Miocene New Zealand Series and Stages correlated with the Global Geochronological Scale. The boundary-defining event for each stage is shown and the boundary stratotype section and point (SSP), or a reference section in brackets, are indicated. Formal SSPs are indicated by solid triangles and informal SSPs by open triangles. Adopted from Cooper et al. (2004).

Tripathi (2008) and are presented in a series of facies tables, two for the Okoko Subgroup (Table 1.1, Glen Massey Formation and Whaingaroa Formation; Table 1.2, Aotea Formation) and one for the Castle Craig Subgroup (Table 1.3). Readers will need to cross reference between the codes on the stratigraphic columns and the corresponding descriptions in the respective tables. The stratigraphic columns also show photograph numbers and the stratigraphic extent of the photographs, which follow the columns in the repoprt.

Arrangement of Columns in the Report

The stratigraphic column locations are shown on Fig. 1.1 and on Enclosure 1. The columns are arranged within this report within NZMS 260 topographical map sheets (R13, R14, R15, R 16, R17 & R18, S14 & S15, S16) following a north-to-south and west-to-east pattern in their arrangement. Individual NZMS 260 map sheets shown at a larger scale than in Enclosure 1, and including the column locations, are incorporated within the volume ahead of the related columns for those areas.

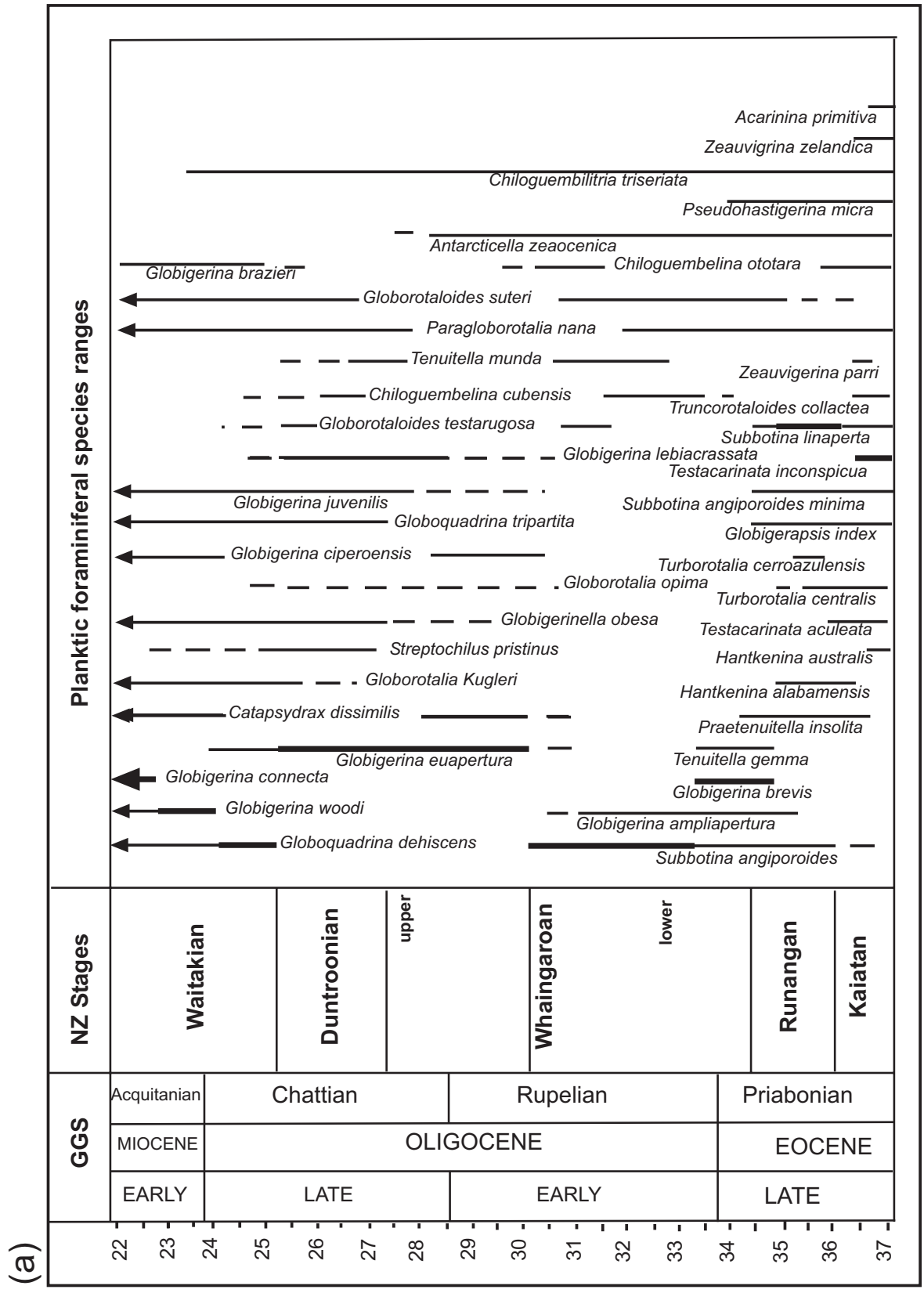

Fig. 1.4: Stratigraphic ranges of selected biostratigraphically useful (a) planktic and (b) benthic foraminifera. Adopted from Cooper et al. (2004).

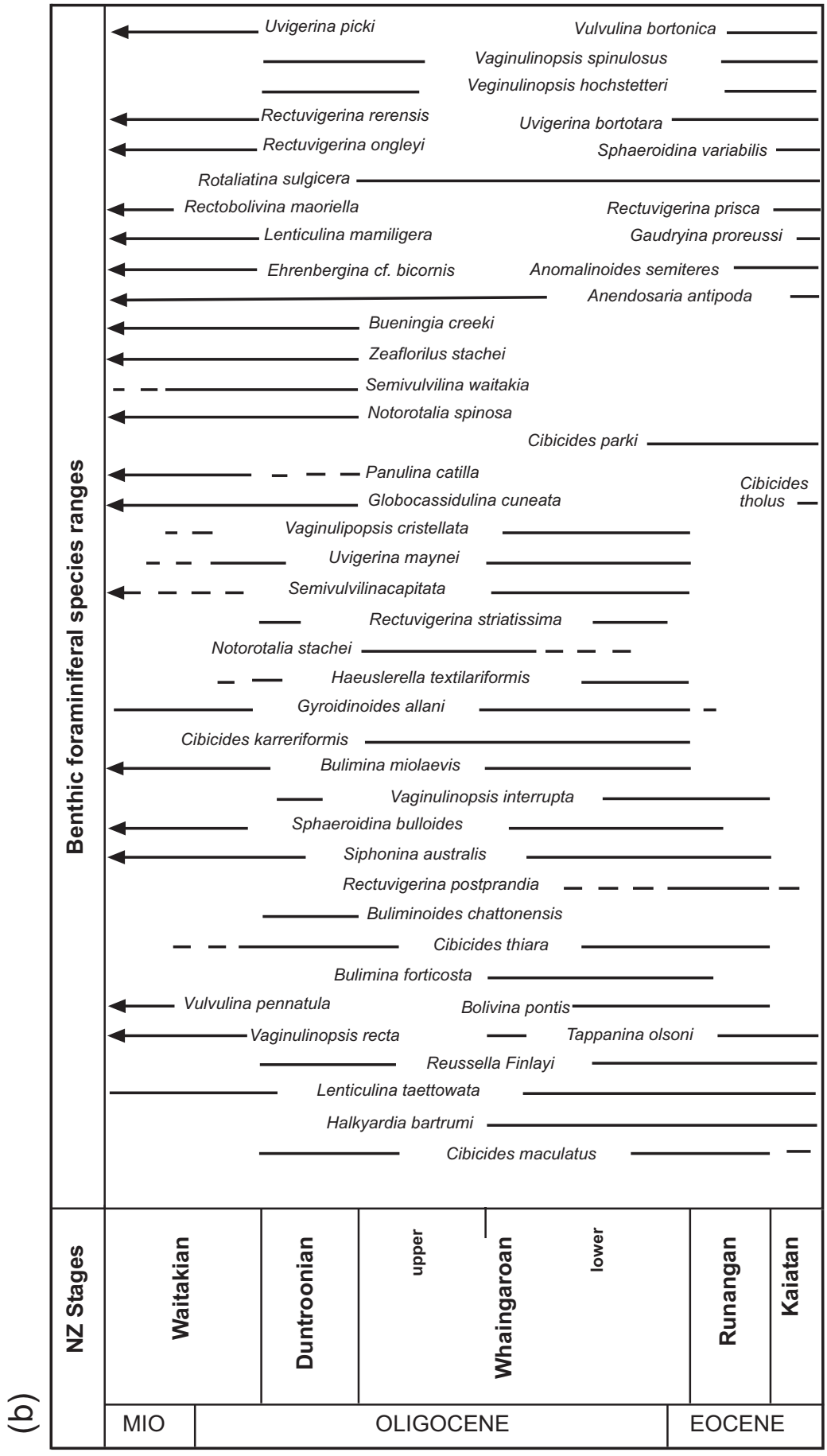

Fig. 1.4(continued): *Stratigraphic ranges of selected biostratigraphicallyuseful (a) planktic and (b) benthic foraminifera. Adopted from Cooper et al. (2004).*

Table 1.1: Summary of sedimentary lithofacies for the Glen Massey Formation and Whaingaroa Formation

Litho-facies	Field characteristics	Wt % $CaCO_3$	Texture	Typical skeletons / bioturbation	Occurrence	Inter-pretation
Limestone lithofacies association (Elgood Limestone Member)						
L_1 Pebbly grain-stone	Common to abundant subrounded clasts averaging 1-10 cm derived from basement; fabric supported by coarse sparry limestone; poor bedding development, often massive in appearance	High (84-95%)	Medium to coarse grainstone-rudstone, frequent large bivalve fragments, very abraded	Fragmented bivalves, notably oysters and pectinids, clasts occasionally encrusted by calcareous red algae, including rhodoliths up to 8-10 cm across	Commonly occurs as trans-gressive basal lag, tens of cm thick	Near shore to inner-most shelf, adjacent to rocky shore-line
L_2 Shelly grain-stone	Disarticulated bivalves haphazardly scattered through the limestone or occasionally concentrated into beds, poor to moderate bed development, irregular (bifurcating) interflags may give outcrop a knobbly appearance	High (85-91%)	Medium to coarse rudstone-grainstone, rare pebble granule clasts, moderately to very abraded	Pectinids, bryozoans, echinoids, *Amphistegina* grains, and coralline red algae	Common at base of limestone unit	Near shore to inner shelf

Table 1.1(continued): *Summary of sedimentary lithofacies for the Glen Massey Formation and Whaingaroa Formation*

