BASIN ANALYSIS OF THE
LATE EOCENE – OLIGOCENE TE KUITI GROUP,
WESTERN NORTH ISLAND,
NEW ZEALAND

A thesis
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ABSTRACT

The Late Eocene – Oligocene Te Kuiti Group crops out extensively in central-western North Island between Port Waikato and Awakino, providing a useful window for examination of a broadly transgressive shelfal to upper bathyal mixed carbonate-siliciclastic basin fill succession. The group accumulated during initiation of Cenozoic glaciations on Antarctica when there may have been associated eustatic changes in sea- level changes, and during the initiation of the Australia-Pacific plate boundary through the New Zealand region, which might also have caused relative changes in sea level in the Waikato Basin.

As part of this study Te Kuiti lithostratigraphy in central-western North Island has been reviewed and rationalized. Special emphasis has been given to correlation of the significant stratigraphic discontinuities (erosional unconformities, depositional hiatuses) between units. Combined with a review of the foraminiferal biostratigraphy and new Sr isotope ages for the group, lithologically diverse formations have been able to be correlated across and along the outcrop belt. In the revised stratigraphic scheme, seven formations and 24 members of Kaiatian to Waitakian (Late Oligocene to Early Miocene) age are identified. The Te Kuiti Group is subdivided into two subgroups, a lower Okoko Subgroup, and an upper Castle Craig Subgroup. The Okoko Subgroup is dominated by calcareous siltstone and sandstone members, with limestone members commonly occurring at the base of formations, whereas the Castle Craig Subgroup is almost entirely comprised of limestone in the south and by calcareous siltstone in the northern parts of the basin.

Six unconformity-bound sequences (TK1 – TK6) have been identified and mapped within the Te Kuiti Group using sequence stratigraphic principles. For several of these sequences (TK2, TK4, TK5 & TK6) detailed facies and sequence analyses have been undertaken based on field characteristics, complemented with laboratory grain size and compositional (carbonate % and thin-section) data. The depositional paleoenvironments have been interpreted for these sequences, with the basin evolution for all sequences summarised in a series of 13 paleogeographic maps representing multiple horizons within the Te Kuiti Group.

TK1 strata are mostly terrestrial coal measures (Waikato Coal Measures) of Late Eocene to earliest Oligocene age that accumulated in paleovalleys concurrent with minor extensional faulting. The upper beds are marginal marine and consist primarily of estuarine and shallow shelf mudstone (Mangakotuku Formation). The Early Oligocene (lower Whaingaroan) Glen Massey Formation (TK2) is entirely marine in origin, its lowermost member (Elgood Limestone Member) marking a significant marine flooding event across the basin with a landward shift in the position of stratal onlap. Whaingaroa Formation (TK3) comprises predominantly siltstone with some limestone (Awaroa Limestone Member) at its base in the south, which reflects expansion of a southern shelf area.

An extensive subaerial unconformity between Whaingaroa Formation (TK3) and Aotea Formation (TK4), combined with a basinward shift in the position of onlap for sequence TK4, indicates a dramatic mid-upper Whaingaroan (c. 29 Ma) change in stratigraphic development and basin dynamics inferred to result from the start of reverse displacement on Taranaki Fault along the basin's western margin. Aotea Formation comprises lithologically diverse facies dominated by limestone (Waimai Limestone Member) in the north, calcareous sandstone (Hauturu Sandstone Member) in the southwest and muddy sandstone (Kihi Sandstone Member) in south-central and eastern areas. A condensed section in the upper parts of Aotea Formation, especially in the north, records relative deepening and reduction of clastic sediment supply into sediment-starved northern parts of the basin.

A major erosional unconformity at the base of the Castle Craig Subgroup in the south and a depositional hiatus in the north reflects a second phase of inversion along the southwestern margin of the basin and reverse displacement on Manganui Fault at c. 27 Ma. The rocky shorelines that consequently formed along the eastern side of the Herangi High supported carbonate factories supplying reworked carbonate to the adjacent shelf (Orahiri Formation and Otorohanga Limestone). These formations pass northward into outer shelf-upper bathyal micritic limestone (Raglan Limestone Member) and calcareous siltstone (marl). Several additional phases of unconformity development are recorded in the Castle Craig Group, but these unconformities had limited extent in the basin, being mainly restricted to the area immediately east of the Herangi High.

Early Miocene Waitemata Group strata unconformably overlie the Te Kuiti Group in the north, reflecting basin inversion and erosion driven from a developing subduction zone to the northeast, whereas early Miocene Mahoenui Group strata in southern parts of the basin are mostly conformable on the Te Kuiti Group, having accumulated in a piggy-back basin carried westward on underlying Taranaki and related faults. Tectonic movements and cycles of subsidence and subtle basin inversion driven by the alternate accumulation and release of strain on Taranaki and related fault are regarded as the primary control on relative sea-level changes within the Te Kuiti Group, which led to sequences TK4-TK6. The accumulation of sequences TK1–TK3 resulted from tectonic subsidence in the Waikato region as the zone of extension widened to the east of Taranaki Basin coupled with progressive landward shifts in the position of coastal onlap. Glacio-eustatic sea- level changes driven from glaciations in Antarctica are not regarded as having generated sea-level changes of sufficient magnitude to impact upon the dynamics of late Eocene and Oligocene sedimentation in the Waikato Basin when the Te Kuiti Group accumulated.

ACKNOWLEDGEMENTS

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Chapter One

Introduction

Overview

This study presents a comprehensive stratigraphic and sedimentologic investigation of the mid Cenozoic Te Kuiti Group exposed within central-western North Island, New Zealand (Fig. 1.1). It aims to improve information, knowledge and understanding about the depositional history of the temperate-latitude mixed siliciclastic-carbonate succession of the Te Kuiti Group and implications for the geological development of wider New Zealand.

The Te Kuiti Group ranges in thickness from 100 to 500 m, comprising a wide variety of carbonate and siliciclastic lithofacies that rest unconformably upon a Mesozoic basement comprised of greywacke and argillite. An historical problem has been disparity between the lithostratigraphic schemes established for northern versus southern regions of central-western North Island. The need to rationalize Te Kuiti Group lithostratigraphy across the whole of its outcrop belt was identified as a prerequisite to better understanding the depositional systems within the group, and hence the origin and significance of this stratigraphic record.

The Te Kuiti Group accumulated during the transition from a greenhouse (L. Eocene) to icehouse (Oligocene) world, an interval traditionally regarded in New Zealand geology as tectonically quiescent, characterised by regional subsidence, marine inundation and limestone formation throughout many parts of New Zealand. It follows that the continental shelf setting in which the group accumulated might therefore contain a record of eustatic sea level changes related to the development of ice on Antarctica, or at least provide a test of interpretations other workers might have made about Oligocene sea level oscillations. This of course depends critically upon the assumption that the Te Kuiti Group record was not influenced by local tectonic movements. To help separate possible tectonic from eustatic controls on relative sea level changes, particular attention has been given to the identification of vertical changes in depositional environments within formations and to the extent and origin of unconformities that bound most of the formations. The unconformities are viewed as sequence boundaries associated with Vail-type sequences. Six sequences have been identified within the group and there has been an emphasis in this study on the likely stratal patterns within sequences, and hence the vertical and horizontal nature and extent of linked depositional systems (systems tracts).

Source: Geographix

Fig. 1.1: Physiography of the New Zealand North and South Islands, with nominal outline of study area. Refer to Fig. 2.5 for names of regional features.

Research objectives

This study has the following research objectives:

1. The development of a comprehensive lithostratigraphic framework for the Te Kuiti Group exposed in central-western North Island. This includes a review of previous lithostratigraphic schemes devised for the group, particularly the inferred stratigraphic relationships between northern and southern parts of the study area.
2. The development of a coherent age model for the group based upon micro- and macro-fossil biostratigraphy, combined with the determination of Sr isotope numerical ages from macro fauna.
3. The development of a robust sequence stratigraphic scheme for the Te Kuiti Group, including subdivision into systems tracts (linked depositional systems) where possible.
4. Completion of facies analysis for several formations of the group as a basis

to interpret the related depositional paleo-environments, and to undertake this in the context of the sequence stratigraphic analysis and the definition of the linked depositional systems (systems tracts).

5. Develop a comprehensive series of paleogeographic maps for multiple horizons within the Te Kuiti Group as a basis to synthesise the development of the basin during the late Eocene through to Early Miocene, and to interpret the controls on sedimentation.

Methods

Detailed field investigations have been undertaken in the main outcrop areas between Port Waikato in the north and Awakino in the south. Numerous stratigraphic sections were measured and described in detail, recording facies types and determining contact types and stratigraphic relationships. This involved the re-examination of stratigraphic sections previously described by other workers, and the collection of samples for petrographic description and analysis. These data are presented in appendices as stratigraphic columns (Appendix I) and compositional and grain size data (Appendices II - V).

Because eastern areas in the Waikato and King Country have comparatively little outcrop, where available, coal exploration drill hole logs were used to establish lithostratigraphic correlations and to better understand the basin architecture. Stratigraphic data from selected petroleum exploration holes located along the eastern margin of Taranaki Basin have also been assimilated into the paleogeographic reconstructions for the study area.

Biostratigraphic age information has been derived from a review of existing fossil collections, particularly microfaunal data as registered in the Fossil Record File. Numerical ages have been derived from the determination of Sr isotope ratios on macrofossils.

Thesis structure and format

The results of this study are presented in a conventional thesis style, and have been compiled in three main parts. 1. Nine chapters in the main part of the thesis give the new knowledge and information established as part of this study, and present interpretations and conclusions. 2. A location map, cross sections and paleogeographic maps for the basin are presented as thesis enclosures (Enclosures 1 - 3). 3. Appendices (I - VII) include supporting data used in the analyses and interpretations presented in the main thesis chapters. Brief descriptions are given in the next sections for each of the chapters.

Chapter Two: Geological Setting

Chapter 2 outlines the geological setting of central-western North Island. It provides an overview of the tectonic setting, the underlying basement geology (including its gravity and magnetic signatures) and a brief description of the major geological events that have affected the region. The chapter also discusses the main physiographic elements of the study area.

Chapter Three: Rationalisation of Te Kuiti Group lithostratigraphy

Chapter 3 provides an overview of previous lithostratigraphic investigations and Te Kuiti Group nomenclature. Rationalisation of the lithostratigraphy and north to south correlations forms a critical component of this study. The chapter presents formal definitions and description of the subgroups, formations and members in the group.

Chapter Four: Biostratigraphy and age

Chapter 4 outlines a coherent age model for the Te Kuiti Group. The ages are based largely on foraminiferal biostratigraphy and molluscan biostratigraphy, with palynoflora (pollen and spores) used to differentiate ages for non-marine and marginal marine parts of the succession. Strontium isotope determinations are also to develop numerical age estimates for horizons within the group.

Chapter Five: Facies analysis, sequence stratigraphy and paleoenvironments of Glen Massey Formation

Chapter 4 describes the facies, facies associations and sequence architecture of the Glen Massey Formation. Facies analysis is the main sedimentologic method applied, together with the derivation and interpretation of petrographic data such as grain size, carbonate content and thin-section petrography for representative samples. The facies and inferred environments are interpreted as linked depositional systems constrained by key sequence stratigraphic surfaces. The combined facies and sequence analysis lead to the development of paleogeographic maps for different parts of the Glen Massey Formation.

Chapter Six: Facies analysis, sequence stratigraphy and paleoenvironments of Aotea Formation

Chapter 6 involves facies and sequence stratigraphic analysis of the Aotea Formation. The approach is the same as for analysis of the Glen Massey Formation. Based on this information, basin wide paleogeographic maps are drawn for early and late parts of the formation. An idealized Aotea sequence is presented at the end of the chapter, expressed as east-west cross-shelf transects representative of northern and southern parts of the study area.

Chapter Seven: Lithofacies, paleoenvironments and sedimentary evolution of Castle Craig Subgroup

Chapter 7 describes and analyses the facies, sequence architecture and paleoenvironments of a carbonate shelf and slope succession that developed during the Late Oligocene, represented by the Castle Craig Subgroup. The carbonate factory is considered to have formed along and around a rocky shoreline on the eastern side of the Herangi High. Fragmented debris principally of sand size was disbursed across the shelf to the east by a combination of storm and tide-driven currents (Orahiri Formation and Otorohanga Limestone). Finer grained carbonate facies were transported down a shallow gradient slope into upper bathyal depths to the north and northeast forming the Raglan Limestone Member and Carter Siltstone Member (marl). An idealised shelf to slope transect and discussion of its inferred evolution are presented in the final section of this chapter.

Chapter Eight: Basin Synthesis

The chapter 8 outlines the paleogeographic development of the basin based upon a series of 13 paleogeographic maps (Enclosure 3) drawn for various horizons in the group. The maps and discussion summarise depositional patterns and events across central-western North Island during the Late Eocene and Oligocene. This leads on to discussion about the stratigraphic architecture of the group and the observed depositional cyclicity and their controls. A chronostratigraphic panel representative of a north-south transect is presented to illustrate the relative age, facies distribution, and key surfaces within the basin-fill with comparisons made with the stratigraphy of the adjacent eastern margin of Taranaki Basin. It is concluded that eustatic sea-level changes cannot explain the cyclicity in the Te Kuiti Group, based upon comparisons between the magnitude and frequency of various global records compared with onlap curves developed for the Te Kuiti Group from its sequences. A tectonic model is developed, based upon a west-east cross section through Awakino that attributes sequence development in the Te Kuiti Group to tectonic cycles of uplift, erosion, subsidence and marine sedimentation driven by a dècollement in the underlying basement linked to the Taranaki Fault. Prior to the c. 29 Ma start of contraction across the Taranaki Fault the eastern margin of Taranaki Basin was controlled by normal faulting, and the Waikato Basin developed as a sag basin with minor normal faulting.

Enclosures

1. Simplified geological map of central-western North Island showing the distribution of basement, Te Kuiti Group as Okoko Subgroup and Castle Craig Subgroup, Pliocene-Pleistocene volcanics and undifferentiated

Neogene strata. Also shown are the locations of stratigraphic columns in relation to roads, streams and place names.

2. Correlation panels (north-south and east-west) showing Te Kuiti Group formations and members in cross-section.
3. Thirteen Late Eocene to Early Miocene paleogeographic reconstructions for the Te Kuiti Group and basal parts of the Waitemata and Mahoenui groups in central-western North Island.

Appendices

Appendix I	Stratigraphic columns
Appendix II	Sample catalogue
Appendix III	Thin section petrography (on DVD only)
Appendix IV	Carbonate % wt. analysis (on DVD only)
Appendix V	Grain size analysis data (on DVD only)
Appendix VI	Foraminifera analysis data (on DVD only)
Appendix VII	Sr isotope, O and C isotope data

Chapter Two

Geological Setting and Physiography

Introduction

The study area covers about 5500 km^2 of the Waikato and King Country regions in central-western North Island, New Zealand. Sedimentary basins in western North Island include the King Country Basin and the Waikato Basin. The boundary between these basins is poorly defined and while discrete depocentres can be mapped, there is overlap between them. The thesis deals principally with a Late Eocene-Oligocene basin stretching from South Auckland to the northern King Country region. For simplicity this is referred to as the Waikato Basin because it is extensive through the Waikato Region. Fig. 2.1 is a simplified geology map showing in particular the distribution of the Te Kuiti Group via its subgroups, the lower one being Okoko Subgroup and the upper one being the Castle Craig Subgroup. These units are well exposed in the hill country of central-western North Island between Port Waikato and Awakino.

Physiographic setting

The landscape of the region is mainly the result of late Cenozoic normal faulting coupled with erosion processes, Pliocene basaltic volcanism, and the emplacement of silicic ignimbrites and fall deposits of Quaternary age sourced from volcanism in central North Island (Taupo Volcanic Zone) (Edbrooke 2005).

The region has several major geomorphic features which reflect the underlying geology (Fig. 2.2). The most prominent of these include the western Waikato hill country extending between Port Waikato in the north and Awakino in the south. This hill country is formed on basement greywacke and argillites of the Murihiku Supergroup and overlying Tertiary sedimentary rocks including calcareous formations of the Te Kuiti Group. Across this region, the Te Kuiti Group is preserved in faulted depressions and as erosional remnants or outliers on the flanks of uplifted basement blocks. The Herangi Range in the west is the highest and most incised of the ranges and reaches an elevation of nearly 800 m above sea level. Limestone and calcareous sandstone formations of the Te Kuiti Group commonly form karst topography with steep bluffs. Karst topography is particularly well developed south of Marokopa Fault, including spectacular cave formations at Waitomo Caves. Composite cones of Pirongia and Karioi volcanoes dominate the landscape in the central parts of the field area. There are substantial coastal inlets along the west coast, including Raglan, Aotea and Kawhia harbours, with extensive dune sand

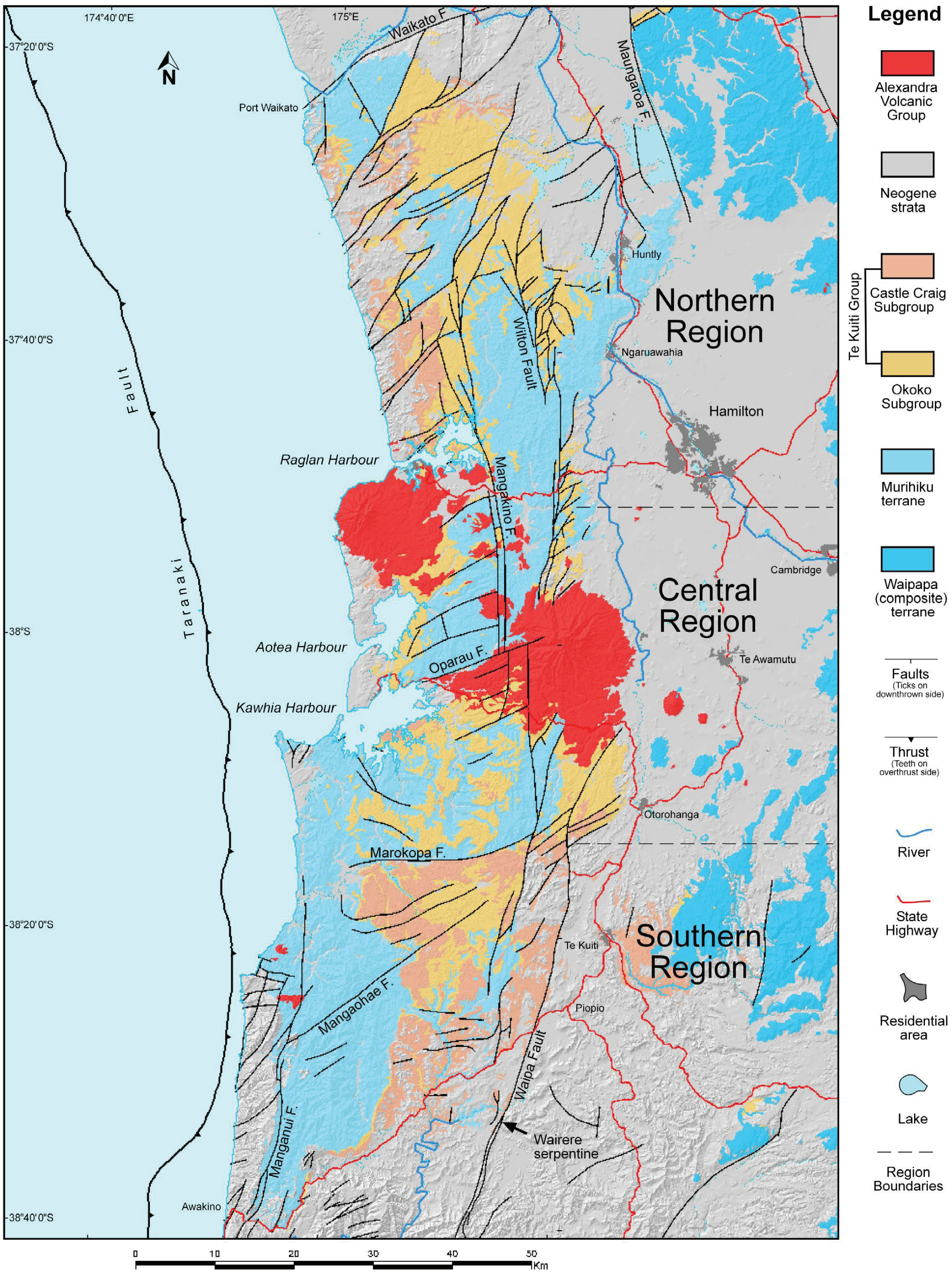


Fig. 2.1: Simplified map of the outcrop geology of the Waikato and King Country regions showing the distribution of Pliocene-Pleistocene volcanics, mid-Cenozoic Te Kuiti Group (Okoko and Castle Craig subgroups) and Mesozoic basement rocks in central-western North Island. Also shown are the major structural features. Map compiled from Edbrooke 2001 and 2005 QMAP Auckland and Waikato).

accumulations along parts of the coastline. Other significant landforms include the Hamilton lowlands, and dissected hill country in the King Country Region, formed mainly on Miocene mudstones. The Rangitoto Range is a substantial range formed in basement rising to 1000 m above sea level to the east of the field area (northern King Country).

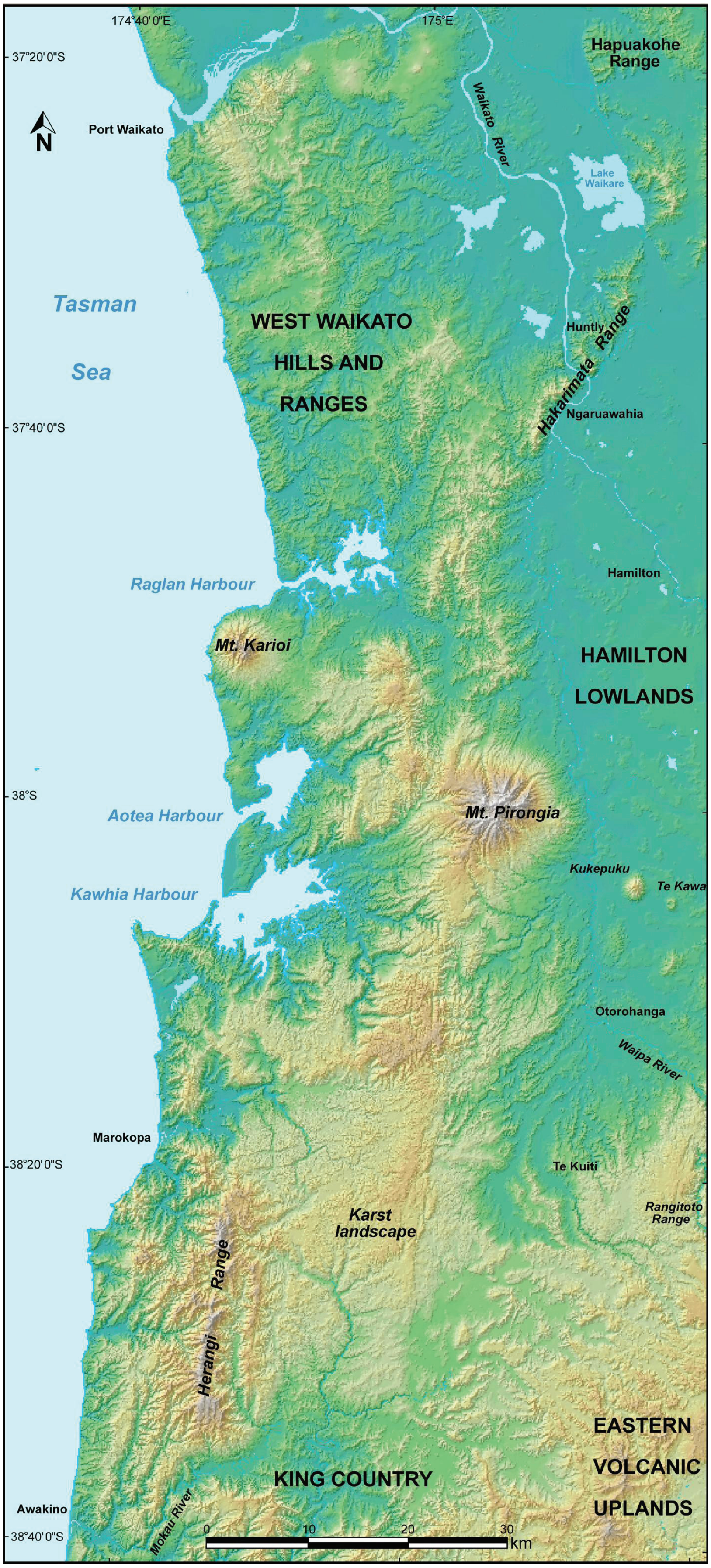


Fig. 2.2: Digital elevation model (DEM), illustrating physiographic features of central-western North Island, and some of the major locality names referred to in this thesis.

Geological and structural setting

At present the study area lies in a backarc setting behind the Taupo Volcanic Zone and Hikurangi margin where oceanic Pacific plate subducts beneath the Australian Plate in a classic ocean-continent convergent margin. A strongly developed set of NE-SW striking normal faults, which breaks up the study area into a series of fault blocks (Fig. 2.1), reflects extension in the backarc region. Most of the fault displacement is probably of Pliocene and Pleistocene age, which coincides with the initiation of extension in the Northern Graben of Taranaki Basin (Hansen & Kamp 2004). A second regional fault set, which strikes N-NW (i.e. the Mangakino and Wilton Faults in the north and the Waipa Fault in the south) are parallel to the strike of the underlying basement terranes, and may in part be re-activation terrane boundaries (Hall et al. 2006). The Murihiku Terrane forms the main basement terrane west of Waipa Fault. The sedimentary succession of Late Triassic and Jurassic age has been gently folded into a north to northwest trending asymmetrical open fold known as the Kawhia Regional Syncline (Spörli 1978; Edbrooke 2005). The limbs of the syncline are parallel and horizontal upper Jurassic beds form the core along its whole axis (Spörli 1978). Secondary asymmetrical folds have formed within the syncline, including the Kawaroa Anticline and Kaimango Syncline (Fig. 2.3). Dips on the limbs of the major folds vary from 20-40°, but can be near vertical on the eastern limb.

Basement Geology

The basement rocks underlying the Cenozoic sedimentary sequences are commonly referred to as “greywacke” and in the Waikato region have been assigned to the Murihiku and Waipapa terranes separated by the Waipa Fault (Mortimer 2004) (Fig. 2.1 & 2.4). A small mass of serpentine crops out between the basement terranes and along a short section of the Waipa Fault, and is regarded as part of the Dun Mountain-Maitai Terrane (Edbrooke 2005). Brief description of these three tectonostratigraphic terranes occurring within the study area is given below.

Murihiku terrane

Late Triassic to Late Jurassic Murihiku terrane rocks crops out in central-western North Island from Port Waikato in the north to Awakino in south, and are particularly well exposed around the southern shores of Kawhia Harbour. Apatite fission-track (FT) thermochronology applied to the youngest beds (Huriwai Group) of this terrane at Port Waikato indicate that Mesozoic accumulation continued into the Early Cretaceous (Kamp & Liddell 2000). Murihiku terrane rocks have been encountered in several offshore exploration wells including Te Ranga-1 and Pluto-1, where they form the leading edge of an overthrust basement wedge forming the hanging

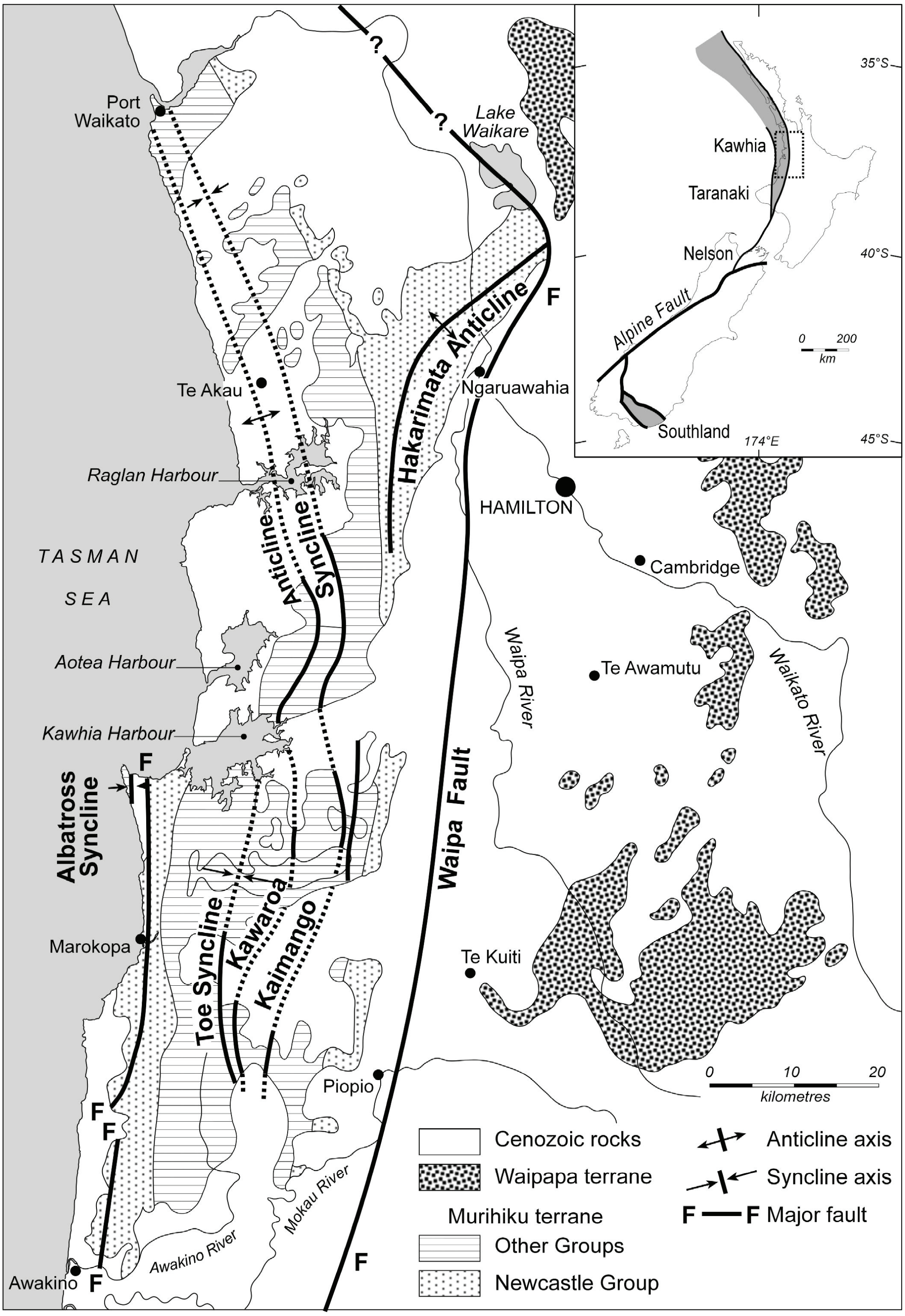


Fig. 2.3: Map of central-western North Island showing the distribution of Murihiku succession and the main structural features. Inset map indicates the present-day distribution (shaded) of the Murihiku succession in New Zealand. From Briggs et al. (2004).

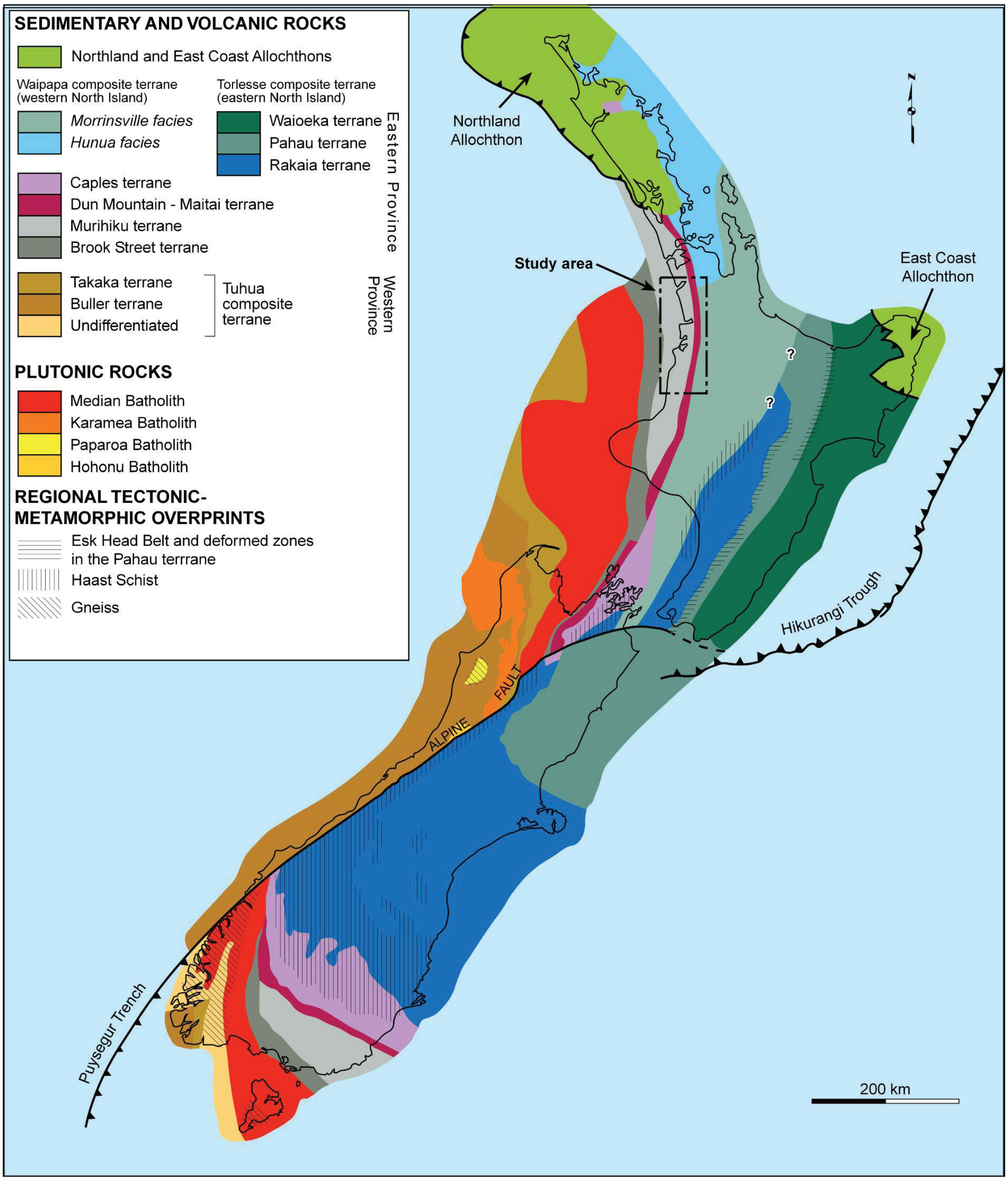


Fig. 2.4: Pre-Cenozoic basement rocks of New Zealand, subdivided into tectonostratigraphic terranes and batholiths, after Mortimer (2004), adapted from Rattenbury et al. (1997). Basement rocks of the study area comprise Murihiku terrane, Dun Mountain - Maitai terrane and Waipapa (composite) terrane (Morrinsville facies).

wall of Taranaki Fault (King & Thrasher 1996). The western limit of the terrane is consequently marked by the offshore Taranaki Fault, and the eastern limit by the Waipa Fault. Murihiku terrane rocks (Fig. 2.1) form a 10 km-thick succession that accumulated in a principal forearc basin along the eastern margin of Gondwanaland influenced by probable west-directed subduction. Rocks in the Murihiku succession are mainly fossiliferous conglomerate, volcaniclastic sandstone and siltstone, carbonaceous beds and tuffs that have undergone burial diagenesis and zeolitisation (Black et al. 1993; Briggs et al. 2004). The Murihiku terrane has been subdivided into five groups on the basis of lithology and faunal content, including the New

Castle, Rengarenga, Kirikiri, Apotu and Huriwai Groups (Campbell & Coombs 1966). These groups crop out as approximately north-south oriented bands on the western, central and eastern sides of the Kawhia Regional Syncline. However, the Murihiku rocks of the Hakarimata and Taupiri ranges (Hakarimata Anticline, Fig. 2.3) have an anomalous northeasterly strike, markedly discordant from the regional N-S structural grain, and lie east of the axis of the Junction Magnetic anomaly that otherwise separates the western Murihiku and eastern Waipapa terranes. These ranges are inferred to have undergone dextral rotation, through an angle of about 50º during the Late Mesozoic (Kirk 1991; Edbrooke et al. 1994).

Dun Mountain-Maitai terrane

Dun Mountain-Maitai terrane rocks crop out as a narrow zone (100m) of sheared serpentine extending for about 500 m along the Waipa Fault at Wairere, south of Piopio (Fig. 2.1). These rocks have been given the name Wairere Serpentinite, and have been correlated with the Early Permian Dun Mountain Ultramafic Group of Nelson and Southland (Hay 1967; O'Brien & Rodgers 1973). They are associated with a strong north-trending positive magnetic anomaly known as the Junction Magnetic Anomaly (Hunt 1978). This positive magnetic anomaly delineates the Dun Mountain Ophiolite Belt, a remarkably linear (typically < 10 km) major boundary zone traceable through most of New Zealand, separating terranes sutured onto the Gondwana margin during the Late Mesozoic (Eccles et al. 2005). Based on sporadic occurrences of the Wairere Serpentine within the Junction Magnetic Anomaly, it is likely that a thin zone of Dun Mountain-Maitai terrane occurs in the subsurface through much of North Island (Fig. 2.4) (Hunt 1978; Spörli et al. 1989).

Waipapa (composite) terrane

Basement rocks east of the Waipa Fault have been assigned to the Waipapa composite terrane, comprising the Omahuta, Bay of Islands and Manaia Hill terranes (Spörli 1978; Black 1996). Waipapa rocks in the Waikato region belong to the Manaia Hill Group, which has two major lithofacies, the Hunua and Morrinsville facies (Kear 1971; Black 1994, 1996). The Hunua facies typically comprise tectonically imbricated lithic volcaniclastic sandstone intercalated with chert and locally basalt. The Morrinsville facies is comparatively less metamorphosed and is dominated by well-lithified, massive to poorly bedded, volcaniclastic sandstone with some interbedded thin siltstone and conglomerate (Kear 1955; Black 1994, 1996). Recently the Morrinsville facies have been interpreted to be an overlap terrane succession overlying older rocks of the Waipapa (composite) terrane (Black 1994; Kear & Mortimer 2003). Morrinsville facies of the Manaia Hill Group crop out in the Rangitoto Range and to the east of Otorohanga, but are mostly covered by

Quaternary ignimbrites. Large scale U-shaped symmetrical folds with vertical axis have been mapped in these rocks exposed in Rangitoto Range (Finlow-Bates 1970).

Regional Tectonic Setting and History

The New Zealand subcontinent consists of large areas of submerged continental crust and a smaller area exposed as islands (Fig. 2.5). The study area lies in central parts of the subcontinent. Rifting within the New Caledonia Basin, of uncertain but probably of mid-Cretaceous age, represents the start of internal fragmentation

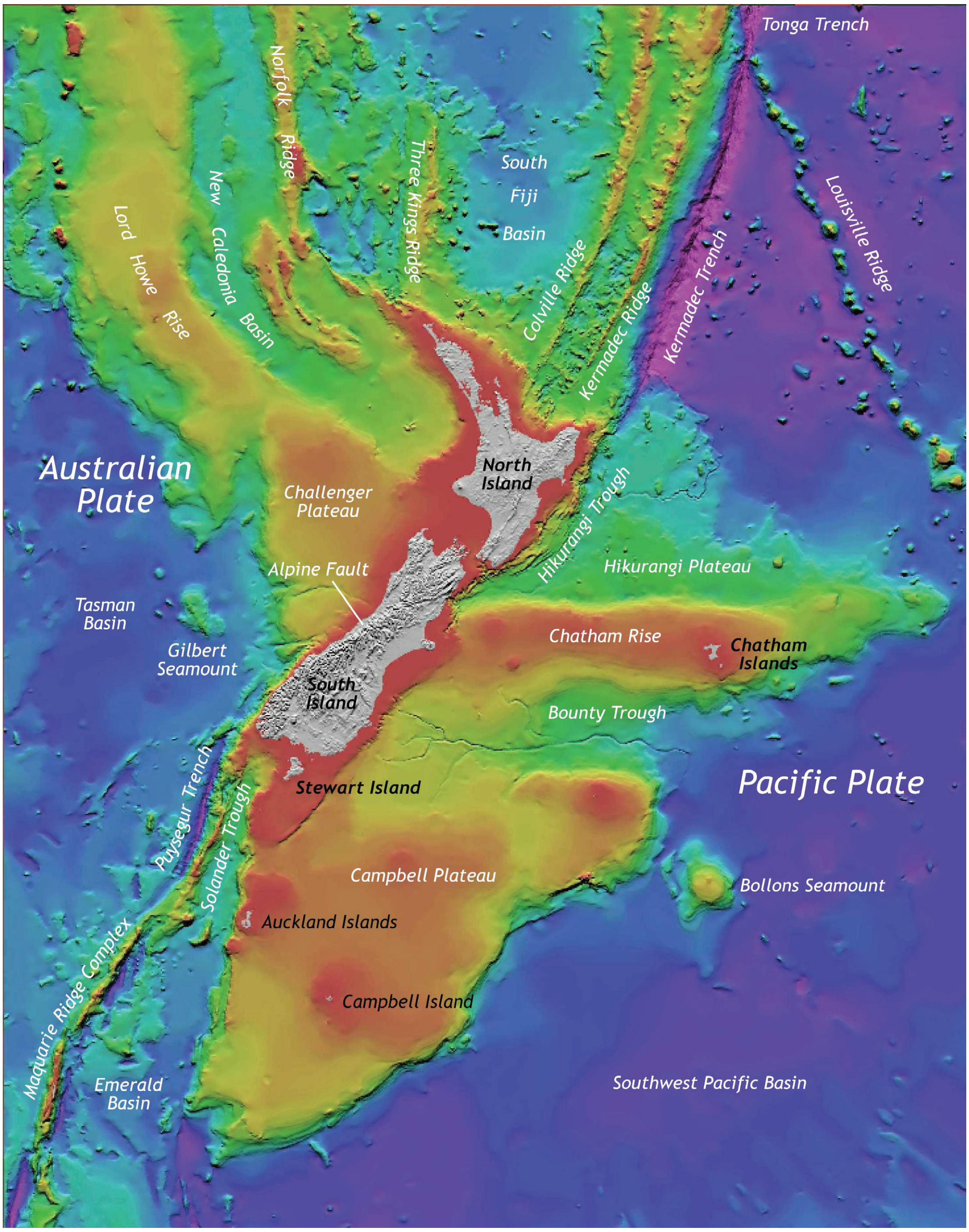


Fig. 2.5: Physiography and major offshore features of the New Zealand sub-continent. Base image adapted from NIWA.

of the subcontinent, and the Bounty Trough is probably a related failed rift. This rifting predated sea floor spreading in the Tasman Sea, which occurred from the Late Cretaceous (c. 83 Ma) to Paleocene (c. 57 Ma) (Veevers & Li 1991). Rifting in the Taranaki Basin of Haumurian age (c. 84-65 Ma) overlaps with spreading in the Tasman Sea. A thick sequence of terrestrial and marginal marine sequences (Pakawau Group) accumulated in the Taranaki Basin during and soon after rifting (King & Thrasher 1996). Murihiku basement immediately east of Taranaki Fault was uplifted and eroded during the Late Cretaceous phase of Taranaki Basin rifting, thus removing the Early Cretaceous sequences of the Murihiku succession (Kamp 1991; Kamp & Liddell 2000). Protracted subaerial erosion of the Murihiku terrane rocks in central-western North Island continued through the Paleocene and into the Late Eocene. This erosion surface, exhumed in places, was the surface upon which the Te Kuiti Group succession was deposited.

Cenozoic sedimentary basin development within the Waikato region can be related to the progressive development of the Australian-Pacific plate boundary though New Zealand from the Late Eocene. The basins evolved within two contrasting tectonic settings: an initial extensional regime, followed by a later (Late Oligocene) strike slip and convergent margin phase, controlled by changes in the style and location of the plate boundary (King & Thrasher 1996; King 2000). Three phases of tectonic development of the wider New Zealand region can be identified:

1. A Late Eocene to mid-Oligocene phase characterised by mild extension within continental crust of western New Zealand associated with seafloor spreading in the Emerald Basin in the southwest. This is the Challenger Rift System of Kamp (1986a,b).
2. A mid-Oligocene to Early Miocene transitional phase of strain accumulation and early reverse movement on pre-existing structures associated with the development of a strike-slip zone oriented NE-SW through the subcontinent and oblique to the earlier rift system.
3. Early Miocene development of a through-going strike-slip plate boundary linking the subduction zone in the north with an oppositely dipping Puysegur subduction zone in in the south. Through the Neogene this strike-slip fault system has evolved into the Hikurangi margin in North Island and the Puysegur Margin in the south (Kamp & Furlong 2006) (Fig. 2.6).

The Paleogene proto-plate boundary

During the Late Eocene, a proto-plate boundary zone propagated through western South Island and into the Taranaki Basin as a continental rift system (Kamp 1986a). The magnitude of extension was greater in the south than it was in the Taranaki

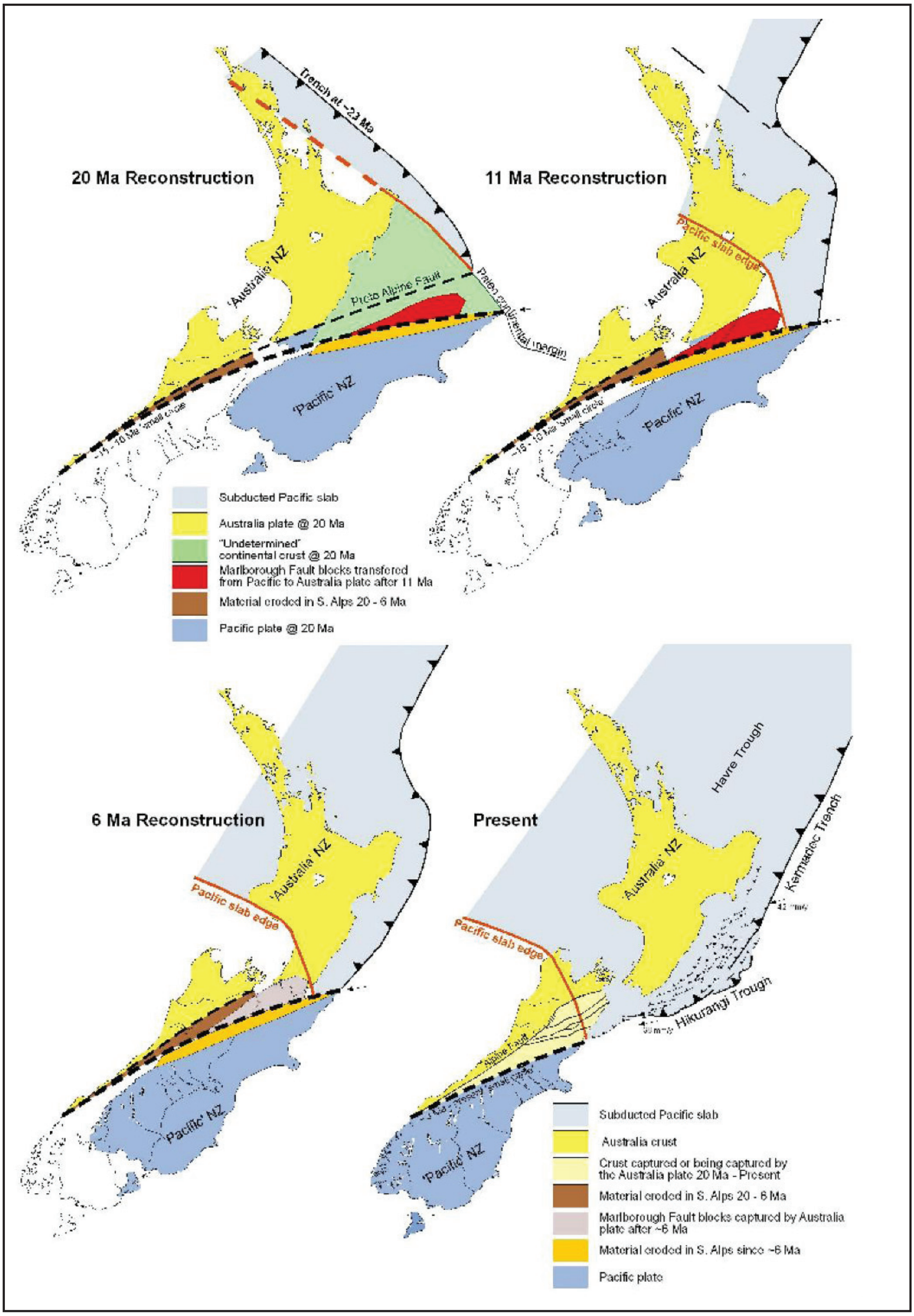


Fig. 2.6: Schematic reconstructions of the evolution of the Australian-Pacific plate boundary zone at 20, 11, and 6 Ma using Euler poles of Cande and Stock (2004). Salient features are: Subduction started c. 23 Ma along the northern continental margin of North Island and the paleo-trench linked to northern end of the Alpine Fault system. The leading edge of the subducted Pacific oceanic slab was progressively emplaced beneath the Australian plate to the southwest and parallel to the plate boundary zone. From Kamp & Furlong (2006).

Basin due to the location of the stage pole in the Coromandel area. This led to substantial seafloor spreading in the south on an eastern extension into New Zealand of the southeast Indian Ocean Ridge. Seafloor formed at this spreading ridge during anomaly 21-7 (Late Eocene – Late Oligocene) is preserved in the Emerald Basin. A continental rift system developed in western South Island and into Taranaki Basin north of the zone of seafloor spreading. This zone of basins was named the Challenger Rift System by Kamp (1986a).

It is generally assumed that Taranaki Fault was an active normal fault in the Late Eocene and Early Oligocene (King & Thrasher 1996). In the Waikato region, the Late Eocene initiation of subsidence was associated with minor normal faulting (Hall et al. 2006), and seems to be a type of sag basin located east of Taranaki Basin. Early deposition in the Waikato Basin involved primarily terrestrial coal measures (Kear & Schofield 1978; King 1978; Kirk et al. 1988; King 2000). Subsequently the subsidence in the Waikato region became more regional and involved accumulation of marginal marine through to fully marine shelf and upper bathyal deposits of Early Oligocene age.

Transitional plate boundary (mid-Oligocene to Early Miocene)

During the mid-Oligocene, the structural development of the region began to change in response to new stresses imposed upon the continental crust of New Zealand in response to the early development of a new plate boundary oriented NE-SW through the continental block, which obliquely bisected the Challenger Rift System. A west to southwest dipping subduction zone is inferred to have propagated southwards from New Caledonia during the Late Eocene and Oligocene to eastern Northland. This is evident from the presence and trend of arc volcanism in the basins to the north of North Island (Ballance et al. 1982; Davey 1982; Hayward 1993; Mortimer et al. 1998). Concurrently, a strike-slip fault system (Alpine Fault) was attempting to form through the continental crust between Milford Sound in the southwest and East Cape in the northeast. The stresses built-up in association with this new boundary resulted in strain being expressed on pre-existing faults, one being the Taranaki Fault. Hence, prior to the development of the through-going transform fault system (Alpine Fault Zone), there was a few million years during the mid to Late Oligocene when the stresses were relieved in part as strain on major structures. In Northland, subduction started along what is now identified as the Vening Meinesz Fault Zone during the latest Oligocene.

The Neogene plate boundary

By the early Miocene, most of the fundamental elements of the "modern" plate boundary were developed as a result of a through-going transform having formed through the New Zealand subcontinent (King & Thrasher 1996; King 2000; Kamp & Furlong 2006). The Alpine Fault Zone cut obliquely (NE-SW) across the pre-existing north-south oriented Eocene-mid Oligocene continental rift in western New Zealand. The subsequent development of the Hikurangi Margin subduction system has been described by Kamp and Furlong (2006) and is illustrated in Fig 2.6.

Key elements of this development have been the progressive emplacement of a slab of Pacific oceanic crust beneath the North Island, the formation and southward migration of arc volcanism, and the building up of an accretionary prism. Central-western North Island was relatively distant from the new subduction margin and hence the tectonic effects have been mild, which has helped expose, but not completely remove the Oligocene Te Kuiti Group strata. During the Early Miocene (Otaian Stage), there was major basement over thrusting on the Taranaki Fault, which followed the mid to Late Oligocene start of reverse movement on this structure. Accompanying the basement overthrusting was the rapid formation of a piggyback basin in the King Country and southern Waikato regions and accumulation within it of the terrigenous Mahoenui Group. However, from the late-Early Miocene (Altonian) the amount of movement on the Taranaki Fault north of Awakino reduced significantly. The Mahoenui depocentre was inverted during the late stage of reverse movement in the section of the Taranaki Fault north of Taranaki Peninsula. During the mid-Miocene sedimentation of about 1.5 - 2 km thickness buried the Te Kuiti Group. This succession was part of a northward prograding continental margin wedge sourced from erosion of the developing Southern Alps in South Island (Kamp et al. 2004).

The exhumation of the Te Kuiti Group from beneath the thick Miocene succession occurred during the Pliocene and Pleistocene as a result of doming of central North Island ahead of the breakout of volcanism in the Taupo Volcanic Zone during the Pleistocene.

Figure 2.7 gives a simplified view of the modern plate boundary configuration through New Zealand. In the northern sector, the Tonga-Kermadec trench and Hikurangi Trough mark a 3,000 km-long plate boundary where the oceanic Pacific plate is subducting beneath the continental Australian plate. The current direction of relative Australian-Pacific plate motion is oblique (c. 40-70º) to the structural trench where the oceanic Pacific plate is subducted, and ranges from 38 to 50 mm/yr. The Hikurangi margin transitions into the Alpine Fault in northeastern South Island where the plate boundary becomes a zone of oblique continent-

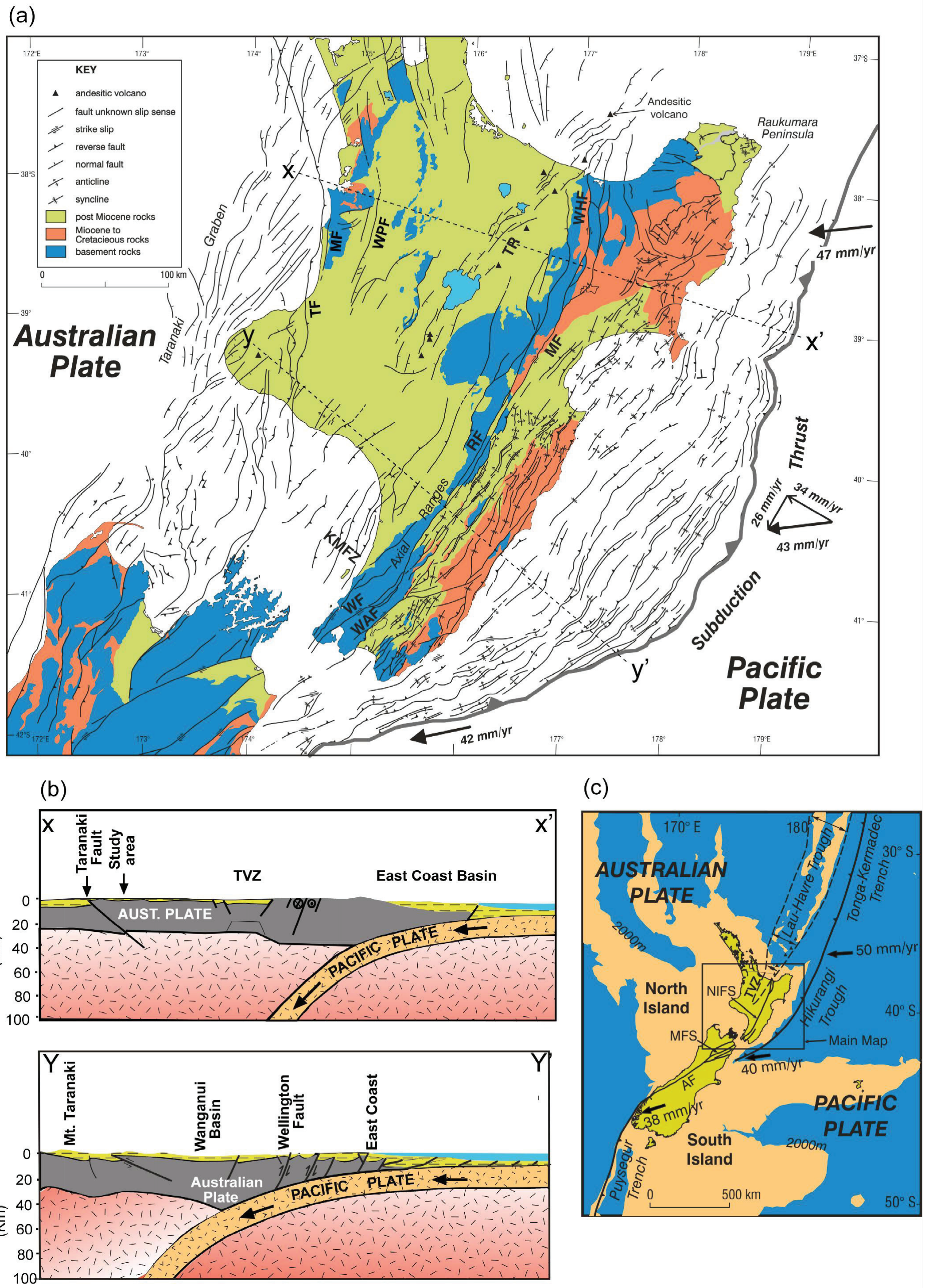


Fig. 2.7: (a) Regional geological map modified from the work of Nicol et al. (2007) showing the onshore distribution of Mesozoic basement (dark blue), post-Cretaceous to Miocene (orange) and post-Miocene (green) rocks. Also shown are the location and types of structures that deform these rocks across the Hikurangi margin. Relative plate motion vectors with margin normal (34 mm/yr) and margin parallel (26 mm/yr) component shown for central margin area from Bevan et al. (2003). (b) Regional cross-sections (X-X' and Y-Y') across the North Island are modified from Stagpoole & Nicol (2008) and Nicol et al. (2007). (c) Present tectonic setting of the Australian-Pacific plate boundary in North Island, showing the Hikurangi margin and the transition in northern South Island to the Alpine Fault system/Southern Alps continent-continent collision zone. Abbreviations KMFZ, Kapiti-Manawatu Fault Zone; MF, Mohaka Fault; RF, Ruahine Fault; TF, Taranaki Fault; TR, Taupo Rift; WAF, Wairarapa Fault; WF Wellington Fault, WPF Waipa Fault. Abbreviations inset map AF, Alpine Fault; MF, Manganui Fault; MFS, Marlborough Fault Zone; NIFS, North Island Fault System; TVZ, Taupo Volcanic Zone.

continent collision. The Alpine Fault then links to the Puysegur subduction zone in the southwest. The Alpine Fault has accommodated approximately 480 km of Neogene dextral displacement and is the main structure associated with uplift of the Southern Alps. The obliquely convergent Puysegur Margin southwest of South Island accommodates subduction of Australian Plate beneath the continental Pacific plate.

Taranaki Fault

The Taranaki Fault is a contractional structure that extends for about ~ 400 km within crust of western North Island (Fig. 2.7 a). Analysis of seismic reflection profiles indicates that the fault is thick-skinned and dips 25-40º to the east to depths of at least 12 km. The fault has accommodated as much as 12-15 km of dip slip displacement, with up to 6 km of vertical offset of basement (Holt & Stern 1994; Nicol et al. 2007). Displacement within the fault zone is considered to have been driven by subduction of oceanic Pacific Plate along the Hikurangi Margin (Stern et al. 1993; Nicol et al. 2007), but an implication of this thesis is that initiation of contraction across this fault zone started before the Miocene development of the Hikurangi Margin.

The Taranaki Fault represents the western boundary of the Murihiku terrane, and the deeply buried basement west of the fault consists mainly or entirely of rocks of Western Province affinity, and specifically Brooke Street terrane (King & Thrasher 1996; Mortimer et al. 1999). The presence of Late Cretaceous to Middle Eocene strata west of Taranaki Fault but not to the east indicates that the Taranaki Fault has probably existed since the Late Cretaceous. During the Late Cretaceous-Middle Eocene basement east of Taranaki Fault was high standing, with evidence for significant amount of erosion (Kamp 1991; Kamp & Liddell 2000). Re-worked Mesozoic pollens in Eocene strata encountered in some exploration wells (Awakino-1, Mokau-1 and Te Ranga-1) along the eastern Taranaki Basin margin also suggest that basement east of Taranaki Fault contributed sediment to Taranaki Basin (de Block et al. 1990). At that time the Taranaki Fault was possibly a normal fault. During the Late Eocene and Early Oligocene, there is no clear evidence whether or not there was normal displacement on the Taranaki Fault as the evidence is masked by later movements and in particular about 12 km of overthrusting. The fault nevertheless influenced sedimentation in the eastern parts of Taranaki Basin (King & Thrasher 1996). One of the conclusions from this thesis is that by the mid-Oligocene reverse movement had started on the Taranaki Fault but this may have been a different structure from the earlier normal fault (see Chapter 8).

Manganui Fault

The Manganui Fault strikes NNE-SSW parallel to the regional strike of the east-dipping Murihiku basement rocks of the regional Kawhia Syncline and within its western limb (Happy 1971). The fault juxtaposes eastward dipping Lower to Middle Jurassic basement rocks to the west against eastward dipping Upper Triassic rocks to the east. The Manganui Fault is inferred primarily to be a Late Mesozoic structure formed during the Rangitata Orogeny (Campbell & Raine 1989). The fault lies along the western margin of the Herangi Range, and strikes sub-parallel to the Taranaki Fault (Fig. 2.1 & Fig. 2.7 a). It is concluded in Chapter 8 that the fault moved as a reverse fault from c. 27 Ma and significantly tilted the Te Kuiti Group, especially in the vicinity of Awakino Gorge, which has been described by Nelson et al. (1994).

Waipa Fault

The Waipa Fault trends NNW to NNE and is a major fault in the southern part of the Waikato region (Fig. 2.1). It closely follows the trace of the Junction Magnetic Anomaly. As outlined earlier, the Waipa Fault juxtaposes the Murihiku and Waipapa terranes. Late Eocene normal movement on the Waipa Fault may be implicated with local subsidence and accumulation of the Waikato Coal Measures at the base of the Te Kuiti Group (Kirk 1985, 1991). Edbrooke et al. (1994) envisaged early movement on the Waipa and related faults as having controlled to some extent the development of valley systems within which the coal measures accumulated. Several tens to hundreds of metres of displacement have occurred on the Waipa Fault during the Miocene and into the Pleistocene, possibly as part of backarc extension (Edbrooke 2005).

Alexandra Volcanic Group

During the Late Pliocene to earliest Pleistocene, stratovolcanoes of the Alexandra Volcanic Group erupted in the central and western parts of the study area (Kear 1960; Kear & Schofield 1978) (Fig. 2.1). There has been about 55 km^3 of mainly basaltic material erupted from several low-angle composite cones, including Karioi, Pirongia, Kakepuku and Te Kawa volcanoes. Mt. Pirongia rises to 959 m above sea level and is the largest volcano in the group, consisting of a composite cone constructed from a succession of basalt and basaltic andesite flows. Mount Karioi is a 756 m high volcanic cone comprising basalt, basaltic andesite, volcanic breccias, tuffs and epiclastic sediments (Briggs 1983). Eruptive centres of the Okete Volcanics are scattered mainly in the areas east of Karioi and south of Raglan Harbour. The Alexandra Group Volcanoes represent back-arc volcanism associated with subduction of the Pacific Plate beneath the Australian Plate. They are considered to be the product of both subduction-related basaltic magmas (e.g. Karioi, Pirongia, Kakepuku and Te Kawa) and intraplate alkalic basalts (Okete) erupted mainly between 2.74 and 1.6 Ma (Briggs et al. 1989). These volcanics cover the Te Kuiti Group in the Central Region.

Quaternary uplift and erosion of central North Island

The outcrop pattern in central-western North Island reflects long wavelength up-doming of Central North Island and associated erosion (Kamp et al. 2004). As a result of this uplift, progressively older formations are exposed to the north along central-western North Island. In the eastern parts of the Waikato and King Country regions, the Cenozoic succession has been almost completely removed by erosion, and exhumed basement is covered by mainly Quaternary ignimbrites derived from the Taupo Volcanic Zone. The uplift appears to be centered on the Taupo Volcanic Zone, possibly related to thermal upwelling and crustal extension (Stern et al. 1987; Smith et al. 1989).

Chapter Three

Rationalisation of Te Kuiti Group Lithostratigraphy

Introduction

While various lithostratigraphic schemes for the Late Eocene-Oligocene Te Kuiti Group have been proposed by earlier workers, a comprehensive understanding of the regional interrelationships amongst the formations and members throughout the whole of the group's extent in central-western North Island has not been robustly developed. This investigation aims to develop that understanding for the region between Port Waikato and Awakino. The combination of marked lithofacies variations within and between formations, erosion of the record in critical areas, and lack of exposure in key areas due to burial by younger sedimentary and volcanic deposits has led to miscorrelation of units in prior schemes and the introduction of multiple names for particular units. Rationalisation of Te Kuiti Group lithostratigraphy is necessary before geological signals (e.g. tectonic and sea level) can be identified and understood for this well exposed neritic to upper bathyal Oligocene succession.

The first regional lithostratigraphic classification of the Te Kuiti Group was made by Kear & Schofield (1959), with subsequent modifications by Kear (1963), and Nelson (1978a). The most recent revision of Te Kuiti Group stratigraphy was proposed in White & Waterhouse (1993), although their's was primarily an extension of Kear & Schofield's (1959) original scheme. The objective of this chapter is to review the established lithostratigraphy of the Te Kuiti Group and to propose its rationalisation. A direct comparison of the White & Waterhouse (1993) scheme and the one proposed in this study is shown in Fig. 3.1.

This chapter deals with high level stratigraphic issues and proposed changes to the lithostratigraphic scheme. Detailed field investigations have demonstrated lateral continuity between strata in some cases previously regarded as belonging to different formations. Some of the unit names in common usage for several years, but not properly defined, are formalised here.

Distribution and structure

The Te Kuiti Group crops out discontinuously in central-western North Island from Papakura in the north to Taumarunui in the south. However, most surface exposures of the group lie between Port Waikato and Awakino, the area that has been the

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. 3.1: 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.

particular focus in this study. Te Kuiti Group marine units are extensively eroded from areas to the east of the main outcrop belt along central-western North Island, as judged by the sub-bituminous rank of the Waikato Coal Measures (Edbrooke et al. 1994), which occur at the base of the group and have the most easterly extent. However, patches of the marine units of the Te Kuiti Group do extend as far east as Coromandel Peninsula (Kear 1955; Dix & Nelson 2006). The northernmost extent of the Te Kuiti Group occurs in Northland (Isaac et al. 1994). The structure of the group is mainly influenced by two sets of normal faults, one striking N and the other NE (Nelson & Hume 1987; Spörli et al. 1989). The normal faults are mainly of late Neogene age. Over most of the outcrop area the beds are horizontal or have dips of a few degrees. The steepest dips at 31^0 occur near Awakino Tunnel on the flanks of the Herangi Range (Nelson et al. 1994).

Mesozoic basement

The basement rocks underlying the Te Kuiti Group are meta-sedimentary greywacke (sandstone), argillite, siltstone, and minor conglomerate, all assigned to two tectonosedimentary terranes of Mesozoic age. The Murihiku Terrane and Waipapa Terrane are separated by the Junction Magnetic Anomaly (JMA), which closely follows the Aria-Waipa Fault Zone. The JMA is correlated with the Dun Mountain Ophiolite Belt of the Maitai Terrane in the east Nelson area. The only exposure of possible Dun Mountain Ophiolite in the field area occurs in the Wairere serpentine quarry near Piopio (Hunt 1978). The Murihiku Terrane within the Kawhia Syncline is of Late Triassic and Jurassic age, and has fossiliferous beds and volcaniclastic lithologies including tuff beds. This terrane is folded into a regional syncline known as the Kawhia Syncline. The Waipapa Terrane is poorly fossiliferous but probably of Jurassic age, and is mainly composed of structurally complex bathyal greywacke and argillite. This terrane probably accumulated within a subduction prism (Spörli 1978).

The Oligocene Te Kuiti Group directly overlies basement, usually with a pronounced angular unconformity. The top basement structure in central-western North Island is strongly influenced by pre-Te Kuiti Group paleotopography, synsedimentary basement uplift, particularly along the western margin, and post-depositional faulting.

Historical nomenclature

The name "Te Kuiti" was first introduced by Henderson & Ongley (1923) for the units overlying basement in the Mokau and Te Kuiti Subdivisions. Calcareous mudstone now considered part of Mahoenui Group was formerly incorporated within the Te Kuiti Series by Henderson & Ongley (1923). Kear & Schofield (1959) redefined the Te Kuiti Series and elevated its status to that of a group. Their investigation introduced six new formations and a reasonably sound stratigraphic framework for the group. The Waikato Coal Measures were identified as the oldest formation in the group, and the Otorohanga Limestone as the youngest. Thus the Te Kuiti Group succession, beginning with basal coal measures and culminating with the deposition of shelfal limestone, was in effect perceived by Kear & Schofield (1959) as a transgressive megasequence. Kear & Schofield's (1959) stratigraphic framework has been modified and extended by subsequent workers to accommodate lithological variations that became apparent from more extensive field work. The stratigraphic terminology applied by earlier workers to the Te Kuiti Group in the South Auckland region is shown in Fig. 3.2.

Lithostratigraphic issues

The stratigraphic nomenclature for the group proposed by previous authors (e.g. Kear & Schofield 1959; Nelson 1978a; White & Waterhouse 1993) has been tested during the course of this study. In particular, issues pertaining to the age, facies distribution and correlation of some of the formations and members within the Group are considered here. Nelson (1978a), working in the Waitomo area, and Waterhouse & White (1994) in the Raglan-Kawhia area, essentially adopted Kear & Schofield's (1959) stratigraphy with minor modification.

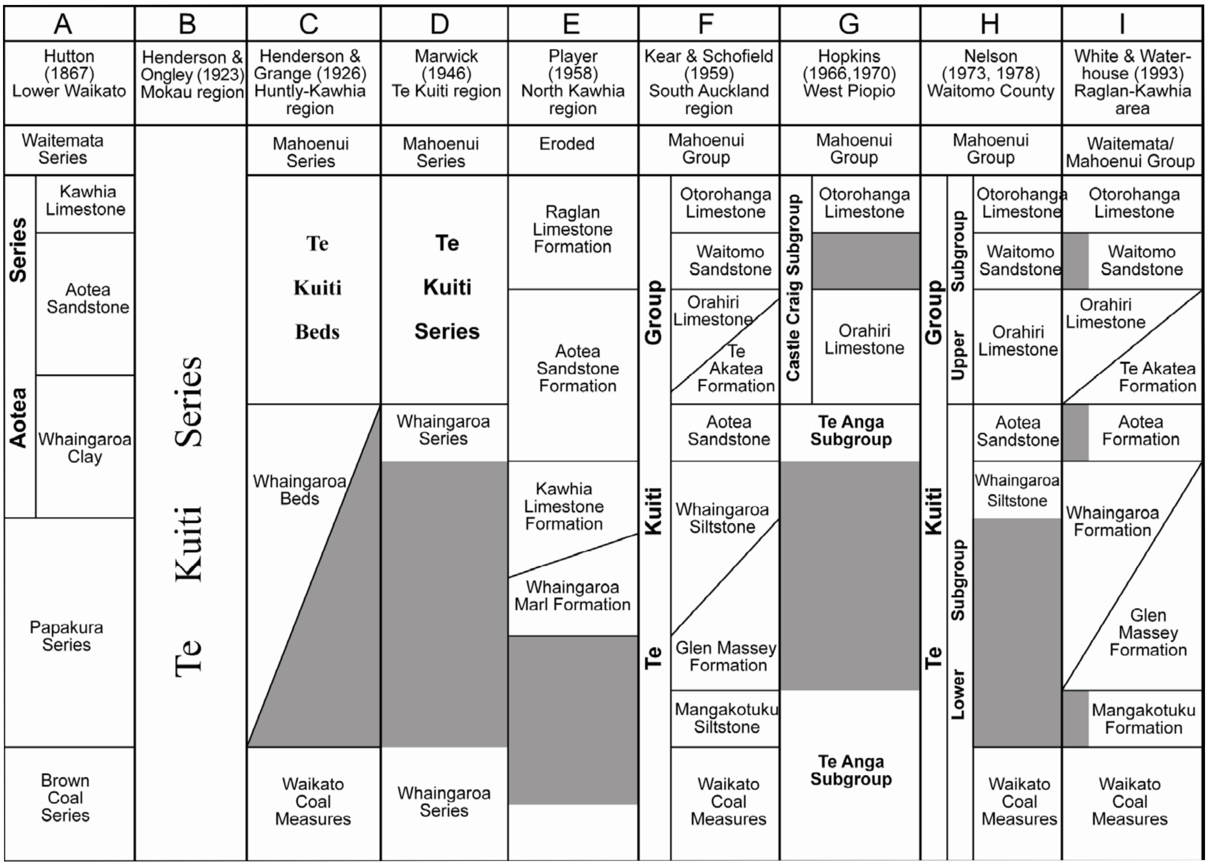


Fig. 3.2: Historic development of stratigraphic terminology for Te Kuiti Group modified and extended from Nelson (1978a). NB: The grey boxes indicate stratigraphy inferred by the respective authors to be absent in particular areas.

In general, there are major differences in the stratigraphy of the Te Kuiti Group north and south of Mt Karioi: calcareous siltstone predominates in the north, and sandstone and limestone predominate in the south (White & Waterhouse 1993). Lithofacies variations within and between different stratigraphic units, combined with a lack of exposure in the vicinity of Mt Karioi where the Te Kuiti Group rocks are buried under Pliocene-Pleistocene Alexandra Group volcanics (Briggs 1983), have always posed a problem for regional correlations.

It is important to highlight the key assumptions and implications of previous stratigraphic schemes (Kear & Schofield 1959; Nelson 1978a; White & Waterhouse 1993) that underpin the understanding of the distribution of lithostratigraphic units in the Group.

1. The region south of Kawhia Harbour was regarded as having had base ment exposed at the surface during the late Eocene while coal measures accumulated to the north; subsequent Oligocene accumulation of coal measures south of Kawhia led to the idea of diachronous north to south basal coal measure onlap.
2. Several formations were regarded as having limited extent (e.g.

Mangakotuku, Glen Massey, and Whaingaroa formations and to some extent Aotea Formation) because of diachronous southward onlap onto previously exposed basement or basal coal measures.

3. The stratigraphically highest formation in the group (Otorohanga Limestone) was considered to represent the culmination of a transgressive Te Kuiti Group succession.

Approach to lithostratigraphic nomenclature

As part of the present study, detailed section descriptions and correlations were made for the known extent of the Te Kuiti Group in central-western North Island. The facies details and inferred contact types and relationships between lithological units are presented in stratigraphic columns (Appendix I). Special emphasis has been given to the significant stratigraphic discontinuities (erosional unconformities, depositional hiatuses) between units. Although several inter- and intra-formational unconformities and disconformities have been reported in past investigations (Kear & Schofield 1959; Nelson 1978a; White & Waterhouse 1993; Waterhouse & White 1994) their extents have not previously been mapped on a regional scale. These stratigraphic discontinuities, when combined with faunal and/or numerical dating, have enabled the correlation of lithologically diverse but time-equivalent stratigraphic units across the study area (Fig. 3.3 and 3.4). The entire Te Kuiti Group is classified into six major unconformity-bound sequences, although conformable boundaries do occur between units in parts of the basin.

For the convenience of describing the stratigraphy in different locations, the present study area is subdivided into three broad geographical areas named northern, central, and southern regions (Chapter 2, Fig. 2.1). The region boundaries coincide with points of change in the stratigraphy.

Lithological qualifiers have been avoided in revised formation names because of the degree of lithological diversity within many of the formations. Lithological qualifiers are used however in member names. Most of the formation and member names have been formally defined in earlier investigations and have long-standing usage. However, a few new names are adopted here to acknowledge significant variations in the lithofacies, and several names have been abandoned to eliminate misapplication from other areas. In all, seven formations and 24 members of Kaiatan to Waitakian (Late Eocene to Early Miocene) age are identified. These units are compared in Fig. 3.1 with the subdivision and nomenclature proposed by White & Waterhouse (1993).

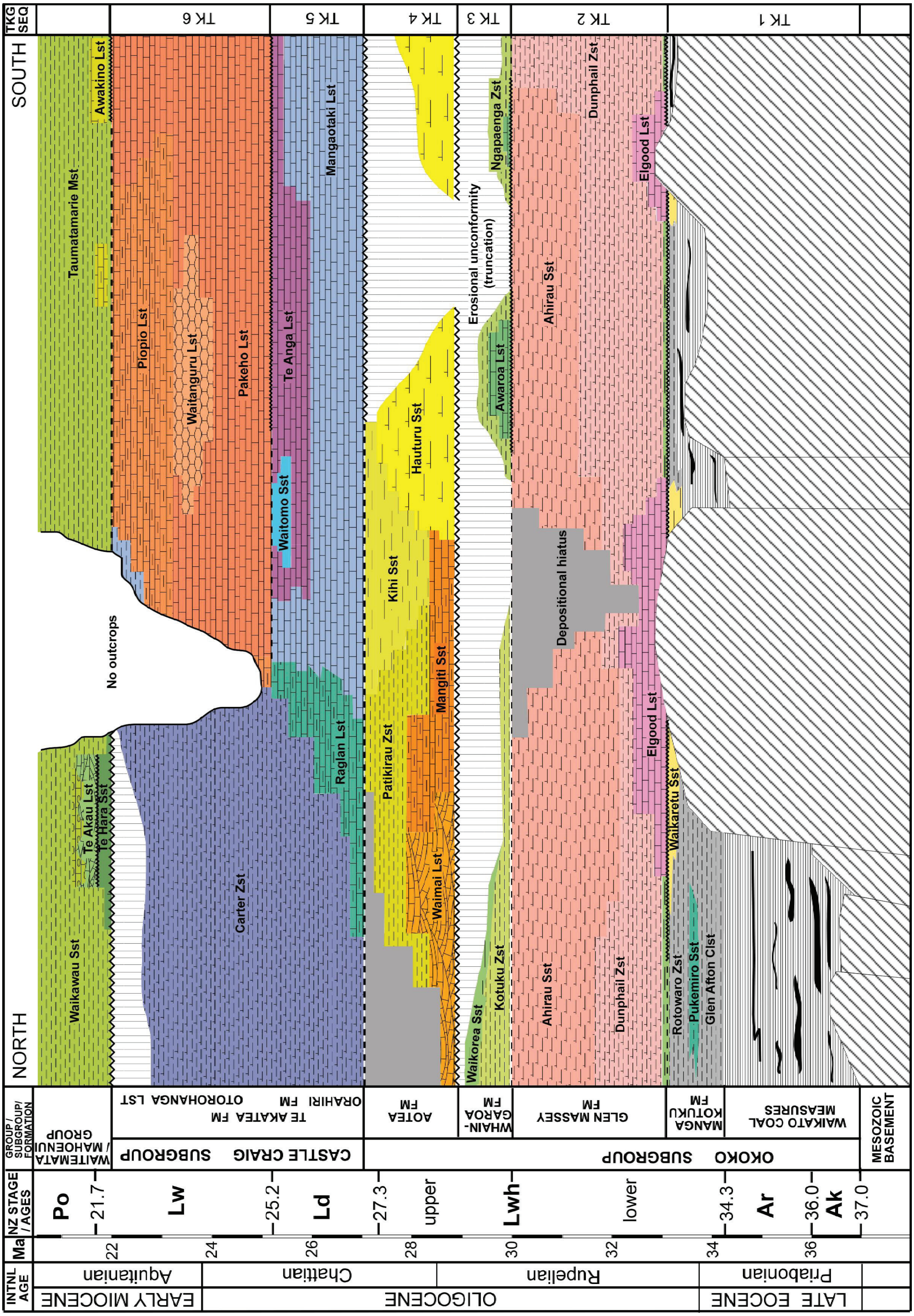


Fig. 3.3: New chronostratigraphic scheme for the Te Kuiti Group, and its transition to Waitemata and Mahoenui Groups, showing the relationship between formations and members, their age, and the extent of sequences.

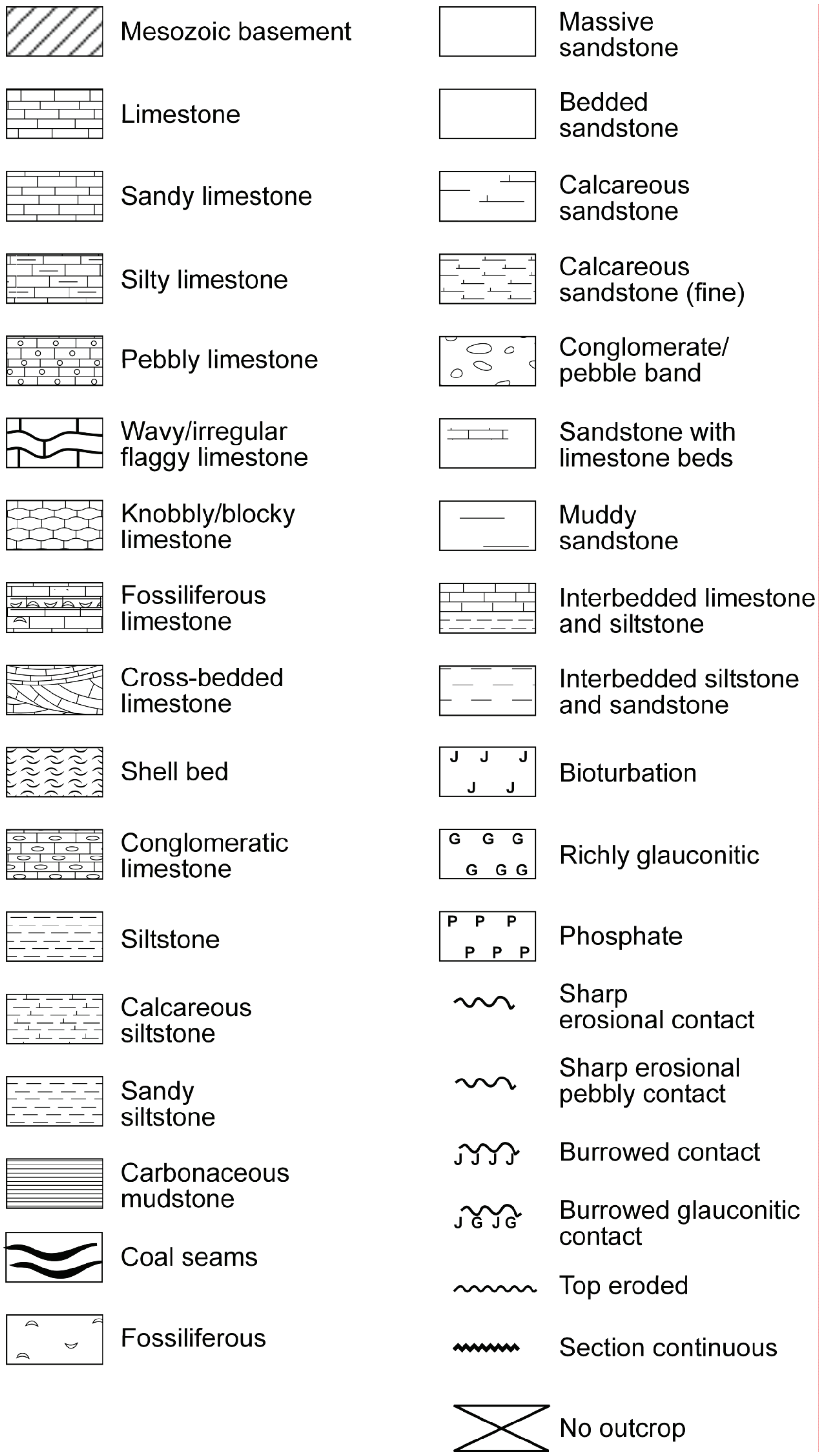


Fig. 3.4: Figure showing the standard symbols used in the chrono- and lithostratigraphic correlation panel (Fig. 3.3) and the stratigraphic column correlations.

The age and facies distribution of stratigraphic units proposed in this study are also illustrated in a litho-chronostratigraphic panel (Fig. 3.3). This figure helps to show new understanding about the lateral and temporal relationships between surfaces and lithofacies within the Te Kuiti Group.

Stratigraphic subdivision

At the broadest level, the Te Kuiti Group can be subdivided into two subgroups, these being the Okoko Subgroup (new) named after Okoko valley in inland Kawhia, and the overlying Castle Craig Subgroup (Barrett 1962, 1967; Hopkins 1966, 1970). Previously the Okoko Subgroup has been called Te Anga Subgroup (Barrett 1962, 1967; Hopkins 1966, 1970) and lower Te Kuiti Subgroup (Nelson 1973, 1978a), but these names are already used as member and group names, hence the new name Okoko Subgroup is adopted here. The two subgroups are separated by a prominent unconformity, marking a pronounced change in lithofacies character, which is one of the more significant unconformities within the Te Kuiti Group, both in extent and degree of erosion. The Orahiri and Te Akatea Formations record widespread Late Oligocene marine onlap at the base of the Castle Craig Subgroup. The Castle Craig Subgroup is characterised by high calcium carbonate content especially in the southern region, and the change across the lower contact from dominantly mixed carbonate-siliciclastic sediment to dominantly carbonate sediment forms the basis for the division into subgroups. This subdivision and its lithological basis have been acknowledged in most previous classifications of the Te Kuiti Group (Fig. 3.2). Nelson (1978a), for the Waitomo area, reported 48% average calcium carbonate content for samples from his Lower Te Kuiti Subgroup (equivalent here to the Okoko Subgroup), whereas his Upper Te Kuiti Subgroup (equivalent to the Castle Craig Subgroup) has a carbonate content of 65-98%.

The two-fold subdivision of the Te Kuiti Group is extended here to the central and northern regions. The lower five formations (Waikato Coal Measures, Mangakotuku, Glen Massey, Whaingaroa, and Aotea) are assigned to the Okoko Subgroup, and the three upper formations (Orahiri, Otorohanga, and Te Akatea) are assigned to the Castle Craig Subgroup (Fig. 3.1).

Waikato Coal Measures

Historical usage

Hochstetter (1864) first referred to the coal measures in the Huntly and Drury areas as “Brown Coal Formation”, followed by Hutton (1867) who used the name Brown Coal Series. Subsequently, Hutton (1871) used the term Waikato and Drury “Brown Coal Series” at Kupakupa Mine, south of Huntly. Henderson & Ongley (1923) introduced the name “Te Kuiti Series” in describing the stratigraphic succession in the Mokau and Te Kuiti districts, and referred the coal measures therein to undifferentiated basal coal measures. Henderson & Grange (1926) differentiated the basal coal measures from the overlying “Whaingaroa Beds”, referring to them as “Coal Measures” at Huntly and in the Kawhia area. The term “Waikato Coal

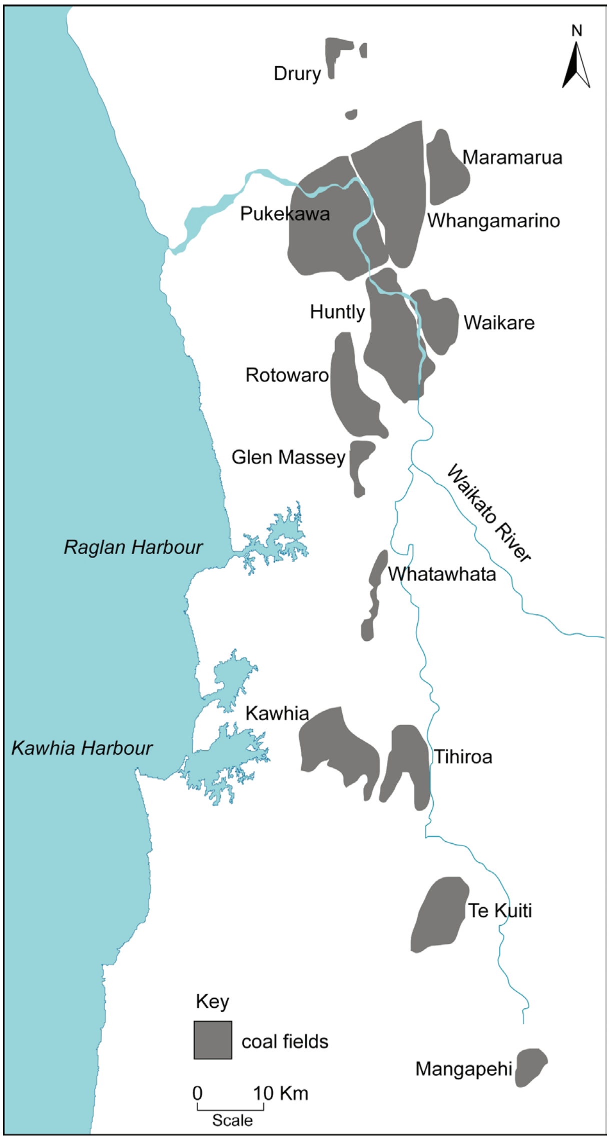


Fig. 3.5: Distribution of coalfields within the study area. (Adapted from Edbrooke et al. 1994).

Measures" was adopted by Kear & Schofield (1959) to describe all the Eocene-Oligocene coal measures across the region from immediately south of Auckland (Drury) to Awakino (Fig. 3.5).

Definition

The term Waikato Coal Measures (WCM) is used here to include Late Eocene and Early Oligocene coal measures and associated siltstone and minor sandstone in the central-western North Island region, following the usage of Kear & Schofield (1959). The WCM is the lowest stratigraphic unit in the Te Kuiti Group and directly overlies basement, usually with pronounced angular unconformity (Fig. 3.6a). The WCM is of Kaiatan (Late Eocene) to earliest Whaingaroan (Early Oligocene) age.

Type and reference sections

Kear & Schofield (1959) designated Hutton's (1871) section at (now abandoned) Kupakupa Mine (S13/002005), located 2 km south of Huntly, as the type section for

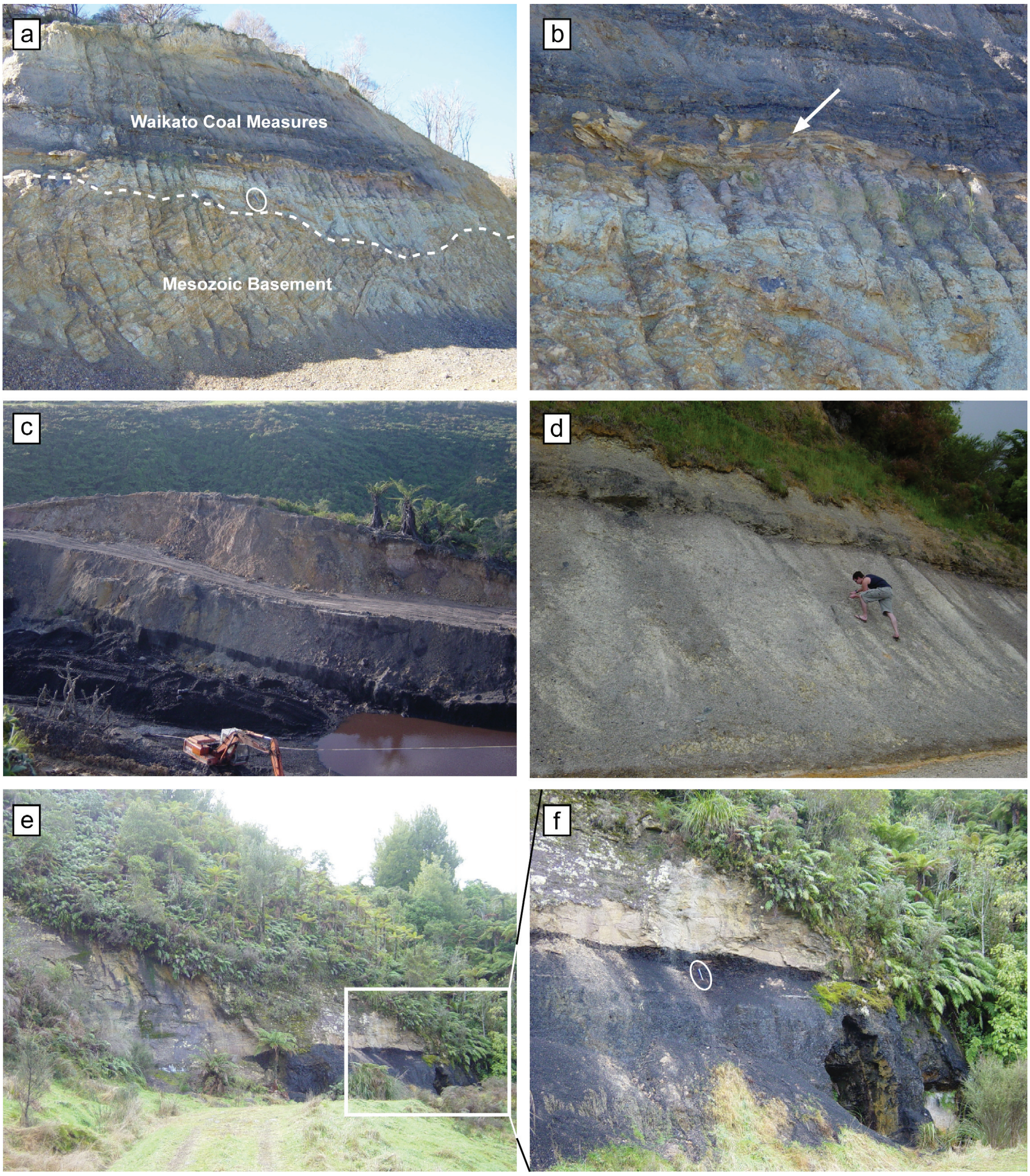


Fig. 3.6: Examples of Waikato Coal Measures in the field. (a) Strong angular unconformity between highly weathered basement and WCM at Huntly Brickworks Quarry (S13/012016). Note the irregular Late Eocene relief upon basement rocks. (b) Close-up of claystone with a siderite concretion band (pointed by arrow) overlain by thin muddy coal streaks interbedded with carbonaceous mudstone. (c) Renown Seam within WCM in open cast mine near Pukemiro (TA-16, S14/905973). (d) Massive carbonaceous mudstone with prominent concretionary band near top exposed in road cut along Kaimango Road, Kawhia (R16/846387). (e) Mangapehi Seam in abandoned Benneydale Coalmine (S17/187960). (f) Close-up view of sharp contact between the Mangapehi Coal Seam and overlying interbedded carbonaceous siltstone and sandstone at Benneydale Coalmine.

the WCM. Edbrooke et al. (1994) nominated two reference sections for the northern region, one at the Huntly Brickworks Section (S13/012016) (Fig. 3.6a & b), and the other as a composite section consisting of exposures at “Maori Farm No.1 Mine” (S14/939977) and a drill hole (7153) at Pukekapia (S13/968055). Another two reference sections nominated by Nelson (1978a) for the southern region (Te Kumi-Te Anga Road Section (C113, R16/861133) and Benneydale Mine section (C197, S17/187960) (Fig. 3.6e & f)) are retained here.

Distribution and thickness

The WCM is widely distributed, extending south from Drury to Awakino. The coal measures accumulated within a series of possibly interconnected depocentres across an area 200 km long and up to 35 km wide, having a north to northeast trend. The thickest development of WCM occurs east of Huntly being up to 200 m thick in the Rotowaro area (Edbrooke et al. 1994). However, in the central and southern regions, the coal measures are typically thinner (less than 80 m) and laterally discontinuous, with significant coal seams restricted to isolated depocentres (e.g. Kawhia, Tihiroa, Te Kuiti, and Mangapehi) (Fig. 3.5). Coal measures present in the southwest, that is, south of the Marokopa Fault and west of the Waipa Fault, are less than 10 m thick (Fig. 3.8). Eight sub-bituminous coal seams have been identified in total, four in the northern region and four in the central and southern regions (Edbrooke et al. 1994) (Table 3.1). The most striking feature of WCM distribution is its absence over virtually the entire western part of the study area.

Table 3.1: Coal seam occurrences between northern and southern parts of central-western North Island, with approximate stratigraphic correlations shown (after Edbrooke et al. 1994).

North	South
	Mangapehi Coal Seam
Ngaro Coal Seam	Okoko Coal Seam
Renown Coal Seam	Waipa Coal Seam
Kupakupa Coal Seam	Pirongia Coal Seam
Taupiri Coal Seam	

Contacts

The WCM unconformably overlies Mesozoic basement, either having lapped onto basement highs or preserved in faulted depressions. The coal measures usually grade up into shallow-marine or marginal marine lithofacies consisting of typically massive non-calcareous mudstone, assigned to Mangakotuku Formation.

Lithology

WCM are dominated by fine-grained lithologies, typically massive but sometimes laminated mudstone to siltstone, with less common sandstone, coal, and conglomerate. Bedding is usually horizontal, but low-angle cross-bedding occurs in sandstone. Siderite concretions are a minor, although significant coal measure lithology common in coalfields of the northern region. They typically form hard reddish-brown (wine-coloured) concretionary bands or elongated nodules (Fig. 3.6b). The siderite cement in these concretions is inferred to form diagenetically soon after burial (Middleton & Nelson 1996), and is typically dominated by methanogenic carbon (Pearson & Nelson 2005). The clays in the WCM are predominantly crystalline kaolinite (80%-85%) with illite (<10%), chlorite (<5%) and rare smectite (Nelson & Hume 1987).

Depositional setting

The WCM were deposited in paleovalleys and faulted sub-basins. The depocentres have a north or northeast trend separated by linear ridges, bounded by buried and steeply dipping fault scarps (Edbrooke et al. 1994). The lithofacies associations in WCM in the northern region are indicative of swamp and overbank deposition on an alluvial flood plain. In the southern and central regions, the terrestrial sub-basins opened eastward into a coastal plain evident from an increase in the degree of marine influence within the coal measures. This less marine influence in northern region coals is demonstrated by mainly low to medium ash (av. 5.8%) and sulphur (≤1%) contents compared with the central and southern region coals that have medium to high ash (av. 11.4%) and sulphur (≥2.21%) contents (Edbrooke et al.1994).

Age

The WCM range in age from Late Eocene (Ak) to early Oligocene (Lwh). The older ages occur in the northern region where the WCM are exclusively Late Eocene (Ak-Ar) in age, whereas at Mangapehi in the south their age is earliest Oligocene (Lwh) (Kear & Schofield 1959; Pocknall 1991). The diachronous nature of the basal coal measures from north to south reflects a major south-directed depositional onlap from the end of the Late Eocene into the Early Oligocene.

Mangakotuku Formation

Historical usage

Kear & Schofield (1959) defined the name "Mangakotuku Siltstone" for predominantly non-calcareous siltstone and minor sandstone gradationally overlying Waikato Coal Measures. The Mangakotuku Siltstone is named after Mangakotuku Stream near Dunphail Bluffs (S14/946933-939936), where this stream cuts through exposures of massive siltstone overlying coal measures. Subsequently, White & Waterhouse (1993) renamed this unit Mangakotuku Formation because Kear & Schofield (1978) had used Mangakotuku for both the formation and one of its constituent members.

Definition

The Mangakotuku Formation is a distinct stratigraphic unit in the coalfields

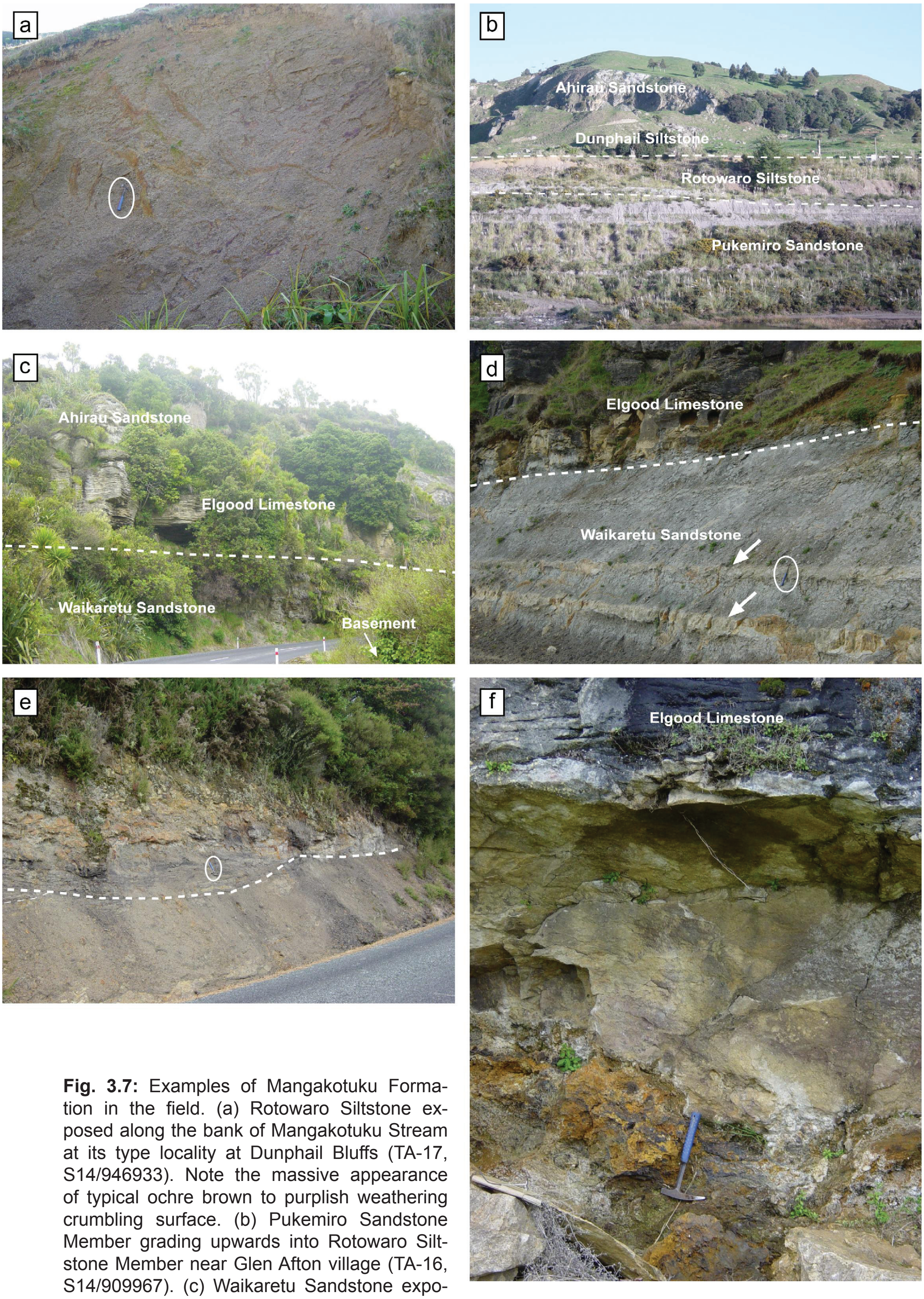


Fig. 3.7: Examples of Mangakotuku Formation in the field. (a) Rotowaro Siltstone exposed along the bank of Mangakotuku Stream at its type locality at Dunphail Bluffs (TA-17, S14/946933). Note the massive appearance of typical ochre brown to purplish weathering crumbling surface. (b) Pukemiro Sandstone Member grading upwards into Rotowaro Siltstone Member near Glen Afton village (TA-16, S14/909967). (c) Waikaretu Sandstone exposures along Waikaretu Valley Road (PW-9, R13/ 701046). Basement is exposed about 2-3 m below road level. (d) Freshly exposed Waikaretu Sandstone Member along a farm track at the end of Waikoha Road (AK-6, S14/941674). Note the cemented sandstone beds (arrows) standing out within massive blue-grey silty sandstone. (e) Exposures of Mangakotuku Formation along Oparure Road (R16/844139) comprising thin coal streaks interbedded within carbonaceous mudstone. (f) Waikaretu Sandstone Member exposed beneath Elgood Limestone Member on the ridge on the north side of Awakino Tunnel.

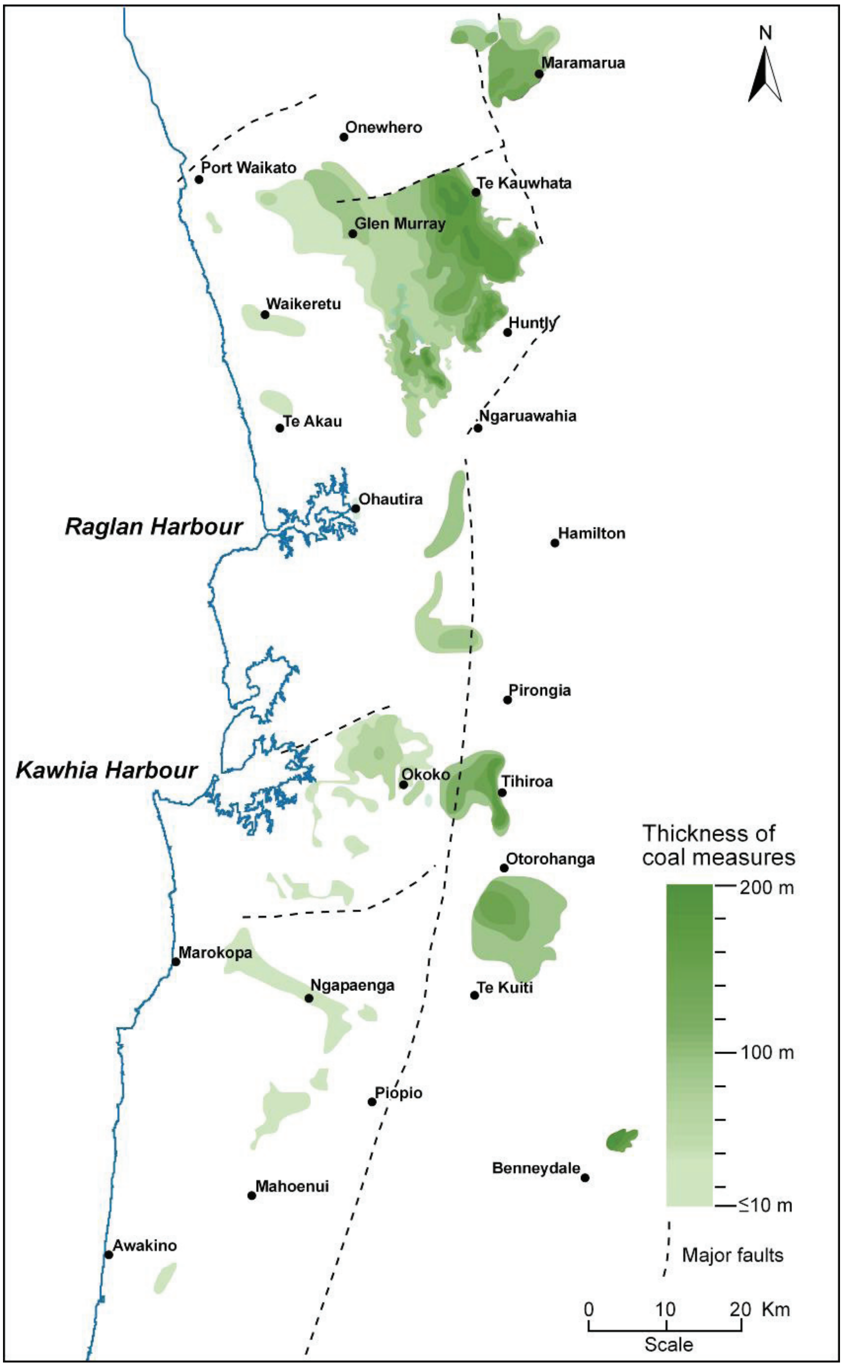


Fig. 3.8: Generalised distribution and thickness of Waikato Coal Measures and Mangakotuku Formation.

of the northern region where it conformably overlies WCM. The formation is dominated by shallow marine to marginal marine lithofacies comprising mainly massive non-calcareous siltstone, but sandstone is prominent in places. In these coalfields the formation is distinguished from WCM by the absence of coal seams. Along the western margin, at localities such as Waikaretu Valley Road (Fig. 3.7c), Mangakotuku Formation rests unconformably on Mesozoic basement, forming the lowest stratigraphic unit of the Te Kuiti Group.

Type and reference sections

Kear & Schofield (1959) nominated massive siltstone exposed in the headwaters of Mangakotuku Stream at Dunphail Bluffs (TA-17, S14/946933-939936) near Ngaruawahia as the type locality for Mangakotuku Formation (Fig 3.7a). This study retains the Dunphail Bluffs type locality and nominates Waikoha Road, Te Pahu (AK-6, S15/941674) (Fig 3.7d), as a reference section for the central region, and a section at Ngapaenga (C-68, R16/814144-808135) as a reference section for the southern region. These sections cover some of the significant variations in the lithofacies and contact relationships of Mangakotuku Formation.

Thickness and distribution

In general, the thickness patterns for the Mangakotuku Formation are similar to those for the underlying WCM. The combined thickness and distribution of WCM and Mangakotuku Formation is depicted in Fig. 3.8. The formation generally thickens to the east and is up to 200 m thick over most of its mapped distribution in the coalfields of the northern region (Edbrooke et al. 1994). In the central and southern regions, the Mangakotuku Formation is generally thin (<10 m) and largely indistinguishable from the coal measures. However, in places the presence of massive mudstone occupying a stratigraphic position between carbonaceous mudstone with thin coal streaks and overlying limestone of the Glen Massey Formation is consistent with inclusion in Mangakotuku Formation.

Contacts

The Mangakotuku Formation is conformable with underlying WCM over most of the northern region coalfields (Kear & Schofield 1978) or onlaps basement along the western margin. The upper boundary, between Mangakotuku Formation and Glen Massey Formation, marks significant marine inundation, probably the earliest that can be defined regionally across the basin. This upper boundary is usually well defined where it involves the basal limestone member (Elgood Limestone) of the Glen Massey Formation, as at its type locality at Dunphail Bluffs (TA-17). However, where Elgood Limestone is poorly developed, the upper contact of Mangakotuku Formation with Glen Massey Formation is marked by burrowed greensand, reflecting a general paucity of clastic sediment input at this time over much of the northern region coalfields (Fig 3.7 b) (Kear & Schofield 1978). In the Te Pahu-Karamu and Awamarino areas, this upper contact is usually intensely burrowed and is either disconformable or abruptly gradational.

Lithology

Mangakotuku Formation typically consists of light to dark grey non-calcareous massive siltstone or mudstone, which weathers to an ochre-brown to purple colour, and to a lesser extent, consists of carbonaceous mudstone, quartzitic sandstone, and rare shell beds or conglomerate. A lack of coal seams and an overall decrease in the carbonaceous content (especially in the lower Glen Afton Claystone Member; Kear & Schofield 1978) of siltstone and claystone beds distinguishes it from WCM. Siderite concretions are not common, however, thin ironstone veinlets criss-cross the massive siltstone, and occasional concretions are recorded in places. The coarsest grained rocks in this formation occur along the western margin.

Depositional setting

The lowest member (Glen Afton Claystone) contains fragments of the brachiopod *Lingula,* indicating accumulation in a shallow marine environment. The presence of abundant ostracods and rare foraminifera (Kear & Schofield 1978) in the glauconite-rich Pukemiro Sandstone Member in the middle of Mangakotuku Formation probably indicates restricted neritic conditions. The degree of marine influence within the formation increases up-sequence, as suggested by plentiful benthic foraminifera, ostracods, and echinoderms in upper parts of the formation, although foraminiferal species are very rare (Hornibrook, in Kear & Schofield 1978). The overall depositional pattern indicates a consistent rise in base level but the maintenance of restricted marine conditions.

Age

Based on palynological dating, the Mangakotuku Formation in the coalfields of the northern region is Late Eocene to Early Oligocene (uppermost Runangan to lowermost Whaingaroan) in age (Kear & Schofield 1978; Pocknall in Edbrooke et al. 1994).

Stratigraphic subdivision

Kear (1963) distinguished three units within the Mangakotuku Formation. All were originally given formation status but Kear & Schofield (1978) subsequently downgraded them to members due to their limited lateral extent. The stratigraphic correlation of Mangakotuku Formation members is complicated by poor exposures, and by the wide geographic separation between various depocentres (Fig. 3.8). Although all three members are retained here (Table 3.2), they are inferred to have distributions restricted mainly to the coalfields of the northern region.

Glen Afton Claystone Member is the lowermost unit of the Mangakotuku Formation in the northern region coalfield. It was named after Glen Afton Colliery by Kear (1963). Penseler (1930) informally referred to this member as “Lingula Claystone” because of the presence of *Lingula waikatoeinsis* (ibid) within it. The member conformably overlies WCM, consists of light grey non-calcareous claystone,

Table 3.2: Historical and proposed subdivision of Mangakotuku Formation.

Kear & Schofield (1978)	**White & Waterhouse (1993)**	**This study**	
		Northern Coalfields	**Western margin**
Mangakotuku Siltstone;	Rotowaro Siltstone	Rotowaro Siltstone	Waikaretu Sandstone
Pukemiro Sandstone;	Pukemiro Sandstone	Pukemiro Sandstone	
Glen Afton Claystone;	Glen Afton Claystone	Glen Afton Claystone	
WCM	WCM	WCM	Basement

which on weathering produces a coating of yellow efflorescence and patchy iron staining. Pocknall (1991) assigned an uppermost Runangan (late Eocene) to earliest Whaingaroan (Early Oligocene) age to Glen Afton Claystone.

Pukemiro Sandstone was formally defined by Kear (1963) as the middle unit within Mangakotuku Formation, being named after Pukemiro village. Penseler (1930) mapped this member as "greensand" because of its high glauconite content, the beds conformably overlying the Glen Afton Claystone at its type section near Glen Afton village (S14/689397). Kear (1963) formally renamed the greensand as Pukemiro Sandstone Member. The member is a good stratigraphic marker between the lower Glen Afton Claystone Member and overlying Rotowaro Siltstone Member (Kear & Schofield 1978) (Fig. 3.7b). Sand-rich Pukemiro Member may represent an intervening marine incursion between the Glen Afton Claystone Member and Rotowaro Siltstone Member. Microfossils indicate an upper Runangan to lower Whaingaroan age and a mainly lower Whaingaroan age for the Pukemiro Sandstone (Kear & Schofield, 1978).

Kear & Schofield (1959) named the uppermost siltstone unit of Mangakotuku Formation "Mangakotuku Siltstone". White & Waterhouse (1993) renamed it Rotowaro Siltstone Member for the reason that the same name was applied to both the formation and one of its constituent members. A section beside Mangakotuku Stream at Dunphail Bluffs (S14/946933 to S/14939936) was nominated by Kear & Schofield (1959) as its type locality. Rotowaro Siltstone Member is widely distributed in the coalfields of the northern region where it forms the bulk of the Mangakotuku Formation. Its thickness is generally about 80-100 m. Kear & Schofield (1978) assigned a lower Whaingaroan age to Rotowaro Siltstone.

An additional "Waikaretu Sandstone Member" of Mangakotuku Formation is introduced here to describe the basin margin facies restricted mainly to the west, or its lateral equivalent elsewhere in the study area.

Waikaretu Sandstone Member (new)

Name and definition

Waikaretu Sandstone Member is defined here as a unit within Mangakotuku Formation, which directly overlies basement and underlies the basal limestone member of Glen Massey Formation. The member is named after Waikaretu Stream alongside Waikaretu Valley Road. Kear (1966) mapped the member at this locality as a correlative of Pukemiro Sandstone. However, the implied correlation is rejected and this study suggests that it is mainly a lateral correlative of Rotowaro Siltstone.

Type section

Waikaretu Sandstone Member is well exposed in the road cut at the western end of Waikaretu Valley Road (PW-9, R13/702046), which is nominated as its type locality. The member is represented by up to 8 m of dark grey siltstone interbedded with fine to coarse sandstone (Fig. 3.7c). A thin laterally discontinuous band of rhodoliths at the base of the unit marks the lower contact with basement.

Distribution and thickness

The member is the coarsest-grained facies of the Mangakotuku Formation, is usually only a few metres thick, and is sporadically distributed, mostly in the west.

Contacts

Waikaretu Sandstone Member rests directly on basement. The contact is marked in places by conglomerate with occasional shell fragments (e.g. Awamarino, C-50; Port Waikato, PW-2) and scattered pebbles and grit with common algal encrustations and rhodoliths, as at its type locality on Waikaretu Valley Road. The member is unconformably overlain by the Elgood Limestone Member of Glen Massey Formation. The sharp and abrupt nature of this contact is due to erosion, possibly marine planation (Fig. 3.7 d & f).

Lithology

The member comprises a variety of lithotypes varying from poorly sorted grit, medium to coarse quartzitic sandstone grading into silty sandstone and siltstone. Coal fragments and large bivalve shell fragments occasionally occur within the sandstone. Rhodoliths and other algal encrustations are commonly associated with the basal conglomerate.

Age

Laird (1967) and Pocknall (1991) assigned a lower Whaingaroan age to this unit at the Te Pahu locality.

Lateral extent of Mangakotuku Formation

Mangakotuku Formation has long been regarded as geographically restricted to the northern region (Kear & Schofield 1959; Nelson 1978a; White & Waterhouse 1993; Edbrooke et al. 1994). Although Nelson (1973) acknowledged that local condensed siliceous mudstone units (lithofacies Wk-2) overlying the coal measures have Mangakotuku Formation affinity and stratigraphic position (e.g. Nelson 1977 in stratigraphic columns C8, C68, C 113 and C121), the formation was not included within his lithostratigraphic framework for Waitomo County. Traditionally, the stratigraphic unit overlying the coal measures in most of the southern region has been regarded as Whaingaroa Formation. However, in the Mangapehi Coalfield, WCM is reported to pass directly into Aotea Formation (Kear & Schofield 1959, stratigraphic column N; Nelson 1973, stratigraphic column C197; Edbrooke et al. 1994, stratigraphic column S16).

The WCM and Mangakotuku Formation are difficult to differentiate from each another in the southern region and have been assigned here to undifferentiated WCM/Mangakotuku Formation, although lithofacies affinity with either the WCM or Mangakotuku Formation may locally occur (e.g. Fig. 3.9, columns A & B). Basal units consisting of marginal marine strata interdigitating with coal measures were recorded by Nelson (1977) in the Mangaohae (C56), Ngapaenga (C68), Te Kumi-Te Anga Road (C113), Mangaotaki (C145), and Awakino (C191) sections, arising from southward marine onlap. In general, the basal Te Kuiti Group units in the south are age equivalent to the Mangakotuku Formation (Pocknall 1991, in Edbrooke et al. 1994). Correlation of these units with the WCM is considered here to be no longer valid. Fully marine thick calcareous siltstone strata in the southern region have previously been assigned to Whaingaroa Formation (Kear & Schofield 1959; Nelson 1978a), but these beds are now regarded as part of Glen Massey Formation (see below).

Glen Massey Formation

Historical usage

Glen Massey Formation was defined by Kear & Schofield (1959) and named after Glen Massey village, 8.5 km west of Ngaruawahia. This formation typically comprises a lower flaggy limestone, with overlying calcareous siltstone and fine sandstone, which were assigned by Kear & Schofield (1959) to three members at Dunphail Bluffs (TA-17, S14/943937), the type locality for the formation (Fig. 3.10a). Elgood Limestone Member is the lowermost unit in the formation and comprises flaggy bioclastic limestone. Dunphail Siltstone Member is the middle

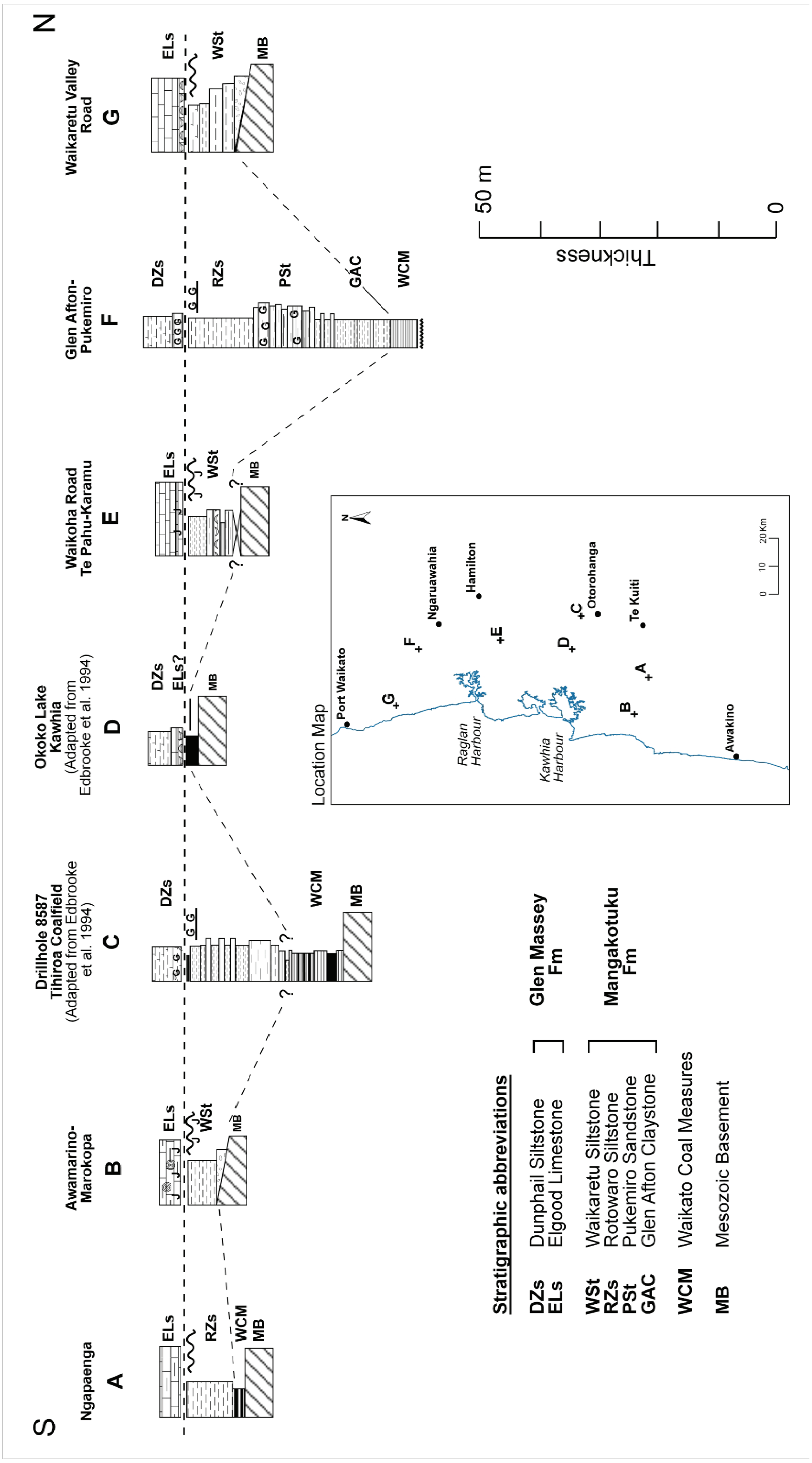


Fig 3.9: Correlation of Mangakotuku Formation members from their type locality at Glen Afton-Pukemiro (column F) to the north at Waikaretu Valley Road (column G) and to the south at Ngapaenga (column A). Note the Mangakotuku Formation is inferred to be more sandy (Waikaretu Sandstone) and/or carbonaceous in some locations. The datum used in this correlation is the base of Elgood Limestone or its correlative (shell beds and highly glauconitic sandstone). No horizontal scale is implied. Refer to Fig. 3.4 for lithology symbols.

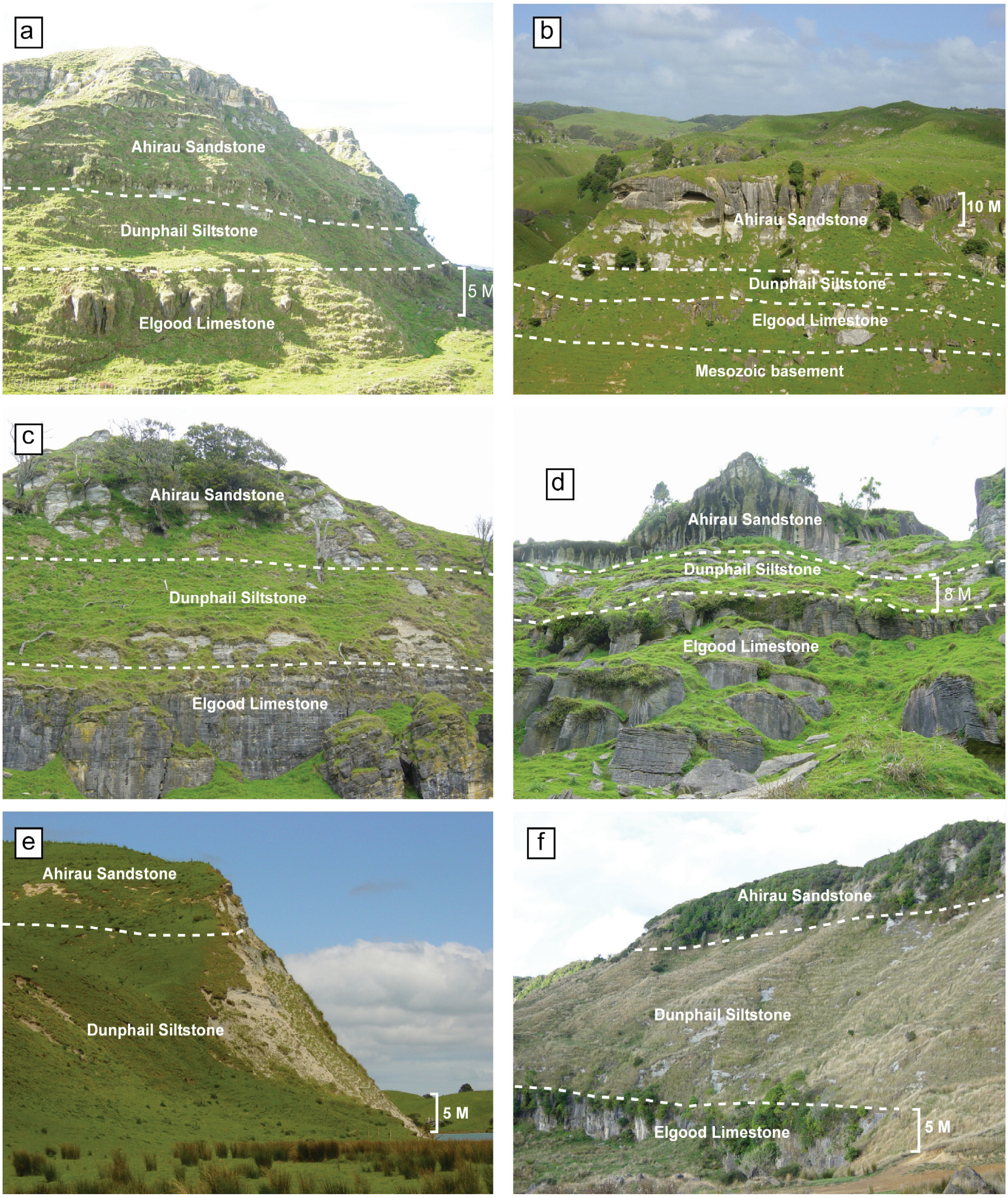


Fig. 3.10: Examples of Glen Massey Formation in the field. (a) Type locality at Dunphail Bluffs (TA-17, S14/943937). Note the distinct break in gradient defining the boundaries of members. (b) View looking to the east across Waimai Stream Valley from Port Waikato-Waikaretu Road (R13/643185). Here Glen Massey Formation rests directly on basement. (c) Section at the end of Waikoha Road (AK-6, S14/941674). Note the interbedded nature of the transition between the Elgood Limestone and Dunphail Siltstone members. (d) Section at Shea Road (AK-4, R15/803646). Note the Dunphail Siltstone grades into bluff-forming Ahirau Sandstone with a prominent overhang. (e) Section at Orotangi Cliff (AK-5, R15/729533) on the eastern shore of Aotea Harbour, view looking south. (f) At the end of Kairimu Road, Awamarino (C-51, R16/674193). Note the thick development of Dunphail Siltstone Member at this locality.

unit, composed of massive calcareous siltstone, and conformably overlies Elgood Limestone. Ahirau Sandstone Member is silty fine sandstone forming the uppermost member of the Formation. To avoid referring to both the formation and one of its constituent members by the same name, White & Waterhouse (1993) renamed "Glen Massey Sandstone" as Ahirau Sandstone Member. It is named after Ahirau Stream.

Definition

Glen Massey Formation has traditionally been identified in the northern region of the study area. The extent of the formation is much expanded here into the central and southern regions. In those regions the beds were formerly mapped by Kear & Schofield (1959) and Nelson (1978a) as Whaingaroa Siltstone. A similar succession exposed around Aotea Harbour (Orotangi Cliffs, AK-5, R15/730533), nominated by White & Waterhouse (1993), Waterhouse & White (1994) (Fig. 3.10e) as a new type locality for part of the Whaingaroa Formation, is shown here to be part of Glen Massey Formation. Along the western margin of the northern region, Glen Massey Formation unconformably overlies marginal marine strata of Mangakotuku Formation, or Mesozoic basement. A paraconformity marks the top of the formation in the north, although in the central and southern regions it is a pronounced erosional unconformity (see contacts, Figs 3.11 & 3.12).

Type and reference sections

The type locality for Glen Massey Formation is the Dunphail Bluffs section (TA-17, S14/943937) at the northern end of Elgood Road, where about 65 m of Glen Massey Formation unconformably overlies Mangakotuku Formation (Kear & Schofield 1959). This section is retained here as the type locality (Fig. 3.10a).

The type section is, however, only partly representative of the lithologic variations and contact relationships occurring in the formation elsewhere in the study area. Three reference sections are additionally nominated for the northern region: Port Waikato (PW-2) (R13/652153-648147) (Fig. 3.10 b), Waikaretu Road (PW-9) (R13/689042-704051), and Te Kotuku Creek (TA-12) (R14/778833-783828) sections. Two reference sections are erected for the central region at Orotangi Cliff, Aotea Harbour, AK-5 (R15/730533) (Fig. 3.10 e) and at Kaimango Road (C-8) (R16/836370-837376). Two reference sections are proposed for the southern region at Awamarino (C-51) (R16/672223-674193) and Mangaotaki (C-145) (R17/787051). The beds in the Orotangi Cliff and Awamarino reference sections were previously regarded as part of Whaingaroa Formation (White & Waterhouse 1993; Waterhouse & White 1994; Nelson 1973).

Distribution and thickness

Glen Massey Formation is widely distributed in a north-south belt parallel to and

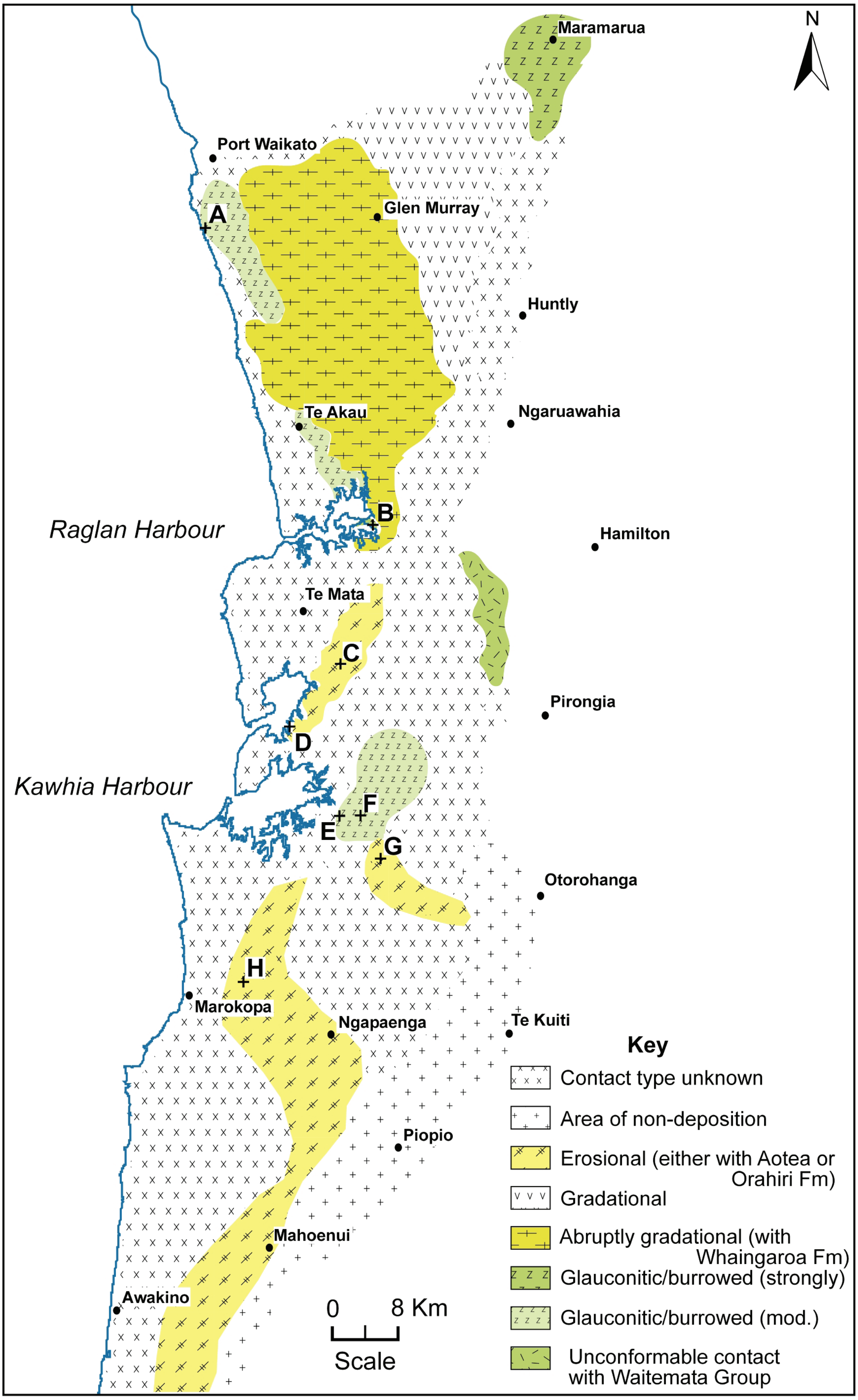


Fig. 3.11: Extent of Glen Massey Formation upper contact types within the study area and their extrapolation to neighbouring areas. A, Waikawau Beach; B, Waitetuna Estuary; C, Shea Road; D, Orotangi Cliff; E, Hautapu Hill; F, Kihi Road; G, Kaimango Road; H, Awamarino.

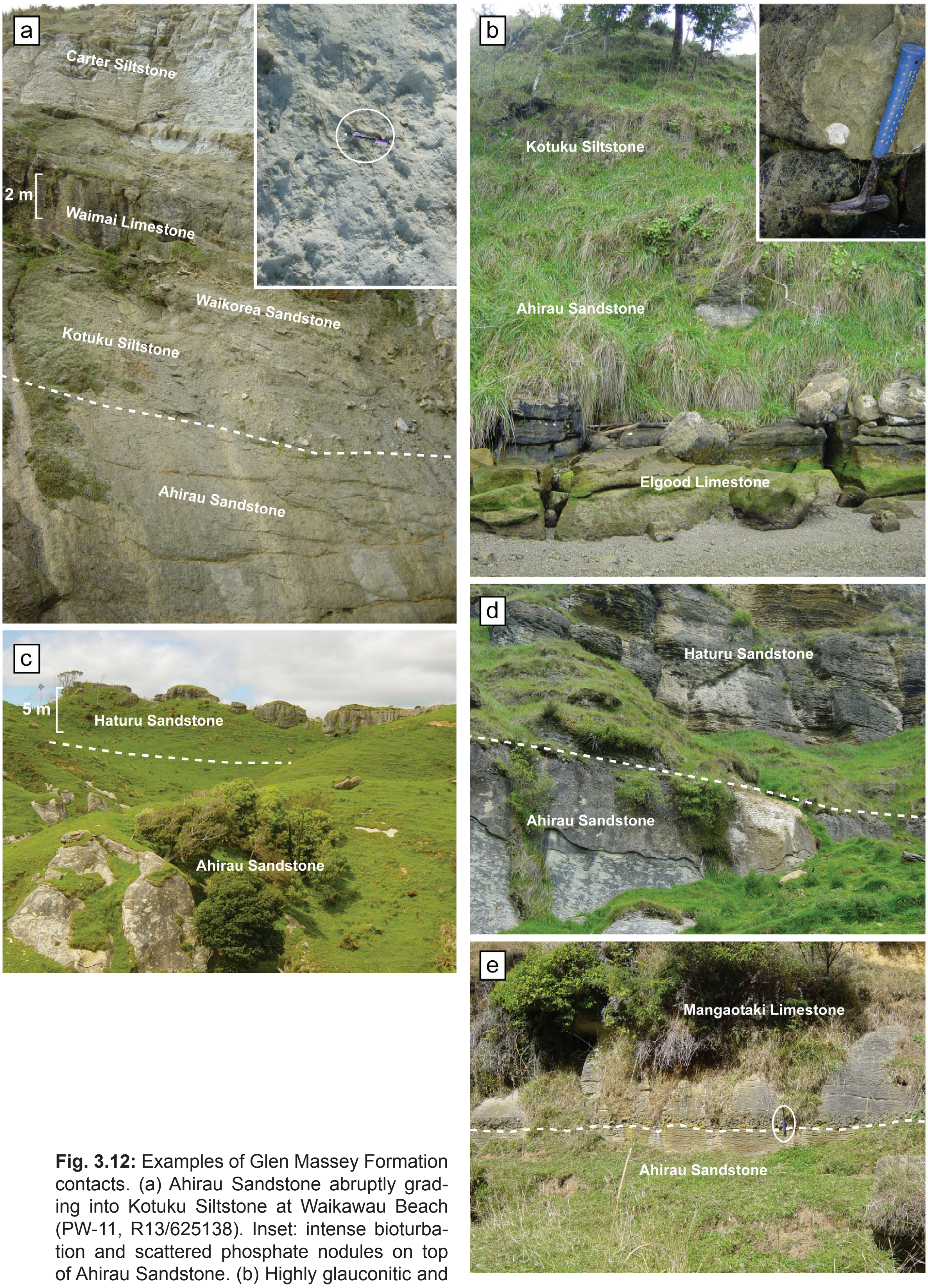


Fig. 3.12: Examples of Glen Massey Formation contacts. (a) Ahirau Sandstone abruptly grading into Kotuku Siltstone at Waikawau Beach (PW-11, R13/625138). Inset: intense bioturbation and scattered phosphate nodules on top of Ahirau Sandstone. (b) Highly glauconitic and bioturbated Ahirau Sandstone sharply grading into Kotuku Siltstone at Waitetuna Estuary (TA-14, R14/834776). Inset: highly glauconitic and fossiliferous Ahirau Sandstone in fallen blocks. (c) Unconformity between Ahirau Sandstone and Hauturu Sandstone inferred (dashed line) inland from Orotangi Cliff (AK-5, R15/736531). (d) Unconformity (dashed line) between Ahirau Sandstone and Hauturu Sandstone in vicinity of Kaimango Road (C-8, R16/838375). (e) Scoured pebbly contact separating “ripply” bedded calcareous sandstone (Ahirau Sandstone) and overlying sandy limestone (Mangaotaki Limestone) at Awamarino (C-50, R16/690232).

inland of the west coast (Fig. 3.13). Here it is readily distinguished by prominent bluffs that show fluted (lapiez) and honeycombed weathering development. Glen Massey Formation is best developed in the Onewhero-Wairamarama area (e.g. PW-7) in the north where it has a thickness of up to 200 m (Fig. 3.13). The Ahirau Sandstone Member of the formation usually manifests itself as steep bluffs, forming prominent topographic features. However, in eastern areas Ahirau Sandstone becomes increasingly finer grained and difficult to differentiate from the overlying Whaingaroa Formation siltstone. In places, such as around Maramarua Coalfield (Kear & Schofield 1959) and Raglan Harbour (e.g. TA-14), the formation can be less than 10 m thick, yet be up to 60+ m in nearby areas (e.g. Waingaro Landing, TA-13). In the northern region, the eastern extent of the formation is limited by a regional southwesterly tilt and associated erosion, which has removed the beds from areas farther east.

In the Te Pahu-Karamu area (e.g. AK-6) west of Hamilton, the formation is remarkably thick (100+ m) and is mainly preserved as outliers in a series of NE-SW oriented fault blocks (Kear & Schofield 1966). The Glen Massey interval exposed along the Aotea-Kawhia Harbour coast has a measured thickness of about 30-40 m, which includes strata formerly assigned to Whaingaroa Formation (White & Waterhouse 1993; Waterhouse & White 1994). An overall thinning of Glen Massey Formation is evident to the east of Kawhia Harbour in inland sections (e.g., Hautapu Hill, C-4 and Kaimango Road, C-8). South of Kawhia Harbour, the most prominent occurrence of the formation is in the vicinity of Awamarino (C-51), where a 70 m-thick succession consisting of a lower limestone member is overlain by massive calcareous siltstone grading into fine calcareous sandstone (Fig. 3.10 f). However the formation generally thins eastwards towards Ngapaenga and Mangaotaki. Farther south, the formation comprises mostly calcareous siltstone and is generally poorly developed, but is up to 140 m thick at Awakino Tunnel (C-191) on SH3. The Glen Massey Formation at this locality consists of basal gravelly limestone facies overlain by thin-bedded then massive calcareous siltstone, formerly all assigned to Whaingaroa Formation (Nelson 1978a; Nelson et al. 1994).

Contacts

The base of Glen Massey Formation along the western margin is commonly marked by a limestone member. At Port Waikato and at Raglan, Aotea and Kawhia harbours, and in areas around Awamarino, Glen Massey Formation laps onto a weathered and wave-planned basement surface with remnant relief. Basement is usually immediately overlain by a pebble and granule layer with common large shell fragments, within a sandy limestone bed up to 1 m thick, comprising the lower

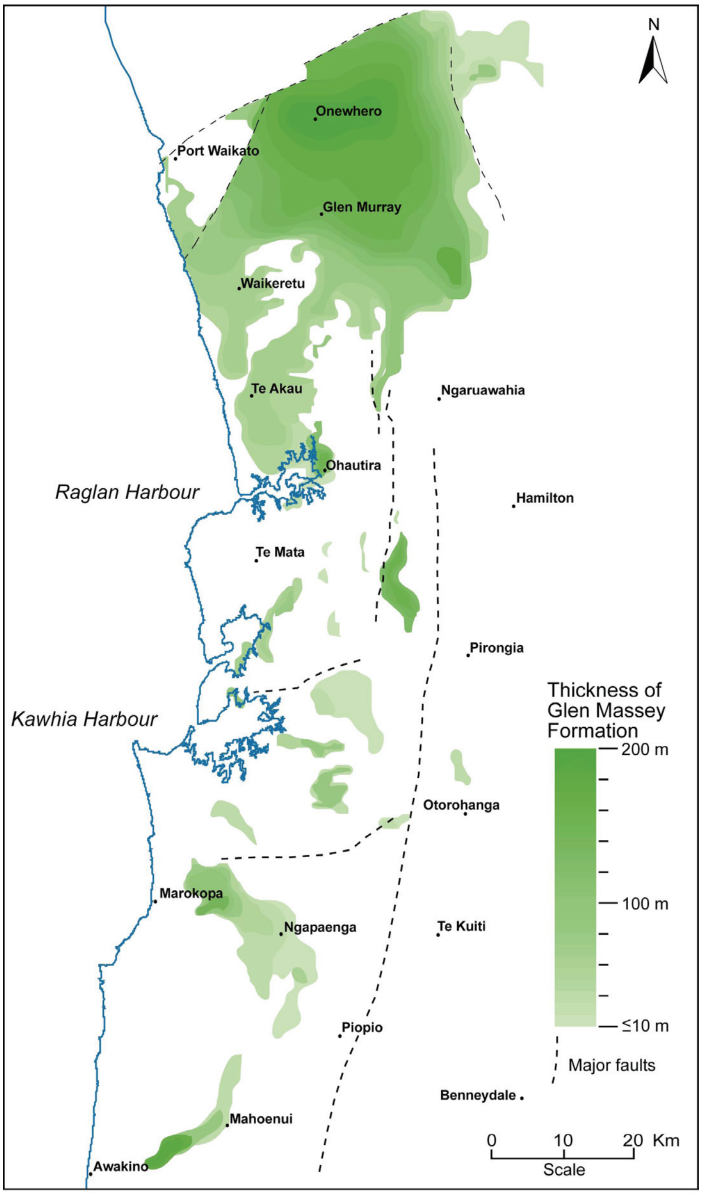


Fig. 3.13: Existing distribution and thickness of Glen Massey Formation.

part of the Elgood Limestone Member.

The upper boundary of Glen Massey Formation is rarely well exposed in sections between Port Waikato and Raglan Harbour, the upper sandstone member being abruptly overlain by calcareous siltstone of the Whaingaroa Formation. This contact is generally conformable although paraconformity development is known in a section at Waitetuna Estuary (Raglan Harbour, TA-14) where a 2-3 m thick greensand occurs between Elgood Limestone Member and Kotuku Siltstone Member of Whaingaroa Formation, representing stratigraphic condensation of Ahirau Sandstone Member (Fig. 3.12b). At the coastal section immediately north of the mouth of Waikawau Stream (Port Waikato, PW-11), the top of Glen Massey Formation is marked by extensive burrowing and scattered phosphate nodules, indicating paraconformity development (Fig. 3.12a).

Glen Massey Formation in the Aotea-Kawhia area is overlain by Aotea Formation in exposures at Shea Road (AK-4), Orotangi Cliff (AK-5), and Kaimango Road (C-8), or by Whaingaroa Formation in the Hautapu Hill (C-4) and Kihi Road (S-13) sections (Fig. 3.11). In the vicinity of Awamarino (e.g. C-50), Orahiri Formation (Castle Craig Subgroup) unconformably overlies Glen Massey Formation. The unconformable contact is defined by pebble conglomerate at the base of Orahiri Formation (Fig. 3.12e). Whaingaroa and Aotea Formations missing in the Awamarino area are inferred to have originally been present but were eroded prior to deposition of Orahiri Formation.

Lithology and members within Glen Massey Formation

The three lithofacies identified as members within Glen Massey Formation are usually well developed, especially along the western margin of the basin. The lithofacies boundaries are generally obvious from marked changes in the weathering profile (Fig. 3.10 a-f). However, locally, Elgood Limestone and Dunphail Siltstone members may either be thinly or poorly developed and, where this occurs, Glen Massey Formation consists almost entirely of Ahirau Sandstone Member. In eastern parts of the northern region, the formation is a calcareous mudstone and lithological distinction from overlying Whaingaroa Formation is difficult to make.

Elgood Limestone, forming the lowermost member of the formation, is well developed along the northwestern margin where it usually onlaps basement, but in places may overlie Mangakotuku Formation (Fig. 3.7 c, d & f). Its main lithofacies include medium to coarse biocalcarenite and occasionally biocalcirudite, the main constituents being skeletal grains consisting of *Amphistegina*, calcareous red algae, bryozoans and occasional echinoids, oysters, pectinids, and brachiopods. The siliciclastic content within the limestone typically varies between 10-15%, comprising mainly fine to medium sandstone and minor siltstone. The detrital sandstone can be scattered throughout the member but is most commonly concentrated in sandy seams between the limestone flags. Locally there is a basal lag consisting of poorly sorted grit and subrounded pebbles derived from basement. In places where the Elgood Limestone is absent, its correlative is represented by greensand such as in parts of the Dunphail Bluffs section (TA-17).

Dunphail Siltstone is predominantly a massive blue-grey calcareous siltstone with conchoidal fracture. The siltstone contains variable amounts of calcium carbonate (typically 40-60%). Where the member rests directly on basement, the calcium carbonate content generally increases towards the base. In the Onewhero-Wairamarama area (e.g. PW-8), thin interbeds of calcareous silty sandstone occur in the lower part of the unit, which then grades upward into massive calcareous siltstone. At the Waiteika Station (AK-8) section at Ruaweke Point east of Aotea Harbour, the facies is uncharacteristically gritty to conglomeratic in the lowermost 2-3 m, likely reflecting nearby exposed Mesozoic basement. The constituent basement-derived granules and pebbles are rounded to subrounded and have glauconitic coatings.

Ahirau Sandstone Member forms the uppermost member of Glen Massey Formation and is best developed in the northern region and western parts of the central region where it is the dominant member of the formation. The main lithofacies is light blue-grey to brownish-grey, variably silty, fine to very fine sandstone. The sandstone is well cemented, with calcium carbonate content ranging between 30-60%. High carbonate content within the sandstone often leads to the development of fluting or lapiez weathering on steep vertical faces of the member. In general, the sandstone is massive, however in uppermost parts horizontal bedding can occur. Large scale trough cross-bedding is apparent in the middle to upper part of Ahirau Sandstone in Waikawau Valley (PW-2) south of Port Waikato. The common presence of dense burrows throughout Ahirau Sandstone Member is indicative of low sediment accumulation rates and high rates of bioturbation. Scattered bivalve fragments within the member usually involve the pectinids *Janupecten polemicus*, *Chlamys williamsoni*, *Lentipecten hochstetteri* and *Janupecten uttleyi*.

Depositional setting

Glen Massey Formation sediments were deposited in inner shelf to upper bathyal water depths that deepened eastwards. Elgood Limestone was deposited in an inner to mid shelf environment, and is essentially a transgressive limestone. It accumulated as transgressive sheets and lenses in shoal areas, particularly shallow depressions around submerged basement knolls. This member onlaps basement in the Port Waikato, Raglan, Kawhia, and Awakino areas, compared with WCM in more eastern parts of the basin. Dunphail Siltstone Member reflects deeper water conditions of sediment accumulation, and is thickest in eastern parts of the basin. The transition from Dunphail Siltstone to Ahirau Sandstone represents coarsening upward, probably indicating up-sequence shoaling. Ahirau Sandstone accumulated in an inner to mid shelf environment. The character and distribution of this sandstone suggests that much of its terrigenous content was derived from basement to the west.

Age

Glen Massey Formation is assigned a lower Whaingaroan age on the basis of *Globigerina angiporoides* in samples from the northern and central regions

(Hornibrook 1985; Waterhouse & White 1994). The common *G. angiporoides* reported by Nelson (1978a) for his "Whaingaroa Formation" in the southern region, is regarded here as supporting the interpretation that these beds are part of Glen Massey Formation.

Relationship between Glen Massey Formation and Whaingaroa Formation

Much of the confusion about Te Kuiti Group lithostratigraphic correlation between the central and southern regions is related to the inferred relationship between the Glen Massey Formation and Whaingaroa Formation. Kear & Schofield (1959) restricted the Glen Massey Formation to the well developed limestone, siltstone, and sandstone succession that could be correlated from Port Waikato southward to Raglan Harbour and Te Pahu. The calcareous siltstone unit overlying coal measures or basement in the Aotea-Kawhia region, and in eastern areas, was regarded as part of Whaingaroa Formation. Whaingaroa Formation was thought to progressively onlap basement to the south. This interpretation was adopted by Nelson (1978a) in Waitomo County. He distinguished three lithofacies within his Whaingaroa Formation: (i) "Basal Beds (Wh-A)" consisting of pure to impure limestone named "Awamarino Limestone", (ii) "Massive Mudstone Beds (Wh-2)", which grade upwards into (iii) "Sandy-Silty Limestone Beds (Wh-3)", as illustrated in Fig. 3.14a. White & Waterhouse (1993) extended this lithofacies subdivision northward into the Aotea-Kawhia area. Furthermore, the "Whaingaroa Formation" was considered by them to rest directly on basement at Orotangi Cliff on the shores of Aotea Harbour. Indeed, Orotangi Cliff was designated by them as a new type locality for Whaingaroa Formation. At this locality, the massive calcareous siltstone exposed at the shoreline was named "Kotuku Siltstone Member", and regarded by White & Waterhouse (1993) as a lateral equivalent of Nelson's (1978a) "Massive Mudstone Beds (Wh-2)" (Whaingaroa Formation). Immediately overlying thick (15 m) calcareous silty sandstone was named "Orotangi Sandstone Member", and regarded as a lateral equivalent of Nelson's (1978a) "Sandy-Silty Limestone Beds (Wh-3)". White & Waterhouse's (1993) stratigraphic correlations are illustrated in Fig. 3.14b.

Understanding the distribution of Glen Massey Formation and the nature of its relationship with Whaingaroa Formation (of prior workers) has been a key focus of this study. Fieldwork has demonstrated that the Glen Massey Formation is contiguous with, and a lateral correlative of, units formerly identified by Kear & Schofield (1959), Nelson (1978a), White & Waterhouse (1993) and Waterhouse & White (1994) as Whaingaroa Formation in the Aotea-Kawhia area and to the south. The lack of Te Kuiti Group exposures in the vicinity of Mt Karioi and Mt

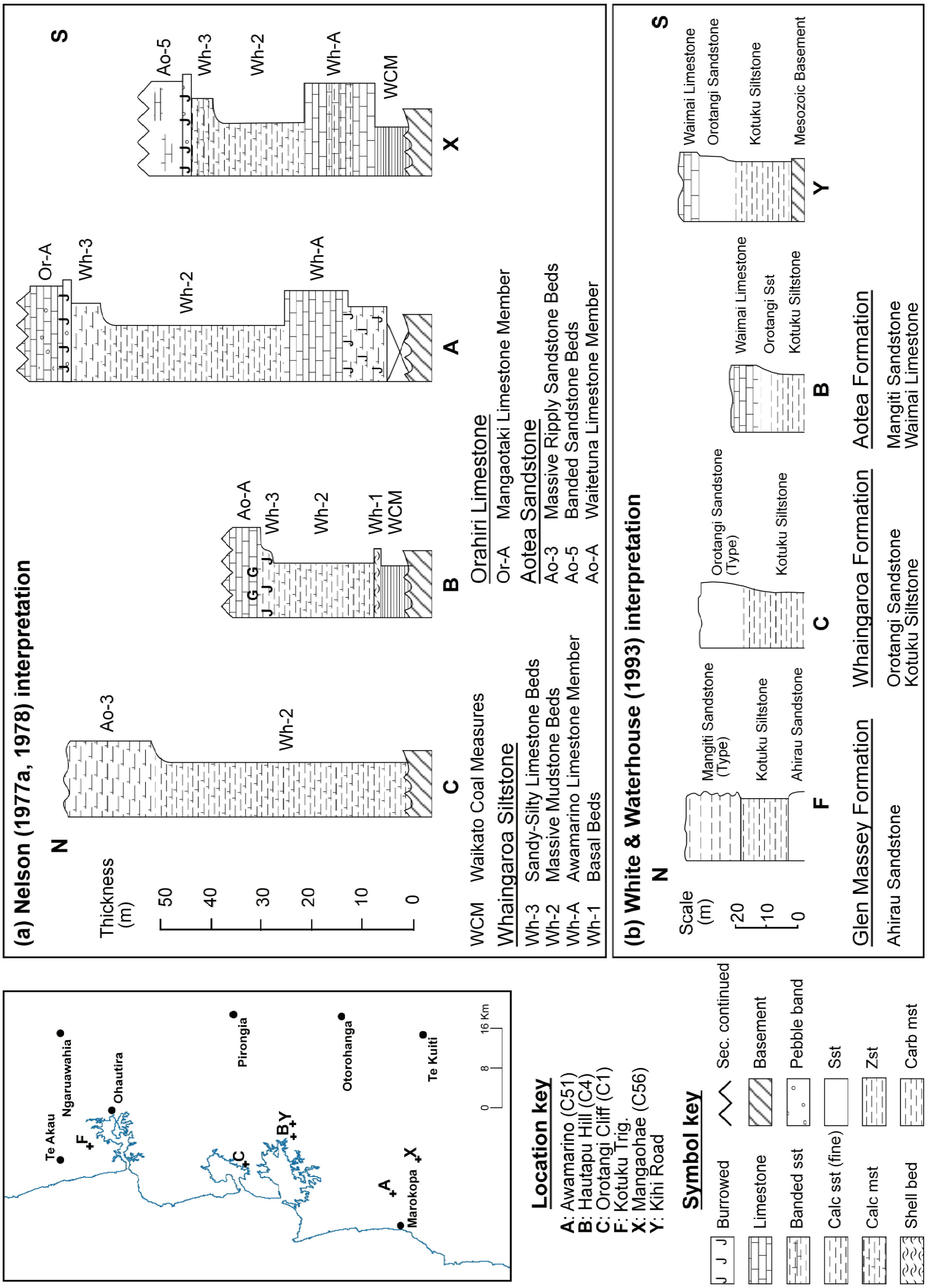


Fig. 3.14: (a) Stratigraphic correlation suggested by Nelson (1977, 1978a) compared with that of White & Waterhouse (1993) in (b). Column numbers within brackets in the location key refer to Nelson's (1977) stratigraphic columns.

Pirongia, and hence the difficulty of correlating units between the northern and southern regions, has always been a source of frustration in stratigraphic correlation of formations within Te Kuiti Group. Fig. 3.15 depicts correlation of Glen Massey Formation between its type section at Dunphail Bluffs and Awamarino.

The Te Kotuku Creek section (Fig. 3.15, column F) immediately north of Raglan Harbour is an important reference section inferred to be representative of the stratigraphic relationship between Glen Massey Formation and Whaingaroa Formation elsewhere in the northern region. There, Glen Massey Formation overlies basement and comprises thin (<2 m) highly calcareous siltstone (Dunphail Siltstone Member) that grades upward into calcareous silty sandstone (Ahirau Sandstone Member), which is up to 30 m thick in well exposed bluffs along Te Kotuku Creek (TA-12). Whaingaroa Formation is readily identifiable in this section as a massive calcareous siltstone about 15 m thick having an abrupt lower boundary with Ahirau Sandstone. The contact between these units is moderately glauconitic and extensively burrowed, suggestive of paraconformity development.

The Orotangi Cliff section on the shore of Aotea Harbour is another important reference section showing Dunphail Siltstone Member grading upward into Ahirau Sandstone Member (Fig. 3.10 e & Fig. 3.15, column C). Dunphail Siltstone there is lower Whaingaroan in age, contrasting with the upper Whaingaroan age of Whaingaroa Formation in the Raglan Harbour area with which it has previously been correlated. Whaingaroa Formation is absent at Orotangi Cliff as Aotea Formation rests unconformably on Glen Massey Formation. This unconformity is readily identifiable in several places in the Aotea-Kawhia area and in areas farther to the south.

Whaingaroa Formation

Historical usage

Whaingaroa Formation was described by Kear & Schofield (1959, p. 699) as "… 150 ft of medium blue-grey calcareous siltstone" at the type locality in Waitetuna Estuary on the eastern shores of Raglan Harbour (Fig. 3.16a). The name "Whaingaroa Clay" was first used by Hutton (1867, p. 6) for "…yellow sandy clay at Whaingaroa Harbour", taking the Maori name for Raglan Harbour. Kear & Schofield (1959) renamed this unit "Whaingaroa Siltstone" because it was inferred to be predominantly massive fine-grained siltstone everywhere in the basin. They also gave the unit formation status. Nelson (1978a) continued with this usage in Waitomo County, and distinguished three lithofacies within the formation. White & Waterhouse (1993) and Waterhouse & White (1994) formalised Nelson's (1973,

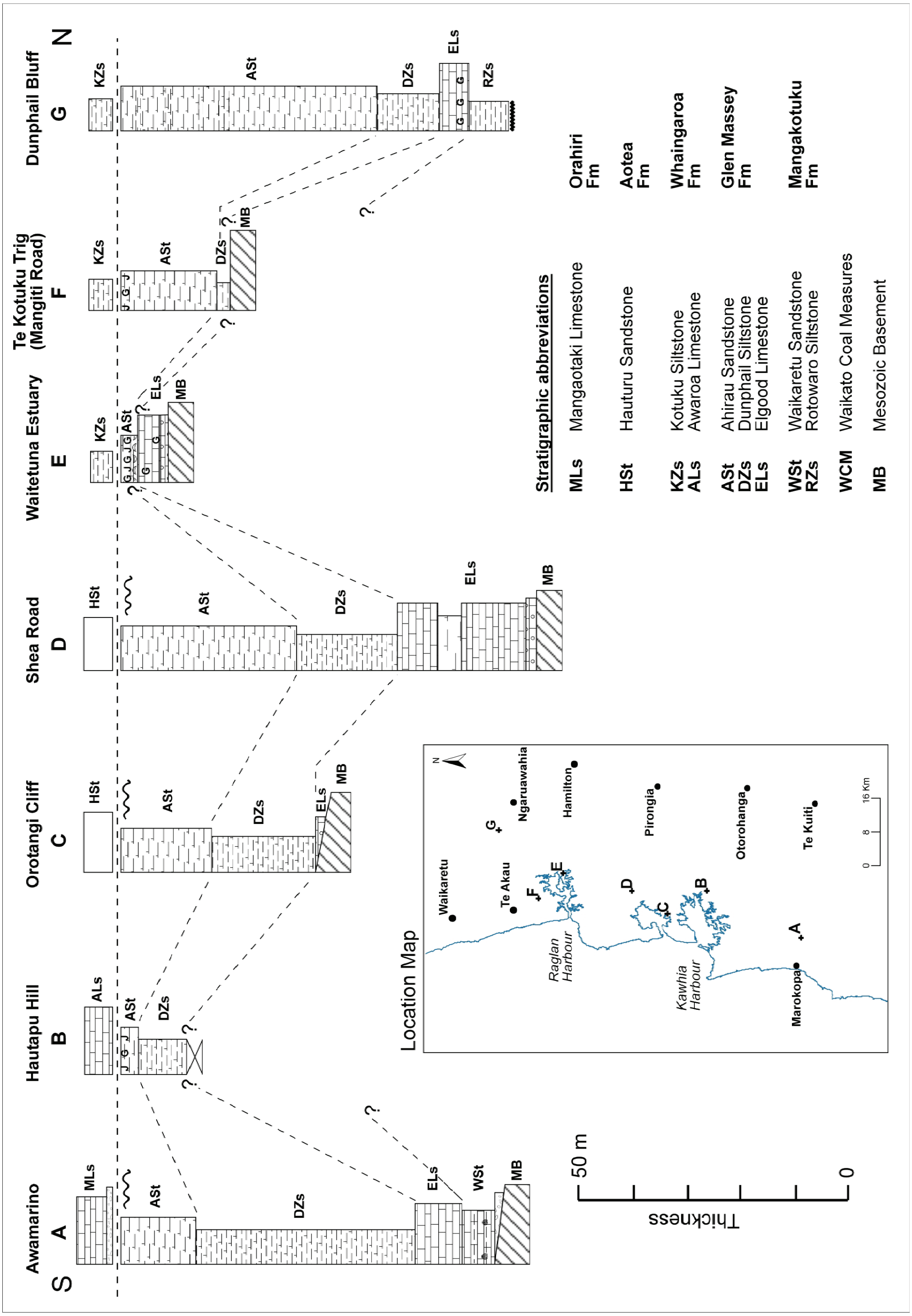


Fig. 3.15: Correlation of Glen Massey Formation members from the type section at Dunphail Bluffs (column G), to Awamarino in the south (column A). The datum used in this correlation is the top of the Ahirau Sandstone Member. No horizontal scale is implied. Refer Fig. 3.4 for lithology symbols.

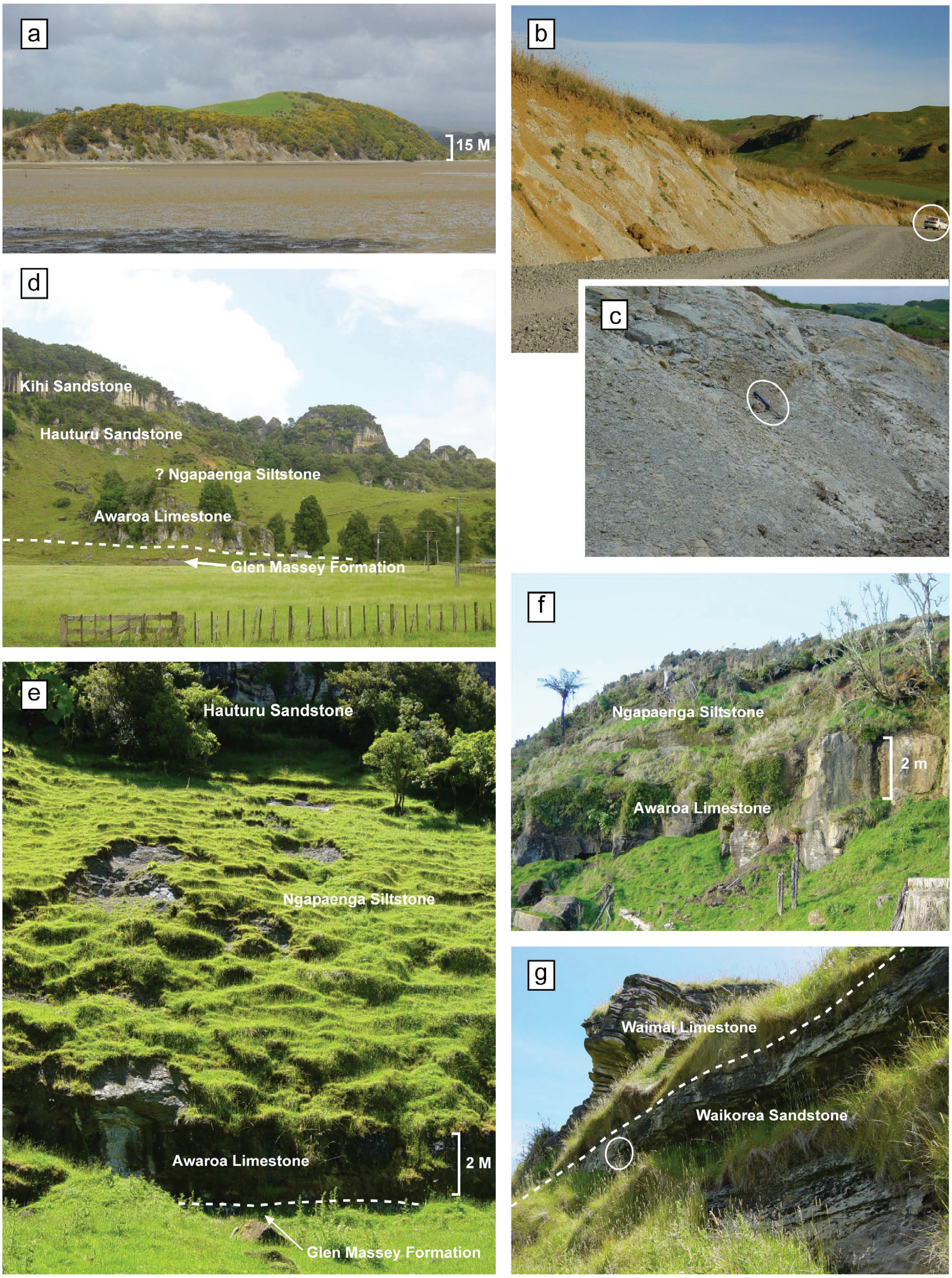


Fig.3.16: Examples of Whaingaroa Formation in the field. (a) Type locality at Waitetuna Estuary (TA-14, R14/836775). (b) Freshly exposed Kotuku Siltstone along Mangiti Road (TA-12, R14/785840). (c) Close-up view of massive calcareous siltstone with typical frittery weathering surface. (d) View of Hautapu Hill (C-4, R15/788422) across the Awaroa River. Awaroa Limestone possibly passing up section into Ngapaenga Siltstone. Note partly exposed Glen Massey Formation at the base of the hill. (e) Ngapaenga Siltstone with Awaroa Limestone exposed near Mangaotaki (C-145 R17/783047). Note partly exposed top of Ahirau Sandstone underlying Awaroa Limestone. (f) Awaroa Limestone grading up into Ngapaenga Siltstone Member near Ngapaenga (C-68, R16/814144). (g) Waimai Limestone Member (Aotea Formation) overlying Waikorea Sandstone Member, with a sharp erosional contact between the two members. The Awaroa Limestone rests on Glen Massey Formation at Waimai Valley (TA-3) (not visible here).

1978a) lithofacies into member status (Awamarino Limestone, Kotuku Siltstone, and Orotangi Sandstone, in ascending order), and renamed the Whaingaroa Siltstone as Whaingaroa Formation (Table 3.3).

Table 3.3: Subdivision and historical nomenclature of Whaingaroa Formation.

Kear & Schofield (1959)	**Nelson (1978)**	**White & Waterhouse (1993)**		**This study**	
		North	South	North	South
	Sandy-Silty Limestone Beds (Wh-3)		Orotangi Sandstone Member	Waikorea Sandstone Member	Ngapaenga Siltstone Member
Whaingaroa Siltstone	Massive Mudstone Beds (Wh-2)	Kotuku Siltstone Member	Kotuku Siltstone Member	Kotuku Siltstone Member	Awaroa Limestone Member
	Awamarino Limestone Member including Basal Beds (Wh-1)		Awamarino Limestone Member		

Definition

All of the units south of Raglan Harbour previously regarded as Whaingaroa Siltstone and Whaingaroa Formation are now included here in Glen Massey Formation. Whaingaroa Formation is however identified above Glen Massey Formation in the southern region, and comprises a lower limestone (Awaroa Limestone Member) and an overlying sandy siltstone (Ngapaenga Siltstone Member). These new members were previously included in Aotea Formation by earlier workers. In the vicinity of Raglan Harbour Whaingaroa Formation occurs as a siltstone (Kotuku Siltstone Member) and this facies extends northward to Port Waikato and eastward across the northern region coalfields. Between Te Akau and Port Waikato, Kotuku Siltstone Member grades rapidly upward into a thin silty sandstone (Waikorea Sandstone Member, new) (Table 3.3).

Type and reference sections

Kear & Schofield (1959) designated the type locality of Whaingaroa Siltstone to be at Waitetuna Creek (TA-14, R14/836775) (Fig. 3.16a) on the eastern shore of Raglan Harbour. The type section is a 40 m high coastal cliff approximately 100 m west of the Te Uku-Waingaro Road. The entire cliff exposure comprises blue-grey to light brownish-grey calcareous siltstone with common conchoidal fracture development. The siltstone is generally massive with faint bedding discernible in places. In the type area, the lower and upper contacts of Whaingaroa Formation are poorly exposed, however the lower contact with Glen Massey Formation crops out in an up-lifted block about 400 m along the shoreline to the west of the main section. Although the stratigraphic relationship of Whaingaroa Formation to other units is not well exposed at this section, it is nevertheless an important locality because typical microfauna of upper Whaingaroan age are well described from it (Stache 1864; Finlay & Marwick 1940; Hornibrook 1971).

To better represent the stratigraphic relationships, a reference section west of Kotuku Trig on Mangiti Road (TA-12, R14/778833-782834) was nominated by White & Waterhouse (1993), and this is retained here (Fig. 3.16b & c). A Mangaotaki River reference section (C-145, R16/787385) west of Piopio (Fig. 3.16e) is also nominated here to represent significant lithofacies variations within the formation in the southern region.

Distribution and thickness

Whaingaroa Formation crops out extensively from Port Waikato to Raglan Harbour (Fig. 3.17) and extends in the subsurface beneath most of the Huntly coalfields and areas farther to the east. The formation is generally mapped as a thin siltstone overlying the "rounded top" of Glen Massey Formation in (1 inch to 1 mile) geology map sheets N51, N55 and N56. The thickest development of the formation occurs in the main coal depocentres of the northern region, where it is a fine-grained siltstone having a total thickness of about 250 m in several coal exploration drill holes (Kear & Schofield 1978; White & Waterhouse 1993) (Fig. 3.17). However, in this area the formation is often lithologically difficult to differentiate from the underlying Glen Massey Formation (Dunphail Siltstone) and overlying younger stratigraphic units of the Te Kuiti Group (Kear & Schofield 1978). Whaingaroa Formation is generally up to 15 m thick along the western margin between Port Waikato and Raglan Harbour, but it is up to 40 m thick in the type area at Waitetuna Estuary. The thickness trends in the northern region indicate that the formation has a wedge-shaped geometry thinning to the west (Fig. 3.17).

Despite widespread occurrence of Whaingaroa Formation siltstone in the northern region, its distribution in outcrop is sporadic in central and southern regions. In the immediate vicinity of Aotea Harbour (e.g. Pakoka Landing, Shea Road, Orotangi Cliff) Whaingaroa Formation is either very thin or absent. The formation is also absent in the Awamarino region and the area farther to the southwest. Limestone and sandy siltstone units now assigned to Whaingaroa Formation are inferred to be present east of this belt at Ngapaenga-Mairoa (Fig. 3.18, column A & B) and at Mangaotaki, and inland at Kawhia Harbour (Hautapu Hill, Kihi Road) (Fig. 3.18, column C). In a few coal exploration drill holes in the West Kawhia Coalfield, a

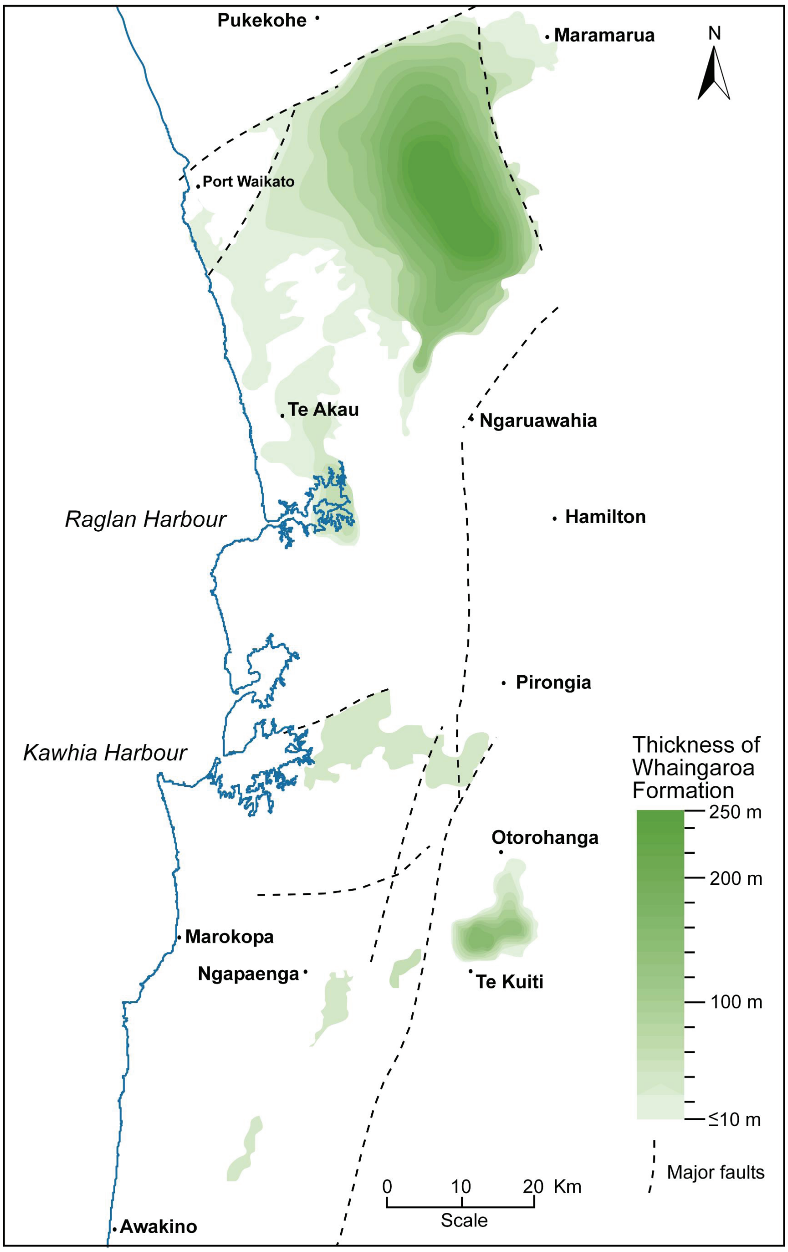


Fig. 3.17: Generalised distribution and thickness of Whaingaroa Formation.

thick siltstone interval intersected below Aotea Formation is included here within Whaingaroa Formation (Fig. 3.18, column D & E). A similar siltstone interval intersected in coal exploration drill holes in the vicinity of Tihiroa and Te Kuiti Coalmine (e.g., DH 6796) is a probable correlative of Whaingaroa Formation.

Contacts

In the northern region, Whaingaroa Formation invariably overlies Glen Massey Formation, the boundary being marked by an abrupt transition from well cemented calcareous sandstone to variably calcareous siltstone, particularly in western parts (Fig. 3.12a). This boundary is glauconitic in places, and probably represents a period of sediment starvation. The top of Whaingaroa Formation is marked by a sharp planar contact with either Waimai Limestone Member or its lateral equivalent, Mangiti Sandstone Member (Aotea Formation). This boundary can be readily traced

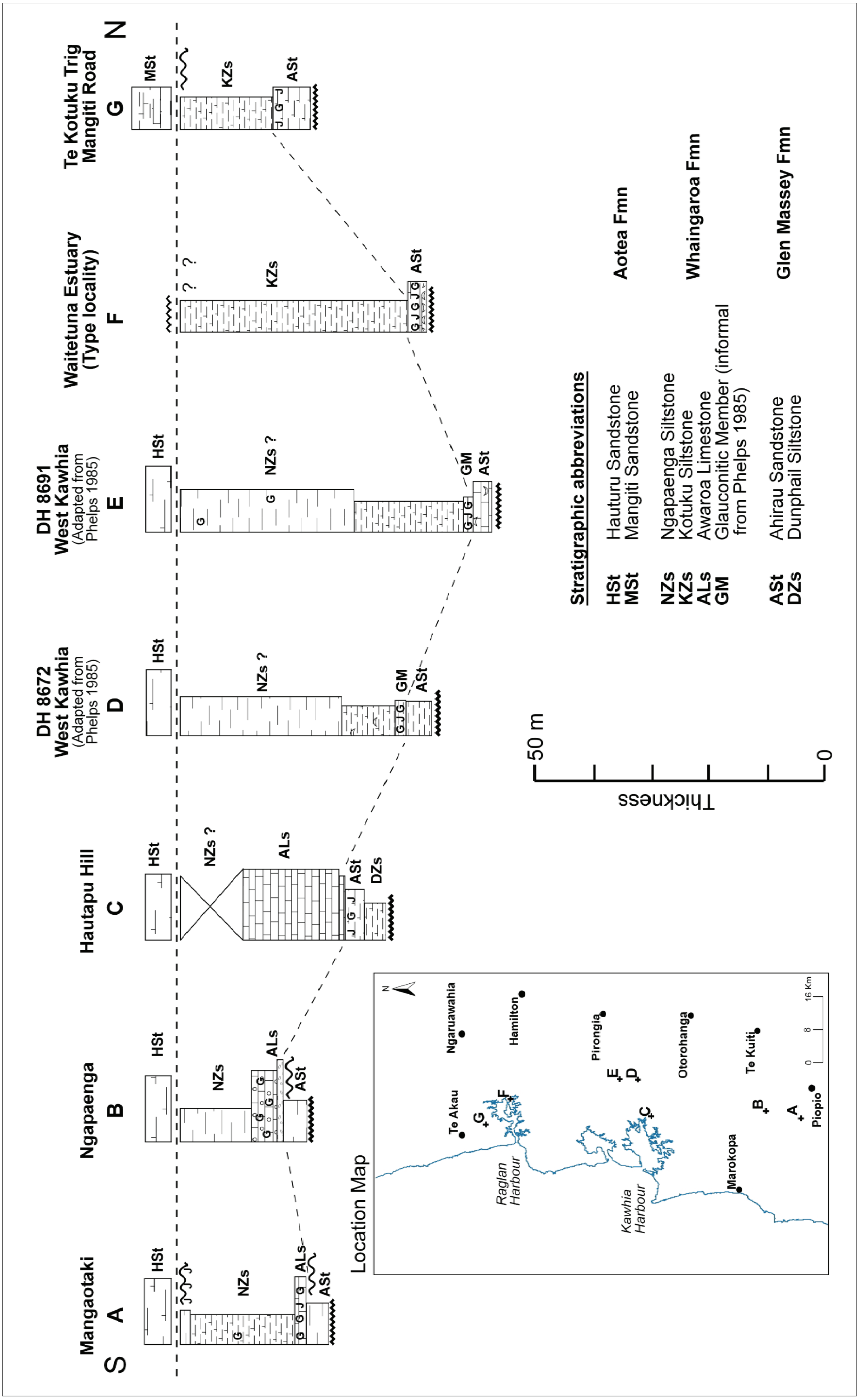


Fig. 3.18: Correlation of Whaingaroa Formation members between the type locality at Waitetuna Estuary and sections to the north (Mangiti Road, column G) and south (columns E to A). Datum is the base of Hauturu Sandstone Member of Aotea Formation, or its lateral equivalent, the Mangiti Sandstone Member. No horizontal scale is implied. Refer Fig. 3.4 for lithology symbols.

along the western margin, particularly from Port Waikato to Raglan Harbour. In the area to the east, a change to more calcareous and coarser clastic sediment marks the base of Aotea Formation.

In the Hautapu Hill and Kihi Road sections, the contact between Awaroa Limestone Member and underlying Ahirau Sandstone has been reported as burrowed, glauconitic, and sharp (Nelson 1978a). This contact is locally marked by a greywacke pebble band in exposures near Ngapaenga (e.g. C-68) and Mangaotaki (C-145). In the Whanuapo Hill section (S-11) east of Kawhia Harbour, Awaroa Limestone Member laps onto basement. The basement surface is irregular having a local relief of 30-40 cm, and the base of the limestone is marked by pebble, grit, or shell lag deposits. A similar direct contact between basement and Awaroa Limestone Member occurs near Mairoa (C-97), where abundant rhodoliths, greywacke cobbles, and a pebble layer up to 2 m thick occur at the base of Awaroa Limestone Member.

Lithology

Siltstone is the most widespread lithology in Whaingaroa Formation (Kotuku Siltstone Member). Limestone and sandy siltstone are secondary lithologies, which predominate in the south. The formation from Port Waikato to Raglan Harbour is usually readily identifiable as a massive siltstone with abrupt lower and upper boundaries. Kotuku Siltstone Member is a featureless blue-grey calcareous siltstone. In places (Port Waikato, PW-2; Te Akau, TA-2) its calcium carbonate content increases upward, as evident from the presence of well cemented siltstone beds in its upper parts. Along the northwestern margin, the top one or so metres of the formation comprise bedded silty sandstone named Waikorea Sandstone Member. The proportion of sand in the upper part of the formation decreases to the east and also to the south towards its type locality.

In central and southern regions, a flaggy limestone (Awaroa Limestone Member) is the main lithology in lower parts of Whaingaroa Formation. The overlying siltstone (Ngapaenga Siltstone Member) is generally massive and variably calcareous, with common thin sandy siltstone interbeds in the middle portion. In places, the formation is condensed and comprises a highly glauconitic sandstone overlying thin pebbly gritty limestone, such as west of Mairoa. Although information for the area north of Otorohanga and in the Te Kuiti area is sparse and limited to a few coal exploration drill holes, the massive variably sandy siltstone interval immediately underlying Aotea Formation has lithofacies similar to the type Kotuku Siltstone Member identified in the northern region.

Depositional setting

Whaingaroa Formation sediments were deposited throughout the northern region within a depocentre that deepened to the east. Large numbers of planktic foraminifera, particularly *Globigerina euapertura* and *G. labiacrassata*, are abundant and indicate fully oceanic environments probably at mid to outer shelf or upper bathyal depths (Hornibrook et al. 1989; Waterhouse & White 1994). In the southern region a transgressive limestone (Awaroa Limestone Member) accumulated in inner to mid shelf environments, followed by accumulation of shelfal siltstone facies.

Age

The presence of *Rotaliatina sulcigera* and *Notorotalia stachei* in samples from the formation in the northern parts of Raglan Harbour suggest a 'mid' Whaingaroan age. *Globigerina euapertura* is a characteristic upper Whaingaroan foraminifera reported from the formation in the Huntly Coalfield. Other reported foraminifera such as *Semivulvulina capitata* and *Haeuslerella textilariformis* also indicate a Whaingaroan age similar to fauna from the Waitetuna Estuary type locality (Hornibrook, in Kear & Schofield 1978). In the vicinity of Awakino Tunnel, Nelson (1978a) reported the occasional occurrence of lower Whaingaroan *Globigerina ampliapertura* from the uppermost part of his "Whaingaroa Siltstone", but lithologic differentiation from the underlying Glen Massey Formation is difficult. The age information from the Whaingaroa Formation in the central and southern regions is presently ambiguous, but stratigraphic correlation is suggestive of mid to upper Whaingaroan age.

The next section briefly describes the new members of Whaingaroa Formation introduced in this investigation.

Awaroa Limestone Member (new)

Name and definition

Awaroa Limestone Member occurs at the base of Whaingaroa Formation, either directly over Glen Massey Formation or Mesozoic basement. The name is derived from Awaroa Stream in the Kawhia area, adjacent to its type locality at Hautapu Hill (Fig. 3.16d). The member comprises flaggy limestone. Previously it was incorporated within Aotea Formation and named "Waitetuna Limestone" (Kear & Schofield 1959; Nelson 1973, 1978a) or "Waimai Limestone" (Ferguson 1986; White & Waterhouse 1993; Waterhouse & White 1994). It was correlated with Waimai Limestone in the northern region because of lithological similarity and perceived stratigraphic position.

Type section

Hautapu Hill (C-4, R14/789424) 4.5 km inland from Kawhia Harbour is nominated as the type locality for Awaroa Limestone Member (Fig. 3.16d). There, about 18 m of flaggy limestone disconformably overlies Ahirau Sandstone in exposures on the western side of Awaroa Stream. It comprises thin (3-5 cm) slightly wavy flags in the lower part of the unit, increasing to thicker flags (6-10 cm) in the upper 8 m of the exposure. The upper contact of the limestone is poorly exposed at this locality. Slumped blocks consisting of burrowed, glauconitic, fine to medium sandy siltstone scattered on the grassy slope above the limestone are inferred to derive from overlying Ngapaenga Siltstone Member.

Distribution and thickness

Awaroa Limestone Member is sporadically distributed in the Kawhia area. It forms the lower 8-10 m directly above Ahirau Sandstone and below sandstone of the Aotea Formation. The member in the type area is identified by moderate to well-developed flags and generally has high calcium carbonate content (av. 94%). The limestone was not encountered in coal exploration holes drilled in the western Kawhia Coalfield immediately to the north and northwest of Hautapu Hill. However an “olive green glauconitic” marker horizon ranging in thickness from a few centimetres up to 3 m, with extensive burrowing in its lower part, was recorded. Because of its widespread presence and distinctive character, Phelps (1985) informally referred to it as “Glauconitic Member”. The unit is probably a highly condensed equivalent of Awaroa Limestone in the West Kawhia Coalfield as it directly overlies Glen Massey Formation (Fig. 3.18, column D & E).

Awaroa Limestone crops out sporadically in the Ngapaenga-Mangaotaki area, but is generally less than 2-4 m thick and not as well developed as in the Kawhia type area. Around Ngapaenga (e.g. C-68) the member is readily identified as a blocky to moderately flaggy limestone overlying Ahirau Sandstone and grading rapidly up-section into silty sandstone (Fig. 3.16f). Less well-developed Awaroa Limestone extends southward as far as Kihikihi Stream Valley near Mangaotaki (Fig. 3.16e).

Contacts

In the type area, the contact between Ahirau Sandstone Member and Awaroa Limestone Member is marked by moderate amounts of glauconite and extensive burrowing. This contact is probably a flooding surface. The glauconitic unit, which is thick in the West Kawhia Coalfield, provides the basis for stratigraphic correlation. In places (e.g. Whanuapo Hill and Mairoa) the limestone was deposited directly on basement and the lower part contains dispersed pebbles and shell material, inferred to be lag deposits associated with transgression. In the Ngapaenga area, a distinct pebble layer at the base of Awaroa Limestone marks a sharp contact with underlying Ahirau Sandstone. The contact between Awaroa Limestone and overlying Ngapaenga Siltstone Member corresponds to a gradational but distinct up-sequence increase in the content of terrigenous clastics.

Lithology

Awaroa Limestone at its type locality is a flaggy relatively pure limestone with traces of fine quartz and lithic sand. However, the limestone in the lower metre or so near the contact is variably sandy. At Whenuapu Hill (S-11) the member is poorly flaggy, gravelly, and shelly, particularly in the lower 3-4 m. Small scale cross-bedding is evident in the lower 1 m. The sandy clastic content within the limestone diminishes up-section.

At Ngapaenga (C-68), west of Mairoa (C-97) and Mangaotaki (C-145), the limestone is moderately to poorly flaggy to blocky in appearance, and includes abundant rounded to subrounded glauconite coated pebbles and grit. The prominent pebble band at the base of the Awaroa Limestone at Ngapaenga and west of Mairoa is interpreted as a lag above a ravinement surface. The member is conspicuously blocky in appearance at Mangaotaki due to a significant increase in the terrigenous component. The lower 10-20 cm near the contact contains abundant glauconite pellets and grit and occasional bivalve shell fragments.

Ngapaenga Siltstone Member (new)

Name and definition

Ngapaenga Siltstone Member is a massive siltstone overlying Awaroa Limestone and underlying Aotea Formation in the southern region. The member is named after the settlement of Ngapaenga where it is well developed. This unit was previously included in Aotea Formation where Nelson (1978a) referred to it as “Massive Ripply Sandstone Lithofacies (Ao-3)” (Ngapaenga, C68) and as an alternation of his “Banded Sandstone (Ao-5)” lithofacies in the Mairoa (C 94) locality.

Type section

A type section is nominated near Ngapaenga (C-68, R16/814144-804137) (Fig. 3.16f) where 12 m of massive siltstone occurs between Awaroa Limestone Member and Hauturu Sandstone Member (Aotea Formation). This section is located approximately 500 m downhill south of Ngapaenga Road, where a small waterfall (R16/814144) marks the exposure. Another good nearby exposure lies west along Whakarotorua Stream (R16/804137) where much of the unit’s thickness is covered by vegetation but a few patchy exposures reveal sandy siltstone grading over the upper 2-3 m into muddy very fine sandstone. The unit is remarkably massive in appearance, but weak horizontal bedding is apparent in the upper 2-3 m. The upper contact with Hauturu Sandstone is marked by an abrupt change in the weathering profile and is inferred to be a sharp surface.

Distribution and thickness

Ngapaenga Siltstone Member occurs sporadically in the Ngapaenga-Mangaotaki area, but is generally less than 18 m thick. To the west of Mairoa there is a 4-5 m-thick sequence (either directly on basement or above a thin pebbly algal Awaroa Limestone) of gritty muddy sandstone grading upward into glauconitic calcareous sandstone. In a drill hole (BH502) near Oparure Limestone Quarry, massive thick siltstone (50 m+) encountered immediately below Aotea Formation is probably Ngapaenga Siltstone (Trisha Simonson, Holcim, pers. comm. 2005). In the Kawhia area, Ngapaenga Siltstone is usually not exposed due to coverage by slope deposits. For example, at Hautapu Hill there is a 10 m thick interval immediately above Awaroa Limestone with no exposures that probably involves Ngapaenga Siltstone. In several coal exploration holes drilled immediately to the north of Hautapu Hill in the west Kawhia Coalfield, a thick silty sandstone interval (up to 55 m thick) encountered immediately above the “Glauconitic Member” (Phelps 1985) is probably Ngapaenga Siltstone Member (Fig. 3.18, columns D & E).

Contacts

In the type Ngapaenga-Mangaotaki area, the contact with the underlying Awaroa Limestone is usually gradational. However, in the absence of Awaroa Limestone there is little lithological distinction between Ngapaenga Siltstone Member and underlying Glen Massey Formation. This is also the case in many of the West Kawhia drill holes. An abrupt facies change occurs across the upper contact of Ngapaenga Siltstone Member, with a change to fine- to coarse-grained Hauturu Sandstone. This contact is sharp and erosional.

Lithology

Ngapaenga Siltstone Member is identified by its massive siltstone lithology, which contrasts with bedded, fine to medium calcareous sandstone of the Hauturu Sandstone Member. The member is variably calcareous, and in exposures the massive siltstone occasionally shows conchoidal fracture development and is punctuated by moderately cemented sandy beds, particularly in the upper parts. West of Mairoa, the member comprises a dark greyish to greenish, highly glauconitic muddy sandstone reflecting depositional condensation. It is likely that the member is a variably calcareous siltstone with thin fine sandstone beds in the West Kawhia and Te Kuiti Coalfields.

Waikorea Sandstone Member (new)

Name and definition

The Waikorea Sandstone Member is introduced here for the sandstone unit at the top of the formation. Its name derives from Waikorea Valley Road (R14/703978). This member is best developed between Port Waikato and Te Akau.

Type section

The type section (TA-3, R14/706948-709950) is designated in Waimai Valley about 800 m north of Waimai Stream Bridge on the eastern side of Te Akau Coast Road (Fig. 3.16g). The member is easily distinguished by it's moderately to strongly bedded nature and sandy texture. The contact with overlying Waimai Limestone Member of Aotea Formation is marked by a sharp planar surface.

Distribution and thickness

The member is best developed in the Waikaretu, Waikorea, and Waimai Stream valleys, where it is up to 5 m thick. In more eastern areas such as in the vicinity of Wairamarama-Onewhero, the member is locally represented by calcareous slightly sandy siltstone up to 1-2 m thick occurring immediately below the contact with overlying Mangiti Sandstone Member (Aotea Formation). It is probably absent in more eastern basinal parts. To the south in the Mangiti Road section, the member is identified in the uppermost metre of the formation before being abruptly overlain by Mangiti Sandstone.

Contacts

The lower contact between Waikorea Sandstone Member and Kotuku Siltstone Member is usually gradational. The member is generally abruptly overlain in the west by cross-stratified Waimai Limestone Member of Aotea Formation, or by its correlative (Mangiti Sandstone) in eastern and southern parts of the northern region. This contact is well defined along the entire western margin comprising a sharp erosional contact such as in the Mangiti Road (TA-12) and Waimai Bridge (TA-3) sections (Fig. 3.16g).

Lithology

Waikorea Sandstone consists of dull brownish-grey calcareous fine sandstone beds and interbeds of massive sandy siltstone. Thin shell fragments occur sporadically. Burrowing is common in the uppermost part of the sandstone and may be associated with post-depositional burrowing down from the overlying marine flooding surface. In the east and south, this sandstone member is not identified.