Litho-facies	Field characteristics	Wt % $CaCO_3$	Texture	Typical skeletons / bioturbation	Occurrence	Inter-pretation
L_3 Cross-stratified grain-stone	Sigmoidal to tabular cross-beds are low (<10^0) to moderate angle (10^0-25^0), in sets from less than 0.5 to up to 1.5 m thick, traceable laterally for a few tens of metres; set base and tops are sharp; well developed bedding is characteristic, typically 2-15 cm thick; bedding planes are typically rich in siliciclastics	High (88-94%)	Moderately to well sorted, medium to coarse grainstone; very to moderately abraded; siliciclastic particles in bedding planes are generally of fine sand to silt grade, rare granule size clasts	Bryozoans, echinoderms, bivalves, red algae and benthic foraminifera	Common along the western margin or developed locally about the flanks of paleo-highs	Sub-aqueous dunes migrating parallel to shore
L_4 Horizont-ally bedded grain-stone	Beds typically well developed and 2-10 cm thick, separated by bedding planes (0.1 -1.5 cm) rich in siliciclastic particles; freshly broken surfaces have a homogeneous crystalline appearance	Moderate to high (68-97%)	Moderately sorted, fine to medium grainstone, moderately abraded	Echinoderms, bryozoans, bivalves, occasional casts/moulds of gastropod, large benthic foraminifera	Widespread along the basin margin, commonly thicken and thin over short distances	Inner to mid shelf

Table 1.1(continued): *Summary of sedimentary lithofacies for the Glen Massey Formation and Whaingaroa Formation*

Litho-facies	Field characteristics	Wt % $CaCO_3$	Texture	Typical skeletons / bioturbation	Occurrence	Inter-pretation
L_5 Massive to mod-erately bedded grain-stone-pack-stone	Irregular bed development, frequently even massive in appearance; undulatory bifurcating interflags; rare horizontal lamination, variably bioturbated (irregular inclined burrows)	Moderate to high (36-92%)	Fine grainstone-packstone, abraded	Abundant echinoids, bryozoans, planktic and benthic foraminifers, occasional echinoid spines/plates	Locally well developed	Lower inner to mid-outer shelf, wave (storm) domin-ated setting
Mixed carbonate-siliciclastic sandstone lithofacies association (Ahirau Sandstone Member)						
S_1 Calcar-eous pebbly-gritty sand-stone	Poorly to moderately well cemented; massive; rounded subrounded granule pebble basement clasts, fabric supported by calcareous fine silty sandstone, clast size shows crude normal grading	Low to moderate (25-77%)	Fine to coarse grained, poorly sorted	Occasional bivalve pectinid, oysters, red algae including rhodoliths, common glauconitised clasts and shell fragments, *Amphistegina*	Common immediately above the contact with basement and at the base of overlying limestone, may represent trans-gressive lag deposits	Inner-most shelf, proximal to rocky coast-line, with a moder-ately high silici-clastic influx
S_2 Calcar-eous silty fine sand-stone	Well cemented, massive fine grained calcareous sandstone and sandy siltstone, heavily bioturbated, poor preservation of primary sedimentary structures, however, locally, low-angle cross bedding is recognisable	Moderate (36-63%)	Fine to very fine sandstone to siltstone, poorly to moderately sorted	Scattered pectinids, echinoid spines, high diversity of trace fossils of mainly *Cruziana* ichnofacies (?)	This facies is well developed along the western margin	Inner to mid shelf with moder-ate to strong bottom currents driven by wind and/ or tides interact-ing with the inherited topo-graphy

Table 1.1(continued): *Summary of sedimentary lithofacies for the Glen Massey Formation and Whaingaroa Formation*

Litho-facies	Field characteristics	Wt % $CaCO_3$	Texture	Typical skeletons / bioturbation	Occurrence	Inter-pretation
S_3 Alter-nating calcar-eous silty fine sand-stone and silt-stone	Consists of alternating calcareous fine sandstone and silty sandstone. Beds range from few centimetres to decimetre thick, with a variable carbonate content; bioturbation present throughout but not abundant	Moderate (33-61%)	Fine to very fine sandstone and siltstone, poorly to moderately sorted	Scattered bivalves, planktic and benthic foraminifera	Commonly forms the upper part of the Glen Massey Formation in northern region	Moderate energy in mid to outer shelf depths below fair-weather but above storm wave base
S_4 Massive muddy sand-stone	Massive muddy sandstone, moderately cemented; heavily bioturbated	Moderate (45-54%)	Fine to very fine sandstone to siltstone, poorly sorted	Scattered pectinids and other bivalve fragments, occasional large burrows	Commonly overlies limestone units (L_4)	Mid shelf
Mixed carbonate-siliciclastic siltstone lithofacies association (Dunphail Siltstone Member)						
S_5 Inter-bedded calcar-eous siltstone and sandy lime-stone	Alternating fine sandy siltstone and sandy limestone beds few centimetres to up to a metre thick, usually grades above into massive calcareous siltstone (S_6)	Moderate to high (40-78%)	Fine to very fine sandstone and siltstone, poorly to moderately sorted	Bivalve shell fragments common in the sandy limestone beds, evidence for intensive bioturbation in silty intervals	Commonly occurs as a transition between underlying limestone (L_4) and overlying massive calcareous siltstone (S_6)	Mid to outer shelf, between fair weather and storm wave base

Table 1.1(continued): *Summary of sedimentary lithofacies for the Glen Massey Formation and Whaingaroa Formation*

Litho-facies	Field characteristics	Wt % $CaCO_3$	Texture	Typical skeletons / bioturbation	Occurrence	Inter-pretation
S_6 Massive calcar-eous siltstone	Massive blue-grey siltstone, well cemented. No obvious structures. Occasional concretionary bands with ellipsoidal shaped con-cretions up to 10 cm in size	Moderate to high (33-79%)	Fine siltstone with occasional traces of very fine to fine sandstone, moderately sorted	Planktic and benthic foraminifera, sparse macrofossils	Widespread throughout basin	Outer shelf to upper bathyal
Chemogenic lithofacies association						
C_1 Phos-phate nodule bed	Scattered phosphate nodules of up to 6 mm in a strongly bioturbated, well cemented, glauconitic fine sandstone-siltstone	Moderate (45-47%)	Fine to very fine sandstone to siltstone, poorly to moderately sorted	Rare bivalve shell fragments (mainly pectinids); abundant burrows	Not common; occurs as phosphat-ised hard-grounds at top of Ahirau Sst Member in Port Waikato area	Mid shelf
C_2 Glau-conitic calcar-eous siltstone-sand-stone	Glauconite occurs as silt and/or fine to medium sand size pellets and also as extrinsic filling within bioclasts; moderately to strongly bioturbated	Moderate (68%)	Fine sandstone to siltstone	Scattered whole and fragmented bivalves, echinoid plates and spines, frequently glauconitised; large benthic and / or planktic foraminifera	Common in certain areas generally occurring as basal facies represent-ing a con-densed trans-gressive deposit or in places marks the transition between TST and HST	Sediment starved shelf
C_3 Glau-conitic sandy-silty grain-stone-pack-stone	Glauconite occurs as abundant pelletal and detrital (?) medium to fine sand size in a moderately bedded grainstone-packstone	High (73-82%)	Medium to fine sandstone to siltstone	Common bivalve shell fragments, *Amphistegina* benthic foraminifera, bioturbation not obvious	Common in some trans-gressive deposits	Sediment starved inner-mid shelf

Table 1.2: *Lithofacies of the Aotea Formation*

Litho-facies	Field characteristics, sedimentary structures, bedding type	Carbonate content / insoluble residue	Grain size range / abrasion/ sorting	Typical fauna / bioturbation	Common occurrence / typical example	Inter-pretation
Limestone lithofacies						
L_1 Pebbly grain-stone/ pack-stone	Common to abundant subrounded pebbles and cobbles reworked from the substrate; fabric supported by bioclastic silty fine sandstone. Occasional well defined horizontal bedding development, but often massive in appearance	Moderate (52-73%)	Medium to coarse grainstone-rudstone, with occasional large pectinid shell fragments, poorly to moderately sorted, and very abraded	Fragmented bivalves, large benthic foraminifers (especially *Amphistegina* sp.), echinoid and bryozoan fragments with clasts occasionally encrusted by calcareous red algae, including rhodoliths	Facies common near the lower contact with basement; inferred as transgressive basal lag deposits tens of cm thick (forms basal part of Waimai Lst Member, Basal Beds "AoA" of Nelson 1978)	Near shore to inner-most shelf adjacent to rocky shoreline
L_2 Cross-strati-fied grain-stone	Sigmoidal to tabular cross-beds have low (< 10^0) to moderate dips (10^0-25^0), occur as 0.3-4.5 m thick cross-sets traceable laterally for few tens of metres; set base and tops are sharp and discordant; cross- beds are generally 2-15 cm thick, and bedding planes are typically rich in siliciclastic material	Moderate to high (56-94%)	Medium to coarse grainstone; rare small pebble size clasts; siliciclastic particles in bedding planes are generally of fine sandstone to siltstone, moderately abraded and moderately well sorted	Bryozoans, echinoderms, benthic foraminifers, occassional bivalves, coralline red algae, rare planktic foraminifers and barnacles	Comprises most of the lower and middle part of Waimai Lst Member along the western margin of the northern region; rare elsewhere	High energy inner to mid shelf domin-ated by strong offshore-directed storm and / or tidal induced currents

Table 1.2 (continued): *Lithofacies of the Aotea Formation*

Litho-facies	Field characteristics, sedimentary structures, bedding type	Carbonate content / insoluble residue	Grain size range / abrasion/ sorting	Typical fauna / bioturbation	Common occurrence / typical example	Inter-pretation
L_3 Hori-zon-tally bedded grain-stone / pack-stone	Beds typically well developed, averaging 2-10 cm are separated by bedding planes (0.1 -1.5 cm) rich in siliciclastic material; freshly broken surface reveals a homogeneous texture	Moderate to high (48-83%)	Fine to medium grainstone; abraded; moderately sorted	Echinoderms, benthic foraminifers, and to lesser extent planktic foraminifers, bryozoans and bivalves	Comprises most of the Waimai Lst Member in the eastern parts of the northern region	Inner to mid wave dominat-ed shelf
L_4 Sandy-silty grain-stone	2-15 cm thick beds, irregular undulating bedding planes laterally discontinuous; cavernously weathered; occasionally low angle ($<10^0$) cross-bedding obvious in places	Moderate to high (51-88%)	Medium to coarse grainstone, common, medium to coarse quartz sand, abraded and moderately sorted	Echinoderms, benthic foraminifers, bryozoans, bivalves and calcareous red algae, planktic foraminifers are rare or absent	Comprises most of the lower part of Aotea Formation in the central/ southern regions. Represents transition between Hauturu Sst and Waimai Lst Member	Inner to mid shelf
L_5 Mas-sive to irregu-larly bedded biotur-bated grain-stone/ pack-stone	Massive to weak horizontal lamination, variably bioturbated (inclined/ vertical burrows)	Moderate (48%)	Fine grainstone-packstone, slightly abraded and moderately sorted	Echinoderms, delicate branching bryozoans, benthic foraminifers	Comprises the upper part of Waimai Lst Member in the northern region area	Lower inner to mid-outer shelf; wave (storm) dominat-ed setting