Aotea Formation

Historical usage

The name "Aotea Sandstone" was first proposed by Hochstetter (1864) for a unit exposed in Orotangi Cliff (R15/730533) on the shores of Aotea Harbour. Kear & Schofield (1959) gave this sandstone formation status. Subsequently "sandstone" was dropped from its name by Kear (1963, 1966) in the belief that its correlatives around Raglan Harbour and areas to the north consisted mostly of limestone and siltstone. Kear & Schofield (1959) also named "Waitetuna Limestone" considering it to represent the entire Aotea Formation at its type locality near Waitetuna Estuary, and correlated it with the limestone occurring at the base of their Aotea Formation in the Kawhia and Waitomo areas. Nelson (1978a) followed their usage in the Waitomo area and distinguished five lithofacies within the formation. Fergusson (1986), in the Kawhia area, correlated Waitetuna Limestone with Waimai Limestone of Kear (1963, 1966). Subsequently, Waterhouse & Kear (1991) recognised that Waitetuna Limestone in its type area is actually Elgood Limestone Member and the name Waitetuna Limestone was discarded. White & Waterhouse (1993) and Waterhouse & White (1994) combined Nelson's (1978a) Aotea Formation lithofacies in the Aotea-Kawhia area into the Hauturu Sandstone Member and overlying Kihi Sandstone Member. The "Aotea Sandstone Member" (Waterhouse 1978) was renamed Mangiti Sandstone Member, and the Patikirau Siltstone Member was retained for a unit around Raglan Harbour and areas farther to the north (White and Waterhouse 1993; Waterhouse & White 1994).

Definition

The White & Waterhouse (1993) definition and subdivision of Aotea Formation is largely followed here. Some of the lateral equivalents of the members identified in the Raglan, Aotea, and Kawhia harbour areas, are correlated into other areas. The unit previously thought to be Waimai Limestone Member of Aotea Formation in the Kawhia area (Waterhouse & White 1994) is now incorporated into Whaingaroa Formation as Awaroa Limestone Member. Hauturu Sandstone Member is identified here as forming most of the lower part of Aotea Formation in the Aotea-Kawhia area, either directly overlying Glen Massey Formation or Whaingaroa Formation. It is now regarded as the lateral facies equivalent of Mangiti Sandstone Member and Waimai Limestone Member of more northern areas (Fig. 3.3). Table 3.4 shows the distribution of Aotea Formation members in the various parts of the study area.

Type and reference section

Table 3.4: Nomenclature and occurrence of members within Aotea Formation in different parts of central-western North Island.

Northern Region		**Central Region**	**Southern Region**	
Northwestern margin (e.g. Port Waikato, Waikaretu & Waimai Valley)	Eastern and southern areas (e.g. Onewhero - Wairamarama, Te Akau and Raglan Harbour)	Aotea Kawhia (Shea Road, Orotangi Cliff, Kihi Road, Hautapu Hill, Kaimango & Mahoe)	Central and southern areas (e.g. Ngapaenga, Mangaohae R., Mairoa, Manga-otaki & Awakino Tunnel)	Eastern and western parts (e.g. Honikiwi, Waitomo Valley Road and Mangaotaki Bridge)
*Patikirau Siltstone Member	Patikirau Siltstone Member	Kihi Sandstone Member	Not developed or preserved	Kihi Sandstone Member
Waimai Limestone Member	Mangiti Sandstone Member	Hauturu Sandstone Member	Hauturu Sandstone Member	Waimai Limestone Member

* Patikirau Siltstone Member occurs as a highly condensed unit in this area.

Type and reference section

The section at Orotangi Cliff (R15/730533) was first described by Hochstetter (1864), and used by Kear & Schofield (1959) and Nelson (1973, 1978a) as the type section for Aotea Formation (Fig. 3.10 e). The 18 m of fine to medium calcareous sandstone overlying massive siltstone at this section was subsequently (Waterhouse & White 1994) assigned to Whaingaroa Formation, but is now considered to comprise Glen Massey Formation. Aotea Formation overlies Ahirau Sandstone Member immediately inland of Orotangi Cliff (AK-5, R15/739542) on the eastern side of Okapu Road. Substantial thicknesses of Aotea Formation are inferred to have been removed by modern erosion processes from this section and only the lower 5 m of Hauturu Sandstone Member is preserved (Fig. 3.12c). Consequently, the Orotangi Cliff section is unsuitable as the type section for Aotea Formation, and is abandoned as such. Aotea Formation and its stratigraphic relationships with surrounding units are relatively well exposed at Shea Road (Fig. 3.19 d) and this section is nominated here as the new type section for Aotea Formation. It is located 10 km to the northeast of Orotangi Cliff.

Shea Road type section (AK-4, R15/794615) (Fig. 3.19d)

This section crops out as a prominent bluff at the end of Shea Road and across a stream flat. The formation is exposed at the highest level of this bluff with a marked overhang. The lower part of the bluff consists of Glen Massey Formation over basement. Hauturu Sandstone Member directly overlies Ahirau Sandstone, although the contact itself is concealed. Hauturu Sandstone in its lower 6-8 m extent

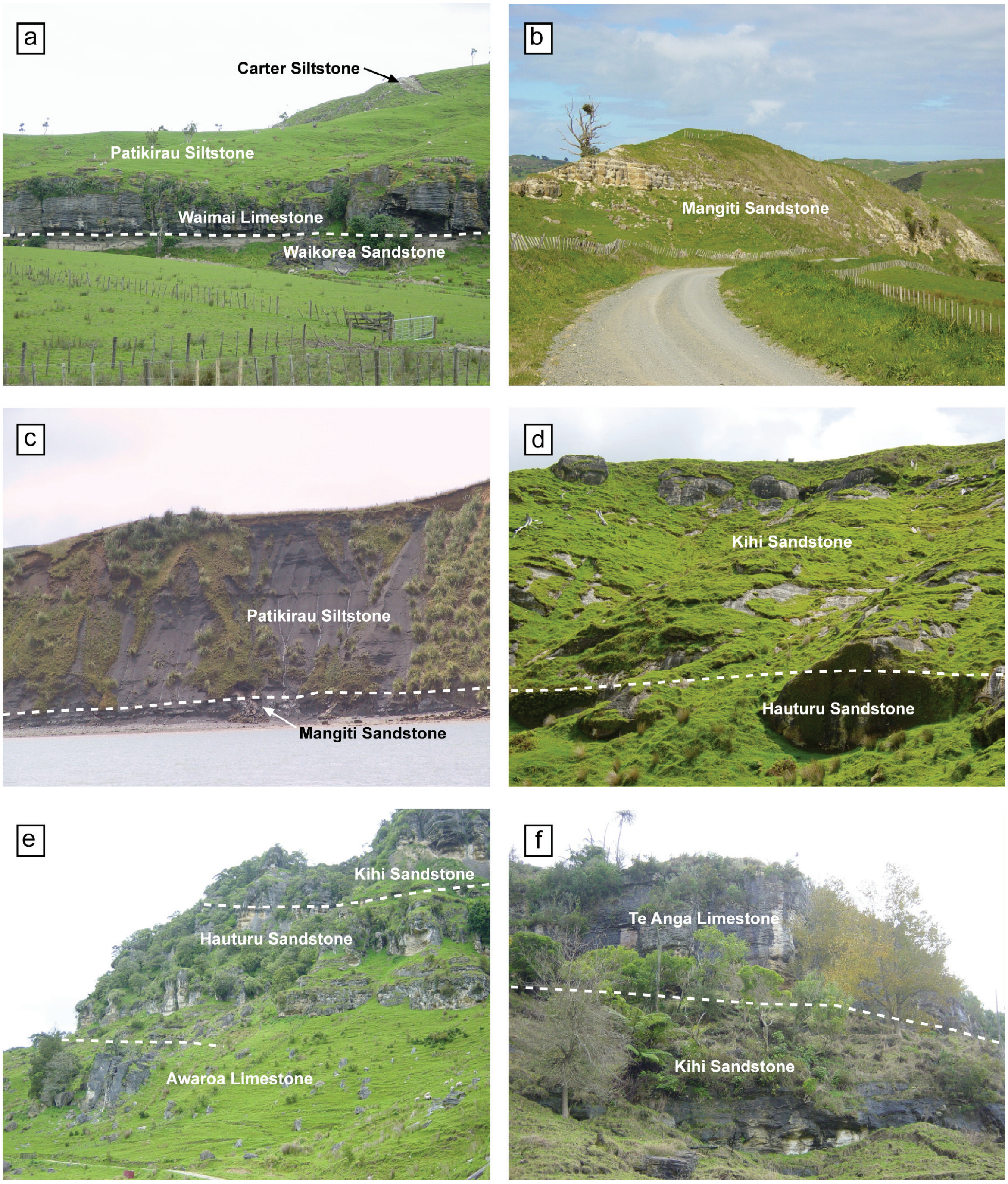


Fig. 3.19: Field examples of Aotea Formation. (a) Waimai Limestone with prominent cross-bedding sharply overlying Waikorea Sandstone along Waimai Stream (TA-3, R13/707943). (b) Mangiti Sandstone exposed along Mangiti Road (TA-12, R14/785835). Note the distinct bedding development within the sandstone. (c) View of Patikirau Bay (TA-20, R14/764778) Raglan Harbour showing Mangiti Sandstone at shore level grading upward into Patikirau Siltstone. (d) Hauturu Sandstone grading upward into Kihi Sandstone at Shea Road (AK-4, R15/794615). (e) Bluff forming Hauturu Sandstone stratigraphically overlying Awaroa Limestone at Hautapu Hill (C-4, R15/789424). (f) Kihi Sandstone overlain by Te Anga Limestone at Waitomo Valley Road (C-32, S16/966297).

comprises fine to medium sandstone, showing well cemented bands alternating with poorly cemented friable sandstone. The sandstone is extensively burrowed and contains scattered shell fragments. It sharply grades upward into Kihi Sandstone Member comprising massive fine to very fine muddy sandstone. Thin silty interbeds are common in the lower 8 m of Kihi Sandstone and there is a significant increase in the mudstone content up-section, evident from common exfoliation weathering. Further upward within Kihi Sandstone the texture grades into massive calcareous silty sandstone to very fine sandy siltstone. The facies transition is marked by an abrupt steepening of the slope about half way up Kihi Sandstone.

Distribution and thickness

Aotea Formation is widespread throughout the study area. The formation is most thickly developed in the Aotea-Kawhia area and is well exposed particularly in the hill country east of Kawhia Harbour. There it is up to 120 m thick and includes both the medium-grained Hauturu Sandstone Member and fine-grained variably calcareous and muddy Kihi Sandstone Member. To the south and southeast the formation thickness averages about 30 m. The bulk of the formation in the south consists entirely of Hauturu Sandstone, such as at the Kokoroa Road (C-40) section (west of Waitomo) and near Mairoa (e.g. C-94). Hauturu Sandstone is distributed in a NNE trending belt east of the Herangi Range and is generally well exposed from Aotea Harbour to Awakino (Fig. 3.20). However, in the Awamarino area (e.g. C-50 & C-51) and elsewhere to the southwest, Hauturu Sandstone is thin or absent, having been depositionally thinned in that direction, as well as having been eroded at the overlying unconformity with Orahiri Formation.

Aotea Formation is exposed around Raglan Harbour (e.g. TA-20) and has a measured thickness of about 70 m, including both fine calcareous sandstone (Mangiti Sandstone Member) and massive siltstone (Patikirau Siltstone Member) facies (Fig. 3.19c). To the north and northeast, the formation thins and is generally less than 40 m thick. In the far north, especially in the vicinity of Port Waikato (e.g. PW-1), Aotea Formation comprises limestone (Waimai Limestone) and overlying glauconitic sandstone with a combined thickness of less than 5 m. The present-day eastern extent of Aotea Formation is limited by modern erosion, the formation having been completely removed over most of the eastern areas. However, in some of the coal exploration holes drilled in the vicinity of Huntly Coalfield, variably calcareous and glauconitic sandstone with Aotea Formation affinity is encountered in the right stratigraphic position (Kear & Schofield 1959; Edbrooke 1984).

Contacts

In general, the base of Aotea Formation corresponds to a major unconformity. This unconformity is well defined and readily correlatable across virtually all of the Aotea-Kawhia area and areas to the south, although it is more pronounced along the western margin. In the immediate inland parts of Aotea-Kawhia Harbour (e.g. Shea

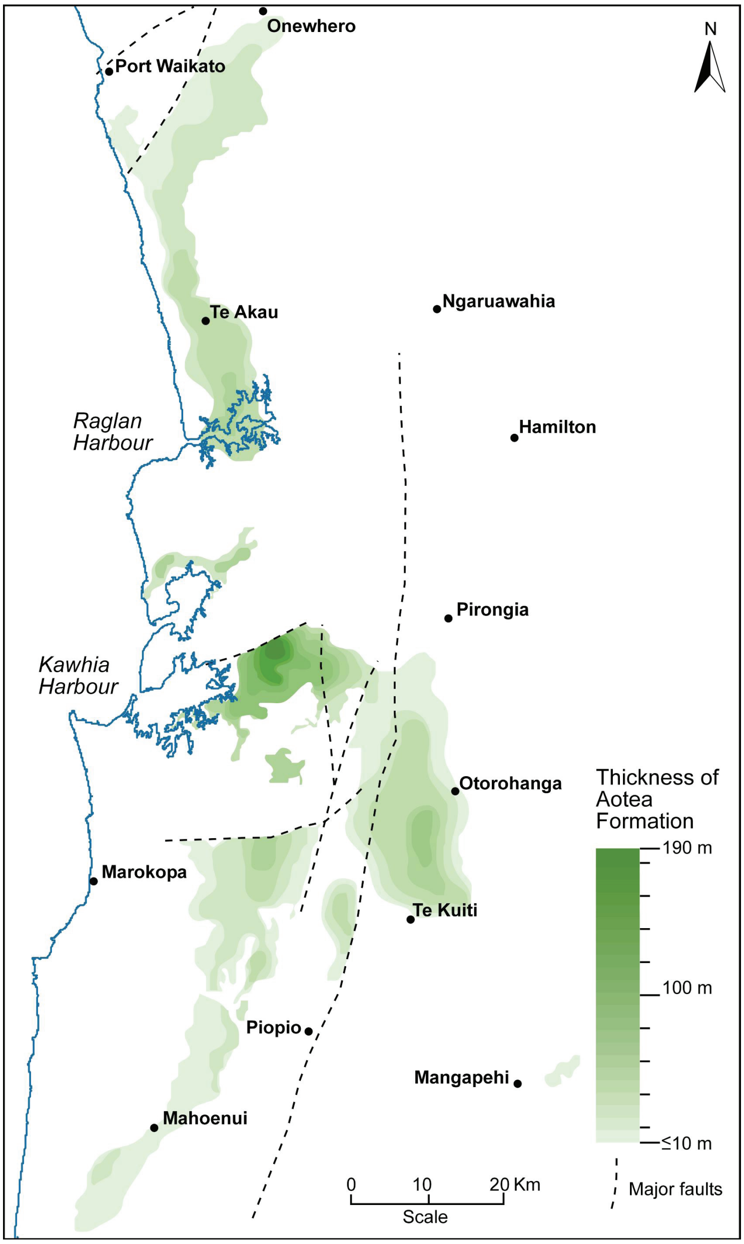


Fig. 3.20: General extent and thickness distribution of Aotea Formation.

Road, AK-4; Ruaweke Point, AK-7; and Orotangi Cliff, AK-5), Hauturu Sandstone unconformably overlies Ahirau Sandstone, Whaingaroa Formation having been removed. In these sections, the unconformable contact between Hauturu Sandstone and underlying Ahirau Sandstone is concealed by slope deposits. However, this contact is well exposed at Kaimango (C-8) and Mahoe Road (C-24) sections, where a pebbly and gritty sandstone (1-2.5 m) unit at the base of Hauturu Sandstone abruptly overlies Ahirau Sandstone (Fig. 3.12d).

In Waitomo Valley (C-32) and at the Mangaotaki Bridge (C-166) and Awakino Tunnel (C-191) sections, and elsewhere in the central and southern regions, another major unconformity lies at the upper contact of Aotea Formation with Orahiri Formation. This unconformity is marked by laterally persistent gritty conglomerate beds 10-20 cm thick in the base of Orahiri Formation. Around Raglan Harbour the upper boundary lies immediately above a thin extensively burrowed glauconitic siltstone within uppermost Aotea Formation. Farther to the north from Waikaretu to Port Waikato this boundary corresponds to prominent fossiliferous burrowed glauconitic sandstone with scattered phosphate nodules that are incorporated in the top of Aotea Formation.

Lithology

Aotea Formation lithologies exhibit considerable lateral variation, which is reflected in the subdivision into members. The formation in the type Aotea-Kawhia area comprises predominantly fine to medium sandstone with varying amounts of carbonate and concretionary development (Hauturu Sandstone Member). The sandstone is moderately well sorted with occasional thin gritty bands and shell hash layers. Small- to medium-scale cross-stratification is evident in places. The sandstone fines upward into massive to crudely bedded fine muddy sandstone (Kihi Sandstone Member). Hauturu Sandstone is well developed in the west but decreases in thickness and sandstone content towards the east. In eastern parts (Waitomo-Honikiwi) Aotea Formation consists almost entirely of bioturbated fine muddy sandstone with thin siltstone interbeds, inferred to be Kihi Sandstone Member (Fig. 3.19f). Localised development of basal carbonate facies (Waimai Limestone Member) is common in places, especially in areas of basement onlap such as in Waitomo Valley (e.g. C-32) and around Mangaotaki Bridge (C-166). The inferred relationship amongst Aotea Formation members is depicted in Fig. 3.21 in a west-east schematic cross section.

Aotea Formation between Raglan Harbour and Te Akau comprises calcareous sandstone with thin siltstone interbeds (Mangiti Sandstone) grading upward into massive siltstone (Patikirau Siltstone). Mangiti Sandstone Member is usually readily identifiable, particularly in the Raglan (e.g. TA-12) and northern inland sections, as horizontally bedded calcareous fine sandstone with distinctive silty interbeds (Fig. 3.19b). Fine to very fine calcareous sandstone commonly develops vertical solution cavities imparting a blocky appearance to outcrops. The massive greyish to light bluish-grey Patikirau Siltstone is best exposed in cliffs along the western parts of Raglan Harbour (Fig. 3.19c). The siltstone is variably calcareous, and contains rare scattered shell fragments. Silty sandstone generally occurs as thin interbeds, especially in the lower part, and thin concretion bands are common throughout. The siltstone is weakly to moderately consolidated and on exposure commonly produces a frittered outcrop surface. The member is well developed in the south but decreases in thickness towards the north and is generally poorly exposed in most inland sections.

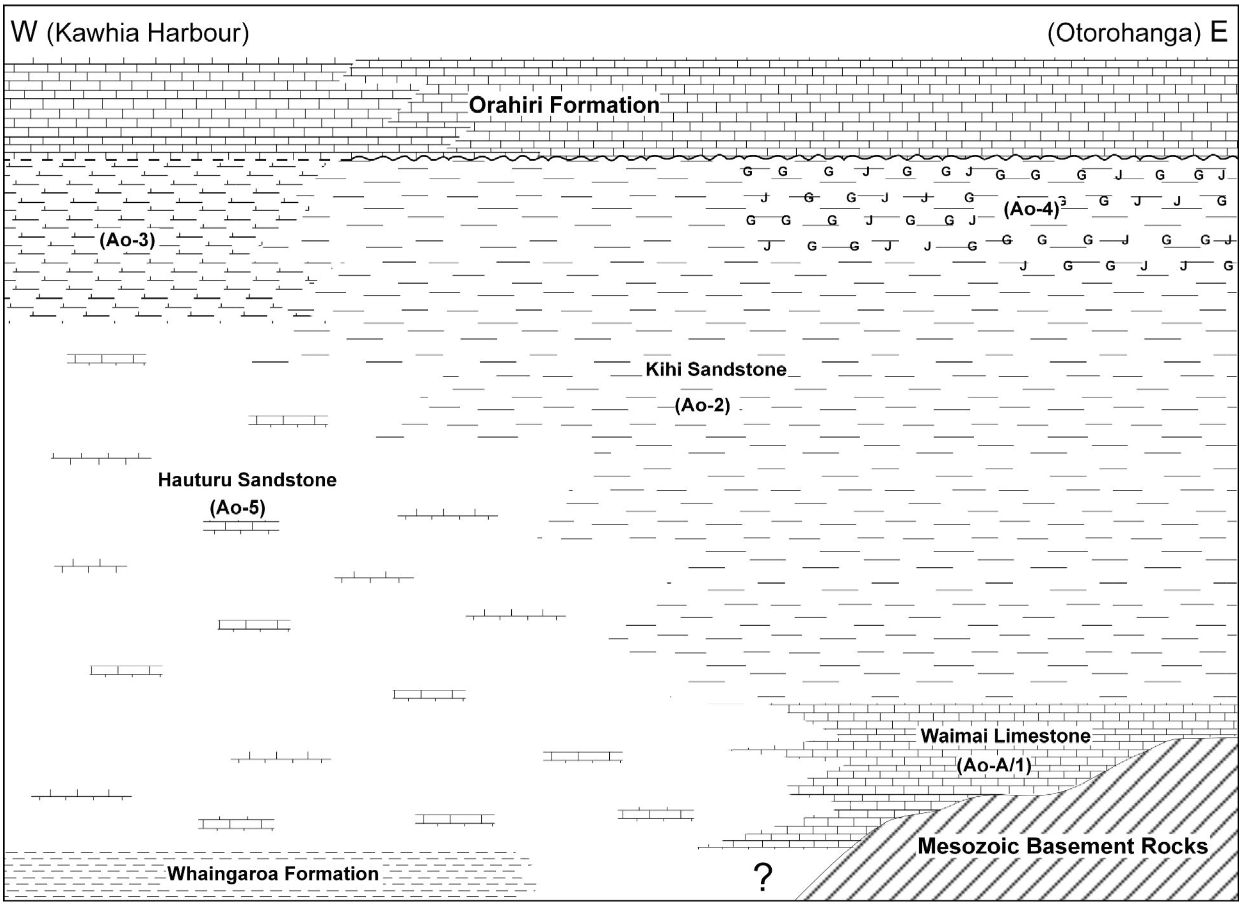


Fig. 3.21: Schematic cross-section from Kawhia Harbour (Hautapu Hill, Kihi Road) to west of Otorohanga (Honikiwi, Waitomo Valley Road) illustrating a complex relationship amongst the members of the Aotea Formation. Abbreviations within brackets represent Nelson's (1978a) lithofacies within Aotea Sandstone. Wavy line corresponds to Aotea-Orahiri unconformable contact. No distance or thickness scale implied.

Between Te Akau and Port Waikato the formation consists of prominently cross-stratified, variably sandy limestone (Waimai Limestone Member) (Fig. 3.19a). The limestone commonly grades through silty limestone into Patikirau Siltstone Member. In the vicinity of Port Waikato, Waimai Limestone forms most of the formation and comprises thin (2-3 m), variably glauconitic limestone grading rapidly upward into fossiliferous glauconitic sandstone. In areas to the east Waimai Limestone grades into Mangiti Sandstone, comprising calcareous sandstone with thin siltstone interbeds. Mangiti Sandstone generally fines upward into variably muddy and calcareous siltstone (Patikirau Siltstone). Patikirau Siltstone is overlain by Carter Siltstone Member of the Te Akatea Formation in northeastern areas.

Depositional setting

The accumulation of Hauturu Sandstone lithofacies represented an abrupt increase in the supply of sand to the basin. Hauturu Sandstone is thickest and best developed in the Aotea-Kawhia area and areas to the south, whereas Kihi Sandstone is thickest and best developed in areas to the east. This pattern indicates that the sandstone was supplied from the south and accumulated as a shore-connected wedge along the eastern side of the Herangi High, at that time a developing structural ridge. Deeper parts of the continental shelf lay immediately to the east where Kihi Sandstone accumulated.

Shelf to upper bathyal water depths developed over most of the northern region following transgressive onlap of Waimai Limestone. The accumulation of cross-bedded limestone (Waimai Limestone Member) reflects shallow marine (less than about 60 m) high current energy depositional environments (Anastas 1997), but the water depth rapidly increased during Waimai Limestone accumulation judging from the accumulation of glauconitic sandstone to mudstone in its uppermost parts in Port Waikato sections.

Age
Foraminiferal content indicates that the Aotea Formation ranges from upper Whaingaroan to Duntroonian in age (Kear & Schofield 1959; Nelson 1978a; Waterhouse & White 1994).

Interrelationships between Aotea Formation members
The name Waimai Limestone was first proposed by Kear (1963, 1966) for the prominent cross-bedded limestone exposed in Waimai Valley to the north of Te Akau. He gave it member status within "Aotea Sandstone Formation". In several locations east of Waimai Stream mouth, and especially near the bridge on Te Akau coast road (TA-3), the member forms a distinctive unit of characteristically cross-stratified variably sandy bioclastic limestone stratigraphically overlying Waikorea Sandstone Member of Whaingaroa Formation. Waimai Limestone is overlain by Patikirau Siltstone at these localities (Fig. 3.22, column J). In eastern and southern areas, Waimai Limestone Member grades laterally into, or interfingers with, interbedded calcareous sandstone and siltstone identified here as Mangiti Sandstone Member. Mangiti Sandstone is well developed and exposed in the lower parts of cliffs along Raglan Harbour and inland to the north (e.g. at its Mangiti Road Type Section, Fig. 3.22, column I).

Mangiti Sandstone is a correlative of Hauturu Sandstone (Plateau Road, AK-3; Shea Road, AK-4; and Ruaweke Point, C-32; Fig. 3.22, column H; Fig 3.22). The transition from Hauturu Sandstone to Mangiti Sandstone is obscured by Pliocene-Pleistocene volcanic deposits between Aotea Harbour and Raglan Harbour. However, an important reference section representative of the transition between

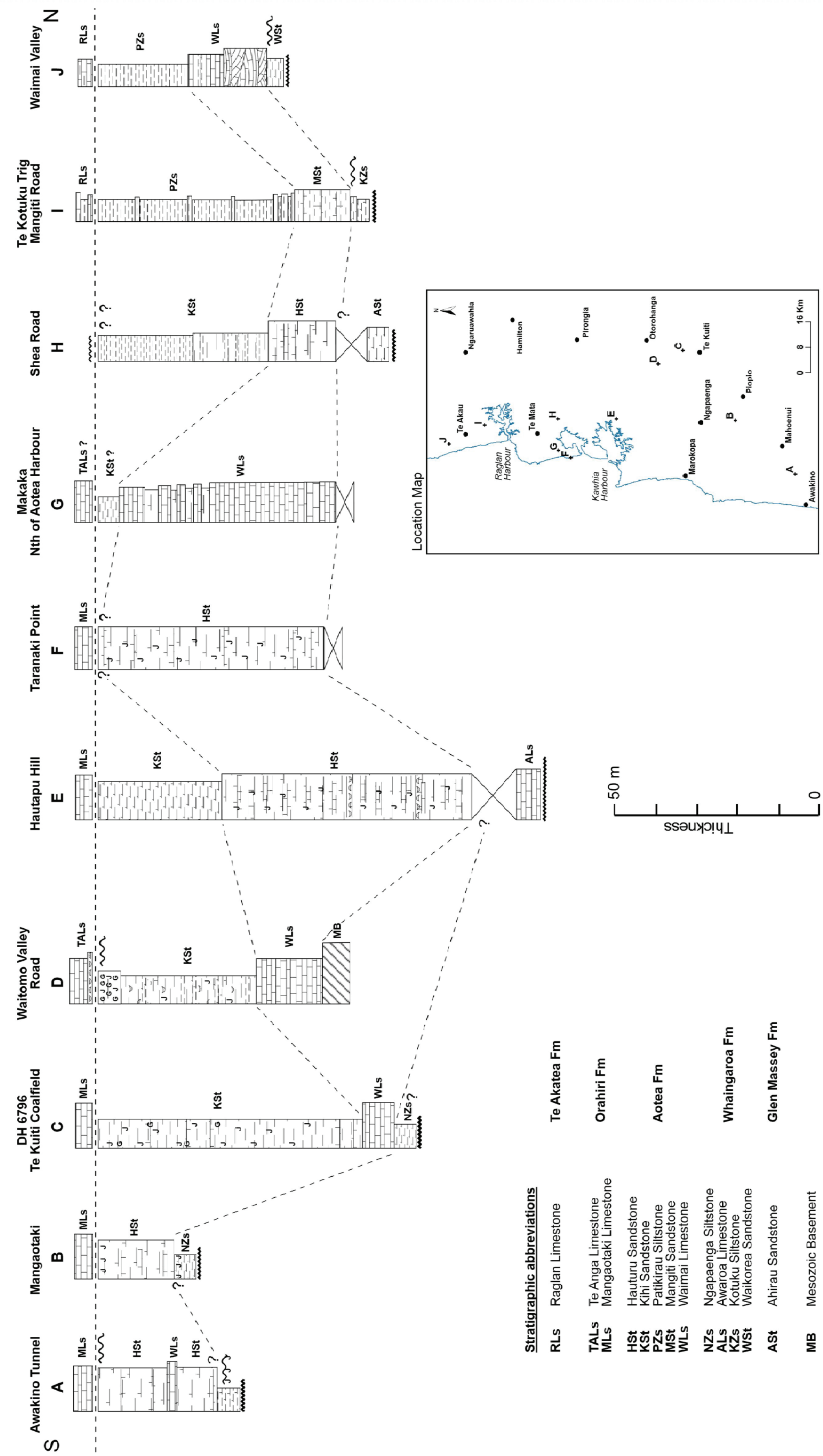


Fig. 3.22: Correlation of Aotea Formation members from Waimai Valley in the north (column J) to Awakino Tunnel (column A) in the south. The datum is the base of Orahiri Formation or its correlative (Te Akatea Formation) in the north. Refer Fig. 3.4 for lithology symbols.

Hauturu Sandstone, Mangiti Sandstone and Waimai Limestone is occurs at Makaka (AK-1) to the north of Aotea Harbour (Fig. 3.22, column G). At this section, about 70 m of moderately flaggy sandy limestone, calcareous sandstone, and flaggy limestone crops out along the edge of a swamp. The 45-50 m of sandy limestone low in the section is Waimai Limestone. It grades upward into a calcareous fine sandstone about 5-6 m thick (Kihi Sandstone Member), which in turn passes up-section into a well-developed flaggy and relatively pure limestone (Te Anga Limestone Member, Orahiri Formation). Waterhouse & White (1994) mapped the lower sandy limestone (Waimai Limestone Member) as part of Orahiri Formation, the intervening calcareous sandstone (Kihi Sandstone Member, Aotea Formation) as part of Waitomo Sandstone, and the uppermost limestone as part of Otorohanga Limestone (Te Anga Limestone Member). However, at several stratigraphic levels and especially in the upper part, the (lower) sandy Waimai Limestone consists of variably calcareous concretionary sandstone bands having affinity to Hauturu Sandstone lithofacies. A similar succession is exposed to the southwest on the coast at Taranaki Point (Fig. 3.22, column F). There, a 50+ m-thick interval containing medium to coarse calcareous sandstone grades into 8-10 m of moderately flaggy limestone in a steep cliff above the sea. It was mapped by Waterhouse & White (1994) as Hauturu Sandstone overlain by Orahiri Formation. This calcareous sandstone interval (Hauturu Sandstone Member) can be directly correlated with the Makaka section and is inferred to be a facies equivalent of Waimai Limestone. The flaggy limestone at the top of the Taranaki Point section is probably the lateral correlative of the well flagged limestone in the Makaka section and is assigned to Orahiri Formation, as mapped by Waterhouse and White (1994).

In the Waitomo-Honikiwi area and in the southern region, Aotea Formation is inferred to progressively onlap basement highs to the east. There it often consists of a basal limestone (Waimai Limestone Member) and overlying Kihi Sandstone. This succession is most noticeable at Waitomo Valley Road (Fig. 3.22, column D) and in the Honikiwi and Mangaotaki Bridge sections, and has previously been assigned by Nelson (1978a) to "Waitetuna Limestone" and correlated by him to the limestone at the base of Hautapu Hill and elsewhere in the western area that is now named Awaroa Limestone Member (Whaingaroa Formation) (Fig. 3.22, column E). Waimai Limestone in the eastern area is generally less than 5-6 m thick and in places, such as at the Mangaotaki Bridge section, occurs as discontinuous lenses. The limestone often contains abundant pebbles, reworked shallow water Amphistegina foraminifera, calcareous red algae, and rhodoliths, especially near the contact with basement. In outcrop the contact between Waimai Limestone and overlying Kihi Sandstone is gradational but marked by a distinct up-sequence increase in terrigenous content. In the vicinity of Te Kuiti, some of the coal exploration drill holes (e.g. DH 6796 and 8508, Fig. 3.22, column C) intersected at depth has a thin limestone immediately beneath sandstone. This limestone is probably a correlative of Waimai Limestone Member and the sandstone is Kihi Sandstone Member. Waimai Limestone is generally absent in western parts of the southern region (e.g. Hautapu Hill, Ngapaenga) where its correlative (Hauturu Sandstone Member) prevails. However, some isolated occurrences of Waimai Limestone are recorded in the inland parts of Kawhia (e.g. Harbour Road) in association with Kihi Sandstone facies. A sandy limestone interval approximately 5 m thick within Hauturu Sandstone at Awakino Tunnel, is assigned to Waimai Limestone Member (Nelson 1978a; Nelson et al. 1994), suggesting that Waimai Limestone is stratigraphically equivalent to Hauturu Sandstone Member (Fig. 3.22, column A).

Orahiri Formation

Historical usage

Orahiri Formation was introduced by Kear & Schofield (1959) for the limestone overlying Aotea Formation at Worth's Quarry (S16/980340) near Waitomo. In this quarry, the upper part of Te Kuiti Group consists of two prominent limestone units separated by sandstone. The lower limestone was named "Orahiri Limestone", the intervening sandstone "Waitomo Sandstone", and the upper limestone "Otorohanga Limestone". All three units were given formation status. Subsequently, Nelson (1978a) subdivided the Orahiri Formation into two members. Mangaotaki Limestone Member (OrA) was assigned to the lower limestone unit, often being impure due to appreciable terrigenous sandstone content. The upper unit, named Te Anga Limestone Member (OrB), is a more pure limestone including common large oyster beds.

Definition

The continued designation of Waitomo Sandstone as a full formation above Orahiri Formation is considered to be stratigraphically unworkable. Instead, Orahiri Formation is expanded to include Waitomo Sandstone, demoted to member status due to its limited lateral extent and uncertain relationship to other units. In the vicinity of Te Akau, the thin (5 m) sandstone overlying Carter Siltstone Member (Te Akatea Formation) previously regarded as Waitomo Sandstone (Kear 1966, 1987), is considered here to be part of the basal facies of the Waitemata Group. Kear & Schofield (1959) used the name Orahiri Limestone, but the revised name Orahiri Formation is preferred because of the wider range of lithologies included within it.

Type locality

A new type section for Orahiri Formation was nominated by Nelson (1978a) at (the now disused) Otorohanga Limestone Company Quarry (C-32, S16/963291) on Waitomo Valley Road, and this location is retained here (Fig. 3.23a). Orahiri Formation is exposed in the upper part of a prominent bluff facing the intersection of the approach road to the quarry and Waitomo Valley Road (S16/963292). At this locality a well defined break between Aotea Formation and Orahiri Formation is marked by a prominent weathering recess. This marks a significant stratigraphic break occurring immediately above thin greensand at the top of Kihi Sandstone Member. The lower 10-15 cm of Orahiri Formation consists of abundant scattered grit and occasional basement pebbles, shell fragments, and extensive burrows infilled with glauconite. Mangaotaki Limestone Member is poorly developed, there being less than half a metre of sandy limestone immediately above the unconformity in the bluff across Waitomo Stream. The overlying limestone is assigned to Te Anga Limestone Member. It is up to 12 m thick and comprises irregularly to wavy, flaggy limestone with common disarticulated oyster shells. The limestone rapidly grades up-section into a 15 m thick Waitomo Sandstone Member consisting of variably calcareous and glauconitic, burrowed, massive fine sandstone (Fig. 3.23b). This sandstone passes upward into cross-stratified flaggy Otorohanga Limestone.

Distribution and thickness

Orahiri Formation is widely distributed in the southern region from northern parts of Aotea Harbour (e.g. S-16) to Awakino Gorge (e.g. C-191). The formation usually forms impressive steep bluffs and near vertical cliffs (Fig. 3.23d). The measured thickness varies between 15 and 30 m in most locations. In the west and southwest, Orahiri Formation includes both Mangaotaki Limestone and oyster-bearing Te Anga Limestone members. To the east (Te Kuiti, Piopio) Orahiri Formation thins and onlaps basement. However, to the north of Te Kuiti, a sandy limestone interval up to 15-20 m thick having Orahiri Formation affinities has been intersected in a few of the coal exploration drill holes, such as DH 6796.

The thick development of Mangaotaki Limestone Member contributes largely to the thick development (up to 60 m) of Orahiri Formation in the Te Anga-Awamarino, Mahoenui and east Kawhia Harbour areas (Fig. 3.24). In the type Waitomo Valley area (C-32), the lesser thickness of Orahiri Formation (<10 m) is due to the thin development or absence of Mangaotaki Limestone Member. The northernmost extent of Orahiri Formation is known from Taranaki Point (S-16, R15/666568) and Pakoka Landing (AK-2, R15/731612). Farther to the north (Raglan Harbour), the formation is inferred to grade laterally into interbedded limestone and calcareous siltstone

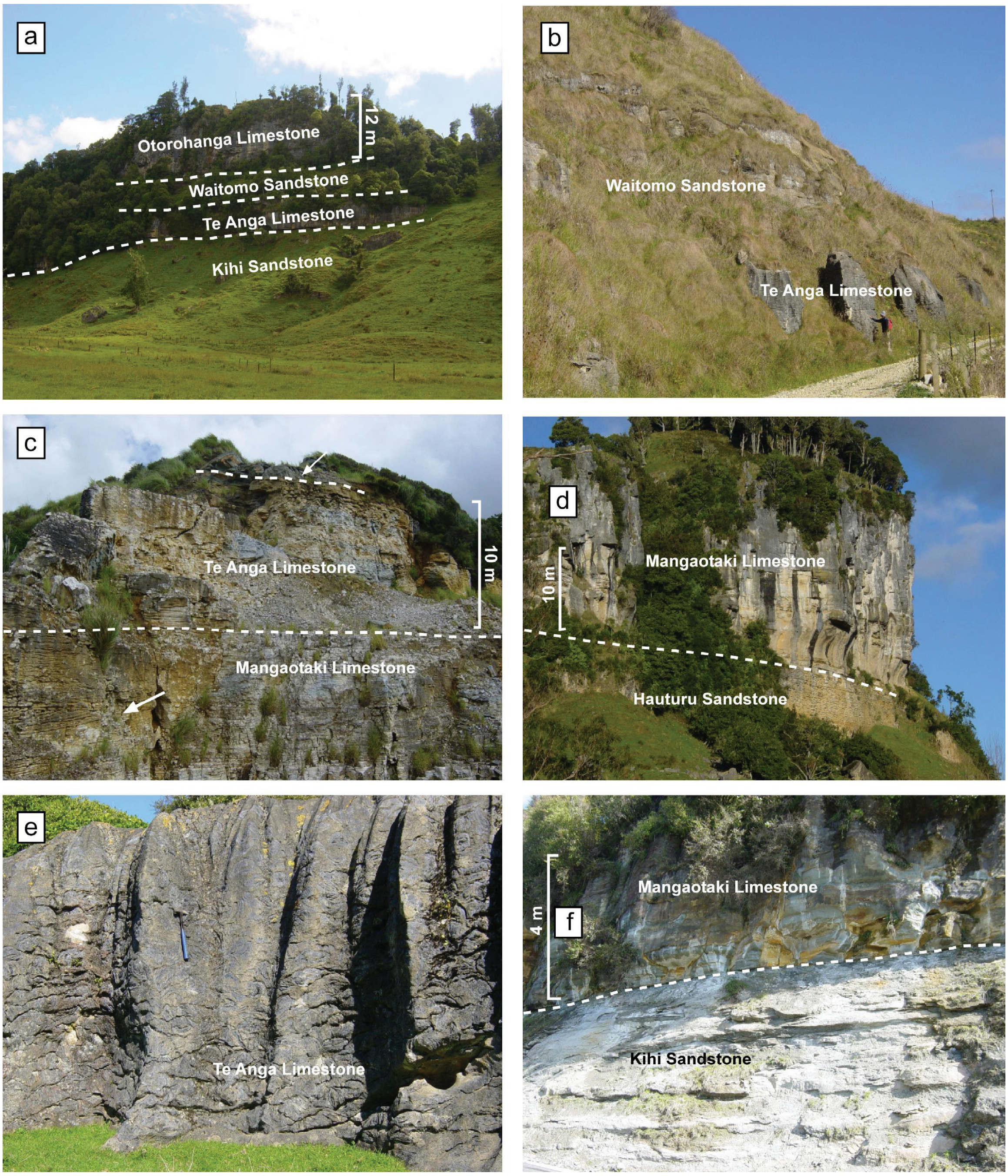


Fig. 3.23: Examples of Orahiri Formation in the field. (a) Cliff on the backside of the now disused limestone quarry facing Waitomo Valley Road (C-32, S16/961292), the type locality of Orahiri Formation and Otorohanga Limestone. Note the sharp contact between the Kihi Sandstone Member and overlying Te Anga Limestone Member. (b) Waitomo Sandstone Member grading up from Te Anga Limestone Member exposed along the approach road to the limestone quarry. (c) View of an abandoned limestone quarry in Rakanui Peninsula (AK-11, R16/755429) showing Mangaotaki Limestone Member passing into Te Anga Limestone Member, which in turn is abruptly overlain by a fossiliferous sandstone unit exposed at the uppermost level (upper arrow). Note the presence of low-angle cross-bedding within the Mangaotaki Limestone Member (lower arrow). (d) Sharp contact between Hauturu Sandstone Member and Mangaotaki Limestone Member near Mangaotaki (C-145, R17/784047). (e) Te Anga Limestone with prominent oyster shell beds near the Mangapohue Natural Bridge (R16/767254). (f) Abrupt contact between Kihi Sandstone Member and Mangaotaki Limestone Member exposed near Mangaotaki River Bridge on SH3 (C-166, R17/764974).

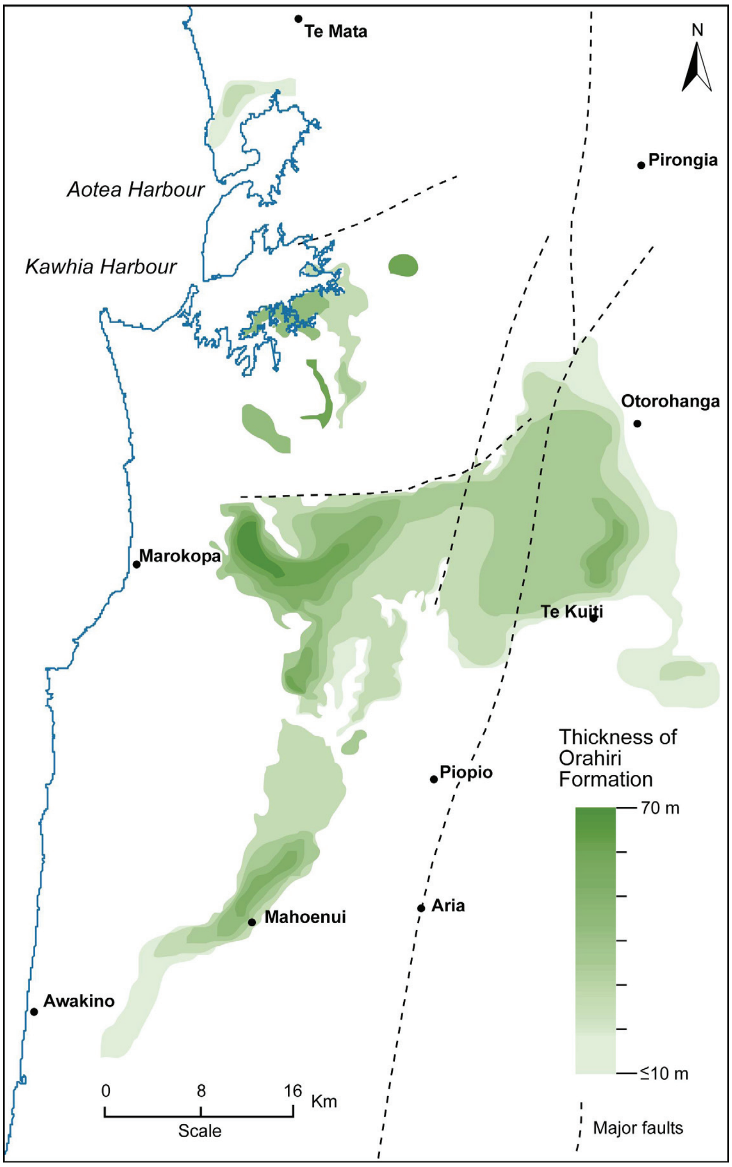


Fig. 3.24: Generalised distribution and thickness of Orahiri Formation, as defined by Nelson (1978a).

ascribed to Raglan Limestone Member at the base of Te Akatea Formation.

Contacts

The base of Orahiri Formation is marked by a regionally correlatable unconformity and a landward shift in lithofacies. The Orahiri Formation either overlies Aotea Formation in the Kawhia, Waitomo-Honikiwi, and Mangaotaki areas, or Glen Massey Formation in the Awamarino area and locally near Mahoenui. To the southeast of Te Kuiti, Orahiri Formation onlaps basement, often as a basal gritty to pebbly limestone with abundant shell hash. In some localities (e.g. Waitomo-Honikiwi, C-32; Mangaotaki Bridge, C-166; Awakino Tunnel, C-191), the basal beds of Orahiri Formation include subangular greywacke pebbles and grit, variably glauconitised, and common shell fragments overlying a sharp planar or scoured surface (Fig. 3.23f). However, in the Aotea-Kawhia area, the transition from sandy Aotea Formation to skeletal Orahiri Formation is more gradational than in the southern and eastern areas.

The upper boundary of Orahiri Formation in the type Waitomo Valley area is a gradational contact between Waitomo Sandstone Member and Otorohanga Formation. The top of Waitomo Sandstone as the basis for separating Orahiri Formation from Otorohanga Limestone can only be used in the vicinity of Waitomo and in a few localities east of Te Kuiti (Contact type 'A', Fig. 3.25). To the west of this area, where Waitomo Sandstone Member is absent, Nelson (1978a) recognised "Fossil-hash Beds (OrB5)" as the top of his Orahiri Limestone. In the Ngapaenga area, the contact is marked by the top of a strongly limonitised pebbly shelly limestone (<2 m) that forms a sharp irregular surface (Contact type 'B', Fig. 3.25). The limonitisation possibly indicates a period of subaerial exposure and weathering prior to deposition of Otorohanga Limestone.

To the west of the Piopio area, Hopkins (1966) reported scattered pebbles and an occasional pebble band between "Member C and Member D" and this is inferred to represent the "Fossil-hash Beds" at the top of Orahiri Formation. Nelson (1978a) traced a "Fossil-hash Bed" into Awakino Gorge, and based on this observation the limestone overlying Orahiri Formation at the entrance to Bexley Tunnel was correlated with Otorohanga Limestone (Contact type 'B', Fig. 3.25). However, in eastern areas, particularly in the vicinity of Te Kuiti (e.g. 94-24), where no stratigraphic break is apparent within a thick limestone succession (up to 70 m), there are no field criteria to separate Orahiri Formation and Otorohanga Limestone.

Lithology

The Orahiri Formation includes a variety of limestone facies ranging from massive sandy limestone to pure flaggy limestone with thick oyster beds, as well as variably calcareous fine sandstone of the Waitomo Sandstone Member. In general, the formation comprises two distinct limestone lithofacies forming the basis for subdivision into a (lower) Mangaotaki Limestone Member and a (upper) Te Anga Limestone Member (Nelson 1978a). The Mangaotaki Limestone is the thicker unit consisting of massive sandy limestone, its fine to medium terrigenous sandstone content typically varying from 5-30%. Sometimes this terrigenous impurity is distinctly bimodal comprising fine to medium and coarse sand grades (Bimodally-sandy Limestone Beds of Nelson 1978a). Outcrops show poor flag development with typical incipient to inverted sandy seams. The Te Anga Limestone Member is distinguished by the presence of large oyster shells averaging 15 cm diameter, which may be scattered haphazardly or be clustered and form entire beds. The oyster beds range in thickness from 1.5 - 6.0 m and are best developed in the Te

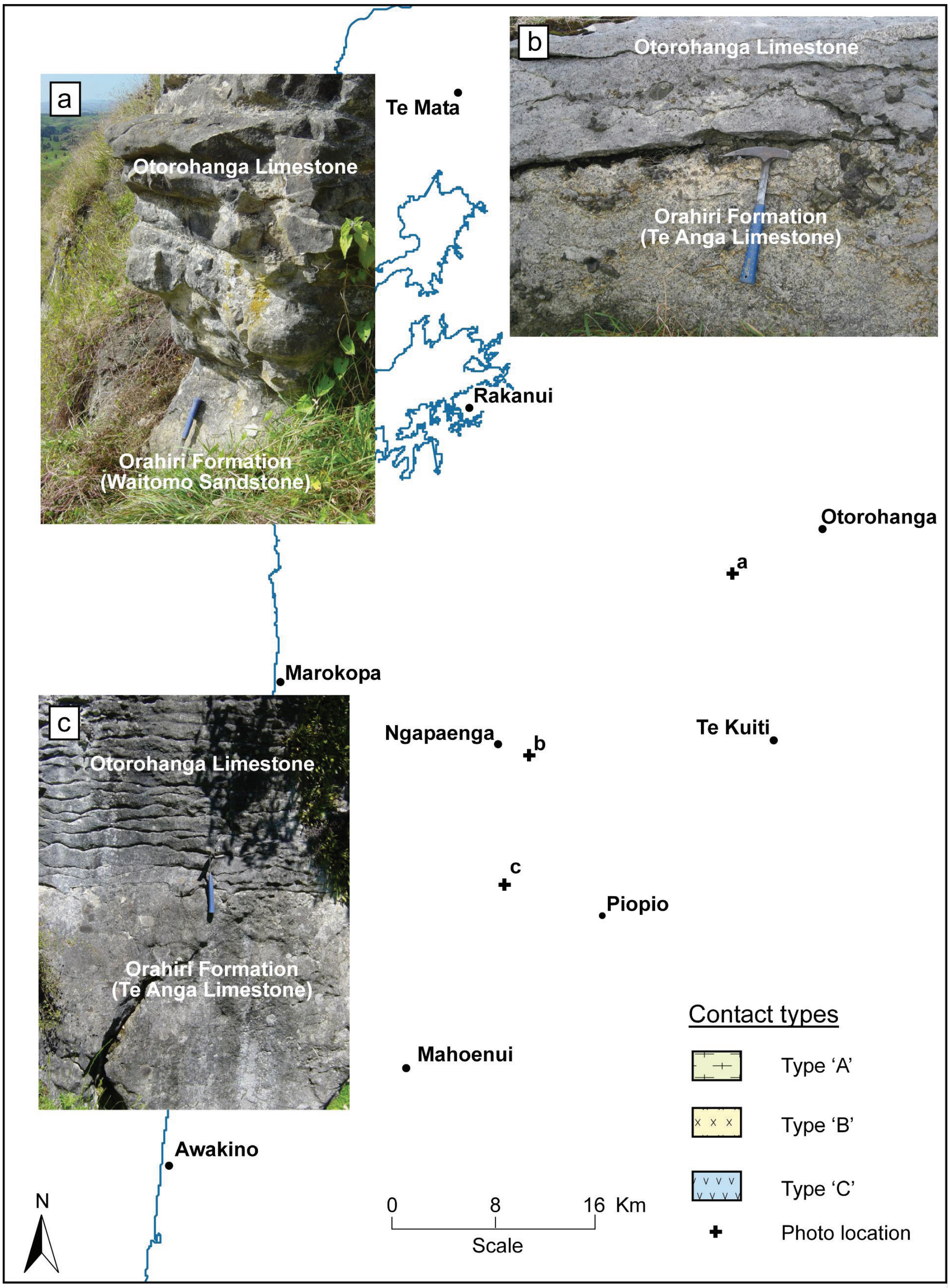


Fig. 3.25: Extent and distribution of different types of Orahiri Formation – Otorohanga Limestone contact. Type 'A' is defined by a gradational contact between Otorohanga Limestone and underlying Waitomo Sandstone Member. See photo (a) Waitomo Valley Road Limestone Quarry (C-32, S16/960295). Type 'B' is a direct contact between Orahiri Formation and Otorohanga Limestone characterised by the presence of "Fossil-hash Beds (OrB5)" (Nelson 1978a). See photo (b) Ngapaenga Road (R16/830147). Type 'C' is also a direct contact between the two formations defined by the presence of scattered pebbles and an occasional pebble band. See photo (c) Mangaotaki (C-145, R17/784047).

Anga and Mairoa areas. The oysters have been considered to be closely related to the *Flemingostreini* tribe *Stenzel*, and shells usually occur as sparsely- to densely-packed 0.3 to 1.5 m thick beds that are laterally discontinuous (Fig. 3.23e) (Nelson et al. 1983). Morgans et al. (2004) considered the oysters to be *Flemingostrea* *wollastoni.* The oyster shells are commonly extensively bored, but are just as commonly articulated as disarticulated. Pectinids and other large bivalve shell hash and pebbles are commonly associated with the oyster clusters. The terrigenous sandstone content is usually less than 5% and the oyster beds characteristically have high micrite (carbonate mud) content, probably as a consequence of predatory action of the shell borers (Nelson et al. 1983). Nelson (1978a) identified 12 beds within Orahiri Formation including "Limestone-in-Limestone Beds (OrB6)", and "Coquinite Beds (OrB7)" restricted to Bexley Tunnel (C-193) on SH3.

Waitomo Sandstone Member is assigned to a 15 m-thick unit of massive fine sandstone in the Waitomo area. It is also tentatively identified in a few locations east of Te Kuiti and apparently in the Kawhia Harbour area (Fergusson 1986). Waitomo Sandstone in the type Waitomo area (C-32) is a moderately to well sorted, fine to very fine sandstone. Because of its moderate (18-40%) calcium carbonate and mudstone content, the sandstone is usually poorly consolidated. The sandstone is characteristically massive in appearance probably due to bioturbation. Elsewhere in the Te Kuiti and Kawhia areas the sandstone is variably calcareous, glauconitic and often highly fossiliferous.

Depositional setting

The sharp unconformable contact of Orahiri Formation limestone over Glen Massey Formation or Aotea Formation along the western margin south of Kawhia Harbour marks a significant fall and rise in base-level and associated erosion. This may have been associated with uplift of the Herangi High. Uplift on the Herangi High and the rocky shoreline it formed, together with subsidence in the eastern parts of the basin, were primary influences on establishment of a carbonate factory, with the carbonate sediment distributed across the shelf where it accumulated as carbonate sand sheets under moderate to high energy conditions (Nelson 1973).

Although the carbonate accumulation is generally indicative of low terrigenous influx, Mangaotaki Limestone Member contains moderately high sandstone content along the western margin, particularly in the Awamarino-Mangaotaki area where the formation is up to 70 m thick. To the east, this terrigenous sandstone content diminishes markedly, and in areas such as Waitomo and Honikiwi the formation is represented only by the (upper) Te Anga Limestone Member. These patterns possibly reflect reworking of eroded Hauturu Sandstone into Mangaotaki Limestone Member.

Age

A Duntroonian age is inferred for Orahiri Formation based on the widespread occurrence of the oyster *Flemingostrea wollastoni* in its upper parts (Morgans et al. 2004). The first occurrence of the benthic foraminifera *Notorotalia spinosa* in the upper parts of the Aotea Formation also helps indicate a Duntroonian age for Orahiri Formation (Waterhouse & White 1994).

Otorohanga Limestone

Historical usage

Kear & Schofield (1959) introduced the name Otorohanga Limestone to describe the uppermost limestone of the Te Kuiti Group cropping out widely in northern King Country. The formation is overlain by Mahoenui Group and in places by Awakino or Cherry Tree Limestone Members within Mahoenui Group. Subsequently, Nelson (1978a) subdivided the formation in the Waitomo district into three members on the basis of distinct weathering patterns and field characteristics: a lower flaggy limestone facies named “Pakeho Limestone Member (OtA)”; an intervening “knobbly” limestone named “Waitanguru Limestone Member (OtB)”; and an uppermost flaggy limestone named “Piopio Limestone Member (OtC)”.

Definition

Although Kear & Schofield’s (1959) definition is largely followed here, the formation is regarded as being restricted to the region south of Raglan Harbour. The earlier mapping of Otorohanga Limestone north of Raglan Harbour (Kear & Schofield 1959; Kear 1987; Waterhouse & White 1994) is considered to be unsupported, and the bioclastic limestone unit in the Te Akau area previously attributed to Otorohanga Limestone is now considered to be part of the basal facies (Te Akau Limestone Member) of the Waitemata Group.

Type section

Nelson (1973) suggested a new type locality for Otorohanga Limestone at Otorohanga Limestone Company’s Quarry on Waitomo Valley Road (C-32, S16/963291) (Figs. 3.23a & 3.26a). At this locality, the formation is about 40 m thick and gradationally overlies Waitomo Sandstone Member of Orahiri Formation. The limestone exhibits prominent low-angle cross-bedding at several stratigraphic levels (Fig. 3.26b). Only the lower and upper flaggy members are distinguishable, the middle “knobbly” limestone member being thinly developed.

Distribution and thickness

An eastward shift in the main depocentre of Otorohanga Limestone carbonate

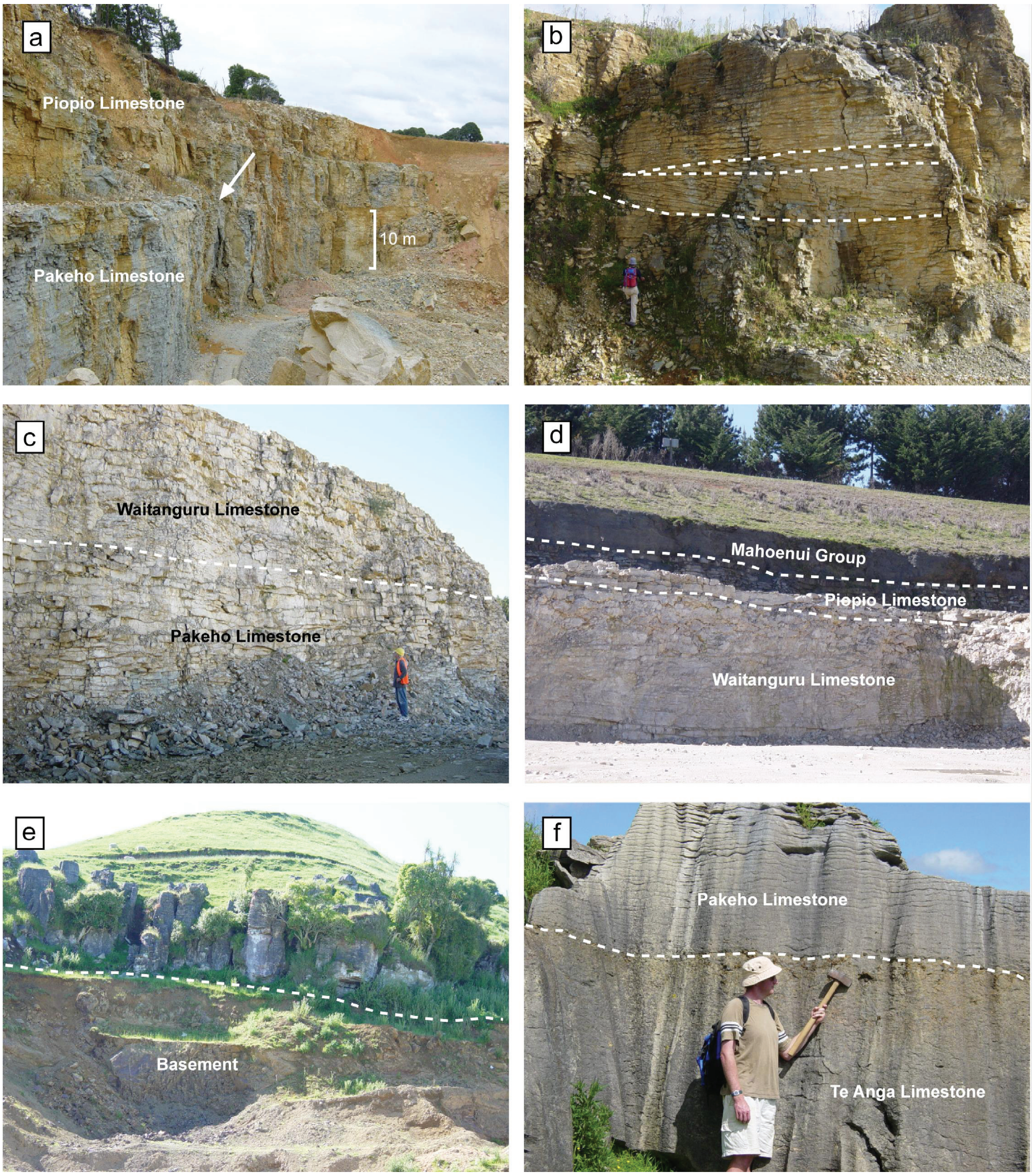


Fig. 3.26: Examples of Otorohanga Limestone in the field. (a) View of Otorohanga Limestone type locality at Waitomo Valley Road limestone quarry (C-32, S16/963291). Note the prominent ledge in the middle of the quarry face marking the contact between the lower cross-bedded Pakeho Limestone Member and the upper horizontally bedded Piopio Limestone Member. (b) Metre scale cross-stratification within the Pakeho Limestone Member, Otorohanga Limestone type section. (c) Waitanguru Limestone Member with characteristic open knobbly weathering feature, overlying flaggy Pakeho Limestone Member at Oparure Limestone Quarry (C-119, S16/917165). (d) Waitanguru Limestone Member grades up into Piopio Limestone Member at Oparure Limestone Quarry. Note the abruptly gradational contact with the Mahoenui Group mudstone. (e) Otorohanga Limestone lapping onto basement near Wilson Rd abandoned quarry (R17/814023). (f) Shell-hash with scattered pebbles marking the sharp contact between Te Anga Limestone Member (Orahiri Formation) and Pakeho Limestone Member (Otorohanga Limestone) near Ngapaenga (C-68, R16/805168).

accumulation is apparent when compared with the Orahiri Formation thickness trend (Figs 3.24 & 3.27). The formation is generally less than 30 m thick along most of the western margin, with the thickest development of Otorohanga Limestone occurring in the Waitomo and Te Kuiti areas and farther to the east where it is up to 80 m

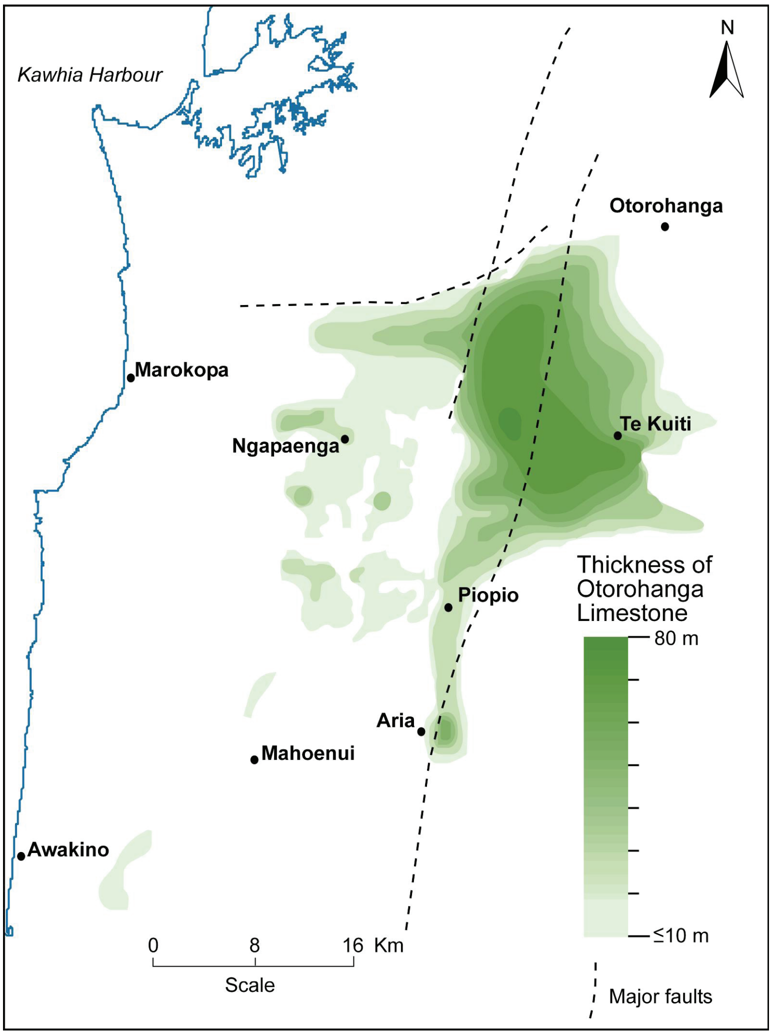


Fig. 3.27: Generalised distribution and thickness trends of Otorohanga Limestone, as defined by Nelson (1978a).

thick, although in the eastern areas there is little lithological distinction between Otorohanga Limestone and underlying Orahiri Formation. The formation appears to be very thinly developed or absent in the vicinity of Mangaotaki Bridge (C-166), and in areas farther to the south (Nelson 1978a), although local occurrences such as around Awakino Gorge are possible. North of Aotea-Kawhia Harbour, Otorohanga Limestone is inferred to grade laterally into Carter Siltstone Member of the Te Akatea Formation.

Contacts

The contact between Orahiri Formation and Otorohanga Limestone along the western margin is usually well defined by the presence at the top of the Orahiri Limestone of a distinctive pebbly shelly limestone bed, as described above (Fig. 3.25, Contact type B). Oyster beds are mostly absent in Otorohanga Limestone, but do occur in the top of this limestone in western and northern parts of the southern region (e.g. C-51).

Otorohanga Limestone grades very rapidly through silty limestone and calcareous siltstone over a metre or so into Mahoenui Group (Fig. 3.26d). This transition marks a regional change from dominantly carbonate to dominantly terrigenous sediment accumulation.

Lithology

Otorohanga Limestone comprises light grey, buff to white, flaggy to knobbly pure limestone with a terrigenous content rarely exceeding 10% (Nelson 1978a). However, in areas of basement onlap, such as in the vicinity of Piopio (e.g. C-154) and Te Kuiti (C-130), a lag deposit consisting of common glauconitised granule or conglomerate and large bivalve shell fragments occurs at the base of Otorohanga Limestone (Basal Beds OtA1 of Nelson 1978a). The Pakeho Limestone Member (OtA) is the most widely occurring member and consists of well developed flaggy limestone. Cross-bedding up to a few metres thick (e.g. at the type locality of Waitomo Valley, C-32) is common (Fig. 3.26 b). Waitanguru Limestone Member invariably falls in the pure carbonate end with calcium carbonate content as high as 98% (Nelson 1978a). In outcrop, the member is distinguished by its blocky, knobbly, and cavernous weathering appearance. In fresh hand specimens the limestone is distinguished by its pure whiteness. The limestone often has relatively high proportions of abraded bryozoans, resulting in an unusual weathering pattern (Fig. 3.26c). Often these unusual weathering bands have sharp lower and upper contacts with the flaggy limestone boundaries, probably reflecting an abrupt change in bioclastic composition. The Piopio Limestone Member (OtC) includes well developed pure flaggy limestone having higher calcium carbonate content compared with the underlying flaggy Pakeho Limestone Member. However, in places where Waitanguru Limestone Member is absent (e.g. in the vicinity of Te Kuiti), there is little lithological distinction between Piopio Limestone Member and underlying Pakeho Limestone Member. The very top of the formation comprises a metre or so of massive or thickly flagged silty limestone alternating with thin mudstone interbeds that rapidly thicken upward over a few metres into massive Mahoenui Group mudstone (Fig. 3.26d).

Depositional setting

In the southern region, thick accumulations of Otorohanga Limestone represent dispersal to eastern areas of carbonate sand from carbonate factories probably located along a rocky shoreline in the west (Herangi Range). The start of submergence of the Piopio basement high probably occurred during accumulation of Otorohanga Limestone, and accelerated with the transition to Mahoenui Group.

Age

A Waitakian age is inferred for accumulation of Otorohanga Formation based on the common occurrence of Athlopecten athleta (Nelson 1978a). The presence of the planktic foraminifera *Globoquadrina dehiscens* in Otorohanga Limestone near Te Kuiti also indicates a Waitakian age (Nelson 1978a).

Review of Orahiri Formation and Otorohanga Limestone stratigraphic division

Nelson (1978a) proposed the presence of oyster beds as a diagnostic feature of Orahiri Formation, and based on this criterion Orahiri Formation was correlated widely in the Waitomo District, extending as far as Awakino Gorge (Fig. 3.28). The presence of oysters in the upper parts of a limestone unit cropping out in a few localities inland of Kawhia Harbour (e.g. S-11, Whanuapo, Fig. 3.28) was used as the basis to assign the limestone to Orahiri Formation by Fergusson (1986) and White & Waterhouse (1994).

However, in a few locations there are some notable exceptions related to the occurrence of oyster beds and perceived stratigraphic designation (Orahiri Formation). In the type Waitomo Valley section (C-32), oyster beds occur in the lower half of the limestone unit that unconformably overlies Aotea Formation. Based on this feature, this limestone unit was named Te Anga Limestone Member by Nelson (1978a), the Mangaotaki Limestone Member being regarded as absent. In the Mangaotaki Bridge area (C-166), Te Anga Limestone Member (Orahiri Formation) is distinguished by the presence of oyster beds in the upper 5 m of the limestone, stratigraphically overlying the Mangaotaki Limestone Member. The Te Anga Limestone Member in this Mangaotaki Bridge area grades abruptly into siltstone of the Mahoenui Group, and the Otorohanga Limestone is regarded as absent (Nelson 1973), which is difficult to explain given the conformable Te Kuiti - Mahoenui Group contact. The stratigraphic division of Orahiri Formation and Otorohanga Limestone in the type Waitomo Valley cannot simply apply in the Mangaotaki Bridge area (Fig. 3.28). Hence, serious questions need to be asked about the reliability of using the facies property of the presence or absence of oysters, or oyster beds, as the basis for identifying Orahiri Formation as distinct from Otorohanga Limestone across the basin. It is possible that in the Mangaotaki Bridge area the oyster-bearing limestone at the top of the limestone section accumulated within Otorohanga Limestone, and the two limestone formations (Orahiri Formation and Otorohanga Limestone) cannot be distinguished from each other (Fig. 3.29, column B). It is difficult to envisage why Otorohanga Limestone was not deposited at Mangaotaki given its thick occurrence to the east over the Piopio High (Fig. 3.29, column C), and there is no evidence that Otorohanga Limestone was eroded in the Mangaotaki Bridge area

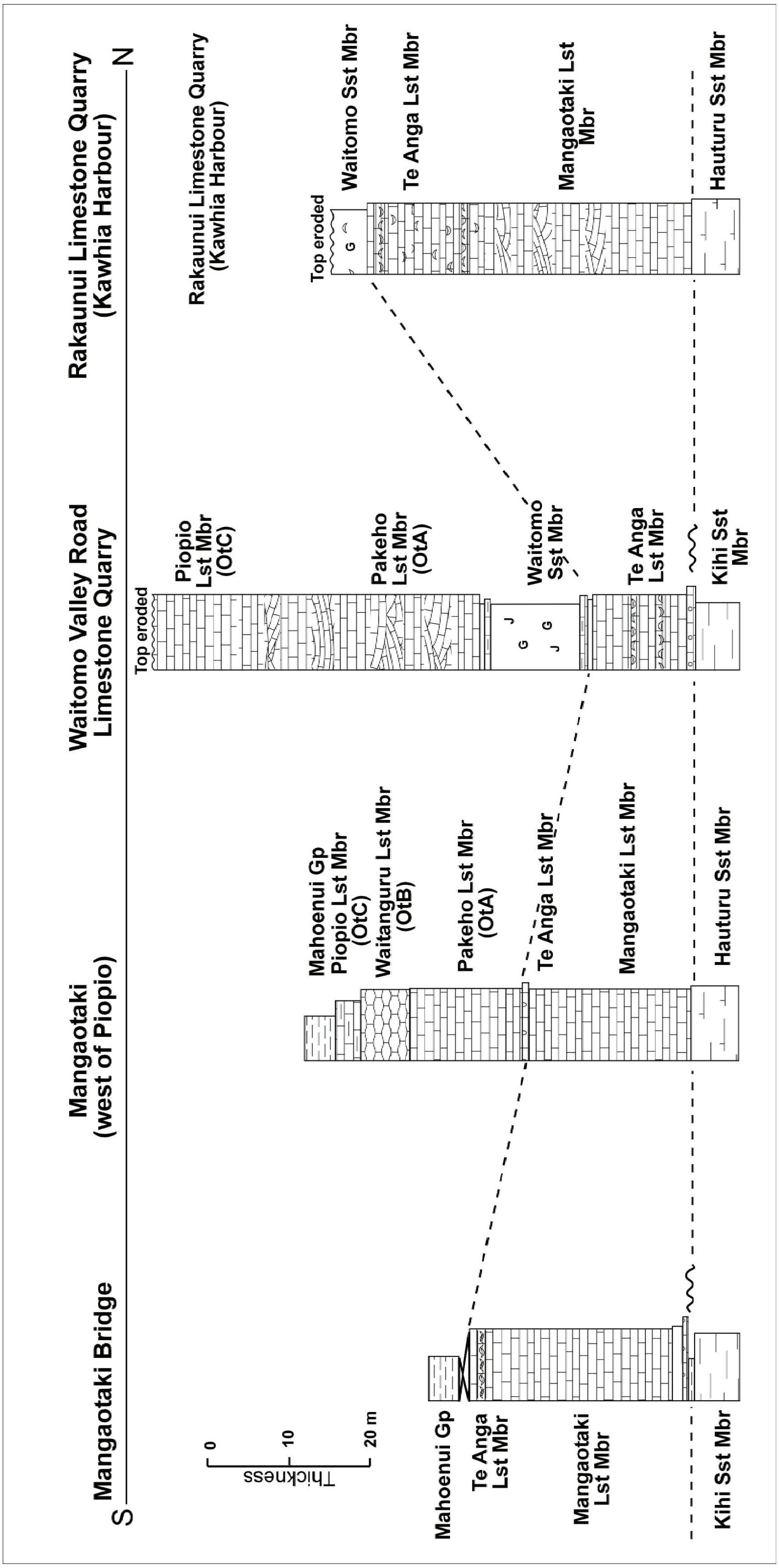


Fig. 3.28: Present understanding of the stratigraphic relationships between members of Orahiri Formation and Otorohanga Limestone, between Waitomo Valley Road Limestone Quarry (type locality), Rakaunui Limestone Quarry, Mangaotaki (west of Piopio), and Mangaotaki Bridge section, using the stratigraphic designations of previous workers. (See Fig. 3.29 for column locations). Refer Fig. 3.4 for lithology symbols.

prior to the conformable transition into the Mahoenui Group.

In the Awakino Gorge area, Nelson (1978a) distinguished Orahiri "Limestone" on the basis of the occurrence of oysters rarely organised into oyster beds within his "Limestone-in-Limestone Beds (OrB6)". The immediately overlying flaggy limestone at Bexley Tunnel (C-193) entrance was correlated with Otorohanga Limestone (Fig. 3.29, column A). The proximity of the Orahiri Formation and Otorohanga Limestone occurrences to the Herangi High near Awakino Gorge, and the evidence for synsedimentary tectonic overprinting (Nelson et al. 1994) and steeper dips, suggest that the stratigraphy there will be more complicated than farther out in the basin, where the beds are subhorizontal.

Using Nelson's definition, the inferred Orahiri and Otorohanga limestone thicknesses show marked variations (Fig. 3.24 compared with Fig. 3.27). An overall thinning of Orahiri Formation to the east is evident when compared with the thicknesses of Otorohanga Limestone. Moreover, the absence of Otorohanga Limestone to the southwest of Piopio in general, and the Mangaotaki Bridge area in particular, is difficult to explain, except for the possibility suggested here that the entire limestone thickness in the Mangaotaki Bridge area incorporates both Orahiri Formation and Otorohanga Limestone. It is possible to distinguish Orahiri Formation from Otorohanga Limestone in the central-western region (Te Anga, Waitomo, Ngapaenga, and west of Piopio) where there is a well-defined break between the two units, exemplified by columns C & D in Fig. 3.29. The absence of any apparent stratigraphic breaks within limestone occurring along the central-eastern and southwestern regions (exemplified by column E in Fig. 3.29), indicates that deposition probably continued uninterrupted from Orahiri Formation into Otorohanga Limestone in these areas. Hence, in the central-eastern region the main limestone unit is assigned to an undifferentiated Orahiri/Otorohanga Formation. In the Ngapaenga area and west of Piopio there is an erosional contact between Orahiri Formation and Otorohanga Limestone (Fig. 3.25, contacts type B & C), reflecting a short interval of tectonic uplift and limited wave planation.

In the inland Kawhia Harbour sections, the occurrence of oyster beds in the upper part of the thick limestone exposures was inferred by earlier workers to imply correlation with Orahiri Formation (exemplified by column G in Fig. 3.29). However, the immediately overlying strata, consisting of calcareous silty sandstone and regarded by earlier workers to be (Duntroonian) Waitomo Sandstone, commonly contain a key Waitakian fauna, Athlopecten athleta (Fergusson 1986; Waterhouse & White 1994). This implies that the immediately underlying limestone interval

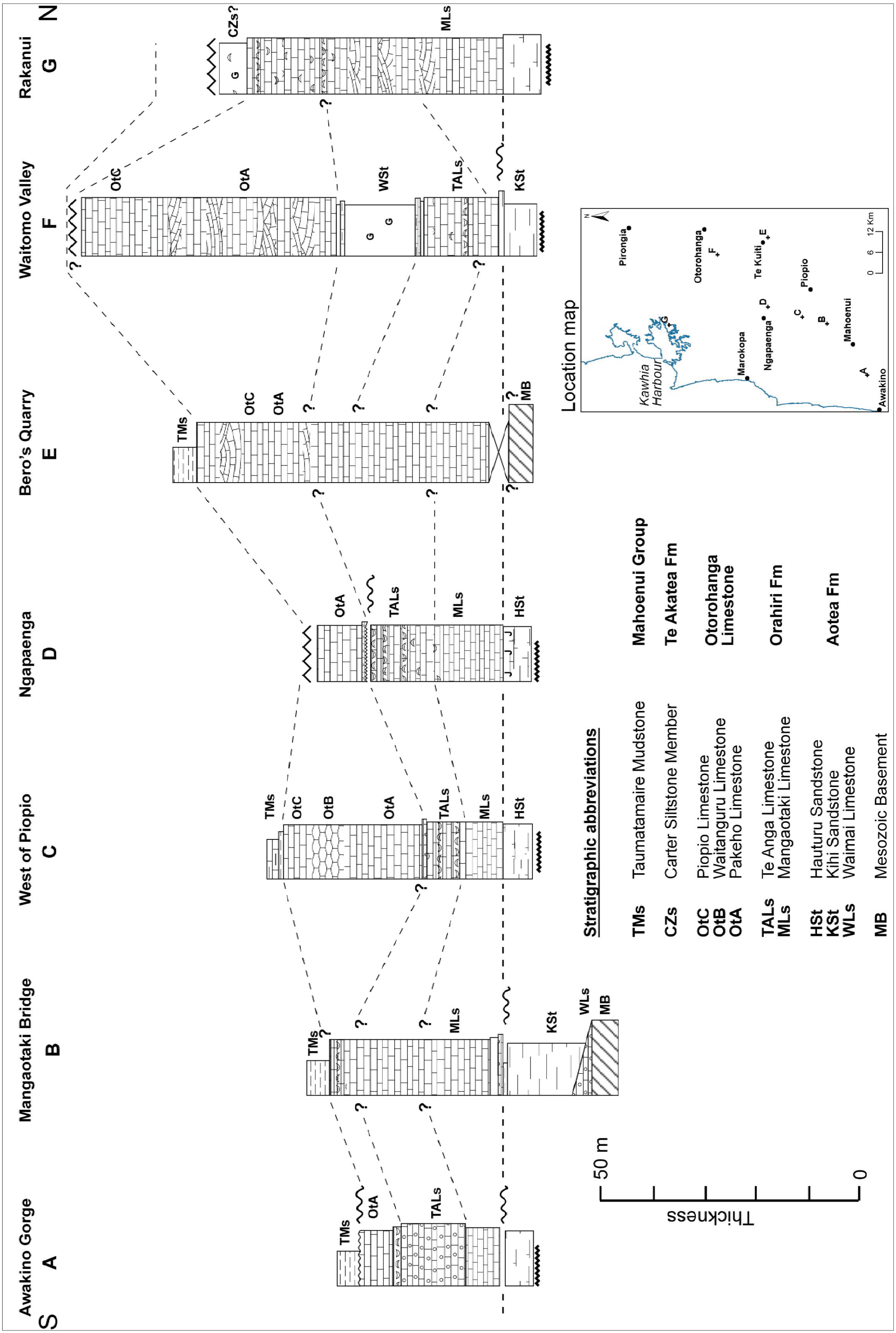

S
N
Awakino Gorge A
Mangaotaki Bridge B
West of Piopio C
Ngapaenga D
Bero's Quarry E
Waitomo Valley F
Rakanui G
TMs
OtA
TALs
MLs
KSt
WLs
MB
OtC
OtB
HSt
WSt
CZs?
G
J
?
Thickness
50 m
0
Location map
Kawhia Harbour
Pirongia
Otorohanga
Te Kuiti
Piopio
Mahoenui
Marokopa
Ngapaenga
Awakino
A
B
C
D
E
F
G
N
0 6 12 Km
Stratigraphic abbreviations
TMs Taumatamaire Mudstone
CZs Carter Siltstone Member
OtC Piopio Limestone
OtB Waitanguru Limestone
OtA Pakeho Limestone
TALs Te Anga Limestone
MLs Mangaotaki Limestone
HSt Hauturu Sandstone
KSt Kihi Sandstone
WLs Waimai Limestone
MB Mesozoic Basement
Mahoenui Group
Te Akatea Fm
Otorohanga Limestone
Orahiri Fm
Aotea Fm

Fig. 3.29 (facing page): Correlation of Orahiri Formation and Otorohanga Limestone and their constituent members between Kawhia Harbour (column G) and Awakino Gorge (column A). The columns have the member designations as inferred by previous investigators. The correlation lines drawn here between the columns make the point that Orahiri Formation and Otorohanga Limestone must be correlatives in northern and eastern parts of the southern region (columns E, F, & G), and at Mangaotaki Bridge section (column B). Oyster beds or bands are evidently not a robust basis to differentiate Orahiri Formation from Otorohanga Limestone in all parts of the basin. In column G, the uppermost unit previously regarded as Waitomo Sandstone is inferred here to be a member correlative with Carter Siltstone Member (Te Akatea Formation). Refer Fig. 3.4 for lithology symbols.

correlates better with Otorohanga Limestone than with Orahiri Formation. The silty sandstone overlying this limestone is considered here to correlate with Carter Siltstone Member of the Te Akatea Formation, as outlined in the next section.

Te Akatea Formation

Historical usage

Te Akatea Siltstone was named by Kear & Schofield (1959) after a calcareous siltstone exposed near Te Akatea Stream and it has been considered to be the uppermost formation of the Te Kuiti Group in the northern region. Kear (1963, 1966) subsequently included within this formation a limestone and siltstone succession cropping out around Raglan Harbour and inland areas to the north. The formation was thus subdivided into two members. The lower succession of interbedded calcareous siltstone and silty limestone was named Raglan Limestone, after Raglan Township, and an overlying calcareous siltstone was named Te Akatea Siltstone Member. Kear (1978) subsequently renamed the upper member “Carter Siltstone” after the siltstone exposed in the coastal cliff along Carters Beach north of Raglan Harbour. White & Waterhouse (1993) discarded the term “siltstone” from Te Akatea Siltstone to acknowledge the lithological diversity within the formation, and renamed it Te Akatea Formation.

Definition

The Te Akatea Formation comprises highly calcareous siltstone. The usage of Kear (1963) and White & Waterhouse (1993) is largely followed here, except that an overlying sandstone and bioclastic limestone at Carters Beach and Gibsons Beach, which they referred to as Waitomo Sandstone and Otorohanga Limestone, respectively, are excluded here from the Te Kuiti Group and attributed instead to the basal part of the Waitemata Group (Fig. 3.30). This leaves the entire region north of Mt Karioi as having Te Akatea Formation forming the uppermost unit of the Te Kuiti Group. Te Akatea Formation is stratigraphically equivalent to the Orahiri Formation and Otorohanga Limestone, which occur south of Kawhia and Aotea harbours.

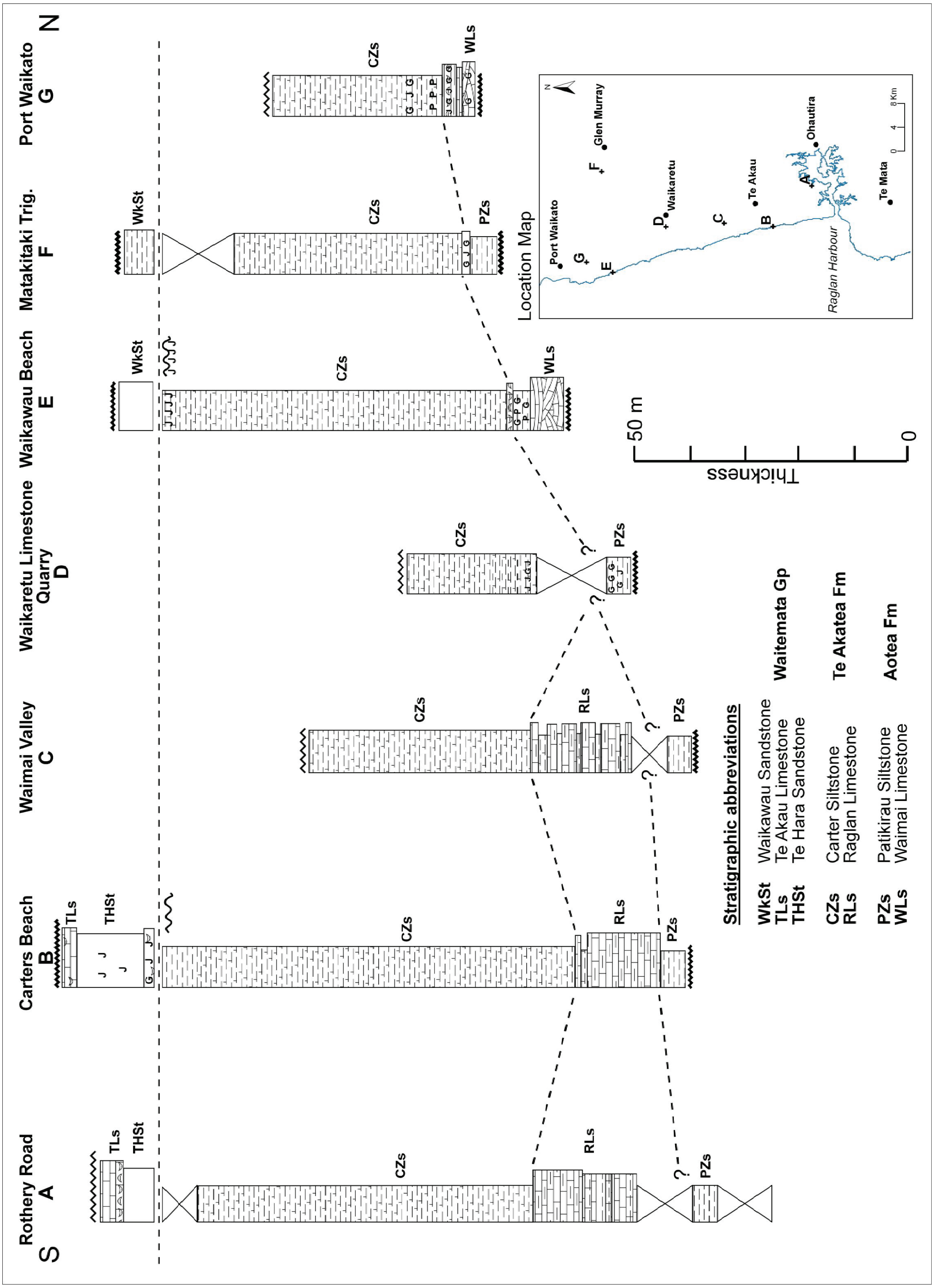


Fig. 3.30: Correlation of Te Akatea Formation members in selected locations from Raglan Harbour (Rothery Road, column A) to Port Waikato (column G). Datum is the top of Carter Siltstone Member. No horizontal scale is implied. Refer Fig. 3.4 for lithology symbols.

Type locality

The type location for Te Akatea Formation was designated by Kear (1963) as the succession exposed in the cliff at Carters Beach (TA-11), located about 5.2 km southwest of Te Akau. The Te Akatea Formation exposed on the southern side of Tauterei Stream mouth, Carters Beach, comprises mainly Raglan Limestone Member (~12 m thick) (Fig. 3.31a & b). Raglan Limestone overlies Patikirau Siltstone Member, which is exposed 200 m inland from Tauterei Stream mouth. Raglan Limestone Member becomes increasingly silty upwards before grading into Carter Siltstone Member. Carter Siltstone is best exposed in a cliff on the north side of Tauterei Stream, where it consists of massive to moderately bedded fine calcareous siltstone grading into sandy siltstone in the upper 10-12 m. Carter Siltstone is exposed on the shore platform and is spectacularly fractured by two sets of joints criss-crossing at regular intervals (Fig. 3.31b). The top of Carter Siltstone is exposed in the upper part of the cliff, dipping into the sea at the northern end of Carters Beach. The contact with Waitemata Group is a sharp planar surface cut across Carter Siltstone (Fig. 3.32f). The Waitemata Group comprises thin horizontally bedded glauconitic fine sandstone that passes upward into massive, poorly cemented, very fine to fine sandstone beds.

Distribution and thickness

Te Akatea Formation is inferred to have been widely deposited in the northern region. The formation is best preserved and exposed in coastal cliffs along the west coast between Raglan Harbour and Waikawau Beach south of Port Waikato, and in areas immediately inland (Fig. 3.33). The formation exposed along the coast is up to 90 m thick. Raglan Limestone Member is a distinct mappable unit in the Raglan Harbour area and has a measured thickness of up to 14 m, and is reported to be up to 23 m thick along the coast at Te Hara Point (R14/705838) (Kear 1987; Waterhouse & White 1994), although the base is not exposed. Raglan Limestone Member thins to the north, and it cannot be distinguished from overlying Carter Siltstone Member facies north of Waimai Valley (Fig. 3.30, column C). Raglan Limestone is not known east of the modern coastline.

In the Te Akau and Te Akau South areas, Carter Siltstone has thicknesses in the range of 30-60 m, usually preserved on the downthrown side of NE-SW striking faults. In areas farther to the east, the formation has been largely eroded except for a few outliers. The eastern extent of the formation is unknown because of the degree of post depositional erosion, however the member is inferred to have extended as far east as the Huntly Coalfield area, judging from its reported occurrence in coal exploration drill holes (Edbrooke 1984). However, in logs for these holes Te Akatea

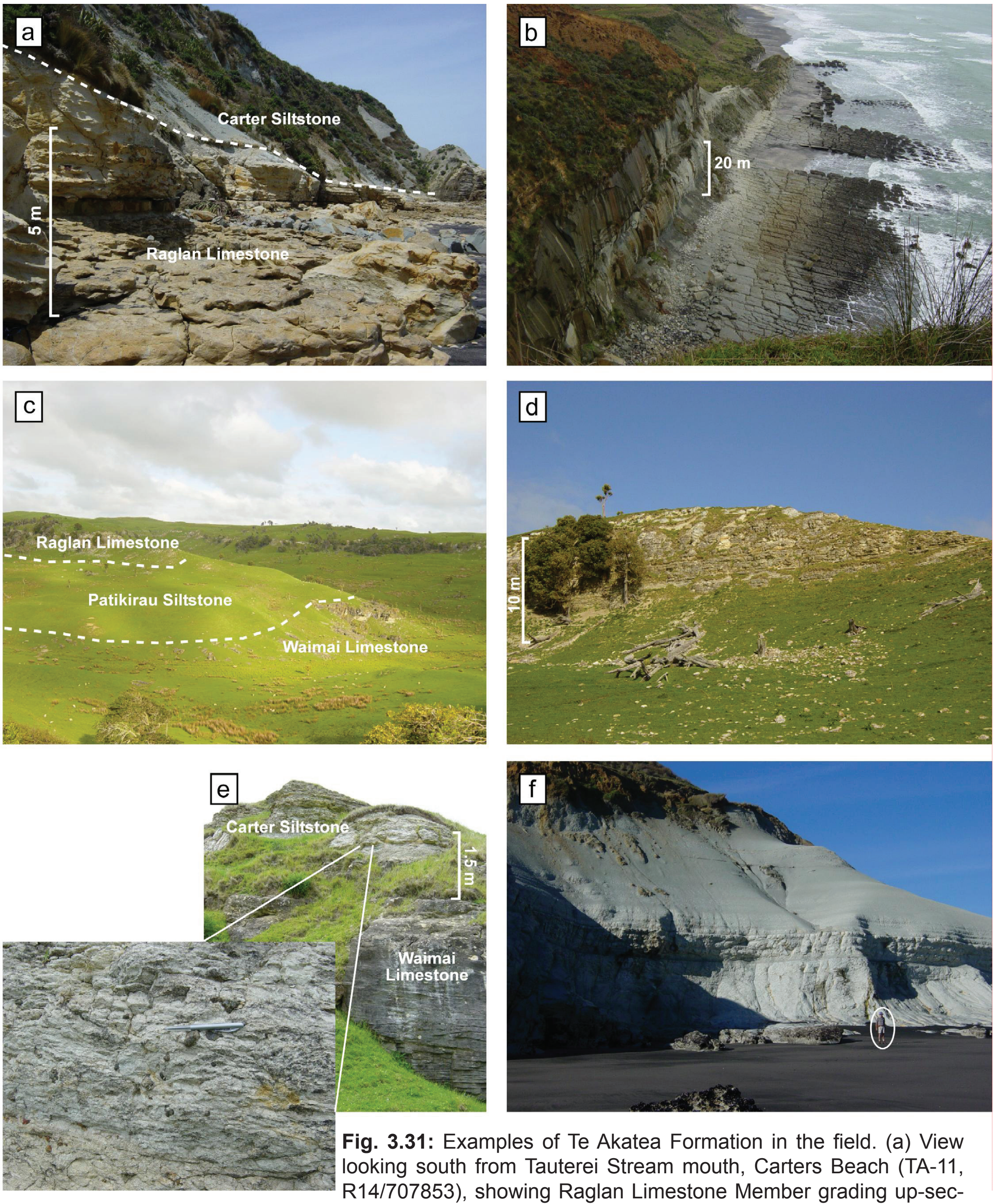


Fig. 3.31: Examples of Te Akatea Formation in the field. (a) View looking south from Tauterei Stream mouth, Carters Beach (TA-11, R14/707853), showing Raglan Limestone Member grading up-section into Carter Siltstone Member. (b) View looking south showing cliff of Carter Siltstone Member at Carters Beach. Note the box-work set of joints on the shore platform within Carter Siltstone. (c) View looking northeast in Waimai Valley (TA-3) showing the stratigraphic relationship of Raglan Limestone Member with underlying Aotea Formation. (d) Thinly bedded Raglan Limestone Member grading upward into massive Carter Siltstone Member at Waimai Valley (TA-3). (e) Carter Siltstone Member conformably overlying fossiliferous glauconitic beds at the top of Waimai Limestone Member near Port Waikato (PW-1, R13/653175). Inset shows phosphatic nodules in the top of Patikirau Siltstone Member. (f) Carter Siltstone Member exposure on the coast just north of Kaawa Stream mouth (PW-12, R13/103096). Note the transition from lower bedded to upper massive Carter Siltstone Member.

Formation is generally undifferentiated from underlying units.

Contacts

In the Raglan Harbour area there is an abrupt boundary between Raglan Limestone

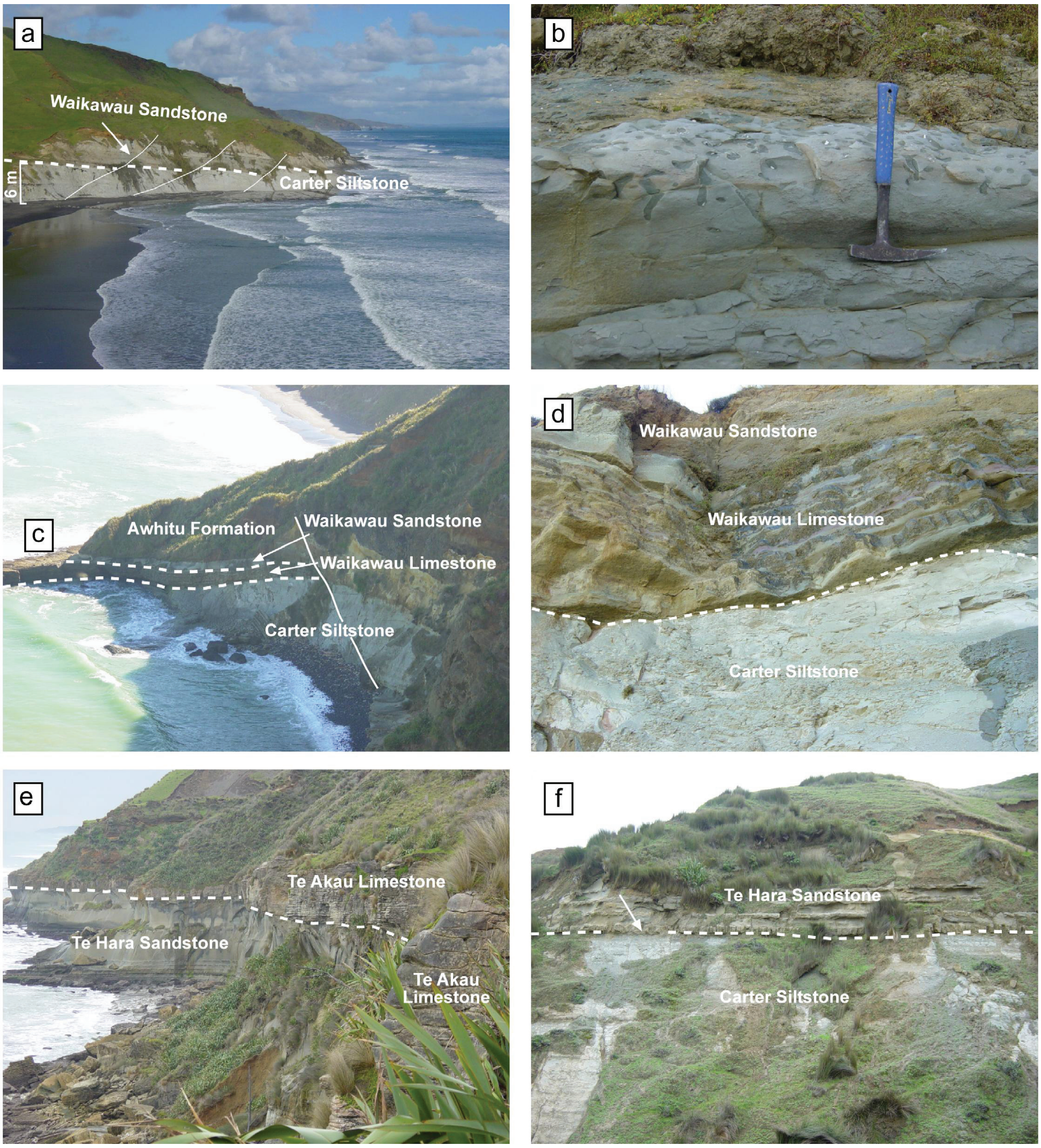


Fig. 3.32: (a) View south from Waikawau Stream mouth (PW-11, R13/625138), showing sharp erosional contact between massive siltstone (Carter Siltstone) and thin-bedded Waikawau Sandstone. The base of the sandstone is the traditional Te Kuiti/Waitemata Group boundary in this section. (b) Close-up showing infaunal burrows at the top of Carter Siltstone in the section at Waikawau Beach. (c) View looking north at Kaawa Beach (PW-12, R13/646088). A cross-bedded coarse shelly sandy limestone (Waikawau Limestone Member) is separated from Carter Siltstone by a sharp planar surface. Waikawau Limestone grades abruptly into bedded Waikawau Sandstone. (d) Close view of contact between Carter Siltstone and Waikawau Limestone exposed along the cliff at Kaawa Beach. (e) View north from the northern end of Carters Beach (TA-11, R14/704865), showing flaggy bioclastic Te Akau Limestone sharply overlying Te Hara Sandstone, the contact being profusely burrowed. (f) Flat wave-planned surface on top of Carter Siltstone forming the unconformable contact (arrowed) with Te Hara Sandstone exposed at the northern end of the Carters Beach (TA-11).

Member and underlying Patikirau Siltstone Member. This contact is also extensively burrowed (e.g. Okete Bay, TA-15) or glauconitic (e.g. Mangiti Road, TA-12; Patikirau Bay, TA-20). In the vicinity of Port Waikato (e.g. PW-1 & 2, Te Akatea Formation conformably overlies highly burrowed muddy glauconitic sandstone

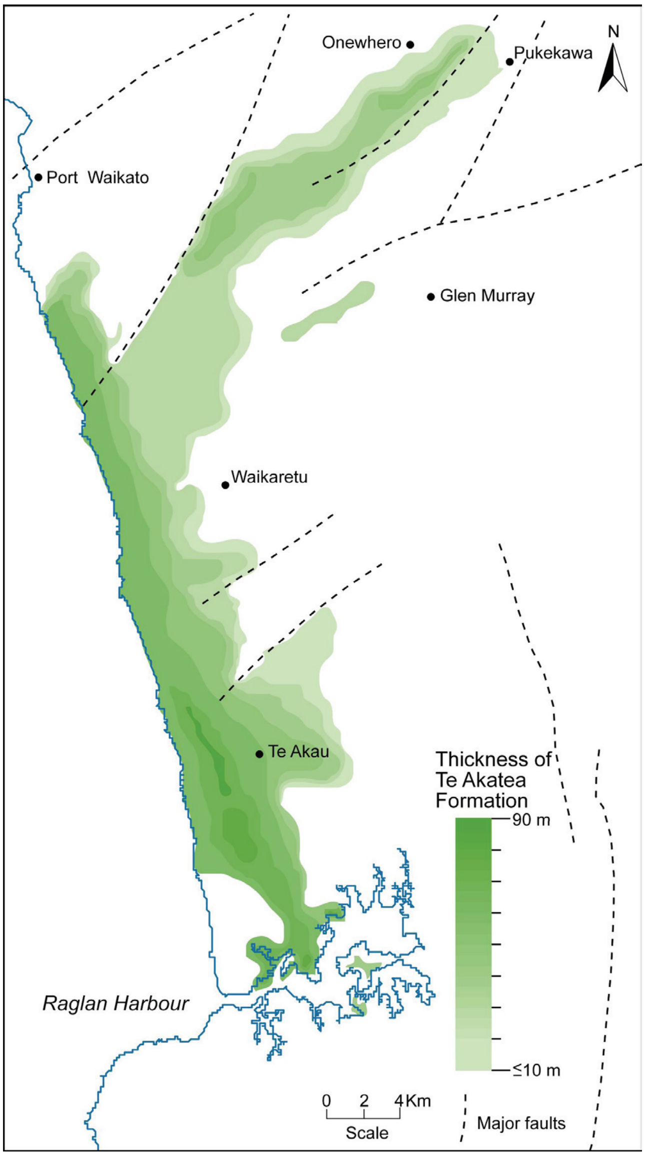


Fig. 3.33: Generalised distribution and thickness trends of Te Akatea Formation.

(condensed Patikirau Siltstone Member) that was previously regarded as part of Te Akatea Formation (Kear & Schofield 1959; Kear 1963; Waterhouse 1978). It consists of common casts and moulds of gastropods, brachiopods, echinoderms, and solitary corals (Flabellum), and shark teeth. A thin (0.3-0.5 m) but conspicuous phosphatic nodule bed occurs at the top of the glauconitic muddy sandstone unit (Fig. 3.31e), and this defines the top of Patikirau Siltstone Member. However, in eastern parts of the northern region (e.g. PW-7) there is little lithological distinction between Patikirau Siltstone and Carter Siltstone, except for the presence of a glauconitic horizon reported in places (Kear & Schofield 1959).

Lithology

Raglan Limestone Member comprises buff to cream-white fine grained foraminiferal limestone with thin interbeds of calcareous siltstone, which are commonly extensively burrowed. The member grades upward through silty limestone into calcareous siltstone of the Carter Siltstone Member (Fig. 3.31a). The Carter

Siltstone is generally massive, but the lower parts are crudely bedded, individual beds being <1 m thick. At Kaawa Beach (PW-12) and Waikawau Beach (PW-11) sections the member has distinct medium to thin beds. The lower bedded siltstone passes upward into massive siltstone with occasional concretionary bands (Fig. 3.31 f). The member commonly forms steep bluffs and exposed surfaces develop fine conchoidal fracture. The carbonate content of the siltstone typically lies in the range 30-74%. The siltstone tends to be coarse and less calcareous in the southern and eastern areas. In the type Carters Beach locality (TA-11), the member comprises primarily fine calcareous siltstone that grades upward into 10-12 m of fine sandy siltstone. The siltstone is commonly strongly bioturbated and in places consists of extensively burrowed glauconitic horizons, which probably represent localised depositional condensation. The member often includes scattered echinoderm and molluscan shell fragments and rare gastropods. The microfauna identified by Hornibrook (Kear & Schofield 1978) in Carter Siltstone are dominated by planktics (Globigerina) and benthics such as Cibicides thiara and Karreriella novozealandica, indicating an outer shelf to upper bathyal depositional environment.

Depositional setting

During the upper Duntroonian to lower Waitakian, a gentle north-facing depositional slope extended from the northern part of Kawhia Harbour to the Te Akau area. In the vicinity of Raglan Harbour, Raglan Limestone Member aggraded the depositional slope and represents a transition between the neritic platform carbonate facies (Orahiri Formation) to the south and the upper bathyal Carter Siltstone facies to the north. In the Port Waikato area, Carter Siltstone accumulated over glauconitic muddy sandstone containing phosphate nodules (Patikirau Siltstone) and brought to a close the preceding interval of depositional condensation.

Age

Macrofossils reported from Raglan Limestone Member such as *Cirsotrema lyratum*, *Lentipecten huttoni (hochstetteri), Chlamys williamsoni,* and *Terebratulina suessi,* indicate Duntroonian to possibly Waitakian age, whereas the common occurrence of the planktic foraminifera *Globoquadrina dehiscens* and *Globigerina brazieri* in Carter Siltstone Member indicate a Waitakian age (Hornibrook in Waterhouse & White 1994).

Contact between Te Kuiti Group and Waitemata/Mahoenui groups

In the northern region, a sharp planar surface separates Te Kuiti Group from Waitemata Group. This surface may reflect broad regional uplift and inversion of the basin associated with wave planation and erosion. The amount of uplift and erosion increased towards the east across South Auckland, as progressively older Te Kuiti Group strata lie beneath the Waitemata Group in that direction (Kear 1963). In some areas, Te Kuiti Group has been completely removed as a result of the uplift and erosion that preceded Waitemata Group deposition (Kear 1963; Kear & Schofield 1978). In sections along the west coast (Waikawau, PW-11; Kaawa, PW-12 and Carters beaches, TA-11) a bored, wave-planed unconformity surface is developed at the top of Carter Siltstone (Figs 3.32 a-d, f & 3.34), indicating uplift was sufficient to elevate it from outer shelf-upper bathyal depths into the wave zone where the erosion occurred. There is other evidence for this regional uplift such as the presence of large specimens of Elphidium and ostracods in the base of the Waitemata Group immediately above the unconformity, indicating accumulation in inner shelf environments (Hornibrook in Kear 1987). Some reworking of microfauna from Carter Siltstone into basal Waitemata Group sediments is also inferred (Hornibrook & Schofield 1963). All of the units unconformably overlying Carter Siltstone are included here within the Waitemata Group, and these units have diversified lithologies reflecting onlap and neritic facies development as the Waitemata Basin formed. At Gibsons Beach (TA-18) a wave-planned surface occurs between Te Hara Sandstone and Te Akau Limestone (Fig. 3.34, columns E, F & G). An erosional unconformity also lies between Te Akau Limestone and overlying conglomeratic limestone beds that have limited extent in the coastal section at Gibson Beach (Fig. 3.34, column G). Te Akau Limestone Member was regarded by Kear (1963, 1987) as Otorohanga Limestone and the unconformity with the conglomeratic limestone as the contact between Te Kuiti Group and Waitemata Group, an interpretation subsequently adopted by Hayward and Brooks (1984). The limestone conglomerate contains a variety of subangular to subrounded pebble and cobble size lithoclasts possibly sourced from the underlying limestone and sandstone. The geometry of the conglomerate beds suggests that they accumulated in nested shelf channels cut into the underlying bioclastic limestone (Te Akau Limestone Member) as the water depth in the Waitemata Basin increased to outer shelf conditions. In some parts of Gibson Beach, the channels have entirely cutout the underlying limestone unit. The channelised limestone conglomerate is known only from part of the Gibsons Beach section (Hayward & Brooks 1984) and lies between a neritic limestone facies (Te Akau Limestone Member) and a bathyal siltstone (Gibson Siltstone Member) of the Waitemata Group. Elsewhere in the coastal sections (Carters Beach, Te Hara Point) and in inland locations (north of Te Akau), the Te Akau Limestone passes conformably into Waikawau Sandstone or Gibson Siltstone.

The distribution of various contact types observed in sections between the Te Kuiti Group and the Mahoenui Group or Waitemata Group in western North Island are

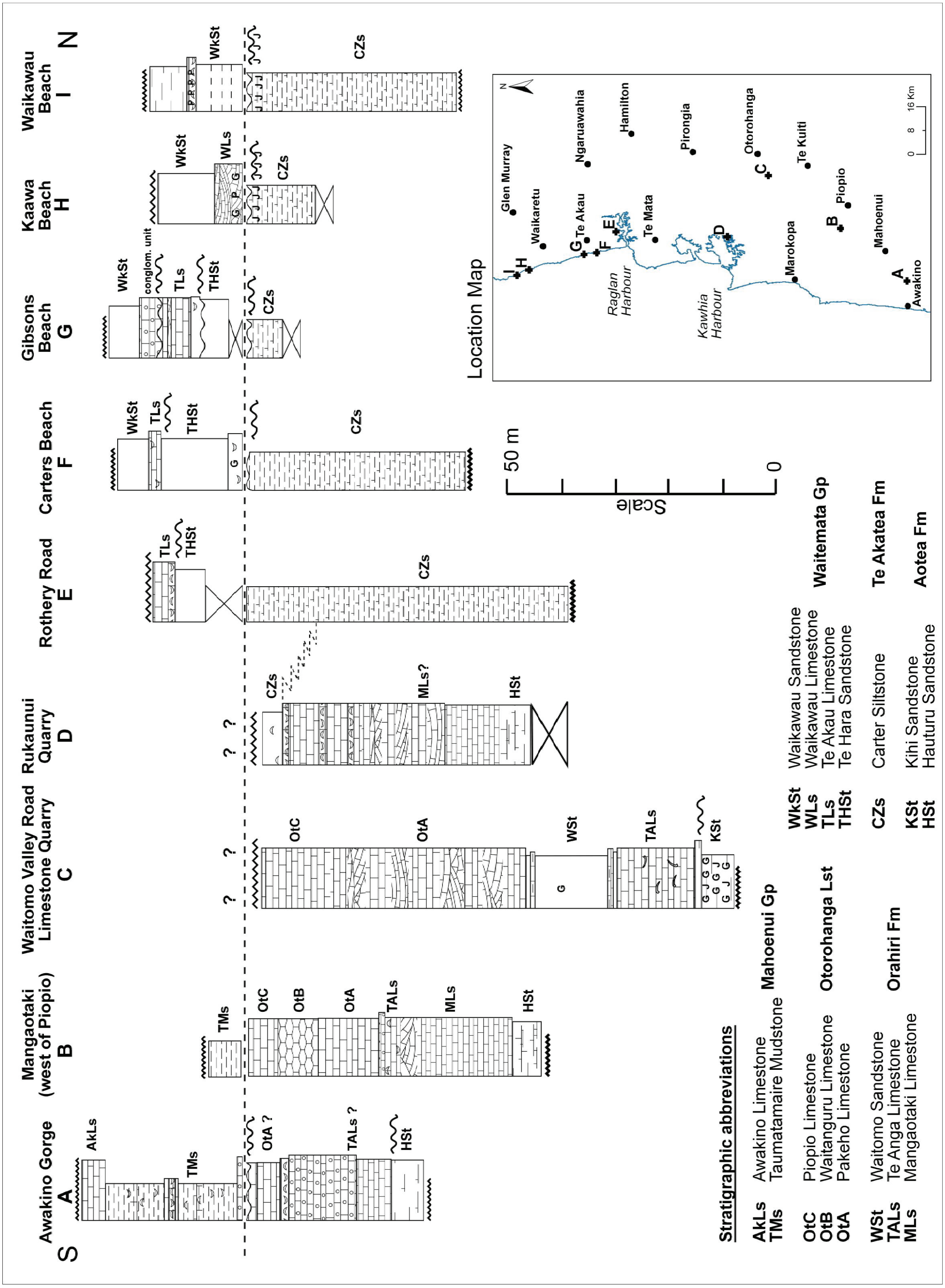


Fig. 3.34: Correlation of Orahiri Formation–Otorohanga Limestone/Te Akatea Formation members and their relationships to the Mahoenui and Waitemata groups in selected locations from Awakino Gorge (column A) to Port Waikato (Waikawau Beach, column I).

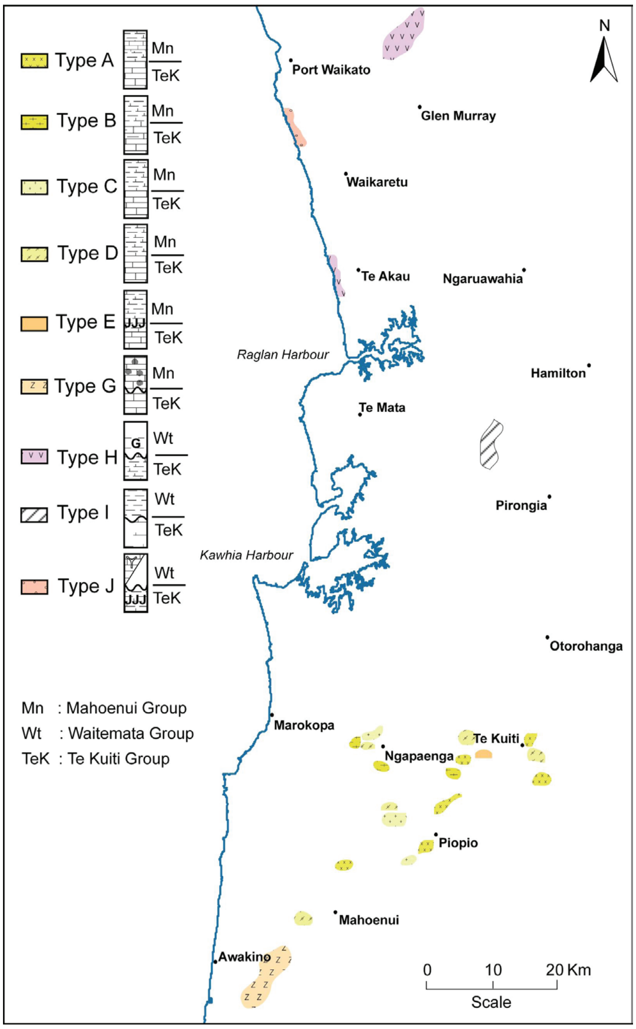


Fig. 3.35: Te Kuiti Group - Mahoenui Group contact types, established by Nelson (1973), and Te Kuiti Group - Waitemata Group contact types established from outcrop observations in this investigation.

illustrated in Fig. 3.35. In most of the southern region, the transition from the Te Kuiti Group into the Mahoenui Group has been reported as conformable (Nelson 1978a) (Fig. 3.36). The variation in the nature of this contact has been classified by Nelson (1973) into seven types. Five of these contact types (A-E) are reported as either being gradational or abruptly gradational and there is no evidence for a hiatus (except in type E). The development of an erosional unconformity at the top of the Te Kuiti Group is evidently less prevalent in the southern region compared with the region north of Raglan Harbour. However, in the Awakino Gorge area there is an erosional contact between the Te Kuiti Group and the Mahoenui Group (type G, Nelson 1973), associated with contemporary movement of the Herangi High due to displacement on the Taranaki and Manganui Faults (Kamp et al. 2004). North of Awakino Tunnel, the Awakino Limestone Member (Mahoenui Group) rests upon Aotea and Orahiri Formations. At Bexley Station tunnel (C-193), the contact is inferred to lie between well flagged bryozoan-rich Otorohanga Limestone and algal-rich Awakino Limestone Member (Nelson 1973). The nature of these contacts reflects local tilting and erosion due to mobility of the Herangi High prior to deposition of Mahoenui Group siltstone and limestone facies (Nelson et al. 1994).

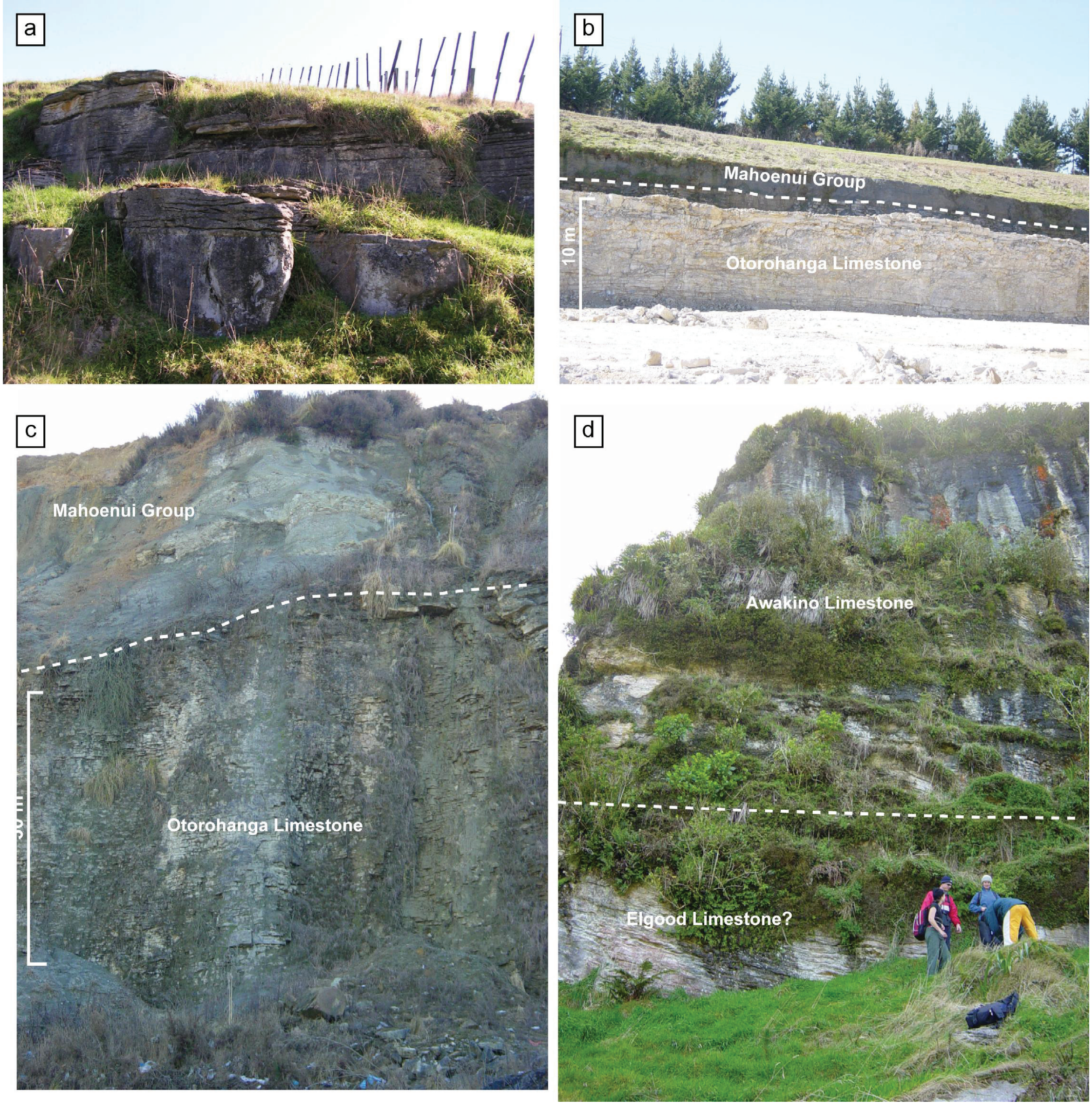


Fig. 3.36: (a) Otorohanga Limestone at a quarry southwest of Piopio (C-154, R17/844005) becomes thinly flagged and argillaceous before passing upward into weathered mudstone of the Mahoenui Group (not seen in this photo). (b) Sharp contact between Otorohanga Limestone and Mahoenui Group mudstone at Oparure Limestone Quarry (C-119, S16/917165). (c) Otorohanga Limestone abruptly grades into massive siltstone alternating with well cemented 'hard' silty sandstone beds (Mahoenui Group) at the abandoned Beros Quarry east of Te Kuiti (94-24, S16/008173). (d) Awakino Limestone Member (Mahoenui Group) unconformably overlying Elgood Limestone Member (Glen Massey Formation) north of Awakino Tunnel. Note the steeper dip of the Elgood Limestone compared with the Awakino Limestone. Mesozoic basement is exposed at the base of Elgood Limestone.

Chapter 4

Biostratigraphy and Chronology

Introduction

This chapter reviews the biostratigraphy of the Te Kuiti Group based upon previously reported microfossil data, and presents and interprets new 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. There are many microfossil and macrofossil collections held at the Institute of Geological and Nuclear Sciences, as well as in the Geology Department at Auckland University.

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). Subsequently, significant gaps in fossil collections in the Te Akau and Waitomo areas were filled 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 here are on 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. With the improved lithostratigraphic framework presented in Chapter 3, it is desirable as part of a basin analysis to develop a robust chronostratigraphic template. This has mostly been developed through the application of biostratigraphy, supplemented with new and existing Sr isotope ages. No new microfossil determinations have been made here. The unconformities between formations and their correlative conformities provide important constraints on the interpretation of ages for various parts of the Te Kuiti Group.

Regional overview of Te Kuiti Group biostratigraphy

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 group. In the overlying marginal marine to shallow marine sequence of the Mangakotuku Formation, a combination of spores and pollen, ostracods, molluscs, and occasionally foraminifera have proved to be useful. As the water depth increased to shelfal depths, foraminifera, dinoflagellates, and calcareous nannofossils have become the most widely used fossil group for age determination, especially in the calcareous sequences of the Te Kuiti Group. Although molluscan fossils are common in the group, they are mainly fragments 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 foraminiferal bio-events, the samples having been sourced from the muddy lithologies. Molluscs are however useful for the assignment of biostratigraphic ages in the Orahiri Formation and Otorohanga Limestone. These limestone formations contain large calcite bivalves (oysters, brachiopods) and the epitoniid gastropod *Cirsotrema*, and are 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).

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 generally more facies dependent. Benthic foraminifera have limited use in biostratigraphy because of the fewer bio-events compared with planktic bio-events that mark the (lower and upper) Whaingaroan Stage and Duntroonian Stage boundaries (Cooper et al. 2004). Nevertheless benthic foraminifera are useful for local correlation, and they have important utility for determination of depositional paleoenvironments (Hayward 1986).

New Zealand Late Eocene-Oligocene-Early Miocene stages

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 4.1 and 4.2. Type and reference sections for these stages, all of them outside the Te Kuiti Group except for the Whaingaroan-Duntroonian boundary (Fig. 4.1), are

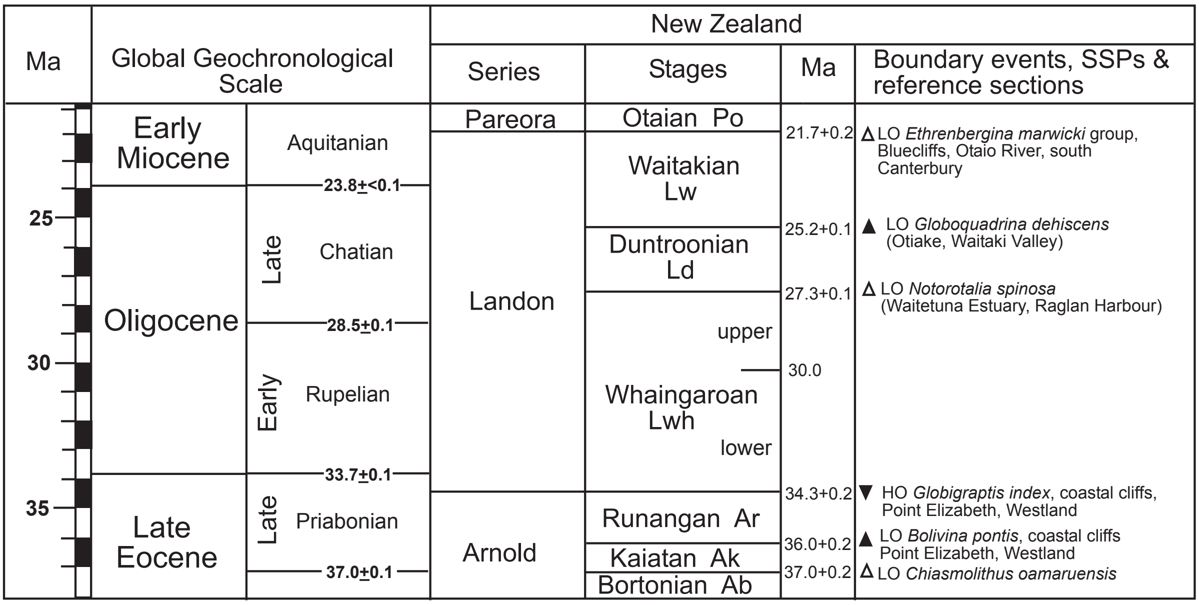


Fig. 4.1: Late Eocene to Early Miocene New Zealand Series and Stages correlated with the Global Geochronological Scale. The boundary-defining event for each stage is shown and the boundary stratotype section and point (SSP), or a reference section in brackets, are indicated. Formal SSPs are indicated by solid triangles and informal SSPs by open triangles. Adopted from Cooper et al. (2004).

described by Cooper et al. (2004), and are not elaborated upon here. Selected fossil samples used here for biostratigraphic correlation are depicted on the composite stratigraphic columns in Fig. 4.3.

In the following section, under subheadings of the successive L. Eocene and Oligocene stages, relevant microfossil samples are described within the context of formations and members, emphasizing the key taxa within samples and the related age (stage) determination. This is highly descriptive but deserving given the need to extract as much information from existing samples as possible, and the importance of determining chronostratigraphic control for the formations in the group to address the thesis objectives.

Kaiatan Stage (Ak)

Hornibrook et al. (1989) summarised the foraminiferal basis for the Kaiatan Stage. The base of the stage is primarily recognised on the disappearance of *Nuttallides truempyi*, *Bulimina subbortonica*, and *Cibicides tholus*. *Sphaeroidina variabilis* ranges through the Kaiatan. No planktonic events mark either the base or top of the Kaiatan. The most well defined planktonic 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. The lowest occurrence of *Ismolithus recurvus*, an event dated at 36.0 Ma (Bergen et al. 1995), is extremely useful for correlating the upper Kaiatan with the international time scale.

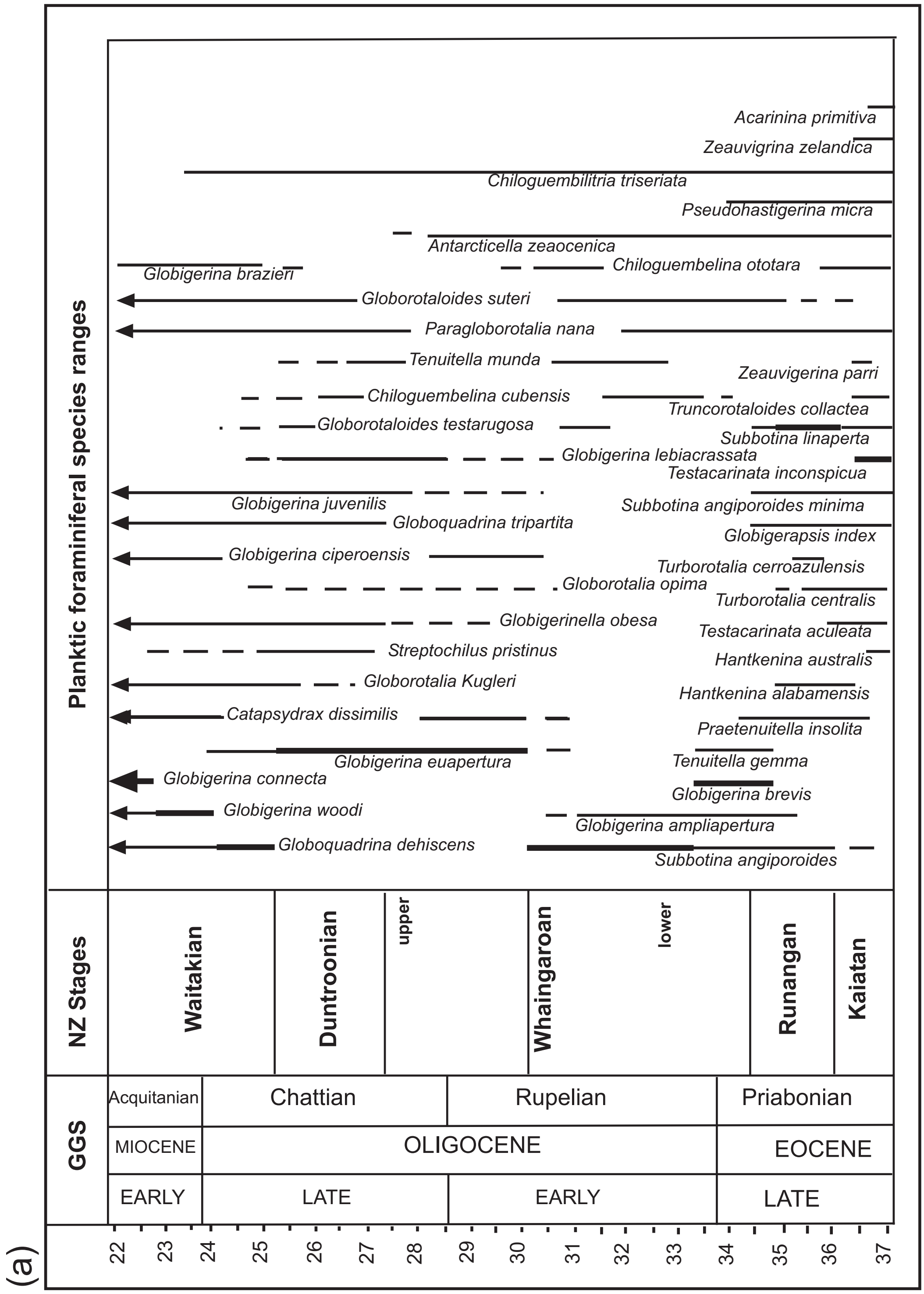


Fig. 4.2: Stratigraphic ranges of selected biostratigraphically useful planktic (a) and benthic (b) foraminifera. Adopted from Cooper et al. (2004).

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 WCM accumulation, and its subdivision into biozones, based on abundance levels of the major palynomorphs. The lowermost spore and pollen zone of the Waikato Coal

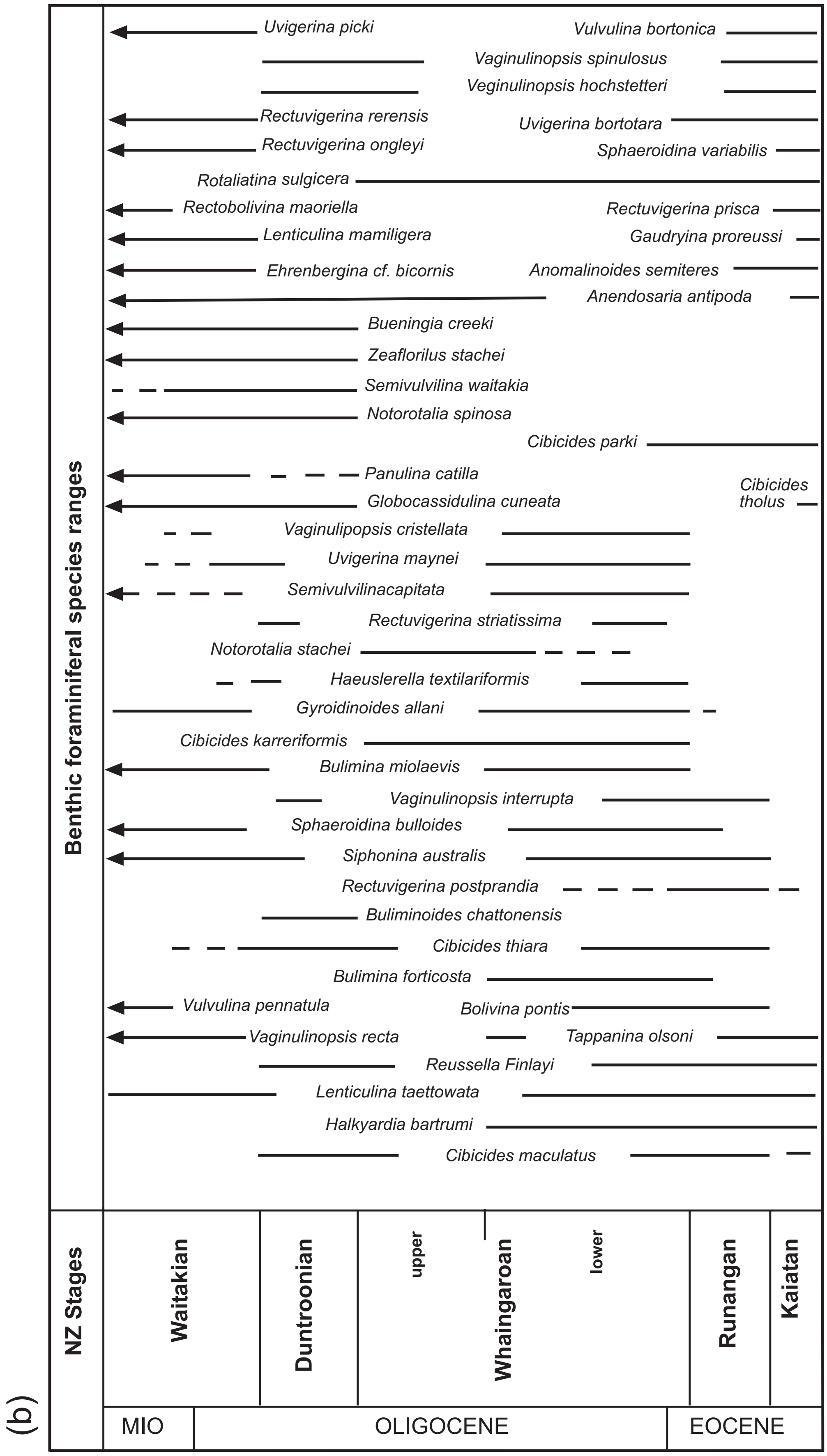


Fig. 4.2(Continued): Stratigraphic ranges of selected biostratigraphically useful planktic (a) and benthic (b) foraminifera. Adopted from Cooper et al. (2004).

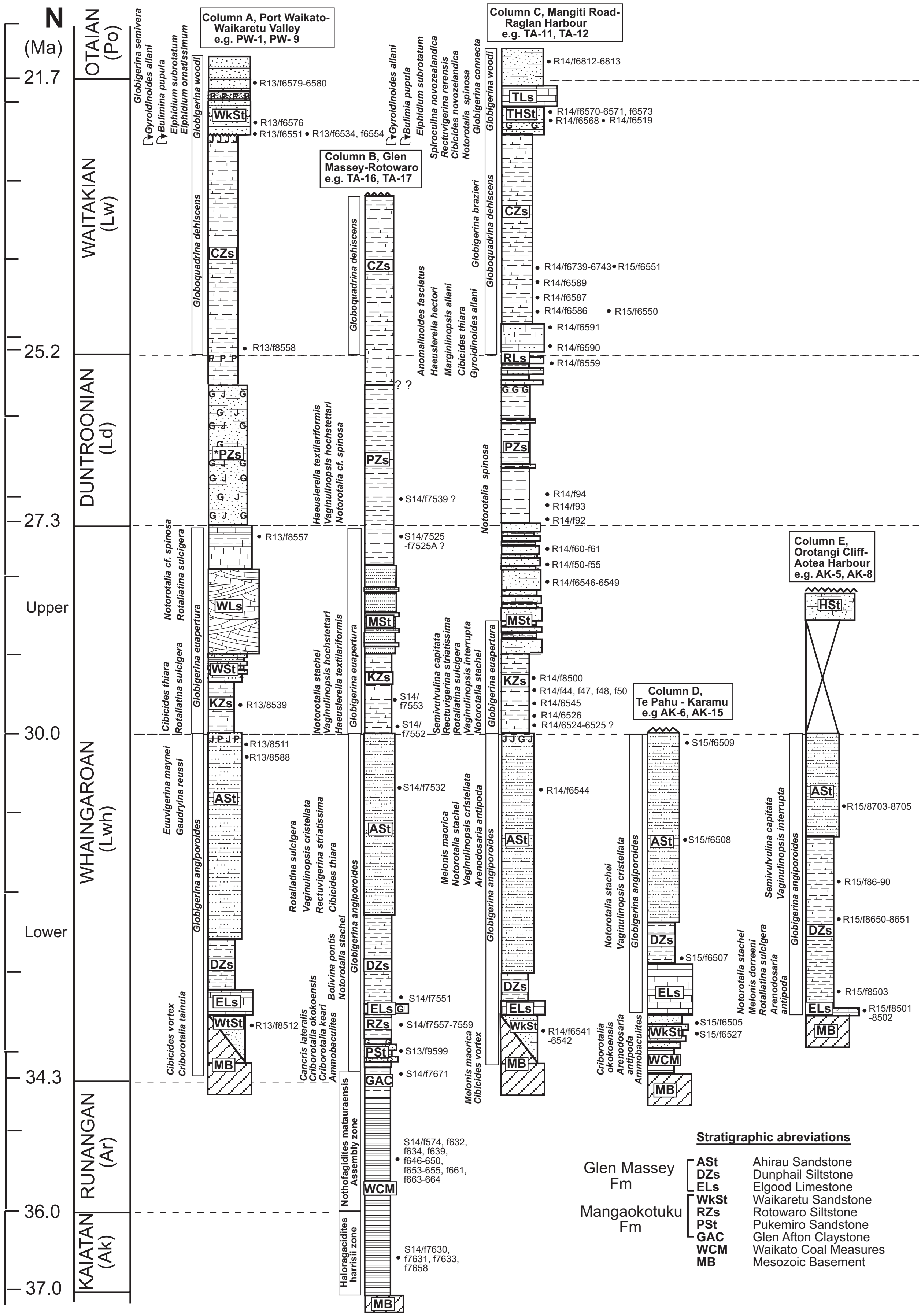
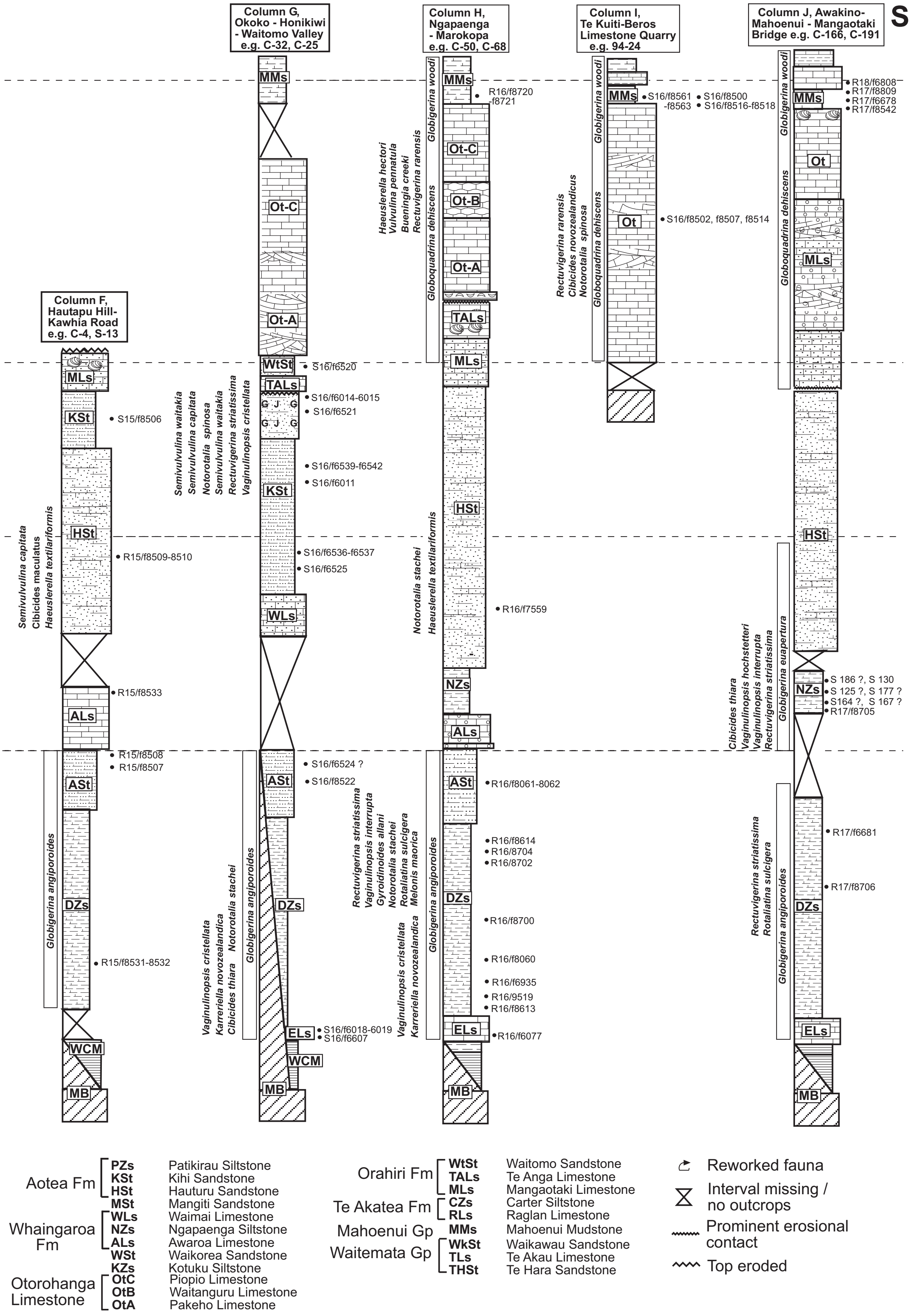


Fig. 4.3: Summary of biostratigraphic correlation from Te Kuiti and basal Mahoenui-Waitemata groups



in the study area, only the most common taxa are shown. The position of the samples in a composite stratigraphic column is an approximate indication.

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 (Column B, Fig. 4.3). Although these are 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 Stages. This assemblage, dominated by *Nothofagus*, is now 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). Palynofloras characteristic of the *Myrtaceidites* Subzone have been identified in samples from the Drury, Maramarua, Huntly, and Rotowaro coalfields.

Whaingaroan Stage (Lwh)

The Whaingaroan is a relatively long stage of 7 m.y. duration and is informally subdivided into lower and upper parts (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 pectinids, 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 parts.

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 **Glen Afton Claystone** containing 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 Ak - lower Lwh age range. Sample S14/f7671, reported in Kear & Schofield (1978), was collected above the top of **Glen Afton Claystone** near the type Pukemiro locality (Column B, Fig. 4.3) , and it contains abundant *Ammobaculites*, suggesting an Ar - lowermost Lwh age range. Sample S13/f9599 collected from **Pukemiro Sandstone** in DH 1768, about 21 m above the coal measures, contains *Haplophragmoides, Elphidium* sp., and *Cancris lateralis*, indicating a lowermost Whaingaroan age (Column B, Fig. 4.3).

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** (Column B, Fig. 4.3), yielded lowermost Whaingaroan age microfauna, however samples S14/f7558 and S14/f7559 contain a macrofaunal assemblage indicating a lowermost Lwh - Ld age range, which seems too young. The abundance of *Criborotalia keari* and *C. okokoensis* favours an upper Ak - lower Lwh age. Sample S12/f9566 collected from drill cuttings (DH4996) near Mercer settlement 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 fine to coarse grained variably muddy sandstone usually overlying Mesozoic basement. Sample R13/f8512 collected from its type locality (TA 9) on Waikaretu Valley Road (Column A, Fig. 4.3) contains a microfaunal assemblage including *Cibicides vortex*, and *Criborotalia tainuia* of lowermost Whaingaroan age. Samples R13/8514 and 8515 collected from Waikorea Road contain the younger microfauna *Notorotalia stachei, Rotaliatina sulcigera*, and *Vaginulinopsis hochstetteri*, suggesting a Whaingaroan age range. Samples R14/6541-6542 collected from north of Waingaro Landing (Column C, Fig. 4.3), contains 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 (Column D, Fig. 4.3), 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* sp, *Operculina* sp, 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 progressive 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 (Column B, Fig. 4.3), 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 range and a deeper water, more open marine depositional setting than that of the underlying Mangakotuku Formation. Sample S14/f7532 collected from **Ahirau Sandstone** exposures along Waingaro Road and north of Glen Massey Village (Column B, Fig. 4.3), includes 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 (Column A, Fig. 4.3) contains *Cibicides thiara, Gaudryina reussi* and *Rotaliatina sulcigera.* Another sample (R13/f8558) collected from Kokonga East Road (Column A, Fig. 4.3), contains *Gaudryina reussi, Rotaliatina sulcigera* and *Uvigerina maynei*, indicating a Whaingaroan age. Sample R14/f6544 collected from Mangiti Road (Column C, Fig. 4.3), 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.

Sample R15/f8501-8502 collected from the "basal facies" of **Glen Massey Formation** exposed along the Mangaora Stream in Kawhia (Column E, Fig. 4.3), contains *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 (Column E, Fig. 4.3) 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 (Column E, Fig. 4.3) contain the middle to outer shelf species *Semivulvulina capitata* and other inferred mid-Whaingaroan microfauna. Samples R15/8650 and 8651 collected from the massive calcareous siltstone (i.e. **Dunphail Siltstone**) exposed at the lower level of Orotangi Cliff at Aotea Harbour (Column E, Fig. 4.3) 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 (Column E, Fig. 4.3) 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 the basement exposed along Kihi Road (R15/813428) (Column F, Fig. 4.3), contains *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) (Column F, Fig. 4.3) also contains *Globigerina angiporoides* and is inferred to be of lower Whaingaroan age.

Samples S16/f8503 collected from 6m below the massive calcareous siltstone (e.g. **Dunphail Siltstone**) in the Okoko Coalmine area contains *Globigerina angiporoides* and is inferred to be of lower Whaingaroan age. Samples S15/f6507-6509 collected from 1, 57, and 82 m above the Elgood Limestone near a limestone quarry on Fillery Road in the Te Pahu-Karamu area (S15/937660) (Column D, Fig. 4.3) contains *Vaginulinopsis cristellata,* and *Notorotalia stachei* and indicates an age range from lower Lwh (f6507) to Lwh-Ld (f6509). Samples S16/f6018-6019 reported from near basal facies (**Glen Massey Formation**) overlying basement exposed along Tapuae Road near Honikiwi (Column G, Fig. 4.3) contains *Cibicides thiara, Vaginulinopsis cristellata, Karreriella novozealandica*, and abundant *Globigerina angiporoides* (f6018), indicating a lower Whaingaroan age. Sample S16/f6607 collected from the basal **Glen Massey Formation** lithologies exposed on top of basement at Tapuae Road end in the Honikiwi area (S16/929313) (Column G, Fig. 4.3) is inferred to contain lower Whaingaroan microfauna, and sample S16/f6608 collected from the lowermost exposed muddy sandstone resting probably on basement contains *Notorotalia stachei* and is inferred to be Lwh - Ld in age.

Samples R16/f8060-8062 collected from **Glen Massey Formation** exposed near the bridge on Mangapohue Stream on Te Anga Road (Column H, Fig. 4.3) 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. 4.3) 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 (Column H, Fig. 4.3) 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 Lwh age range. Sample R16/f8702 from **Dunphail Siltstone** west of Mairoa (Column H, Fig. 4.3) 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 (C 56, Column H, Fig. 4.3) exposure contains *Semivulvulina capitata* and *Vaginulinopsis interrupta,* indicating a Lwh to possibly Ld age range. Sample R16/9519 collected from the lowermost exposed calcareous siltstone along the Mairoa-Te Kuiti Road near Pakeho (Column H, Fig. 4.3) contains *Globigerina angiporoides* and is inferred to be of lower Whaingaroan age. Sample R16/f6077 (Column H, Fig. 4.3) collected from probably the basal facies near Waitere and Taharoa Road intersection (R16/677316) contain abundant *Globigerina angiporoides* and another sample R16/f6935 collected from the same area contains *Globigerina* sp. and is likely to be of lower Whaingaroan age. Sample R17/ 8706 collected from the same unit exposed in Mangaorongo Road (Column J, Fig. 4.3), contains *Rotaliatina sulcigera, Rectuvigerina striatissima* and *Globigerina angiporoides* indicating a lower Lwh age. Sample R17/f6681 collected from Puketiti Station (Column J, Fig. 4.3), south of Mangaotaki contains *Globigerina angiporoides* and is inferred to be of lower Lwh age. Three samples (R17/f656-658) collected from massive calcareous siltstone (e.g. Dunphail Siltstone) exposed along SH3 near Bexley Station (C 193) contains lower Lwh foraminifera.

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 *S. angiporoides* and containing *Notorotalia stachei*. In Taranaki Basin, the uppermost Whaingaroan is defined on the highest occurrence of the benthic foraminifera *Rotaliantina sulcigera*, a useful and ubiquitous event. The co-occurrence of *Globigerina euapertura* and *Rotaliantina 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 Member** of **Whaingaroa Formation** in Tawatahi River Valley (Column C, Fig. 4.3) in the northern inland part of Raglan Harbour, as identified by Hornibrook, contains typical upper Whaingaroan fauna including *Cibicides thiara, Notorotalia stachei, Rectuvigerina striatissima, Rotaliatina sulcigera*, and *Vaginulinopsis interrupta.* Samples R14/f44, f47, f49, f50 reported by Waterhouse & White (1994) from the type area of **Whaingaroa Formation** in Raglan Harbour (TA 14) contains most of the typical upper Whaingaroan fauna and lacks *Globigerina angiporoides* (Column C, Fig. 4.3). Sample R14/f8500 reported from Te Uku Landing (Waterhouse & White 1994) include *Gaudryina reussi*, the deeper water species *Semivulvulina capitata,* and the planktic *Globigerina euapertura,* indicating a Lwh-Ld age range (Column C, Fig. 4.3). 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 is a highly condensed unit and poorly exposed at this locality (see Chapter 3). Similarly, samples R14/f6524-6525 reported from **Ahirau Sandstone** north of Ohautira (Column C, Fig. 4.3) 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 in Ohautira contains a faunal assemblage typical of Whaingaroan age (Column C, Fig. 4.3). Samples S14/f7552-7553 reported from 8.5 and 42.5 m above the **Ahirau Sandstone** (Fig. 4.3), north of Dunphail Bluff (TA 17) contain *Globigerina euapertura* and are inferred to be of Lwh-Ld 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, Rotaliatina sulcigera* and is inferred to be of Lwh age (Column B, Fig. 4.3).

Sample R15/f8508 was reported from the "bored contact" between the **Glen Massey** Formation and **Awaroa Limestone** at Kihi Road (Column F, Fig. 4.3) and contains rare *Globigerina angiporoides* and other fauna of lower Whaingaroan age. Another sample R15/f8533 reported from immediately above the **Awaroa Limestone** (Column F, Fig. 4.3) 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 (C183) (Column J, Fig. 4.3) 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 Lwh-Ld transition fauna (Column J, Fig. 4.3). Samples S121-122 reported from the basal conglomerate in the upper Awakino Valley (C185) are also inferred to be of Lwh-Ld age range. Samples S164 and S167 reported from the lowermost exposed massive calcareous mudstone near Ototohu Stream, Mahoenui, are inferred to contain Lwh-Ld transition fauna; however S164 is more likely to be upper Lwh as it contains *Globigerina euapertura.* Sample S130 reported from the stratigraphically equivalent facies exposed in Bexley Station (C 193) contains rare *Globigerina euapertura* and is inferred to indicate a mid or upper Lwh age. Sample R17/f8705 collected from the calcareous siltstone exposed along Gibbon Road (R17/697919) near Mahoenui (Column F, Fig. 4.3) contains *Vaginulinopsis interrupta*, *Vaginulinopsis hochstettari, Globocassidulina subglobosa,* and *Cibicides thiara,* indicating a Lwh-Ld age range.

Samples R15/f8509-8510 collected from **Hauturu Sandstone** and **Kihi Sandstone** exposed at Hautapu Hill (C 4) (Column F, Fig. 4.3) are inferred to contain Lwh-Ld fauna. Sample R16/f7559 collected from Hauturu Sandstone 12 m above basement (R16/879274) is inferred to be of Whaingaroan age (Column H, Fig. 4.3). Sample S16/f6536-6537 collected from Aotea Sandstone (tentatively identified as **Kihi Sandstone**) exposed along SH31 (north of Otorohanga) (S16/025388) has an upper Whaingaroan fauna but S16/f6536 contains *Semivulvulina waitakia* and is possibly of Duntroonian age (Column G, Fig. 4.3). Sample S182 reported by Stainton (1964) 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 Lwh-Ld age. Sample S16/f6524 collected from the base of the Kihi Sandstone in Waitomo Valley section is inferred to have a lower Lwh (?) 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** exposed to the east of Te Kotuku Trig (Mangiti Road, TA 12)) (Column C, Fig. 4.3) 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 sample R14/f0060-61 from Paritata Peninsula contain *Rectuvigerina striatissima and Notorotalia stachei,* indicating an upper Whaingaroan age (Column C, Fig. 4.3). Sample R14/f0092 collected 1m above the contact between Mangiti Sandstone and **Patikirau Siltstone** at the type locality of Patikirau Siltstone at Patikirau Bay (TA 20) is inferred to contain Lwh-Ld transition fauna (Column C, Fig. 4.3). Sample R13/f8557 reported by Kear (1963) from the seams within Waimai Limestone exposed near Kokanga East Road (Column A, Fig. 4.3) contains *Rotaliatina sulcigera* and *Notorotalia cf. spinosa* and is inferred to be of Lwh-Ld 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, and the **Orahiri Formation** contains closely-packed banks of enormously thick-shelled *Flemingostrea wollastoni* (Morgans et al. 2004). Microfaunally, the lowest occurrence of the benthic foraminifer *Notorotalia spinosa* (replacing the Whaingaroan index, *N. stachei*) defines the base of the Duntroonian Stage. Planktic foraminifera or calcareous nanofossil events are not known at the base of the Duntroonian (Morgans et al. 2004).

Most of the lower Duntroonian ages occur within the **Kihi Sandstone Member** of Aotea Formation. Sample S16/6521 reported by Nelson (1978a) from the top of the **Kihi Sandstone** exposed at the Waitomo Valley Road section (C 32) (Column G, Fig. 4.3) contains *Vaginulinopsis cristellata and Notorotalia spinosa*. Samples S16/6539-6542, all collected from **Kihi Sandstone** near Te Raumauku (S16/998346) (Column G, Fig. 4.3), 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 Ld-Lw transition fauna (Column G, Fig. 4.3). 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 (Column F, Fig. 4.3).

Samples R14/f0093-0094 reported by Waterhouse & White (1994) from 12 m and 20m respectively above the base of the **Patikirau Siltstone** at Patikirau Bay (Column C, Fig. 4.3), 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** (Column B, Fig. 4.3). 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** (Column B, Fig. 4.3).

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 1978a). Sample S16/f6520 collected from **Waitomo Sandstone** exposed near Te Raumauku Caves (C29) (Column G, Fig. 4.3) contains macrofauna, *Haeuslerella textilariformis*, *Semivulvulina capitata and Notorotalia spinosa,* indicating a Duntroonian to possibly Waitakian age (Nelson 1978a). 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 Duntroonian to possibly Waitakian age (Kear 1987; 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 1978, Graham et al. 2000). 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) has 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 (94-24) (Column I, Fig. 4.3) contain the common Waitakian fauna *Notorotalia spinosa, Cibicides novozelandicus, Rectuvigerina rerensis* and the planktic *Globoquadrina dehiscens* (Nelson 1978a). *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 1978a). 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 base and top of the 8.5 m-thick **Raglan Limestone** exposed near Te Akau (Column C, Fig. 4.3), 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 Ld-Lw age. Samples R14/f6586-6588 collected 5 m, 24 m and 32 m, respectively, above the **Raglan Limestone** near Te Kotuku Trig (TA12) are all inferred to be of Waitakian age (Column C, Fig. 4.3). Samples R14/f6739-6743 reported by Waterhouse & White (1994) from the **Carter Siltstone** 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 are inferred to be of Lw 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) yield Waitakian fauna.

Sample R14/f6568 reported by Kear (1987) from **Te Hara Sandstone** (regarded here as a basal unit of the Waitemata Group) at the southern end of Te Hara Point (Column C, Fig. 4.3), contains Waitakian to Otaian (?) fauna (e.g. *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 Ld-Lw 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* & *Rhizothyris curta*) occur in the **Te Akau Limestone** exposed at Carters and Gibson Beach, indicating a Waitakian age (Kear 1987). 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 (Column A, Fig. 4.3) mouth 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 foram *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 (Column I, Fig. 4.3) are inferred to contain Waitakian fauna. Samples S16/f8516-f8518 collected 15 cm, 0.3m 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*.

Strontium isotope dating

Introduction

Strontium isotope ratios are an increasingly common means of determining the age

Table 4.1: Summary data showing average 87Sr/ 86Sr isotope ratio derived age plotted in Figs 4.5 and 4.6.

Sample Number	Sample	Locality	Formation/Member	Age (Ma)
Mangakotuku Formation				
36	AU12890	S12/Q08 (0)		39.85
38	AU7842b	S15 (19)		34.52
1	WU01	S14/ Waikoha Road	Waikaretu Sandstone	32.91
2	WU02	R13/ Waikaretu	Waikaretu Sandstone	32.94
Glen Massey Formation				
39	AU2045	N73/803	Whaingaroa Siltstone	53.36
40	AU2000	N82/689	Whaingaroa Siltstone	32.72
41	AU1090	N91/745	Whaingaroa Siltstone	33.43
43	AU4173	R13 (10)	Sub Elgood Limestone	34.13
44	AU9529	R13 (7)	Elgood Limestone	38.77
45	AU2468	R13 (13)	Elgood Limestone	33.23
46	AU8998	N51/675	Dunphail Siltstone	32.48
47	AU2460	S14 (17)	Dunphail Siltstone	31.96
48	AU1331	R13 (7)	Ahirau Sandstone	31.89
49	AU8003	S15 (19b)	Glen Massey	31.46
51	AU3037	N64/558	Aotea Sandstone	30.49
52	AU1974(a)	N73/936	Aotea Sandstone	32.07
4	WU04	R13/ Port Waikato	Ahirau Sandstone	21.59
7	WU07	S14/ Elgood Road	Elgood Limestone	32
8	WU08	R14/ Waitetuna	Ahirau Sandstone	30.68
M1	AHR01	R15/ Shea Road	Elgood Limestone	31.67
M2	AHR02	R15/ Shea Road	Dunphail Siltstone	30.49
M3	AHR03	R15/ Shea Road	Ahirau Sandstone	30.68
M4	AHR04	R15/ Shea Road	Ahirau Sandstone	29.42
M5	AHR05	R15/ Kawhia Harbour	Dunphail Siltstone	32.61
M6	AHR06	R14/ Waitetuna Estuary	Ahirau Sandstone	30.85
M7	AHR07	R15/ Palteaue Road	Dunphail Siltstone	31.87
Whaingaroa Formation				
9	WU09	R16/ Ngapaenga	Awaroa Limestone	29.66
10	WU010	R17/ Mangaotaki	Ngapaenga Siltstone	28.43
Aotea Formation				
50	AU1330	R13 (6)	Waimai Limestone	30.65
53	AU1978	N74/609	Aotea Sandstone (Ao-2)	29.32
54	AU1979	N74/610	Aotea Sandstone	28.22
55	AU1991	N74/613	Aotea Sandstone	27.72
56	AU1087	N91/741	Aotea Sandstone	29.96
57	AU1536	R13 (4)	Aotea Sandstone	29.74
58	AU2441	R15 (6)	Te Ak-Waimai bdy	26.67
59	M8	Mangaotaki	Aotea Sandstone	35.4
3	WU03	S16/ Waitomo Valley	Kihi Sandstone	29.47
5	WU05	R15/ Harbour Road	Kihi Sandstone	27.79
6	WU06	R15/ Kawhia Road	Kihi Sandstone	27.99
11	WU011	R13/ Kaawa Stream	Patikirau Siltstone	30.82
12	WU012	S16/ Waitomo Valley	Aotea-Orahiri U/C	27.69
13	WU013	R15/ Kihi Road	Hauturu Sandstone	30.3
14	WU014	R13/ Waikaretu	Waimai Limestone	27.79
18	WU018	R15/ Makaka	Waimai Limestone	29.75
19	WU019	R15/ Waimaori Road	Waimai Limestone	31.58

Table 4.1(continued): Summary data showing average 87Sr/ 86Sr isotope ratio derived age plotted in Figs 4.5 and 4.6.

Sample Number	Sample	Locality	Formation/Member	Age (Ma)
Castle Craig Subgroup (Orahiri Formation /Otorohanga Limestone-Te Akatea Formation)				
60	M7	Mangaotaki	Orahiri Limestone	31.37
61	M5	Mangaotaki	Orahiri Limestone	32.61
62	M1	Mangaotaki	Orahiri Limestone	29.71
63	AU2053	N74/566	Orahiri Limestone	26.99
64	AU2007	N82/708	Orahiri Limestone	32.54
65	AU2008	N82/709	Orahiri Limestone	27.82
66	AU2014	N82/715	Orahiri Limestone	30.57
67	AU1088	N91/743	Orahiri Limestone	26.08
68	AU1298a	R14 (5)	Carter Siltstone	22.86
69	AU4184	N51/678	Te Akatea Siltstone	26.7
70	AU4179	N51/1096	Te Akatea Siltstone	24.05
71	AU6387	R13 (2)	Te Akatea Siltstone	25.1
72	AU7995	R15 (6)	Waitomo Sandstone	24.68
73	AU2050	N74/563	Otorohanga Limestone	25.06
74	AU2028	N83/557	Otorohanga Limestone	24.38
75	AU2029	N83/558	Otorohanga Limestone	25.91
76	AU2026	N83/555	Otorohanga Limestone	30.27
77	AU2039	N91/807	Otorohanga Limestone	24.8
15	WU015	R14/ Raglan Harbour	Raglan Limestone	23.31
16	WU016	R14/ Carters Beach	Raglan Limestone	23.51
17	WU017	R17/ Bexley Station	Orahiri Formation	21.24
20	WU020	R15/ Rakanui Peninsula	Waitomo Sandstone	26.68
22	WU022	R15/ Waimaori Station	Otorohanga Limestone	27.23
26	WU026	R15/ Rakanui Peninsula	Orahiri Formation	26.52
Basal Waitemata Group				
21	WU021	R14/ Carters Beach	Te Hara Sandstone	23.88
23	WU023	R14/ Gibson Beach	Te Akau Limestone	28.87
24	WU024	R14/ Gibson Beach	Te Akau Limestone	21.8
25	WU025	R14/ Gibson Beach	Te Akau Limestone/ Conglomerate	21.98

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 sea water 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 sea water mainly via co-precipitation in biogenic carbonate.
3. The ^{87}Sr/ ^{86}Sr ratio in fossil skeletons is identical to that of the sea water 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 was highest during the Oligocene to Early Miocene (36-16 Ma), enabling determination of numerical ages to within 0.5 m.y. resolution during this interval. Although planktic foraminifera are preferred for the calibration of ocean water curves, there is no

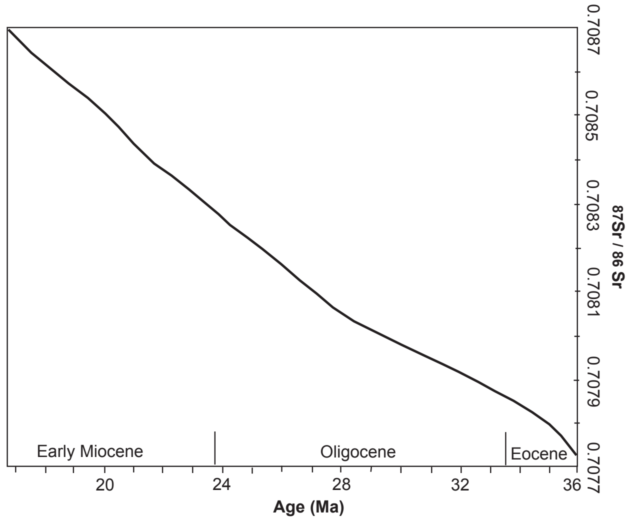


Fig. 4.4: Calibration curve relating 87Sr/86Sr isotope ratio in marine fossil shells to numerical age for the Late Eocene to Early Miocene (after Oslick et al. 1994).

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/Otiake 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) has helped to constrain the age of several mid-Cenozoic stage boundaries. Of the 77 samples, 43 samples derived from the Te Kuiti Group and 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 (Table 4.1).

Methods

Twenty six samples of unweathered shell material, mainly pectin, brachiopods and oyster, 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 normalized to ^{88}Sr/^{86}Sr = 8.375209 using exponential law. Normalized 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) and the hence the composition of modern sea water range from 0.709154-0.709184, averaging 0.709168 ± 26 (2 SD). Age assignments was made 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 et al. (1997).

Analytical Results

The ^{87}Sr/ ^{86}Sr results are presented in Table 4.1. The absolute ages derived from the ^{87}Sr/ ^{86}Sr isotope ratios are plotted in Fig. 4.5 in relation to the New Zealand time scale (Cooper et al. 2004). The sample data show a broad trend of decreasing age from Bortonian to Otaian age (Fig. 4.5). 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 4.6 shows the ages plotted for each of the Te Kuiti Group formations.

Stable oxygen and carbon isotopes 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 (δ^{18}O) and carbon (δ^{13}C) isotope compositions of subsamples of the fossil shell material were also determined using standard methods (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.

Analytical results

All δ^{18}O and δ^{13}C values of the shell samples are presented in Appendix VII. The δ^{13}C values range between -10.36 and 2.91, and δ^{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. 4.7. 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 δ^{13}C of a few samples (AU2438, AU12890, WU01 and WU021) suggest growth in a marginal marine environment.

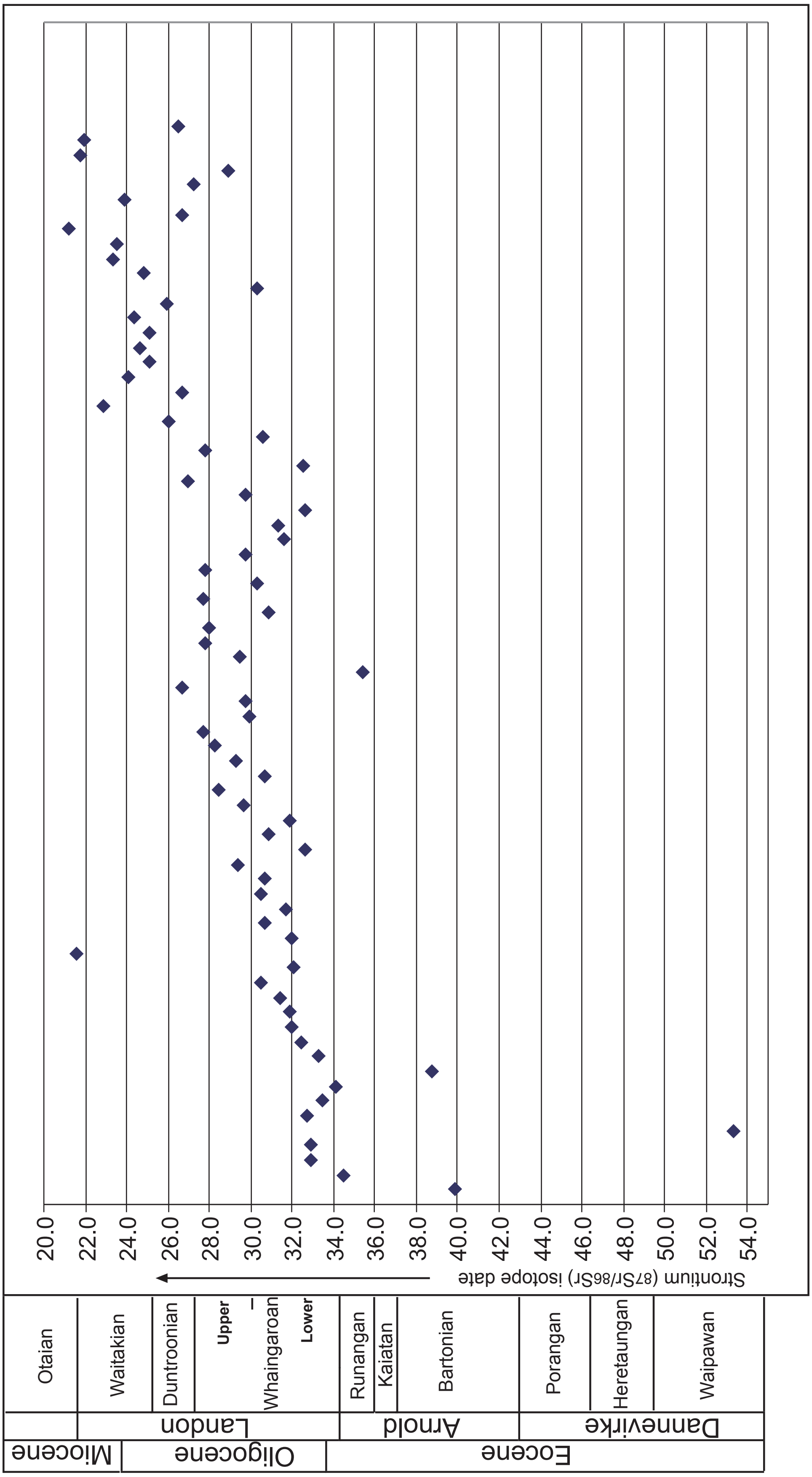


Fig. 4.5: Plot of 87Sr/ 86Sr isotope age versus stratigraphic position of shell samples from within the Te Kuiti Group and basal units of the Waitemata Group.

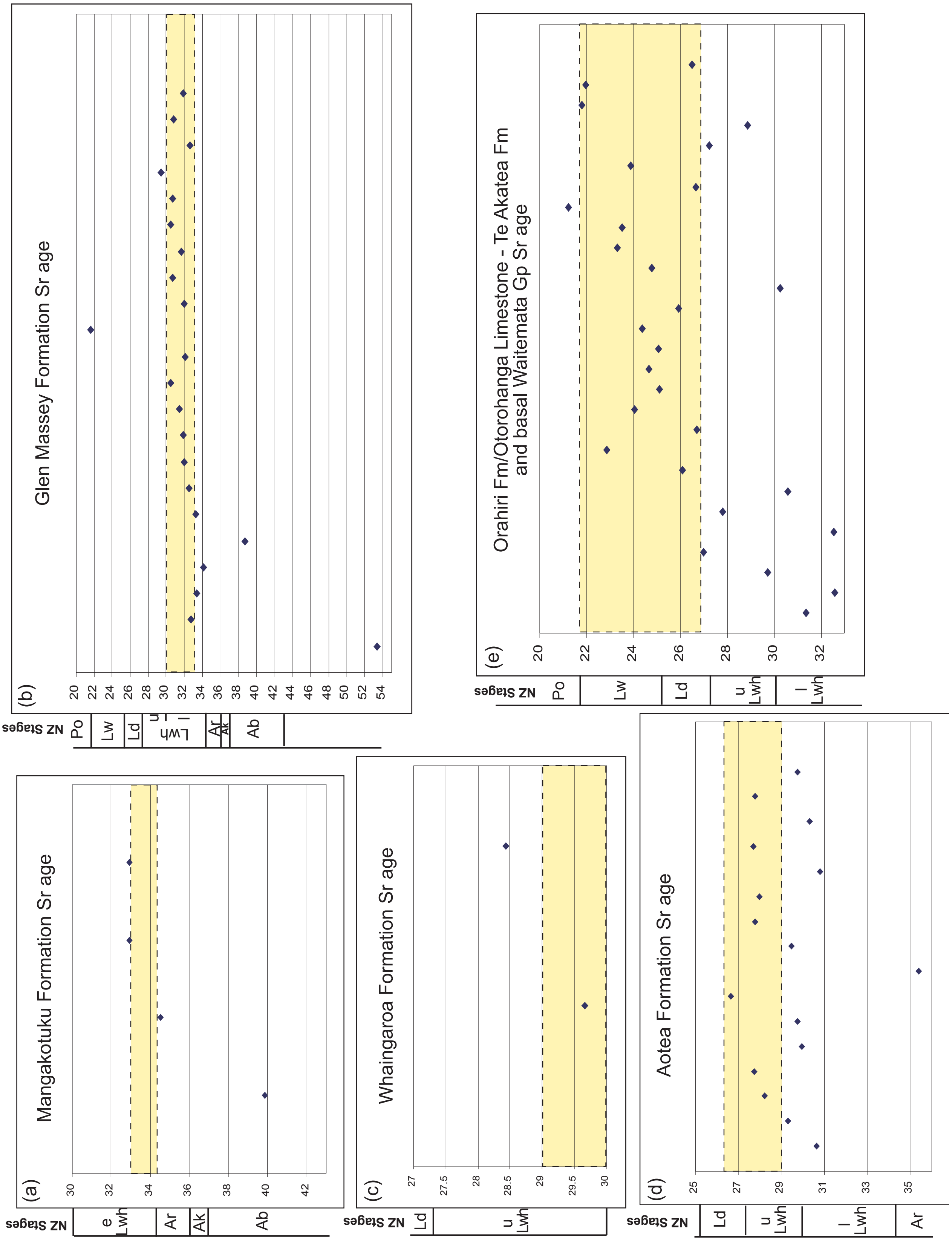


Fig. 4.6 : Strontium (87Sr/86Sr) isotope derived ages of fossil shell samples collected from various formations are plotted against the previously published biostratigraphic stage assigned to them (dashed line).

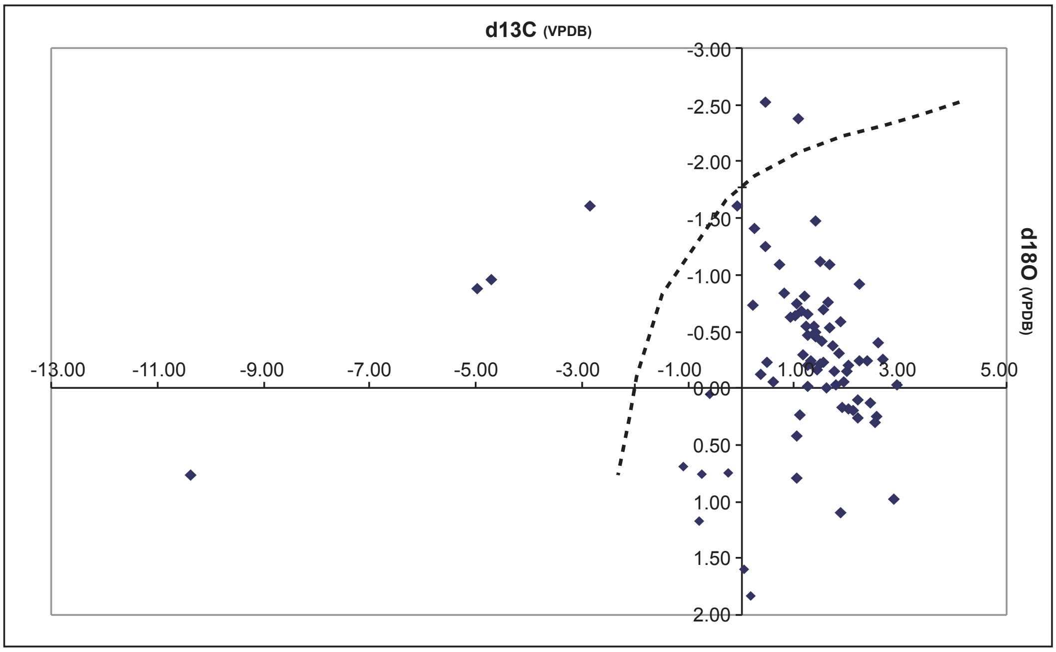


Fig. 4.7: Cross-plot of stable oxygen isotope versus carbon isotope values for Te Kuiti Group and basal units of the Waitemata Group shell samples for which Sr isotope ratios were also determined.

The numerical ages of four shell samples from the Mangakotuku Formation range between 39.85 - 32.91 Ma (Fig. 4.6a). Three of these ages conform 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 based on its $\delta^{13}C$ value (4.96) (Fig. 4.7) could have a marginal marine origin, and therefore not have a Sr ratio that reflected a contemporary oceanic Sr ratio. 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, it shows a predictable age of 32.91 Ma.

The numerical ages of 22 samples from the Glen Massey Formation fall within the range 53.36 - 21.59 Ma. Eighteen of these ages conform to its biostratigraphic age (lower Whaingaroan) (Fig. 4.6b). One brachiopod shell (AU2045) collected from south of Kawhia yielded an age of 53.36 Ma, while another brachiopod shell (AU9529) collected from the north end of Huriwai Beach near Port Waikato yielded an age of 38.77 Ma, both being much older than anticipated. These samples came from basal facies of Glen Massey Formation where it rests on Mesozoic basement, and both samples may have 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 age range.

The numerical ages of two samples from the Whaingaroa Formation are in the range 29.66 - 28.44 Ma (Fig. 4.6). Sample WU010, with an age of 28.43 Ma being younger than the mid-upper Whaingaroan age assigned to the Whaingaroa Formation.
The numerical ages of 16 samples from the Aotea Formation lie in the range 35.4 - 26.67 Ma (Fig. 4.6d). Eight sample ages conform to the ages assigned to the upper Whaingaroan to Duntroonian Aotea Formation from biostratigraphic criteria. Seven samples (AU1330, AU1087, AU1536, WU011, WU013, WU018 & WU019) are marginally older than the mid-upper Whaingaroan age (~29 Ma), and one (sample M8) from the upper part of Kihi Sandstone Member in the Mangaotaki Bridge section is markedly older (35.4 Ma).

The numerical ages of 28 samples from the Orahiri Formation, Otorohanga Limestone and Te Akatea Formation fall in the range 32.37 - 21.24 Ma (Fig. 4.6 e). Of the 28 ages, nine fall outside the biostratigraphic stages assigned to those formations (i.e. Duntroonian to upper Waitakian). Eight of them show lower to upper Whaingaroan ages, which seem unreasonable. 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 1978a) and this age is clearly too young, possibly affected by the porous nature of the host facies.

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

Discussion

The biostratigraphic ages assigned to formations in the lower parts of the Te Kuiti Group have long been known to be inconsistent, particularly for localities north and south of Raglan Harbour. The 30-40 m of massive calcareous siltstone exposed at Waitetuna Estuary was nominated by Finlay (1939) as the stratotype for the Whaingaroan Stage. Subsequently, Hornibrook et al. (1989) identified the planktic fauna from this unit as being characteristic of Jenkin's (1966) *Globigerina euapertura* zone assigned to the Upper Whaingaroan Substage. However, the planktic fauna identified from "Whaingaroa Siltstone" in the southern region of the field area are characteristic of Jenkin's (1966) *Globigerina brevis* and *Subbotina angiporoides* zones assigned to the Lower Whaingaroan Substage (Hornibrook et al. 1989). Even though the age range of the "Whaingaroa Siltstone" in the south is older than its stratotype, it was regarded as the same formation by previous workers despite the fact they also inferred south-directed marine transgression and progressive onlap of successive formations to the south (Kear & Schofield 1959;

Nelson 1978a). These inconsistencies were also emphasized by the fact that the planktic fauna reported from the top of the Ahirau Sandstone in the northern region and from the "Aotea Sandstone" (Kear & Schofield 1959; Nelson 1978a) in the Aotea Harbour area, are included within the *Globigerina angiporoides* zone (lower Whaingaroan), indicating that these units are correlatives, all now incorporated in the Glen Massey Formation, rather than indicating that the formation boundaries are time transgressive.

Based upon the biostratigraphy of the Te Kuiti Group formations summarized in Fig. 4.3, Sr isotope ages, and the constraints provided by inter-formational unconformities and their correlative conformities, a reasonably good chronostratigraphy has been developed for Te Kuiti Group. This is illustrated in relation to the lithostratigraphy in Fig. 3.3 (Chapter 3). One of the features of Fig 3.3 is the classification of the Te Kuiti Group made here into six unconformity bounded sequences, labeled TK1 to TK6. They are considered to be Vail-type sequences, an understanding developed in more depth in Chapter 8. The unconformities and correlative conformities between these sequences constrain interpretation of the accuracy of the Sr isotope ages (Fig. 4.6). The following sections summarise the biostratigraphy and Sr isotope ages in the context of sequences TK1 to TK6.

Waikato Coal Measures (WCM) and Mangakotuku Formation

The base of the WCM in the northern region lies within the *Haloragacidites harrisii* Zone, corresponding approximately to the Kaiatan Stage (Pocknall 1991). The *Nothofagidites matauraensis* Assemblage Zone forms the upper part of the WCM and the Mangakotuku Formation. This assemblage zone is subdivided into a lower *Myrtaceidites* Subzone, which dominates the middle part of the WCM in the northern region, and lies predominantly within the Runangan Stage. Spores and pollen belonging to an upper *Araucariacites australis* Subzone occurs in the uppermost part of the WCM and Mangakotuku Formation in the northern region, and in WCM occurring in the central and southern regions. The *Araucariacites australis* Subzone is of upper Runangan to lower Whaingaroan age (Pocknall & Mildenhall 1984; Pocknall 1991). Three shells (out of four) extracted from the Mangakotuku Formation yielded ^{87}Sr/ ^{86}Sr ages in the range 34.52 - 32.91 Ma, conforming to the upper Runangan to lower Whaingaroan interval.

Glen Massey Formation

The *Globigerina angiporoides* Zone occurs within the Dunphail Siltstone Member of the Glen Massey Formation in the Dunphail Bluff type section. *Globigerina angiporoides and G. ampliapertura* occur consistently throughout the Dunphail

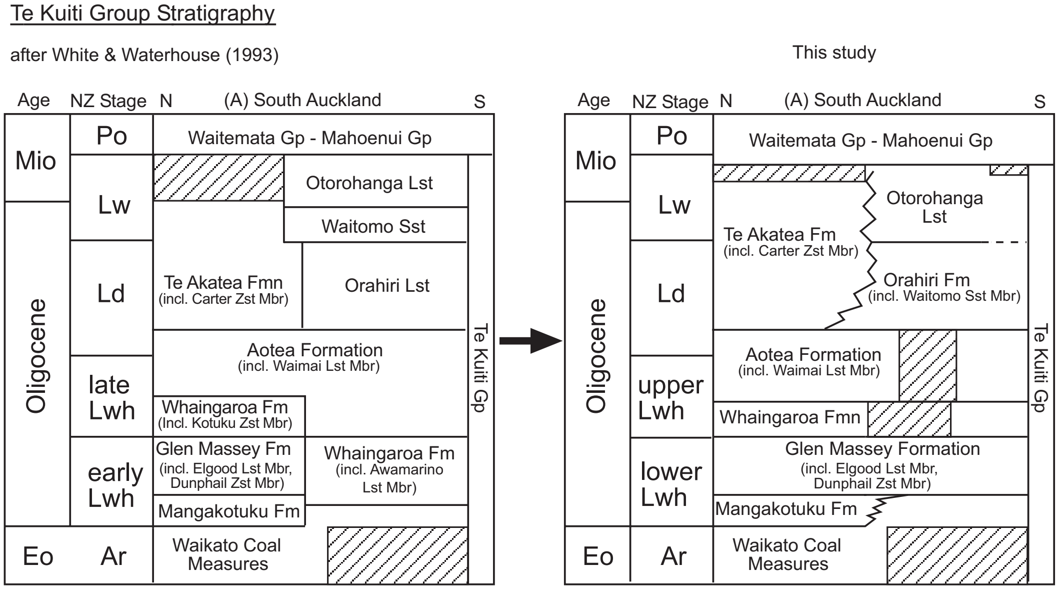


Fig. 4.8: Biostratigraphic model for the Te Kuiti Group from White & Waterhouse (1993) versus the one proposed here.

Siltstone Member in the Kawhia, Marokopa, and Awakino areas, where this siltstone has previously been mapped as "Whaingaroa Siltstone" (Fig. 4.8), even though it's lower Whaingaroan age conflicts with the upper Whaingaroan age of Whaingaroa Formation at its Waitetuna Estuary type section, as outlined previously (Chapter 3). The lower Whaingaroan age of Glen Massey Formation is supported by 18 of 22 Sr isotope ages.

Whaingaroa Formation

The upper Whaingaroan age of Kotuku Siltstone Member on the north side (Waitetuna Estuary) of Raglan Harbour is already well established (Hornibrook et al. 1989). The foraminifera *Globigerina euapertura* and *Notorotalia stachei* have their lowest occurrence at the base of Kotuku Siltstone Member in the Waitetuna and Te Kotuku (Mangiti Road) sections. Two samples (WU08 & AHR06) collected from the top of the condensed Glen Massey Formation facies along Raglan Harbour have yielded ^{87}Sr/ ^{86}Sr derived ages in the range 30.68 - 30.85 Ma, which corresponds to the very top of the lower Whaingaroan Stage (Copper et al. 2004), in support of the lower to upper Whaingaroan intra stage boundary lying between Glen Massey Formation and Whaingaroa Formation. The age of the Whaingaroa Formation south of Raglan Harbour remains poorly constrained because of poor exposure and the absence of age diagnostic fauna in samples collected from it. Foraminifera typical of the upper Whaingaroan occur in the lower part of Ngapaenga Siltstone near Awakino, but most sections are poorly exposed. Only two ^{87}Sr/ ^{86}Sr ages were derived from Whaingaroa Formation in the southern region and they lie in the range 29.66 - 28.44 Ma, which conforms to the lower part of the upper Whaingaroan Stage (Cooper et al. 2004).

Aotea Formation

Aotea Formation may have a faunal succession spanning the Whaingaroan-Duntroonian boundary. The lower part of the Aotea Formation appears to lie within the upper part of the Whaingaroan Stage. The upper Whaingaroan Stage is identified by *Rectuvigerina striatissima* and occurs in the Mangiti Sandstone Member near its type locality north of Raglan Harbour. Hauturu Sandstone in Aotea Formation in the Aotea-Kawhia region, which occurs as thick neritic calcareous sandstone, has poorly preserved foraminiferal assemblages of very limited biostratigraphic value. Recovery of foraminifera is also difficult from Waimai Limestone Member, which forms much of the Aotea Formation in northwestern parts of the study area. 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/Mangiti Sandstone in the northern region. Eleven out of seventeen shell samples analysed for ^{87}Sr/ ^{86}Sr from the Aotea Formation yielded ages of 29.96 - 27.72 Ma, falling within the upper Whaingaroan Stage. The majority of them were collected from the lower members of the formation (Waimai Limestone/Hauturu Sandstone/Kihi Sandstone). Two samples (AU2441, WU011) came from the Patikirau Siltstone Member and one (AU2441) yielded an age (26.67 Ma) in the lower part of the Duntroonian Stage; the other (WU012), sourced from within the prominent unconformity between the Aotea-Orahiri Formation in the Waitomo Valley section, yielded an ^{87}Sr/ ^{86}Sr age of 27.69 Ma (upper Whaingaroan), which is a little older than expected.

Orahiri Formation/Otorohanga Limestone/Te Akatea Formation

Not much is known about the foraminiferal biostratigraphy of the Orahiri Formation as age-diagnostic faunas have proved very difficult to extract. However, molluscan biostratigraphy, especially the abundance of *Flemingostrea wollastoni* in the Te Anga Limestone Member in the Waitomo-Te Anga area, is a good indicator of Duntroonian age. Duntroonian molluscan fauna such as *Cirsotrema lyratum* and *Lentipecten huttoni (hochstetteri)* are also reported from the Raglan Limestone in exposures north of Raglan Harbour. Although the recovery of foraminifera is also difficult from the Otorohanga Limestone, some of the Waitakian fauna reported from the siliciclastic interflags within limestone at Beros Quarry near Te Kuiti include *Notorotalia spinosa, Cibicides novozelandicus, Rectuvigerina rerensis* and the planktic species *Globoquadrina dehiscens*. Only three (out of eleven) ^{87}Sr/ ^{86}Sr isotope ages from the Orahiri Formation fall within the Duntroonian Stage, the majority (eight) of them falling within the Whaingaroan Stage, which is too old. Three (out of six) strontium ages from Otorohanga Limestone fall within the Waitakian Stage, the remaining three lying within the Whaingaroan-Duntroonian age range, which is too old. All six strontium ages from the Te Akatea Formation have ages in the range 26.7 - 22.86 Ma, falling within the Duntroonian and Waitakian stages.

Basal Waitemata/Mahoenui Group

Coastal sections between Port Waikato and Raglan Harbour contain good exposures of the unconformable contact between the Te Kuiti Group and the Waitemata Group. Lower Waitakian to Otaian planktic foraminifera (e.g. *Globigerina woodi*, *Globigerina connecta*) and the benthic foraminifera *Rectuvigerina rerensis* and *Spiroloculina novozealandica* have been reported from the lower part of Te Hara Sandstone Member in basal parts of the Waitemata Group in these costal sections. Correlation of Te Hara Sandstone Member with Waitomo Sandstone of the Te Kuiti Group conflicts with biostratigraphic constraints and the occurrence of a substantial unconformity between the Te Kuiti and Waitemata groups. Sample S16/6520 collected from Waitomo Sandstone in the type Waitomo area contains Duntroonian-Waitakian foraminifera (e.g. *Cibicides maculates* and *Notorotalia spinosa*), whereas the Te Hara Sandstone is clearly Waitakian to Otaian in age. This is also supported by a strontium (^{87}Sr/ ^{86}Sr) isotope age of 23.88 Ma (WU020) from an oyster shell sampled from Te Hara Sandstone at Carters Beach. The overlying Te Akau Limestone contains large molluscs last recorded from Waitakian rocks, including *Athlopecten athleta*, *Cirstotrema lyratum, Lentipecten huttoni (hochstetteri),* and *Flemingostrea wollastoni*. Two (out of three) ^{87}Sr/ ^{86}Sr ages from this limestone have yielded ages in the range 21.8-21.98 Ma, which is slightly older than the Waitakian-Otaian boundary. An upper Waitakian age is also indicated for basal parts of the Mahoenui Group in the vicinity of Te Kuiti from the presence of the planktic foraminifera *Globoquadrina dehiscens*, occasional *Globigerina woodi*, and the benthic foraminifera *Haeuslerella hectori.*

Summary

An objective in this thesis has been to rationalize the lithostratigraphy of the Te Kuiti Group and to develop a robust chronostratigraphic template for it so that the depositional systems can be reconstructed and interpreted. The chronostratigraphic template (Fig. 3.3) has been developed from the assignment of biostratigraphic stages, the boundaries of which now have precise numerical ages (Cooper et al. 2004), and from the constraints provided by new Sr isotope numerical ages. An additional constraint developed in this thesis has been the occurrence and extent of inter-formational unconformities and correlative conformities, which have been described in Chapter 3 and enable six Vail-type sequences to be identified. These unconformities provide important constraints to assess the validity of the Sr isotope ages that fall outside the expected biostratigraphic stage or stages for particular formations, as described in the preceding sections. Fig. 4.8 shows how the biostratigraphic age model of White and Waterhouse (1993) differs from the new scheme developed in this thesis.

Chapter 5

Lithofacies, sequence stratigraphy and paleoenvironments of the Glen Massey Formation

Introduction

The main purpose of this chapter is to describe the lithofacies in the Glen Massey Formation, interpret the corresponding paleoenvironments and develop a sequence stratigraphic interpretation for the formation. Facies analysis is a fundamental descriptive sedimentologic approach for the characterisation of bodies of rock based on their lithological, physical and biological attributes. In the context of sequence stratigraphy, facies analysis is particularly relevant to the study of cyclic changes in the processes that form individual depositional systems in response to base-level shifts (Walker & James 1992). The characteristics of lithofacies, their associations and related paleoenvironments provide critical clues for paleogeographic reconstructions, as well as for the definition of systems tracts and depositional systems in sequence stratigraphic investigations. Stratal geometries, properties of sedimentary facies, and the nature of sequence bounding unconformities in the Glen Massey Formation have been investigated to evaluate a complex interaction of antecedent topography, relative sea level changes, local tectonics, sediment supply, and sedimentary processes. A reconstruction of the inferred depositional setting and the development of a model sequence are presented in the later part of this chapter.

Lithofacies Analysis

Overview

As a result of extensive outcrop analysis carried out in this study, the Glen Massey Formation is now recognised from Port Waikato to Awakino (Chapter 3). This new correlation and revised definition of the unconformity-bounded Glen Massey Formation provides new insights into the sedimentary evolution of the basin during the lower Whaingaroan. Glen Massey Formation across much of the study area was deposited on a continental shelf, and it comprises a diverse assemblage of carbonate and mixed carbonate-siliciclastic strata that have reasonably good lateral facies continuity across the basin. Previous investigations (e.g. Kear & Schofield 1959; Kear 1963, 1987; White & Waterhouse 1993) have traditionally subdivided the Glen Massey Formation into three major facies types based on gross vertical changes in lithology and differences in sedimentary style (*viz.* Elgood Limestone Member, Dunphail Siltstone Member, and Ahirau Sandstone Member). The distribution of these facies in the basin is depicted in Figs 5.1, 5.2 and 5.3.

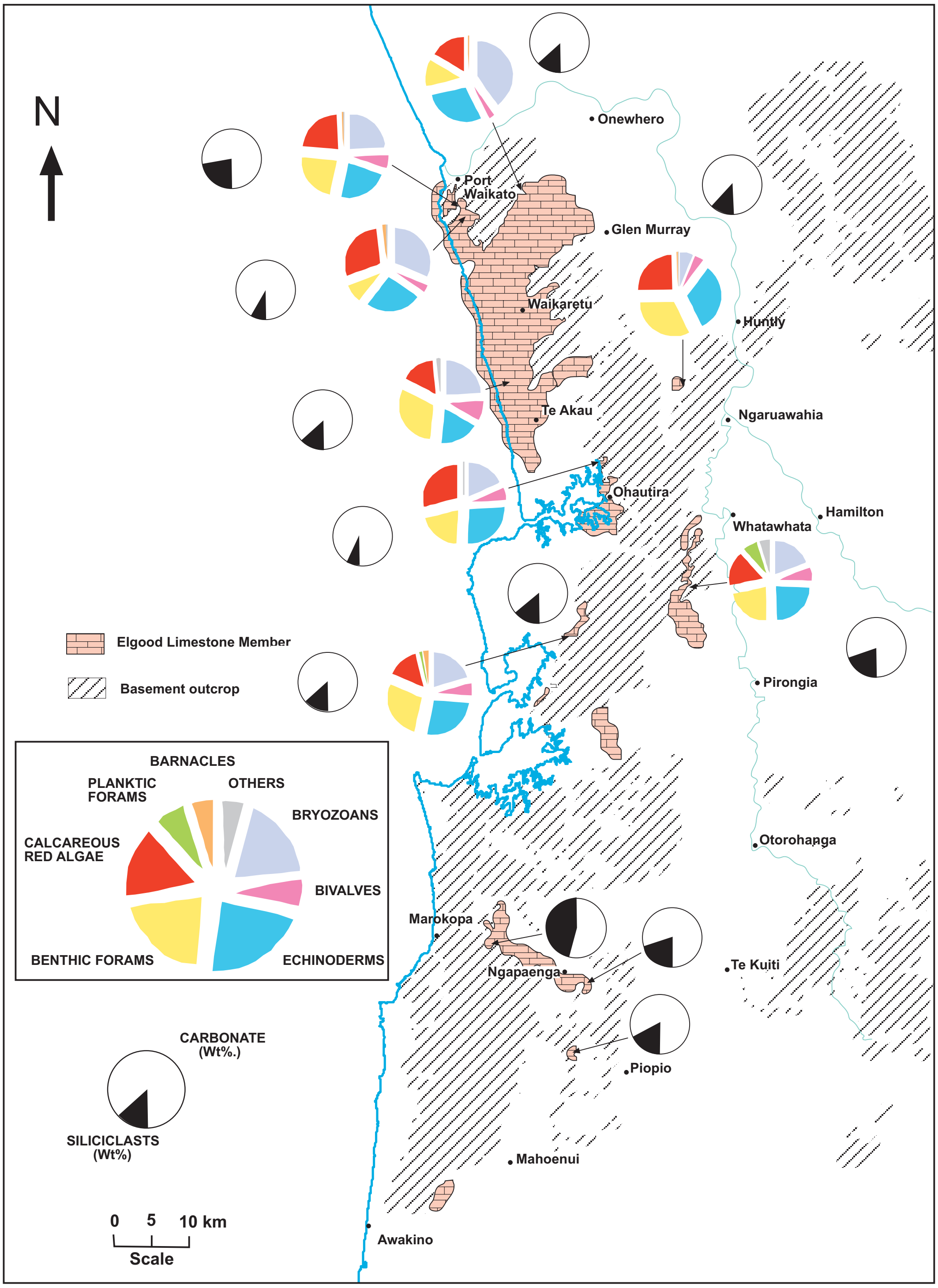


Fig. 5.1: Generalised outcrop distribution of the Elgood Limestone Member and pie-diagrams of its average whole rock bioclastic, and carbonate versus siliciclastic composition. Distribution extending to the west of present day coastline is inferred.

In a broad sense the limestone, calcareous siltstone and calcareous sandstone tripartite subdivision is a general lithofacies subdivision and this study expands on it. A field based lithofacies subdivision supplemented with laboratory data has been developed, which incorporates information such as bedding character, physical and biological sedimentary structures, and composition (e.g. siliciclastic vs. carbonate,

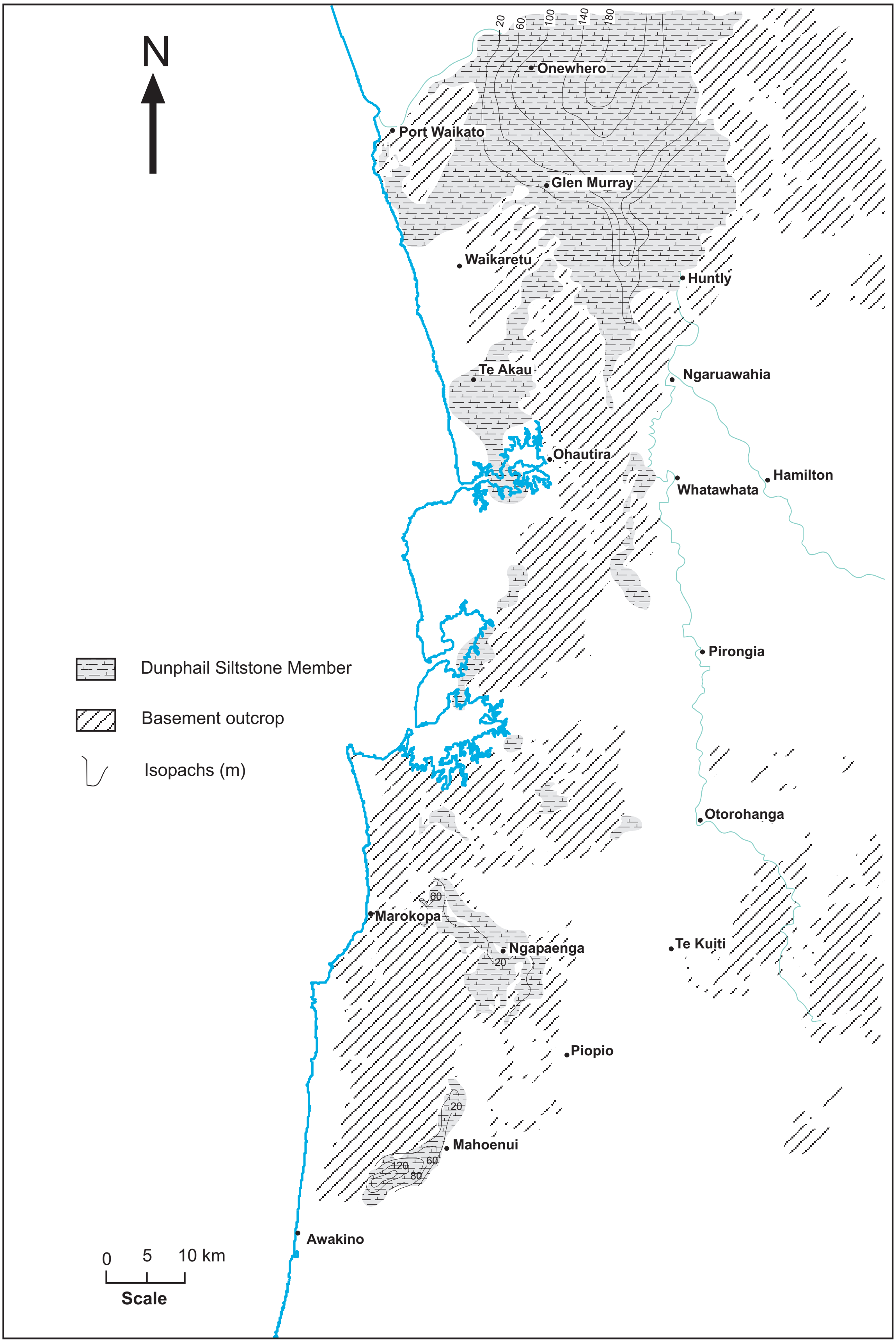


Fig.5.2: Simplified map showing existing distribution and isopachs for the Dunphail Siltstone Member.

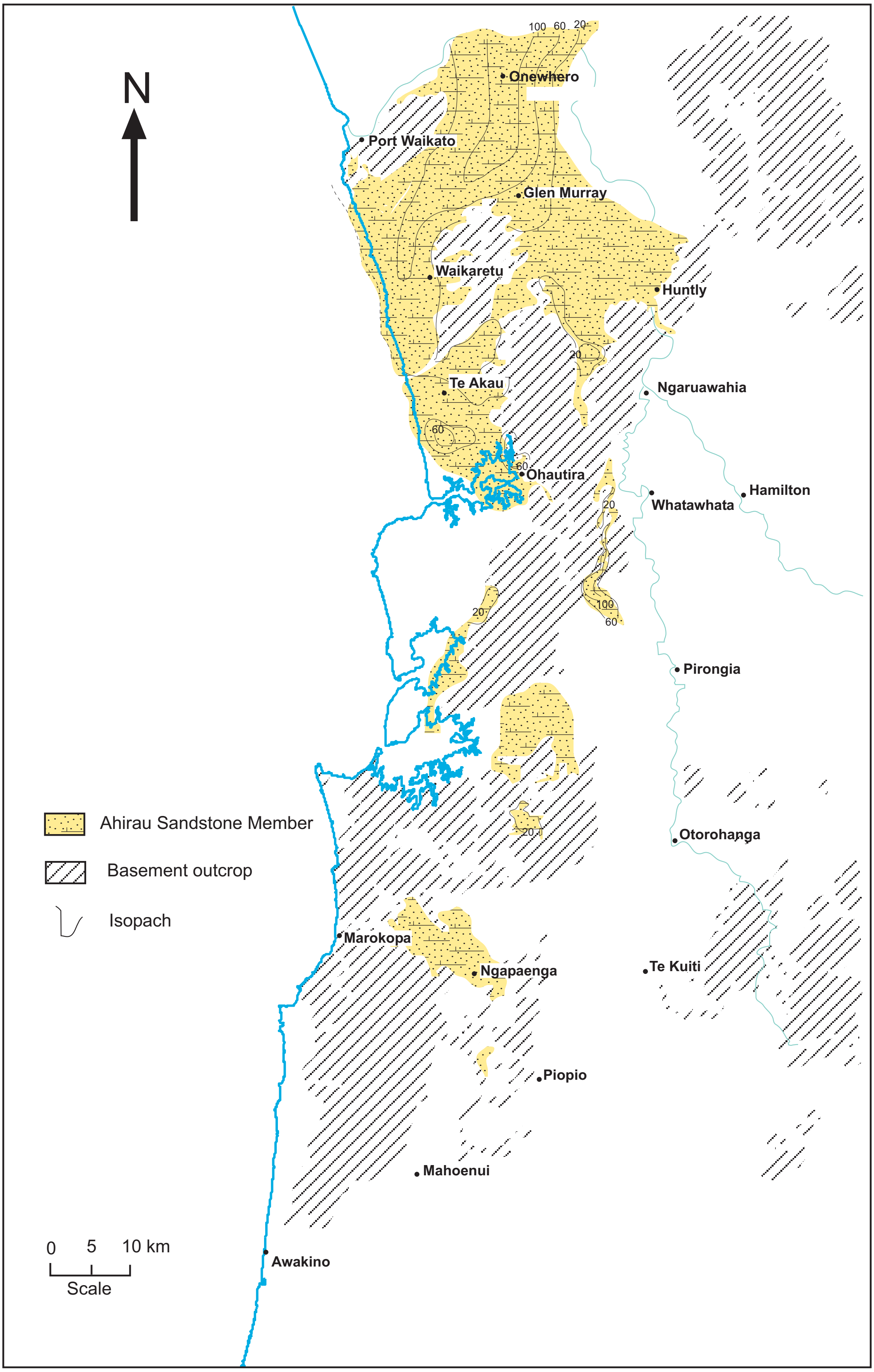


Fig.5.3: Map showing generalised outcrop distribution and isopachs for the Ahirau Sandstone Member.

major skeletal constituents, and concentration of glauconite and/or phosphate). Textural information and sedimentary structures are important facies parameters for the interpretation of paleoenvironments. Unfortunately, primary depositional structures are often difficult to discern in outcrops of the Glen Massey Formation because of extensive bioturbation, and a degree of diagenetic overprinting in carbonate-dominated lithofacies. Ichnology, biotic composition and taphonomy provide additional facies insights.

Methods

Closely spaced and detailed measured outcrop sections together with Coal Resources Survey drillhole core-log data, make up the database for this investigation. Correlations between measured sections were made using significant stratigraphic discontinuities bounding the formation and within it. Large samples representative of the field lithologies were collected from key stratigraphic sections and sub-samples of a selection of these were digested using dilute acid (10% HCl) to determine their $CaCO_3$ percentage. The insoluble residue was then used to establish the siliciclastic texture using a fully computerised Malvern laser-based particle size analyser. The objective was to quantitatively document the vertical variations in $CaCO_3$ content and variations in siliciclastic grain size distributions to aid in the characterisation of the various lithofacies.

A ternary plot depicting the $CaCO_3$-sand-mud% for samples from members of the Glen Massey Formation shows clear segregation in the results (Fig. 5.4). Textural and compositional changes for selected columns of the Glen Massey Formation members are (Fig. 5.5) illustrated in a series of detailed measured logs (Fig 5.6 a-i). Importantly, the finest-grained mixed carbonate-siliciclastic facies immediately overlie the carbonate-dominated lithofacies, which typically forms the lowermost part of the sequence, and the grain size then gradually increases upwards through to the top of the Ahirau Sandstone Member.

Lithofacies and facies associations

The Glen Massey Formation is characterised by a diverse array of facies and fourteen of them have been differentiated in this study. In general, most facies can be grouped into one of four lithofacies associations on the basis of facies parameters. Associations are named limestone, mixed carbonate-siliciclastic sandstone, siltstone, and chemogenic, after their dominant lithology. Individual facies and facies associations are interpreted in terms of depositional processes and paleobathymetry to establish a sedimentological model. Individual facies have been given brief descriptive names (e.g. low angle cross-bedded limestone) and

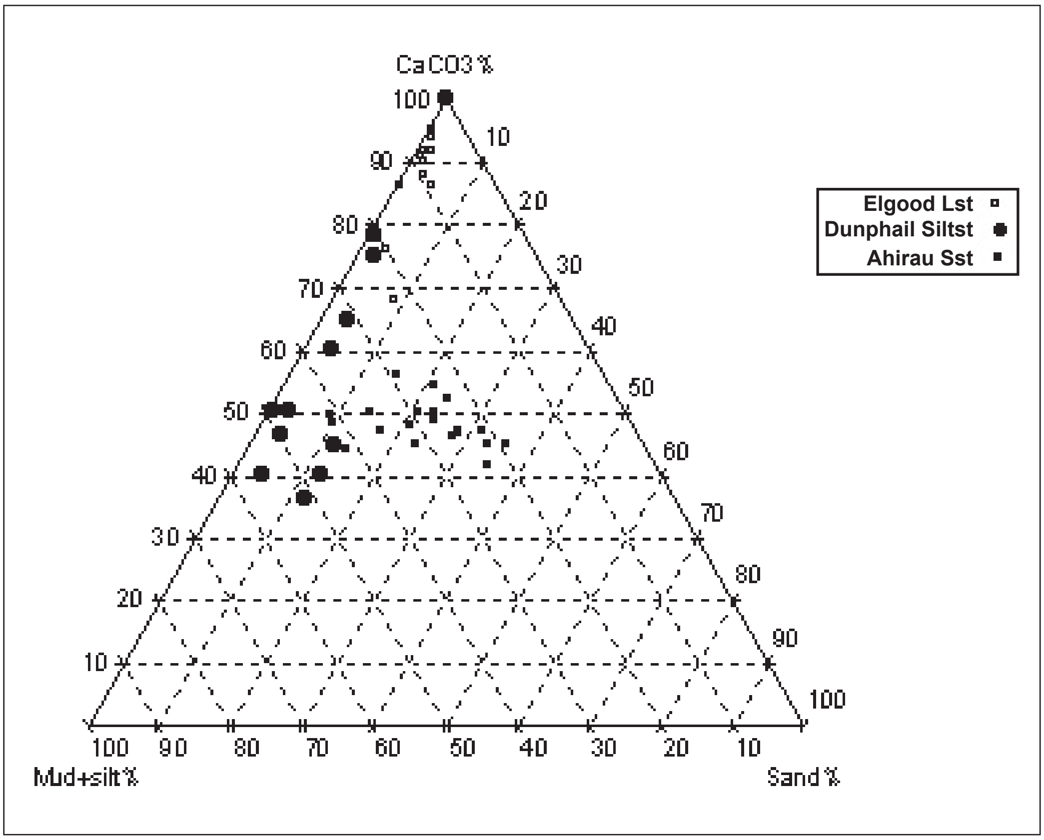


Fig. 5.4: CaCO3-siliciclastic silt & clay and sand percentages for the Glen Massey Formation are depicted in this ternary plot. It is based on 51 analyses of representative samples from the formation in the Port Waikato area. The CaCO3 end member includes all soluble carbonate material, the silt & clay end member includes all insoluble fraction of size < 63 μm, and the sand end member includes all insoluble fraction of size > 63 μm. The three members of the Glen Massey Formation lie in separate areas of the plot. Note the high overall carbonate content and the increase in sand content from Dunphail Siltstone Member to Ahirau Sandstone Member.

paleoenvironmental interpretations have been made for each of the facies and their associations. The diagnostic characteristics of these lithofacies are summarised in Table 5.1. A series of lithofacies cross-sections for the Glen Massey Formation have been constructed by linking the more landward zones (towards the west) with more basinal ones (towards the east) and these are illustrated in Fig 5.7 (a-e). The geographical distribution of the columns and selected cross-sections used for correlation are shown in Fig. 5.5.

Limestone lithofacies (L_1 to L_5)

Carbonate-dominated lithofacies include a spectrum of skeletal-rich, sparry grainstone to mixed grainstone/packstone rock types. Stratigraphically, they occur in the Elgood Limestone Member. For facies classification purposes, calcium carbonate content is the most effective basis to separate the limestone lithofacies association from their associated mixed siliciclastic-carbonate lithofacies, the latter having comparatively lower $CaCO_3$ content averaging 50%. The carbonate lithofacies in the Elgood Limestone Member represent one of the most extensive

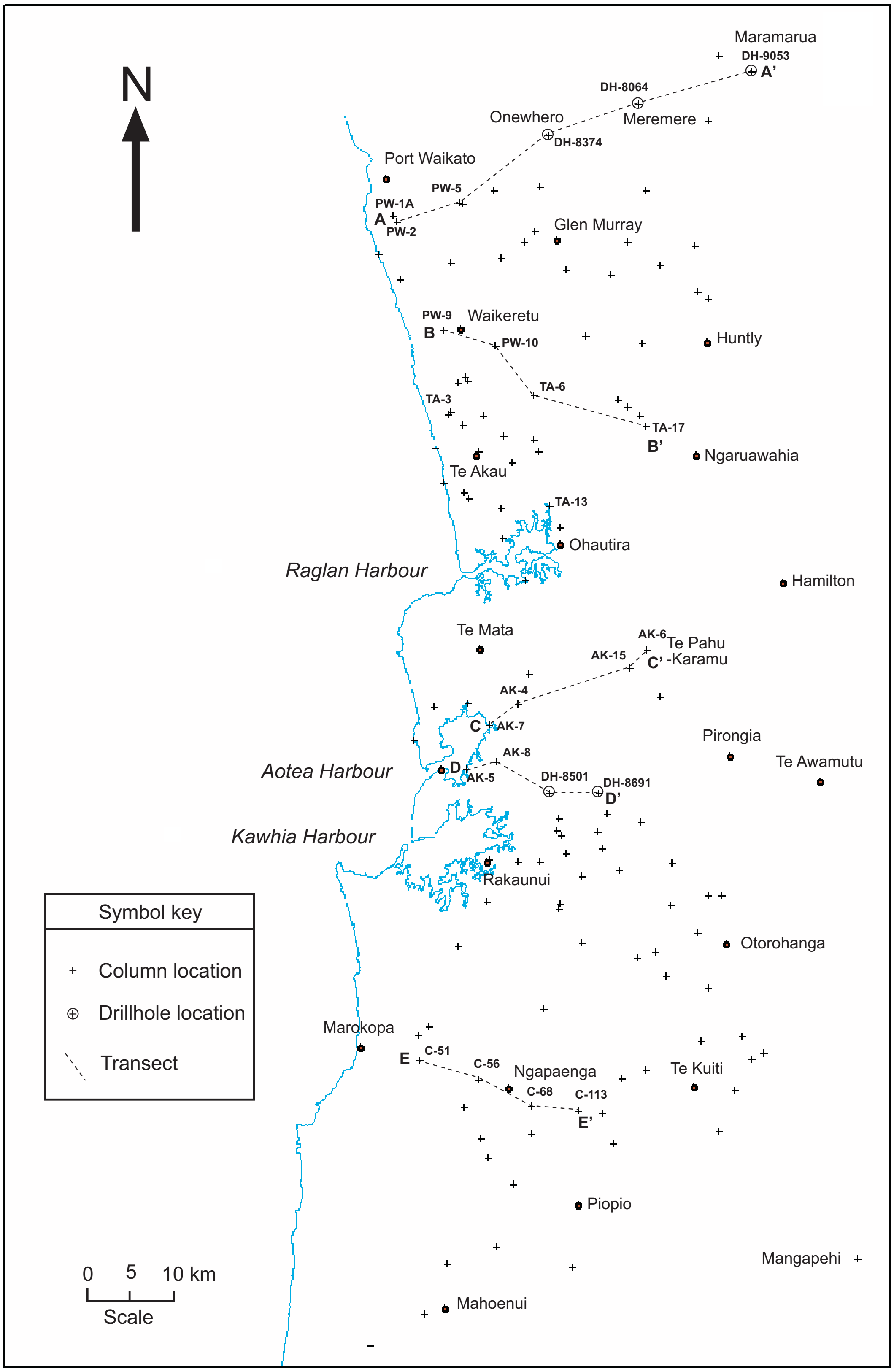


Fig. 5.5: Stratigraphic columns for the Te Kuiti Group, and selected columns and drill hole locations used for cross sections (See Fig. 5.6a-e) through Glen Massey Formation

Table 5.1: Summary of sedimentary lithofacies for the Glen Massey Formation

Lithofacies	Field characteristics	Wt % $CaCO_3$	Texture	Typical skeletons / bioturbation	Occurrence	Interpretation
Limestone lithofacies association (Elgood Limestone Member)						
L_1 Pebbly grainstone	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 transgressive basal lag, tens of cm thick (Fig. 5.9 a & g)	Near shore to innermost shelf, adjacent to rocky shoreline
L_2 Shelly grainstone	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 (Fig. 5.9 b)	Near shore to inner shelf

Litho-facies	Field characteristics	Wt % $CaCO_3$	Texture	Typical skeletons / bioturbation	Occurrence	Inter-pretation
L_3 Cross-stratified grainstone	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 (Fig. 5.9 c)	Sub-aqueous dunes migrating parallel to shore.
L_4 Horizontally bedded grainstone	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 (Fig. 5.9 d)	Inner to mid shelf

Litho-facies	Field characteristics	Wt % $CaCO_3$	Texture	Typical skeletons / bioturbation	Occurrence	Inter-pretation
L_5 Massive to moderately bedded grainstone-packstone	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 (Fig. 5.9 e & f)	Lower inner to mid-outer shelf, wave (storm) dominated setting
Mixed carbonate-siliciclastic sandstone lithofacies association (Ahirau Sst Member)						
S_1 Calcareous pebbly-gritty sandstone	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 transgressive lag deposits (Fig. 5.9 g)	Inner-most shelf, proximal to rocky coastline, with a moderately high siliciclastic influx
S_2 Calcareous silty fine sandstone	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 (Fig. 5.12 a & b)	Inner to mid shelf with moderate to strong bottom currents driven by wind and/ or tides interacting with the inherited topography

Lithofacies	Field characteristics	Wt % $CaCO_3$	Texture	Typical skeletons / bioturbation	Occurrence	Interpretation
S_3 Alternating calcareous silty fine sandstone and siltstone	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 (Fig. 5.12 c)	Moderate energy in mid to outer shelf depths below fair-weather but above storm wave base.
S_4 Massive muddy sandstone	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) (Fig. 5.12 h)	Mid shelf
Mixed carbonate-siliciclastic siltstone lithofacies association (Dunphail Siltst. Member)						
S_5 Interbedded calcareous siltstone and sandy limestone	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) (Fig. 5.12 d)	Mid to outer shelf, between fair weather and storm wave base.

Litho-facies	Field characteristics	Wt % $CaCO_3$	Texture	Typical skeletons / bioturbation	Occurrence	Inter-pretation
S_6 Massive calcareous siltstone	Massive blue-grey siltstone, well cemented. No obvious structures. Occasional concretionary bands with ellipsoidal shaped concretions 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 (Fig. 5.12 e, f & g)	Outer shelf to upper bathyal
Chemogenic lithofacies association						
C_1 Phosphate 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 phosphatised hardgrounds at top of Ahirau Sst Member in Port Waikato area (Fig. 5.13 a)	Mid shelf
C_2 Glauconitic calcareous siltstone-sandstone	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 representing a condensed transgressive deposit or in places marks the transition between TST and HST (Fig. 5.13 b)	Sediment starved shelf.
C_3 Glauconitic sandy-silty grainstone-packstone	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 transgressive Deposits (Fig. 5.13 c)	Sediment starved inner-mid shelf.

carbonate shelf accumulations in the Te Kuiti Group. This has generally not been appreciated in past investigations, probably because of stratigraphic miscorrelation in the southern region as discussed in Chapter 3. In places, these carbonate lithofacies reach thicknesses of more than 30 m (e.g. TA-13), although overall they contribute less than 10% of the total thickness of the Glen Massey Formation. Their resistance to erosion leads to conspicuous (flaggy) limestone occurrences. In general, limestone lithofacies are inferred to have accumulated on those parts of a paleo-shelf wherever the levels of siliciclastic input were relatively low so that these slowly accumulating carbonates were not diluted nor buried by terrigenous deposits (e.g. Nelson 1978a).

The Elgood Limestone Member is mainly composed of skeletal material derived from shallow water epibenthic communities living on rocky, gravelly and coarse shelly sea bottoms around ridges, banks and islands that provided the stable, firm substrate (e.g. Nelson 1988a). These shallow-water skeletal-rich limestones show a close association with structural paleo-highs along the western margin of the study area (Fig. 5.1). Strong bottom currents generated by a combination of oceanic and/or tidal current flows amongst uneven topography, particularly when storm assisted, played a significant role in the generation and dispersal of skeletal hash from the shallow-water carbonate factories (e.g. Nelson 1988a, Anastas et al. 1997). The bioclastic fraction (averaging 76.5%) of the Elgood Limestone Member is dominated by high energy taxa such as bryozoans, echinoderms, benthic foraminifera (especially *Amphistegina*), calcareous red algae and to lesser extent bivalves. Planktic foraminifera, barnacles, spicules and spines, and gastropods occur in minor quantities (see Fig. 5.1 for average bioclastic compositional variation). The modal size of bioclasts decreases steadily from about medium sand (1-1.25 mm) near the base to fine sand (0.5-0.25 mm) near the top of the member. Grain sizes are occasionally bimodal involving the introduction of very coarse sand to granule size bivalve fragments amongst medium to fine carbonate sand. Bioclasts characteristically have moderately to very abraded margins, and are poorly to moderately sorted. The modal grain size of the siliciclasts, consisting of quartz, feldspar and sedimentary and igneous rock fragments, lies in the range of medium to fine sand. Grains are commonly subangular to subrounded and moderately to poorly sorted. Glauconite is generally of minor importance, but becomes very common (20-40%) near the top of the Elgood Limestone Member and occasionally at its base. Intrinsic matrix-cement occupies from 10-20% of the limestone, with higher values ($\geq$ 30%) near the base being mainly sparite, or near the top being mainly micrite.

The carbonate lithofacies range in $CaCO_3$ content (% by weight) from about 62% to 98%, with an average of 86% (see Fig. 5.1 for average Wt % $CaCO_3$). In places, $CaCO_3$ content displays a steady increase up section (e.g. columns TA-13 and C-51 Figs 5.6 f & h). On inner-shelf areas and over paleo-highs the limestone facies are dominated by cross-bedded skeletal grainstone, while further offshore these facies pass into either horizontally bedded wackestone-packstone or variably sandy-silty skeletal grainstone (Fig. 5.8). A total of five limestone lithofacies have been distinguished in this study, and the main facies characteristics are summarised in Table 5.1.

$L_{1.}$ Pebbly grainstone:

This facies usually overlies the contact with basement and occurs commonly along the western margin (cross sections A-A' to E-E' in Fig. 5.7). The pebbly grainstone lithofacies usually passes up into either lithofacies $L_{2,}$ L_3 or L_4 (Fig. 5.9 a).

Moderately to poorly sorted, rounded to subrounded basement pebbles and occasionally cobbles (size up to 10 cm), occur in beds up to a few tens of centimetres thick and rarely as much as 2.5 m thick. The beds are poorly stratified and may show crude normal-grading. Clasts are supported by sandy or granule-rich calcareous matrix. Fragmented large bivalves such as pectinids and oysters along with large benthic foraminifera are common (Fig. 5.10 a). Pebbles and shell fragments are sometimes glauconitised and bored. Occurrences of rhodoliths associated with this facies have been recorded in some sections (e.g. PW-9, C-50) (Nalin et al. 2008).

Interpretation: This facies is inferred to have been deposited directly over basement underlying paleotopographical highs during marine inundation of steep coastal zones. Pebbles, granules and coarse siliciclastic sand were derived by wave erosion from basement with reworking in the innermost shelf environment by wave and tidal currents. The coarse skeletal fragments are derived from rocky shoreline communities, including oysters and pectinids. In some locations, fragments of coralline red-algae and rhodoliths (nodules of encrusting coralline algae) (Fig. 5.9 h) dominate the sediments and may represent the lee side of islands where water flow is high but wave energy is not so intense (e.g. James 1997; James et al. 2001; Nalin et al. 2008). The common occurrence of benthic foraminifera (*Amphistegina* sp., *Elphidium* sp. and *Cibicides maculatus*) indicates deposition in the shallow

Fig. 5.6 (facing and following pages): Textural and compositional changes through selected stratigraphic columns PW-1A, PW-2, PW-5, TA-3, TA-17, TA-13, C-51, C-56 and C-68 (see Fig. 5.5 for column locations). The sections reflect local variations in unit thickness and vertical lithofacies relationship. Siliciclastic textures include grain sizes (coarse, medium, fine sand, silt and clay) of insoluble fraction. The CaCO3 content (wt %) includes all soluble carbonate material. Inferred depositional environment, systems tracts and key stratigraphic surfaces are shown in right hand columns. Abbreviations: SB- Sequence boundary; DLS- Downlap surface; CS- condensed section; f.u.- fining upwards; c.u.- coarsening upwards, TST- transgressive systems tract; HST- highstand systems tract; RST- regressive systems tract.

Fig. 5.6 (a)

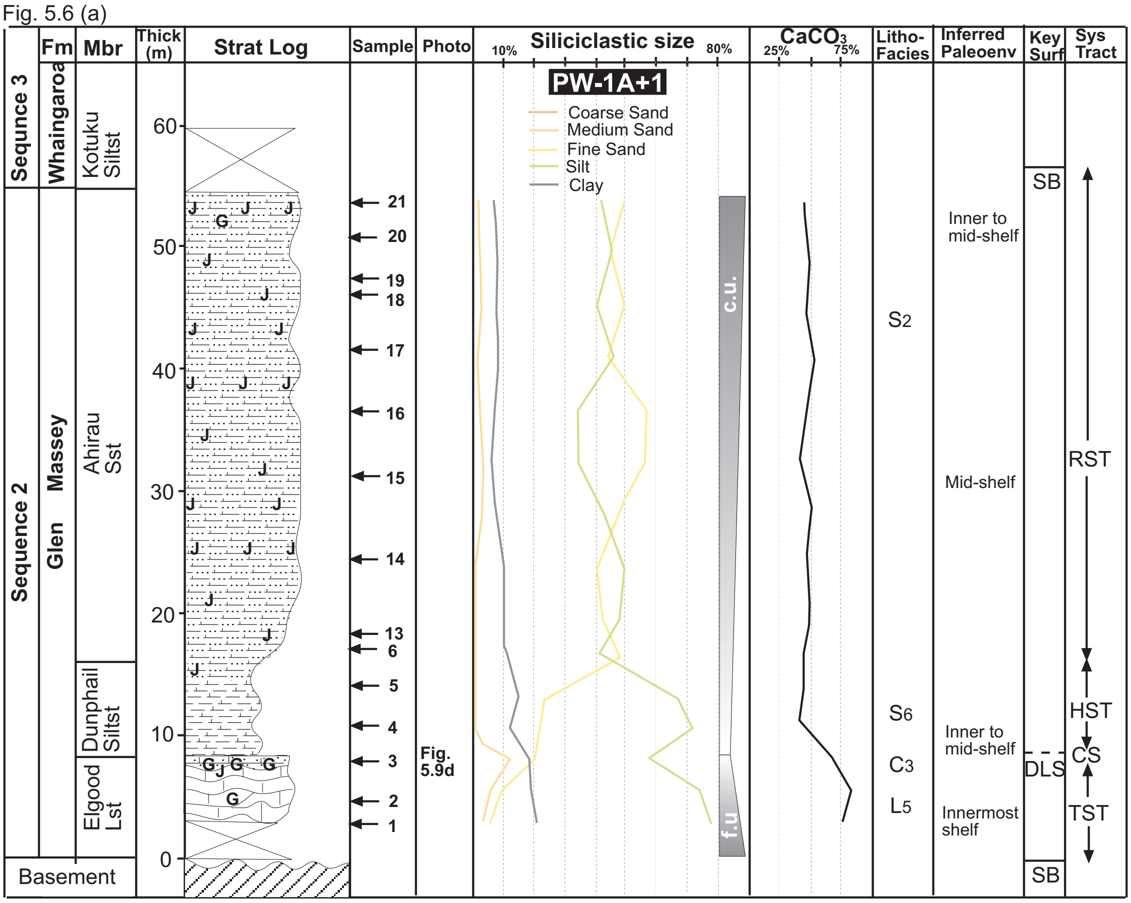
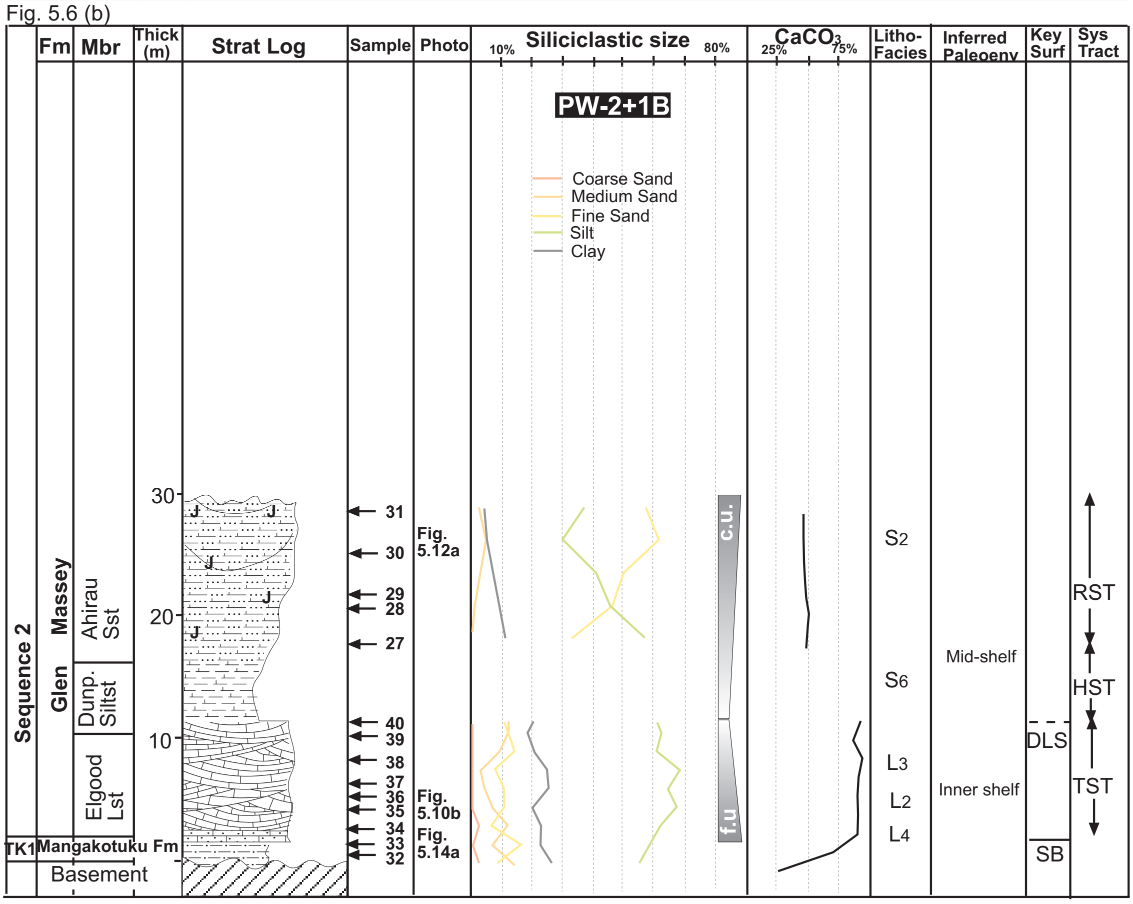


Fig. 5.6 (b)



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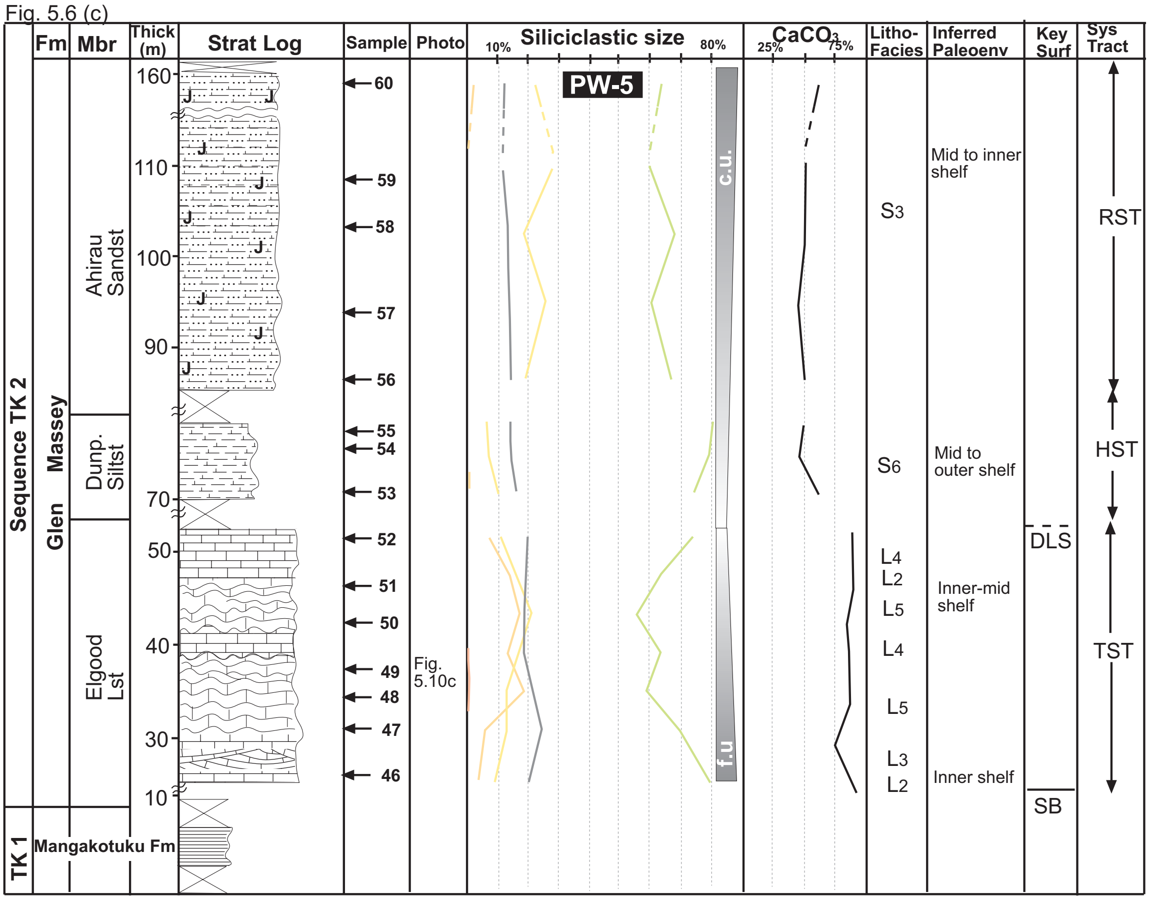
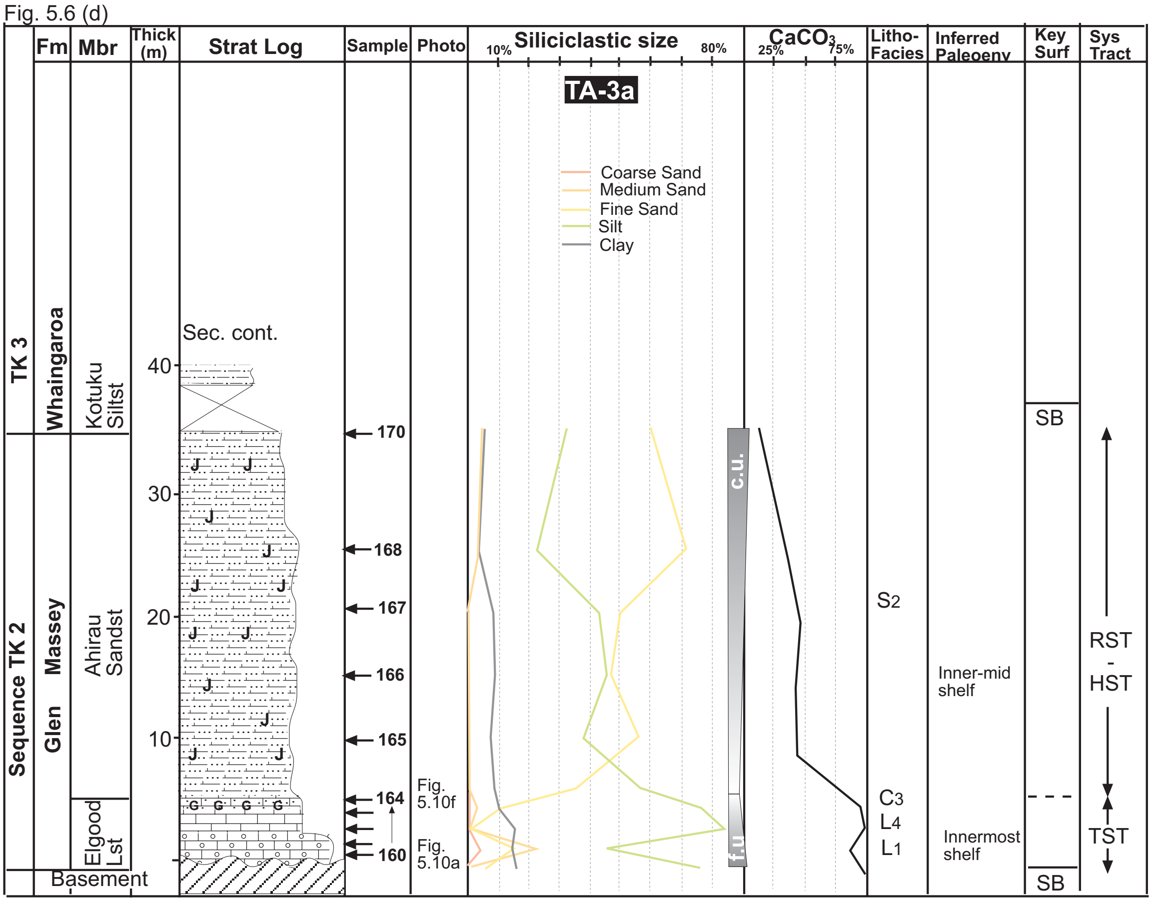


Fig. 5.6 (d)



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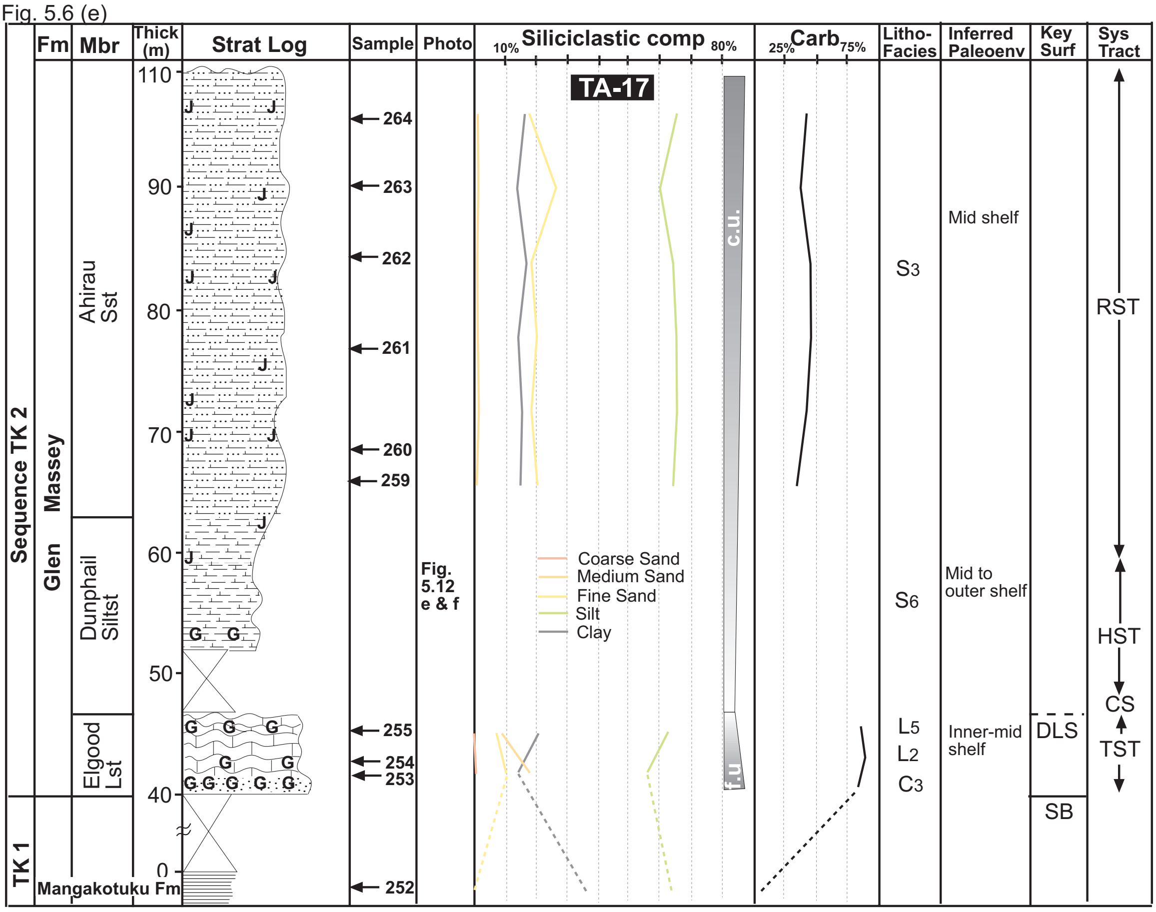

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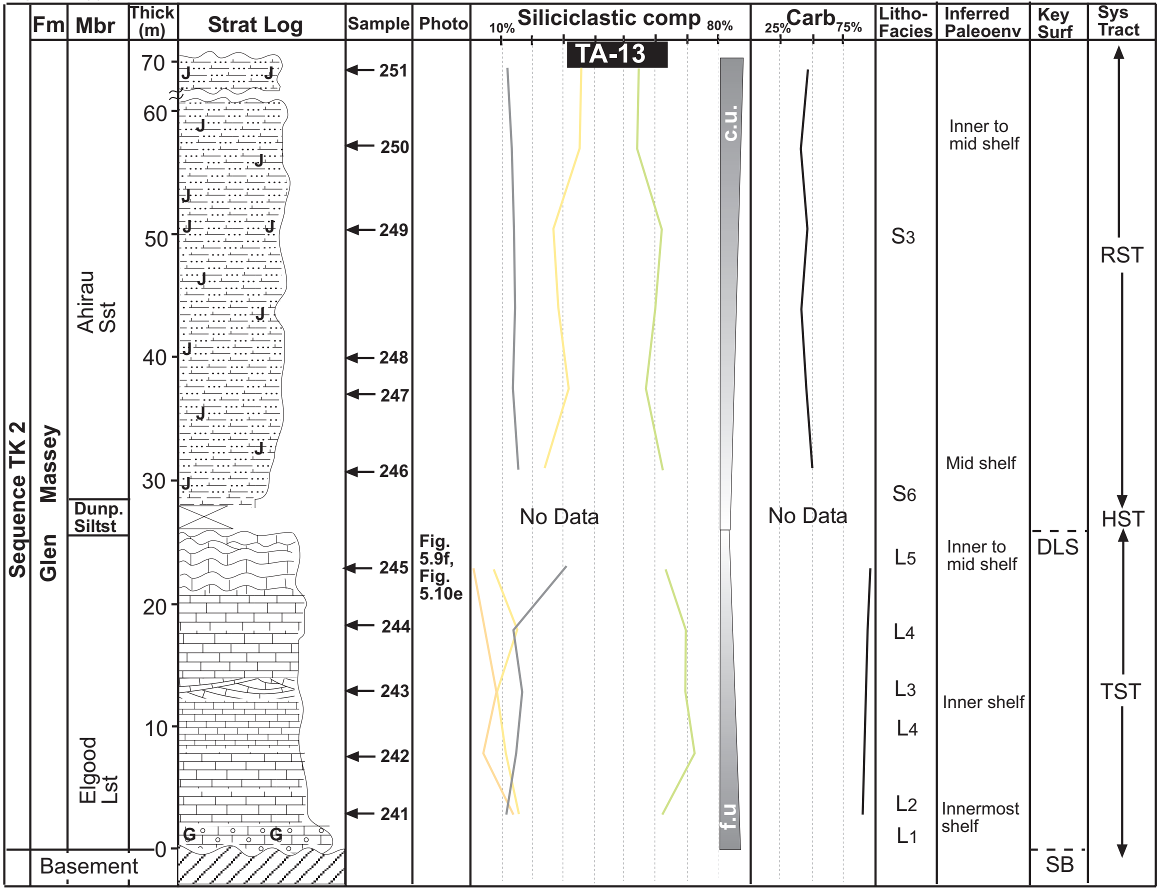


Fig. 5.6 (g)

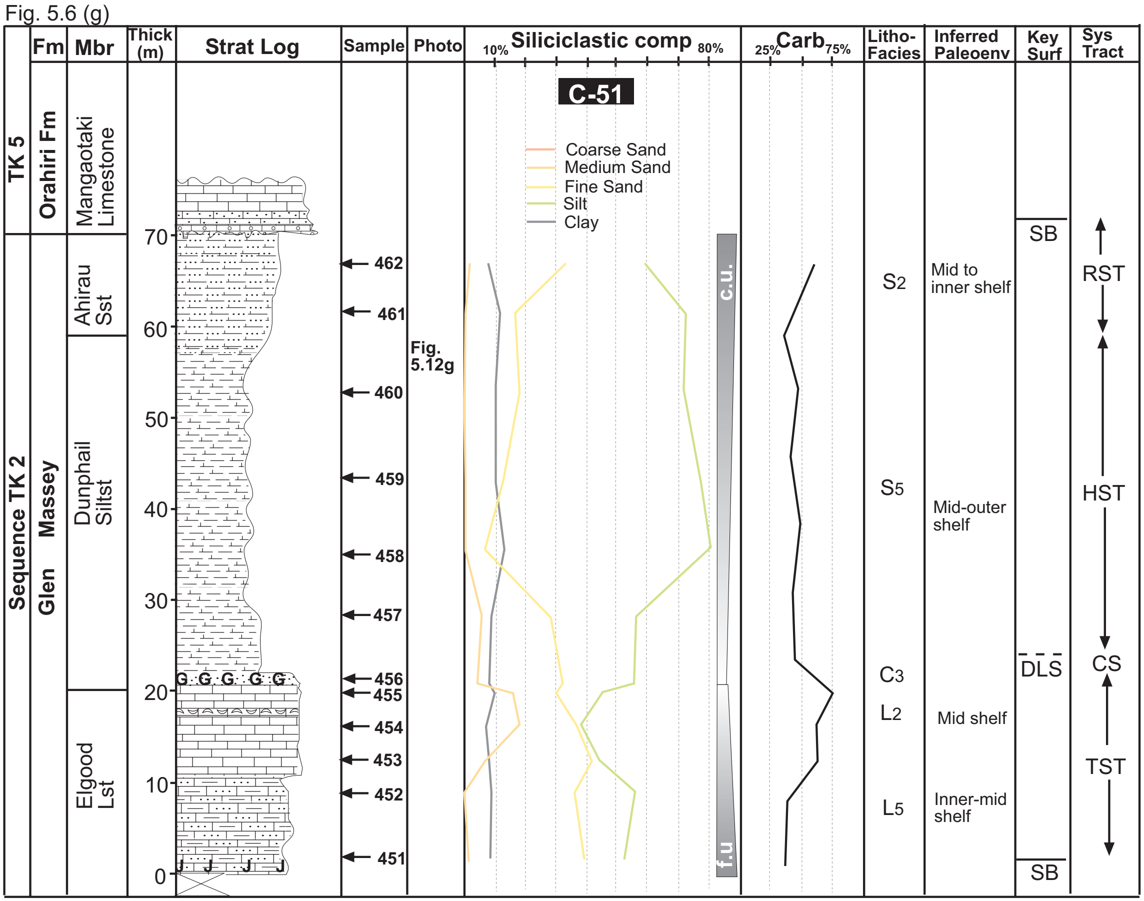


Fig. 5.6 (h)

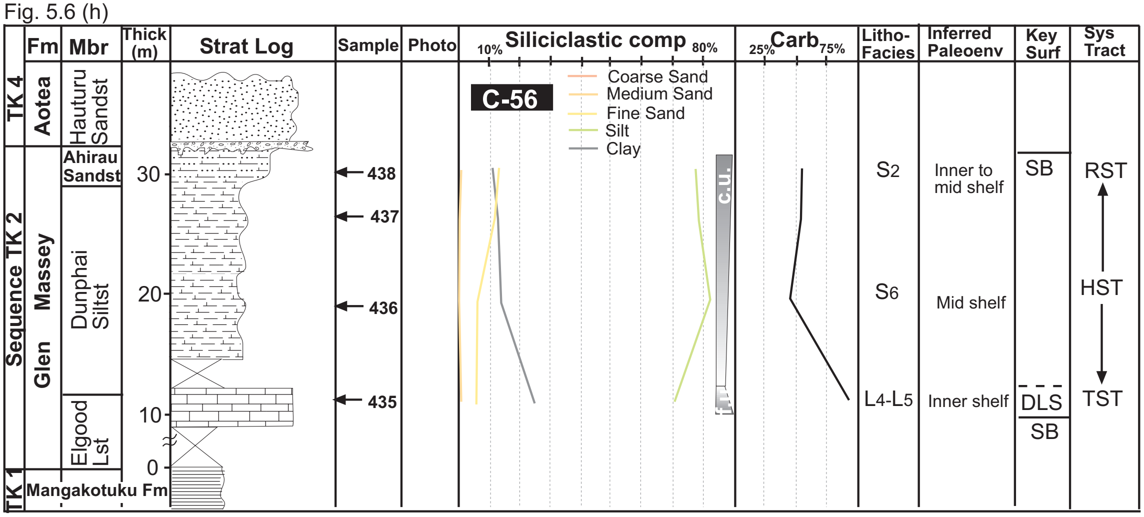
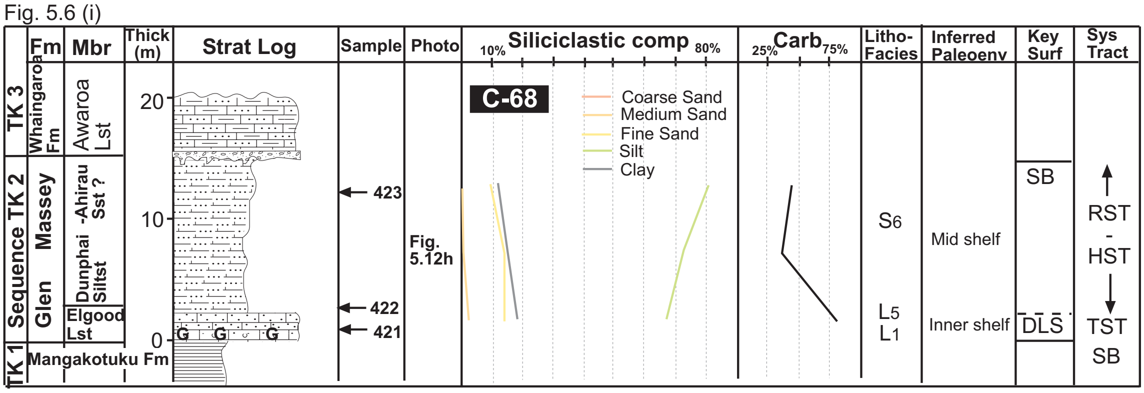


Fig. 5.6 (i)



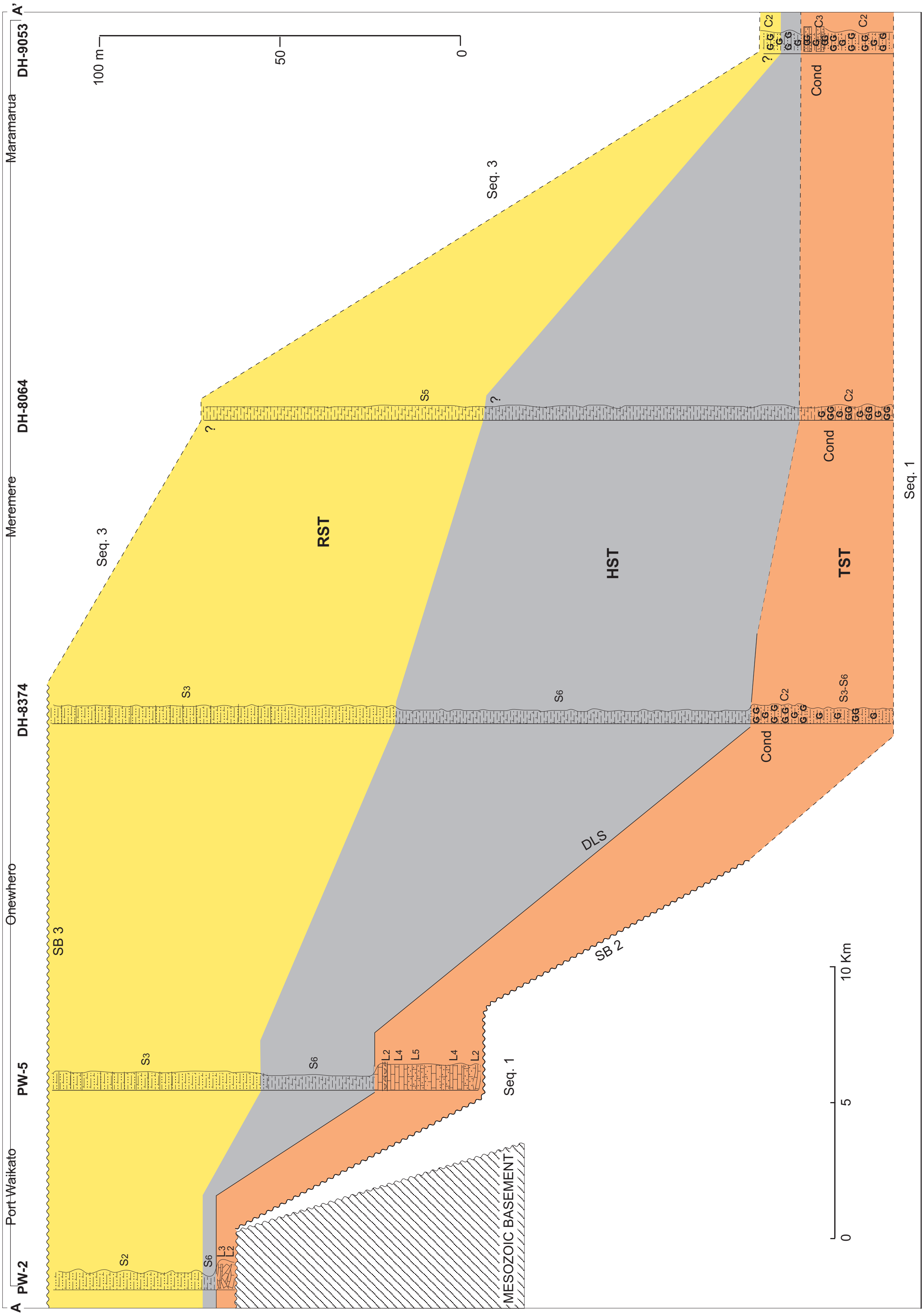


Fig. 5.7a: Cross section A-A' through Glen Massey Formation (location shown in Fig. 5.5)

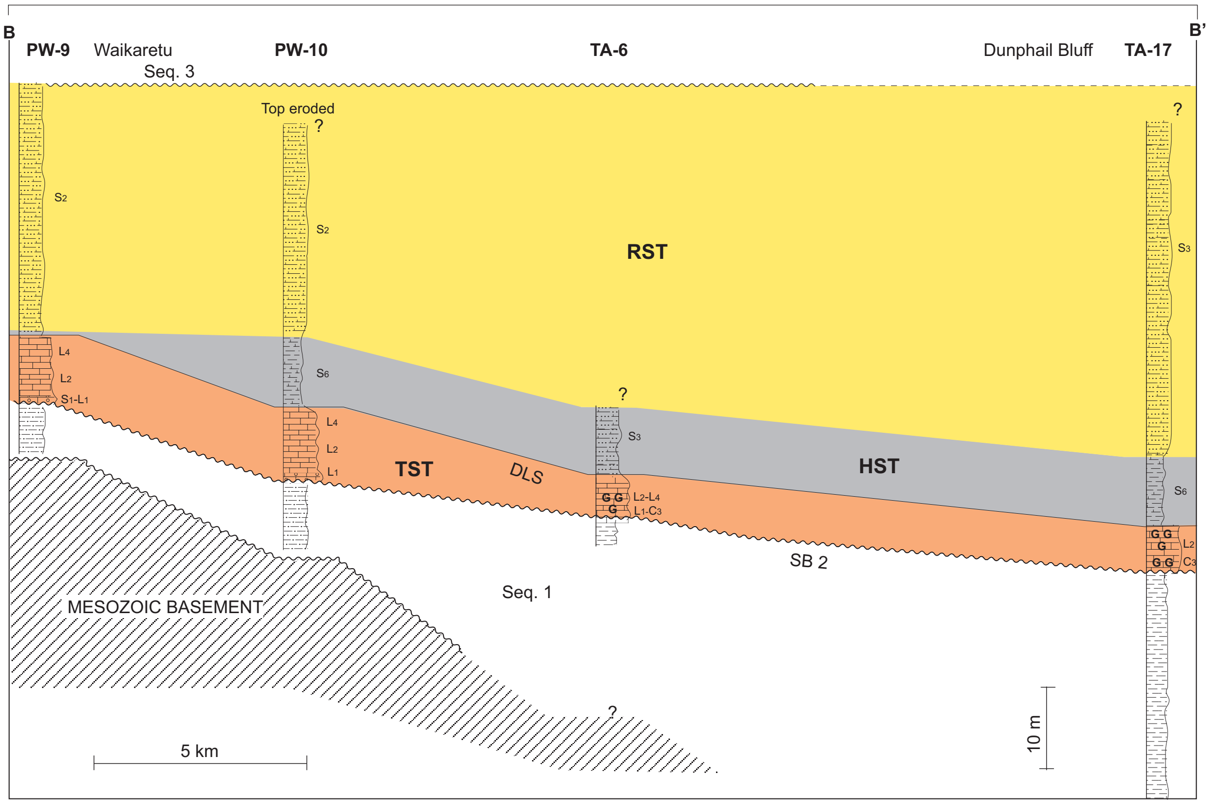


Fig. 5.7b: Cross section B-B' through Glen Massey Formation (see Fig. 5.5 for location)

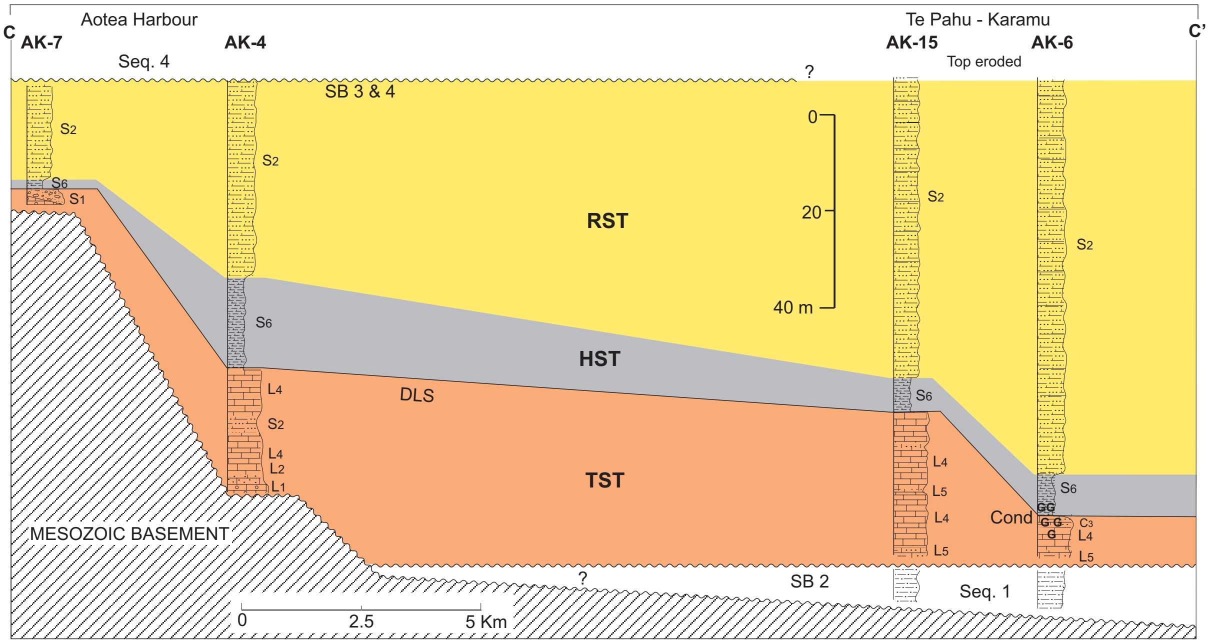


Fig. 5.7c: Cross section C-C' through Glen Massey Formation (location shown on Fig. 5.5)

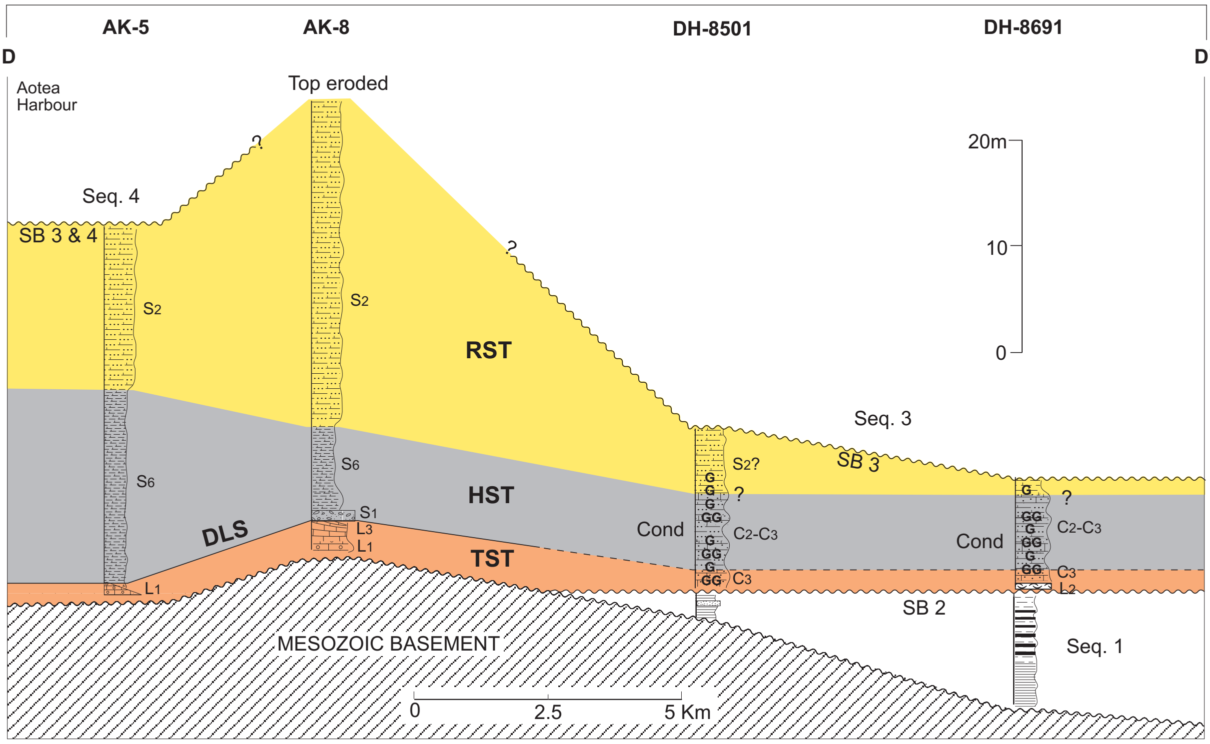


Fig. 5.7d: Cross section D-D' through Glen Massey Formation (location shown on Fig. 5.5).

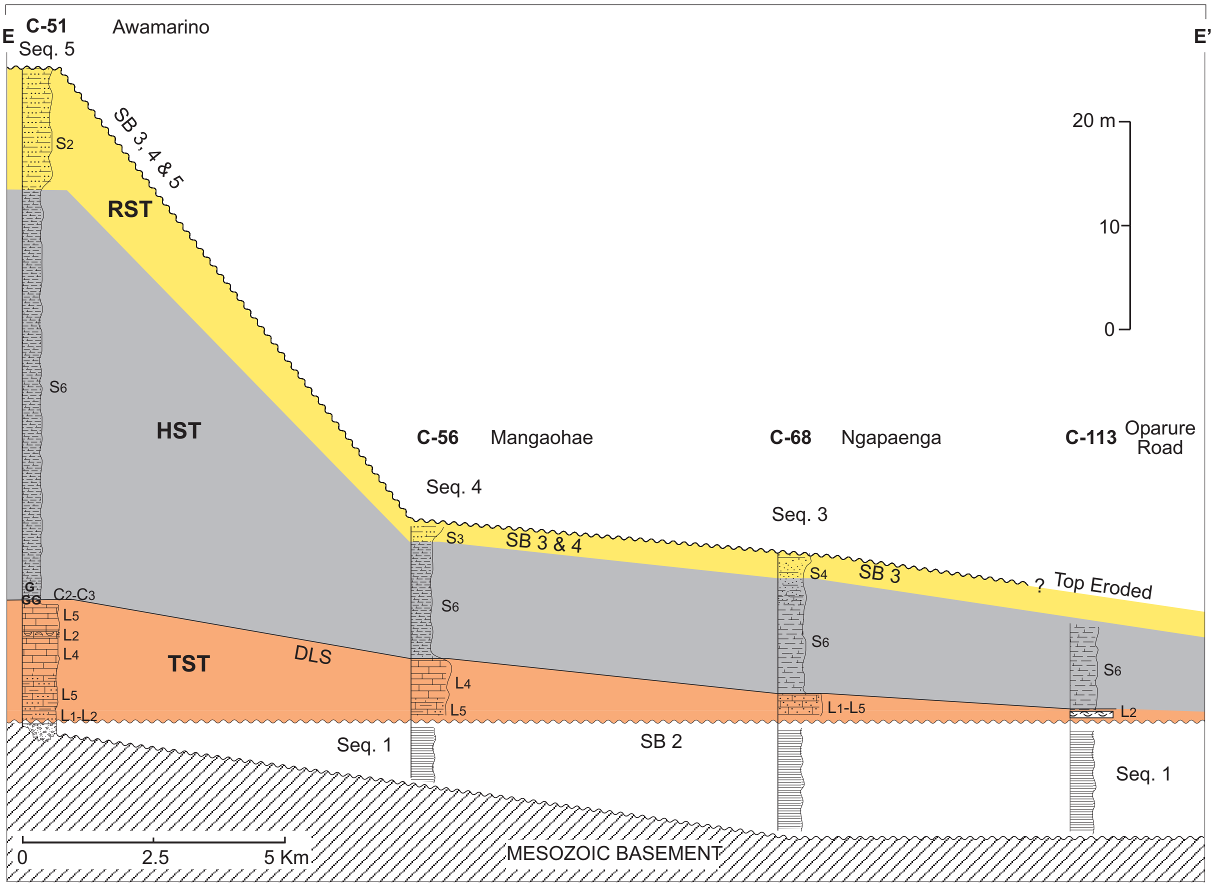


Fig. 5.7e: Cross section through Glen Massey Formation (location shown on Fig. 5.5).

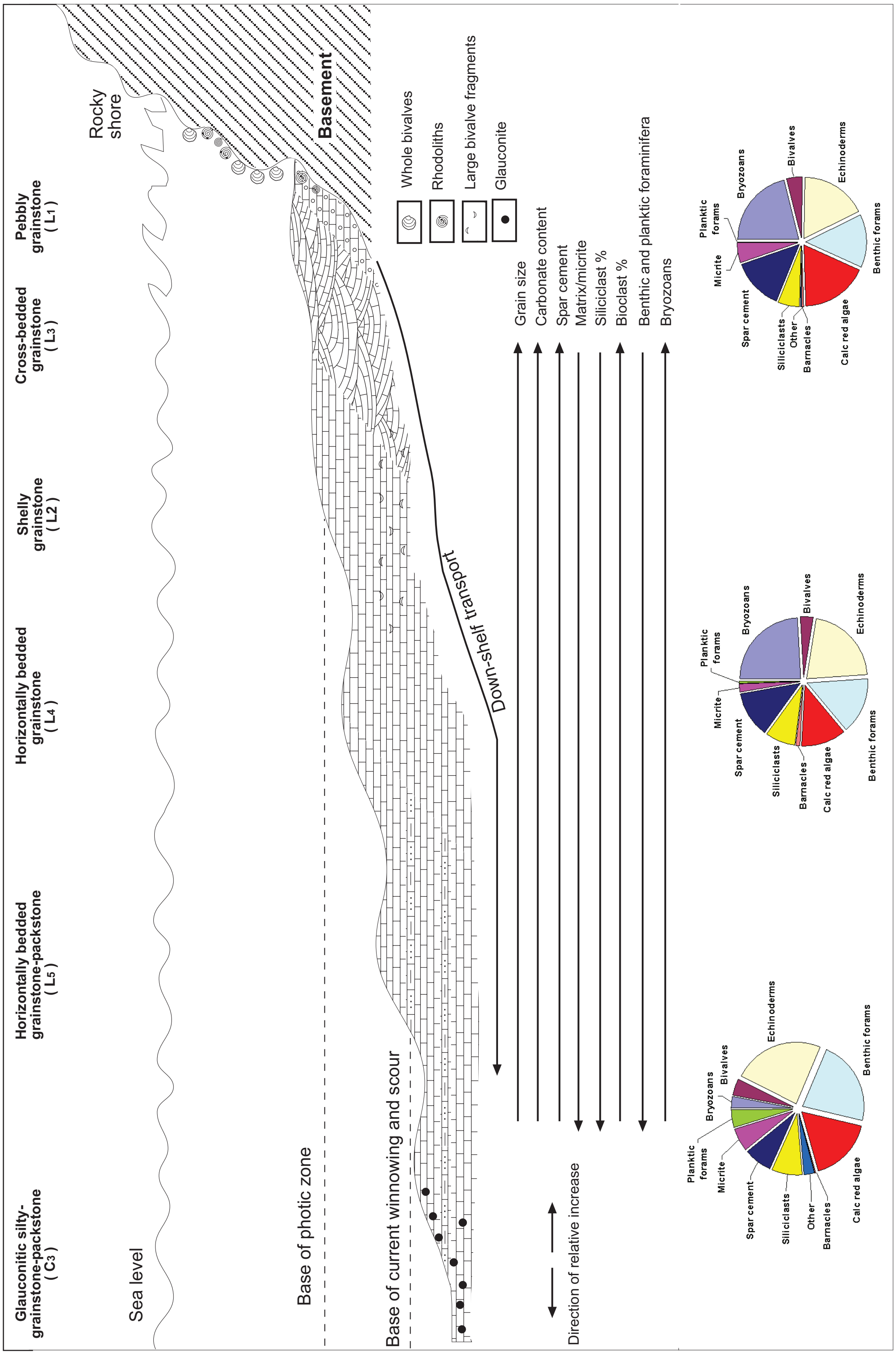


Fig. 5.8: Schematic dip section from the western basin margin to a more offshore eastern part, depicting the main constituents of the Elgood Limestone Member rock type, biotic composition and interpreted depositional environments. The transect incorporates data from different stratigraphic levels. Note, not all facies occur at any given time on the shelf. The zone of dominant carbonate production and accumulation is inferred to be located in the inner and mid shelf portion. Summary of general petrographic trends and Pie diagrams show average proportion of bioclasts, siliciclasts, spar cement and matrix/micrite derived from point counting. The faunal compositional break-up shows bryozoans, echinoderms, calcareous red algae and benthic foraminifers are the major contributors to the sediment supply.

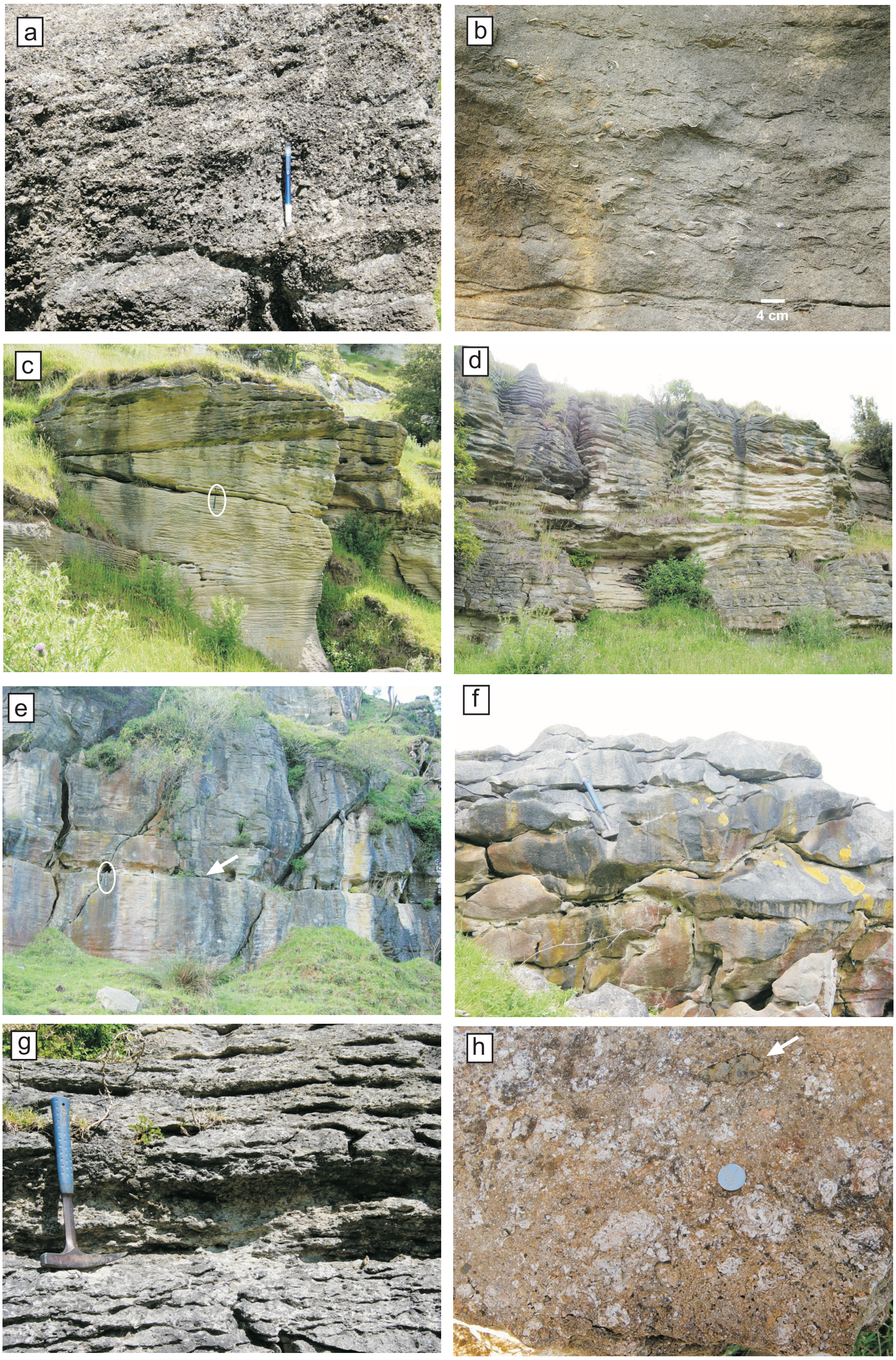


Fig. 5.9: Field examples of lithofacies in the Elgood Limestone Member (a) Pebbly grainstone lithofacies (L1) occurring at the base of Elgood Limestone Member at Plateau Road (AK-3). The rock includes common rounded-subrounded basement pebbles in a gritty-sandy bioclastic-rich matrix. This is a common recurring facies along the basin margin where the Elgood Limestone Member laps onto basement. Pen (14 cm) for scale. (b) Small bivalve coquina composed mostly of whole and broken pectinids floating in a mixed bioclastic fine sandy-silty matrix, a typical example of "Shelly limestone" lithofacies (L2). Coarser grainstone lithologies occur in the lower part of the photograph, taken near Waikaretu Limestone Quarry.(PW-9). (c) Low to moderate angle tabular cross-bedded grainstone,

a typical example of “Cross-stratified limestone” lithofacies (L3). Cross-set boundaries are strongly recessed, accentuating foreset truncation. Hammer for scale. Photo location Port Waikato-Waikaretu Road. (PW-2). (d) Horizontally bedded grainstone lithofacies (L4) showing well-developed flagginess Individual beds vary in thickness from 8-15 cm and are separated by recessed (interflag) seams. Exposure approximately 5 m thick, near Waikaretu Limestone Quarry.(PW-9). (e) Massive to weakly bedded grainstone-packstone lithofacies (L5). Arrow points to thin intensely bioturbated (Thalassinoides) strongly recessed horizon indicating period of non-deposition or very slow deposition related to flooding event. Photo location Quarry Road, Te Pahu-Karamu (AK-15). Hammer for scale. (f) Typical “knobbly” weathering characteristic possibly due to high (50%) matrix content . These irregularly bedded grainstone-packstone facies (L5) occur at the top of Elgood Limestone Member at Halliday Road location. (TA-13). (g) Contact interval between “Cross-bedded grainstone” (L3) and overlying “Pebbly sandy/silty” bed (S1) comprising abundant rounded subrounded basement clasts in a glauconitic-rich mixed siliciclastic-carbonate matrix. Hammer rest on contact. Photo location Waiteika, Aotea Harbour. (AK-8). (h) Rhodoliths (nodules of encrusting coralline algae) along with various clasts of granule to cobble size incorporated into a red algal pebbly grainstone lithofacies (L1). This facies is typical near the base of Elgood Limestone where it laps onto basement. Coin for scale. Photo location Awamarino (C-50).

photic zone of the shelf (e.g. Hayward et al. 1986; Hornibrook et al. 1989; Lukasik et al. 2000).

$L_{2.}$ *Shelly grainstone:*

This facies has restricted occurrence and is readily distinguished in outcrop by its weak to moderate bedding and relatively high macrofossil density. Randomly oriented bivalves are mostly pectinids (*Lentipecten, Chlamys*) supported by a bioclastic spar-cemented grainstone with minor terrigenous fine sand-silt matrix (<15%). Bivalves are rarely in life position and are mostly disarticulated. Occasional oyster clusters and solitary corals (*Flabellum* sp.) are observed. Accessory fauna include bryozoans, echinoids, and large benthic foraminifers (Fig. 5.9 b & 5.11 f). This facies generally occurs in association with Pebbly grainstone lithofacies (L_1) along the western margin (cross sections A-A’, B-B’ in Fig. 5.7). However, Shelly grainstone facies also occur sporadically in more offshore shelf settings where it is often represented by a thin shellbed (cross sections D-D’ & E-E’ in Fig. 5.7).
Interpretation: This facies is inferred to have been deposited in an area immediately seaward of basement highs and also in shoal areas above submerged basement knolls within a relatively shallow, near shore - inner shelf environment. The epifaunal bivalve- dominated lithofacies is most commonly associated with sandy substrate in shallow shelf waters (Nelson 1988a; James et al. 2001). The occurrence of this facies in more offshore settings represents stratigraphic condensation, and is inferred to be an equivalent of the “compound shellbeds” as described by Naish and Kamp (1997) in Wanganui Basin.

$L_{3.}$ *Cross-stratified grainstone:*

These cross-stratified deposits exhibit tabular and occasionally complex sigmoidal foreset configurations. Individual cross-beds are inclined from moderate to low angles (<10º-25º), occur in sets and cosets 0.3-1.5 m thick, and are generally

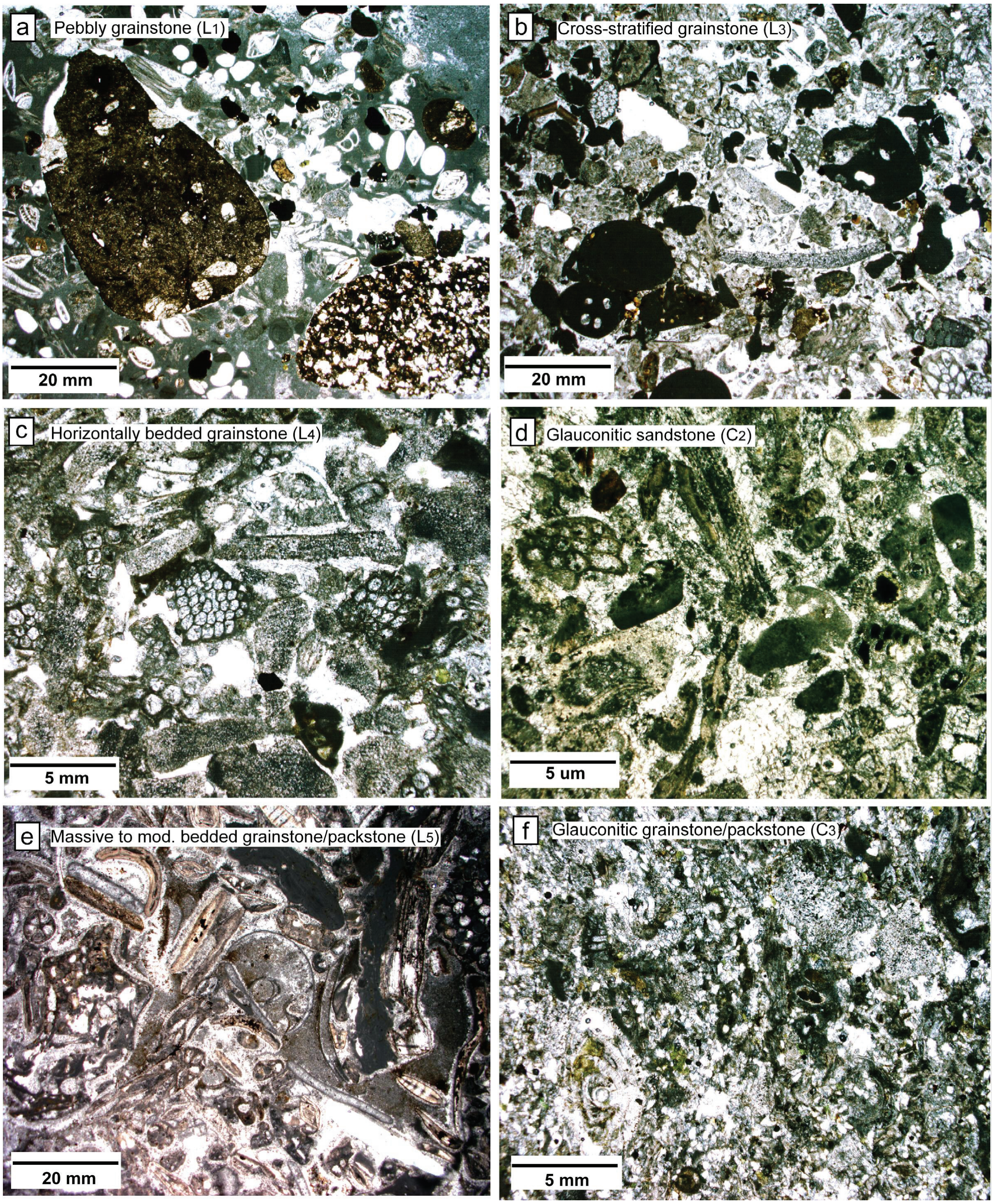


Fig.5.10: Photomicrographs of representative samples of Elgood Limestone lithofacies types in northern region (Port Waikato-Raglan Harbour). (a) Benthic foraminiferal rich with lithics of igneous origin in a coarse grained bioclastic grainstone from the base of Elgood Limestone near Te Akau (TA-3) (sample 160). (b) Bryozoan/echinoderm/calcareous red algae and bivalves in coarse sparry grainstone from near Port Waikato (PW-2) (sample 35) (c) Bryozoan/echinoderm/benthic foraminiferal sparry grainstone from near Onewhero (PW-5) (sample 49). (d) Glauconitic sandy grainstone containing echinoid and bryozoan in a sparry matrix. Sample from top of Elgood Limestone Member near Port Waikato (PW-1A) (sample 3). (e) Benthic foraminifera, echinoderm, calcareous red algae in a mixed grainstone/ packstone from near Raglan Harbour (TA-13) (sample 245). (f) Echinoderms/ benthic foraminifers with glauconite in a mixed grainstone/packstone matrix from top of Elgood Limestone Member, near Te Akau (TA-3) (sample 164).

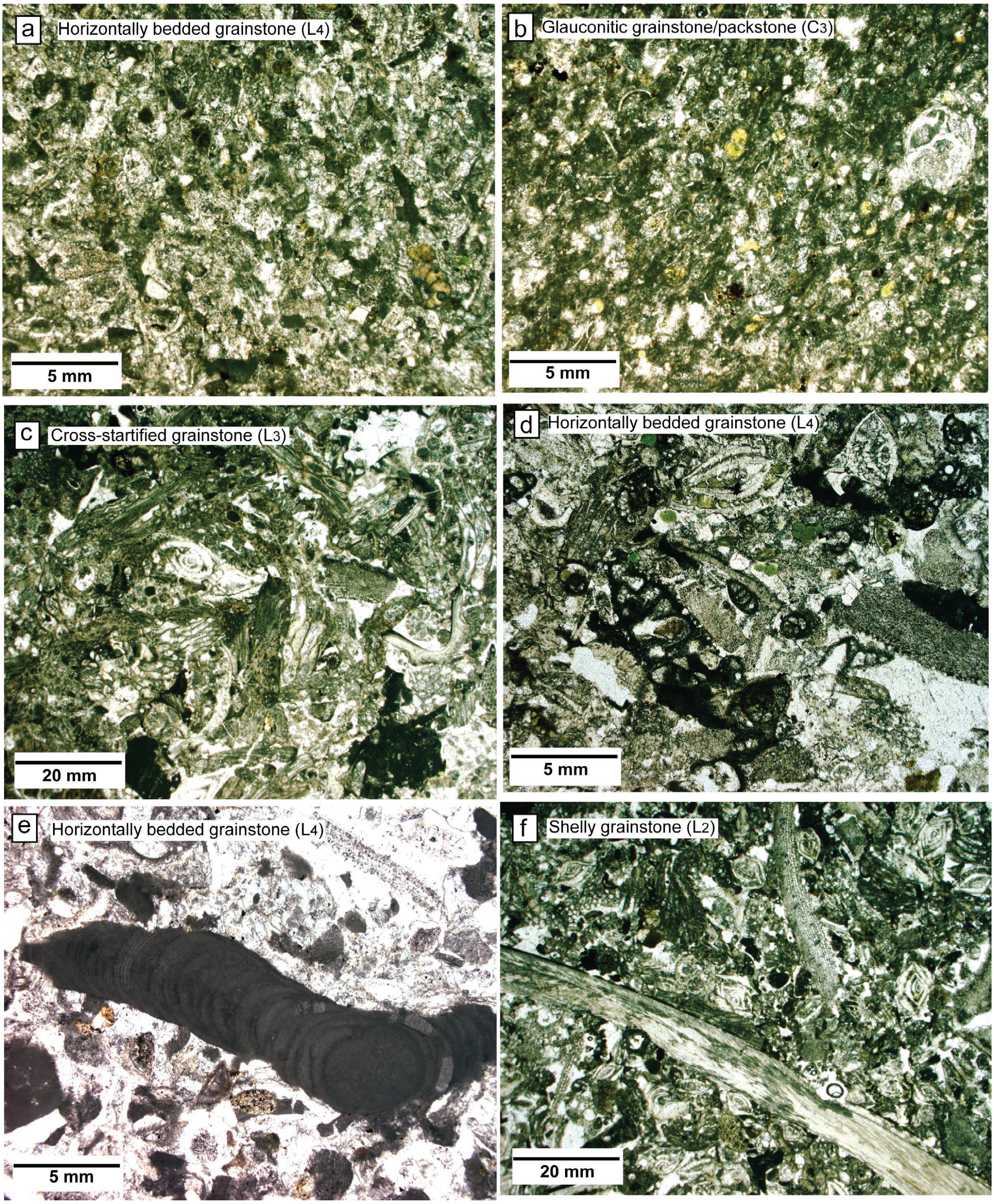


Fig. 5.11: Photomicrographs of representative samples of Elgood Limestone lithofacies types in central region (Raglan-Te Pahu-Aotea Harbour) (a) Fine-grained bioclastic grainstone of lithofacies L4; benthic foraminifers, echinoiderms, planktic foraminfers and glauconite pellets are recognisable, sample from lower part of Elgood Limestone Member at Waikoha Road, near Te Pahu-Karamu (AK-6) (sample 328). (b) Bivalves/echinoiderms/planktic/benthic foraminiferal assemblages in a glauconite rich matrix of micritized silty packstone, sample from near top of Elgood Limestone Mbr at Waikoha Road, near Te Pahu-Karamu (AK-6) (sample 332). (c) Coarse-grained bryozoan dominated grainstone of lithofacies L3, Waitiki near Aotea Harbour (AK-8) (sample 378). (d) Benthic foraminifera, echinoderm, calcareous red algae and glauconite (pallets and infills) in a sparry grainstone from near Aotea Harbour (AK-4) (sample 304). (e) Red coralline algae with lithics and bivalve fragments in a matrix of sparry grainstone (polarised light), sample from base of Elgood Limestone Member at Halliday Road near Raglan Harbour (TA-13) (sample 241) (f) Bivalve-rich/benthic foraminiferal (Amphistegina) grainstone, Shea Road near Aotea Harbour (AK-4) (sample 302).

separated by 0.5-1.5 cm thick siliciclastic-rich bedding planes (Fig. 5.9 c). Set bases and tops are generally sharp. Rocks are skeletal-rich limestone composed largely of bryozoans, echinoids, bivalve shell fragments and benthic foraminifera (Fig. 5.10 b & 5.11 c). The seams (bedding planes) consist of very fine sandstone and siltstone and in places rare rounded subangular granules. This facies is generally well developed wherever the skeletal carbonate onlaps basement and passes laterally and vertically into "Horizontally bedded limestone" lithofacies L_4 (cross sections A-A', D-D' in Fig. 5.7).

Interpretation: Cross-stratification is the product of migration of sub-aqueous dunes by oceanic currents generated by storms and/or tides, and enhanced by complex topography (e.g. Anastas 1997; Pomar & Tropeano 2001). The high degree of bioclast fragmentation and abrasion indicates a high level of physical reworking. This effectively limited the amount of bioturbation, leading to generally good preservation of cross-bed sedimentary structures (e.g. Lukasik et al. 2000)

L_4. Horizontally bedded grainstone:

This lithofacies is the most widespread in the study area and is readily recognizable in outcrop by well developed "flaggyness" resulting from preferential weathering of the siliciclastic seams, often representing bedding planes (Fig. 5.9 d). The seam thickness varies from a few millimetres to up to 1.5 - 2 cm and can be regular to undulating, or irregular and bifurcating. Physical sedimentary structures are rare and consist of occasional horizontal laminations and wave-ripples. The main constituents are fragmented skeletal material derived primarily from bryozoans, echinoderm plates and/or spines, benthic foraminifera, bivalves and coralline red algae (Figs. 5.10 c & 5.11 a, d & e). The siliciclastic content includes fine to very fine sand and silt size quartz and feldspar, and to lesser extent glauconite pellets. The "Horizontally bedded grainstone" lithofacies commonly occur in the mid to upper parts of the Elgood Limestone Member along the western margin. In more offshore (eastern) settings, this facies often occurs in association with the "Massive to moderately bedded grainstone-packstone" lithofacies (L_5) (cross sections B-B', C-C', E-E' in Fig. 5.7).

Interpretation: The skeletal sand forming the bulk of the "Horizontally bedded grainstone" lithofacies is inferred to have been derived by dislodgement, fragmentation and abrasion of rocky shoreline communities by the physical action of waves and currents, especially during storm events. These physical processes acting on the shelf are not only an important mechanism of skeletal grain formation and modification, but they also control the composition, style of transportation and accumulation (e.g. Nelson 1988a). The horizontal bedding style, the absence of cross-bedding and the fine-medium grained character of this lithofacies supports a moderate energy depositional setting. The characteristic bedding defined by the alternation of relatively enriched and impoverished siliciclastic material is likely a result of selective sorting and segregation by the action of waves and wind-driven bottom currents (Nelson 1978b).

$L_{5.}$ Massive to moderately bedded grainstone-packstone

Bedding in this facies is commonly irregular to slightly undulating, but also often massive (Fig. 5.9 e). The main skeletal types are bryozoans, echinoderm plates and spines, and planktic and benthic foraminifers (Figs 5.10e & 5.11b). In places, discontinuous shell hash beds, often rich in whole and fragmented echinoderms along with occasional scattered granule size siliciclasts, are also observed. Siliciclastic material is generally silt size, and locally includes significant amounts of glauconite. Bioturbation is characteristic of this lithofacies and in places has completely destroyed physical structures (e.g. Lukasik et al. 2000). The Massive to moderately bedded grainstone-packstone lithofacies occurs commonly in more offshore positions of the carbonate paleo-shelf (cross sections C-C', E-E' in Fig. 5.7).

Interpretation: This facies is inferred to have been deposited in wave (storm) dominated settings with bioturbation occurring during fair-weather conditions. The uncommon occurrence of echinoid coquina and terrigenous granules is probably a result of episodic storm reworking. The overall fine grained character and intensity of bioturbation, coupled with an increased content of planktic foraminifers, reflects a deeper water (mid-outer shelf) depositional setting (e.g. Boreen et al. 1993) than for underlying facies within the Elgood Limestone Member.

Mixed carbonate-siliciclastic lithofacies association (S_1 to S_6)

This lithofacies typically has a hybrid carbonate-siliciclastic composition, and it may include up to 70% carbonate content. The mixed siliciclastic-carbonate lithofacies are composed of two broad sub-facies associations, namely mixed carbonate-siliciclastic sandy siltstone and silty sandstone, typical of the Dunphail Siltstone, and Ahirau Sandstone, respectively. They occur in the field as two distinct mappable members and are laterally continuous but of variable thickness. However, there is not always a well-marked segregation between the sub-facies associations. Expectedly, the latter contains the higher proportion of fine to very fine sandstone, which is typically better cemented and more resistant to erosion than the siltstone, and as a result stands out in the landscape as "bluffy" units.

In general, and towards the western and northwestern parts of the basin, the mixed carbonate-siliciclastic lithofacies are characterised by a coarsening-upward trend from sandy siltstone to silty fine sandstone. However, the grain size of the silty sandstone facies decreases markedly in a basinward (easterly) direction, merging with the underlying siltstone facies.

At the stratigraphic level, the mixed siliciclastic-carbonate lithofacies association normally overlies carbonate-dominated facies, reflecting a smothering of carbonate "platforms" by a major pulse of siliciclastic sedimentation. Rapid vertical and lateral changes between the carbonate and mixed carbonate-siliciclastic lithofacies associations is common and facies boundaries are usually either abrupt or abruptly gradational. The Mixed siliciclastic-carbonate lithofacies of the Dunphail Siltstone and Ahirau sandstone are far more laterally extensive and volumetrically important than the Elgood Limestone Member, ranging in thickness from a few metres to about 100 metres thick.

Four mixed carbonated-siliciclastic sandstone (S_1-S_4) and two mixed carbonate-siliciclastic siltstone lithofacies (S_5-S_6) have been identified in this study.

$S_{1.}$ Calcareous pebbly-gritty sandstone:

This facies typically occurs in units from 0.2-1.0 m thick and is characterised by conspicuous concentrations of grit (1-4 mm) with common to abundant rounded to subrounded pebbles (average 2-3 cm) supported in a fine calcareous sandstone-siltstone matrix. Scattered bivalve fragments, glauconite pellets and glauconitised clasts and shells fragments are also common. Coralline red algae, including rhodoliths, are common near the base. This facies generally occurs in association with the Pebbly grainstone lithofacies (L_1), overlying basement although in rare instances may sharply overlie cross-stratified limestone (lithofacies C_3) (cross sections A-A' to C-C' & E-E' in Fig. 5.7). It passes up into either lithofacies L_1 or "Massive calcareous siltstone" lithofacies S_6.

Interpretation: The common occurrence of the benthic foraminifera *Arenodosaria antipoda and Melonis dorreeni,* along with coralline red algae and rhodoliths indicates accumulation in shallow waters (inner-shelf) (e.g. Hayward 1986; Hayward et al. 1999; James et al. 2001; Cooper et al. 2004). The common to abundant pebbles are inferred to have been sourced from nearby exposed basement and transported by storm processes a short distance from the shoreline.

$S_{2.}$ Calcareous silty fine sandstone:

This facies consists of variably calcareous fine to very fine sandstone and siltstone that is intensely bioturbated, so that primary inorganic structures are rarely identifiable. Locally, despite the bioturbation, ghosts of low-angle metre-thick trough cross-bedding is visible (Fig. 5.12 a). The trace fossils (*Skolithos* and/or *Cruziana*?) are abundant and characterised by a mixed association of vertical, inclined, and horizontal tubular structures of low diversity (Fig. 5.12 b). Scattered whole pectinids (e.g. *Chlamys williamsoni, Lentipecten hochstetteri*), occasional *Cucullaea sp*., echinoiderm plates and/or spines are common. Calcareous silty fine sandstone occurs mostly in the Ahirau Sandstone Member along the western margin (cross sections A-A' to E-E' in Fig. 5.7).

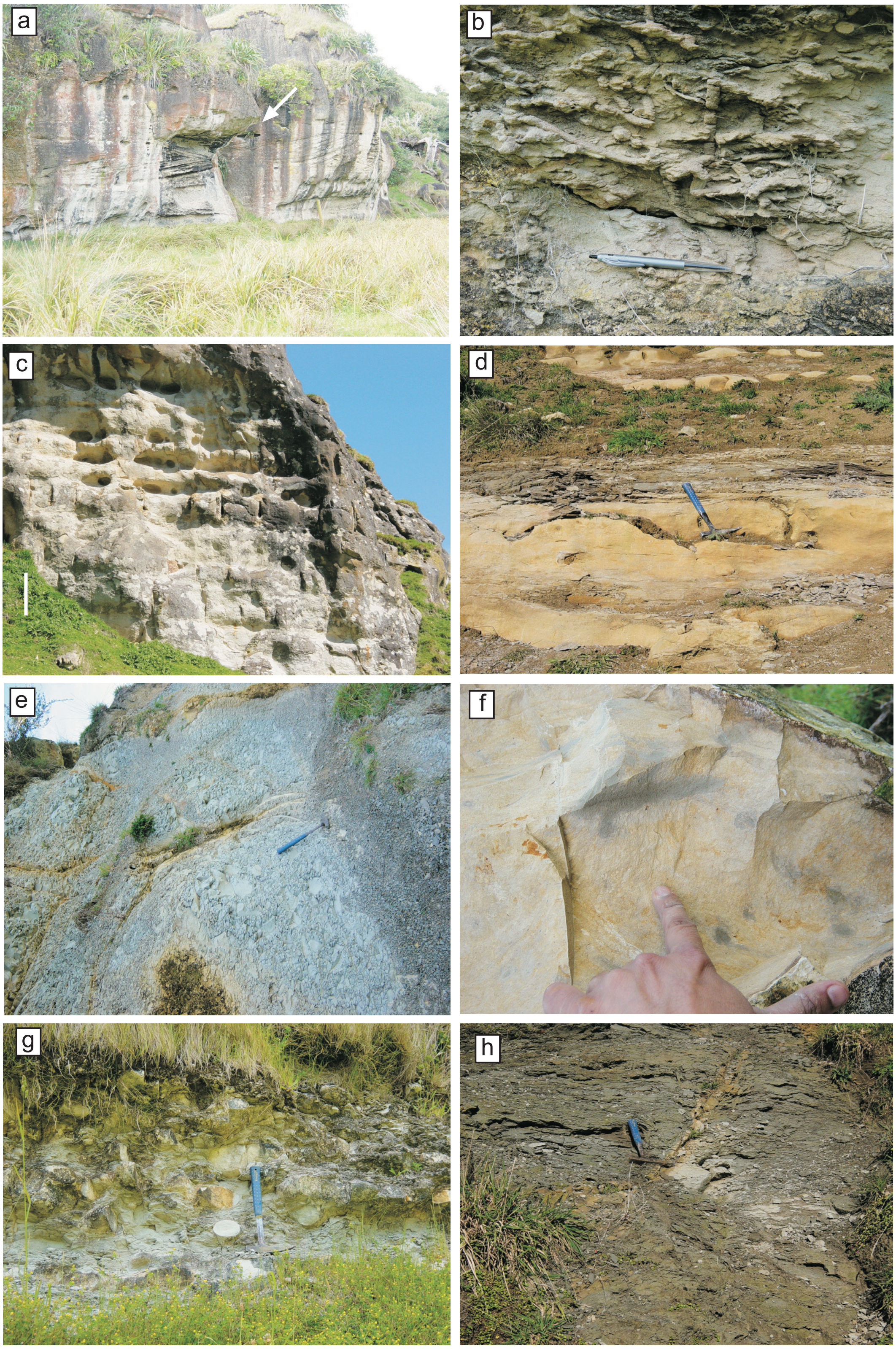
Interpretation: Common occurrence of benthic foraminifera (e.g. *Gaudryina reussi*, *Vaginulinopsis cristellata*, *Rectuvigerina striatissima, Euuvigerina maynei, Melonis maorica, Notorotalia stachei Rotaliatina sulcigera* and *Cibicides thiara*) indicates inner to mid shelf depths of sediment accumulation (e.g. Hayward 1986; Hornibrook et al. 1989; Cooper et al. 2004). Profusion of burrows belonging to the *Skolithos* and/or *Cruziana* ichnofacies, is indicative of relatively high levels of wave and current energy, and typically developed in slightly muddy, unconsolidated to shifting substrates (Lukasik et al. 2000; Pemberton et al. 2001). Locally, the presence of low-angle trough cross-stratification indicates deposition affected by current activity. This may be the result of deposition under relatively high energy levels near the existing basement highs, thus limiting the amount of bioturbation, leading to some preservation of primary sedimentary structures.

$S_{3.}$ Alternating calcareous silty fine sandstone and sandy siltstone:

This lithofacies consists of silty sandstone and sandy siltstone interbeds in which the thickness of beds range from 10 to 90 cm and interbed contacts are abruptly gradational (Fig. 5.12 c). Bivalves including mainly Pectinids (e.g. *Chlamys williamsoni, Lentipecten hochstetteri, Janupecten polemicus)* are common with occasional *Panopea* sp. Trace fossil types are similar to those in lithofacies $S_{3,}$ but there is comparatively less bioturbation overall. This facies is more characteristic of the upper parts of the Ahirau Sandstone Member in the central parts of the northern region (cross sections A-A' to D-D' in Fig. 5.7).

Interpretation: This facies represents an open shelf depositional setting. Subhorizontal bedding planes probably record high-energy (storm) events. Storm activity was probably responsible for transporting fine siliciclastic sediment into mid to outer shelf water depths, where it was mixed with carbonate material (Nelson et al. 1988). The common occurrence of benthic foraminifera such as *Cibicides thiara, Melonis*

Fig. 5.12 (facing page): (a) Trough cross-stratification (pointed to by arrow) in Calcareous silty-fine sandstone facies (S2) passes to more massive unit above, near Waikawau Stream bridge, Port Waikato-Waikaretu Road (PW-2). Fence post for scale. (b) Extensive burrow network (?Rhizocorallium) consisting of a mixed association of vertical, inclined and horizontal structures is a common feature in Calcareous silty fine sandstone lithofacies (S2). Location Waimai Stream (PW-2), pen (14 cm) for scale. (c) Typical weathering character of Alternating calcareous silty fine sandstone and siltstone lithofacies (S3), near Bothwell Road (PW-8). Note positive relief on more sandy beds as



compared to recessed silty interbeds. Bar for scale is 30 cm. (d) Photo of Interbedded calcareous siltstone and sandy limestone facies (S5). Hammer for scale. Photo location Bothwell Road (PW-8). (e) “Frittered” surface, a typical weathering character of massive calcareous siltstone facies (S6), at Dunphail Bluff (TA-17). Hammer for scale. (f) Close-up of “stirred or mottled” structure indicating pervasive bioturbation apparent in the massive calcareous siltstone lithofacies (S6) at Dunphail Bluff (TA-17). (g) Concretionary bands define bedding characteristics in the upper part of Massive calcareous siltstone lithofacies (S6), near Awamarino (C-51). Hammer for scale. (h) “Frittered” surface weathering typical of moderately bioturbated Massive muddy sandstone (S4), forming the upper part of Glen Massey Formation near Ngapaenga (C-68). Hammer for scale.

maorica, Vaginulinopsis cristellata and Euvigerina maynei support mid to outer shelf depths (e.g. Hayward 1986; Hornibrook et al. 1989).

S_4. Massive muddy sandstone:

This facies gradationally overlies "Massive calcareous siltstone" (lithofacies S_6), and is characterised by an increase in the content of fine to very fine siliciclastic sandstone compared with lithofacies S_6 (Fig. 5.12 h). In outcrop this massive muddy sandstone is moderately highly bioturbated with common inclined and sub-horizontal burrows that probably resulted in obliteration of most of the primary sedimentary structures. The facies is variably calcareous, and contains scattered bivalve (mainly pectinid) fragments. This facies is restricted mainly to the upper parts of the Glen Massey Formation in the southwestern parts of the basin and laterally grades into massive calcareous siltstone (lithofacies S_6) in an offshore direction (cross section E-E' in Fig. 5.7).

Interpretation: The introduction of fine to very fine sand (compared with the underlying massive calcareous siltstone lithofacies S_6) is probably due by storm currents, or it may reflect a change in sediment supply. The trace fossil assemblage is characteristic of the mixed *Skolithos*-C*ruziana* ichnofacies, indicating a depositional environment below fair-weather but above storm wave-base (e.g. Lukasik et al. 2000; Pemberton et al. 2001).

S_5. Interbedded calcareous siltstone and sandy limestone:

This facies consists of sandy limestone beds about 5-18 cm thick, alternating with 10-30 cm-thick calcareous siltstone beds. The bedding is discrete with the individual sandy limestone beds having sharp bases and tops (Fig. 5.10 d). The interbedded siltstone is variably bioturbated. The interbedded calcareous siltstone and sandy limestone facies commonly overlie lithofacies L_5, and in turn pass up into massive calcareous siltstone (lithofacies S_6). This facies has a restricted occurrence such as at Bothwell Road and Matakitaki Trig within the Onewhero area, where it forms the lower part of the Dunphail Siltstone Member.

Interpretation: The sandy limestone interbeds are inferred to have been transported from inner-shelf areas and deposited at mid to outer shelf depths by storm processes, interrupting otherwise tranquil background sedimentation of fine calcareous silt in an overall low-energy shelf environment (e.g. Nelson 1988a)..

S_6. Massive calcareous siltstone:

This lithofacies is widespread and forms the bulk of the Glen Massey Formation, particularly in more basinal central and eastern areas (Fig. 5.2). The siltstone is blue-grey to brownish and lacks any primary sedimentary structures. This massiveness is occasionally interrupted by concretionary bands (Nelson 1973) (Fig. 5.12 g). Individual trace fossils are not identifiable but in places there is an overall “stirred or mottled” aspect to the rock suggestive of pervasive bioturbation (Fig. 5.12 e & f). In places, the massive siltstone contains scattered whole bivalve shells and fragments. The carbonate content usually falls in the range 40-50% and the siltstone may contain small amounts of very fine to fine terrigenous sand. Occasionally a few thin very glauconitic laminae are present, especially near the base or top of this facies. Along the western belt of Glen Massey exposures, the massive calcareous siltstone facies commonly passes upward into the sandstone lithofacies (S_1-S_4) association (cross sections A-A’ to E-E’ in Fig. 5.7).

Interpretation: This facies is inferred to have been deposited in open outer-shelf to upper bathyal depths. The predominance of fine terrigenous siltstone (Fig. 5.4) suggests deposition below fair-weather wave-base and possibly even beneath the wave- base of the most intense storms. The regional extent of this facies strongly suggests an extensive depocentre, quite removed from any coarse siliciclastic input, and therefore probably relatively deep. The benthic foraminifers *Cibicides thiara, Semivulvulina capitata, Gyroidinoides allani, Sphaeroidina bulloides*, *Cibicides perforatus,* and *Globocassidulina subglobosa* all suggest slightly deeper (outer shelf to upper bathyal) water depths (e.g. Hayward 1986; Hornibrook et al. 1989).

Chemogenic lithofacies (C_1-C_3)

Although glauconite is ubiquitous throughout the Glen Massey Formation, sometimes it can reach unusually high concentrations (≥10%). The name chemogenic lithofacies is used here for those lithologies rich in glauconite and/or phosphate, commonly associated with abundant bioturbation.

The glauconite and or phosphate-rich horizons occur at significant stratigraphic levels such as near the base and top of the formation. At Dunphail Bluffs, the type locality of Glen Massey Formation, a medium to coarse glauconitic calcareous sandstone occurs at the base of the formation. Glauconite (or greensand) is more abundant at the base particularly over most of the Huntly Coalfield and in western parts of the Kawhia Coalfield. In these areas the glauconitic-rich units are inferred to represent stratigraphic condensation of Glen Massey Formation (Kear & Schofield 1959, 1978).

The colour and morphology of the glauconite grains suggests that allochthonous (reworked) grains are more common than autochthonous (in place) material in the Te Kuiti Group, although both may occur within the same unit (Nelson 1973, 1978b). The morphology of glauconite in the Glen Massey Formation is dominated by ovoidal forms (c. 60%) suggesting some degree of reworking (Compton 1989). Both allocthonous and autochthonous glauconite in New Zealand are attributed to very slow sedimentation rates (Nelson 1978b).

Several authors have related the abundance of glauconite and other authigenic minerals to extremely low sedimentation rates associated with times of relative sea-level rise (e.g. Posamentier et al. 1988; Loutit et al. 1988; Amorosi 1995). The events that produce high concentrations of authigenic minerals are commonly associated with marine hiatus and often occur either as thin but continuous zones of burrowed slightly lithified beds (omission surfaces) or marine hardground (Loutit et al. 1988). Three chemogenic lithofacies have been identified in this study.

$C_{1.}$ Phosphate nodule bed:

This facies is characterised by scattered authigenic phosphate nodules and an abundance of cm-scale sub-horizontal and inclined burrows capping the calcareous silty fine sandstone lithofacies (S_2), such as at Waikawau Beach (PW-11) near Port Waikato. It is also moderately glauconitic and is abruptly overlain by massive siltstone (Kotuku Siltstone Member) of the Whaingaroa Formation (Fig. 5.13 a).

Interpretation: The phosphate nodule bed is inferred to be a marine phosphatic hardground/firmground formed during deepening of a former relatively shallow-water, high energy setting during times when sediment accumulation was low. The phosphatic and glauconitic concentration associated with the hardground indicates its formation was perhaps related to local upwelling during drowning. The abundance of burrowing suggests open marine, well oxygenated and nutrient rich conditions, probably induced by upwelling. These types of hardground are common on high-energy shelves with cool, upwelling waters and slow terrigenous sedimentation rates, typical of the modern-day cool-water carbonates off South Australia (James et al. 1992; Boreen et al. 1993).

$C_{2.}$ Glauconitic calcareous siltstone-sandstone:

This facies is characterised by the presence of pale to dark green glauconite pellets, of up to 0.4 mm size, scattered in massive, intensely bioturbated fine to medium sandstone and/or siltstone (Fig. 5.10 d). These sandstone and siltstone beds are typically poorly to moderately cemented, and contain scattered bivalve shell fragments, which are themselves frequently glauconitised (Fig. 5.13 b). This facies occurs as multiple glauconite rich horizons near the base of the Glen Massey Formation, forming a distinct stratigraphic marker in many drill holes within the Huntly region (Kear & Schofield 1959, 1978; Edbrooke 1984) (cross section A-A' & D-D' in Fig. 5.7). Along the western margin, this facies occurs locally in close

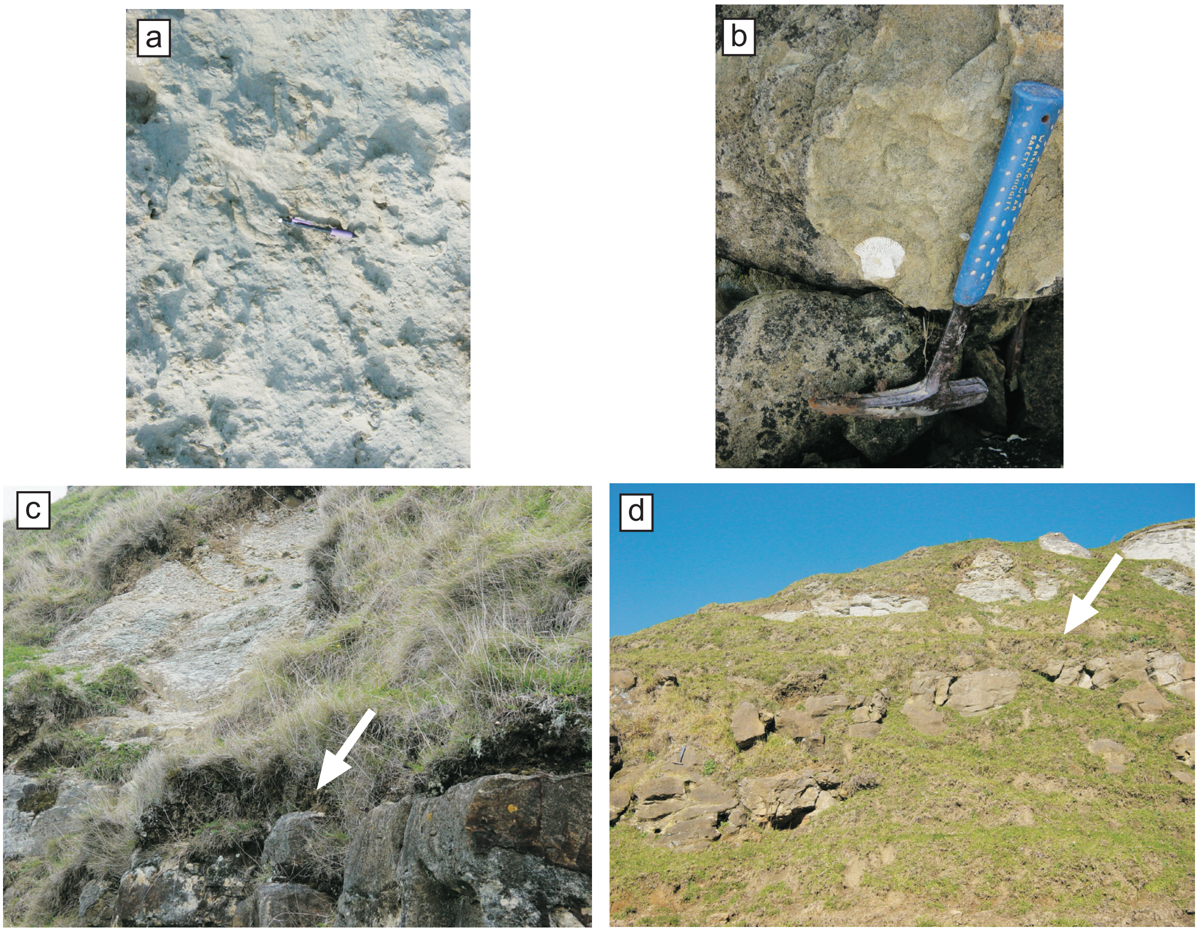


Fig. 5.13: The surface comprising moderately glauconitic silty sandstone with phosphate nodules (lithofacies C1), and abundance of sub-horizontal and inclined burrows. This surface is inferred to be a marine firmground/hardground, forming a conformable but sharp lithostratigraphic contact between the Glen Massey Formation and the overlying Whaingaroa Formation at Waikawau Beach (PW-11). Pen (14 cm) for scale. (b) Large pectinid coquina in highly glauconitic calcareous sandstone (lithofacies C2) at Waitetuna Estuary, Raglan Harbour (TA-14). Hammer for scale. (c) Outcrop expression of maximum flooding surface (pointed by arrow). This surface comprises grainstone-packstone with high concentration of glauconite (lithofacies C3). Transgressive and highstand systems tracts, respectively occur under and over the maximum flooding surface. Bar for scale is 30 cm long, Photo location Waikoha Road, Te Pahu-Karamu (AK-6). (d) Massive to moderately bedded grainstone-packstone (lithofacies L5) capped by glauconitic sandstone (pointed by arrow) that represent the maximum flooding surface that passes upwards into massive calcareous siltstone (lithofacies S6). Hammer for scale. Photo location Port Waikato (PW-1A).

association with calcareous pebbly-gritty sandstone (lithofacies S_1), overlying a significant regional unconformity.

Interpretation: The widespread occurrence of "greensand" or glauconitic sandstone at the base of Glen Massey Formation has been reported over much of the Huntly Coalfield area. This facies is inferred to have accumulated in low-energy deep water conditions and to be indicative of progressive basinward sediment starvation. It includes both autochthonous glauconite reflecting a sediment starved outer-shelf area and allochthonous glauconite, which was probably remobilised seawards by waves and storm events from shallower marine settings (e.g. Amorosi 1995). Extremely slow sedimentation rates allowed burrowing organisms sufficient time to homogenise the sediment. Sporadic occurrences of this facies along the western margin, especially in association with the high energy deposits of lithofacies S_1, is probably due to localised sediment bypass during an initial rise in relative sea-level.

C_3. Glauconitic sandy-silty grainstone-packstone:

The "Glauconitic grainstone-packstone" lithofacies occurs in close association with carbonate facies, and is characterised by a high concentration of glauconite ($\geq$10%), either near the base of the "Pebbly and/or Shelly grainstone" lithofacies L_1/L_2) or more commonly near the top of the Massive to moderately bedded grainstone-packstone (lithofacies L_5); that is, at the top of the Elgood Limestone Member (cross section C-C' to E-E' in Fig. 5.7). The occurrence of facies C_3 near the base of L_1/L_2 is most noticeable at a few localities along the western margin, where it also contains variable amounts of siliciclastic medium to coarse sandstone, pectinids and oyster shell fragments, large benthic foraminifera (*Amphistegina*) and coralline algae. In some localities facies C_3 interfingers or grades laterally into glauconitic calcareous siltstone-sandstone (lithofacies C_2). This facies also occurs as finely disseminated glauconite-rich horizons in the uppermost portion of moderately bedded grainstone-packstone (lithofacies L_5) and lowermost massive calcareous siltstone (lithofacies S_5). It displays variable bioturbation and abundance of bivalves and increased abundance of planktic foraminifera (Fig. 5.10 f , 5.11 b & Fig. 5.13 c, d).

Interpretation: The presence of this facies at the base of pebbly and/or shelly grainstone (lithofacies L_1/L_2) is interpreted to represent an initial period of base-level rise resulting in flooding and sediment starvation of previously exposed land areas, which may provide favourable conditions for the growth of glauconite (e.g. Amorosi 1995). The presence of large benthic foraminifera (e.g. *Amphistegina)* and calcareous red algae reflects shallow-water reworking by waves and tidal currents (James et al. 2001). However, the presence of facies C_3 at the top of grainstone-packstone (lithofacies L_5) is indicative of increased water depth and resultant sediment starvation, which are also favourable for glauconite accumulation (e.g. Loutit et al. 1988; Amorosi 1995).

Facies distribution and paleoenvironmental implications

The facies described in the previous section have shown that the Glen Massey Formation in the western areas comprises three main facies associations. The Elgood Limestone is dominated by carbonate lithofacies (L_1-L_5), the Dunphail Siltstone by mixed carbonate siliciclastic siltstone (S_5, S_6), and the Ahirau Sandstone by mixed carbonate-siliciclastic sandstone (S_1-S_4). Apart from these main facies, the chemogenic lithofacies with high concentrations of glauconite and/or phosphate occur in association with either carbonate or mixed carbonate-siliciclastic sandstone lithofacies. The restriction of the main lithofacies to related stratigraphic members is summarised in Table 5.2. The lateral and vertical facies distribution within the Glen Massey Formation is shown for five transects through the basin in Fig. 5.7 (a-e).

Table 5.2: Lithofacies distribution within the members of the Glen Massey Formation.

Members	Lithofacies
Ahirau Sandstone	S_2, S_3, S_4, C_1
Dunphail Siltstone	S_1, S_5, S_6
Elgood Limestone	S_1, L_1, L_2, L_3, L_4, $L_{5,}$ $C_{2,}$ C_3

The onset of Glen Massey deposition was marked by significant marine flooding across the basin. The initial transgressive deposits consist of carbonate lithofacies (L_1-L_5) that accumulated close to shore along the western margin, as well as upon isolated basement paleohighs. The majority of the shallow water, high energy carbonate lithofacies (L_1-L_3) is common in the lower part of the Elgood Limestone Member along the western margin. These shallow water facies pass eastward into horizontally bedded to massive grainstone/packstone facies (L_4-L_5) inferred to have been deposited in a more open, deep water shelf setting. The horizontally bedded to massive grainstone/packstone facies in turn grades eastward into calcareous siltstone/sandstone (sandy marl) with relatively high concentrations of glauconite (lithofacies C_2, C_3). The lateral facies relationships in the lower part of the Elgood Limestone Member are shown in Fig. 5.8. In summary, the depositional setting for the carbonate lithofacies is interpreted to have been a low-gradient shelf, with shallower areas towards the west. The strong development of carbonate lithofacies in the northwest compared with the central and southern areas, suggests that the shelf areas in the northwest were located away from significant siliciclastic input (Fig. 5.1). The facies pattern within Elgood Limestone in northwestern areas in general shows a transition from the “Pebbly and Shelly cross-bedded skeletal grainstone” lithofacies (L_1-L_3) to “Horizontally bedded grainstone” lithofacies (L_4) indicative of deepening upward or retrogradation. The localised occurrence of thin (1-1.5 m) “Glauconitic grainstone and foraminiferal siltstone” (i.e. lithofacies C_2 and C_3) over the “Massive to moderately bedded grainstone-packstone” (lithofacies L_5) in more eastern localities (best exemplified by AK-6 in Fig. 5.7 c and C-51 in Fig. 5.7 e), provides evidence for a similar deepening trend.

The carbonate lithofacies pass upward into mainly “Calcareous siltstone” lithofacies (S_6). The S_6 lithofacies is thickest (up to 180 m) towards the east and northeast (Fig. 5.2), and in southern localities are the main deposits (Fig. 5.7 e). This facies contains mainly silt and clay-sized detrital material and some fine to medium sandstone (Fig. 5.6 a-h). The lithological composition and faunal content suggests deposition via suspension in a low energy outer shelf to upper bathyal setting.

In the western and northwestern parts of the basin, the “Calcareous siltstone” lithofacies (S_6) of the Dunphail Siltstone Member grade upward into well-cemented “Calcareous silty fine sandstone” (i.e. S_2), which in turn passes laterally to the east into alternating calcareous fine silty sandstone and siltstone (i.e. S_3). The lithofacies S_1 and S_2 containing the higher proportion of fine sandstone Ahirau Sandstone (Fig. 5.6) typically exhibits a high intensity of bioturbation and the scattered presence of bivalves (pectinids). S_2 lithofacies have some indication of low-angle trough cross bedding in the northwestern area (e.g. PW-2 in Fig. 5.7 a). Compared with underlying “Calcareous siltstone” lithofacies (S_6), the “Sandstone” lithofacies (i.e. S_1-S_4) indicate a shallower water depositional environment probably in an inner to mid-shelf setting, with the clastic input inferred to have been derived from the basement exposed to the west. These sandstone lithofacies are largely absent towards the eastern and southern areas (i.e. south of Kawhia Harbour), where “Calcareous siltstone” (S_6) occurs as the main lithofacies.

Sequence stratigraphy

Introduction

This section applies sequence stratigraphic concepts and terminology to the Glen Massey Formation. The traditional lithofacies descriptions made earlier in this chapter is the basis for interpretation of related depositional paleoenvironments and assist in the development of a sequence stratigraphic model for Glen Massey Formation. Sequence stratigraphy is fundamentally about the identification of key surfaces, stratal patterns between key surfaces, and linked depositional systems. In this section the sequence architecture within the Glen Massey Formation is outlined from consideration of these elements, and it leads to an improved understanding of the evolution of the early part of the basin fill.

Mitchum’s (1977) definition of the term “sequence” as a relatively conformable succession of genetically related strata bounded by unconformities or their correlative conformities is adopted here. Sequence stratigraphy is the recognition and correlation of stratigraphic surfaces, which represent changes in depositional patterns in sedimentary rocks. Such changes were generated by the interplay of sedimentation, subsidence and oscillating base level which can be determined from sedimentologic analysis and geometric relationships (Embry 2001). The identification and correlation of key stratigraphic surfaces (sequence boundary, transgressive surface of erosion, downlap surface and maximum flooding surface) provide the framework for grouping facies within linked depositional systems or systems tracts. In this study, “relative sea level” means the integration of eustatic changes in sea-level with changes in the rate of subsidence; relative sea-level controls the rate of change in accommodation, which is fundamentally expressed in the stratal patterns of onlap, downlap, toplap and offlap.

Overview and general setting

Kear & Schofield’s (1959) observations may be considered to be the first identification of stratigraphic cyclicity in the Te Kuiti Group, whereby unconformities provided the basic subdivision of the Te Kuiti Group rock record. The importance of unconformities in subdividing the Te Kuiti Group was explicitly emphasised by Nelson (1973, 1978a), who stated that “formations and members are commonly bounded by unconformities, mainly disconformities…”. A novel study investigating cyclicity in the Te Kuiti Group succession, and the relationship between sedimentation, unconformities and changes in base level, which are directly relevant to sequence stratigraphy, was written by Vella (1967) prior to the birth of the modern concepts of sequence stratigraphy. He proposed a global sea-level cycle chart that linked the cyclicity observed in New Zealand’s Eocene and Oligocene strata (including the Te Kuiti Group) to similar age strata occurring in other parts of the world, based on the underlying assumption that glacio-eustacy is the main driving force behind the cyclicity. This study utilises the insights from these previous studies, and builds upon them by interpreting Te Kuiti Group strata in a sequence stratigraphic framework.

Good exposures of the Glen Massey Formation along the western sector of the basin provide reasonably continuous outcrop sections of mixed carbonate-siliciclastic basin margin facies over the scale of hundreds of metres. However, despite good local continuity of outcrop and exposure, it is difficult to construct lateral facies transitions from nearshore to offshore locations, because of the generally widely scattered nature of outcrops and drill holes.

The early Oligocene paleogeography, and especially the presence of a semi-continuous basement structural high along the western margin (envisaged to have extended from present day Port Waikato to some distance south of Marokopa), had a strong influence on deposition of the Glen Massey Formation. This basement high passed eastwards via a gently sloping shelf into the basin. However, it should be noted that a shelf-slope-basin system of continental margin scale is not envisaged here. The greatest water depths occurred over the axis of the Waikato Coal Region, but basinal water depths probably never exceeded a few hundred metres at most.

In general, the vertical facies succession within the Glen Massey Formation consists of three lithofacies end members: (i) limestone, (ii) mixed carbonate-siliciclastic siltstone, and (iii) mixed carbonate-siliciclastic sandstone. Because of lateral variations, however, different vertical successions may be present along the paleoshelf. These vertical facies transitions and their inferred depositional paleoenvironments imply that the Glen Massey sequence is made up generally of a lower deepening, and an upper shoaling component; that is, a transgressive systems tract and a regressive systems tract.

Sequence architecture

The architecture of the Glen Massey sequence observed today in outcrop is essentially a function of the particular part of the paleoshelf that is now exposed. All the distinct characteristics or variations in the sequence architecture are depicted in Fig. 5.14. The architecture comprises the following system tracts and surfaces in ascending stratigraphic order: (i) a basal unconformable sequence boundary superposed by a transgressive surface of erosion or its correlative conformity, (ii) a variably thick (<1-30 m) transgressive systems tract (TST) composed of carbonate facies (lithofacies L_1-L_5), (iii) a maximum flooding surface (MFS) closely associated with a downlap surface (DLS), (iv) a highstand systems tract (HST) ~1-40 m thick that typically comprises an aggradational interval of calcareous siltstone (lithofacies S_6) that gradationally passes upward into, (v) a regressive systems tract (RST) ~ 2-80 m thick that comprises progradational calcareous silty sandstone (lithofacies S_2-S_4) (Fig. 5.12). The different styles depicted in Fig. 5.14 represent the different motifs or expressions of sequence architecture observed in the field as a result of different thicknesses and facies influenced largely by paleoposition on the shelf to basin profile.

The Glen Massey sequence in more offshore paleoshelf positions contains a thin transgressive system tract reflecting stratigraphic condensation, similar to the asymmetric sequence architecture documented for Late Pliocene-Early Pleistocene sequences in the Rangitikei Group (Naish & Kamp 1997).

The following sections describe and interpret the key stratigraphic surfaces and systems tracts for the Glen Massey sequence. The interpretation of stratigraphic surfaces is based on two types of observations: the type of stratigraphic contact (conformable or unconformable) and the nature of the facies (depositional systems) either side of the contact.

Sequence boundary

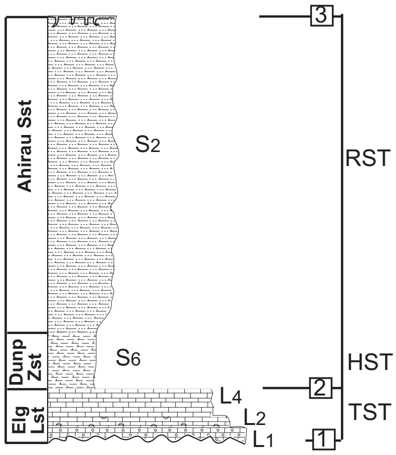
The sequence boundary at the base of the Glen Massey sequence represents a ‘flooding surface’. A flooding surface is defined as a ‘surface separating younger from older strata across which there is evidence of an abrupt increase in water depth’ (Van Wagoner 1995). This deepening is commonly accompanied by minor wave or submarine erosion or non deposition. A flooding surface which shows appreciable evidence of erosion during transgression is regarded as a ‘transgressive surface of erosion’ (TSE) or transgressive ravinement surface (Posamentier & Allen 1999; Nummendal & Swift 1987). The lower sequence boundary of the Glen Massey Formation is a sharp planar surface truncating the strata below, and qualifies as a TSE superimposed on a pre-existing subaerial erosion surface. In the deeper water setting of the eastern part of the basin, however, there is probably a correlative conformity (Fig. 5.15 a, b & c). TSEs are commonly overlain by a thin lag deposit, including granules, coarse sandstone and shell hash, indicating a variable degree of erosion by waves and current action in the process of their formation (Fig. 5.15 d). During sediment transport, coarse clasts and large bivalve fragments are left behind as a transgressive lag on top of the wave planned ravinement surface (e.g. Swift 1976). The greatest amount of erosion is associated with the zones of highest energy, normally being the wave zone, and as sea level rises on wave dominated coastlines, the zone of erosion will be translated landward. Within the Glen Massey sequence, the lower sequence boundary with a sharp contact and well developed transgressive lags are observed along the western margin, comprising architectural styles 2, 10 and 13 (Fig. 5.14). The presence of a transgressive lag consisting of pebble-size to cobble-size clasts above the TSE are the major controlling factor for the development of rhodoliths during the initial stages of transgression in the Glen Massey sequence (Nalin et al. 2008).

A different type of flooding surface from the erosional type described above involves the development of firmgrounds and hardgrounds. In this case the substrate beneath the flooding surface is characterized by extensive burrowing, and possibly by seafloor cementation (Fig. 5.15 h). Transgressive lag deposits or other evidence of erosion is not apparent with this type of flooding surface. A period of non-deposition is inferred during the formation of firmgrounds (omission surfaces) (e.g. Catuneanu 2006). Such flooding surfaces and sequence boundaries are interpreted to have been associated with significant stages of deepening and sediment starvation. In the field area, firmgrounds are represented in the Glen Massey sequence by styles 1 and 4 (Fig. 5.14).

The sequence boundary flooding surface can be demarcated by the high

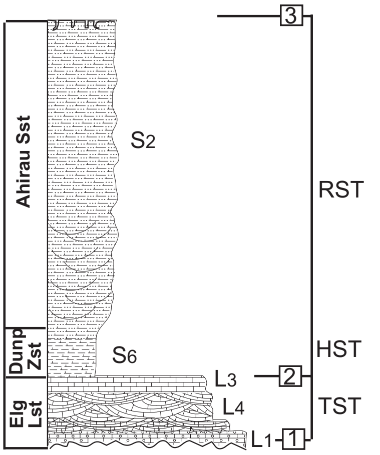
Style 1

Example: Port Waikato, Shea Road



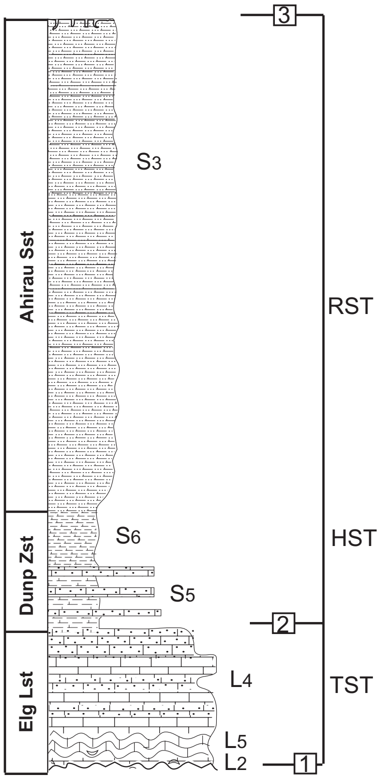
Style 2

Example: Port Waikato-Waikaretu Road



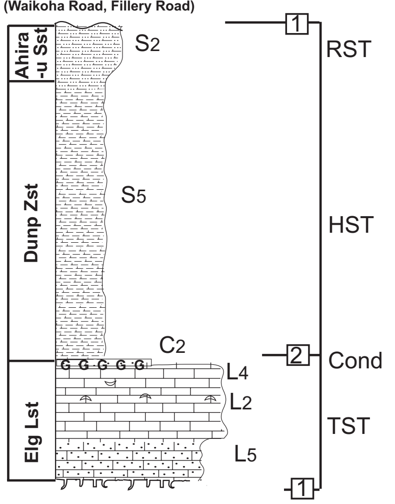
Style 3

Example: Wairamarama-Onewhero (Matataki Trig), Bothwell Road



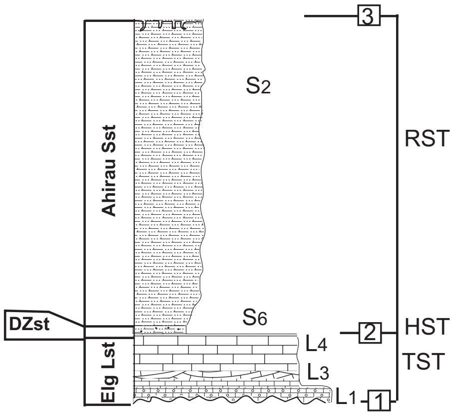
Style 4

Example: Awamarino, Te Pahu-Karamu (Waikoha Road, Fillery Road)



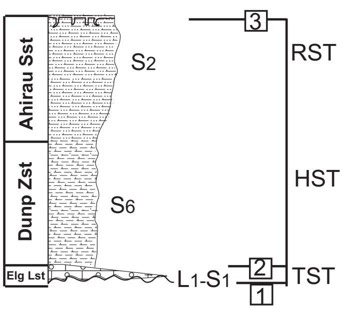
Style 6

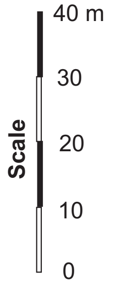
Example: Waikaretu, Waimai Valley

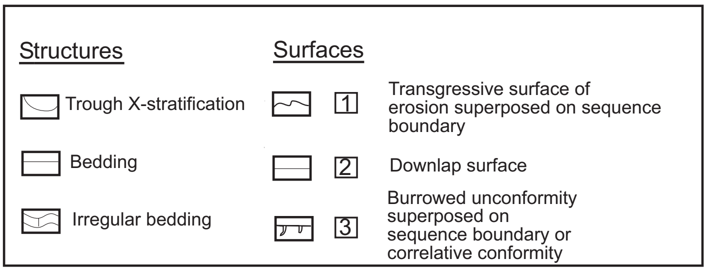


Style 5

Example: Aotea-Kawhia Harbour (Orotangi Cliff)







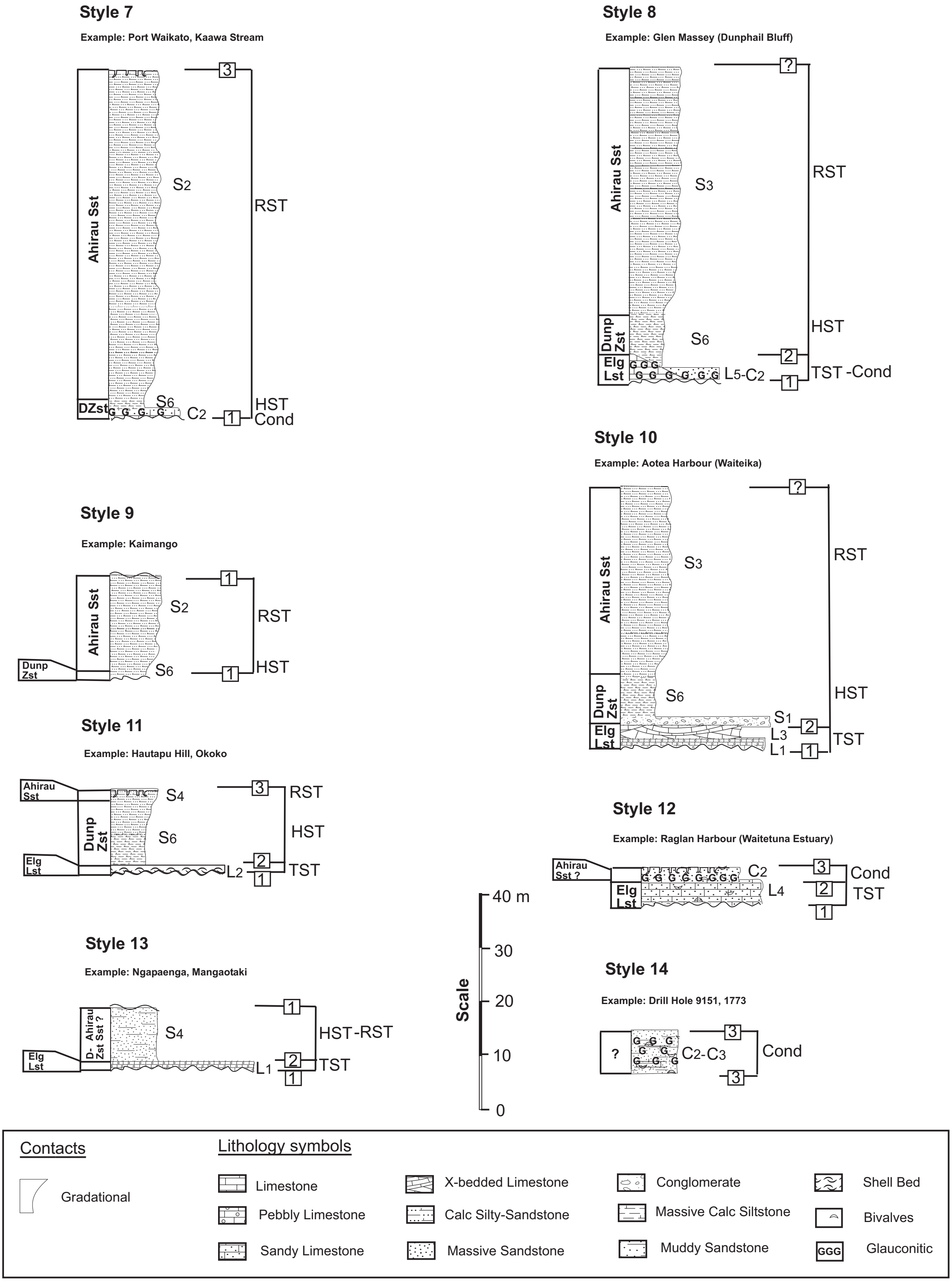


Fig.5.14 (facing page & this page): Detailed lithologic logs for Glen Massey Formation showing the variation in sequence architecture, the vertical lithofacies successions developed within the component system tracts, and the stratigraphic surfaces defined in relation to the relative base-level change. See Table 5.1 for lithofacies abbreviations. Abbreviations: TST- transgressive systems tract; HST- highstand systems tract; RST- regressive systems tract; CS- condensed section.

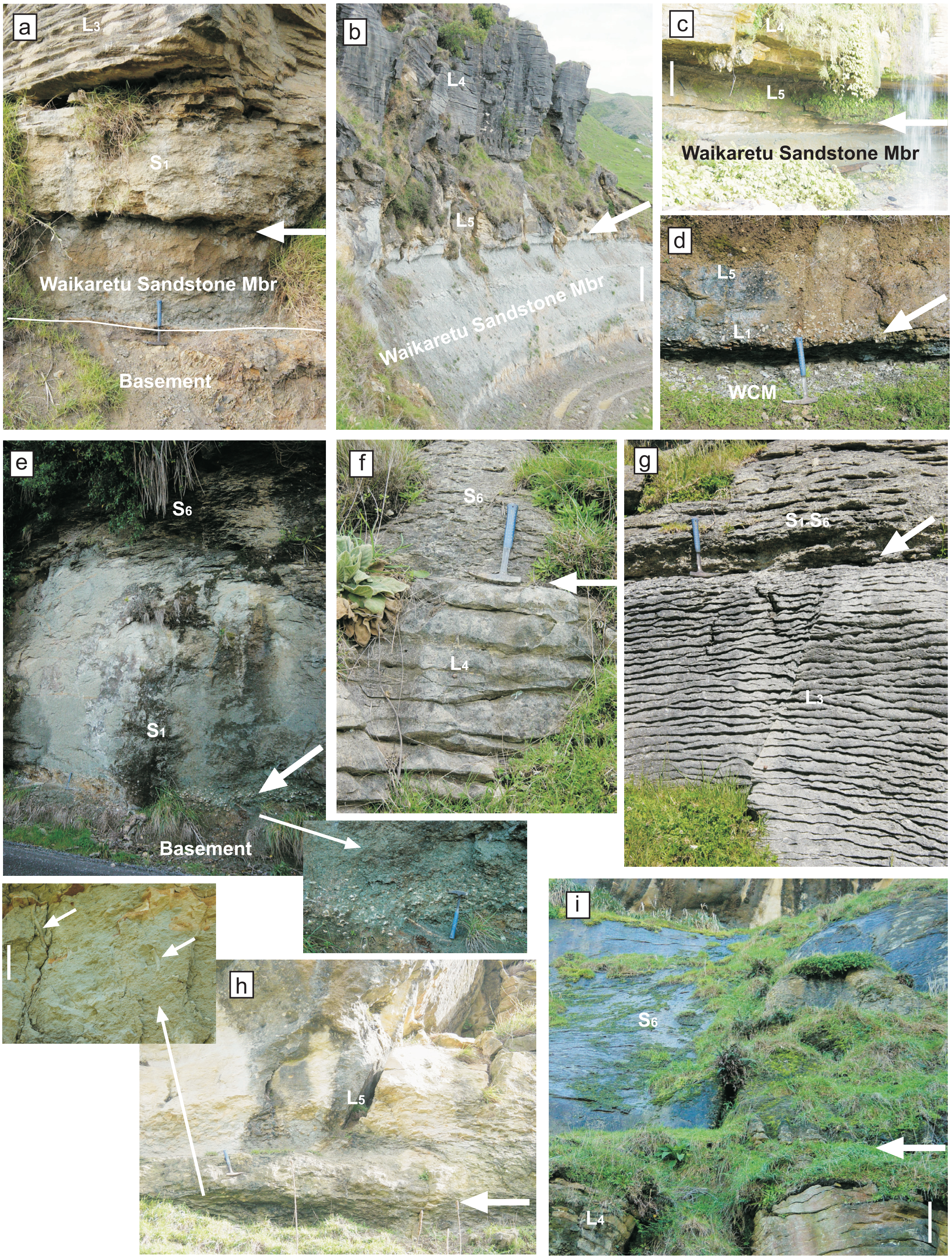


Fig. 5.15: Photos of outcrop expression of stratal surfaces (a) A transgressive wave-ravinement surface (arrow) at the contact between muddy-sandstone (with common pebble size basement clasts and coal fragments inferred as transgressive lag) estuarine highstand deposit (sequence 1) below (Waikaretu Sandstone Member) and a transgressive shallow marine "Pebbly-gritty calcareous sandstone" (lithofacies S1) above (Elgood Limestone Member) near Waikawau Stream bridge Port Waikato-Waikaretu Road (PW-2). Note micro-relief on this contact caused by wave scouring. This surface fits the definition of 'flooding surface', is part of sequence boundary. Hammer for scale.

concentrations of glauconite in stratigraphic sections such as depicted in style 7 (Fig. 5.14). This probably represents localised sediment bypass. However, concentrations of glauconite are more commonly observed in stratigraphic sections such as represented in style 8 (Fig. 5.14), located farther offshore relative to the shoreline position at the onset of transgression. The association of glauconitic rich deposits with the sequence boundary is most evident in the basinal areas to the east where they delineate an abrupt contact between Waikato Coal Measures and Mangakotuku siltstone and overlying condensed transgressive deposits such as depicted in style 14 (Fig. 5.14).

Downlap Surface

The downlap surface (DLS) is a surface that can be mapped in seismic reflection profiles as a result of more steeply dipping beds overlying beds with a shallower dip. In outcrops, a DLS can be inferred between beds that accumulated during landward directed onlap and subsequent strata that accumulated during offlap. The DLS usually coincides with or lies a short distance (< 1m) above the maximum flooding surface (MFS), which marks seafloor at the point of maximum shoreline elevation (e.g. Carter et al. 1996). Hence the DLS separates retrograding strata below from prograding strata above, and the DLS starts to form when accommodation is no longer formed at the shoreline and sediment being supplied across the shoreline

(b) A flooding surface (sequence boundary) demarcated by firmground/hardground (arrow) at the contact between muddy sandstone below (Waikaretu Sandstone Member) and massive to moderately bedded grainstone-packstone (Elgood Limestone Member) above. Bar for scale is 2 m. Photo location Waikoha Road (AK-6), Te Pahu-Karamu. (c) Wave-ravinement surface (arrow) separating transgressive “Massive to moderately bedded grainstone-packstone” (lithofacies L5) from underlying moderately carbonaceous muddy sandstone (Waikaretu Sandstone Member). Note sharp lithological contact between sandstone below to limestone above suggests this as a ‘flooding surface’, near Waikaretu walkway (PW-9). Bar for scale is 30 cm. (d) An example of transgressive lag deposits (arrow) comprising abundant rounded-subrounded pebble band associated with wave-ravinement surface (sequence boundary) at the contact between Elgood Limestone Member and Waikato Coal Measure (WCM), near Mangaotaki (C-145), West of Piopio. Hammer for scale. (e) Transgressive lag deposits comprising “Pebbly-gritty sandstone” (lithofacies S1) with occasional bivalve shell fragments and rhodoliths at the base in contact with basement, near Ruaweke Point AK-7), on the eastern shore of Aotea Harbour. Close-up showing rhodolithic conglomerate immediately above the sequence boundary. Hammer for scale. (f) Limestone unit (lithofacies L4) top (arrow) marks a maximum flooding level (or DLS), and it is overlain by the highstand “Massive calcareous siltstone” lithofacies (S6). Note sharp facies transition at this surface. Hammer for scale. Photo location near Waikaretu walkway (PW-9). (g) Downlap surface (arrow) at the contact between transgressive “Cross-bedded grainstone” (lithofacies L3) and the overlying highstand glaucontic siltstone with abundant rounded subrounded pebbles and granules (S1) passing upwards into massive calcareous siltstone (S6). Note the contact is sharp but conformable with no evidence of erosion. Hammer for scale. Photo location Waiteika (AK-8), inland of Aotea Harbour. (h) The ‘flooding surface’ inferred as sequence boundary (arrow) at the contact between transgressive “Massive grainstone-packstone” (lithofacies L5) (Elgood Limestone Member) and the underlying highstand muddy sandstone (Waikaretu Sandstone Member) of sequence 1, at Quarry Road (AK-15), Te Pahu-Karamu.. The substrate immediately underlying the flooding surface is extensively burrowed. No lag deposit, or other evidence of scouring, is associated with this flooding surface. Hammer for scale. Close-up showing large tubular burrows (Planolites). Bar for scale is 10 cm. (i) Downlap surface (DLS) at the conformable facies contact between transgressive “Horizontally bedded grainstone” (L4) and overlying highstand “Massive variably calcareous siltstone” (lithofacies S6), at Shea Road (AK-4). Bar for scale is 30 cm.

has to be moved basinward (Posamentier et al. 1988; Van Wagoner et al. 1988; Galloway 1989). In effect, the DLS marks the top of a TST and the maximum rise of relative sea-level as described by Catuneanu (2006).

The field expression of the DLS is marked in the Glen Massey Formation by the lithological contrast between the Elgood Limestone Member and the Dunphail Siltstone Member, typically exemplified by styles 1, 2, 5 and 8 (Fig. 5.14) and (Fig. 5.15 f, g & i). However, this surface is more of a zone in certain localities, such as represented by style 3 (Fig. 5.14). In this case, the transition between the TST and HST is marked by interbedded calcareous siltstone and sandy limestone intervals (lithofacies S_5), which is a gradational interbedded facies. In this case it is difficult to pinpoint a single surface as the DLS, but the approach adopted has been to place it at the base of the first siltstone bed greater than 10 cm thick. Under restricted detrital supply conditions, the DLS/MFS may also be marked by condensed sections of carbonate facies, such are depicted in style 4 (Fig. 5.14). In rare instances as in style 10 (Fig. 5.14), the DLS is marked by an abrupt transition from "Cross-bedded grainstone" (L_3) into "Calcareous silty sandstone" with abundant scattered glauconite pallets, pebbles and granules (S_1), with some pebbles showing glauconitic coating (Fig. 5.15 g). In stratigraphic sections located farther offshore, such as over much of the Huntly Coalfield, the DLS lies at the top of the regionally extensive condensed sections, which formed when the shoreline reached its maximum landward position.

Transgressive Systems Tract

The base of a transgressive systems tract (TST) is bounded by either a sequence boundary or a transgressive surface of erosion (TSE), or by a correlative conformity. The downlap surface bounds the top of a TST. A TST forms during relative sea-level rise when the rate of rise outpaces the rate of sediment accumulation and the shoreline tracts landward. TSTs are recognised from a diagnostic retrogradational (backstepping) stacking pattern, which results in overall deepening-upwards and commonly fining- upwards profiles. In the paleo shelf preserved along the western sector and elsewhere in the basin, well-developed TSTs are common, such as represented by sequence architectural styles 1-6 (Fig. 5.14) and (Fig. 5.16 a, c, d & e). A combination of high rates of basin subsidence and relative sea-level rise during transgression are known to trap siliciclastics along shorelines in back-stepping wedges, essentially starving the offshore inner-mid shelf of sediment supply, allowing carbonate sediments to accumulate (e.g. Gillespie & Nelson 1997). These calcareous transgressive facies display broadly similar characteristics to those interpreted as reflecting relative siliciclastic sediment starvation on a Middle

Pleistocene shelf during rising sea level exposed in the western part of Wanganui Basin (Abbott & Carter 1994; Naish & Kamp 1997).

The average $CaCO_3$ content (88%) in the Elgood Limestone Member is highest in the Port Waikato-Raglan region and both regions contain extensive areas where the $CaCO_3$ content is >90%. Terrigenous sediment being input at the time may have been bypassed to deeper water by the high energy hydrodynamic regime (e.g. Nelson et al. 1988a; James et al. 1992; Boreen et al. 1993). In stratigraphic sections located farther offshore and in the southern region, where there was a higher terrigenous content, the proportion of $CaCO_3$ is comparatively less at ~54-87% (Fig. 5.1) and the environment of lower energy (e.g. James 1997; Gillespie & Nelson 1997).

There are three main factors controlling the TST facies architecture in the Glen Massey sequence: (i) rate of carbonate and/or terrigenous sediment flux, (ii) rate of relative sea-level rise, and (3) paleobasinal position of a particular outcrop. In inner to mid shelf regions, the Glen Massey sequence has a thick (up to 30 m) TST dominated by carbonate facies (L_1-L_5) consisting mainly of medium to coarse fragmented skeletal carbonate sandstone. The most abundant contributors to the skeletal fraction are bryozoans, echinoderms, benthic foraminifera (especially *Amphistegina*, but also *Lepidocyclina)*, calcareous algae (commonly large rounded coralline red algal fragments and occasionally open algal frameworks), with varying amounts of bivalves (micro-bores infilled with limonite) and minor proportions of other components such as planktic foraminifera, gastropods and barnacles (Fig. 5.1). Compositional analysis of the limestone facies in the Elgood Limestone Member indicates increasing bivalve and planktic foraminiferal content upwards, with a corresponding decrease in red algae, benthic foraminifera and echinoderm content (Fig. 5.8). These bioclast compositional trends support a deepening of water depth up-section within the transgressive systems tract.

The overall thickness of the TST decreases basinwards. In deeper water areas where the DLS almost converges with the sequence boundary, a thin sediment starved TST is represented by a shellbed (lithofacies L_2), best exemplified by style 11 (Fig. 5.14) and/or by a condensed deposit as illustrated in style 14 (Fig. 5.14). Thin shellbeds representing sediment-starved TSTs in more offshore shelf settings are equivalent to the "compound shellbed" described by Naish and Kamp (1997) in the Pliocene-Pleistocene cyclothems exposed in Wanganui Basin.

The top of the Glen Massey sequence TST may or may not have a glauconite-rich condensed section. Style 4 in Fig 5.14 provides an example of a glauconitic

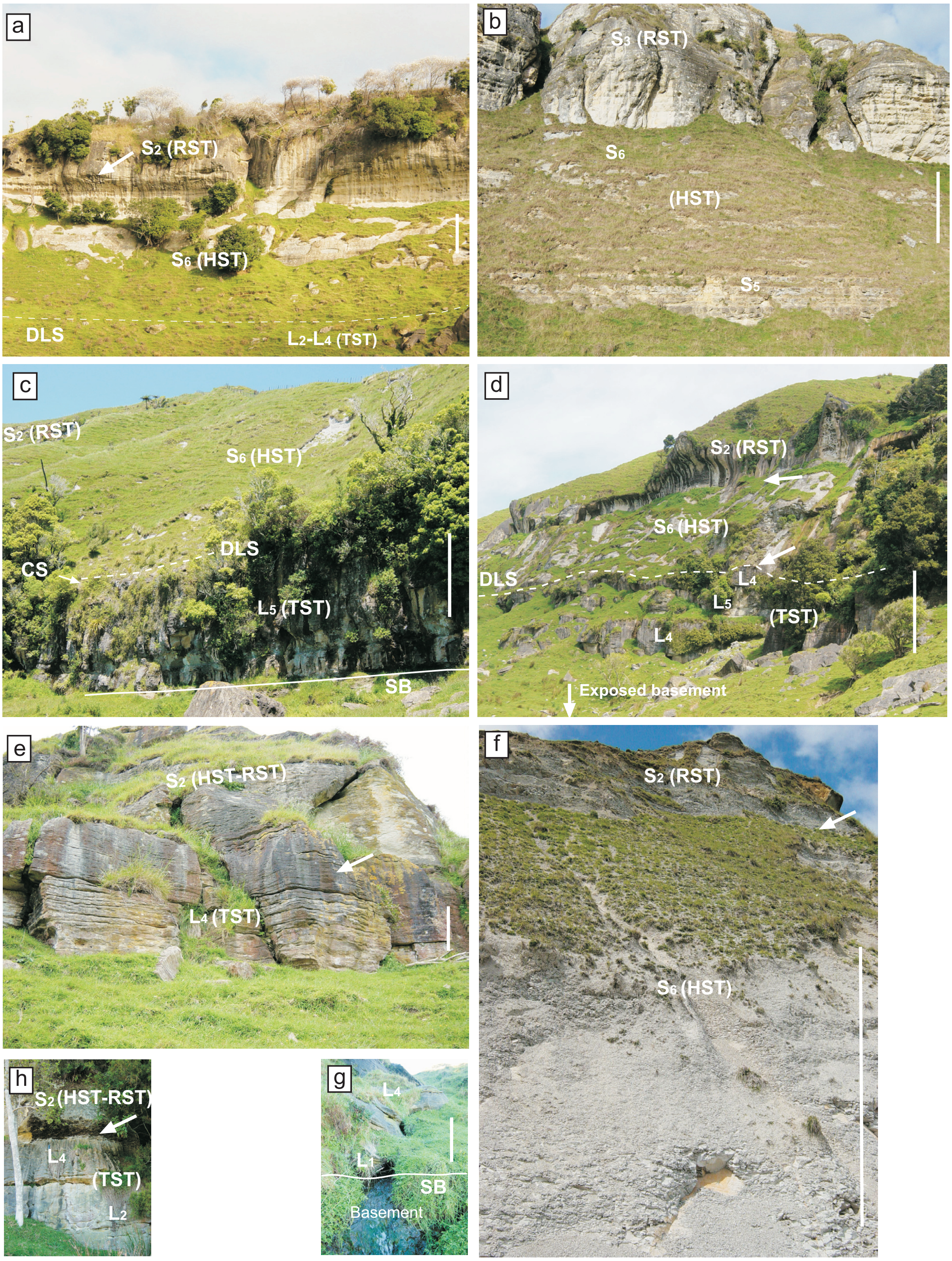


Fig. 5.16: Photos of outcrop examples illustrating facies association and significant stratigraphic surfaces within Glen Massey sequence along the western margin (a) A typical facies association starts with carbonate dominated transgressive deposits (lithofacies L2 and L4) that overlie an early Whaingaroan-age sequence boundary (not visible in the photo). The downlap surface (DLS) marks a sharp but conformable facies contact between carbonate dominated TSTs and fine-grained mixed carbonate-siliciclastic highstand "Massive calcareous siltstone" (lithofacies S6), deposits, which in turn grade upwards to a prograding relatively coarser lithofacies (S2) inferred as regressive systems tract (RST). Note the presence of trough cross-bedding (pointed by arrow) suggesting increase in depositional energy with time. Bar for scale is 4 m high. Location Waikawau Stream bridge on Port

condensed section possibly formed by a cut-off of carbonate terrigenous sediment supply during the late stage of transgression. There are two aspects to the end of carbonate accumulation at the top of the TST in the Glen Massey sequence. One is drowning of the carbonate factory, resulting in reduction and ultimately elimination of the carbonate supply from it (e.g. Simone & Carannante 1988). The other aspect is burial of the carbonate factory and site of carbonate accumulation through the progradation of mixed carbonate (foraminifera)-siliciclastic siltstone as the early part of the subsequent HST, broadly similar to the carbonate deposits (TST) overlain by prograding terrigenous highstand siliciclastics on the contemporary Wanganui shelf described by Gillespie and Nelson (1997).

Highstand Systems Tract

The highstand systems tract (HST) forms during the late stage of relative sea-level rise, stillstand, and early fall of sea-level (Vail 1987; Posamentier et al. 1988). Consequently, depositional trends and stacking patterns are dominated by a combination of aggradation and progradation (Catuneanu 2006). In the Glen Massey sequence, the base of the HST is marked by a downlap surface or MFS overlain by a progradational siltstone and/or sandstone ascribed to the regressive systems tract (RST). However, it should be noted that the gradational boundary between the HST and RST is not an isochronous time plane (e.g. Carter et al. 1998). The HST in the

Waikato-Waikaretu Road (PW-2). (b) A relatively thick (approximately 25 m) highstand deposits comprising “Interbedded calcareous siltstone and sandy limestone” (lithofacies S5) in the lower portion passes into “Massive calcareous siltstone” (lithofacies S6), which coarsen upwards into “bluff maker” regressive Alternating calcareous silty fine sandstone and siltstone (lithofacies S3). The relatively increased thickness of Glen Massey in this example represents a more offshore setting, is attributed to higher accommodation available for accumulation of sediment influx that reached these distal areas of paleo-shelf. Bar for scale is 10 m high. Location Bothwell Road (PW-8). (c) Well-developed carbonate dominated (lithofacies L5) transgressive system tracts are common in the lower portion of Glen Massey sequence. The TST in this example is capped by “Glauconitic rich silty-packstone” (lithofacies C3) passing into “Massive calcareous siltstone” (lithofacies S6) suggesting an abrupt increase in water depth. The DLS marks a conformable but abruptly gradational contact with overlying “Massive calcareous siltstones” (lithofacies S5) interpreted as HST, which coarsen upwards into regressive “Calcareous silty fine sandstone” (lithofacies S2). Location Awamarino (C-51). (d) Three main components of Glen Massey sequence are separated by ‘conformable’ facies contacts (pointed by arrows), the TST consists of lower “Pebbly grainstone” (lithofacies L1) that directly overlie the subaerial unconformity (SB), shown in photo (g), which grades upward to “Horizontally bedded grainstone” (lithofacies L4) with intervening “Moderately to massive bedded grainstone/packstone” (lithofacies L5). The end of transgression is marked by an abrupt shift to fine-grained (low depositional energy) in response to aggradation during early highstand base-level rise or standstill. The HST-RST succession displays a characteristic break in slope gradient indicates textural changes across the surface, a coarsening-upwards profile suggests a normal regression that develops in response to the base-level fall and resulting progradation. Bar for scale is 5 m. Location Shea Road (AK-4). (e) An example of more shoreward position of Glen Massey sequence where the typical highstand siltstone deposits are missing. This results in an abruptly gradational contact between the transgressive carbonate deposits (lithofacies L4) and undifferentiated highstand-regressive sandstones (lithofacies S2). Location Waikorea Valley Road (TA-2). Bar for scale is 1 m. Close-up in photo (h) shows an abrupt aggradation to progradational shift of facies. Hammer for scale. Location Waikorea (TA-2). (f) Massive highstand calcareous siltstone (lithofacies S5) grade upwards to regressive relatively coarser “Calcareous silty fine sandstone” (lithofacies S2). These lithostratigraphic facies contact (pointed by arrow) is probably diachronous, younging in the basinward direction (i.e. the direction of progradation / coarse sediment spillover). Bar for scale is 10 m. Location Orotangi Cliff (AK-5).

Glen Massey sequence usually comprises 8-30 m of massive, sparsely fossiliferous, variably calcareous siltstone (lithofacies S_5 to S_6) (Fig. 5.16 b & f). In a few of the stratigraphic sections (e.g. PW-9 in Fig. 5.7 b) along the western basin margin, the typical highstand siltstone occupies only the lower few centimeters of a coarsening-upward HST/RST profile, as exemplified by architectural style 6 (Fig. 5.14), or siltstone facies may be absent altogether through non-deposition of this facies (Fig. 5.16 e & h). In these more shoreward positions of the sequence it is often difficult to differentiate HST deposits from overlying RST deposits (cross section B-B' in Fig. 5.7) as both may have a sandy texture, emphasising the point that the HST-RST boundary is more of a facies transition rather than an isochronous surface marking a boundary between different systems tracts as linked depositional systems.

In more basinward locations where significant paleobathymetry has developed by the end of TST, together with additional subsidence during the HST, there is thick development of HST siltstone, as illustrated in architectural style 4 (Fig. 5.14) and (Fig. 5.16 b).

In rare cases, such as illustrated in architectural style 10 (Fig. 5.14), the lower part of the HST includes a thin (< 2 m) siltstone, with or without rounded-subrounded glauconitised greywacke pebbles and granules in the lower ~ 2m, which in turn pass upwards into calcareous siltstone (lithofacies S_6). These pebbles and granules are inferred to have been re-worked down the shelf possibly during storm events (Fig. 5.15 g).

Regressive Systems Tract

The regressive systems tract (RST), as defined by Embry (1995), includes all deposits that accumulated during shoreline regression and in this term may include the HST deposits. As originally defined, the RST or forced regressive systems tract (FRST) includes regressive deposits that accumulated during the interval of more rapid fall in relative sea-level (Embry 1993; Naish & Kamp 1997), and this is the concept adopted here. The RST is characterised by a progradational stacking pattern formed fundamentally as the loss of accommodation space. Within the inner to mid shelf portions of the basin, the RST in the Glen Massey sequence is easily identified by a relatively thick coarsening-upwards variably silty calcareous sandstone facies (lithofacies S_2, S_3, S_4) overlying HST siltstone. The RST displays a gradational contact with the underlying HST marked by a progressive increase in the sandstone content over approximately 2-5 m of vertical section (Figs 5.16 a, b, d; & 5.17 c). Similar regressive systems tracts have been described from Pliocene-Pleistocene cyclothems by Naish and Kamp (1997) in Wanganui Basin. These are distinguished

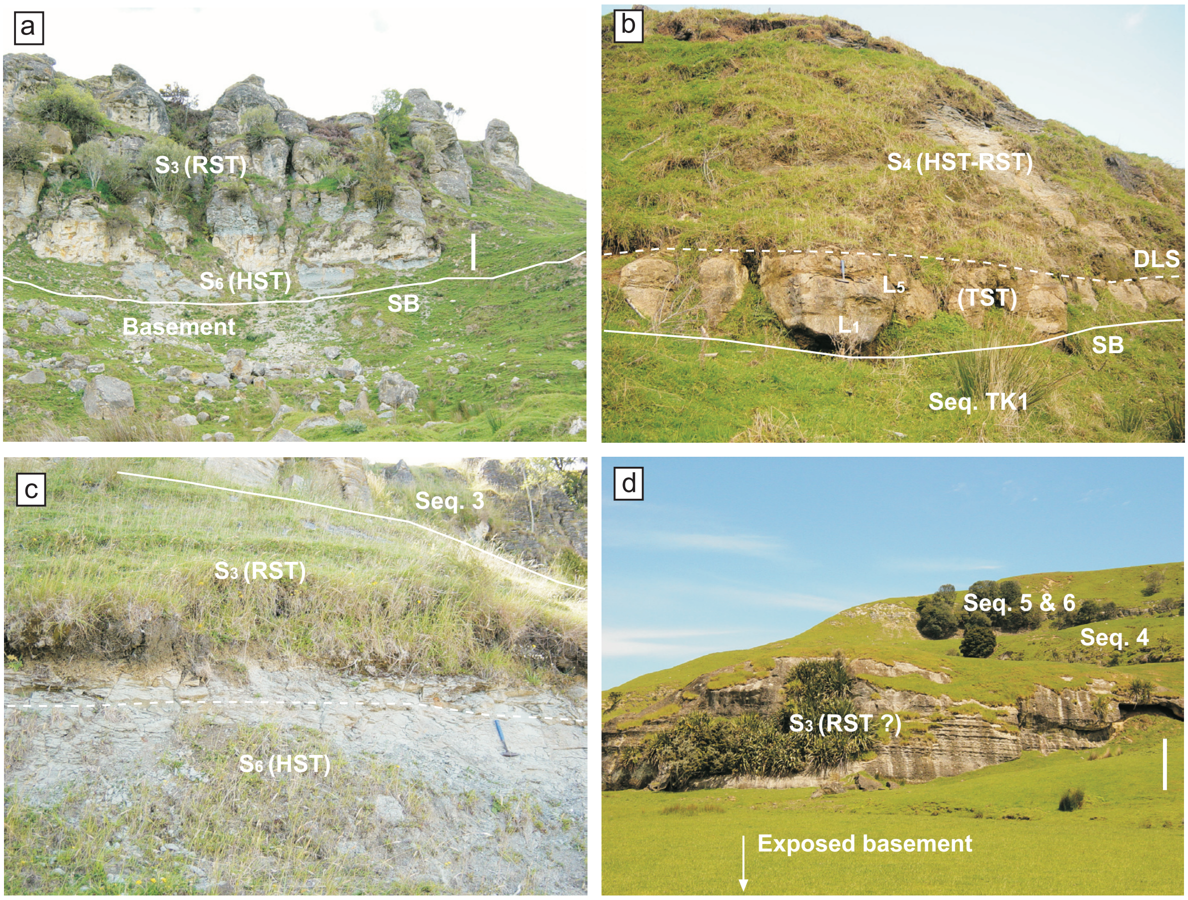


Fig. 5.17: (a) An outcrop example of non-development of typical transgressive carbonate facies, the highly calcareous siltstone (lithofacies S6) that is typical of highstand here directly overlie the sequence boundary. The carbonate facies are common towards the base of the sequence along the basin margin is absent on this site probably due to high rate of fine clastic influx during transgression. Bar for scale is 2 m. Location Te Kotuku Creek (TA-12), north of Raglan Harbour (b) Photo illustrate a ‘starved’ Glen Massey sequence that overlie the TK1 (Waikato Coal Measures). The transgressive facies directly overlie the sequence boundary comprise thin pebbly and shelly, “Moderately glauconitic grainstone” (lithofacies L1-L2) which passes into “Massive to moderately bedded grainstone-packstone” (lithofacies L5). The top of limestone marks a downlap surface, and is overlain by the HST-RST “Massive muddy sandstone” (lithofacies S4). Such thin sequence development may represent a distal position from sediment supply. Hammer for scale. Location Ngapaenga (C-68). (c) Outcrop example of a subtle transition between highstand siltstone (lithofacies S6) and regressive sandstone (lithofacies S3). The dashed line marks the peak of finest sediment (top of aggrading succession). This facies transition is difficult to pinpoint because of lack of obvious lithological contrast. Hammer for scale. Location Hautapu Hill (C-4). (d) Outcrop example of in separable transgressive and highstand facies. The entire exposed succession is represented by “Alternating fine silty sandstone and siltstone” (lithofacies S3) that is a typical of RSTs directly overlie the sequence boundary (not visible in photo). Note overlying depositional sequences in the background. Bar for scale is 5 m. Location Te Akau (TA-8).

from forced regressive systems tracts (Hunt & Tucker 1992; Walker & Wiseman 1995) which are defined as having an erosional contact with the underlying HST, and typically occur as a succession of stacked progradational lobes.

The RST in the Glen Massey sequence is usually thick (up to 100 m), but in rare instances a 1-2 m thick fossiliferous greensand representing undifferentiated HST-RST deposits occurs, for example at the Waitetuna Estuary section (style 12 in Fig. 5.14) due to lack of terrigenous supply, possibly due to the significant water depth in the Waitetuna area at the time. This thin glauconitic moderately cemented sandstone sharply overlies a 5 m-thick variably calcareous sandstone, and is then abruptly overlain by massive calcareous siltstone of the next sequence (Whaingaroa Formation).

The $CaCO_3$ content in the regressive sandstone of the Glen Massey sequence ranges from 42-58%. The highly bioturbated nature of the sandstone and the presence of variable amounts of glauconite suggest slow rates of mixed carbonate-siliciclastic accumulation. The siliciclastics were probably sourced from a Murihiku basement ridge exposed to the west, as the thickness of RST sandstone increases in that direction (Fig. 5.3). The slow rate of RST accumulation in the Glen Massey sequence suggests that the relative sea-level fall was slow. The fluvial discharge of sand to the paleoshore was also slow and suggests that there was minimal relief where the basement was exposed. This is particularly true for the areas south of Aotea Harbour, where in general the Glen Massey sequence displays poorly developed RST sandstone (Fig. 5.17 b).

The top of the RST in the Port Waikato-Raglan region (e.g. Waikawau Beach section) is comprised of a thin bed of intensely burrowed, moderately glauconitic and rarely phosphatic nodules (lithofacies C_1), which display the characteristics of a marine firmground/hardground, suggesting some degree of hiatus. However, in stratigraphic sections farther to the south, the RST is bounded above by a TSE of the overlying sequence.

Condensed Section

Condensed sections are inferred to be the product of extremely low carbonate and siliciclastic sediment supply during times of either rapid rise or still-stand of relative base level (Loutit et al. 1988; Amorosi 1995). These intervals can often be distinguished from overlying and underlying deposits by their higher concentration of glauconite.

Although glauconite is ubiquitously scattered throughout the Glen Massey sequence, specific stratigraphic levels have high glauconite content: (i) at the top of the TST and in the lower parts of HST in western areas, where it can comprise up to 15% of bed composition, and (ii) in thin TST on sediment starved portions of the offshore shelf.

The Waikoha Road (Fig. 5.13 c) and Awamarino sections (style 4 in Fig. 5.14) are good examples where the top of the TST is marked by firmground/hardground development with a high concentration of authigenic mineralisation such as glauconite and pyrite. They are often intensely burrowed and highly fossiliferous as there is less sediment to ‘dilute’ the fossils, which keep accumulating on the seafloor. These condensed sections are interpreted to correspond to a period of very low sedimentation or non-deposition during the period of rapid relative sea-level rise and the supply of sediment offshore is therefore restricted at the time of maximum transgression (e.g. Van Wagoner et al. 1988). The lack of clastic input allows glauconite formation and concentration, intense seafloor burrowing and increased cohesiveness of the substrate (e.g. Ghibaudo et al. 1996). In drill holes 9151 and 1773 near Maramarua (style 14, Fig. 5.14), glauconite-rich thin TST development ($C_{2,}$ C_3) reflects sediment starvation in the more offshore shelf to upper-bathyal setting.

In condensed sections observed in Glen Massey sequence, glauconite occurs as pellets and infills and includes both autochthonous and allochthonous (detrital) types, and is typically associated with pyrite grains, abundant fossils, and intense burrowing. Variable amounts of glauconite are also generally present at the sequence boundary, marking the base of the overlying TST; illustrated in architectural styles 7 and 8 (Fig. 5.14). This may be attributed to the remobilisation of glauconite in shallow-marine settings by waves, currents and storms, which may strongly influence the distribution of glauconite in high energy deposits (e.g. Amorosi 1995).

A model Glen Massey sequence

Despite good local continuity of outcrops, it is not possible to directly trace lateral facies changes within the Glen Massey sequence from nearshore to offshore parts of the paleoshelf because the more basinward parts have mostly been eroded through post-depositional uplift and erosion. Cross-sections constructed using outcrop and drillhole data showing the distribution of the main facies and systems tracts are illustrated in Fig. 5.7 (a-e). Fourteen distinctive ‘styles’ of Glen Massey sequence architecture are depicted in Fig. 5.14. These illustrate the architecture at different positions across the paleoshelf. Analysis of all of the fourteen styles shows that broadly similar facies recur up-section. By integrating the characteristics of all fourteen ‘styles’, an idealised sequence stratigraphic model has been developed that provides a simplified two-dimensional representation of the key surfaces and systems tracts (Fig. 5.18).

The model illustrates an idealised depositional profile from basin margin to deeper parts of the basin, all probably of shelf to upper bathyal depth. In the more landward positions, the vertical facies succession includes shelfal bioclastic limestone (TST) overlain by thin marine calcareous siltstone (HST), passing up

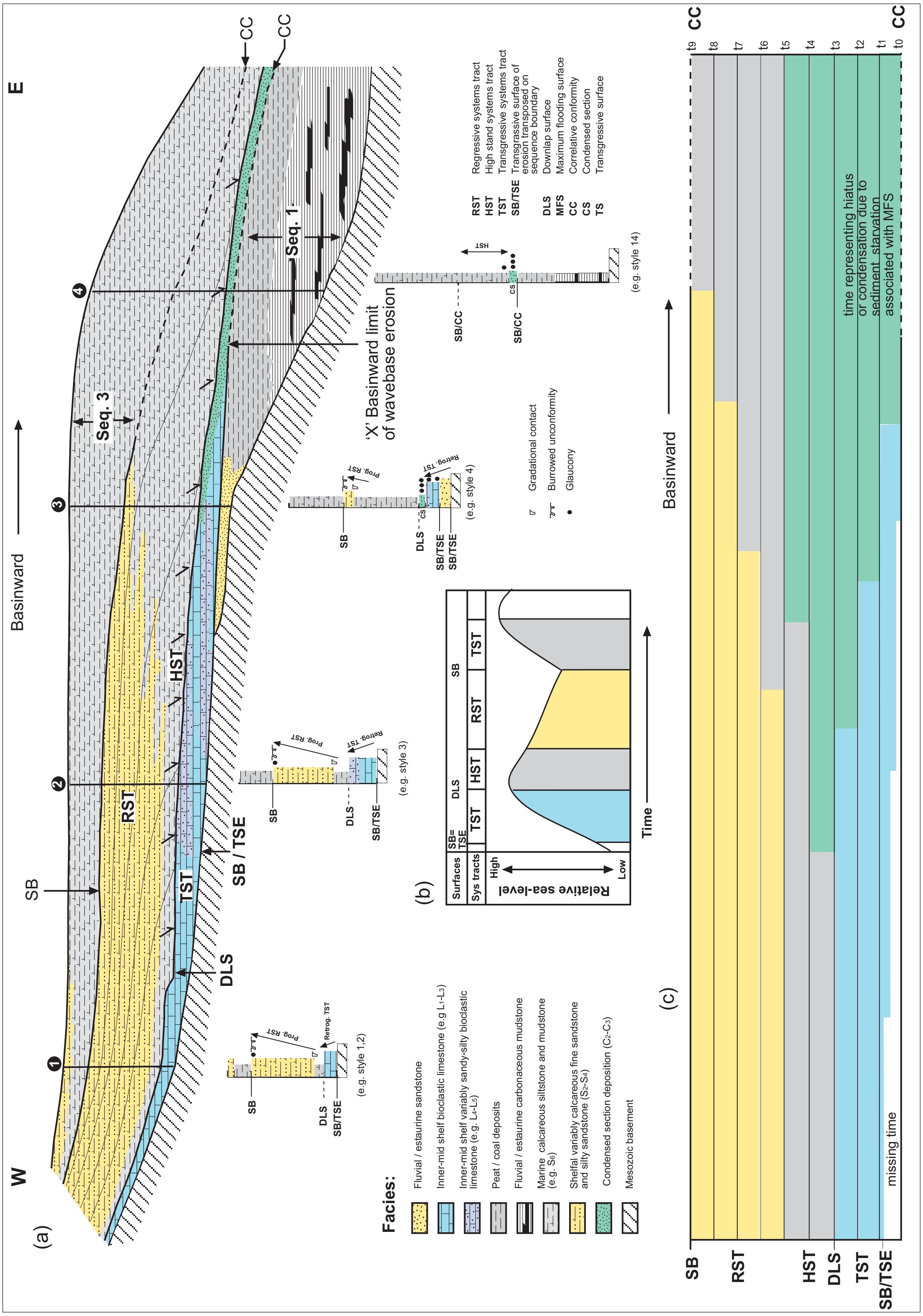


Fig. 5.18: (a) Dip-oriented idealised cross section through the Glen Massey sequence in the northern region. The section depicts predictive distribution of shallow marine to marine facies of the Glen Massey Formation in relation to marginal marine and fluvial facies of sequence 1 in a sequence stratigraphic framework. The section is approximately 35 km long. (b) Key surfaces and systems tracts associated with a theoretical relative sea-level curve. (c) A hypothetical chronostratigraphic diagram show the time (t0-t9) represented by the systems tract, condensed sections and maximum flooding surface.

into variably calcareous fine sandstone and silty sandstone (RST), represented by hypothetical column location 1 in Fig. 5.18 a. In middle-shelf positions, the vertical succession includes relatively thick, variably sandy-silty limestone (TST), overlain by coarsening-upwards siliciclastics (HST-RST), represented by hypothetical column 2. In more distal portions of the shelf represented by hypothetical column 3, the limestone facies (TST) are capped by a condensed section interpreted to reflect sediment starvation, overlain by thick highstand siltstone and relatively thin regressive sandstone. In the more basinward locations represented by hypothetical column 4, the vertical facies succession is dominated by variably calcareous glauconite-rich sandstone and siltstone representing stratigraphic condensation.

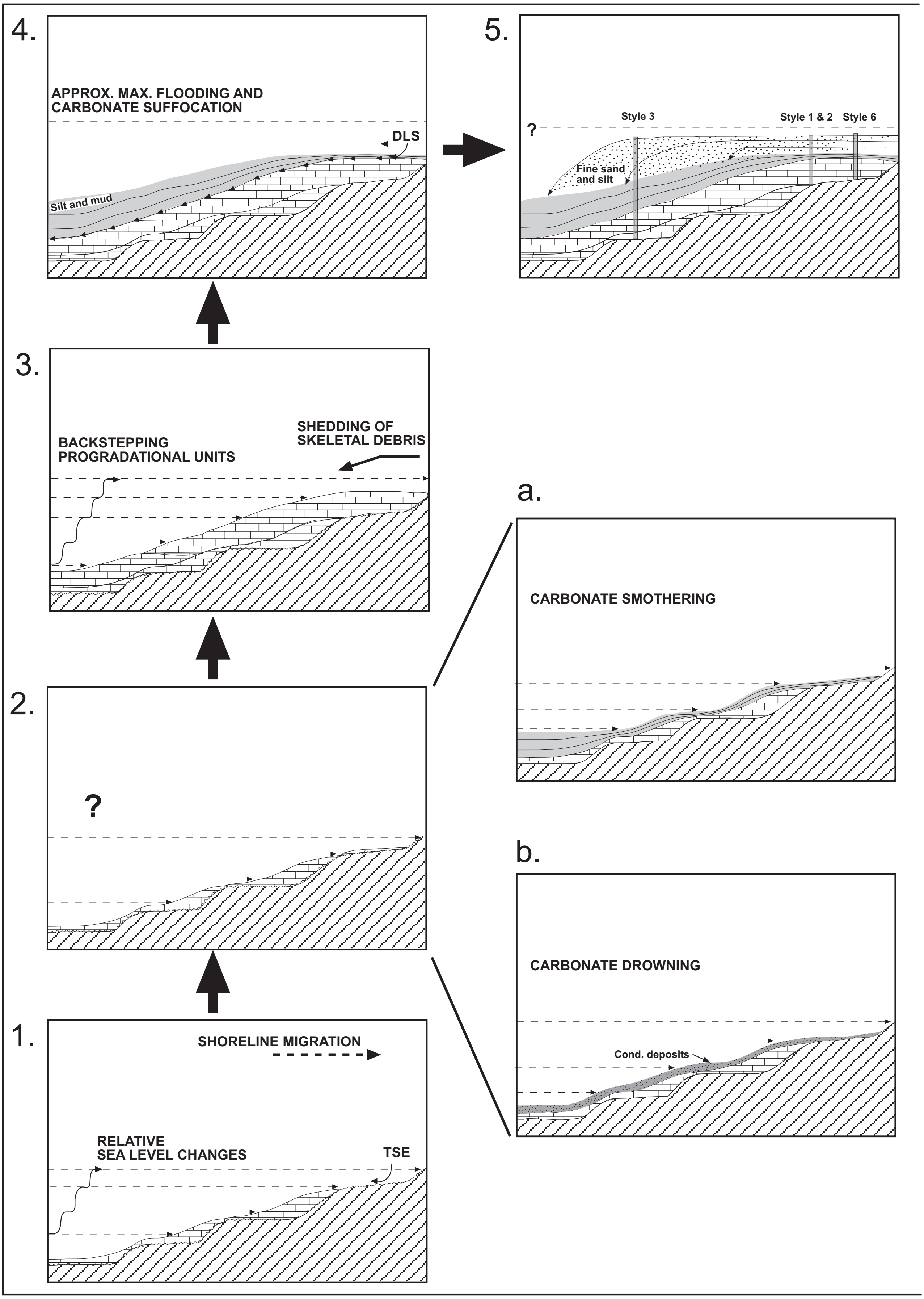
Fig. 5.18 (b) illustrates the position and timing of the key sequence stratigraphic surfaces and systems tracts in relation to a relative sea-level curve. A hypothetical chronostratigraphic panel in Fig. 5.18 (c) depicts the lateral changes in the facies pattern across the paleoshelf through accumulation of the sequence. This emphasises how different depositional processes occurred at different points in time. Note that sediment starvation reached it's most landward position at nearly the maximum point of relative sea-level rise t_4 (green area in Fig. 5.18 c), however sediment starvation in more basinward areas continued for longer than in more landward areas of the shelf.

Controls on sequence development

A series of conceptual block diagrams in Fig. 5.19 show scenarios for the development of the Glen Massey sequence based on the different architectural styles presented earlier. The central theme of this idealised Glen Massey sequence development is that the character of system tracts and stratigraphic surfaces are controlled mainly by the interplay of relative sea-level changes, sedimentation rates, and position on the shelf profile.

Step 1 shows an onlapping wedge of skeletal carbonate sand derived from rocky shorelines. The bulk of this carbonate sand was generated near the shoreline as a result of mechanical erosion by waves, currents and by bioerosion (e.g. Nelson 1988a). These carbonate wedges shift landward during transgression, onlapping the landscape underlain by Mesozoic basement and infilling local topographical lows.

Step 2 involves early termination of limestone accumulation caused by smothering by siliciclastic siltstone (step 2a) or by drowning of the carbonate source areas (step 2b). Smothering by siliciclastic siltstone and/or sandstone is a most likely cause for the end of carbonate production. This is similar to the rapid demise of late


4.
APPROX. MAX. FLOODING AND
CARBONATE SUFFOCATION
DLS
Silt and mud
5.
?
Style 3
Style 1 & 2
Style 6
Fine sand
and silt
3.
BACKSTEPPING
PROGRADATIONAL UNITS
SHEDDING OF
SKELETAL DEBRIS
a.
CARBONATE SMOTHERING
2.
?
b.
CARBONATE DROWNING
Cond. deposits
1.
SHORELINE MIGRATION
RELATIVE
SEA LEVEL CHANGES
TSE

Step 1. Aggradation of initial platform.

Step 2. Platform development stops or slows down either owing to environmental factors e.g. smothering of carbonate production by fine siliciclastic sediments (Step 2a) or submergence of carbonate platform from continuation of subsidence or a continuation of sea-level rise (Step 2b).

Step 3. Platform continue to grow composed of progradational units, which are stacked in backstepping configuration and onlap onto the Mesozoic basement as a result of punctuated transgression.

Step 4. Later drowning and / or deposition of siliciclastics (silts and mud) shuts off the carbonate factory (Steps 2 a & b combined).

Step 5. The ensuing relative sea-level fall leads to the deposition of prograding fine sand and silt of the regressive system tract.

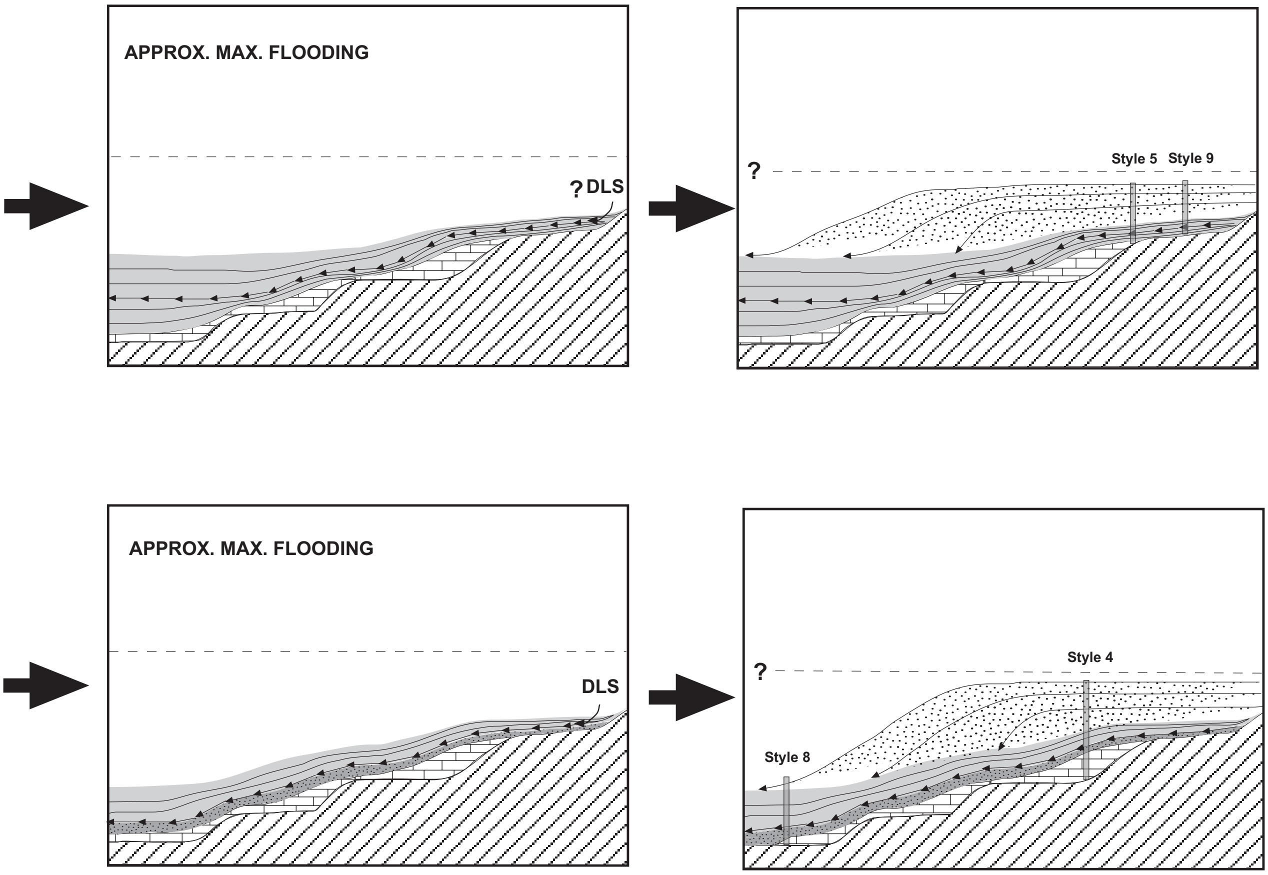


Fig. 5.19 (facing page and this page): Conceptual block diagrams showing the steps for the likely Glen Massey sequence development.

Quaternary Wanganui carbonate accumulation when terrigenous sediment input exceeded critical levels (Gillespie & Nelson 1997). In step 2b, the drowning could have been either eustatically controlled or tectonically induced, or a combination of both. Condensed section development immediately above the TST limestone is a clear indication of rapid marine submergence. The development of drowning unconformities is well documented for tropical limestone sequences (Schlager 1981, 1992). Whether it is appropriate for temperate carbonates remains a topic of debate (Simone & Carannante 1988; Boreen & James 1993; James 1997). Step 3, describes the situation where thick TST limestone occurs and overall there is evidence for fining and deepening upwards indicative of a retrogradational stacking pattern. The thickness of the TST is due to the development of accommodation space, but more importantly access to a supply of carbonate components down-shelf of the factory areas. The transgressive deposits may potentially be thick (unlike that is shown in step 2a and 2b), due to the high rate of sediment supply stimulated by the available accommodation. Step 4, involves a late stage or a decelerating base-level rise where transgression gives way to highstand condition and the carbonate accumulation in the TST ends because the factory area is smothered by siliciclastic sediments, as well as the areas of carbonate accumulation. Step 5, involves the gradual progradation of calcareous silty fine sand during a RST.