Table 1.2 (continued): *Lithofacies of the Aotea Formation*

Litho-facies	Field characteristics, sedimentary structures, bedding type	Carbonate content / insoluble residue	Grain size range / abrasion/ sorting	Typical fauna / bioturbation	Common occurrence / typical example	Inter-pretation
Mixed carbonate-siliciclastic sandstone lithofacies						
S_1 Variably calcareous fine to medium-sandstone	Massive to concretionary bedded sandstone; well cemented centimetre-thick hard sandstone bands alternate with friable sandstone. Low angle cross-stratification and layered bands of shell hash and reworked granule-size basement clasts. Burrows and bioturbation structures abundant	Low to moderate (26-56%) carbonate rich and carbonate poor zones	Fine to medium sandstone, moderately sorted	Echinoderms, bryozoans and benthic foraminifera with occasional minor presence of calcareous red algae and bivalves	Most common towards the western margin in the southern region, absent in the north (Hauturu Sst Member / Banded Sandstone Beds “Ao-5 “ of Nelson 1978)	Storm dominated fore-shore to mid shelf
S_2 Massive to thin bedded calcareous silty-sandstone	Well cemented, massive fine calcareous sandstone and siltysandstone; moderately bioturbated, poor preservation of primary sedimentary structures; thin centimetre–scale horizontal bedding may be discernible in places	Low to moderate (26-39%)	Fine to very fine sandstone to siltstone, poorly to moderately sorted	Benthic foraminifera, rare bivalves, echinoid spines	Commonly forms the upper part of Aotea Formation in the central region (Kihi Sst Member / Massive Ripply Sandstone Beds “Ao-3” of Nelson 1978)	Mid to outer shelf

Table 1.2 (continued): *Lithofacies of the Aotea Formation*

Litho-facies	Field characteristics, sedimentary structures, bedding type	Carbonate content / insoluble residue	Grain size range / abrasion/ sorting	Typical fauna / bioturbation	Common occurrence / typical example	Inter-pretation
S_3 Inter-bedded calcar-eous sand-stone and sandy silt-stone	Calcareous fine sandstone with thin silty interbeds; beds range from few centimetres to tens of centimetres thick, burrows common in the silty interbeds	Moderate (46-65%)	Poorly to moderately sorted, fine to very fine sandstone and siltstone	Rare scattered echinoderm fragments, sparse macrofossils	Commonly forms the lower part of the Aotea Formation in the northern region (Mangiti Sst Member)	Moderate energy mid shelf depths below fair-weather but above storm wave base
S_4 Mass-ive biotur-bated muddy-sand-stone	Massive muddy sandstone; moderately cemented; occasional pebble –granule bands; heavily bioturbated	Moderate (47-55%)	Fine to very fine sand to silt, poorly sorted	Common *Janupecten polemicus, Panopea worthingtoni* and occasional other bivalve fragments, foraminifers	Most common towards eastern areas (Kihi Sst Member/ Massive Muddy Sandstone Beds “Ao-2” of Nelson 1978)	Low energy mid to mid-outer shelf, above storm wave base
Mixed carbonate-siliciclastic siltstone lithofacies						
Z_1 Mass-ive variably calcar-eous sandy silt-stone	Massive blue-grey siltstone, moderately to well cemented. No obvious structures except infrequent concretionary sandstone beds.	Low to high (29-73%)	Fine siltstone with minor amounts of moderately sorted very fine to fine sandstone	Planktic and benthic foraminifera, sparse macrofossils	Widespread in the northern region forming the upper part of Aotea succession, not common in south but present locally in some areas (Patikirau Siltstone Member)	Mid-outer shelf to possibly upper bathyal

Table 1.2 (continued): *Lithofacies of the Aotea Formation*

Litho-facies	Field characteristics, sedimentary structures, bedding type	Carbonate content / insoluble residue	Grain size range / abrasion/ sorting	Typical fauna / bioturbation	Common occurrence / typical example	Inter-pretation
Chemogenic lithofacies association						
C_1 Glau-conitic silt-stone and sand-stone	Massive, glauconite occurs as silt and/or fine to medium sand size pellets and also as extrinsic filling within bioclasts, heavily bioturbated	Low to moderate (27-48%)	Fine to medium sandstone to siltstone	Highly fossiliferous scattered whole and fragmented bivalves (*Janupecten polemicus*, *Lentipecten hochstetteri*) and solitary corals (F*labellum* sp.); occasional whole echinoids, plates and spines	Common in some areas near the top of Aotea Formation (Glauconitic Sandstone Beds "Ao-4" of Nelson 1978)	Sediment starved mid-outer shelf
C_2 Glau-conitic pack-stone / wacke-stone	Glauconite occurs as abundant pelletal and glauconitised shells and infills; moderately bedded –packstone / wackestone; bioturbation abundant	Moderate to high (48-82%)	Medium to fine sandstone to siltstone	Common bivalve shell fragments, occasional whole echinoderms, benthic and planktic foraminifera	Common in some transgressive deposits. Restricted to the northwest (Waimai Lst Member)	Sediment starved inner to mid shelf

Table 1.3: Lithofacies of the Castle Craig Subgroup.

Litho-facies code and name	Field characteristics, sedimentary structures, bedding type	Carbonate content/ insoluble residue	Texture size range /abrasion/ sorting	Typical fauna / bioturbation	Common occurrence / typical example	Inter-preta-tion
Limestone association						
L_1 Pebbly grain-stone -pack-stone.	Common to abundant subrounded pebbles and cobbles may occur as pebble bands, or fabric supported by bioclastic silty fine sandstone, usually massive in appearance	Moderate (50-60%)	Medium to coarse grainstone-rudstone, occasional large shell fragments, poorly to moderately sorted; very abraded	Fragmented pectinids, oysters, echinoderm, clasts occasionally encrusted by calcareous red algae, including rhodoliths	Common near the lower contact with basement, and/or mark erosional contact with the underlying formation; up to tens of centimetres thick. "Basal Beds" (OrA1/ OtA1 of Nelson 1978a)	Near shore to inner shelf adjac-ent to rocky shore-line
L_2 Cross-stratified grain-stone	Sigmoidal to tabular cross-beds are low (< 10^0) to moderate angle (10^0-25^0); occur as 0.3-4.5 m thick cross-sets traceable laterally for few tens of metres; base and tops of sets are sharp and discordant, cross-beds are generally 2-15 cm thick	High (91-96%)	Medium to very coarse grainstone, rare small pebbles and granules. Siliciclastic particles in bedding planes are generally of fine sandstone to siltstone, moderately abraded, poorly to moderately sorted	Bryozoans, echinoderms, benthic foraminifers, occasional bivalves, coralline red algae, rare planktic foraminifers	Developed locally in the lower, mid and upper parts of Orahiri Formation and Otorohanga Limestone.	High energy inner to mid shelf domin-ated by strong off-shore-directed storm and or tidal induced currents

Table 1.3 (continued): *Lithofacies of the Castle Craig Subgroup.*

Litho-facies code and name	Field characteristics, sedimentary structures, bedding type	Carbonate content/ insoluble residue	Texture size range /abrasion/ sorting	Typical fauna / bioturbation	Common occurrence / typical example	Inter-preta-tion
L_3 Horizon-tally bedded grain-stone	Beds typically well developed, averaging 2-10 cm; well developed flagginess is characteristic	High (81-99%)	Medium to very coarse grainstone, abraded, poorly to moderately sorted	Bryozoans, echinoderms, benthic foraminifers, and occasional bivalves and calcareous red algae; planktic foraminifers rare or absent	Comprises most of the Orahiri Formation and Otorohanga Limestone. "Flaggy Limestone Beds" (OrB1, OtA2, OtC1) of Nelson 1978a	Inner to mid wave domin-ated shelf
L_4 Sandy grain-stone-pack-stone	Commonly varying from massive to tabular bedded units, bedding plane (0.1 - 1.5 cm) rich in siliciclastic material is obvious in places	Moderate to high (42-87%)	Coarse to very coarse grainstone, common medium to coarse quartz sand grains, abraded, and poorly to moderately sorted	Echinoderm, large benthic foraminifers (*Amphiste-gina*), bryozoans, and occasional bivalves and calcareous red algae; planktic foraminifers rare or absent	Comprises most of the Mangaotaki Limestone Member mainly in western areas. "Sandy Limestone Beds" (OrA3, OrA4, OrA5, OrB4) of Nelson 1978a.	Inner to mid shelf
L_5 Massive to irregul-arly bedded, fossilifer-ous rud-stone-grain-stone	Massive to irregularly bedded, occasionally well bedded 20-100 cm thick beds, commonly develops "knobbly" to blocky weathering feature, frequently cavernously weathered	High (98-100%)	Medium to coarse grainstone, common large skeletal fragments, abraded, poorly to moderately sorted	Bryozoans (up to 80 %), echinoderms, benthic foraminifers, common bivalves and gastropod moulds and occasional calcareous red algae	Comprises most of the Waitanguru Limestone Member (Otorohanga 'B'). "Blocky and Knobbly Limestone Beds" (OtB1, OtB2, OtB3) of Nelson 1978a	Bryo-zoan mound buildup indicat-ing high energy inner-mid shelf depths

Table 1.3 (continued): *Lithofacies of the Castle Craig Subgroup.*

Litho-facies code and name	Field characteristics, sedimentary structures, bedding type	Carbonate content/ insoluble residue	Texture size range /abrasion/ sorting	Typical fauna / bioturbation	Common occurrence / typical example	Inter-preta-tion
L_6 Pebbly-oyster float-stone-pack-stone.	Massive to irregularly bedded, tens of centimetre thick; beds laterally traceable for few metres	High (77-97%)	Medium to very coarse with pebbles (<2 cm), clasts and matrix supported, poorly sorted	Articulated / disarticulated, randomly orientated oysters (*Flemingo-strea sp.*), bryozoans, echinoderms, benthic foraminifers, bivalves and occasional calcareous red algae, solitary corals (*Flabellum*)	Comprises most of the Te Anga Limestone Member. "Oyster and Fossil Hash Beds" (Or B2, OrB5) of Nelson 1978a	Oyster reefs com-monly associ-ated with sandy grain-stone -pack-stone, high energy tide swept inner-mid shelf
L_7 Con-glom-eratic limestone	Bedded units 0.5-3 m thick with abundant clasts of limestone, calcareous sandstone and rounded-subrounded basement pebbles, which are frequently profusely bored	Moderate to high	Coarse to very coarse sparry grainstone with 1-10 cm size clasts, poorly sorted	Bryozoans, echinoderms, benthic foraminifers, oysters and occasional calcareous red algae encrusting basement pebbles	Occurs as conspicuous unit within Orahiri Formation near Awakino Tunnel. "Limestone in Limestone Beds" (OrB6) of Nelson 1978a	Inter-preted as carbon-ate debrite/ mass em-placed unit - deposit-ed at shelf depths in re-sponse to tilting