Chapter 6

Lithofacies, paleoenvironments and sequence stratigraphy of the Aotea Formation

Introduction

The chapter focuses on the description, architecture and interpretation of lithofacies identified in the Aotea Formation to help reconstruct the contemporary depositional environmental setting. The lithofacies analysis forms the basis for subsequent development of a sequence stratigraphic framework for the Aotea Formation. The chapter is thus divided into three main parts. The first part describes the lithofacies identified on the basis of sedimentological and faunal features; the second part considers the sequence stratigraphic character of the formation through the identification of surfaces and discontinuities marking significant shifts in the depositional systems. The third part considers the distinctive style of sequence architecture in the Aotea Formation and attempts to develop a simplified Aotea model sequence for each of the northern and southern regions.

Lithofacies Analysis

The thickness of the Aotea Formation is quite asymmetrical, with the thickest parts occurring over the central area of its distribution; particularly east of Aotea-Kawhia Harbour where it is up to 180 m thick (refer Chap 3). In this area and the southern region, the formation comprises a wedge running parallel to the paleo-shoreline and thinning to the east. In the northern region, Aotea Formation comprises a range of rock types including cross-bedded limestone, interbedded fine calcareous sandstone and siltstone, and sandy siltstone, all forming a comparatively thin succession (2-70m).

Facies classifications have been prepared in previous investigations of the Aotea Formation (Hopkins 1966; Nelson 1973, 1978a; Fergusson 1986). White & Waterhouse (1993) recognised significant lithofacies variations within the Aotea Formation between the Aotea-Kawhia and Raglan Harbour areas, and broadly subdivided these into four members (i.e. Hauturu Sandstone Member and Kihi Sandstone Member in the Aotea-Kawhia Harbour area, and Mangiti Sandstone Member and Patikirau Siltstone Member in the Raglan Harbour area). Paleocurrent and associated lithofacies analysis on the Waimai Limestone Member was carried out by Anastas (1997). Where appropriate, these facies schemes have been used as a basis in this chapter for the development of a new and comprehensive lithofacies scheme for the Aotea Formation.

Between the northern and southern parts of the study area, the Aotea Formation is composed of many lithofacies types, with variably calcareous sandstone and muddy sandstone predominating in the central and southern regions, and carbonate lithofacies predominating north of Raglan Harbour. The much reduced siliciclastic input north of Raglan Harbour led to carbonate accumulation and the overlying glauconitic sandstone and siltstone. Four broad lithofacies types have been identified within Aotea Formation, including: (i) limestone lithofacies, (ii) mixed carbonate-siliciclastic sandstone lithofacies, (iii) mixed carbonate-siliciclastic siltstone lithofacies, and (iv) chemogenic lithofacies. The essential features of each of the lithofacies identified and defined are summarized in Table 6.1.

Typical expressions of limestone lithofacies in the field are illustrated in Fig. 6.1 and their vertical and lateral relationship across the paleoshelf are shown in a series of schematic cross-sections in Fig. 6.2. The average whole rock and bioclastic compositional trends within the limestone lithofacies are depicted in Fig. 6.3. Photomicrographs of some of the limestone and chemogenic lithofacies types are illustrated in Fig. 6.4. The typical field expression of the mixed carbonate-siliciclastic sandstone and chemogenic lithofacies are illustrated in Fig. 6.5 - 6.8, including "Variably calcareous fine to medium sandstone" lithofacies (S_1) and its distribution and thickness trends across the southwestern and central areas of the basin (Figs 6.5 & 6.6). The vertical and horizontal relationships between the various lithofacies are depicted in north-south and east-west transects in Figs 6.8 - 6.14. The location of these transects are shown in Fig. 6.7.

Table 6.1: 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 grainstone/ packstone	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) Fig. 6.1 (a, b)	Near shore to inner-most shelf adjacent to rocky shoreline
L_2 Cross-stratified grainstone	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 Fig. 6.1 (c, d)	High energy inner to mid shelf dominated by strong offshore-directed storm and / or tidal induced currents

Lithofacies	Field characteristics, sedimentary structures, bedding type	Carbonate content / insoluble residue	Grain size range / abrasion/ sorting	Typical fauna / bioturbation	Common occurrence / typical example	Interpretation
L_3 Horizontally bedded grainstone / packstone	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 Fig. 6.1 (e)	Inner to mid wave dominated shelf
L_4 Sandy-silty grainstone	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 Fig. 6.1 (f, g)	Inner to mid shelf
L_5 Massive to irregularly bedded bioturbated grainstone/ packstone	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 Fig. 6.1 (h)	Lower inner to mid-outer shelf; wave (storm) dominated setting

Lithofacies	Field characteristics, sedimentary structures, bedding type	Carbonate content / insoluble residue	Grain size range / abrasion/ sorting	Typical fauna / bioturbation	Common occurrence / typical example	Interpretation
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) Fig. 6.1	Storm dominated foreshore 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) Fig. 6.7 (a)	Mid to outer shelf

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 Interbedded calcareous sandstone and sandy siltstone	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) Fig. 6.7 (b, c)	Moderate energy mid shelf depths below fair-weather but above storm wave base
S_4 Massive bioturbated muddy-sandstone	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) Fig. 6.7 (d, e, f)	Low energy mid to mid-outer shelf, above storm wave base
Mixed carbonate-siliciclastic siltstone lithofacies						
Z_1 Massive variably calcareous sandy siltstone	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) Fig. 6.8 (a, b)	Mid-outer shelf to possibly upper bathyal

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 Glauconitic siltstone and sandstone	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) Fig. 6.8 (c, d)	Sediment starved mid-outer shelf
C_2 Glauconitic packstone / wackestone	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

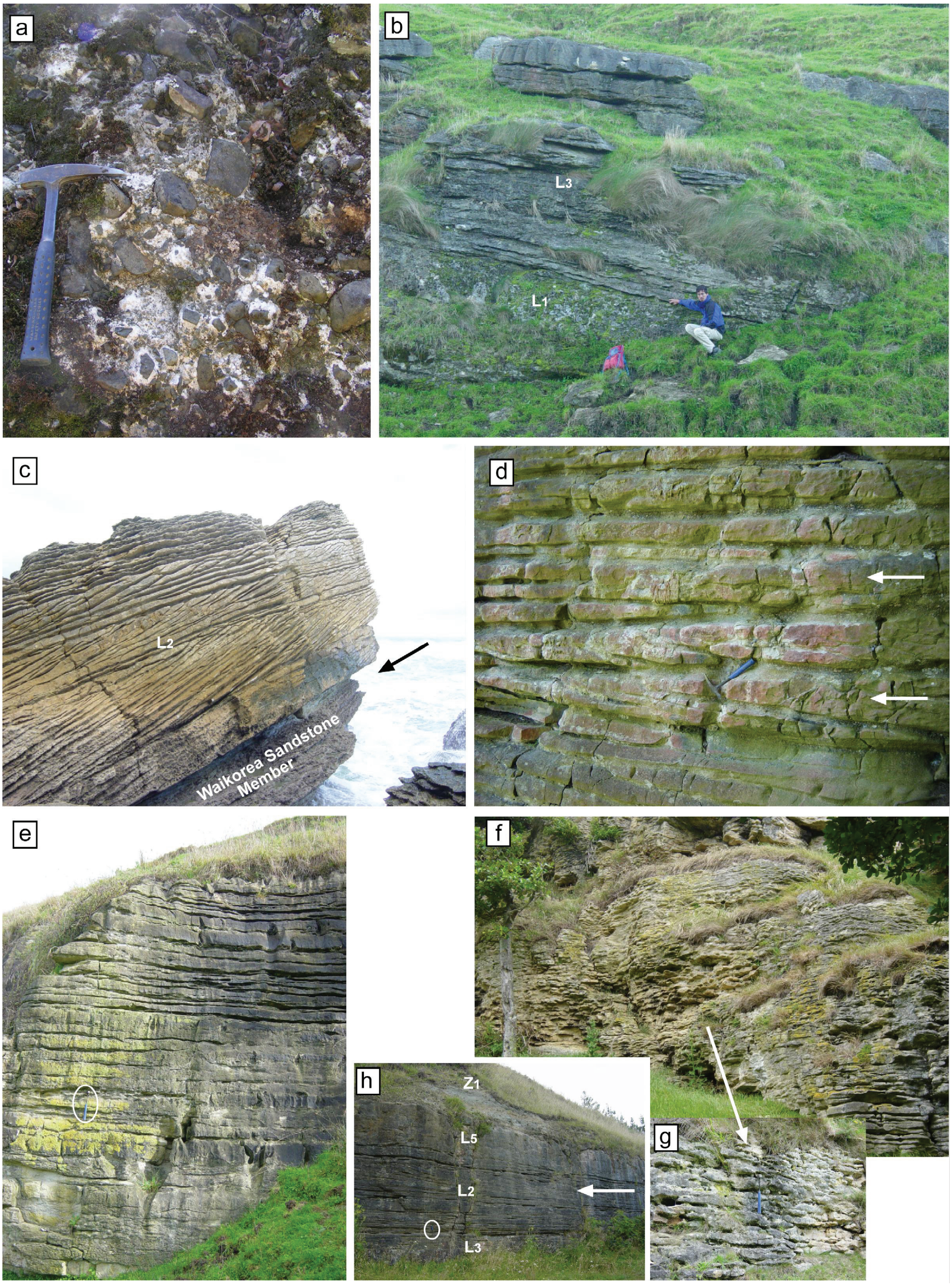


Fig. 6.1: Field photographs of the typical carbonate lithofacies in the Aotea Formation exposed in the study area (a) A unit of “Rhodolithic bearing conglomerate” (lithofacies L1) onlapping Mesozoic basement rocks. This conglomeratic layer at the base of Waimai Limestone Member in the Honikiwi section (C-25) is interpreted as a transgressive lag deposit formed in an advancing shoreline. (b) Massive pebbly grainstone/packstone lithofacies (L1) passing upwards into “Horizontally bedded grainstone/packstone” (lithofacies L3) with common scattered granules and pebbles. These facies are inferred to be transgressive marking a gradual onlap and submergence of elevated basement areas. Photo location Honikiwi Road (C-25). (c) Low to moderate angle tabular cross-bedded grainstone lithofacies (L2) typical of Waimai Limestone Member in the northern region, Waikawau Beach,

Limestone lithofacies types (L_1 - L_5)

The carbonate lithofacies in the Aotea Formation show similarities with the carbonate lithofacies identified in the Glen Massey Formation (Chapter 5). As with Glen Massey Formation, carbonate lithofacies occur in the lower parts of the Aotea Formation. The shallow-water bioclastic limestone is most conspicuous and volumetrically important in the Port Waikato- Te Akau areas where it forms large-scale, cross-bedded units up to 18 m thick and contribute around 60-80% to the thickness of the Aotea Formation. The carbonate lithofacies extend south into the central and southern regions, but they generally thin and sporadic, lapping onto basement. The common occurrence of greywacke pebble-grit in the limestone beds and the discontinuous nature of limestone facies in the south is consistent with their accumulation on the flanks of basement highs.

The carbonate lithofacies tend to represent inner- to mid-shelf water depths. Thin section analysis of representative samples of the Waimai Limestone Member from the northern region, shows that the bioclastic fraction (averaging 70%) principally comprises echinoderms, bryozoans, benthic and planktic foraminifers, and to lesser extent bivalves and calcareous red algae. Barnacles are rare. The modal size of bioclasts varies from about 0.10-1.20 mm (very fine to coarse sand) and can show a bimodal size distribution with fine sand and coarse sand modes. Bioclasts characteristically show moderate to abraded margins, and are poorly to moderately sorted. The modal grain size of the insoluble siliciclasts, consisting mainly of quartz, feldspar and minor amounts of igneous and sedimentary rock fragments, lies in the range of fine to very fine sand, which is moderately to well sorted. Pyrite grains and glauconite are ubiquitously present in minor quantities both as pellets and infills. The intrinsic matrix-cement generally makes up 10-25% of the limestone, with sparite being more common compared with micrite.

(Fig. 6.1 continued) Port Waikato (PW-11). Note well defined set boundaries enclosing the foresets. The Waikorea Sandstone Member of Whaingaroa Formation is erosionally truncated (arrow) and overlain by strongly cross-bedded skeletal grainstone unit in the lower half of the photo. Exposure approximately 2.5 m high. (d) Low angle tabular cross-bedded (arrows) grainstone lithofacies (L2), Waimai Limestone Member. Note recessed siliciclastic rich bedding planes. Hammer for scale. Photo location: Waikorea (TA-2). (e) Horizontally bedded grainstone/packstone lithofacies (L3) in Waimai Limestone Member exposed near Te Akau (TA-9). Note thickness variation in individual beds. Hammer for scale. (f) Sandy silty grainstone lithofacies (L4) in Waimai Limestone Member. This facies is common in the south and central regions where it represents transition between Hauturu Sandstone and Waimai Limestone Members. Exposure is approximate 4 m high. Photo location: Makaka, north of Aotea Harbour (AK-1). (g) Close-up view of the “Sandy silty grainstone” lithofacies (L4). Note its uncanny resemblance to “Fine to medium grained sandstone” lithofacies S1 (Hauturu Sandstone Member). Photo location Makaka (AK-1), North of Aotea Harbour. (h) Horizontally bedded grainstone/packstone lithofacies (L3) passing upwards into “Low angle tabular cross-bedded grainstone” lithofacies (L2) (arrow), which in turn grade upwards into “Massive bioturbated grainstone/packstone” lithofacies (L5), which is abruptly overlain by massive poorly cemented slightly to “Moderately glauconitic siltstone” Z1 (Patikirau Siltstone Member). Entire succession is broadly transgressive and displays the complete spectrum from moderate to high energy inner-mid shelf skeletal grainstone at the base, to deep water outer shelf siltstone at the top. Hammer for scale. Photo location: Waikaretu (PW-9).

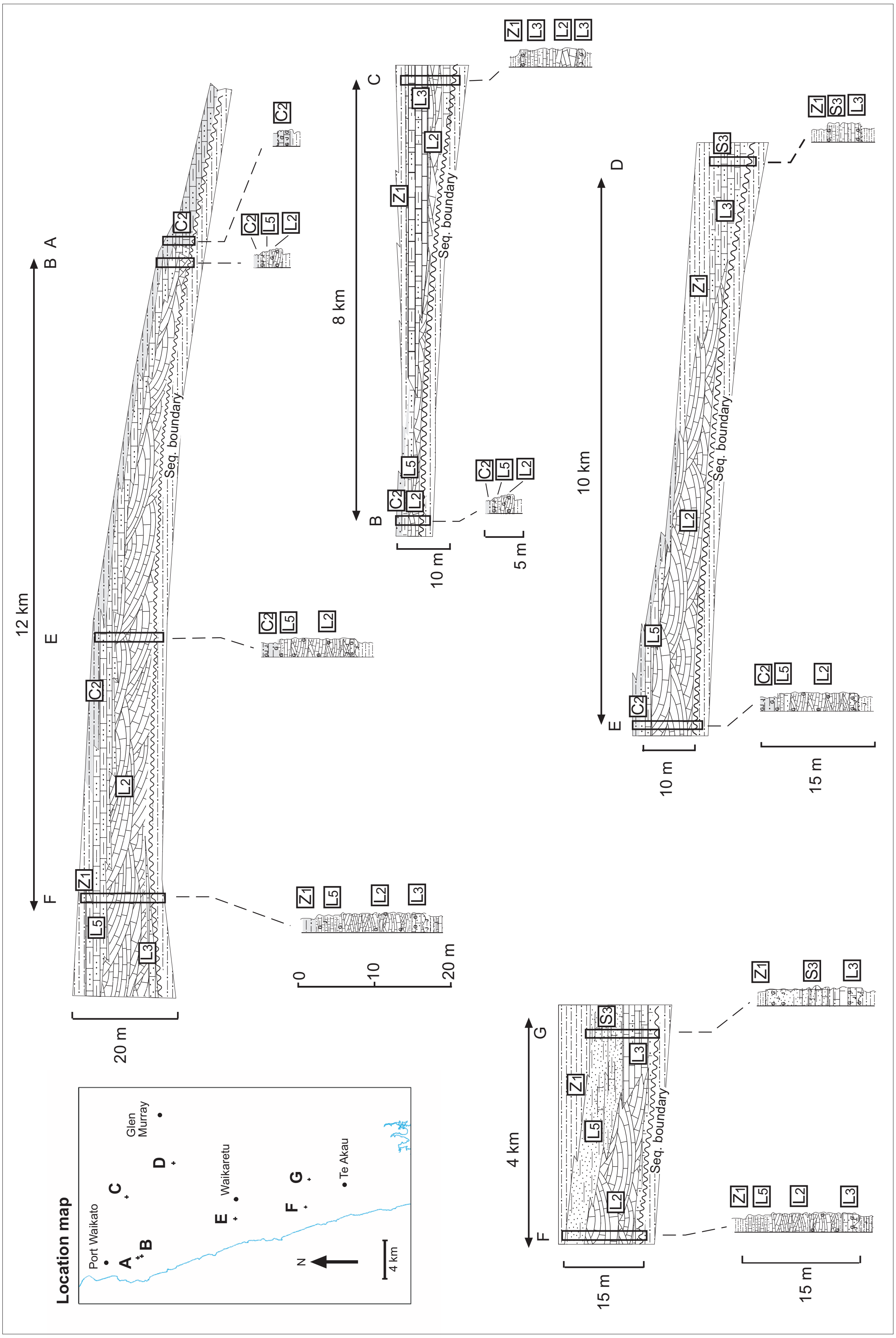


Fig. 6.2: Schematic cross sections showing the major lithofacies and their thickness trends apparent within the Waimai Limestone Member in the northern region. Also shown is the nature of the sequence boundary below the Waimai Limestone Member, and the relationship with overlying units. Location map shows selected stratigraphic columns used to construct schematic cross sections, and detailed petrographic analysis (refer Fig. 6.3). Location A=PW-1A, B=PW-1, C=PW-5, D=PW-8, E=PW-9, F=TA-3, G=TA-5.

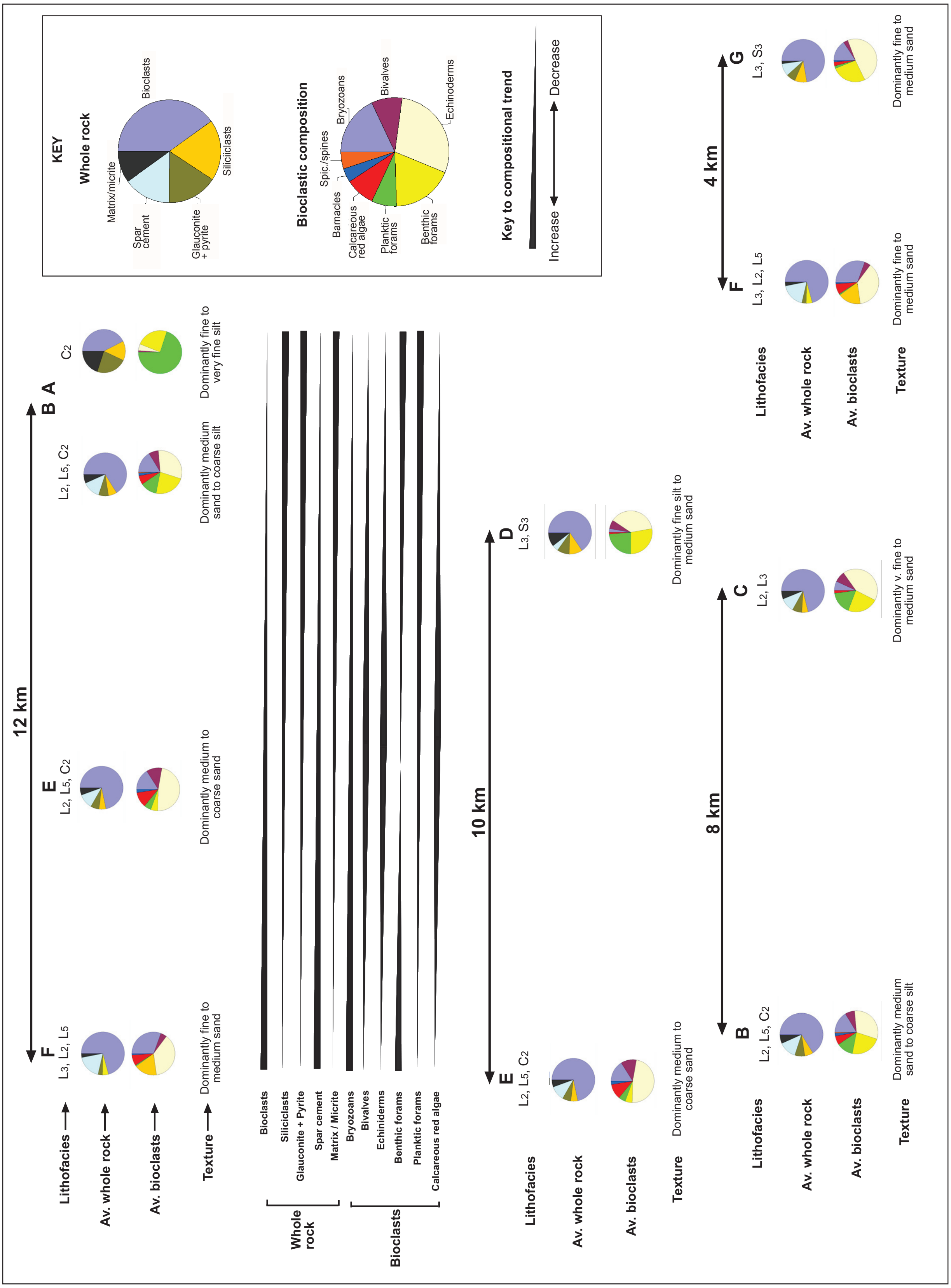


Fig. 6.3: Summary of average whole rock and bioclastic compositional trends amongst lithofacies within Waimai Limestone Member in the locations shown in Fig 6.2.

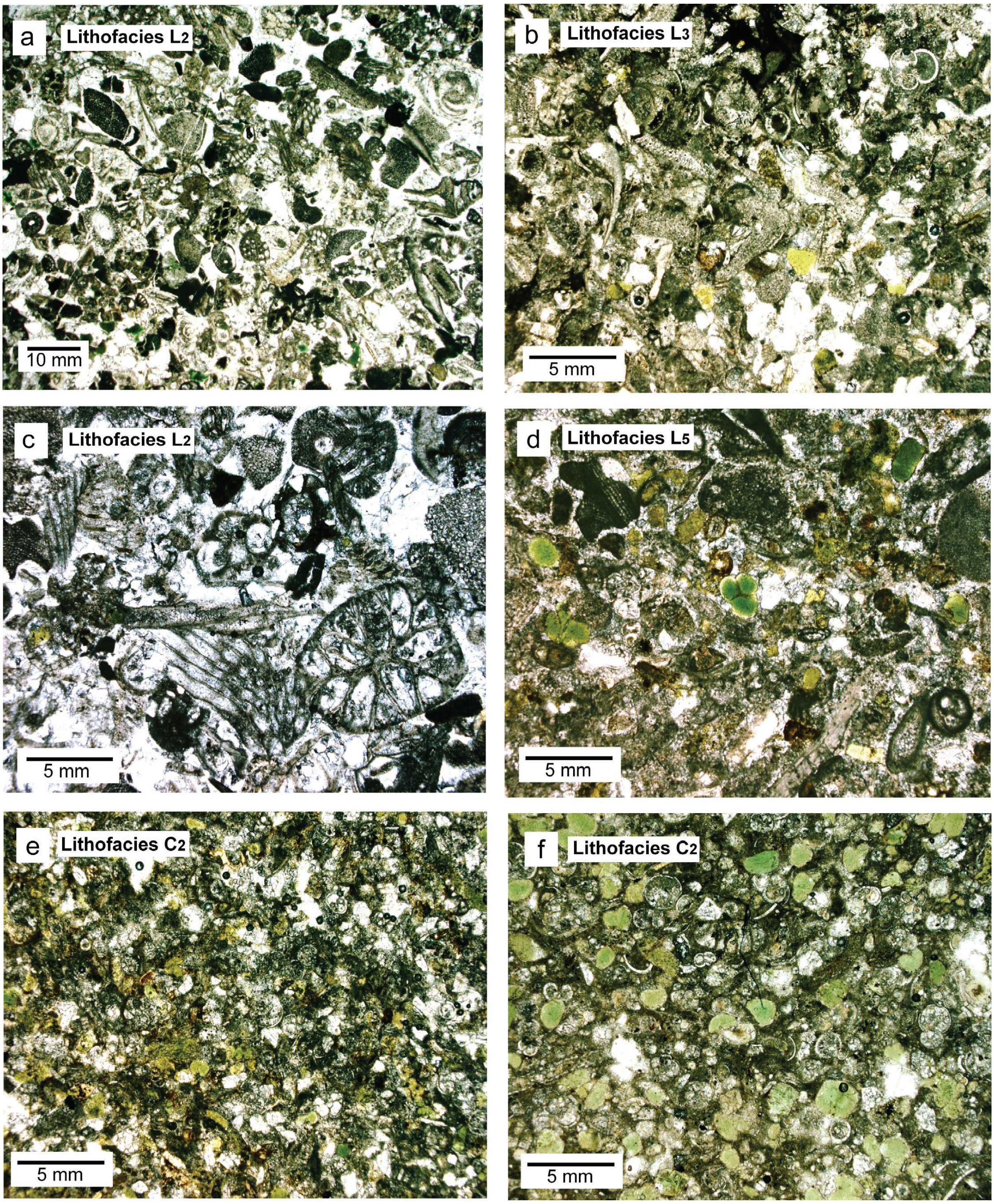


Fig. 6.4: Photomicrographs of representative samples from lithofacies types in the Waimai Limestone Member, and overlying condensed units. (a) Bryozoan/echinoderm/ bivalve/ calcareous red algae in a cross-bedded sparry grainstone lithofacies L2, location E (Fig. 6.2). Sample 120. (b) Echinoderm/ benthic/planktic foraminiferal assemblages along with copious amounts of glauconite, in lithofacies L3, location D (Fig. 6.2). Sample 96. (c) Bryozoan/echinoderm/benthic foraminiferal assemblage in a “Cross-bedded sparry grainstone” lithofacies L2, location F (Fig. 6.2). Sample 177. (d) Echinoderm/ calcareous red algae/benthic foraminifera along with glauconite in a “Mixed grainstone/packstone” lithofacies L5, location B. (Fig. 6.2). Sample 25. (e) Planktic foraminifera rich wackestone with abundant glauconite pellets and infills, lithofacies C2, location A (Fig. 6.2). Sample 8. (f) Planktic/benthic foraminiferal assemblages in a wackestone (lithofacies C2) with abundant glauconite pellets and infills, supportive of deepwater depositional environment, location B (Fig. 6.2). Sample 26.

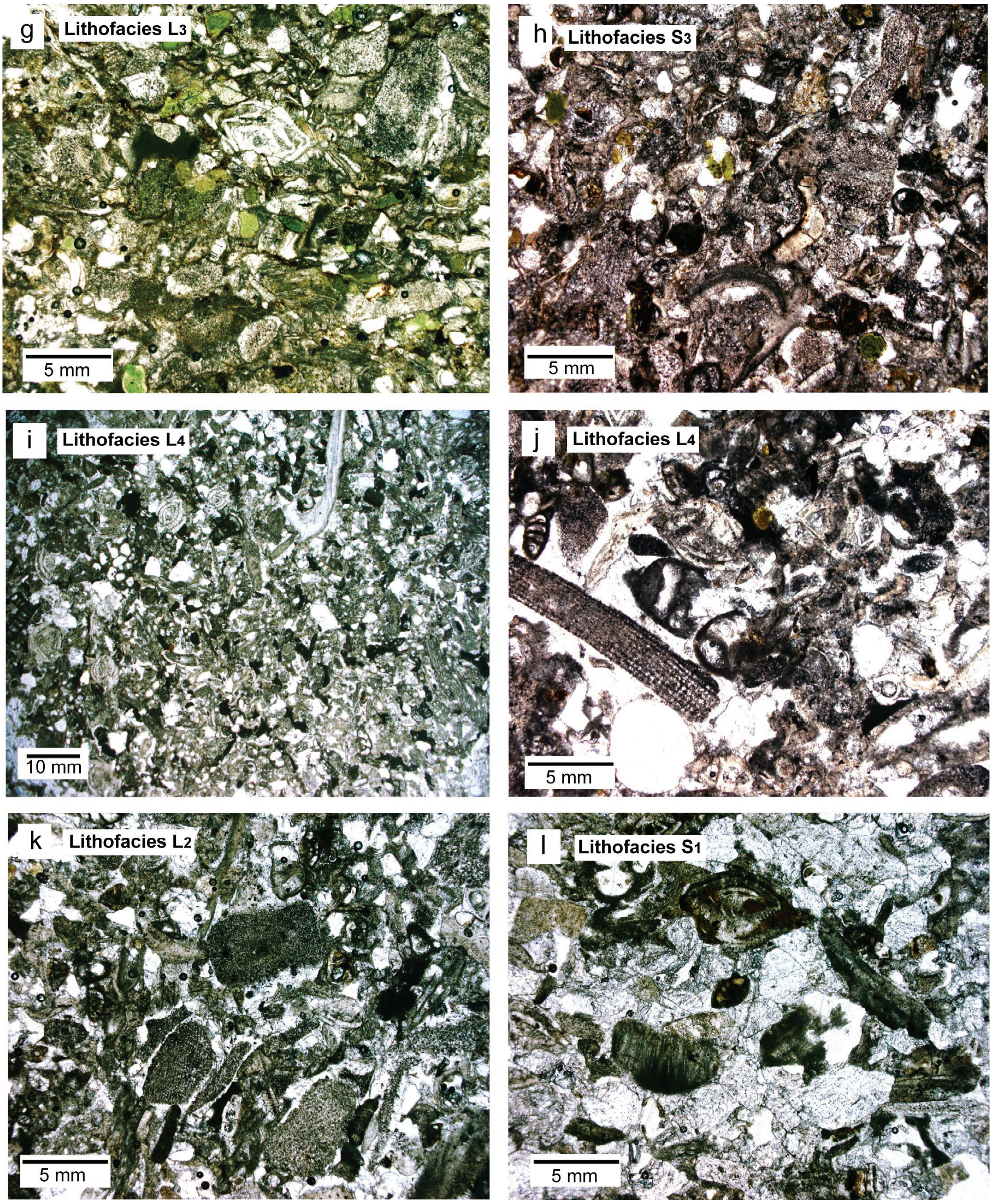


Fig. 6.4 (continued): Photographs of representative samples from lithofacies types in Waimai Limestone Member and Mangiti Sandstone Member (g) Echinoderm/benthic foraminiferal assemblage with glauconite pellets in a “Mixed grainstone/packstone” L3 facies, location G (Fig. 6.2). Sample 196. (h) Echinoderm/benthic foraminifera/bryozoan in a “calcareous sandstone” S3 facies, location G (Fig. 6.2). Sample 197. (i) Echinoderm/benthic foraminifera/calcareous red algae/bivalves in lithofacies L4, location AK-1. Sample 349. (j) Bryozoan/echinoderm/benthic foraminiferal assemblage in a “Mixed grainstone/packstone” lithofacies L4, location AK-1. Sample 350. (k) Echinoderm/bryozoan/calcareous red algae in a “Cross-bedded grainstone” lithofacies L2, location AK-1. Sample 353. (l) Echinoderm/bivalves/benthic foraminiferal assemblages in “Calcareous sandstone” lithofacies S1, location AK-1. Sample 355.

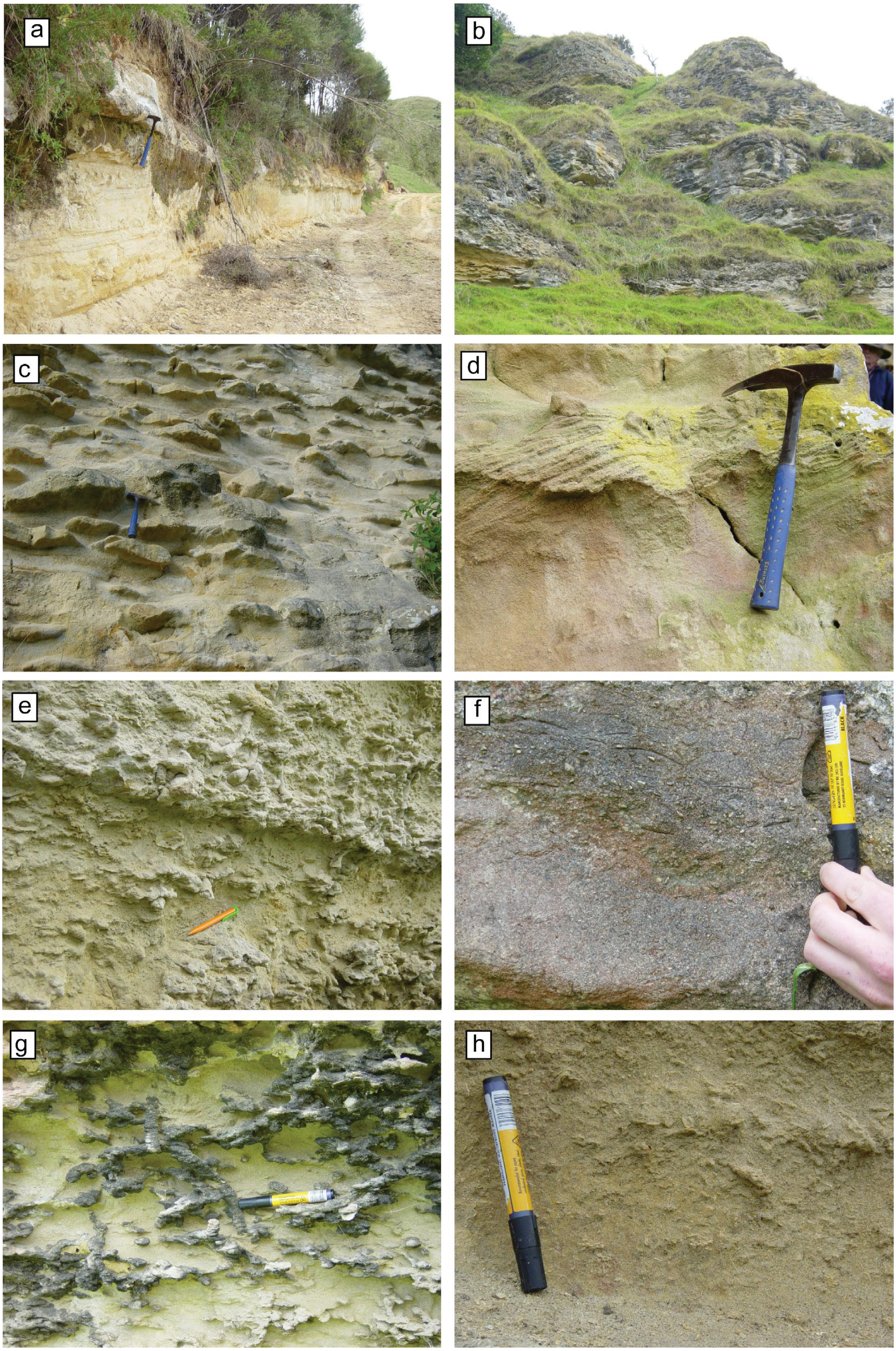

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Fig. 6.5 (facing page): Field photographs of “Variably calcareous fine to medium sandstone” lithofacies S1 (Hauturu Sandstone Member) in the study area. (a) Massive buff coloured friable sandstone exposed near Kokakoroa Road, Te Anga. (C-40). (b) Medium to thick bedded calcareous sandstone packages, often amalgamated, Kihi Road (S-13). Exposure is approximate 20 m high. (c) Typical weathering character consisting of alternation of recessive and laterally discontinuous ellipsoidal shaped well cemented blocks, exposed near Mangaotaki, West of Piopio. (C-145). (d) Massive friable fine to medium grained sandstone gradually passing upwards into low angle cross-bedded sandstone with medium to coarse echinoderm coquina. Photo location Awakino Tunnel. (C-191). (e) Extensively burrowed sandstone bed with scattered rounded to subrounded granules and bivalves (whole shells and broken pectinid fragments), and echinoderm fragments. Photo location Kihi Road. (S-13) (f) Pebble-granule band with abundant bivalve molds chaotically oriented, a common occurrence in this lithofacies. Photo location Kaimango. (C-8). (g) Extensive burrow networks present near the lower unconformable contact of this unit with the Glen Massey Formation. Photo location Okapu, east of Aotea Harbour. (AK-5). (h) Sandstone bed containing abundant echinoderm debris as well as unidentified skeletal fragments, which is a common feature of this lithofacies. Photo location: Kihi Road (S-13).

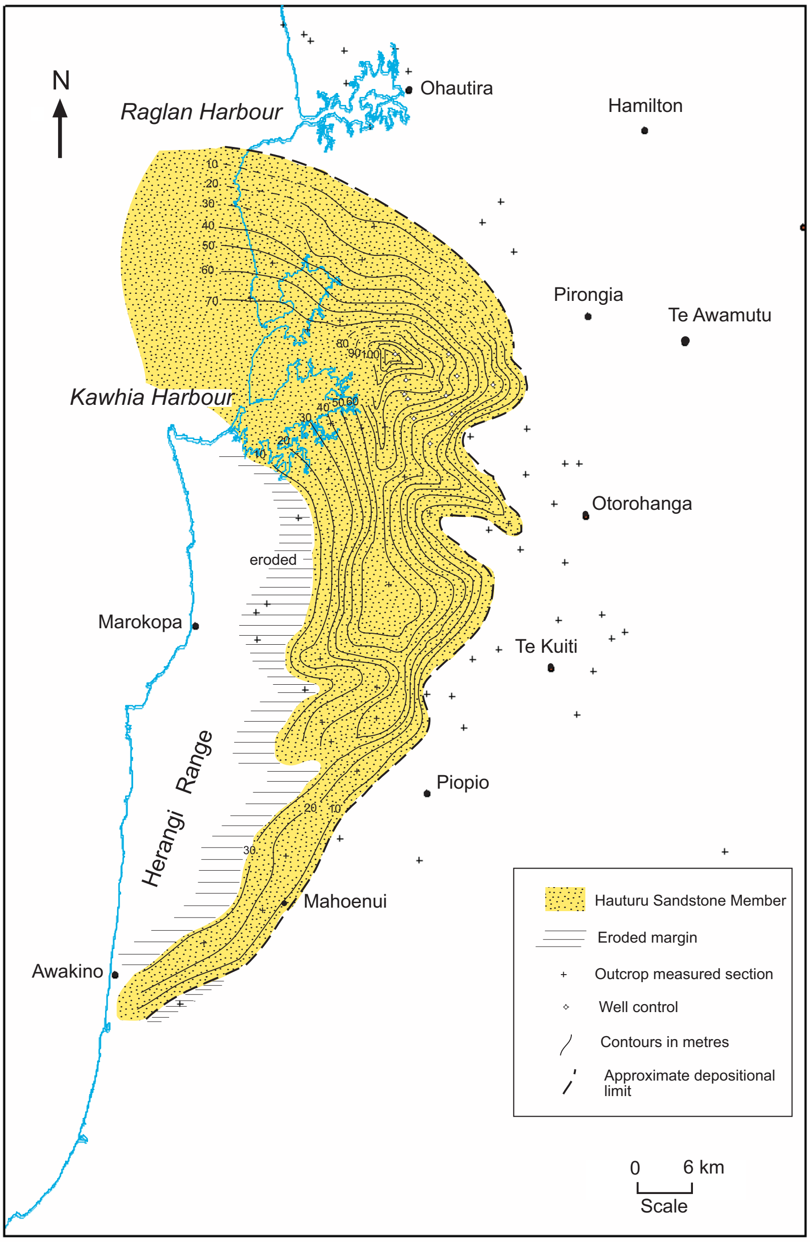


Fig. 6.6: Hauturu Sandstone Member (lithofacies S1) distribution and thickness map. Isopach data derived from outcrops and drill holes (circles). Contour interval 10 m. A sediment fairway into the adjoining eastern margin of Taranaki Basin is suggested by the observed thickness trend the sandstone.

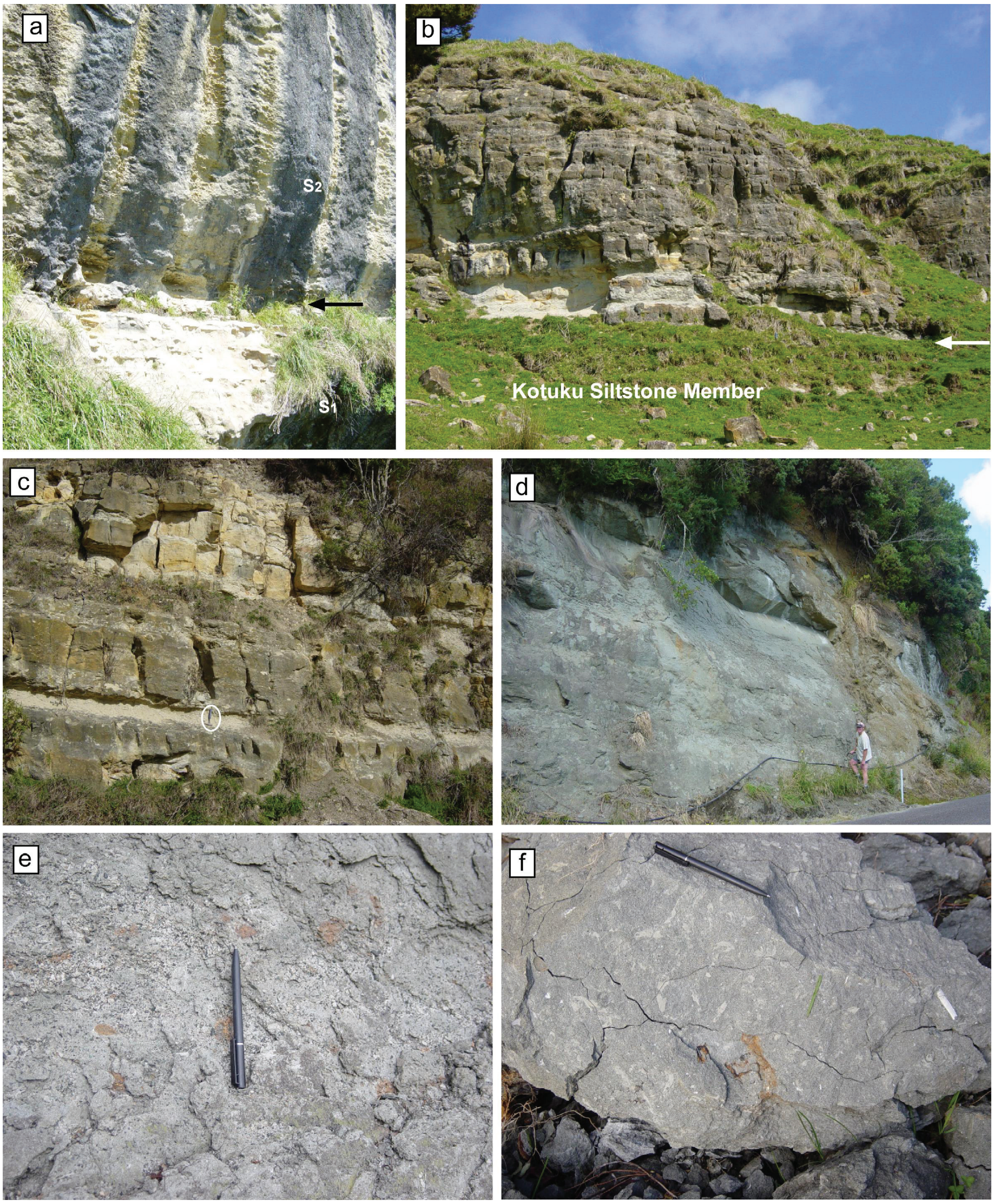


Fig. 6.7: Field photographs of mixed carbonate-siliciclastic sandstone lithofacies in the Aotea Formation across the study area. (a) Sharp facies transition between “Fine to medium sandstone” lithofacies S1 (Hauturu Sandstone Member) and well cemented “Calcareous silty sandstone” lithofacies S2 (Kihi Sandstone Member). Note the sharp break (arrow) in the weathering profile marking the facies transition. Exposure is about 8 m high. Photo location: Hautapu Hill. (C-4). (b) Interbedded calcareous sandstone and sandy siltstone lithofacies S3 (Mangiti Sandstone Member) sharply overlying massive siltstone unit (Kotuku Siltstone Member of Whaingaroa Formation). The Mangiti Sandstone and Kotuku Siltstone Members are separated by an erosional surface (arrow). Exposure is approximate 10 m high. Photo location: near Matakitaki Road, Glen Murray. (PW-7). (c) Buff coloured fine to very fine calcareous sandstone interbedded with thin sandy siltstone from the lower part of the Mangiti Sandstone Member at its type locality Mangiti Road, north of Raglan Harbour. (TA-12). Note prominent vertical solution cavities imparting a blocky appearance is a typical weathering feature of this facies. (d) Bioturbated bluish-grey muddy sandstone lithofacies S4 (Kihi Sandstone Member) exposed along Honikiwi Road. (AK-14). (Note exfoliation weathering is typical feature of this facies. (e) Close-up showing rounded-subrounded granules scattered within “Bioturbated muddy sandstone” lithofacies (S4). Note light rusty brown patches indicating the presence of burrows. Photo location: Honikiwi Road. (AK-14). (f) Mottling due to extensive soft-bodied infaunal burrowing activity is common within these “Muddy sandstone” lithofacies S4. Photo location: Honikiwi Road (AK-14).

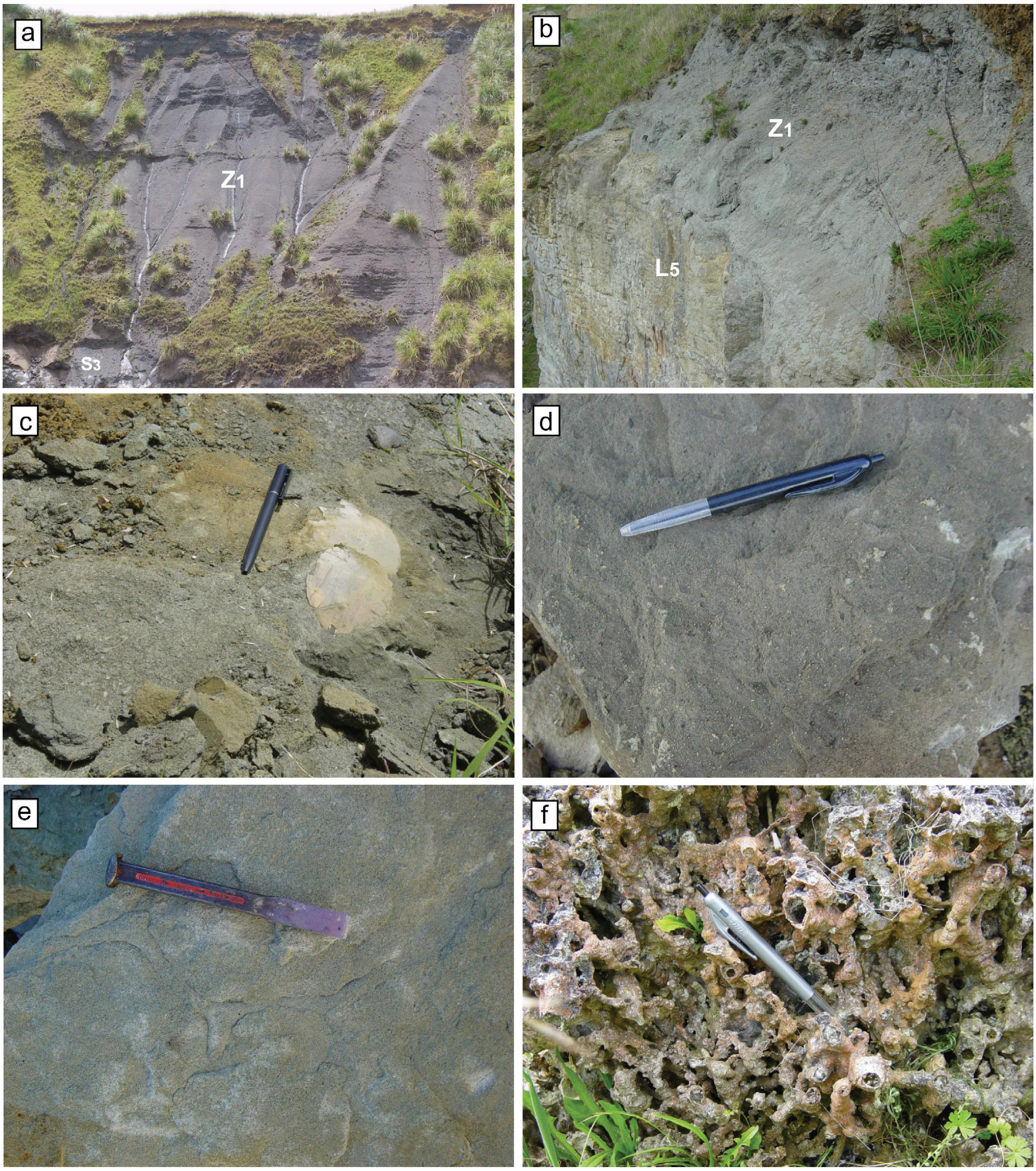


Fig. 6.8: Photographs of the typical field expression of lithofacies in the Aotea Formation across the study area. (a) Medium to dark bluish-grey massive sandy siltstone lithofacies Z1 (Patikirau Siltstone Member) overlying interbedded calcareous sandstone and sandy siltstone lithofacies S3 (Mangiti Sandstone Member; visible on the left hand corner), exposed in a sea eroded cliff at its type locality Patikirau Bay, Raglan Harbour. (TA-20). Note thin silty sandstone interbeds in the lower and upper-middle part of the section. The exposure is approximate 50 m high. (b) Massive to moderately bedded grainstone/packstone lithofacies L5 of Waimai Limestone Member abruptly passing upwards into moderately glauconitic massive sandy siltstone lithofacies Z1 (Patikirau Siltstone Member). Photo location Waikaretu Limestone quarry. (PW-9). (c) Large Lentipecten hochstetteri shells in a highly glauconitic sandstone lithofacies C1. Photo location Honikiwi Road. (AK-14). (d) Close-up showing medium to coarse sand grade glauconitic pellets scattered in an extensively burrowed sandstone lithofacies C1 from the upper part of Aotea Formation (Kihi Sandstone Member). Photo location Waitomo Valley Road. (C-32). (e) Thalassinoides burrows in cross-bedded grainstone lithofacies L2. Photo location : Waikaretu Limestone Quarry. (PW-9). (f) Extensive Thalassinoides burrow network preserved in a fallen block of horizontally bedded grainstone / packstone lithofacies L2. Photo location: Baker Road, east of Limestone Downs (PW-4).

The Waimai Limestone Member in the southern region has coarser bioclast sizes, and higher calcareous red algae and siliciclastic contents (up to 40%); (Nelson 1973), possibly indicating a shallower water depositional setting than for the northern region. A total of five carbonate lithofacies have been distinguished in this study, their details being summarised in Table 6.1.

L_1. *Pebbly grainstone/packstone:*

The "Pebbly grainstone/packstone" lithofacies is limited in occurrence to the southern region, especially where Waimai Limestone Member laps onto basement. This lithofacies is characterised by moderate to poorly-sorted, rounded-subrounded, basement derived pebbles and cobbles up to 15 cm in diameter. Clasts are supported by a calcareous sandstone or siltstone matrix that is poorly stratified but may occasionally exhibit horizontal bedding such as at Honikiwi (e.g. C-25). The majority of the clasts near the lower contact with basement are coated by algal laminae, and rhodoliths can comprise more than 50% of the algal material (Fig. 6.1a). Other common biota include echinoiderm fragments, bryozoans, benthic foraminifers especially *Amphistegina* sp., *Arenodosaria antipoda*, and *Notorotalia spinosa* e.g. S15/f8504, f8505. Planktic foraminifers are rare. Occasional large pectinid bivalve shell fragments are also present. Glauconitised shells and clasts are common together with glauconite pellets especially in the lower part. The clasts fine upwards within limestone such that pebbles at the base of Waimai Limestone Member are succeeded by granules, and pass upsection into "Horizontally bedded grainstone" (lithofacies L_3). This facies corresponds to the "Basal Beds (AoA)" of the Aotea Formation described by Nelson (1973, 1978a) in the Waitomo (e.g. C32) and Honikiwi (e.g. C25) areas (Nelson 1973, 1977).

Interpretation: This facies is similar to the "Pebbly grainstone" (L_1) lithofacies of Glen Massey Formation. It is inferred to have formed as a transgressive lag deposited at the base of Waimai Limestone Member during marine encroachment onto basement, as indicated by its stratigraphic position and the abundance of basement derived clasts. Coralline algae, including rhodoliths, large benthic foraminifera (*Amphistegina*) and other biogenic components in this facies suggest a shallow marine inner shelf environment of deposition (James et al. 1997; Nalin et al. 2008).

L_2. *Cross-stratified grainstone:*

The "Cross-stratified grainstone" lithofacies occurs mainly in the lower part of the Waimai Limestone Member between Port Waikato and Waimai Valley (localities PW-11, PW-3 & PW-4 in Fig. 6.10 and PW-9, TA-2 & TA-3 in Fig. 6.11). This facies is characterised by moderate (10-20º) to low angle (<10º) cross-bedding, and occurs in 0.3 - 4.5 m thick sets and cosets that are traceable laterally for up to a few tens of metres. Cross-set bases and tops are sharp; foresets are commonly truncated sharply along their upper bounding surface (Fig. 6.1 c). Cross-beds vary from 2 - 15 cm thick, and are separated by 0.5 to 1.5 cm thick sliciclastic-rich seams (Fig. 6.1 d). The grainstone is spar-cemented (av. 15%) and forms up to 20% of the whole rock composition in some samples. This lithofacies is notably bioclast rich (av. 72%). Bioclasts are coarse grained and typically of medium to coarse sand size. Siliciclastic content is low (av. 5%) and includes quartz, feldspar, and rare traces of fine to coarse sand size rock fragments, although solitary rounded to subrounded pebbles and granules are occasionally present. Grainstones are dominated by echinoderm (av. 28%), bryozoan (av. 17.6%), benthic foraminfera (*Discorotalia tenuissima*, *Rotaliatina sulcigera*, *Notorotalia* cf *spinosa* e.g. R13/f8557) and less commonly by bivalves or calcareous red algae. Planktic foraminifera average only 1.6% (Fig. 6.4 a, c & k). Glauconite and/or pyrite are usually present in small quantities (av. 4.8%). Trace fossils include *Thalassinoides* and/or *Scolicia*, and *Arenicolites* (Anastas 1997) are common especially at the base of “Cross-stratified” lithofacies where they occur near a scoured surface a few centimetres deep (Fig. 6.8 f). Skeletal grains are moderately well sorted and abraded. The “Cross-stratified grainstone” lithofacies pass gradationally upwards into “Massive to moderately bedded, bioturbated, grainstone-packstone” (lithofacies L_5). Lithofacies L_2 passes offshore (i.e. eastwards) into “Horizontally bedded grainstone lithofacies” L_3 (Fig. 6.2).

Interpretation: The “Cross-stratified grainstone” lithofacies is interpreted to have been deposited within a large (>30 km long) carbonate dune field in a current-dominated NNE-SSW oriented seaway (Anastas 1997) roughly parallel to the basin axis. Strong offshore-directed currents controlled by structural highs modified and shaped the carbonate shelf into a complex system of sand waves. Paleocurrent data for the northern region indicate an east to NNE direction of net sediment transport, reflecting the influence of basement topography on current direction along the western margin (Anastas 1997). The presence of minor quantities of coralline algae in this lithofacies suggests carbonate production and deposition was in the subphotic environment, probably up to 70 m deep (e.g. Nelson et al. 1988a, James et al. 1992). The benthic foraminifera in this facies indicate inner to mid shelf depth ranges (e.g. Hayward 1986; Cooper et al. 2004). The cross-bed thicknesses decrease upwards suggests waning mean current strength (Anastas 1997) and reducing current velocities possibly due to an increase in relative sea-level (deepening).

L_3. Horizontally bedded grainstone/packstone:

The “Horizontally bedded grainstone” lithofacies comprise the major part of

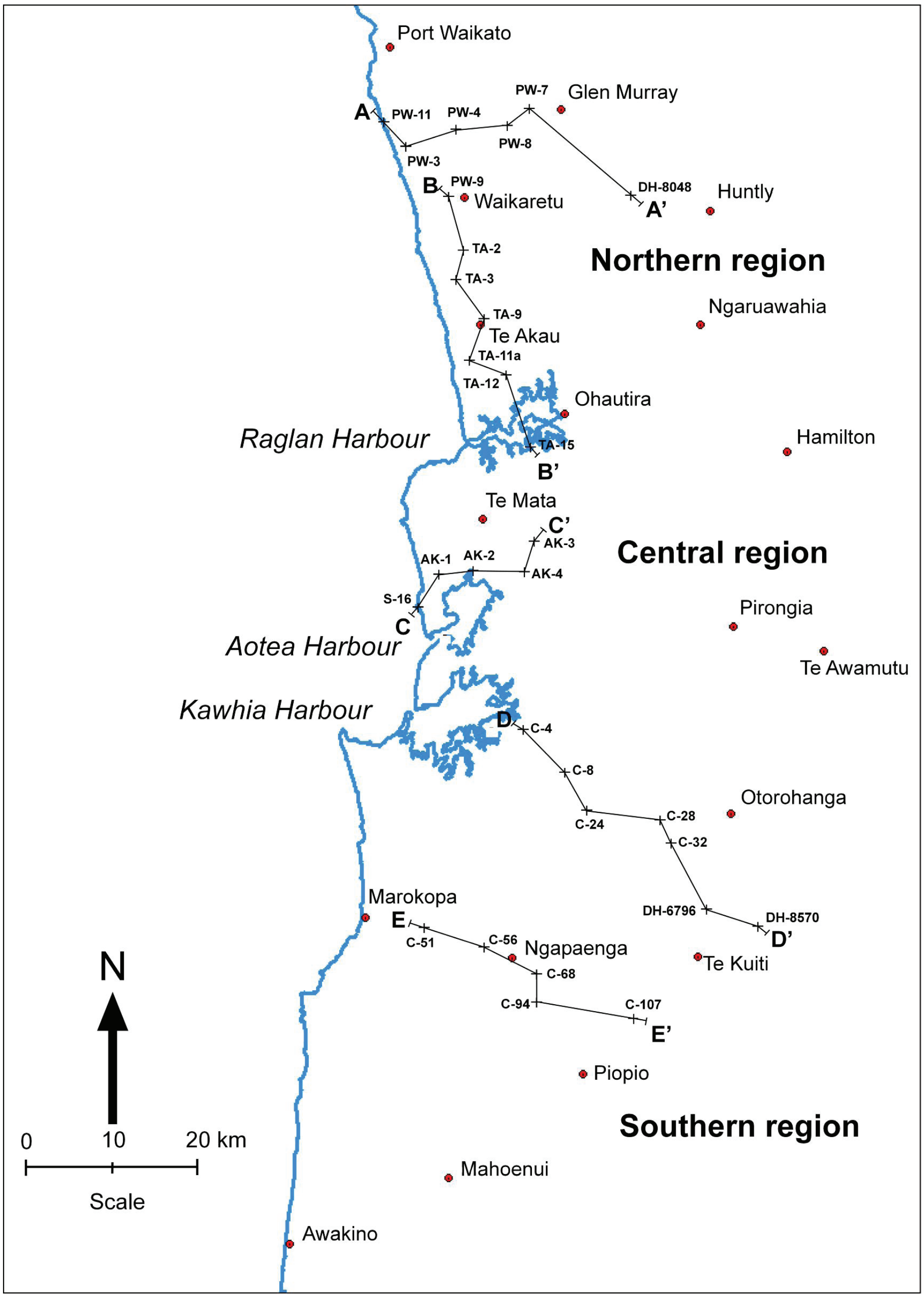


Fig. 6.9: Map showing the locations of five transects illustrated in Fig. 6.10, 6.11, 6.12, 6.13 and 6.14.

Waimai Limestone Member occurring within the northern region (e.g. Onewhero and Te Akau) exemplified by localities PW-8 and PW-7 in Fig. 6.10 and TA-9 in Fig. 6.11. In some locations such as TA-2 and TA-3 (Fig. 6.11), L_3 is intercalated with “Cross-stratified grainstone” lithofacies $L_{2,}$ which represents a transition between “Cross stratified grainstone” lithofacies L_2 and “Interbedded calcareous sandstone and sandy siltstone” lithofacies S_3 (best exemplified by location TA-11a in Fig. 6.11). This facies is characterised by horizontal beds or flags ranging from 2 to 18 cm thick separated by 0.5 to 1.5 cm thick seams with concentrations of siliciclastic fine sandstone (Fig. 6.1e). Some of the thickest beds in the lower part of Waimai Limestone Member show internal bedding or layering. The siliciclastic

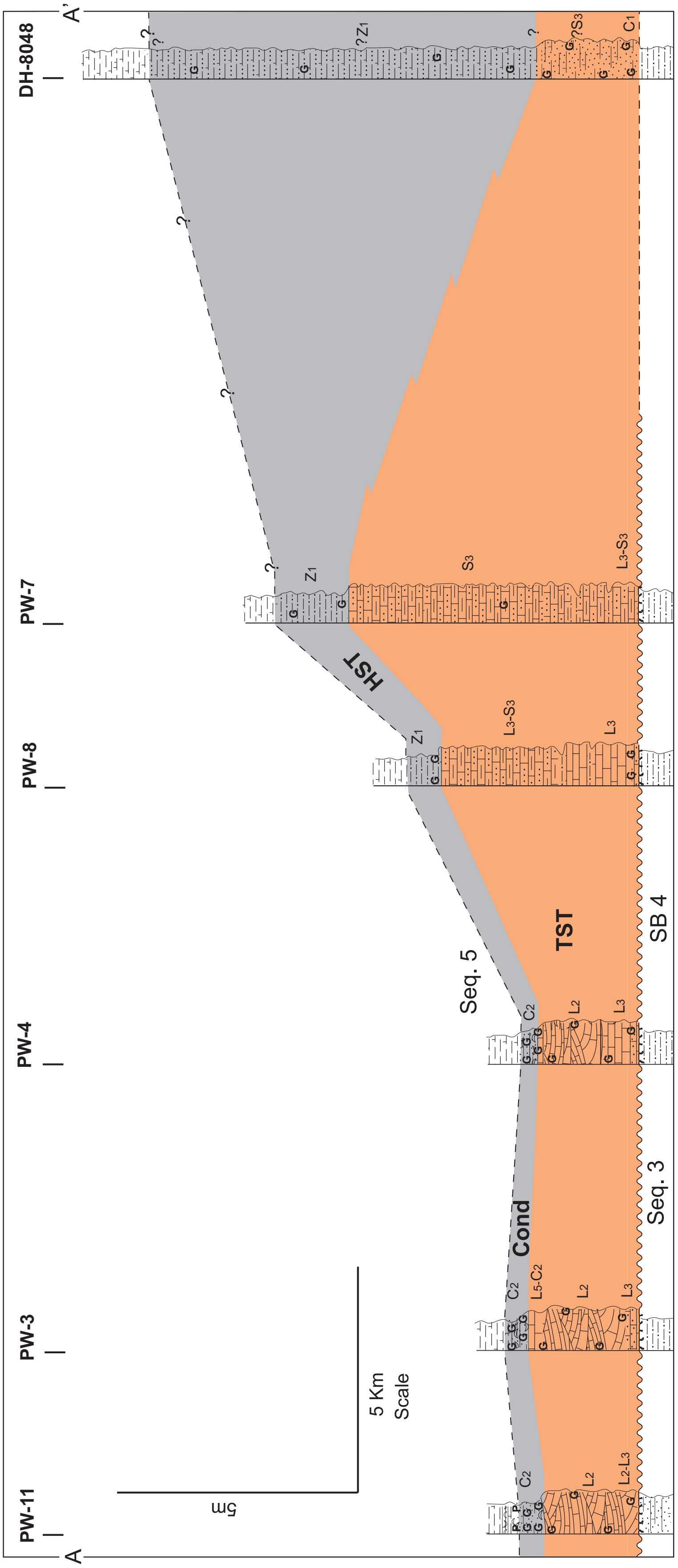


Fig. 6.10: Northwest-southeast transect across the northern part of the study area. Datum: Sequence boundary (SB 4) between Whaingaroa (seq. 3) and Aotea Formation (see Fig. 6.9 for column locations).

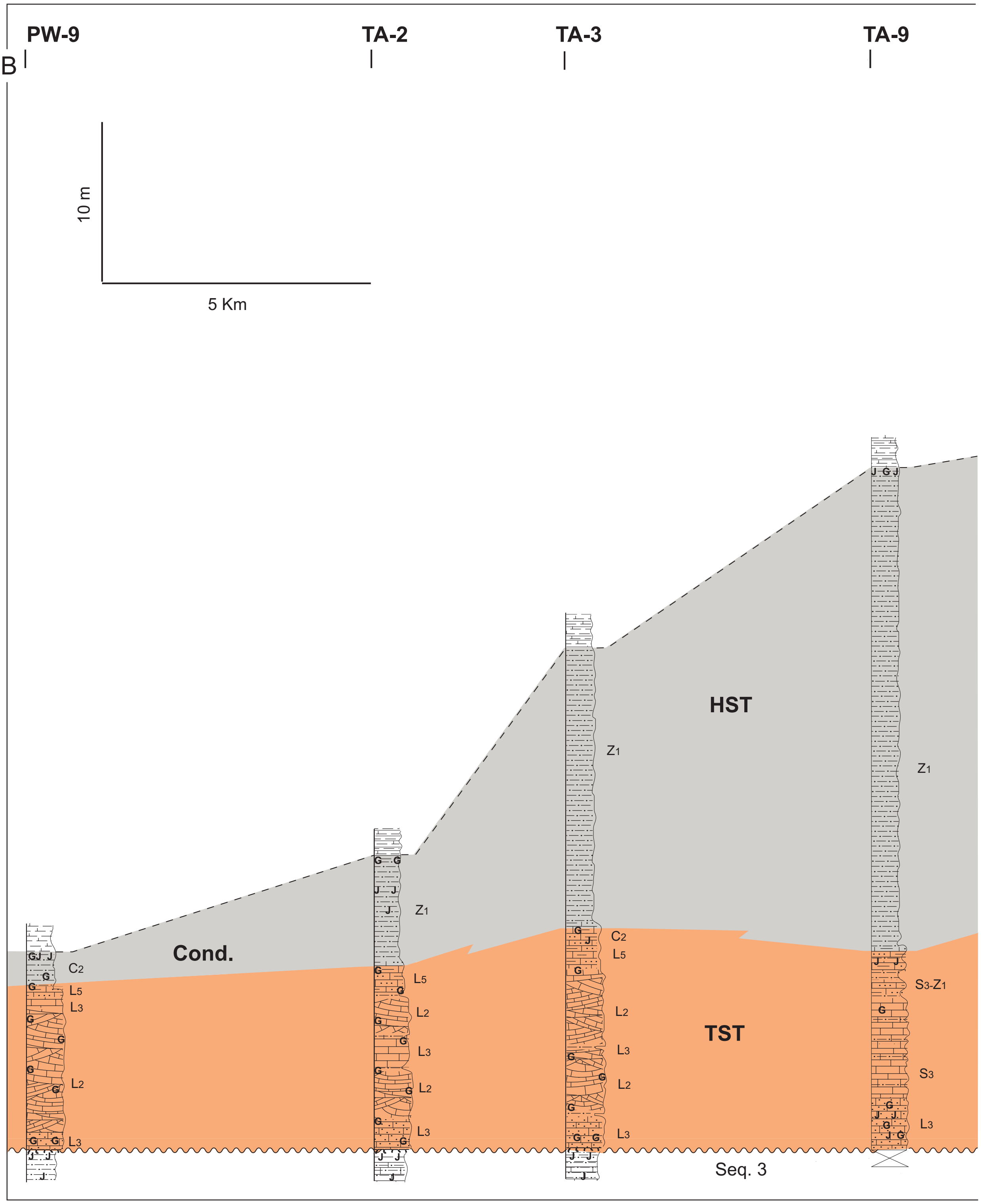
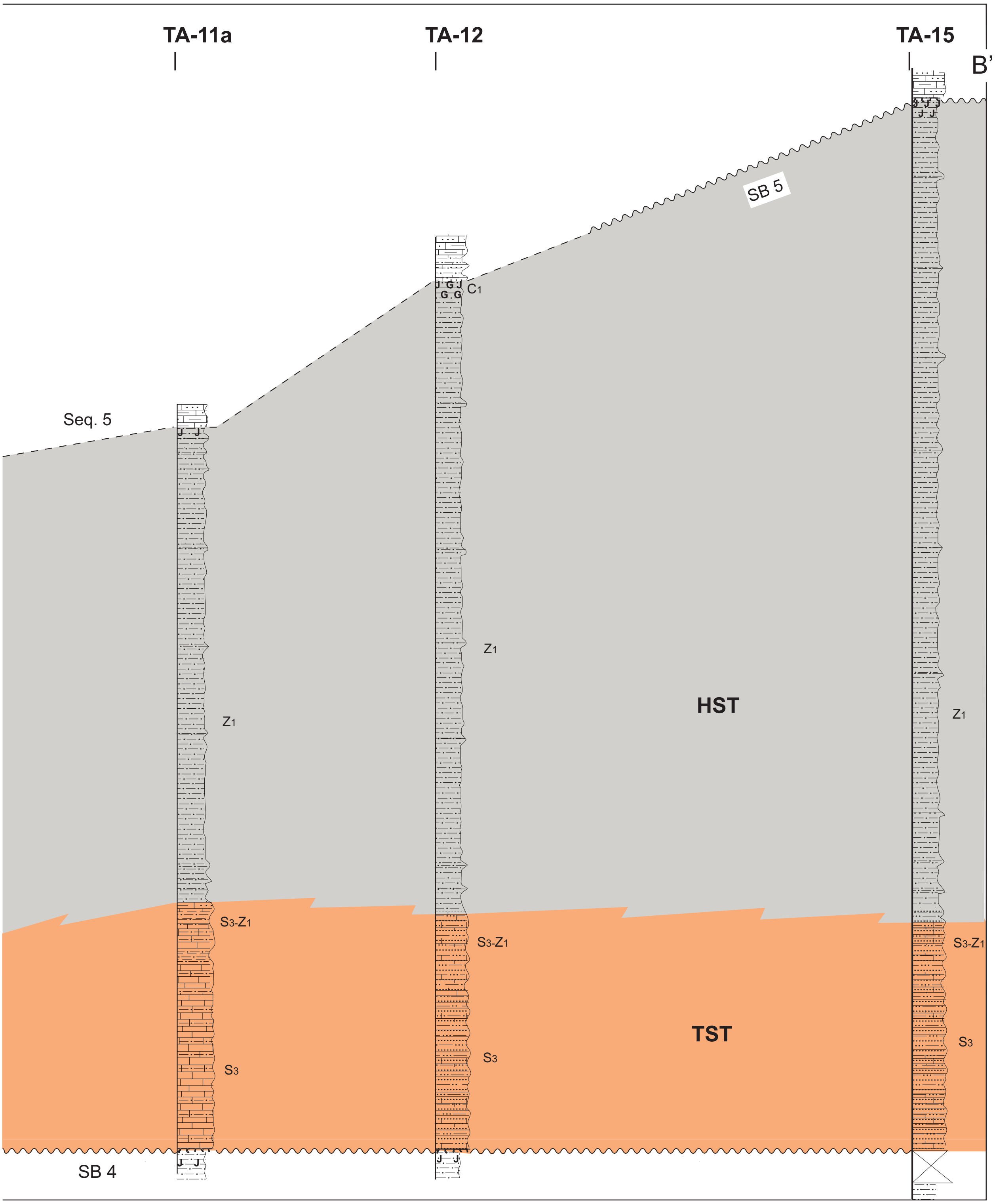


Fig. 6.11 (two page spread): North-south transect across the western parts of the northern region. Datum: Sequence boundary between Whaingaroa Formation top (seq. 3) and Aotea Formation (Seq. 4). See Fig. 6.9 for column locations.


TA-11a
TA-12
TA-15
B'
SB 5
Seq. 5
C1
Z1
HST
Z1
Z1
S3-Z1
S3-Z1
S3-Z1
TST
S3
S3
S3
SB 4

material consists of quartz and feldspar of very fine to fine sand grade and rare rock fragments. Bioclasts are typically of medium sand grade, averaging 68.6% of the whole rock composition. Bioclasts are dominated by echinoderm fragments (av. 29.4%), benthic foraminifera (av. 17.4%) and to a lesser extent planktic foraminifera (9.1%), bryozoan (av. 7.1%) and bivalves (av. 4.6%). Calcareous red algae, barnacles, spicules and spines form minor components (Fig. 6.4 b & g). The micrite matrix (av. 8%) and spar cement (av. 10%) content is highly variable. Glauconite and or pyrite pellets and infills are usually ubiquitous, averaging 7%, and may be locally abundant. This facies passes gradationally upwards into "Massive to moderately bedded and bioturbated, grainstone-packstone" lithofacies L_5 (Fig. 6.2).
Interpretation: This facies is similar to the "Horizontally bedded grainstone" (lithofacies L_4) described in Chapter 5. The facies is inferred to have been deposited in an inner to mid shelf setting characterised by bedding defined by the alternation of relatively enriched and impoverished siliciclastic material, probably the result of a complex interplay between wave and storm and/or wind induced currents (e.g. Nelson 1978b).

L_4. Sandy-silty grainstone:
The "Sandy-silty grainstone" lithofacies is thickest (up to 60 m) to the north of Aotea Harbour (locality AK-1 in Fig. 6.12) where it comprises the major part of the Waimai Limestone Member. The facies typically comprise grain-supported, spar-cemented grainstone beds rich in bioclasts (av. 69.4%). The bioclasts are considerably coarser grained (av. 0.60 mm), especially in TA-1, and typically of medium to coarse sand size. The bioclasts are variably dominated by echinoderm (av. 21.4%), benthic foraminifera (av. 17.8%), bryozoan (av. 12.2%), and to a lesser extent by bivalves (av. 8%) and calcareous red algae (8.9%). Other bioclasts include rare barnacles, spicules and spines. Planktic foraminifera are rare or absent (Fig. 6.4 i & j). In places, discontinuous shell hash often consisting of echinoid coquinas (rare whole echinoderms) has been observed. Skeletons are slightly abraded and are mainly moderately sorted. Siliciclasts are of medium to coarse sand size quartz with feldspar and lesser amounts of igneous rock fragments. Other minor components include glauconite and or pyrite. The micrite matrix content averages only 2%, while spar cement content averages 12%. This facies typically intergrades with the "Variably calcareous fine to medium sandstone" lithofacies S_1 (locality AK-1 to AK-2 in Fig. 6.12 and locality C-8 to C-4 in Fig. 6.13). This facies exhibits peculiar cavernous weathering characteristics, which in places resemble the variably calcareous fine to medium sandstone lithofacies L_5, however it is commonly more calcareous than L_5, and may include discrete moderately cemented sandstone beds (Fig. 6.1 f & h). It contains irregular to slightly undulating beds ranging in thickness

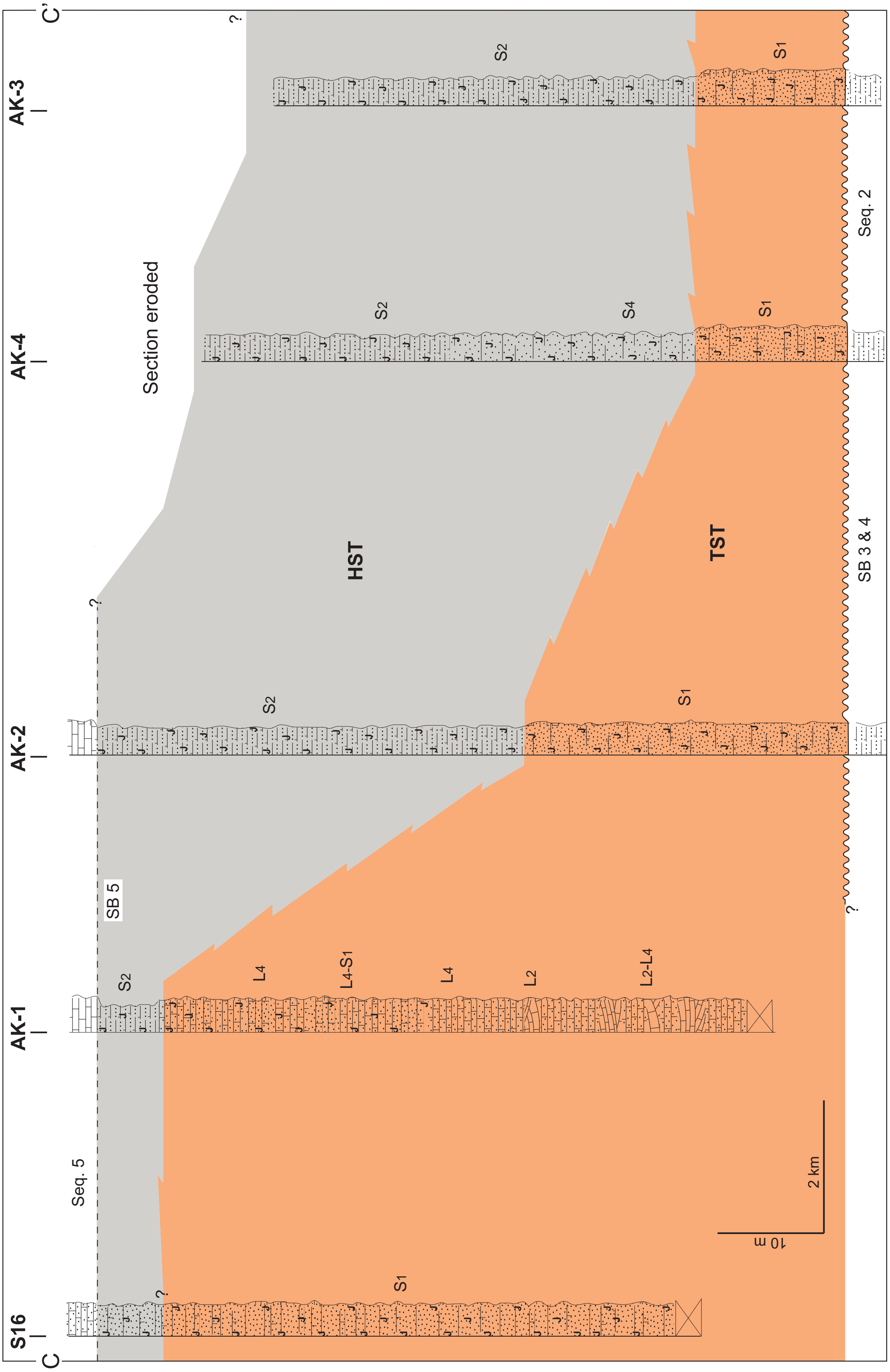


Fig. 6.12: Southwest-northeast transect across the northern parts of Aotea Harbour. Datum is sequence boundary between Glen Massey Formation (seq. 2) and Aotea Formation (seq. 4). See Fig. 6.9 for column locations.

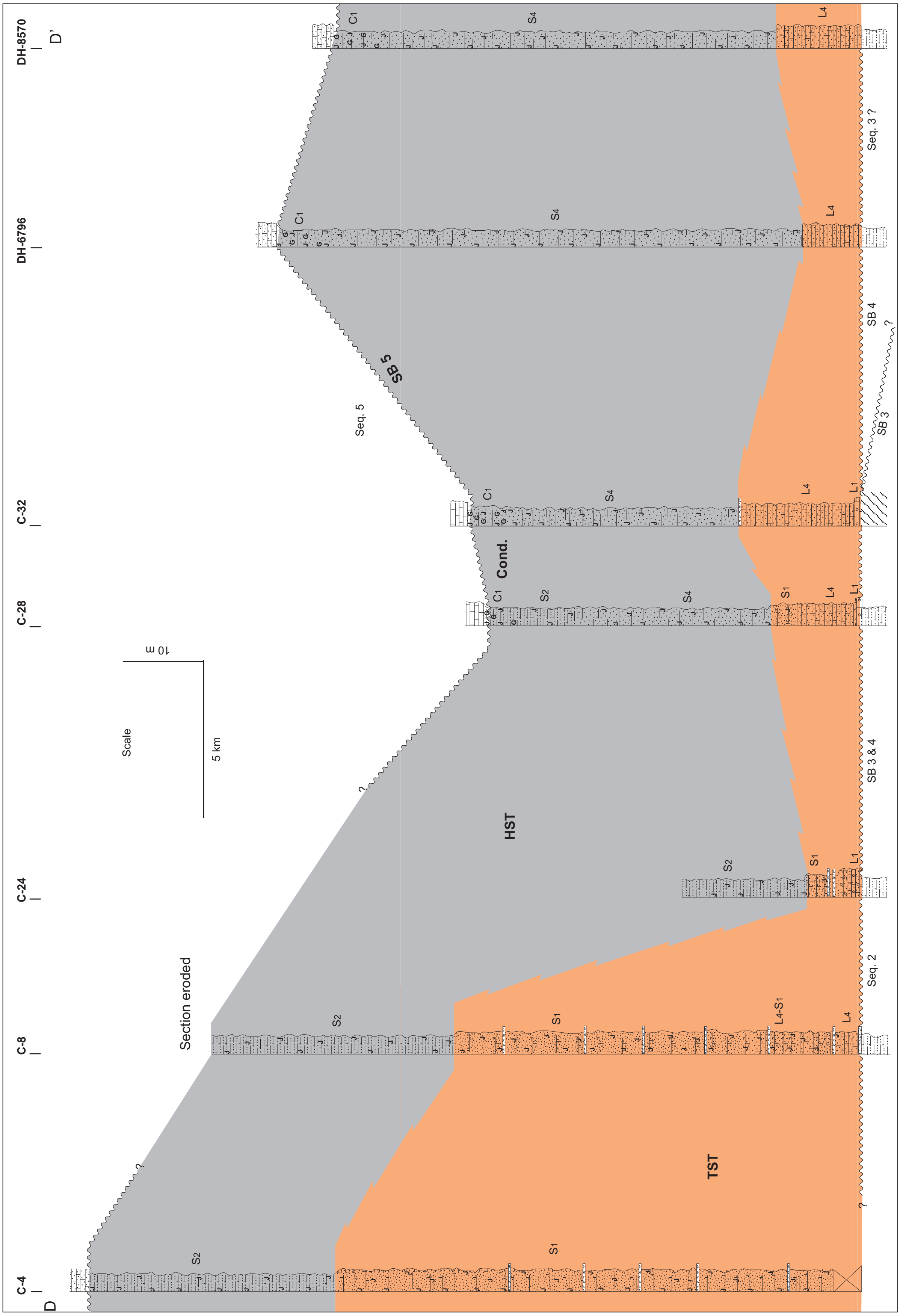


Fig. 6.13: Northwest-southeast transect across the central-southern region of the study area. Datum is sequence boundary between Glen Massey Formation (seq. 2) and Aotea Formation (seq. 4) on the western end, and Whaingaroa Formation (seq. 3) and Aotea Formation (seq. 4) on the eastern end. Note Aotea sequence laps onto the basement at location C 32. See Fig. 6.9 for column locations.

from 2 to 12 cm, but massive to weakly bedded units are also common. It is cross-stratified at many localities, especially in localities north of Aotea Harbour. The "Sandy-silty grainstone" lithofacies is inferred to be a transitional facies between the Waimai Limestone Member and Hauturu Sandstone Member.
Interpretation: The "Sandy-silty grainstone" lithofacies represents deposition in an inner to middle shelf setting that was episodically affected by storms. The occurrence of echinoid coquina and granule beds probably reflect storm emplacement (e.g. Nelson et al. 1988a). The occasional cross-stratification reflects the migration of megaripples and sand waves across the shelf in response to storm and/or tidal induced currents (Anastas et al. 1997).

L_5. Massive to irregularly bedded, bioturbated, grainstone/packstone:
This lithofacies is restricted to the upper parts of the Waimai Limestone Member in northwestern parts of the field area (exemplified by locations PW-9, TA-2 & TA-3 in Fig. 6.11). The lithofacies has a dull blue-grey colour with common greyish-green patches. This lithofacies is massive to irregularly bedded (Fig. 6.1g). Some bedding exhibits diffuse and irregular upper and lower contacts. Bioclasts average 68% of the whole rock composition and are dominantly fragmental and of fine sand size (av. 0.13 mm). The skeletal grains are variously dominated by echinoderm, benthic foraminifera and delicate branching bryozoans (Anastas 1997). Other bioclasts include bivalves, planktic foraminifers and rare calcareous red algae. Siliciclastic particles are generally fine to medium sand size quartz and feldspar and may comprise up to 6% of the rock (Fig. 6.4 d). Moderate concentrations of glauconite and pyrite occur throughout the grainstone-packstone interval. This facies passes vertically into either "Massive variably calcareous sandy-siltstone" lithofacies Z_1 or "Glauconitic packstone/wackestone" lithofacies C_2 (Fig. 6.2).
Interpretation: This facies is inferred to have been deposited in mid to mid-outer shelf water depths. The relative paucity of physical sedimentary structures compared with underlying "Cross-stratified grainstone" (L_2) and the intensity of bioturbation probably reflects increasing paleobathymetry. This is further corroborated by an increase in the content of delicate bryozoans (Anastas 1997; Nelson et al. 1988b). Common greyish-green muddy patches are probably compressed burrows suggesting the substrate was non-cohesive (Anastas 1997).

Mixed carbonate-siliciclastic sandstone lithofacies (S_1 – S_4)
Variably calcareous sandstone and muddy-sandstone (hereafter referred to as sandstone lithofacies) comprises the majority of the Aotea Formation over much of the central and southern parts of the study area. Sandstone lithofacies probably constitute all of the total Aotea Formation thickness in the area from Aotea Harbour

to Awakino, except where thin basal limestone facies (Waimai Limestone Member) occur. The Hauturu Sandstone Member and Kihi Sandstone Member of the Aotea Formation, forming most of the sandstone lithofacies, are exposed extensively in the hill country east of Aotea-Kawhia Harbour and probably extend in the subsurface beneath most of Karioi and Pirongia Volcanoes (White & Waterhouse 1993), and areas to the south. In the area east of Aotea-Kawhia Harbour, the sandstone lithofacies are of up to 180 m thick.

In both the Hauturu Sandstone Member and Kihi Sandstone Member the sandstone lithofacies are characterised by heterogeneity of lithology. The Hauturu Sandstone Member occurs mainly in western areas (Aotea Harbour to Awakino), comprises "Variably calcareous fine to medium sandstone" (lithofacies S_1) with negligible mud content, and forms distinctive well cemented hard bands encasing soft friable sandstone. The Kihi Sandstone Member differs from the Hauturu Sandstone (S_1) in having higher mudstone content and in being fine to very fine sandstone (S_4). This facies (S_4) occurs mainly in the eastern parts of the field area but it also stratigraphically overlies the Hauturu Sandstone Member (S_1), especially in the Aotea-Kawhia area.

Four mixed carbonate-siliciclastic sandstone lithofacies are identified in the Aotea Formation. The essential characteristics of these lithofacies are summarised in Table 6.1.

S_1. Variably calcareous fine to medium grained sandstone:

This facies comprises the Hauturu Sandstone Member exemplified by localities C-4 and C-8 in Fig. 6.13. In the southern part of the field area this facies constitutes almost the entire Aotea Formation (e.g. localities C-56 & C-68 in Fig. 6.14), which is also the case at Taranaki Point (S-16 in Fig. 6.12). This variably calcareous sandstone lithofacies is the "Banded Sandstone Beds (Ao-5)" of Aotea Formation described by Nelson (1978). Sandstone is of fine to medium grade with carbonate content ranging from a few percent to up to 56% (Nelson 1973). The distribution and thickness trend of S_1 is depicted in Fig. 6.6. Facies S_1 is typified by well cemented concretionary bands (up to few tens of centimeters long) alternating with friable to poorly cemented sandstone (Fig. 6.5c). In several locations east of Kawhia Harbour, the lithofacies consist of thick-bedded sandstone packages 5 to 10 m thick overlain by comparatively thin bedded sandstone, often amalgamated (Fig. 6.5b). Internal stratification features are subtle but include small to medium scale, low-angle cross-stratification in fine to medium sandstone, with some indications of hummocky cross-stratification (Fig. 6.5 d). Maximum foreset dips rarely exceed 10º. Rounded to subrounded granule to pebble bands are common within some sandstone beds (Fig. 6.5 f). The deposits frequently consist of densely bioturbated beds up to tens of centimeters thick. Robust millimetre diameter subvertical to inclined *Skolithos* and/or *Thalassinoides* burrows are common. Shell hash layers, some containing pholad bored bivalves, are also common, especially in Hautapu Hill and Kihi Road exposures (Fig. 6.5 e, f, g & h). The whole rock composition is typically siliciclastic-rich (av. 57%), moderately sorted fine to medium quartzo-feldspathic sandstone. Other components include traces of rock fragments, glauconite and pyrite. The bioclasts of coarse sand size are dominated by echinoderm fragments, bryozoans, benthic foraminifera, and occasionally calcareous red algae (Fig. 6.4 l) (Nelson 1973).

Interpretation: The variably calcareous fine to medium sandstone is interpreted to have been deposited in a combination of wave, tide and storm dominated inner/mid shelf setting. The common occurrence of trough cross-stratification indicates deposition on a storm influenced shelf (e.g. Dott & Bourgeois 1982; Swift et al. 1983; Walker 1984). The abundance of burrows indicates that there were also extensive fair-weather conditions between storm events. Bioturbation was able to keep pace with physical sedimentation (e.g. Howard 1978). Winnowed granule and pebble lags along with shell hash layers were probably re-worked from the adjacent beach environment and deposited under the influence of storm currents (e.g. Driese et al. 1991). The presence of benthic foraminifera such as *Gyroidinoides* sp., *Amphistegina* sp., *Elphidium* sp. (e.g. R15/f8509) and *Anamalinoides fasciatus*, *Arenodosaria* sp. and *Notorotalia* sp. (e.g. R16/f7559) indicate high energy inner to mid shelf environments (Hayward 1986; Cooper et al. 2004). Planktic foraminifera are insignificant to trace amounts in this lithofacies.

S_2. Massive to thin-bedded calcareous silty-sandstone:

“Massive to thin-bedded calcareous silty-sandstone” lithofacies comprise the major part of westernmost exposures of Kihi Sandstone Member within the Aotea-Kawhia area, stratigraphically overlying the Hauturu Sandst one Member. They occur mainly in the upper part of the Aotea succession (exemplified by localities AK-2, AK-3, AK-4 in Fig. 6.12 & C-4, C-8 in Fig. 6.13). This facies was encountered in the majority of the West Kawhia Coalfield drill holes and was described by Phelps (1985) as “Upper Aotea Sandstone” stratigraphically overlying the Hauturu Sandstone Member (lithofacies S_1). Further south, it is commonly interbedded with “Variably calcareous fine to medium sandstone” lithofacies S_1 (locations C-56 & C-94 in Fig. 6.14). This facies resembles the “Massive bioturbated muddy-sandstone” lithofacies S_4, in that it is chiefly composed of siltstone and fine to very fine sandstone. However, unlike lithofacies S_4, this facies consists of thin beds of calcareous sandy-siltstone and

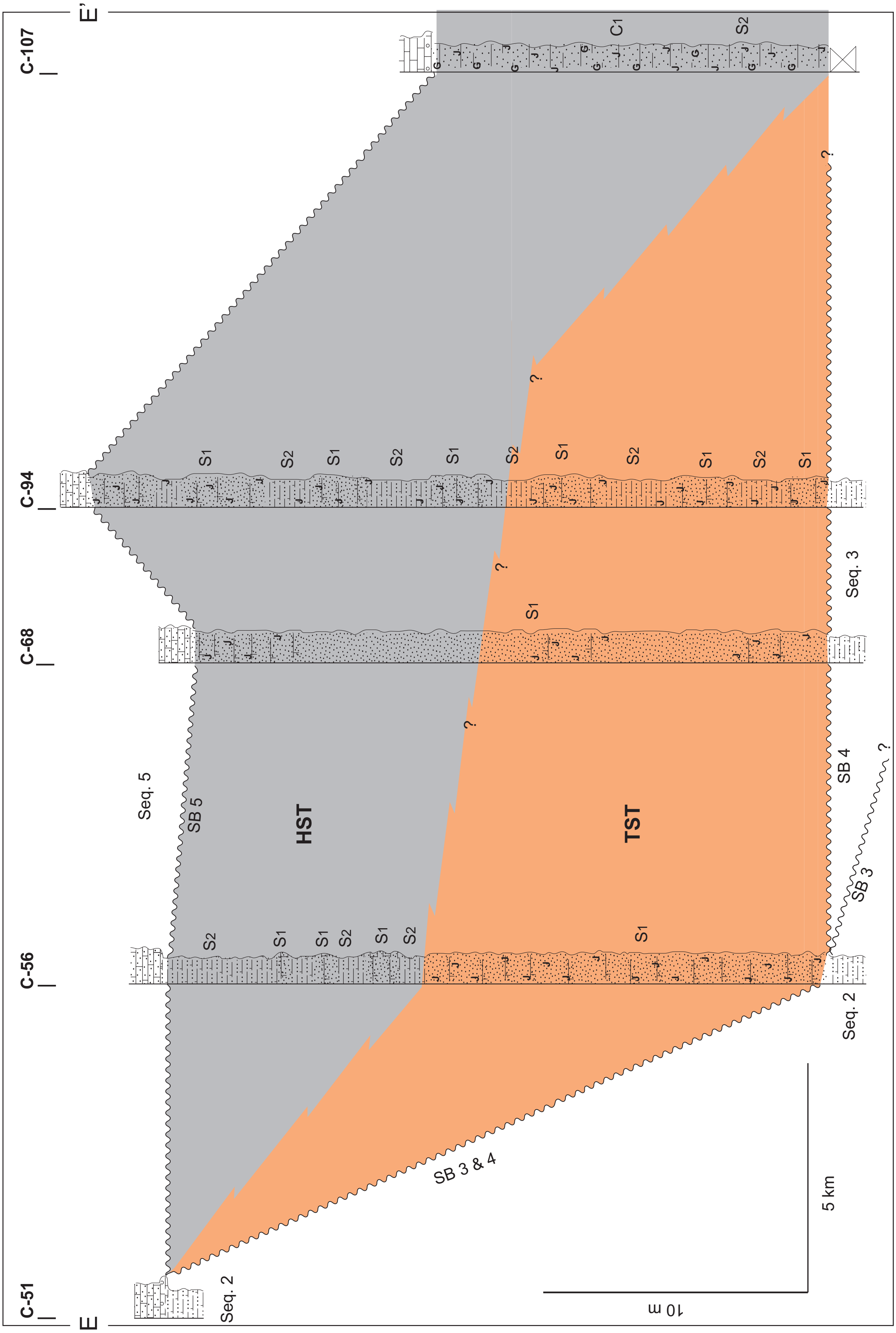


Fig. 6.14: Northeast-southwest transect across the southern region. Datum is sequence boundary between Glen Massey Formation (seq. 2) and Aotea Formation (seq. 4) on the western side, and Whaingaroa Formation (seq. 3) and Aotea Formation (seq. 4) on the eastern side. Note that the Aotea Formation at C-51 is inferred to have been subsequently eroded. See Fig. 6.9 for column locations.

fine sandstone, which are comparatively well cemented and resistant to weathering. They form a peculiar bulbous weathering profile and may exhibit uneven surface and/or lapiez weathering features and often exhibit sharp facies transitions with the underlying lithofacies S_1 (Fig. 6.7a). Bioturbation is common and locally can be extensive. Bioclasts average 47% of the whole rock composition and are dominantly fragmental and comprise medium to coarse echinoderm fragments, bryozoan and benthic foraminifera. Other bioclasts include scattered bivalves (e.g. pectinids and panopea sp.) and rare traces of calcareous red algae. This facies is similar to the "Massive Ripply Sandstone Beds" (Ao-3) of Aotea Formation described by Nelson (1978) and occur at the same stratigraphic position.

Interpretation: The "Massive to thin-bedded calcareous silty-sandstone and fine sandstone" lithofacies is similar in character to "Alternating calcareous silty sandstone and sandy siltstone" lithofacies S_3 of Glen Massey Formation. The presence of common shallow water benthic foraminifers such as *Arenodosaria antipoda and Cibicides maculates* along with several deeper water species such as *Anomalinoides fasciatus*, *Melonis maorica*, *Semivulvina capitata* and *Haeuslerella textilariformis* (e.g. R15/f8510) indicate a mid to outer shelf depositional environment, with some transport of inner shelf fauna into deeper water during episodic storms (e.g. Hayward 1986; Hornibrook et al. 1989; Hayward et al. 1999).

S_3. Interbedded calcareous sandstone and sandy-siltstone:

"Interbedded calcareous sandstone and sandy siltstone" lithofacies comprise the major part of the Mangiti Sandstone Member in the vicinity of Raglan Harbour (best exemplified by localities TA-12 and TA-15 in Fig. 6.11). This member occurs in the lower part of Aotea Formation, and grades upward into "Massive variably calcareous sandy siltstone lithofacies" Z_1. This facies also constitutes a minor proportion of Aotea Formation in drillhole sections, but only in eastern areas (PW-7 and DH 8048 in Fig. 6.10). This lithofacies generally consists of well cemented fine to very fine calcareous sandstone beds, 20-50 cm thick, with thin (1-10 cm) interbeds of sandy-siltstone (Fig.6.7 b). Contacts between fine calcareous sandstone beds and silty sandstone interbeds are usually diffuse. The fine sandstone bed thickness typically decreases upwards with a proportionate increase in the thickness of siltstone interbeds, reflecting an overall fining upwards within the member. The beds are cut by vertical solution cavities that impart a blocky appearance to many outcrops (Fig. 6.7 c). Trace fossils include vertical to subvertical tubes (4-6 cm), which occur at the base of the sandstone beds, and along top surfaces, and are associated with thin sandy-siltstone interbeds. Echinoid fragments and spines are occasionally present but whole echinoids and other bivalve shell fragments are rare (Fig. 6.4 h).

Interpretation: Lithofacies S_3 constitutes the majority of Mangiti Sandstone Member in the Raglan Harbour area and in the areas lying east of Port Waikato and Te Akau. This member is a correlative of the Waimai Limestone Member (lithofacies L_2) in the southern and eastern parts of the northern region (Fig. 6.10 & 6.11). Anastas (1997) attributed the absence of cross stratification in the Mangiti Sandstone Member to accumulation in protected (wave-dominated) areas that existed locally in an otherwise current dominated seaway. However, the deeper water middle to outer shelf environment of deposition characterized by high-energy storm deposition alternating with low-energy background terrigenous silt deposition is a better interpretation. Fair-weather conditions are also suggested by the high burrowing density confined mainly to the sandy-siltstone interbeds.

The presence of benthic foraminifera such as *Melonis maorica*, *Rectuvigerina striatissima, Martinotiella communis, Lenticulina* sp., and *Haeuslerella textilariformis* (e.g. R14/f55, f60, f61) suggest a mid shelf to (uppermost ?) bathyal water depth (e.g. Hayward 1986; Hayward et al. 1999).

S_4. Massive bioturbated muddy sandstone:

“Massive bioturbated muddy sandstone” lithofacies (S_4) occur mainly within the Kihi Sandstone Member, and comprise the major part of it in central-eastern areas such as around Honikiwi and Waitomo Valley (localities C-28, C-32, DH 6796 and DH 8570 in Fig. 6.13). This facies also constitutes a minor proportion of Kihi Sandstone Member in the Shea Road section (locality AK-4 in Fig. 6.12). The massive bioturbated muddy sandstone lithofacies are the same as the “Massive Muddy Sandstone Beds (Ao-2)” of Aotea Formation described by Nelson (1978). The dominant lithology of this lithofacies is massive variably calcareous muddy sandstone and sandy mudstone that often exhibits exfoliation weathering in exposures (Fig. 6.7 d). Internal stratification features are rare. In places (e.g. Waitomo Valley Road and Mangaotaki Bridge locality) it may include alternating more-and-less resistant beds of slightly calcareous and muddy sandstone ~50-80 cm thick and massive sandy mudstone. Basement derived granules and small pebbles are scattered within muddy sandstone in some beds (Fig. 6.7 e). Bioturbation is locally very extensive and often so thoroughly burrow-homogenised that no physical sedimentary structures are visible (Fig. 6.7 f). Burrows include sub-vertical to inclined 3-5 cm long tubular structures, mottling due to extensive soft-bodied infaunal churning. Epifaunal bivalves such as *Janupecten polemicus*, *Chlamys williamsoni*, *Lentipecten hochstetteri*, *Cucullaea* sp and infaunal *Panopea worthingtoni* are common. A rich foraminiferal assemblage from this facies includes *Anomalinoides fasciatus, Arenodosaria antipoda, Haeuslerella textilariformis, Melonis maorica, Gyroidnoides allani, Bulimina pupula, Rectuvigerina striatissima, Sphaeroidina* *bulloides, Semivulvina capitata, Hanzawaia scopos, Vaginulinopsis cristellata* and *Notorotalia spinosa* (e.g. S16/f6523-6524, f6536-6542, f6011, f6014-6015).

Interpretation: The massive bioturbated muddy sandstone facies within the Kihi Sandstone Member exhibit a few subtle differences in comparison with lithofacies S_2 described earlier, for there is an overall increase in mud content and a greater degree of bioturbation. The high density of burrows and the fine-grained character suggests a moderate to low energy mid to outer shelf depositional setting. However, the occurrence of bedding in some sections and the presence of scattered granules and pebbles are indicative of changes in energy levels probably due to episodic storm events, which may have introduced the coarser sediments into the depositional setting (e.g. Hamblin & Walker 1979). The foraminifera within this facies indicate a depth range from inner-mid shelf (e.g. *Arenodosaria antipoda, Bulimina pupula, Notorotalia spinosa*), to outer shelf depths from the occurrence of several deep water species e.g. *Haeuslerella textileariformis, Melonis maorica, Sphaeroidina bulloides, Semivulvina capitata* (e.g. Hayward 1986; Hayward et al. 1999). The shallow water benthic foraminifera may have been reworked seawards into deeper water.

Mixed carbonate-siliciclastic siltstone lithofacies (Z_1)

Only one mixed carbonate-siliciclastic siltstone lithofacies (hereafter referred to as the siltstone lithofacies) is identified in the Aotea Formation (Table 6.1). It comprises the major part of Aotea Formation, mainly within the Raglan Harbour area, but it probably also extends into the subsurface beneath the coalfields in the northern region.

Z_1. Massive variably calcareous sandy siltstone:

This facies consists mainly of massive, medium to blue-grey variably calcareous sandy siltstone and siltstone with occasional thin concretionary horizons. Bedding is often discernible within otherwise massive siltstone from the occurrence of thin interbeds of silty sandstone, as exposed in coastal cliffs around Raglan Harbour (Fig. 6.8 a). The siltstone is slightly to moderately cemented and typically exhibits crumbly weathering characteristics. This lithofacies contains isolated burrows but in places mottling indicates pervasive bioturbation. The intensity of burrowing generally increases and is abundant below the Raglan Limestone Member of the Te Akatea Formation. Lithofacies Z_1 is locally capped by "Glauconitic siltstone-sandstone" lithofacies C_1 in the vicinity of Raglan Harbour, but more extensively to the north (Fig. 6.2), reflecting its stratigraphic condensation.

Lithofacies Z_1 comprises the bulk of the Patikirau Siltstone Member, exemplified by localities TA-2 to TA-15 in Fig. 6.11. It stratigraphically overlies lithofacies S_3 (Mangiti Sandstone Member) (localities TA-12 & TA-15 in Fig. 6.11) and lithofacies L_5 (Waimai Limestone Member) in northern areas (localities Ta-2 & TA-3 in Fig. 6.11), and grades laterally into "Glauconitic packstone/wackestone" (lithofacies C_2) in Port Waikato area (localities PW-11 to PW-4 in Fig. 6.10 and PW-9 in Fig. 6.11). This facies also comprises a major part of Aotea Formation in eastern areas such as in Onewhero (DH 8048 in Fig. 6.10) and intergrades laterally with lithofacies C_2 in the west (locations PW-4, PW-3 & PW-11 in Fig. 6.10). However, the easternmost extent of this facies is unknown because of poor exposures and minor lithological differences between the Patikirau Siltstone Member (Z_1 lithofacies) and overlying Carter Siltstone Member of the Te Akatea Formation.

Interpretation: The regional extent of this fine-grained facies implies a quiet depositional environment, probably at outer shelf water depths. However, the presence of thin sandy siltstone interbeds indicate that the seafloor was within the reach of major storm wave action. The presence of *Sphaeroidina bulloides, Cibicides novozelandicus, Sipholina australis* and *Haeuslerella textileariformis* indicate that the water depth may have been in the range of outer shelf to possibly upper-bathyal depths, with transport of inner and mid shelf faunas (e.g. *Arenodosaria antipoda, Bulimina pupula, Melonis maorica* in R14/f92-94) into deeper water (e.g. Van Markhoven et al. 1986; Hayward 1986).

Chemogenic lithofacies association (C_1 – C_2)

The chemogenic lithofacies identified within the Aotea Formation are similar to those described earlier in Chapter 5. The lithofacies contains high concentrations ($\geq$10%) of glauconite, which accumulated in a shelf setting characterised by extremely low terrigenous or carbonate sedimentation rates, probably associated with relative sea-level rise (e.g. Posamentier et al. 1988; Loutit et al. 1988; Amorosi 1995). However, the stratigraphic position of chemogenic lithofacies within the Aotea Formation differs slightly from those in the Glen Massey Formation. In Aotea Formation this facies is most common near the top of the S_4 lithofacies (Kihi Sandstone Member) in central-eastern areas, or at the top of Z_1 lithofacies (Patikirau Siltstone Member) in central-northern areas.

Two chemogenic lithofacies have been identified in this study (Table 6.1).

C_1. Glauconitic siltstone and sandstone:

This lithofacies is similar to the "Glauconitic Sandstone Beds (Ao-4)" described by Nelson (1978) in the Waitomo District. It constitutes the uppermost 4-5 m of the Kihi Sandstone Member, but only in the Honikiwi-Waitomo Valley area (localities

C-28 & C-32 in Fig. 6.13) and to the north of Te Kuiti (DH 6796 & DH 8570 in Fig. 6.13). It probably comprises the bulk of the Aotea succession at locality C-107, west of Troopers Road (Fig. 6.14) and in the Mangapehi-Bennydale area (av. 5-20% pelletal glauconite, Nelson 1973). The upper part of the Patikirau Siltstone Member (lithofacies Z_1) is comprised of the "Glauconitic siltstone and sandstone" lithofacies around Raglan Harbour (locality TA-12 in Fig. 6.11). This facies is characterised by the presence of green to greenish black glauconite pellets of fine to medium sandstone and may contain scattered glauconitised rock fragments. Glauconitised rounded to subrounded basement clasts are common in the basal 10-15 cm of the Orahiri Formation in the Waitomo and Mangaotaki Bridge areas. Whole pectinid shells (*Janupecten polemicus*, *Lentipecten hochstetteri*), *Dentalium* sp. and solitary corals (*Flabellum* sp.) (Fig. 6.8 c) are common within C_1 lithofacies. Bioturbation (including *Ophiomorpha*-like burrows, Nelson & Hume 1987) is generally very extensive and the intensity increases progressively upwards. The facies comprises 50% bioclasts, dominated by planktic (37%) and benthic foraminifera (10%). Bivalve and echinoderm bioclasts form minor components. Matrix/micrite content is substantially high (25%). Siliciclasts are dominantly sand and coarse silt sized quartz and feldspar grains. Other significant components include glauconite and pyrite that form 11% of the whole rock composition (Nelson 1973).

Interpretation: The presence of this facies at the top of the Aotea Formation in the central-eastern parts of the study area reflects sediment starvation associated with increasing water depths.

C_2. Glauconitic packstone/wackestone:

A glauconitic packstone/wackestone lithofacies comprises the uppermost part of the Aotea Formation mainly within the Port Waikato and Waikaretu areas exemplified by localities PW-11, PW-3 and PW-4 in Fig. 6.10 and PW-9 in Fig. 6.11. It forms the upper parts of the Waimai Limestone Member and grades upwards into calcareous siltstone/marl (Carter Siltstone Member). In the Port Waikato area, whole *Lentipecten, Terebratulina, Dentalium, and Flabellum* are common macrofauna within this facies. Here, Lithofacies C_2 represents condensed sediments with bioclasts comprising 43% of the total components. Skeletons are dominated by planktic (av. 30%) and benthic foraminifera (av. 10%). Other bioclasts include echinoderms and rare bivalves. Glauconite and pyrite comprise around 23% of the total content. Glauconite is common as infills within planktic foraminiferal tests and as scattered pellets. The micrite matrix accounts for 20% of the average whole rock composition. Siliciclasts are dominated by subangular to subrounded quartz and feldspar of mainly very fine sand size (Fig. 6.4 e & f).

Interpretation: The glauconitic packstone/wackestone lithofacies C_2 is similar to the

‘Glauconitic sandy-silty grainstone/packstone” lithofacies (C3) described earlier (Chapter 5). Both facies were deposited in outer shelf to upper bathyal settings characterised by low rates of sedimentation. The presence of this facies in the upper part of “Horizontally bedded grainstone” lithofacies L_3, or above lithofacies L_5 is indicative of increased water depth and resultant sediment starvation with consequent sedimentation of chemical minerals (e.g. Loutit et al. 1988; Amorosi 1995). This inference is also supported by the increase in planktic foraminifera and a high intensity of bioturbation.

Lithofacies distribution and paleoenvironmental implications

The wide spectrum of Aotea Formation lithofacies and their distribution between the northern and southern regions are summarised in Table 6.2. The vertical and lateral facies transitions across the basin are depicted in selected measured sections along north-south and east-west transects (Figs. 6.10 - 6.14). The measured sections provide control over the facies and thickness distribution from landward (west) to basinward (east) areas. From the detailed facies analyses discussed earlier, it is apparent that the Aotea Formation can be subdivided into two broad facies groups. The vertical succession within these groups is marked by sharp transitions and reveals overall deepening upwards. The lower group of facies, especially along the western margin, are comprised of carbonate lithofacies (L_1-L_5) belonging to the Waimai Limestone Member, or by variably calcareous fine to medium sandstone (S_1, S_3) belonging to Hauturu Sandstone Member and Mangiti Sandstone Member. They accumulated in relatively high energy neritic environments.

In contrast, the upper group of facies consists mainly of bioturbated fine muddy sandstone, and sandy siltstone (S_2-S_4 & Z_1) belonging to Kihi Sandstone Member and Patikirau Siltstone Member. The facies at the top of these members include condensed intervals (lithofacies C_1 & C_2) indicating low-energy deep water environments with terrigenous sediment starvation. The main features of the lower and upper group of facies are shown in Figs. 6.15 and 6.16.

Table 6.2: Aotea Formation lithofacies distribution

	North		South	
	Member	Facies	Member	Facies
Upper group of facies	Patikirau Siltstone	Z_1, C_2	Kihi Sandstone	S_2, S_4, C_1
Lower group of facies	Mangiti Sandstone	S_3	Hauturu Sandstone	S_1, L_4
	Waimai Limestone	L_2-L_5	Waimai Limestone	L_1, L_3, L

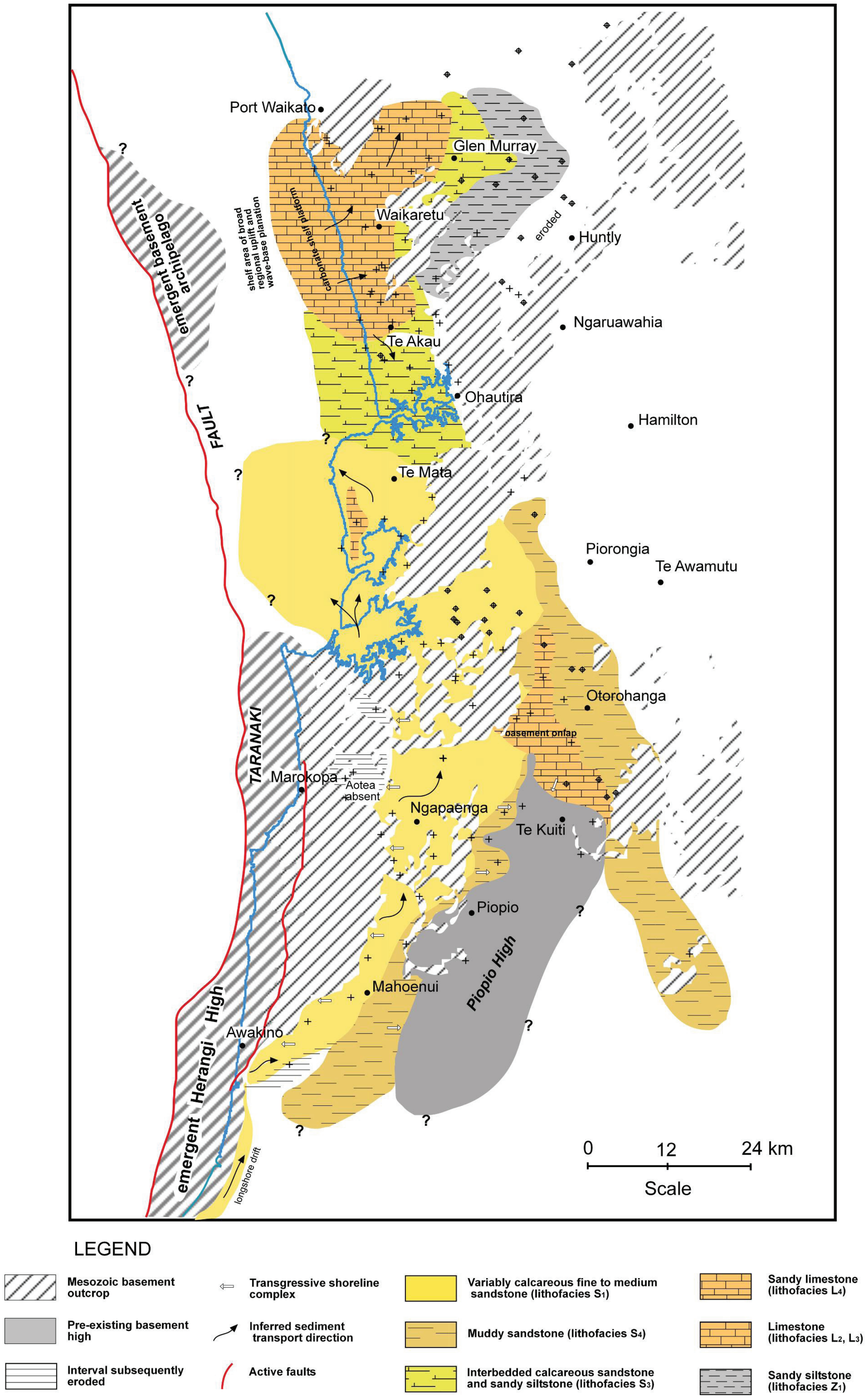


Fig. 6.15: Map showing the distribution of the lower group of lithofacies in Aotea Formation and key paleogeographic elements.

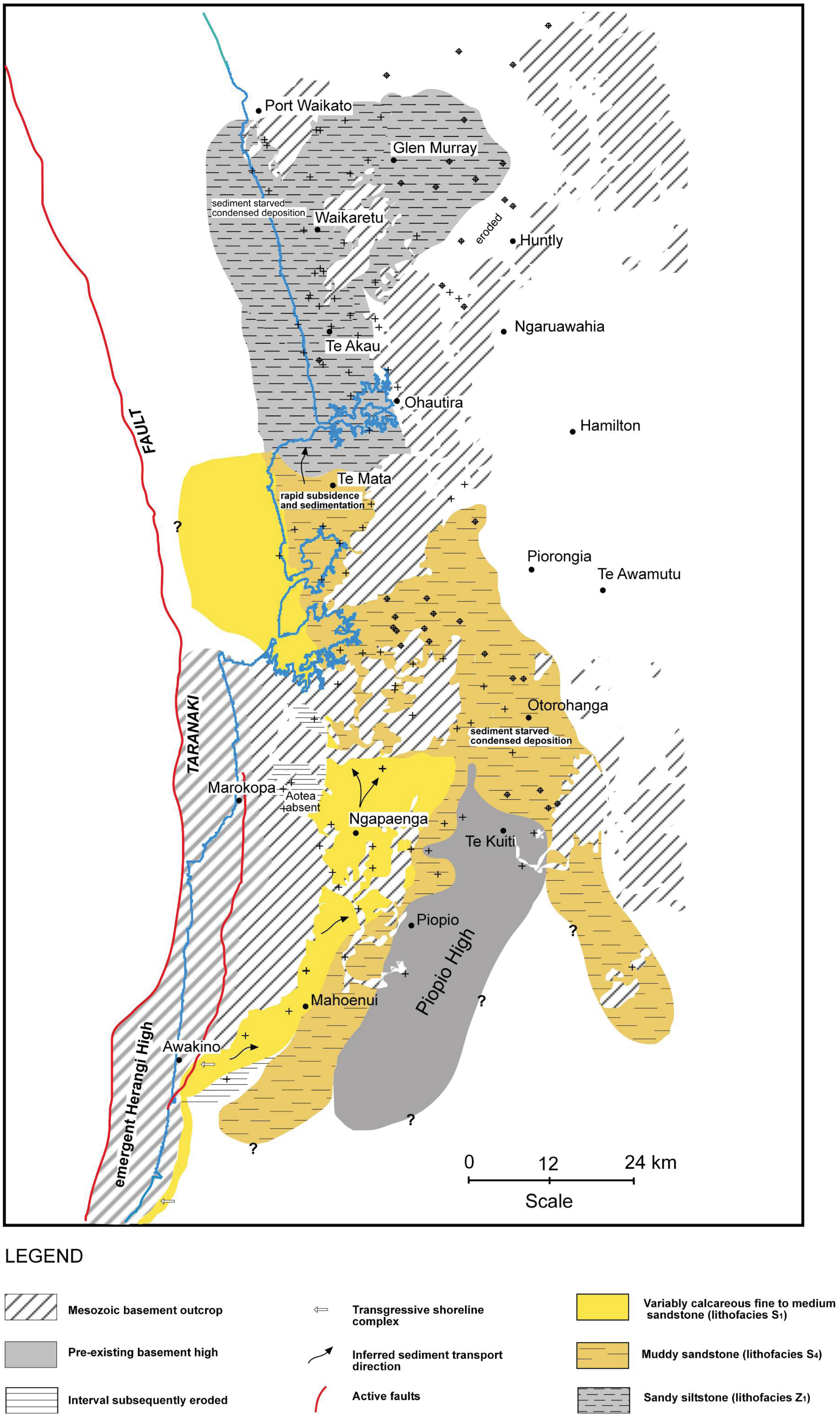


Fig. 6.16: Map showing the distribution of the upper group of lithofacies in Aotea Formation and key paleogeographic elements.

Distribution and depositional setting of the lower facies group

The transition from Whaingaroa Formation to Aotea Formation deposition was marked by a large basinward shift in the position of marine onlap. This is evident from the unconformity between these formations, which shows evidence of wave planation during the transgression into Aotea Formation, particularly along the western margin of the basin. During accumulation of the lower part of the Aotea Formation a shore-connected wedge of sandstone (Hauturu Sandstone Member, lithofacies S_1) accumulated along the eastern margin of the Herangi High, and concurrently shelf muddy sandstone (Kihi Sandstone Member, lithofacies S_4) accumulated farther east. A carbonate shelf formed along the northwestern margin (Port Waikato - Te Akau) as well as around the northern fringe of the Piopio High (west of Otorohanga). Fig. 6.15 shows the lateral distribution of the main facies in the lower part of the Aotea Formation.

Facies S_1, which corresponds to Hauturu Sandstone Member, is the most proximal lithofacies known in the formation, consisting of mixed carbonate and clastic lithologies. The S_1 lithofacies comprises horizontally to cross-bedded fine to medium sandstone often with local abundance of burrows, fragmented shell debris and granules. This facies is interpreted as having been deposited as a shore-connected wedge of sandstone along the basin's southwestern margin influenced by wave and storm currents. Its character and distribution strongly suggests that the terrigenous sediment was transported from a source area well to the south of the basin northwards by long shore drift along the eastern margin of the Herangi High. The transport of this sand across the shoreface was chiefly accomplished through offshore (eastward) directed storm flows. S_1 lithofacies is thickest east of the Kawhia Harbour area (Fig. 6.6). This facies passes basinward (eastward) into massive bioturbated muddy sandstone Lithofacies S_4 (Kihi Sandstone Member) (see transect D-D' & E-E' in Figs. 6.13 & 6.14).

The middle to outer shelf was dominated by massive bioturbated muddy sandstone (lithofacies S_4) corresponding to the Kihi Sandstone Member. This lithofacies consists chiefly of very fine to fine sandstone and muddy sandstone deposited in a offshore moderate to low energy mid to outer shelf environment. The muddy sandstone with scattered pectinid bivalves displays extensive bioturbation. The intermittent occurrence of granule and pebble bands within muddy sandstone could have formed as tempestites during storm events. Most of the Kihi Sandstone Member occurring in the Otorohanga and Piopio areas is representative of this facies.

In the central-eastern region, a carbonate "platform" fringed a structural (Piopio) basement high (see transect D-D’ in Fig. 6.13). This limestone facies contains bryozoans, scattered bivalves including pectinids, large benthic foraminifera, locally abundant rhodoliths and rounded to subrounded basement clasts (lithofacies L_1), which were deposited in shallow water. The facies marks the onset of subsidence and marine transgression across parts of the high. The basal “Pebbly limestone” lithofacies (L_1) forms lenses passing upwards into “Horizontally bedded sandy silty grainstone” (lithofacies L_4).

Along the northwestern margin (Port Waikato-Te Akau) of the basin, a carbonate platform/shelf developed over and around a basement high, inferred to have been located west of the present day coast. This high also influenced deposition of the underlying Glen Massey Formation and Whaingaroa Formation. The low to medium angle tabular cross-bedded skeletal rich grainstone Lithofacies L_2 (Waimai Limestone) were deposited at inner-shelf depths (see transect B-B’ in Fig. 6.11) with a gradual slope to the east (and south). The skeletal sand generated in shallow water around the high was transported eastwards and reworked by offshore-directed tidal and bottom currents. This is evident in paleocurrent data from cross-beds in the Waimai Limestone Member indicating a highly variable pattern of unidirectional flow mainly eastwards (Anastas 1997).

The “Interbedded calcareous sandstone and sandy siltstone” (lithofacies S_3/Mangiti Sandstone Member) accumulated in a position intermediate between the “Variably calcareous fine to medium sandstone” (lithofacies S_1/Hauturu Sandstone Member) in the south and the carbonate lithofacies in the northwest (Waimai Limestone Member). The siliciclastic and carbonate components in this lithofacies are characteristically mixed (46-65 Wt% $CaCO_3$) because of contributions of carbonate components from the west and contributions of siliciclastic (sand) components from the south. In the Glen Murray area, “Interbedded calcareous sandstone and sandy siltstone” (lithofacies S_3/Mangiti Sandstone Member) represent a transition between a carbonate shelf to the west and a terrigenous-dominated basin centre (see transect A-A’ in Fig. 6.10). Alternation of storm and fair-weather conditions resulted in this interbedded facies.

Distribution and depositional setting of the upper facies group

Fig. 6.16 summarises the distribution of the facies in the upper part of the Aotea Formation. In the central region, the S_1 lithofacies (i.e. Hauturu Sandstone Member) passes upward into “Massive to thinly bedded calcareous silty sandstone” (lithofacies S_2 /Kihi Sandstone Member), indicating a retrogradational stacking pattern. This fining-upwards shelf succession is best exposed in the Aotea-Kawhia

Harbour region (see transect D-D' in Fig. 6.13). Subsidence in the central region combined with limited sediment supply led to sediment starvation, especially in the Waitomo-Honikiwi area, as evident from condensed fossiliferous sandstone and siltstone with high glauconitic concentrations (lithofacies C_1). In neighbouring more offshore areas such as at Mangapehi, the condensed C_1 facies form the major part of the stratigraphic thickness of the Aotea Formation (see transect E-E' in Fig. 6.14). However, southwestern parts (east of Marokopa-Awakino) of the basin remained at inner to mid shelf depths and continued to accumulate S_1 and/or intercalated S_1 and S_2 lithofacies, reflecting proximity to a paleoshoreline along the eastern margin of the Herangi High.

In the vicinity of Raglan Harbour and in areas to the north, fining upwards within the lithofacies succession is reflected in the accumulation of "Massive variably calcareous sandy siltstone" (lithofacies Z_1, Patikirau Siltstone Member), which overlies lithofacies S_3 (i.e. Mangiti Sandstone Member) (see transect B-B' in Fig. 6.11). Farther north, the "Cross-bedded limestone" lithofacies L_2 passes upward into "Massive to horizontally bedded grainstone/packstone" lithofacies L_3 and L_5 (i.e. Waimai Limestone Member), which in turn is overlain by a highly fossiliferous condensed interval with high concentrations of glauconite (lithofacies C_2), and an abundance of planktic foraminifera (see transect A-A' in Fig. 6.10). This indicates substantial foundering of the shelf area.

Sequence stratigraphy

This study has clarified the vertical and lateral stratigraphic extent of the Aotea Formation across central-western North Island by clearly identifying its bounding unconformities. This has provided a new stratigraphic framework for facies and sequence analysis. The Aotea Formation consists of successive genetically related systems tracts forming a depositional sequence. This section applies sequence stratigraphic concepts to the Aotea Formation the aim being to: (i) define the key surfaces defining the boundaries of the systems tracts, (ii) group diverse lithofacies into linked depositional systems (systems tracts), (iii) discuss the facies distribution within successive systems tracts, (iv) to develop a model Aotea sequence, and (v), to illustrate how the interplay of subsidence and sediment flux controlled the distribution of facies within successive systems tracts.

Overview

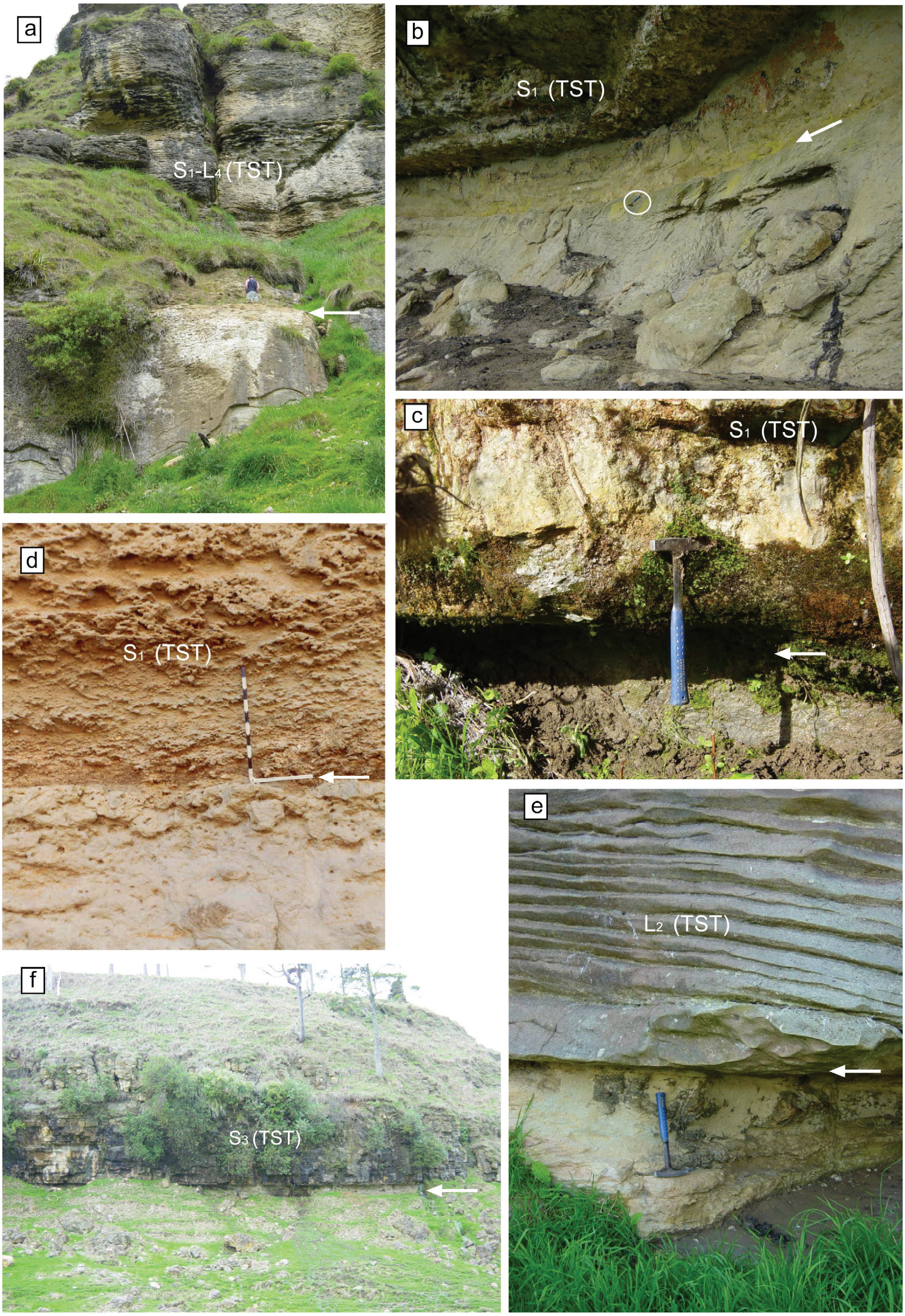
The mid-upper Whaingaroan to lower Duntroonian Aotea sequence ranges from ~ 2 to 180 m thick and crops out extensively in central-western North Island. It is particularly well exposed in the west from Port Waikato to Awakino and surrounding areas. The sequence contains a wide variety of facies from shallow marine carbonate to mixed carbonate- siliciclastic, to condensed deposits of outer shelf-upper bathyal environments. Extensive field work involving measurement of stratigraphic sections has enabled description and interpretation of the systems tract boundaries, which have been able to be traced from proximal to distal locations in the basin. However, it should be noted, that there is limited continuity between outcrops, especially between Raglan and Aotea harbours, which precludes direct correlation of many of the stratigraphic sections.

The sequence stratigraphic methodology, as described in the previous chapter, included: (i) the identification of lower and upper sequence boundaries, which were picked at discontinuity surfaces, such as erosional boundaries or abrupt facies transitions, (ii) interpretation of stratal patterns from broad facies trends and especially evidence of deepening, and (iii), the delineation of system tracts between flooding surfaces including the sequence boundary.

Sequence boundaries

The lower bounding surface of Aotea sequence is, by far, the most prominent sequence boundary within the Te Kuiti Group succession. Its more dramatic expression occurs along the western margin, where it is represented by an erosional unconformity. This basal unconformity is a transgressive surface of erosion (TSE) (e.g. Posamentier & Vail 1988), that formed originally as a subaerial erosional surface upon the Whaingaroa Formation. There are some local indications of erosional truncation associated with this surface (Fig. 6.17). The principal evidence is complete erosion of Whaingaroa Formation in the inland Aotea-Kawhia Harbour area, such as at Shea Road, Kaimango Road and the Orotangi Cliff sections. At

Fig. 6.17 (facing page): Photographs of the typical field expression of sequence boundaries in the Aotea sequence across the study area. (a) Arrow points to the truncated older sequence (Ahirau Sandstone Member of Glen Massey Formation) below the sequence boundary and overlying highly calcareous “Fine to medium sandstone and sandy limestone” lithofacies S1-L4 (Hauturu Sandstone Member). Photo location: Kaimango. (C-8). (b) Scoured contact (arrow) inferred as sequence boundary between massive calcareous silty sandstone (Ahirau Sandstone Member) and fine to medium grained calcareous sandstone (Hauturu Sandstone) containing abundant granule-pebble size rounded subrounded clasts with common medium to large burrows. This basal pebbly unit immediately overlying the contact is inferred to represent the transgressive lag deposits before passing upwards (above the sharp overhang in the photo) into alternatively friable to well cemented medium to coarse sandstone with common gritty-pebbly bands of lithofacies S1. Photo location Mahoe Road. (C-24). (c) Sharp contact (arrow) inferred as a sequence boundary between medium bluish-grey sandy siltstone (Ngapaenga Siltstone Member of Whaingaroa Formation) and overlying moderately to well cemented coarser sandstone lithofacies S1 (Hauturu Sandstone Member). Note the presence of large burrow tube to the left of hammer. Photo location Mangaotaki, west of Piopio. (C-145). (d) Sequence boundary (arrow) showing erosional relief and a burrowed contact between fine silty sandstone (Ahirau Sandstone Member) and overlying burrowed fine to medium grained sandstone lithofacies S1 (Hauturu Sandstone Member) exposed near Harbour Road, Kawhia (R15/807440). Photo courtesy D. Fergusson (1986). (e) Arrow pointing to erosionally truncated calcareous silty sandstone (Waikorea Sandstone Member) below sequence boundary with Waimai Limestone Member above. The boundary displays centimeter scale relief, and is extensively burrowed. Photo location Kaawa



(Fig. 6.17 continued) stream valley, near Limestone Downs. (PW-3). (f) The sequence boundary displaying centimeter scale erosional relief separating massive calcareous siltstone and sandy siltstone of an older sequence (Whaingaroa Formation) from the overlying bedded calcareous sandstone with thin silty interbeds of lithofacies S3 of Mangiti Sandstone Member. Exposure is approximate 25 m high. Photo location near Te Kotuku Trig. north of Raglan Harbour (TA-12).

these localities the Aotea sequence directly overlies Glen Massey sequence with erosional truncation of the whole of the Whaingaroa Formation (Fig. 6.17 a, b & d). In the Awakino Tunnel section (Nelson 1978a; Nelson et al. 1994) the base of the Aotea sequence is a wave cut surface with glauconitic infilled burrows extending down into outer shelf calcareous siltstone (Dunphail Siltstone Member of Glen Massey Formation). The sequence boundary was subsequently further lowered by wave planation during shoreline transgression (e.g. Demarest & Kraft 1987; Abbott 1998).

Immediately above the sequence boundary over wide areas is a transgressive lag, which is especially well developed at the Kaimango Road and Mahoe Road sections (Fig. 6.17 b). Transgressive lag deposits are also well developed in the base of Waimai Limestone Member where it overlies basement in sections west of Otorohanga. In places the TSE is marked by the concentration of glauconite.

Where parts of the Whaingaroa Formation are preserved, such as near Kawhia, Ngapaenga and Mangaotaki, there is a sharp contact between outer shelf sandy siltstone (Ngapaenga Siltstone Member, Whaingaroa Formation) and overlying transgressive shoreface fine to medium calcareous sandstone (Hauturu Sandstone Member) (Fig. 6.17 c). In locations such as Kihikihi Valley near Mangaotaki, the contact and exact position of the TSE is difficult to place due to unlithified siltstone and sandy siltstone from the underlying sequence having been reworked into the overlying sandstone.

In stratigraphic sections along the western margin of the northern region there is a sharp planar wave-cut surface, commonly with profuse burrowing extending downwards into the Whaingaroa Formation. This boundary shows up to 0.5 m of broad relief in sections located between Port Waikato and Raglan Harbour, and areas immediately inland such as at Mangiti Road and Waimai Stream (Fig. 6.17 e & f). There is no transgressive lag above the TSE in the northern region.

Downlap Surface (DLS)

On seismic reflection data sets, a downlap surface separates retrograding strata below from prograding strata above. This surface approximates the stratigraphic position of a maximum flooding surface (MFS) and separates a TST from overlying HST (e.g. Posamentier et al. 1988; Van Wagoner et al. 1988). In the Aotea Sequence, the downlap surface often corresponds to a sharp lithofacies transition between transgressive limestone or calcareous sandstone and overlying muddy sandstone and siltstone, belonging to an aggradational to retrogradational HST. This sharp transition is best observed in the stratigraphic sections located inland from Aotea-Kawhia Harbour, where massive muddy sandstone (S_4) of the Kihi Sandstone Member sharply overlies variably calcareous fine to medium sandstone (S_1) of the Hauturu Sandstone Member (Fig. 6.18 a & b).

In the study area the transition from TST to HST is not always marked by a sharp lithofacies change. In some cases, the contact may correspond to a gradational (extending over 1-2 m) but distinct up-sequence increase in fine terrigenous sediment. This is best observed in cliff sections located around Raglan Harbour. The DLS is usually a transitional interval corresponding to the contact between Mangiti Sandstone Member (S_3) and Patikirau Siltstone Member (Z_1). This transition consists of sandy siltstone (Z_1) with thin interbeds of calcareous sandstone (S_3), passing upward into sandy siltstone (Z_1) (Fig. 6.19 e). In inland sections, this transition is poorly exposed but often evident from a break in weathering profile. Farther north (Port Waikato to Waikaretu), the DLS corresponds to a limestone/glauconitic packstone-wackestone (C_2) lithological contact, suggesting shut-off of carbonate sediment supply as highstand conditions developed.

Transgressive Systems Tracts (TST)

A transgressive systems tract is bounded by a sequence boundary or TSE at its base and by a MFS/DLS at the top. The TST comprises all contemporaneous strata having retrogradational stacking patterns deposited during the early to middle stages of base-level rise. The development of a TST is directly controlled by the rate of increase in accommodation (a function of the rate of eustatic sea-level change and the rate of subsidence) and the rate of sediment supply. The TST in the Aotea sequence may potentially be thick, due to relatively high sediment accumulation rates stimulated by the available accommodation, or they may be thin due to lack of terrigenous and/or carbonate sediment supply and a regime of rapid relative sea-level rise with marked flooding of the shelf. Numerous studies have documented the factors controlling the architecture of transgressive facies and relationships to the rates of sediment supply, rate of relative sea-level rise, and the position of the particular outcrop in relation to paleo position on the shelf (e.g. Nummedal & Swift 1987; Demarest & Kraft 1987; Naish & Kamp 1997).

In the southwestern and central regions of the study area, the Aotea sequence consists of a thick TST, comprising mainly mixed carbonate-siliciclastic sandy lithofacies (S_1, L_4) belonging to Hauturu Sandstone Member. The lower, variably calcareous sandstone beds (i.e. lithofacies S_1) are ascribed to the TST because of their stratigraphic position and overall vertical and lateral facies architecture. The

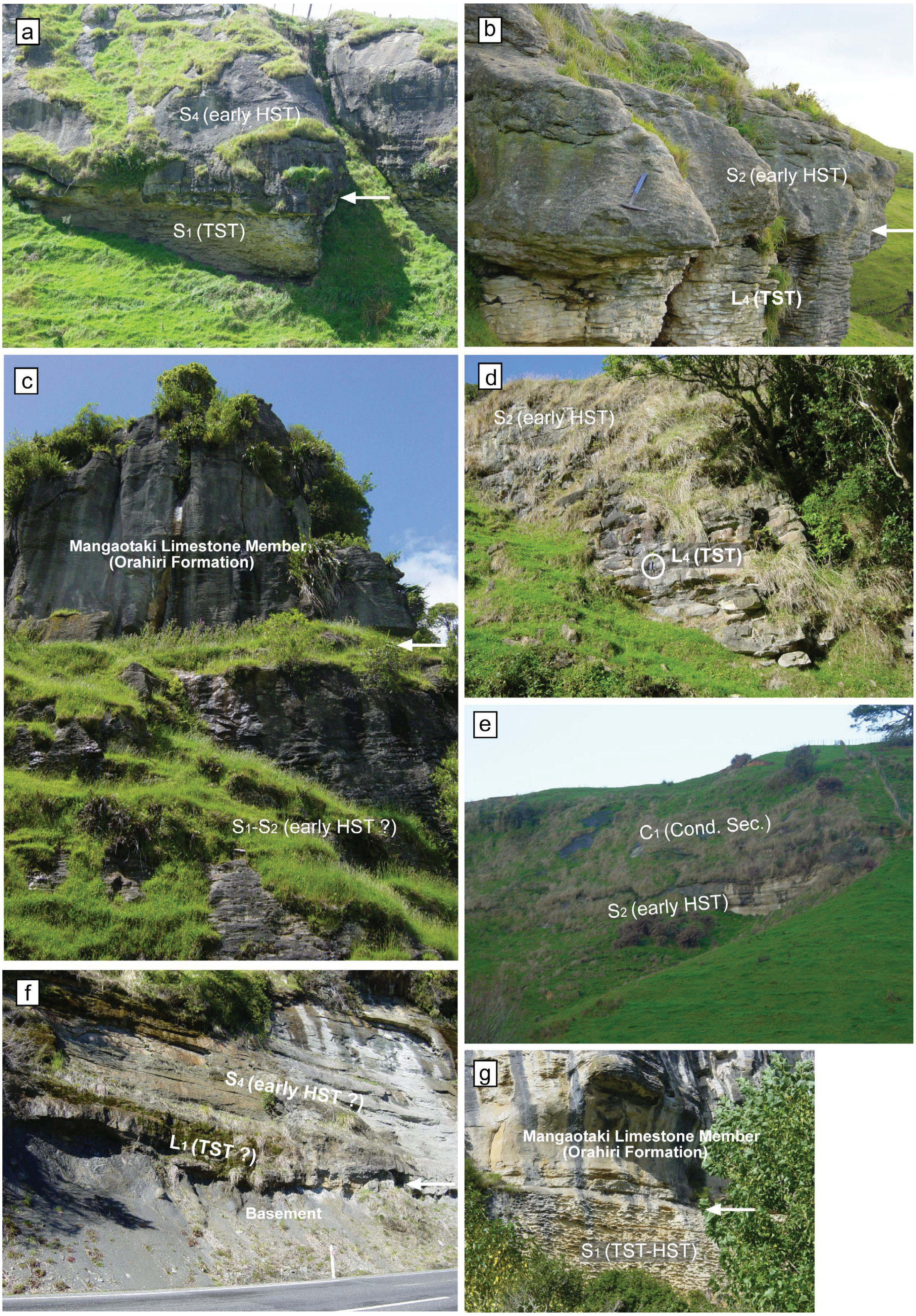


Fig. 6.18: Field photographs of typical lithofacies relationships in the Aotea Formation, and inferred systems tracts and sequence boundaries in the northern and central regions. (a) Normal deepening upwards succession, showing a conformable transition from "Fine to medium calcareous sandstone" (lithofacies S1; Hauturu Sandstone Member) to "Massive muddy sandstone" (lithofacies S1; Kihi Sandstone Member). The arrow points to a conformable facies contact and possibly indicates the initiation of early highstand deposition. Photo location: Shea Road (AK-4). Exposure is approximately

TST reaches a maximum thickness of up to 120 m east of Kawhia Harbour, where it comprises packages of burrowed calcareous fine to medium sandstone (lithofacies S_1) probably stacked in a retrogradational (deepening-up) pattern, suggesting that the rate of subsidence exceeded the rate of sediment supply. This facies is interpreted to have accumulated in inner to mid shelf environments, with the sediment having been derived from a shoreline along the eastern margin of the Herangi High. The TST thickness diminishes toward the north and east (i.e. basinward) away from the Herangi High (Fig. 6.6). The reduction in thickness is gradational and coupled with a facies transition to more open shelf lithofacies (i.e. lithofacies S_3; Mangiti Sandstone Member) to the north (e.g. Raglan Harbour area), or to bioturbated muddy sandstone (lithofacies S_4, Kihi Sandstone Member) in neighbouring more basinal areas to the east (e.g. west of Otorohanga). The thin TST occurrence (less than 30 m) in the southwestern areas near the Herangi High result from limited accommodation with incoming sediment bypassed to medial and distal parts of the paleo-shelf.

A comparatively thin TST comprising mainly pebbly to sandy horizontally bedded grainstone/packstone (lithofacies L_1, L_2 & L_4), was deposited in the central-eastern areas on the northern and western fringes of the Piopio High. These transgressive limestone facies contain common large benthic foraminifera, calcareous algae, rhodoliths and fragmented large bivalves interpreted to have been deposited in a neritic setting not far from the rocky shoreline carbonate factory around the Piopio basement high.

(Fig. 6.18 continued) 6 m high. (b) Conformable facies contact (arrow) between the “Cross-bedded sandy silty grainstone/ packstone” lithofacies (lithofacies L4; Waimai Limestone/Hauturu Sandstone Member) and “Massive calcareous silty sandstone” lithofacies S2 (Kihi Sandstone Member). The facies transition indicates an abrupt decrease in energy level across the contact possibly due to deepening. Photo location: Makaka, north of Aotea Harbour. (AK-1). (c) Alternation of fine grained calcareous sandstone lithofacies S1 and “Calcareous silty sandstone” lithofacies S2 (Hauturu Sandstone Member) comprises much of the upper part of Aotea sequence at this location. The overlying cross-bedded sandy limestone (Mangaotaki Limestone Member of Orahiri Formation) is separated by the sequence boundary at the narrow ledge (arrow). Exposure is about 25 m high. Photo location: Mangaohae Stream. (C-56). (d) Sandy grainstone lithofacies L4 (Waimai Limestone/Hauturu Sandstone Member) inferred to be transgressive deposits gradually passing upwards into early highstand deposits comprising “Massive calcareous silty sandstone” lithofacies S2 (Kihi Sandstone Member). Photo location: Te Raumauku near Honikiwi. (C-28). (e) Thin bedded calcareous sandy siltstone lithofacies S2 (Kihi Sandstone Member) gradually passing upwards into dark coloured “Glauconitic silty sandstone” lithofacies C1 representing condensed sediment. Exposure is approximate 12 m high. Photo location: near Bromley and Honikiwi Road intersection (S16/ 976364). (f) Basement onlap succession made up of basal lenticular “Pebbly-gritty grainstone/ packstone” lithofacies L1 (Waimai Limestone Member) overlain by bedded “Muddy sandstone” lithofacies S4 (Kihi Sandstone Member). Note highly irregular top of Mesozoic basement. The entire succession is broadly transgressive and displays inner shelf carbonates at the base, to mid-outer shelf siltstone at the top (not shown in photograph). Photo location: SH3, near Mangaotaki Bridge. (C-166). Road marker for scale. (g) Wave planed surface (arrow) inferred as sequence boundary at the contact between “Calcareous fine to medium sandstone” lithofacies S1 (Hauturu Sandstone Member) and sandy limestone (Mangaotaki Limestone Member) of the overlying Orahiri Formation at Mangaotaki (C-145).

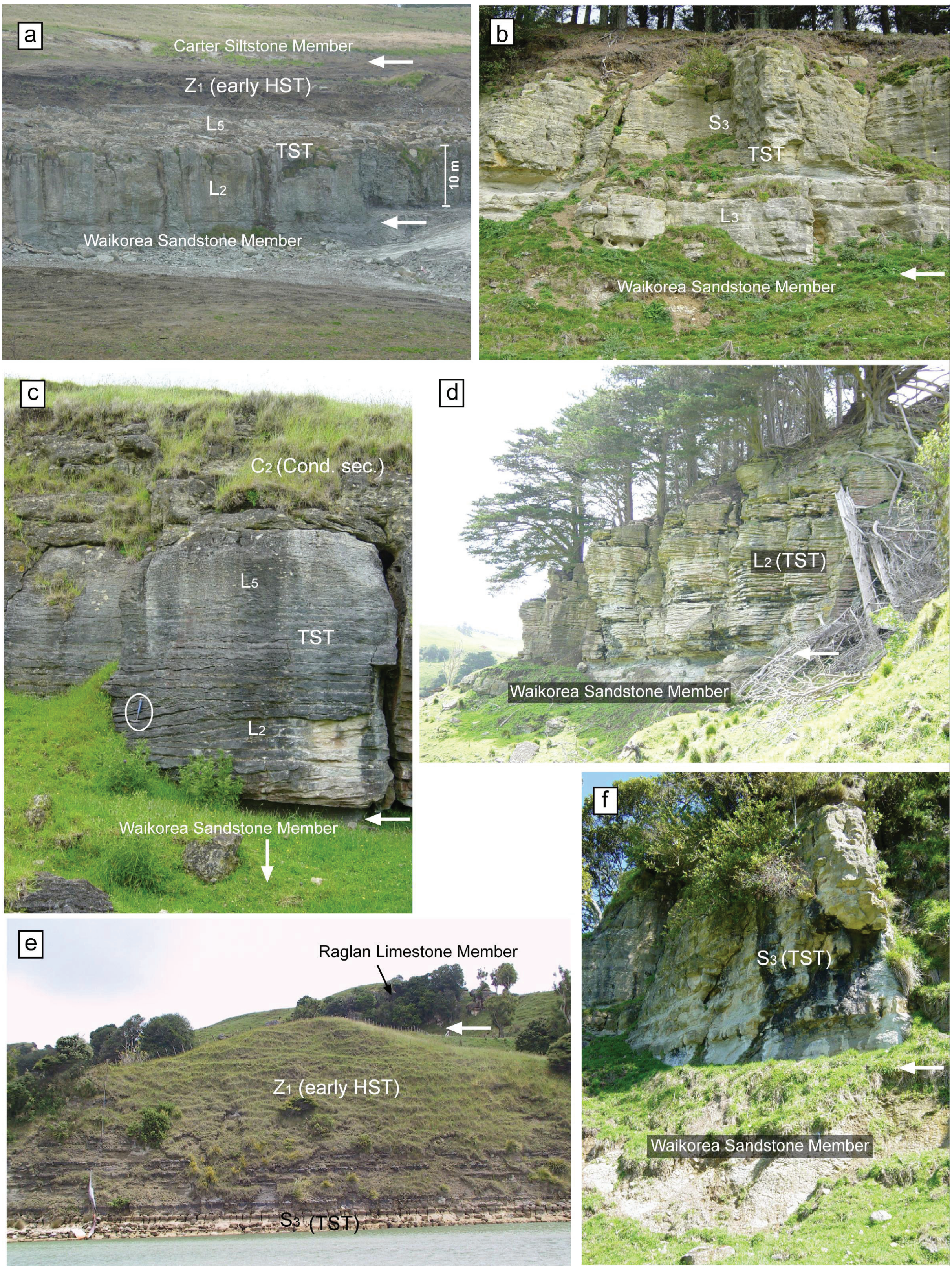


Fig. 6.19: Field photographs of typical lithofacies relationships in Aotea sequence, and inferred systems tract and sequence boundaries in the northern region. (a) The Aotea sequence consisting of "Cross-bedded grainstone" lithofacies L2 passing upwards into "Massive to irregularly bedded grainstone/packstone" lithofacies L5 (Waimai Limestone Member), which in turn passes upwards into "Moderately glauconitic sandy siltstone" lithofacies Z1 (Patikirau Siltstone Member). The lower sequence boundary (arrow) is a wave planed surface cutting into moderately calcareous silty sandstone (Waikorea Sandstone Member). Note dark coloured massive sandy siltstone (Patikirau Siltstone Member) passing upwards into light coloured calcareous siltstone (Carter Siltstone Member

The TST within the Aotea sequence in the northern region is never thick (reaching a maximum of 18-20 m in the Waimai Limestone Member) and is composed largely of low to medium-angle cross-bedded skeletal limestone (lithofacies L_2) or horizontally bedded grainstone/packstone (lithofacies L_3). The thickness of the transgressive limestone facies reduces towards the northwest (Port Waikato and the vicinity of the modern coastline), where it is generally 2-3 m thick. Facies within the Waimai Limestone Member are arranged such that the cross-bedded lithofacies (L_2) pass upwards into "Horizontally bedded grainstone" lithofacies (L_3), which in turn passes into "Massive to irregularly bedded planktic foraminiferal rich grainstone/packstone" (lithofacies L_5), capped by condensed facies (C_2) recording the drowning of the carbonate shelf. This pattern is illustrated in Figs 6.2 and 6.3. Cross-bedded limestone facies (i.e. L_2) are not present in the east (e.g. Glen Murray). In these areas the TST consists of horizontally bedded grainstone/packstone (facies L_3) and interbedded calcareous sandstone and sandy siltstone (facies S_3 i.e. Mangiti Sandstone Member). This mixed carbonate and siliciclastic character in the east is the result of reworking of carbonate material from the west into deeper portions of the shelf where silt and fine to very fine sand accumulated as background deposits in a comparatively low energy setting.

Highstand Systems Tract (HST)

A highstand system tract (HST) forms during the late stage of relative sea-level rise through the early part of sea-level fall. The HST in the Aotea sequence is

(Fig. 6.19 continued) of Te Akatea Formation). The arrow points to a paraconformity inferred to be a correlative conformity. Photo location: Waikaretu limestone quarry. (PW-9). (b) Horizontally bedded grainstone/packstone lithofacies L3 (Waimai Limestone) is separated by a sequence boundary (arrow) from the underlying Waikorea Sandstone Member of Whaingaroa Formation. The lower 10-15 cm of limestone unit is also moderately glauconitic suggesting a minor hiatus. Note the presence of thin silty interbeds in the lower middle part of the outcrop marking the gradual upward transition to "Interbedded calcareous sandstone and sandy siltstone" lithofacies S3 (Mangiti Sandstone Member). Exposure is approximate 8 m high. Photo location: Bothwell Road, west of Glen Murray. (PW-8). (c) A typical deepening/ fining upwards cycle in the Aotea sequence. Wave planed surface (arrow) cutting into the underlying calcareous silty sandstone (Waikorea Sandstone Member) interpreted as a sequence boundary, is overlain by "Low angle cross-bedded skeletal grainstone" lithofacies L2 which passes upwards into "Massive to irregularly bedded grainstone/packstone" lithofacies L5 (Waimai Limestone Member). The highly glauconitic and fossiliferous glauconitic packstone/wackestone lithofacies C2 marks the condensed sediment indicating drowning of the carbonate platform. Photo location: Port Waikato.(PW-1). (d) The gently undulating contact (arrow) inferred as a sequence boundary between calcareous silty sandstone (Waikorea Sandstone Member) and the overlying tabular low angle "Cross-bedded grainstone" lithofacies L2 (Waimai Limestone Member). Exposure about 10 m high. Photo location Waikorea-Matira. (TA-2). (e) Bedded calcareous sandstone lithofacies S3 of Mangiti Sandstone Member at the shore level gradually passes upwards through an interbedded transition zone into "Massive sandy siltstone" lithofacies Z1 of Patikirau Siltstone Member. Note thin calcareous sandstone beds at the transition interval. The arrow points to a paraconformity (inferred as a correlative conformity) between the Patikirau Siltstone Member and Raglan Limestone Member of the Te Akatea Formation. Exposure is approximate 50 m high. Photo location Patikirau Bay, Raglan Harbour. (TA-20). (f) Moderately calcareous silty sandstone (Waikorea Sandstone Member) is erosionally truncated (arrow) and overlain by interbedded calcareous sandstone and sandy siltstone (Mangiti Sandstone Member). Exposure is approximate 8 m high. Photo location: Matakitaki Road, near Glen Murray.(PW-7).

easily distinguished by its fine-grained siliciclastic facies that accumulated in mainly outer shelf environments. As increased accommodation developed and the shoreline position started to stabilize, a muddy 'highstand prism' started to prograde basinward with silty sand and sandy silt accumulating slowly in mid to outer shelf environments.

The HST of the Aotea sequence in the southern and central regions comprises up to 80 m of massive highly bioturbated muddy sandstone (S_4) and thin bedded silty sandstone (S_2) (i.e. Kihi Sandstone Member). Massive sandy siltstone (Z_1) up to 70 m thick inferred to be HST occurs in and around Raglan Harbour (i.e. Patikirau Siltstone Member). These facies are inferred to have been deposited in an outer shelf setting. It should be noted, however, that the development of highstand deposits varies greatly within the sequence, being comparatively thick only in the central Aotea-Kawhia-Raglan Harbour area, probably as a result of high rates of sediment supply combined with sufficient subsidence. The trapping of fine grained terrigenous sediment within this part of the basin possibly diminished the amount of terrigenous sediment supplied to more northern and eastern parts of the shelf, where the HST is relatively thin and often capped by highly burrowed glauconitic sandstone e.g. lithofacies C_1 at the top of Kihi Sandstone Member at Waitomo and Honikiwi. In the vicinity of Port Waikato, the highstand deposits are only a few metres thick and are genuinely of condensed character.

In the southwestern region the highstand deposits as well as the TST deposits lie within the Hauturu Sandstone Member (e.g. lithofacies S_1 intercalated with lithofacies S_2 at C-56 in Figs. 6.14 & 6.18c). This arises because of the high energy shoreline position of the unit such that sand being supplied by longshore drift was always available to be deposited. In other nearby sections such as at C-68 (Fig. 6.14), the entire Aotea sequence is comprised of lithofacies S_1 (Hauturu Sandstone Member). The lack of space in relatively proximal (to paleo-shoreline) shelf areas may be responsible for the poor development of S_2/S_4 lithofacies ascribed to HST in other parts of the basin.

The overall trend in the HST of the Aotea sequence is one of a decrease in the amount of terrigenous sandstone delivered to shelf areas. The depositional processes upwards within the HST became increasingly dominated by accumulation of fine sand and silt, expressed as Kihi Sandstone over Hauturu Sandstone. The fining-upwards profile reflects an aggradational to retrogradation stacking pattern.

Because of their vertical lithofacies distribution and stratigraphic position, the

HST of the Aotea sequence is more consistent with an early phase of highstand as defined by Catuneanu (2006), compared with the late phase of highstand. The early phase of the highstand is defined by relative sea-level rise, which results in a stacking pattern with an aggradational component, whereas the late phase of the highstand corresponds to relative sea-level fall, which results in a progradational stacking pattern that probably never developed during Aotea deposition, or has been subsequently eroded.

Condensed sections

Condensed sections are marked by unusually high (≥ 5-40%) concentrations of glauconite and are interpreted to correspond to a period of very low rates of sedimentation or nondeposition, usually during maximum shoreline transgression. They are generally associated with the maximum flooding surface (MFS) and/or the top of transgressive deposits, especially in the more distal portions of the paleoshelf (Loutit et al. 1988). A similar association of the occurrence of condensed section with MFS and/or top of TST has been described for the Glen Massey sequence (Chapter 5). However, in the case of Aotea sequence the condensed section usually occurs in the upper part of the HST, forming a thin cap (2 – 4 m) of intensely burrowed glauconitic sandstone/siltstone (lithofacies C_1) on top of either massive muddy sandstone or sandy siltstone (lithofacies S_4 / Z_1), such as in the Waitomo Valley, Honikiwi and Raglan Harbour sections (Fig. 6.18 e). These condensed sections are characterised by high concentrations of glauconite pellets (locally up to 40%), rich fossil assemblages and burrows infilled with glauconitic sandstone/siltstone, suggesting firmground or hardground development. In these areas, they reflect partial condensation of the HSTs, inferred to have been triggered by waning terrigenous sediment supply, possibly due to a marked increase in water depth associated with tectonically induced subsidence. Similar condensed deposits are widespread in the Port Waikato-Waikaretu areas where they overlie Waimai Limestone and thin Patikirau Siltstone facies. There, the stratigraphic condensation involves the whole of the HST (e.g. location A in Fig. 6.2).

Qualitative Model for Aotea sequence

Successful application of sequence stratigraphic models to outcrop sections requires two or three dimensional modeling of the sedimentary succession and its stratal patterns by comparison with the architecture of the sequence as measured in sections. Such models idealise reality in the sense that they provide simplified representation of how the lithofacies architecture and stratigraphic surfaces are expected to be expressed in the field. The lack of outcrop in key locations is a limiting factor in testing models, and hampers resolution and reliability of the predicted sequence stratigraphic model. For example, the most landward parts of the Aotea sequence along the Herangi High have either been removed through uplift and erosion, or, in the Port Waikato-Waikaretu area, lie offshore to the west. Similarly, more basinward parts have been either removed by erosion or remain in the subsurface and are therefore not accessible. Nevertheless, the qualitative model developed in this study shows a 'big picture' stratigraphic framework for the Aotea sequence (Fig. 6.20 & 6.21). The smaller scale features are shown in simplified stratigraphic columns across the model sequence. However due to lack of outcrop windows in some of the key areas, some assumptions have had to be made, particularly along the landward and basinward portions of the paleoshelf.

Control on sequence architecture

It is apparent that local tectonism (i.e. subsidence and uplift) represent the main driving force behind the development of the Aotea sequence, chiefly through control of sediment supply and subsidence. This has determined the overall facies distribution and stacking patterns. The sediment flux and proximity to the shoreline supplying the terrigenous sandstone (Hauturu Sandstone Member) had significant influence upon the thickness of the TST and HST in the southwestern region. Similarly, variations in subsidence rate modified the paleo-bathymetry within the study area. Basic contrasts in the depositional setting between the northern and southern areas and the resulting expression as stratigraphic architecture are shown in Figs. 6.20 and 6.21. Figure 6.20 represents the sequence architecture for a west-east shore normal profile in the northern region, and Fig. 6.21 represents the sequence architecture for a NW-SE profile in the central region.

The cyclicity of the Aotea sequence may be of 3rd order. The overall architecture of the sequence reflects long term accommodation change driven chiefly by tectonic movements.

A model Aotea sequence for the northern region

A simplified view of the distribution of Aotea lithofacies and sequence architecture along a cross-shelf transect is depicted in Fig 6.20. Prior to accumulation of the Aotea sequence, uplift along the western margin elevated the shelfal muds of the underlying Whaingaroa Formation into a subaerial environment. The subsequent transgression wave planed the Whaingaroa strata and formed a sharp flat surface (TSE). This sequence boundary grades basinward into a correlative conformity where Whaingaroa Formation was not subaerially exposed and hence not wave planed.

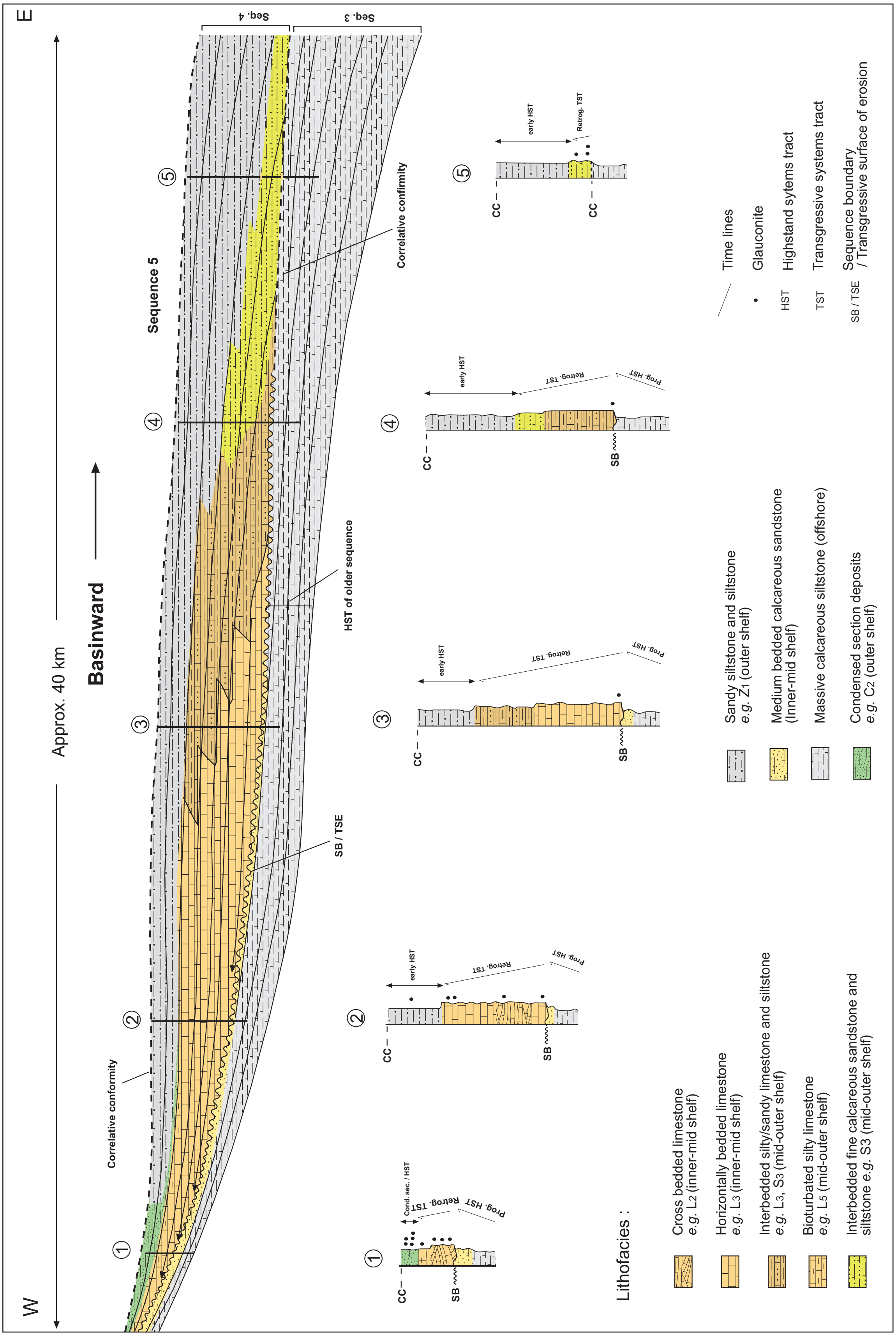


Fig. 6.20: Organisation of Aotea depositional sequence within a sequence stratigraphic framework along a northwest-southeast profile (approximately from Port Waikato to Huntly; location on Fig. 6.9). The sequence boundary erosionally truncates the underlying Whaingaroan Formation (seq. 3) as observed on the western margin, whereas to the east it is inferred to be a correlative conformity.

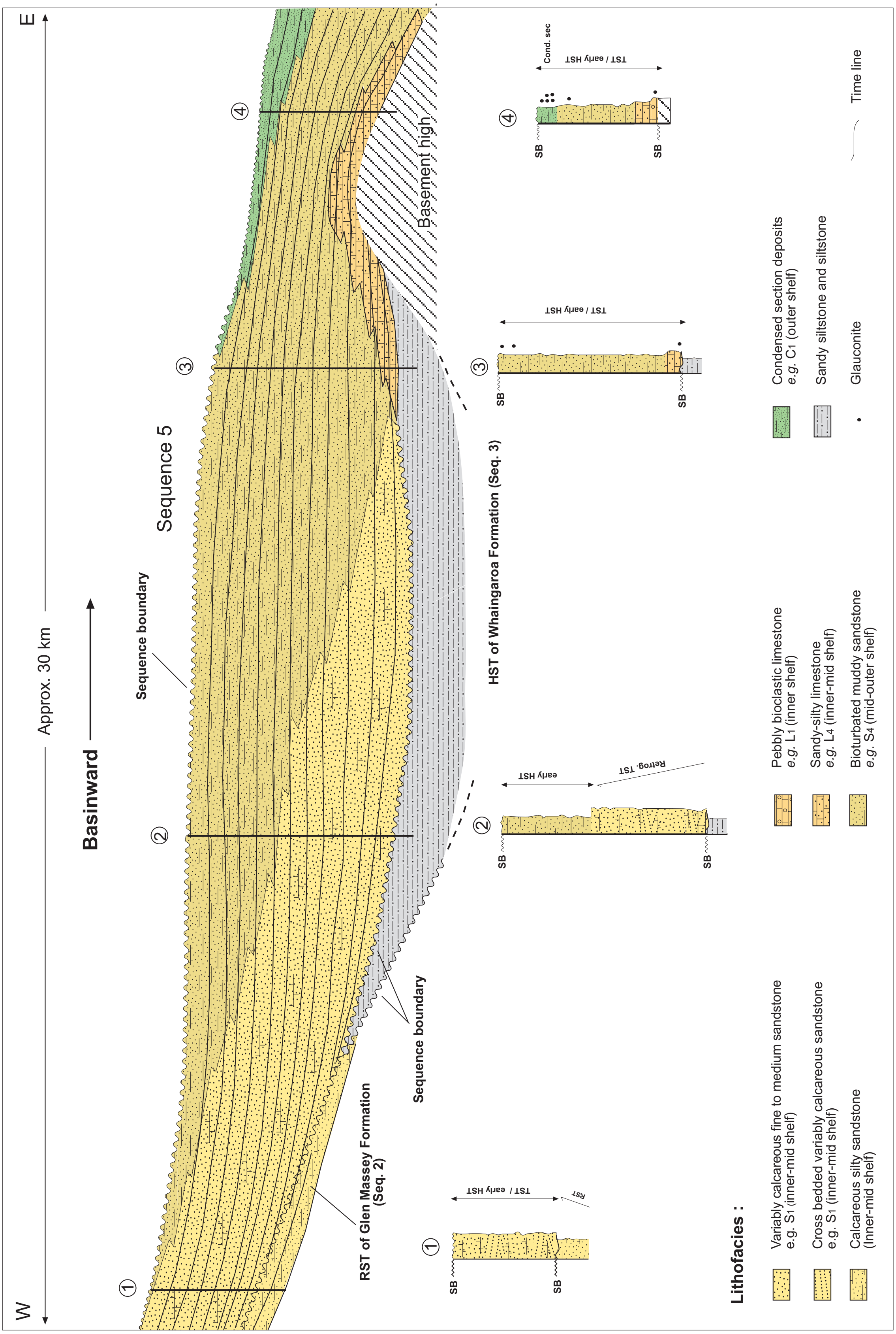


Fig. 6.21: Organisation of Aotea depositional sequence within a sequence stratigraphic framework along a northwest-southeast profile (approximately from east of Kawhia Harbour to south of Otorohanga; location on Fig. 6.9). The sequence boundary truncates a progressively older sequence in a westward direction. The Aotea sequence laps onto a paleo-basement high to the east. This high separates the southern region into two parts. TST comprising calcareous fine to medium sandstone (Hauturu Sandstone Member) is restricted mainly to the west of this intra-basinal high.

During the ongoing transgression in the early part of the Aotea sequence, the bulk of the coarse skeletal sand generated around the rocky shorelines was reworked across the shelf assisted by wave and storm currents. The TST in inner to mid-shelf settings is represented by "Cross-bedded, moderately well sorted skeletal grainstone" lithofacies L_2 passing upward into "Massive to irregularly bedded, bioturbated grainstone/packstone" (L_5). The cross-bedded grainstone facies accumulated as skeletal sand megadunes on mainly inner parts of the contemporary shelf that sloped to the east. Paleocurrent directions measured by Anastas (1997) indicate mainly west to east migration of the carbonate dune fields with some local NNE and SSW transport as well. The grainstone is mainly composed of echinoderms, bryozoans, benthic foraminifers, and a minor proportion of calcareous red algae and fragmented bivalves. The cross-bedded grainstone passes offshore into horizontally bedded skeletal grainstone (L_3) reflecting a lower energy environment. Further offshore, the lithofacies L_3 pass through intercalated silty/sandy limestone (L_3) and calcareous silty sandstone (S_3) into interbedded fine calcareous sandstone and siltstone (S_3) that probably accumulated at outer shelf depths. The proportion of siliciclastics increases in a seaward direction making it difficult to differentiate TST deposits from the later system tract.

The upper parts of the TST are characterised by increasing intensity of bioturbation and an increasing percentage of planktic foraminifera, and slightly higher siliciclastic content, suggesting increasing paleobathymetry. Rapid transgression can result in cessation of carbonate productivity (e.g. Simone & Carannante 1988) reducing the delivery of carbonate sediment seaward. Accommodation that continues to develop into the subsequent highstand may therefore only be infilled by siliciclastic sediment provided this available (e.g. Gillespie & Nelson 1997). For the Aotea sequence in the northern region, sufficient terrigenous sediment was not available to fill the accommodation space and this is reflected in progressive deepening and the inferred retrogradational stacking pattern. Interestingly, sedimentation rates were much lower in the inner parts of the shelf compared with outer parts. This gave rise to a thin HST made up of condensed deposits over a thin backstepping inner to mid shelf carbonate dominated TST.

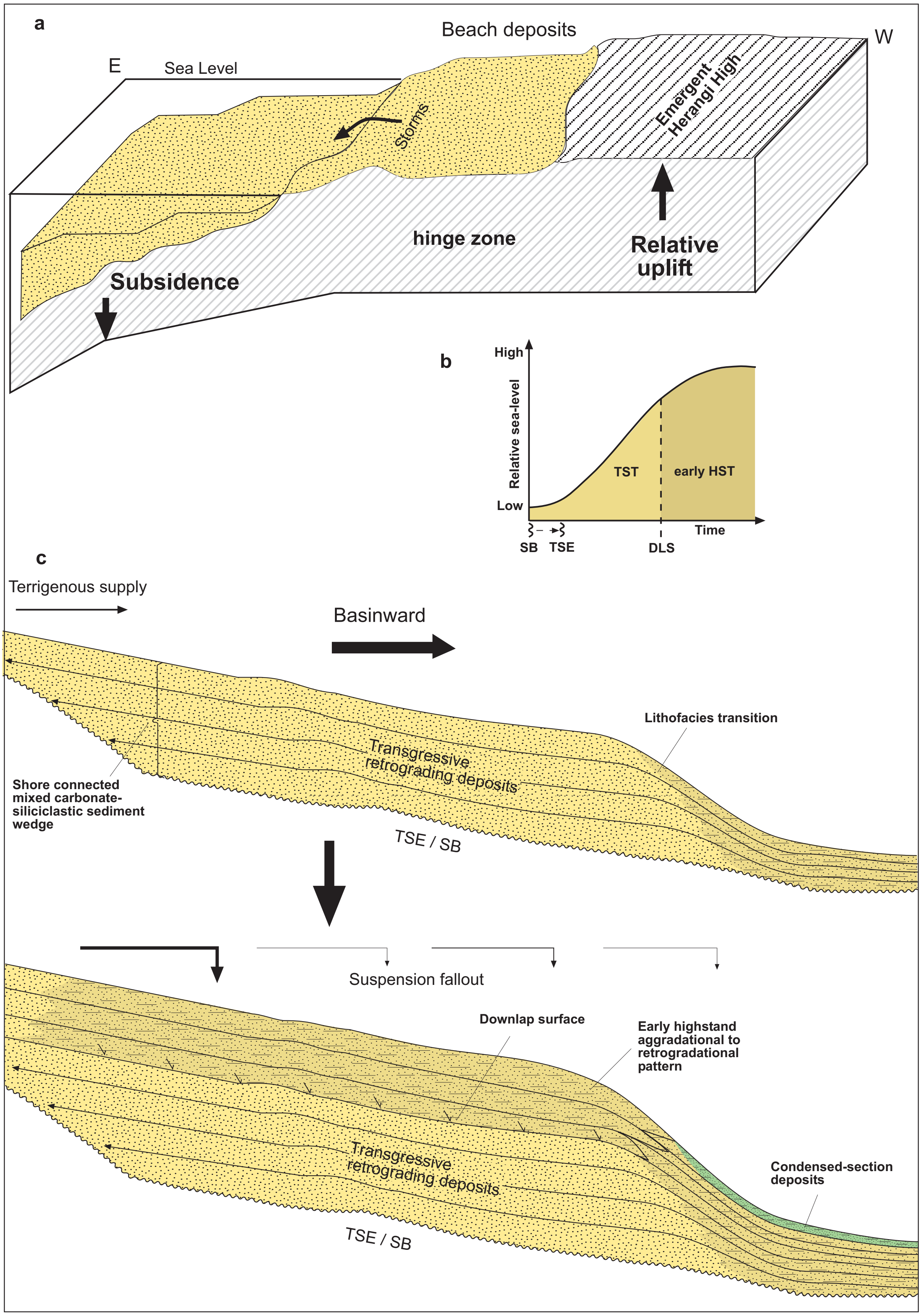
A model Aotea sequence for the southern central region

A simplified model of the distribution of lithofacies and systems tracts in the Aotea sequence in the south-central region is illustrated in Fig 6.21. The western margin of the basin is formed by the Herangi High, which is not shown in the model. Prior to the start of accumulation of the Aotea sequence the basin was inverted, which resulted in uplift of the underlying Whaingaroa Formation and its subaerial exposure. Hence an erosional surface (sequence boundary) truncates progressively older Te Kuiti Group strata in a westward direction, which also reflects the differential uplift of the Herangi High. The sequence boundary was modified by wave erosion forming a TSE (e.g. Swift 1976). TST deposits that accumulated immediately basinward of the paleo-shoreline are formed of packages of variably calcareous, moderately well sorted, cross-bedded to bioturbated fine to medium sandstone (S_1). These beds have a wedge-shaped geometry thinning towards the paleo-shoreline and thickening out into the basin. This mixed carbonate-siliciclastic wedge is inferred to be shore-connected, and the seaward transport of the sediment from the shoreface onto the shelf resulted from a combination of wave, tide and storm induced currents (Fig. 6.22 A and C). Shell hash and basement derived pebbles are common throughout these transgressive mixed carbonate-siliciclastic facies, pointing to material having been re-worked from the adjacent beach environment. Most of the coarse-grained sediments were deposited in the inner shelf with finer fractions being winnowed and deposited in mid to outer shelf areas as muddy sandstone (S_4) where they were heavily bioturbated.

The part of TST made up of limestone (L_1, L_3 & L_4) is restricted to the flanks of a basement paleo-high and also in shoal areas above submerged basement knolls. These deposits display broadly similar characteristics to the carbonate deposits on the contemporary inner to mid shelf in the northern region.

As the relative sea level continued to rise during accumulation of the sequence, sand supply was gradually cut-off to the mid shelf areas leading to the accumulation of muddy sandstone (S_4) and thin bedded calcareous siltstone (S_2), both classified as early HST deposits. As a result the stratigraphic profile of a fully developed Aotea sequence in the Aotea-Kawhia area displays fining upwards, which is an expression of retrogradation (6.22 c). An unusual thickness profile can develop if a sandstone shore-connected wedge continues to accumulate during the highstand,

Fig. 6.22 (facing page): (a) The shoreline is a hinge zone that separated the uplifted Herangi High to the west from the actively subsiding shelf area to the east, which accumulated the Aotea Formation siliciclastic wedge. The sediment is moved basinward from the shoreline primarily by episodic storm surges. (b) The timing of development of major stratigraphic surfaces and systems tracts interpreted within the Aotea depositional sequence are shown with respect to a simplified relative sea-level curve. (c) Conceptual block diagrams showing the dominant depositional process involved during the early transgression and late transgression/early highstand phase. In the early stage of transgression, when the shoreline is close to the shelf area with deposition, the sediment supply is relatively higher and depositional processes are dominated by a combination of storm surges in proximal and medial portion and suspension sedimentation in distal portion. As transgression proceeds and the shoreline become more distant from the basin center, the sediment supply diminishes and the accumulation of the siliciclastic wedge continues primarily from suspension fallout. The rate of sedimentation from suspension fallout diminishes progressively, and as a result the proximal side of the wedge grows thicker with time relative to the distal portion, which eventually is starved of terrigenous sediment.


a
Beach deposits
W
E
Sea Level
Storms
Emergent Herangi High
hinge zone
Relative uplift
Subsidence
b
High
Relative sea-level
Low
TST
early HST
Time
SB
TSE
DLS
c
Terrigenous supply
Basinward
Lithofacies transition
Transgressive retrograding deposits
Shore connected mixed carbonate-siliciclastic sediment wedge
TSE / SB
Suspension fallout
Downlap surface
Early highstand aggradational to retrogradational pattern
Transgressive retrograding deposits
Condensed-section deposits
TSE / SB

as was evidently the case with the Aotea sequence in the southern region (Fig. 6.21 & 6.22). Out in the basin, condensed glauconitic sandstone formed at the top of the HST as a result of the waning of terrigenous sediment supply caused by the relative sea-level rise, whereas thick TST and HST sandstone accumulated in proximal areas (Fig. 6.22 c). The Aotea sequence does not contain RST deposits.

Chapter 7

Lithofacies, paleoenvironments and sedimentary evolution of the Castle Craig Subgroup

Introduction

The Castle Craig Subgroup contains the main limestone units within the Te Kuiti Group, which are an important economic resource as well as being of importance for tourism and recreation in the region. In the first part of this chapter a lithofacies scheme is developed for the subgroup, which is followed by their systematic description and interpretation in terms of related depositional environments. Particular emphasis is given to the horizontal and vertical distribution of the lithofacies, and from them, determination of the broad stratal patterns. An important feature of the subgroup is the occurrence of an extensive unconformity (sequence boundary) at the base of the Castle Craig Subgroup. The sedimentary evolution of the Castle Craig Subgroup has been relatively complex, but can be divided into two main phases of development. In the first phase the sedimentation patterns were characterised by shelf progradation to the north and east; in the second there is a regional transition to aggradation followed by retrogradation towards the south but continuing progradation to the east, reflecting a rise in relative sea-level, probably driven by tectonic subsidence.

In this study the prior stratigraphic distinctions between the Orahiri Formation and Otorohanga Limestone are reviewed and new insights are presented about how the various limestone facies are related across (east-west) and along (north-south) the basin.

Thick limestone accumulations in the upper parts of the Te Kuiti Group have been interpreted in the past as the result of southward directed marine inundation of the basement high, and overall considered to reflect tectonically quiescent conditions. This transgressive phase was regarded as part of New Zealand-wide submergence and marine inundation (Fleming 1979; Nelson & Hume 1987). This study however regards syndepositional tectonism as the main driving force behind prolific limestone accumulation of the Castle Craig Subgroup. This chapter aims to develop a better understanding of the role of tectonism, relative sea-level change, and sediment supply on accumulation of the subgroup.

Lithofacies analysis

The Castle Craig Subgroup contains a broadly transgressive sedimentary record of Duntroonian to Waitakian age, overlain by a thick (up to 1300 m) early Miocene terrigenous succession comprising the Waitemata Group in the north and the Mahoenui Group in the south. The Castle Craig Subgroup comprises three major lithostratigraphic units: the Te Akatea Formation, the Orahiri Formation and the Otorohanga Limestone (Chapter 3). These formations unconformably, or conformably in deeper water settings, overlie largely terrigenous facies of the Aotea Formation, except in southeastern parts of the basin where they progressively onlap the Piopio High. The southern and central regions contain a spectrum of shelf carbonate lithologies represented by the Orahiri Formation and Otorohanga Limestone. The northern region contains the Te Akatea Formation, a sequence of predominantly deep water (slope/upper bathyal) marl and marly limestone, with rare sandy siltstone beds. The transition between the shelfal Orahiri Formation and/or Otorohanga Limestone and the basinal Te Akatea Formation is largely concealed by Pliocene-Early Pleistocene volcanics or have been removed by modern erosion, although a few isolated outcrop windows occur in the inland parts of the Aotea-Kawhia area.

The Castle Craig Subgroup exhibits significant lithological and facies changes from south to north. The lateral facies changes between these two areas broadly reflect changing basin morphology and gradual drowning of the carbonate shelf caused by relative sea-level rise.

In the areas east and south of Kawhia Harbour, the rocks belonging to the Castle Craig Subgroup form ‘flaggy’ to massive nearly vertical limestone cliffs up to 80 m high with karst topography. Earlier investigations of these skeletal limestone successions have established facies classification schemes for them (e.g. Barrett 1967; Hopkins 1970; Nelson 1973; 1978a, b). Nelson (1973, 1978a) in particular developed a lithostratigraphic scheme for the limestone formations. That scheme has been used as a basis for this study. Paleocurrent and associated lithofacies analysis carried out by Anastas (1997) has also proved to be useful in the analysis undertaken here. In the northern region (Raglan-Te Akau), earlier work has established two broad facies for the Te Akatea Formation, the lower part being dominated by marly limestone (Raglan Limestone Member), and middle to upper parts by calcareous siltstone/marl (Carter Siltstone Member) (Kear 1987; White & Waterhouse 1993). In the northernmost areas (Port Waikato), the formation is comprised entirely of calcareous siltstone/marl with localised occurrences of bioturbated glauconitic and/or phosphatic horizons.

This study has erected twelve lithofacies within the Castle Craig Subgroup. These are grouped into three lithofacies associations on the basis of sedimentological and faunal features. The associations are named carbonate, mixed carbonate-siliciclastic sandstone, and mixed carbonate-siliciclastic siltstone after the dominant lithologies. Typical expressions of "Carbonate" lithofacies in the field are illustrated in Figs 7.1-7.3 and their photomicrographs in Fig. 7.4. The typical field expression of "Mixed carbonate-siliciclastic" lithofacies is shown in Fig. 7.5. Their character reflects accumulation on different parts of a shelf to upper slope "ramp" that deepened northwards along central-western North Island. The diagnostic characteristics of each lithofacies and inferred environments of deposition are summarised in Table 7.1. More detailed descriptions of these lithofacies and their paleoenvironments are given in the following sections. The vertical and horizontal relationships between the various lithofacies are depicted in north-south and east-west transects in Figs 7.7 to 7.11. The location of these transects are shown in Fig. 7.6.

Table 7.1: Lithofacies of the Castle Craig Subgroup.

Lithofacies 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	Interpretation
Limestone association						
$L_{1.}$ Pebbly grainstone-packstone.	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). Fig. 7.1 (a & b)	Near shore to inner shelf adjacent to rocky shoreline
L_2. Cross-strati-fied grainstone	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. Fig. 7.1 (c & d)	High energy inner to mid shelf dominated by strong offshore-directed storm and or tidal induced currents.

Lithofacies 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	Interpretation
L_3. Horizontally bedded grainstone.	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. Fig. 7.1 (d)	Inner to mid wave dominated shelf.
L_4. Sandy grainstone-packstone.	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 (*Amphistegina*), 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. Fig. 7.1 (e-h)	Inner to mid shelf.
L_5. Massive to irregularly bedded, fossiliferous rudstone-grainstone.	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. Fig. 7.2 (a -d)	Bryozoan mound buildup indicating high energy inner-mid shelf depths.

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 (*Flemingostrea 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. Fig. 7.2 (f & g)	Oyster reefs commonly associated with sandy grainstone -packstone, high energy tide swept inner-mid shelf
L_7. Conglomeratic 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 Fig. 7.2 (e)	Interpreted as carbonate debrite/ mass emplaced unit - deposited at shelf depths in response to tilting

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 horizontally bedded skeletal packstone-wackestone.	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. Fig. 7.3 (a-h)	Outer shelf to slope
$S_{1.}$ Massive glauconitic muddy sandstone.	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) Fig. 7.3 (i)	Mid to outer shelf.
$S_{2.}$ Fossiliferous silty sandstone 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 (*Flemingostrea 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. Fig. 7.1 (i & j)	Mid-outer shelf above storm wave base.

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 calcareous 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 Fig. 7.5	Outer shelf to upper bathyal
Z_2. Massive calcareous 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. Fig. 7.5	Outer shelf to upper bathyal

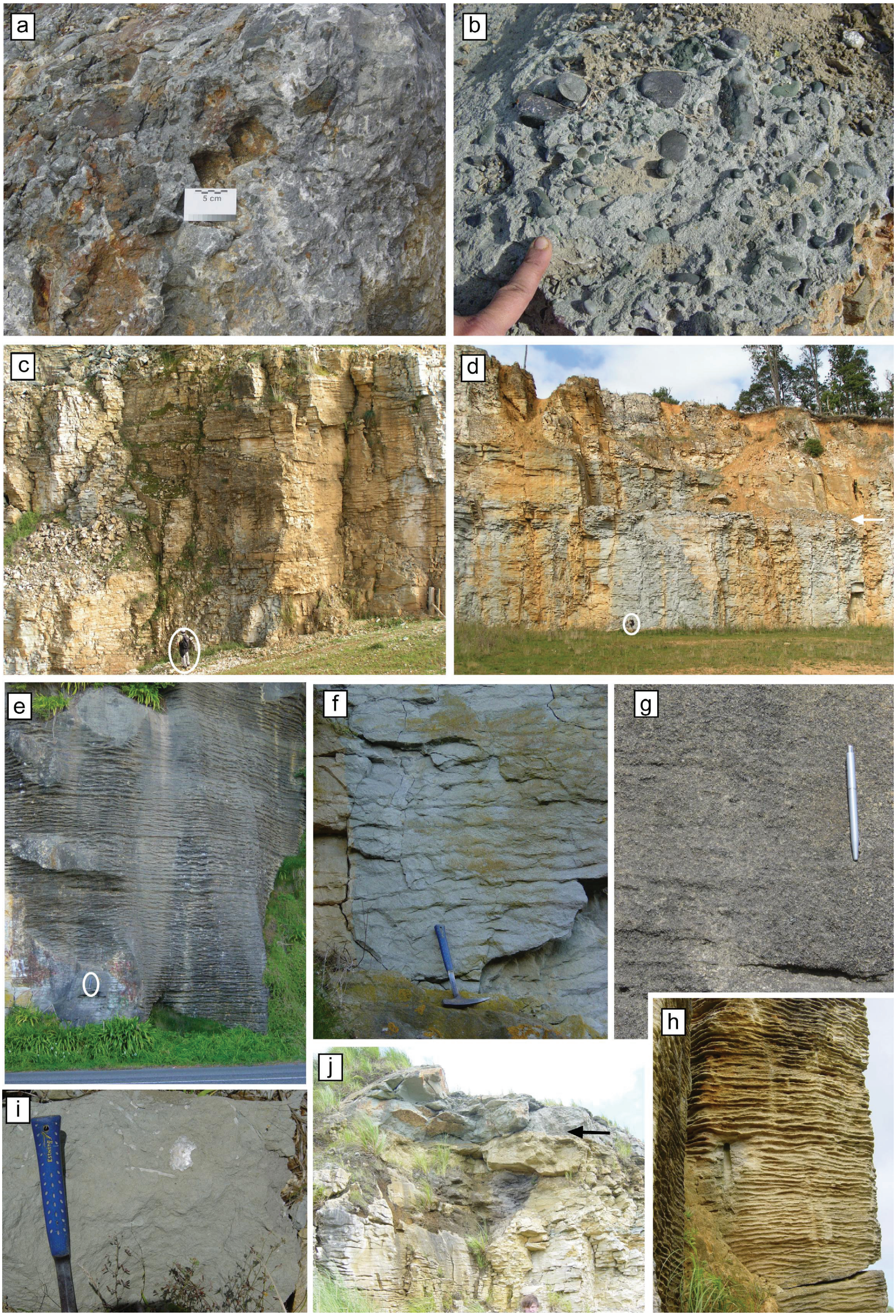
Limestone association (L_1 - L_8)

The carbonate dominated lithofacies in the Castle Craig Subgroup comprise the bulk of the thickness of stratigraphic sections in the central and southern regions of central-western North Island. In particular, they comprise the major part of the Orahiri Formation and all of the Otorohanga Limestone, with a combined thickness of up to 100 m. In both the Orahiri Formation and Otorohanga Limestone the limestone lithofacies association is characterised by a wide variety of limestone types, ranging from massive to moderately bedded sandy and pebbly limestone through to cross-bedded and pure skeletal flaggy limestone. The limestone association also constitutes the Raglan Limestone Member of the Te Akatea Formation in the Raglan Harbour area that grades laterally into the thinly-bedded to massive calcareous siltstone/ marl of the Carter Siltstone Member farther to the north. The Raglan Limestones Member is a packstone to wackestone rich in planktic and benthic foraminifera, echinoderm and occasional bivalve fragments. The limestone lithofacies comprising the Orahiri Formation and Otorohanga Limestone are typically skeletal calcarenite or calcirudite composed predominantly of fragmental bryozoan and echinoderm remains, benthic (rarely planktic) foraminifera and epifaunal bivalves, with lesser contributions from calcareous red algae, brachiopods and barnacles. An exception is planktic foraminiferal-rich packstone/wackestone occurring in the uppermost part of the Otorohanga Limestone in parts of the southern region (Nelson 1973, 1978a).

L_1. Pebbly grainstone/packstone:

The "Pebbly grainstone/packstone" lithofacies, ranging from 0.5 to 1.5 m in thickness, are limited to the southern region, particularly where Orahiri Formation/ Otorohanga Limestone laps onto basement. This lithofacies is characterised by moderate to poorly-sorted, rounded-subrounded pebbles and cobbles (Fig. 7.1 a & b), with common calcareous red algae, oysters, pectinids and other coarse bivalve skeletal hash. Other common biota includes echinoderm and bryozoan fragments, and large benthic foraminifers such as *Amphistegina* sp. This facies occurs in a stratigraphic position similar to that occupied by the "Basal Beds (OrA1) / (OtA1)" at the base of Orahiri/Otorohanga Limestone described by Nelson (1973, 1978a) near Te Kuiti (e.g. C 114, C 124, C 130) and Piopio (e.g. C 104, C 174) (Nelson 1977 stratigraphic columns). The distribution of this lithofacies occurring at the contact with the basement is illustrated in Fig. 7.12.

The L_1 facies has also been recorded at the sharp broadly undulatory lower erosional contact with the underlying Aotea Formation at localities C-32 (Fig. 7.9), BH-502 (Fig. 7.10), C-191, C-166 (Fig. 7.11), and with Glen Massey Formation at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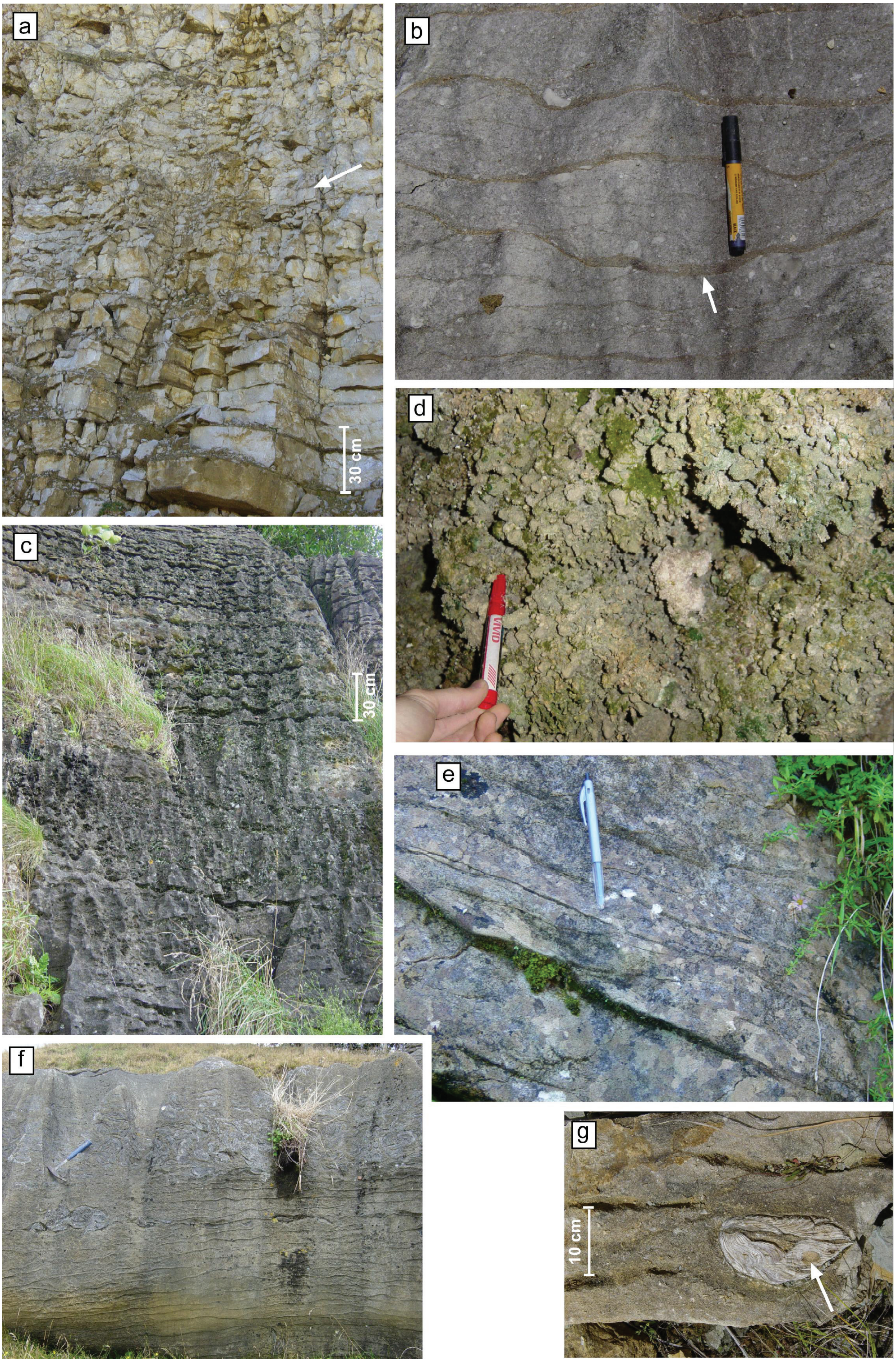
localities C-51 (Fig. 7.8) and C-47 (Fig. 7.9). At these sites the facies comprises abundant subrounded to well rounded pebbles and cobbles derived primarily from basement, infilling scours up to 30 cm cutting deep into the underlying formation. Also commonly associated are vertical to subvertical burrows extending down from the contact and coarse bioclastic lag (commonly pectinids, oyster and echinoderm fragments).

Interpretation: The pebbly grainstone/packstone lithofacies overlying the basement is similar to the "Pebbly grainstone (L_1)" lithofacies of the Aotea Formation, inferred to have been deposited during marine encroachment. Coralline algae, large benthic foraminifera (*Amphistegina*) and other biogenic components in this facies suggest a high energy inner shelf environment (e.g. Nelson et al.1988a; James et al. 1997).

L_2. Cross-stratified grainstone:

Cross-stratified grainstone packages are 0.3-4.5 m thick and usually interbedded with horizontally bedded and/or sandy grainstone (lithofacies L_3, L_4). Much of the observed cross-stratification occurs in the Mangaotaki Limestone Member (Orahiri Formation) and in Otorohanga Limestone (Fig. 7.1 c & d) in the area between Kawhia Harbour and Awakino (localities C-51, AK-11 & AK-12 in Fig. 7.8 & C-32 in Fig. 7.9). This facies is similar to "Cross-stratified grainstone lithofacies L_2" described previously in the Waimai Limestone Member of Aotea Formation in the northern region (Chapter 6). However, this lithofacies in the Orahiri Formation and Otorohanga Limestone differs from the Waimai Limestone in that cross-bedded units are lenticular bodies surrounded by horizontally bedded units, whereas L_2 in Waimai Limestone comprises laterally continuous tabular cross-bedded units (Anastas 1997). The cross-stratification contains complex horizontal and inclined surfaces that define the bedding planes and set boundary surfaces, often having

Fig. 7.1 (facing page): Outcrop photographs illustrating typical field expression of lithofacies identified within the Castle Craig Subgroup across the southern central region of the study area. (a) Basal "Pebbly grainstone/packstone" (L1) unit located near the lower contact with basement. This conglomeratic unit is up to 1 m thick comprised of subangular to subrounded clasts mainly supported by calcareous matrix that include calcareous red algae and rare rhodoliths. Serpentine Quarry (R17/859934), Aria. (b) Pebbly grainstone/ packstone (L1) unit marking the lower contact of Castle Craig Subgroup with the Aotea Formation. Note various rounded and subrounded basement pebbles and occasional cobble supported by glauconitic sandy grainstone matrix. Mangaotaki Bridge section (C-166). (c) Tabular cross-bed sets of grainstone (L2). Person for scale. Limestone quarry at Waitomo Valley Road (C-32). (d) Cross-bedded grainstone (L2) overlain by horizontally bedded grainstone (L3). Person for scale. Limestone quarry at Waitomo Valley Road (C-32). (e) Thinly bedded sandy grainstone/packstone (L4) succession. Hammer for scale. SH 3, near Mangaotaki Bridge (C-166). (f) Freshly exposed surface exhibiting massive to irregularly bedded sandy grainstone-packstone (L4) with siliciclastic rich seams. SH3, near Mangaotaki Bridge (C-166). (g) Massive sandy grainstone-packstone (L4) with abundant medium to coarse quartz sand grains exposed at the surface (C-51). Awamarino. (h) Horizontal to low angle cross-beds defined by preferential weathering of siliciclastic rich seams in sandy grainstone-packstone lithofacies (L4). Limestone quarry, Raukanui Peninsula (AK-11). (i) Fossiliferous silty sandstone (S2) with abundant bivalve fragments in a muddy matrix. Limestone quarry, Raukanui Peninsula (AK-11). (j) Sharp vertical transition (arrow) between "Irregularly bedded pebbly oyster floatstone-packstone" (L6) and overlying "Fossiliferous silty sandstone" (S2) unit. Limestone quarry, Raukanui Peninsula (AK-11).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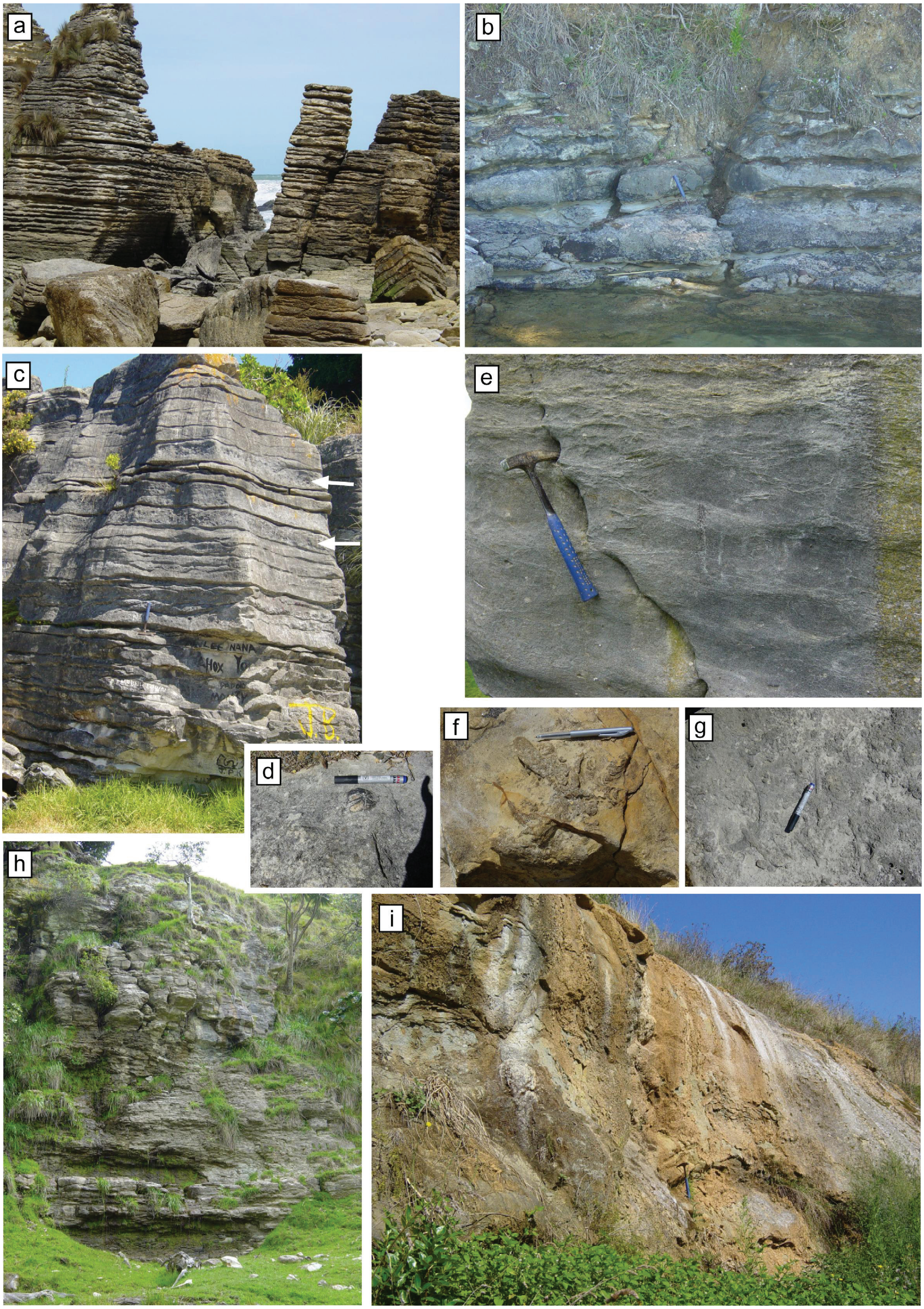
relatively high concentrations of siliciclastic material and glauconite content. These rocks are generally coarse calcarenite dominated by bryozoans, echinoderms and benthic foraminifers with lesser amounts of bivalves, barnacles and coralline red algae (Fig. 7.4 b) (Nelson 1973; Anastas 1997; Anastas et al. 1997).

Interpretation: The wide distribution of largely unidirectional cross-stratified lenticular units in the Orahiri Formation and Otorohanga Limestone suggests that they were produced by migrating (1-5 km) long subaqueous megadunes to sand waves within a sea way between basement highs. These bedforms are inferred to have developed in response to strong seaway-parallel tidal and bottom currents generated by rugged topography. Irregular topography enhanced by tectonic movement of basement strongly influenced the paleocurrent distribution and in general shows a variation from ENE in the southern region to NNE in the central region (Anastas 1997). The presence of benthic foraminifera (*Amphistegina*) and coralline red algae in many of the units imply inner to mid shelf depths (e.g. Nelson et al. 1988; James et al. 1992).

$L_{3.}$ Horizontally bedded grainstone:

The "Horizontally bedded grainstone" lithofacies forms units up to tens of metres thick and constitutes much of upper part of the Orahiri Formation and most of Otorohanga Limestone (exemplified by localities C-51 and AK-11 in Fig. 7.8, C-47, C-40 & DH-6796 in Fig. 7.9, BH-502 & C-126 in Fig. 7.10). The horizontally bedded limestone is locally intercalated by "Cross-stratified grainstone and/or Sandy grainstone-packstone" units (Fig. 7.1 d). The distribution of this lithofacies along with L_2 is shown in Fig. 7.13. Moderately to well developed flagginess is characteristic of this facies, and individual flag thickness ranges from 2-25 cm. Bedding planes (1-1.5 cm) are often enriched in siliciclastic material and often exhibits a gradational transition into flags. Apart from rare *Scolicia* and *Thalssinoides* burrows, the bedding is largely devoid of depositional structures other than the flagginess. This facies is similar to the "Flaggy Limestone Beds (OrB1), Lower

Fig. 7.2 (facing page): Field examples of lithofacies within Castle Craig Subgroup from the south-central region (a) Cavernous weathering (pointed by arrow) characterizes an "Irregularly bedded rudstone-grainstone" (L5) unit overlying prominent "Flaggy grainstone" (L3). Oparure Limestone quarry (C-119). (b) Irregularly bedded, fossiliferous rudstone-grainstone (L5). Arrow points to slightly recessed siliciclastic-rich bedding plane layer defining the flag geometry. Mangaohae Stream section (C-56). (c) Massive to medium bedded, fossiliferous rudstone-grainstone (L5). Cavernous/honeycombed appearance is due to the preferential weathering of skeletal components. Waipuna Road, Kawhia Harbour (R15/728419). (d) Massive bryozoan grainstone (L5) showing open grain fabric with conspicuous visual intergranular porosity. Bexley Station tunnel, Awakino Gorge (C-193). (e) Conglomeratic limestone (L7) with abundant highly irregular, angular to subangular limestone and basement clasts (dark grey), ranging in size from 1-6 cm. Clasts are chaotically orientated suggesting their transport by debris flow. Near Awakino Tunnel SH-3 (C-191). (f) Hammer rest on "Pebbly oyster floatstone-packstone" bed (L6) overlying "Massive to irregularly bedded sandy grainstone" (L4). Mairoa (C-97). (g) Irregularly bedded pebbly oyster floatstone-packstone (L6) unit showing close-up of oyster shell with tubular boring (pointed by arrow) infilled with host limestone. Limestone quarry, Rakanui Peninsula (AK-11).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Flaggy Limestone Beds (OtA2) and Upper Flaggy Limestone Beds (OtC1)" of the Orahiri Formation/Otorohanga Limestone described by Nelson (1978a). The rocks are mainly coarse grained, from medium to very coarse sandstone. Compositionally they are skeletal-rich, include bryozoans, echinoderms, benthic foraminifers, and occasional bivalves and calcareous red algae, with variable quantities of glauconite and quartz grains (Nelson 1973).

Interpretation: The horizontally bedded grainstone lithofacies is indicative of deposition in a wave and tide swept inner to mid shelf setting. Intercalations with cross-bedded limestone lithofacies (L_2) suggests conditions fluctuated from a wave to current dominated shelf and its lateral transition into L_2 indicates that these settings varied locally due to complex topography (Anastas 1997).

L_4. Sandy grainstone-packstone:

The "Sandy grainstone-packstone" lithofacies occur in the lower part of the Orahiri Formation and comprise the major part of the Mangaotaki Limestone Member (Orahiri A; Nelson 1978a). This facies comprises much of the spectacular cliff forming unit in the western areas, ranging in thickness from 4 to 60 m (exemplified by AK-12 & AK-11 in Fig. 7.8; C-47 & C-40 in Fig. 7.9; C-56, C-61, C-68 & C-126 in Fig. 7.10; C-185a & C-166 in Fig.7.11). This facies is similar in character to "Massive Sandy Limestone Beds (OrA3)/(OrB4), Upper Banded Sandstone Beds (OrA4) and Bimodal-sandy Limestone Beds (OrA5)" of the Orahiri Limestone as described by Nelson (1978a). The aerial distribution of the sandy grainstone-packstone lithofacies is shown in Fig. 7.12. This lithofacies exhibits great similarity to the "Sandy-silty grainstone lithofacies (L_4)" described previously in the Aotea Formation (Chapter 6), however unlike that lithofacies, there is a lack of discrete sandy beds. The "Sandy grainstone-packstone" lithofacies is typified by massive or irregular to tabular bedded units up to 2.5 m thick. Contacts between the beds tend to be diffuse. In places, resistant beds ("flags") and recessive seams ("interflags")

Fig. 7.3 (facing page): Photographs (a-h) illustrating typical field character of "Massive to bedded skeletal packstone and wackestone" lithofacies L8 (Raglan Limestone Member) across the northern region of the study area. (a) Strongly bedded fine-grained packstone-wackestone with thin silty bioturbated interbeds. Note sub-parallel bedding typical of this facies. Exposure is approximately 8 m high. Photo location: Carters Beach (TA-11). (b) Alternation of hard carbonate-rich beds and recessively weathered carbonate deficient silty wackestone interbeds. Note beds have sharp bases. Raglan Harbour (R14/745774). (c) Arrow pointing to highly burrowed layers in the Raglan Limestone Member at Raglan Harbour (R14/745774). (d) Whole delicate spatangoid tests are common in Raglan Limestone Member indicative of minimum transport and relatively deep, quiet water environments. Raglan Harbour. (e) Remnant traces of wavy bed forms apparent in Raglan Limestone Member. Te Kotuku Trig. Mangiti Road (TA-12). (f) View along a bedding plane showing large Scolacia burrows. Carters Beach (TA-11). (g) Bedding plane illustrating extensive Scolicia burrows. Raglan Harbour (R14/745774). (h) Thinly interbedded silty packstone and wackestone grading upwards into more resistant beds in the top half of the photograph. Exposure is approximately 20 m high. Waimai Valley (TA-3). (i) Massive glauconitic muddy sandstone (S1) comprise Waitomo Sandstone Member of the Orahiri Formation. The moderately cemented fine sandstone is variably glauconitic and exhibits extensive bioturbation in places.

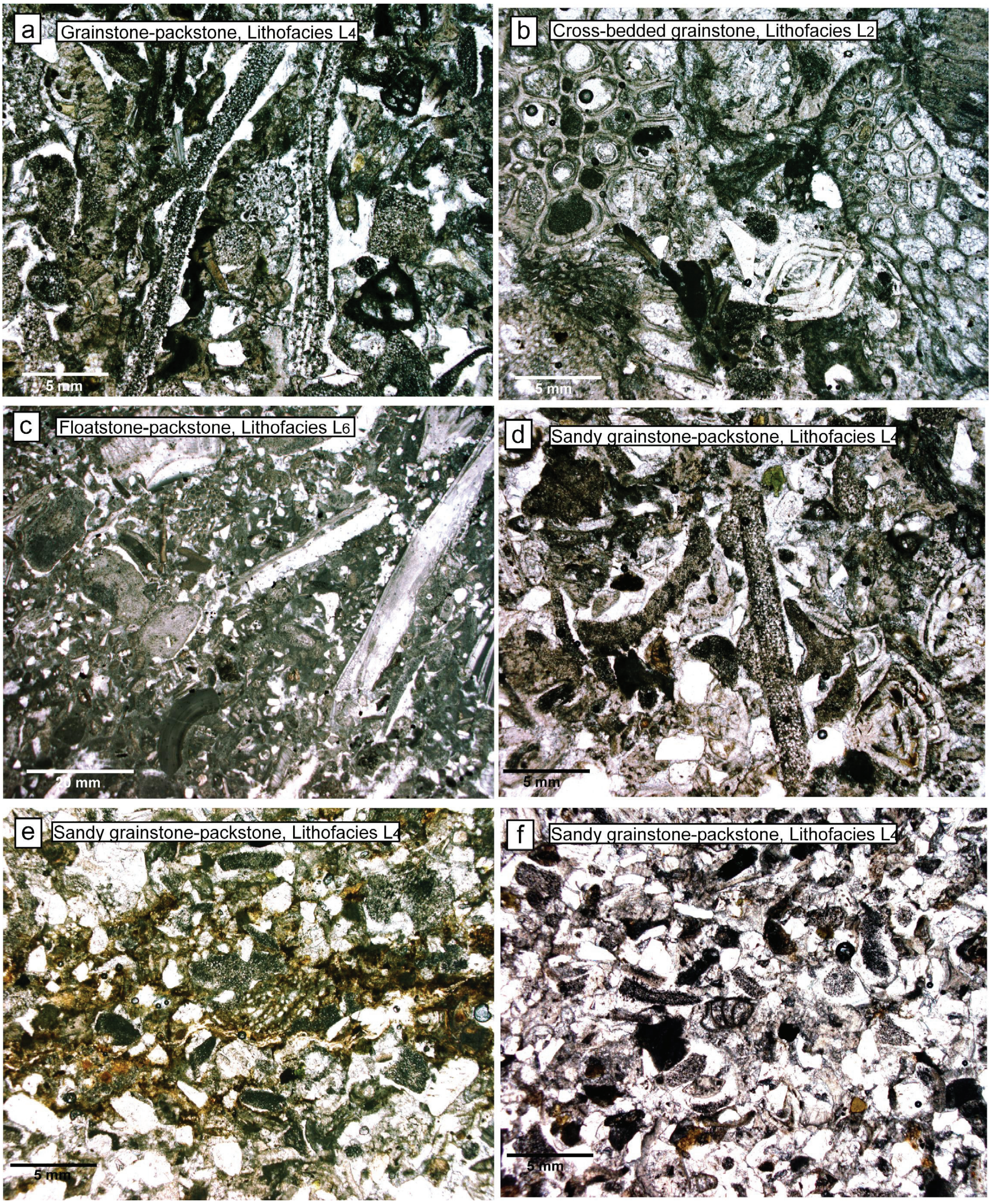


Fig. 7.4 (i): Photomicrographs of representative samples from the Castle Craig Subgroup carbonate lithofacies from central region(a) Echinoderm /benthic foraminifer rich sandy grainstone-packstone (lithofacies L4).Note syntaxial overgrowth cement around echinoid plates. Limestone Quarry, Rakaunui Peninsula (AK-11) Sample 367. (b) Bryozoan dominated cross bedded grainstone (lithofacies L2) with Common benthic foraminifers (Amphistegina).Limestone Quarry, Rakaunui Peninsula (AK-11) Sample 368. (c) Pebbly oyster floatstone-packstone (lithofacies L6) showing large bivalve fragments in coarse bryozoan/benthic foraminifer rich matrix. Limestone Quarry, Rakaunui Peninsula (AK-11) Sample 369 (d) Echinoderm/benthic/bryozoan sandy grainstone-packstone (lithofacies L4). Whanuapo Hill (S-11) Sample 391. (e) Echinoderm-rich/benthic/bryozoan/calcareous red algal grainstone-packstone (lithofacies L4). Whanuapo Hill (S-11) Sample 392. (f) Benthic foraminifera /echinoderm /bryozoan/calcareous red algal sandy grainstone-packstone (lithofacies L4). Whanuapo Hill (S-11) Sample 395.

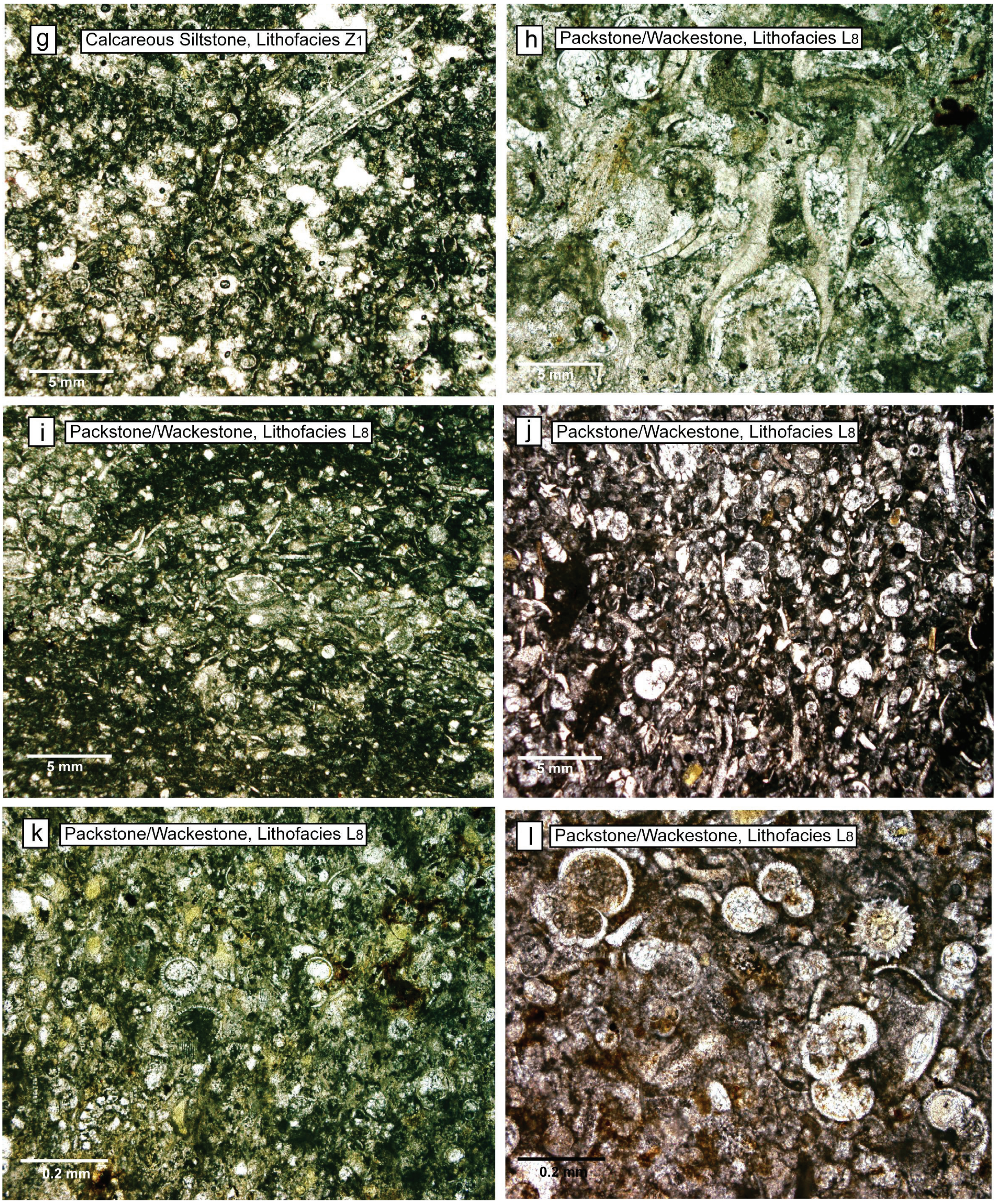
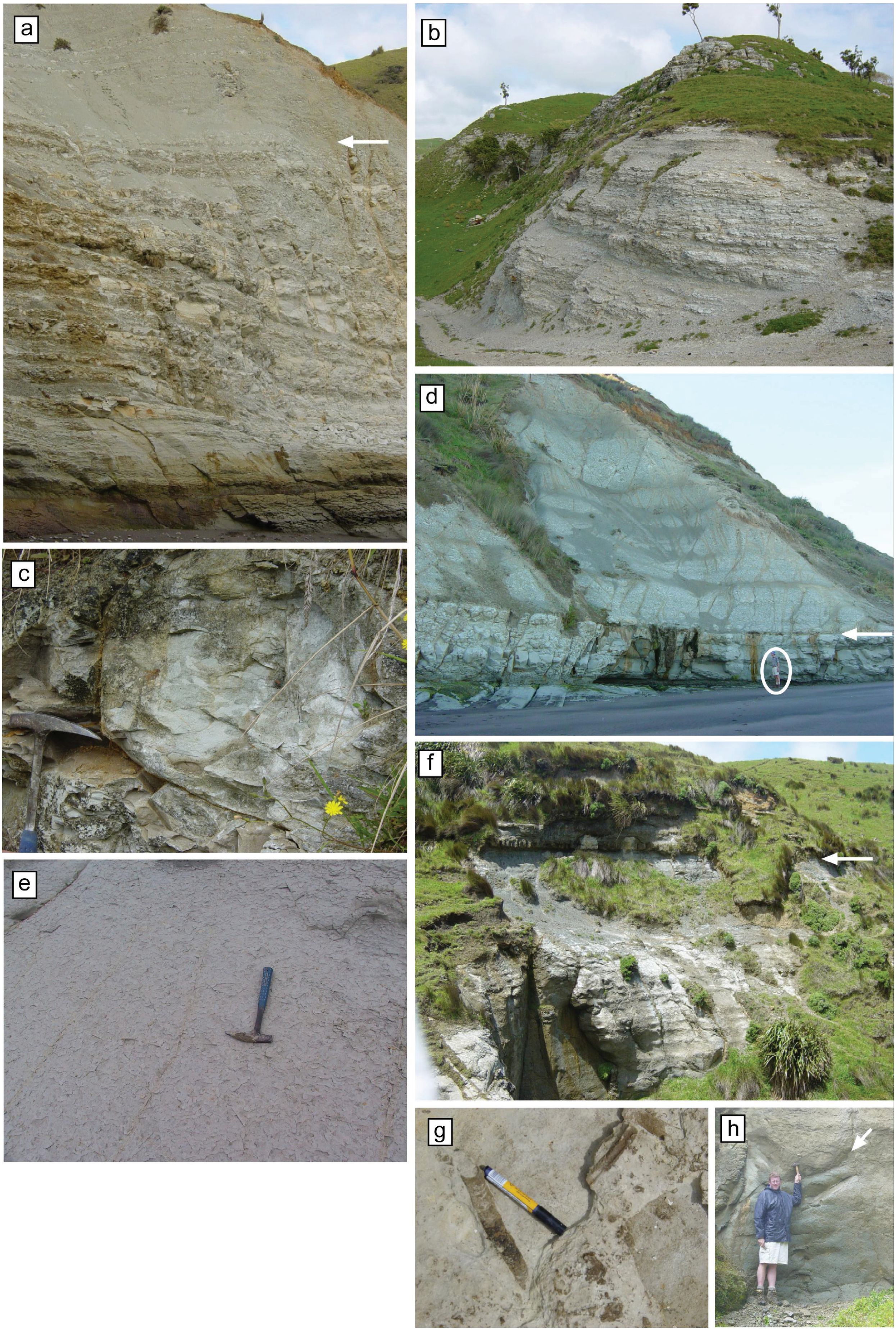


Fig. 7.4 (ii): Photomicrographs of representative samples from the Castle Craig Subgroup carbonate lithofacies from northern region (g) Planktic foraminifer dominated medium bedded calcareous siltstone (lithofacies Z1). Note echinoid spine in the surrounding planktic foraminifer rich micritic matrix. Waikawau Beach, Port Waikato (PW-11). Sample 133 (h) Bivalve and echinoderm fragments in a planktic foraminifer rich packstone / wackestone (lithofacies L8). Rothery Road. (TA-19) Sample 276 (i) Plankticforaminifera dominated wackestone (lithofacies L8) with abundant micritic matrix. Carters Beach (TA-11) Sample 280. (j) Planktic foraminiferal-rich/bivalves/echinoderm packstone -wackestone (lithofacies L8) North of Te Akau (TA-3). Sample 185. (k) Planktic foraminiferal-rich/ bivalve/echinoderm/benthic foraminiferal assemblage in a packstone-wackestone (lithofacies L8). Carters Beach (TA-11).Sample 281. (l) Planktic foraminiferal-rich/echinoderm packstone/wackestone lithofacies (L8). Mangiti Road (TA-12). Sample 234.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are common giving the rocks a layered to wavy flagged appearance (Fig. 7.1 e, f, g & h). Compositionally, L_4 lithofacies is skeletal dominated, with variable quantities (5-50%) of fine to coarse sand sized quartz grains. The terrigenous grain size distribution can be bimodal with fine to medium and coarse sand grades. Bioclasts include co-dominant bryozoans and echinoderms, and large benthic foraminifera (*Amphistegina*), with minor proportions of calcareous red algae and bivalves (Fig. 7.4 a, d, e & f) (Nelson 1973, 1978a).

Interpretation: This facies is inferred to have accumulated on a moderate to high energy wave dominated inner to mid shelf. The presence of large *Amphistegina* and calcareous red algae, coupled with an appreciable quartz sand component, are supportive of a nearshore shallow depositional setting (e.g. Nelson et al. 1988a; James et al. 1992). Subsequent reworking of sediments by intense bioturbation destroyed most of the primary depositional structures giving the rocks a massive appearance.

L_5. Massive to irregularly bedded fossiliferous rudstone-grainstone:

The “Massive to irregularly bedded, fossiliferous rudstone-grainstone” lithofacies forms isolated 0.2-12 m thick units (exemplified by localities C-56 and BH-502 in Fig. 7.10) and comprises much of the Waitanguru Limestone Member (Otorohanga B; Nelson 1978a). This lithofacies is similar to ‘Blocky Limestone Beds (OtB1), Packed Knobbly Limestone Beds (OtB2) and Open Knobbly Beds (OtB3)” of the Otorohanga Limestone described by Nelson (1978a). The aerial distribution of L_5 lithofacies is shown in Fig. 7.13. This lithofacies is characterised by a peculiar blocky to irregularly bedded “knobbly” weathering feature, although in places massive to honeycombed weathered units with no obvious bedding have also been observed (Fig. 7.2 a-d). The rocks are typified by light blue to white, coarse to very coarse spar-cemented skeletal-rich grainstone with whole or fragmented bivalve fragments

Fig. 7.5 (facing page): Photographs of the typical field expression of lithofacies within the Te Akatea Formation (Carter Siltstone Member), across the northern region. (a) Medium bedded calcareous siltstone lithofacies (Z1). Arrow marks the gradual upward transition into “Massive calcareous siltstone” lithofacies (Z2). Cliff is approximately 20 m high. Waikawau Beach, Port Waikato (PW-11). (b) Thinly bedded calcareous siltstone lithofacies (Z1) forming the lower part of the Carter Siltstone Member. Bedding is interpreted to be the result of storm-current driven depositional processes. Waikorea Valley Road. Exposure is approximately 30 m high (TA-2). (c) Extensively burrowed calcareous siltstone interval with abundant glauconite siltstone filled Thalassinoides burrows in the lower part of medium bedded calcareous siltstone (Z1), indicating a period of non-deposition or very slow deposition. Photo location: Port Waikato-Waikaretu Road, near Waikaretu Limestone Quarry (PW-9). (d) Arrow marks the rapid facies transition between “Medium bedded” (Z1) and “massive calcareous siltstone” (Z2) lithofacies. North of Kaawa Beach (PW-12). Person for scale. (e) Massive calcareous siltstone lithofacies (Z2) showing extensive bioturbation is a common feature in this lithofacies. Raglan Harbour. (f) Fossiliferous sandy siltstone (S2) occurring at the top of the Carter Siltstone Member. Arrow points at erosional unconformity with overlying distinctly bedded sandstone of Waitemata Group. Exposure is approximately 15 m high. Carters Beach, North of Raglan Harbour (TA-11). (g) Close up view of large tubular burrows occurring in “Fossiliferous sandy siltstone” (S2) unit shown in photo f. (h) Hammer and arrow pointing to scattered whole oysters within “Fossiliferous sandy siltstone” (S2) unit shown in photo f.

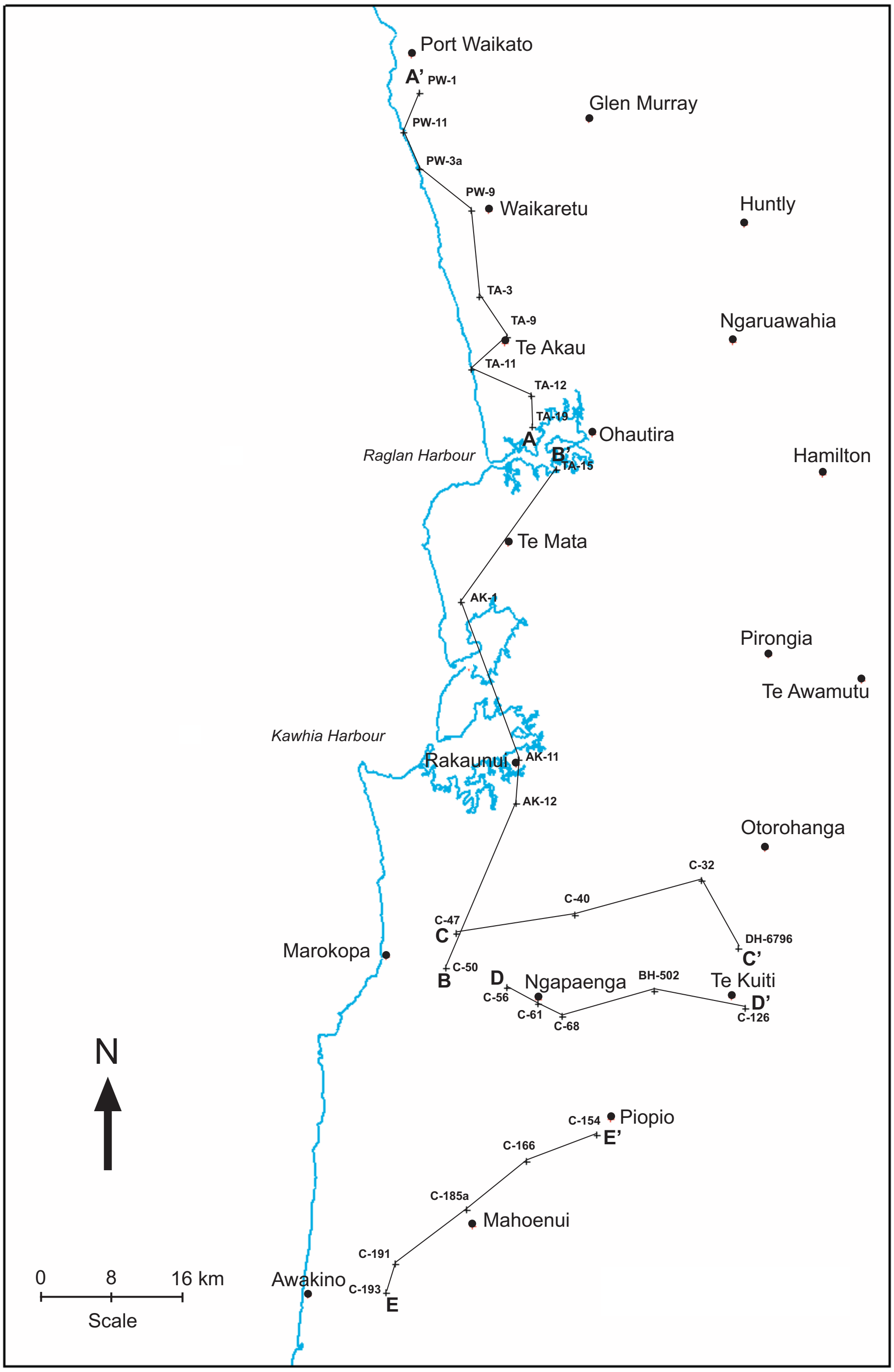


Fig. 7.6: Map of the study area and location of the cross sections illustrated in Figs 7.7 to7.11.

including oysters, pectinids and bryozoan colonies. Large benthic foraminifers, echinoderm fragments, occasional calcareous red algae, and gastropods form minor components (Nelson 1978a; Anastas 1997).

Interpretation: This lithofacies is interpreted to have accumulated in a high energy shelf setting with substantial wave and/or current agitation indicated by the presence of isopachous sea floor cements (Nelson et al. 2000). Large *Amphistegina* and calcareous red algae, coupled with course to very coarse texture, also indicate shallow shelf depositional conditions (e.g. James et al. 1992).

L_6. Pebbly oyster floatstone-packstone:

The "Pebbly oyster floatstone-packstone" lithofacies occurs mainly within the Te Anga Limestone Member (OrB; Nelson 1978a). This facies is often interbedded with horizontally bedded grainstone (L_3) and/or sandy grainstone-packstone lithofacies (L_4) (exemplified by C-40 in Fig. 7.9, C-56, C-61 & C-68 in Fig. 7.10, C-185A & C-166 in Fig. 7.11), and forms units up to 9 m thick. The aerial distribution of lithofacies L_6 is shown in Fig. 7.12 and 7.13. This lithofacies is similar to "Oyster Beds (OrB2) and Fossil-hash Beds (OrB5)" of Orahiri Formation described by Nelson (1978a). The presence of large articulated and disarticulated oysters (> 10 cm wide and up to 25 cm long), randomly scattered or clustered in laterally discontinuous beds commonly 30-40 cm to up to metre thick, is the diagnostic feature of this lithofacies (Fig. 7.2 f). Oyster shells have been commonly intensively bored (Fig. 7.2 g). Coarse skeletal fragments especially of oysters, pectinids and to lesser extent bryozoans and echinoderms are commonly associated with this lithofacies (Fig. 7.4 c). It generally consists of abundant interstitial carbonate mud/micrite forming the matrix. Subangular to subrounded pebbles are commonly scattered throughout the rock or occur as discreet bands. The uppermost parts of "Pebbly oyster floatstone-packstone" units in the Te Anga Limestone Member at Te Anga, Ngapaenga and Awakino are capped by beds with distinct large fragmented oysters, pectinids, and shell hash with occasional *Flabellum* and shark's teeth, and common limonitised pebbles. This facies occurs in association with a sharp upper erosional surface with a relief of tens of centimetres (locality C-40 in Fig.7.9, C-56 & C-68 in Fig. 7.10, C-191 in Fig. 7.11).

Interpretation: This lithofacies with oyster biostromes/banks and abundant pebble lag is inferred to have accumulated in a current-swept inner to mid shelf setting (Nelson 1978b; Nelson et al. 1983). The disarticulated and random orientation of oysters, a matrix supported fabric, and the presence of pebbles suggests periodic reworking probably as a result of storms (Anastas 1997). The presence of micritic matrix may look anomalous in the interpreted high energy setting for this facies but may have been the result of entrapment of fine calcareous mud within the oyster banks. Their probable modern analogues are the oysters in Foveaux Strait between South Island and Stewart Island (Fleming 1952).

L_7. Limestone conglomerate:

The "Limestone conglomerate" lithofacies occurs mainly in the upper part of the Orahiri Formation at Awakino Tunnel (locality C 191 in Fig. 7.11). This lithofacies is the same as the "Limestone-in-Limestone Beds (OrB6)" described by Nelson (1978a) and Nelson et al. (1994). The beds range from 0.5 – 3 m thick, are interbedded with sandy irregularly flaggy grainstone lithofacies $L_{4,}$ and are overlain by "Pebbly-oyster floatstone-packstone" lithofacies L_6. This facies is characterized by the presence of 1-10 cm-size angular calcareous sandstone and limestone intraclasts, and rounded subrounded pebbles derived from basement (Fig. 7.2 e). The sandstone and limestone clasts are commonly encrusted by calcareous red algae and are frequently pholad bored and have been infilled with micritic to coarse sparry calcite cement. Texturally the rocks are coarse to very coarse sparry grainstone. Bioclasts are dominated by coarse bryozoan fragments, benthic foraminifera, echinoderms and minor proportions of calcareous red algae (Nelson 1973, 1978a; Nelson et al. 1994).

Interpretation: This lithofacies is inferred to be the result of high-energy gravity flows triggered by basement uplift and tilting about the Manganui and/or Taranaki Faults, and emplaced across a shelf accumulating skeletal carbonates to produce an interbedded succession of limestone conglomerate (L_7) and sandy limestone lithofacies (L_4) (Nelson et al. 1994).

L_8. Massive to horizontally bedded skeletal packstone-wackestone:

The massive to horizontally bedded skeletal packstone to wackestone lithofacies comprises the lower part of the Te Akatea Formation in the Raglan Harbour to Te Akau outcrop belt (localities TA-19, TA-12, TA-11, TA-9 & TA-3 in Fig. 7.7 & TA-15 in Fig. 7.8). These massive to bedded limestone units up to 22 m thick are distinguished as Raglan Limestone Member. The aerial distribution of lithofacies L_8 is shown in Figs 7.12 and 7.13. In the vicinity of Raglan Harbour (localities TA-19, TA-12 & TA-11 in Fig.), the lithofacies is characterized by well bedded (4-18 cm) fine-grained bioclastic packstone (Av. 80% $CaCO_3$) frequently with thin silty bioturbated interbeds especially in the lower and upper parts of the member. Most beds have sharp flat bases but slightly diffuse to irregular tops owing to extensive bioturbation (Fig. 7.3). Resistant beds (flags) and recessive interbeds (interflags) give this limestone a strongly layered appearance in weathered outcrops. However, in places, these rocks have massive appearance with the rare presence of wavy bedding (Fig. 7.3 e). The beds are often rich in echinoderm fragments, spicules and spines with occasional whole echinoderms, gastropod (*Cirsotrema lyrata)*, bivalves (*Lentipecten huttoni, Chlamys williamsoni, Terebratulina suessi)*, and abundant planktic foraminifers (Fig. 7.4 h-l). The more northern sections (localities TA-9 & TA-3 in Fig. 7.7) exhibit an increase in the terrigenous clastic content (Av. 72% $CaCO_3$) with lithofacies characterized by moderately to well bedded calcareous siltstone intercalated by massive packstone-wackestone interbeds. The rocks in general lack the presence of macrofauna, except for rare fish teeth and small calcareous nanofossils. Farther north, this lithofacies intergrades with "Thin-bedded calcareous siltstone" lithofacies Z_1 (locality PW-9 in Fig. 7.7).

Lithofacies L_8 exhibits great similarity with the "Argillaceous Limestone Beds (OtC2)" described by Nelson (1978a), occurring at the very top of the Otorohanga Limestone, mainly in the vicinity of Te Kuiti (exemplified by DH 6796 in Fig. 7.9 & C-126 in Fig. 7.10). This lithofacies is characterized by planktic foraminifera-rich, bioturbated argillaceous limestone with thin shaley interbeds (Nelson 1978a). It rapidly passes upwards into deep-water planktic foraminiferal rich siliciclastic beds (Mahoenui Group mudstone).

Interpretation: The massive to horizontally bedded lithofacies display numerous features indicative of deposition in a storm influenced outer shelf-upper bathyal setting. The facies has extensively bioturbated siliciclastic interbeds representing sediment that probably accumulated during quieter periods (post-storm), and they alternate with relatively higher energy fine-grained packstone-wackestone beds possibly deposited during storm events. Quiescent periods allowed accumulation of silty interbeds with abundant *Scolicia* burrows built by infaunal deposit feeders. Burrowers may have been unable to homogenise sediments where the interval between storms were short. Highly burrowed beds may reflect longer durations between storms, or periods when the density of infaunal taxa was high. Consequently, all gradations from little burrowed, to burrow homogenised limestones beds are present. The common occurrence of highly fragmented skeletal debris intermixed with planktic foraminifera within these beds probably resulted from storm-induced currents originating on the shelf with redeposition into outer shelf-upper bathyal depths. In most modern cool-water carbonate systems, the carbonate mud and marl accumulation occurs only at depths greater than 200 m (Nelson et al.1988; James et al. 1992; Boreen et al. 1993). The content of mud, carbonate or terrigenous, has been shown to consistently increase with increasing water depth on modern cool water carbonate shelves and slopes (e.g. Gillespie & Nelson 1997; James et al. 1999; James et al. 2001). The abundance of planktic foraminifer-dominated carbonate mud, the intensity of bioturbation, and the occasional occurrence of whole (commonly spatangoid) preserved delicate skeletal components indicate relatively deep, quiet water environments (e.g. Boreen & James 1995).

Mixed carbonate-siliciclastic sandstone association

The sandstone lithofacies are the least common of the three lithofacies associations identified in the Castle Craig Subgroup. Two sandstone lithofacies have been defined in this study, and their details are summarized in Table 7.1. Beds with sandstone lithofacies are usually up to 15 m thick, and typically overlie limestone lithofacies (e.g. L_3, L_6). The sandstones lithofacies vary from sparsely fossiliferous to highly

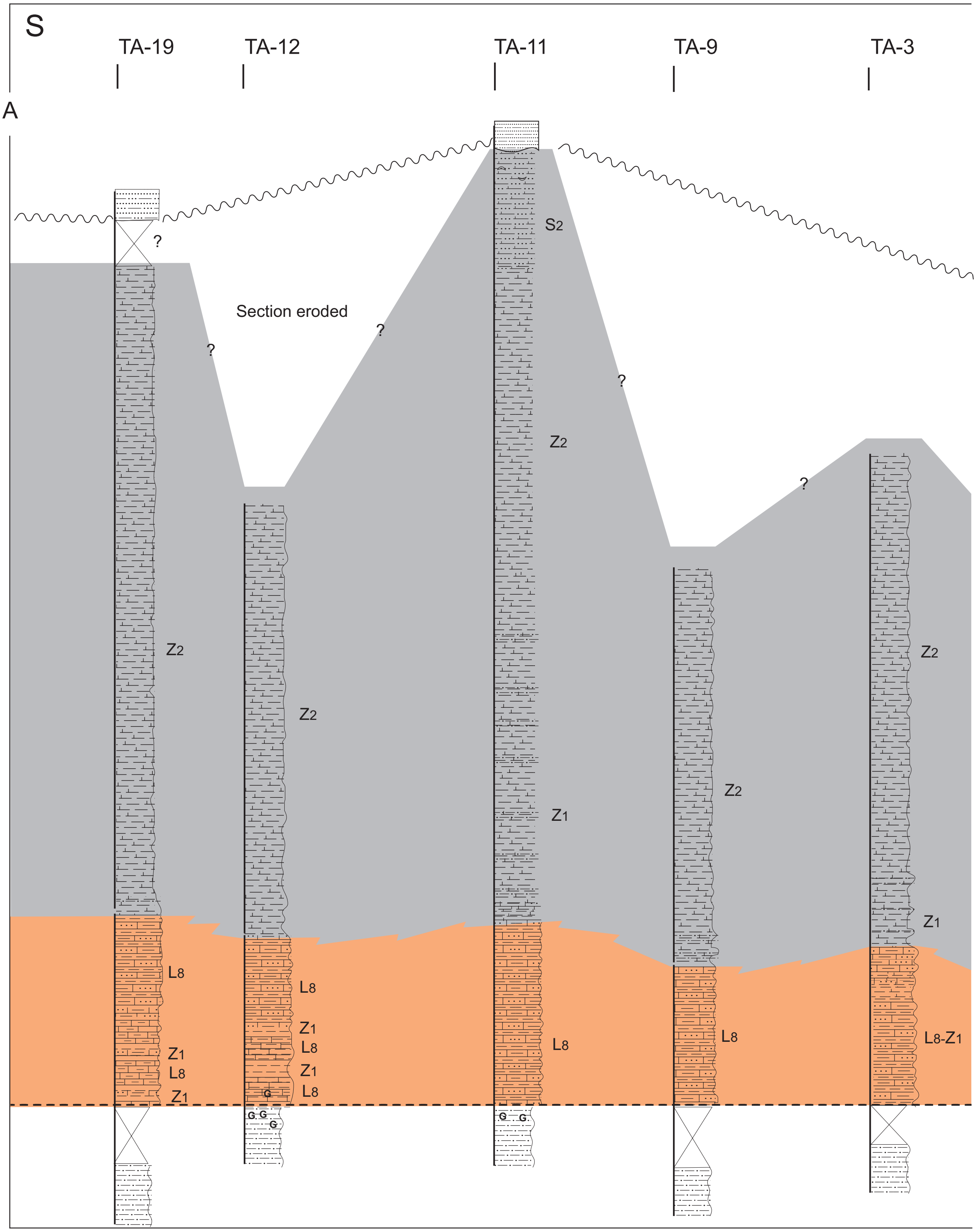
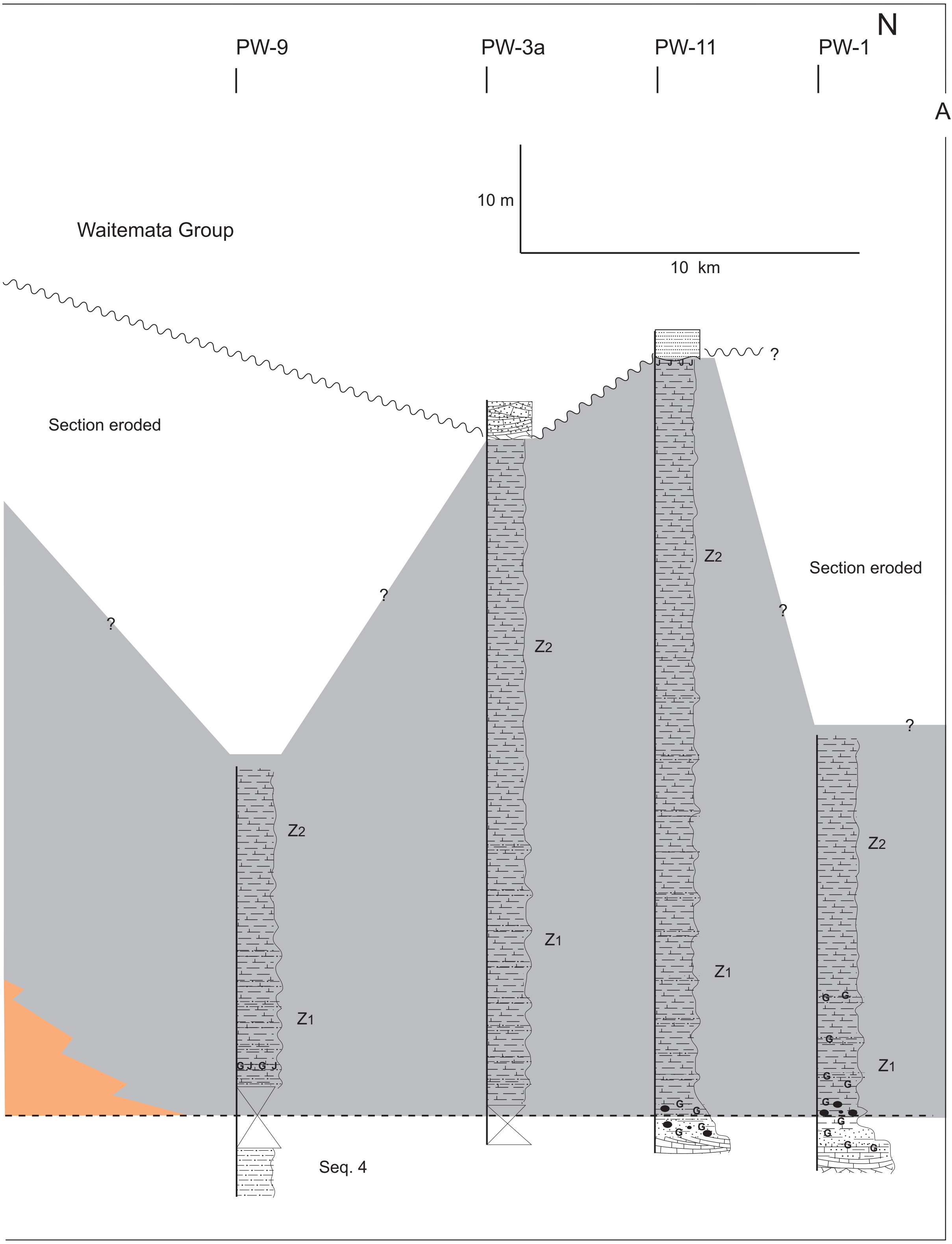


Fig. 7.7 (two-page spread): South (Raglan Harbour) to north (Port Waikato) correlation of Te Akatea Formation and distribution of lithofacies within it. Also shown is its lower sequence boundary (dashed line, Aotea Formation-Te Akatea Formation contact) and unconformity (zig zag line) with the overlying Waitemata Group. Orange colour indicates carbonate lithofacies (i.e. Raglan Limestone Member) and grey colour indicates mixed carbonate-siliciclastic lithofacies (i.e. Carter Siltstone Member). See Fig. 7.6 for cross section and column locations.


N
PW-9
PW-3a
PW-11
PW-1
A’
10 m
10 km
Waitemata Group
Section eroded
Section eroded
?
?
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Z2
Z1
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GJ G J
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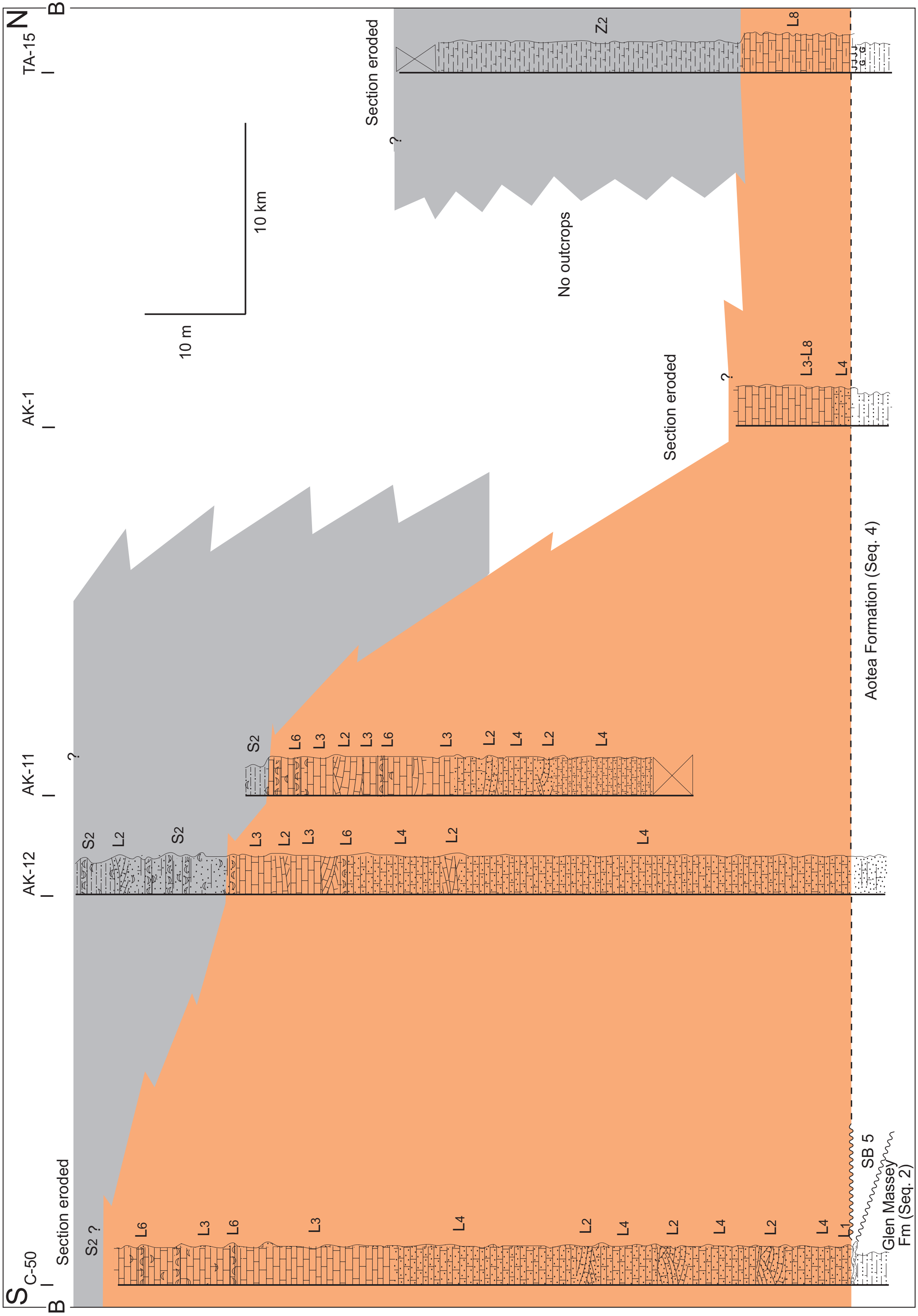


Fig. 7.8: South (Awamarino) to north (Raglan Harbour) correlation of Castle Craig Subgroup and distribution of lithofacies and significant facies transition. The sequence boundary at the base of the Subgroup at Awamarino (C-51) is a erosional unconformity (zig zag line), but in the north (TA-15) it is a correlative conformity. In the Aotea-Kawhia area (AK-12, AK-11 and AK-1) the contact between Aotea Formation and Castle Craig Subgroup is apparently conformable. Orange colour indicates carbonate lithofacies and grey colour indicates mixed carbonate-siliciclastic lithofacies. See Fig. 7.6 for cross section and column locations.

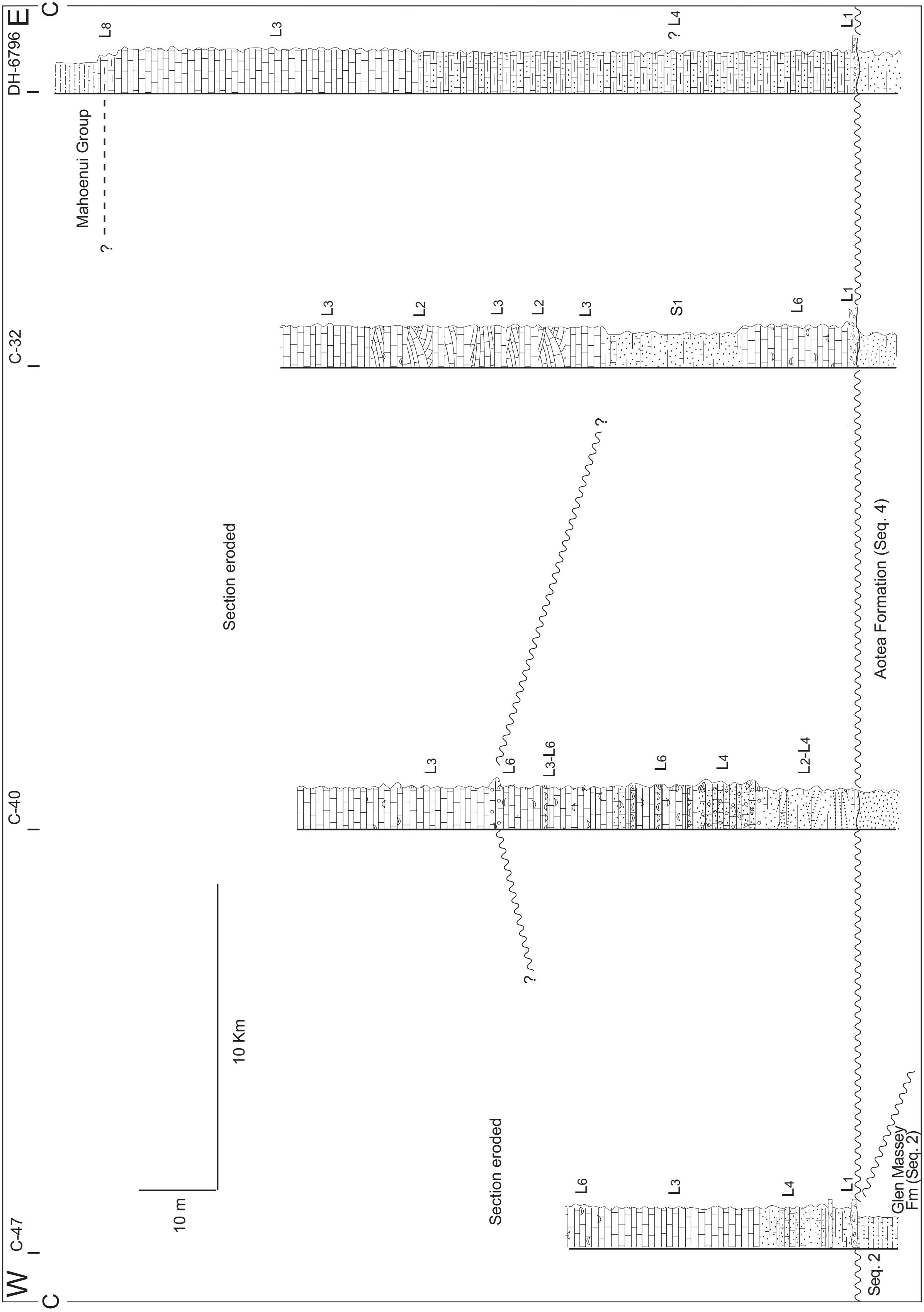


Fig. 7.9: West (Awamarino) to east (Te Kuiti) correlation of Orahiri Formation/ Otorohanga Limestone units, and distribution of lithofacies. The lower boundary of Castle Craig Subgroup is an erosional unconformity (zig zag line) with Glen Massey Formation at Awamarino (C-47) and with Aotea Formation in the eastern localities (C-40, C-32 and DH-6796). There is a conformable contact with the overlying Mahoenui Group in DH-6796. See Fig. 7.6 for cross section and column locations.

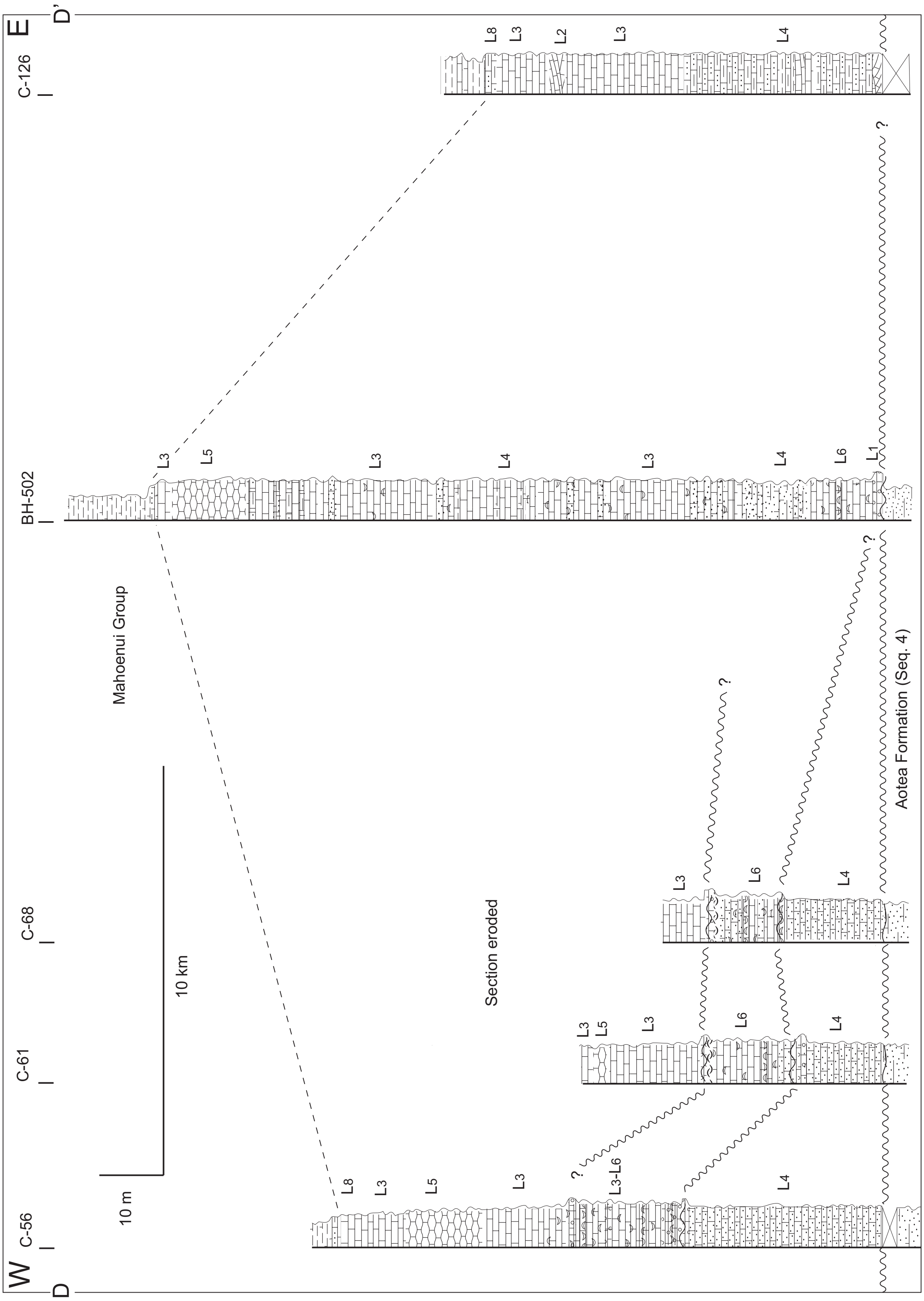


Fig. 7.10: West (Ngapaenga) to east (Te Kuiti) correlation of Orahiri Formation/ Otorohanga Limestone units, and distribution of lithofacies association. The boundary of Castle Craig Subgroup is an erosional unconformity (lowermost zigzag line). Prominent intra-formational unconformities of localised extent occur through the middle of the columns at C-56, C-61 and C-68 but are not obvious in more easterly localities e.g. BH-502 and C-126. The topmost unconformity defines the contact between Orahiri Formation and Otorohanga Limestone at C-61 and C-68. There is a conformable contact with the overlying Mahoenui Group at C-56, BH-502 and C-126. (dashed line) . See Fig. 7.6 for cross section and column locations.

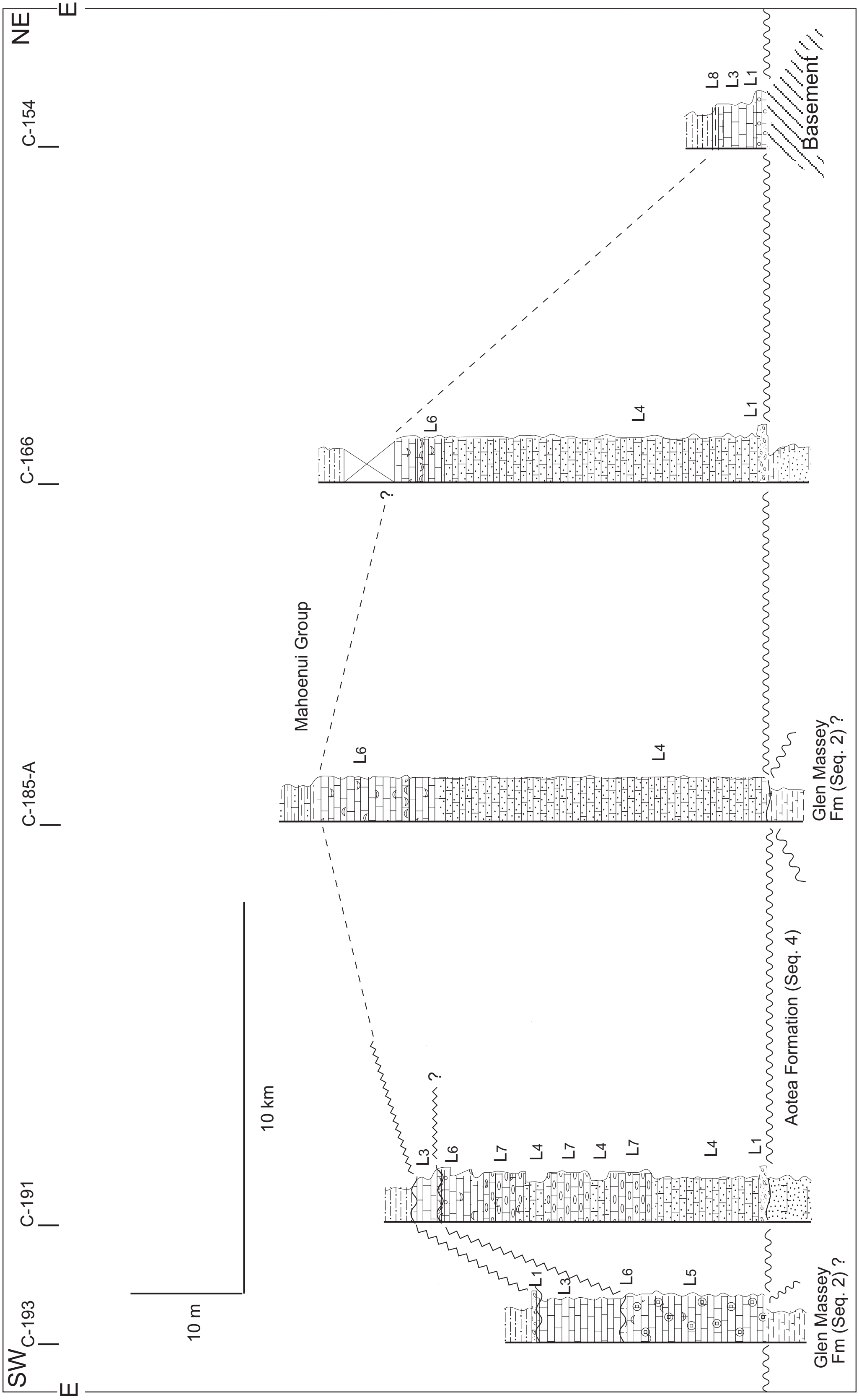


Fig. 7.11: Southwest (Awakino Gorge) to northeast (Piopio) correlation of Orahiri Formation/Otorohanga Limestone units, and distribution of lithofacies. Lower boundary of Castle Craig Subgroup is a erosional unconformity with Glen Massey Formation at C-193 and C-185A, and with Aotea Formation at C-191 and C-166. The middle unconformity (zig zag line) defines the contact between Orahiri Formation and Otorohanga Limestone of Nelson (1973, 1978a). There is an erosional unconformity between the subgroup and overlying Mahoenui Group at C-193 and C-191, whereas it is a conformable contact at more eastern localities. See Fig. 7.6 for cross section and column locations.

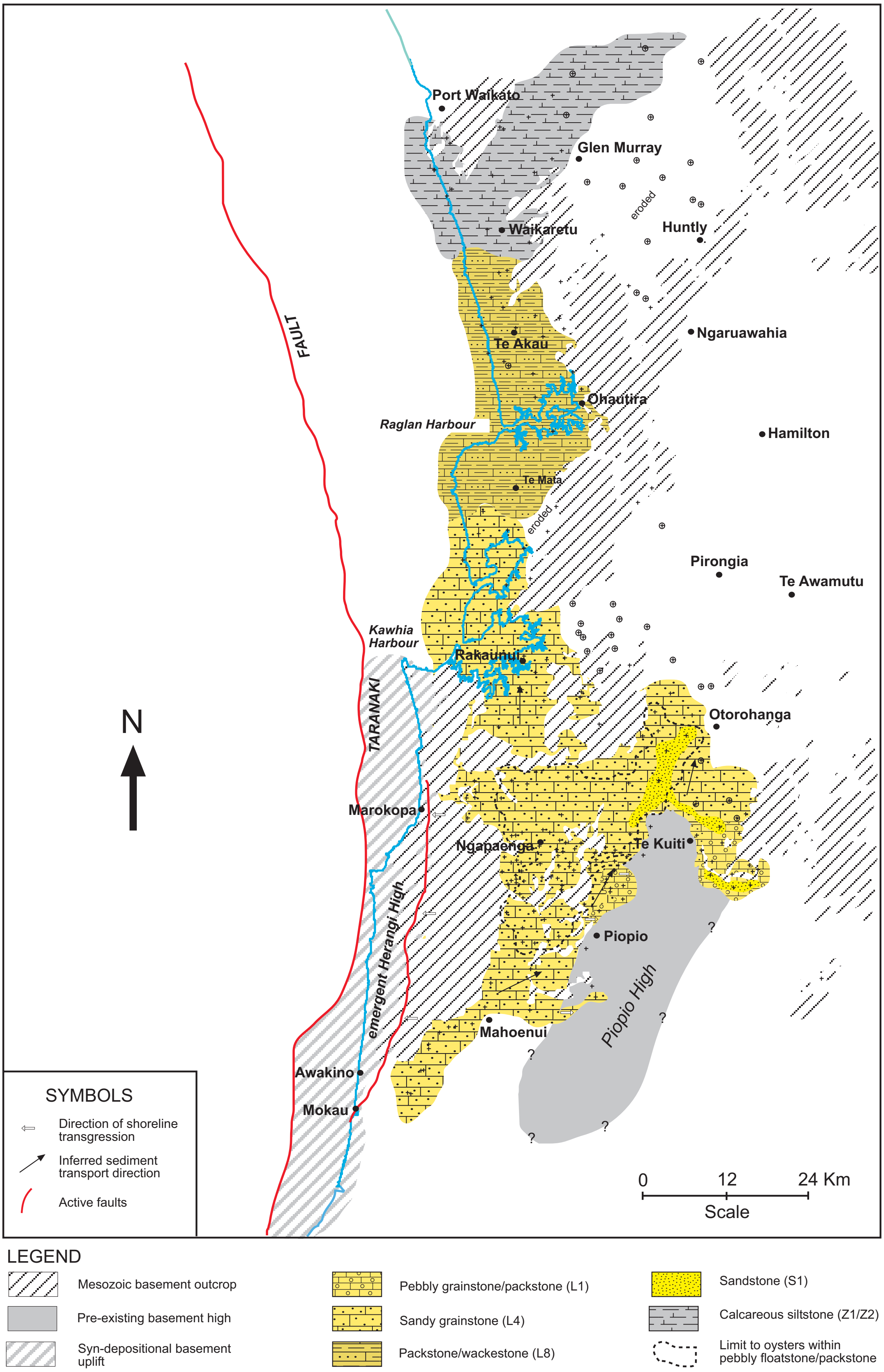


Fig. 7.12: Distribution of main lithofacies in the lower Castle Craig Subgroup in relationship to major paleogeographic elements. The lithofacies distribution depicted between Kawhia and Raglan Harbours are partly inferred because of poor exposures.

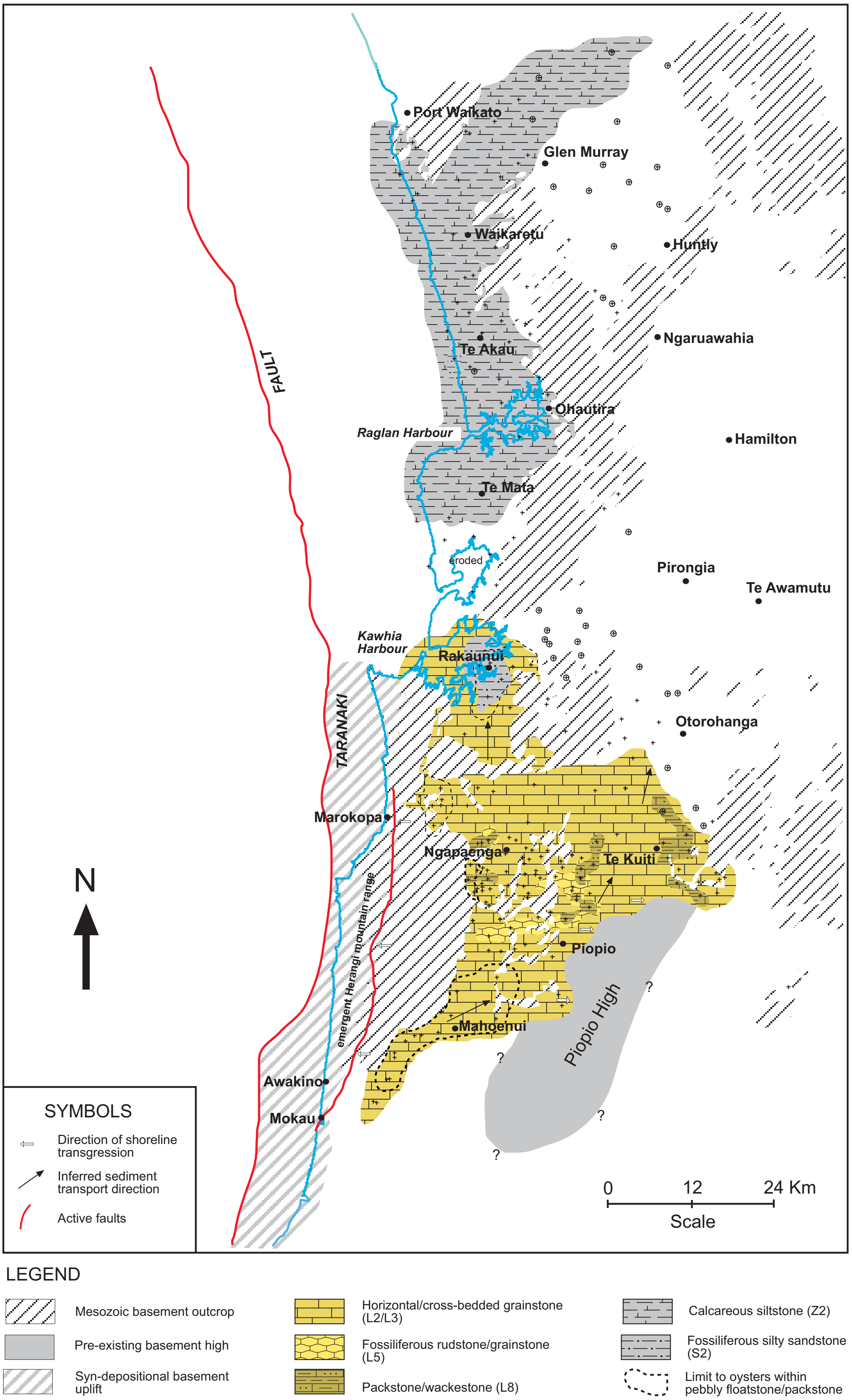


Fig. 7.13: Distribution of main lithofacies in the upper Castle Craig Subgroup in relationship to major paleogeographic elements. The lithofacies distribution depicted between Kawhia and Raglan Harbour is partly inferred because of poor exposures.

fossiliferous, with a diverse range of macrofaunal taxa. They are either overlain by horizontally to cross-stratified grainstone or occur at the very top of the thick limestone succession, possibly associated with an increase in water depth.

S_1. Massive glauconitic muddy sandstone:

The "Massive glauconitic muddy sandstone" lithofacies occurs mainly within the vicinity of Waitomo (exemplified by C-32 in Fig. 7.9), but also forms isolated lensoidal bodies within the Orahiri Formation/Otorohanga Limestone in exposures east of Te Kuiti. This lithofacies is essentially the "Waitomo Sandstone" described by Nelson (1978a) from the type Waitomo locality (Fig. 7.3 i). A distinctive outcrop feature is its massive appearance with a smooth weathering profile. It generally consists of poorly to moderately cemented muddy fine sandstone with a variable detrital glauconite content ranging from 3-20%. Macrofossils are sparse, although thin-sections indicate the presence of variable amounts of bryozoan and echinoderm fragments, and bioturbation structures are common throughout the lithofacies. Microfaunal components include benthic foraminifera with rare planktonic foraminifera (Nelson 1973).

Interpretation: The massive fine-grained character of this lithofacies suggests moderate energy in the environment of deposition. Bioturbation was able to continuously kept pace with the slow rate of sediment accumulation, leading to the massive and homogenised character of this lithofacies. The restricted occurrence of lithofacies S_1 may be the result of increased terrigenous sediment input, possibly associated with active faulting in the vicinity. It may also represent localised subsidence associated with fault movement or changes in the hydrodynamic regime.

S_2. Fossiliferous silty sandstone and sandy siltstone:

The "Fossiliferous silty sandstone and sandy siltstone" lithofacies S_2 occurs in the upper part of the Otorohanga Limestone in sections inland of Ka whia Harbour (exemplified by localities AK-12, AK-11 in Fig. 7.8). It gives rise to a rounded weathering profile capping the near vertical limestone cliffs (Fig. 7.1 i & j). Approximately 15 m of this lithofacies is exposed at Whenuaupo Hill (TA-12), but the true thickness is unknown because of its eroded top. This lithofacies resembles the "Massive glauconitic muddy sandstone" lithofacies S_1 described above, as it is chiefly composed of massive to crudely bedded, moderately calcareous, fine-grained glauconitic sandstone and sandy siltstone. However, unlike lithofacies S_1, it is rich in a diverse range of macrofaunal taxa, especially whole and disarticulated oysters, either scattered or clustered within beds. Other bivalve species include *Athletopecten athleta*, *Panopea sp.*, *Lentipecten hochstetteri* and other common brachiopoda (*Rhyzothyris* sp), and occasional echinoderm fragments (Fergusson 1986). The lithofacies probably constitutes the uppermost 8-10 m of the Te Akatea Formation, at the Carters Beach locality (TA-11 in Fig. 7.7), reflecting retrogradation of the facies belt. This unit contains well cemented, massive to faintly bedded, sandy siltstone with scattered articulated and disarticulated oysters, with a sharp erosional contact with the overlying Waitemata Group (Fig. 7.5 f, g & h).

Interpretation: This lithofacies is characterised by the presence of a wide range of bivalves and coarse fossil allochems mixed into a fine silty sandstone matrix indicating deposition in a storm-influenced shelf setting. Strong currents may have remobilised oyster shells and other shell debris into a protected, muddy, probably deeper water environment that was subsequently colonized by infaunal bivalves.

Mixed carbonate-siliciclastic siltstone association

The Siltstone lithofacies association makes up the majority of the thickness of units in the Te Akatea Formation in the northern region, and occurs mainly within the Carter Siltstone Member. This association overlies the "Massive to horizontally bedded skeletal packstone-wackestone (S_8)" in the outcrop belt between Raglan Harbour and Te Akau. In the more northern sections, the "Calcareous siltstone" lithofacies conformably overlies the condensed Patikirau Siltstone Member of Aotea Formation. The preserved thickness of the "Calcareous siltstone" lithofacies is up to 80 m and it is best exposed in the cliffs along the coast between Raglan Harbour and Waikawau Beach (Port Waikato), and areas immediately inland. This lithofacies association is predominantly comprised of light blue-grey marl with diverse planktic and benthic foraminiferal assemblages indicating accumulation in open marine environments. The siliciclastic marl is inferred to have accumulated as an extensive blanket over much of the northern region; however the present day eastern extent of the Carter Siltstone Member is limited by post depositional uplift and erosion. This member has been intercepted in a few of the Coal Resources Survey drill holes in eastern parts of northern Waikato (Edbrooke 1984). Along the western areas of the northern region, an erosional surface at the top of the Carter Siltstone Member separates this lithofacies association from overlying diverse basal facies of the Waitemata Group. Three siltstone lithofacies have been defined in this study, and are summarized in Table 7.1.

Z_1. Medium-bedded calcareous siltstone:

The "Medium bedded calcareous siltstone" lithofacies occur mainly within the lower part of the Carter Siltstone Member (exemplified by localities PW-1, PW-11, PW-3a, PW-9 and TA-11 in Fig. 7.7). This lithofacies is distinguished by 10-50 cm-thick light-grey to creamy-white calcareous siltstone beds with occasional thin discrete glauconitic sandy siltstone interbeds (15-20 cm), which are particularly noticeable in the Port Waikato area (Fig. 7.5 a-d). Contacts between the beds are diffuse, and commonly exhibit a blocky with common "frittery" surface weathering profile. The carbonate (weight %) content ranges from 41-75% with an average of 55%. In thin sections, the observed siliciclastic content accounts for at least one-quarter of the whole rock composition and typically comprises clay- to silt with minute proportions of very fine to fine sand size quartz and feldspar grains. Glauconite and pyrite are common authigenic minerals within this facies. Glauconite occurs as scattered pellets as well as infills of foraminiferal tests, and is abundant in thin interbeds especially as burrow infills. Bioclasts constitute 51-63%, are dominated by planktic foraminifera with subequal amounts of benthic foraminifers, fragments of echinoderms and bivalves, and traces of ostrocods (Fig. 7.4 g) (Khandarosa 1989).

Interpretation: The medium-bedded calcareous siltstone lithofacies represents deposition in an outer shelf to upper bathyal environment. Bedding development is attributed to reworking produced by storm events. On the modern south Australian temperate carbonate shelf, large storms produce offshore-directed storm currents that have the potential to rework sediments to depths of 250 m (Schahinger 1987; Collins 1988). The sporadic occurrence of thin glauconitic interbeds commonly exhibiting extensive bioturbation in the lower parts of this facies coincides with low terrigenous influx.

Z_2. Massive calcareous siltstone:

This lithofacies comprises the bulk of the Carter Siltstone Member. It comprises up to 80 m thickness and is best exposed in cliffs along the west coast between Raglan Harbour and Port Waikato. It both overlies and grades laterally into medium bedded calcareous siltstone lithofacies Z_1, as at localities TA-11, PW-9, PW-3a and PW-11 (Fig. 7.7). The aerial distribution of the "Massive calcareous siltstone" lithofacies (Z_2) is shown in Figs. 7.12 and 7.13. In outcrop, this facies exhibits peculiar weathering characteristics, which include conchoidal fracture when rocks are freshly exposed, and "fine frittery" appearance (crumbles into 4 - 20 mm polygonal pieces) after prolonged exposure. Lithofacies Z_2 comprises primarily homogenous, light blue-grey variably calcareous siltstone, but locally may include thin (< 20-30 cm) sandy siltstone beds containing concentrations of glauconite and/or pyrite. Facies Z_2 is similar to facies Z_1 described earlier, however it exhibits subtle differences in that bedding is not obvious, and there is an overall greater degree of bioturbation. Bedding is only discernible from occasional resistant sandy siltstone beds and is more obvious from a distance than up close. Common trace fossils include *Zoophycus* ichnofacies and occasional inclined and sub-horizontal (up to 15 cm) tubular burrows. In general, bioturbation is commonly so extensive that individual trace fossils cannot be identified (Fig. 7.5 e). Macrofossils are rare and are generally dominated by *Lentipecten hochstetteri*, *Chalmys williamsoni*, *Flabellum sp*. and *Dentalium sp*. The carbonate content (weight %) varies from a low of 25% to moderately high values of 65%, with mud (clay + silt) content much higher than sand content. In thin section analysis bioclasts constitute an average 59% of the whole rock composition and are dominated by planktic foraminifera (Av. 33%). Echinoderm and bivalve fragments, benthic foraminifers, and ostrocods are the order of decreasing abundance of bioclasts (Kandharosa 1989).

Interpretation: The "Massive calcareous siltstone" lithofacies is interpreted to represent deposition in outer shelf to upper bathyal water depths. The abundant bioturbation including *Zoophycus* in this lithofacies is generally indicative of a quiet-water, poorly oxygenated sea floor below the storm wave base, where suspension sedimentation dominates (e.g. Seilacher 1967). However, the siliciclastic marl implies significant ongoing siliciclastic influx. The skeletal component is dominated by planktic foraminifera such as common *Globoquadrina dehiscens*, *Globigerina brazieri* (R14/f6739-6743) and other benthic foraminifera (*Cibicides*, *Karreriella*, *Notorotalia*, *Sphaeroidina)* reported by earlier workers (e.g. Kandharosa 1989; White & Waterhouse 1994). The microfauna are indicative of outer shelf-upper bathyal water depths (e.g. Hayward 1986; Hayward et al. 1999). The presence of rare benthic foraminifera *Amphistegina,* which are intermixed with outer shelf to upper bathyal fauna, suggest seaward reworking of these shallow shelfal fauna, probably by rare muddy gravity flows. However, clear physical evidence of mass-emplaced deposits is lacking. The occurrence of sandy siltstone beds in some localities probably indicates that slightly coarser grained sediments may have been introduced by currents into a quiet muddy environment, if not by mass-emplacement. Overall, deposition was dominated by hemipelagic settling of background sedimentation. Widespread presence of *Zoophycus* ichnofacies in this facies is generally indicative of marine, quiet-water, muddy substrates, and may reflect either "bathyal" or "intermediate" water depths (Seilacher 1967; Ekdale et al. 1984).

Lithofacies distribution and paleoenvironmental implications

The lithologically diverse facies in the Castle Craig Subgroup outlined in the previous section, ranging from coarse sparry rudstone/grainstone through to fine packstone/wackestone to calcareous siltstone and marls, represents a wide paleobathymetric range from shallow shelf to slope-upper bathyal settings. The vertical and lateral facies relationships and their thicknesses from the inferred shelf (south) to slope (north) are depicted in selected stratigraphic columns along a series of north-south and east-west transects (Figs 7.6 - 7.11). Although lithofacies transitions occurring in the Aotea-Harbour area are sketchy due to a lack of outcrops, isolated outcrop windows do provide some clues about the stratigraphic development of the Castle Craig Subgroup to the south and north of this area. The distribution of the identified lithofacies within various formations and members belonging to the Subgroup are summarised in Table 7.2.

Table 7.2: Broad lithofacies distribution within Castle Craig Subgroup

South			North		
Formation	**Member**	**Facies**	**Formation**	**Member**	**Facies**
Otorohanga Limestone	Piopio Limestone	L_1, L_3-L_4, L_8	**Te Akatea**	Carter Siltstone	Z_1-Z_2, S_2
	Waitanguru Limestone	L_5			
	Pakeho Limestone	L_1-L_4			
Orahiri	Waitomo Sandstone	S_1		Raglan Limestone	L_8, Z_1
	Te Anga Limestone	L_1, L_3-L_5, L_6			
	Mangaotaki Limestone	L_1-L_4, L_7			

The geographical extent of the main lithofacies within the subgroup and key paleogeographic elements that are inferred to have had a major influence on depositional environments and processes are illustrated in Figs 7.12 and 7.13.

The onset of deposition of the Castle Craig Subgroup in the southern region is marked by an extensive unconformity at the base of Orahiri Formation that may have involved subaerial exposure and erosional truncation of the Aotea Formation. In some areas (e.g. locality C-51 in Fig. 7.8 & C-47 in Fig.7.9) the Aotea Formation has been completely removed as the result of this uplift and erosion that preceded deposition of the Orahiri Formation. The basal facies of the Orahiri Formation resting on this erosional unconformity in southern areas is a "Pebbly grainstone-packstone" (L_1), which is up to tens of centimetres thick. This basal L_1 facies commonly passes upwards into "Sandy grainstone-packstone" (L_4) which makes up major parts of the Orahiri Formation thicknesses in the majority of the stratigraphic sections located between Kawhia Harbour and Awakino in the western belt (Fig. 7.12). Facies L_4 is locally intercalated with "Cross-bedded grainstone" (L_2) and "Horizontally bedded grainstone" (L_3). The widespread occurrence of L_4 lithofacies (i.e. Mangaotaki Limestone Member) typically comprising fine to coarse quartzitic sand in variable proportions (up to 50% by volume) along with medium to coarse skeletal fragments (e.g. bryozoans, echinoderms and large benthic foraminifers) is interpreted to have accumulated as calcareous sand sheets under moderately to high energy in a seaway at inner to mid shelf depths along the eastern margin of the Herangi High. Only in one locality (e.g. C-191 in Fig. 7.11) facies L_4 is interbedded with “Conglomeratic limestone” (L_7) indicating syn-depositional tilting and eastward re-working of shelf derived carbonate lithoclasts (Nelson et al. 1994; King & Thrasher 1996).

The ‘Sandy grainstone-packstone” (L_4) is commonly overlain by “Pebbly floatstone/packstone facies” (L_6) with laterally discontinuous oyster beds, forming most of the Te Anga Limestone Member in the south-central area (Fig. 7.12). The facies contact between L_4 and L_6 is generally conformable, however in the vicinity of Ngapaenga (e.g. localities C-56, C-61 and C-68 in Fig. 7.10) a sharp erosional surface of localised extent marks this contact. Lithofacies L_6 contains up to metre-thick oyster biostromes/banks and other common large bivalves (mainly pectinids) generally associated with pebble lags and abundant micritic matrix, indicating accumulation in a inner to mid shelf current-swept seaway (Nelson et al. 1983). Although the oyster-bearing L_6 lithofacies is a useful stratigraphic marker of the Te Anga Limestone Member in south-central areas, this facies occurs sporadically in the lower parts (e.g. C-32 in Fig. 7.9) of the Orahiri Formation, as well as in the upper 4-5 m of the undifferentiated Orahiri Formation/Otorohanga Limestone (e.g. AK-11 in Fig. 7.8 & C-166 in Fig. 7.11). In the vicinity of Waitomo, facies L_6 grades upwards into a moderately glauconitic muddy fine sandstone (e.g. Waitomo Sandstone Member/lithofacies S_1), which generally appears massive throughout (e.g. C-32 in Fig. 7.9). Thin sandstone units of similar lithofacies affinity and with variable amounts of glauconite and calcareous content also occur sporadically within the limestone to the east and northeast of Te Kuiti (Nelson 1973, 1978a). Their occurrence is difficult to explain other than being sourced locally from basement probably exposed due to syndepositional faulting.

In southwestern areas (e.g. Ngapaenga, west of Piopio), a sharp erosional surface with associated basement-derived pebbles, fragmented bivalves and occasional iron-oxide mineralization separates S_6 lithofacies (Te Anga Limestone Member) from the overlying well flaggy lithofacies L_3 is locally interstratified with cross-bedded L_2 units with relatively higher $CaCO_3$ (Av. 90%) content and both are assigned to Otorohanga Limestone (best exemplified by localities C-56, C-61 & C-68 in Fig. 7.10). In places they also include a limestone formation (Waitanguru Limestone Member) with an unusual field weathering feature including massive, irregularly or “knobbly” to “blocky” appearance, very pure limestone (containing almost up to 100% $CaCO_3$) facies L_5 (Nelson 1973). Facies L_5 is most noticeable in areas west of Piopio and the Mangaohae River sections (e.g. C-56 in Fig. 7.10). The geographical extent of L_5 facies is shown in Fig. 7.13. These early marine cemented limestone units (lithofacies L_5) comprise organic mounds constructed by bryozoans and may also include large shell fragments mainly of oyster and/or pectinids. They are inferred to be associated with relatively high-energy settings caused by local base level fluctuations (Nelson & James 2000). They commonly grade through "Horizontally bedded grainstone" (L_3) into planktic foraminifera-rich, bioturbated packstone and wackestone (lithofacies L_8). The L_8 facies grades into terrigenous lithologies of the Mahoenui Group. Facies L_8 reflects deepening of water depths in the upper parts of the Otorohanga Limestone, reflecting a retrogradational stratal pattern. In the vicinity of Te Kuiti, interbedded foraminiferal limestone (L_8) and calcareous siltstone mark this transition as well (e.g. locality C-126 in Fig. 7.10) (Nelson 1973; Anastas 1997).

The distribution of Otorohanga Limestone extends to the east and southeast of Te Kuiti, and also in the vicinity of Piopio and Aria, where it was deposited directly on basement and represents flooding of the Piopio High. The basal onlap facies L_1, marks the contact with basement on the northern and eastern low-lying fringes of this paleogeographic high (Fig.7.12).

In the central Aotea-Kawhia Harbour region, the vertical succession of lithofacies within the subgroup is somewhat different compared to the south and south-central areas discussed above. Three parts can broadly be identified. The lower two-thirds of the subgroup thickness are composed of either "Sandy grainstone-packstone" (L_4) or locally intercalated with low angle "Cross-bedded grainstone" L_2 facies (Fig. 7.8). The upper part of the subgroup is composed of relatively pure limestone comprising mainly "Horizontal bedded grainstone" (L_3) passing upwards into "Oyster floatstone-packstone" (L_6) which in turn grades into "Fossiliferous silty sandstone and sandy siltstone (S_2)" with scattered oysters and other common bivalves (*Atlopecten athleta*, *lentipecten, panopea*). The present day extent of exposure of this lithofacies is limited by erosion, but is tentatively identified at the uppermost eroded top of the C-51 section (Fig. 7.8) in the south, and at a similar stratigraphic position in inland sections east of Kawhia Harbour and north of Aotea Harbour.

In the northern region, the base of the Castle Craig Subgroup corresponds to a major paraconformity, which contains extensively burrowed and fossiliferous siltstone and sandy siltstone with high concentrations of glauconitic. It grades into "Massive to horizontally bedded skeletal packstone/wackestone" (L_8) of the Raglan Limestone Member, or medium bedded calcareous siltstone (Z_1) of the Carter Siltstone Member in more northern localities (Fig. 7.7). The distribution of this deep-water micritic and foraminiferal limestone (L_8) is recorded in stratigraphic sections located in an area extending from Te Akau to Raglan Harbour (i.e. from TA-3 to TA-19 in Fig. 7.7), and probably also extends south of Raglan Harbour (Fig. 7.13). The Raglan Limestone is absent over much of the northernmost sections (Port Waikato-Waikaretu i.e. localities PW-1 to PW-9 in Fig. 7.7) and areas farther to the east where it laterally grades into "Medium bedded calcareous siltstone lithofacies" (Z_1) of the Carter Siltstone Member. The Z_1 lithofacies in the Port Waikato-Waikaretu area often contains thin (< 50 cm) extensively burrowed glauconitic and phosphatic horizons, probably reflecting sediment starvation in more distal areas of the basin. Raglan Limestone Member in effect represents a transition between the shelf carbonates (L_1-L_7) to the south of Aotea Harbour and outer shelf to upper bathyal marls (Z_1-Z_2) to the north. Alternation of storm and fair-weather conditions resulted in the strongly bedded character of deposits of this environment. The density of burrows in the thin calcareous siltstone interbeds represent quiescent periods when flow intensities waned. Most of the Raglan Limestone Member (lithofacies L_8) occurring in the vicinity of Raglan Harbour, is representative of this environment. The Raglan Limestone Member displays a silting upwards trend before grading upwards into "Medium bedded to Massive calcareous siltstone" (Z_1/Z_2) of the Carter Siltstone Member. In a few sections located to the north of Raglan Harbour (e.g. TA-11 in Fig. 7.7) where the top part of the Carter Siltstone Member is well preserved, the Z_2 lithofacies grade into 8-10 m thick extensively burrowed calcareous sandy siltstone with scattered oysters and occasional other large bivalves having a similar lithofacies affinity to S_2. The top of this calcareous sandy siltstone unit is erosionally truncated as a result of uplift and erosion that preceded the deposition of the Waitemata Group.

Sedimentary evolution of the carbonate shelf – slope succession in the Castle Craig Subgroup

Overview and setting:

The detailed horizontal and vertical facies distribution within the Castle Craig Subgroup outlined in the previous section reveals a complex evolving depositional system. It is evident from the observed facies associations and paleoenvironmental setting that the Orahiri Formation and Otorohanga Limestone in the areas to the south of Aotea Harbour are predominantly skeletal calcarenite or calcirudite comprising mainly fragmented bryozoans, echinoderms, and benthic foraminifera, bivalves with local oyster beds, and other biomounds. The primary depositional setting for these carbonate sediments, which show a wide range of horizontal- and cross-bedded structures is a current and wave dominated shallow shelf and tide-dominated seaway (Nelson 1978a; Anastas 1997). In contrast, most of the carbonate and mixed carbonate-siliciclastic facies of the Te Akatea Formation accumulated contemporaneously in the northern region. They are rich in foraminifera with lesser contributions from other skeletal assemblages. A distinctive feature is their overwhelmingly micritic and fine terrigenous silty nature. Collectively, these features are consistent with accumulation of the Te Akatea Formation in an open marine setting, probably an outer shelf to upper bathyal one with an open connection westward to the Taranaki Basin.

The occurrence of these very different facies types between the northern and southern areas reflect an overall paleobathymetric trend of a shallow shelf in the south to outer shelf-upper bathyal slope in the north. The lateral transition between the neritic carbonate facies of the Orahiri Formation and Otorohanga Limestone occurring to the south of Aotea Harbour, and deepwater mixed carbonate-siliciclastic facies of the Te Akatea Formation to the north of Raglan are buried beneath the Plio-Pleistocene volcanics in the central Aotea-Kawhia region. There are however few isolated exposures within the Aotea-Kawhia region that provide important windows linking the depositional systems to the south and north of the basin.

The section below first describes the nature of the lower sequence boundary and how it varies from south to north, and is followed by a discussion of the two stages in the evolution of shelf to slope depositional system within the subgroup.

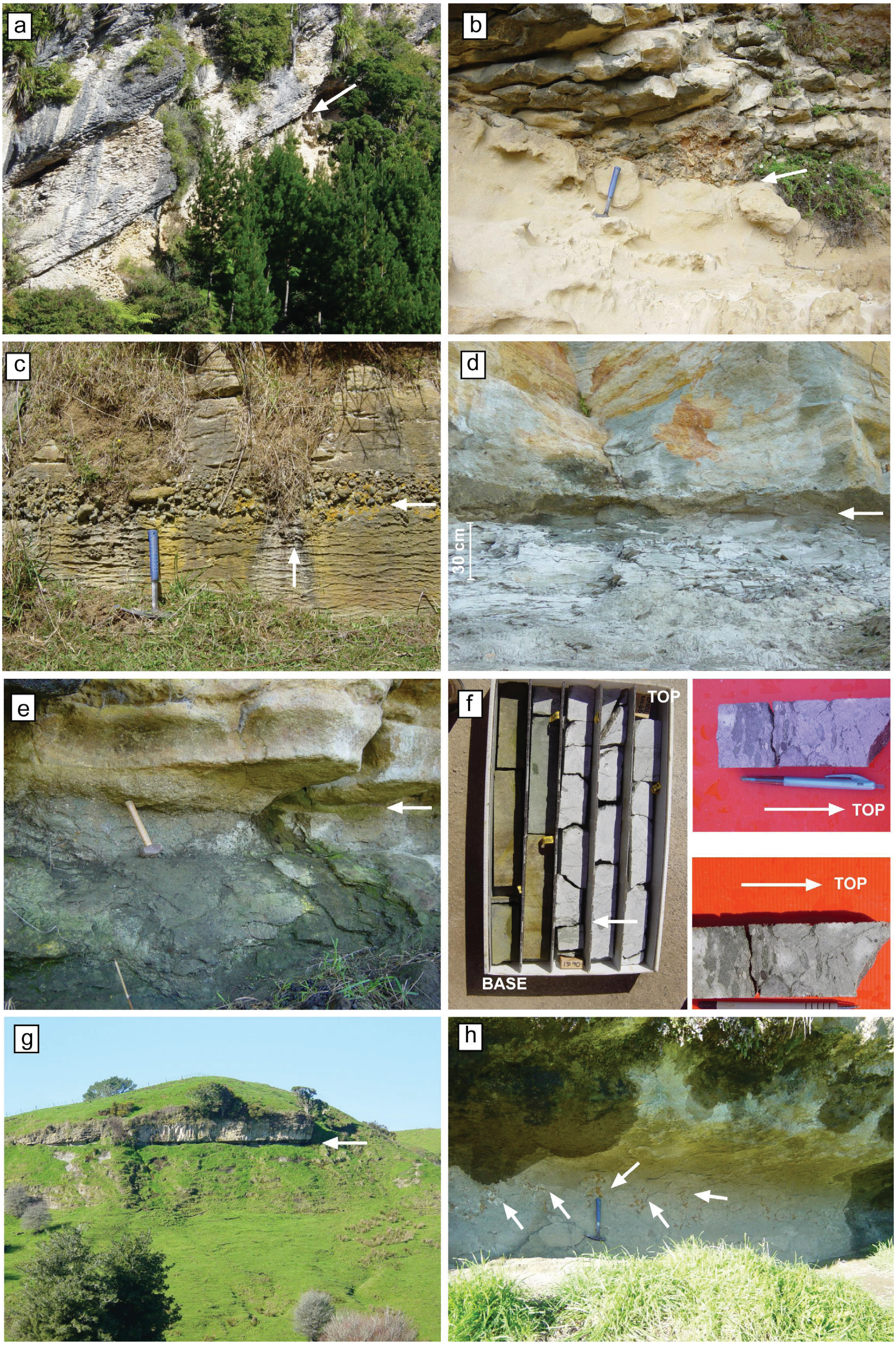
Sequence boundary

The base of the Castle Craig Subgroup corresponds to a widespread unconformity, which has different origins in different parts of the basin. The unconformity south of Kawhia Harbour may have involved sub-aerial exposure of the entire southwestern region associated with uplift of the Herangi High. In the Awakino Tunnel section, this unconformity is an irregular surface with scours up to 40 cm deep in the underlying Hauturu Sandstone Member of the Aotea Formation (Fig. 7.14 a & b). The immediately overlying basal unit of the Orahiri Formation comprises basement derived rounded cobbles and pebbles. A sharp undulatory contact between Kihi Sandstone Member and the overlying basal unit of the Orahiri Formation, with abundant sub-rounded pebbles, glauconite pellets, small solitary corals and shell hash concentrations, is evident at many localities such at the Mangaotaki Bridge, Waitomo Valley Road and Honikiwi sections (Fig. 7.14).

This erosional unconformity in the southern region is interpreted to be a transgressive surface of erosion (TSE) (e.g. Nummendal & Swift 1987) that formed through wave planation following earlier lowering by subaerial erosion processes. The amount of lowering of this erosional surface can hardly be confidently estimated; however, given it truncates the underlying formation, the amount of erosion is probably in the order of a few tens of metres. This will certainly be the case in the Awamarino area where the unconformity separates Glen Massey Formation from Orahiri Formation, the whole of the Whaingaroa Formation and Aotea formation having been removed (Fig. 7.14 c). The contact in this area is an uneven surface with shallow scours filled with subrounded pebbles and cobbles cutting a few centimeters into the underlying calcareous sandstone (Ahirau Sandstone Member). Occasional bivalve shell fragments, moderate concentrations of glauconite grains and large inclined burrows are also commonly associated with this surface. This implies that the intensity of erosion associated with this unconformity was probably higher along the eastern margin of the Herangi High.

In a few sections located inland from the Aotea-Kawhia Harbour area, the contact between the Aotea Formation and the overlying Orahiri Formation in general is difficult to pinpoint. The sandy limestone of Orahiri Formation overlies the Aotea Formation with apparent conformity. This contact corresponds to a gradational to abruptly gradational transition between the formations and is commonly marked by a gradual increase in flaggy character of the overlying sandy limestone reflecting an increasing carbonate content upsection (Fig. 7.15). Any evidence for erosion or non-deposition at this contact is difficult to ascertain. In general, a change to more calcareous sedimentation marks the base of the Castle Craig Subgroup in this area.

In the northern region, the base of the Castle Craig Subgroup is a major paraconformity corresponding to a period of non-deposition. This paraconformity occurs at the base of the Raglan Limestone and Carter Siltstone Member; it marks an abrupt lithological change and is present in the sections located in the western areas. In the vicinity of Raglan Harbour, the paraconformity exposed at the base of the Raglan Limestone Member is marked by a high concentration of glauconite and a dense network of *Thallasinoides* and/or *scolicia* burrows, indicating non-deposition and substrate stabilisation, characteristics of firmground to hardground development (Fig. 7.16). The abruptness of this vertical facies transition and its association with glauconite and intensive burrowing indicates a considerable hiatus. A similar nature to the contact is evident in sections located to the north of Raglan Harbour. In the vicinity of Port Waikato the contact at the base of the Carter Siltstone comprises a glauconitic and phosphatic burrowed zone about 30 cm thick. The glauconite and phosphatic nodules indicate starved sediment conditions (Fig. 7.16 a). In a few sections located to the east of Port Waikato (e.g. Glen Murray) a glauconite-rich stratigraphic horizon is less conspicuous, being marked by a change to calcareous


a
b
c
d
30 cm
e
f
TOP
BASE
131.90
TOP
TOP
g
h

siltstone (Carter Siltstone Member) from underlying Patikirau Siltstone.

In sequence stratigraphic terminology this extensively burrowed omission zone qualifies as a correlative conformity and is inferred to merge with the erosional unconformity or sequence boundary present at the base of the Castle Craig Subgroup in the southern region.

Stages in evolution of Castle Craig Subgroup

A complex evolution of a carbonate shelf to slope depositional system is inferred from stratal patterns reconstruction between the southern and northern regions within the Castle Craig Subgroup. The following two major stages of evolution can be distinguished.

Stage A: progradation:

The main paleogeographic elements inferred during the deposition of Orahiri Formation and the lower units of the Te Akatea Formation include the Herangi High, a broad shelf between the Herangi High and the Piopio High, and a gentle north and northeast sloping ramp (Av. ~1° angle) extending from Kawhia Harbour to Port Waikato (a distance of approximately 85 km). The lack of obvious turbidites, slump structures, or other types of mass emplacement highlights the very gentle gradient of probably less than one degree.

Fig. 7.14 (facing page): Photographs illustrating typical field expression of sequence boundaries (TSE) in the Castle Craig Subgroup across the south central region of the study area. (a) Massive to thin bedded, variably calcareous fine sandstone (Hauturu Sandstone Member) is truncated (pointed by arrow) and overlain by sandy grainstone-packstone (L4) of the Orahiri Formation. The Orahiri Formation dips 31° E. Exposure is approximately 30 m high at Awakino Tunnel (C-191). (b) Close-up of contact shown in photo a. Arrow points at the scoured contact infilled with rounded basement cobbles and pebbles. (c) Horizontal arrow points at erosional unconformity surface overlain by cobbles and pebbles (transgressive lag deposits). This unconformity separates the highly calcareous sandstone (Ahirau Sandstone Member) from the overlying sandy grainstone-packstone unit (Orahiri Formation). Note the pebble filled scour pockets associated with transgressive erosion (vertical arrows). Awamarino (C-50). (d) Wave-ravinement surface truncates the top of muddy sandstone unit of the Kihi Sandstone Member overlain by sandy grainstone-packstone of the Orahiri Formation. Note the presence of a thin pebble band with high concentration of glauconite pellets (transgressive lag deposit) at the base of the overlying sandy grainstone-packstone unit. Mangaotaki Bridge (C-166) (e) A bioturbated glauconitic sandstone unit (Kihi Sandstone Member) is truncated at the top by a wave planed surface (arrow), overlain by slightly sandy grainstone (Orahiri Formation) with a thin basal pebble grit and containing abundant skeletal fragments (transgressive lag deposit). Waitomo Valley Road (C-32). (f) Slightly irregular scoured contact (arrow) between dark greenish-grey muddy glauconitic sandstone (Kihi Sandstone Member) and overlying sandy grainstone-packstone (Orahiri Formation). Two insets show close-ups of this contact. Note the glaucontic, burrowed mottled texture of the sandstone below the contact and rounded pebbles in the overlying glauconitic grainstone-packstone unit. Photograph of core from BH-502, Oparure Limestone Quarry. C-119 (g) Sharp and broadly undulatory contact (arrow) between bioturbated muddy sandstone (Kihi Sandstone Member) and overlying low-angle cross-bedded grainstone (Orahiri Formation). Outcrop is approximately 20 m high. Honikiwi (C-25). (h) Close-up of the contact shown in photo g. Arrow pointing to Thallasinoides burrows penetrate downwards into the sandstone from the erosional unconformity. The burrows are infilled with carbonate sand from the overlying Orahiri Formation.

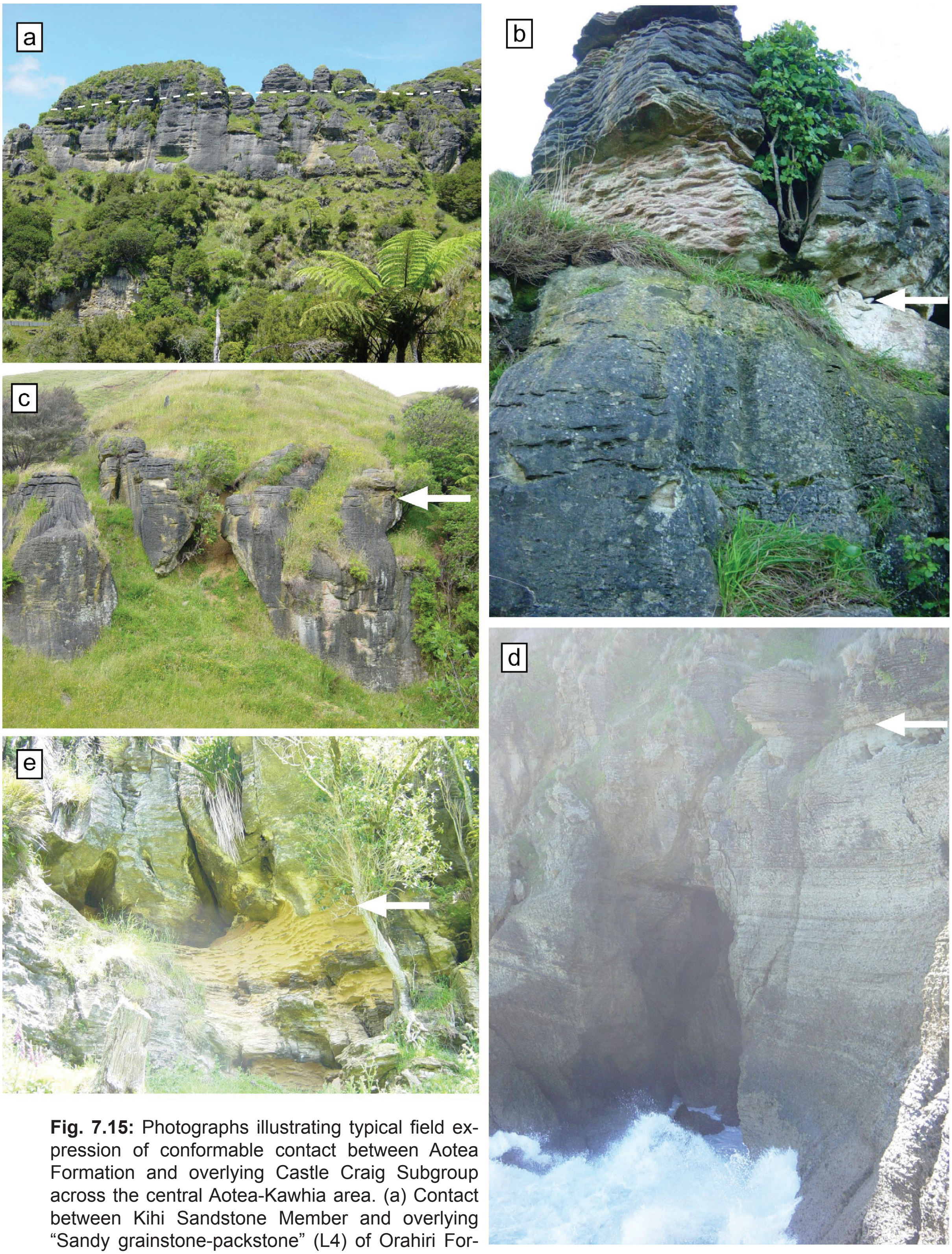


Fig. 7.15: Photographs illustrating typical field expression of conformable contact between Aotea Formation and overlying Castle Craig Subgroup across the central Aotea-Kawhia area. (a) Contact between Kihi Sandstone Member and overlying “Sandy grainstone-packstone” (L4) of Orahiri Formation (dashed line). Exposure is about 50 m high. Hautapu Hill (AK-10) (b) Arrow points to abruptly gradational contact between Kihi Sandstone Member and overlying “Horizontally bedded grainstone” (L3) of Orahiri Formation. Note change in increased carbonate content is reflected in flagginess of the overlying unit. Exposure is about 6 m high. Makaka, north of Aotea Harbour (AK-1). (c) Arrow points to conformable contact between Kihi Sandstone Member and overlying “Sandy grainstone-packstone” (L4) of Orahiri Formation at Pakoka Landing, north of Aotea Harbour R15/726621.Exposure is about 5 m high. (d) Abruptly gradational contact between Hauturu Sandstone and “Sandy grainstone-packstone” (L4) of Orahiri Formation (arrow) at Taranaki Point (S16). Cliff is about 50 m high. (e) Gradational contact between Hauturu Sandstone Member and overlying “Sandy grainstone-packstone” (L4) of Orahiri Formation at Whanuapo Hill, Toi Road, South of Kawhia Harbour (R16/755379).

The overall depositional system in the lower part of the Castle Craig Subgroup (Orahiri Formation and Raglan Limestone Member) is envisaged to be mildly progradational, controlled mainly by the relatively high flux of sediment that may have slightly outpaced subsidence. The depositional model envisages a rocky shoreline on the eastern side of the Herangi High that provided ideal conditions for the growth of skeletal fauna and flora. The relatively high terrigenous sand (up to 50%) content within the lower part of the Orahiri Formation (Mangaotaki Limestone Member, lithofacies L_4) adjacent to Herangi High implies contemporaneous erosion of Hauturu Sandstone Member in response to uplift of the Herangi High. Evidence for this syndepositional tectonism is also provided by the presence of conglomeratic limestone facies (L_7) in the Awakino Tunnel area (Nelson et al. 1994). The widespread occurrence of "Horizontally and Cross-bedded grainstone facies" (lithofacies L_2 & L_3) within the Orahiri Limestone suggests that the carbonate accumulated in a current to wave dominated seaway (Nelson 1978a) (Fig. 7.17). The cross-bedded units (L_2) formed from the migratio n of large (1-5 km long) dune fields migrating within this seaway in water depths up to 40-60 m deep. Much of the energy to entrain sediments and move dunes forward probably came from tidal currents which were strengthened by irregular topography and being forced through the seaway (Anastas 1997). It is inferred that the skeletal carbonate sediment supply was sufficient to prograde the carbonate shelf eastwards to onlap the flanks of Piopio High and to form a carbonate ramp to the north (Fig. 7.18).

The predominant calcarenite nature of the shelf limestone accumulation in the southern region implies that large volumes of carbonate mud must have been generated during the process of skeletal fragmentation and abrasion (Nelson 1978b). Much of this fine carbonate material will have been flushed out from the calcarenite deposits and transported down the ramp as part of the suspension load. The carbonate mud may have been swept farther out into the medial parts of the ramp primarily by north-directed currents interpreted by Anastas (1997) from dip directions in cross-bedded limestone occurring in the lower part of Castle Craig Subgroup in the vicinity of Kawhia. The Raglan Limestone Member has carbonate contents as high as 89% implying that much of the fine carbonate material was transported as suspension load into the deeper parts of the ramp and intermixed with background terrigenous mud. Raglan Limestone Member is generally well bedded, the bedding being defined by alternation of carbonate-rich beds and less carbonate rich siltstone interbeds. The beds, ranging in thickness from 10-50 cm, typically have diffuse tops and bases and have been extensively burrowed by *Scolicia,* particularly along the bedding planes. With increasing distance to the north and northeast of the basin, the Raglan Limestone Member became less calcareous with average contents of 72%

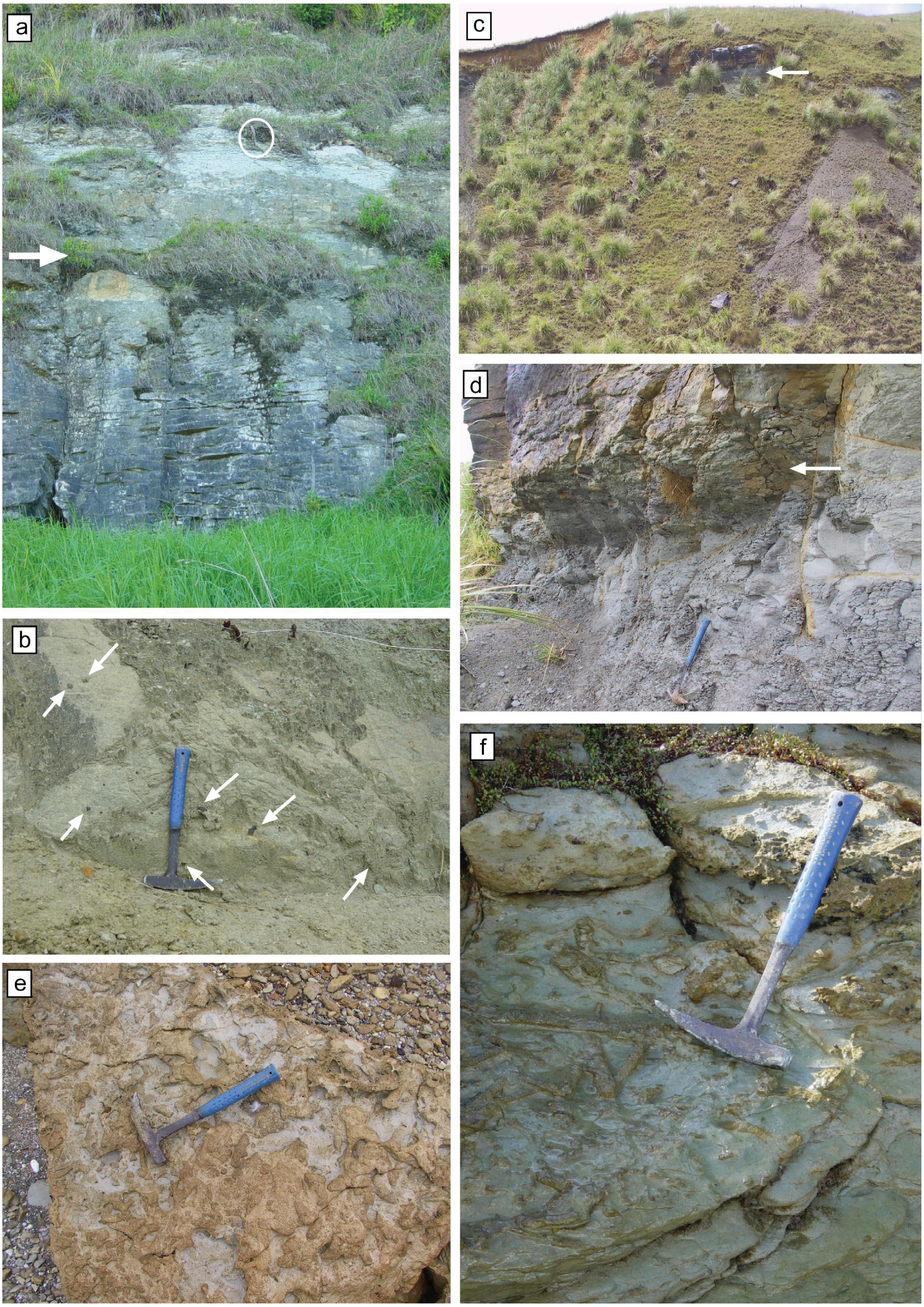


Fig. 7.16: Photographs illustrating typical field expressions of sequence boundaries of the Castle Craig Subgroup across the Northern Region of the study area. (a) The Waimai Limestone Member passing into massive calcareous siltstone (Z1/Carter Siltstone Member) through a highly fossiliferous greensand (condensed Patikirau Siltstone Member of Aotea Formation) pointed by arrow. This facies contact is inferred to be a sequence boundary (correlative conformity) at the base of the Te Akatea Formation in the Port Waikato area. Hammer for scale. Photo location: Port Waikato-Waikaretu Road

in the vicinity of Te Akau. This is also evident from the lateral facies transition from L_8 (i.e. Raglan Limestone Member) into Z_1 and/or Z_2 facies (i.e. Carter Siltstone Member) approximately midway between Raglan Harbour and Port Waikato. In the far northern (e.g. Waikaretu-Port Waikato) and eastern parts (e.g. Glen Murray) of the basin, mixed calcareous and terrigenous deposits of the Carter Siltstone Member prevail (Fig. 7.12).

Stage B: retrogradational:

The second stage in the accumulation of the Castle Craig Subgroup involved a long term rise in relative sea level that increased accommodation on the shelf and terminated the earlier northward progradation of the carbonate shelf. This is well expressed in the northern region by deposition of the Carter Siltstone Member over the Raglan Limestone Member. This vertical facies transition from L_8 into Z_1 and/or Z_2 facies is interpreted as a retrogradational shift in the facies belt. As the depositional system retrograded southwards into the Aotea-Kawhia region, a similar vertical facies transition from dominantly carbonate (i.e. L_2-L_6) to dominantly terrigenous sandy siltstone (i.e. S_2) is apparent in a few sections in Kawhia (e.g. localities AK-11 & AK-12 in Fig. 7.8).

In the south-central region, Otorohanga Limestone overlies Orahiri Formation, which in general marks a change to more pure carbonate sedimentation with terrigenous content rarely exceeding 10% (Nelson 1973; 1978a). The minimal siliciclastic input during the accumulation of Otorohanga Limestone probably reflects progressive submergence of siliciclastic source areas. An overall deepening trend apparent within the Otorohanga Limestone has been interpreted from variations in the bryozoan growth forms (Nelson et al. 1988; Anastas 1997). However the occurrence of "Massive to irregularly bedded fossiliferous rudstone-grainstone" (L_5) forming most of the Waitanguru Limestone Member, indicates a high energy depositional condition possibly related to the lowering of the relative sea- level (Nelson 1973; Nelson et al. 1988).

(Fig. 7.16 continued) section (PW-2). (b) Arrows points to scattered phosphate nodules near the conformable contact between the greensand (condensed Patikirau siltstone Member of Aotea Formation) and overlying massive calcareous siltstone (Z2/Carter Siltstone Member). Waikawau Beach (PW-11). (c) Arrow points to a sharp but conformable facies contact (an inferred sequence boundary) between massive sandy siltstone (Patikirau Siltstone Member) and the overlying highly bioturbated packstone-wackestone (L8/Raglan Limestone Member). Cliff is approximately 30 m high. Patikirau Bay, Raglan Harbour (TA-20). (d) Close-up view of the conformable facies contact shown in photo c. Note extensively bioturbated base (pointed by arrow) of the packstone-wackestone unit (L8/Raglan Limestone Member). Locally conspicuous glauconitisation and /or glauconite pellets are also observed at this contact (e) Close-up of burrowed hardground surface exposed in one of the fallen blocks from the contact shown in photo c. (f) Abundant Scolicia and Thallasinoides burrows marking an inferred sequence boundary between sandy siltstone (Patikirau Siltstone Member) and "Silty packstone-wackestone" (L8/ Raglan Limestone Member). Okete Bay, Raglan Harbour (TA-15).

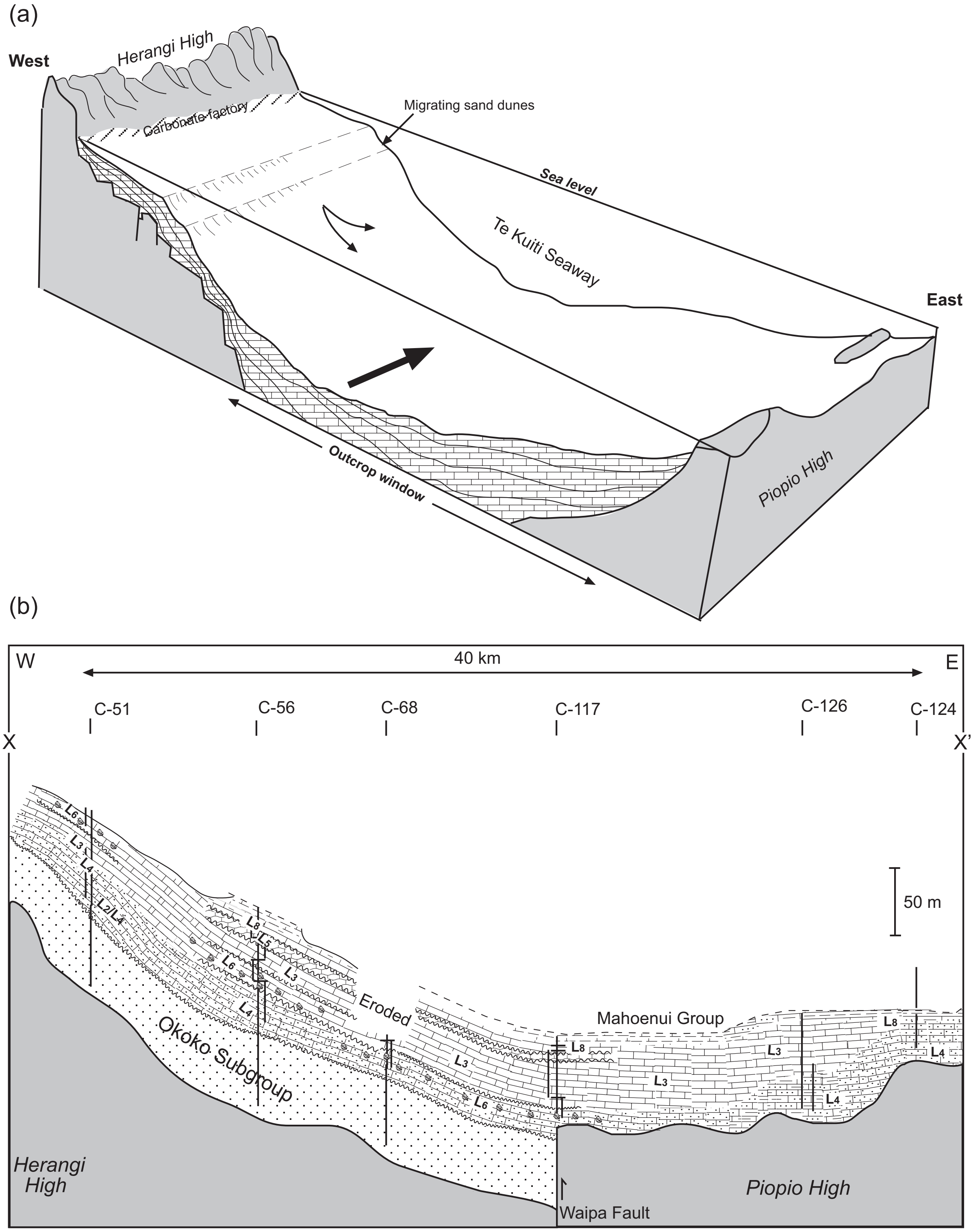


Fig. 7.17: (a) Idealised paleogeographic reconstruction for the southern region showing the high-energy, clastic carbonate seaway (not to scale) that produced a mosaic of lithofacies types in the Castle Craig Subgroup (refer text for details). (b) Schematic cross-section showing main facies relationships from westerly localities and more distal eastern localities (see Fig. 7.20 for column locations). Stratigraphic thicknesses shown against the columns are approximate. Note the oyster-bearing limestone facies (L6) in C-117 occurs at a lower level whereas they occur at higher levels in the more western located columns (C-51). Zig zag lines indicate unconformities including the prominent erosional unconformity that marks the contact between Okoko Subgroup and overlying Castle Craig Subgroup. Other unconformities occur in the limestone succession west of Waipa Fault, but are not obvious in the east. These unconformities are probably of tectonic origin and may have developed in response to local fault movement. Piopio High was probably more tectonically stable during limestone accumulation. No vertical scale implied.

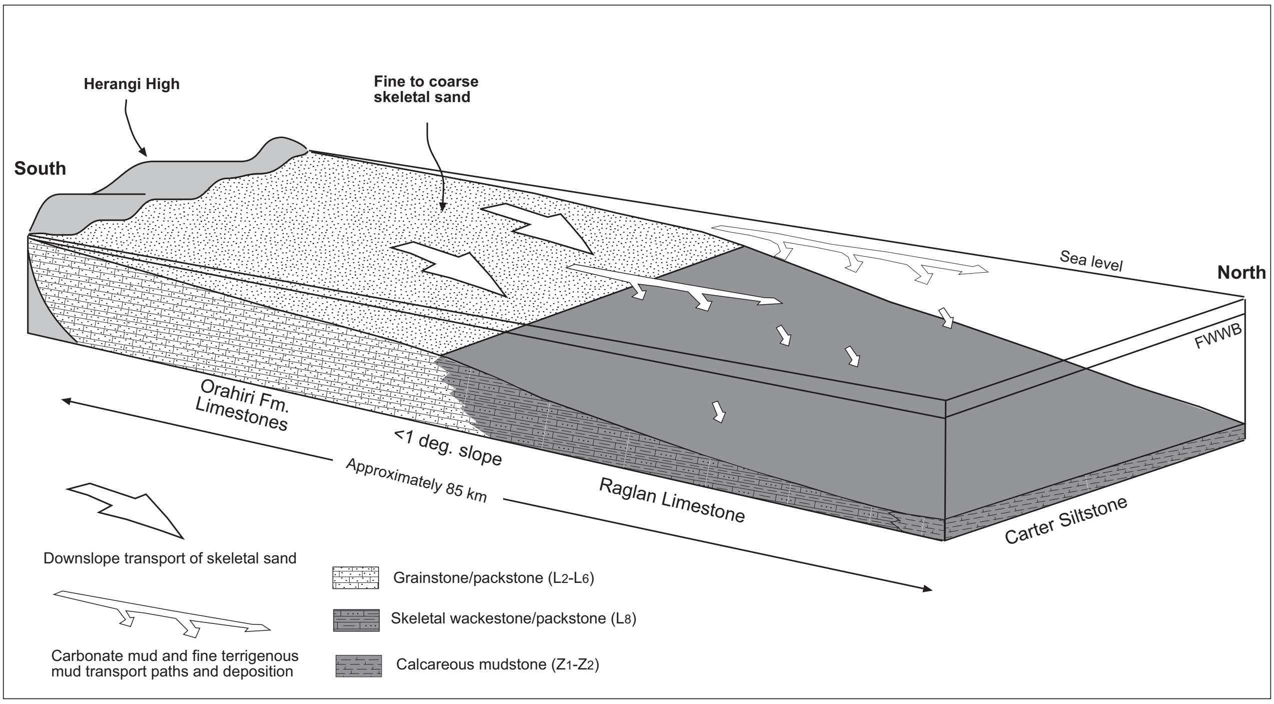


Fig. 7.18: Conceptual model illustrating carbonate shelf to slope transition via a gentle northward sloping ramp from Marokopa (south of Kawhia Harbour) to Port Waikato in the western sector of central north region (No scale or specific correlation implied). Broad lateral facies transition along this transect reflect hydrodynamic conditions. Well developed “Medium to coarse sandy grainstone/ packstone” (L2-L5) in the south derived mainly from skeletal sands produced by wave abrasion processes on the rocky shoreline of the Herangi High were transported down the ramp by storm and/or tidal currents. The carbonate mud and fine terrigenous fraction was flushed out and swept off farther into the outer shelf/upper bathyal environment and accumulating by suspension fallout. This fine carbonate material forms the Raglan Limestone Member in the north part of this transect (L8/ Massive to horizontally bedded skeletal packstone-wackestone facies). The Raglan Limestone Member (L8) laterally grades into Carter Siltstone Member (Z1-Z2) farther north, where it was partly diluted by background terrigenous mud.

The Otorohanga Limestone succession rests directly on basement in the vicinity of Piopio and Aria, implying that sediment supply was not only sufficient to keep pace with subsidence, but also enough to enable eastward progradation of the carbonate shelf. The start of the retrogradational phase in the southern region is marked by the deposition of lithofacies L_8 in the upper part of Piopio Limestone Member. Previous estimates of paleobathymetry based on textural and paleontological evidence suggest a gradual increase in depth of deposition within the upper part of the Otorohanga Limestone (Nelson 1973, 1978a). The top of Otorohanga Limestone become progressively rich in fine terrigenous silt before grading into overlying Mahoenui Group often via a interbedded packstone-wackestone (lithofacies L_8), reflecting a decline in carbonate productivity from factory sites as the siliciclastic input increased concurrent with bathymetric deepening.

Overview of vertical facies succession and the definition of Orahiri and Otorohanga depositional units

The Castle Craig Subgroup in the south central region of the study area has a complex mosaic of facies. Nelson (1978a) used a terminology of OrA, OrB, Wt, OtA, OtB, and OtC to describe individual depositional units within what is named here the Castle Craig Subgroup, and constructed east-west correlation panels showing facies relationship between the eastern and western parts of the Waitomo District (Nelson 1978a, Figs 31 & 32). The inferred facies relationships in these cross-sections indicate multiple stacked rock units consisting mainly of OrA, OrB, OtA, OtB and OtC along the western sector, progressively pinching out to the east against a topographical high. The limestone succession overlying the basement high (Piopio High) was shown to consist of OtA and OtC rock units, implying that the entire eastern sector was emergent during the deposition of OrA and OrB units. The inferred absence of OtA, OtB and OtC rock units in many localities lying in the western sector was explained by non deposition and/or erosion as a result of basin margin inversion and tilting (Nelson et al. 1994).

To determine more fully the implied relationship between the Orahiri Formation and Otorohanga Limestone, additional east-west cross-sections were constructed in this study (Fig. 7.20 & 7.21) focusing on the stratigraphic location of oyster beds used by Nelson (1978a) as a marker to differentiate Orahiri Formation (OrB) from Otorohanga Limestone. The significance of unconformities and associated marine-cemented units within the limestone succession, used by previous workers to differentiate the Orahiri and Otorohanga depositional units, are also discussed here.

Location of oyster beds:

The geographical extent of oyster beds (L_6) within the limestone succession are shown in Figs 7.12 and 7.13, and their stratigraphic positions are shown in three E-W transects (Figs 7.20 b & 7.21). In cross-section A-A’ (Fig. 7.20 b), oyster beds at C-166 occur at the top of the limestone succession, whereas at C-184 they occur mainly in the lower and middle parts of Castle Craig Subgroup. Sandy grainstone (L_4), which is a commonly occurring facies in the Mangaotaki Limestone Member, forms the bulk of stratigraphic thickness at these localities. Oyster beds are absent in sections located farther to the east (e.g. C-174). In all three localities, the Castle Craig Subgroup is overlain by Mahoenui Group with apparent conformity, which implies that there is no missing limestone interval from the top of the subgroup. In cross-section B-B’ (Fig. 7.21), the oyster beds are present near the base of the limestone at localities C-117, C-99/C-100 and C-80, but they are absent in the nearby

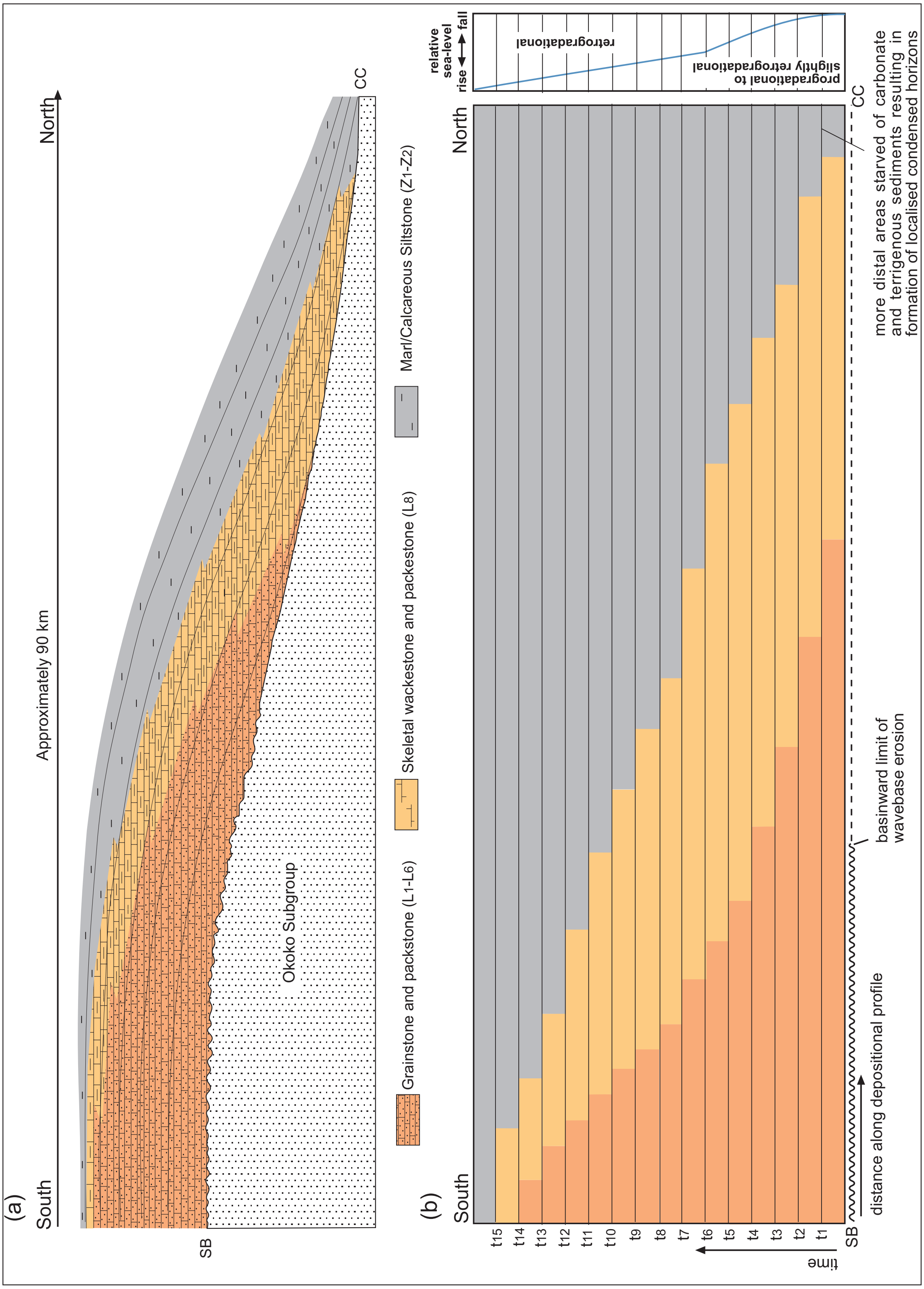


Fig. 7.19: (a) Schematic depositional model and chronostratigraphic panel (b) showing the inferred distribution of the main lithofacies in the Castle Craig Subgroup along a north-south profile. In the lower part of the model the carbonate shelf and slope was mildly progradational, as shown by the occurrence of the Raglan Limestone (L8) sourced from the south. Subsequently the system became retrogradational, a southward migration of the facies belt is inferred with mixed carbonate and siliciclastic siltstone (Z1-Z2) progressively accumulating over the carbonate lithofacies

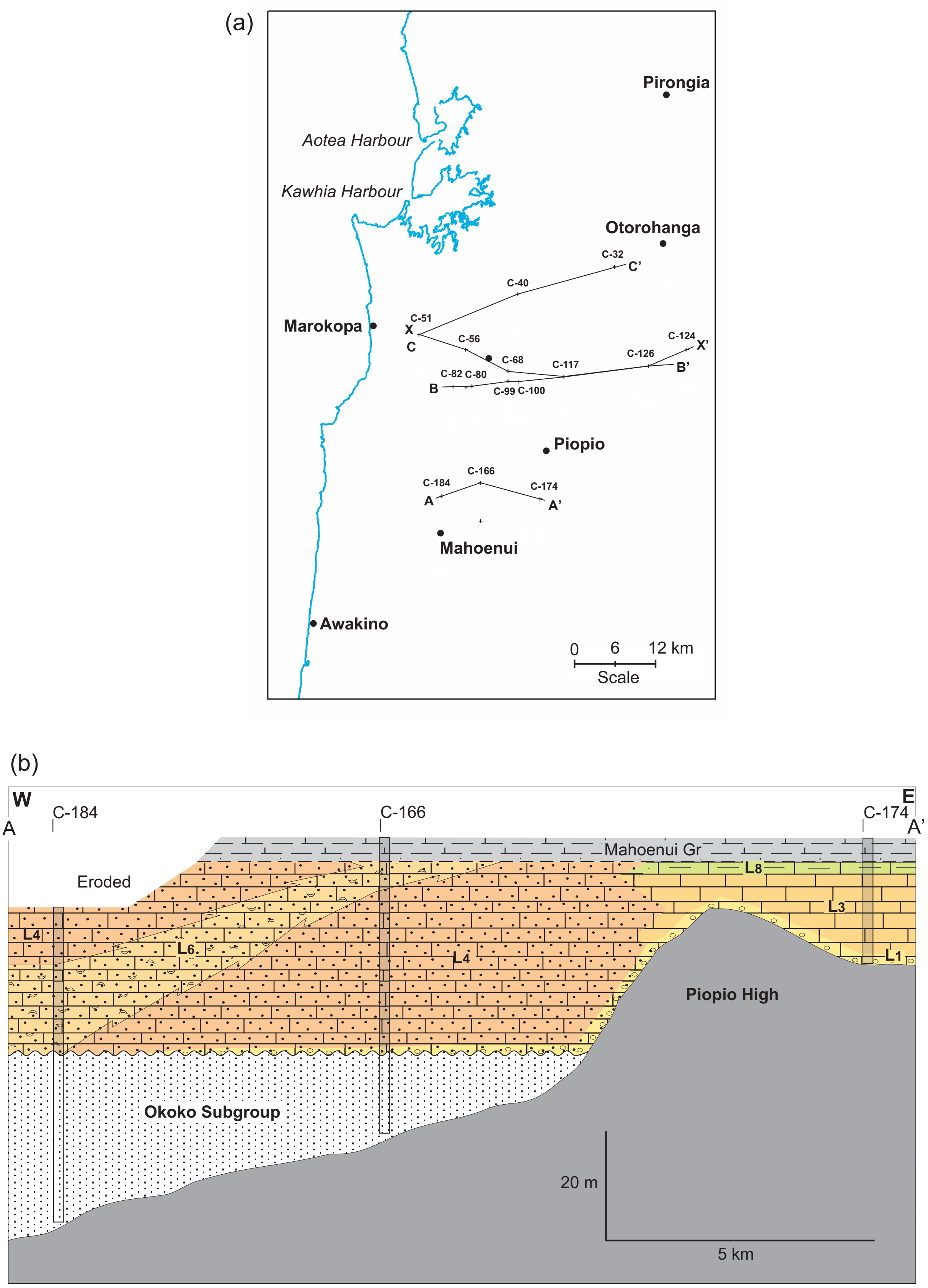


Fig. 7.20: (a) Map showing the location of cross sections illustrated in Fig. 7.17 (b) and Fig. 7.21 (a) and (b). (b) West to east stratigraphic correlation through the Orahiri Formation/Otorohanga Limestone. The datum is the basal erosional unconformity with the Okoko Subgroup.

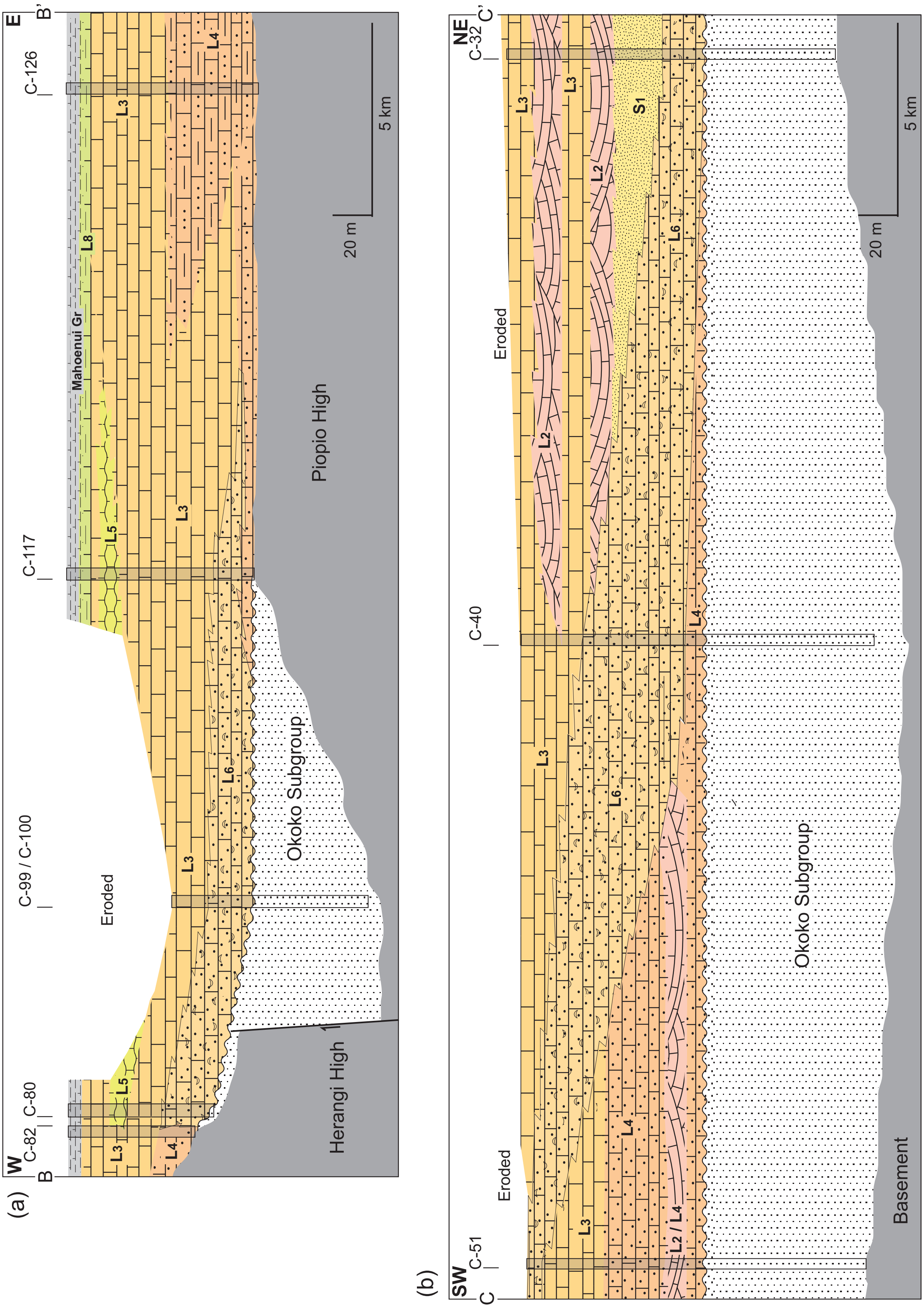


Fig.7.21: (a) West to east stratigraphic correlation through the Orahiri Formation/ Otorohanga Limestone. The datum is the erosional unconformity with the Okoko Subgroup. (b) Southwest to northeast stratigraphic correlation through the Orahiri Formation/Otorohanga Limestone. The datum is the Okoko Subgroup with the Okoko Subgroup. See Fig. 7.20 (a) for cross section and column locations.

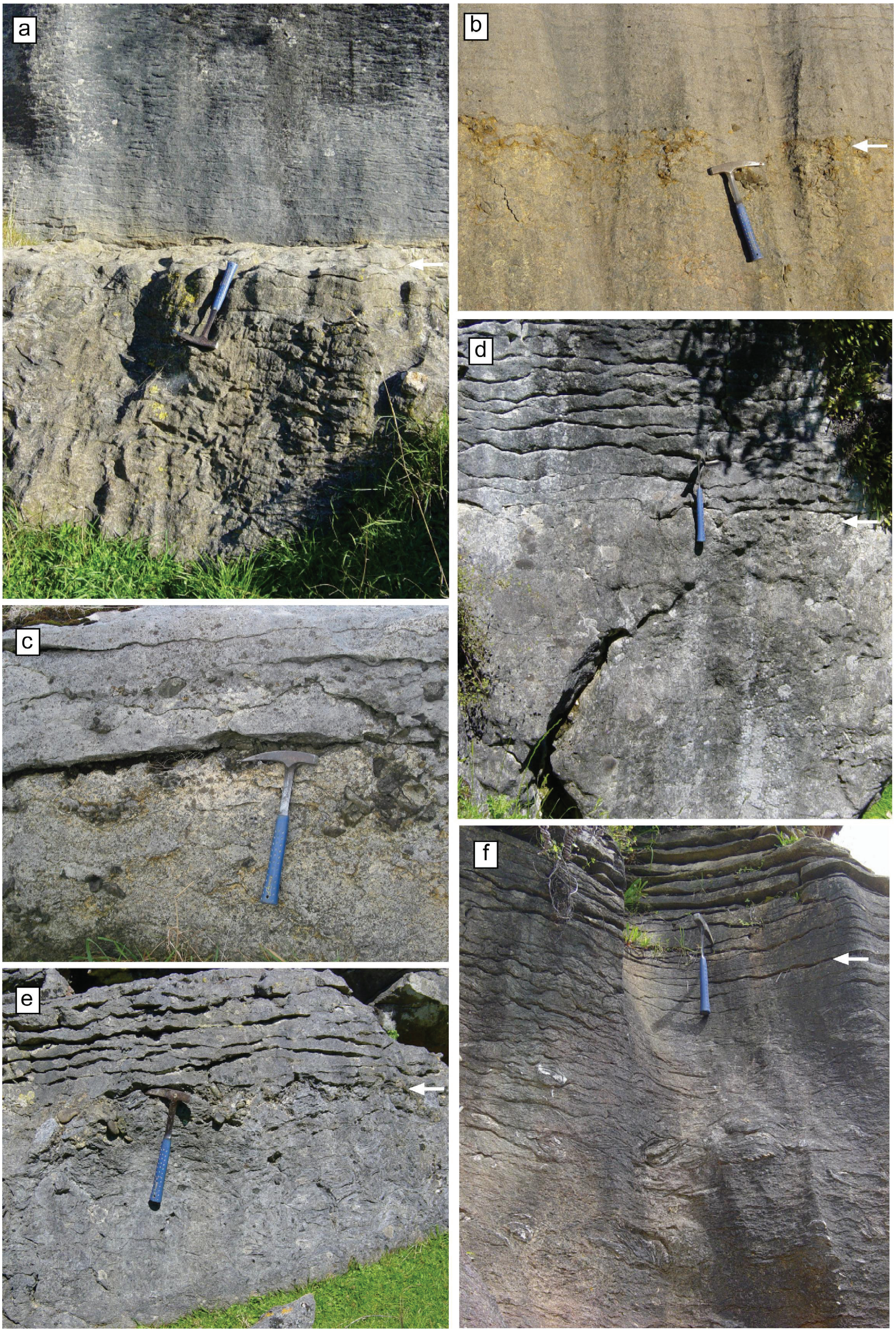
section C-82 located to the west. Oyster beds are also absent in the east at C-126. In cross-section C-C’, oyster beds occupy stratigraphic positions high in the limestone such as at locality C-51, and progressively lower positions northeastward into C-32. The schematic east-west cross-section X-X’ in Fig. 7.17b also shows a similar trend of oyster beds occurring at the lower levels of the limestone in the east.

All of the sedimentological evidence discussed previously suggests that the oyster facies (lithofacies L_6) were deposited in a current swept inner to mid shelf setting (Nelson et al. 1983). It is likely that the favourable environmental conditions for oysters to thrive such as strong currents and elevated nutrient supply existed at various time across the southern region. Favourable environmental conditions for oyster growth seem to have migrated from east to west and to the southwest (Awakino) with time Nelson (1973). The absence of oysters in the thick limestone succession (Otorohanga Limestone) in the vicinity of Te Kuiti (e.g. C-126) probably indicates that favourable conditions for oyster growth were not present at that time. It is therefore suggested that the use of oyster beds to identify Orahiri Formation as distinct from Otorohanga Limestone is not always valid.

Regional significance of unconformities and associated marine cemented units

The Castle Craig Subgroup over the south central area is punctuated by several unconformities. In the vicinity of Ngapaenga and west of Piopio, past workers (Hopkins 1966; Nelson 1973, 1978a) have mapped or correlated several unconformities which generally mark abrupt facies transitions. Nelson and James (2000) observed that many of these unconformities are associated with marine-cemented units, either below, or sometimes immediately above the unconformity surfaces. In outcrop, these unconformities are typically marked by irregular, sharp, erosion surfaces, and may include scattered basement derived pebbles, occasional limestone clasts and conspicuous fragments of pectinids, oyster and bryozoan colonies concentrated below the surface and also immediately above (Fig. 7.22).

Fig. 7.22 (facing page): Typical field expression of unconformities and marine-cemented limestone units in the southern region of the study area. (a) Arrow points at the erosion contact between “Pebbly oyster bearing floatstone-packstone” (L6, Te Anga Limestone Member) and overlying horizontally bedded grainstone (L3, Pakeho Limestone Member). Mangaohae Stream section (C-56) (b) The arrow points at the slightly irregular nature of the erosion surface between marine-cemented micritic “Oyster floatstone-packstone” (L6, Te Anga Limestone Member) and overlying horizontally bedded grainstone (L3, Pakeho Limestone Member). Note light rusty brown colouration on clasts and skeletons indicating iron oxide staining. Ngapaenga (C-68). (c) The hammer head at the sharp erosional contact between “Pebbly oyster bearing floatstone-packstone” (L6, Te Anga Limestone Member) and overlying “Irregularly bedded grainstone” (L3, Pakeho Limestone Member). Note scattered subangular to rounded basement clasts occurring both below and above the contact surface. Ngapaenga (C-68). (d) Sharp vertical facies transition (arrow) between “Massive fossiliferous rudstone-grainstone” (L5) with scattered oysters and “Irregularly bedded grainstone” (L3). Mangaotaki (C-145) (e) Hammer head rests at irregular, sharp contact between “Pebbly oyster bearing floatstone-packstone” (L6) and



(Fig. 7.22 continued) “Low angle cross-bedded grainstone” (L2). Note abundant basement clasts near the contact surface. Mangapohue Natural Bridge. (f) Arrow points at vertical facies transition between “Oyster bearing floatstone-packstone” (L6, Te Anga Limestone Member) and “Horizontally bedded grainstone” (L3, Pakeho Limestone Member). Mangaohae Stream secton (C-56).

Erosion surfaces superimposed on a submarine hardground locally exhibit rusty-brown iron oxide, phosphatic mineralisation, and concentrations of glauconite pellets and/or glauconitised clasts and shell fragments. Collectively, these features along with marine cementation were associated with stratigraphic condensation and relatively high-energy sediment reworking at this surface during periods of relative lowstand (Nelson & James 2000). One of the most prominent unconformities is used by Nelson (1978a) to delineate the boundary between Orahiri Formation and Otorohanga Limestone (refer chapter 3). A significant shoaling of the water depth has been suggested at this contact based on the variation in bryozoan growth-form trends (Nelson et al. 1988).

However, these unconformities and their associated features are only recognisable locally in the south central area lying to the west of the Waipa Fault (Fig. 7.17). This is also evident from the varying distribution of the associated facies belts. The unconformities probably have a local origin related to local fault-related movement and resultant relative sea-level fall rather than necessarily indicating regional base level change. Definite physical evidence of subaerial exposure is not apparent except in a few localities in the vicinity of Ngapaenga where red iron oxide coating on the pebbles present on the unconformity surface probably indicate a period of subearial exposure. This implies in the majority of the cases, that the hardgrounds were not developed in the subaerial environment but instead by shoaling into the inner shelf zone of non-deposition and wave abrasion. The development of unconformities and marine-cemented limestone units are not evident in areas east of the Waipa Fault and within that eastern depocentre subsidence seems to have continued relatively uninterrupted through the limestone accumulation. This implies that the area lying to the east of the Waipa Fault was tectonically stable during most of the accumulation of the Castle Craig Subgroup.

Chapter 8

Basin Synthesis

Introduction

In central-western North Island the Late Eocene-Oligocene shelf marine succession ought to contain a record of global change as well as a record of more local events resulting from tectonic movements. The Te Kuiti Group will also be a useful stratigraphic record against which ideas about the early evolution of the Australia-Pacific plate boundary through New Zealand can be tested. The primary aim of this chapter therefore is to establish the paleogeographic development of central-western North Island from analysis of the Te Kuiti Group undertaken in earlier chapters, and from it to interpret the controls on sedimentation of the group and to contribute information, if possible, to the wider geological development of New Zealand.

The general stratigraphy and elements of the paleogeography of the Te Kuiti Group have been previously outlined and discussed by several people (Kear 1963; Nelson 1973, 1978a; Kear & Schofield 1978; White & Waterhouse 1993; Nelson & Hume 1977, 1987; Nelson et al. 1994; Edbrooke et al. 1994). This chapter presents an updated synthesis based primarily on extensive field studies of the Te Kuiti Group and the character of its transition into the overlying Waitemata and Mahoenui groups. MED open file subsurface data, primarily geophysical well logs, have considerably aided the development of understanding about the origin and significance of the Te Kuiti Group record.

The Te Kuiti Group comprises a wide variety of facies from coal measures to hemipelagic limestone; they record an almost continuous environmental spectrum from terrestrial to upper bathyal marine settings. Two distinct stages of basin evolution can be identified; each controlled by a different tectonic style and with characteristic linked depositional systems.

1. The first stage (Late Eocene to mid-Oligocene) is characterised by an extensional tectonic setting. There was regional downwarping or sag basin development accompanied by minor normal faulting (e.g. Hall et al. 2006).
2. The second stage (mid-Oligocene to E. Miocene) coincided with mild contraction across the region expressed as reverse movement on the Taranaki Fault and the related Manganui Fault. This displacement appears to have been associated with repeated phases of basin inversion and subsidence.

This chapter develops the case to interpret the basin fill in terms of these two phases of development, particularly the second one.

The Te Kuiti Group has marked cyclicity and is punctuated by several unconformities the origins of which have historically been attributed to eustatically controlled sea-level fluctuations (Vella 1967). This chapter compares the cyclicity with recent "global" records of eustatic sea level change, but there is not a convincing fit between them and the Te Kuiti Group sequences. Rather, the sequence stratigraphy appears to be better interpreted in terms of local tectonism; that is, a model in which repeated basin inversion and subsidence cycles have been caused by the development of reverse movement on the Taranaki Fault.

The chapter concludes by summarising the paleogeographic evolution of the Te Kuiti Group in the context of the wider late Paleogene tectonic interactions between the Australian and Pacific plates through the New Zealand region with reference to prior work (e.g. Kamp 1986; King and Thrasher 1996; and King 2000).

Paleogeographic Reconstructions

Paleogeographic reconstructions of the Waikato and King Country areas in which the Te Kuiti Group accumulated; that is, between Port Waikato and Awakino, are presented for thirteen intervals during the L. Eocene and Oligocene (Enclosure 3). These are based upon integration of the lithostratigraphy, biostratigraphy and chronology, facies and inferred paleoenvironments for the Te Kuiti Group as developed in preceding chapters, as well as interpretations about contemporary faults and paleotopography. The maps are drawn for key phases in the development of the basin and accumulation of the succession. The present-day coastline has only been used for reference, and it is obvious that the shape of the underlying crustal blocks and terranes would have changed considerably during phases of deformation, particularly in the Late Oligocene and earliest Miocene. A schematic north-south chronostratigraphic panel that illustrates the depositional trends and paleobathymetry through time, as well as the time value of unconformities, is also included on Enclosure 3. In each of the next sections, successive maps are described, in effect summarizing the geological development of the basin, its margins and adjacent areas.

Map 1 (Enclosure 3): Late Eocene (Kaiatan-Runangan) Waikato Coal Measures

During the Late Eocene, sedimentation was limited to the northern Waikato where an alluvial plain lay between basement ridges to the west and east. There may have been north-south striking faults active at the time (Hall et al. 2006). Sedimentation started after a long period of landscape erosion. There appears to have been a fine balance between subsidence and sedimentation such that a muddy coal measure environment persisted for some millions of years resulting in accumulation of the Waikato Coal Measures (Kear & Schofield 1978; King 1978; Kirk et al. 1988). A south to north fluvial drainage system meandered across the alluvial plain (Edbrooke et al. 1994). The terrestrial fine grained sediment, chiefly mudstone, enclosing the coal seams was sourced from a deeply weathered regolith beneath the basement surface (Nelson & Hume 1987). The coal measures are almost entirely comprised of fine grained lithologies including dark grey to brownish grey carbonaceous mudstone and siltstone (75%), intercalated muddy quartz-rich sandstone (12%), coal seams (12%), and conglomerate (1%). Conglomeratic facies within the coal measures are prominent in a few places, and are inferred to have been deposited on low angle alluvial fans adjacent to locally active fault scarps (Kear & Schofield 1978; Edbrooke et al. 1994).

The eastern limit of coal measure deposition is poorly constrained because of uplift and erosion of the Te Kuiti Group prior to deposition of the Waitemata Group, but a few preserved remnants show depositional thinning to the east (Edbrooke et al. 1994). Prominent paleo ridges such as the present day Hakaramata-Taupiri Range influenced the distribution of the coal measures and possibly restricted their accumulation in the Late Eocene to lie to the north of this ridge (Edbrooke et al. 1994). There are coal measures in Te Rapa-1 well but their age is not known (Katz 1968). A striking feature of the regional sedimentation pattern is the absence of Late Eocene sedimentation over virtually the entire southern part of the region.

A relatively thick Late Eocene succession including the Turi Formation is present along the eastern margin of Taranaki Basin. The Turi Formation contains recycled Mesozoic pollen indicating a source in exposed Murihiku basement rocks east of Taranaki Fault (King & Thrasher 1996). In Mokau-1 located just west of Taranaki Fault, slightly calcareous mudstone and sandy siltstone with quartz-rich sandstone intervals occur within the Turi Formation, suggesting sediment supply from a shelf, which will have to have been narrow and controlled by a major (Taranaki) fault separating it from a ridge of exposed Murihiku basement in the vicinity of the Herangi Range. Other wells in the Northern Taranaki region and west of Taranaki Fault (Waihi-1 PR 1862; Awakino-1, PR 1140) have intersected Turi Formation with shelfal bedded mudstone and minor sandstone. In Turi-1, the Turi Formation comprises L. Eocene shelf calcareous siltstone with common benthic foraminifers (open file PR 659). The thick accumulation of Turi Formation east of Taranaki Fault suggests that this fault controlled subsidence at this time. Evidence of whether it was a normal or reverse fault is difficult to establish due to the subsequent amount of basement overthrusting (King & Thrasher 1996), which has covered over or disrupted much of the structural and stratigraphic evidence.

Map 2 (Enclosure 3): latest Eocene (lowermost Whaingaroan) Waikato Coal Measures and Mangakotuku Formation

During the latest Eocene the extent of subsidence and sedimentation in the Waikato region increased, indicating regional onlap across basement. Deposition in localised coal measure depocentres continued into the earliest Whaingaroan. There is no evidence for a depositional break between the Waikato Coal Measures and the Mangakotuku Formation, which overlies the coal measures in the northern region (Kear & Schofield 1978). A large shallow marine embayment with estuarine and inner shelf environments extended over much of the northern region during the latest Eocene. The Mangakotuku Formation includes non-calcareous siltstone, muddy sandstone and shell beds (Kear 1963; Edbrooke et al. 1994). Glauconitic sandy facies (Pukemiro Sandstone Member) within the Mangakotuku Formation probably represents an interval of marine encroachment. Sand-rich coastal facies of the Waikaretu Sandstone Member accumulated along and offshore of a western shoreline. These sandy facies grade laterally into siltstone (Rotowaro Siltstone Member) of the Mangakotuku Formation to the east. In general, the absence of planktic foraminifera within the Mangakotuku Formation indicates a restricted marine environment and deposition in inner shelf water depths, possibly in a large embayment (Hornibrook et al. 1989). The degree of marine influence within the Mangakotuku Formation increases up-section, indicating a rise in base level (Kear & Schofield 1978). The location of the northeastern margin of the basin is poorly constrained, whereas low lying basement extended along much of the western margin forming a barrier between the Waikato and Taranaki basins. The elevation of basement along this western margin may have been maintained by unloading of the footwall on a normal Taranaki Fault.

In the southern region Waikato Coal Measures accumulated in narrow valleys, possibly including the Hamilton subbasin, where they are the age equivalent of the Mangakotuku Formation, which accumulated in the northern region (Pocknall 1991). The accumulation of coal measures in the south represents basement onlap. Shallow marine siltstone facies are interbedded with thin coal seams and silty sandstone facies with thin shell beds and conglomerate in places (Chapter 3), suggesting that terrestrial and marginal marine environments were in close proximity (Edbrooke et al. 1994). The Piopio High formed a dividing ridge between eastern and western areas of coal measure accumulation. The eastern limit of coal measure deposition is poorly constrained, but a few drill holes east of the Tihiroa Coalfield intersected thin coal measures indicating eastward thinning of the Waikato Coal Measures (Kirk 1985). A similar trend is apparent in the Te Kuiti Coalfield, where a wedge-shaped body thins eastward lapping basement of the Rangitoto Range. The overall pattern of asymmetric westward thickening suggests that contemporary faults may have been controlling subsidence in the south and southeast parts of the basin. The lack of exploratory drill holes between the Te Kuiti and Mangapehi Coalfields, mean that the paleogeography is poorly constrained, although coal measure deposition is known to have occurred in isolated fault-controlled depressions in the vicinity of Bennydale (Edbrooke et al. 1994).

Along the eastern margin of Taranaki Basin, thin glauconitic fine calcareous sandstone and limestone (Matapo Sandstone Member of Otaraoa Formation) are intersected Mokau-1, Waihi-1, Awakino-1 and Tirua-1, indicating that condensation shelf conditions developed across the earlier muddy shelf deposits (Turi Formation) (King & Thrasher 1996).

Map 3 (Enclosure 3): Early Oligocene (Lower Whaingaroan) Elgood Limestone and Dunphail Siltstone Member

During the Lower Whaingaroan there was substantial shoreline transgression to the west, south and east, and marine conditions became established across most of the basin. A striking feature in the northern region is the development of a carbonate shelf (Elgood Limestone Member) that fringed the western margin. The Elgood Limestone Member typically comprises flaggy, medium to coarse bioclastic limestone that accumulated in an inner to mid shelf environment. The limestone includes a high proportion of abraded shallow water foraminifera, particularly *Amphistegina*, and calcareous red algae, but mostly the carbonate contributors have been transported from their source areas. The Elgood Limestone is a TST deposit where the paleobathymetry deepened upward. To the east, marginal marine lithofacies (Mangakotuku Formation) are overlain by transgressive glauconite-rich sandy limestone and/or calcareous sandstone, indicating that the shallow marine embayment present during the lowermost Whaingaroan deepened to outer shelf conditions. The facies belts within the Elgood Limestone Member suggest a gently sloping shelf to the east, where correlative strata intersected in drill holes (over much of the Huntly Coalfield) comprise greensand (Kear & Schofield 1959; 1978; Edbrooke et al. 1994), interpreted as a condensed transgressive systems tract resulting from clastic sediment starvation. Calcareous siltstone (Dunphail Siltstone Member) accumulated as highstand system tract deposits in shelf depths above the TST deposits.

In the southern region a 10-40 km wide embayed carbonate shelf may have extended along the western margin. Limestone is inferred to have been deposited around structural highs and as shoal areas above submerged basement knolls. Elsewhere, lower Whaingaroan deposition was dominated by calcareous siltstone (Dunphail Siltstone Member), becoming glauconitic and occasionally shelly towards the base. The entire region east of this shelf embayment is inferred to have comprised basement above sea level (Piopio High), although coal measure deposition occurred in the Mangapehi sub-basin (Edbrooke et al. 1994). Basement above sea level occurred as islands in central areas (east of Raglan-Aotea-Kawhia harbours), until inundated by the Elgood Limestone Member.

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Along the eastern margin of Taranaki Basin, the lower Whaingaroan succession is represented by Otoraoa Formation with Matapo Sandstone Member at the base (Mokau-1, Waihi-1, Awakino-1 and Tirua-1) (Open files PR 1396, 1862, 1140, 1688). The formation marks a change to more calcareous sedimentation and comprises mainly muddy glauconitic sandstone, calcareous siltstone and silty limestone, inferred to have been deposited in a mid to outer shelf setting. Basement exposed between Taranaki and Waikato basins remained emergent throughout the lower Whaingaroan perhaps maintaining a continuous barrier between the basins.

Map 4 (Enclosure 3): Early Oligocene (lower Whaingaroan) Ahirau Sandstone Member

The accumulation of Ahirau Sandstone Member reflects eastward progradation of terrigenous sandstone across the northern and central parts of the basin. This sandstone is silty fine to very fine grained and variably calcareous and is inferred to have been deposited at inner to mid shelf depths along much of the western margin of the basin. A characteristic feature of this member is its extensive bioturbation, indicative of very low rates of accumulation. From regional evidence for the eastward direction of progradation of this systems tract, the sandstone is considered to have been sourced from erosion of Murihiku basement located between the present coastline and the Taranaki Fault, and possibly from a basement high immediately east of the Taranaki Fault.

The main axis for Ahirau Sandstone deposition lies between Onewhero in the north and Awamarino just south of Kawhia Harbour. The proportion of sand within the member progressively diminishes to the east of this axis, the eastern areas being dominated by correlative siltstone. In the vicinity of Te Akau and Raglan Harbour, the sandstone is remarkably thin and the facies glauconitic indicating greater paleobathymetry than would be anticipated, possibly due to fault movement and greater subsidence in the vicinity of the present harbours. Eastern areas of the basin, particularly north of Kawhia Harbour, accumulated facies equivalent to the Dunphail Siltstone, probably at outer shelf to upper bathyal conditions.

Ahirau Sandstone is poorly developed along the western margin south of Awamarino, where, south to Awakino, Dunphail Siltstone facies at least 100 m thick accumulated contemporaneously. This indicates that the basement high that previously had maintained a topographic barrier between the Waikato Basin and Taranaki Basin had subsided, possibly allowing a marine connection through to Taranaki Basin across what later became the Herangi High.

Along the eastern margin of Taranaki Basin, Otaraoa Formation accumulated as calcareous siltstone with limestone and silty limestone interbeds in an outer shelf to upper bathyal setting (King & Thrasher 1996).

Map 5 (Enclosure 3) Early Oligocene (mid Whaingaroan) Whaingaroa Formation

The mid Whaingaroan corresponds to a gradual but distinct deepening of the basin accompanied by the widespread deposition of predominantly calcareous siltstone (Kotuku Siltstone Member). In the northern region, a thick siltstone succession in the eastern and central parts progressively thins to the west. The outer shelf to upper bathyal depositional environments of this massive calcareous siltstone is indicated by the microfaunal assemblage, especially the abundance of planktic foraminifera such as *Globigerina euapertura* and *Globigerina labicrassata* (Hornibrook et al. 1989). Late in the accumulation of this formation the bathymetry became shallower, particularly in the Port Waikato-Waikaretu area where the top of the formation contains calcareous silty sandstone with interbeds of massive sandy siltstone (Waikorea Sandstone Member). These sandier facies represent a short-lived regression, with the sand derived from the remnants of the basement high to the west that earlier had supplied the Ahirau Sandstone. This basement source may also have supplied the terrigenous siltstone comprising the bulk of the Whaingaroa Formation; that is, the Kotuku Siltstone Member.

In the south, the distribution of Whaingaroa Formation is poorly constrained due to limited exposures. The strata belonging to Whaingaroa Formation are absent over much of the area immediately inland from Aotea-Kawhia Harbour, and some areas farther south, resulting in a marked unconformity between the Glen Massey Formation and the Aotea Formation. This unconformity indicates down cutting of at least a few tens of metres (i.e. the inferred thickness of the Whaingaroa Formation). Nevertheless, deposition is likely to have occurred over much of the central and western sector during mid-Whaingaroan time. The main control points are the distribution of shallow water carbonate facies (Awaroa Limestone Member), occurring in close geographic proximity to basement highs along the southeastern margin of the basin. With the onset of more regionally widespread subsidence, some elevated basement areas which had persisted as islands during Glen Massey accumulation (Map 4), became submerged during the mid-Whaingaroan. This is shown by the occurrence of Awaroa Limestone Member directly on basement in localities inland of Aotea and Kawhia harbours. In deeper parts of the shelf to the east (East Kawhia Coalfield) glauconitic sandstone and siltstone accumulated as a lateral equivalent of the Awaroa Limestone forming an important stratigraphic marker in many coal exploration drill holes in this area (Phelps 1985). There is a gradational transition from Awaroa Limestone and/or glauconitic sandstone into the overlying predominantly sandy siltstone (Ngapaenga Siltstone Member). This member is inferred to have accumulated in mid-outer shelf depths. The slightly coarser-grained character of this member compared with its correlative Kotuku Siltstone Member, probably reflects proximity to locally emergent basement source areas. Outer shelf-upper bathyal depths persisted in the mid-Whaingaroan across most of the eastern sector, and sedimentation was dominated by the Kotuku Siltstone Member.

Map 6 (Enclosure 3): mid Whaingaroan sub-Aotea unconformity

The most extensive unconformity within the Te Kuiti Group occurs at the base of the Aotea Formation within the upper Whaingaroan at about 29 Ma. The extent of this unconformity is shown in Map 6. The development of this unconformity involved inversion of western parts of the basin and erosion of the underlying formations. It was particularly pronounced in southwestern areas between Awakino and inland Kawhia Harbour and north to Port Waikato, representing a zone about 30km wide east of the Taranaki Fault. In these areas the Whaingaroa Formation was substantially eroded by subaerial processes, the degree of incision amounting to a few tens of metres and not sufficient to strip the whole of the lower part of the Te Kuiti Group. The inversion is considered to have been associated with the start of reverse movement on the Taranaki Fault and elevation of the Herangi High as uplift of the hanging wall. The subaerial erosion of the Whaingaroa Formation was followed by wave planation during inundation associated with subsidence and the start of accumulation of Aotea Formation. Much of the southern region east of the Waipa Fault may not have been inverted and eroded, and in the northeastern parts of the basin the unconformity passes into a correlative conformity.

Map 7 (Enclosure 3): Mid Oligocene (mid to upper Whaingaroan) lower parts of the Aotea Formation

The basin inversion that had affected the western parts of the basin during the mid Whaingaroan was followed by regional subsidence, wave planation, and accumulation of the lower units of the Aotea Formation. The deposition of the Hauturu Sandstone Member represents the introduction of exotic sediments to the basin sourced from the south. This sandstone was deposited as shoreface deposits immediately east of exposed basement of the Herangi High, and this member extended northwards via longshore drift. This system was fed by fine to medium quartzofeldspathic sand. This sand was re-worked across the inner shelf to the east by storm processes coupled with strong tidal currents. The thickness trend of the Hauturu Sandstone suggests that at the northern end of the Herangi High sand was fed offshore to the west into Taranaki Basin, forming possible submarine fan deposits. The Hauturu Sandstone facies generally thins in an eastward direction and grades laterally into bioturbated muddy sandstone facies of the Kihi Sandstone Member. With ongoing subsidence shallow marine environments encroached upon the Piopio High resulting in deposition of pebbly and sandy limestone facies (Waimai Limestone Member). This sandy limestone consists of shallow shelf fauna (e.g. *Amphistegina* foraminifera and calcareous red algae) reworked from adjacent rocky platforms fringing the basement high (Nelson 1973, 1978a).

In northern parts of the basin, terrigenous sedimentation was minimal compared with the central and southern regions. By the mid-upper Whaingaroan a carbonate shelf platform formed around the northwestern margin forming the Waimai Limestone Member. This limestone has characteristic large-scale cross-stratification, representing the migration of a carbonate dune field at inner to mid shelf depths through the action of tidal currents (Alexis 1997). The carbonate sands were derived from carbonate banks and shoals fringing a low lying basement ridge east of Taranaki Fault. The Waimai Limestone Member grades into interbedded calcareous sandstone and siltstone (Mangiti Sandstone Member) that accumulated in mid-outer shelf depths in the eastern and southern areas. This limestone reaches its thickest development at Waimai Valley north of Raglan Harbour. Outer shelf to upper bathyal water depths persisted across most of the eastern sector into the mid-upper Whaingaroan where sedimentation was dominated by calcareous siltstone with intercalated fine sandstone and glauconitic horizons.

Within the eastern margin of Taranaki Basin Tariki Sandstone Member was deposited between the Taranaki Fault and the Tariki Fault Zone as a submarine fan succession within slope deposits of the Otaraoa Formation. The shelf-slope break was pinned to the Taranaki Fault (King & Thrasher 1996).

Map 8 (Enclosure 3): mid Oligocene (upper Whaingaroan to lower Duntroonian) upper parts of the Aotea Formation

Accumulation in the northern region of Patikirau Siltstone Member as thin glauconitic and phosphatic muddy siltstone occurred during substantial foundering of the inner to mid shelf across which Waimai Limestone had earlier accumulated. This stratigraphic interval is highly condensed and probably spans the upper Whaingaroan to Duntroonian. The extremely low sedimentation rates reflect distance from any source of terrigenous input and drowning of the shelf. A similar deepening trend is evident along the entire western margin of the northern region, where the cross-bedded Waimai Limestone Member and its lateral correlative (Mangiti Sandstone Member) grades upwards into horizontally bedded units and then into massive sandy siltstone (Patikirau Siltstone Member). This foundering of the shelf appears to have migrated from north to south. In northeastern parts of the basin upper bathyal environments are inferred to have become more extensive.

In the Aotea-Kawhia region in central parts of the basin, the Hauturu Sandstone Member grades upwards into heavily bioturbated, variably calcareous muddy sandstone lithofacies of the Kihi Sandstone Member. This also indicates foundering of the shelf. In the vicinity of Waitomo and Honikiwi (area shown to the north of Piopio High in Map 8), there was subsidence to outer shelf depths with accumulation of Kihi Siltstone, but the supply of siltstone evidently decreased markedly by the upper Whaingaroan to earliest Duntroonian, leading to the deposition of a fossiliferous glauconitic sandstone (Nelson 1973, 1978a). Immediately east of the Herangi High the Hauturu Sandstone Member is the only element of the Aotea Formation; while the Kihi Siltstone may have been eroded, it is inferred that the Hauturu Sandstone continued to accumulate during highstand conditions.

In the eastern margin of Taranaki Basin, as shown by the records in Mokau-1 and Awakino-1 (Open files PR 1396, 1140), the mid-Oligocene record comprises variably calcareous, clastic strata of the Otaraoa Formation (King & Thrasher 1996).

Map 9 (Enclosure 3): mid Oligocene (upper Whaingaroan to lower Duntroonian) extent of the sub-Castle Craig Subgroup unconformity

A significant unconformity lies at the base of the Castle Craig Subgroup in the southern region. This unconformity is most strongly developed west of the Herangi High between Awakino and Awamarino, but it also occurs in south-central areas (Waitomo-Honikiwi) where the Aotea Formation was erosionally truncated by wave planation. In the Awakino Tunnel section this unconformity between the Aotea and Orahiri formations is a scoured erosional surface overlain by a prominent pebble band including basement clasts and bored calcareous lithoclasts (Nelson et al. 1994). At the Mangaotaki Bridge section the unconformity is a sharp planar surface and the amount of section removed by subaerial processes as opposed to subsequent wave planation is difficult to assess. In the vicinity of Awamarino, this unconformity marks a direct contact between Glen Massey Formation and Orahiri Formation, implying lowering of at least a few tens of metres (i.e. the thickness of missing Aotea interval). This unconformity is also present in the south- central region (e.g. Waitomo, Honikiwi and Oparure), its origin possibly related to movement on the Waipa Fault, together with subsequent wave planation. However, in the central inland Aotea-Kawhia region, the contact between the Aotea and overlying Castle Craig Subgroup appears to be gradational. A change to more calcareous sedimentation marks the base of the Castle Craig Subgroup in these areas.

In the northern region, a correlative unconformity marks the contact between the Aotea Formation and the Te Akatea Formation. This contact is better described as a paraconformity characterized by an intensely burrowed glauconitic and phosphatic zone some 30-50 cm thick. This depositional hiatus was primarily caused by sediment starvation. Hence outer shelf to upper bathyal conditions became widespread across the northern region as there is no indication of the inversion evident in the southern region.

Map 10 (Enclosure 3): Late Oligocene (Duntroonian) lower parts of the Castle Craig Subgroup

Following basin inversion (Map 9) in the southern region, subsidence resumed and marine conditions were re-established during the Duntroonian across this part of the basin leading to accumulation of the lower parts of the Castle Craig Subgroup. A substantial area of carbonate shelf developed east of the Herangi High. The paleogeographic conditions that had introduced the quartzofeldspathic sand (Hauturu Sandstone) to the basin had clearly changed, shutting off the supply of this terrigenous sandstone. This was a major factor in enabling extensive carbonate production along the shoreline with the Herangi Range, particularly. Hence Map 10 shows a narrow seaway stretching NNE-SSW rimmed on its western and eastern sides by the Herangi and Piopio basement highs, respectively, and it was the rocky shoreline along these highs where the carbonate was produced. This seaway would have had strong tidal currents and together with storms were important as mechanisms to break up the carbonate contributors and disperse the fragmental bioclasts (coarse to very coarse bryozoan-benthic foraminiferal-echinoid skeletal grainstone) from the shorelines onto the inner and mid shelf (Nelson 1973, 1978a; Alexis 1997). The Mangaotaki Limestone Member at the base of the Orahiri Formation is a yellowish sandy limestone. The terrigenous sand within this formation was probably derived from erosion of parts of the Hauturu Sandstone. The overlying Te Anga Limestone Member is a more pure limestone, typified by the presence of common large oysters amongst pebbly, micritic, very coarse, bryozoan-bivalve-benthic foraminiferal limestone (Nelson 1983).

The sea floor gradually deepened to the north and in the vicinity of Raglan Harbour and farther northward, sedimentation occurred in outer shelf and upper bathyal water depths. Hence the shelf grainstone (Orahiri Formation) south of Raglan passes north into micritic limestone (Raglan Limestone Member) and farther north into marl (Carter Siltstone Member). Raglan Limestone Member reaches its maximum thickness of about 18 m around the Raglan Harbour where it comprises micritic limestone with marl interbeds of variable thickness rich in planktic foraminifera. Paleocurrent patterns for the Orahiri Formation (Anastas 1997) indicate northward sediment transport in support of the interpretation of a northward paleoslope. North of Raglan Harbour, the Raglan Limestone undergoes a gradual change to basinal marl facies (Carter Siltstone Member).

In the south-central region there are two carbonate formations (Orahiri Formation and Otorohanga Limestone) separated by an unconformity, however farther to the east the carbonate comprises one progradational succession.

Map 11 (Enclosure 3): Late Oligocene to earliest Miocene (Waitakian) upper parts of the Castle Craig Subgroup

During the Waitakian the seafloor in the northern region was at upper bathyal depths and calcareous siltstone accumulated across most of this part of the basin. The Raglan Limestone was supplanted by accumulation of Carter Siltstone Member, and upper parts of this member have a higher terrigenous content than lower parts.

In the southern parts of the basin extensive grainstone of the Otorohanga Limestone accumulated at shelf depths, with progradation of the carbonate sand eastward and across northern parts of the Piopio High. Throughout the lower Waitakian there may have been continuing uplift of the Herangi High giving rise to limited unconformities between Orahiri Formation and Otorohanga limestone and between members of the Otorohanga Limestone, reflecting displacement on the Taranaki and Manganui faults and minor inversion of the basin. For example, the marine-cemented micritic oyster-bearing top of the Te Anga Limestone Member (Orahiri Formation) is truncated by an irregular surface veneered by iron-stained basement and/or limestone clasts, and overlain by well flagged Otorohanga Limestone (Nelson 1978a; Nelson et al. 2000). In the vicinity of Te Kuiti and Piopio, the entire limestone succession was deposited on basement, implying progradation of the limestone sheets to the east.

In the Aotea-Kawhia Harbour area, there is a transition from limestone to highly fossiliferous silty sandstone at the top of the Otorohanga Limestone. This silty sandstone is equivalent to the Carter Siltstone Member and represents retrogradation of the depositional systems to the south. This encroachment will have been at the expense of the extent of limestone accumulation, as shown by differences between Maps 10 and 11.

The Tikorangi Formation, which has limestone as a major component is well developed in parts of the eastern margin of Taranaki Basin (Hood et al. 2003). In Mokau-1, Waihi-1, Awakino-1 and Turi-1, a sequence of calcareous siltstone, silty limestone, and sparry grainstone up to 70 m thick within Tikorangi Formation is inferred to have been deposited on a continental slope immediately west of the Taranaki Fault. There would have been a very narrow shelf over parts of the Patea-Tongaporutu High at this time, which sourced the carbonate detritus to the slope environment (Hood et al. 2003).

Map 12 (Enclosure 3): Early Miocene (uppermost Waitakian to lowermost Otaian) extent of the sub-Waitemata – Mahoenui Group unconformity

During the mid Waikatian there were substantial changes in the paleogeography of the basin due to tectonic movements. In the northern region the basin was inverted, with erosion of parts of the Te Kuiti Group. The erosion at this level has previously been described by Kear (1963, 1987) and Kear & Schofield (1978). They noted how the Waitemata Group rests on progressively older Te Kuiti group formations in a northeast direction, with deposition on basement in the Hunua Range where the Te Kuiti Group was completely eroded. The basin inversion, uplift and erosion of the Te Kuiti Group were least along the present (western) coastline. The inversion carried the Carter Siltstone from upper bathyal depths into the zone of wave erosion, leading to its planar truncation; in some sections there is evidence of a slight coarsening upwards in the top of the member suggestive of regressive sedimentation. The amount of erosion of Carter Siltstone in these coastal sections is difficult to estimate, but probably only involves 10 m of so. Map 12 shows how the uplift in the Waikatian was focused to the northeast.

Except in sections close to the Herangi High, the southern part of the basin subsided dramatically during the mid Waitakian, leading to accumulation of the Mahoenui Group, which is dominated by calcareous siltstone. This subsidence, and especially the introduction of rapidly deposited terrigenous siltstone, terminated prior accumulation of the Otorohanga Limestone. The Piopio High, which was already subsiding prior to the start of Mahoenui Group deposition, was almost completely overtopped by the end of the Waitakian. A shoreline existed along the eastern margin of the Herangi High where neritic limestone (Black Creek and Awakino Limestone Members) accumulated intercalated with silty sandstone and silty sandstone (Nelson 1978a; Nelson et. al. 1994).

Map 13 (Enclosure 3): Early Miocene (uppermost Waitakian to lowermost Otaian) basal Waitemata Group and Mahoenui Group

Following mid Waitakian uplift and erosion in the northern region, this area started to subside to form a new basin known as the Waitemata Basin, which is best known in the Auckland region (e.g. Edbrooke 2001). The basal sediments in the Waitemata Basin between Port Waikato and Raglan appear to be of upper Waitakian age (Hornibrook & Schofield 1963), so the prior inversion, uplift and erosion phase was short-lived. The lowermost sediments in the Waitemata Group comprise different lithologies in each of the coastal sections, reflecting diversified basal facies (Hayward & Brook 1984). It may be that sedimentation at the base of the Waitemata Group started in the west and onlapped eastward, but there are virtually no constraints on this pattern, which is inferred in Map 13. Within a few tens of metres of the lower contact the basal facies pass into the Gibson Siltstone, which accumulated at bathyal depths.

In the southern region Mahoenui Group accumulated at upper to mid bathyal depths. The Herangi High persisted through the upper Waitakian and Otaian as a basement high, but any previous high to the east became completely submerged within the Otaian.

In the eastern margin of Taranaki Basin the Tikorangi Formation is abruptly overlain by bathyal Taimana Formation, comprising mainly calcareous siltstone or marl with varying proportions of fine sandstone and thin limestone. The Taimana Formation is a correlative of the Mahoenui Group, but it has higher carbonate content, reflecting a more distal location from the main source of terrigenous sediments, being the evolving Australia-Pacific plate boundary to the southeast (King & Thrasher 1996).

Overview of stratigraphic architecture of late Paleogene mixed carbonate-siliciclastic shelf sequences of Te Kuiti Group

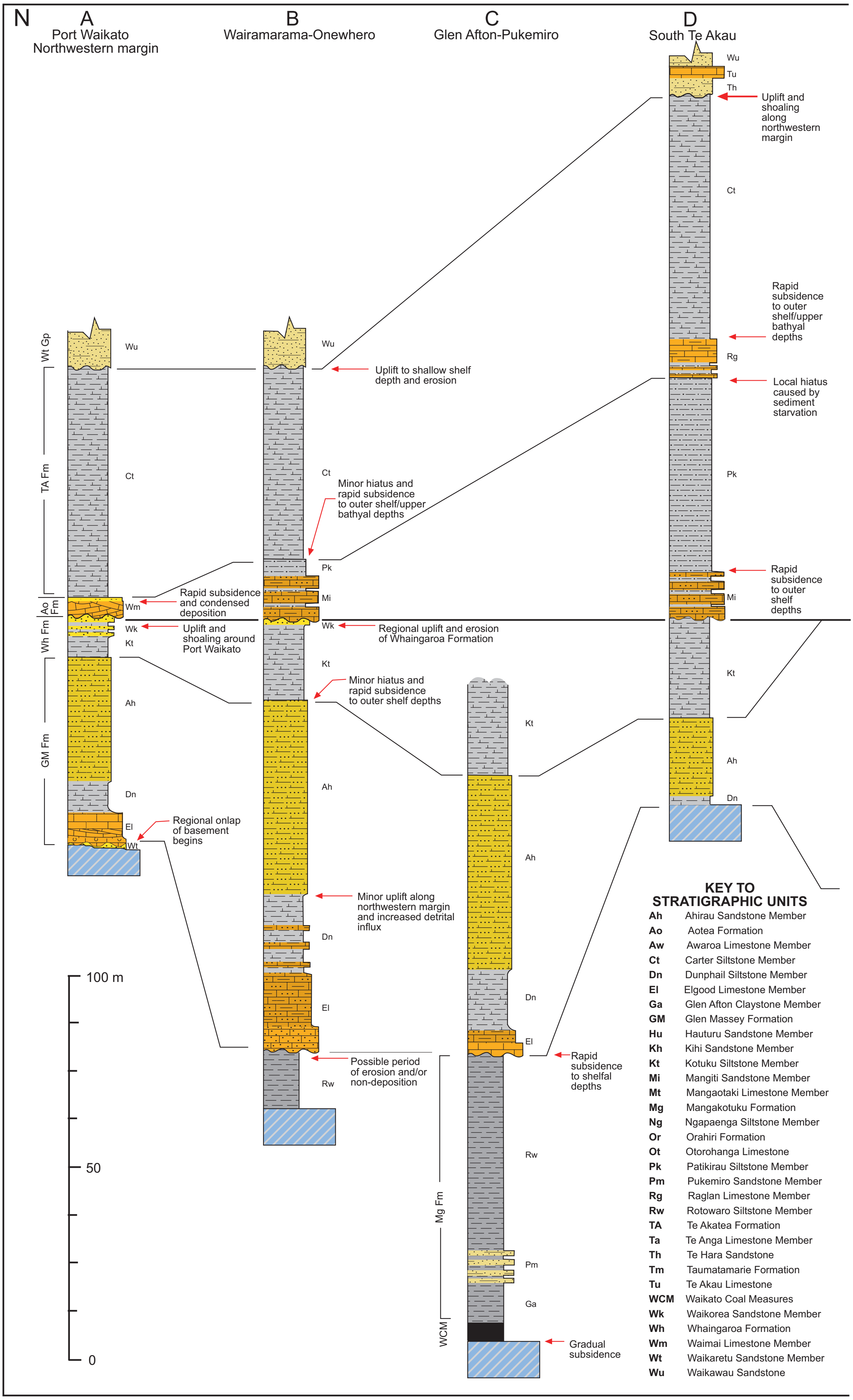
Fig 8.1 is a north-south regional transect constructed from composite stratigraphic sections illustrating information about the distribution, lithology, stratigraphic nomenclature and thickness of the Te Kuiti Group in key outcrop areas. Key unconformities and associated events are also highlighted. A related and simplified chronostratigraphic panel has also been constructed showing in a very general way the linked depositional systems (Fig. 8.2). It depicts the generalised depositional patterns and sequence architecture along a North - South section through the western side of the basin. In all, six carbonate-siliciclastic or pure carbonate depositional sequences (TK1-6) of third- or fourth-order are identified and correlated across the study area. It is appreciated, however, that the sequence bounding unconformities or their correlative conformities may not be synchronous everywhere. The unconformity at the base of each depositional cycle typically represents a period of base level fall, and the overlying section represents the ensuing transgression and highstand. In the more basinal positions in the east, unconformities are less pronounced and correlative conformities more common. The vertical and lateral distribution of these facies appears complex, but when considered within the proposed sequence stratigraphic framework, the patterns are simplified and provide useful insight into the complex interplay of local tectonics, sediment supply, inherited basement morphology, depositional processes, and possible glacio-eustatic sea-level oscillations. Also shown in Fig. 8.2 is a first-order correlation of the Te Kuiti Group sequences with the lithostratigraphic nomenclature for the eastern margin of Taranaki Basin.