Table 1.3 (continued): *Lithofacies of the Castle Craig Subgroup.*

Litho-facies code and name	Field characteristics, sedimentary structures, bedding type	Carbonate content/ insoluble residue	Texture size range /abrasion/ sorting	Typical fauna / bioturbation	Common occurrence / typical example	Inter-preta-tion
Mixed carbonate-siliciclastic sandstone association						
L_8 Massive to horizon-tally bedded skeletal pack-stone-wacke-stone	Massive to well bedded (2-25 cm) with prominent sub-horizontal to bifurcating thin (0.5 -1.5 cm) silty interbeds	Moderate to high (59-89%)	Predominantly micritic with scattered whole and fragmented bivalves (pectinids) and echinoderms, poorly to moderately sorted	Moderate to abundant planktic foraminifera with subequal proportions of echinoderms, benthic foraminifers and bivalve fragments, occasional whole well preserved echinoderms. Bryozoans and calcareous red algae are absent or present in traces	Comprises most of the Raglan Limestone Member in the northern region; also occurs as a transition facies near the upper contact with Mahoenui Group. "Argillace-ous Limestone Beds" (OtC2) of Nelson 1978a	Outer shelf to slope
S_1 Massive glauco-nitic muddy sand-stone	Typically massive with smooth weathering profile, poorly to moderately cemented, and bioturbated	Low to moderate (20-60%)	Fine to very fine sandstone, poorly sorted	Echinoderms, bryozoans and benthic foraminifers with rare presence of calcareous red algae and bivalves.	Most common in the Waitomo Valley area. "Waitomo Sandstone Formation" of Nelson 1978a)	Mid to outer shelf
S_2 Fossilif-erous silty sand-stone and sandy siltstone	Massive, dull brownish grey, moderately cemented, occasional hard concretionary glauconitic sandstone bands, bioturbated	Moderate (38-62%)	Fine silty sandstone with scattered large bivalve and skeletal fragments, poorly sorted	Oysters (*Flemingo-strea sp.), Athlopecten athleta, Lentipecten hochstetteri, Panopea worthingtoni, Dosinia* sp., solitary corals (*Flabellum* sp.), abundant *pectinid fragments* and benthic foraminifers	Mostly forms the top part of the limestone (Orahiri Formation/ Otorohanga Limestone) at inland Kawhia Harbour area	Mid-outer shelf above storm wave base

Table 1.3 (continued): *Lithofacies of the Castle Craig Subgroup.*

Litho-facies code and name	Field characteristics, sedimentary structures, bedding type	Carbonate content/ insoluble residue	Texture size range /abrasion/ sorting	Typical fauna / bioturbation	Common occurrence / typical example	Inter-preta-tion
Mixed carbonate-siliciclastic siltstone association						
Z_1 Medium bedded calcar-eous siltstone	Light grey to creamy yellow, moderately to well bedded (10-50 cm), occasional glauconitic in-filled burrowed horizons (10-30 cm) locally present	Moderate (51-75%)	Medium to coarse siltstone, occasional whole bivalves, gastropods and echinoderms, poorly to moderately sorted	Dominated by planktic foraminifers with variable proportion of benthic foraminifers, echinoderms and bivalves, bryozoans	Common in the lower part of Carter Siltstone Member	Outer shelf to upper bathyal
Z_2 Massive calcar-eous siltstone	Massive, light bluish grey to brownish grey, characteristic conchoidal fracture when fresh, weathers into a finely frittered surface	Low to moderate (24-73%)	Predominantly medium to coarse siltstone, however admixture of very fine to fine sand grains may be observed locally, fine-sand sized planktic foraminifera commonly recognisable, poorly to moderately sorted	Bioclasts are dominated by planktic foraminifers with minor proportion of benthic foraminifers, echinoderms and bivalve whole shell fragments	Wide-spread in the northern region forming most of the Carter Siltstone Member	Outer shelf to upper bathyal

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Stratigraphic columns and correlations for the Late Eocene-Oligocene Te Kuiti Group, central-western North Island, New Zealand

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The initial drafting of the columns was undertaken by Anand Tripathi. We acknowledge Betty-Ann Kamp for assistance with this task, for bringing the columns into a common template, for arranging the columns in a systematic order, and for the production of this report. We also acknowledge the assistance of Austin Hendy with macrofossil identifications and paleoecological interpretations. We thank the various land owners and farm managers in central-western North Island for kind access to their properties to undertake the stratigraphic descriptions. Funding to undertake different aspects of our research on the Te Kuiti Group and eastern Taranaki Basin margin more widely, has been provided by the New Zealand Foundation for Research Science and Technology (Contract UOWX0301), which has been gratefully appreciated.

Executive Summary

This report presents a compilation of stratigraphic columns for geological sections and outcrops of Late Eocene – Oligocene Te Kuiti Group units in central-western parts of North Island, New Zealand, between Port Waikato and Awakino. The columns have been prepared as part of a basin analysis investigation undertaken by the Sedimentary and Petroleum Geology Research Group in the Department of Earth and Ocean Sciences at the University of Waikato, and have been compiled into a common format from recent MSc and PhD theses to make the information more readily available, principally to assist hydrocarbon exploration activities in the region. The columns represent a level of detail underpinning a rationalized lithostratigraphy of the Te Kuiti Group presented in a companion report (Tripathi et al. 2008). This report contains two enclosures, one showing the location of columns in relation to the distribution of the two subgroups (Okoko Subgroup, Castle Craig Subgroup) of the Te Kuiti Group, and the other showes a series of north-south and west-east column correlation panels.

Introduction

Numerous naturally exposed geological sections and outcrops of Te Kuiti Group strata in central-western North Island (Fig. 1.1, Enclosure 1), some associated with road cuts, have been described in detail as part of a basin analysis investigation undertaken by University of Waikato researchers. This report brings together in a common format the stratigraphic columns for this investigation, most of which appeared initially in an MSc thesis (Fergusson 1986) and three PhD theses (Nelson 1973, Anastas 1997, Tripathi 2008). Nelson (1977) reported numerous stratigraphic columns for the area covered by the former Waitomo County and key columns/sites from that report have been revisited, described and redrafted for incorporation in this report.

The report is a companion to another Petroleum Report entitled: "Late Eocene-Oligocene (Te Kuiti Group) lithostratigraphy east of Taranaki Basin in central-western North Island, New Zealand" by Tripathi, Kamp and Nelson (2008), which comprehensively describes the lithostratigraphy for much of the basin. The stratigraphic logs reproduced here form an important level of detail underpinning the revised lithostratigraphy. Enclosure 2 gives a series of lithostratigraphic correlation panels drawn through key columns to form north-south and west-east transects. These panels provide a useful level of generalisation of the lithostratigraphy and help show the thickness distribution of the formations and members. The panels are flattened on the base of the Aotea Formation or the equivalent stratigraphic horizon, and show the location and extent of conformable and unconformable contacts between the various units.

Stratigraphic nomenclature

The Te Kuiti Group is subdivided into two subgroups, a lower Okoko Subgroup and an upper Castle Craig Subgroup. The revised stratigraphic scheme for the Te Kuiti Group has seven formations and 24 members of Kaiatian to Waitakian (Late Oligocene to Early Miocene) age (Fig. 1.2).

The Okoko Subgroup comprises the Waikato Coal Measures, Mangakotuku Formation, Glen Massey Formation and Whaingaroa Formation. The Castle Craig Subgroup comprises the Te Akatea Formation, Orahiri Formation and Otorohanga Limestone. The Orahiri Formation and Otorohanga Limestone can be difficult to distinguish from each another over extensive areas of the outcrop belt, especially in the vicinity of Kawhia Harbour, Te Kuiti and Awakino Gorge, and hence is referred to as undifferentiated Orahiri Formation/Otorohanga Limestone. In areas north of Raglan Harbour, units mapped by Kear (1963) and Waterhouse and White (1994) as Waitomo Sandstone and Otorohanga Limestone above Carter Siltstone are now included as basal units within the Waitemata Group.

Early Miocene Waitemata Group strata unconformably overlie the Te Kuiti Group in the north, reflecting basin inversion and erosion driven by uplift focused in the northeast. Early Miocene Mahoenui Group strata conformably overlie the Te Kuiti Group over much of the southern parts of the basin, with unconformable relationships along southeastern parts the Herangi Range (Nelson et al. 1994).

Readers are referred to the companion volume (Tripathi et al. 2008) for a full description of the lithostratigraphy of the Te Kuiti Group and its relationship to overlying units. The lithostratigraphy is underpinned by the numerous stratigraphic column descriptions contained in this report.

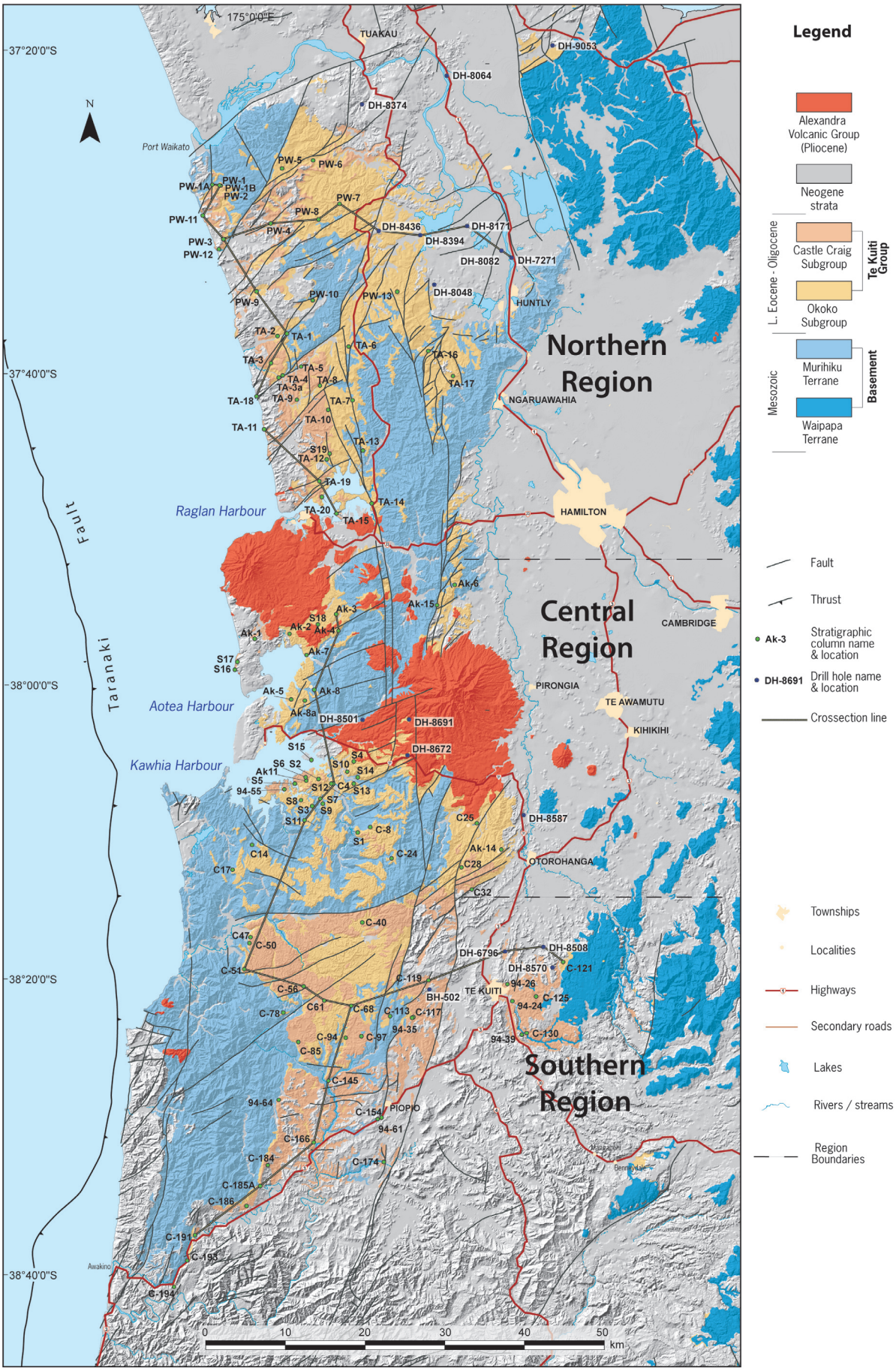

Fig. 1.1: Simplified map of the outcrop geology of the Waikato and King Country regions showing the distribution of Pliocene-Pleistocene volcanics, mid-Cenozoic Te Kuiti Group (Okoko and Castle Craig subgroups) and Mesozoic basement rocks in central-western North Island. Also shown are the major structural features. Map compiled from Edbrooke 2001 and 2005 QMAP Auckland and Waikato).