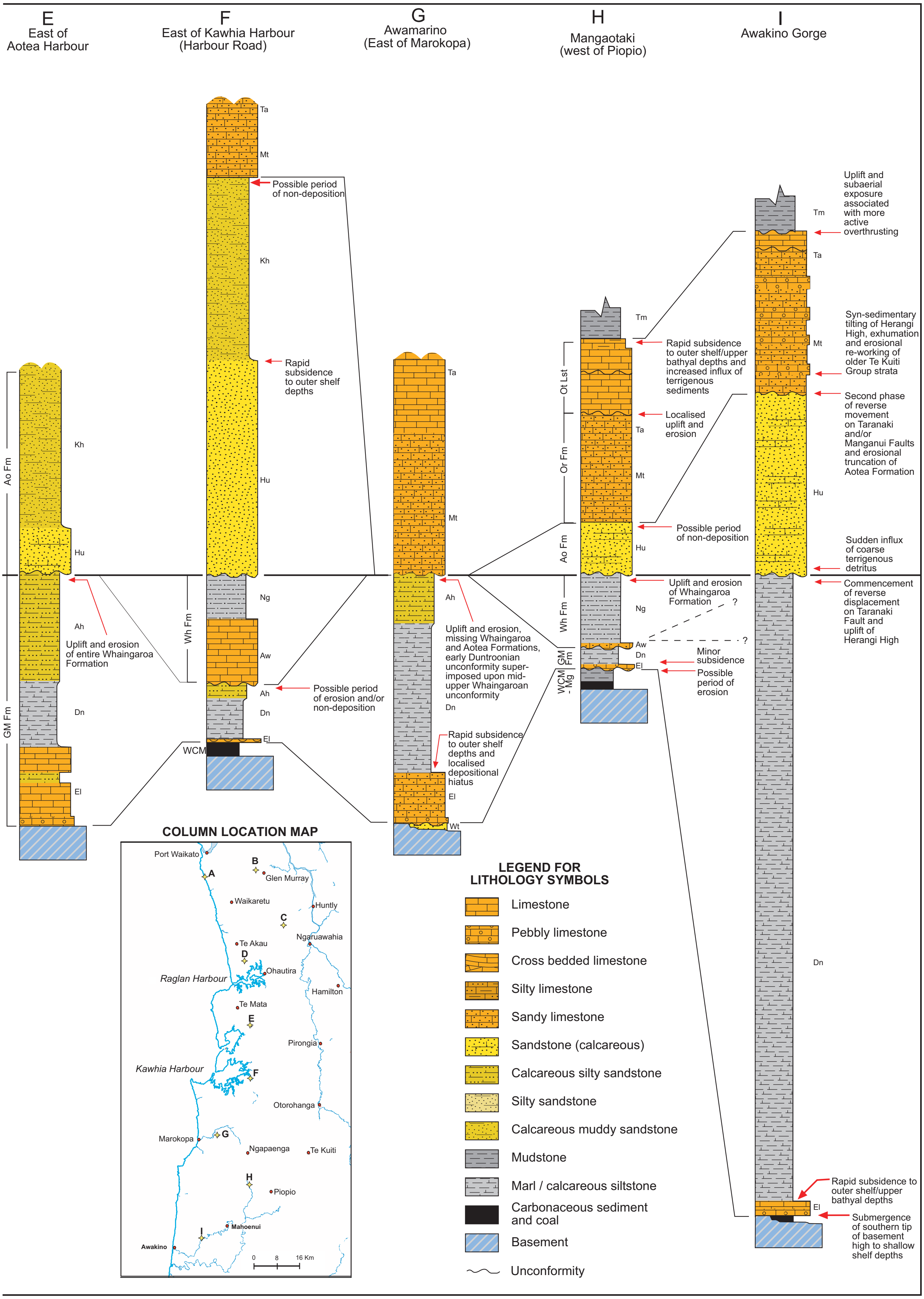
Controls on depositional patterns

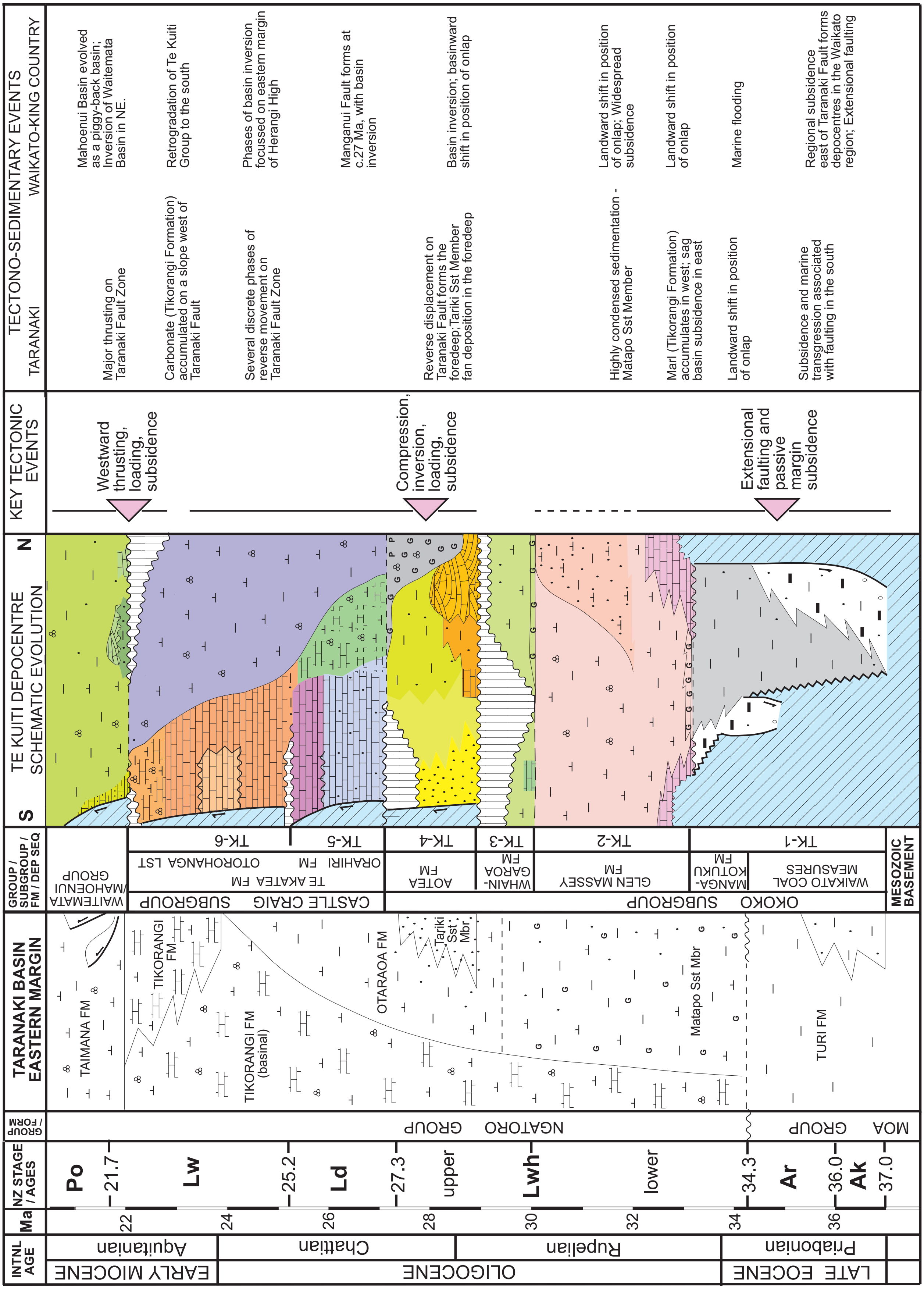
Evaluation of the relative effects of tectonism and eustasy on the basin fill:

One of the thesis objectives is to investigate the impact of global sea-level fluctuations on the character of the basin fill. Well before Vail et al. (1977) published on the principles of sequence stratigraphy, Vella (1967) argued that the unconformity-bound stratigraphic units of the Te Kuiti Group and other neritic strata of similar age occurring around New Zealand may have formed in response to global eustatic sea-level fluctuations. He reported apparent matches between the Paleogene cyclothemic record of New Zealand and South Australia, Eastern U.S.A and Western Europe, and attributed them to eustatic sea-level changes. Since the development of sequence stratigraphic concepts, the results of various studies of basins around

Fig. 8.1 (following two-page spread): North-south regional transect showing composite stratigraphic column correlation for the Te Kuiti Group and basal Waitemata/Mahoenui Group. Also shown are six depositional sequences and their lateral extent based on nine composite columns (A-I). Solid lines represent major unconformities/sequence boundaries bounding each depositional sequence. Other significant depositional events are also highlighted. Datum line coincides with the mid-Late Oligocene unconformity (sub-Aotea unconformity).


N
A
Port Waikato
Northwestern margin
B
Wairamarama-Onewhero
C
Glen Afton-Pukemiro
D
South Te Akau
Wt Gp
TA Fm
Ao Fm
Wh Fm
GM Fm
Wu
Ct
Wm
Wk
Kt
Ah
Dn
El
Wt
Pk
Mi
Rw
Pm
Ga
Tu
Th
Rg
Mg Fm
WCM
Uplift and shoaling along northwestern margin
Rapid subsidence to outer shelf/upper bathyal depths
Local hiatus caused by sediment starvation
Rapid subsidence to outer shelf depths
Uplift to shallow shelf depth and erosion
Minor hiatus and rapid subsidence to outer shelf/upper bathyal depths
Rapid subsidence and condensed deposition
Uplift and shoaling around Port Waikato
Regional uplift and erosion of Whaingaroa Formation
Minor hiatus and rapid subsidence to outer shelf depths
Regional onlap of basement begins
Minor uplift along northwestern margin and increased detrital influx
Possible period of erosion and/or non-deposition
Rapid subsidence to shelfal depths
Gradual subsidence
100 m
50
0
KEY TO STRATIGRAPHIC UNITS
Ah Ahirau Sandstone Member
Ao Aotea Formation
Aw Awaroa Limestone Member
Ct Carter Siltstone Member
Dn Dunphail Siltstone Member
El Elgood Limestone Member
Ga Glen Afton Claystone Member
GM Glen Massey Formation
Hu Hauturu Sandstone Member
Kh Kihi Sandstone Member
Kt Kotuku Siltstone Member
Mi Mangiti Sandstone Member
Mt Mangaotaki Limestone Member
Mg Mangakotuku Formation
Ng Ngapaenga Siltstone Member
Or Orahiri Formation
Ot Otorohanga Limestone
Pk Patikirau Siltstone Member
Pm Pukemiro Sandstone Member
Rg Raglan Limestone Member
Rw Rotowaro Siltstone Member
TA Te Akatea Formation
Ta Te Anga Limestone Member
Th Te Hara Sandstone
Tm Taumatamarie Formation
Tu Te Akau Limestone
WCM Waikato Coal Measures
Wk Waikorea Sandstone Member
Wh Whaingaroa Formation
Wm Waimai Limestone Member
Wt Waikaretu Sandstone Member
Wu Waikawau Sandstone


E
East of Aotea Harbour
F
East of Kawhia Harbour (Harbour Road)
G
Awamarino (East of Marokopa)
H
Mangaotaki (west of Piopio)
I
Awakino Gorge
Ao Fm
GM Fm
Wh Fm
WCM
Ot Lst
Or Fm
GM Fm
WCM - Mg
Kh
Hu
Ah
Dn
El
Ta
Mt
Ng
Aw
Wt
Tm
Uplift and erosion of entire Whaingaroa Formation
Possible period of non-deposition
Rapid subsidence to outer shelf depths
Possible period of erosion and/or non-deposition
Uplift and erosion, missing Whaingaroa and Aotea Formations, early Duntroonian unconformity super-imposed upon mid-upper Whaingaroan unconformity
Rapid subsidence to outer shelf depths and localised depositional hiatus
Rapid subsidence to outer shelf/upper bathyal depths and increased influx of terrigenous sediments
Localised uplift and erosion
Possible period of non-deposition
Uplift and erosion of Whaingaroa Formation
?
Minor subsidence
Possible period of erosion
Uplift and subaerial exposure associated with more active overthrusting
Syn-sedimentary tilting of Herangi High, exhumation and erosional re-working of older Te Kuiti Group strata
Second phase of reverse movement on Taranaki and/or Manganui Faults and erosional truncation of Aotea Formation
Sudden influx of coarse terrigenous detritus
Commencement of reverse displacement on Taranaki Fault and uplift of Herangi High
Rapid subsidence to outer shelf/upper bathyal depths
Submergence of southern tip of basement high to shallow shelf depths
COLUMN LOCATION MAP
Port Waikato
A
B
Glen Murray
Waikaretu
Huntly
C
Te Akau
Ngaruawahia
D
Ohautira
Raglan Harbour
Hamilton
Te Mata
E
Pirongia
Kawhia Harbour
F
Otorohanga
Marokopa
G
Ngapaenga
Te Kuiti
H
Piopio
Mahoenui
I
Awakino
0
8
16 Km
LEGEND FOR LITHOLOGY SYMBOLS
Limestone
Pebbly limestone
Cross bedded limestone
Silty limestone
Sandy limestone
Sandstone (calcareous)
Calcareous silty sandstone
Silty sandstone
Calcareous muddy sandstone
Mudstone
Marl / calcareous siltstone
Carbonaceous sediment and coal
Basement
Unconformity



TARANAKI

Major thrusting on Taranaki Fault Zone

Carbonate (Tikorangi Formation) accumulated on a slope west of Taranaki Fault

Several discrete phases of reverse movement on Taranaki Fault Zone

Reverse displacement on Taranaki Fault forms the foredeep; Tariki Sst Member fan deposition in the foredeep

Highly condensed sedimentation - Matapo Sst Member

Marl (Tikorangi Formation) accumulates in west; sag basin subsidence in east

Landward shift in position of onlap

Subsidence and marine transgression associated with faulting in the south

WAIKATO-KING COUNTRY

Mahoenui Basin evolved as a piggy-back basin; Inversion of Waitemata Basin in NE.

Retrogradation of Te Kuiti Group to the south

Phases of basin inversion focussed on eastern margin of Herangi High

Manganui Fault forms at c.27 Ma, with basin inversion

Basin inversion; basinward shift in position of onlap

Landward shift in position of onlap; Widespread subsidence

Landward shift in position of onlap

Marine flooding

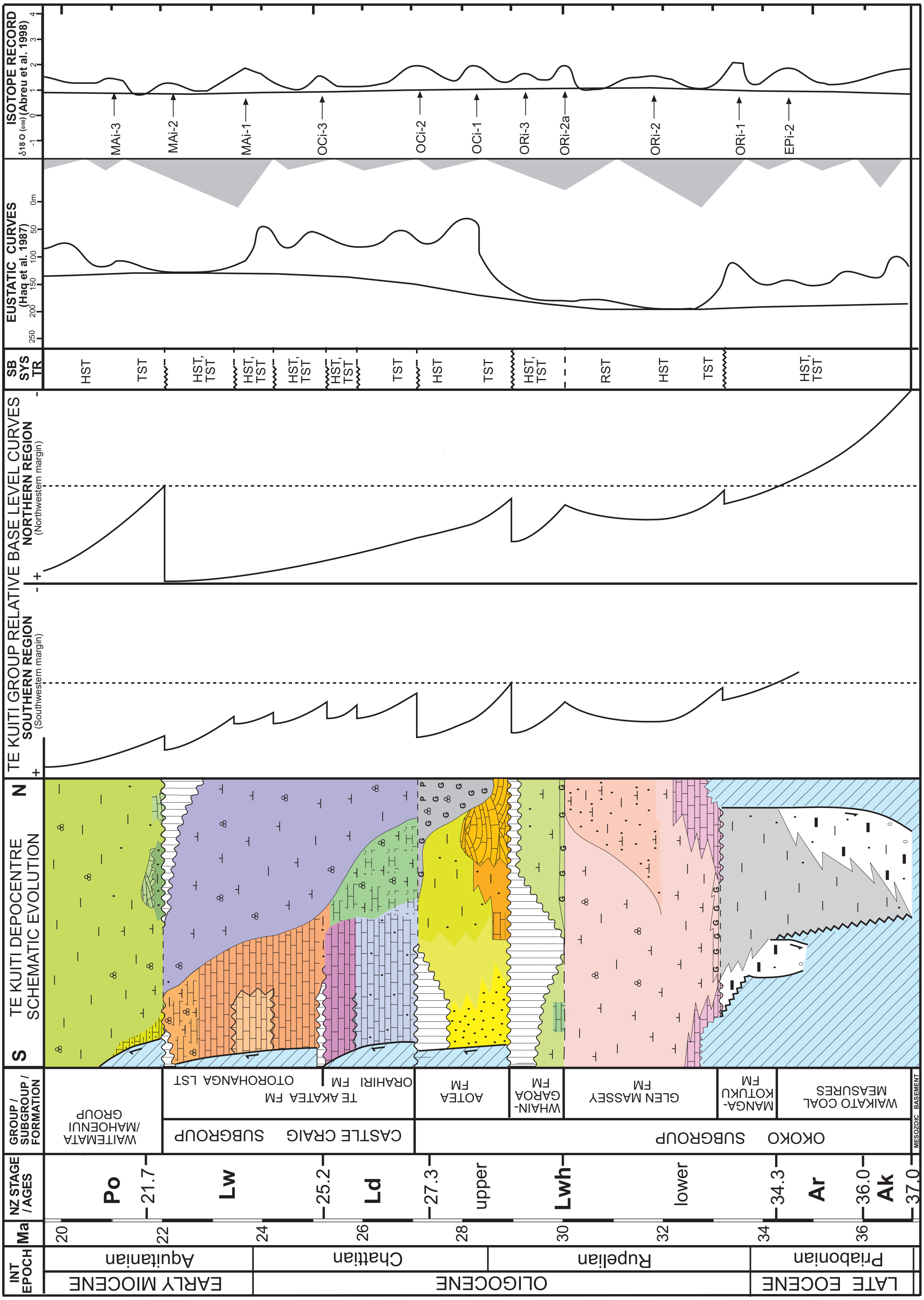
Regional subsidence east of Taranaki Fault forms depocentres in the Waikato region; Extensional faulting the world were drawn together to derive a "global sea-level curve" for the Mesozoic and Cenozoic (Haq et al. 1987, Hardenbol et al. 1998). Other researchers have also published Oligocene eustatic curves derived through sequence stratigraphic analyses of passive margin successions such as the New Jersey continental margin, and from proxy sea-level curves inferred from the oxygen isotope record (Miller et al. 1996; Pekar & Miller 1996, Pekar et al. 2001, 2003). These authors along with Abreu et al. (1998) have demonstrated the existence of up to 7 to 8 eustatic sea level fluctuations during the Oligocene.

The Oligocene record in New Zealand generally corresponds to an interval of slow regional subsidence and maximum submergence of the New Zealand subcontinent. The Oligocene sediments consist predominantly of carbonates, and traditionally the widespread development of limestone lithofacies has been attributed to the effects of maximum transgression, minimum land area and therefore minimum terrigenous sediment input. The Oligocene limestone units in New Zealand basins often contain several unconformities of uncertain origin, although several possible causes have been postulated. Nelson & Hume (1977), after investigating the relative intensity of tectonic events within the Te Kuiti Group and younger Tertiary sediments cropping out in the King Country, concluded that there was tectonic quiescence during the Oligocene in the region. However new work suggests that there was tectonic deformation during the Oligocene associated with the early development of the Australia-Pacific plate boundary through the subcontinent (Kamp 1986; King et al. 1999; King 2000).

Tectonic vs. glacio-eustatic cyclicity in the Te Kuiti Group:

To evaluate the relative effects of tectonism and glacio-eustasy on the development of the Te Kuiti Group stratigraphic record, a relative base level curve for each of the northern and southern regions of the basin have been constructed as a proxy for changes in available accommodation space, and also to reflect broad shifts in depositional patterns (Fig. 8.3). Overall, the curves show an intermittent but persistent rise in relative base level from the latest Eocene (Runangan) to the earliest Miocene (upper Waitakian) when maximum marine inundation occurred. Thereafter, a regressive depositional pattern has predominated. The relative base level curves derived for the Te Kuiti Group in western central North Island are compared with Haq's et al's (1987) eustatic sea-level curve and the smoothened oxygen isotope record of Abreu et al. (1998). There is little resemblance between

Fig. 8.2 (facing page): North-south chronostratigraphic synthesis panel for the Te Kuiti Group showing broad depositional patterns, major unconformities and stratigraphic architecture. Also shown are the stratigraphic correlation with the neighboring eastern margin of Taranaki Basin (on the left panel), and comparison with broad late-Paleogene tectonic development of the New Zealand subcontinent (on the right panel).


INT EPOCH
LATE EOCENE
OLIGOCENE
EARLY MIOCENE
Priabonian
Rupelian
Chattian
Aquitanian
Ma
20
22
24
26
28
30
32
34
36
NZ STAGE / AGES
Po
21.7
Lw
25.2
Ld
27.3
upper
Lwh
lower
34.3
Ar
36.0
Ak
37.0
GROUP / SUBGROUP / FORMATION
WAITEMATA/MAHOENUI GROUP
CASTLE CRAIG SUBGROUP
OKOKO SUBGROUP
MESOZOIC BASEMENT
OTOROHANGA LST
TE AKATEA FM
ORAHIRI FM
AOTEA FM
WHAINGAROA FM
GLEN MASSEY FM
MANGAKOTUKU FM
WAIKATO COAL MEASURES
TE KUITI DEPOCENTRE SCHEMATIC EVOLUTION
S
N
TE KUITI GROUP RELATIVE BASE LEVEL CURVES
SOUTHERN REGION
(Southwestern margin)
NORTHERN REGION
(Northwestern margin)
+
-
SB SYS TR
HST
TST
HST, TST
RST
EUSTATIC CURVES (Haq et al. 1987)
0m
50
100
150
200
250
ISOTOPE RECORD δ18 O (‰) (Abreu et al. 1998)
-1
0
1
2
3
4
MAi-3
MAi-2
MAi-1
OCi-3
OCi-2
OCi-1
ORi-3
ORi-2a
ORi-2
ORi-1
EPi-2

the Te Kuiti Gp relative sea level curves and the Haq et al. and Abreu et al. curves. In particular the substantial and permanent drop in the Haq curve at about 29 -28 Ma is not evident in the Te Kuiti Group curves. However, some unconformities bounding third- to fourth-order cycles in the Te Kuiti Group could match base-level shifts on the global eustatic curves, but specific correlations are difficult to make given the uncertainty in the ages of strata in all the records. Although there is a major shoaling event at about 28 - 29 Ma in the Haq record, this is not evident in the Abreu curve, but does coincide with the base of Cycle 4 (Aotea sequence). Although it is difficult to scale the magnitude of relative sea level change in absolute terms, the relative movements in the Te Kuiti Group, involving exposure of inner to mid shelf areas at several unconformities, is greater than the magnitude that can be inferred from the isotope record or the records from the New Jersey margin of about 25 m or so.

The third-order depositional cyclicity observed within the Te Kuiti Group therefore has not been interpreted as being due primarily to glacio-eustatic sea level oscillations. Each depositional sequence in the Te Kuiti Group is of the order of 1-3 m.y., which is too long to be associated with Milankovitch cyclicity, and the sequences are therefore more likely to have a local tectonic origin. Certainly, the origin of the cyclic sequences that needs to be excluded first is the local tectonic origin. Albeit incomplete, each of the Te Kuiti Group cycles typically contain transgressive and highstand systems tracts, with regressive systems tracts being less common and absent in the case of some of the sequences (e.g. Aotea sequence, Castle Craig Subgroup sequence). Taken together, the nature of the sequence record in the Te Kuiti Group suggests that tectono-eustasy rather than glacio-eustasy is the driving force behind the origin of the cyclicity.

Subsidence and sediment supply:

Late Eocene to earliest Miocene sediment accumulation rate histograms along a north-south transect through the study area are illustrated in Fig. 8.4. Histograms of sediment accumulation rate calculated using average formation thicknesses (not corrected for compaction) divided by their duration provide approximations of changes in accumulation rates and hence long term subsidence for locations, and enable comparisons to be made between the main sub regions in the field area. Subsidence began in the Late Eocene in the northern region (exemplified by

Fig. 8.3(facing page): The schematic curve of relative base level changes for the northern and southern region is compared with the Te Kuiti chronostratigraphic panel to illustrate changes in available accommodation space through time. The dashed line in the centre represents present day shoreline position (zero datum). The relative base level curve is regarded as proxy for sea level changes and it is also compared with eustatic curve of Haq. et al. (1987) and the smoothened oxygen isotope record of Abreu et al. (1998). The grey triangles represent maximum flooding events inferred by Haq et al. (1987).

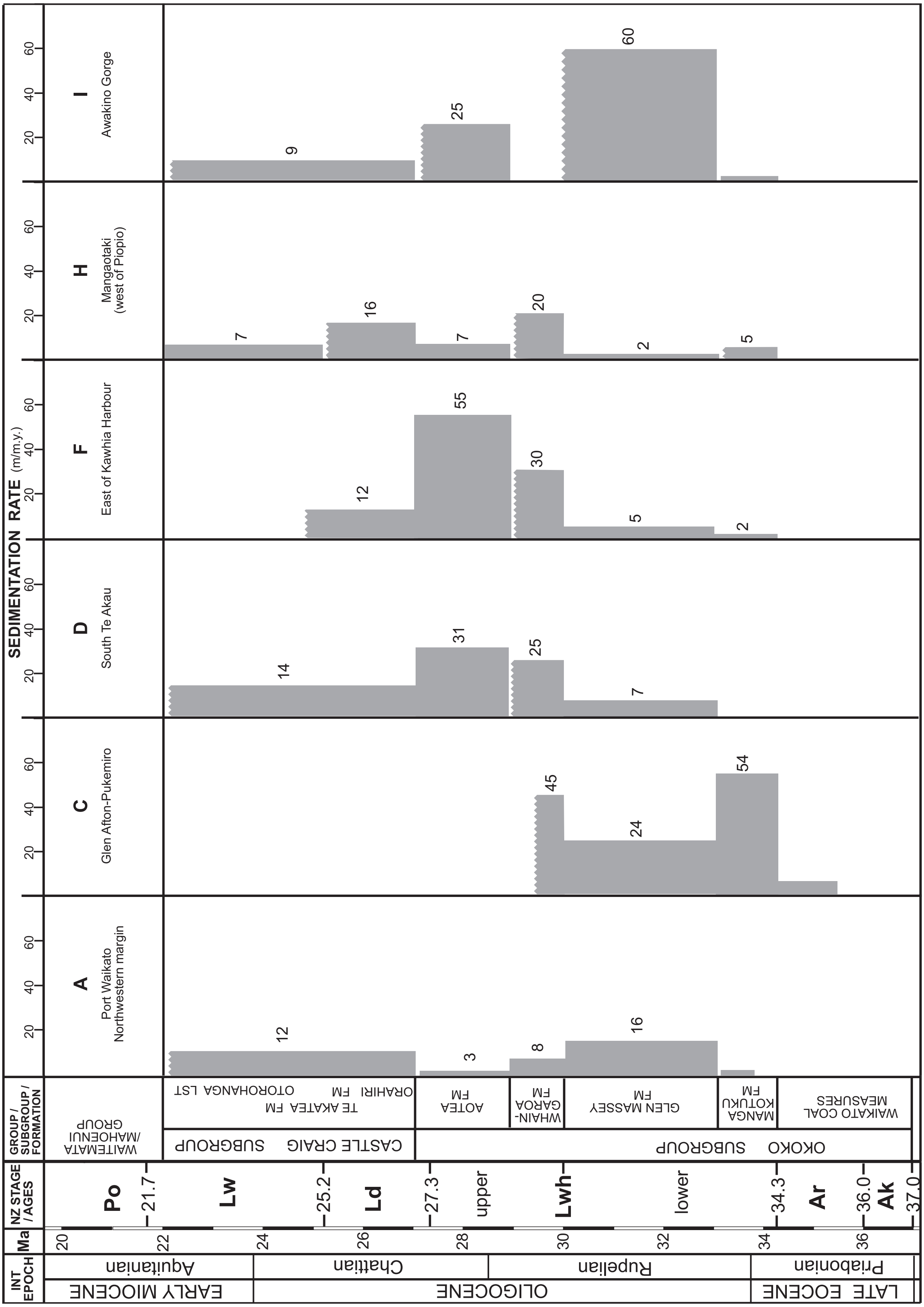


Fig. 8.4: Net sedimentation rates (metres/m.y.) are plotted for six locations on a north-south transect (see location map in Fig. 8.1). Thicknesses are not corrected for compaction.

location C in Fig.8.4) and progressed southwards through the earliest Oligocene. At that time rates of sediment accumulation and subsidence are inferred to have been in balance as deposition remained within terrestrial and marginal marine settings. Subsidence and sediment accumulation was established basin-wide by the early Oligocene (lower Whaingaroan). The sediment accumulation rate varied considerably within shelf paleoenvironments (exemplified by location A, C & D in Fig. 8.4), ranging between 7m/m.y. and 24 m/m.y., but are not as great as 70 m/m.y. in the Awakino Gorge area (location I in Fig. 8.4) (Nelson et al. 1994). Another phase of relatively rapid subsidence began during the mid-upper Whaingaroan, indicated by a marked increase in paleo-water depths, accompanied by relatively thick sediment accumulation in the northern central and eastern areas.

After the mid-Whaingaroan, subsidence and net sediment accumulation across the basin varied, possibly influenced by local deformation. The degree of uplift and erosion was highest along the western margin, particularly in areas such as inland Aotea Harbour where the uplift was as much as a few tens of metres to account for the complete absence of the Whaingaroa Formation. Nevertheless, almost all parts of the basin were areas of subsidence and net sediment accumulation during the upper Whaingaroan and lower Duntroonian. However, net sediment accumulation rates in the Raglan Harbour and inland Aotea-Kawhia Harbour areas were highly variable between 31m/m.y. and 55 m/m.y. (exemplified by locations D & E in Fig. 8.4), reducing to 7 m/m.y. in areas farther south (location H in Fig. 8.4). In the northwestern area (exemplified by location A in Fig. 8.4) sediment accumulation rates of only 3 m/m.y. occur. The sediment starvation continued throughout the Duntroonian as enhanced subsidence in the central Aotea-Kawhia and Raglan Harbour regions provided a barrier for the northward transport of sediments.

Slow regional subsidence and flooding of areas previously uplifted in the basin along the western margin of the Herangi High lead to the establishment of an extensive shallow marine carbonate shelf with waning terrigenous sand supply, which caused net sedimentation rates to fall between 7 m/m.y. and 9 m/m.y. between Aotea Formation and the Castle Craig Subgroup (exemplified by location H & I in Fig. 8.4).

Tectonic evolution of the eastern margin of Taranaki Basin: Mid to Late Oligocene basin inversion - subsidence cycles

This section develops the idea that the sequences within the Te Kuiti Group have a tectonic origin, and in particular that from the mid-upper Whaingaroan at about 29 Ma the stratigraphic record accumulated in a type of piggy-back basin immediately east of the Taranaki Fault, which responded to phases of reverse movement expressed as inversion and subsidence cycles. The text is modified from a paper by Tripathi and Kamp presented at the 2008 New Zealand Petroleum Conference, Auckland 10-12th March 2008.

Two types of unconformity occur between the various Te Kuiti sequences (Fig 8.2). The unconformities at the base of each of sequences TK2 and TK3 have originated mainly through wave planation, whereas those at the base of each of sequences TK4, TK5 and TK6 mark subaerial erosion with subsequent wave planation as well. Between sequences TK 1 and 2 the stratal pattern is one of successive onlap with minimal intervening subaerial erosion; the Waikaretu Sandstone Member is a very thin (0.5 to several metres) regressive sandstone marginal to residual basement topography, and the transition to Sequence TK2 is associated with a marked landward shift in onlap, as shown by the open shelf paleoenvironments of the Elgood Limestone Member. Between sequences TK2 & TK3 there is also a marked landward shift in stratal onlap. Over the northern and central regions of the basin the contact between these sequences is a correlative conformity, with marked deepening from inner shelf accumulation of Ahirau Sandstone Member into mid- to outer-shelf Kotuku Siltstone Member, and only south of Kawhia Harbour where Awaroa Limestone Member accumulated, is a wave-planned unconformity developed. Hence, accumulation of sequences TK1 -TK3 are interpreted as arising from progressive, albeit punctuated, marine onlap and inundation of a prior landscape, driven chiefly by regional subsidence marginal to Taranaki Basin associated with minor extensional faulting and sag basin formation.

The transition from sequences TK3 to TK 4 marks a substantial change in unconformity and basin development. Sequence TK3 is deeply incised across the whole of its outcrop extent and completely eroded in parts of central and southern regions of the basin, which is remarkable given the preceding mid- to outer-shelf depositional paleoenvironment of the Kotuku Siltstone and Ngapaenga Siltstone members of the Whaingaroa Formation. The unconformity between these sequences was also subsequently wave-planned, and Sequence TK4 marks a substantial basinward shift in the position of onlap, as inferred from the shoreface to inner shelf paleoenvironments of Waimai Limestone Member and Hauturu Sandstone Member. The unconformity between sequences TK4 & TK5 west of the Herangi Range is superimposed on the unconformity between TK3 & TK4 removing Hauturu Sandstone as well as most of the Whaingaroa Formation, whereas it is a correlative conformity in the northern parts of the basin. The more limited erosional extent of the unconformity at the base of TK5 compared with the one at the base of TK4 reflects the persistent subsidence at this time north of Kawhia Harbour compared with a repeated phase of emergence of the basin south of Kawhia Harbour. We also note that the transition from Sequence TK4 to TK5 marked the start of extensive limestone accumulation (Mangaotaki Limestone Member), albeit sandy (from reworked Hauturu Sandstone) to start with, with development of the carbonate factory along rocky shorelines around an uplifted Herangi High south of Kawhia Harbour; the limestone facies, everywhere where they are exposed today, are fragmental and have been transported from where the primary fauna and flora grew, except for the oyster banks (Nelson 1978a). The Manganui Fault probably moved as a reverse fault at c. 27 Ma when the lower sequence boundary to TK5 formed. The unconformity between sequences TK5 and TK6 is erosional east of the Herangi High and separates limestone facies. The same pattern of persistent subsidence in the north and emergence at sequence boundaries in the south is evident for both sequences TK5 and TK6, although the occurrence of mild retrogradation points to southward migration of the tectonic hinge along the western basin margin (Fig. 8.2).

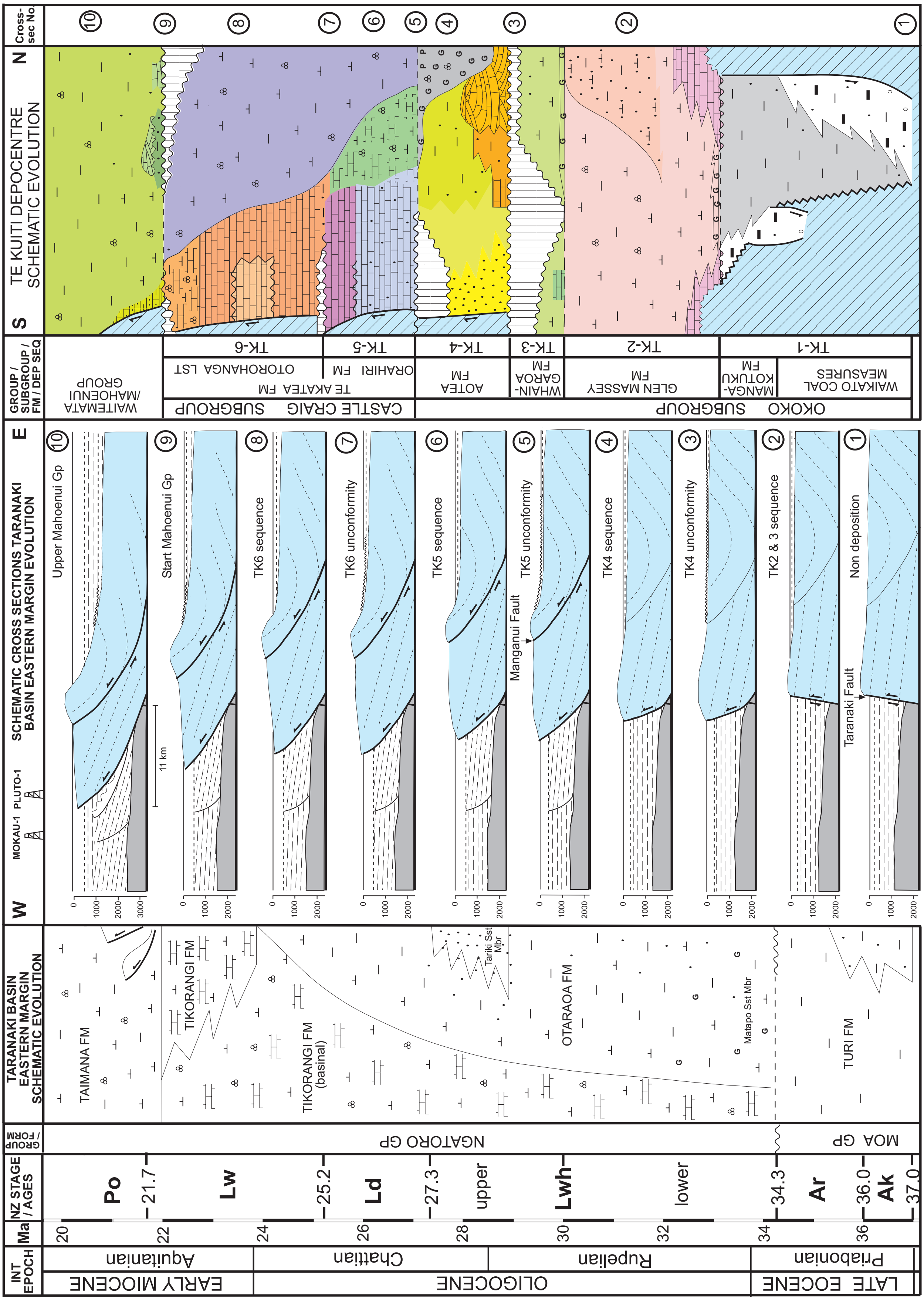
The unconformity between the Te Kuiti and Waitemata groups is strongly erosional and involved uplift of Carter Siltstone Member form an upper bathyal environment, where it was accumulating, to one where it was wave planed. The northern part of this Late Eocene - Oligocene basin was completely inverted, with uplift and erosion increasing to the northeast (Hunua Range) and tapering to the west, and south towards Kawhia Harbour; tectonic uplift at this unconformity was focused along the eastern coast of Auckland compared with the prior focus along the Taranaki Fault Zone (Enclosure 3, Map 13). The contact between the Te Kuiti and Mahoenui groups is mostly conformable, involving substantial subsidence, increased paleobathymetry by 400-600 m, and a marked landward shift in the position of marine onlap, especially to the south and east. Along the western margin with the Herangi Range however, there is evidence for initial uplift and erosion of the Te Kuiti Group, with onlap onto basement and continuous tilting of a narrow shelf (Kamp & Vonk 2006).

In summary, the character and extent of inter-formational unconformities together with the stratal patterns within the Te Kuiti sequences (such as they can be inferred from their depositional systems), indicate a major change in the basin's development at c. 29 Ma (mid-upper Whaingaroan) during the termination of Sequence TK3. The three unconformities between sequences TK3 & TK6 each involved phases of subaerial erosion and subsequent wave planation, with the extent of successive unconformity development decreasing and becoming more focused with time on the margin with the Herangi High. Sequences TK4 – TK6 are considered to each represent tectonic cycles of subsidence and basin inversion. There is paleogeographic unity between a tectonic origin for these sequences, the characteristics of the respective depositional systems within them, and the major facies differences between them (e.g. appearance of the exotic composition of the Hauturu Sandstone Member; conditions for development of the TK5 & 6 carbonate factories; and southward retrogradation of sequences TK5 & 6). The unconformities between the Te Kuiti and overlying Waitemata and Mahoenui groups also have tectonic origins, reflecting for the Waitemata Group, uplift and erosion associated with the start of subduction to the northeast (east Northland, east Auckland, Bay of Plenty), and for the Mahoenui Group, an Otaian phase of thrusting on the Taranaki Fault Zone near Awakino.

Displacement model for Taranaki Fault Zone

The Oligocene and Early Miocene successions in the Waikato and King Country regions are considered as providing useful constraints on the history of vertical motion of the Herangi High and wider basement topography east of the Taranaki Fault Zone. Fig. 8.5 is a 1st-order model of the Oligocene to earliest Miocene vertical and horizontal displacement of basement on the Taranaki Fault Zone for a west–east transect through Awakino. This model is drawn to true scale for different time horizons keyed into the Te Kuiti sequences, and honours the structure of the fault zone and known constraints on the total amount of horizontal displacement on it, as well as the magnitude and extent of subsidence and uplift/inversion for successive inter-formational unconformities within the Te Kuiti Group. The qualitative elements of the model are the partitioning of the total amount of horizontal (thrust) displacement into the successive inversion phases during the Oligocene; that is, the intervals of unconformity development at the base of each of sequences TK4, TK5, TK6 and within Sequence TK6. The interpretations in the model are as follows. (i) Reverse displacement on the Taranaki Fault started at c. 29 Ma, corresponding to the development of the unconformity at the base of Sequence TK4, which we infer involved (the first phase of) widespread inversion of the Te Kuiti Group depocentre along the whole of the margin east of the northern section of Taranaki Fault (Awakino to Port Waikato). (ii) The mid- to Late Oligocene displacement on the thrust fault at Awakino and to the north was episodic, which we infer from the repeated tectonic cycles of uplift-erosion-subsidence-shelf sedimentation, represented by sequences TK4 – TK6 and their bounding unconformities. The

Fig. 8.5: Reconstruction orientated roughly east-west illustrating incremental Oligocene-Miocene subsidence, and progressive deformation conceptualised on the basis of Te Kuiti Group stratigraphic record preserved along the eastern margin of Taranaki Basin. Each reconstruction is annotated on Te Kuiti chronostratigraphic panel to illustrate the age range and corresponding uplift and subsidence event evident in the stratigraphic record. Depth scale in metres below the sea level. See text for description.


INT EPOCH
LATE EOCENE
OLIGOCENE
EARLY MIOCENE
Priabonian
Rupelian
Chattian
Aquitanian
Ma
20
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28
30
32
34
36
NZ STAGE / AGES
Ak
37.0
36.0
Ar
34.3
lower
Lwh
upper
27.3
Ld
25.2
Lw
21.7
Po
GROUP / FORM
MOA GP
NGATORO GP
TARANAKI BASIN EASTERN MARGIN SCHEMATIC EVOLUTION
TURI FM
Matapo Sst Mbr
OTARAOA FM
Tariki Sst Mbr
TIKORANGI FM (basinal)
TIKORANGI FM
TAIMANA FM
SCHEMATIC CROSS SECTIONS TARANAKI BASIN EASTERN MARGIN EVOLUTION
W
E
MOKAU-1
PLUTO-1
0
1000
2000
3000
11 km
Non deposition
Taranaki Fault
TK2 & 3 sequence
TK4 unconformity
TK4 sequence
TK5 unconformity
Manganui Fault
TK5 sequence
TK6 unconformity
TK6 sequence
Start Mahoenui Gp
Upper Mahoenui Gp
①
②
③
④
⑤
⑥
⑦
⑧
⑨
⑩
GROUP / SUBGROUP / FM / DEP SEQ
OKOKO SUBGROUP
CASTLE CRAIG SUBGROUP
WAITEMATA/MAHOENUI GROUP
WAIKATO COAL MEASURES
MANGA-KOTUKU FM
GLEN MASSEY FM
WHAIN-GAROA FM
AOTEA FM
ORAHIRI FM
TE AKATEA FM
OTOROHANGA LST
TK-1
TK-2
TK-3
TK-4
TK-5
TK-6
TE KUITI DEPOCENTRE SCHEMATIC EVOLUTION
S
N
Cross-sec No

model demonstrates that the Oligocene – earliest Miocene thrust belt involving basement was very narrow at about 15 km wide. North of Kawhia Harbour there will have been a different displacement history with most of the total displacement occurring during the development of the c. 29 Ma unconformity at the base of Sequence TK4 (Whaingaroa – Aotea Formation contact, Fig. 8.2). The model also shows that, unlike Late Miocene structural inversion of prior normal faults in southern Taranaki Basin (e.g. Knox 1982), the start of reverse/thrust displacement on Taranaki Fault must have involved the development of a completely new fault trace(s); this new fault dips east, whereas the prior normal "Taranaki Fault" must have dipped to the west, judging from the relative elevation of the top of basement either side of the fault between the Late Cretaceous and Early Oligocene. This 3-5 km mid-Oligocene offset in basement elevation, its co-location with the Murihiku – Brook Street basement terrane boundary, and the 10-45 degree easterly dips within the western limb of the Kawhia Syncline probably determined the eastern Taranaki location of where some of the mid-Oligocene – earliest Miocene (30-23 Ma) stress originating in the proto plate boundary zone in eastern North Island would be taken up. The structurally truncated upper end of the pre-existing normal "Taranaki Fault" (Fig 8.5) has not been identified in deep parts of industry seismic reflection profiles across the eastern margin of Taranaki Fault, possibly because of a lack of coherent acoustic signal some 12 -15 km east of the tip of the fault. In terms of a mechanism linking mid- to Late Oligocene thrust displacement on a shallow east-dipping fault zone to sequence TK4 – TK6 basin inversion events, periodic locking of the dècollement is envisaged, the accumulating strain causing uplift in the basin east of the fault zone, followed by free displacement, relaxation in the upper crust and its subsidence. It is appreciated, and the model shows, that there was minimal horizontal displacement at the start (c. 29 Ma) and during subsequent Late Oligocene phases of deformation, possibly being only 1 to a few km. The majority of the total displacement in the Awakino transect occurred during the Otaian when the Mahoenui Group was accumulating east of the Herangi High, and at the end of the Otaian when this basin was inverted (Kamp & Vonk 2006).

Taranaki Basin stratigraphic test of the timing of the start of crustal shortening

The Oligocene subsurface succession in Taranaki Basin might be expected to contain stratigraphic signals of the mid-upper Whaingaroan (c. 29 Ma) transition from extension to shortening across Taranaki Fault, and provide a test of the interpretation and timing established here from the Te Kuiti Group. Fig. 8.5 shows in comparative chronostratigraphic panels, one for Taranaki Basin and the other for the Te Kuiti Group succession, how the respective lithostratigraphy may relate.

Key points arising from stratigraphic comparisons include the following:

(i) The Late Eocene start of Te Kuiti Group sedimentation (Waikato Coal Measures) corresponds to accumulation of Turi Formation (shelf siltstone), both indicative of regional subsidence and depositional onlap. Middle-Late Eocene strata in Taranaki Basin are thickest along the eastern margin of the basin thickening into Taranaki Fault, and given evidence of synsedimentary normal faulting in the Waikato Coal Measures to the east (Hall et al. 2006) and on the Manaia Fault to the west (Cardiff-1 area; Hoolihan and Yang 1992), it is probable that the Taranaki Fault was a master normal fault during the Late Eocene (Kamp 1986). Late Eocene coal measure sedimentation in fault-controlled grabens in southern Taranaki Basin (King & Thrasher 1996) may also have an extensional origin. Overall the Middle – Late Eocene depositional setting is one of east-stepping and younging extensional or sag basins (Waikato/Te Kuiti Group depocentre developed east of Taranaki Basin in the L. Eocene-Oligocene), with south-directed depositional onlap, and the non marine - marine facies transition occurring further south in Taranaki Basin than in the Waikato region, possibly due to lesser amounts of extension in the north (Waikato) compared with farther south (southern Taranaki Basin).

(ii) Latest Eocene and earliest Oligocene strata in Taranaki Basin are generally highly condensed, reflecting very low terrigenous sediment supply (King & Thrasher 1996); the signal is one of minimal tectonism consistent with a weakly extensional setting and inconsistent with concurrent shortening across Taranaki Fault and the generation of associated topography, which would produce copious sediment supply. The Matapo Sandstone Member in eastern Taranaki Basin is lower Whaingaroan in age, thin (8-15 m), shelf, glauconitic calcareous sandstone indicating stratigraphic condensation during marked south-directed depositional onlap (King & Thrasher 1996).

(iii) A significant distinction is made between the Matapo Sandstone Member and the rest of the Otaraoa Formation, which comprises up to 1200 m of upper Whaingaroan fine-grained calcareous clastic sediment. The start of significant shortening across the Taranaki Fault is placed stratigraphically at the top of the Matapo Sandstone Member. The Tariki Sandstone Member, which lies a few metres stratigraphically above Matapo Sandstone, was deposited west of Taranaki Fault as a 250-320 m-thick submarine fan system in a rapidly deepening north-south oriented trough (de Bock et al. 1990). The rapid increase in paleobathymetry and the dramatic increase in terrigenous sediment supply associated with the Tariki Sandstone are consistent with a significant change in tectonic setting and the start of shortening across Taranaki Fault. Moreover, the petrography of the Tariki Sandstone suggests that it is a correlative of the Hauturu Sandstone Member (Aotea Formation, Sequence TK4), which immediately postdates the first basin inversion event east of the Taranaki Fault Zone. The delivery of the Hauturu Sandstone facies into the Waikato-King Country region required, paleogeographically, the development of a north-south trending shoreline east of the Herangi High, and by implication first required uplift of the high, achieved by shortening across the Taranaki Fault Zone after c. 29 Ma. The Herangi High east of the fault could also have supported the shoreline that sourced the Tariki Sandstone facies to eastern Taranaki Basin in the Taranaki Peninsula area.

(iv) Otaraoa Formation becomes increasing calcareous upwards in eastern Taranaki Basin, culminating with Waitakian Tikorangi Formation limestone facies (King & Thrasher, 1996; Hood et al., 2003) in the vicinity of, and north of, Taranaki Peninsula. It accumulated on a west-facing continental slope, the shelf-slope break being pinned to the tip of the basement wedge on the hanging wall of the Taranaki Fault, with the carbonate factory being located around rocky shorelines atop the high (Hood et al., 2004). The Tikorangi Formation limestone is a correlative of the Otorohanga Limestone (Sequence TK6), and the development of limestone facies was intimately associated with the development of clean, current-swept, stable rocky shorelines that typically develop around islands and ridges formed in basement rocks.

Overview of Te Kuiti Group development associated with late Paleogene New Zealand wide tectonic evolution

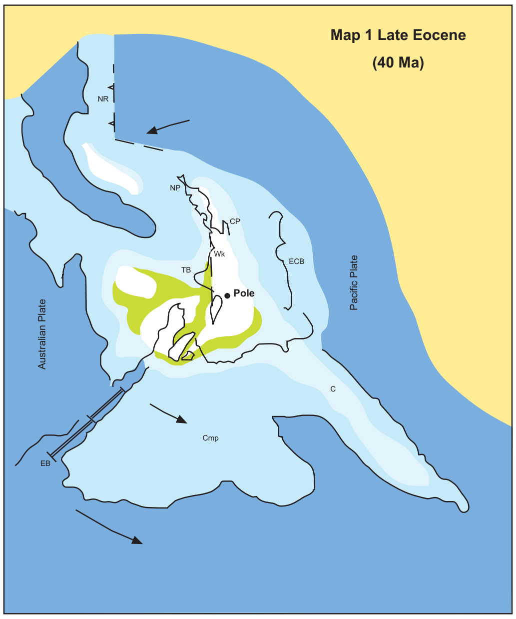
Taranaki Fault is one of the major Late Cretaceous and Cenozoic geological structures in New Zealand. In the previous sections a model has been developed that attributes Te Kuiti Group sequence development, particularly of sequences TK4-6, to the structural development of this fault zone. In this section an attempt is made to place the Taranaki Fault and the Te Kuiti Group record into a wider context of the evolution of the Australia-Pacific plate boundary through the New Zealand subcontinent.

There have been several attempts to place the Cenozoic geological development of New Zealand into a wider tectonic context, and some into a plate tectonic context taking into account information about the finite rotation poles for the Australia and Pacific plates. An early model was published by Kamp 1986a, b). He developed the concept of the Challenger Rift System to unify the evidence for the Late Eocene-Oligocene development of a zone of basins through the continental basement of western South Island and Taranaki Basin. This north-south zone of continental rifting was linked to the tectonic development of the South Pacific and in particular the propagation of the Southeast Indian Ocean Ridge into southern New Zealand, thereby driving the continental rifting. It was envisaged that during the late Oligocene (mid Waitakian) at about 23 Ma, that the rift system was obliquely bisected by the Alpine Fault having a northeast-southwest strike, the fault having formed as a small circle to the new pole of rotation. The Alpine Fault remains part of the modern Australia-Pacific boundary, which has subsequently evolved into a more complex structure with subduction zones at its northern (Hikurangi margin) and southern (Puysegur margin) ends (Kamp & Furlong 2006). King (2000) produced an updated version of the tectonic development of the plate boundary that was also concerned with the movement of basement blocks and development of basins. The earlier model of Kamp (1986a) was updated to the extent that the Challenger Rift was shown not to have propagated all the way north through Taranaki Basin and into western Northland as envisaged prior to the availability of more recent seismic data for the basin. In addition, King (2000) articulated that the rift system was actually the Australia-Pacific plate boundary during the Late Eocene-Oligocene prior to its change to a NE-SW orientation. Usefully, King (2000) presented reconstructions showing the location of basement blocks and basins in relation to the major tectonic features in the New Zealand region and the contemporary pole of rotation. His reconstructions for the late Eocene through to the Early Miocene are reproduced here and are used as the basis for the discussion below.

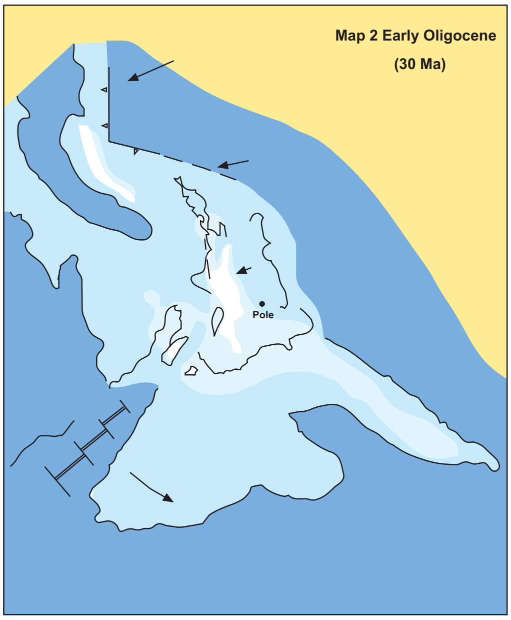
Late Eocene (mid Bortonian, c.40 Ma) (Fig. 8.6, Map 1):

The key features depicted on the 40 Ma reconstruction are the pole for the relative motion between the Australian and Pacific plates, and the early stages of sea floor spreading in the Emerald Basin to the southwest of New Zealand. Subduction is envisaged at this time north of North Island, forming the Norfolk ridge as a volcanic arc. The pole of rotation was considered the have been located in central New Zealand.

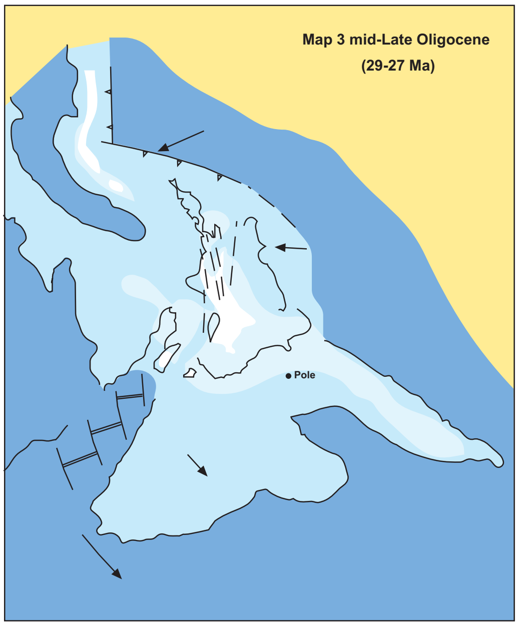
By the end of Eocene, the continental rift zone (Challenger Rift system) associated with the Emerald Basin had propagated northwards forming a series of sub-basins trending N-S through central-western New Zealand. This lineament was effectively the initial manifestation of the modern Australian-Pacific plate boundary through New Zealand. The rifting is envisaged to have resulted from normal extension. Most of the central parts of continental New Zealand are envisaged as subdued topography, with broad coastal plains with the accumulation of coal measures and shelf marine deposits.



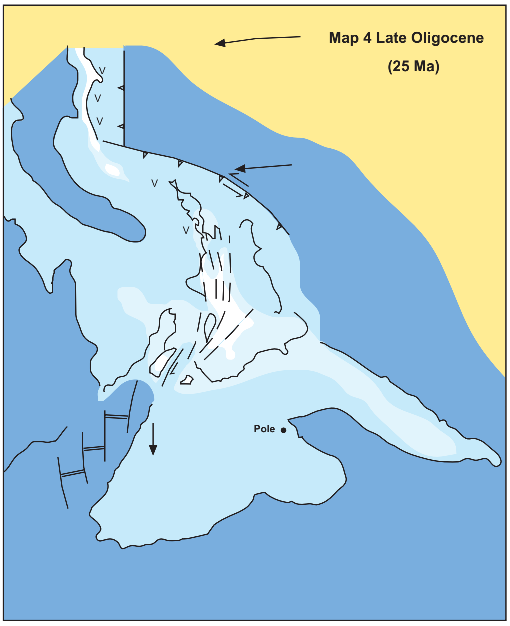
Map 1 Late Eocene
(40 Ma)



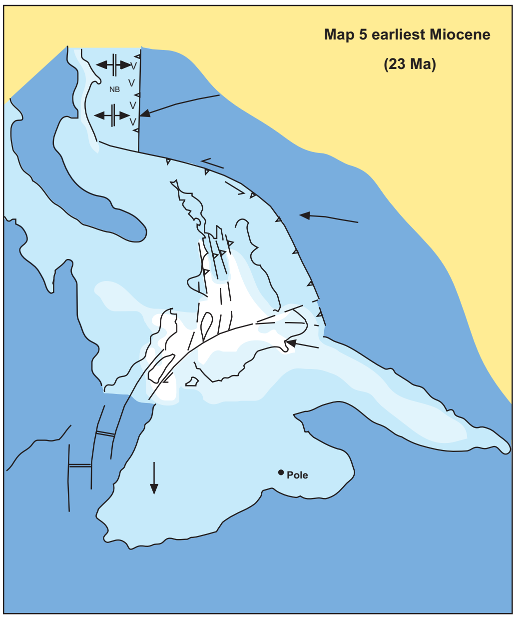
Map 2 Early Oligocene
(30 Ma)



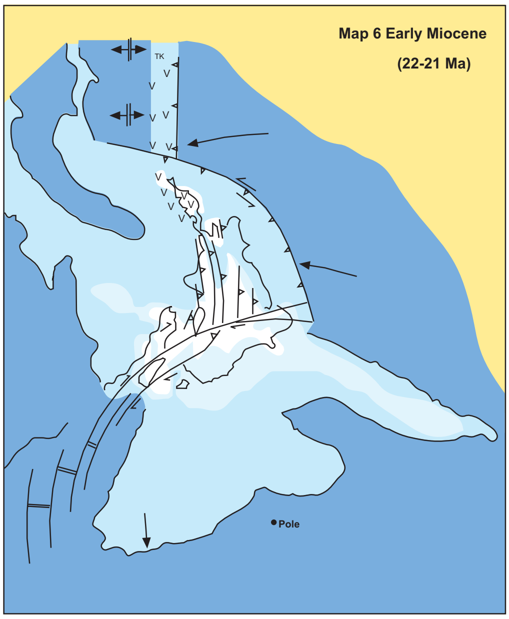
Map 3 mid-Late Oligocene
(29-27 Ma)



Map 4 Late Oligocene
(25 Ma)



Map 5 earliest Miocene
(23 Ma)



Map 6 Early Miocene
(22-21 Ma)

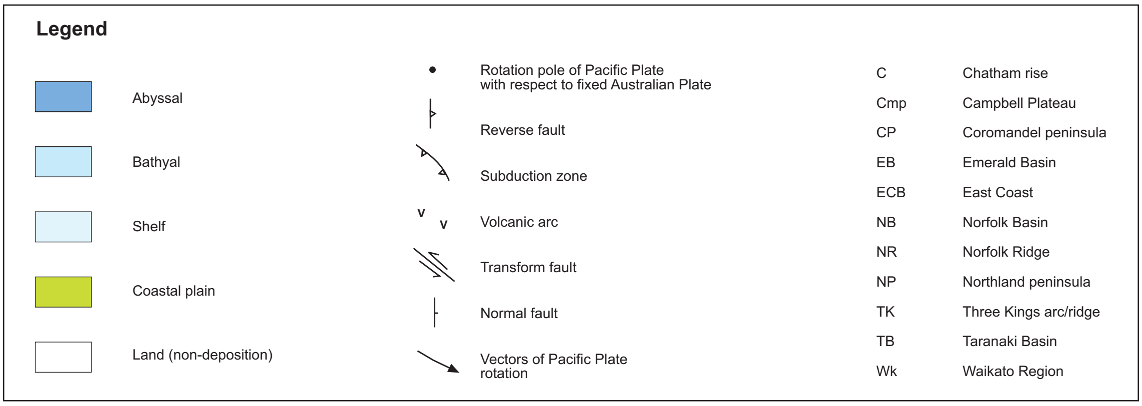


Fig. 8.6 (Maps 1-6): Schematic reconstruction of the proto- Australian-Pacific plate boundary development through New Zealand subcontinent during Late Eocene to Early Miocene, from King (2000).

The initiation of subsidence in the Waikato Basin during the Late Eocene led to the accumulation of the Waikato Coal Measures in a series of sub basins partly controlled by N-S trending normal faults (e.g. Kear & Schofield 1978; King 1978; Kirk et al. 1988; Hall et al. 2006). Some workers have suggested that the coal measure deposition may not have been strongly fault controlled compared with other factors such as basement paleotopography, sediment supply, and rise in base level (Edbrooke et al. 1994). Hall et al. (2006) have constrained the timing of normal displacement on faults in the Waikato Coal Field as occurring during the Runangan (c. 34-36 Ma). This evidence of Late Eocene extension is consistent with circumstantial evidence for concurrent extensional faulting in Taranaki Basin (King & Thrasher 1996). One of the difficulties with interpretation of the Taranaki Basin record of faulting is the amount of Late Oligocene-Miocene basement overthrusting on the Taranaki Fault, which has obscured the evidence for the nature of the fault up to the Late Oligocene.

If the evidence for extensional faulting, albeit minor, in the Waikato and Taranaki Basins is to be believed, it suggests that the pole of rotation must have been located north of where it is shown in Fig 8.6 map 2. If it lay in the vicinity of Auckland City or southern Northland, this would better describe the N-S zone of sea floor spreading in the Emerald Basin passing directly into a continental rift system that progressively reduced the degree of extension northward as far as about Port Waikato. As the pole position stands, it would imply that the Taranaki Fault was a reverse fault at 40 Ma. This makes it hard to explain late Eocene normal faulting in the Waikato Basin, whereas a pole located to the north would be consistent with it and could explain the regional subsidence in the northern Waikato marginal to an extensional Taranaki Basin.

Early Oligocene (c. 30 Ma, mid-Whaingaroan) (Fig. 8.6 Map 2):
The key features depicted on the 30 Ma reconstruction are continuing sea floor spreading in the Emerald Basin, N-S rifting through western New Zealand, widespread subsidence, marine inundation, and carbonate dominated sedimentation. Spreading and extension are considered in the King (2000) model to have been obliquely extensional at 30 Ma, which is implied by the estimated position of the pole at that time.

In the Waikato region, regional subsidence was more widespread than it had been in the Late Eocene, leading to significant marine onlap in the lower parts of the Te Kuiti Group (TK1-3). There is not much, if any, evidence for faulting during the Early Oligocene, but it is envisaged that a mildly extensional regime would allow sag basin subsidence in the Waikato region east of Taranaki Fault. The pole of rotation therefore is more likely to have lain at this time in the Auckland to Coromandel area.

Mid-Late Oligocene (c. 29-27 Ma, mid-upper Whaingaroan to lowermost Duntroonian) (Fig. 8.6 Map 3):
The key features depicted in the King (2000) reconstruction are oblique spreading in the Emerald Basin, a west to southwest dipping subduction zone beneath northernmost North Island, and a pole position to the southeast of Banks Peninsula. A shear zone was also depicted in the Waikato region (illustrated by dashed lines) implying that the Taranaki Fault and related faults to the east were contractional at that time.

While the position of the pole of rotation at this time may be refined in the future, the key implication about the contractional nature of the Taranaki Fault at about 29-27 Ma fits with the conclusions drawn above from Te Kuiti Group sequence stratigraphy about the timing when this fault became a reverse fault. In fact, the details outlined above suggest that there was a first phase of contraction across the fault at 29 Ma, followed by a second phase of deformation and basin inversion at about 27 Ma.

Late Oligocene (c.25 Ma, Duntroonian/Waitakian boundary) (Fig. 8.6 Map 4):
Key features of the 25 Ma reconstruction are the increasingly oblique sea floor spreading in the Emerald Basin and the propagation of subduction down the eastern coast of Northland and Auckland. The pole of rotation has migrated farther away

from the South Island. A surprising feature of the pole position is how far it has migrated to the southeast without significant displacement having been shown on the Alpine Fault. It would seem that the pole should be closer to the North Island at this time.

In the Waikato region at this time an extensive carbonate platform became established to the east of the Herangi High. From the 25 Ma reconstruction one could infer uplift of the Herangi High immediately east of the Taranaki Fault. Indeed, the rocky shorelines so produced, associated with strong tidal flows, were required to provide the marine environments in which the main carbonate producers could grow and develop. The 25 Ma reconstruction would also allow for continuing contraction on the Taranaki and Manganui Faults expressed as reverse displacement. The eastern margin of Taranaki Basin is considered to have formed as a foredeep in response to loading by the hanging wall of Taranaki Fault (King & Thrasher 1996).

Earliest Miocene (c.23 Ma, mid to late Waitakian) (Fig. 8.6 Map 5):
The key features of the 23 Ma reconstruction are the formation of a through-going Alpine Fault, highly oblique movement in the Emerald Basin (it is not clear if sea floor spreading continues), the start of emplacement of the Northland Allochthon and the East Cape Allochthon, backarc spreading in the Norfolk Basin, and substantial contraction across the Taranaki and related faults in central-western North Island. The pole of rotation is shown as distant from the plate boundary zone.

The plate tectonic model (Fig. 8.6, map 5) is rather crude in relation to the relationship between structure and sedimentation in the Waikato Basin. However it is realistic to the extent that there was continuing displacement on the Taranaki and Manganui faults in the sector south of Kawhia Harbour. The map interval (c. 23 Ma) corresponds to the boundary between the Te Kuiti Group and the Waitemata and Mahoenui groups and hence near the end of the period of extensive carbonate sedimentation in central-western North Island.

Early Miocene (22-21 Ma, latest Waitakian to earliest Otaian) (Fig. 8.6 Map 6):
The key features of the 22-21 Ma reconstruction are the full development of the Alpine Fault, the connection of the Hikurangi subduction zone with the northern end of the Alpine Fault, and the appearance of arc volcanism in Northland. A zone of strike-slip faults had also developed in southwestern South Island, linking the Alpine Fault to spreading on the Pacific-Antarctic ridge. The pole of rotation continued to move to the southeast, thereby accelerating displacement on the Alpine Fault. Central New Zealand at the time is shown to be fully under contraction.

The Early Miocene represents a time of profound change in the geological development of the Waikato Basin. In the northern region the Te Kuiti Group was inverted, uplifted and eroded, the focus of uplift lying in the area east of Auckland. This was likely driven by the start of subduction along the continental margin east of Auckland. After a few hundred thousand years of uplift, the region underwent flexural subsidence leading to formation of the Waitemata Basin. Initially sedimentation was in shelf environments, but by the Otaian there was rapid subsidence and accumulation of flysch, which is a typical foreland or subduction related basin signature. The southern region did not experience regional uplift, and instead subsided rapidly together with the introduction of terrigenous mud and flysch to form the Mahoenui Group. This basin formed as a piggyback basin east of the Taranaki Fault and was carried westward by overthrusting of the hanging wall. The contraction was more likely driven by shortening across the Alpine Fault sector of the plate boundary (i.e. a continent-continent shortening) than by shortening across the subduction thrust, which at that time lay mostly to the north of the King Country region where most of the Mahoenui Group occurs.

In conclusion, there is an accord between the geological development of the Te Kuiti Group and Taranaki Fault in central-western North Island and the wider context of the evolution of the Australia-Pacific plate boundary through the New Zealand subcontinent as described in the most recent model (King 2000). There are differences however particularly for the late Eocene and Early Oligocene intervals that suggesting that the pole of rotation must have been located north of Port Waikato.

Chapter nine

Summary and Conclusions

The Te Kuiti Group of Late Eocene and Oligocene age (Kaiatian to Waitakian) crops out extensively in central-western North Island over an area of about 5500 km^2. It directly overlies basement, usually with a pronounced angular unconformity. This study is mainly confined to areas east of the modern coastline where the main exposures occur and where the entire succession is best preserved; that is, between Port Waikato in the north and Awakino in the south (Fig. 2.1). The interpretations and conclusions presented in this thesis are based mainly on detailed field investigations and examination of outcrop exposures at a range of scales, as well as laboratory data collected about samples tied to stratigraphic column descriptions. Coal Resources Survey core-log data have also been used in this study. The key objective of this study is to improve understanding about the character, development and significance of the Te Kuiti Group, which contains valuable limestone and coal resources.

Rationalisation of Te Kuiti Group Lithostratigraphy

The lithostratigraphic subdivision of the Te Kuiti Group has been problematical. The combination of marked lithofacies variations within and between formations, erosion of the record in critical areas, and burial by younger volcanic deposits has historically led to the miscorrelation of units and the introduction of multiple names for particular units. Rationalisation of the lithostratigraphy of the Te Kuiti Group has been a necessary prerequisite to being able to identify the geological signals within it. As part of the present study, a comprehensive re-assessment of the lithostratigraphy of the Te Kuiti Group was undertaken. Special emphasis has been given to the significant stratigraphic discontinuities (erosional unconformities, depositional hiatuses) between units. These stratigraphic discontinuities, when combined with faunal and/or numerical dating, have enabled the correlation of lithologically diverse but time-equivalent stratigraphic units (i.e. depositional systems) across the known extent of the Te Kuiti Group in central-western North Island.

The first lithostratigraphic scheme for the group was established by Kear and Schofield (1959). Where possible, previously defined subgroups, formations, and members have been retained in this thesis, although there have had to be some changes to the prior schemes. A significantly revised lithostratigraphy is proposed for the group in central-western North Island in an attempt to work towards a more unified stratigraphic framework (Fig. 3.3). At the broadest level, the Te Kuiti Group is sub-divided into two subgroups: the Okoko Subgroup (new) and overlying Castle Craig Subgroup. This broad subdivision into two subgroups, previously based on significant differences in the lithological composition of the constituent formations in southern areas, is now extended to the entire study area.

The Okoko Subgroup comprises the Waikato Coal Measures, Mangakotuku Formation, Glen Massey Formation and Whaingaroa Formation. Most revisions to the lithostratigraphy in this subgroup have been made in the inferred relationship between the Glen Massey Formation and the Whaingaroa Formation. Most of the lithostratigraphic units cropping out in the area south of Kawhia Harbour previously defined as Whaingaroa Formation are now regarded as members of the Glen Massey Formation. In a few localities south of Raglan Harbour, a limestone and overlying siltstone unit of limited lateral extent, previously assigned to the Aotea Formation, are now included in the Whaingaroa Formation, and have been defined as two new members: Awaroa Limestone Member and Ngapaenga Siltstone Member.

The Castle Craig Subgroup, which contains the bulk of the limestone facies in the Te Kuiti Group, especially in the areas south of Raglan Harbour, comprises the Te Akatea Formation, Orahiri Formation and Otorohanga Limestone. It is proposed that the Waitomo Sandstone, formerly of formation status as defined by Kear and Schofield (1959) and Nelson (1973, 1978a), be relegated to member status and become incorporated into the Orahiri Formation. The Orahiri Formation and Otorohanga Limestone are usually difficult to differentiate from each another, especially in the Kawhia, Te Kuiti and Awakino areas and the stratigraphic subdivision of Kear and Schofield (1959) and Nelson (1973) is not really applicable. The approach taken here is to assign them to an undifferentiated formation loosely refereed to as the Orahiri Formation/Otorohanga Limestone. In the areas north of Raglan Harbour, all of the lithostratigraphic units unconformably overlying the Carter Siltstone, previously correlated by Kear (1963) and Waterhouse and White (1994) with the Waitomo Sandstone and Otorohanga Limestone, are now defined as basal units of the Waitemata Group.

Biostratigraphy and Age

New age control has been achieved by a review of existing foraminiferal biostratigraphy combined with determination of Sr isotope ages from macrofossil samples. The base of the Waikato Coal Measures (WCM) in the Huntly Coalfield area contains spores and pollens assigned to the *Haloragacidites harrisii* Zone, which corresponds approximately to the Kaiatan Stage (Pocknall 1991). The WCM appears to become younger in the Kawhia Coalfield and areas to the south as it contains spores and pollens of the upper *Araucariacites australis* Subzone, which has been assigned to the upper Runangan to lower Whaingaroan. The spores and pollens belonging to the upper *Araucariacites australis* Subzone are identified in the uppermost part of the WCM and Mangakotuku Formation in the Huntly Coalfield area (Pocknall & Mildenhall 1984; Pocknall 1991). In general, this implies that the WCM occurring in the southern parts of the basin are age equivalent to the Mangakotuku Formation in the northern parts of the basin.

The key lower Whaingaroan planktic foraminifera *Globigerina angiporoides and G. ampliapertura* occur in the calcareous siltstone unit now defined as Dunphail Siltstone Member of Glen Massey Formation. The numerical ^{87}Sr/ ^{86}Sr ages of macrofossils collected from this unit yield ages in the range 34.13 - 30.49 Ma, conforming to a lower Whaingaroan age. The lowest occurrence (LO) of *Globigerina euapertura* and *Notorotalia stachei* occur in the Kotuku Siltstone Member of the overlying Whaingaroa Formation at Waitetuna Estuary (type section in Raglan Harbour) and at Te Kotuku (Mangiti Road), which is a reference section (Hornibrook et al. 1989; Cooper et al. 2004). The age of the Whaingaroa Formation south of Raglan Harbour remains poorly constrained because of lack of exposure and the absence of age diagnostic fauna.

The Aotea Formation may have a complete faunal succession spanning the upper Whaingaroan - Duntroonian stage boundary (27.3 Ma). The Mangiti Sandstone Member has an inferred upper Whaingaroan age based on the occurrence of *Rectuvigerina striatissima,* and *Notorotalia stachei*. The majority of the ^{87}Sr/ ^{86}Sr age estimates from lower members of the Aotea Formation (i.e. Waimai Limestone Member; Hauturu Sandstone Member) yield ages in the range 29.96 - 27.72 Ma, falling within the upper Whaingaroan. The upper part of the Kihi Sandstone Member (Aotea Formation) especially in the Honikiwi-Waitomo area contains the L.O. of *Notorotalia spinosa* and *Semivulvulina waitakia,* indicating a Duntroonian age. The overlying Orahiri Formation is of Duntroonian age based on the common occurrence of *Flemingostrea wollostoni* in the Te Anga Limestone Member. Duntroonian molluscan fauna such as *Cirsotrema lyrata, Lentipecten huttoni (hochstetteri)* are also reported from the Raglan Limestone Member (Te Akatea Formation) north of Raglan Harbour, Raglan Limestone being a deeper water correlative of the Orahiri Formation. The Otorohanga Limestone has a Waitakian age, based on the occurrence of the planktic foraminifera *Globoquadrina dehiscens*. This foram species and another key Waitakian planktic foram (*Globigerina brazieri*) are reported from siliciclastic interbeds within the upper parts of Raglan Limestone Member and from the overlying Carter Siltstone Member of the Te Akatea Formation. The

Waitakian-Otaian boundary (21.7 Ma) probably lies within the basal members of the Waitemata and Mahoenui groups, the former being separated from the Te Kuiti Group by a significant unconformity. Strontium ($^{87}Sr/^{86}Sr$) isotope ages from the basal limestone units of the Waitemata Group in the Gibsons Beach section have yielded ages of 21.8 - 21.98 Ma, which lies close to the Waitakian-Otaian boundary.

Lithofacies, paleoenvironments and sequence stratigraphy of the Glen Massey Formation

Analysis of closely spaced and detailed measured outcrop sections has led to the identification of fourteen lithofacies that can be grouped into one of four lithofacies associations. The associations are named limestone, mixed carbonate-siliciclastic siltstone, sandstone, and chemogenic after their dominant lithology. The limestone lithofacies comprising skeletal-rich grainstone-packstone accumulated close to a shoreline along the western margin, as well as upon isolated basement paleo highs. The carbonate lithofacies usually pass upwards into mainly mixed carbonate-siliciclastic siltstone lithofacies, which forms the bulk of the Glen Massey Formation thickness towards the east and northeast, and in southern parts of the basin. The mixed carbonate-siliciclastic siltstone lithofacies grades upward into sandstone lithofacies, which are prominent in the landscape forming bluffs and hilltops especially in the western and northwestern parts of the study area. The chemogenic lithofacies are least common and are mostly restricted to more offshore parts of the paleoshelf.

A Vail-type Glen Massey sequence architecture observed in outcrop along the western margin has a basal unconformable sequence boundary having being formed by wave planation (transgressive surface of erosion) or its correlative conformity; a variably thick (<1-30 m) transgressive systems tract (TST) composed of limestone (lithofacies L_1-L_5); a maximum flooding surface (MFS) closely associated with a downlap surface (DLS); a highstand systems tract (HST) ~1-40 m thick that typically constitutes an aggradational interval of calcareous siltstone (lithofacies S_6) gradationally passing upward into a regressive systems tract (RST) ~2-80 m thick dominated by progradational calcareous silty sandstone (lithofacies S_2-S_4).

Fourteen distinctive ‘styles’ illustrating the architecture of Glen Massey sequence across the paleoshelf have been identified. By integrating the characteristics of all fourteen ‘styles’, an idealized sequence stratigraphic model has been developed that provides a simplified two-dimensional representation of the key sequence stratigraphic surfaces and systems tracts. While these ‘styles’ share similar characteristics and show broadly similar facies changes upsection, they result from a unique interplay of relative sea-level changes, sedimentation rates, and position on the shelf profile.

Lithofacies, paleoenvironments and sequence stratigraphy of the Aotea Formation

Detailed field analysis of Aotea Formation exposures between the northern and southern parts of the study area has led to the identification of a wide spectrum of lithofacies that can be grouped into four main lithofacies associations named limestone lithofacies, mixed carbonate-siliciclastic sandstone lithofacies, mixed carbonate-siliciclastic siltstone lithofacies, and chemogenic lithofacies. The lower group of facies, especially along the western margin, are comprised of limestone lithofacies (L_1-L_5) belonging to the Waimai Limestone Member, or by variably calcareous fine to medium sandstone (S_1, S_3), belonging to Hauturu Sandstone Member and Mangiti Sandstone Member. They accumulated in relatively high energy neritic environments. The upper group of facies consists mainly of bioturbated fine muddy sandstone, and sandy siltstone (S_2-S_4 & Z_1) belonging to Kihi Sandstone Member and Patikirau Siltstone Member. The upper facies group in parts of the study area passes upsection into condensed intervals (C_1 & C_2) indicating low-energy deep water environments with terrigenous sediment starvation.

The Aotea sequence comprises a lower sequence boundary, which is an erosional unconformity (transgressive surface of erosion). The transgressive systems tract (TST) within the Aotea sequence in the southwestern and central regions comprise a combination of mixed carbonate-siliciclastic sandstone and limestone lithofacies of variable thickness (120 - < 1 m). However, the TST within the Aotea sequence in the northern region is relatively thin (20 - < 1 m) and is largely composed of low to medium dipping cross-bedded skeletal limestone (facies L_2), or interbedded calcareous sandstone and sandy siltstone (S_3). The downlap surface (DLS) corresponds to a sharp lithofacies transition between the TST and the overlying highstand systems tract (HST). The HST of the Aotea sequence in the Aotea-Kawhia-Raglan Harbour areas typically comprises highly bioturbated mixed calcareous-siliciclastic sandstone and siltstone lithofacies (e.g. S_2, S_4 & Z_1) up to 80 m thick. These facies are inferred to have been deposited in an outer shelf setting. The HST in more northern and eastern parts of the study area is relatively thin and often capped by highly condensed deposits (C_1, C_2). In the Port Waikato area, the HST may be reduced to a condensed section a few 10s of cm thick.

An idealised two-dimensional model for the Aotea sequence has been synthesised to better understand the distribution of the various lithofacies, systems tracts and sequence stratigraphic surfaces across the paleoshelf.

Lithofacies, paleoenvironments and sedimentary evolution of the Castle Craig Subgroup

Detailed field investigations undertaken in this study have identified twelve lithofacies within the Castle Craig Subgroup. These are grouped into three lithofacies associations named carbonate, mixed carbonate-siliciclastic sandstone, and siliciclastic sandstone after the dominant lithologies. In areas south of Aotea Harbour the subgroup comprises a wide variety of limestone types with variable siliciclastic content, dominated by coarse skeletal rudstone/grainstone (L_1-L_7), comprising mainly fragmental bryozoans, echinoderms, benthic foraminifers and epifaunal bivalve shells. This limestone accumulated at mainly shelf depths in a moderate to high energy seaway and can have an aggregate thickness of up to 100 m. Around Raglan Harbour and in areas to the north, the subgroup comprises predominantly planktic foraminiferal-rich packstone to wackestone (L_8) and calcareous siltstone/marl (Z_1, Z_2) that accumulated mainly in slope/upper bathyal settings. Pliocene and Pleistocene volcanics bury the transition between the neritic carbonate facies of the Orahiri Formation and Otorohanga Limestone south of Aotea Harbour and the upper bathyal mixed carbonate-siliciclastic facies of the Te Akatea Formation to the north of Raglan Harbour.

The base of the Castle Craig Subgroup corresponds to a widespread unconformity, which is erosional in sections south of Kawhia Harbour, whereas it is a paraconformity in sections around Raglan Harbour. The sedimentary evolution of the subgroup has been relatively complex, but can be subdivided into two major phases. In the first phase, sedimentation patterns were characterised by shelf progradation to the east and to the north (Raglan Limestone Member). The second phase involves a change to aggradation, followed by south-directed retrogradation, represented by deposition of Carter Siltstone Member over Raglan Limestone Member. In the south around Kawhia Harbour, retrogradation in response to marked subsidence is recorded by the accumulation of terrigenous siltstone (L_8) above Otorohanga Limestone, but in general subsidence east of the Herangi High was less than the carbonate sediment flux forcing eastward progradation of the carbonate shelf.

Basin synthesis

The mid-Cenozoic geological history of central-western North Island can be subdivided into two distinct phases of evolution, each controlled by different tectonic regimes and with characteristic linked depositional systems. The first phase (Late Eocene to mid-Oligocene) was characterised by an extensional tectonic setting. There was regional downwarping or sag basin development accompanied by minor normal faulting. The second phase (mid-Oligocene to Early Miocene) coincided with mild contraction across the region expressed as reverse movement on the Taranaki Fault and the related Manganui Fault. This displacement appears to have been associated with repeated phases of basin inversion and subsidence.

Six unconformity-bound sequences (TK1-TK6) have been identified and mapped within the Te Kuiti Group. The start of Te Kuiti deposition (Waikato Coal Measures) during the Late Eocene was marked by depositional onlap with minor synsedimentary normal faulting. The subsequent accumulation of Mangakotuku (TK1), Glen Massey (TK2) and Whaingaroa (TK3) formations was associated with progressive, albeit punctuated, marine onlap and inundation of a prior landscape, driven mainly by regional subsidence and sag basin formation. A major subaerial unconformity between the Whaingaroa Formation (TK3) and Aotea Formation (TK4), combined with a basinward shift in the position of onlap, indicate a dramatic mid-upper Whaingaroan (c. 29 Ma) change in stratigraphic development and basin dynamics, corresponding to a change from mild extension to contraction across the Taranaki Fault Zone. The top of the Aotea Formation is marked by another phase of basin inversion at c. 27 Ma. The erosional unconformity at this level south of Kawhia Harbour passes northward into a correlative conformity, reflecting persistent subsidence in northern parts of the basin. The transition from Aotea Formation (TK4) to Orahiri Formation (TK5) also marks the start of extensive limestone accumulation in the south associated with the establishment of productive carbonate areas along rocky shorelines on the eastern side of the Herangi High underlain by basement. The prior pattern of subsidence in the north and emergence in the south is indicated by the unconformity developed at the base of the Otorohanga Limestone (TK6), although the occurrence of a retrogradation stratal pattern at the top of this limestone points to southward migration of the tectonic hinge along the western basin margin. Sequences TK4 - TK6 (i.e. Aotea Formation, Orahiri Formation & Otorohanga Limestone) are inferred to each represent tectonic cycles of basin inversion and subsidence attributed to periodic locking of the Taranaki Fault dècollement in underlying Murihiku basement, the accumulating strain causing uplift in the basin east of the fault zone.

The unconformity between the Te Kuiti Group and the overlying Waitemata Group is strongly erosional and involved uplift and erosion, the magnitude of which increased to the northeast (Hunua Range) and decreased to the west and south (towards Kawhia Harbour). The associated tectonic uplift was focused along the eastern coast of Auckland and marked the Early Miocene start of subduction to the northeast (east of Northland and Bay of Plenty). The contact between the Te Kuiti Group and the Mahoenui Group is mostly conformable, involving substantial subsidence, however in the Awakino Gorge area this contact is erosional (Nelson 1973), reflecting an Otaian phase of reverse faulting on the Manganui Fault.

A 1st–order tectonic model (Fig. 8.5) of the Late Oligocene to earliest Miocene vertical and horizontal displacement on the Taranaki Fault Zone for a west-east transect through Awakino infers that the mid- to Late Oligocene displacement on the fault zone in the vicinity of Awakino was episodic, and that the thrust belt was narrow (c. 15 km). North of Kawhia Harbour there will have been a different displacement history with most of the total displacement occurring at c. 29 Ma, coinciding with the unconformity at the base of sequence TK4 (Aotea Formation). The tectonic model also shows that the start of reverse/thrust displacement on the Taranaki Fault Zone must have involved the development of a completely new fault trace(s), rather than involving a change of sense of movement on the pre-existing normal fault.

There is an accord between the geological development of the Te Kuiti Group and Taranaki Fault in central-western North Island and the wider context of the evolution of the Australian-Pacific plate boundary through the New Zealand subcontinent, as described by the most recent tectonic model of King (2000). It is suggested however that the Late Eocene and Early Oligocene Australia-Pacific pole of rotation must have been located north of Port Waikato to explain the regional subsidence in the northern Waikato marginal to an extensional Taranaki Basin at this time.

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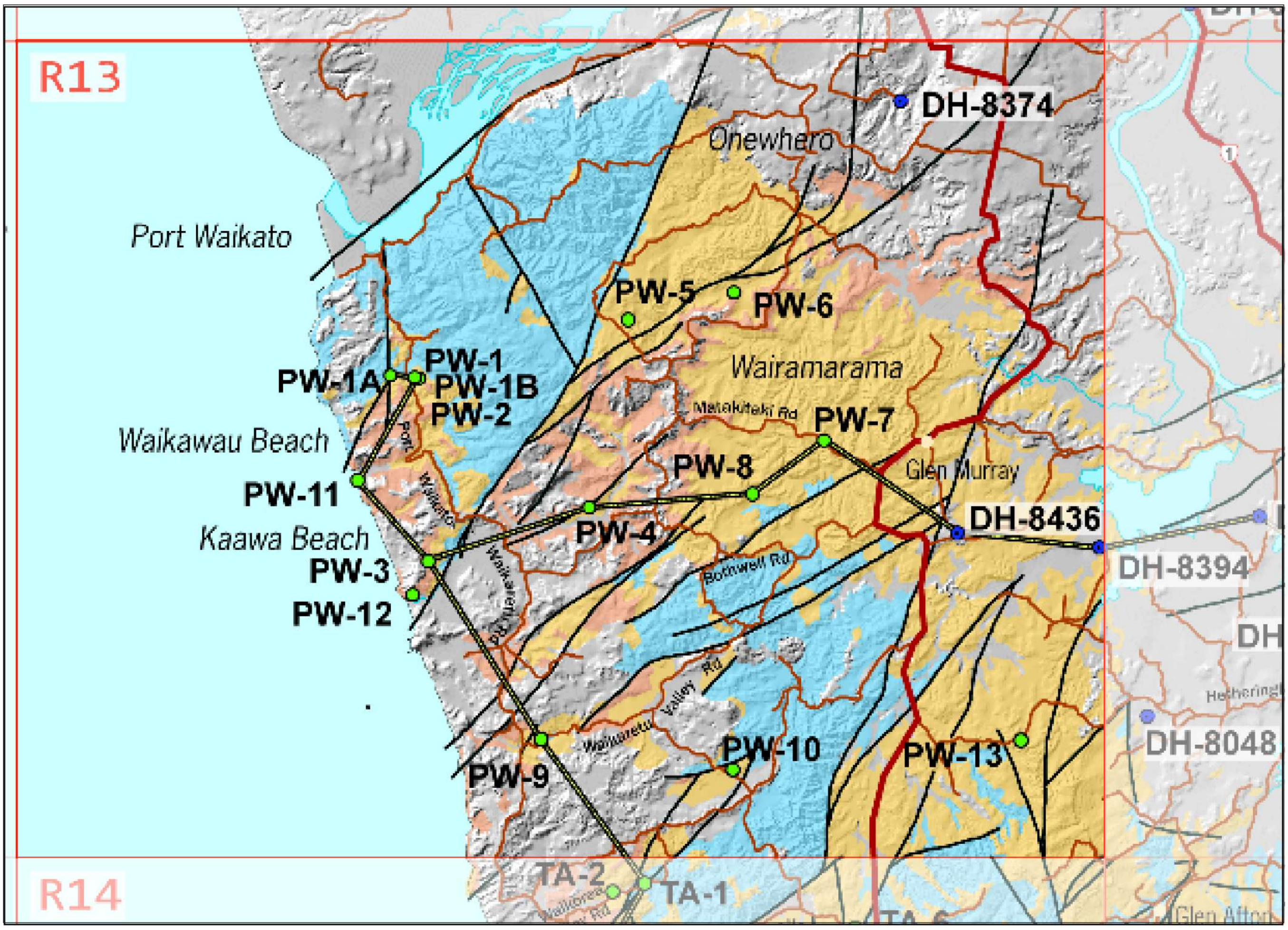
APPENDIX I

Stratigraphic Columns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Onewhero
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PW-5
PW-6
PW-1
PW-1A
PW-1B
PW-2
Wairamarama
Waikawau Beach
Port Waikato Rd
Matakitaki Rd
PW-7
Glen Murray
PW-8
PW-11
DH-8436
Kaawa Beach
PW-4
PW-3
DH-8394
Waikaretu Rd
Bothwell Rd
PW-12
DH-8048
Waikaretu Valley Rd
PW-10
PW-13
PW-9
R14
TA-2
TA-1
Glen Afton

Stratigraphic Column No: *PW-1A* **_Grid Reference:_**

Region: Port Waikato

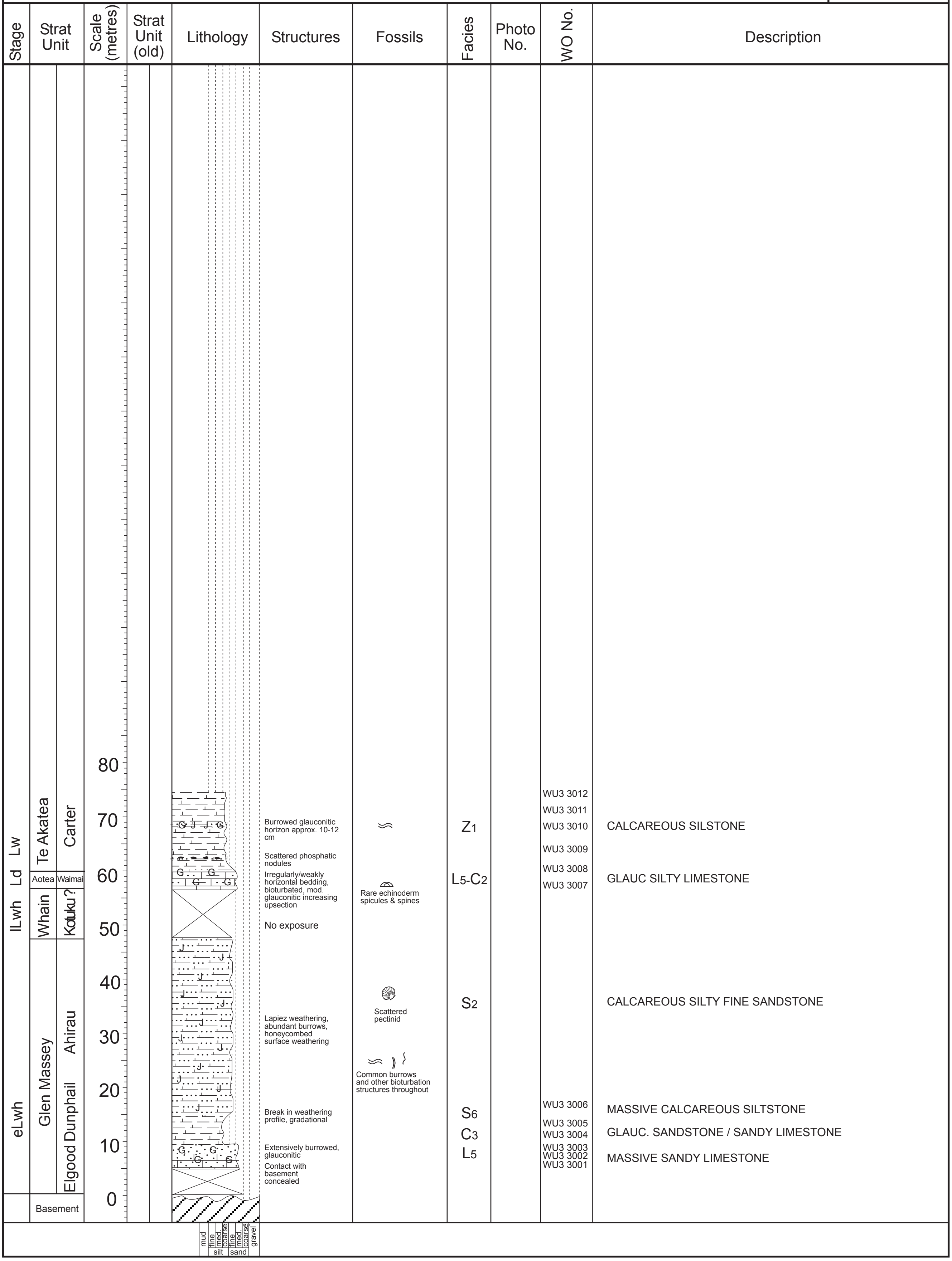
Location: Port Waikato, Waikaretu Road, Sunset Farm

E: 2663800 -

N: 6417650 -

NZMS 260 Sheet: R13/638176

Page 1 *of* 1 **Author:** A. Tripathi



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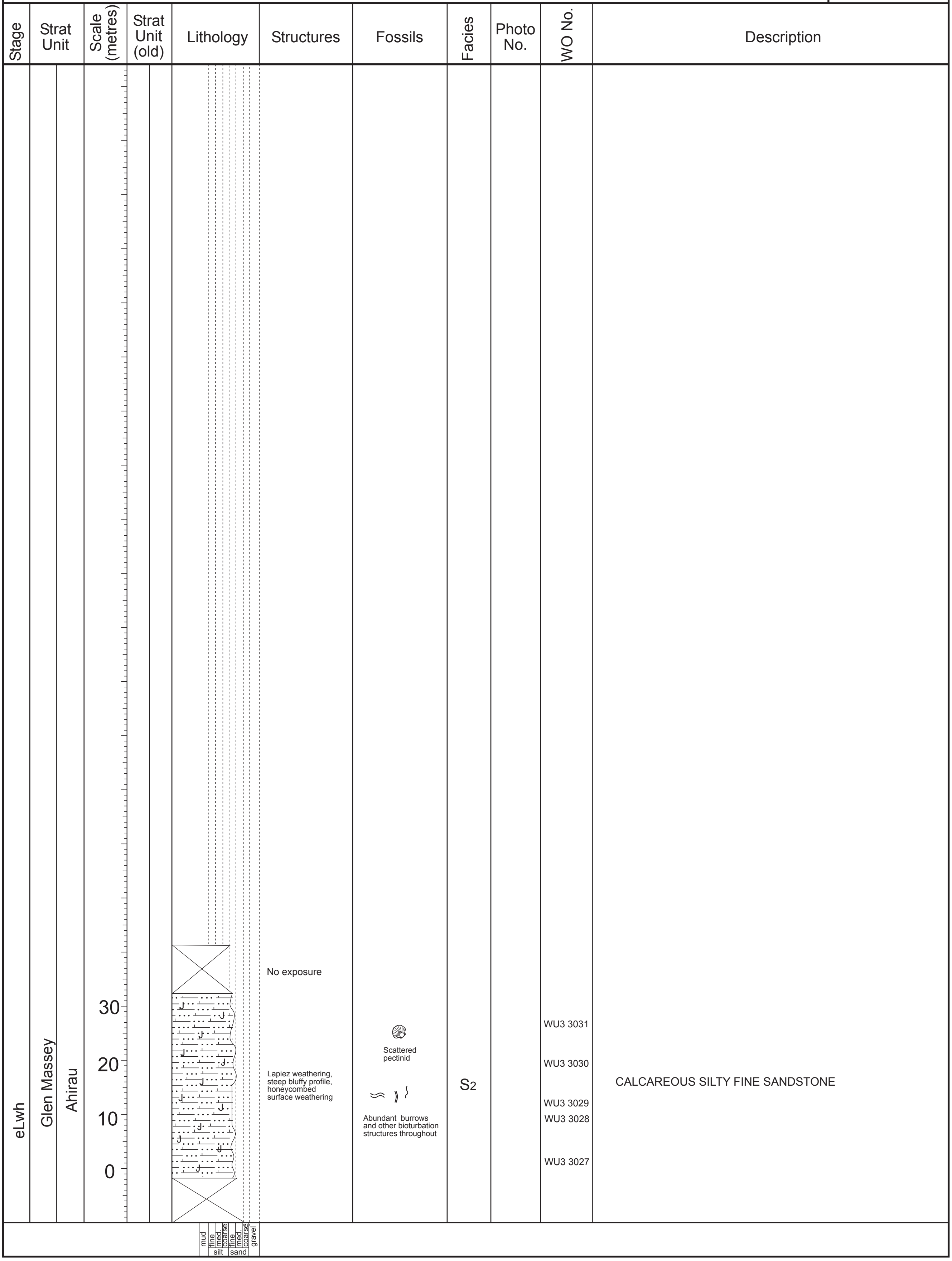
NZMS 260 Sheet: R13/646176 *Page* 1 *of* 1 **Author:** A. Tripathi



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Location: Port Waikato Waikaretu Road,
Sunset Farm

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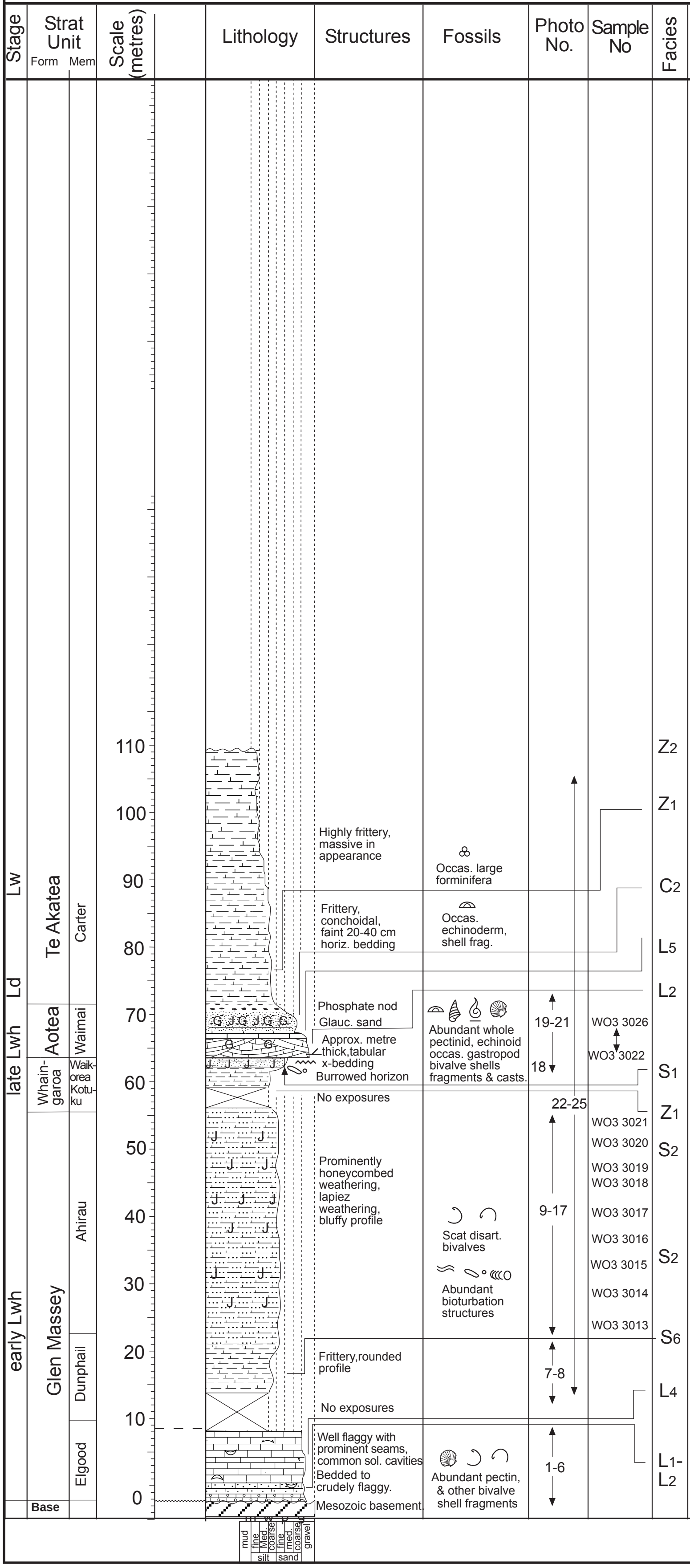
N:	6418307	6417568

NZMS 260 Sheet: R13/1643183

Page 1 **Author:** A. Tripathi



Description

CALC. SILTSTONE / MARL : Very light greyish to almost whitish, massive to rarely shows faint bedding (15-40 cm) development, highly frittery, very fine silt in a highly calc (micritic) matrix, massive homogenous unit, zoophycus traces evident in places, occas echinoderm frag & large foraminifers.

CALC. SILTSONE : Light greyish white(exposed) to brownish grey, highly frittery, moderately hard, breaks off with conchoidal fracture surface, frequently showing iron staining along the joints, highly calcareous siltstone, lower 6-8 m consist of common bioturbated glauconitic horizons.

PHOSPHATIC SILTSTONE : Light greyish to brownish grey, moderately hard, abundant granule to pebble size phosphatic nodules , some phosphatised cast and moulds

GLAUCONITIC SANDSTONE :Dull brownish grey, soft & friable, massive, fine to med sand, abundant glauconite pellets , extensively bioturbated, highly fossiliferous (mainly bivalve, gastropod, echinoderms and rare shark tooth)

GLAUCONITIC SILTY LIMESTONE: Dull rusty brown, soft to mod hard massive to crudely bedded, abundant glauconite pellets, extensively bioturbated

CROSS-BEDDED LIMESTONE : Greyish white, hard to very hard, well developed flags showing poorly flag development towards upper 1/2 m ,thickness varying 5-50 cm separated by glauconitic sandstone rich prominent seams 4-6cm, frequently showing large solution cavities, glauconitic fine to coarse sparry grainstone, centimeter scale tabular cross sets, sets base and tops are discordant, common glauconite pellets.

CALCAREOUS SITY SANDSTONE: Dull brownish grey, massive, calcareous fine sandstone to silty sandstone, extensively bioturbated, lower part poorly exposed, sharp upper probably a scoured contact.

CALCAREOUS SILTSTONE : Blue-grey, soft to mod. hard, massive, frittered appearance on weathered outer surface, poorly exposed.

CALCAREOUS SILTY SANDSTONE : Dull grey to brownish, moderately hard, lapiez weathering, silt to very fine sand grade, common bioturbation structures

CALCAREOUS SAND STONE : Greyish to buff to creamish white, mod. hard, very fine to fine sand (comparatively coarser than the lower unit) grading into silty sandstone, faint indication of cm scale bedding apparent in places, extensively bioturbated with common tubular burrows, scattered bivalves

CALCAREOUS SILTY SAND STONE : Light greyish to light brownish grey, moderately hard, massive, silt to very fine grade sand in a calc. cement, overall extensively bioturbated with common 5-8 cm long subvertical tubular burrows, degree of bioturbation increasing upwards.

CALCAREOUS SILTSTONE : Light greyish to light bluish grey, hard, massive, common frittery appearance, rounded weathering profile, mainly coarse occas. mottled bioturbation structure evident, silt in a highly calc cement, grading upwards into fine silty sandstone.

FLAGGY LIMESTONE : Dirty white to buff to greyish white, thinly flagged (2-5 cm), med to coarsely sparry (comparatively even more coarse sparry towards top with common large bioclasts), frequently highly fossiliferous, abundant disart bivalves cast & moulds specially at the bottom 1 m prominent silty sandy rich seams showing preferential weathering feature.

PEBBLY LIMESTONE : Dull greyish white, massive to faint flaggy development, abundant rounded /subrounded to subangular pebbles to rare cobbles (derived from basement) occas. concentrated in pockets, abundant bivalve fragments, med. to coarse sparry grainstone, concentration of gluaconitic medium to coarse sandy material at the basal contact with irregular basement surface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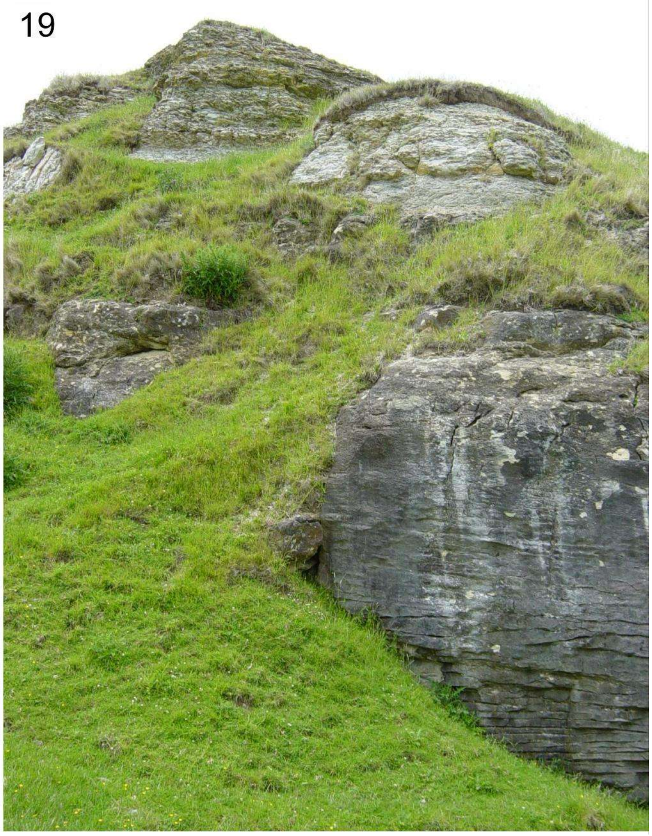
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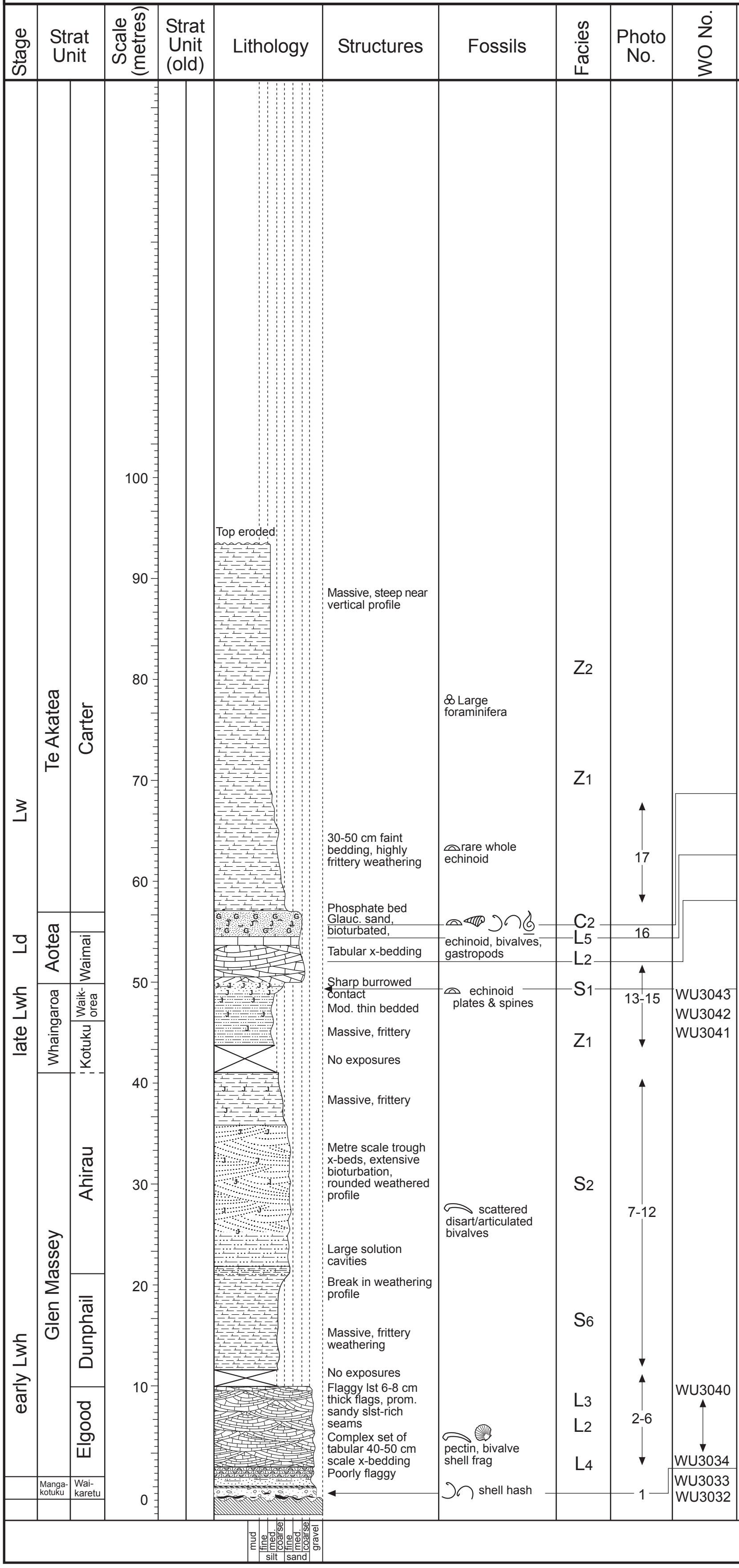
Stratigraphic Column No: *PW-2* ***Grid Reference:***
Region: Port Waikato ***E:*** 2664798
Location: Waikaretu Road, Ngapururu Farm ***N:*** 6417569

NZMS 260 Sheet: R13/647175 *Page* 1 *of* 5 **Author:** A. Tripathi



Description

CALCAREOUS SILTSTONE: Massive creamish white siltstone, highly frittery breaks into 1-2mm fritters, occ. glauconite pellets visible, occ. thin sandy siltstone laminate near the upper eroded top.

CALCAREOUS SILTSTONE: Light greyish white, mod. hard, highly frittery, numerous curvilinear joints, freq. iron stained, faint 30-40 cm bedding apparent in places, few granule size phosphate nodules and glauconite pellets in the lowermost 1 m, fine highly calcareous, common bioturbation features

GLAUCONITIC SANDSTONE: Light dull greenish grey to brownish, soft & friable mainly fine to occ. medium grade sand, fossiliferous & bioturbated, com. glauconitised shells and infilled burrows,conformable contact with lower unit.

GLAUCONITIC SILTY LIMESTONE: Dull brownish grey, massive to faint bding abundant glauconitic pellets, extensively bioturbated with common burrow structures, occ. glauconitised shell and casts.

X-BEDDED FLAGGY LIMESTONE: Light greyish white, hard, well developed flags 8-15 cm separated by thin glauconitic sandy seams 3-5 cm, flags becoming less developed towards top and bottom 1/2 m, 60-70 cm low angle tabular cross sets in the middle part, moderately to highly glauc., overall med. to coarse sparry grainstone.

CALCAREOUS SILTY SANDSTONE: Dull creamish to muddy brown, fine sand to muddy, mod. cemented, faint to mod. centimetre scale bding, intensely bioturbated particularly near the upper very sharp contact, occ. glauconite pellets visible near the contact

SILTSTONE: Brownish grey to light greyish, soft to mod hard, freq. bioturbated, massive in appearance.

CALC. SILTY SANDSTONE: Light greyish white,very fine sand to silt, apparently with higher calcareous cement, extensive burrow network obvious all throughout the exposure.

CALC. SANDSTONE: Light brownish grey, moderately hard, extensively bioturbated, metre scale trough cross sets apparent in the middle part.

SANDY SILTSTONE: Very light greyish to creamish white, mod. hard, massive freq. frittery, at times flaky, some ind. of bioturbation, overall very fine sand to calcareous siltstone.

CALCAREOUS SILTSTONE: Blue grey, massive, com. frittered appearance on weathered outer surface.

Contact with above unit not exposed.

X-BEDDED FLAGGY LIMESTONE: Light brownish to greyish to buff, hard, well flaggy,planar cross bedding approx. 1/2 thick cross sets, prom. seams infilled with sandy siltstone, bottom 1 metre is highly fossiliferous with abun. bivalve frag., cast and moulds, overall medium to coarse sparry crystalline grainstone.

PEBBLY SANDSTONE: Greyish to rusty brown, mod hard, pebbly gritty sandst. 5-cm thick coal streak & carb. matter, 4-cm thick shell hash bed in the middle, overall abundant coal & basement clast in a calc. sandy matrix, sandy limestone layer immediately above contact with irregular b/ment surface.

MESOZOIC BASEMENT: Highly weathered argillite.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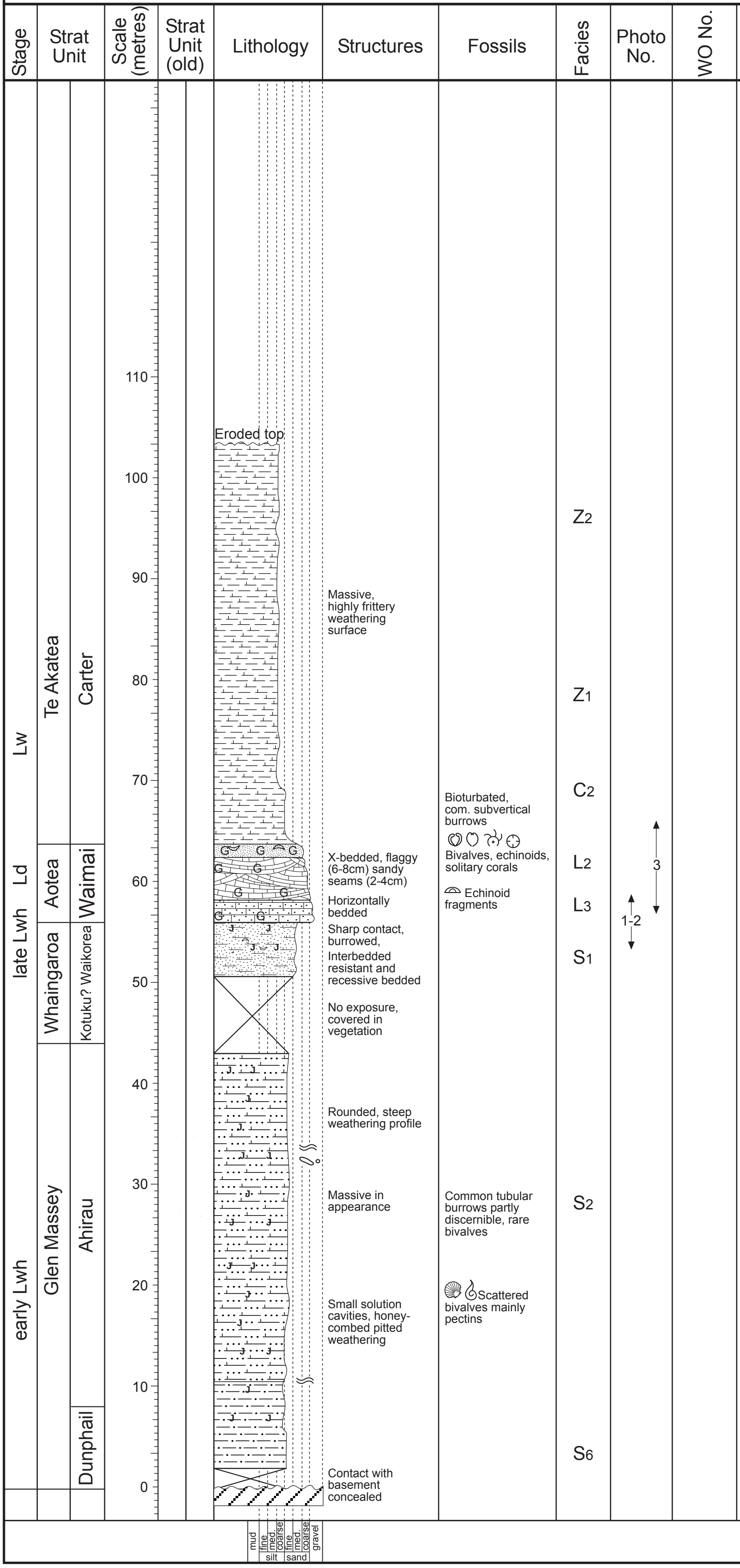
Stratigraphic Column No: *PW-3* **Grid Reference:**

Region: Port Waikato **E:** 2665150

Location: 2 1/2 km SW from the Kaawa stream bridge on Port Waikato Waikaretu Road **N:** 6410851

NZMS 260 Sheet: R13/651108 *Page* 1 *of* 2 **Author:** A. Tripathi



Description

CALCAREOUS SILTSTONE: Massive creamish white highly calcareous siltstone/marl, poorly exposed, steep weathering profile.

CALC. SILTSTONE: Light greyish white to light bluish grey, massive, highly frittery, iron-staining along numerous curvilinear joints, faint 30-40 cm bedding apparent in the lower 6-8 m.

CALC SANDY SILTSTONE: Light greyish to brownish white, massive, fine sandy siltstone, abundant glauconite pellets, bioturbated.

GLAUC. FOSSILIFEROUS SST: Dull greyish, soft to mod. hard, massive med. to coarse sand, occ. gritty, abundant glauconised bivalves,echinoid, rare solitary corals, casts and moulds.

X-BEDDED LIMESTONE: Light greyish, low angle tabular cross bedding,10-15 cm beds, common glauconite pellets, glauc. conc. increasing upwards med. to coarse sparry grainstone.

HORIZONTALLY BEDDED LIMESTONE: Buff coloured, horizontally bedded 10-20 cm beds, thin silty sandstone interbeds, subvertical burrows, glauconite pellets, coarse echinoid fragments, medium to coarse sparry grainstone.

CALCAREOUS SILTY SANDSTONE: Light brownish grey, horizontally bedded common recessive silty sandstone and resistant calcareous sandstone beds, vertical and horizontal burrows, glauconite pellets, calc. cement increasing upsection.

CALC. SANDY SILTSTONE/SILTY SANDSTONE: Dull greyish to brownish grey, mod. hard, mainly very fine silty sand in a calc. muddy matrix, bioturbated, scattered bivalve weakly glauconitic in places.

CALC. SILTY SANDSTONE: Light greyish to brownish grey, mod. hard,massive fine silty sandstone, well cemented, common 4-8 cm tubular burrows, scattered articulated/disarticulated bivalves.

CALCAREOUS SILTSTONE: Light bluish grey, massive, well cemented siltstone, poorly exposed.

MESOZOIC BASEMENT: Highly weathered argillite

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Stratigraphic Column No: *PW-4*

Region: Port Waikato

Location: Along Kaawa stream, Pungatiki stream bridge on Baker Road

NZMS 260 Sheet: R13/710128

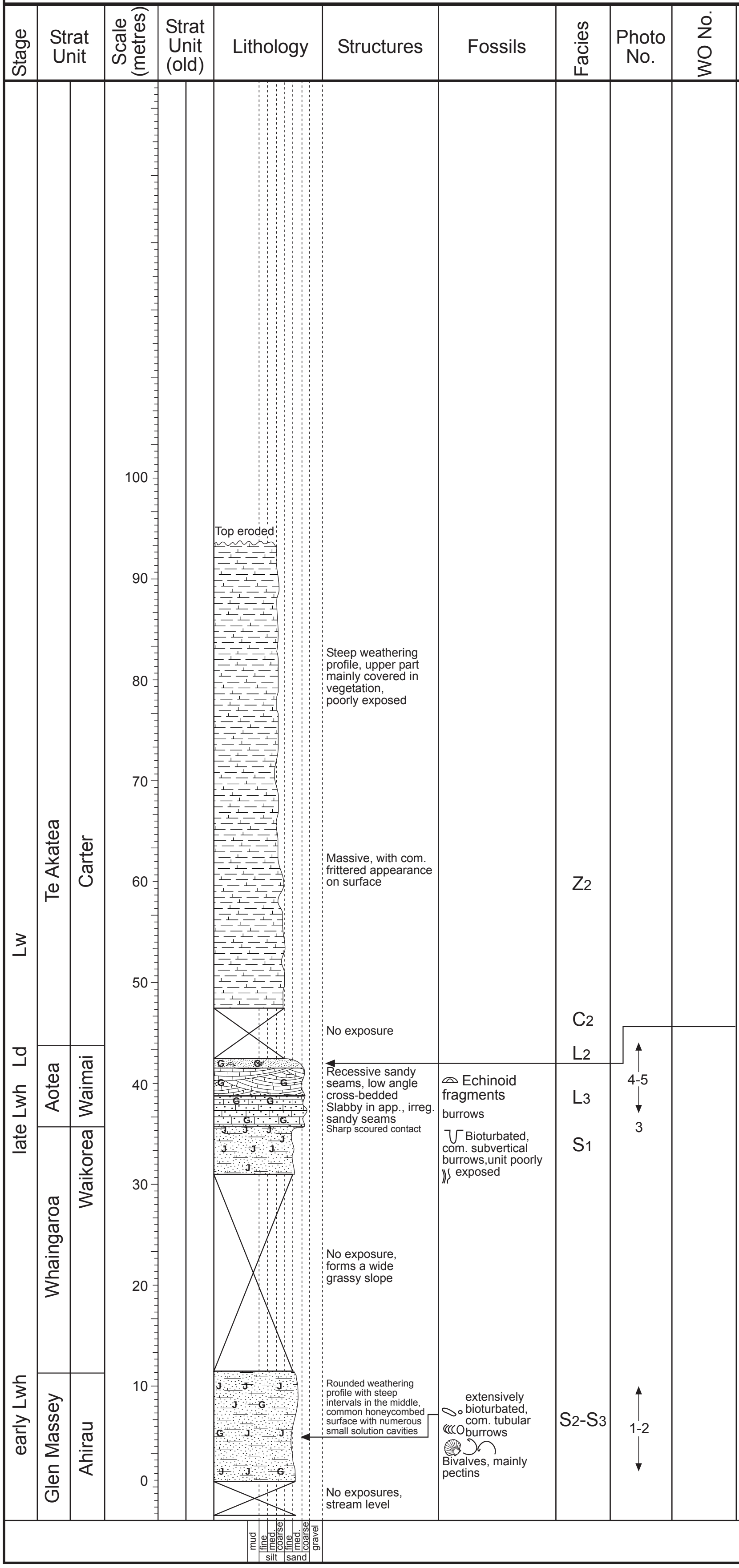
Grid Reference:

E: 2671096

N: 6412816

Page 1 *of* 1

Author: A. Tripathi



Description

CALC. SILTSTONE: Light bluish grey to creamy white, massive, well cemented fine calcareous siltstone/marl.

GLAUC. SANDSTONE: Light dull greenish grey, soft and friable, bioturbated, abundant glauconite pellets and fossiliferous.

X-BEDDED LIMESTONE: Light dull greyish, hard, med. to coarse sparry grst., glauconitic, low angle x-bedding, well dev. flags, sand rich seams common towards bottom, comparatively less terrigenous sand content.

HORIZONTALLY BEDDED LIMESTONE: Light greyish to brownish grey, hard to very hard, mod. flaggy (8-15 cm; poorly flaggy to massive in lower (30-40 cm)) sandy grainstone, glauconitic.

CALC. SILTY SANDSTONE: Light bluish grey to brownish grey, massive, fine grained sandstone, calcareous content increasing upsection, bioturbated, sharp scoured contact with overlying unit.

CALC SILTY SANDSTONE: Dull greyish to brownish grey, mod. hard, massive, very fine to fine sandstone, comparatively less silty, calc. content increasing upwards, bioturbated

CALC. SILTY SANDSTONE: Dull greyish to brownish, well cemented, massive, mainly very fine to fine sand with variable proportion of calcareous silt, mod. glauconitic, extensively bioturbated, scattered disart. bivalves especially at stream level

Lower contact not exposed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***Stratigraphic Column No:** PW-5*

Grid Reference:

Region: Port Waikato

Location: Brien Road, Wairamarama

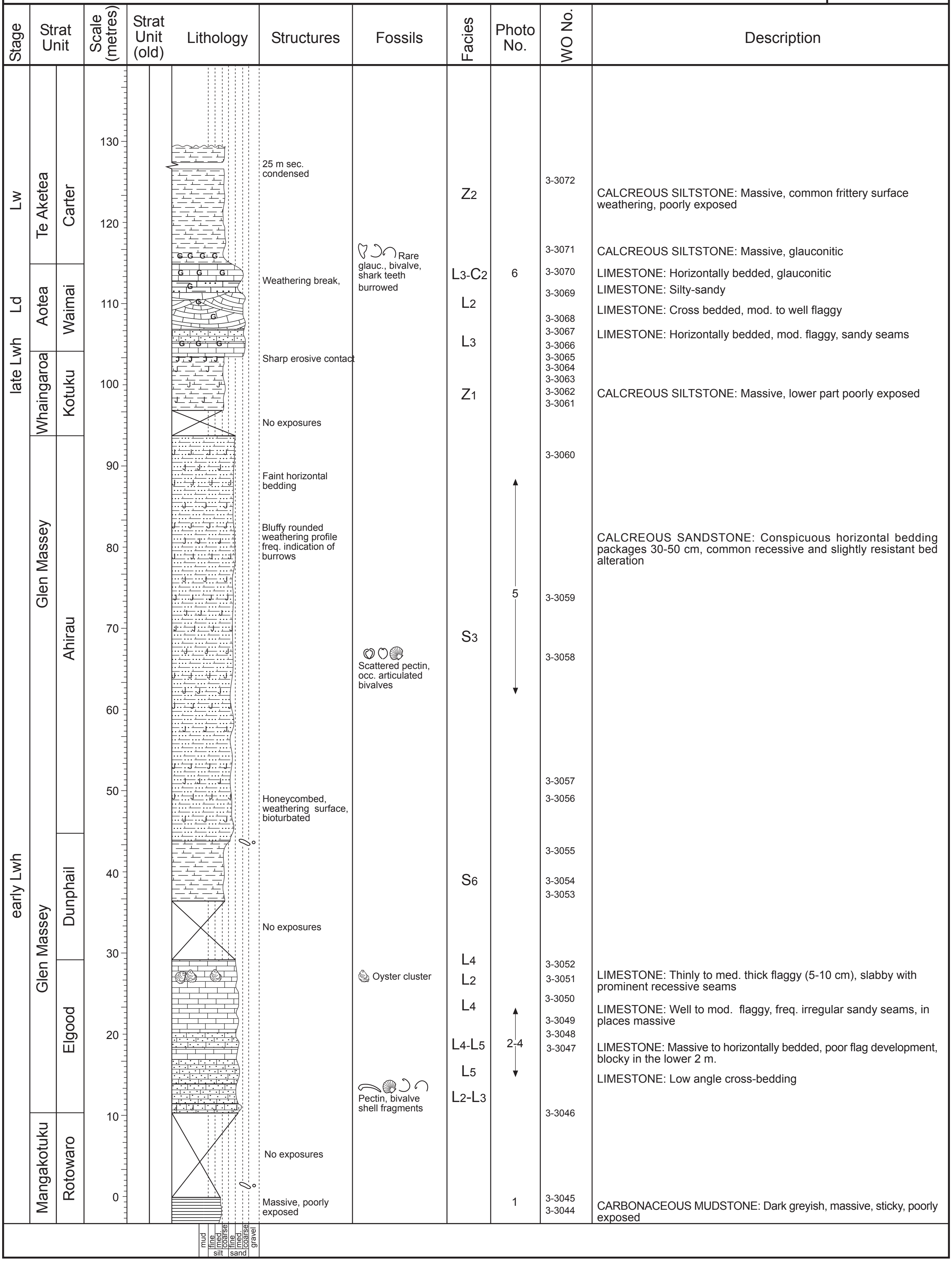
E: 2672040 - 2672503

N: 6419829 - 6419729

NZMS 260 Sheet: R13/722197-724195

Page 1 *of* 2

Author: A. Tripathi



CALCREOUS SILTSTONE: Massive, common frittery surface weathering, poorly exposed

CALCREOUS SILTSTONE: Massive, glauconitic

LIMESTONE: Horizontally bedded, glauconitic

LIMESTONE: Silty-sandy

LIMESTONE: Cross bedded, mod. to well flaggy

LIMESTONE: Horizontally bedded, mod. flaggy, sandy seams

CALCREOUS SILTSTONE: Massive, lower part poorly exposed

CALCREOUS SANDSTONE: Conspicuous horizontal bedding packages 30-50 cm, common recessive and slightly resistant bed alteration

LIMESTONE: Thinly to med. thick flaggy (5-10 cm), slabby with prominent recessive seams

LIMESTONE: Well to mod. flaggy, freq. irregular sandy seams, in places massive

LIMESTONE: Massive to horizontally bedded, poor flag development, blocky in the lower 2 m.

LIMESTONE: Low angle cross-bedding

CARBONACEOUS MUDSTONE: Dark greyish, massive, sticky, poorly exposed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Stratigraphic Column No: *PW-6* ***Grid Reference:***

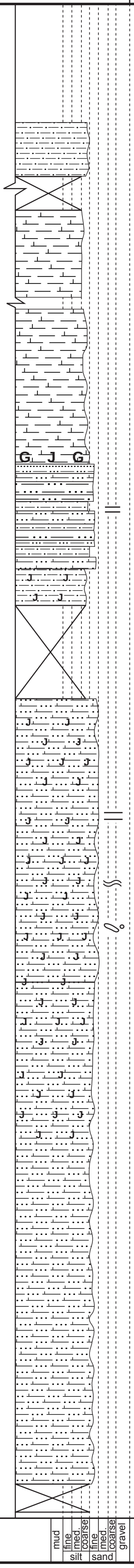
Region: Port Waikato

Location: Wairamarama Onewhero Road

E:	2676236	-	2676384
N:	6421335	-	6420714

NZMS 260 Sheet: R13/762133

Page 1 *of* 2 **Author:** A. Tripathi



Stage	Strat Unit		Scale (metres)	Strat Unit (old)	Structures	Fossils	Facies	Photo No.	WO No.	Description
Po	Waitemata									SANDY SILTSTONE: Greyish to brownish grey, mass. poorly-mod. cemented, exposed in the road cut.
			170							
			140		Approx. 30 m gap in exposures.					
			110		Section condensed					
Lw	Te Akatea	Carter			Poor exposure, mainly covered by grassy surface		Z2	5		
			100							CALC. SILTSTONE: Light greyish to creamish, massive, frittered weathered surface exposed in between mainly grassy mod. to steeply sloping surface.
Ld					Bioturbated at contact, poorly exposed		S 3			INTERBEDDED CALC SST AND SANDY SILTSTONE: Dull greyish to light greyish, mod. hard, fine calc. silty sst. beds 12-30 cm thick separated by recessive sandy siltstone interbeds, silty interbeds becoming thicker upsection, bioturbation common especially in the interbeds, occasional glauconite pellets moderate concentration seen at the upper contact, scattered bivalve and echinoderm fragments.
	Aotea	Mangiti	90		Distinctly horizontally bedded,					
					Erosive sharp contact	Disart bivalves and echinoid fragments		4		
late Lwh					Bioturbated, partic. near upper sharp contact, poorly exposed		Z1			CALC SILTSTONE: Light brownish grey to light greyish, soft to mod. hard,massive, bioturbated, variably muddy but calc. content increasing upsection, forming sharp upper contact.
	Whaingaroa	Kotuku	80		No exposures, gently sloping grassy landscape					
			70							
	Glen Massey				Faint horiz. bedding discernible, rounded bluffy weathering profile	Abundant bioturb.				CALCAREOUS SILTY SANDSTONE: Light brownish grey, hard well cemented very fine sandstone to silty sandstone showing faint interbedding, bioturbated 4-6 cm tubular burrows seen occasionally.
			60							
					Vertical fluting apparent, steep surface		S3			
		Ahirau	50					1-3		
					Honeycombed weathering, surface riddled with lge solution cavities separated by 10-15 cm sub-horizontal bedding planes	Scattered pectins and other bivalves				CALCAREOUS SILTY SANDSTONE: Light greyish to brownish grey, hard, mainly very fine to fine sand and silty sand in a calcareous cement, extensively bioturbated commonly indicated by very honeycombed weathered surface and large solution cavities, centimeter scale bedding apparent in places.
			40							
					Steepening of weathering profile marking the grad. contact between lower and upper members					
			30							
early Lwh					Common slumped blocks		S6			
			20							CALC. SILTSTONE: Light bluish grey, mod. hard to hard, massive with com. frittered weathered surface,occ. indication of bioturbation, exposed mainly as slumped/tilted blocks.
	Glen Massey	Dunphail	10							
			0		Contact with b/ment not known					No exposure bellow the stream level, unit probably extends in the subsurface.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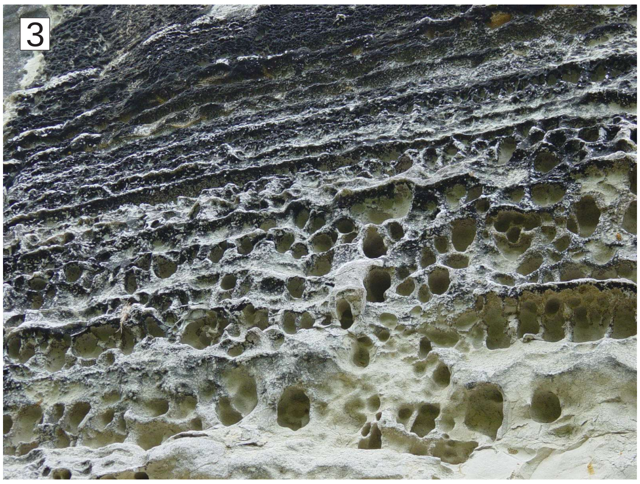
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Waitemata Gp
Carter Siltstone
Mangiti Sandstone

Stratigraphic Column No: *PW-7* ***Grid Reference:***

Region: Port Waikato

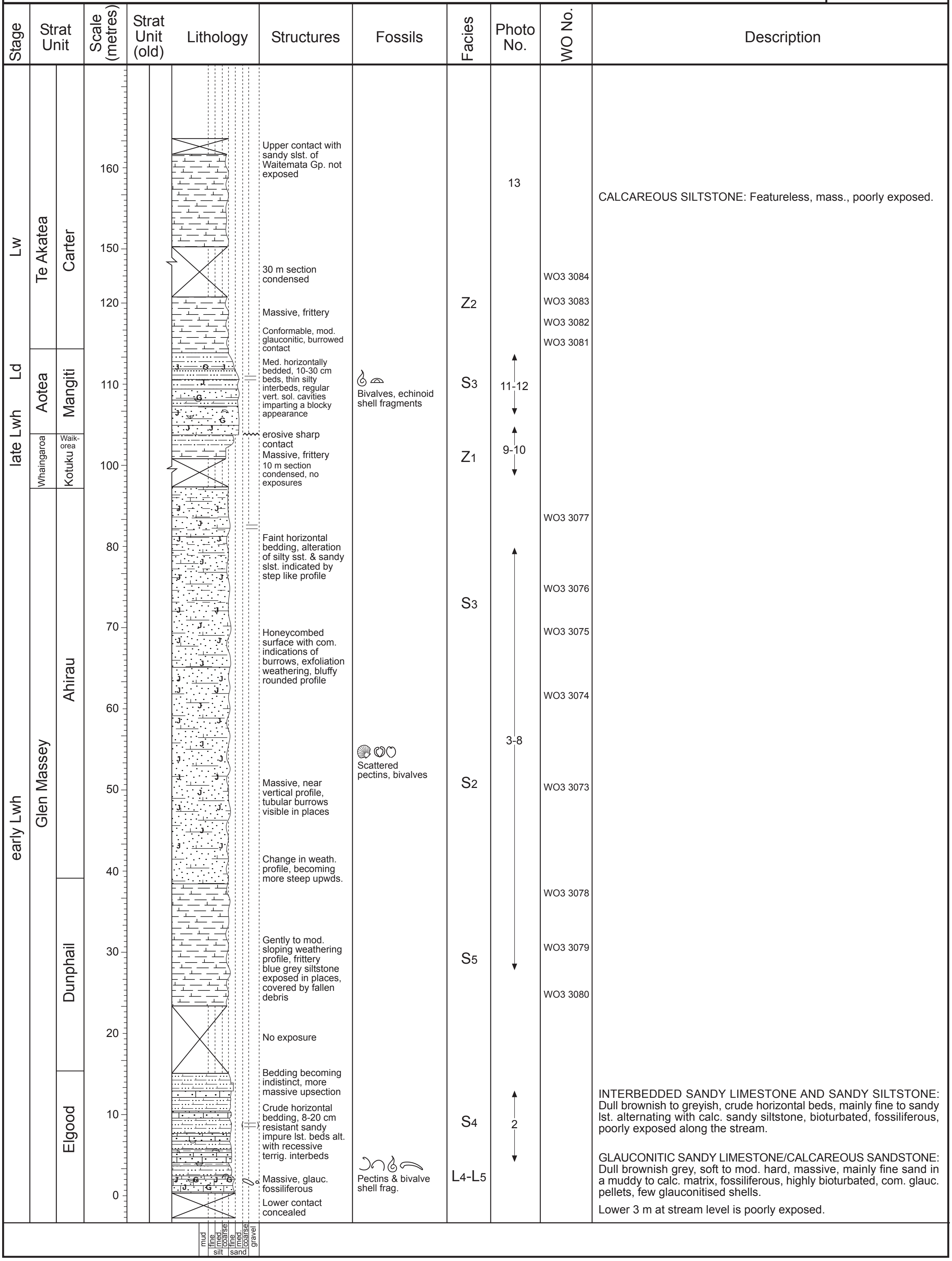
Location: Matakitaki Road, Matakitaki Trig

E: 2680994 - 2679710

N: 6416438 - 6415270

NZMS 260 Sheet: R13/797152-809164

Page 1 *of* 3 **Author:** A. Tripathi



Upper contact with sandy slst. of Waitemata Gp. not exposed

30 m section condensed

Massive, frittery

Conformable, mod. glauconitic, burrowed contact

Med. horizontally bedded, 10-30 cm beds, thin silty interbeds, regular vert. sol. cavities imparting a blocky appearance

erosive sharp contact

Massive, frittery

10 m section condensed, no exposures

Faint horizontal bedding, alteration of silty sst. & sandy slst. indicated by step like profile

Honeycombed surface with com. indications of burrows, exfoliation weathering, bluffy rounded profile

Massive, near vertical profile, tubular burrows visible in places

Change in weath. profile, becoming more steep upwds.

Gently to mod. sloping weathering profile, frittery blue grey siltstone exposed in places, covered by fallen debris

No exposure

Bedding becoming indistinct, more massive upsection

Crude horizontal bedding, 8-20 cm resistant sandy impure lst. beds alt. with recessive terrig. interbeds

Massive, glauc. fossiliferous

Lower contact concealed

Bivalves, echinoid shell fragments

Scattered pectins, bivalves

Pectins & bivalve shell frag.

CALCAREOUS SILTSTONE: Featureless, mass., poorly exposed.

INTERBEDDED SANDY LIMESTONE AND SANDY SILTSTONE: Dull brownish to greyish, crude horizontal beds, mainly fine to sandy lst. alternating with calc. sandy siltstone, bioturbated, fossiliferous, poorly exposed along the stream.

GLAUCONITIC SANDY LIMESTONE/CALCAREOUS SANDSTONE: Dull brownish grey, soft to mod. hard, massive, mainly fine sand in a muddy to calc. matrix, fossiliferous, highly bioturbated, com. glauc. pellets, few glauconitised shells.

Lower 3 m at stream level is poorly exposed.

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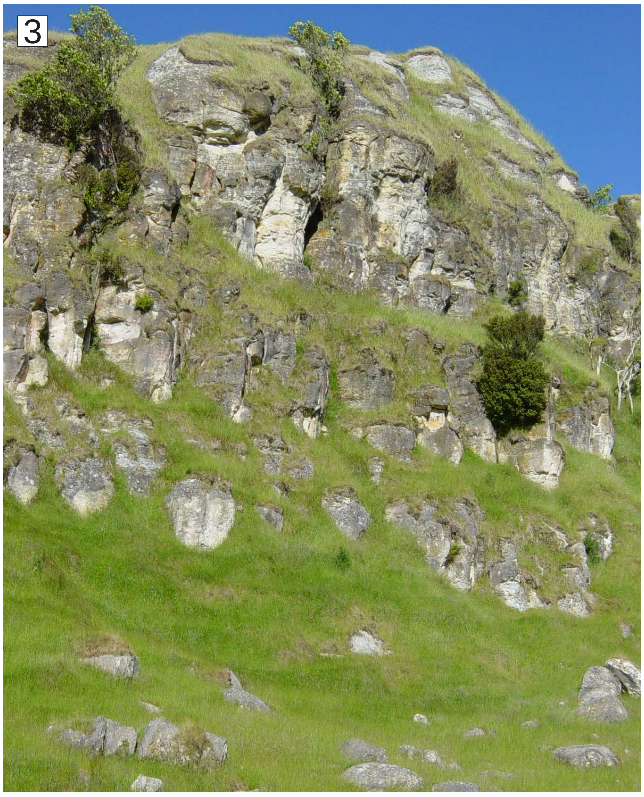

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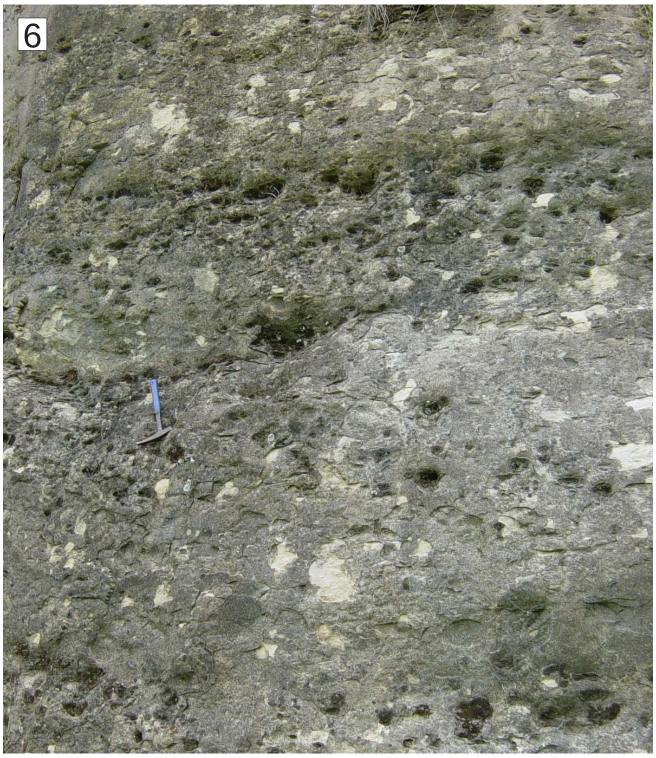

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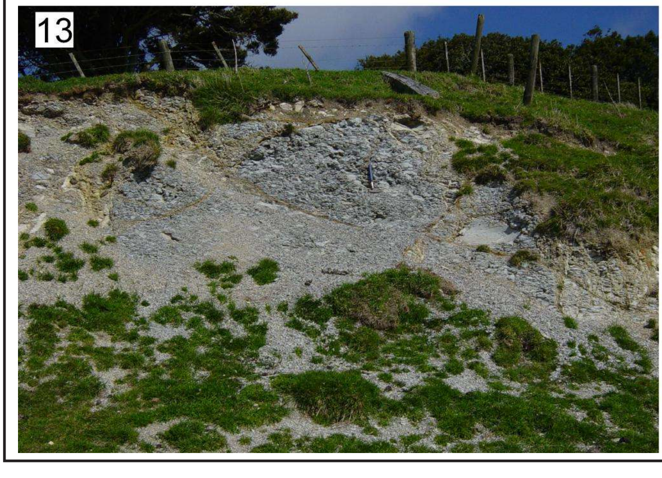


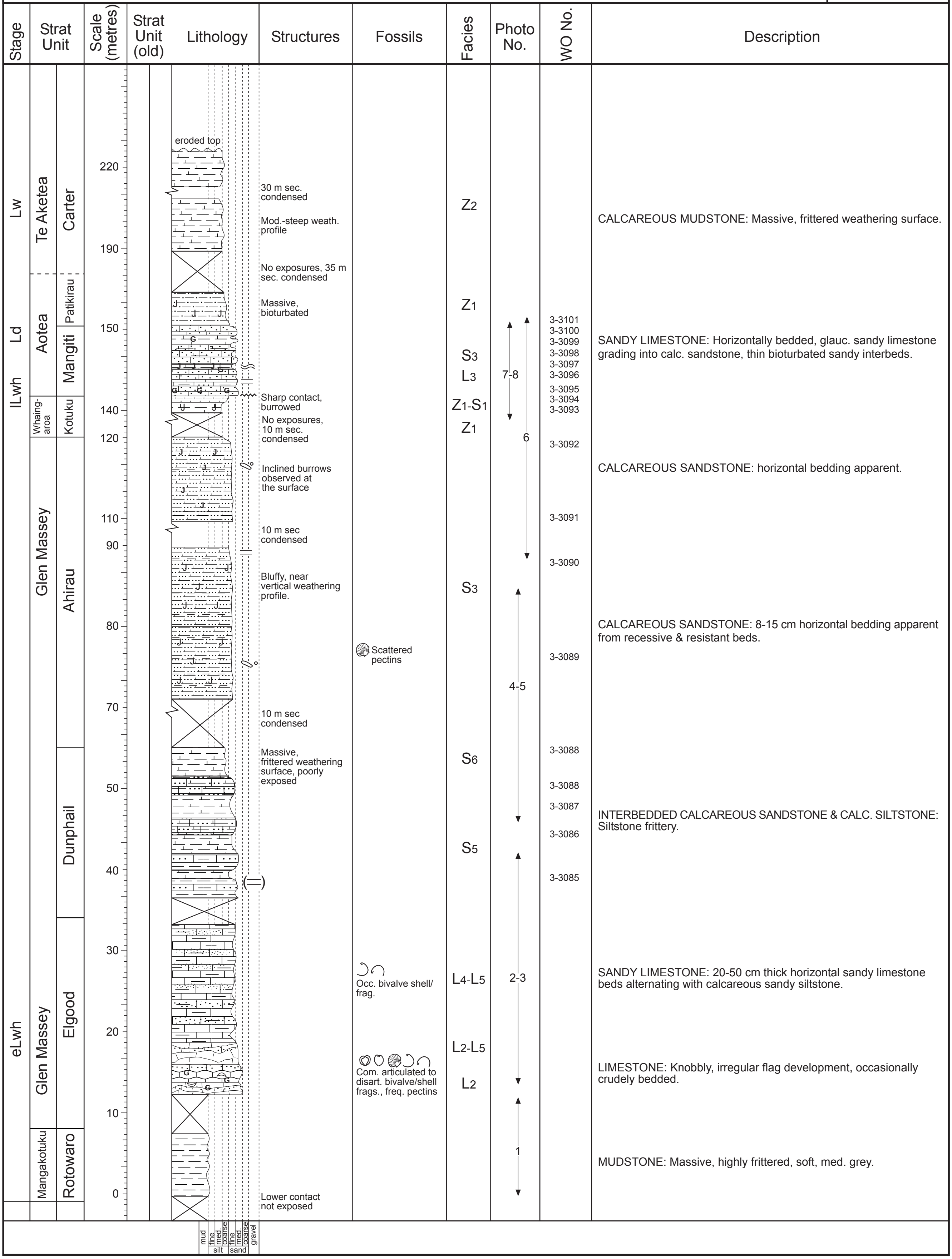
Stratigraphic Column No: *PW-8*
Region: Port Waikato
Location: Bothwell Road

Grid Reference:

E:	2677081	-	2674948
N:	6413325	-	6411892

NZMS 260 Sheet: R13/770133-749118

Page 1 *of* 3 **Author:** A. Tripathi



CALCAREOUS MUDSTONE: Massive, frittered weathering surface.

SANDY LIMESTONE: Horizontally bedded, glauc. sandy limestone grading into calc. sandstone, thin bioturbated sandy interbeds.

CALCAREOUS SANDSTONE: horizontal bedding apparent.

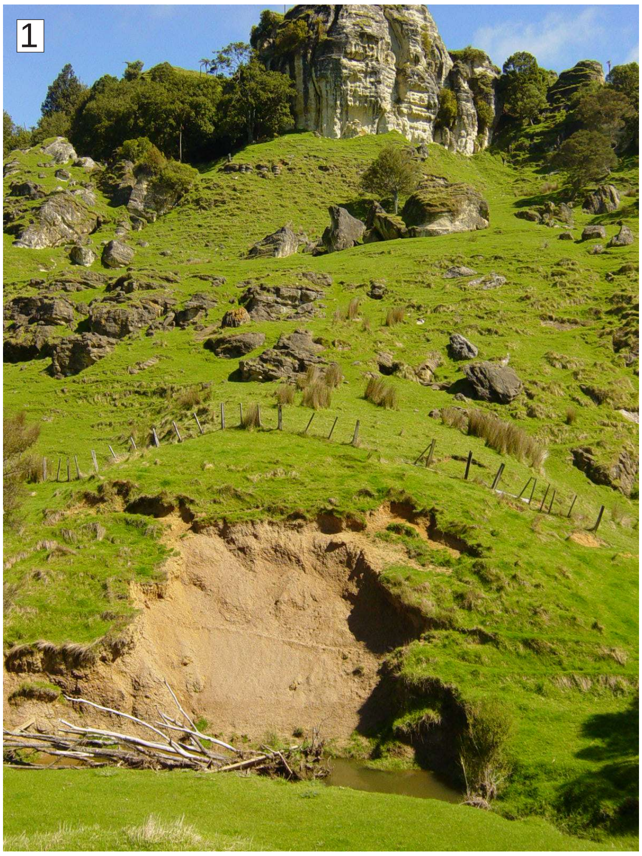
CALCAREOUS SANDSTONE: 8-15 cm horizontal bedding apparent from recessive & resistant beds.

INTERBEDDED CALCAREOUS SANDSTONE & CALC. SILTSTONE: Siltstone frittery.

SANDY LIMESTONE: 20-50 cm thick horizontal sandy limestone beds alternating with calcareous sandy siltstone.

LIMESTONE: Knobbly, irregular flag development, occasionally crudely bedded.

MUDSTONE: Massive, highly frittered, soft, med. grey.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Mangiti Sandstone Mbr
Kotuku Siltstone Mbr
Ahirau Sandstone Mbr

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Stratigraphic Column No: *PW-9* ***Grid Reference:***

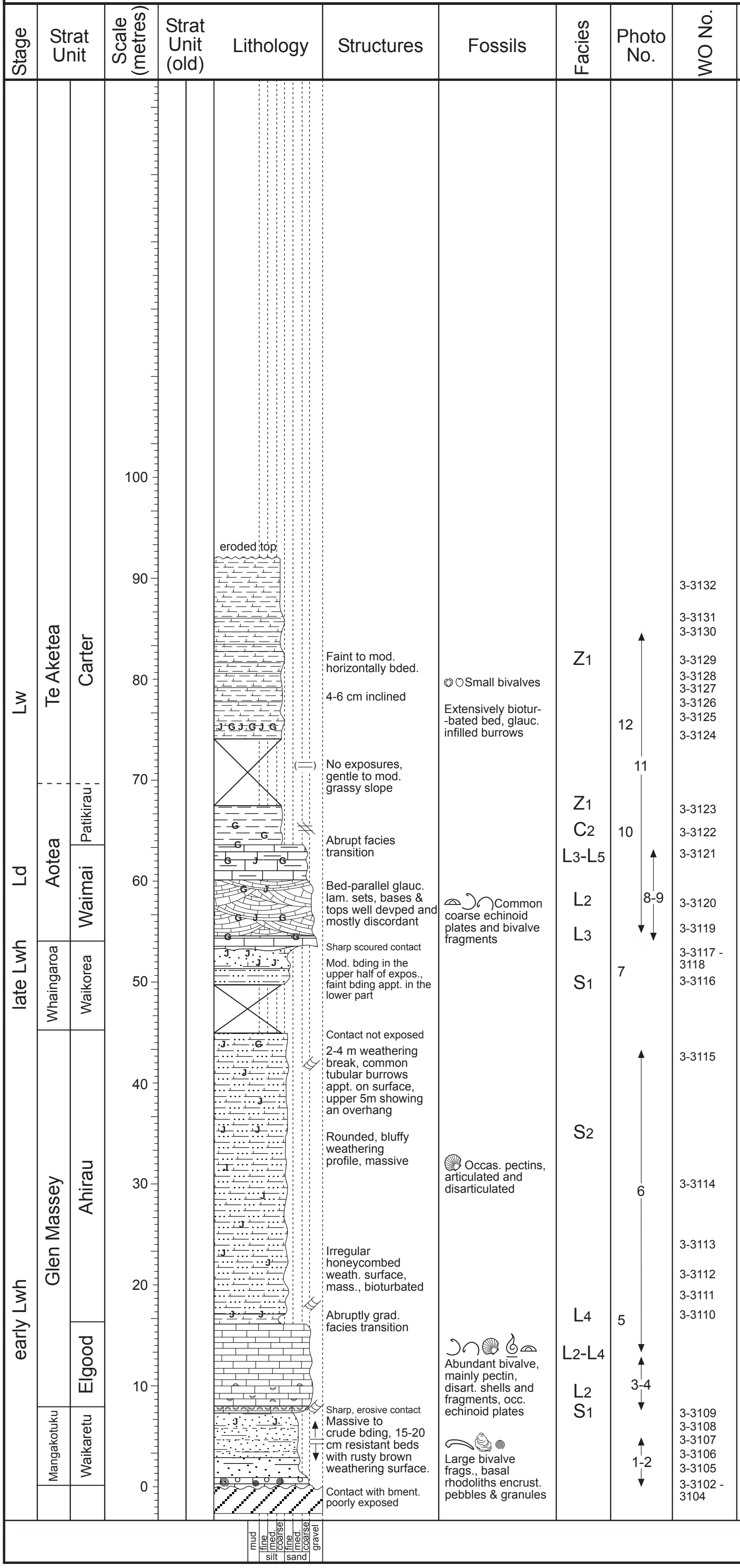
Region: Port Waikato

Location: Waikaretu Valley Road

E:	2670254	-	2669300
N:	6404961	-	6404300

NZMS 260 Sheet: R13/702049 - 693043

Page 1 *of* 3 **Author:** A. Tripathi



Description

CALCAREOUS SILTSTONE: Light creamish to brownish grey, medium horizontal 20-30 cm bedding packages apparent, common frittered weathered surface, extensively bioturbated horizon with large glauconitic infilled burrow in the lowermost exposed part, scattered small bivalves, unit becoming comparatively massive in the upper 4-5 m of the exposure

CALC. SANDY SILTSTONE: Light greyish, soft to mod hard, occ. showing faint laminations 5-8 cm in the lower 0.3-0.5 m, overall massive and bioturbated, mod. to highly glauconitic.

HORIZONTALLY BEDDED LIMESTONE: Dull brownish grey, mod. hard to hard, 6-24 thick beds separated by 1-1.5 cm thick bedding planes rich in siliciclastic particles, common indication of bioturbation, bioturbation increasing upsection, concentration of glauconite pellets all throughout, abrupt upwards transition into the overlying siltstone unit

CROSS BEDDED GLAUC. LIMESTONE: Greyish to greyish white, hard, about .3-.8 m thick mod. to low angle tabular cross sets, beds average 6-10 cm sep. by glauconitic rich seams, common coarse bioclasts, common echinoderm plates and rare whole shells, medium to coarse sparry grainstone.

CALC. SILTY SANDSTONE: Light greyish to bluish grey, faint to med. thin horizontally bedded (2-4 cm), bedding not apparent in the lower 1 m, fine calc. silty sandstone grading into sandy siltstone in the lower part.

Not exposed, forming a broad grassy slope.

CALC. SILTY SANDSTONE: Light brownish to bluish grey, mod. well cemented, massive, very fine to fine calcareous sandstone grading into silty sandstone, bioturbated, occ. burrows, steep bluffy weathering profile, mod. glauconite pellet concentration towards top, scattered bivalves, occ. cast and mould.

CALC. SANDY SILTSTONE: Greyish to dull greyish brown, mod. hard, bioturbated, in abrupt contact with the flaggy limestone, forms a 30-50 cm thick transitionary unit between the underlying limestone and overlying calcareous silty sandstone.

FLAGGY LIMESTONE: Light greyish to brownish grey, mod. hard to hard, horizontally bedded, flaggy, 8-12 cm flags separated by recessive 1-2.5 cm thick terrigenous seams, medium to coarse sparry lst., more sandy intervals marked by cavernous poor flag development, abundant bivalve and echinoderm shells in the lower portion consisting of mainly fragmented shells con. along bedding parallel beds & occ. pockets, bioclast concentration decreasing upsection.

CALC. SILTY SANDSTONE: Light brownish grey, hard to very hard, 12 -15 cm thick horizontal bedding separated by 2-3 cm thick silty/muddy interbeds, fine to med. sand in a silty calcareous cement, forming sharp apparently erosive contact with the overlying limestone unit.

MUDDY SANDSTONE: Dark greyish to medium grey, soft/crumbly to mod. hard beds alternating with massive to crudely bedded units, medium to coarse quartoze sand, poorly sorted grading into muddy sandstone, freq. showing rusty brown iron staining pebbly to gritty in the lower half metre, rare large bivalves/oyster shell fragments, 20-30 cm thick lensoidal rhodolith basal beds overlying the basement.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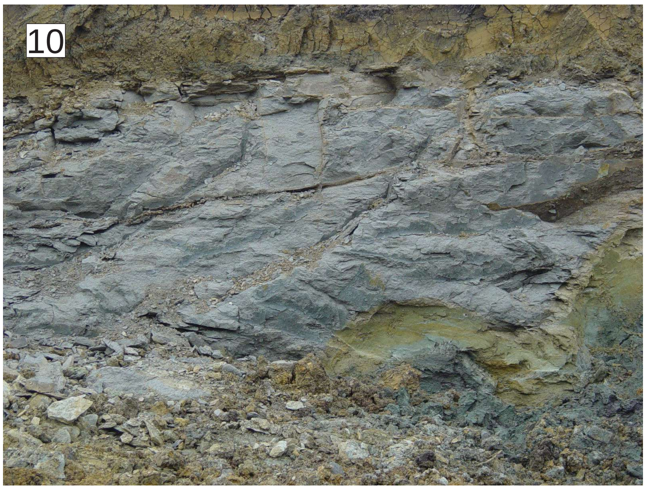
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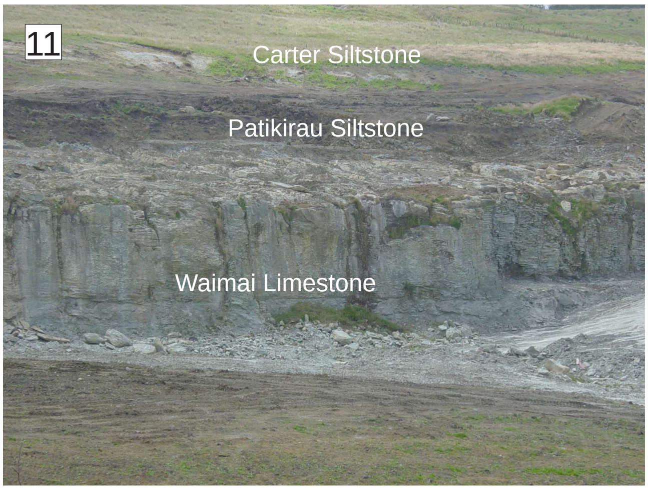
11


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Stratigraphic Column No: *PW-10*

Region: Port Waikato

Location: Waikorea Road

Grid Reference:

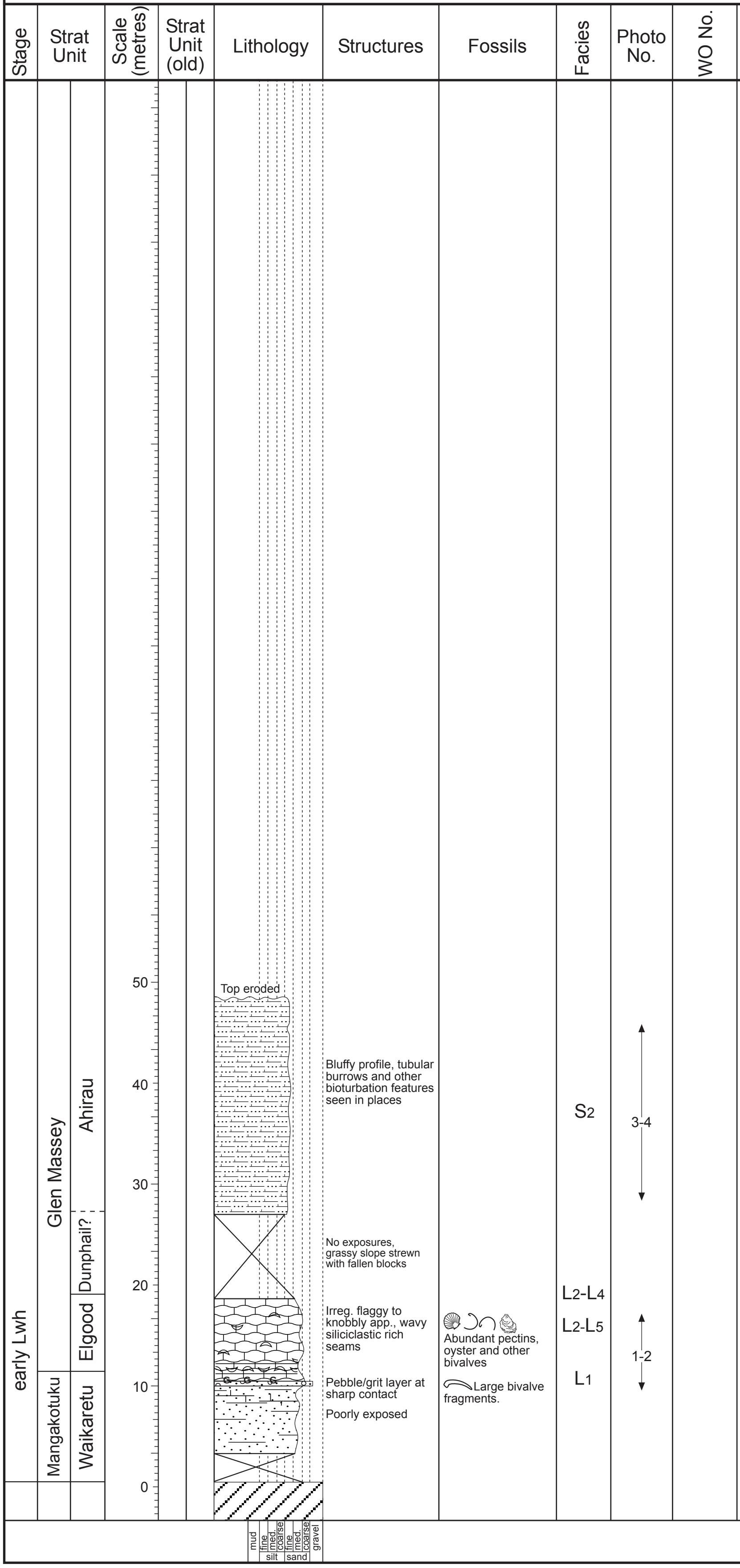
E: 2676359

N: 6403131

NZMS 260 Sheet: R13/762032

Page 1 *of* 2

Author: A. Tripathi



Description

CALC. SILTY SANDSTONE: Light grey to brownish grey, hard, mainly silt to very fine sand in a calcareous cement, massive, freq. with mod. hard silty lenses, common bioturbation features, bluffy steep weathering profile.

FOSSILIFEROUS SANDY LIMESTONE: Dull brownish grey, mod. hard to hard, irregular flag development, flags 8-15 cm thick separated by 1-1.5 cm sandy seams, occ. subrounded granules in the lower 0.5 m, abundant bioclasts scattered randomly but also concentrated as shell bed near the lower contact, overall very coarse bioclastic sandy grainstone.

GRITTY CALC. SANDSTONE: Dull brownish grey, 0.20 - 0.30 m bed containing abundant pebble and granule size, subrounded basement clasts, well cemented and concentration of glauconite pellet.

ARGILLACEOUS CALC. SANDSTONE: Dull greyish to buff, common rusty brown iron staining, massive, soft crumbly to mod. hard, mainly fine to medium muddy sandstone, calcareous cement increasing upsection becoming hard and well cemented particularly 0.30-0.50 m interval below the upper contact.

Contact with basement not exposed,contact probably lies at the stream level.

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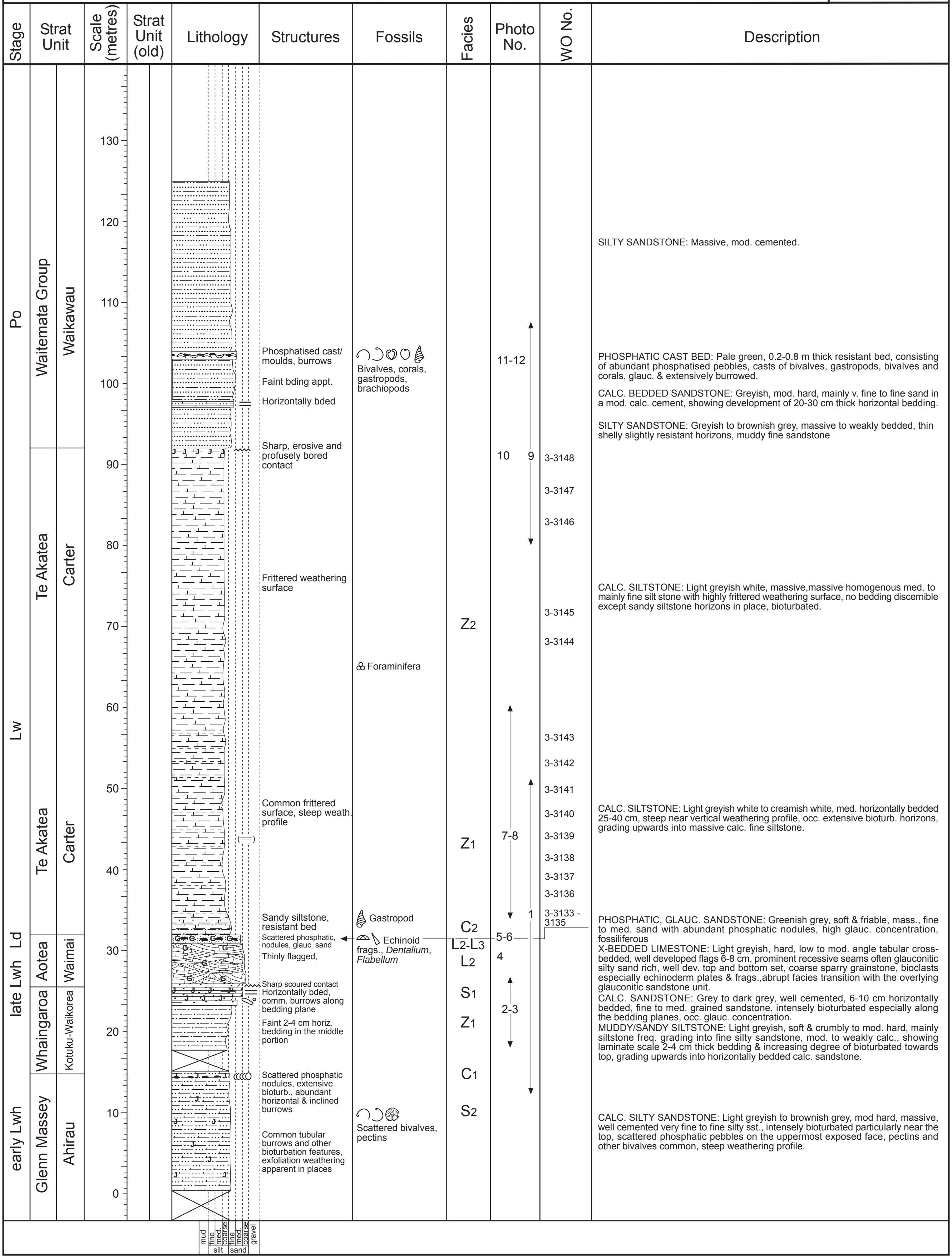
Stratigraphic Column No: *PW-11*
Region: Port Waikato
Location: Waikawau beach

Grid Reference:
E: 2662576
N: 6413802

NZMS 260 Sheet: R13/625138

Page 1 *of* 3 **Author:** A. Tripathi



SILTY SANDSTONE: Massive, mod. cemented.

PHOSPHATIC CAST BED: Pale green, 0.2-0.8 m thick resistant bed, consisting of abundant phosphatised pebbles, casts of bivalves, gastropods, bivalves and corals, glauc. & extensively burrowed.

CALC. BEDDED SANDSTONE: Greyish, mod. hard, mainly v. fine to fine sand in a mod. calc. cement, showing development of 20-30 cm thick horizontal bedding.

SILTY SANDSTONE: Greyish to brownish grey, massive to weakly bedded, thin shelly slightly resistant horizons, muddy fine sandstone

CALC. SILTSTONE: Light greyish white, massive,massive homogenous med. to mainly fine silt stone with highly frittered weathering surface, no bedding discernible except sandy siltstone horizons in place, bioturbated.

CALC. SILTSTONE: Light greyish white to creamish white, med. horizontally bedded 25-40 cm, steep near vertical weathering profile, occ. extensive bioturb. horizons, grading upwards into massive calc. fine siltstone.

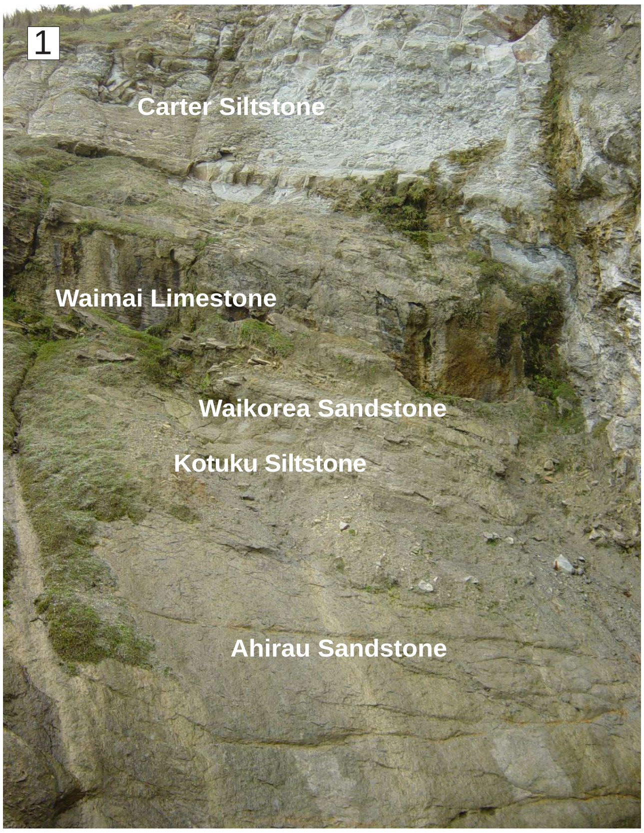
PHOSPHATIC, GLAUC. SANDSTONE: Greenish grey, soft & friable, mass., fine to med. sand with abundant phosphatic nodules, high glauc. concentration, fossiliferous

X-BEDDED LIMESTONE: Light greyish, hard, low to mod. angle tabular cross-bedded, well developed flags 6-8 cm, prominent recessive seams often glauconitic silty sand rich, well dev. top and bottom set, coarse sparry grainstone, bioclasts especially echinoderm plates & frags.,abrupt facies transition with the overlying glauconitic sandstone unit.

CALC. SANDSTONE: Grey to dark grey, well cemented, 6-10 cm horizontally bedded, fine to med. grained sandstone, intensely bioturbated especially along the bedding planes, occ. glauc. concentration.

MUDDY/SANDY SILTSTONE: Light greyish, soft & crumbly to mod. hard, mainly siltstone freq. grading into fine silty sandstone, mod. to weakly calc., showing laminate scale 2-4 cm thick bedding & increasing degree of bioturbated towards top, grading upwards into horizontally bedded calc. sandstone.

CALC. SILTY SANDSTONE: Light greyish to brownish grey, mod hard, massive, well cemented very fine to fine silty sst., intensely bioturbated particularly near the top, scattered phosphatic pebbles on the uppermost exposed face, pectins and other bivalves common, steep weathering profile.


1
Carter Siltstone
Waimai Limestone
Waikorea Sandstone
Kotuku Siltstone
Ahirau Sandstone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Stratigraphic Column No: *PW-12*

Region: Port Waikato

Location: Kaawa beach

Grid Reference:

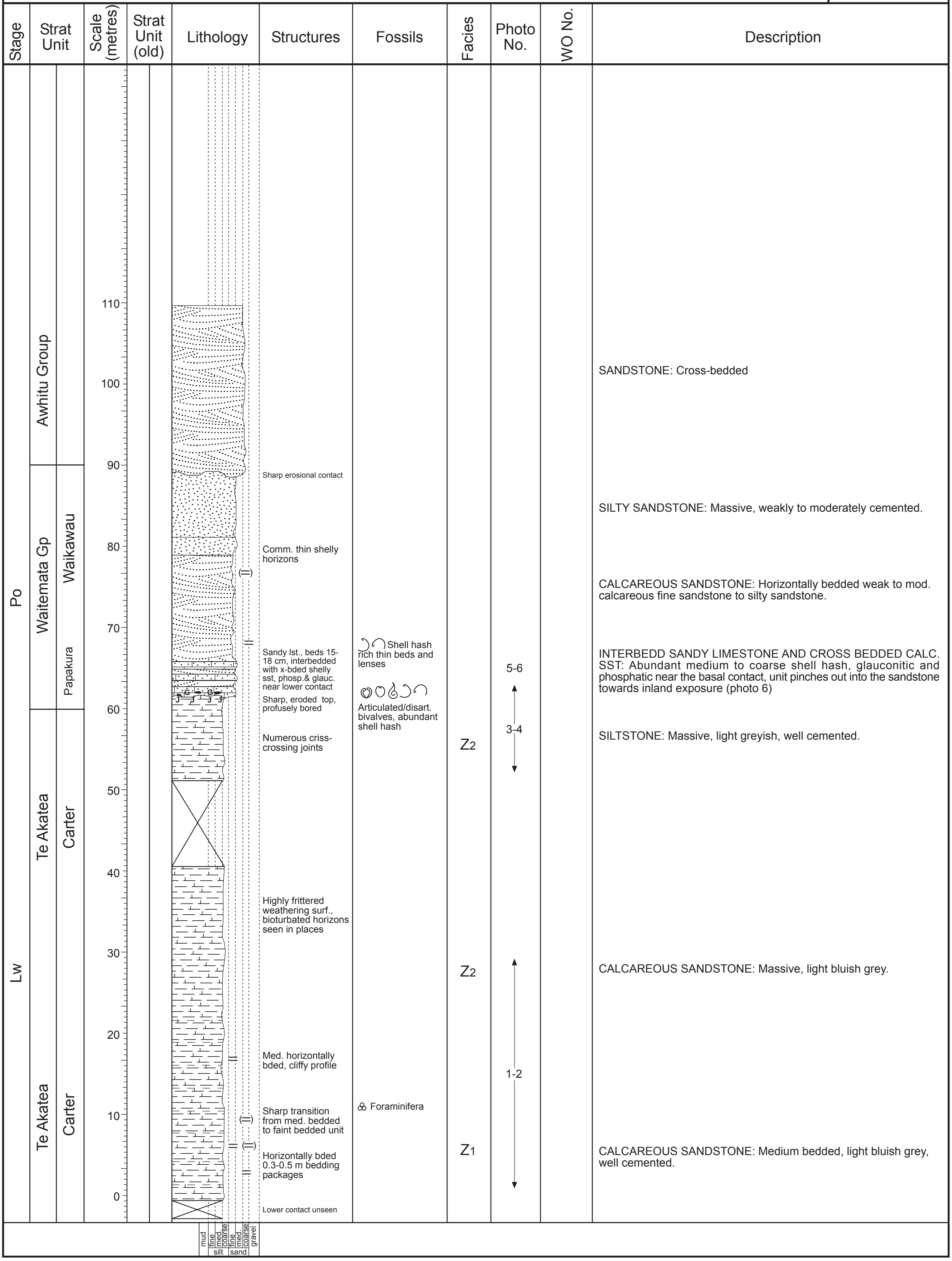
E: 2664350 - 2664600

N: 6408300 - 6409580

NZMS 260 Sheet: R13/643083-646095

Page 1 *of* 2

Author: A. Tripathi



Sharp erosional contact

Comm. thin shelly horizons

Sandy lst., beds 15-18 cm, interbedded with x-bded shelly sst, phosp.& glauc. near lower contact

Sharp, eroded top, profusely bored

Numerous criss-crossing joints

Highly frittered weathering surf., bioturbated horizons seen in places

Med. horizontally bded, cliffy profile

Sharp transition from med. bedded to faint bedded unit

Horizontally bded 0.3-0.5 m bedding packages

Lower contact unseen

Shell hash rich thin beds and lenses

Articulated/disart. bivalves, abundant shell hash

Foraminifera

SANDSTONE: Cross-bedded

SILTY SANDSTONE: Massive, weakly to moderately cemented.

CALCAREOUS SANDSTONE: Horizontally bedded weak to mod. calcareous fine sandstone to silty sandstone.

INTERBEDD SANDY LIMESTONE AND CROSS BEDDED CALC. SST: Abundant medium to coarse shell hash, glauconitic and phosphatic near the basal contact, unit pinches out into the sandstone towards inland exposure (photo 6)

SILTSTONE: Massive, light greyish, well cemented.

CALCAREOUS SANDSTONE: Massive, light bluish grey.

CALCAREOUS SANDSTONE: Medium bedded, light bluish grey, well cemented.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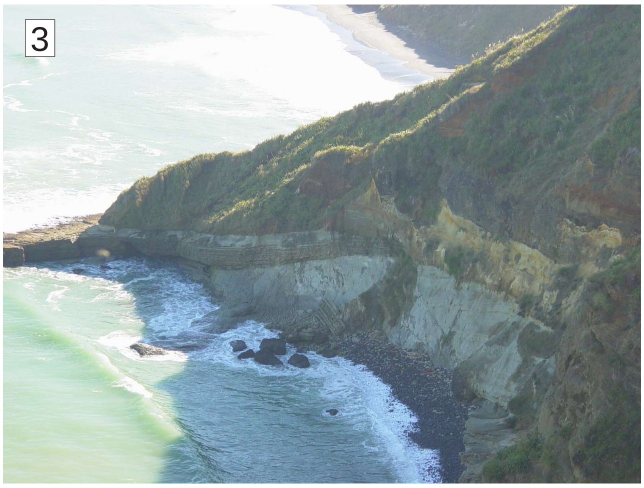
3


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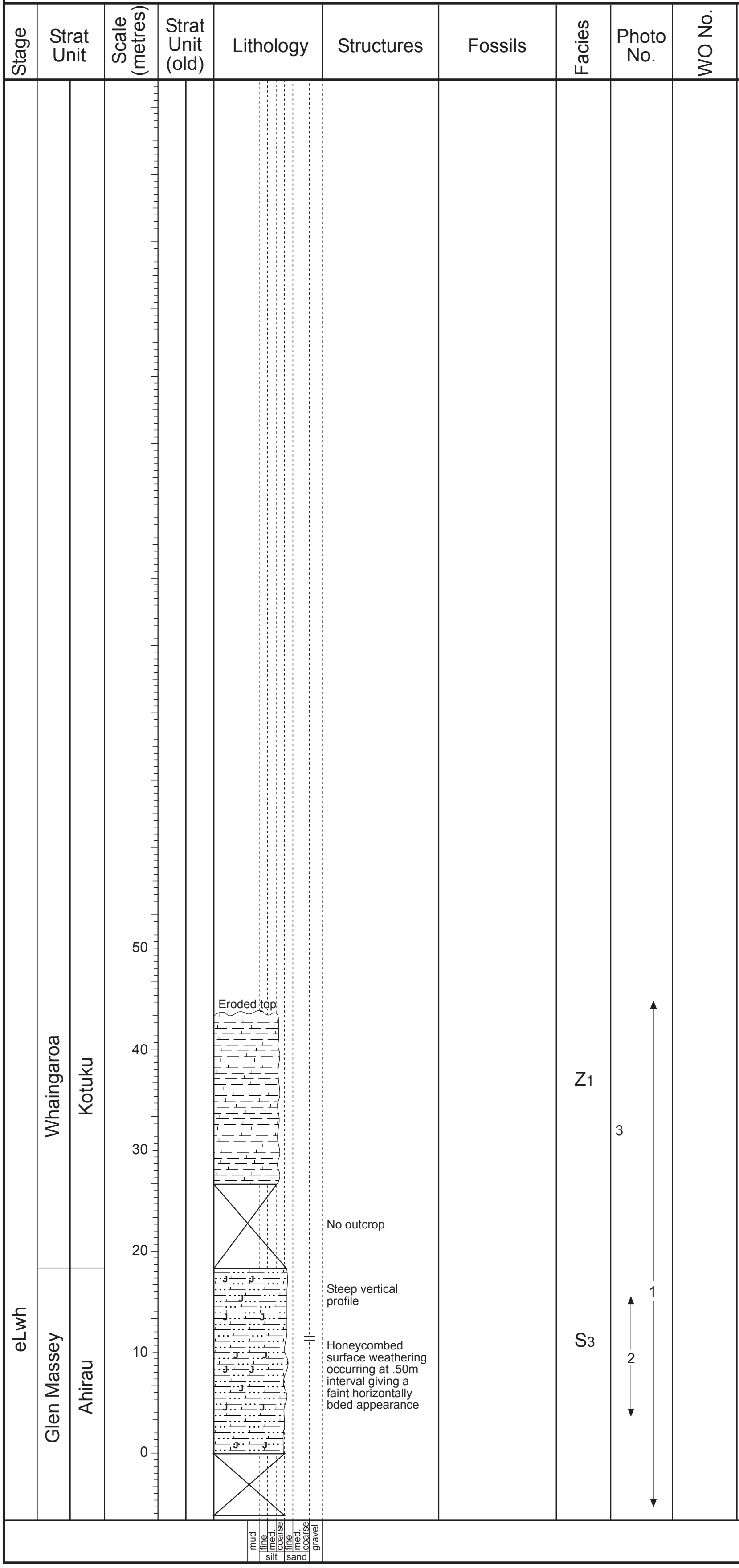
Stratigraphic Column No: *PW-13*
Region: Port Waikato
Location: Hetherington Road

Grid Reference:
E: 2686944
N: 6404266

NZMS 260 Sheet: R13/ 904942

Page 1 *of* 2 **Author:** A. Tripathi



Description

CALCAREOUS SILTSTONE: Light bluish grey, massive only 0.3 to 0.5 m crude bedding apparent in places, frittered weathering surface, fritters breaks off with typical conchoidal fracture, overall poorly exposed.

CALC. SILTY SANDSTONE: Dull greyish to brownish grey, mod. well indurated with occ. soft silty sandstone lenses, massive in appearance but faint silty beds apparent in places, common honeycombed surface occurring at regular approx. 0.5 m interval, tubular burrows seen on surface, large solution cavities, mainly variably calcareous very fine sandstone grading into silty sandstone, bluffy weathering profile.

Lower contact not exposed.


1
Whaingaroa Fm
Glen Massey Fm
Mangakotuku Fm


2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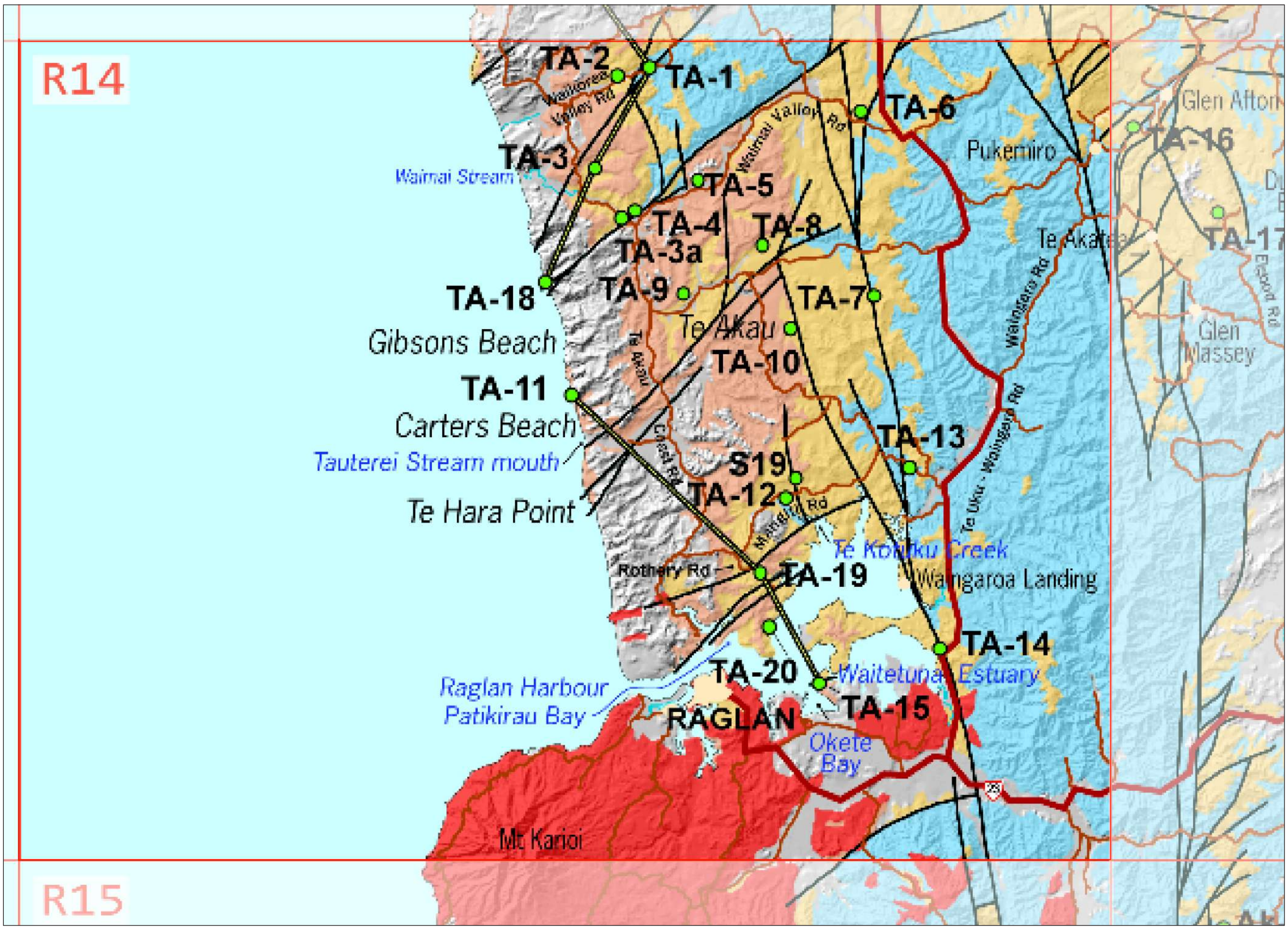

R14
TA-2
TA-1
Waitorea Valley Rd
TA-6
Waimai Valley Rd
Glen Afton
TA-16
Pukemiro
TA-3
Waimai Stream
TA-5
TA-4
TA-8
TA-3a
Te Akatea
TA-17
Esdon Rd
Waingaro Rd
TA-18
TA-9
TA-7
Te Akau
Te Akau Rd
Glen Massey
Gibsons Beach
TA-10
TA-11
Carters Beach
Tauterei Stream mouth
Coast Rd
TA-13
S19
TA-12
Te Uku - Waingaro Rd
Te Hara Point
Rd
Te Kotuku Creek
Rothery Rd
TA-19
Waingaroa Landing
TA-14
TA-20
Waitetuna Estuary
Raglan Harbour
Patikirau Bay
RAGLAN
TA-15
Okete Bay
23
Mt Karioi
R15

Stratigraphic Column No: *TA-1*

Region: Te Akau

Location: Waikorea Valley Road

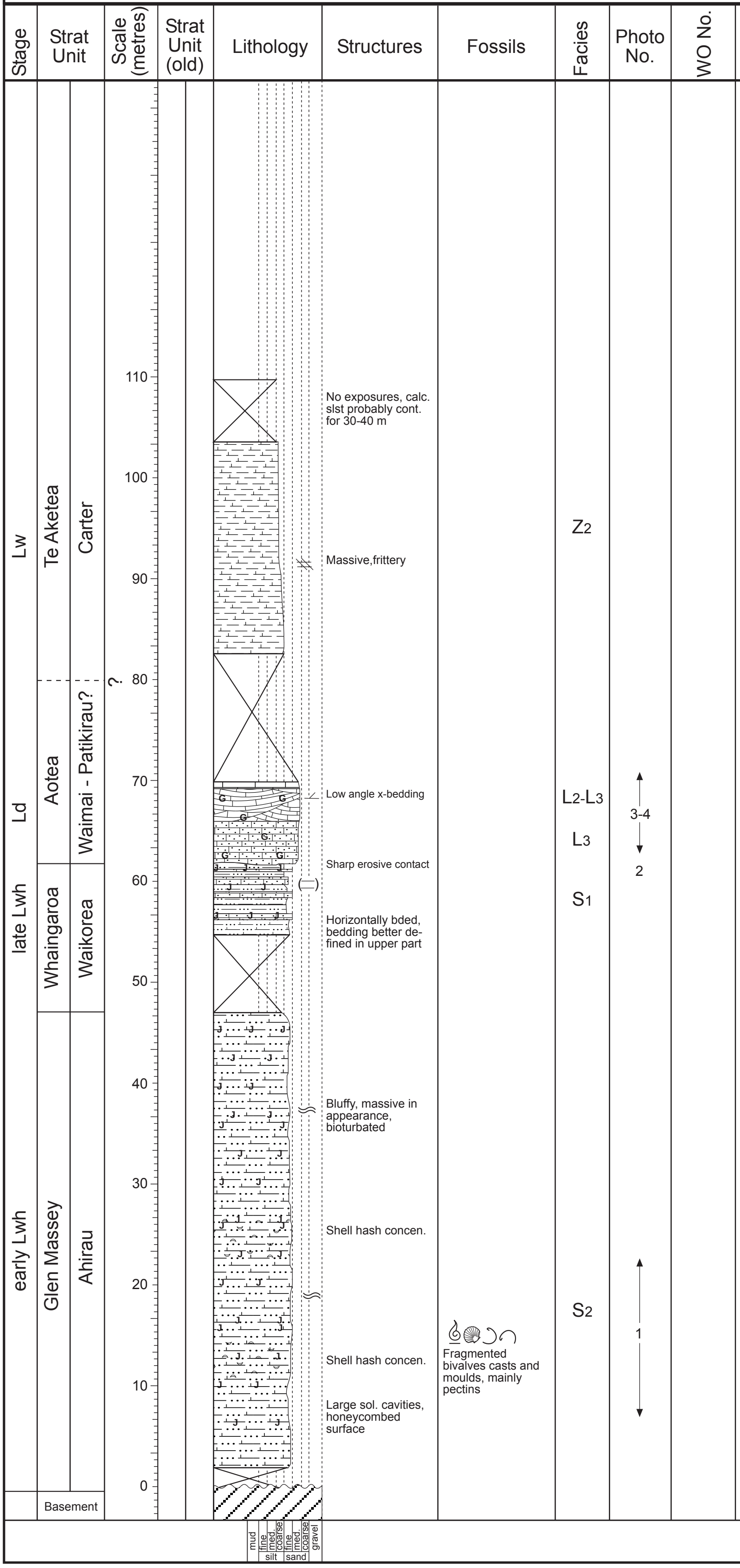
Grid Reference:

E: 2672787 - 2673113

N: 6399417 - 6398985

NZMS 260 Sheet: R14/727994

Page 1 *of* 2 **Author:** A. Tripathi



Description

CALC SILTSTONE: Light grey to creamish, massive, highly frittered weathering surface exposed through the grassy mod. steep slope.

CROSS BEDDED LIMESTONE: Light greyish to greenish grey, flaggy, 0.4-0.6 cm thick recessive seams, low angle planar x-bedding apparent in the middle part, glauconitic, medium to coarse sparry grainstone.

FLAGGY SANDY LIMESTONE: Light greyish, horizontally bedded, mod. well dev. flags 3-8 cm thick sep. by recessive weath. siliciclastic rich seams, glauc. partic. in lower 10-15 cm, vert. sol. joints imparts a somewhat blocky app.

INTERBEDDED CALC SANDSTONE AND SILTY SANDSTONE: Dull brownish grey, med. horizontally bedded comparatively hard calc. sst beds with thin mod. hard silty sst beds, bding better defined in upper 1 m near the contact, bioturb.

SILTY SANDSTONE: Dull brownish grey, mod. cemented, massive to faint horizontal bedding visible in the middle part, calcareous content increasing up-section, common bioturbation features.

CALC. SILTY SANDSTONE: Light brownish grey, hard, extensive bioturbation, common honeycombed weathering surface, weakly glauconitic in places, steep bluffy profile.

CALC. SILTY SANDSTONE: Light greyish to brownish grey, mod. well cem., massive, very fine to fine calc. sst grading into silty sst, bioturbated, freq. burrows visible on the surface, com. scattered bivalves mainly of pectins, occ. cast and mould, rounded bulbous weathering profile.

Contact with basement is not exposed

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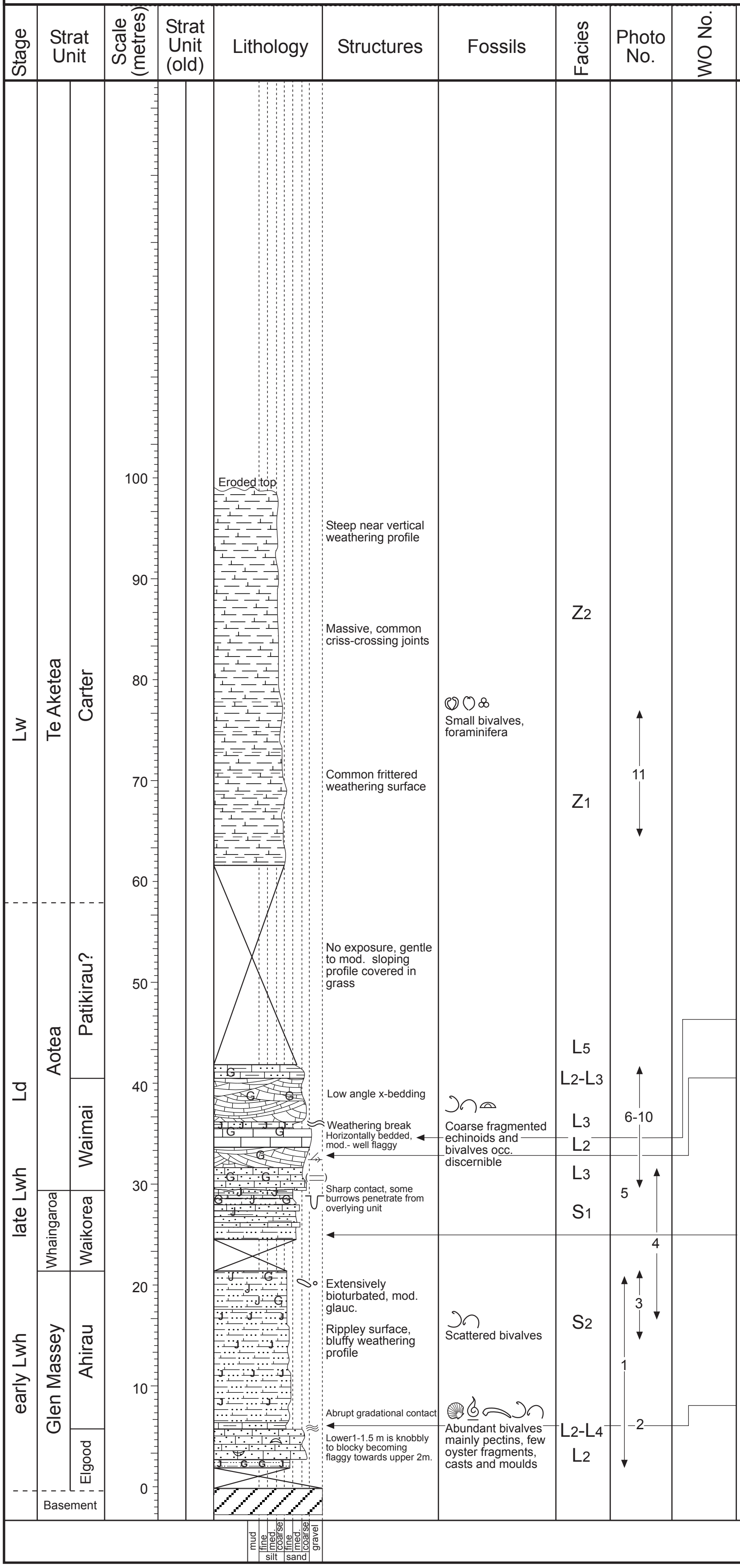
Stratigraphic Column No: *TA-2*
Region: Te Akau
Location: Waikorea Valley Road

Grid Reference:
E: 2671923
N: 6398706

NZMS 260 Sheet: R14/719987

Page 1 *of* 3 **Author:** A. Tripathi



Description

MASSIVE CALC. SILTSTONE: Light bluish grey to creamish, massive although faint horizontal bedding is discernible in places, foraminifera occ. visible.

WEAKLY BEDDED CALC. SILTSTONE: Light greyish white to light bluish grey, faint horizontal bedding package 0.25 cm to 0.40 cm thick, highly frittery weathering surface.

GLAUC. SANDY LIMESTONE: Light dull greyish, mod. flaggy 8-12cm to 2-3 cm flags, towards top showing wavy irregular pattern & fossiliferous mainly bivalve shell frags, the upper 10-15 cm of exposure consists of silty lst, glauc.

CROSS BEDDED GLAUC. LIMESTONE: Light greyish white, mod. to well flaggy low to med. angle cross-bedded, about 1m thick cross sets, prominent recessive siliciclastic seams, med. to coarse sparry grainstone, coarse bioclasts visible in places, glauc., thin bioturbated calc. sandy siltstone interbed occurring in the middle part.

GLAUC. SANDY LIMESTONE: Dull greenish grey, mod. flaggy 5-12 cm thick flags separated by calc. silty sst rich seams, seams in places consists of medium sst with rare rounded-subrounded granule and pebbles, conc. of glauc. pellets common within the seams and flags.

MEDIUM BEDDED CALC. SILTY SST: Dull brownish to greenish grey, medium horizontally bedded consisting of comparatively resistant calc. silty sandstone with massive sandy siltstone interbeds, calc. content increasing towards top, glauc., bioturbated particularly in the sandy siltstone interbeds.

CALC. SILTY SANDSTONE: Light brownish grey, mod. well cemented, massive, very fine to fine sand grading into silty sandstone, extensively bioturbated, intensity of bioturbation glauc. content increasing in the uppermost 3-4 m of the exposure, scattered bivalves.

CALC. SILTY SANDSTONE: Light brownish grey, fine silty sst, mass., honey-combed surface, com. bioturb. features, occ. tubular burrows visible on surface.

FLAGGY LIMESTONE: Greyish to brownish white, freq. mod. glauc, mod. flaggy 5--8 cm, wavy incipient siliciclastic dominant seams , becoming more sandy towards top, freq. with bivalve shell frags.

SANDY LIMESTONE: Dirty white to brownish, fine sand, medium to coarse sparry bioclastic lst, irregular flaggy to blocky, glauc, freq. with pectins, oysters & other bivalves, thin calc. glauc. sst bed forming the lowermost exposure.

Contact with basement is not exposed.

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Stratigraphic Column No: *TA-3*

Grid Reference:

Region: Te Akau

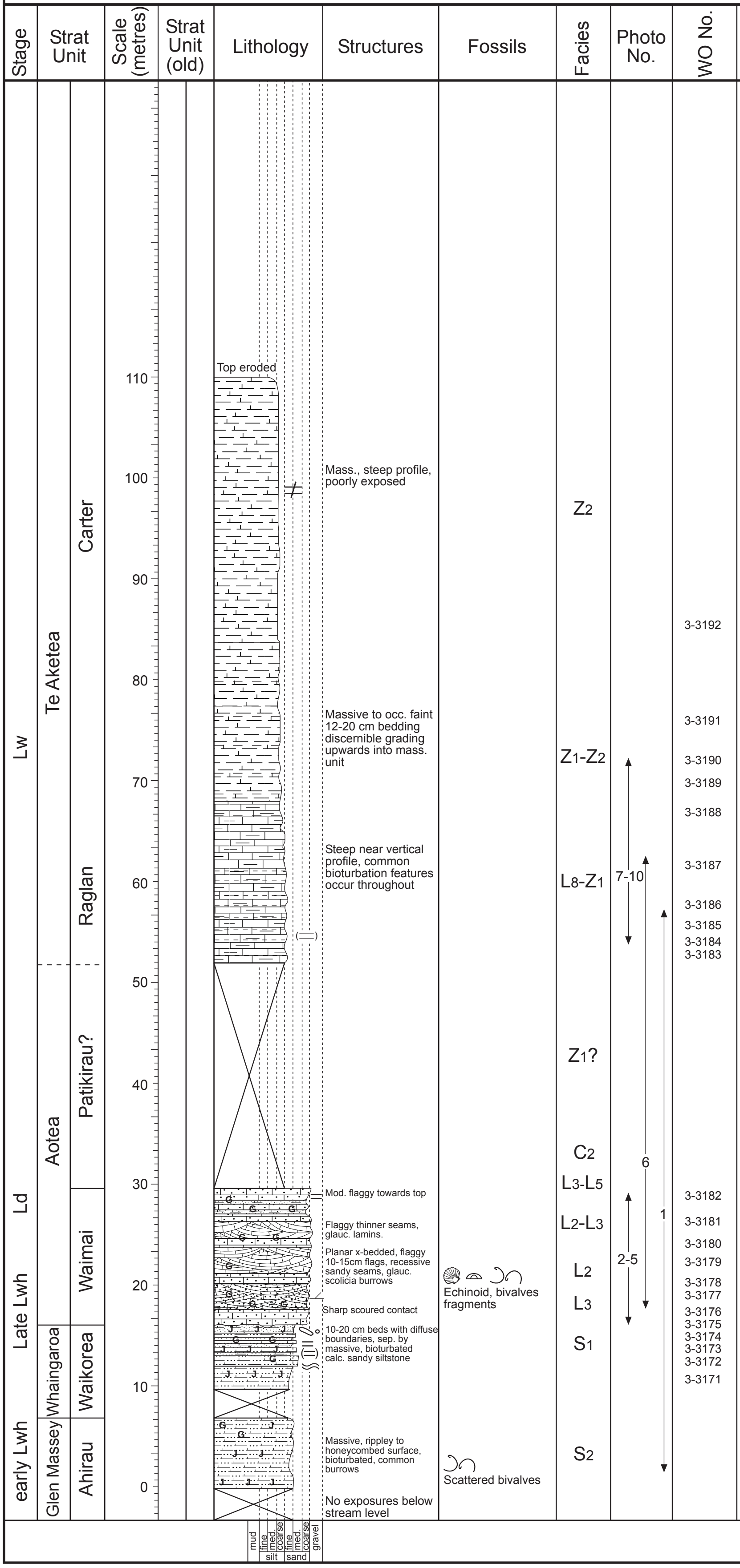
E: 2670889 - 2671126

Location: Waimai Valley, Waimai-Waikorea coast Road

N: 6395081 - 6395283

NZMS 260 Sheet: R14/708950

Page 1 *of* 3 **Author:** A. Tripathi



Description

CALC. SILTSTONE: Off white to light creamish grey, massive & frittery, in places, showing crude horizontal bedding to blocky appearance, homogenous, becoming more massive fine calc. siltstone upsection.

HORIZONTALLY BEDDED CALC. SILTSTONE: Light greyish to creamish, faint to medium bedded 20-30 cm resistant beds separated by frittered massive siltstone, bioturbated.

No exposures, gentle to moderately sloping grass covered slope

HORIZONTALLY BEDDED LIMESTONE WITH INTERVENING CALC. SILTY SANDSTONE BEDS: Dull brownish grey, horiz bedded packstone-grain-stone becoming more argillaceous upsection, 20-30 cm recessive bioturbated sandy siltstone beds are conspicuous the lower 4-6 m.

GLAUC. CROSS BEDDED LIMESTONE: Light greenish grey to greyish white, med. to coarse sparry grainstone, glauc., low to med. angle planar cross bedding, 0.8-1.2 m cross sets, flags 4-12 cm, comparatively thinner seams 1.5-3 cm silty sst dominated, com. bioclasts especially echinoid plates and occ. bivalves, disseminated glauconite pellets.

HORIZONTALLY BEDDED LIMESTONE: Light brownish grey, flaggy 10-15 cm, flags separated by recessive silty sandstone rich seams 2-5 cm thick.

INTERBEDDED SANDY LIMESTONE & CALC. SILTY SANDSTONE: Dull greyish, horizontally bedded resistant calcareous silty sst beds alternating with massive 5-10 cm bioturbated sandy siltstone, glauconitic.

CALC. SILTY SANDSTONE: Greyish white to brownish, mod. hard to hard, flaky to wavy rippely surface, occ. honeycombed, fine sand in a calc. cement, bioturbated towards the bottom, glauc. towards top, showing a subtle coarsening upwards from silty sst to fine sandstone.

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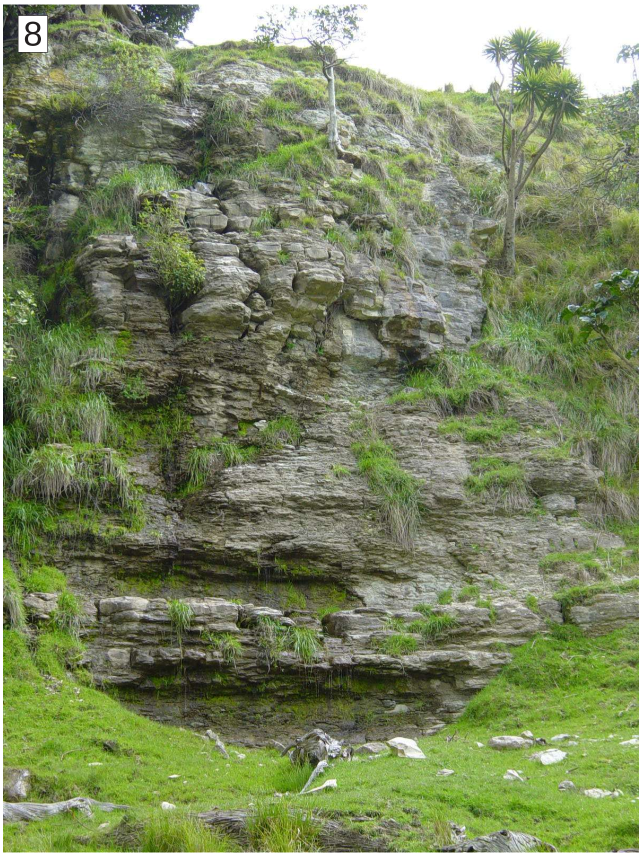


9

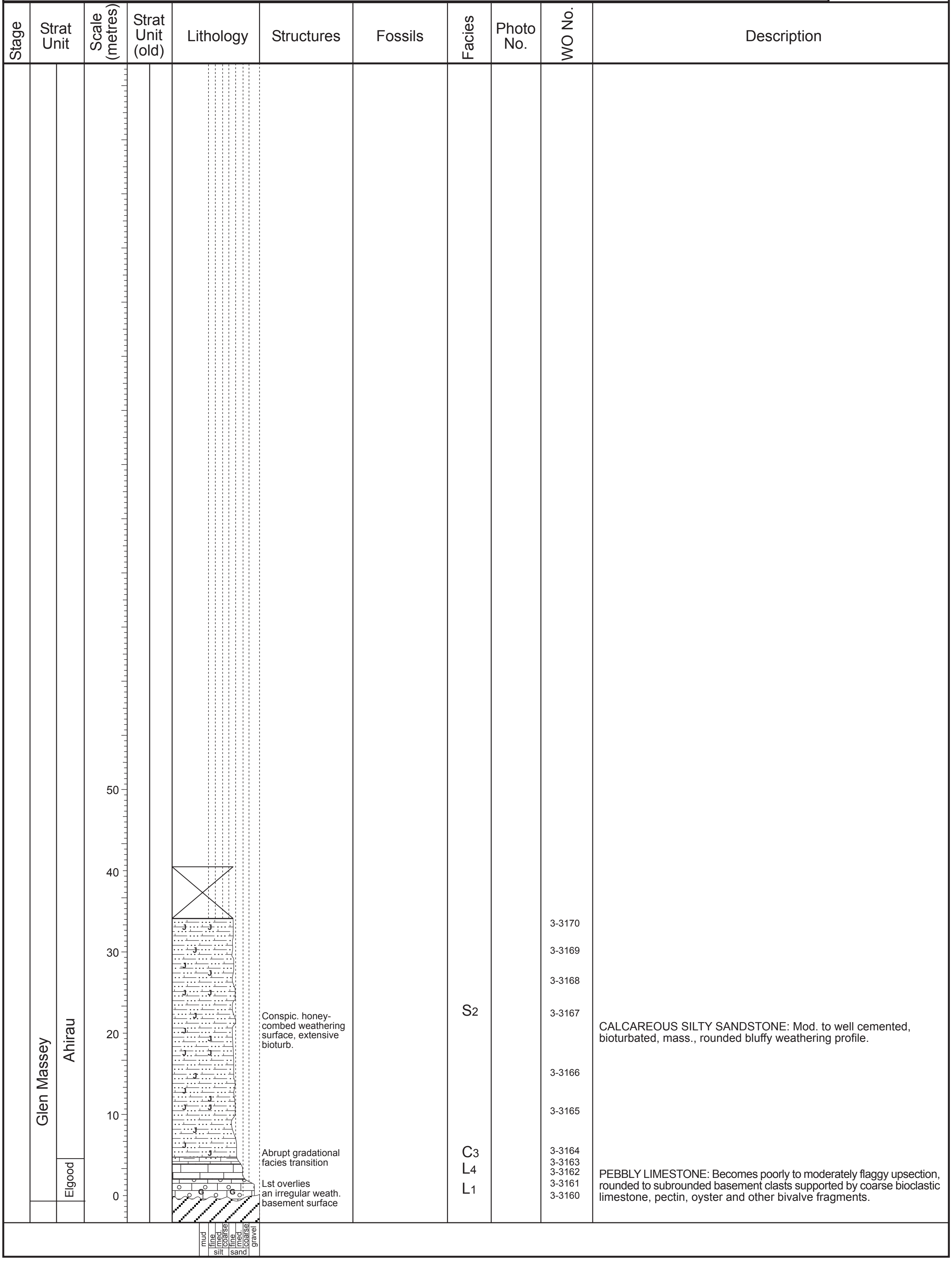
10

Stratigraphic Column No: *TA-3a*
Region: Te Akau
Location: Waimai-Waikorea Coast Road

Grid Reference:
E: 2672100
N: 6393450

NZMS 260 Sheet: R14/721934

Page 1 *of* 1 **Author:** A. Tripathi



Conspic. honey-combed weathering surface, extensive bioturb.

Abrupt gradational facies transition

Lst overlies an irregular weath. basement surface

CALCAREOUS SILTY SANDSTONE: Mod. to well cemented, bioturbated, mass., rounded bluffy weathering profile.

PEBBLY LIMESTONE: Becomes poorly to moderately flaggy upsection, rounded to subrounded basement clasts supported by coarse bioclastic limestone, pectin, oyster and other bivalve fragments.

Stratigraphic Column No: *TA-4* ***Grid Reference:***

Region: Te Akau

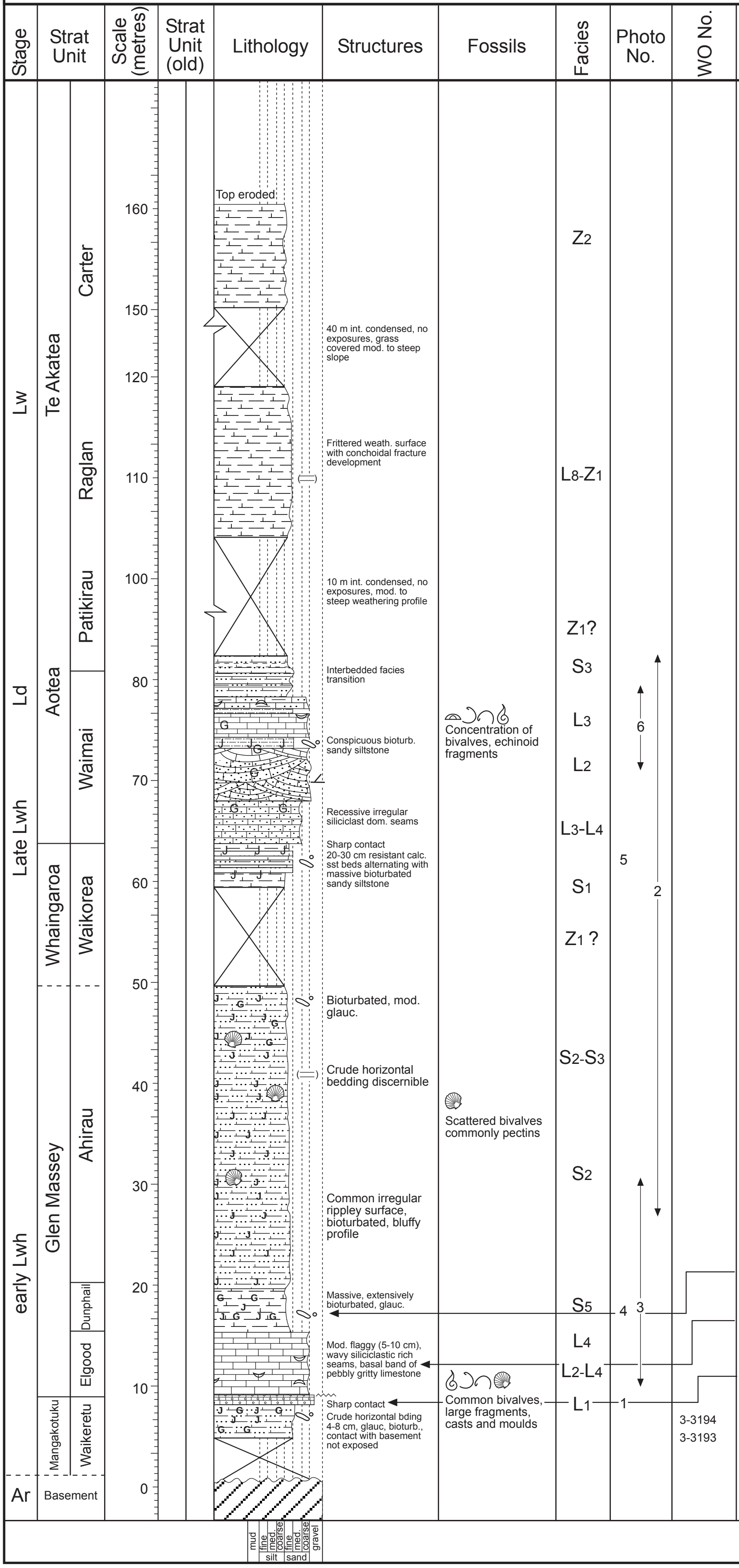
Location: Waimai Valley Road

E: 2672573

N: 6393743

NZMS 260 Sheet: R14/729944

Page 1 *of* 2 **Author:** A. Tripathi



Description

CALC SILTSTONE/MARL: Light greyish to dirty white, 30-40 cm faint bedding discernible in the lower 3-4 m, becomes massive with typical frittered weathered surface upsection

CALC. SILTSTONE: Light grey to off white, massive homogenous unit, mainly massive but faint bedding 20-30 cm apparent in places, bioturbation features visible in the lower part.

No exposures, gap of approx. 30 m

ALTERNATING SANDY SILTY LIMESTONE AND SANDY SILTSTONE: Dull brownish grey,alternation of resistant sandy-silty limestone beds and massive frittery calc. sandy siltstone, common bivalve frag, massive silty beds become thicker upsection.

HORIZONTALLY BEDDED LIMESTONE: Light brownish grey, hard, med. to coarse sparry grainstone to packstone, common bioclasts, glauconitic, conspicuous recessed 0.2-0.4 m very bioturbated sandy siltstone interbeds.

CROSS-BEDDED GLAUC. SANDY LIMESTONE: Light brownish grey, med. to coarse sparry, low angle planar x-bded, cross sets up to 1-1.2 m thick, beds 8-10 cm, siliciclastic dominated seams 0.4-1cm, gluaconitic becoming comparatively more glauc. in the upper part, com. horizontal burrows along the bedding plane.

SANDY FLAGGY LIMESTONE: Dull greyish to greyish white, fine to med. sand in a crystalline/sparitic calc. cement, freq. mod. glauc., 8-12 cm flags, 1-2 cm sand dominated prominent seams, calcite veins common.

ALTERNATING CALC. SILTY SANDSTONE AND SILTSTONE: Dull greyish to brownish grey, mod. cemented silty sandstone beds alternating with bioturbated frittery calc. siltstone, lower part poorly exposed and consists apparently of massive siltstone covered mainly by vegetation.

Contact not exposed

CALC SILTY SANDSTONE: Light greyish to brownish grey, mod. hard, wavy to rippley to flaky surface common, bluffy bulbuous weathering profile, towards top forming a step like profile, top 5-6 m is mod. to weakly glauc. mainly fine sand to freq. silty in a calc. cement, massive, homogenous unit. from a distance gives appearance of crude bedding.

GLAUC. SILTY SANDSTONE: Muddy brown to buff coloured, mod. hard, very fine to fine sandstone grading into silty sandstone, glauc.

GLAUC. CALC. SILTSTONE: Greenish grey to buff, well cemented, frittered weathering surface, extensive bioturbated, high concentration of glauc.

FLAGGY LIMESTONE: Reddish brownish to greyish, med. to coarsely sparry grainstone, flags 3-6 cm separated by siliciclastic dominated seams 0.2-0.5 cm, flags thickening towards top, glauc., common bioclasts.

PEBBLY CALC. SANDSTONE: Dirty brownish white, rounded to subrounded pebble band in a sandy calc matrix, common bivalve fragments, glauc.

GLAUC. CALC. SANDSTONE: Dull greyish to greenish brown, fine to medium grained sandstone, mod. well cemented with crude horizontal bedding in the upper 1-1.5 m, mod. to weakly cemented in the lower part, scattered granule and bivalve fragments, glauc. concentration at the upper sharp contact.

Contact with basement not exposed, 15 m high mound from the stream level,covered with grass, no exposures.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Waimai Limestone
Ahirau Sandstone


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Stratigraphic Column No: *TA-5* **Grid Reference:**

Region: Te Akau

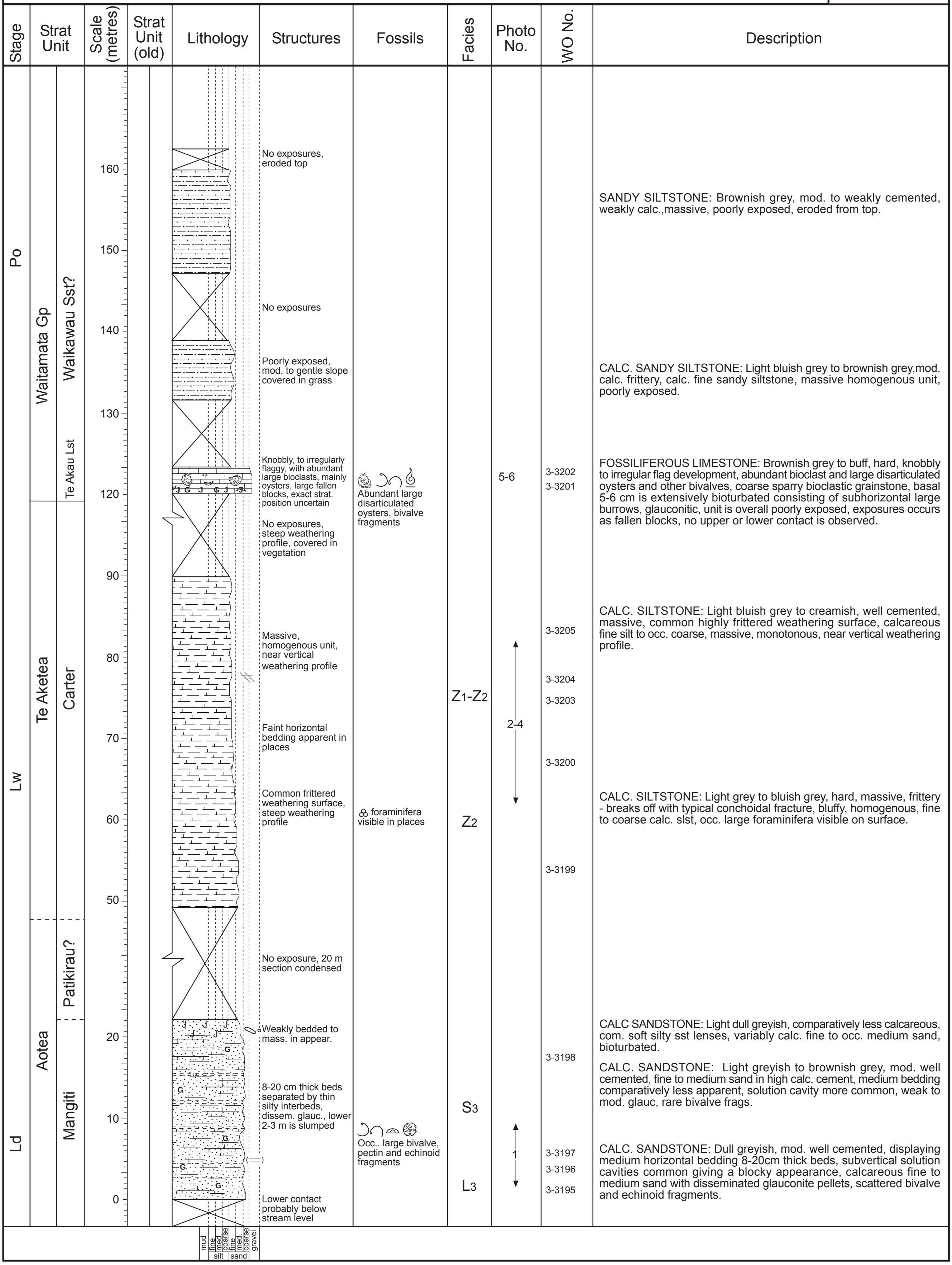
E: 2674421 - 2674905

Location: Waimai Valley Road, a prominent ridge on the north side across the Waimai Stream

N: 6394652 - 6394839

NZMS 260 Sheet: R14/744946

Page 1 *of* 2 **Author:** A. Tripathi



SANDY SILTSTONE: Brownish grey, mod. to weakly cemented, weakly calc.,massive, poorly exposed, eroded from top.

CALC. SANDY SILTSTONE: Light bluish grey to brownish grey,mod. calc. frittery, calc. fine sandy siltstone, massive homogenous unit, poorly exposed.

FOSSILIFEROUS LIMESTONE: Brownish grey to buff, hard, knobbly to irregular flag development, abundant bioclast and large disarticulated oysters and other bivalves, coarse sparry bioclastic grainstone, basal 5-6 cm is extensively bioturbated consisting of subhorizontal large burrows, glauconitic, unit is overall poorly exposed, exposures occurs as fallen blocks, no upper or lower contact is observed.

CALC. SILTSTONE: Light bluish grey to creamish, well cemented, massive, common highly frittered weathering surface, calcareous fine silt to occ. coarse, massive, monotonous, near vertical weathering profile.

CALC. SILTSTONE: Light grey to bluish grey, hard, massive, frittery - breaks off with typical conchoidal fracture, bluffy, homogenous, fine to coarse calc. slst, occ. large foraminifera visible on surface.

CALC SANDSTONE: Light dull greyish, comparatively less calcareous, com. soft silty sst lenses, variably calc. fine to occ. medium sand, bioturbated.

CALC. SANDSTONE: Light greyish to brownish grey, mod. well cemented, fine to medium sand in high calc. cement, medium bedding comparatively less apparent, solution cavity more common, weak to mod. glauc, rare bivalve frags.

CALC. SANDSTONE: Dull greyish, mod. well cemented, displaying medium horizontal bedding 8-20cm thick beds, subvertical solution cavities common giving a blocky appearance, calcareous fine to medium sand with disseminated glauconite pellets, scattered bivalve and echinoid fragments.

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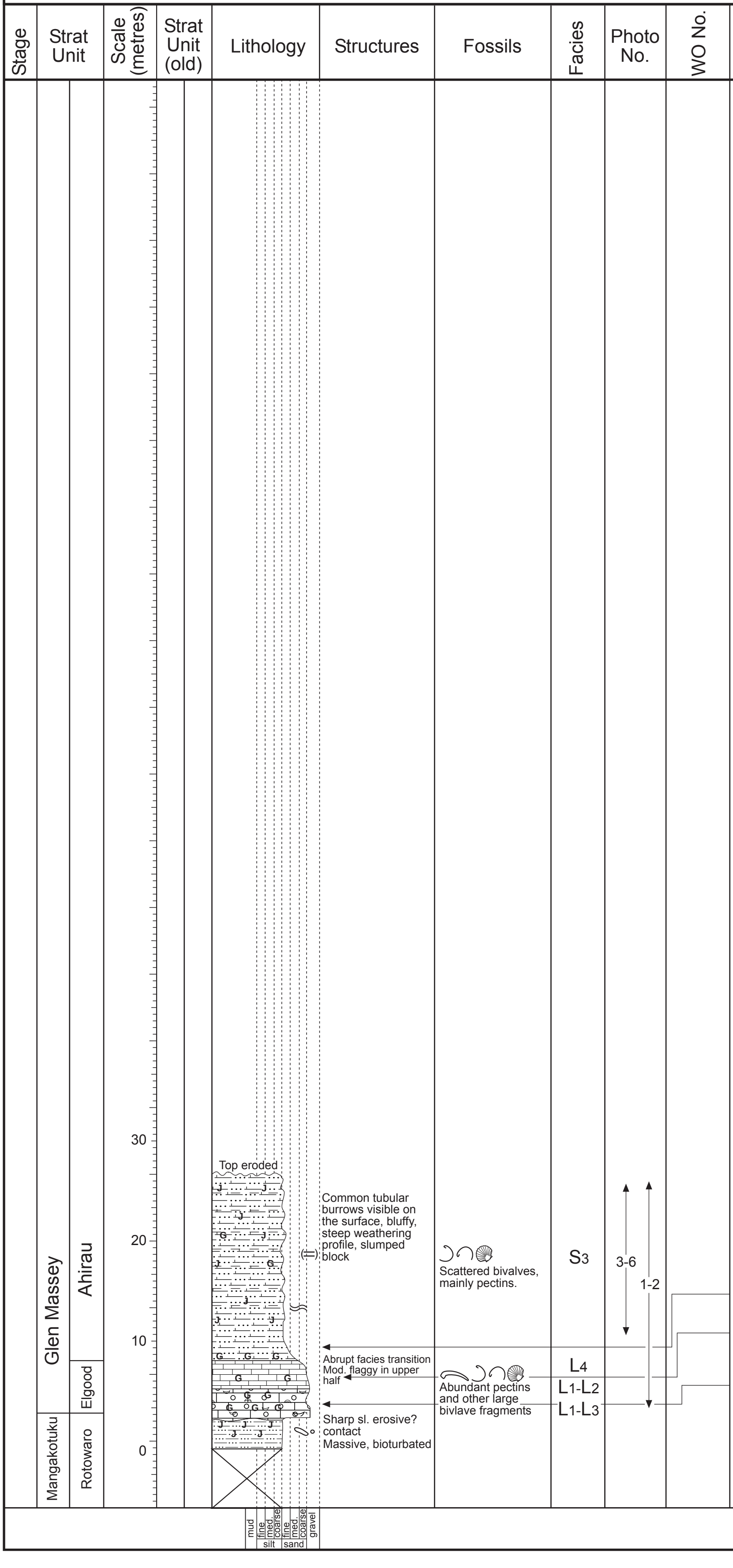
Stratigraphic Column No: *TA-6*
Region: Te Akau
Location: Waimai valley road

Grid Reference:
E: 2680867
N: 6397337

NZMS 260 Sheet: R14/808973

Page 1 *of* 2 **Author:** A. Tripathi



Description

CALC. SILTY SANDSTONE: Light greyish to brownish grey, well cemented, 0.5-1 m horizontal bedding apparent from conspicuous occurrence of solution cavities, very calcareous silty sandstone, occ. soft sandy siltstone lenses probably indicating leaching of calc. cement occurs throughout, weakly to mod. glauconitic in places, extensively bioturbated.

CALC. GLAUC. SANDSTONE: Light greenish to brownish grey, mod. well cemented, massive, fine to medium calcareous sandstone with mod. to high concentration of glauconite, bioturbated.

FLAGGY LIMESTONE: Brownish to greyish white, comparatively mod. to well flaggy, common large bioclasts, glauc, occ. siliciclastic rich recessive seams, medium to coarse bioclastic, glauconitic grainstone.

PEBBLY/GLAUCONITIC LIMESTONE: Light greyish to greenish grey, massive to mod. flaggy, abundant rounded to subrounded b/ment granules and med. to coarse sand in the lower 1-1.5 m, com. large bivalves frags, coarse bioclastic glauconitic grainstone.

SANDY SILTSTONE: Light brownish grey to muddy yellow, soft & crumbly, non/weakly calcareous, fine sandy siltstone, poorly exposed, mainly covered by grass forming a rolling landscape, prob. few tens of meters thick, lower contact with basement not seen.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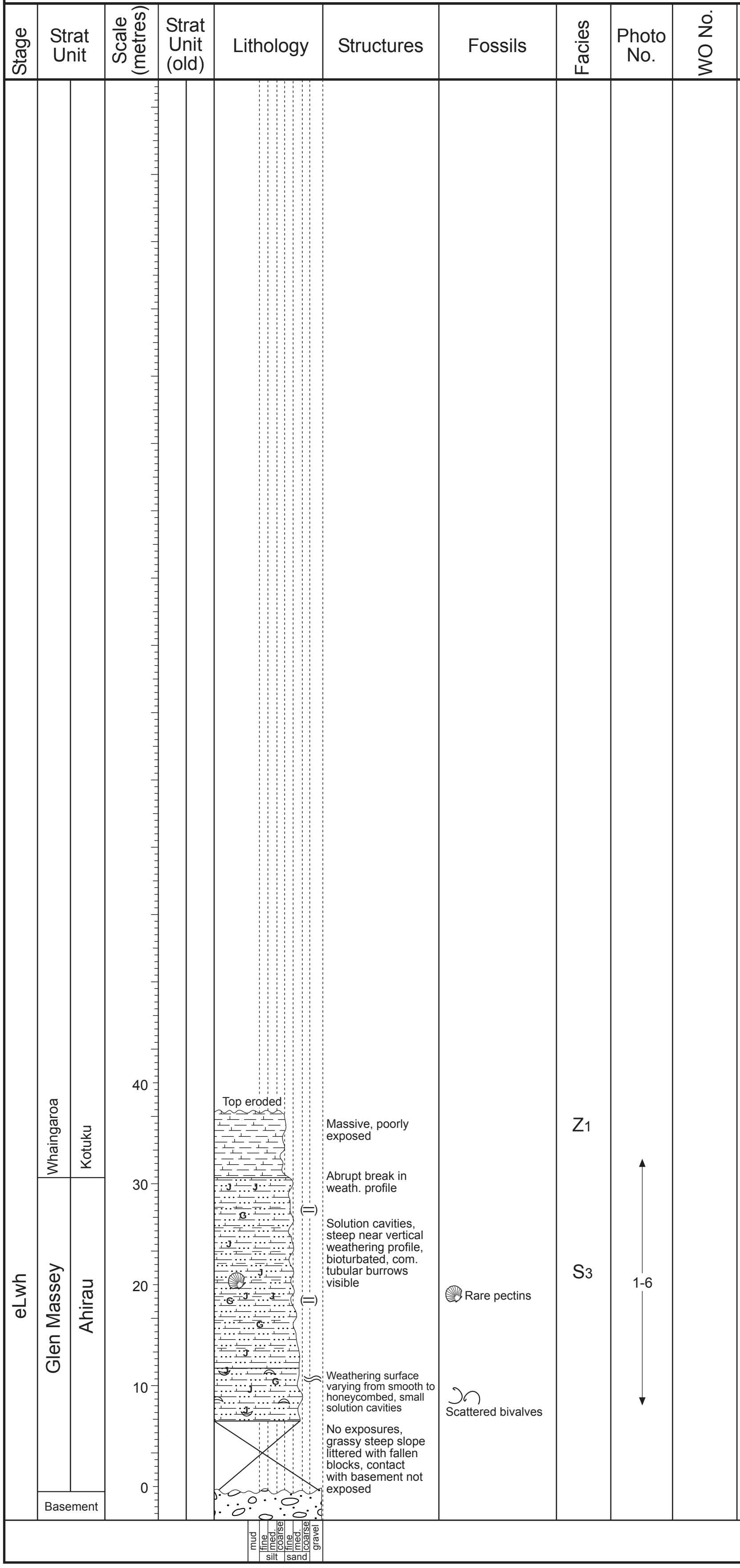
Stratigraphic Column No: *TA-7*
Region: Te Akau
Location: Te Akau Road, near Coleman basement quarry
NZMS 260 Sheet: R14/807920

Grid Reference:
E: 2680768 - 2681363
N: 6392003 - 6390595

Page 1 *of* 2 **Author:** A. Tripathi



Description

MASSIVE CALC. SILTSTONE: Light bluish grey with com. frittered weathered surface overlying abruptly on the bluffy calcareous silty sandstone unit.

CALC. SILTY SANDSTONE: Light brownish grey, very well cemented, horizontal bedding discernible by solution cavities parallel to bedding occurring at approx. 0.4-0.6 m interval, highly calcareous fine silty sandstone, bioturbated, occ. weakly to mod. glauconitic.

CALC. SILTY SANDSTONE: Light greyish to brownish grey, well cemented, scattered large bivalve fragments, occ. inclined tubular burrows 2-4 cm.

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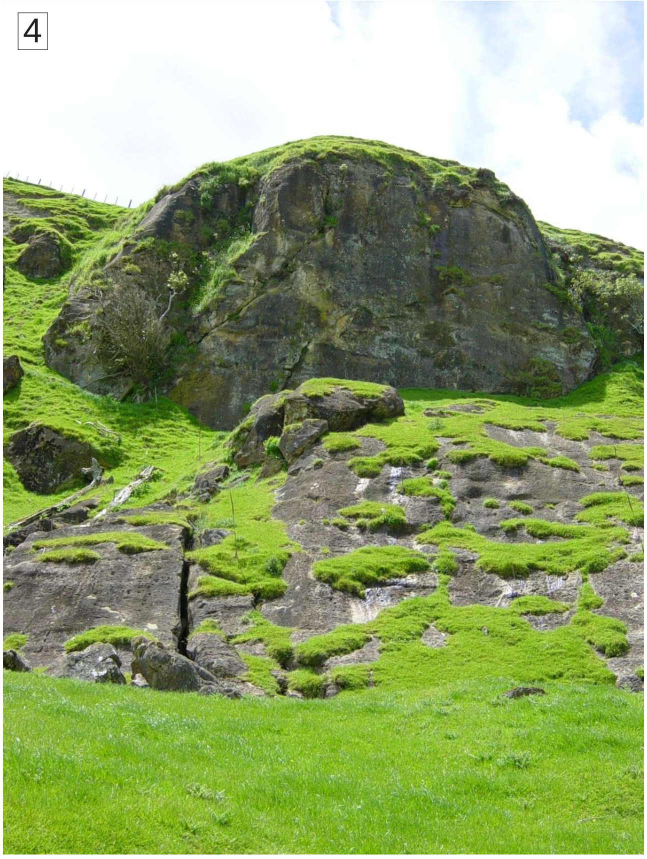


5

Stratigraphic Column No: *TA-8*

Grid Reference:

Region: Te Akau

E: 2677285

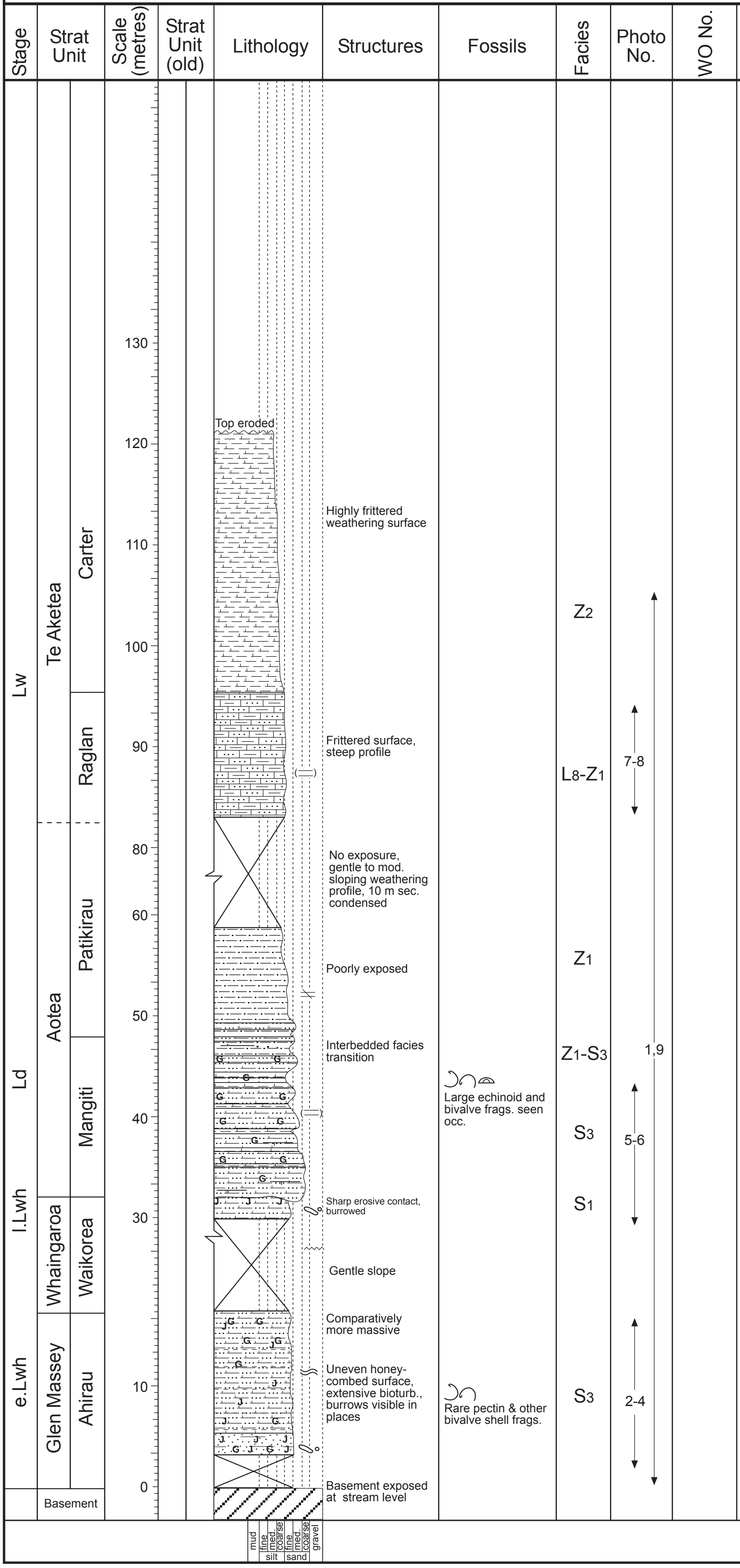
Location: Te Akau Road near the intersection with Ruakiwi Road, ridge across the Mangati Stream

N: 6392484

Page 1 *of* 2

Author: A. Tripathi

NZMS 260 Sheet: R14/772924



Description

CALCAREOUS SILTSTONE: Light greyish to creamish white, massive to occ. showing faint bedding, homogenous unit, fine highly calcareous siltstone with typical frittered weathering surface.

HORIZONTALLY BEDDED SILTY LIMESTONE: Light grey to buff, 6-30 cm horizontally bedded unit, fine packstone grading into wackestone especially in the upper 4-5 m before grades into overlying massive calcareous siltstone, common frittered surface, steep weathering profile.

CALC. SANDY SILTSTONE: Greyish to med. bluish grey, mass., mod. to poorly cemented, fine calcareous sandy siltstone, poorly exposed mainly covered with grass.

INTERBEDDED CALC. SANDSTONE AND SANDY SILTSTONE: Dirty brownish grey, resistant calcareous sandstone beds interbedded with sandy siltstone, bioturbated, sandy siltstone bed thickness increase upsection.

GLAUC. CALC. SANDSTONE: Greyish to brownish grey, well cemented, faint to medium horizontally beds (8-15 cm) separated by thin silty interbeds, bedding become less distinct upsection, glauconitic.

CALC. SANDY SILTSTONE: Light dull grey to brownish grey, mod. cemented, fine calc. sandy siltstone, bioturbated, poorly exposed.

No exposures, grassy slope.

MOD. GLAUC. CALC. SILTY SANDSTONE: Light dull greyish, mod. cemented, disseminated glauconite pellets, bioturbated, occ. tubular burrows seen on surface.

CALC. SILTY SANDSTONE: Light greyish to greyish, mod. well cemented, calc. fine silty sst, medium horizontal bedding (6-10 cm) apparent particularly in the middle part, extensive bioturbation, weakly to mod. glauconitic.

CALC. SANDY SILTSTONE: Light brownish grey, soft to mod. hard, highly weathered fine calc. sandy siltstone grading into silty sst, bioturbated, glauc.

BASEMENT: Conglomerate, no direct contact exposed.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Mangiti Sandstone
Ahirau Sandstone
Basement


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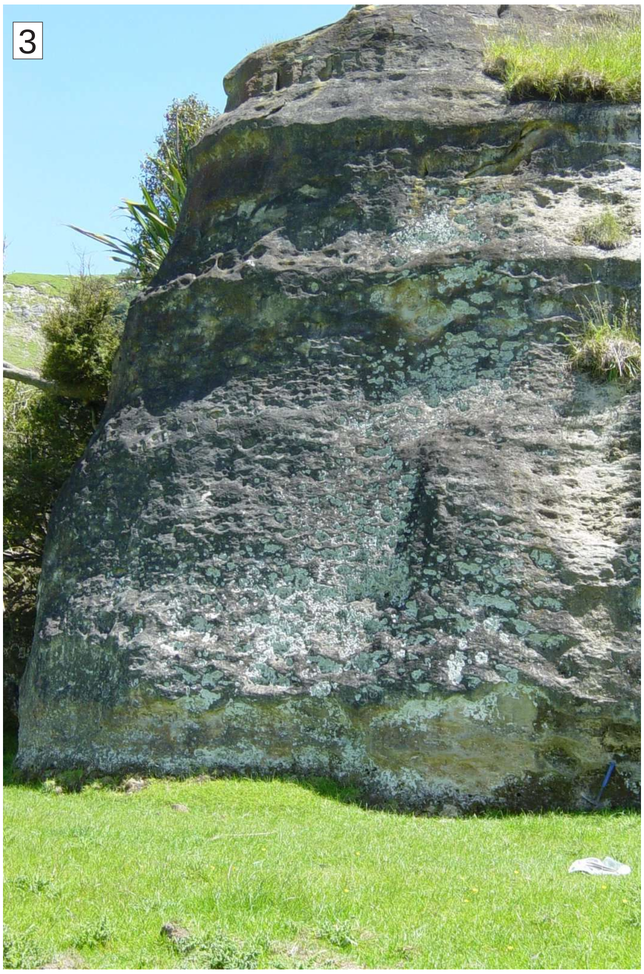
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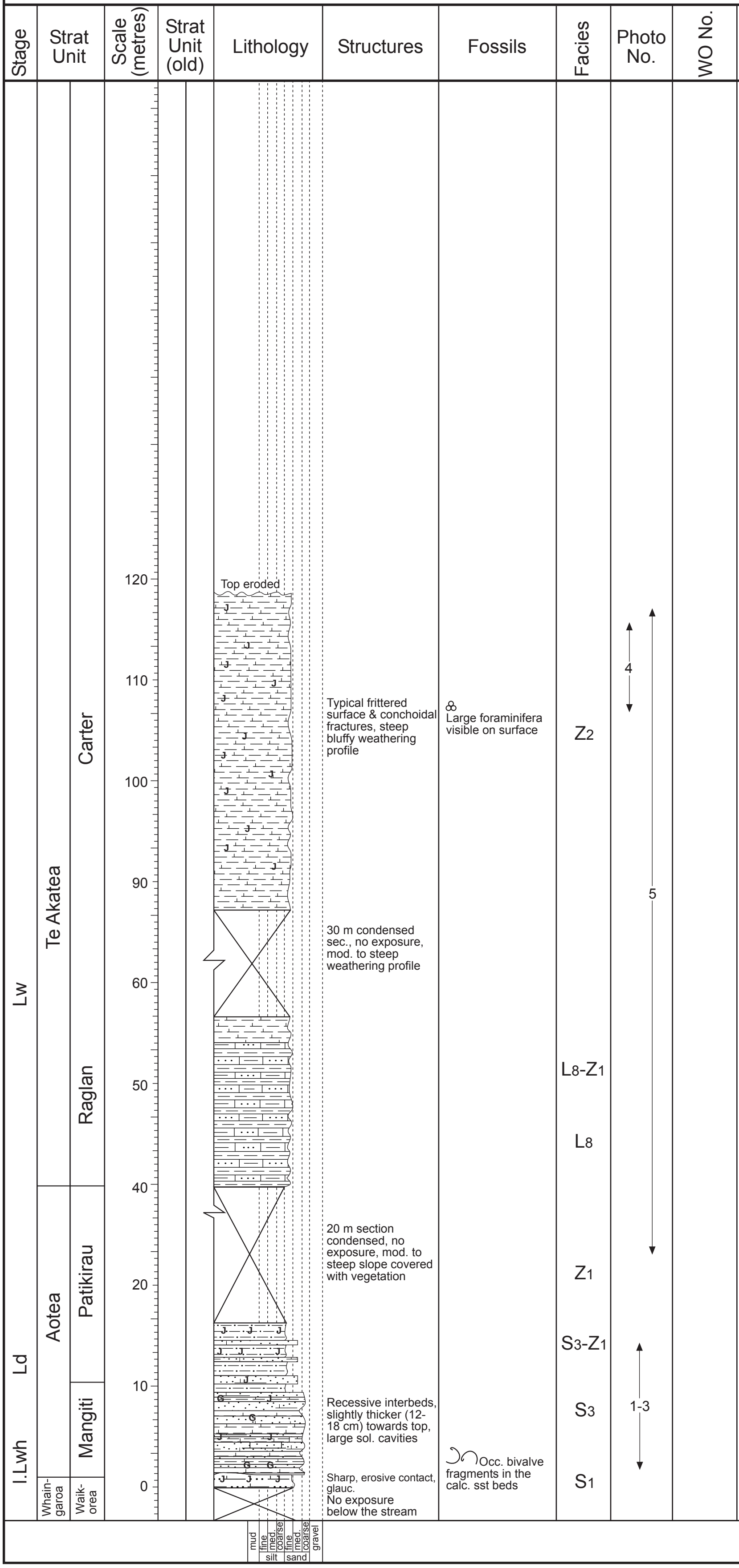
Stratigraphic Column No: *TA-9*
Grid Reference:
Region: Te Akau
E: 2674359
Location: Whaingaroa, Te Akau Village, Te Akau Road
N: 6390673
NZMS 260 Sheet: R14/743906

Page 1 *of* 2 **Author:** A. Tripathi



Typical frittered surface & conchoidal fractures, steep bluffy weathering profile

Large foraminifera visible on surface

30 m condensed sec., no exposure, mod. to steep weathering profile

20 m section condensed, no exposure, mod. to steep slope covered with vegetation

Recessive interbeds, slightly thicker (12-18 cm) towards top, large sol. cavities

Occ. bivalve fragments in the calc. sst beds

Sharp, erosive contact, glauc.
No exposure below the stream

Description

MASSIVE CALC. SILTSTONE: Light bluish grey to grey, mass., well cemented, common frittered surface, abundant bioturbation features observed throughout, rounded bluffy weathering profile.

HORIZONTALLY BEDDED SILTY LIMESTONE: Greyish white to creamish white, well cemented, medium horizontal bedded (varying from 15-20 cm - 25-30 cm) silty lst with thin silty interbeds (2-2.5 cm), bioturbation apparent in the silty interbeds, vertical solution cavities at regular intervals give a blocky appearance, the horizontally bedded unit abruptly grades into more massive calcareous slst although 10-14 cm faint bedding is discernible in places.

INTERBEDDED CALC. SANDSTONE AND SANDY SILTSTONE: Medium blue grey, massive, bioturbated sandy siltstone with dull grey to brownish grey calc. silty sandstone resistant interbeds, unit becomes massive & consists mainly of massive bioturbated sandy siltstone upsection, poorly exposed.
HORIZONTALLY BEDDED CALCAREOUS SANDSTONE: Dull greyish to light brownish grey, mod. to well cemented, medium to well bedded (6-8 cm), beds separated by thin recessive silty sandstone interbeds, mod. concentration of glauc. in the calc. sst beds, silty interbeds are com. bioturbated with frittery surface, occ. scattered bivalve frags., highly calcareous very fine to fine sst.
CALC. SANDY SILTSTONE: Dull greyish brown, massive, bioturbated, glauc. poorly exposed.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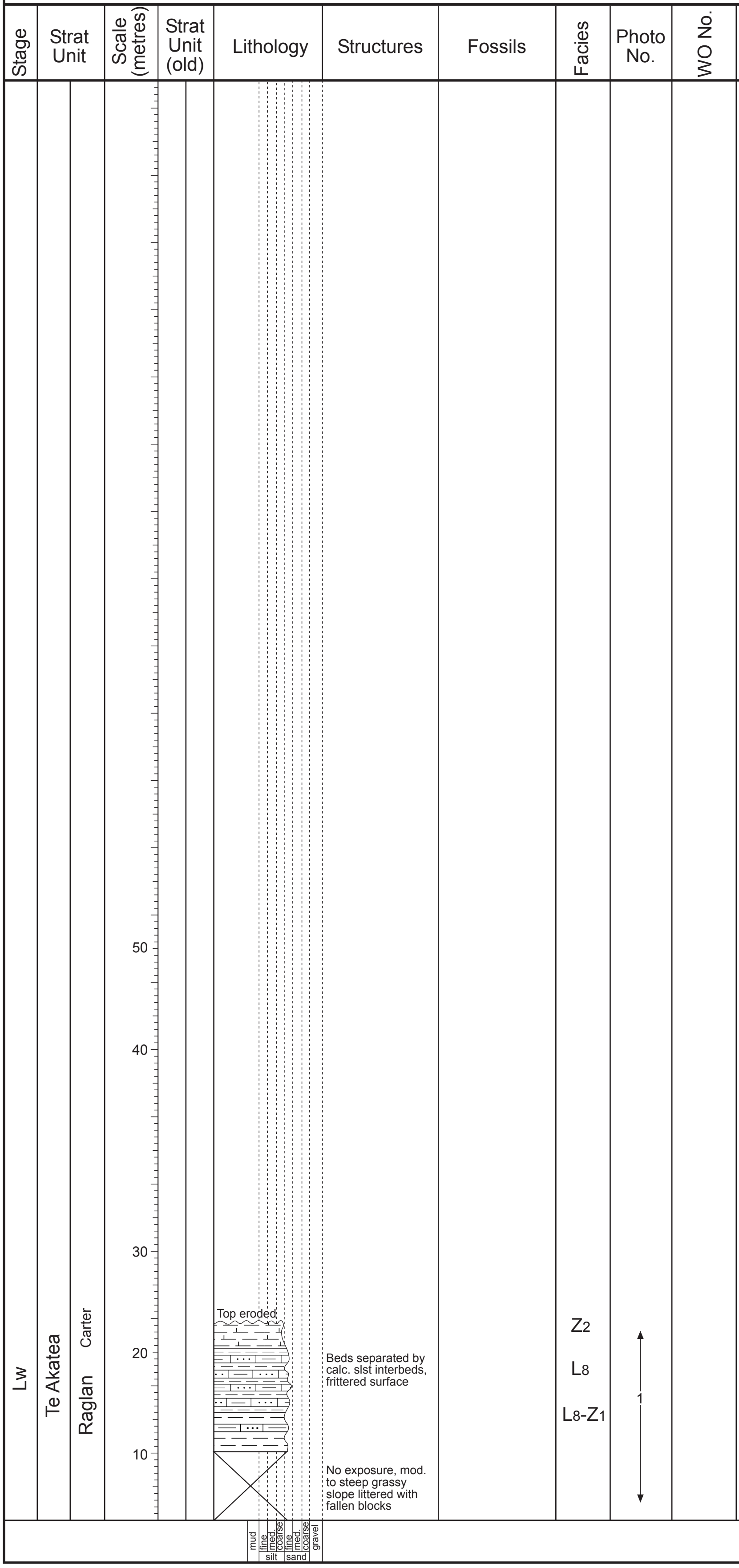
Stratigraphic Column No: *TA-10*
Region: Te Akau
Location: Ruakiwi Road

Grid Reference:
E: 2678286
N: 6389438

NZMS 260 Sheet: R14/782894

Page 1 *of* 2 **Author:** A. Tripathi



Description

MASSIVE CALCAREOUS SILTSTONE: Massive blue grey calcareous slst, common frittered surface, bioturbation features common.

HORIZONTALLY BEDDED SILTY LST WITH SILTY INTERBEDS: Light greyish to blue grey, medium horizontally bedded, beds average 8-14 cm but occ. up to 30 cm thick, thin silty interbeds with frittered surface, grades upward into massive siltstone unit.

MASSIVE CALC. SILTSTONE WITH SILTY LIMESTONE INTERBEDS: Light greyish to cement grey, massive to faint horizontal bedded calcareous siltstone with 15-20 cm thick silty limestone interbeds, poorly exposed.

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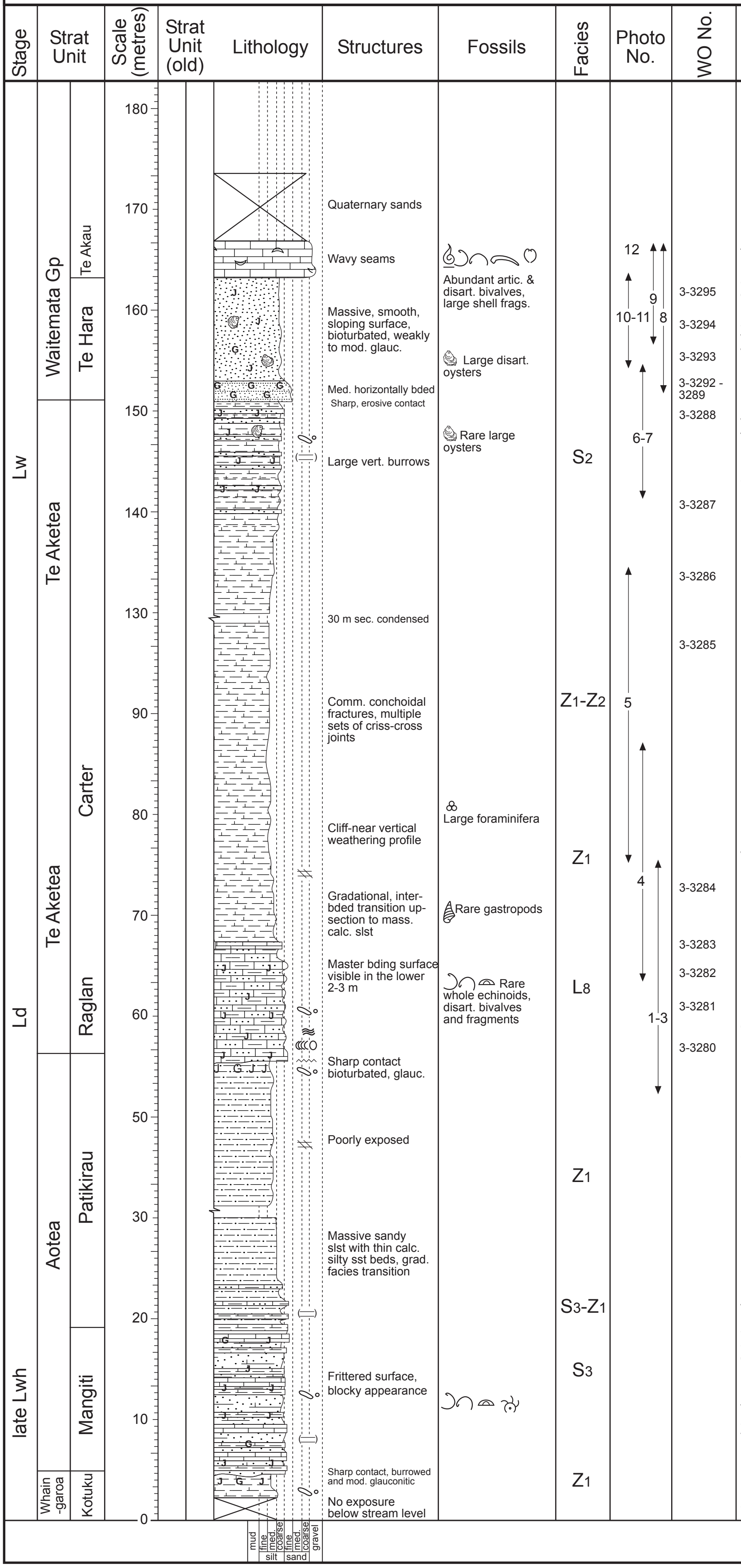
Stratigraphic Column No: *TA-11* **Grid Reference:**

Region: Te Akau

Location: Section continuous from the bluff overlooking Tauterei Stream flat at the end of Nielson Rd & extends towards Carters Beach

E:	2672629	-	2670273
N:	6385845	-	6386975

NZMS 260 Sheet: R14/726858 - 702869 *Page* 1 *of* 3 **Author:** A. Tripathi



Description

FLAGGY BIOCLASTIC LIMESTONE: Dull greyish to whitish, irregular flaggy 15-20 cm thick flags, recessive seams 0.5- 1 cm with shell hash concentration, abundant articulated & disarticulated bivalves, and medium to large fragments, very coarse sparry bioclastic grainstone.

MASSIVE SANDSTONE: Brownish grey to greyish, massive, soft and friable, very fine to fine sandstone grading into silty sandstone, weakly calc. to non calcareous, mod. glauconitic, very smooth weathering surface.

HORIZONTALLY BEDDED GLAUC, SANDSTONE: Dull greyish to brownish grey, weakly to mod. cemented, distinct 20-30 cm slightly resistant mod. calc. silty sandstone beds alternating with massive, weakly cemented, bioturbated glauc. silty sandstone, common bivalve frags. and occ. disart. oysters.

CALC SANDY SILTSTONE: Light bluish grey to brownish grey, faint 14-25 cm bedding, bedding planes diffused/amalgamated beds, well cemented, calcareous sandy siltstone, common large 6-8 cm tubular burrows, rare large oysters.

FAINT HORIZONTALLY BEDDED CALC SILTSTONE: Light greyish, massive in appearance but faint bedding (30-40 cm) apparent in few places, vertical/diagonal joints, well cemented.

MASSIVE CALC. SILTSTONE: Bluish grey to brownish grey, massive, well cemented, very frittered weathering surface, rare gastropod.

HORIZONTALLY BEDDED SILTY LIMESTONE: Light brownish to buff, 4-12 cm fine silty limestone beds (4-12 cm) separated by recessive silty interbeds with extensive bioturbation, common *scolicia* burrows, scattered large bivalve and echinoid frags., rare whole echinoderms, conspicuous surface/master bedding in the lower 2-3 m, interbedded transition to overlying massive calc. siltstone.

MASSIVE SANDY SILSTONE: Greyish to medium blue grey, massive, common frittered weathering surface, weakly to mod. cemented, poorly exposed, mod. steep weathering profile.

ALTERNATING CALC. SILTY SANDSTONE & SANDY SILTSTONE: Light greyish white to greyish, 6-10 cm thick calc. silty sandstone alternating with 5-6 cm thick fine calc. sandy siltstone with frittered surface, in the upper part calc. sandy siltstone becomes thicker with only thin silty sandstone interbeds before grading upwards into massive sandy siltstone unit.

HORIZONTALY BEDDED FINE CALC. SANDSTONE: Brownish grey, well cemented, medium horizontally bedded (6-10 cm) fine calcareous sandstone with irregular silty interbeds usually 0.5 cm but up to 5 cm thick in places, vertical sol. cavities imparts blocky appearance, bioturbated especially in the silty interbeds

CALC SILTSTONE: Greyish to brownish grey, mod. cemented, massive,bioturbated, mod. glauc., poorly exposed, most likely continuous in the subsurface below stream level.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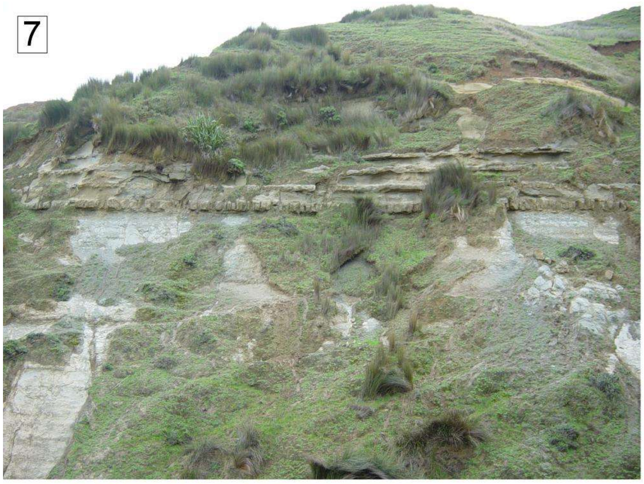

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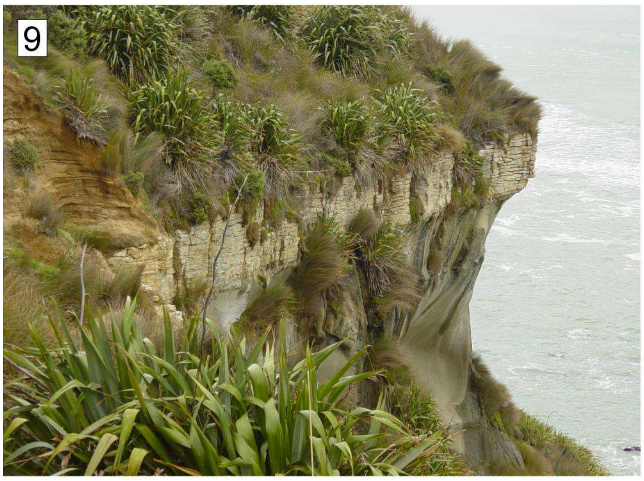

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Stratigraphic Column No: *TA-12* **Grid Reference:**

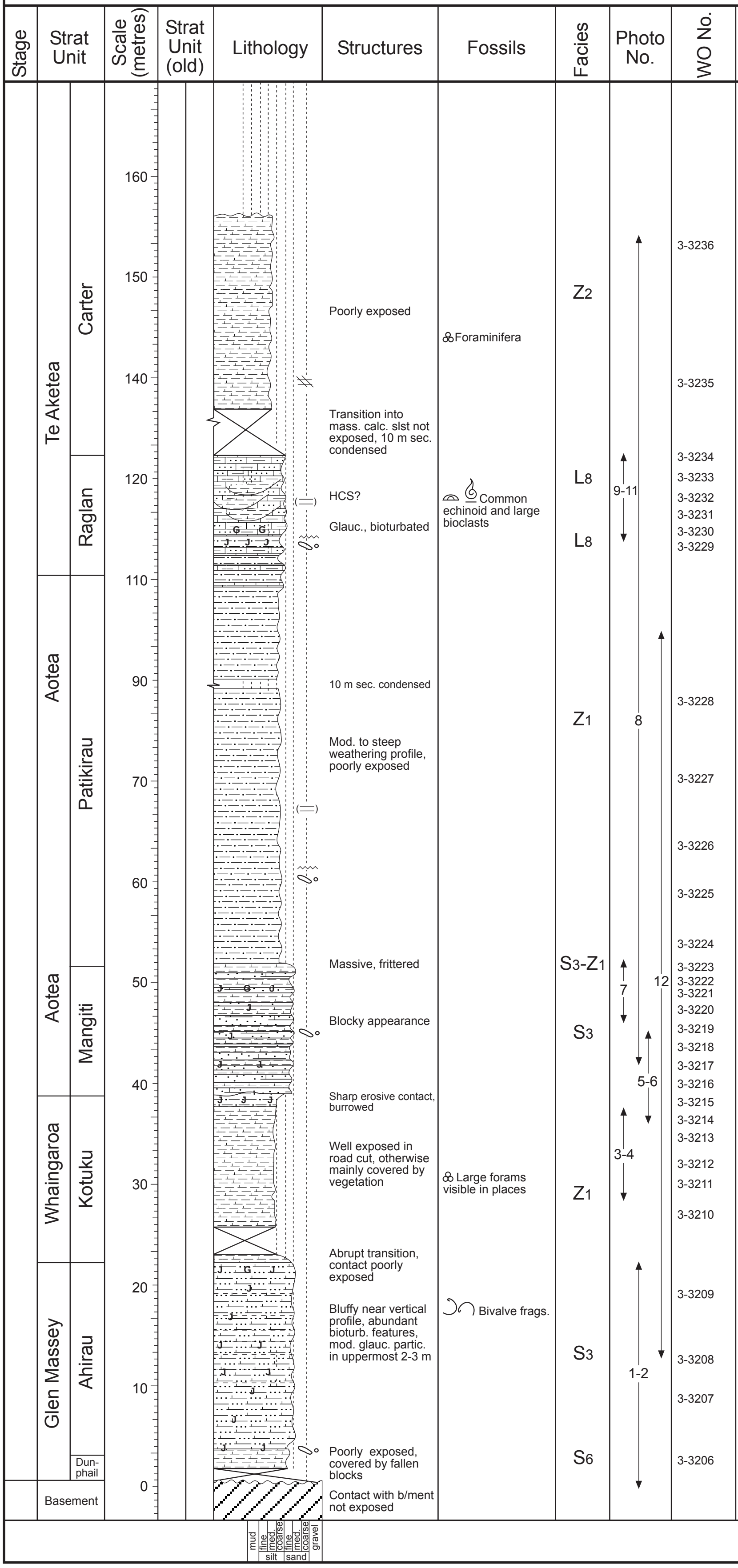
Region: Port Waikato

Location: Te Kotuku Trig. Mangiti Road, section continues from bluff opposite Te Kotuku beach & extends to the NW

E:	2676986	-	2678100
N:	6384012	-	6383200

NZMS 260 Sheet: R14/781832-769840

Page 1 *of* 3 **Author:** A. Tripathi



Description

CALC SILTSTONE: Light grey to creamish, massive, frittered weathering surface.

CALC SILTSTONE: Light greyish, massive, faint indication of HCS visible in the lower half, abundant large bioclasts consisting mainly of echinoids and occ. whole specimen, the lowermost few centimeters is extensively bioturbated and glauconitic.

CALC SILTSTONE ALTERNATING WITH SILTY LIMESTONE: Light grey to brownish grey, massive, frittered weathering surface, resistant silty lst beds 15-20 cm thick, mod. glauconitic.

CALC. SANDY SILTSTONE: Medium greyish to bluish grey, massive, variably calcareous but usually soft and weakly cemented, slst grading into sandy slst, poorly exposed forming a mod. to steep sloping weathering profile.

INTERBEDDED CALC. SILTY SANDSTONE & SANDY SILTSTONE: Light dull greyish to blue grey, 30 to 50 cm thick massive sandy slst alternating with resistant calc. silty sst beds becoming thinner upsection before grading into overlying massive sandy slst.

HORIZONTALLY BEDDED CALC. SILTY SANDSTONE: Light brownish grey to buff, mod. well cemented, 0.25-1.1m calc. silty sst beds with frittered silty interbeds, vertical solution cavities impart blocky appearance, silty interbeds apparently extensively bioturbd, large horizontal and inclined burrows visible in places, occ. mod. glauc.

MASSIVE CALC SILTSTONE: Bluish grey to brownish grey, massive, frittered weathering surface with common conchoidal fractures.

GLAUC. CALC. SANDSTONE: Light greyish to brownish grey, weakly to mod. cemented, mod. glauconite concentration, extensively bioturbated, common large inclined tubular burrows.

CALC. SANDSTONE: Light greyish to brownish grey, mod. well cemented, massive but common faint horizontal bedding apparent from the sol. cavities occurring at regular interval which is inferred having relatively higher calc. content, bluffy weathering profile, com. honeycombed surface, calc. very fine to fine silty sst.

CALC. SILTSTONE: Light creamish to buff, massive, well cemented, fine very calc. slst grading into silty sst, weakly to mod. glauc., bioturbated.

BASEMENT: Highly weathered slst/zst exposed at the stream level.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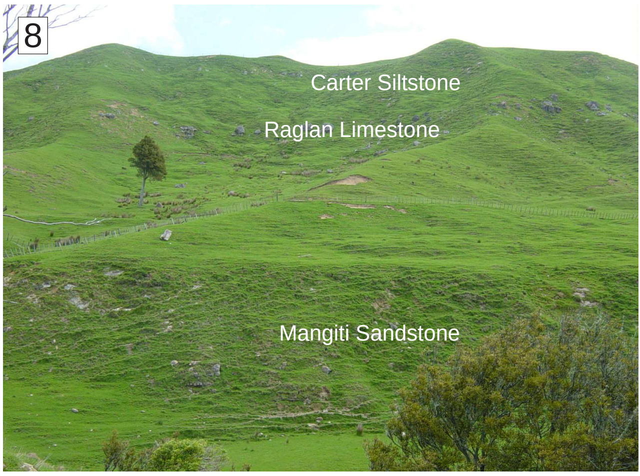
Carter Siltstone
Raglan Limestone
Mangiti Sandstone

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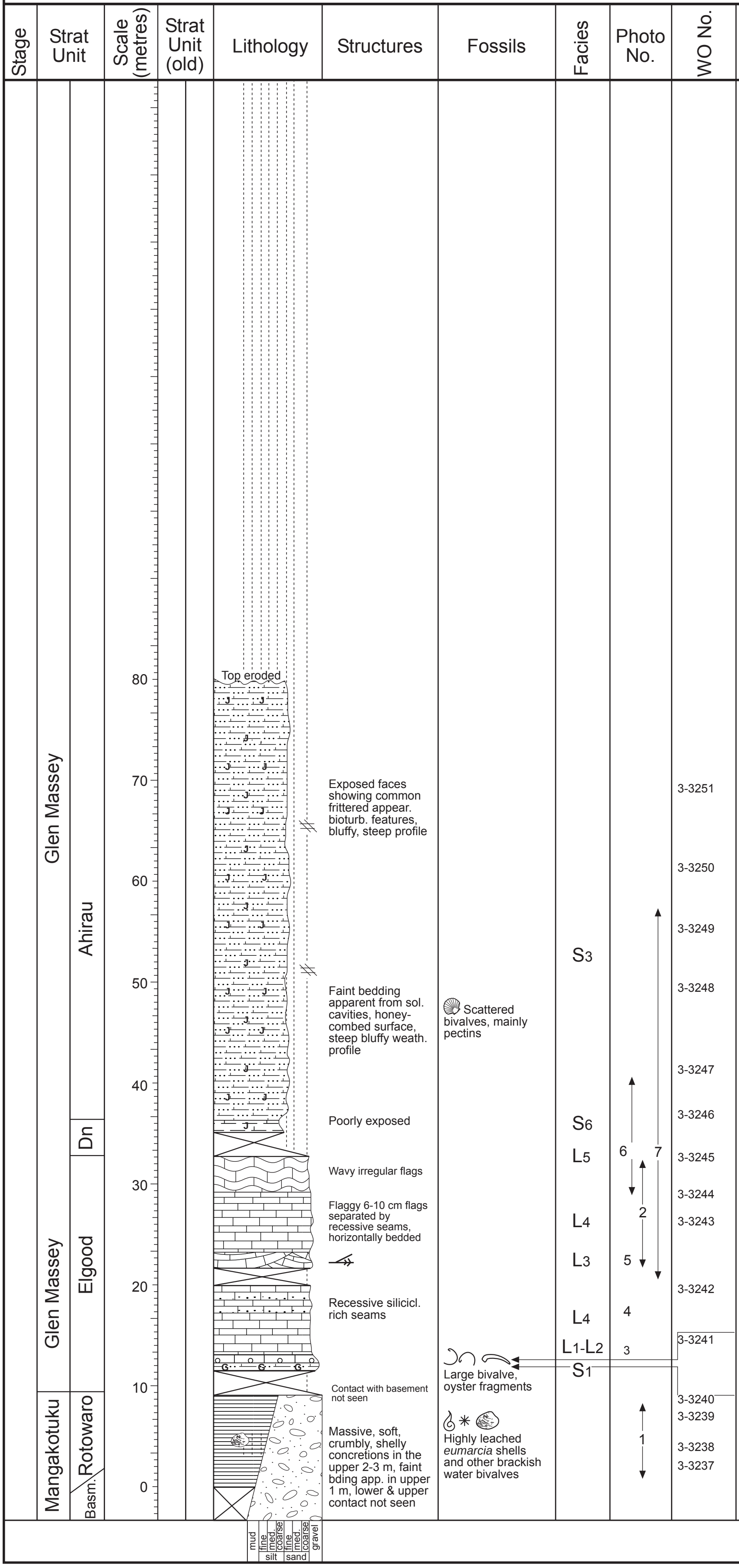
Ahirau Sandstone
Patikirau Siltstone
Mangiti Sandstone

Stratigraphic Column No: *TA-13*
Region: Te Akau
Location: Limestone Droppings near Mangiti Road Halliday Road intersection
NZMS 260 Sheet: R14/826843

Grid Reference:
E: 2683100 - 2682656
N: 6384050 - 6384331

Page 1 *of* 2 **Author:** A. Tripathi



Description

CALC. SILTY SANDSTONE: Light brownish grey, well cemented, massive to occ. faintly bedded, commonly frittery to occ. honeycombed surface weathering, calcareous fine silty sst, highly bioturbated, occ. scattered disarticulated pectin/bivalves.

CALC. SILTSTONE: Greyish to dark greyish, mod. cemented, bioturbated fine calc. slst, massive, covered by fallen debris.

KNOBBLY LIMESTONE: Light greyish to off-white, hard, irregularly flaggy to knobbly, discontinuous, irregular bifurcating dissolution seams, coarse sparry grainstone.

CROSS BEDDED LIMESTONE: Light greyish to brownish, hard, mod. flaggy, low angle tabular cross-bedded 0.3-0.5 m cross set, medium to coarse sparry bioclastic lst, rare pebble grit.

FLAGGY LIMESTONE: Light greyish to buff, mod. to well flagged, thin 6-8 cm flags, recessive seams occ. inverted, med. to coarse sparry bioclastic lst.

PEBBLY LIMESTONE: Light brownish to buff, massive to poorly flaggy varying from 8 to 12 cm, recessive siliciclastic dominated seams 0.2-1.2 cm thick com. subrounded basement pebbles, glauconitic, coarse sparry bioclastic lst.

CALC. SANDSTONE: Dull greyish, well cemented, calc. gritty med. to coarse sandstone, common glauconitised rounded subrounded basement clasts, large bivalves fragments occ. oyster fragment.

CARBONACEOUS MUDSTONE: Dark greyish to yellowish to muddy brown, soft & sticky, highly frittered surface, limonite & sideritic highly oxidised Fe staining, highly leached *eumarcia* shells and concretions made up of shell material, faint bedding apparent in the upper 1 m of exposure.

Conglomeratic basement, commonly occurring as boulders.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Stratigraphic Column No: *TA-14*

Region: Te Akau

Location: Waitetuna estuary, Waingaro-Ohautira Road

NZMS 260 Sheet: R14/837777

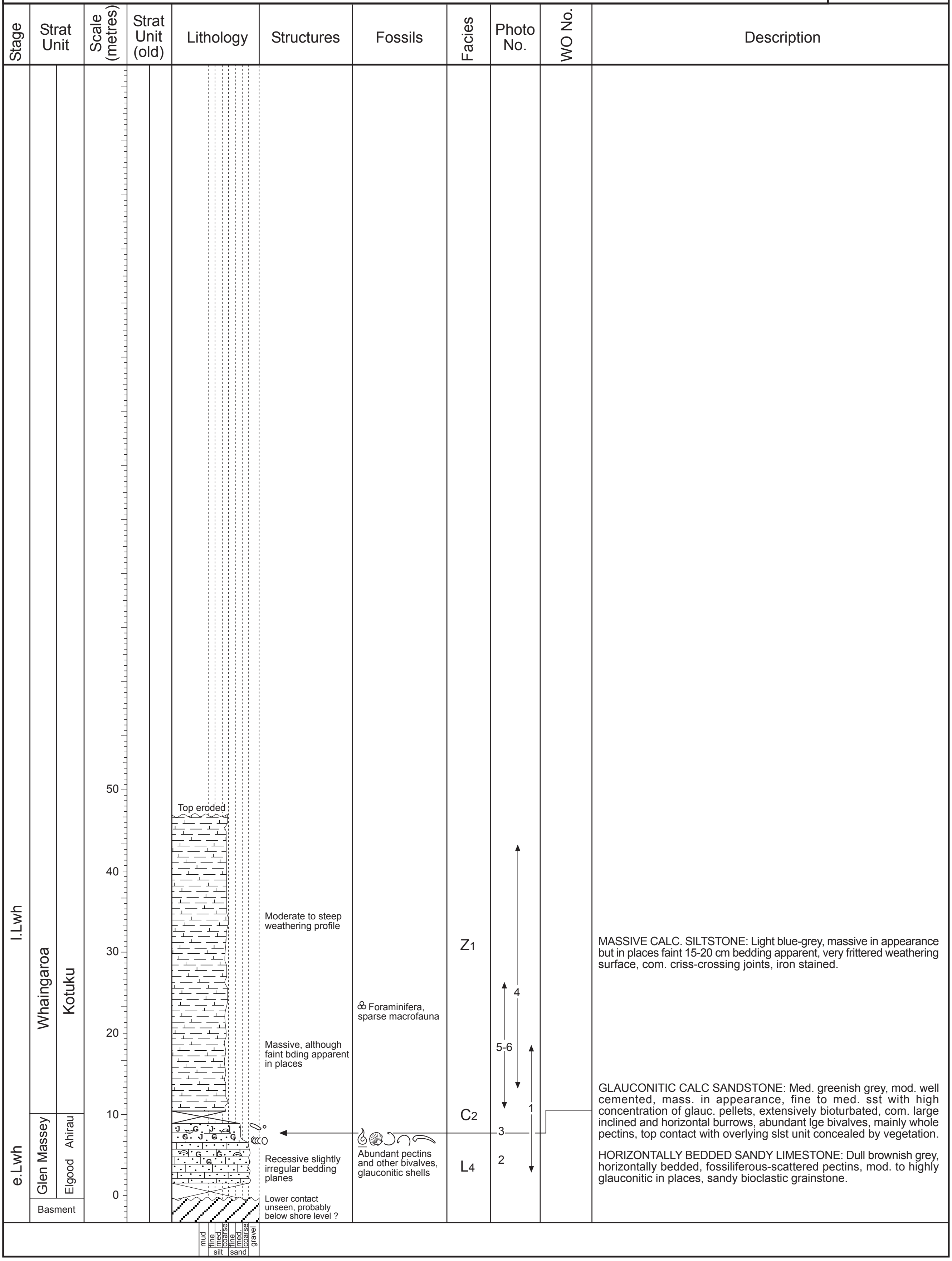
Grid Reference:

E: 2683300 - 2683750

N: 6377450 - 6377700

Page 1 *of* 2

Author: A. Tripathi



MASSIVE CALC. SILTSTONE: Light blue-grey, massive in appearance but in places faint 15-20 cm bedding apparent, very frittered weathering surface, com. criss-crossing joints, iron stained.

GLAUCONITIC CALC SANDSTONE: Med. greenish grey, mod. well cemented, mass. in appearance, fine to med. sst with high concentration of glauc. pellets, extensively bioturbated, com. large inclined and horizontal burrows, abundant lge bivalves, mainly whole pectins, top contact with overlying slst unit concealed by vegetation.

HORIZONTALLY BEDDED SANDY LIMESTONE: Dull brownish grey, horizontally bedded, fossiliferous-scattered pectins, mod. to highly glauconitic in places, sandy bioclastic grainstone.

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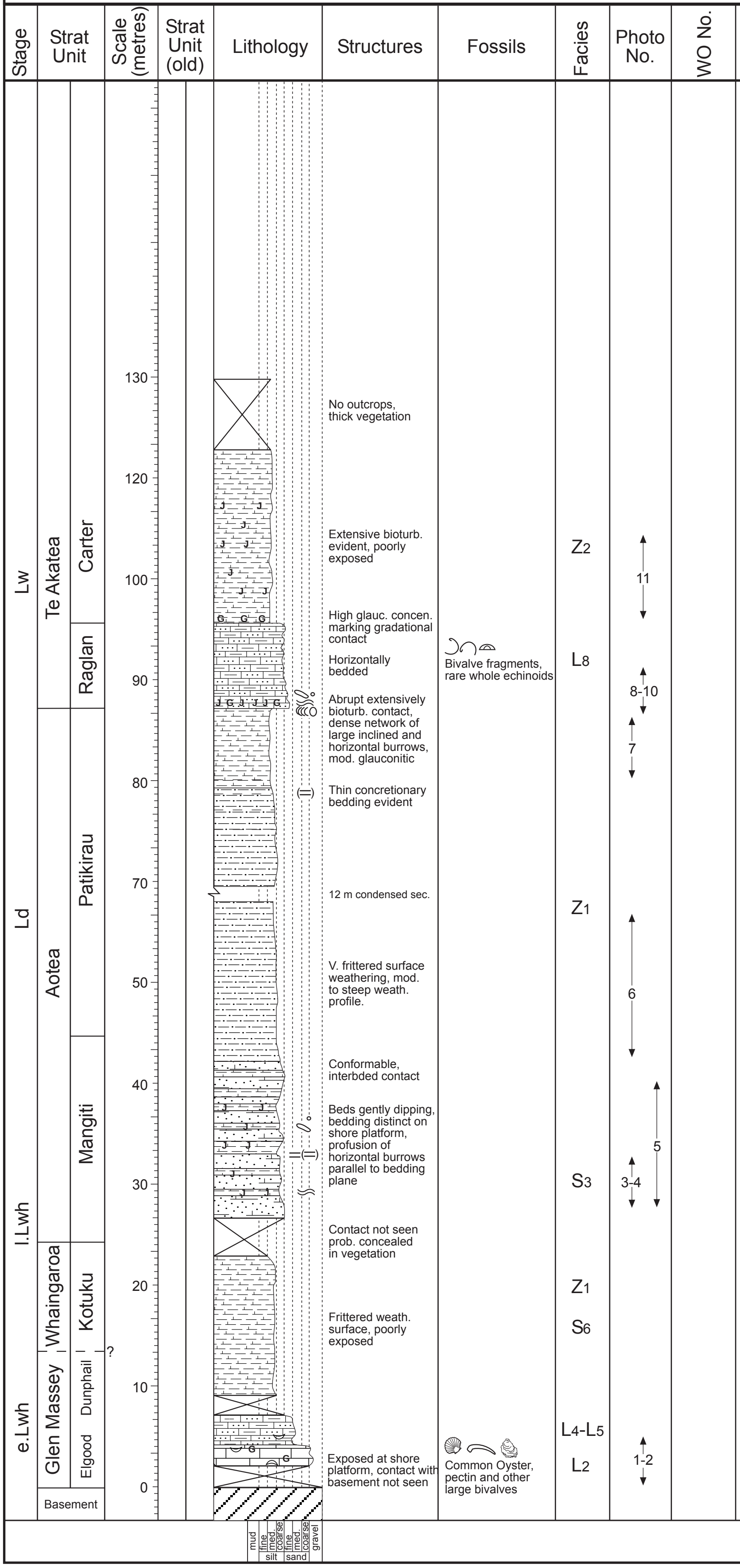
Stratigraphic Column No: *TA-15* **Grid Reference:**
Region: Te Akau **E:** 2679343
Location: Okete Bay, Raglan Harbour **N:** 6376388

NZMS 260 Sheet: R14/793763 *Page* 1 *of* 3 **Author:** A. Tripathi



Description

CALCAREOUS SILTSTONE: Brownish grey to light grey, massive, freq. frittery, calcareous muddy siltstone, bioturbated.

GLAUC. SILTSTONE: Greenish grey, soft, massive, glauc. fine to coarse calc. siltstone.

SILTY LIMESTONE: Light greyish white, hard, flaggy 10-12 cm, fine grained, intensely bioturbated especially along bedding planes, silt dominated horizontal interflags 4-5 cm, wavy flags towards top 2-3 m with thinner interflags.

CALC. SILSTONE: Light greyish, mod. well cemented, mass. to faint cm-scale bedding evident, intensity of bioturb. & calc. content increasing towards top, fine calcareous siltstone.

SANDY SILTSTONE: Dark greyish, mod. cemented, frittery, massive, siltstone grading into sandy siltstone, thin concretionary bedding evident in places.

INTERBEDDED CALC. SILTSTONE & SILTSTONE: Light brownish grey, mod. well cemented 15-20 cm horizontal beds alternating with soft calcareous slst with characteristic frittered surface, bioturbated.

INTERBEDDED CALC. SANDSTONE AND SILTSTONE: Cement grey to dull grey, mod. well cemented fine calcareous sandstone beds 25-30 cm alternating with fine silty interbeds.

CALCAREOUS SILTSTONE: Greyish to brownish grey, massive, frittery, mod. cemented, homogenous unit.

SILTY LIMESTONE: Buff to creamish white, massive to poorly flaggy 3-4 cm, wavy irregular seams, fine silty, bioturbated, becoming silty upsection.
FOSSILIFEROUS FLAGGY LIMESTONE: Light greyish to greyish white, hard, poorly-mod. flaggy 4-6 cm, coarse sparry, abundant shell fragments, oysters, pectins and other bivalves specially in lower 1 m of exposure.
Lower contact with basement not exposed, probably extends in subsurface?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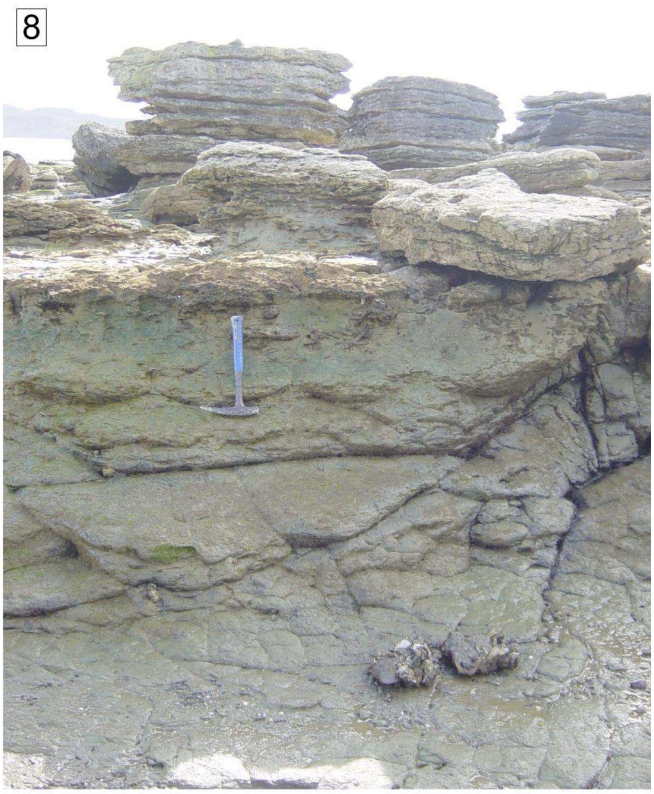

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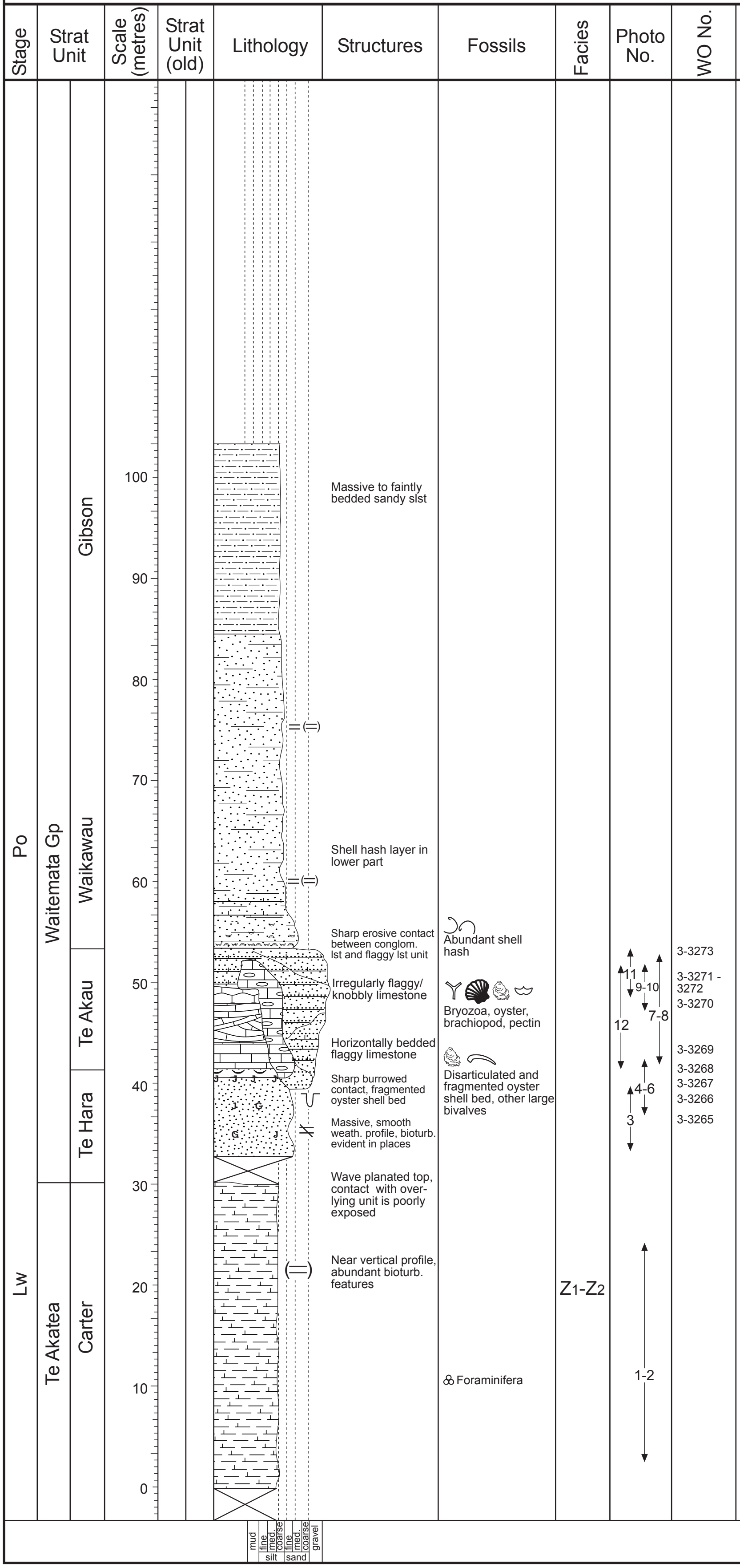
Stratigraphic Column No: *TA-18* ***Grid Reference:***
Region: Te Akau ***E:*** 2670100 - 2669318
Location: Gibson Beach ***N:*** 6389220 - 6391120

NZMS 260 Sheet: R14/701892 *Page* 1 *of* 3 **Author:** A. Tripathi



Description

BEDDED SILTY SANDSTONE: Muddy brown to grey, weakly to mod. cemented, faint - medium horizontally bedded, bed thickness varying from 30-80 cm, variably calcareous very fine to fine sandstone grading into silty sandstone, commonly bioturbated.

HORIZONTALLY BEDDED SILTY SANDSTONE: Light brownish grey, weakly to moderately cemented, common centimeter thick resistant beds few cms thick alternating with massive weakly to moderately cemented silty sst, conspicuous shell hash rich layers, bioturbation features seen occasionally.

CONGLOMERATIC LIMESTONE: Light dull greyish to brownish grey, massive to crudely bedded in places, angular to sub-rounded pebble to cobble size limestone clasts, fabric clast supported to in places supported by shell hash rich sandstone matrix, clasts poorly sorted showing no preferred orientation, sharp erosive lower contact with the underlying flaggy limestone.

FLAGGY LIMESTONE: Light dull greyish white, mod. to well flaggy, flags 5-8 cm, irregularly wavy flaggy to knobbly in the upper 1-1.5 m, low angle cross bedded approx. 1.2 m thick in the middle part, horizontally bedded in the lower part, well developed flags with recessive seams, medium to coarse bioclastic grainstone.

FOSSILIFEROUS LIMESTONE: Light dull greyish white, hard, mod. flaggy to blocky, abundant mainly disart. and fragmented oysters concentrated in the basal 40-50 cm, med. to coarse sparry slightly sandy near the lower contact, sharp erosive lower contact, large inclined burrows, some penetrate into the underlying sandstone.

SANDSTONE: Grey to greenish grey, soft & friable to weakly cemented, mass., very fine to fine sandstone, glauconitic, bioturbated, hard concretions near the upper contact.

MASSIVE CALCAREOUS SILTSTONE: Light grey to creamish, massive to faint horizontally bedded evident in places, bioturbated.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Waikawau Sandstone
Te Hara Sandstone


8
Waikawau Sandstone
Te Akau Limestone
Te Hara Sandstone


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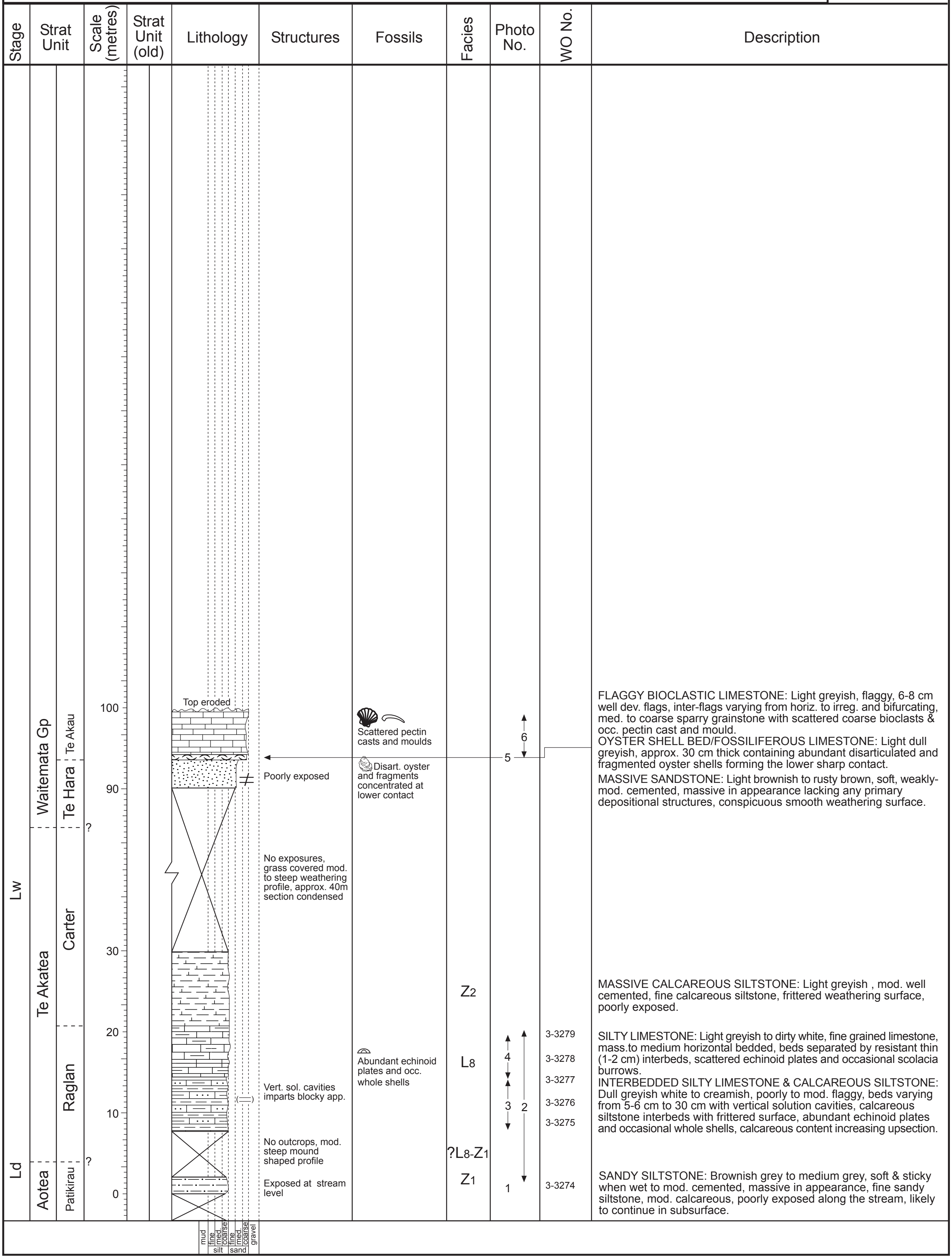
Stratigraphic Column No: *TA-19*
Region: Te Akau
Location: Rothery Road, Raglan Harbour

Grid Reference:
E: 2677195
N: 6380485

NZMS 260 Sheet: R14/771804

Page 1 *of* 2 **Author:** A. Tripathi



FLAGGY BIOCLASTIC LIMESTONE: Light greyish, flaggy, 6-8 cm well dev. flags, inter-flags varying from horiz. to irreg. and bifurcating, med. to coarse sparry grainstone with scattered coarse bioclasts & occ. pectin cast and mould.

OYSTER SHELL BED/FOSSILIFEROUS LIMESTONE: Light dull greyish, approx. 30 cm thick containing abundant disarticulated and fragmented oyster shells forming the lower sharp contact.

MASSIVE SANDSTONE: Light brownish to rusty brown, soft, weakly-mod. cemented, massive in appearance lacking any primary depositional structures, conspicuous smooth weathering surface.

MASSIVE CALCAREOUS SILTSTONE: Light greyish , mod. well cemented, fine calcareous siltstone, frittered weathering surface, poorly exposed.

SILTY LIMESTONE: Light greyish to dirty white, fine grained limestone, mass.to medium horizontal bedded, beds separated by resistant thin (1-2 cm) interbeds, scattered echinoid plates and occasional scolacia burrows.

INTERBEDDED SILTY LIMESTONE & CALCAREOUS SILTSTONE: Dull greyish white to creamish, poorly to mod. flaggy, beds varying from 5-6 cm to 30 cm with vertical solution cavities, calcareous siltstone interbeds with frittered surface, abundant echinoid plates and occasional whole shells, calcareous content increasing upsection.

SANDY SILTSTONE: Brownish grey to medium grey, soft & sticky when wet to mod. cemented, massive in appearance, fine sandy siltstone, mod. calcareous, poorly exposed along the stream, likely to continue in subsurface.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Stratigraphic Column No: *TA-20*

Grid Reference:

Region: Te Akau

E: 2676400 - 2677500

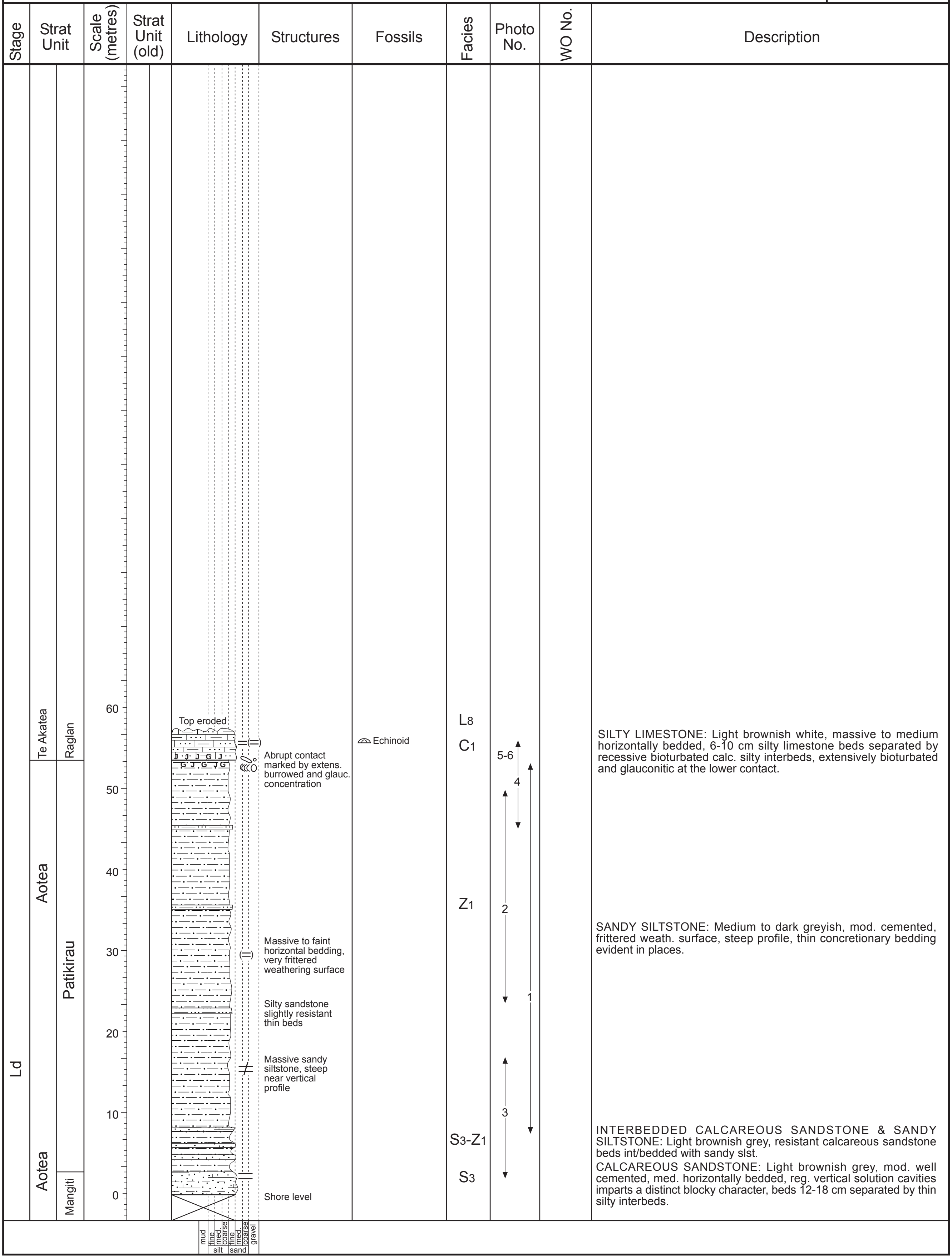
Location: Patikirau Bay, Raglan Harbour

N: 6377800 - 6378500

NZMS 260 Sheet: R14/764778

Page 1 *of* 2

Author: A. Tripathi



SILTY LIMESTONE: Light brownish white, massive to medium horizontally bedded, 6-10 cm silty limestone beds separated by recessive bioturbated calc. silty interbeds, extensively bioturbated and glauconitic at the lower contact.

SANDY SILTSTONE: Medium to dark greyish, mod. cemented, frittered weath. surface, steep profile, thin concretionary bedding evident in places.

INTERBEDDED CALCAREOUS SANDSTONE & SANDY SILTSTONE: Light brownish grey, resistant calcareous sandstone beds int/bedded with sandy slst.

CALCAREOUS SANDSTONE: Light brownish grey, mod. well cemented, med. horizontally bedded, reg. vertical solution cavities imparts a distinct blocky character, beds 12-18 cm separated by thin silty interbeds.

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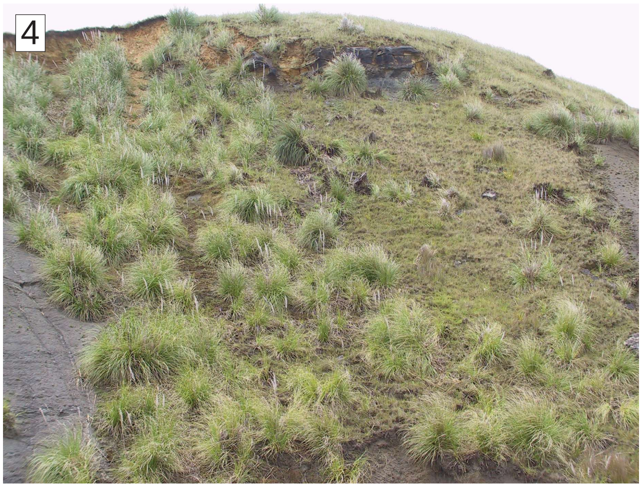

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Stratigraphic Column No: S19 *Grid Reference:*

Region: Te Akau

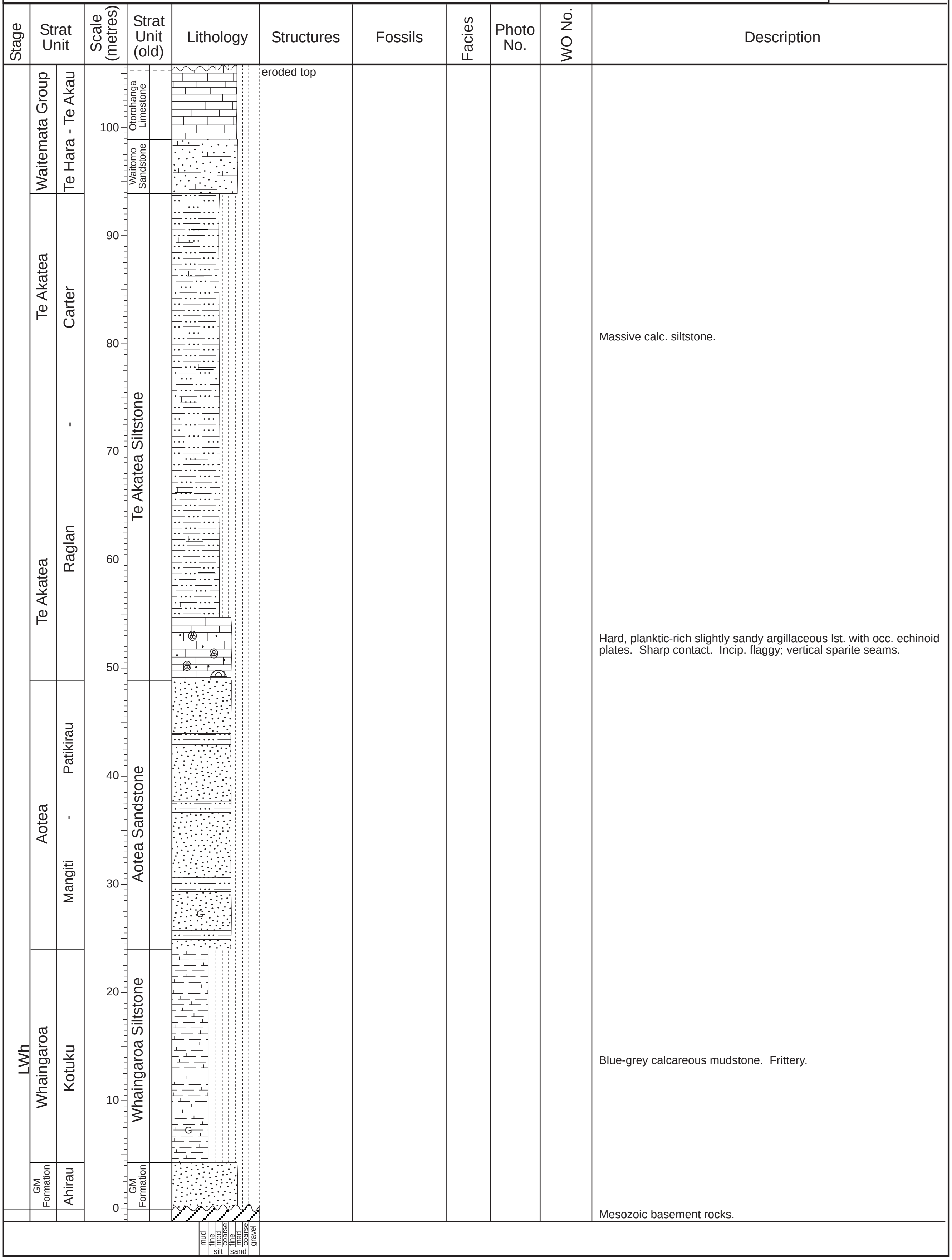
E: 2678478

Location: Section 'T' (Kear 1963); New Kotuku trig (Kotuku West; north side Raglan Harbour)

N: 6383941

NZMS 1 Sheet: R14

Page 1 *of* 1 **Author:** D. Fergusson

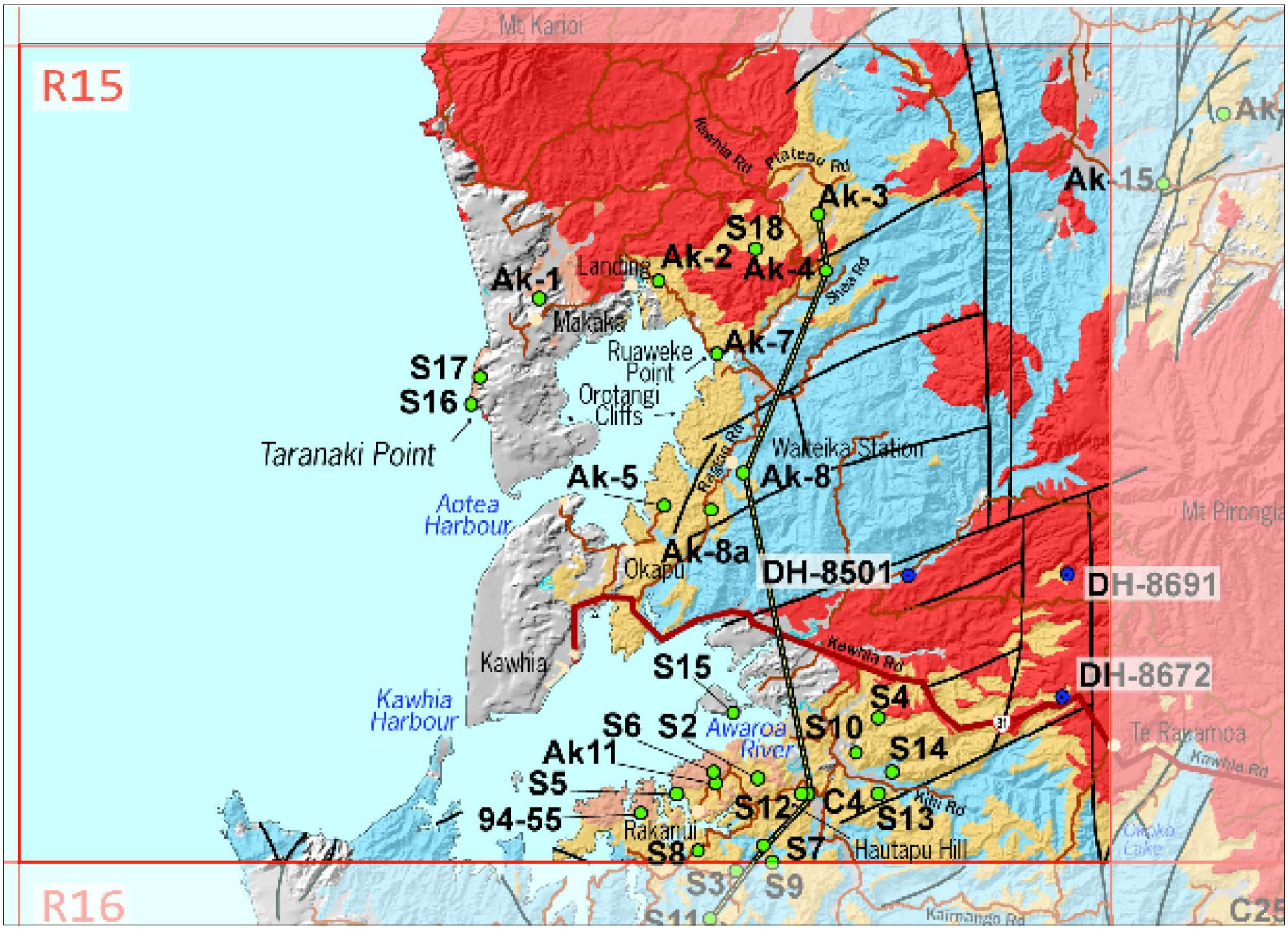


Massive calc. siltstone.

Hard, planktic-rich slightly sandy argillaceous lst. with occ. echinoid plates. Sharp contact. Incip. flaggy; vertical sparite seams.

Blue-grey calcareous mudstone. Frittery.

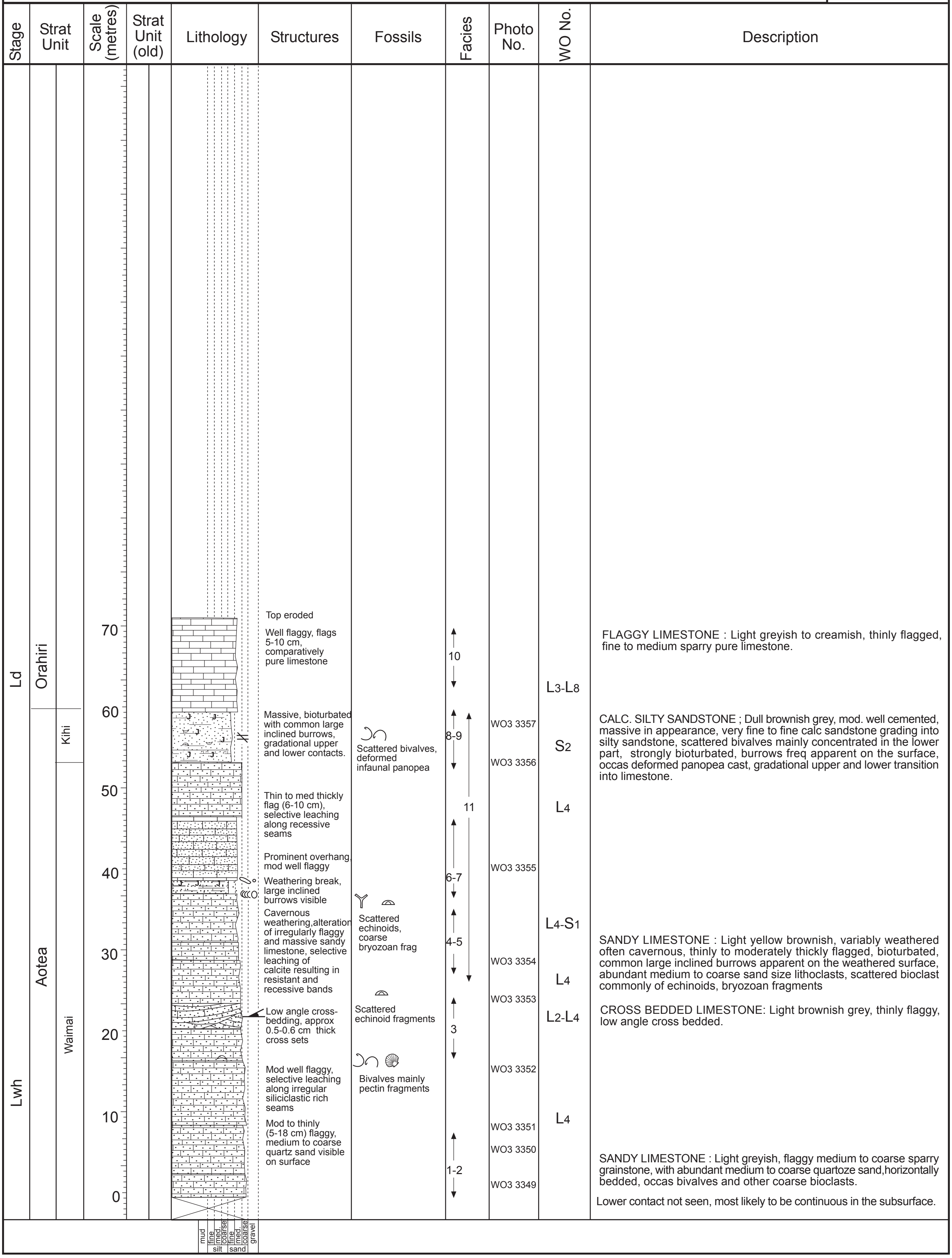
Mesozoic basement rocks.


Mt Karioi
R15
Kawhia Rd
Plateau Rd
Ak-3
S18
Ak-2
Ak-4
Landing
Ak-1
Makaka
Shea Rd
Ak-7
Ruaweke Point
S17
S16
Orotangi Cliffs
Taranaki Point
Waikeika Station
Raglan Rd
Ak-5
Ak-8
Aotea Harbour
Ak-8a
Okapu
DH-8501
DH-8691
Ak-15
Ak
Mt Pirongia
Kawhia
Kawhia Rd
S15
DH-8672
Kawhia Harbour
S4
Awaroa River
S6
S2
S10
S14
31
Te Rauamoa
Kawhia Rd
Ak11
S5
94-55
S12
C4
Kiwi Rd
S13
Rakanui
Hautapu Hill
S8
S7
R16
S3
S9
S11
Kaimango Rd
C25

Stratigraphic Column No: *Ak-1*
Region: Aotea-Kawhia
Location: Makaka settlement, Phillips Road, north of Aotea Harbour
NZMS 260 Sheet: R15/690606

Grid Reference: **Top** **Bottom**
E: 2669064
N: 6360694

Page 1 *of* 3 **Author:** A. Tripathi



Top eroded

Well flaggy, flags 5-10 cm, comparatively pure limestone

Massive, bioturbated with common large inclined burrows, gradational upper and lower contacts.

Thin to med thickly flag (6-10 cm), selective leaching along recessive seams

Prominent overhang, mod well flaggy

Weathering break, large inclined burrows visible

Cavernous weathering,alteration of irregularly flaggy and massive sandy limestone, selective leaching of calcite resulting in resistant and recessive bands

Low angle cross-bedding, approx 0.5-0.6 cm thick cross sets

Mod well flaggy, selective leaching along irregular siliciclastic rich seams

Mod to thinly (5-18 cm) flaggy, medium to coarse quartz sand visible on surface

Scattered bivalves, deformed infaunal panopea

Scattered echinoids, coarse bryozoan frag

Scattered echinoid fragments

Bivalves mainly pectin fragments

FLAGGY LIMESTONE : Light greyish to creamish, thinly flagged, fine to medium sparry pure limestone.

CALC. SILTY SANDSTONE ; Dull brownish grey, mod. well cemented, massive in appearance, very fine to fine calc sandstone grading into silty sandstone, scattered bivalves mainly concentrated in the lower part, strongly bioturbated, burrows freq apparent on the surface, occas deformed panopea cast, gradational upper and lower transition into limestone.

SANDY LIMESTONE : Light yellow brownish, variably weathered often cavernous, thinly to moderately thickly flagged, bioturbated, common large inclined burrows apparent on the weathered surface, abundant medium to coarse sand size lithoclasts, scattered bioclast commonly of echinoids, bryozoan fragments

CROSS BEDDED LIMESTONE: Light brownish grey, thinly flaggy, low angle cross bedded.

SANDY LIMESTONE : Light greyish, flaggy medium to coarse sparry grainstone, with abundant medium to coarse quartoze sand,horizontally bedded, occas bivalves and other coarse bioclasts.

Lower contact not seen, most likely to be continuous in the subsurface.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Stratigraphic Column No: *Ak-2*

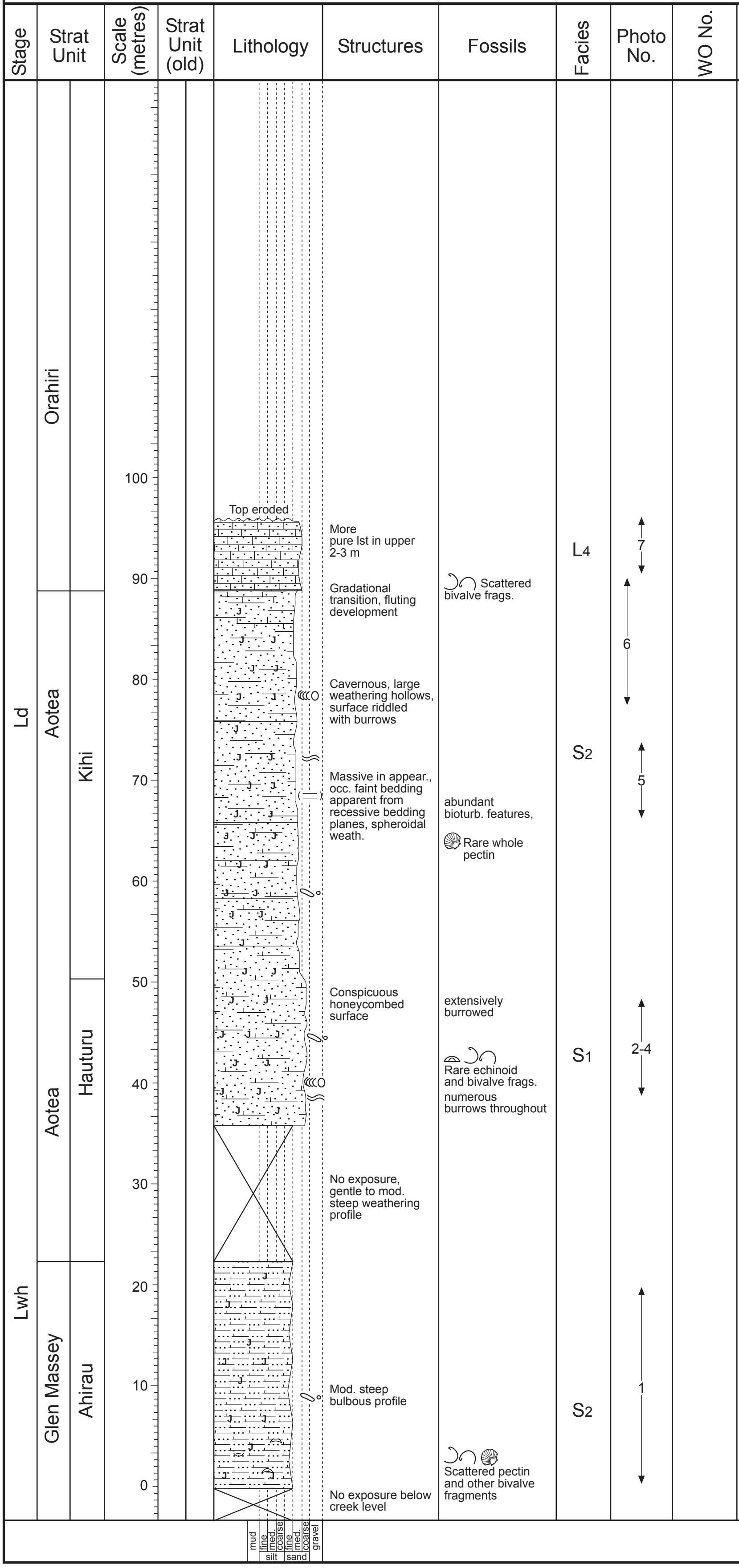
Region: Aotea-Kawhia

Location: Pakoka Landing, Motakotako Creek, Te Mata-Te Papatapu Road

NZMS 260 Sheet: R15/734613

Grid Reference:	***Top***	***Bottom***
E:	2673135	2673450
N:	6361205	6361300

Page 1 *of* 2 **Author:** A. Tripathi



Description

SANDY LIMESTONE: Buff to creamish white, irregularly flaggy to knobbly, small solution cavities, conformable transitional from underlying calc. sandstone unit, sandy sparry grainstone becoming pure upsection, scattered bivalve fragments.

CALC. SILTY SANDSTONE: Light dull greyish to bluish grey, mod. well cemented, spheroidal weathering surface, in places horizontal cavities probably representing bedding surfaces, extensively bioturbated, abundant burrows
visible on surface especially within large weathering hollows.

CALC. SANDSTONE: Light brownish yellow, variably cemented hard concretionary bands alternating with moderately soft slightly friable sst bands with leached calcite cement, common highly honeycombed surface, exposure surface riddled with large and medium burrows and other bioturbation structures, variably calc. fine sandstone, steep bluffy profile.

CALCAREOUS SILTY SANDSTONE: Dull greyish to brownish grey, mod. well cemented, massive although 0.3-0.5 m faint horizontal bedding apparent in places, rippley to honeycombed surface, very fine to fine silty sandstone, com. tubular burrow structures visible on surface, scattered disart. pectins and fragments especially in lower part.

Bottom contact not exposed, likely to continue below water level.

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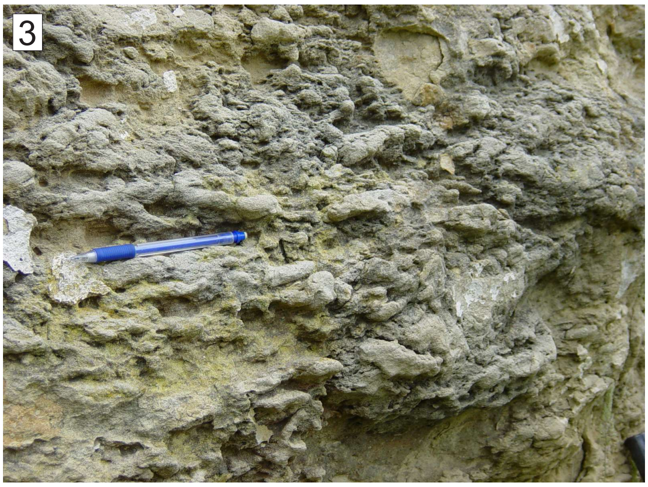

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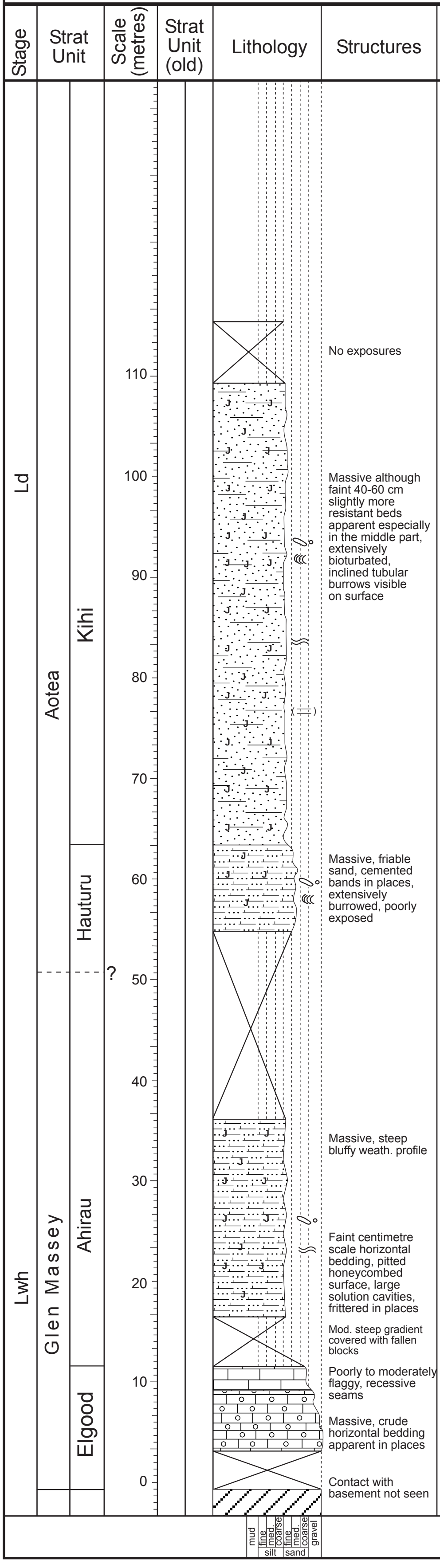
Stratigraphic Column No: *Ak-3*
Region: Aotea-Kawhia
Location: Plateau Road, Te Mata

NZMS 260 Sheet: R15/803646

Grid Reference:	***Top***		***Bottom***
E:	2680323	-	2679280
N:	6364630	-	6363770

Page 1 *of* 2 **Author:** A. Tripathi



Structures	Fossils	Facies	Photo No.	WO No.	Description
No exposures					
Massive although faint 40-60 cm slightly more resistant beds apparent especially in the middle part, extensively bioturbated, inclined tubular burrows visible on surface	Rare pectins	S2			CALC. SILTY SANDSTONE: Dull greyish to brownish grey, mod. cemented massive to occ. faintly bedded, spheroidal weathering surface, extensively bioturbated, variably calcareous silty sandstone.
Massive, friable sand, cemented bands in places, extensively burrowed, poorly exposed		S1			CALC. SANDSTONE: Light yellowish brown, weakly cemented with occ. cemented bands, extensively bioturbated, fine to medium quartzo-feldspathic sandstone, unit is poorly exposed.
Massive, steep bluffy weath. profile Faint centimetre scale horizontal bedding, pitted honeycombed surface, large solution cavities, frittered in places	bioturbated	S2	4-5 3		CALC. SILTY SANDSTONE: Light greyish to br'nish grey, mod. well cemented, massive, however faint horizontal bedding apparent in places, burrowed throughout indicated by honeycombed weathering surface, calc. very fine - fine sandstone to silty sandstone.
Mod. steep gradient covered with fallen blocks					Contact not exposed
Poorly to moderately flaggy, recessive seams		L4	1-2		FLAGGY LIMESTONE: Light greyish white, poorly flaggy becoming mod. well flaggy in the upper 2.5 m (6-10 cm) flags, rare granule size clasts, medium to coarse sparry limestone.
Massive, crude horizontal bedding apparent in places	Scattered bivalves, mainly pectins	L1			PEBBLY LIMESTONE: Dull greyish to brownish grey, massive, abundant rounded to subrounded basement pebbles, frequently concentrated in thin bands, poorly sorted, pebble size showing normal grading, coarse bivalve fragments mainly of pectins.
Contact with basement not seen					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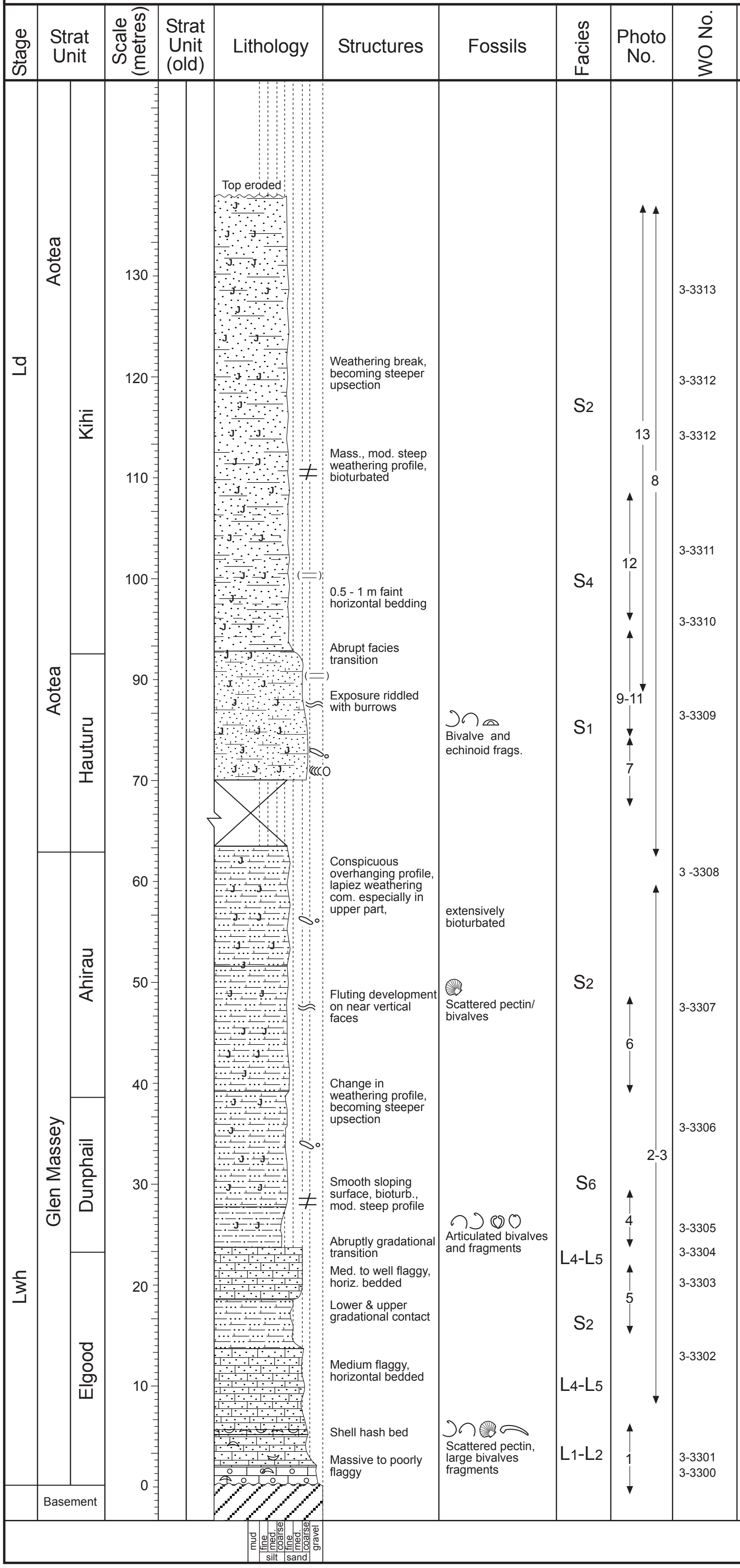
Stratigraphic Column No: *Ak-4*
Region: Aotea-Kawhia
Location: O’Shea Road

NZMS 260 Sheet: R15/790610

Grid Reference:	**Top**		**Bottom**
E:	2679058	-	2679580
N:	6361050	-	6361670

Page 1 *of* 3 **Author:** A. Tripathi



Description

CALC. SANDY SILTSTONE/SILTY SANDSTONE: Buff to brownish grey, well cemented, calcareous fine sandy siltstone grading into silty sandstone, massive homogenous unit, calcareous content probably increasing upsection?

CALC. MUDDY SANDSTONE WITH THIN SILSTONE INTERBEDS: Medium brownish grey, mod. cemented, fine silty sandstone, thin siltstone interbeds occurring at 0.5-0.8 m interval, extensively bioturbated with common tubular burrows visible on weathered surface, spheroidal weathering common, unit forms a distinct mod. steep sloping weathering profile.

CALC. SANDSTONE: Buff to brownish yellow, variably cemented, alternation of well cemented and friable quartzofeldspathic sandstone, fine to med. sandstone extensively burrowed, faint indication of low angle cross bedding seen in places.

Poor exposure, mainly of overlying fallen sst, 10 m sec. condensed

CALC. SILTY SANDSTONE: Light greyish to brownish grey, well cemented, massive, calcareous very fine to fine sandstone grading into sandy siltstone, bluffy, forming a overhanging profile, vertical fluting common on steeper vertical faces, common honeycombed weathering surface, extensively bioturbated, highly weathered surfaces shows abundant burrows and other bioturbation features.

CALC. SILTY SANDSTONE: Light dull greyish, massive, mod. well cemented, calcareous very fine sandstone to siltstone, freq. bioturbated, rare bivalve frag., forming a mod. steep weathering profile.

CALC. SANDY SILTSTONE: Medium greyish to greyish, massive, smooth weathering surface, medium cemented, scattered bivalves concentrated above the lower abruptly gradational contact, weakly glauconitic.

FLAGGY LIMESTONE: Light dull greyish to brownish grey, mod. well flaggy, (6-10 cm) comparatively with less siliciclastic content, occ. scattered bivalves and rare pebbles, medium to coarse grainstone.

CALCAREOUS SANDSTONE: Dull brownish grey, massive, well cemented, highly calcareous very fine sandstone grading into silty sandstone.

SANDY LIMESTONE: Light greyish, mod. flaggy (8-12 cm) to mass. in places, flags separated by calc. silty sst rich seams, medium to coarse sparry bioclastic grainstone with noticeable siliciclastic impurity.

PEBBLY LIMESTONE: Dull greyish brown, massive to poorly flaggy (becoming better flaggy upsection), abundant rounded subrounded pebbles and granule grade basement clasts, common pectin and other large bivalves, fragments occ. concentrated in thin shell beds, disseminated glauconite pellets, unit directly overlies the basement.

BASEMENT: Highly weathered greywacke/argillite.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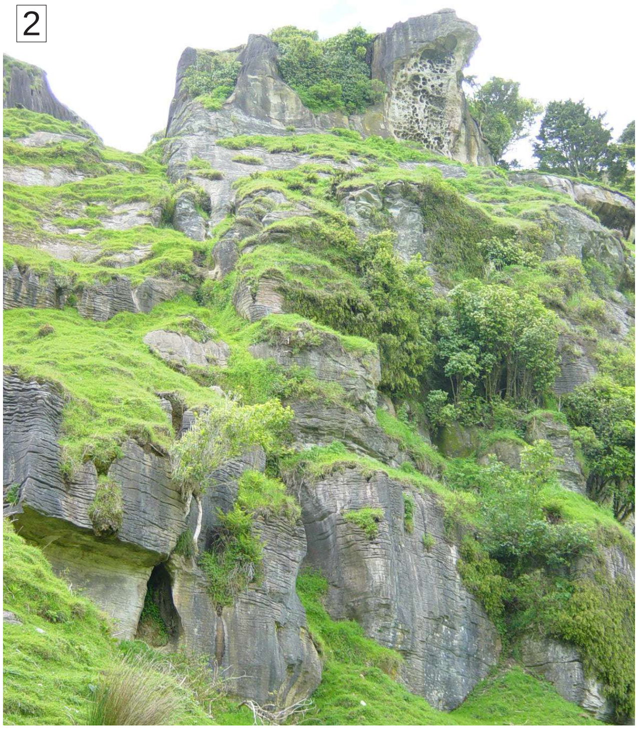
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Stratigraphic Column No: *Ak-5*

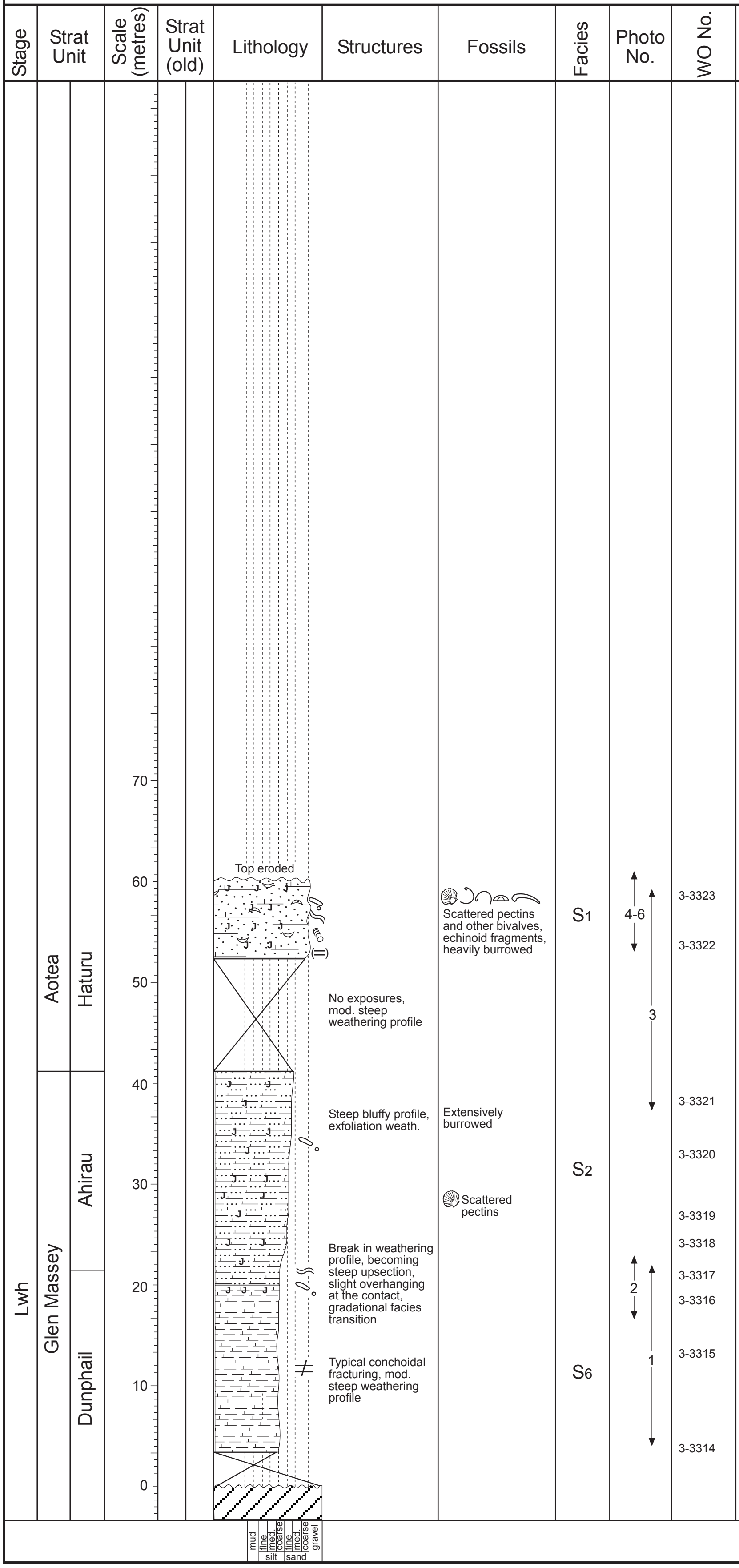
Region: Aotea-Kawhia

Location: Orotangi Cliffs, Okapu Station, Aotea Harbour

NZMS 260 Sheet: R15/729533

Grid Reference:	***Top***		***Bottom***
E:	2672961	-	2673640
N:	6353369	-	6353050

Page 1 *of* 2 **Author:** A. Tripathi



Description

CALCAREOUS GRITTY SANDSTONE: Dull brownish grey, faint horizontal bedding apparent from large solution cavities parallel to bedding surface, scattered rounded to subrounded granule within fine to medium grained calcareous sandstone, extensively bioturbated, weathered surface shows dense inclined and horizontal burrow network, scattered bivalve and echinoid frags.

CALC SILTY SANDSTONE: Light greyish to brownish grey, mod. well cemented, massive, common exfoliation surface weathering, slight overhanging profile near the lower gradational contact, very fine to fine calcareous sandstone grading into calcareous silty sandstone, extensively bioturbated especially at the contact, scattered bivalves mainly pectin.

CALC. SILTSTONE: Light bluish grey to brownish grey, well cemented, massive, frittered weathering surface, conchoidal fracturing common, freq. iron stained curvilinear joints, fine calcareous siltstone.

Contact with basement probably lies below the shore level?

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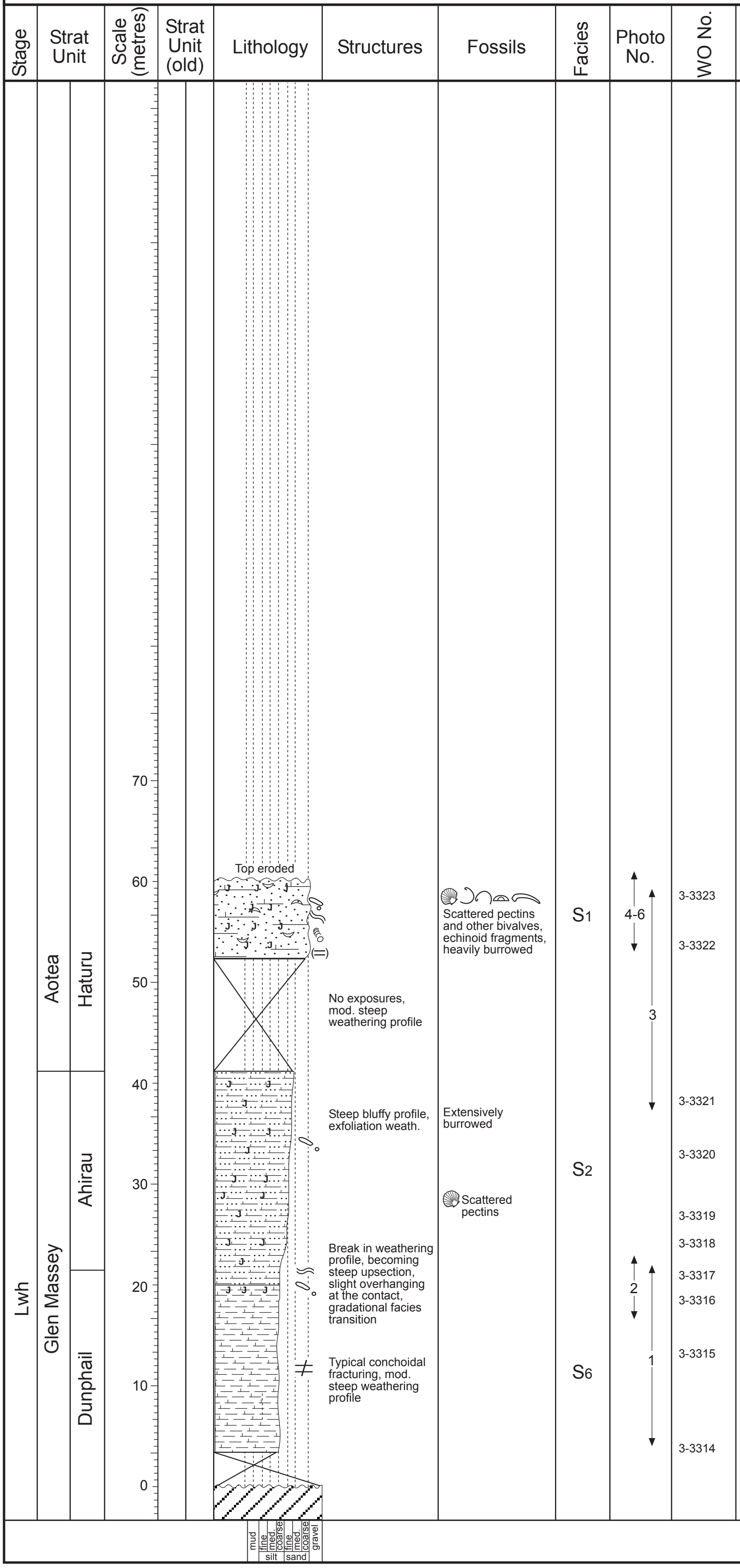
Stratigraphic Column No: *Ak-5*
Region: Aotea-Kawhia
Location: Orotangi Cliffs, Okapu Station, Aotea Harbour
NZMS 260 Sheet: R15/729533

Grid Reference:	***Top***		***Bottom***
E:	2672961	-	2673640
N:	6353369	-	6353050

Page 1 *of* 2 **Author:** A. Tripathi



Description

CALCAREOUS GRITTY SANDSTONE: Dull brownish grey, faint horizontal bedding apparent from large solution cavities parallel to bedding surface, scattered rounded to subrounded granule within fine to medium grained calcareous sandstone, extensively bioturbated, weathered surface shows dense inclined and horizontal burrow network, scattered bivalve and echinoid frags.

CALC SILTY SANDSTONE: Light greyish to brownish grey, mod. well cemented, massive, common exfoliation surface weathering, slight overhanging profile near the lower gradational contact, very fine to fine calcareous sandstone grading into calcareous silty sandstone, extensively bioturbated especially at the contact, scattered bivalves mainly pectin.

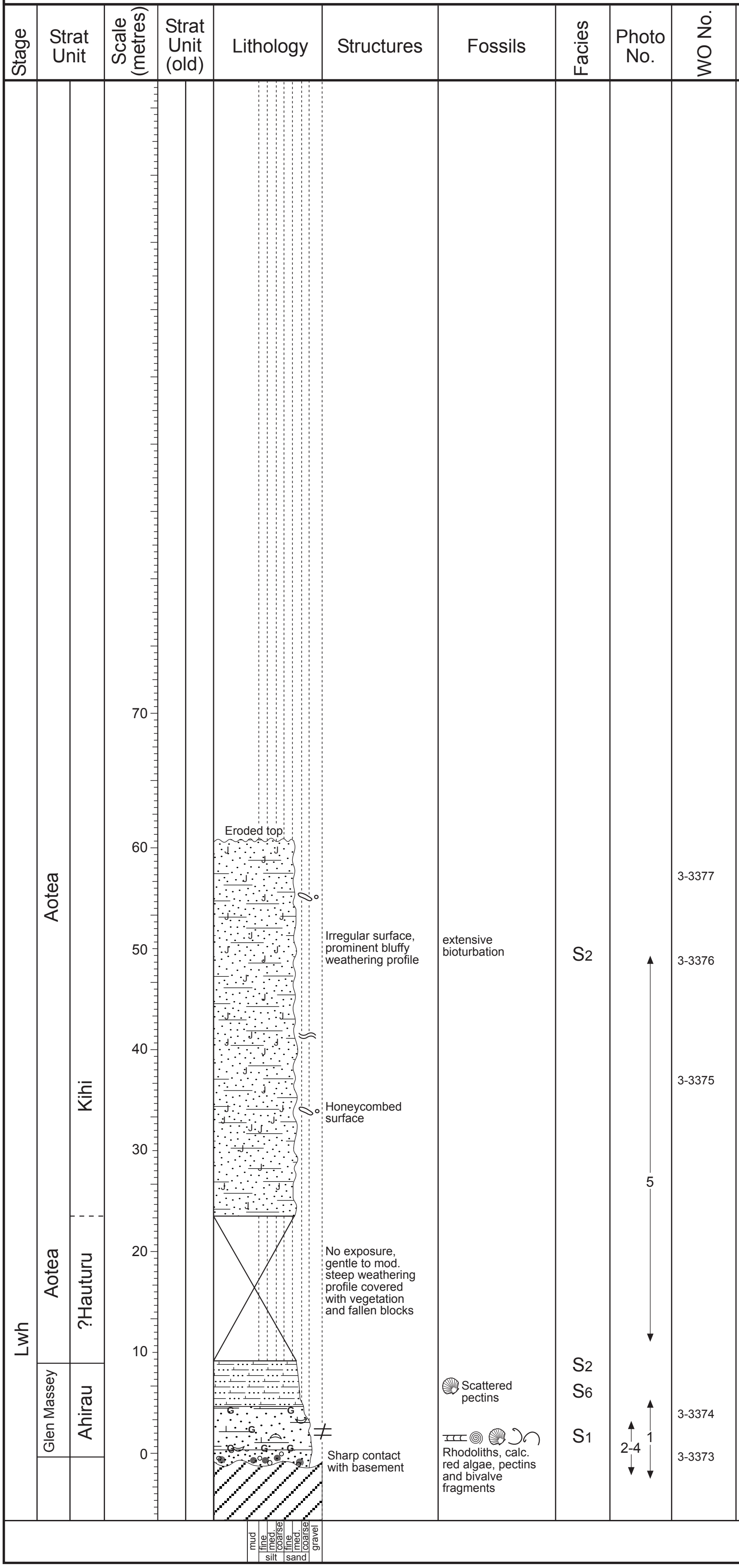
CALC. SILTSTONE: Light bluish grey to brownish grey, well cemented, massive, frittered weathering surface, conchoidal fracturing common, freq. iron stained curvilinear joints, fine calcareous siltstone.

Contact with basement probably lies below the shore level?

Stratigraphic Column No: *Ak-7*
Region: Aotea-Kawhia
Location: Ruaaweke Point, Te Papatapu, Aotea Harbour
NZMS 260 Sheet: R15/756586

Grid Reference:	**Top**	**Bottom**
E:	2675602	
N:	6358630	

Page 1 *of* 2 **Author:** A. Tripathi



Description

CALC. MUDDY SANDSTONE: Light dull brownish grey, moderately well cemented, massive, extensively bioturbated often indicated by highly irregular surface, exfoliation weathering common.

CALCAREOUS SILTY SANDSTONE: Light creamish to brownish grey, well cemented, massive with slightly frittered surface, calcareous very fine to fine sandstone grading into sandy siltstone.

PEBBLY CALC SANDSTONE: Dull bluish grey, weakly to mod cemented (soft and crumbly in places), massive, poorly sorted calcareous silty sandstone with abundant scattered rounded and subrounded granules and pebbles especially in the lower 15-20 cm contact with basement; the basal conglomerate consists of rhodoliths and large bivalve fragments, disseminated glauconite pellets in the lower 1.5-2 m.

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Stratigraphic Column No: *Ak-8*

Grid Reference:

Region: Aotea-Kawhia

E: 2676531

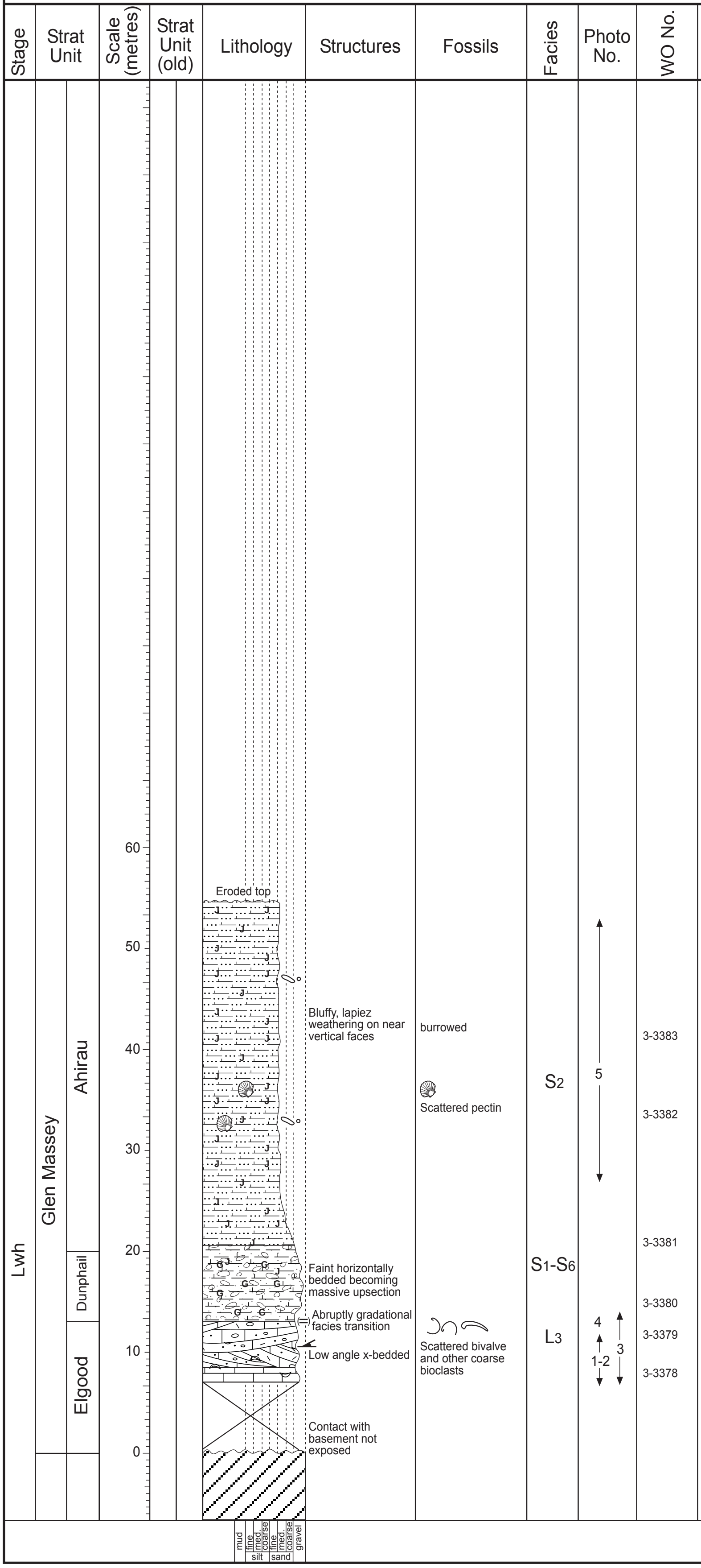
Location: Waiteira Station, Raglan Kawhia Road

N: 6354284

NZMS 260 Sheet: R15/765542

Page 1 *of* 2

Author: A. Tripathi



Description

CALC. SILTY SANDSTONE: Light brownish grey, mod. well cemented, massive, lapiez weathering, honeycombed weathering surface, extensively bioturbated, prominent bluffy with near vertical profile.

PEBBLY GLAUC. SILTSTONE: Dull greyish to greenish grey, weakly to mod. cemented (crumbly in places), faintly horizontally bedded to massive, abundant scattered rounded-subrounded pebbles frequently glauconitised, fabric supported by poorly sorted glauconitic variably calcareous siltstone matrix, abrupt gradational lower contact with limestone

CROSS- BEDDED PEBBLY LIMESTONE: Light greyish to whitish, well flaggy, thin wavy flags 4-8cm, recessive irregular seams, low angle cross bedded 0.2-0.4 m thick cross sets, abundant scattered granule and occ. pebble, common scattered bivalve fragments, disseminated glauconite pellets, medium to coarse bioclastic grainstone.

Weathered basement greywacke, contact with limestone not exposed.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Stratigraphic Column No: *Ak-8A*

Grid Reference:

Region: Aotea-Kawhia

E: 2675350

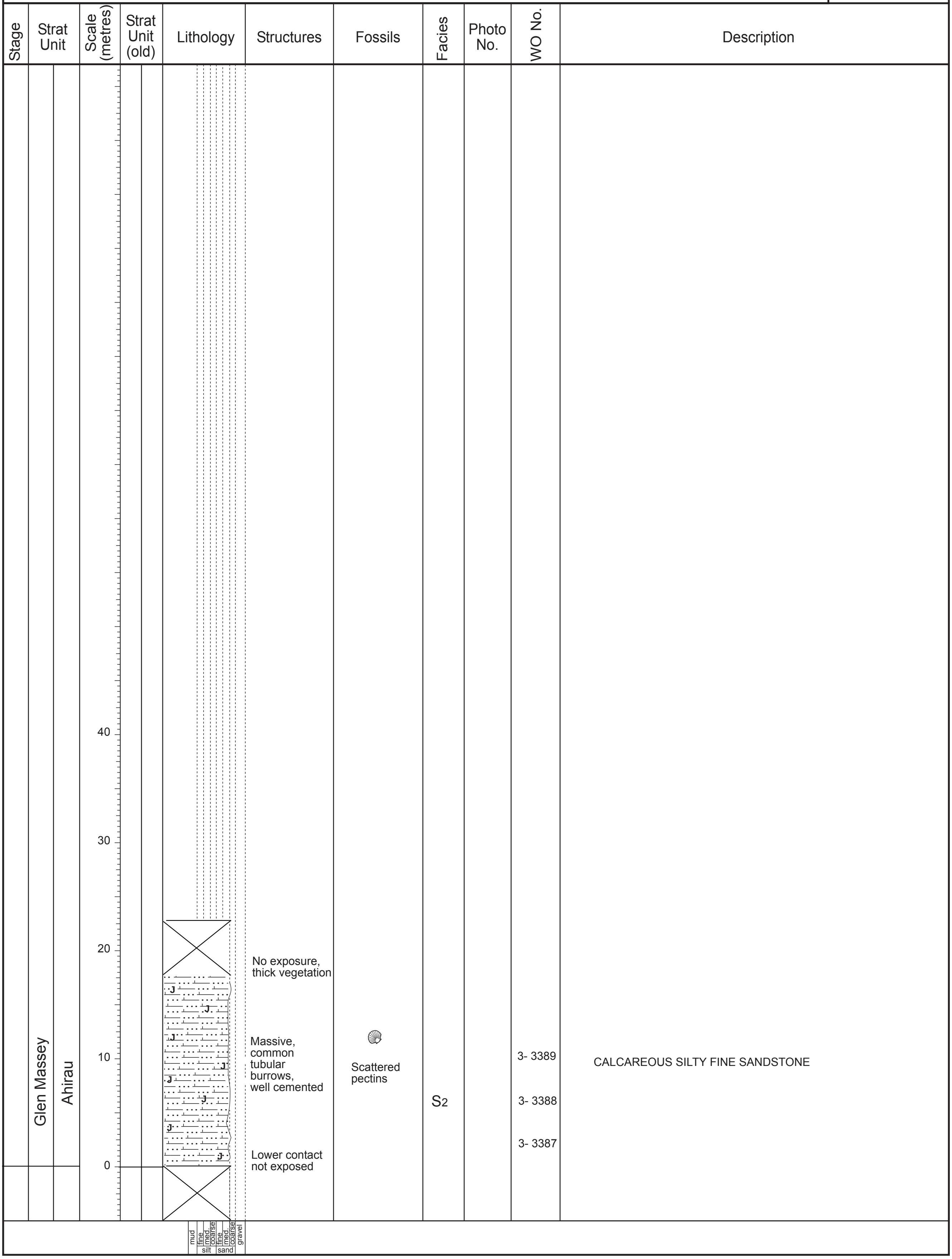
Location: Mangaora Stream, Kawhia-Raglan Road

N: 6352900

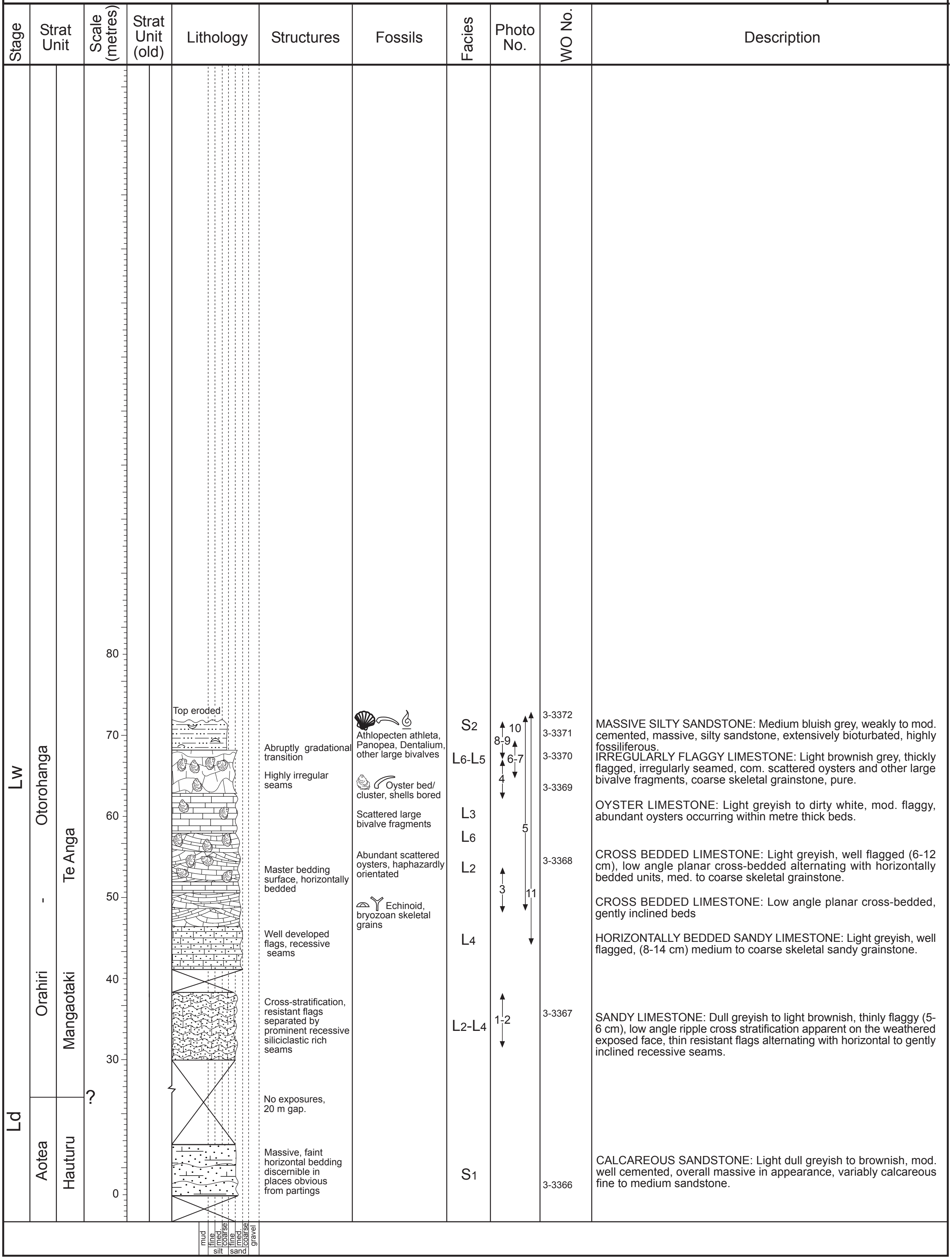
NZMS 260 Sheet: R15/753529

Page 1 *of* 2

Author: A. Tripathi



Stratigraphic Column No: *Ak-11* **Grid Reference:**
Region: Aotea-Kawhia **E:** 2675565
Location: Rakanui Peninsula, abandoned quarry on Rakanui Road, Kawhia Harbour **N:** 6342909
NZMS 260 Sheet: R15/755429 *Page* 1 *of* 3 **Author:** A. Tripathi



Stage	Strat Unit	Structures	Fossils	Facies	Photo No.	WO No.	Description
Lw	Otorohanga - Orahiri; Te Anga		Athlopecten athleta, Panopea, Dentalium, other large bivalves	S2	10, 8-9	3-3372 3-3371	MASSIVE SILTY SANDSTONE: Medium bluish grey, weakly to mod. cemented, massive, silty sandstone, extensively bioturbated, highly fossiliferous.
		Abruptly gradational transition		L6-L5	6-7	3-3370	IRREGULARLY FLAGGY LIMESTONE: Light brownish grey, thickly flagged, irregularly seamed, com. scattered oysters and other large bivalve fragments, coarse skeletal grainstone, pure.
		Highly irregular seams	Oyster bed/ cluster, shells bored		4	3-3369	OYSTER LIMESTONE: Light greyish to dirty white, mod. flaggy, abundant oysters occurring within metre thick beds.
			Scattered large bivalve fragments	L3 L6	5		
		Master bedding surface, horizontally bedded	Abundant scattered oysters, haphazardly orientated	L2	3	3-3368	CROSS BEDDED LIMESTONE: Light greyish, well flagged (6-12 cm), low angle planar cross-bedded alternating with horizontally bedded units, med. to coarse skeletal grainstone.
			Echinoid, bryozoan skeletal grains		11		CROSS BEDDED LIMESTONE: Low angle planar cross-bedded, gently inclined beds
		Well developed flags, recessive seams		L4			HORIZONTALLY BEDDED SANDY LIMESTONE: Light greyish, well flagged, (8-14 cm) medium to coarse skeletal sandy grainstone.
	Mangaotaki	Cross-stratification, resistant flags separated by prominent recessive siliciclastic rich seams		L2-L4	1-2	3-3367	SANDY LIMESTONE: Dull greyish to light brownish, thinly flaggy (5-6 cm), low angle ripple cross stratification apparent on the weathered exposed face, thin resistant flags alternating with horizontal to gently inclined recessive seams.
		No exposures, 20 m gap.					
Ld	Aotea; Hauturu	Massive, faint horizontal bedding discernible in places obvious from partings		S1		3-3366	CALCAREOUS SANDSTONE: Light dull greyish to brownish, mod. well cemented, overall massive in appearance, variably calcareous fine to medium sandstone.

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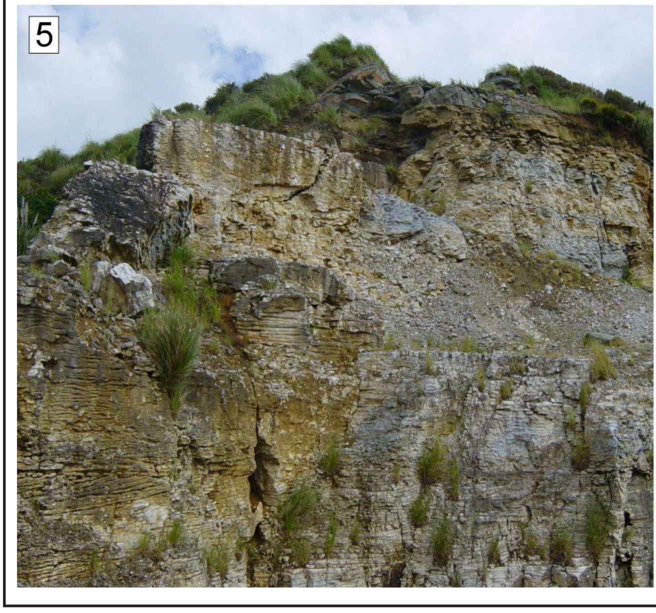

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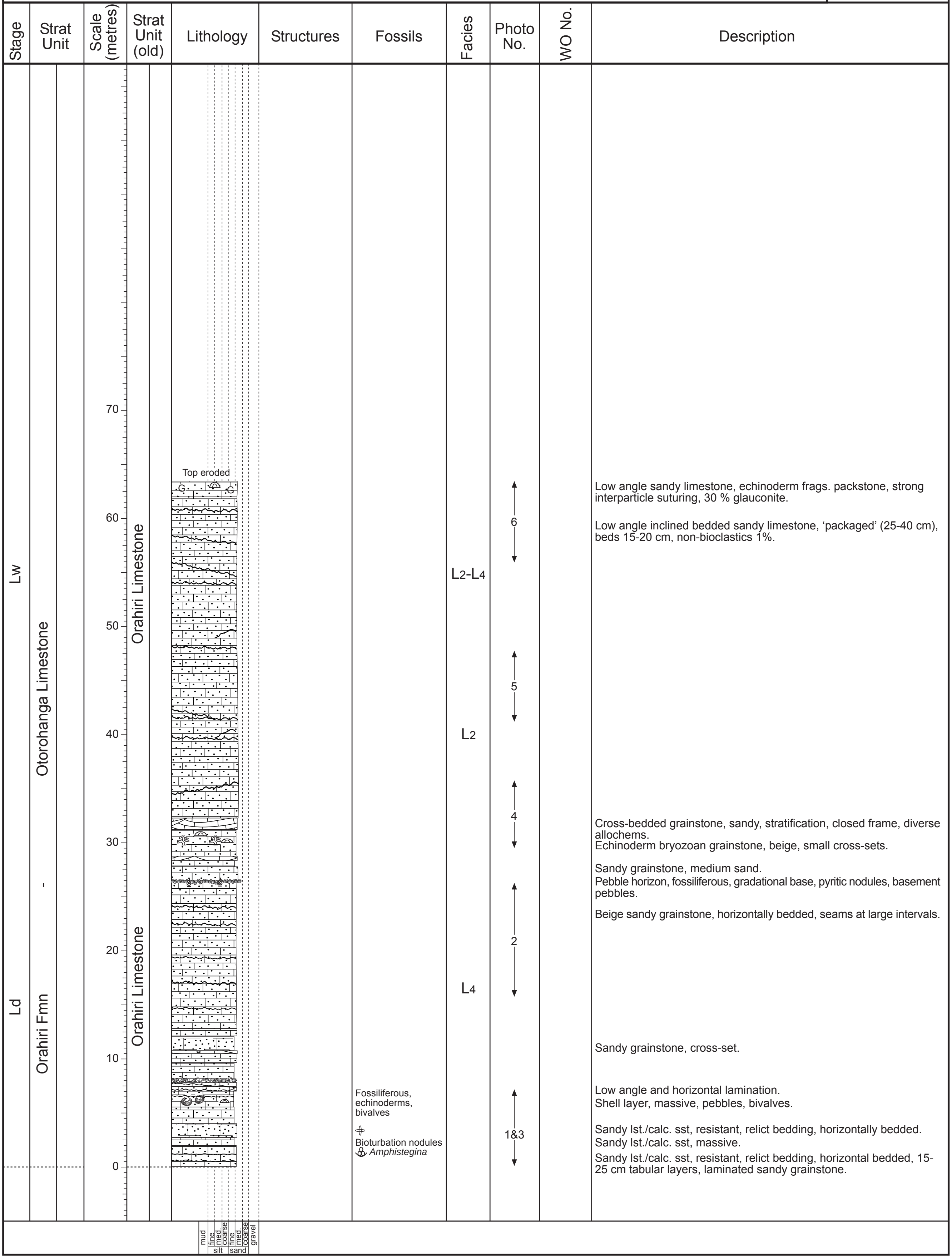
Stratigraphic Column No: *94-55* ***Grid Reference:***
Region: Aotea - Kawhia ***E:*** 2672800
Location: Waipuna Station, Kawhia Harbour ***N:*** 6341800

NZMS 260 Sheet: R15/728418 *Page* 1 *of* 2 **Author:** A.S. Anastas
Modified: A. Tripathi



Low angle sandy limestone, echinoderm frags. packstone, strong interparticle suturing, 30 % glauconite.

Low angle inclined bedded sandy limestone, ‘packaged’ (25-40 cm), beds 15-20 cm, non-bioclastics 1%.

Cross-bedded grainstone, sandy, stratification, closed frame, diverse allochems.
Echinoderm bryozoan grainstone, beige, small cross-sets.

Sandy grainstone, medium sand.
Pebble horizon, fossiliferous, gradational base, pyritic nodules, basement pebbles.

Beige sandy grainstone, horizontally bedded, seams at large intervals.

Sandy grainstone, cross-set.

Low angle and horizontal lamination.
Shell layer, massive, pebbles, bivalves.

Sandy lst./calc. sst, resistant, relict bedding, horizontally bedded.
Sandy lst./calc. sst, massive.
Sandy lst./calc. sst, resistant, relict bedding, horizontal bedded, 15-25 cm tabular layers, laminated sandy grainstone.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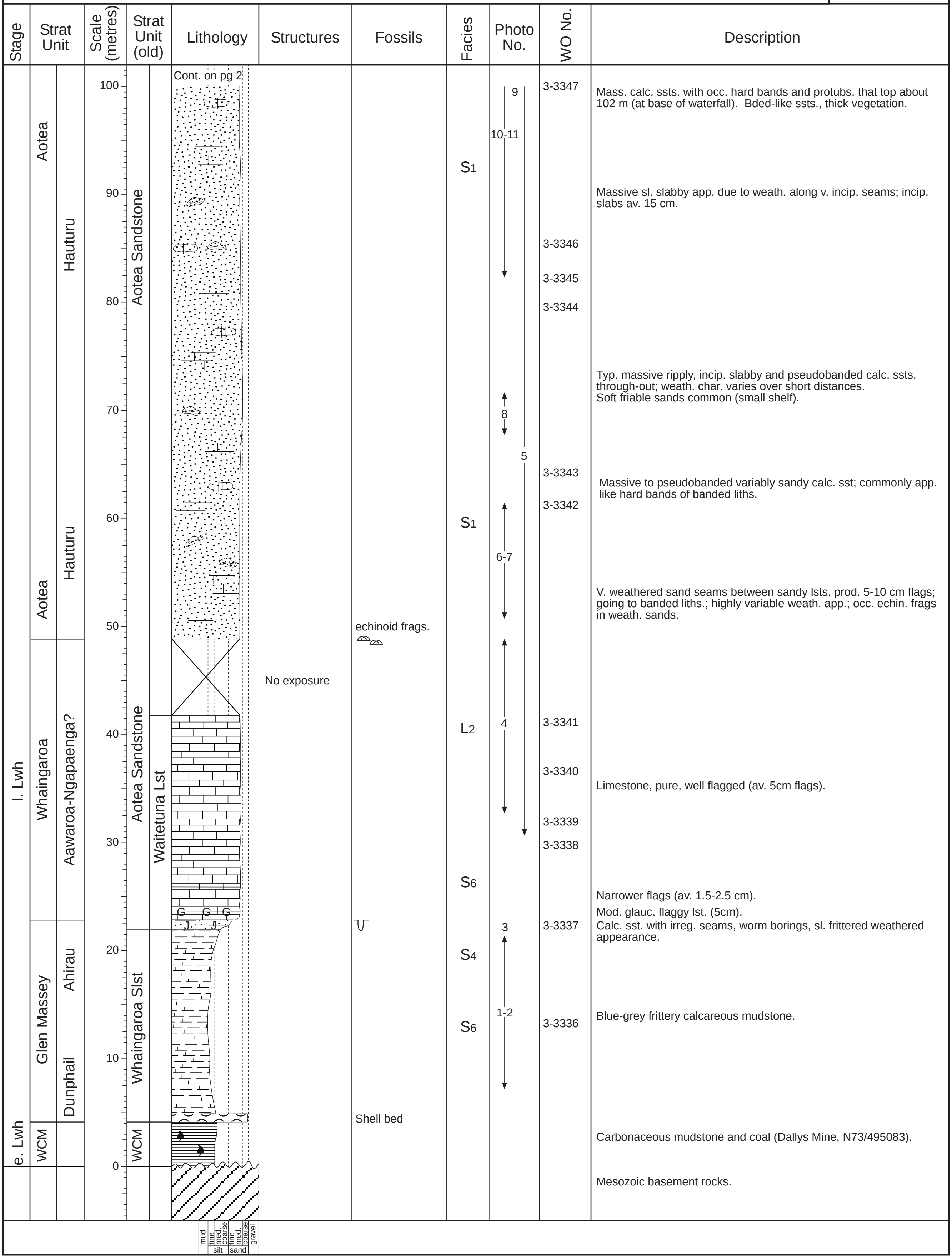
Stratigraphic Column No: *C. 4*
Region: King Country/Waitomo
Location: Hautapu Hill, east of Hauturu

Grid Reference:
E: 2678955
N: 6342499

NZMS 1 Sheet: R15/789924

Page 1 *of* 2

Author: C. Nelson
Modified: A. Tripathi



Mass. calc. ssts. with occ. hard bands and protubs. that top about 102 m (at base of waterfall). Bded-like ssts., thick vegetation.

Massive sl. slabby app. due to weath. along v. incip. seams; incip. slabs av. 15 cm.

Typ. massive ripply, incip. slabby and pseudobanded calc. ssts. through-out; weath. char. varies over short distances.
Soft friable sands common (small shelf).

Massive to pseudobanded variably sandy calc. sst; commonly app. like hard bands of banded liths.

V. weathered sand seams between sandy lsts. prod. 5-10 cm flags; going to banded liths.; highly variable weath. app.; occ. echin. frags in weath. sands.

Limestone, pure, well flagged (av. 5cm flags).

Narrower flags (av. 1.5-2.5 cm).
Mod. glauc. flaggy lst. (5cm).
Calc. sst. with irreg. seams, worm borings, sl. frittered weathered appearance.

Blue-grey frittery calcareous mudstone.

Carbonaceous mudstone and coal (Dallys Mine, N73/495083).

Mesozoic basement rocks.

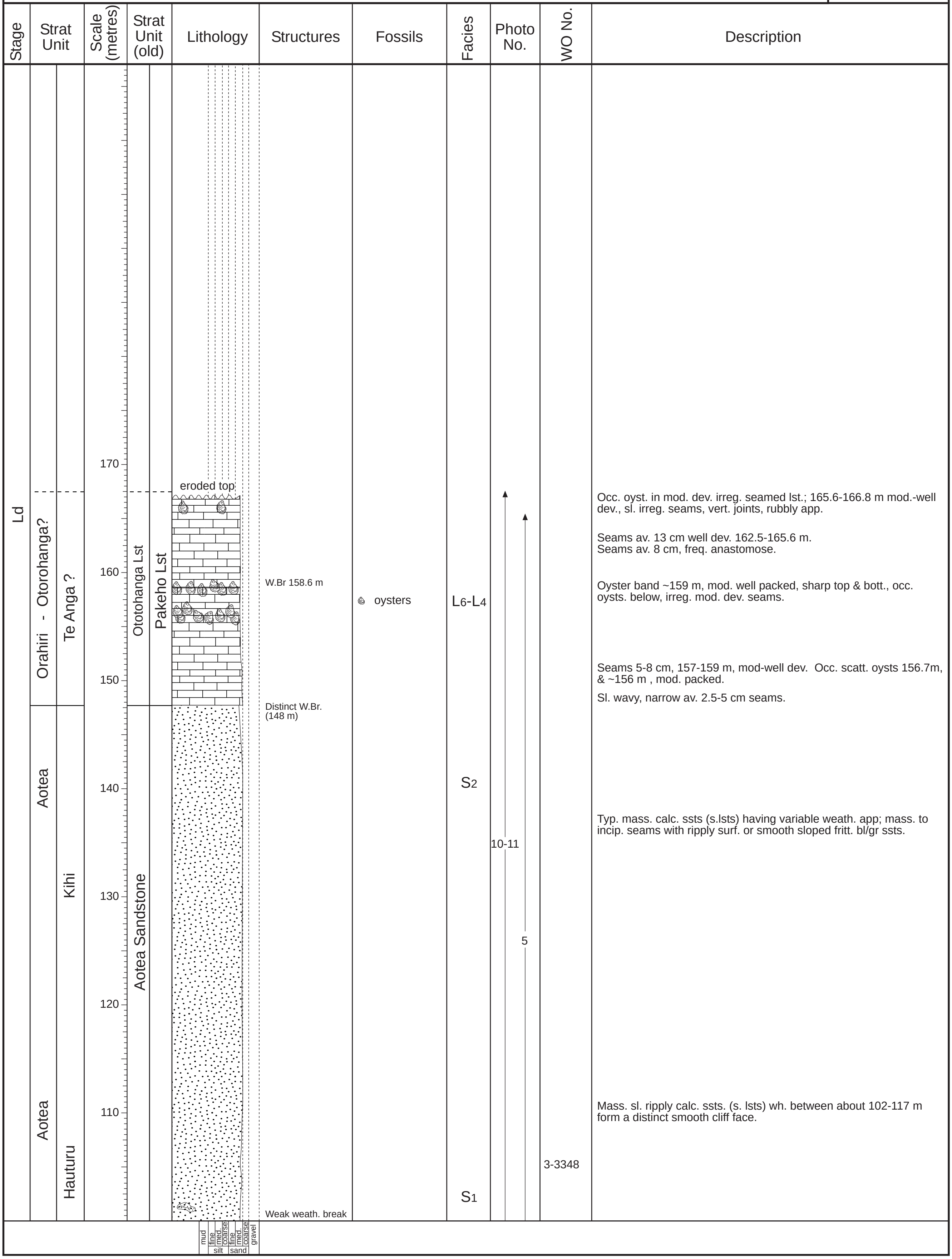
Stratigraphic Column No: *C. 4*
Region: King Country/Waitomo
Location: Hautapu Hill, east of Hauturu

Grid Reference:
E: 2678955
N: 6342499

NZMS 1 Sheet: R15

Page 2 *of* 2

Author: C. Nelson
Modified: A. Tripathi



Occ. oyst. in mod. dev. irreg. seamed lst.; 165.6-166.8 m mod.-well dev., sl. irreg. seams, vert. joints, rubbly app.

Seams av. 13 cm well dev. 162.5-165.6 m.
Seams av. 8 cm, freq. anastomose.

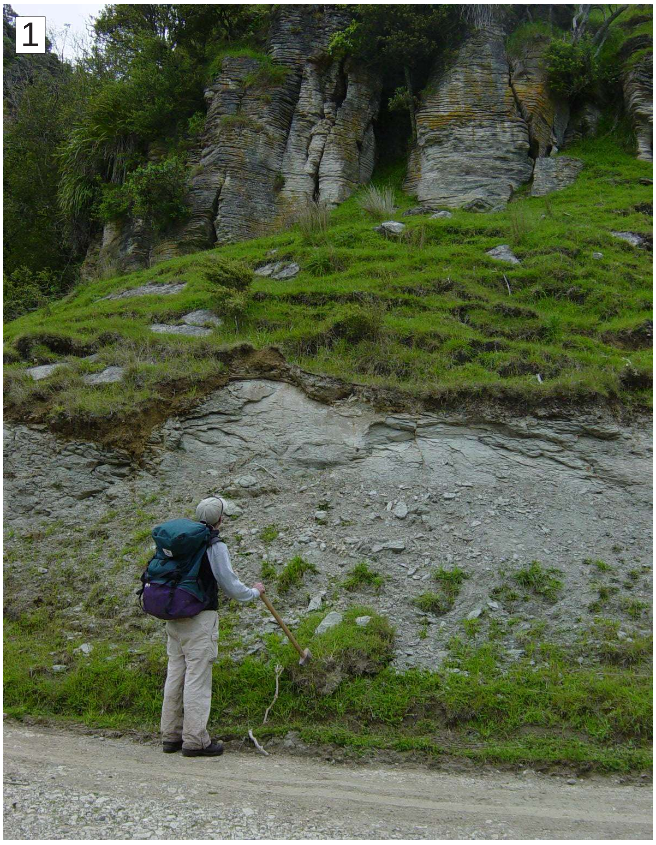
Oyster band ~159 m, mod. well packed, sharp top & bott., occ. oysts. below, irreg. mod. dev. seams.

Seams 5-8 cm, 157-159 m, mod-well dev. Occ. scatt. oysts 156.7m, & ~156 m , mod. packed.

Sl. wavy, narrow av. 2.5-5 cm seams.

Typ. mass. calc. ssts (s.lsts) having variable weath. app; mass. to incip. seams with ripply surf. or smooth sloped fritt. bl/gr ssts.