Waikato (north)				King Country (south)			
White & Waterhouse (1993)		This study		White & Waterhouse (1993)		This study	
Waitemata Group				Mahoenui Group			
Castle Craig Subgroup				Castle Craig Subgroup			
Otorohanga Lst		Regarded as Waitemata Group basal units		Otorohanga Lst	Piopio Lst Waitanguru Lst Pakeho Lst	Otorohanga Lst	Piopio Lst Waitanguru Lst Pakeho Lst
Waitomo Sst				Waitomo Sst			
Te Akatea Fm	Carter Zst Raglan Lst	Te Akatea Fm	Carter Zst Raglan Lst	Orahiri Lst	Te Anga Lst Mangaotaki Lst	Orahiri Fm	Waitomo Sst Te Anga Lst Mangaotaki Lst
Okoko Subgroup				Okoko Subgroup			
Aotea Fm	Patikirau Zst Mangiti Sst Waimai Lst	Aotea Fm	Patikirau Zst Waimai Lst / Mangiti Sst	Aotea Fm	Kihi Sst Hauturu Sst Waimai Lst	Aotea Fm	Kihi Sst Hauturu Sst / Waimai Lst
Whaingaroa Fm	Kotuku Zst	Whaingaroa Fm	Waikorea Sst Kotuku Zst	Whaingaroa Fm	Orotangi Sst Kotuku Zst Awamarino Lst	Whaingaroa Fm	Ngapaenga Zst Awaroa Lst
Glen Massey Fm	Ahirau Sst Dunphail Zst Elgood Lst	Glen Massey Fm	Ahirau Sst Dunphail Zst Elgood Lst	Glen Massey Fm	Ahirau Sst Elgood Lst	Glen Massey Fm	Ahirau Sst Dunphail Zst Elgood Lst
Mangakotuku Fm	Rotowaro Zst Pukemiro Sst Glen Afton Cst	Mangakotuku Fm	Waikaretu Sst Rotowaro Zst Pukemiro Sst Glen Afton Cst	Mangakotuku Fm	Undifferentiated	Mangakotuku Fm	Waikaretu Sst Rotowaro Zst
Waikato Coal Measures		Waikato Coal Measures		Waikato Coal Measures		Waikato Coal Measures	

Fig. 1.2: Comparisons between White & Waterhouse's (1993) lithostratigraphy for the Te Kuiti Group in northern and southern areas of central-western North Island versus the rationalised lithostratigraphy developed in this study.

Age and timescale

The stratigraphic columns show age expressed in terms of New Zealand stage names. The stage designations have been chiefly determined from microfossil content, and for selected units from their microfossil content. Historically, the biostratigraphy of the Te Kuiti Group was developed principally from Kear & Schofield's (1959) fossil collections of units cropping out between Papakura (southern Auckland) and Taumarunui (King Country). More recently, the formations and members within the group have been assigned stage designations based mainly upon N. Hornibrook's foraminiferal identifications (Hornibrook et al. 1989). Significant gaps in fossil collections in the Te Akau and Waitomo areas were filled by collections made by Kear (1963) and Nelson (1978a), respectively. Waterhouse & White (1994) made important additional fossil collections in the Raglan-Kawhia area. The majority of the biostratigraphic data used in this study are open file in the New Zealand Fossil Record Database (FRED).

Despite the advances of prior investigations, understanding about the biostratigraphy of the Te Kuiti Group remains problematic, being a combination of few biostratigraphic events during the Oligocene, and the difficulty of separating from tightly cemented limestone facies the foraminiferal species upon which the stages are based. The unconformities between formations and their correlative conformities provide important constraints on the interpretation of ages for various parts of the Te Kuiti Group.

The current biostratigraphic basis for defining the Late Eocene to Early Miocene stages in New Zealand, covering the age range of the Te Kuiti Group, are summarised in Figs 1.3 and 1.4. Type and reference sections for these stages, all of them outside the Te Kuiti Group except for the Whaingaroan-Duntroonian boundary (Fig. 1.3), are described by Cooper et al. (2004), and are not elaborated upon here.

Stratigraphic columns

The stratigraphic columns originate from various MSc and PhD theses, but have been imported into a common template and redrafted, with key information about the location of the various sections and outcrops standardized. Clearly indicated on each column is the author of the original column description. In addition to the descriptive text included on the columns, facies codes are listed for the various depositional units. The facies codes have been standardized in Tripathi (2008) and are presented in a series of facies

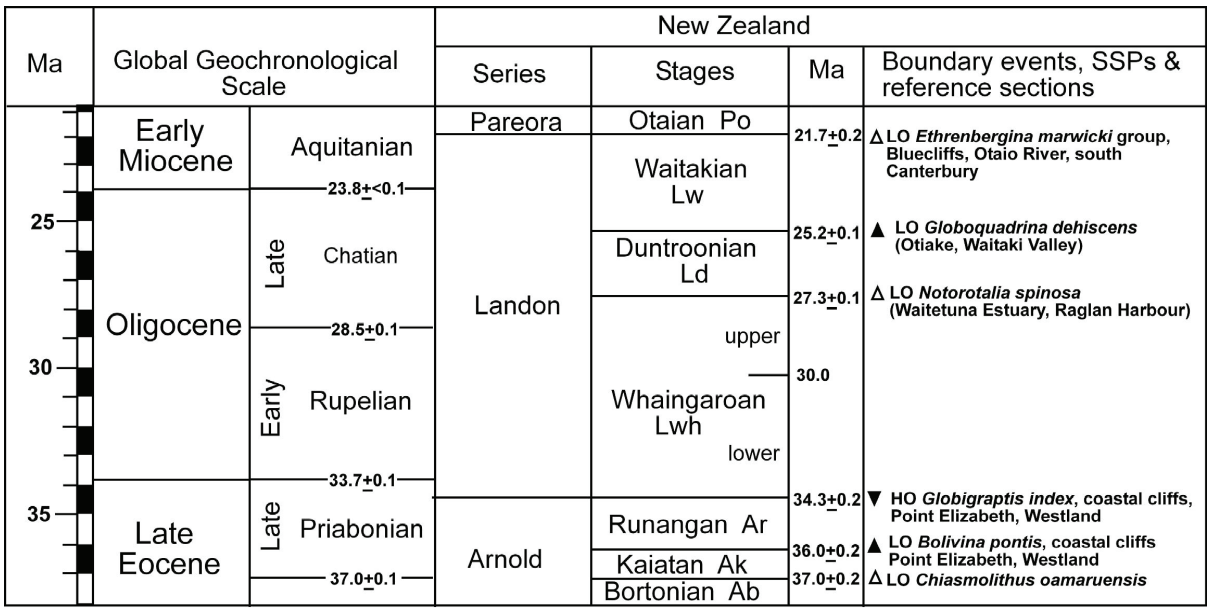

Fig. 1.3: Late Eocene to Early Miocene New Zealand Series and Stages correlated with the Global Geochronological Scale. The boundary-defining event for each stage is shown and the boundary stratotype section and point (SSP), or a reference section in brackets, are indicated. Formal SSPs are indicated by solid triangles and informal SSPs by open triangles. Adopted from Cooper et al. (2004).

tables, two for the Okoko Subgroup (Table 1.1, Glen Massey Formation and Whaingaroa Formation; Table 1.2, Aotea Formation) and one for the Castle Craig Subgroup (Table 1.3). Readers will need to cross reference between the codes on the stratigraphic columns and the corresponding descriptions in the respective tables. The stratigraphic columns also show photograph numbers and their stratigraphic range, with the photographs following each of the columns.

Arrangement of the columns in the report

The stratigraphic column locations are shown on Fig. 1.1 and on Enclosure 1. The columns are arranged within this report within NZMS 260 topographical map sheets (R13, R14, R15, R 16, R17 & R18, S14 & S15, S16) following a north-to-south and west-to-east pattern in their arrangement. Individual NZMS 260 map sheets shown at a larger scale than in Enclosure 1, and including the column locations, are incorporated within the volume ahead of the related columns for those areas.

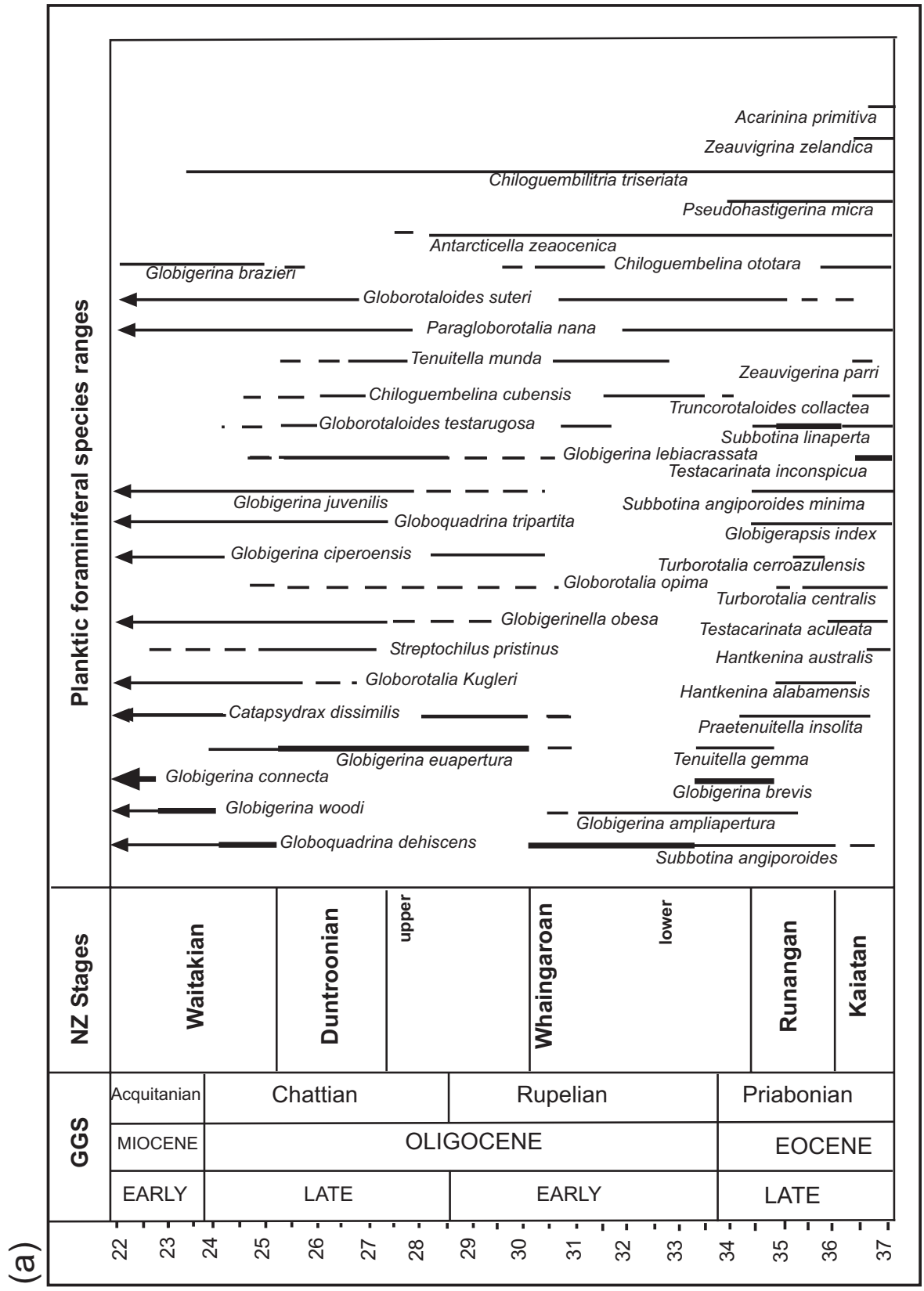

Fig. 1.4: Stratigraphic ranges of selected biostratigraphically useful planktic (a) and benthic (b) foraminifera. Adopted from Cooper et al. (2004).

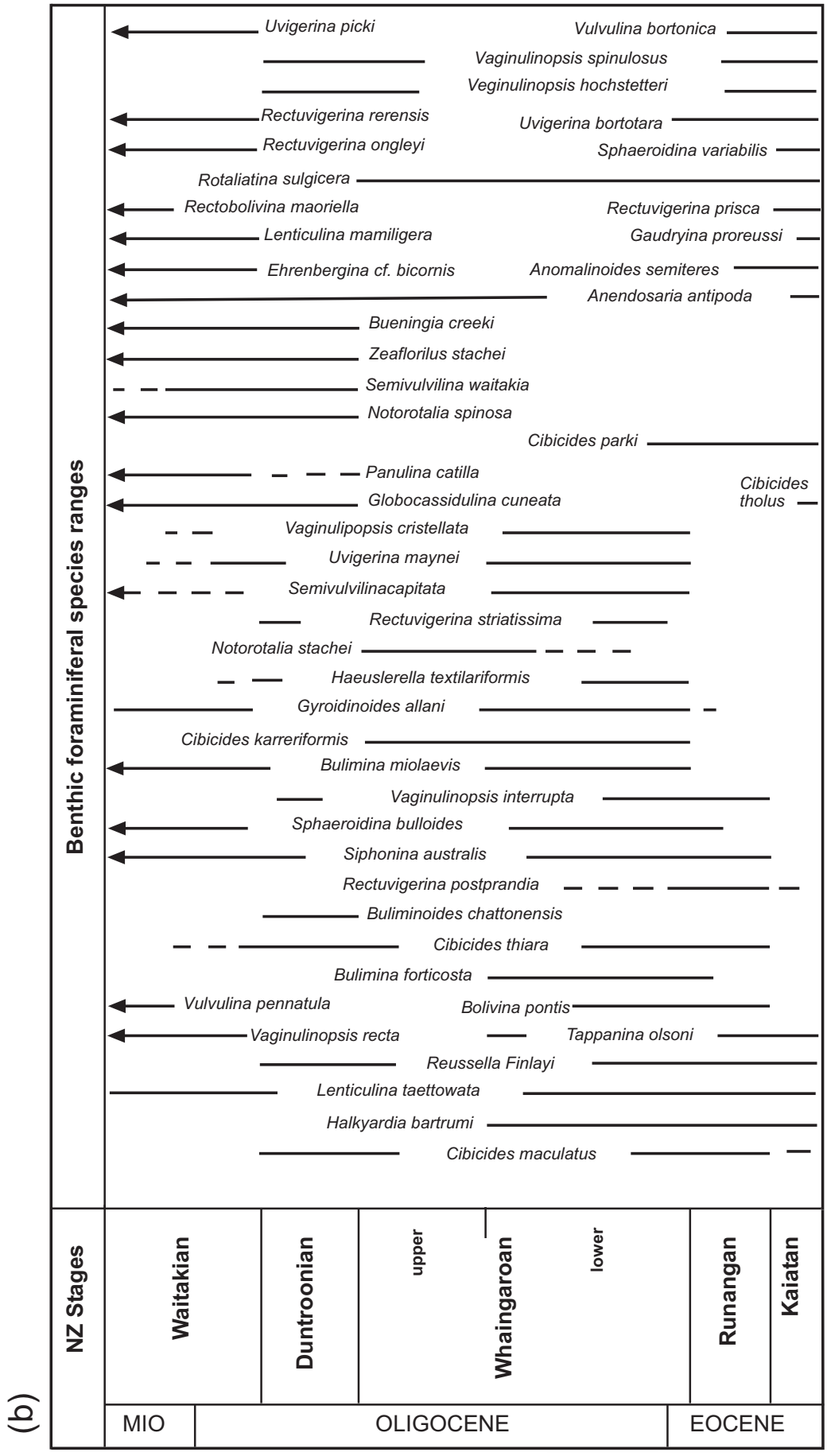

Fig. 1.4(continued): *Stratigraphic ranges of selected biostratigraphically useful planktic (a) and benthic (b) foraminifera. Adopted from Cooper et al. (2004).*

Table 1.1: Summary of sedimentary lithofacies for the Glen Massey Formation and Whaingaroa Formation

Litho-facies	Field characteristics	Wt % $CaCO_3$	Texture	Typical skeletons / bioturbation	Occurrence	Inter-pretation
Limestone lithofacies association (Elgood Limestone Member)						
L_1 Pebbly grain-stone	Common to abundant subrounded clasts averaging 1-10 cm derived from basement; fabric supported by coarse sparry limestone; poor bedding development, often massive in appearance	High (84-95%)	Medium to coarse grainstone-rudstone, frequent large bivalve fragments, very abraded.	Fragmented bivalves, notably oysters and pectinids, clasts occasionally encrusted by calcareous red algae, including rhodoliths up to 8-10 cm across	Commonly occurs as trans-gressive basal lag, tens of cm thick	Near shore to inner-most shelf, adjacent to rocky shore-line
L_2 Shelly grain-stone	Disarticulated bivalves haphazardly scattered through the limestone or occasionally concentrated into beds, poor to moderate bed development, irregular (bifurcating) interflags may give outcrop a knobbly appearance	High (85-91%)	Medium to coarse rudstone-grainstone, rare pebble granule clasts, moderately to very abraded	Pectinids, bryozoans, echinoids, *Amphistegina* grains, and coralline red algae	Common at base of limestone unit	Near shore to inner shelf

Table 1.1(continued): *Summary of sedimentary lithofacies for the Glen Massey Formation and Whaingaroa Formation*

Litho-facies	Field characteristics	Wt % $CaCO_3$	Texture	Typical skeletons / bioturbation	Occurrence	Inter-pretation
L_3 Cross-stratified grain-stone	Sigmoidal to tabular cross-beds are low (<10^0) to moderate angle (10^0-25^0), in sets from less than 0.5 to up to a 1.5 m thick, traceable laterally for a few tens of metres; set base and tops are sharp; well developed bedding is characteristic, typically 2-15 cm thick; bedding plain are typically rich in siliciclastics	High (88-94%)	Moderately to well sorted, medium to coarse grainstone; very to moderately abraded; siliciclastic particles in bedding planes are generally of fine sand to silt grade, rare granule size clasts	Bryozoans, echinoderms, bivalves, red algae and benthic foraminifera	Common along the western margin or developed locally about the flanks of paleo-highs	Sub-aqueous dunes migrating parallel to shore.
L_4 Horizont-ally bedded grain-stone	Beds typically well developed and 2-10 cm thick, separated by bedding planes (0.1 -1.5 cm) rich in siliciclastic particles; freshly broken surfaces have a homogeneous crystalline appearance	Moderate to high (68-97%)	Moderately sorted, fine to medium grainstone, moderately abraded	Echinoderms, bryozoans, bivalves, occasional casts/moulds of gastropod, large benthic foraminifera	Widespread along the basin margin, commonly thicken and thin over short distances	Inner to mid shelf

Table 1.1(continued): *Summary of sedimentary lithofacies for the Glen Massey Formation and Whaingaroa Formation*

Litho-facies	Field characteristics	Wt % $CaCO_3$	Texture	Typical skeletons / bioturbation	Occurrence	Inter-pretation
L_5 Massive to mod-erately bedded grain-stone-pack-stone	Irregular bed development, frequently even massive in appearance; undulatory bifurcating interflags; rare horizontal lamination, variably bioturbated (irregular inclined burrows)	Mod. to high (36-92%)	Fine grainstone-packstone, abraded	Abundant echinoids, bryozoans planktic and benthic foraminifers, occasional echinoid spine/ plate	Locally well developed	Lower inner to mid-outer shelf, wave (storm) domin-ated setting
Mixed carbonate-siliciclastic sandstone lithofacies association (Ahirau Sst Member)						
S_1 Calcar-eous pebbly-gritty sand-stone	Poorly to moderately well cemented; massive; rounded subrounded granule pebble basement clasts, fabric supported by calcareous fine silty sandstone, clast size shows crude normal grading	Low to moderate (25-77%)	Fine to coarse grained, poorly sorted	Occasional bivalve pectinid, oysters, red algae including rhodoliths, common glauconitised clasts and shell fragments, *Amphistegina*	Common immediately above the contact with basement and at the base of overlying limestone, may represent trans-gressive lag deposits	Inner-most shelf, proximal to rocky coast-line, with a moder-ately high silici-clastic influx
S_2 Calcar-eous silty fine sand-stone	Well cemented, massive fine grained calcareous sandstone and sandy-siltstone, heavily bioturbated low preservation of primary sedimentary structures however, locally, low-angle cross bedding is recognizable	Moderate (36-63%)	Fine to very fine sandstone to siltstone, poorly to moderately sorted	Scattered pectinids, echinoid spines, high diversity of trace fossils of mainly *Cruziana* ichnofacies (?)	This facies is well developed along the western margin	Inner to mid shelf with moder-ate to strong bottom currents driven by wind and/ or tides interact-ing with the inherited topo-graphy

Table 1.1(continued): *Summary of sedimentary lithofacies for the Glen Massey Formation and Whaingaroa Formation*

Litho-facies	Field characteristics	Wt % $CaCO_3$	Texture	Typical skeletons / bioturbation	Occurrence	Inter-pretation
S_3 Alter-nating calcar-eous silty fine sand-stone and silt-stone	Consists of alternating calcareous fine sandstone and silty-sandstone. Beds range from few centimetres to decimetre thick, with a variable carbonate content; bioturbation present throughout but not abundant	Moderate (33-61%)	Fine to very fine sandstone and siltstone, poorly to moderately sorted	Scattered bivalves, planktic and benthic foraminifera	Commonly forms the upper part of the Glen Massey Formation in northern region	Moderate energy in mid to outer shelf depths below fair-weather but above storm wave base.
S_4 Massive muddy sand-stone	Massive muddy sandstone, moderately cemented; heavily bioturbated	Moderate (45-54%)	Fine to very fine sandstone to siltstone, poorly sorted	Scattered pectinids and other bivalve fragments, occasional large burrows	Commonly overlies limestone units (L_4)	Mid shelf
Mixed carbonate-siliciclastic siltstone lithofacies association (Dunphail Siltst. Member)						
S_5 Inter-bedded calcar-eous siltstone and sandy lime-stone	Alternating fine sandy-siltstone and sandy limestone beds few centimeters to up to a metre thick, usually grades above into massive calcareous siltstone (S_6)	Moderate to high (40-78%)	Fine to very fine sandstone and siltstone, poorly to moderately sorted	Bivalve shell fragments common in the sandy limestone beds, evidence for heavy bioturbation present in silty intervals.	Commonly occurs as a transition between underlying limestone (L_4) and overlying massive calcareous siltstone (S_6)	Mid to outer shelf, between fair weather and storm wave base.

Table 1.1(continued): *Summary of sedimentary lithofacies for the Glen Massey Formation and Whaingaroa Formation*

Litho-facies	Field characteristics	Wt % $CaCO_3$	Texture	Typical skeletons / bioturbation	Occurrence	Inter-pretation
S_6 Massive calcar-eous siltstone	Massive blue-grey siltstone, well cemented. No obvious structures. Occasional concretionary bands with ellipsoidal shaped con-cretions up to 10 cm in size	Moderate to high (33-79%)	Fine silt with occasional traces of very fine to fine sandstone, moderately sorted	Planktic and benthic foraminifera, sparse macrofossils	Widespread throughout basin	Outer shelf to upper bathyal
Chemogenic lithofacies association						
C_1 Phos-phate nodule bed	Scattered phosphate nodules of up to 6 mm in a heavily bioturbated, well cemented, glauconitic fine sandstone-siltstone	Moderate (45-47%)	Fine to very fine sandstone to siltstone, poorly to moderately sorted	Rare bivalve shell fragment (mainly pectinids); abundant burrows	Not common; occurs as phosphat-ised hard-grounds at top of Ahirau Sst Member in Port Waikato area	Mid shelf
C_2 Glau-conitic calcar-eous siltstone-sand-stone	Glauconite occurs as silt and/or fine to medium sand size pellets and also as extrinsic filling within bioclasts; moderately to heavily bioturbated.	Moderate (68%)	Fine sandstone to siltstone	Scattered whole and fragmented bivalves, echinoid plates and spines frequently glauconitised; large benthic and / or planktic foraminifera	Common in certain areas generally occurring as basal facies represent-ing a con-densed trans-gressive deposit or in places marks the transition between TST and HST	Sediment starved shelf.
C_3 Glau-conitic sandy-silty grain-stone-pack-stone	Glauconite occurs as abundant pelletal and detrital (?) medium to fine sand size in a moderately bedded grainstone-packstone	High (73-82%)	Medium to fine sandstone to siltstone	Common bivalve shell fragments, *Amphistegina* benthic foraminifera, bioturbation not obvious	Common in some trans-gressive Deposits	Sediment starved inner-mid shelf.

Table 1.2: *Lithofacies of the Aotea Formation*

Litho-facies	Field characteristics, sedimentary structures, bedding type	Carbonate content / insoluble residue	Grain size range / abrasion/ sorting	Typical fauna / bioturbation	Common occurrence / typical example	Inter-pretation
Limestone lithofacies						
L_1 Pebbly grain-stone/ pack-stone	Common to abundant subrounded pebbles and cobbles reworked from the substrate; fabric supported by bioclastic silty fine sandstone. Occasional well defined horizontal bedding development, but often massive in appearance	Moderate (52-73%)	Medium to coarse grainstone-rudstone, with occasional large pectinid shell fragments, poorly to moderately sorted, and very abraded	Fragmented bivalves, large benthic foraminifers (esp. *Amphistegina* sp.), echinoid and bryozoan fragments with clasts occasionally encrusted by calcareous red algae including rhodoliths	Facies common near the lower contact with basement; inferred as transgressive basal lag deposits tens of cm thick. (forms basal part of Waimai Lst Member, Basal Beds "AoA" of Nelson 1978)	Near shore to inner-most shelf adjacent to rocky shoreline
L_2 Cross-strati-fied grain-stone	Sigmoidal to tabular cross-beds have low (< 10^0) to moderate dips (10^0-25^0), occur as 0.3-4.5 m thick cross-sets traceable laterally for few tens of metres; set base and tops are sharp and discordant; cross- beds are generally 2-15 cm thick, and bedding planes are typically rich in siliciclastic material	Moderate to high (56-94%)	Medium to coarse grainstone; rare small pebble size clasts; siliciclastic particles in bedding planes are generally of fine sandstone to siltstone, moderately abraded and moderately well sorted	Bryozoans, echinoderms, benthic foraminifers, occas. bivalves, coralline red algae, rare planktic foraminifers and barnacles	Comprises most of the lower and middle part of Waimai Lst Member along the western margin of the northern region; rare elsewhere	High energy inner to mid shelf domin-ated by strong offshore-directed storm and / or tidal induced currents

Table 1.2 (continued): *Lithofacies of the Aotea Formation*

Litho-facies	Field characteristics, sedimentary structures, bedding type	Carbonate content / insoluble residue	Grain size range / abrasion/ sorting	Typical fauna / bioturbation	Common occurrence / typical example	Inter-pretation
L_3 Hori-zon-tally bedded grain-stone / pack-stone	Beds typically well developed, averaging 2-10 cm are separated by bedding planes (0.1 -1.5 cm) rich in siliciclastic material; freshly broken surface reveals a homogeneous texture	Moderate to high (48-83%)	Fine to medium grainstone; abraded; moderately sorted	Echinoderms, benthic foraminifers, and to lesser extent planktic foraminifers, bryozoans and bivalves	Comprises most of the Waimai Lst Member in the eastern parts of the northern region	Inner to mid wave dominat-ed shelf
L_4 Sandy-silty grain-stone	2-15 cm thick beds, irregular undulating bedding planes laterally discontinuous; cavernously weathered; occasionally low angle ($<10^0$) cross-bedding obvious in places	Moderate to high (51-88%)	Medium to coarse grainstone, common. medium to coarse quartz sand, abraded, and moderately sorted	Echinoderm, benthic foraminifers, bryozoan, bivalves and calcareous red algae, planktic foraminifers are rare or absent	Comprises most of the lower part of Aotea Formation in the central/ southern regions. Represents transition between Hauturu Sst and Waimai Lst Member	Inner to mid shelf
L_5 Mas-sive to irregu-larly bedded biotur-bated grain-stone/ pack-stone	Massive to weak horizontal lamination, variably bioturbated (inclined/ vertical burrows)	Moderate (48%)	Fine grainstone-packstone, slightly abraded, and moderately sorted	Echinoderms, delicate branching bryozoans, benthic foraminifers	Comprises the upper part of Waimai Lst Member in the northern region area	Lower inner to mid-outer shelf; wave (storm) dominat-ed setting

Table 1.2 (continued): *Lithofacies of the Aotea Formation*

Litho-facies	Field characteristics, sedimentary structures, bedding type	Carbonate content / insoluble residue	Grain size range / abrasion/ sorting	Typical fauna / bioturbation	Common occurrence / typical example	Inter-pretation
Mixed carbonate-siliciclastic sandstone lithofacies						
S_1 Variably calcareous fine to medium-sandstone	Massive to concretionary bedded sandstone; well cemented centimeter-thick hard sandstone bands alternate with friable sandstone. Low angle cross-stratification and layered bands of shell hash and reworked granule-size basement clasts. Burrows and bioturbation structures abundant	Low to moderate (26-56%) carbonate rich and carbonate poor zones	Fine to medium sandstone, moderately sorted	Echinoderms, bryozoans and benthic foraminifera with occasional minor presence of calcareous red algae and bivalves	Most common towards the western margin in the southern region, absent in the north. (Hauturu Sst Member / Banded Sandstone Beds “Ao-5 “ of Nelson 1978)	Storm dominated fore-shore to mid shelf
S_2 Massive to thin bedded calcareous silty-sandstone	Well cemented, massive fine calcareous sandstone and silty-sandstone; moderately, bioturbated, low preservation of primary sedimentary structures; thin centimetre–scale horizontal bedding may be discernible in places	Low to moderate (26-39%)	Fine to very fine sandstone to siltstone, poorly to moderately sorted	Benthic foraminifera, rare bivalves, echinoid spines	Commonly forms the upper part of Aotea Formation in the central region. (Kihi Sst Member / Massive Ripply Sandstone Beds “Ao-3” of Nelson 1978)	Mid to outer shelf

Table 1.2 (continued): *Lithofacies of the Aotea Formation*

Litho-facies	Field characteristics, sedimentary structures, bedding type	Carbonate content / insoluble residue	Grain size range / abrasion/ sorting	Typical fauna / bioturbation	Common occurrence / typical example	Inter-pretation
S_3 Inter-bedded calcar-eous sand-stone and sandy silt-stone	Calcareous fine sandstone with thin silty interbeds; beds range from few centimeters to tens of centimetres thick burrows common in the silty interbeds	Moderate (46-65%)	Poorly to moderately sorted, fine to very fine sandstone and siltstone	Rare scattered echinoderm fragments, sparse macrofossils	Commonly forms the lower part of the Aotea Formation in the northern region (Mangiti Sst Member)	Moderate energy mid shelf depths below fair-weather but above storm wave base
S_4 Mass-ive bioturbated muddy-sand-stone	Massive muddy sandstone; moderately cemented; occasional pebble –granule bands; heavily bioturbated	Moderate (47-55%)	Fine to very fine sand to silt, poorly sorted	Common *Janupecten polemicus, Panopea worthingtoni* and occasional other bivalve fragments, foraminifers	Most common towards eastern areas (Kihi Sst Member/ Massive Muddy Sandstone Beds “Ao-2” of Nelson 1978)	Low energy mid to mid-outer shelf, above storm wave base
Mixed carbonate-siliciclastic siltstone lithofacies						
Z_1 Mass-ive variably calcar-eous sandy silt-stone	Massive blue-grey siltstone, moderately to well cemented. No obvious structures except infrequent concretionary sandstone beds.	Low to high (29-73%)	Fine siltstone with minor amounts of moderate-ly sorted very fine to fine sandstone	Planktic and benthic foraminifera, sparse macrofossils	Widespread in the northern region forming the upper part of Aotea succession, not common in south but present locally in some areas (Patikirau Siltstone Member)	Mid-outer shelf to possibly upper bathyal

Table 1.2 (continued): *Lithofacies of the Aotea Formation*

Litho-facies	Field characteristics, sedimentary structures, bedding type	Carbonate content / insoluble residue	Grain size range / abrasion/ sorting	Typical fauna / bioturbation	Common occurrence / typical example	Inter-pretation
Chemogenic lithofacies association						
C_1 Glau-conitic silt-stone and sand-stone	Massive, Glauconite occurs as silt and/or fine to medium sand size pellets and also as extrinsic filling within bioclasts, heavily bioturbated.	Low to moderate (27-48%)	Fine to medium sand stone to siltstone	Highly fossiliferous scattered whole and fragmented bivalves (*Janupecten polemicus*, *Lentipecten hochstetteri*) and solitary corals F*labellum* sp.; occasional whole echinoids, plates and spines.	Common in some areas near the top of Aotea Formation (Glauconitic Sandstone Beds “Ao-4” of Nelson 1978)	Sediment starved mid-outer shelf
C_2 Glau-conitic pack-stone / wacke-stone	Glauconite occurs as abundant pelletal and glauconitised shells and infills moderately bedded –packstone / wackestone; bioturbation abundant.	Moderate to high (48-82%)	Medium to fine sandstone to siltstone	Common bivalve shell fragments, occasional whole echinoderms, benthic and planktic foraminifera	Common in some transgressive deposits. Restricted to the northwest. (Waimai Lst Member)	Sediment starved inner to mid shelf

Table 1.3: Lithofacies of the Castle Craig Subgroup.

Litho-facies code and name	Field characteristics, sedimentary structures, bedding type	Carbonate content/ insoluble residue	Texture size range /abrasion/ sorting	Typical fauna / bioturbation	Common occurrence / typical example	Inter-preta-tion
Limestone association						
$L_{1.}$ Pebbly grain-stone -pack-stone.	Common to abundant subrounded pebbles and cobbles may occur as pebble bands, or fabric supported by bioclastic silty fine sandstone, usually massive in appearance	Moderate (50-60%)	Medium to coarse grainstone-rudstone, occasional large shell fragments, poorly to moderately sorted; very abraded	Fragmented pectinids, oysters, echinoderm, clasts occasionally encrusted by calcareous red algae including rhodoliths	Common near the lower contact with basement, and/or mark erosional contact with the underlying formation; up to tens of centimeters thick. "Basal Beds" (OrA1/ OtA1 of Nelson 1978a).	Near shore to inner shelf adjac-ent to rocky shore-line
L_{2}. Cross-strati-fied grain-stone	Sigmoidal to tabular cross-beds are low (< 10^0) to moderate angle (10^0-25^0); occur as 0.3-4.5 m thick cross-sets traceable laterally for few tens of metres; base and tops of sets are sharp and discordant, cross-beds are generally 2-15 cm thick	High (91-96%)	Medium to very coarse grainstone, rare small pebbles and granules. Siliciclastic particles in bedding planes are generally of fine sandstone to siltstone, mod. abraded, poorly to moderately sorted.	Bryozoans, echinoderms, benthic foraminifers, occas. bivalves, coralline red algae, rare planktic foraminifers.	Developed locally in the lower, mid and upper parts of Orahiri Formation and Otoro-hanga Limestone.	High energy inner to mid shelf domin-ated by strong off-shore-direct-ed storm and or tidal induc-ed cur-rents.

Table 1.3 (continued): *Lithofacies of the Castle Craig Subgroup.*

Litho-facies code and name	Field characteristics, sedimentary structures, bedding type	Carbonate content/ insoluble residue	Texture size range /abrasion/ sorting	Typical fauna / bioturbation	Common occurrence / typical example	Inter-preta-tion
L_3. Horizon-tally bedded grain-stone.	Beds typically well developed, averaging 2-10 cm; well developed flagginess is characteristic	High (81-99%)	Medium to very coarse grainstone, abraded, poorly to moderately sorted.	Bryozoans, echinoderms, benthic foraminifers, and occasional bivalve, calcareous red algae; planktic foraminifers rare or absent	Comprises most of the Orahiri Formation and Otorohanga Limestone. “Flaggy Limestone Beds” (OrB1, OtA2, OtC1) of Nelson 1978a.	Inner to mid wave domin-ated shelf.
L_4. Sandy grain-stone-pack-stone.	Commonly varying from massive to tabular bedded units, bedding plane (0.1 - 1.5 cm) rich in siliciclastic material is obvious in places	Moderate to high (42-87%)	Coarse to very coarse grainstone, common medium to coarse quartz sand grains, abraded, and poorly to moderately sorted.	Echinoderm, large benthic foraminifers (*Amphiste-gina*), bryozoan, and occasional bivalves calcareous red algae; planktic foraminifers rare or absent.	Comprises most of the Mangaotaki Limestone Member mainly in western areas. “Sandy Limestone Beds” (OrA3, OrA4, OrA5, OrB4) of Nelson 1978a.	Inner to mid shelf.
L_5. Massive to irregul-arly bedded, fossilifer-ous rud-stone-grain-stone.	Massive to irregularly bedded, occasionally well bedded 20-100 cm thick beds, commonly develops “knobbly“ to blocky weathering feature, frequently cavernously weathered	High (98-100%)	Medium to coarse grainstone, common large skeletal fragments, abraded, poorly to moderately sorted.	Bryozoans (up to 80 %), echinoderms, benthic foraminifers, common bivalves and gastropods moulds and occasional calcareous red algae.	Comprises most of the Waitanguru Limestone Member (Otorohanga ‘B’). “Blocky and Knobbly Limestone Beds” (OtB1, OtB2, OtB3) of Nelson 1978a.	Bryo-zoan mound buildup indicat-ing high energy inner-mid shelf depths.

Table 1.3 (continued): *Lithofacies of the Castle Craig Subgroup.*

Litho-facies code and name	Field characteristics, sedimentary structures, bedding type	Carbonate content/ insoluble residue	Texture size range /abrasion/ sorting	Typical fauna / bioturbation	Common occurrence / typical example	Inter-preta-tion
L_6. Pebbly-oyster float-stone-pack-stone.	Massive to irregularly bedded, tens of centimeter thick; beds laterally traceable for few metres	High (77-97%)	Medium to very coarse with pebbles (<2 cm), clasts and matrix supported, poorly sorted.	Articulated / disarticulated, randomly orientated oysters (*Flemingo-strea sp.*), bryozoans, echinoderms, benthic foraminifers, bivalves and occasional calcareous red algae, solitary corals (*Flabellum*).	Comprises most of the Te Anga Limestone Member. "Oyster and Fossil Hash Beds" (Or B2, OrB5) of Nelson 1978a.	Oyster reefs com-monly associ-ated with sandy grain-stone -pack-stone, high energy tide swept inner-mid shelf
L_7. Con-glom-eratic limestone	Bedded units 0.5-3 m thick with abundant clasts of limestone, calcareous sandstone and rounded subrounded basement pebbles, which are frequently profusely bored	Moderate to high.	Coarse to very coarse sparry grainstone with 1-10 cm size clasts, poorly sorted	Bryozoans, echinoderms, benthic foraminifers, oysters and occasional calcareous red algae encrusting basement pebbles	Occurs as conspicuous unit within Orahiri Formation near Awakino Tunnel "Limestone in Limestone Beds" (OrB6) of Nelson 1978a	Inter-preted as carbon-ate debrite/ mass em-placed unit - deposit-ed at shelf depths in re-sponse to tilting

Table 1.3 (continued): *Lithofacies of the Castle Craig Subgroup.*

Litho-facies code and name	Field characteristics, sedimentary structures, bedding type	Carbonate content/ insoluble residue	Texture size range /abrasion/ sorting	Typical fauna / bioturbation	Common occurrence / typical example	Inter-preta-tion
Mixed carbonate-siliciclastic sandstone association						
L_8. Massive to horizon-tally bedded skeletal pack-stone-wacke-stone.	Massive to well bedded (2-25 cm) with prominent sub-horizontal to bifurcating thin (0.5 -1.5 cm) silty interbeds	Moderate to high (59-89%)	Predominantly micritic with scattered whole and fragmented bivalve (pectinids) and echinoderms, poorly to moderately sorted.	Moderate to abundant planktic with subequal proportions of echinoderms, benthic foraminifers and bivalve fragments, occasional whole well preserved echinoderms. Bryozoans and calcareous red algae are absent or present in traces.	Comprise most of the Raglan Limestone Member in the northern region; also occurs as a transition facies near the upper contact with Mahoenui Group. "Argillace-ous Limestone Beds" (OtC2) of Nelson 1978a.	Outer shelf to slope
S_1. Massive glauco-nitic muddy sand-stone.	Typically massive with smooth weathering profile, poorly to moderately cemented, and bioturbated	Low to moderate (20-60%)	Fine to very fine sandstone, poorly sorted	Echinoderms, bryozoans and benthic foraminifers with rare presence of calcareous red algae and bivalves.	Most common in the Waitomo Valley area, "Waitomo Sandstone Formation" of Nelson 1978a)	Mid to outer shelf.
S_2. Fossilif-erous silty sand-stone and sandy siltstone.	Massive, dull brownish grey, moderately cemented, occasional hard concretionary glauconitic sandstone bands, bioturbated.	Moderate (38-62%)	Fine silty sandstone with scattered large bivalve and skeletal fragments, poorly sorted	Oysters (*Flemingo-strea sp.), Athletopecten athleta, Lentipecten hochstetteri, Panopea worthingtoni, Dosinia sp*., solitary corals (*Flabellum* sp.), abundant *pectinid fragments* and benthic foraminifers.	Mostly forms the top part of the limestone (Orahiri Formation/ Otorohanga Limestone) at inland Kawhia Harbour area.	Mid-outer shelf above storm wave base.

Table 1.3 (continued): *Lithofacies of the Castle Craig Subgroup.*

Litho-facies code and name	Field characteristics, sedimentary structures, bedding type	Carbonate content/ insoluble residue	Texture size range /abrasion/ sorting	Typical fauna / bioturbation	Common occurrence / typical example	Inter-preta-tion
Mixed carbonate-siliciclastic siltstone association						
$Z_{1.}$ Medium bedded calcar-eous siltstone	Light grey to creamy yellow, moderately to well bedded (10-50 cm), occasional glauconitic in-filled burrowed horizons (10-30 cm) locally present	Moderate (51-75%)	Medium to coarse siltstone, occasional whole bivalve, gastropod and echinoderm, poorly to moderately sorted	Dominated by planktic foraminifers with variable proportion of benthic foraminifers, echinoderms and bivalves, bryozoans	Common in the lower part of Carter Siltstone Member	Outer shelf to upper bathyal
Z_{2}. Massive calcar-eous siltstone	Massive, light bluish grey to brownish grey, characteristic conchoidal fracture when fresh, weathers into a finely frittered surface.	Low to moderate (24-73%)	Predominantly medium to coarse siltstone, however admixture of very fine to fine sand grains may be observed locally, fine-sand sized planktic foraminifera commonly recognisable, poorly to moderately sorted.	Bioclasts are dominated by planktic foraminifers with minor proportion of benthic foraminifers, echinoderms and bivalve whole shells fragments.	Wide-spread in the northern region forming most of the Carter Siltstone Member.	Outer shelf to upper bathyal

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