Mass. sl. ripply calc. ssts. (s. lsts) wh. between about 102-117 m form a distinct smooth cliff face.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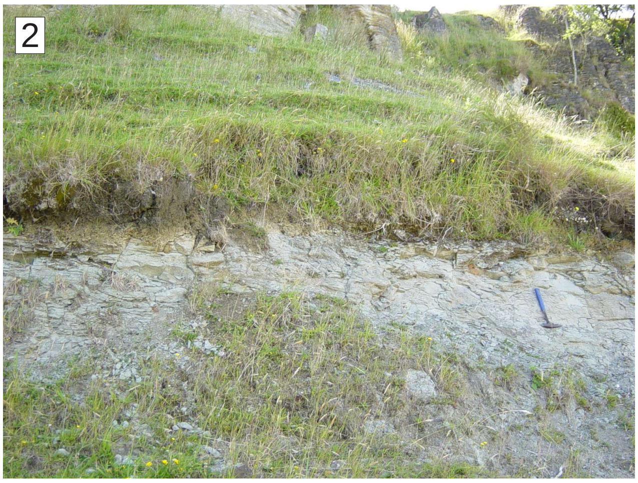
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Mangaotaki Lst
Kihi Sst
Hauturu Sst
Awaroa Lst
Dunphail Zst

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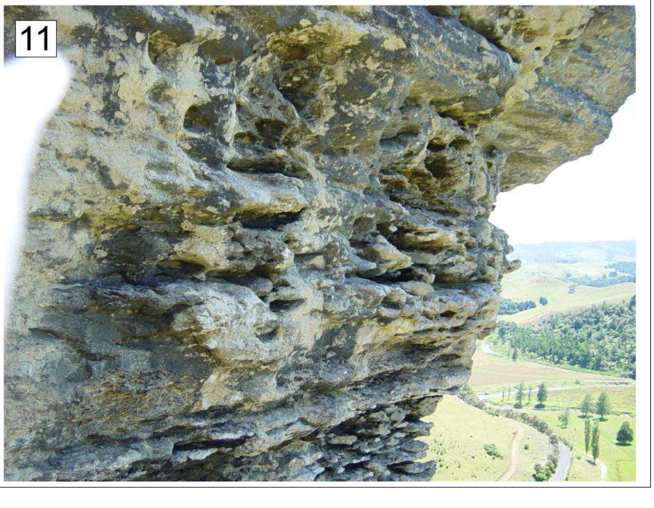


Stratigraphic Column No: *S10, Ivans* **Grid Reference:**

Region: Aotea - Kawhia

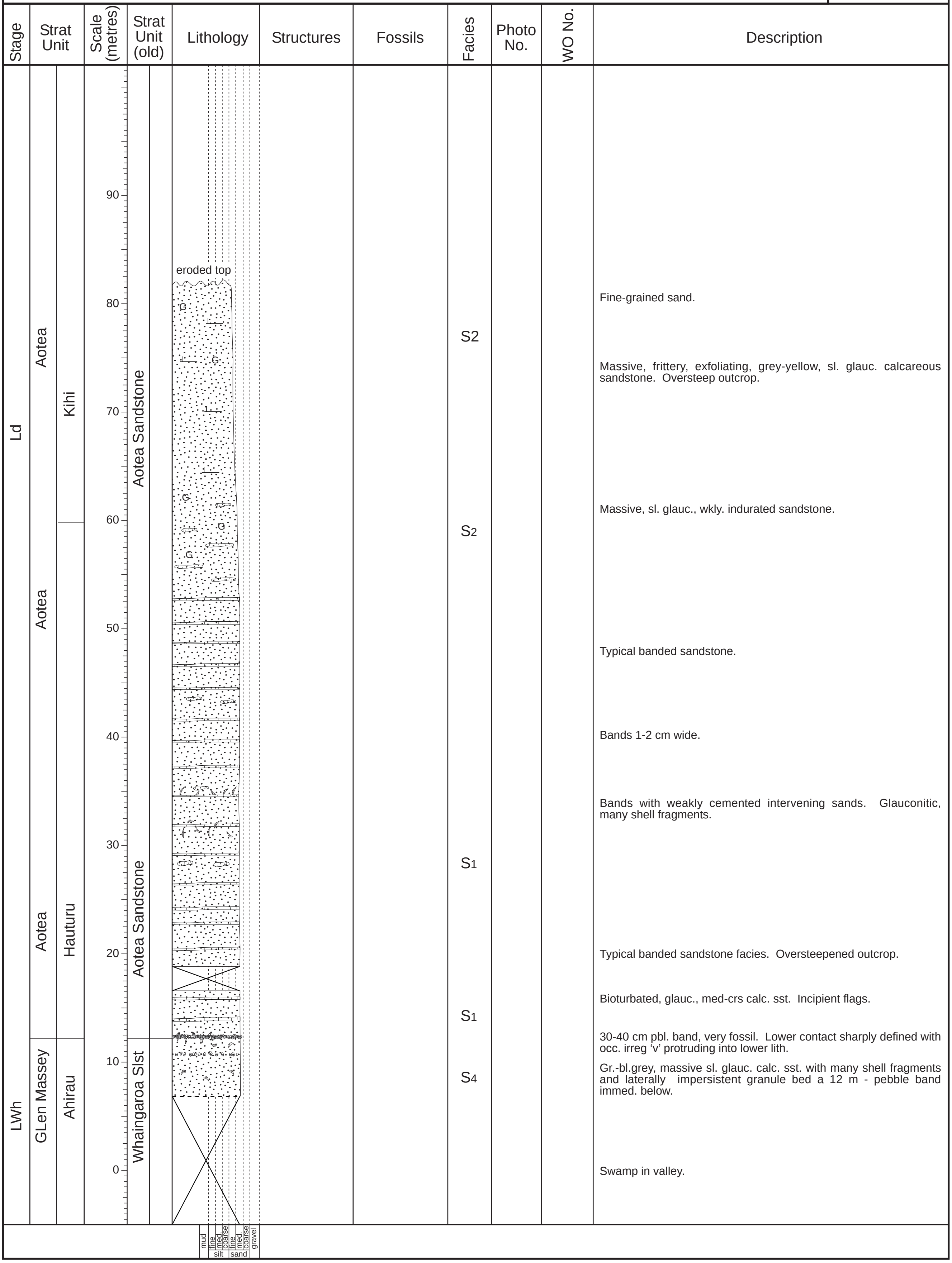
E: 2680700

Location: 1 km NE of Kihi Rd/Kawhai Harbour Rd intersection

N: 6344000

NZMS 260 Sheet: R15/807440

Page 1 *of* 1 **Author:** D. Fergusson



Fine-grained sand.

Massive, frittery, exfoliating, grey-yellow, sl. glauc. calcareous sandstone. Oversteep outcrop.

Massive, sl. glauc., wkly. indurated sandstone.

Typical banded sandstone.

Bands 1-2 cm wide.

Bands with weakly cemented intervening sands. Glauconitic, many shell fragments.

Typical banded sandstone facies. Oversteepened outcrop.

Bioturbated, glauc., med-crs calc. sst. Incipient flags.

30-40 cm pbl. band, very fossil. Lower contact sharply defined with occ. irreg ‘v’ protruding into lower lith.

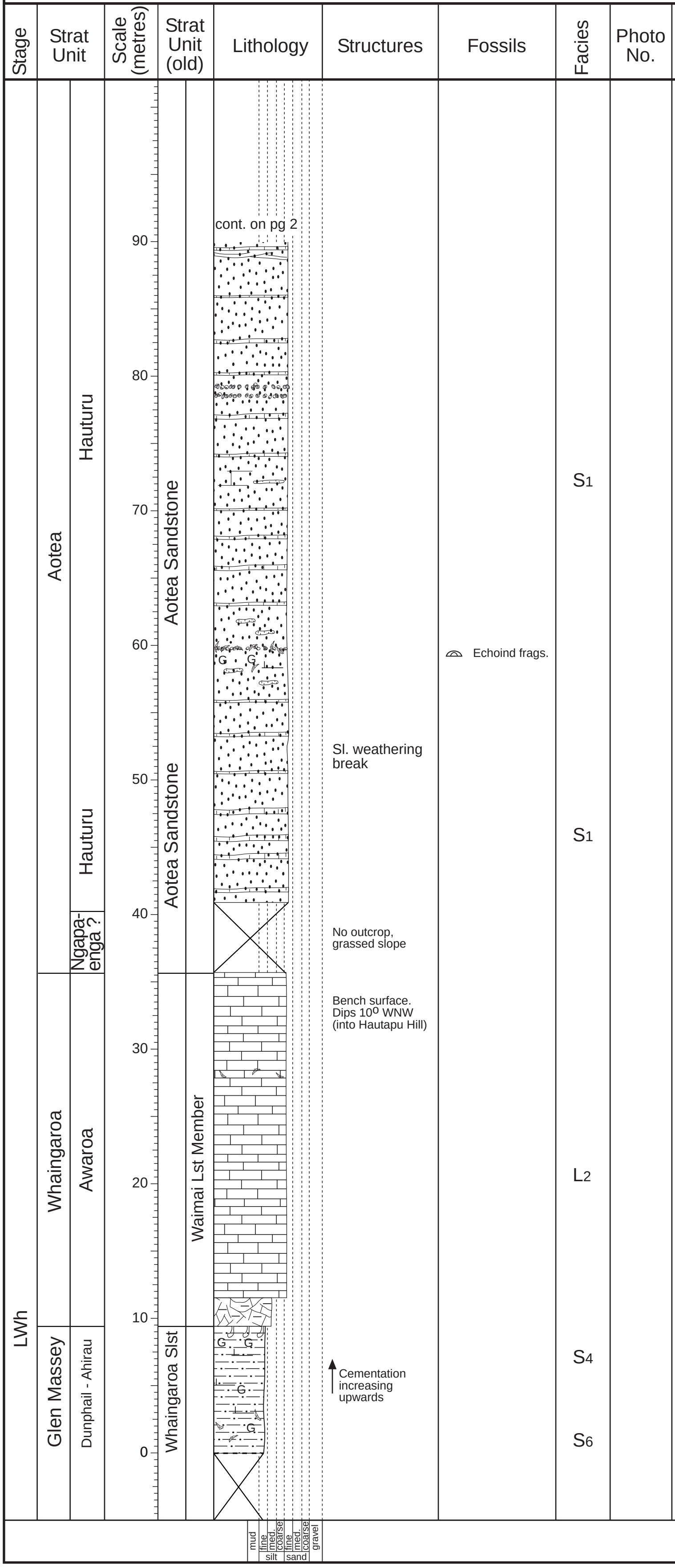
Gr.-bl.grey, massive sl. glauc. calc. sst. with many shell fragments and laterally impersistent granule bed a 12 m - pebble band immed. below.

Swamp in valley.

Stratigraphic Column No: *S12*
Region: Aotea - Kawhia
Location: Hautapu Hill, 3/4 km west of Hauturu
NZMS 260 Sheet: R15/787425

Grid Reference:
E: 2678700
N: 6342500

Page 1 *of* 2 **Author:** D. Fergusson



Description

Banded calc. sst-v. s. lst(?), ver occasional cross-bedded strata.

Thin granule bands.

Banded calc. sst-v. s. lst(?).

Wk. ind., poorly cemented, sl. glauc., calc. (fsu) sst with rare-some granules/pebbles.

Peb. band, weakly ind., poorly cemented, mod. glauc., calc. s. (fsu-msL) conglomerate. Density of pbls. dec. upwards - gran.-sm. pbl (av.) with rare med. pebble Whole abraded echinoid frags., many whole/frag. macrofossils.

Wk. ind., mod.-v. glauc., calc. (fsu-msL) sst with rare shell frags.

Lapiez solution.

Seams less distinct.

Tan-cr., well ind., cryst. lst (gran.-sm. pbl. bioclasts visible). Flags 6-10 cm, seams 1 cm, sl. wavy. relief on flags 5 cm.

Pinkish, cryst. lst. Flags thicken upwards.

Or.-tan, mod.-well ind., cryst. lst. Flags 3-5 cm, wavy, occ. pinchout.

Lt. or.-tan, sl.-mod. ind., v. sl. glauc, muddy lst. sl. cryst. Incip. flaggy, vague x-bedded near contact.

Lt. br.-gr., weakly ind., moderately glauc., s.c mst-m.c. sst.

Massive, frittery-exfol. occ. curv. joint, Fe stained.

Bl.-gr., wk. ind., sl. f.s calc mst/muddy sst. Occ. mud filled, pyr. burrows (Fe stained). Pectin frags.

Base not seen, Awaroa River

Stratigraphic Column No: *S12*

Region: Aotea - Kawhia

Location: 3/4 km west of Hauturu

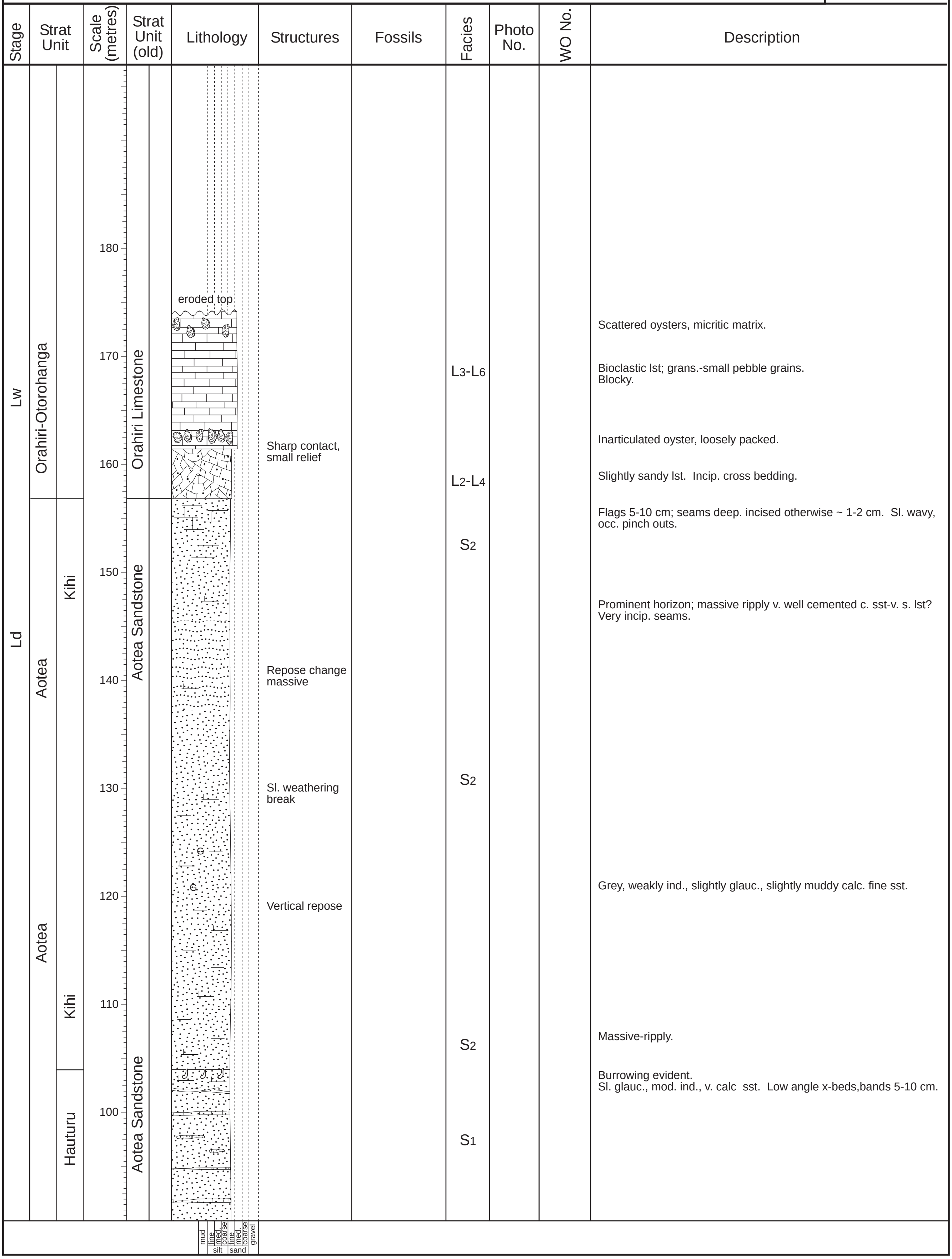
Grid Reference:

E: 2678700

N: 6342500

NZMS 260 Sheet: R15/787425

Page 2 *of* 2 **Author:** D. Fergusson



Structures:

Sharp contact, small relief

Repose change massive

Sl. weathering break

Vertical repose

Description:

Scattered oysters, micritic matrix.

Bioclastic lst; grans.-small pebble grains. Blocky.

Inarticulated oyster, loosely packed.

Slightly sandy lst. Incip. cross bedding.

Flags 5-10 cm; seams deep. incised otherwise ~ 1-2 cm. Sl. wavy, occ. pinch outs.

Prominent horizon; massive ripply v. well cemented c. sst-v. s. lst? Very incip. seams.

Grey, weakly ind., slightly glauc., slightly muddy calc. fine sst.

Massive-ripply.

Burrowing evident.
Sl. glauc., mod. ind., v. calc sst. Low angle x-beds,bands 5-10 cm.

Stratigraphic Column No: *S13, Te Turutu*

Grid Reference:

Region: Aotea - Kawhia

E: 2681500

Location: ca. 2 km east of Hauturu, south side of Kihi Rd

N: 6342500

NZMS 260 Sheet: R15/815425

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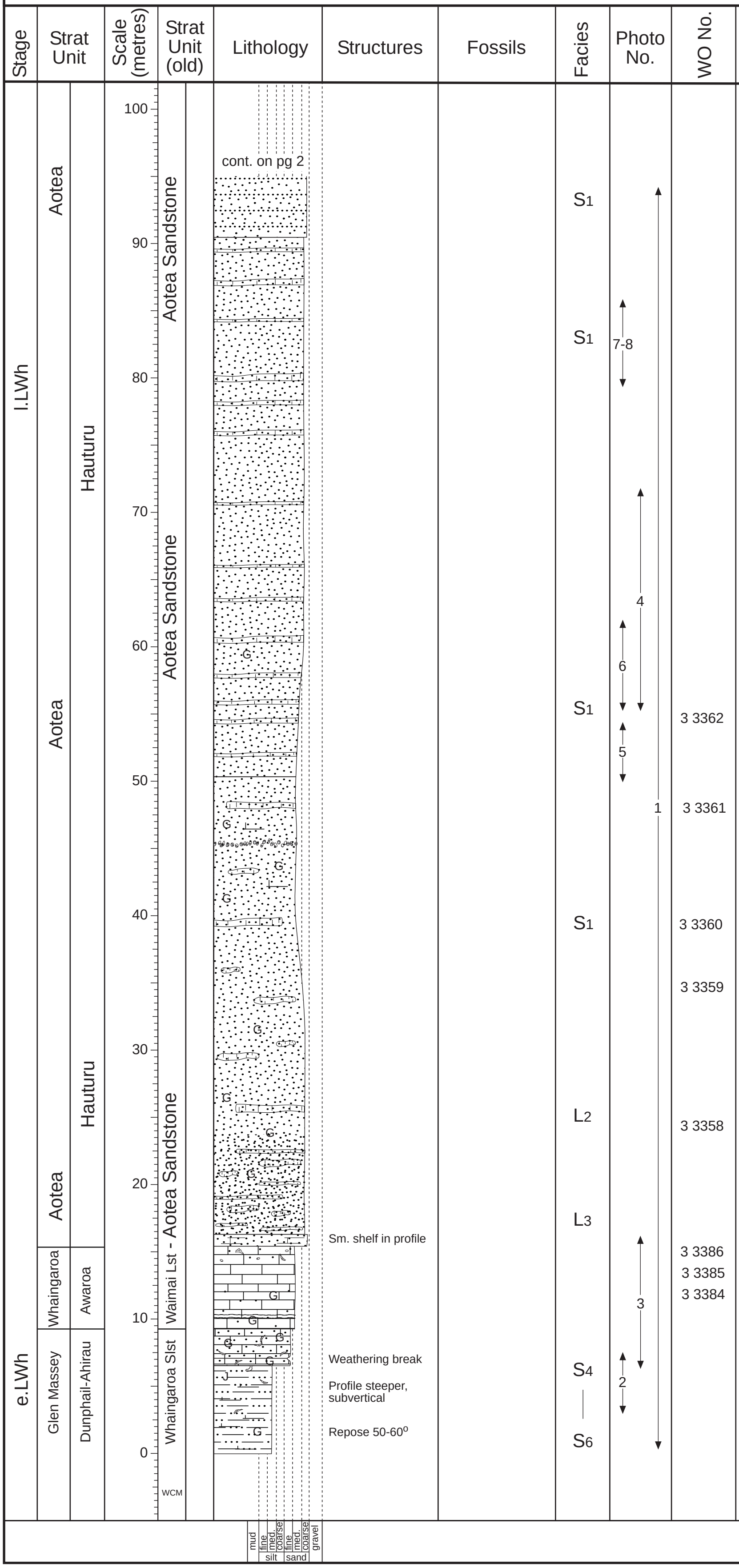

Description

Banded.

Lt. tan/cr., mod. ind., v. sl. glauc., c. sst (s = msL).

Pebble band; sm.-med. pebs. (well rded.) in calc. sst. matrix. Cr., mod. ind., sl. (-mod.) glauc., calc. sst . (s=fsu-msL). Knobbly bedded.

Mod. ind., sl.(-mod.) glauc., c. sst. Fe-staining. (s=fsu; qtz feld). Knobbly-banded?

Vegetation partly obscures outcrop surface.

Mod.-str. ind., sl. glauc, v.c. sst - s. lst (s= fsu-msL).

Mod. ind., glauc, gran.-sm. pbly lst. Pectinid frags.

Sl. f.s. cryst bioclastic lst. Flaggy, flags 3-5 cm.

Decrease in sand content.

Strongly ind., sl. glauc. f.s. bioclastic lst. Flaggy.

Fe-stained, cr., mod.-str. ind., sl. glauc., f.s. lst, (cryst). Terrig. seams, 1-2 cm spacing.

Lt. or.-br., mod.-strongly indurated, very sl. glauc., f.s. lst, poss. cryst; conspic. bioclasts.

Lt. or.-br., mod. ind., v. sl. glauc., sl. m. f sst/f.s. lst? Conspic. bioclasts (rare).

Lt. br.-gr., mod. ind., sl. glauc., m.f. calc. siltstone. Mud lenses, mica? Rare shell frags. Evidence of bioturbation in terms of micro-lith. differences inside/outside mud coated elliptical trace. Massive, exfoliating.

Lt. br.-gr., mod. ind., v. sl. glauc., f.s. calc. siltstone. conspic. mud lenses, rare micaceous flakes.

Base not seen, overlies WCM; slumped topography?

Stratigraphic Column No: *S13, Te Turutu* **Grid Reference:**

Region: Aotea - Kawhia

E: 2681500

Location: ca. 2km east of Hauturu, south side of Kihi Rd

N: 6342500

NZMS 260 Sheet: R15/815425

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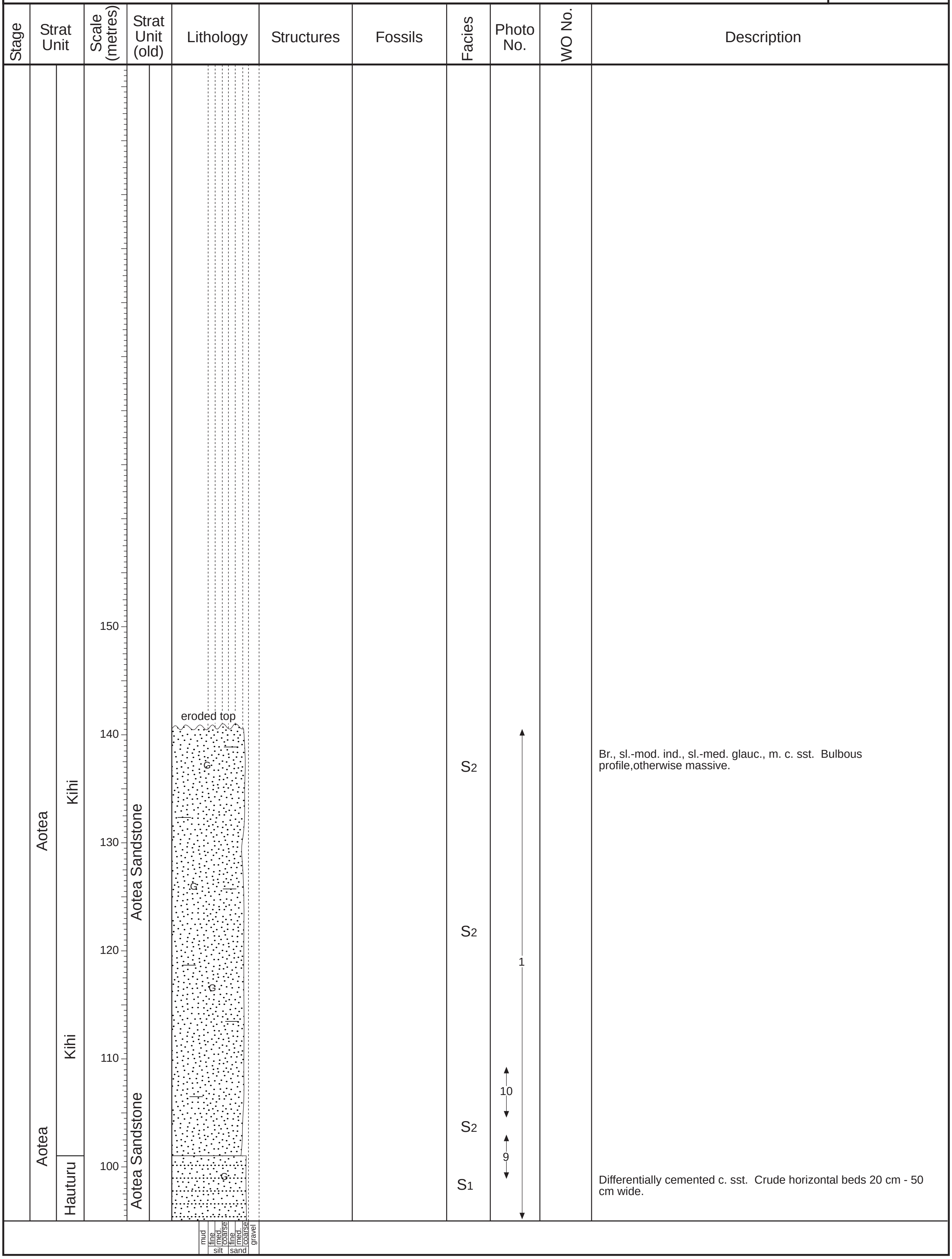

Br., sl.-mod. ind., sl.-med. glauc., m. c. sst. Bulbous profile,otherwise massive.

Differentially cemented c. sst. Crude horizontal beds 20 cm - 50 cm wide.


1
Kihi Sandstone
Hauturu Sandstone
Awaroa Limestone
Ahirau Sandstone


2


3


4


5


6

7

8

9

10

Stratigraphic Column No: *S14, Maturangi*
Region: Aotea - Kawhia
Location: ca. 2 km east of Kihi Rd/Kawhia Harbour Rd
NZMS 260 Sheet: R15/820433

Grid Reference:
E: 2682000
N: 6343300

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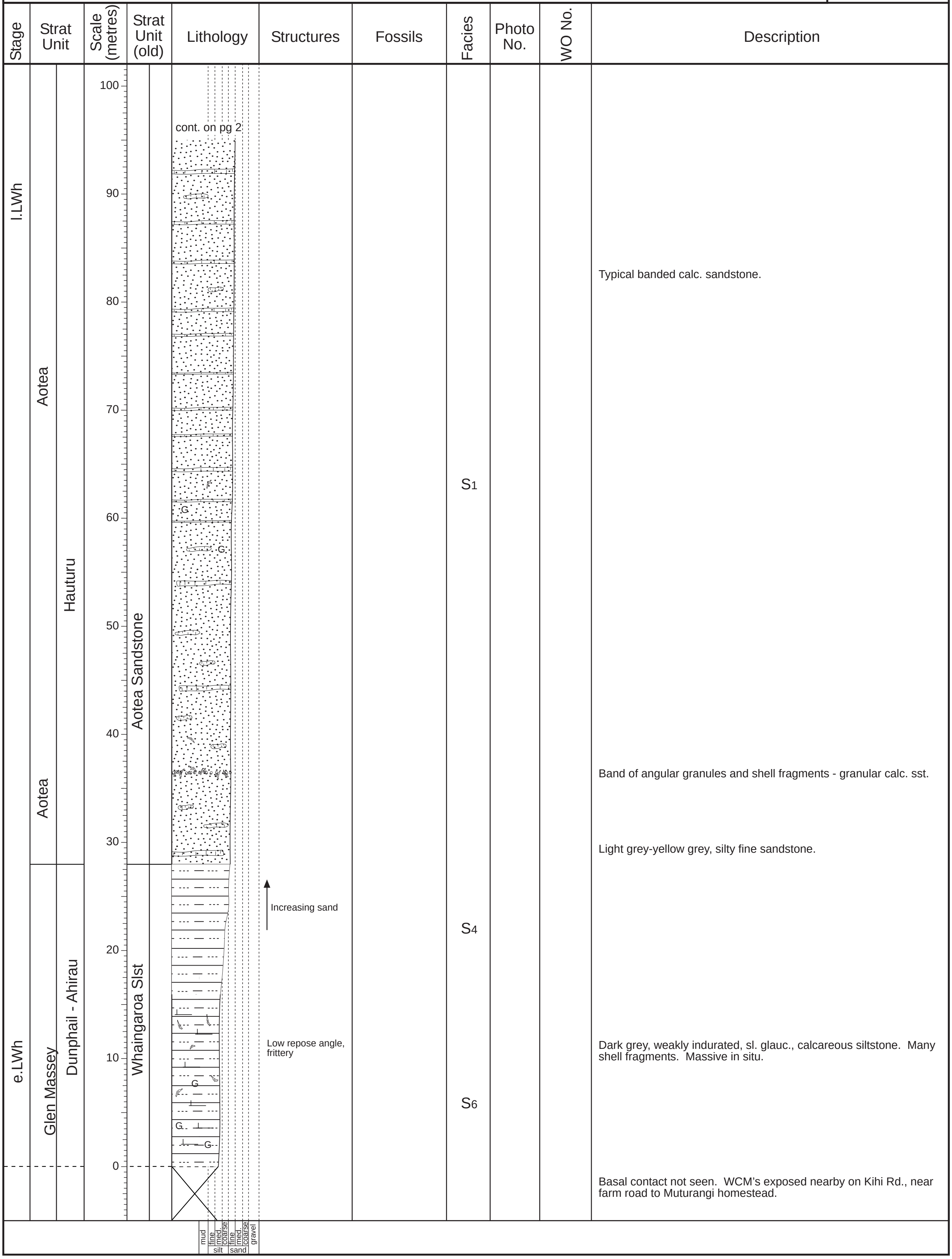

Typical banded calc. sandstone.

Band of angular granules and shell fragments - granular calc. sst.

Light grey-yellow grey, silty fine sandstone.

Dark grey, weakly indurated, sl. glauc., calcareous siltstone. Many shell fragments. Massive in situ.

Basal contact not seen. WCM's exposed nearby on Kihi Rd., near farm road to Muturangi homestead.

Stratigraphic Column No: *S14, Maturangi*
Region: Aotea - Kawhia
Location: ca. 2 km east of Kihi Rd/Kawhia Harbour Rd
NZMS 260 Sheet: R15/820433

Grid Reference:
E: 2682000
N: 6343300

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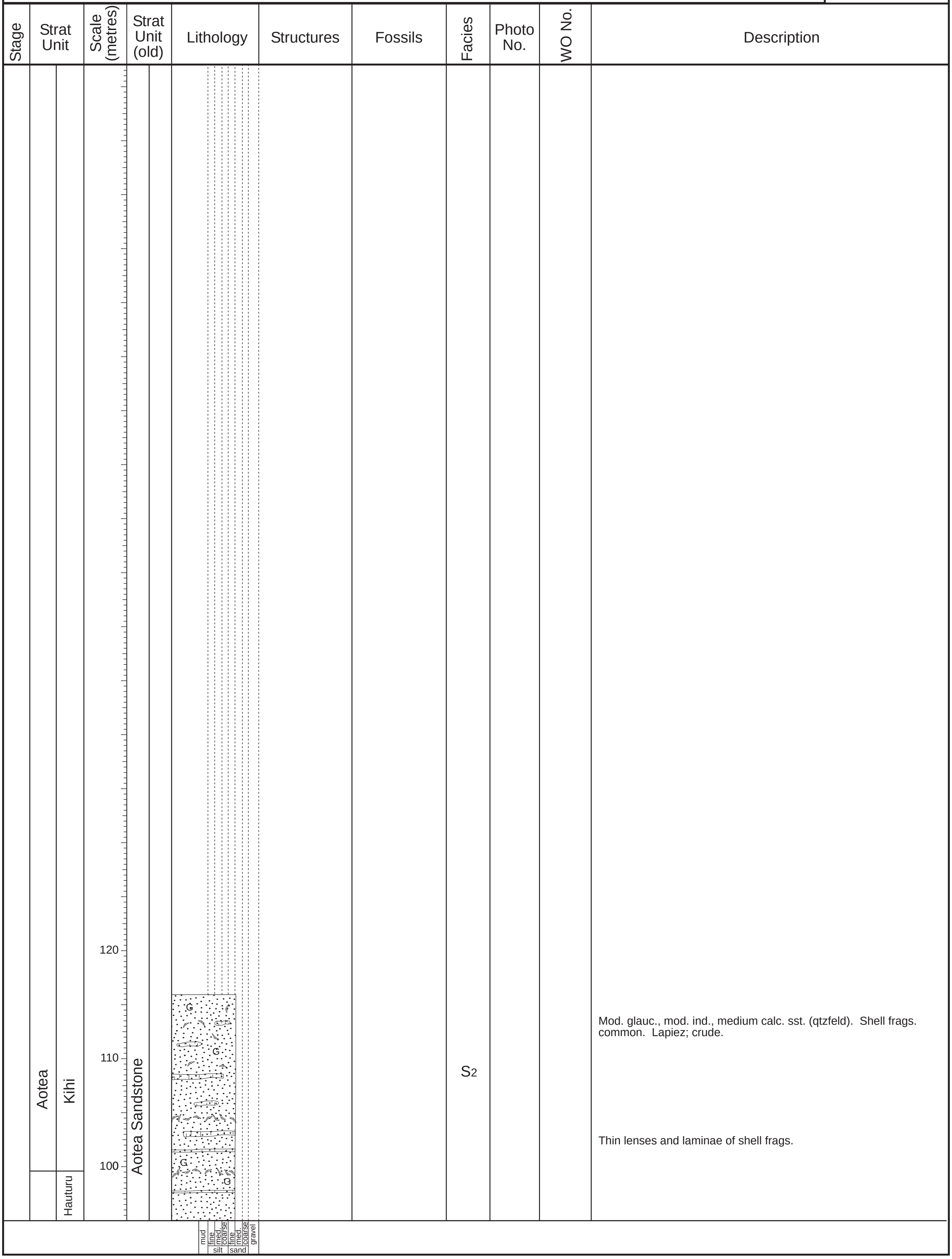

Mod. glauc., mod. ind., medium calc. sst. (qtzfeld). Shell frags. common. Lapiez; crude.

Thin lenses and laminae of shell frags.

Stratigraphic Column No: *S15*

Region: Aotea - Kawhia

Location: Tiritirimatangi Peninsula, southern coastline

NZMS 260 Sheet: R15/762455

Grid Reference:

E: 2676200

N: 6345500

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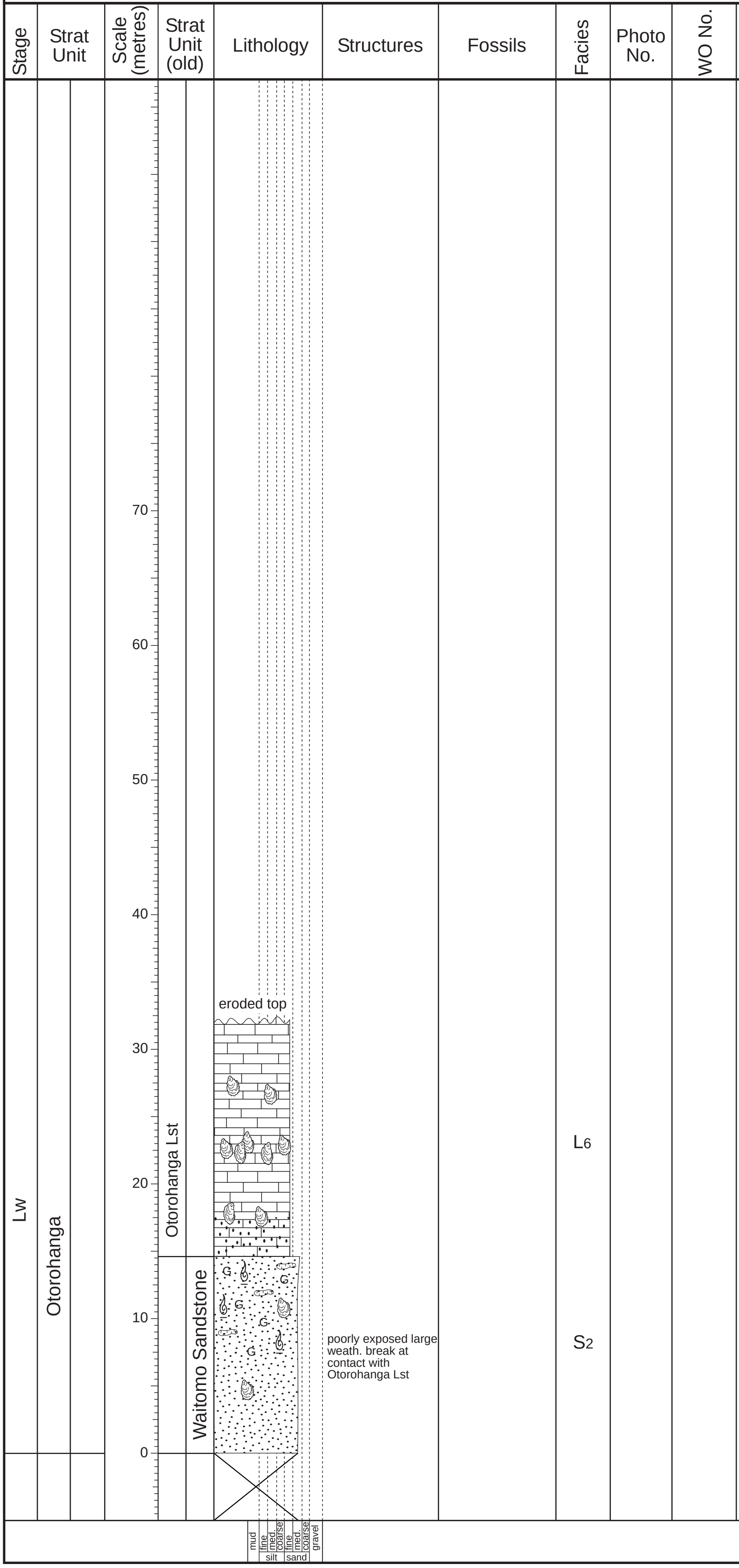


poorly exposed large weath. break at contact with Otorohanga Lst

Description

Fine biocalcarenite. Flags 5-< 10 cm; best developed in upper part of unit.

Scattered oysters.

Variably weathered.

V. glauc., med.-crs sst. (glaucarenite). Fe-staining/Fe seams and burrows fossiliferous. Abundant traces.

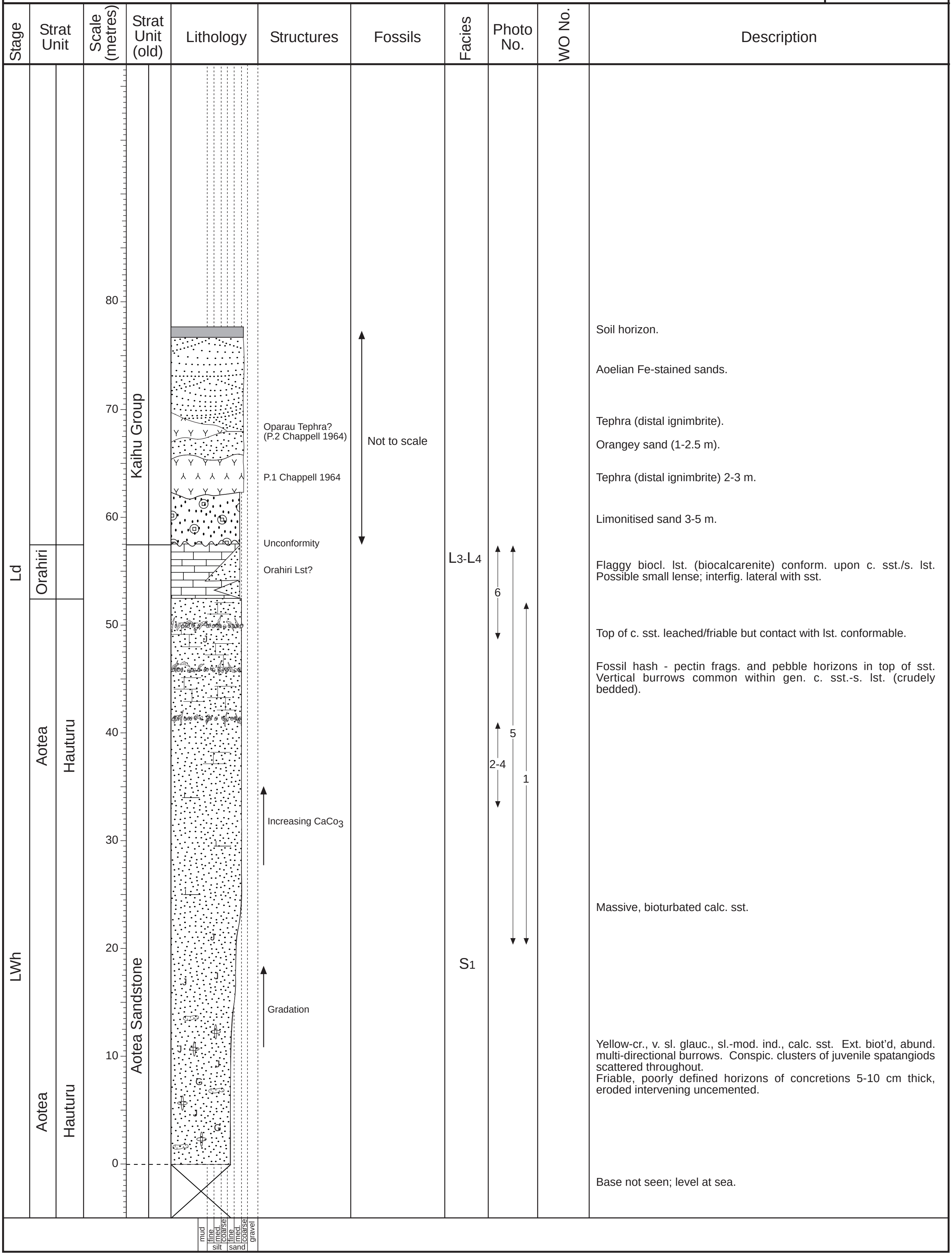
Thickness indeterminate 3-4 m o/c; bench platform on southern side of Tiritiri Peninsula. Limestone lenses in upper part of unit. Scattered oysters.

Stratigraphic Column No: S16
Region: Aotea - Kawhia
Location: Taranaki Point, West Aotea Harbour

Grid Reference:
E: 2666600
N: 6356800

NZMS 260 Sheet: R15/666568

Page 1 *of* 1 **Author:** D. Fergusson



Soil horizon.

Aoelian Fe-stained sands.

Tephra (distal ignimbrite).

Orangey sand (1-2.5 m).

Tephra (distal ignimbrite) 2-3 m.

Limonitised sand 3-5 m.

Flaggy biocl. lst. (biocalcarenite) conform. upon c. sst./s. lst. Possible small lense; interfig. lateral with sst.

Top of c. sst. leached/friable but contact with lst. conformable.

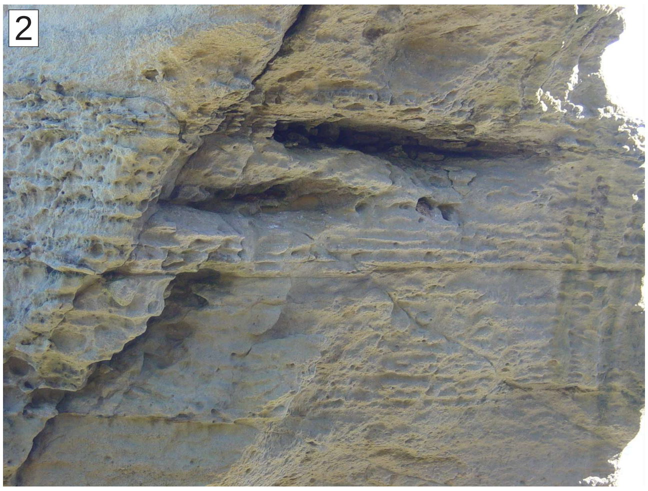
Fossil hash - pectin frags. and pebble horizons in top of sst. Vertical burrows common within gen. c. sst.-s. lst. (crudely bedded).

Massive, bioturbated calc. sst.

Yellow-cr., v. sl. glauc., sl.-mod. ind., calc. sst. Ext. biot'd, abund. multi-directional burrows. Conspic. clusters of juvenile spatangiods scattered throughout.
Friable, poorly defined horizons of concretions 5-10 cm thick, eroded intervening uncemented.

Base not seen; level at sea.


1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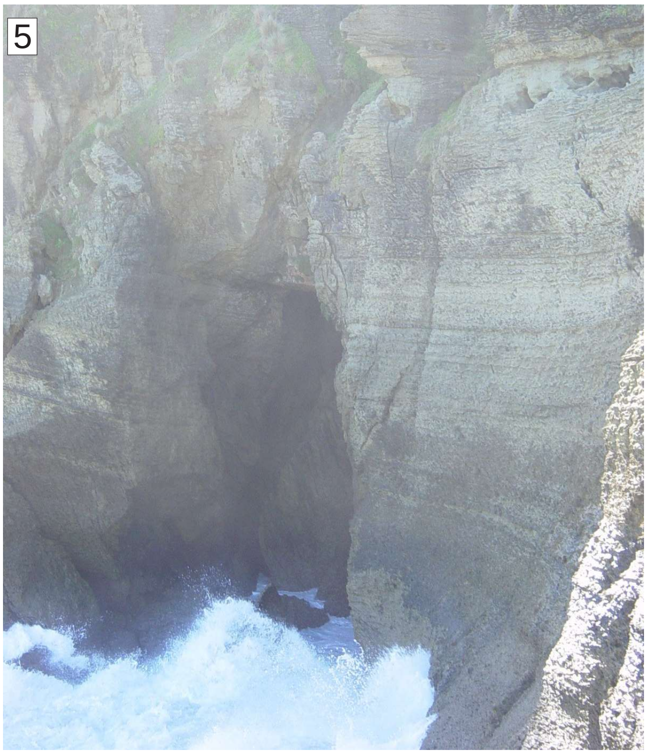
4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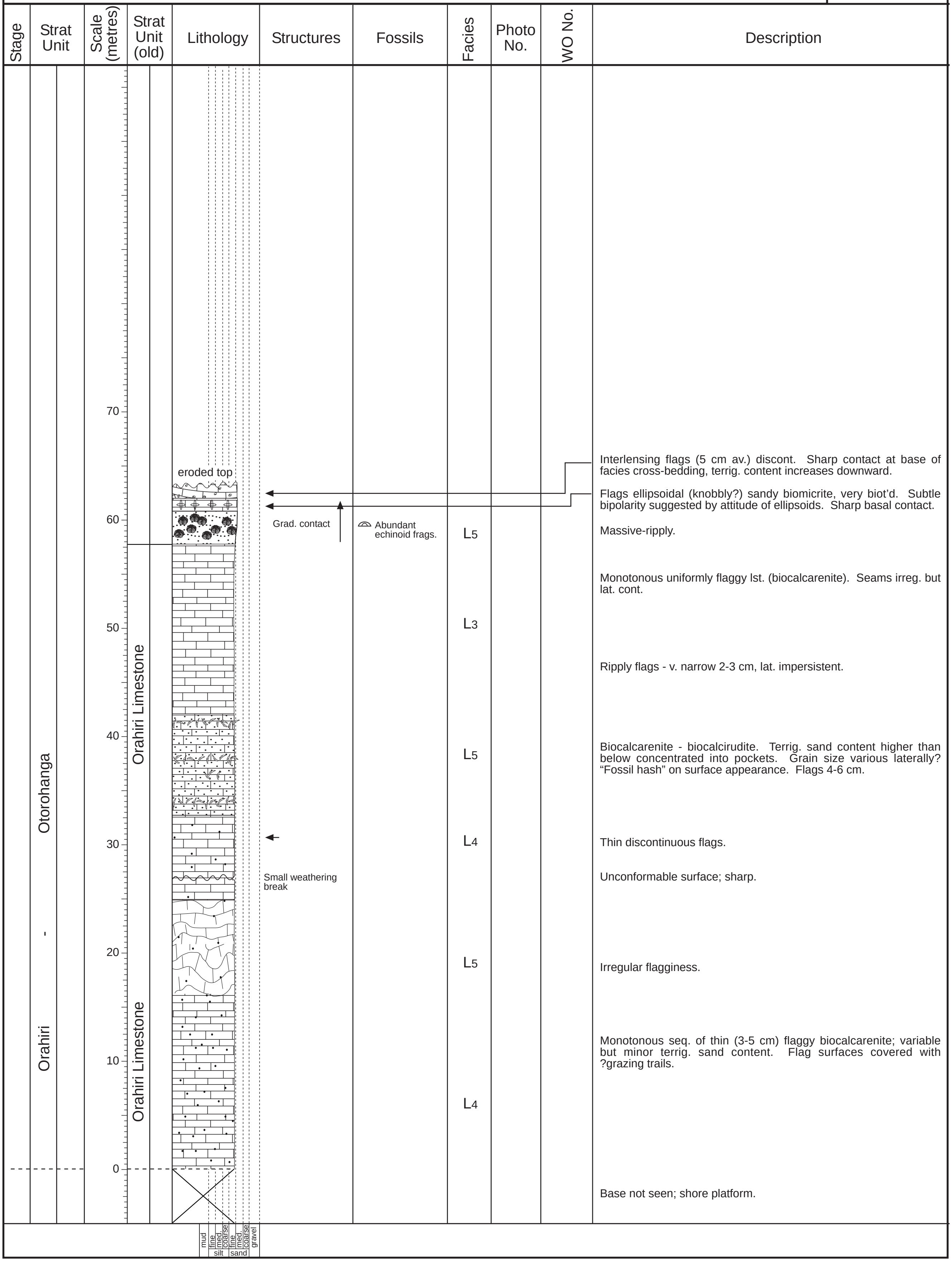
6

Stratigraphic Column No: *S17* **Grid Reference:** **Top**

Region: Aotea - Kawhia **E:** 2666900

Location: Pohotangi stream, 1 km N Taranki
Point (west Aotea Harbour) **N:** 6357800

NZMS 260 Sheet: R15/669578 *Page* 1 *of* 1 **Author:** D. Fergusson



Interlensing flags (5 cm av.) discont. Sharp contact at base of facies cross-bedding, terrig. content increases downward.

Flags ellipsoidal (knobbly?) sandy biomicrite, very biot'd. Subtle bipolarity suggested by attitude of ellipsoids. Sharp basal contact.

Massive-ripply.

Monotonous uniformly flaggy lst. (biocalcarenite). Seams irreg. but lat. cont.

Ripply flags - v. narrow 2-3 cm, lat. impersistent.

Biocalcarenite - biocalcirudite. Terrig. sand content higher than below concentrated into pockets. Grain size various laterally? "Fossil hash" on surface appearance. Flags 4-6 cm.

Thin discontinuous flags.

Unconformable surface; sharp.

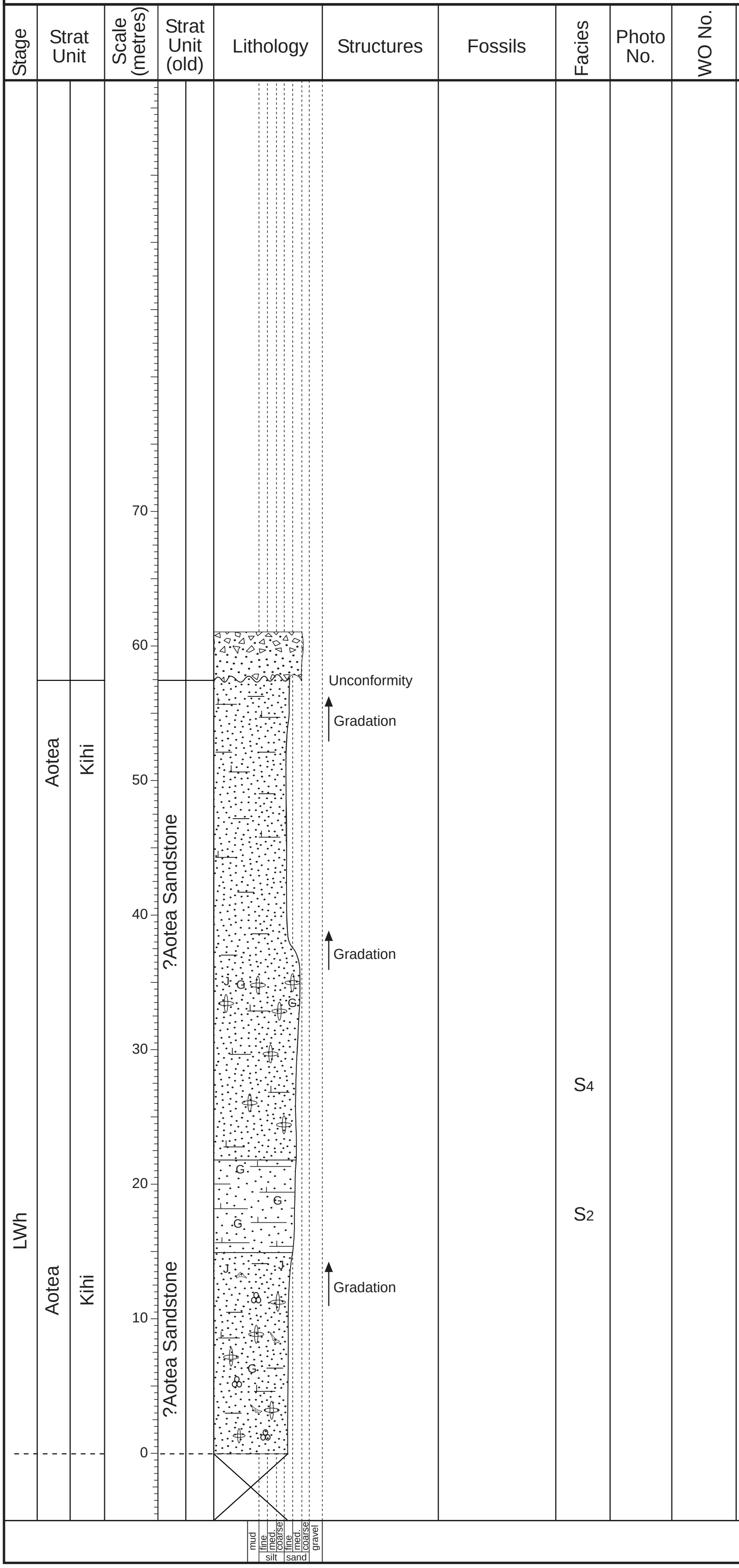
Irregular flagginess.

Monotonous seq. of thin (3-5 cm) flaggy biocalcarenite; variable but minor terrig. sand content. Flag surfaces covered with ?grazing trails.

Base not seen; shore platform.

Stratigraphic Column No: *S18; Whataipu* **Grid Reference:**
Region: Aotea-Kawhia **E:** 2677000
Location: Te Mata, Raglan south **N:** 6362500

NZMS 260 Sheet: R15/770625 *Page* 1 *of* 1 **Author:** D. Fergusson



Description

General sequence incomplete due to post-Oligocene/pre Okete erosion. General NW dip 4°. Okete Lavas have flow along paleodip slope.

Correlation must be considered very tentative owing to poor strat. exposure.

Concordant upper surface - in places overlain by Okete volcanics (basalt flows).

Massive, sl. muddy, f.m. calc. sst. Better ind. than below, prominent horizon.

Crudely bedded (diff. cementation) muddy fine calc. sst. - f. sandy calc. mudstone.

Massive, sl.. glauc., med. calc. sst. Ext. biot'd. Subvert. oversteepened 'bulge'

Transition in profile.

Massive, sl.-mod. glauc., f.m. calc. sst.
Lapiez, subvert. repose

Massive, slightly muddy (includes mud lenses), very sl. glauc., fine calc sst. Extremely biot'd, occ. macrofaunal frag., microfossil tests conspic. Frittery, incip. exfoliation of outcrop surface.

Base not seen; swamp.

Stratigraphic Column No: *S2*
Region: Aotea - Kawhia
Location: Tawairoa trig station

Grid Reference:
E: 2677100
N: 6343100

NZMS 260 Sheet: R15/771431

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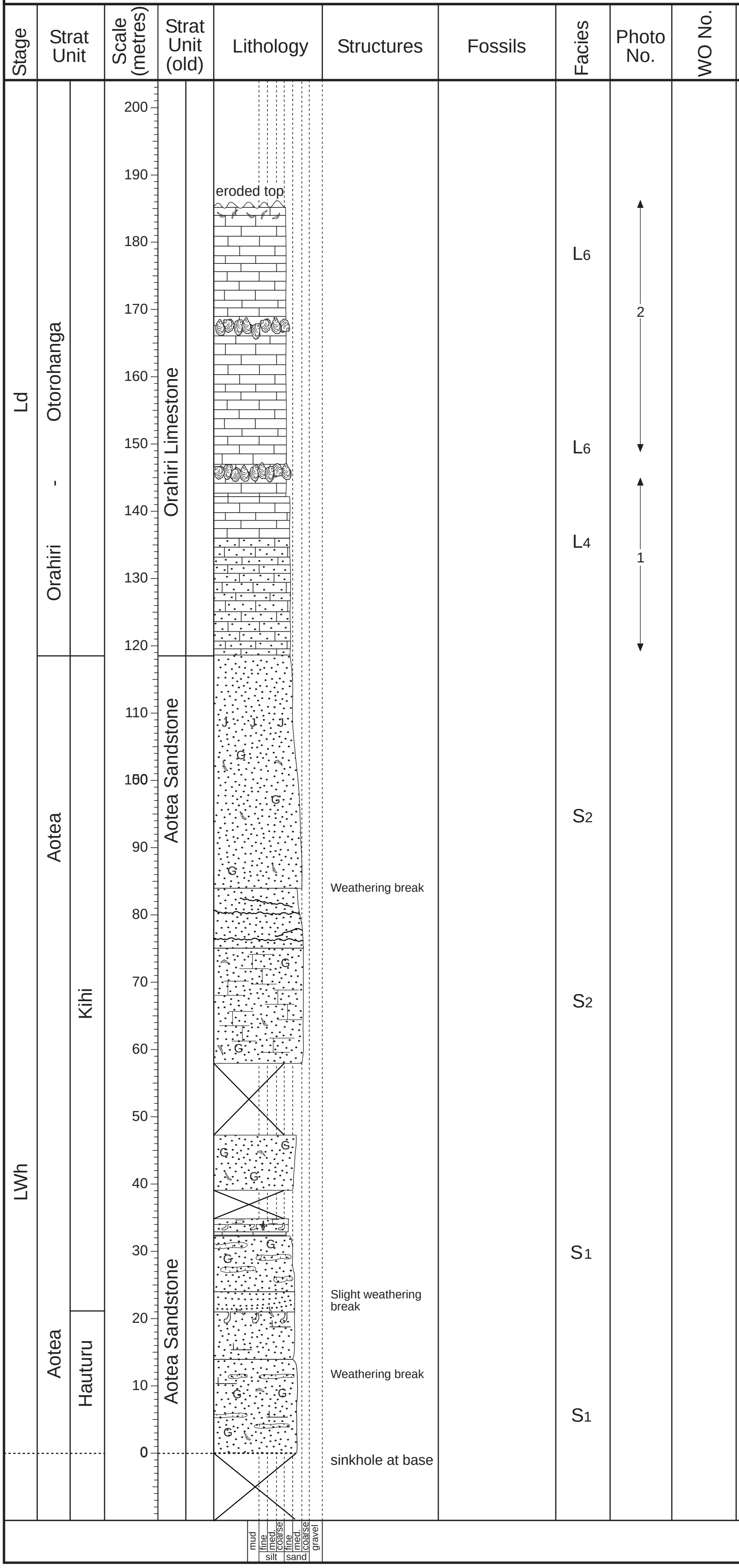

Description

Oyst. frags-micritic lst.

Lt. br. cr. well ind., cryst. v. sl. glauc. v. sl s. lst.; micritic cement. Flags uneven; seams lat. cont., occ. pinch-out.

Blocky-flaggy; 8-15 cm beds. Scour and fill relatns. discern. in flags.

1/2 m oyst. band, mod.-tightly packed.

Well ind. cryst. bioclastic lst. Flaggy; flags 8-12 cm sl. wavy seams, but lat. cont.

Terrig. content decreases upward. Flaggy lst; flags 3-5 cm, interflags 2 cm, sl. wavy.

Cr. well ind., cryst., s. lst.

Cr. - lt. br., mod. ind., v. sl. glauc., sl. cryst., f.s. lst. (- v.c. sst?). Cementation increases upwards. Incip. flaggy; seams irreg. (1-2 cm). Beds 5-8 cm, pinch-out laterally.

Br.-or., mod. ind., v. sl. glauc., sl. m. v.s. f. sst - f.s. lst with rare shell frags. Mass.-ripply.

Fe-stained burrows.

Br.-gr., wk. ind., sl. glauc., calc. f. sst. with some shell frags (conspic. on smooth surf.).

Rare calcite pebbs. (sm); ‘random’ joints conspic.

Or.-br., wk.-mod. ind., sl. glauc. sl. m. f. c.sst. with some shell frags. Smooth, mass. surf. exfoliating.
Fine sst (no appt. change in outcrop form).

Or.-gr., mod. ind., crs. s. calc. sst. with rare-some crs. sand - grans. SRF. Gradual lith. change.

Ol.-gr.; mod. ind., v. sl. glauc., sl. cryst. v.c. sst-v.s. lst. (?) with pocket of crs. s. shell frags. and rare granules of SRF. Incip. flaggy-flaggy seams 3-4 cm, beds 5-12 cm.

Lt. or.-ol./gr.; mod. ind., sl. glauc., (med. s), sl. cryst., v.c. sst. -v.s. lst. (f-med. s) with rare shell frags. but often many (concentrated) in seams. Incip. flaggy, mass. ripply, irreg. seams 2-5 cm.

Outcrop grass covered.

Lt. or.-gr., wk.-mod. ind., v. sl. glauc., sl. cryst., f-m slst.-v.c. sst.(?). Shell frags. concen. in seams. Mass.-ripply; irreg. seams, some com., pinch-outs, 2-5 cm thick, beds 10-15 cm.

Grassed ledge, prob. grad. into above lith.

Lt. or.-gr. (Fe stained) mod.-str. ind., sl. cryst. f.s. lst.

Grad. lith. change. Knobbly bedded; very irreg.

Lt. or.-gr., mod. ind., v. sl. glauc. (sl. cryst.) v.c.f. sst.-f.s. lst. X-bded. app. dip 17^{o}E, planar foresets. shell frags.

Massive, w. ind., sl. calc. sst.

Light br.-or., wk. ind.-friable, sl. glauc. sl. calc. sst. Occ. shell frags. Knobbly-bded: beds v. irreg. , 5-8 cm thick, often only remnant ‘knobs’ in leached sst matrix.

Lower contact not seen, probably basal lst. on Jurassic basement rocks.

2

1

Stratigraphic Column No: S4
Region: Aotea - Kawhia
Location: 2 km due W of Te Kauri Lodge

Grid Reference:
E: 2681500
N: 6345300

NZMS 260 Sheet: R15/815453

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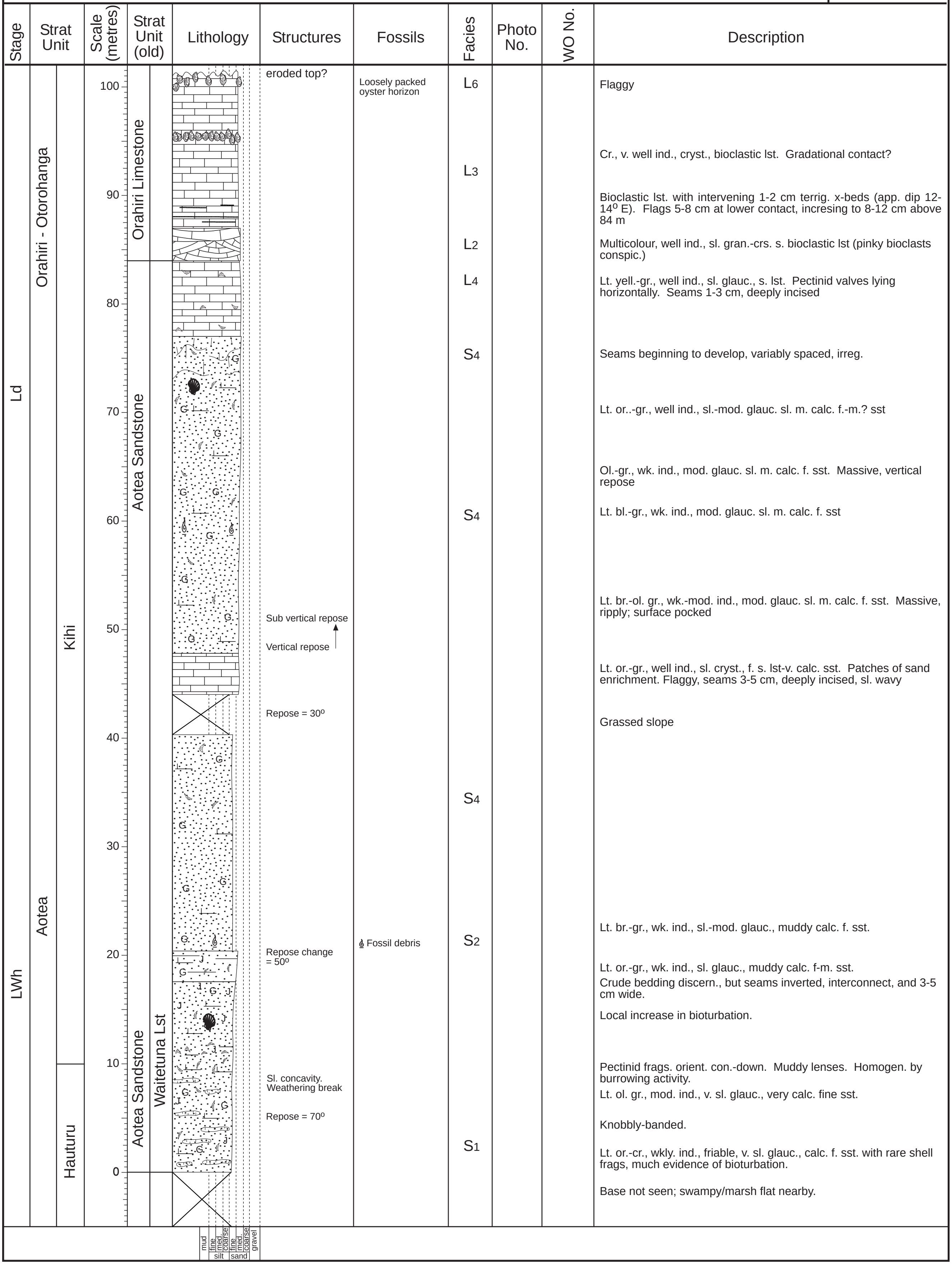

eroded top?
Loosely packed oyster horizon
L6 Flaggy
Cr., v. well ind., cryst., bioclastic lst. Gradational contact?
L3
Bioclastic lst. with intervening 1-2 cm terrig. x-beds (app. dip 12-14^o E). Flags 5-8 cm at lower contact, incresing to 8-12 cm above 84 m
L2 Multicolour, well ind., sl. gran.-crs. s. bioclastic lst (pinky bioclasts conspic.)
L4 Lt. yell.-gr., well ind., sl. glauc., s. lst. Pectinid valves lying horizontally. Seams 1-3 cm, deeply incised
S4 Seams beginning to develop, variably spaced, irreg.
Lt. or..-gr., well ind., sl.-mod. glauc. sl. m. calc. f.-m.? sst
Ol.-gr., wk. ind., mod. glauc. sl. m. calc. f. sst. Massive, vertical repose
S4 Lt. bl.-gr., wk. ind., mod. glauc. sl. m. calc. f. sst
Lt. br.-ol. gr., wk.-mod. ind., mod. glauc. sl. m. calc. f. sst. Massive, ripply; surface pocked
Sub vertical repose
Vertical repose
Lt. or.-gr., well ind., sl. cryst., f. s. lst-v. calc. sst. Patches of sand enrichment. Flaggy, seams 3-5 cm, deeply incised, sl. wavy
Repose = 30º
Grassed slope
S4
Lt. br.-gr., wk. ind., sl.-mod. glauc., muddy calc. f. sst.
Repose change = 50º
Fossil debris
S2
Lt. or.-gr., wk. ind., sl. glauc., muddy calc. f-m. sst.
Crude bedding discern., but seams inverted, interconnect, and 3-5 cm wide.
Local increase in bioturbation.
Pectinid frags. orient. con.-down. Muddy lenses. Homogen. by burrowing activity.
Sl. concavity. Weathering break
Lt. ol. gr., mod. ind., v. sl. glauc., very calc. fine sst.
Repose = 70º
Knobbly-banded.
S1 Lt. or.-cr., wkly. ind., friable, v. sl. glauc., calc. f. sst. with rare shell frags, much evidence of bioturbation.
Base not seen; swampy/marsh flat nearby.

Stratigraphic Column No: *S5*
Grid Reference:
Region: Aotea - Kawhia
E: 2674100
Location: Trig A on Rakanui Peninsula
N: 6342500

NZMS 260 Sheet: R15/741425

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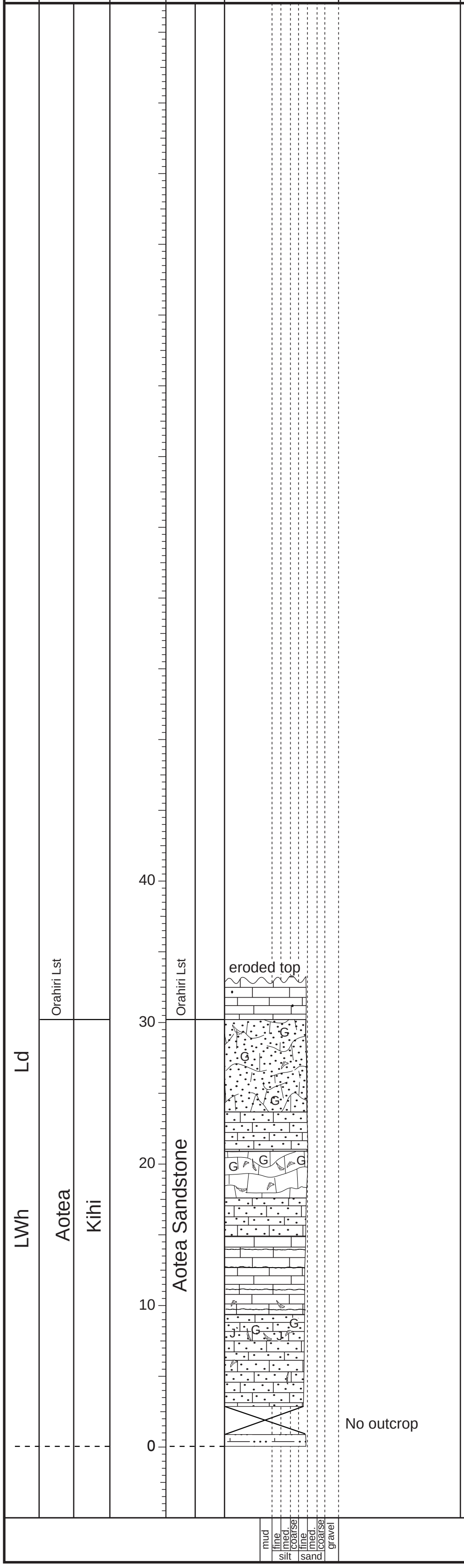
Stage | Strat Unit | Scale (metres) | Strat Unit (old) | Lithology | Structures | Fossils | Facies | Photo No. | WO No. | Description



Facies	Description
L4	Cr. grey, v. well ind., bioclastic lst with rare s. grains and laminae. Flaggy.
S2	Gr. grey, v. well ind., mod. glauc., v. calc. sst-v.s. lst(?), rare shell frags (sand = msu-crsSL). Thicker, wavy 'flags', seams less distinct.
	Lt. br., well ind., sl.glauc., s lst-v. calc. sst(?); (sand = fsl-fsu). 'Flags' 3-5 cm. Wavy, lat. discont., 1-2 cm thick seams.
	Gr. grey, well ind., sl.-mod. glauc. v.s. lst.-v. calc. sst (sand = msu).
S2	Yell.-gr., sl. glauc., s. lst. (sand = msu). Irreg. seams impart wavy flagginess.
	Or.-gr., v. well ind., s. lst. with thin beds of crs. s. (qrtz) app. concen. at base of ind. unit.
	Gr. grey, mod. ind., sl. glauc. sl. s. lst. with conspic. shell frags. (sand = fsu).
	Gr. grey, mod. ind., sl.-mod. glauc. f.s. lst., sl. muddy? Burrowed/bored.
S2	Yell.-or.gr., well ind., sl. glauc., f.s. lst. with rare shell frags.
	Leached calc. sst.

Stratigraphic Column No: *S6; Rakanui* **Grid Reference:**

Region: Aotea - Kawhia

E: 2675500

Location: Central Rakanui Peninsula, north of Rakanui Road

N: 6343300

NZMS 260 Sheet: R15/755433

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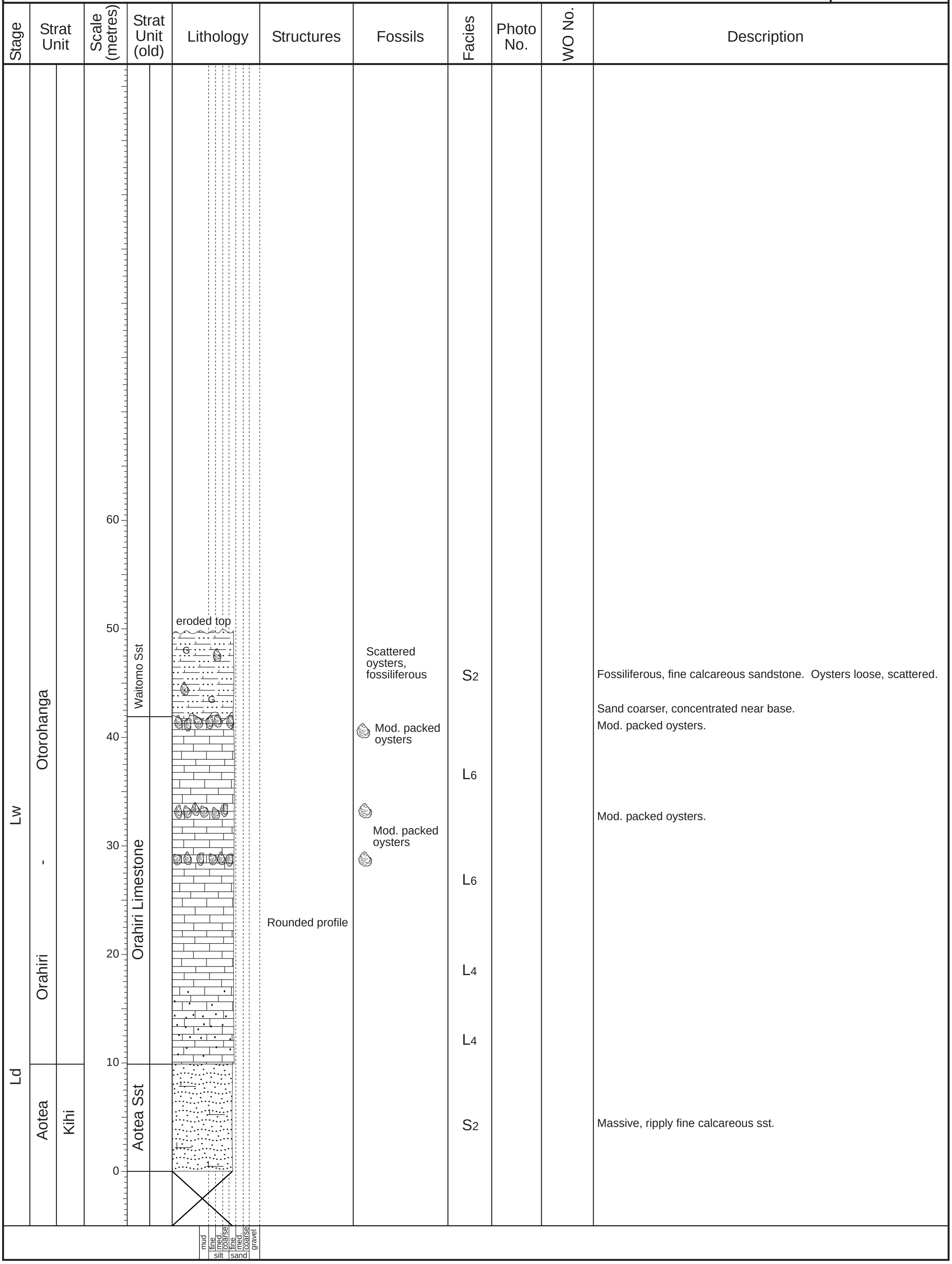


Fossiliferous, fine calcareous sandstone. Oysters loose, scattered.

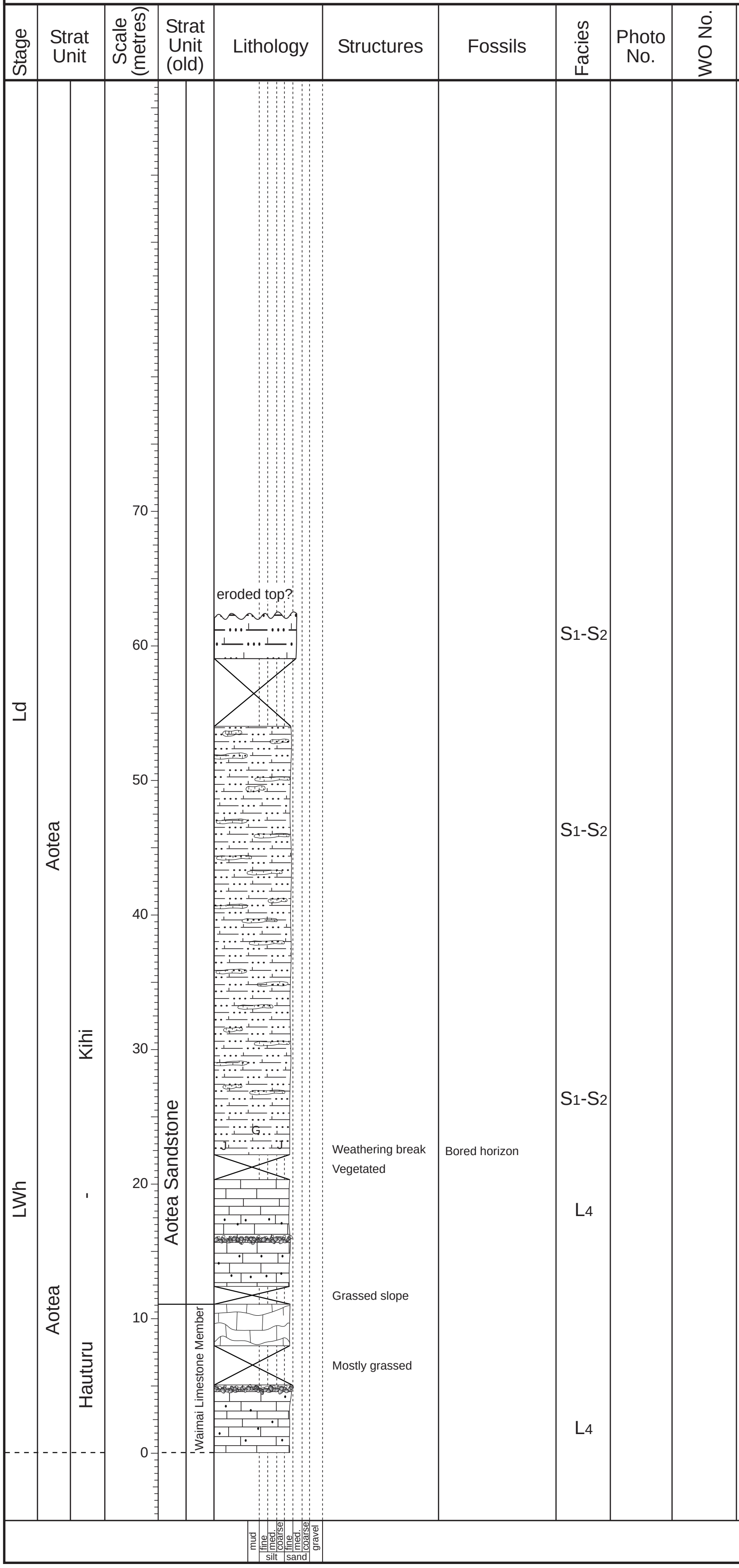
Sand coarser, concentrated near base.

Mod. packed oysters.

Mod. packed oysters.

Massive, ripply fine calcareous sst.

Stratigraphic Column No: S7; Otaki **Grid Reference:**
Region: Aotea - Kawhia **E:** 2677300
Location: 1.5 km S of Kawhia harbour Rd/Rakanui Rd interception **N:** 6340600
NZMS 260 Sheet: R15/773406 *Page* 1 *of* 1 **Author:** D. Fergusson



Description

Massive, sl. m. calc. sst., variably cemented.

Monotonous sequence of knob-bded calc. sst.

Slightly-mod. calc sst, intensely bioturbated. Rough-pocked surface, bands barely discern.

Cr., well ind., sl. glauc., cryst., lst-calc. sst. Mass. - incip. bded. Wavy, poorly devl. seams.
Fe-stained, sl. glauc.,m calc. sst.
Cr., well ind., v. sl. glauc., cryst., bioclastic lst. Seam spacing increasing.
Terrig. sand size decreases.

Reddish/cr., well ind. cryst., crs. s. lst. Flaggy.

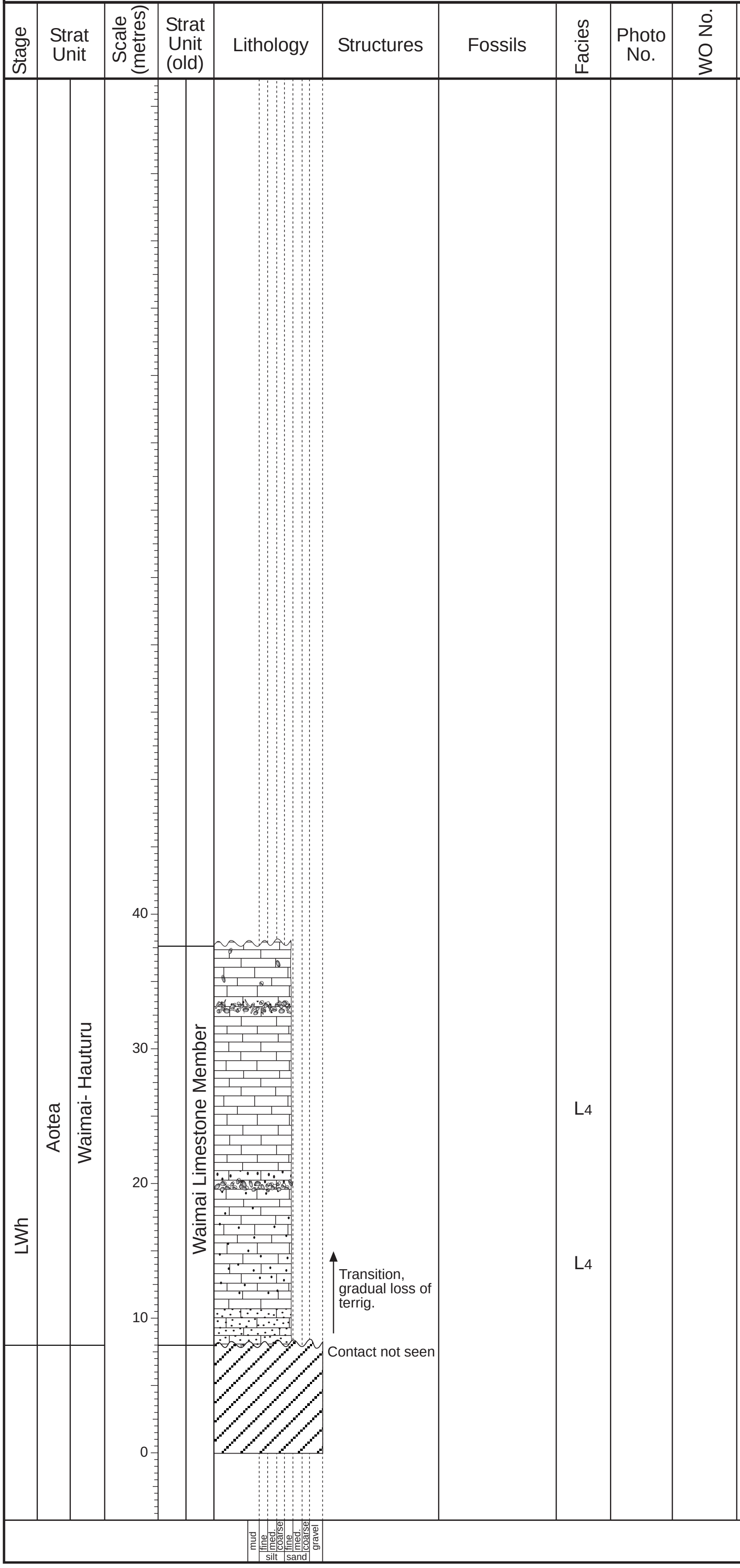
Pebble band. Pbls. > conc. in lower 2 m of band. Mostly subrd. VRF/SRF. matrix = Fe-stained, well ind., (crsu, crssc) v.s. lsts. Seams more regular, sl. wavy bands 3-8 cm.

Cr. well ind., pure bioclastic lst. Smooth o/c, seams < 1cm, profuse anastomisation. Bands 2-5 cm, flaggy where seams better weath.

Pebble band, suban.-subrd., matrix supported, evenly dist.
Matrix = well ind. cryst. s. $CaCo_3$. Flaggy 4-6 cm flags.

Well ind. sl. glauc. sl. f.s. bioclastic lst. Smooth-ripply; shell frags. impart rough texture, irreg. 1 cm seams, beds 5-8 cm.
Basal contact not seen.

Stratigraphic Column No: *S8; Pukenoi* **Grid Reference:**
Region: Aotea - Kawhia **E:** 2674900
Location: 1/2 km east of Toi Rd/Kawhia Harbour Rd interception **N:** 6340400
NZMS 260 Sheet: R15/749404 *Page* 1 *of* 1 **Author:** D. Fergusson



Eroded but continues in sections nearby for about 25 m. Lt. or.-br., mod. ind., sl. glauc., cryst., bioclastic calc. sst (s=fsu). Macrofossil fragments throughout outcrop.

Pebbs. scattered throughout, but gen. rare. Bioclastic lst.

Pebb. band, ungraded gran.-sm. pbl., terrig. clasts (rded.). Shell frags. common
Cr., mod. ind., sl. glauc., cryst. lst. with much terrig. sand.

Flags well developed.

Mod.- str. ind., cryst. f.s. lst.

Pebb. band; scat. pebbles and minor lenses in mod. ind., sl. glauc. f.s. lsts. Gran. - v. lge pebbs. (subang.-sbrd.), rare pt-pt contacts; clasts compressed, axis parallel to bedding.
Lt. or.-cr., well ind., sl. cryst., sl. glauc., v.f.s bioclastic lst. Rare limonite zones. Ripply-smooth o/c, occ. criss-cross seams (<1 cm). Slight lapiez development.

Cr. str. ind., sl. glauc., cryst. bioclastic lst.
Incip. flaggy; seams v. irreg (2-3 cm) flag interval 5-8 cm.

Creamy white, well ind., cryst., crs s-sm. pebbly. (terrig.) bioclastic. lst.

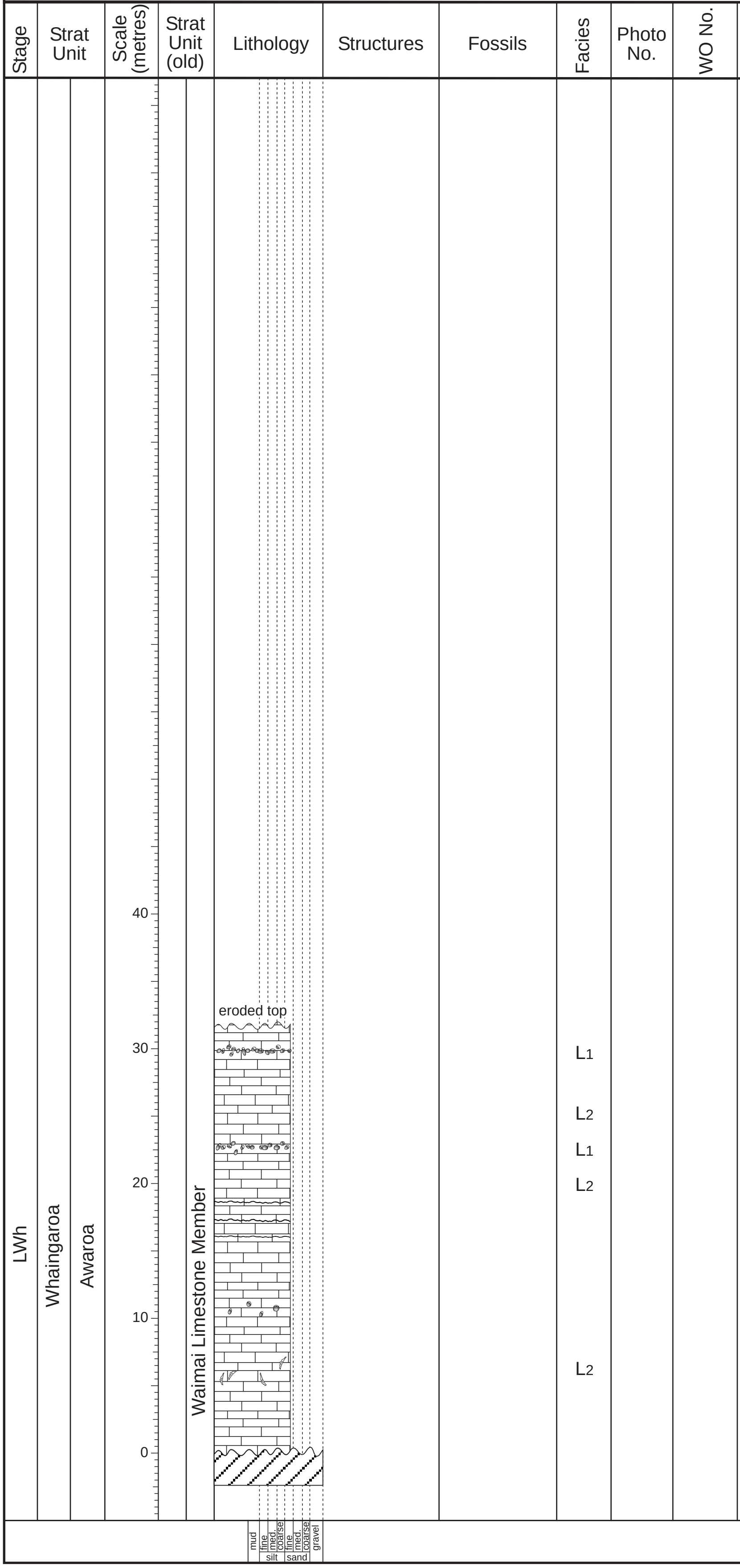
Puti Siltstone; well jointed 2 sets; 039/90 & 124/78 NNE. Bedding 056/14 NW.

Stratigraphic Column No: *S9*
Region: Aotea - Kawhia
Location: 1/2 km south of Otaki

Grid Reference:
E: 2677600
N: 6340000

NZMS 260 Sheet: R15/776400

Page 1 *of* 1 **Author:** D. Fergusson



Description

Cr., strongly ind., cryst., sl. s. glauc., bioclastic (up to crs) lst. Lapiez, incip. seams < 1 cm. Pebble band; sm.-med.-lge. pbls, subrded. pt-pt contacts rare, mainly matrix supported.Cr. (pure), well ind., very slightly glauc., bioclastic cryst. lst. Flaggy, seams 2-3 cm, wavy, pinch-out.

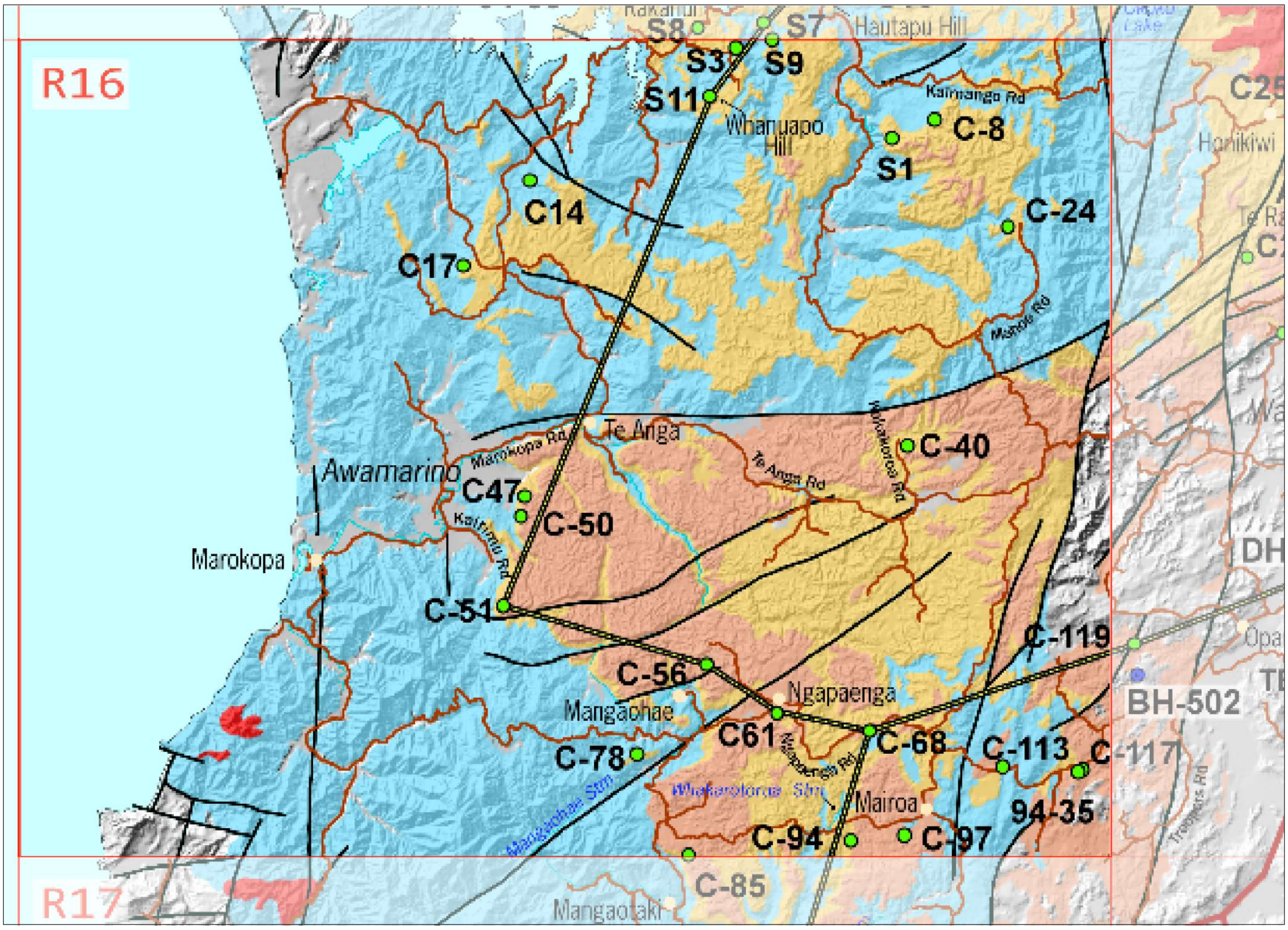
Pebble band, pbls. subrd.-subang. Matrix = $CaC0_3$ cement and terrigenous sand.

Cr., strongly ind., v. sl. glauc. bioclastic (crs-gran.) lst. Thin terrig. seams spaced 2-3 cm.

Cr., strongly ind., mod. glauc., gran.- sm./med. pebl. bioclastic lst.

Cr., mod. ind., mod. glauc., v.f.s. lst. Pectinid fragments. Flaggy, 5-15 cm spacing.

Contact not seen.
Siltstone with thin sandstone beds and laminae 179/33 W -bedding surface.

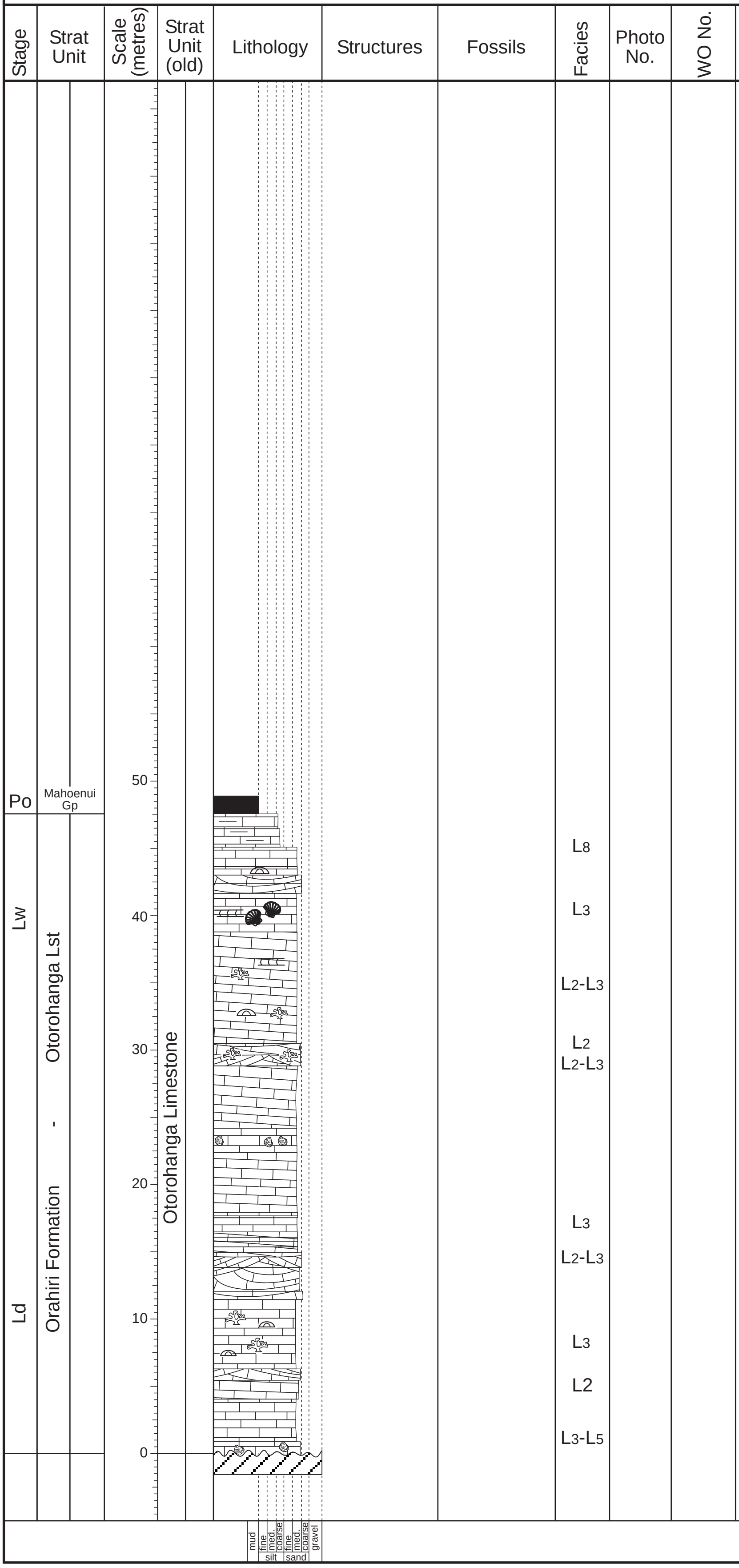

R16
R17
Rakanui
S8
S7
Hautapu Hill
S3
S9
S11
Whanuapo Hill
Kaimango Rd
C-8
S1
C14
C-24
C17
Manoe Rd
C25
Honikiwi
Te Ra
C2
Te Anga
Marokopa Rd
Te Anga Rd
Waikaroro Rd
C-40
Awamarino
C47
C-50
Kaitimu Rd
Marokopa
C-51
C-119
C-56
Ngapaenga
Mangachae
C61
C-68
C-113
C-117
C-78
Whakarotorua Strm
Mairoa
94-35
Mangachae Strm
C-94
C-97
C-85
Mangaotaki
BH-502
DH
Opa
TE
Wa

Stratigraphic Column No: 94-35
Region: Te Kuiti
Location: Boddies Farm

NZMS 260 Sheet: R16/890132

Grid Reference:
E: 2689000
N: 6313200

Page 1 *of* 1 **Author:** A.S. Anastas
Modified: A. Tripathi



Description

Argillaceous lst., massive with seams 3-5 cm apart.

Horizontally bedded lst., 1% glauc. grains, irregular bedding planes.

Grainstone, large (1-3 mm) echinoderms common.
Planar cross-beds.

Horizontally bedded lst., pectins, red algae, sharp upper contact, thickly bedded.

Gently inclined beds, bryozoans, echinoderms, algae, possibly crossbedded, beds decrease in size upwards.

Cross-beds, packstone, large bryozoans.

Gently inclined beds.

Bryozoan echinoderm grainstone.

Tabular cross-set.
Cross-bedded bryozoan-echinoderm packstone.

Horizontally to gently inclined beds (cross-bedded).
Cross-bedded.

Horizontally bedded lst., top 1 m shows packaging, beds 5-15 cm.

Large cross-bed, packstone, foresets 7-12 cm.
Tabular bedded lst., toesets?

Horizontally bedded lst., 5-10 cm beds, undulatory.
Horizontally bedded lst., wacke-packstone, oysters.
Basement.

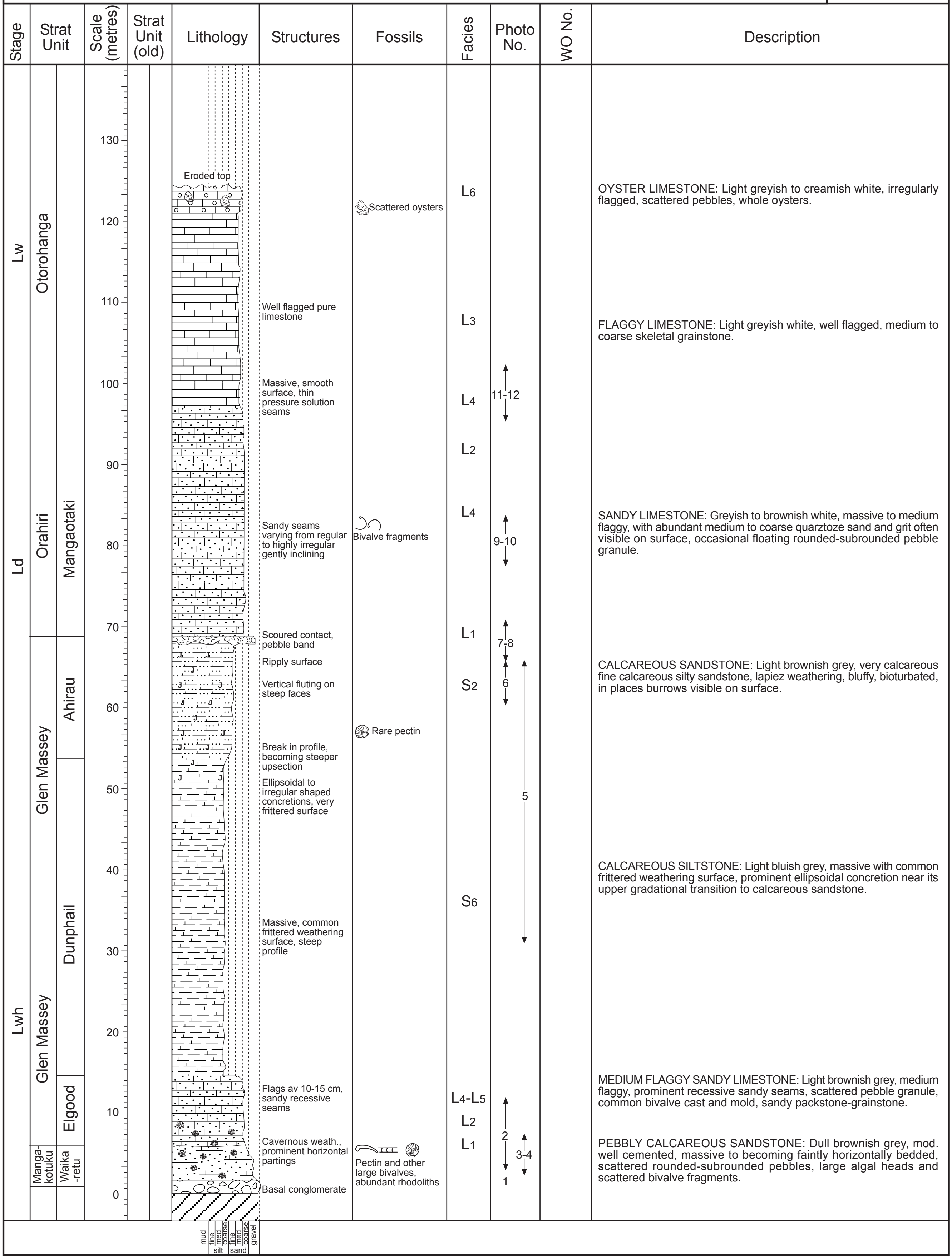
Stratigraphic Column No: *C-50*
Region: Te Kuiti
Location: Southeast of Awamarino

Grid Reference:	**Top**	**Bottom**
E:		2668419
N:		6322490

NZMS 1 Sheet: R16

Page 1 *of* 3

Author: C. Nelson
Modified: A. Tripathi



Well flagged pure limestone

Massive, smooth surface, thin pressure solution seams

Sandy seams varying from regular to highly irregular gently inclining

Scoured contact, pebble band

Ripply surface

Vertical fluting on steep faces

Break in profile, becoming steeper upsection

Ellipsoidal to irregular shaped concretions, very frittered surface

Massive, common frittered weathering surface, steep profile

Flags av 10-15 cm, sandy recessive seams

Cavernous weath., prominent horizontal partings

Basal conglomerate

Scattered oysters

Bivalve fragments

Rare pectin

Pectin and other large bivalves, abundant rhodoliths

OYSTER LIMESTONE: Light greyish to creamish white, irregularly flagged, scattered pebbles, whole oysters.

FLAGGY LIMESTONE: Light greyish white, well flagged, medium to coarse skeletal grainstone.

SANDY LIMESTONE: Greyish to brownish white, massive to medium flaggy, with abundant medium to coarse quarztoze sand and grit often visible on surface, occasional floating rounded-subrounded pebble granule.

CALCAREOUS SANDSTONE: Light brownish grey, very calcareous fine calcareous silty sandstone, lapiez weathering, bluffy, bioturbated, in places burrows visible on surface.

CALCAREOUS SILTSTONE: Light bluish grey, massive with common frittered weathering surface, prominent ellipsoidal concretion near its upper gradational transition to calcareous sandstone.

MEDIUM FLAGGY SANDY LIMESTONE: Light brownish grey, medium flaggy, prominent recessive sandy seams, scattered pebble granule, common bivalve cast and mold, sandy packstone-grainstone.

PEBBLY CALCAREOUS SANDSTONE: Dull brownish grey, mod. well cemented, massive to becoming faintly horizontally bedded, scattered rounded-subrounded pebbles, large algal heads and scattered bivalve fragments.

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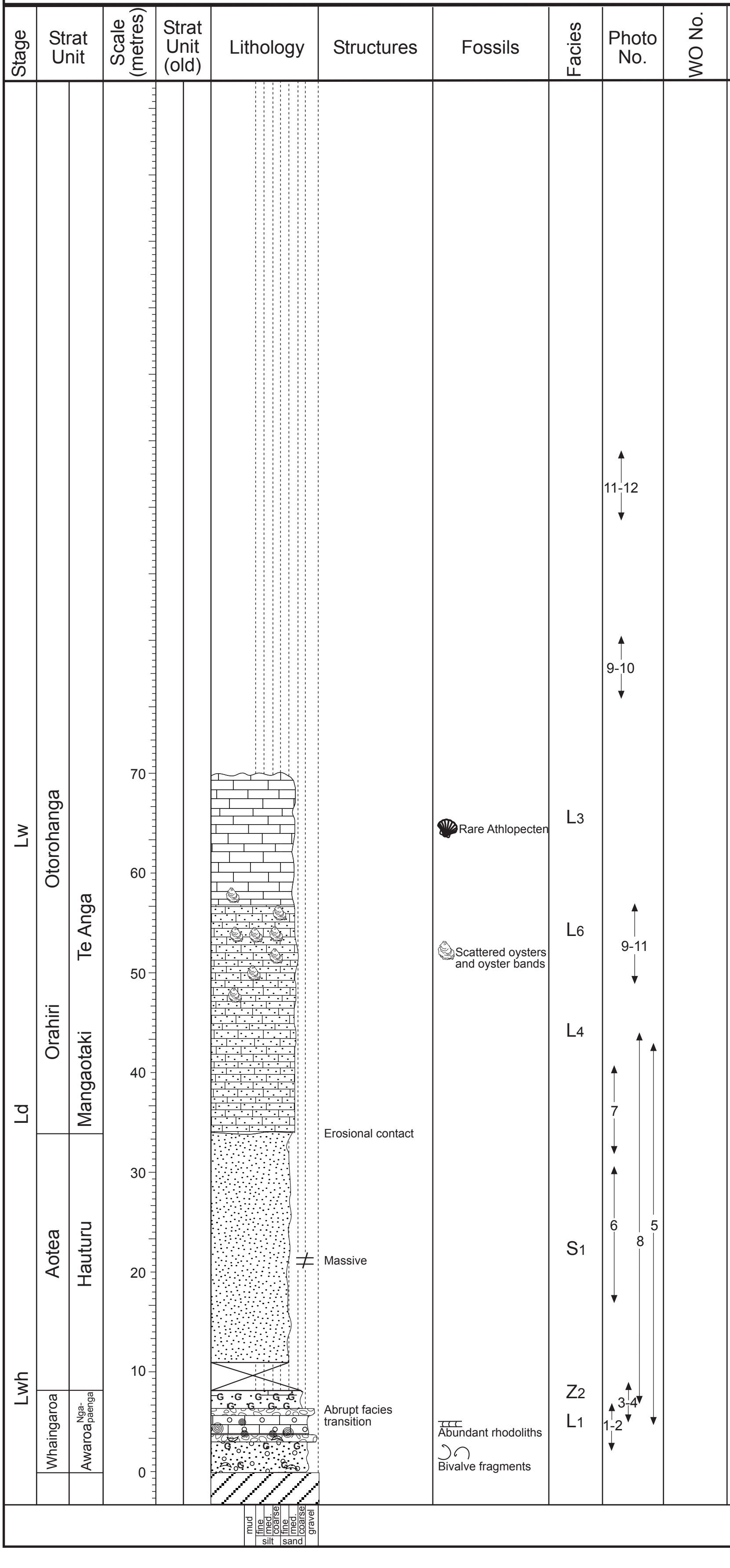
Stratigraphic Column No: *C-97*
Region: Te Kuiti
Location: Southeast of Mairoa settlement

Grid Reference:	**Top**	**Bottom**
E:	2682532	- 2682460
N:	6310568	- 6310800

NZMS 260 Sheet: R16

Page 1 *of* 3

Author: C. Nelson



Description

FLAGGY LIMESTONE: Light greyish white to dirty white, well flagged, flags 5-6 cm separated by recessive seams, medium to coarse skeletal grainstone.

SANDY LIMESTONE: Light greyish white, ripply bedded with prominent horizontal to gently inclined inverted seams 3-6 cm apart, scattered whole oysters in the upper 10 m, occ. oyster concentrated in band, medium to coarse sand grains visible on surface, medium to coarse skeletal grainstone.

MASSIVE SANDSTONE: Medium yellowish brown, weakly cemented, often soft and friable, massive, fine to medium quartzo-feldspathic sandstone.

GLAUCONITIC PEBBLY SANDSTONE: Dark greyish to greenish grey, massive, massive, mod. cemented, fine to medium sandstone with common scattered pebbles and granules, very high concentration of glauconite.

PEBBLY LIMESTONE: Dull brownish grey, poorly to medium flaggy, scattered rounded-subrounded pebbles and granules supported by calcareous matrix, pebbles concentrated in band at the base and top of the lst unit, abundant rhodoliths in lower part and scattered bivalve fragments, medium to strongly glauconitic especially the basal sandy/gritty unit overlying the basement.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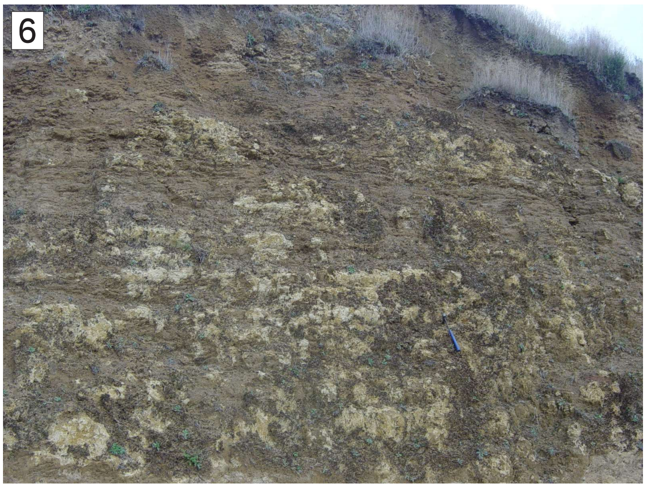
6

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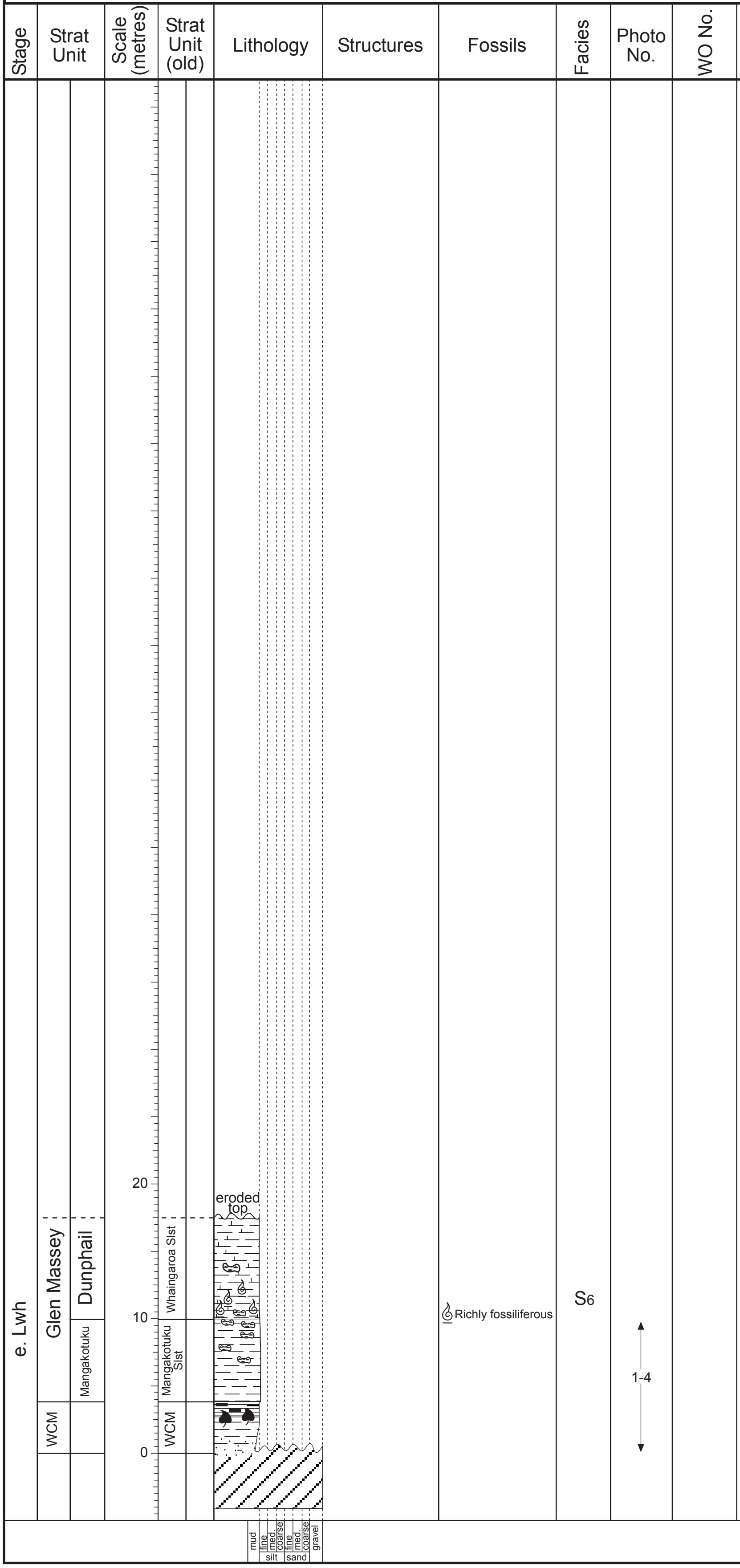
Stratigraphic Column No: *C-113*
Grid Reference:
Region: King Country/Waitomo
E: 2686084
Location: Near basement quarry, Oparure Road
N: 6313302

NZMS 1 Sheet: R16

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



Description

Blue-grey massive calc. mst., frittery surface upon weathering.

Richly ff. blue-grey calc. mst. with rare calc. concret., fossils include turrids, Panopea, gastropods, bivalves.
Gradual contact, increase in concrets. along transition zone.

Purple silty msts., mass. fritt., concret. , comm. dumb-bell shape, to 23 cm long, av. 5 cm.
Nearby much of this interval shows alternations of grey silty sandy msts and carb. pebbly msts., pebbles leached greywacke.
Carbonaceous mst. and coal streaks and lenses.
Green-fawny purple siliceous mst., rare carbonaceous streaks
Strongly leached yellow-white puggy clays grad. down into basement rocks.

Mesozoic basement rocks.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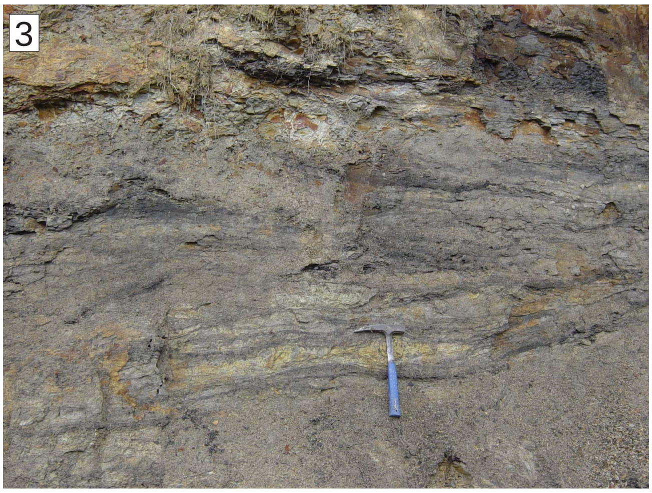

3


4

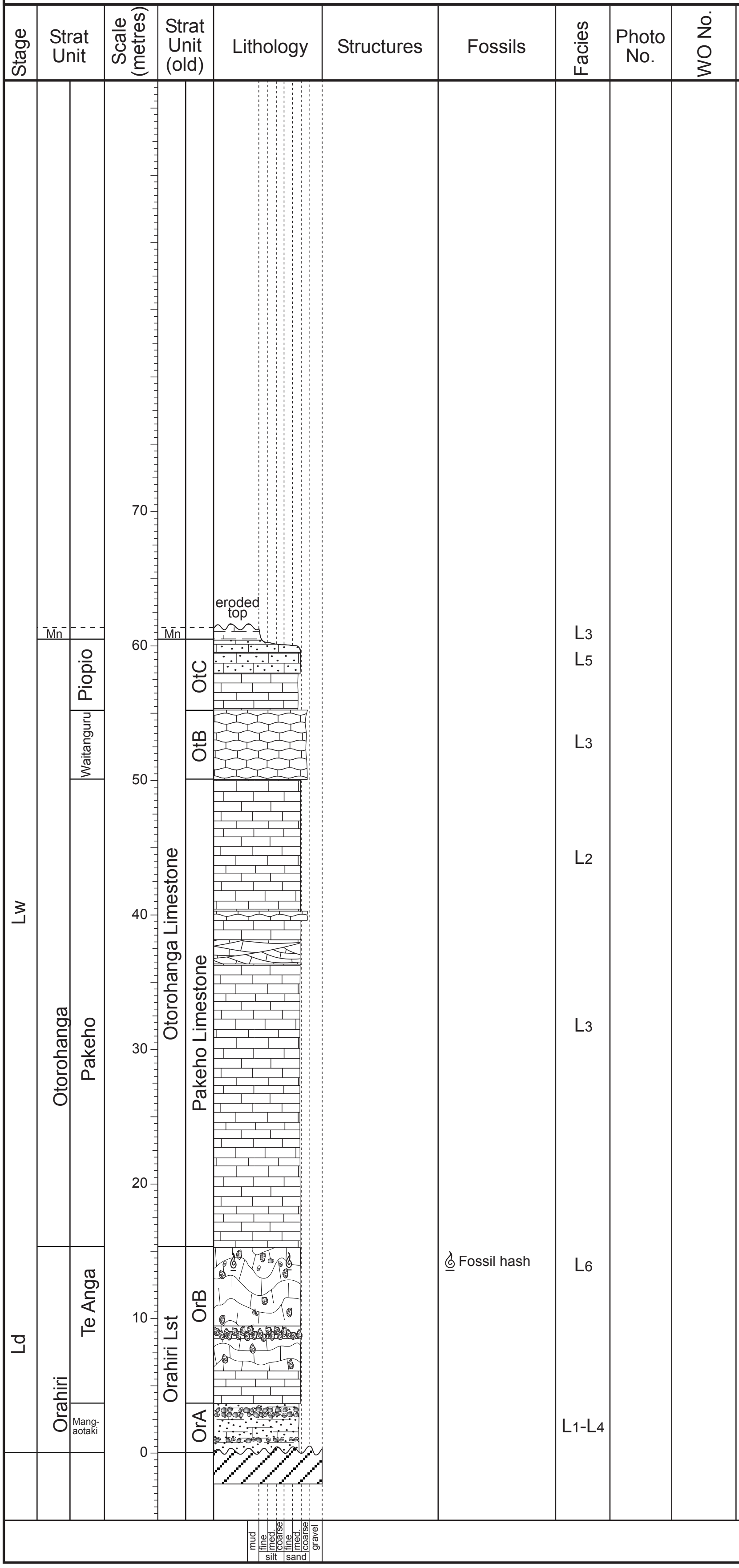
Stratigraphic Column No: *C-117*
Region: King Country/Waitomo
Location: South of Pakeho, Oparure Road

Grid Reference:
E: 2688823
N: 6313133

NZMS 1 Sheet: R16

Page 1 *of* 1

Author: C. Nelson
Modified: A. Tripathi



Description

Bl/gr. frittery calc. mst., Mn mst.
Gradual contact; top 90 cm of harder muddy lst. bands 7.6-30 cm thick separated by 1.3-2.5 cm shaley zones. 58-59.5 m massive inv. seamed, 1-5 cm apart, sandy lst.

Incip.-mod. flaggy lst., minor shale units, corresponds to seams.

Semiknobbly-knobbly, slappy ap., slabs av. 20 cm, vertical joints, sl.-mod. irregular weathered, widish seams.

Well flagged 2.5-7.6 cm, av. 5 cm lst., occ. ‘dogtooth’ flags.

Knobbly-slabby lst., vertical joints.
Well dev. flags to 15 cm, av. 7.6 cm, occ. vertical joints.

Cross-beds, dip 5o E.

Seams mod.-well developed, 2.5-5 cm apart, slightly irregular.

Seams 5-7.6 cm apart.

Very occ. tiny pebb. in irreg. mod.-well developed seamed biomicrite, ff-hash, brachs., Athlopecten, barnacles (on oysters) shark teeth.

Scattered oysters in irreg. seamed 2.5-7.6 cm apart lst.

Oysters=matrix.

Irreg. seamed, av. 7.6 cm apart, lst., scattered oysters.

Flaggy 7.6 cm lst.

60-90 cm conglom. pebbles>matrix, rounded. greywacke pebbles to 20 cm, av. 3.8 cm, sharp contacts.
Very calc. sst.-s. lst. with scattered pebble horizons.

Mesozoic basement rocks.

Stratigraphic Column No: *C-119*

Grid Reference:

Region: King Country/Waitomo

E: 2691133 - 2690877

Location: McDonald Lime Quarry, Oparure Road

N: 6317183 - 6317831

NZMS 1 Sheet: R16

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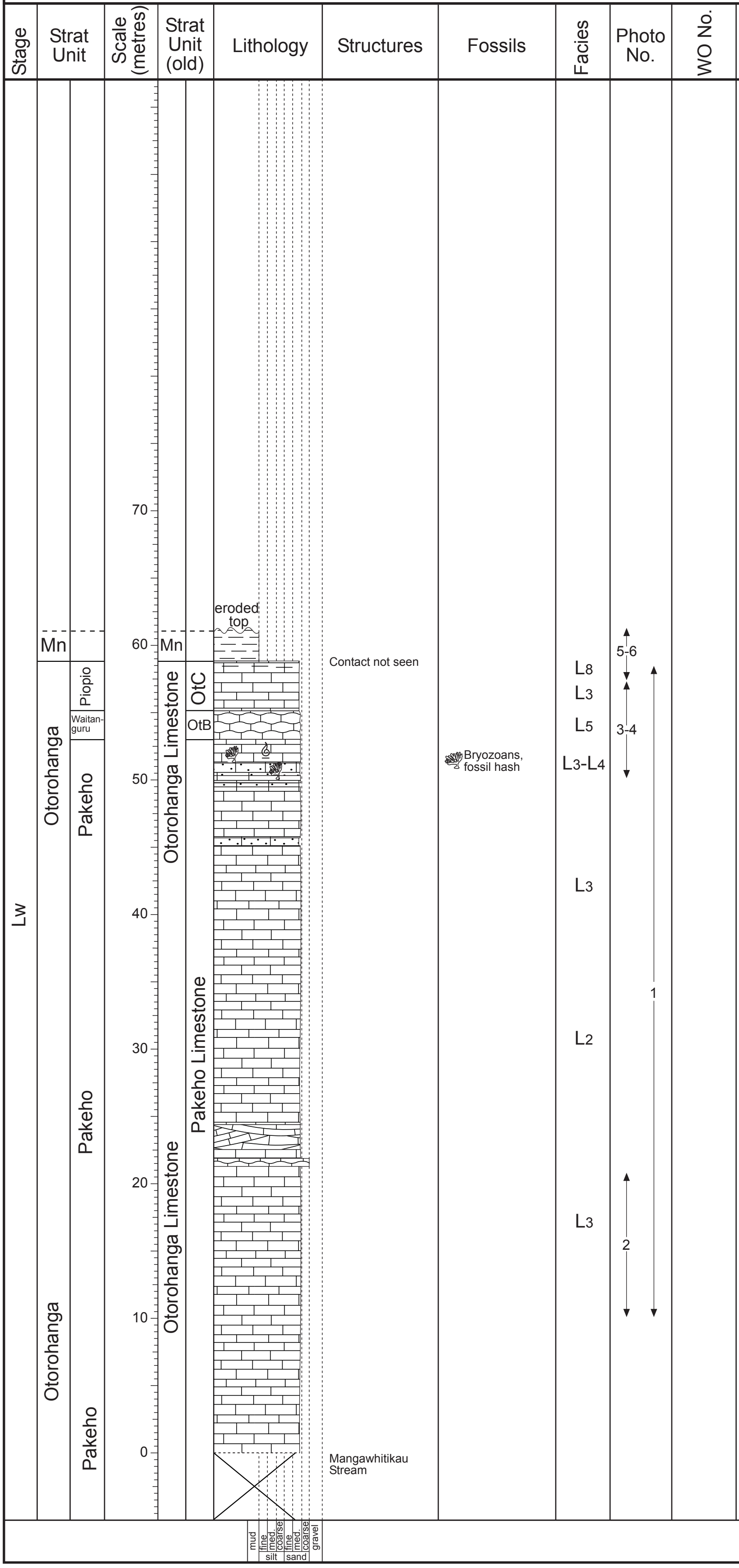
Author: C. Nelson
Modified: A. Tripathi



Description

Blue-grey calc. mst., Mn mst.

Smooth flags, av. 13 cm, slightly irregular and sandy seams.

Mod.-well developed flaggs, to 30 cm, occ. vertical joints, rough surface, var. flag width.

Irregular pseudoknobbly lst., cavernous weathering not advanced.

Moderately-well flagged, av. 2.5-7.6 cm, smooth-slightly wavy seams, becomes sandy downwards where mass., slightly frittery, fossiliferous (esp. bryoz.). Above unit repeated 49.4-50.3 m.

Pure flaggy av. 5 cm lst., slightly wavy seams.

Frittery sandy lst., similar to above sandy horizons.

Well flagged av. 5-7.6 cm lst., seams occ. slightly wavy.

Occ. veining in 5 cm flagged lst., sl. honeycomb weath. appearance to lst.

Crossbeds, dip 10o to NW, c/gr. lst., variable flag width, comm. large.

21.3-22 m vert. jointed, slightly knobbly-slabby unit.

Well flagged, av. 7.6 cm pure lst. as monotonous sequence down to river.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Stratigraphic Column No: C14 ***Grid Reference: R16***

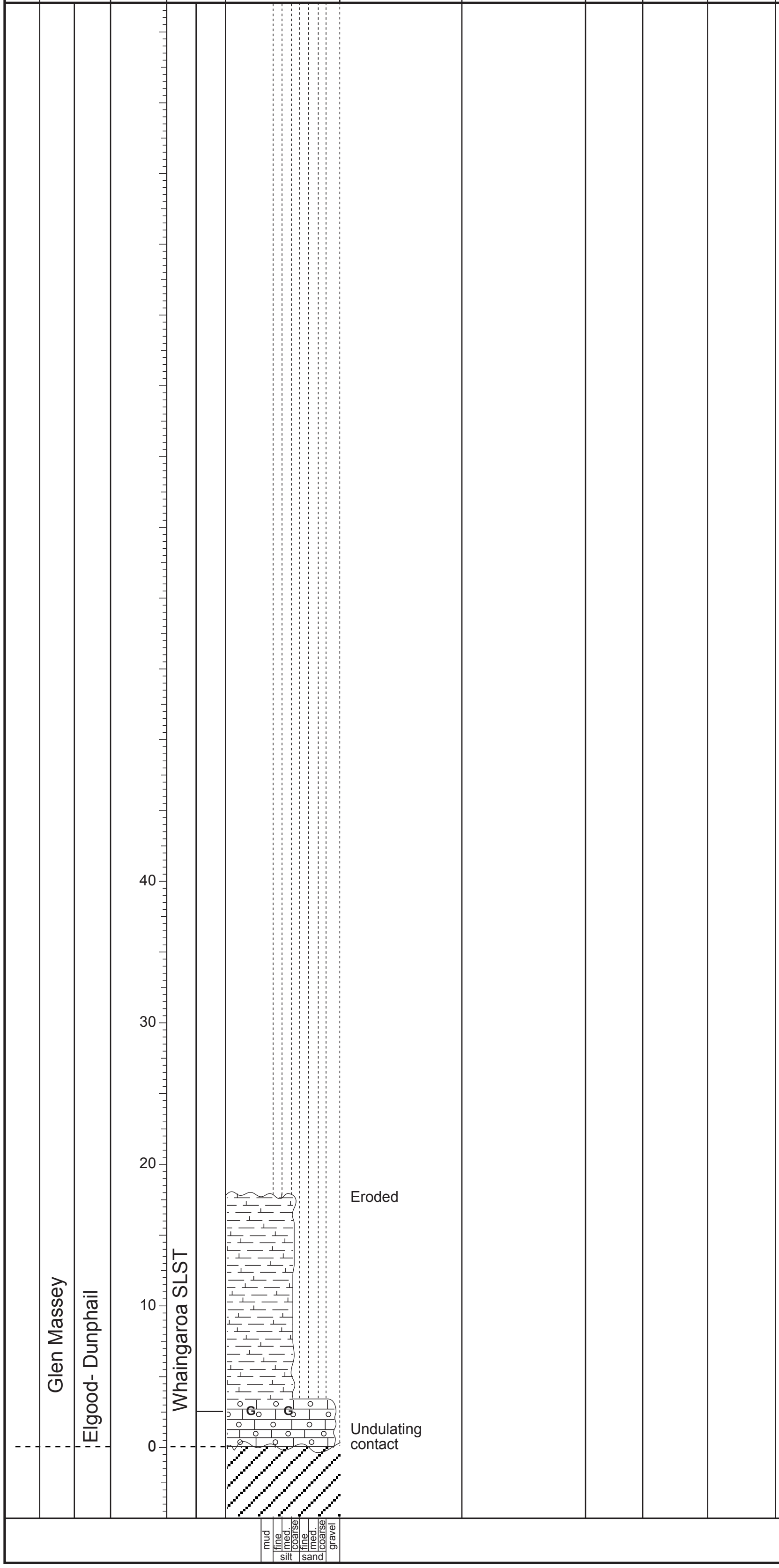
Region: Aotea - Kawhia ***E:*** 2668750

Location: Te Waitere Road, south of Kawhia ***N:*** 6334800

NZMS 260 Sheet: R16/687348 *Page* 1 *of* 1 **Author:** C. Nelson

Modified: A. Tripathi

Stage	Strat Unit	Scale (metres)	Strat Unit (old)	Lithology	Structures	Fossils	Facies	Photo No.	WO No.	Description



Calcareous siltstone: Massive, blue grey

Calcareous Sandstone: Massive, gritty with occas. pebble (0.3 cm), glauconitic

Pebbly Limestone: 2.5-5 cm flags, ripply, pebbles av.0.3-0.5 cm, 22-30 cm thick basal conglomerate with pebble supported framework

Stratigraphic Column No: C17 **Grid Reference:** R16

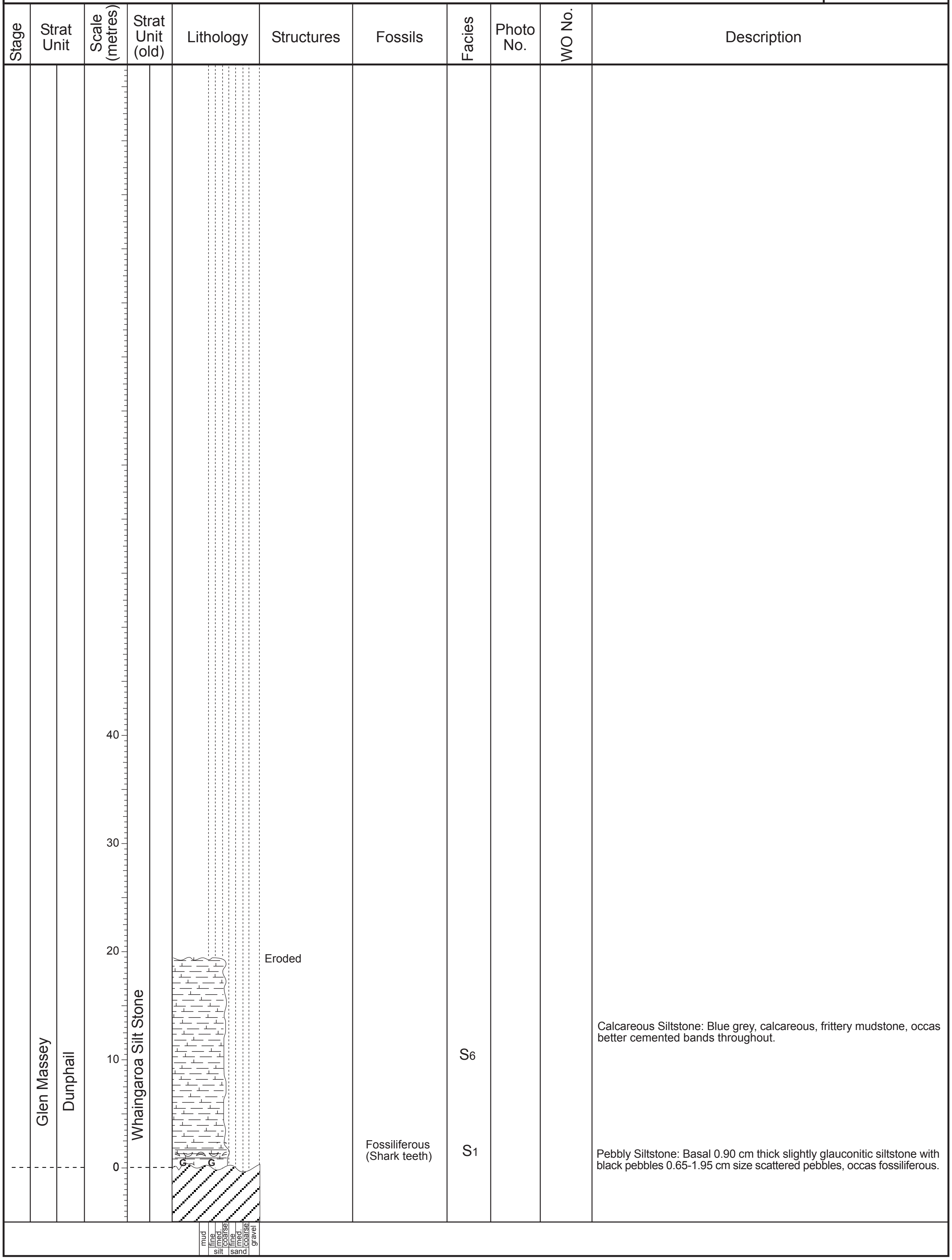
Region: Aotea - Kawhia **E:** 2666300

Location: Taharoa Road, south of Kawhia **N:** 6331700

NZMS 260 Sheet: R16/663317

Page 1 *of* 1 **Author:** C. Nelson

Modified: A. Tripathi



Calcareous Siltstone: Blue grey, calcareous, frittery mudstone, occas better cemented bands throughout.

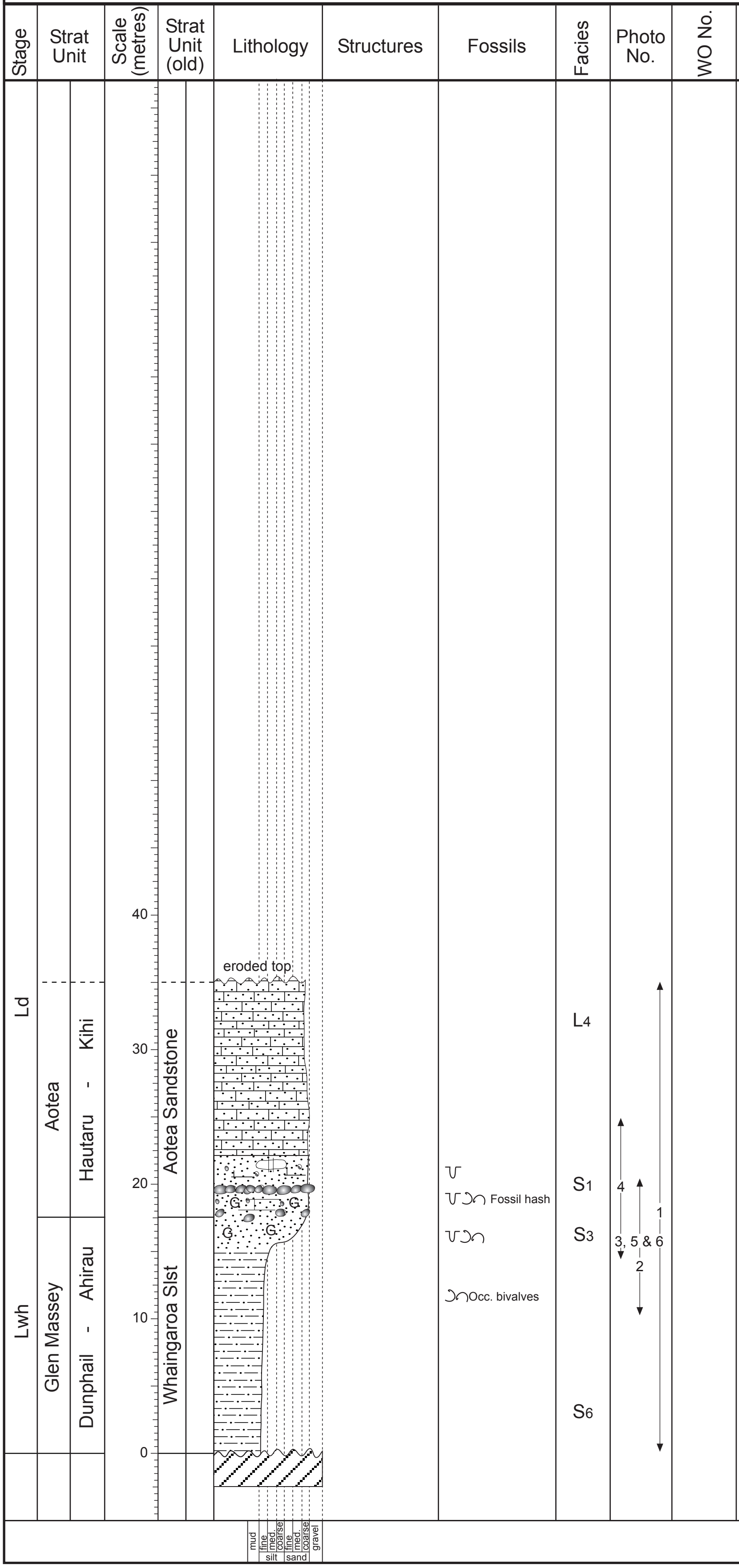
Pebbly Siltstone: Basal 0.90 cm thick slightly glauconitic siltstone with black pebbles 0.65-1.95 cm size scattered pebbles, occas fossiliferous.

Stratigraphic Column No: *C-24*
Region: King Country/Waitomo
Location: Mahoe Road, Southwest of Honikiwi

Grid Reference:
E: 2686462 - 2686282
N: 6333138 - 6333144

NZMS 1 Sheet: R16

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



Description

Mass.-incip. ripply s. lst. 22.2-35 m; prom. nose-like cliff 22.2-30 m Certain horizon app. calc. ssts. This face forms char. outcrop north to Omarama trig in bushed country.

Psuedobeded - bded sst., beneath vegetn. free, damp overhangs
Scattered pebbs. in burrowed calc. sst.

At 19.8 m packed pebb. band 0-30.5 cm thick, pebbs. av. 1.2 cm, max 3.1 cm, eroded. Well weath. pebbs. > matrix; pebbs. fill pocket incr. width of band to 30.5 cm. Rel. sharp top and bottom, v. occ. bivalve debris.
18.3-19.8 m mass. gritty-v.f. pebbly sandy glauc. lst. or grit. occ. borings plus scatt. pebbs near top, v. weath and much ff. debris.
17.6-18.3 m scatt. pebb. calc. sst, pebbs. av. 0.3 cm, max. 2 cm, occ. fine ff. mat. and borings, poss. intraclasts.
Below 17.6 m coarse fritty calc. glauc. sst., occ. bivalves and borings passing by 15.2 m down into mass. fritt. blue-grey s. msts.

Blue/grey sandy msts.

Swamp

Mesozoic basement rocks, paleorelief char. irreg. in area.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Hauturu Sst
Ahirau Sst


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Stratigraphic Column No: *C-40* **Grid Reference:**

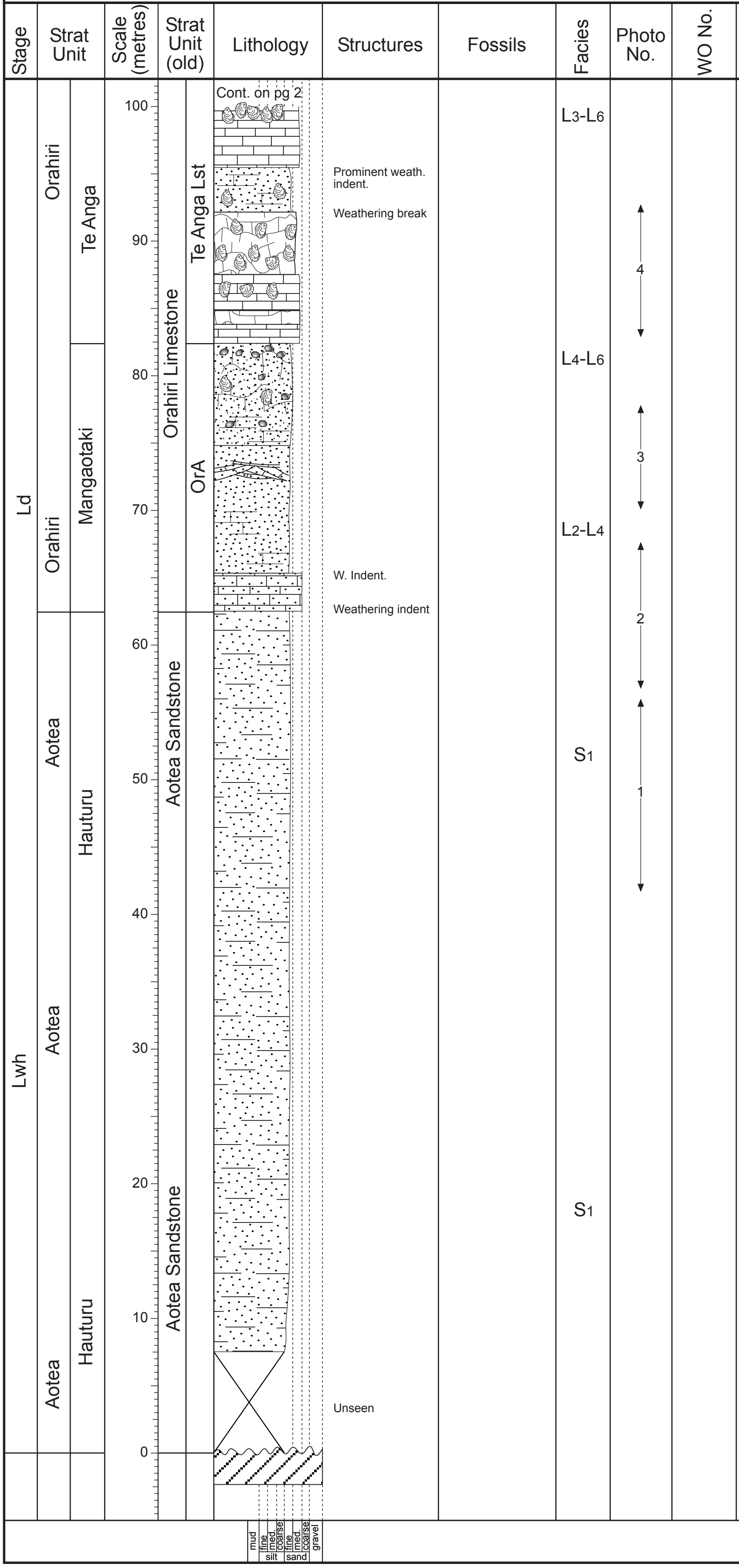
Region: King Country/Waitomo

Location: Kokakaroa Road, west of Waitomo

E:	2681942	-	2682577
N:	6325309	-	6325108

NZMS 1 Sheet: R16

Page 1 *of* 2 **Author:** C. Nelson
Modified: A. Tripathi



Description

Mod. oyst. bands, oysts. par. bed., re. mass.-inv. seams, av. 2.5-5 cm apart. Invisible seams below and characteristic.

Mass.-incip. seams, sl. ripply lst., v. occ. oysts. 93.3 m.

Incip. seams, 2.5 cm apart, scatt. oysters.

Succession of oyster bands showing mod.-well packed oysts., incip. sl. irreg. seams, freq. invisible.

Incip. irregular seams, scatt.-mod. oysts., scatt. pebbs. av. 0.95 cm, max.10 cm with pebbly horizon immed. below 82.3 m, oysters artic. and disartic.

Incip. flagged slightly sandy lst.

Crossbeds, complex sets, dip as gt. as 19o between N-NE, only vaguely defined by incipient dev. seams in slightly sandy lst.

Mass. ripply sandy lst., incip. seams 2.5-5 cm apart, main cliff above 65.2 m.

Mass.-incipient ripply sandy lst., smooth surface.

Monotonous seq. of mass. ripply calc. sst., occ. seams av. 5-7.6 cm apart, forms lower cliff-face into Marokopa R.; on roadside commonly weaths. to produce yellow friable sands, elsewhere bded ssts. obvious; well exposed on Waitomo-Te Anga Rd. in this area.

Near base becomes muddier, bl/gr., weathered fritt., calc. muddy fine ssts.

Mesozoic basement rocks.

Stratigraphic Column No: *C-40*

Region: King Country/Waitomo

Location: Kokakaroa Road, west of Waitomo

NZMS 1 Sheet: R16

Grid Reference:

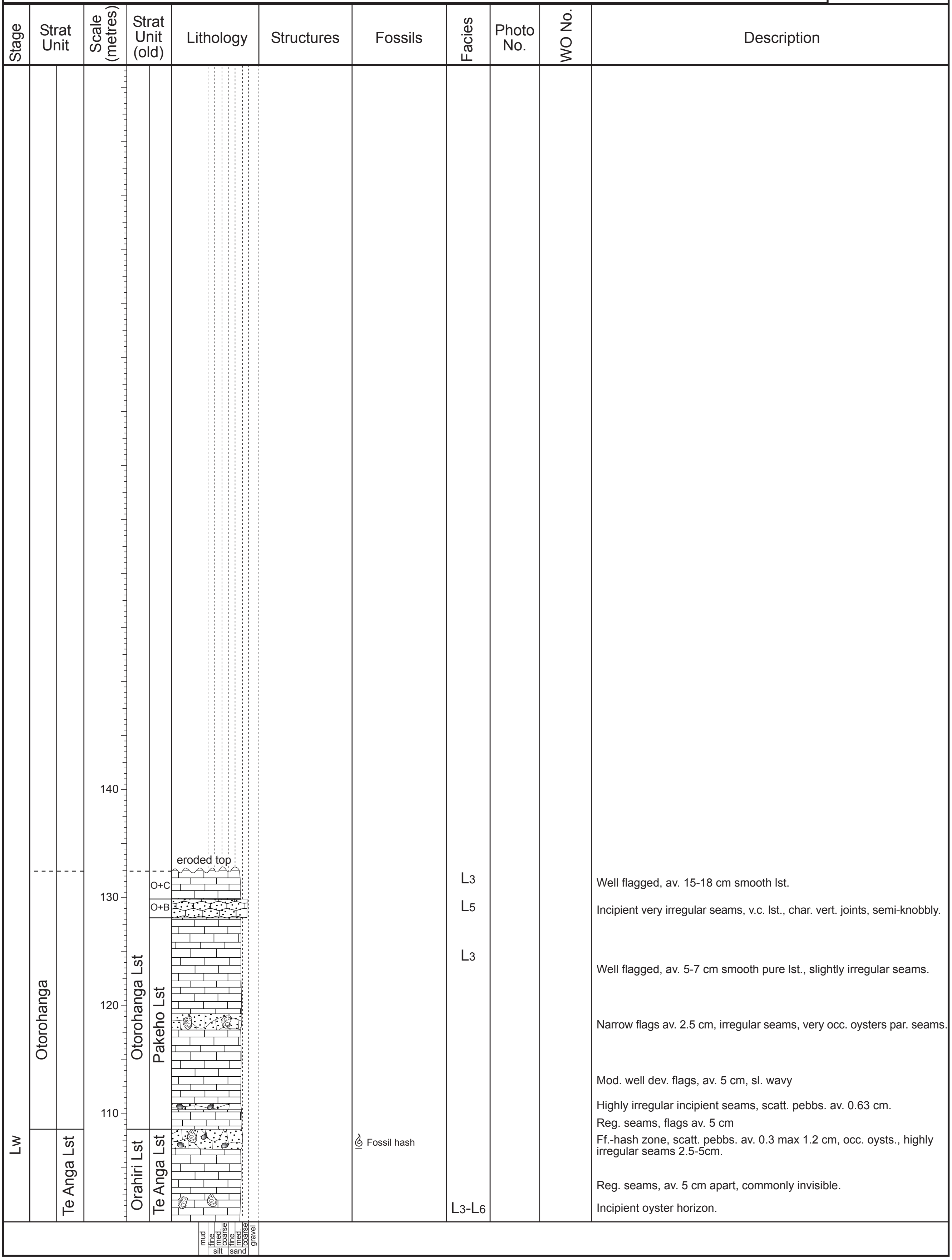
E: 2681942 - 2682577

N: 6325309 - 6325108

Page 2 *of* 2

Author: C. Nelson

Modified: A. Tripathi



Facies	Description
L3	Well flagged, av. 15-18 cm smooth lst.
L5	Incipient very irregular seams, v.c. lst., char. vert. joints, semi-knobbly.
L3	Well flagged, av. 5-7 cm smooth pure lst., slightly irregular seams.
	Narrow flags av. 2.5 cm, irregular seams, very occ. oysters par. seams.
	Mod. well dev. flags, av. 5 cm, sl. wavy
	Highly irregular incipient seams, scatt. pebbs. av. 0.63 cm.
	Reg. seams, flags av. 5 cm
	Ff.-hash zone, scatt. pebbs. av. 0.3 max 1.2 cm, occ. oysts., highly irregular seams 2.5-5cm.
	Reg. seams, av. 5 cm apart, commonly invisible.
L3-L6	Incipient oyster horizon.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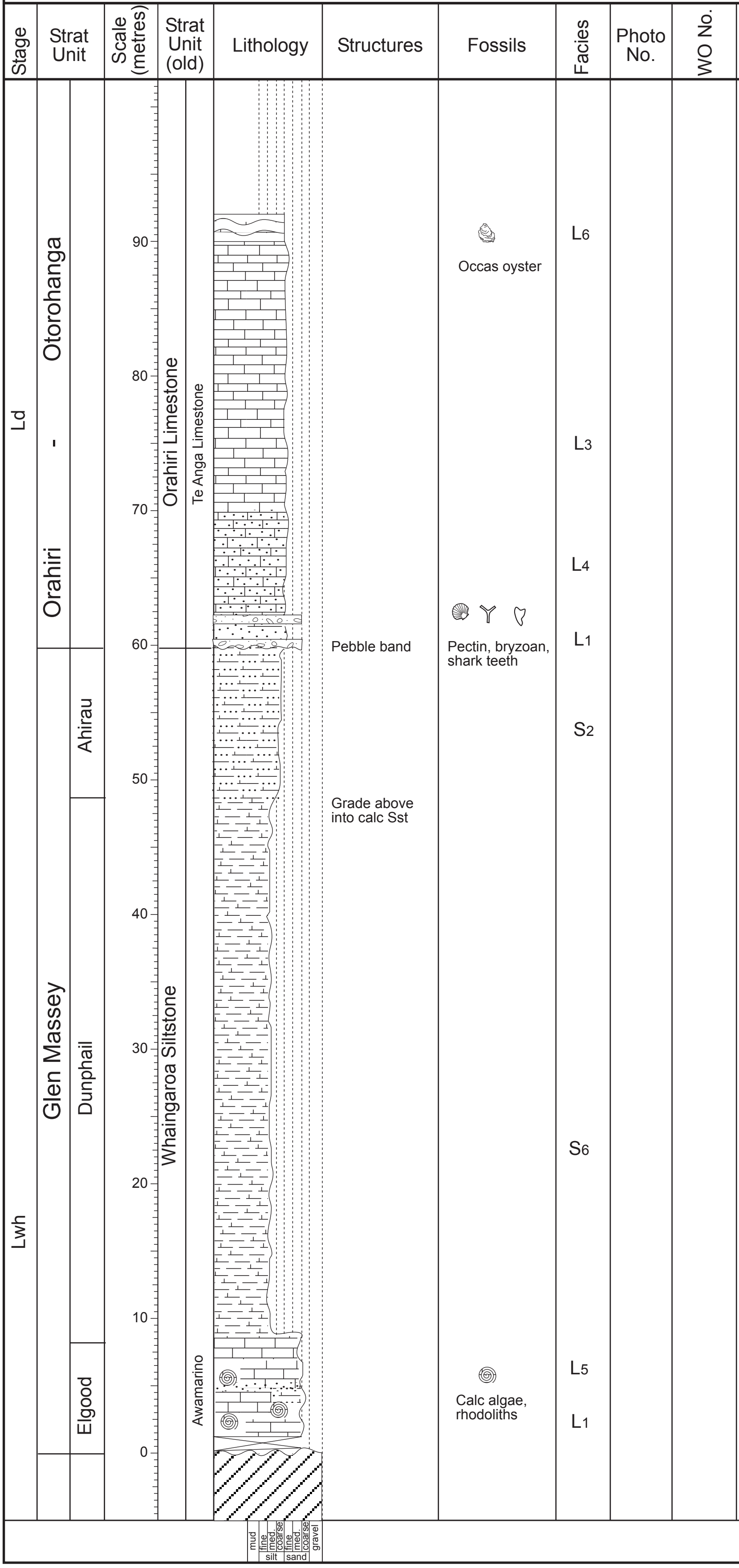
Stratigraphic Column No: C-47
Grid Reference:
Region: King Country/Waitomo
E: 2668531-2669436
Location: Awamarino
N: 6323219-6322336

NZMS 260 Sheet:
Page 1
Author: C. Nelson
Modified: A. Tripathi



Description

Semi knobbly Lst at top, incipient irregular seams, leaching of seam material evident

Semi knobbly occas vertical joints, incipient mod seams, irregular 1.25-5 cm apart, sand conc on some seams, occas oyster.

Flaggy 2.5-5 cm, seams wavy, more prominent wider flags, wide incipient seams between, sand concentrated on flag surface, occas veining

Well flagged 2.5-5 cm Lst

Very irregular seamed, extremely coarse sandy gritty Lst

Pebble band variable width to 15 cm, pebbles 5 cm av 0.9 cm of yellow Mst + greywacke, fossil debris, esp pectinids,bryozoans, sharks teeth, concentration on seams, scoured surface, pebbles scattered

Ripply-massive sandy Lst, sandier at base

Pebble band, variable 5-10 cm wide, pebbles mod. packed to 7.5 cm, av 1.5 cm, lacks yellow Mst pebbles, grad. contact, occas up to 25 cm wide

Massive incipient ripply sandy Lst- calc Sst, burrowed, ocass. laminated, honeycombed weathering seen, occas irregular incipient seams.

Monotonous sequence of massive blue grey calcareous mudstone, frittery weathering surface, commonly slumps and covers lower Lst, incipient bedding sometimes evident in upper part.

15-20 cm mod flagged, av 5 cm smooth Lst grading down through Lithothamnium rich Lst into scattered pebbly horizon, pebbles to 12 cm av. 2 cm algal headscommon, the down to very massive, incipient-mod flags at times massive-microhoneycombed incipient highly irregular seamed Lst, very occas 0.3 cm pebbles 35-45 cm soft and hard algal mat Lst, occas fossiliferous mat and carb. mat, frittery appearance, below 35 cm irregular incipient seams,occas joints, algal Lst to 30 cm with 30 cm massive band below 1.5-3 m frittery blue gray muddy calcareous fine Sst with unseen interval.

Stratigraphic Column No: *C-51*

Grid Reference:

Region: King Country/Waitomo

E: 2667777 - 2668359

Location: Kairimu Road, south of Awamarino

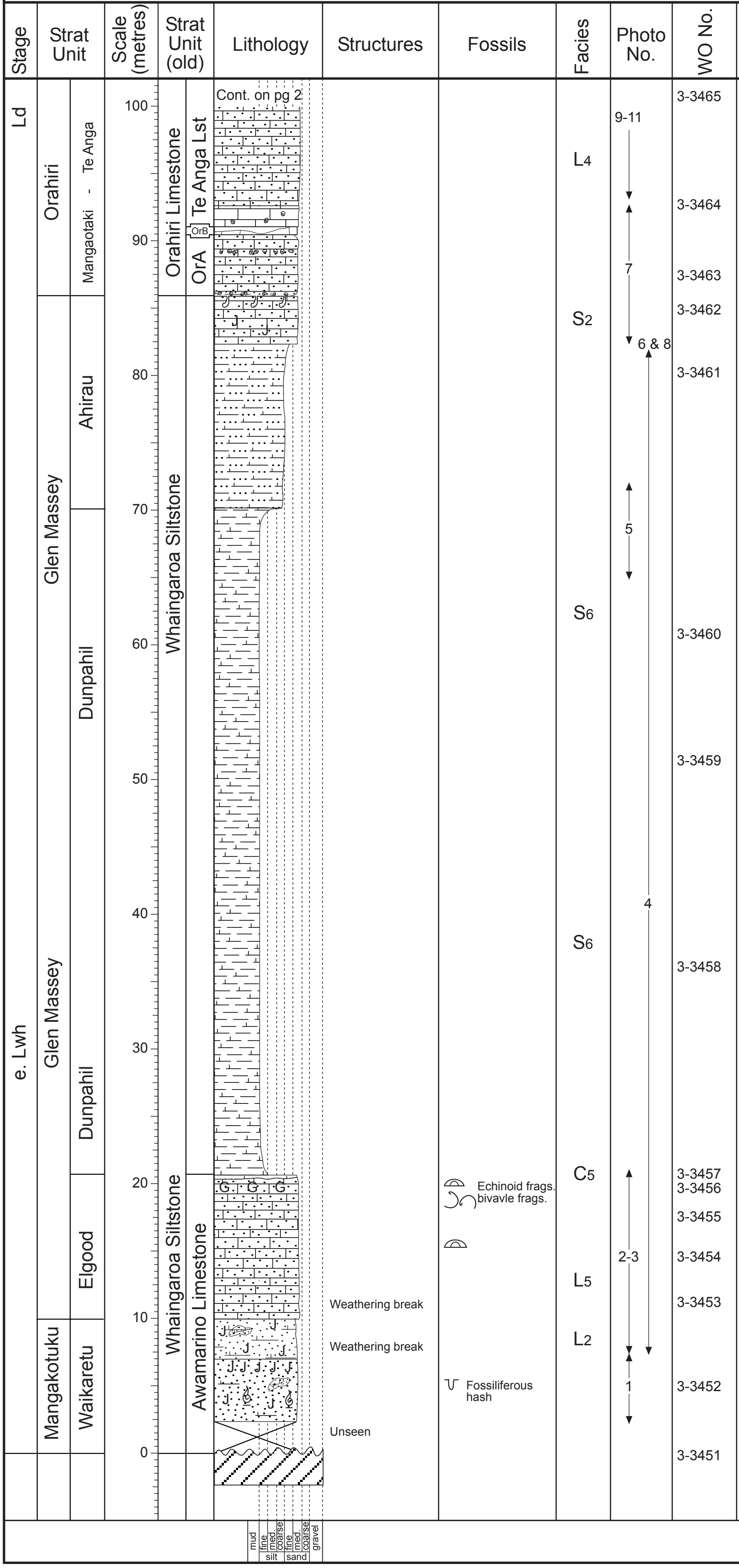
N: 6319216 - 6320388

NZMS 1 Sheet: R16

Page 1 *of* 2

Author: C. Nelson

Modified: A. Tripathi



Scatt. pebbles in well flagged 2.5-5 cm lst.

Irreg. seams prod. pseudoknobbly pure lst., irreg. weathering; below 2.5-5 cm flags sep. by sandy pebbly seams, very incip. pebble band at 89.3 m, pebbles av. 0.95 cm, max. 2.5 cm, abundant coarse sand. Below typical sand-pebb. layers, streaks, ellipses, circles (?borings) between and within slightly sandy lst. flags, av. 2.5-5 cm occ. molluscs and pebbles.

Top of Wh. Slst. seen as deep weathering indent in sandy-silty lst., sl. fritt., occ. borings throughout, overlain by 25 cm of highly burrowed calc. sst. with mod. abund. pebbles at top, av. 1.3 cm, max 3.2 cm, occ. pebbles within borings, pebble unit little thickness, borings 0.6 cm - 1.8 cm diam., ellipt., horizontal orientation. & better cem., below about 15.25 m of mass. silty-s.lst.,m grad. into some 53.4 m of mst.

(Gap of 52 m, upper 12m of silty-s. lst., remain. bl/gr. mst)

Massive blue-grey calc. mst., frittered weathered surface.

7.5 cm massive calc. sst., slightly weathered, mod. sharp lower boundary.

Rel. massive, slightly irregular surface sandy lst., echinoids seen.

Mass. incip. ripply, pseudoflags, typically wide av. 12.7 cm. Bivalve debris comm., echinoids, incip. sl. sandy seams, sl. sandier downwards.

Massive calc. ssts., common borings.

Massive calc. ssts., occ. harder parts, borings common.

Soft, w., tending fritt. calc. sst., borings typical and abund. ff-hash debris, occ. harder concret. borings better cem., prolific borings immed. below 7 m.

Mesozoic basement rocks (slst).

Stratigraphic Column No: *C-51* **Grid Reference:**

Region: King Country/Waitomo

Location: Kairimu Road, south of Awamarino

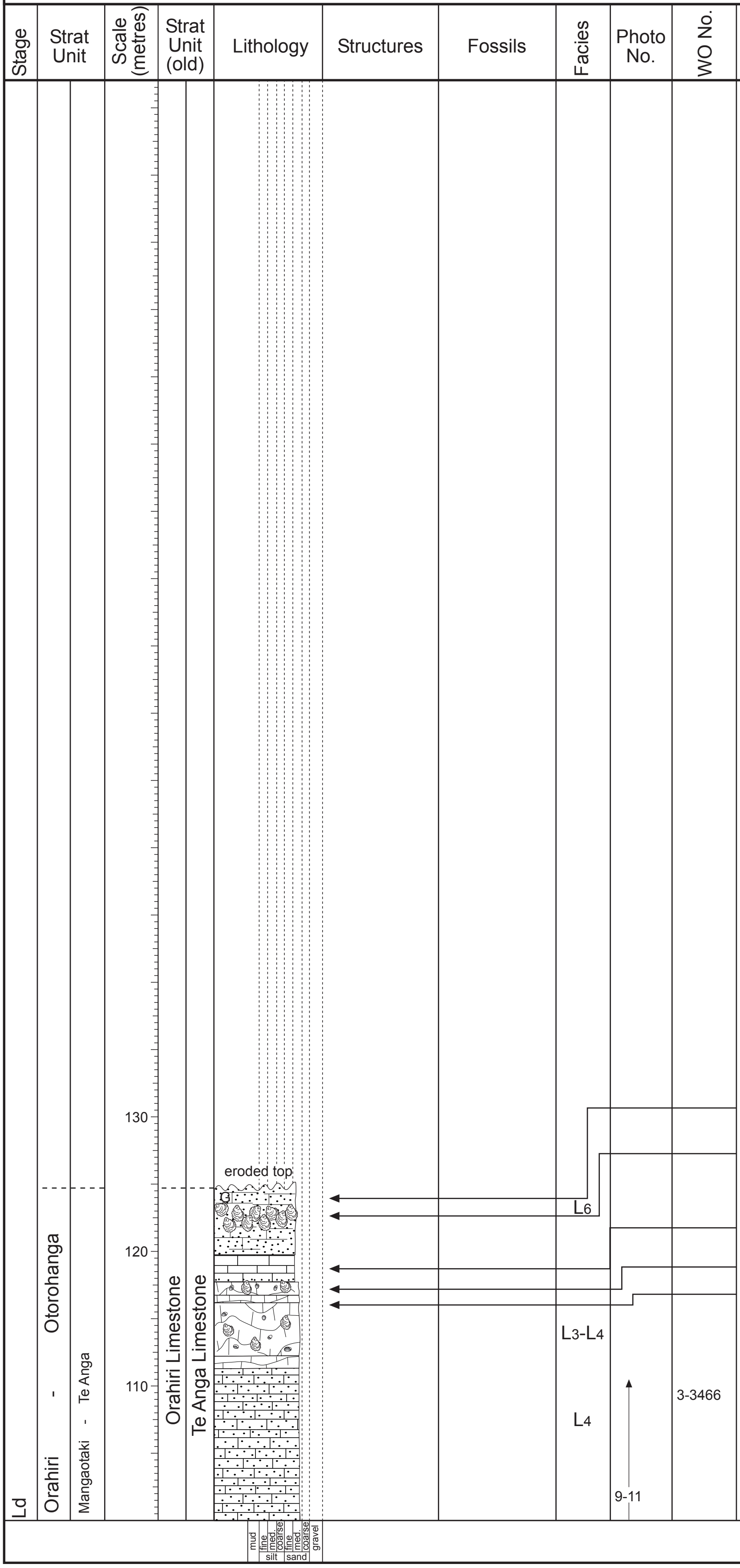
E: 2667777 - 2668359

N: 6319216 - 6320388

NZMS 1 Sheet: R16

Page 2 of 2

Author: C. Nelson
Modified: A. Tripathi



V. weath. s. lst., mass. with microripply surf., packed with bryozoans, 15.2-23 cm band of mass. hard. slightly glauconitic lst at base.

Oyst. bands near top, mid and bott. of unit, unorient., artic. and disartic., some iron-staining, incip.-mod. irreg. seams av. 2.5-5 cm. below 121.6 m pure, mod.-well dev. seams, down into jointed lst., in turn foll. by 0.9 m of mass, s. gritty lst.

V. white pure, mod. flagged, av. 5 cm seams shelve, gritty at base where mod.-well dev. flags, av. 2.5-5 cm.

Scatt. oysters and pebbles, av. 0.6, max 2.5 cm, oysts. unorient., disartic., incipient irregular seams, av. 5 cm apart.

116.2-116.8 m massive-incipient flags, vert. joints, pure, semiknobbly app.

Incip.-mod. flags 2.5-5 cm w. scatt. pebbs. av. 0.6 cm, oysters common, artic. and disartic., haphaz., bryoz., seams less obvious downwards, pebbles not abund., yellow mst. liths. in compos. occ., oysters disappear by 112.2 m. Below 7.6 cm irreg. seams, av. 7.6 -10 cm apart, micritic.

Mod.-well flagged 2.5-5 cm lst., occ. veining, scatt. grit 110-111 m, featureless flaggy lst., flagginess better developed below 103.7 m.

2.5-5 cm flaggy lst. with quartz grains etched on lst. surface, only sl. sandy lst. however.

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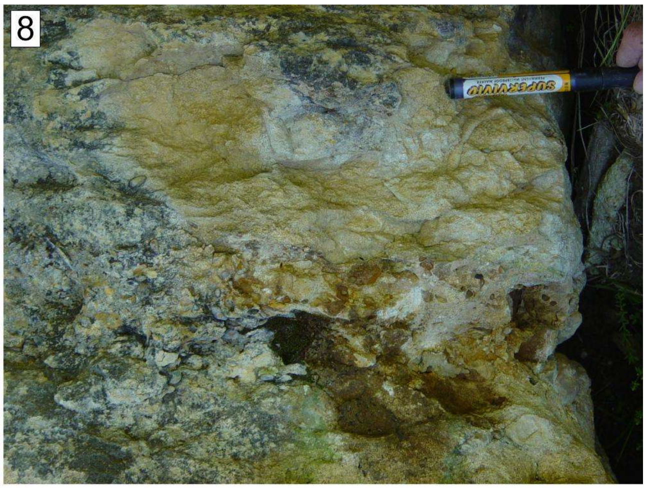
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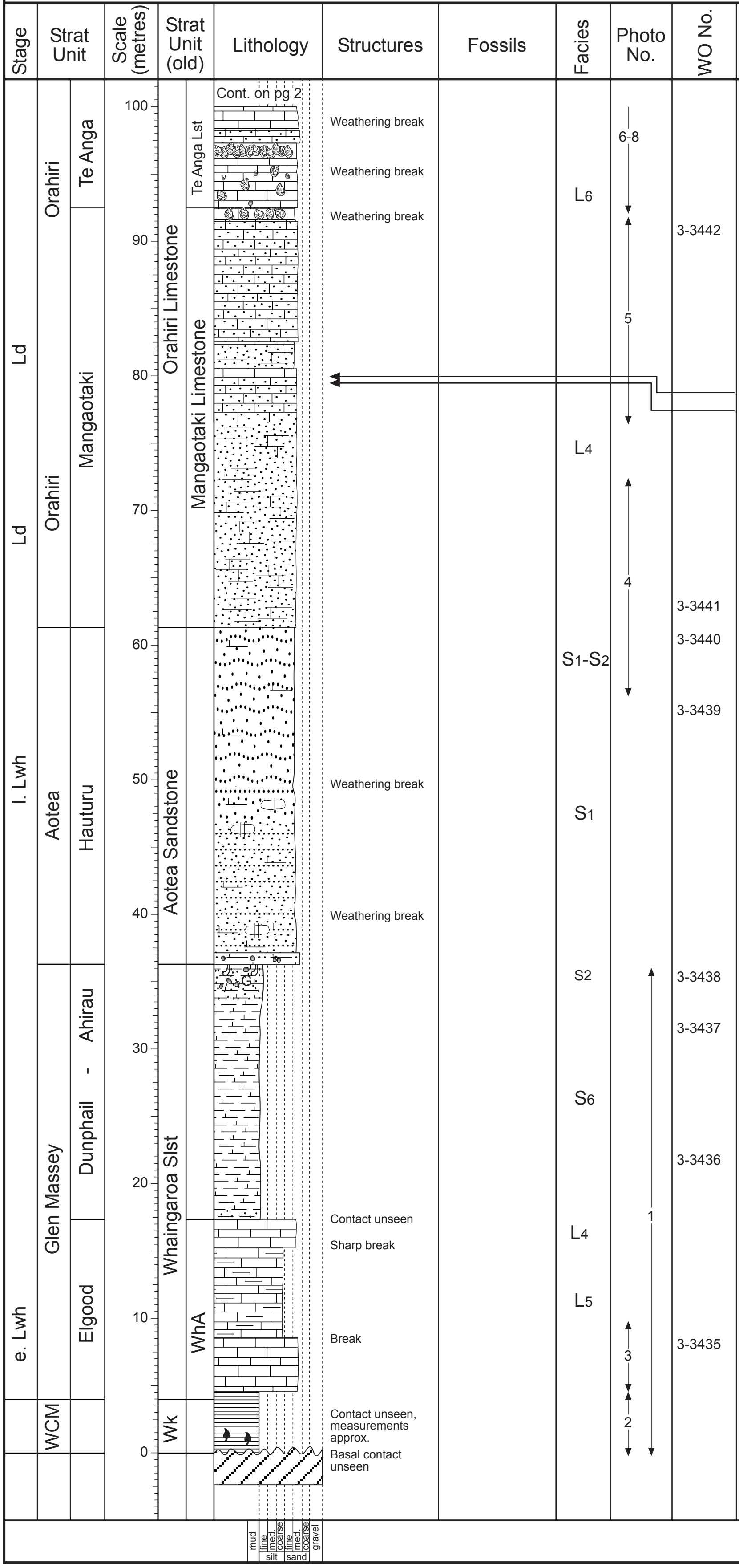
Stratigraphic Column No: *C-56*
Region: King Country/Waitomo
Location: Mangaohoe Stream

NZMS 1 Sheet: R16

Grid Reference:
E: 2674344 - 2675224
N: - 6317359

Page 1 *of* 2

Author: C. Nelson
Modified: A. Tripathi



Description

Red iron-staining above 97.3 m, mass. sandy lst. dev. incip.-mod. flags upwards, sl. glauc.

Oysters > matrix.

Incip. flagged 2.5-5 cm oyster scatt. throughout, occ. prolific, gen. disartic., oyster clusters, very occ. pebbles.

Scatt. pebbles, max 2, av. 1.6 cm, more conc. immed. below 92.4 m where to 2.5 cm, micritic lst.

91.8-92.1 m - oyster band, matrix > oysters gen., disartic., intraclasts present.

Mass.-very incipient seams, irreg., sandy lst.

Incip. seams - ripply, 2.5 cm apart.

Red iron-stained zone, v. incip. seams-ripply, v. thin yellow zone above

Ripply surf. lst., ripples av. 2.5 cm.

'Honeycomb' weath., sl. more mass., bimodal terrig. grain sizes evident.

Ripple surf. s. lst. (calc. sst).

'Honeycomb' weathering unit.

Mass. ripply s. lst., ripples app. as inv. seams av. 2.5 cm apart.

Mass.-inv. ripply s. lst.

Mass.-incip. ripply calc. f. ssts.

Ssts. app. bded.-like along strike, variable weath. appearance.

Bedded. sst.

Mass. ripply calc. ssts., surface ripples accentuated.

Mass. ripply and bded. calc. ssts., often bding. weak and irreg. distrib.

36.6-37.2 m mass. smooth surf. calc. sst. with very occ. pebbles. Bored contact, ellip.-circ. borings av. 1.25-2.5 cm, in pebbly glauc. s. mst., pebbs. to 5 cm, av. 2 cm, mass. and fritt., undermined, contact blurred for 15 cm.

Bl/gr. calc. mst., fritt. weath. surf., sl. sandier at base and very sandy 33.5-36.6 m.

Pure well-flagged av. 10-15 cm, lst.

Mass. lsts., tends fritt., muddy.

Mass.-incip. seamed lst., thick seams.

Variable horizon of coals, carb. mst., leached red and white puggy clays, irregular distrib. and local.

Mesozoic basement rocks.

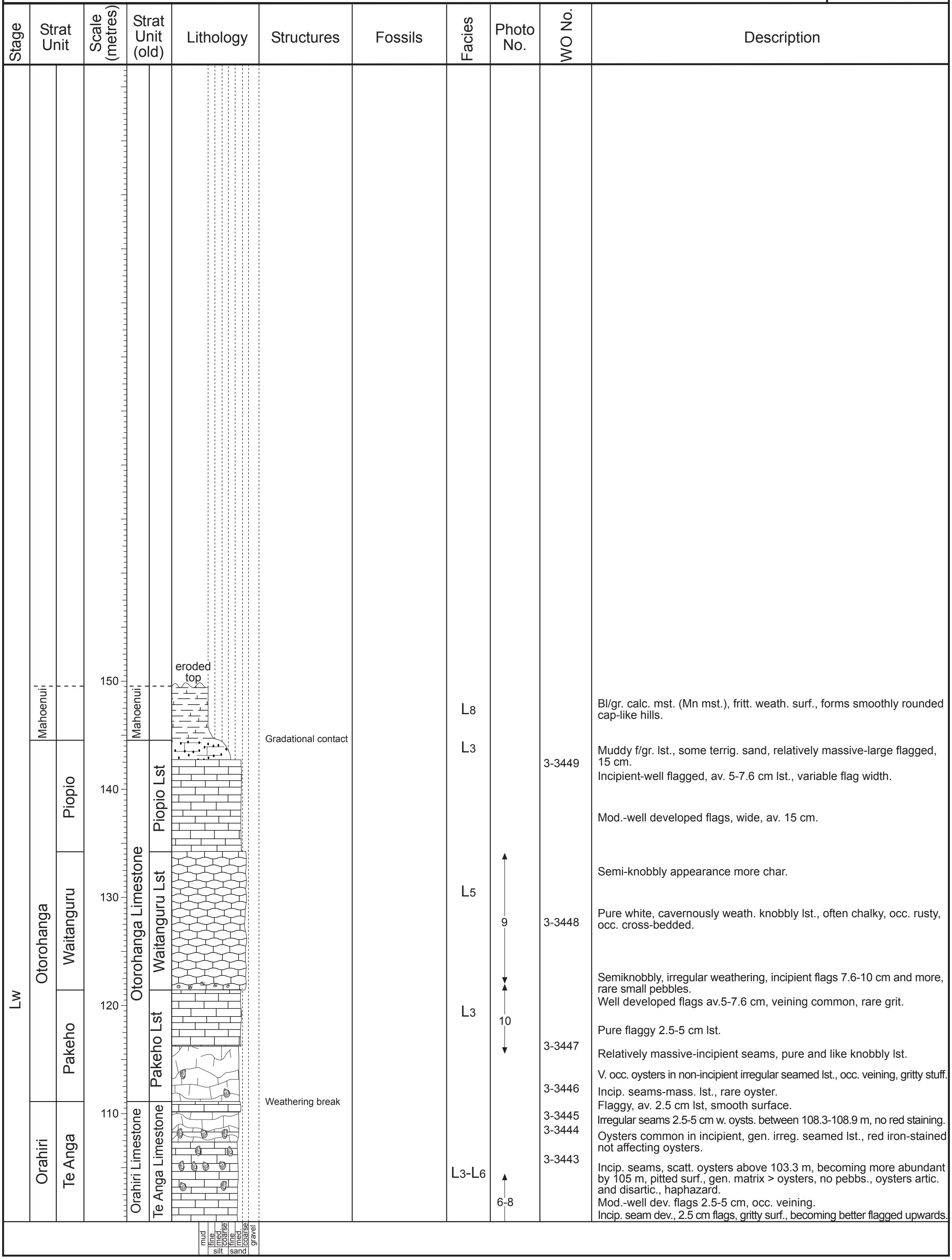
Stratigraphic Column No: *C-56*
Region: King Country/Waitomo
Location: Mangaohoe Stream

Grid Reference:
E: 2674344 - 2675224
N: 6318573 - 6317359

NZMS 1 Sheet: R16

Page 2 *of* 2

Author: C. Nelson
Modified: A. Tripathi



Bl/gr. calc. mst. (Mn mst.), fritt. weath. surf., forms smoothly rounded cap-like hills.

3-3449 Muddy f/gr. lst., some terrig. sand, relatively massive-large flagged, 15 cm.

Incipient-well flagged, av. 5-7.6 cm lst., variable flag width.

Mod.-well developed flags, wide, av. 15 cm.

Semi-knobbly appearance more char.

3-3448 Pure white, cavernously weath. knobbly lst., often chalky, occ. rusty, occ. cross-bedded.

Semiknobbly, irregular weathering, incipient flags 7.6-10 cm and more, rare small pebbles.

Well developed flags av.5-7.6 cm, veining common, rare grit.

Pure flaggy 2.5-5 cm lst.

3-3447 Relatively massive-incipient seams, pure and like knobbly lst.

V. occ. oysters in non-incipient irregular seamed lst., occ. veining, gritty stuff.

3-3446 Incip. seams-mass. lst., rare oyster.

Flaggy, av. 2.5 cm lst, smooth surface.

3-3445 Irregular seams 2.5-5 cm w. oysts. between 108.3-108.9 m, no red staining.

3-3444 Oysters common in incipient, gen. irreg. seamed lst., red iron-stained not affecting oysters.

3-3443 Incip. seams, scatt. oysters above 103.3 m, becoming more abundant by 105 m, pitted surf., gen. matrix > oysters, no pebbs., oysters artic. and disartic., haphazard.

Mod.-well dev. flags 2.5-5 cm, occ. veining.

Incip. seam dev., 2.5 cm flags, gritty surf., becoming better flagged upwards.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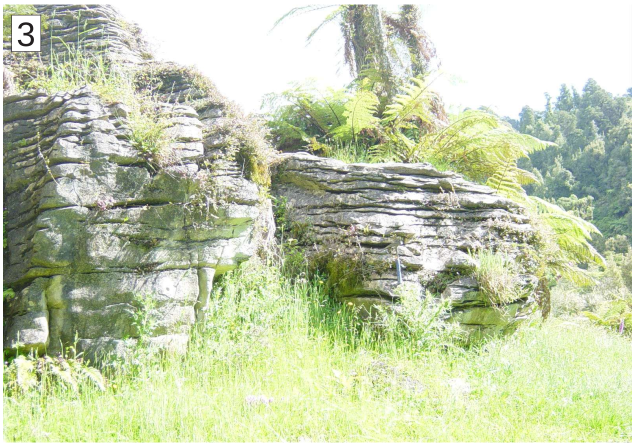
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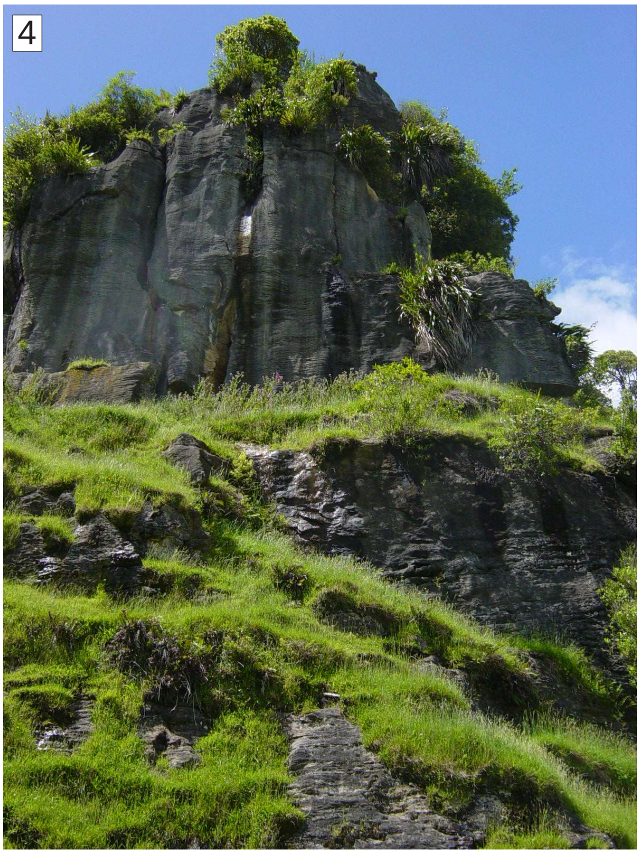
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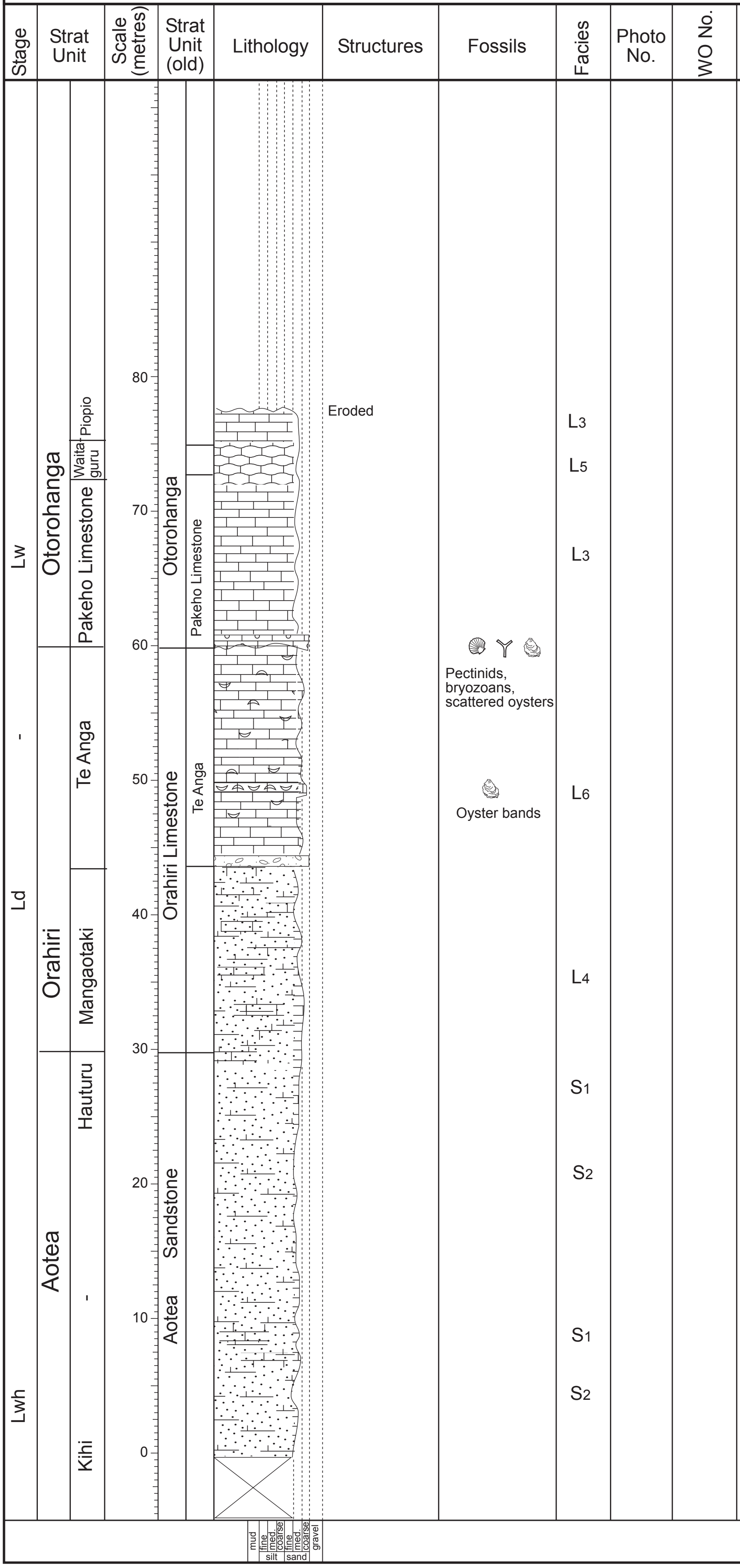
Stratigraphic Column No: C 61
Grid Reference:
Region: Waitomo/King Country
E: 2677818
Location: Ngapaenga
N: 6315274

NZMS 260 Sheet: R16
Page 1 of 1
Author: C. Nelson
Modified: A. Tripathi



Description

Mod well flagged limestone, variable flag width, generally wide

Well developed knobbly limestone, slabby to semi-knobbly in the lower part

Monotonous sequence of mod well developed flaggy 2.5-8cm limestone, occas veining, smooth surface

Scattered tiny pebble, above irregular contact, fossiliferous hash zone, incipient seams, iron stained, pectinids, occas oysters, scattered pebbles

Mod - well flagged 2.5-5 cm limestone, occas oyster

Oyster bands, generally disarticulated, with scattered pebbles, irregular seams semi knobbly appearance, occas haphazard oysters

Pebble bands, slightly gritty surface, fossil hash

Massive smooth to incipient ripply sandy limestone

Bedded calcareous sandstone, highly weathered, honeycombed surface appearance

Massive ripply variable sandy, calcareous sandstone-sandy limestone, occas bedding, some calcite veining, sandy seams evident

Massive ripply calcareous sandstone, banded appearance at several horizons

Slabby bedded calcareous sandstone

Calcareous Sandstone: Massive, ripply, well developed sandy seams, wavy

Stratigraphic Column No: *C-68*

Region: King Country/Waitomo

Location: Southeast of Ngapaenga

NZMS 1 Sheet: R16

Grid Reference:

E: 2680545 - 2681183

N: 6313887 - 6314630

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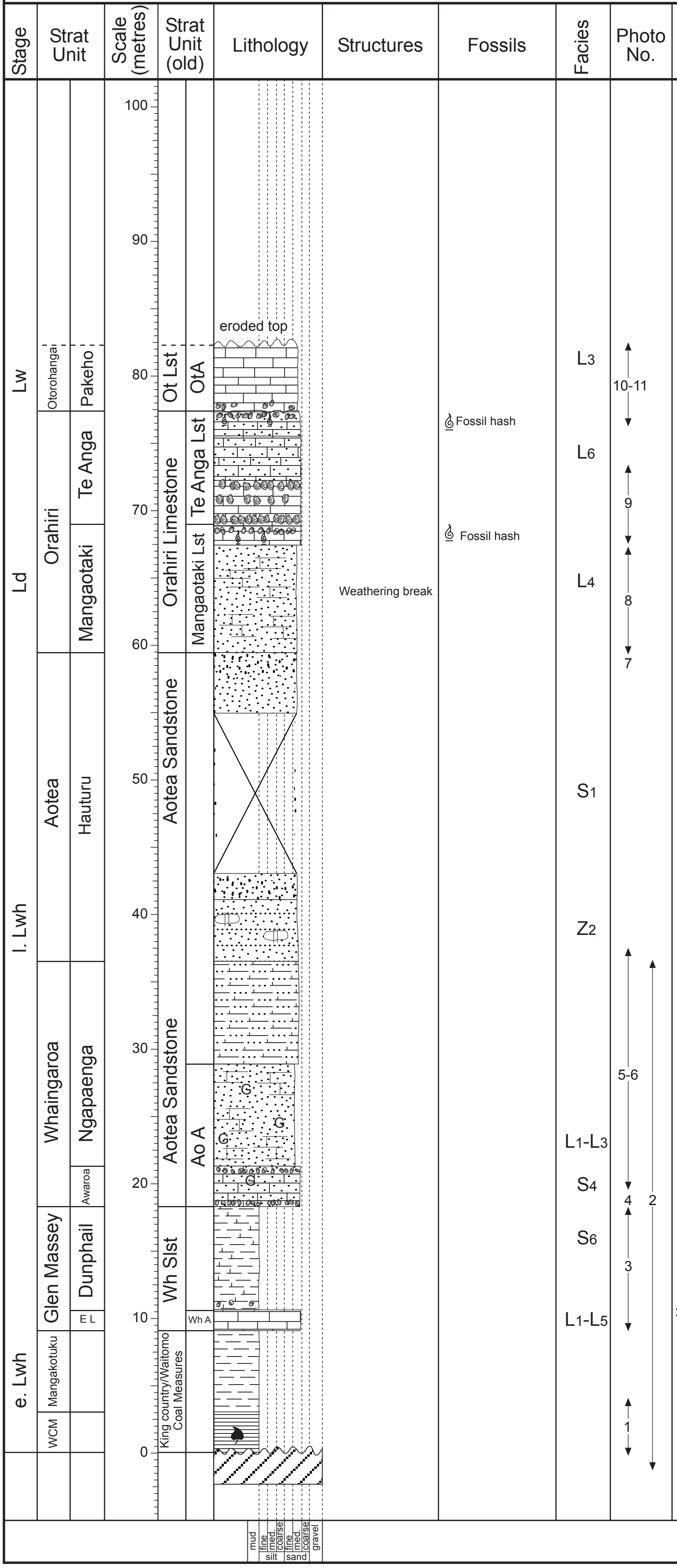
Author: C. Nelson

Modified: A. Tripathi



WO No.	Description
3-3434	
3-3433	Pure flaggy, av. 2.5 cm lst., gritty surf. feel, occ. Athlopectin seen.
3-3432	Pebbs. to 2.5 cm scatt. near base, subang.-subrded., veining present.
	Iron-stained ff-hash zone, pebbs. to 15 cm scatt., mass., non-seamed, upper bdy. irreg.-pocket-like, mass. below.
3-3431	Sl. sandy lst. w. incip. flags 2.5-5 cm, no glauc., red colour in lower part.
	Oyst. band, oyst. = matrix, v. haphazard.
	Incip. seams, tend ripply, gritty surf. feel, v. occ. pebb. to 1.3 cm, incip. oyst. band at 71 m.
	1 m oyster band.
	Pebb. horizon, to 13 cm seen, v. incip. seams, tends mass., ff-hash and occ. semi-knobbly.
3-3430	
	Massive large ripply sandy lst.
	Ripply, massive sandy lst., occasional veining.
3-3429	
3-3428	
	Steep grass slopes w. no obvious exposures. Presum. highly weath. bded. sst. liths.
	Incip.-mod dev. bded. ssts., hard bands 5-15 cm sep. by soft sand 2.5-5 cm.
	V. mass. calc. sst., smooth surf. weaths. fritt., forms ledge in area.
3-3427	
	Poorly exposed glauc. s. lst., mass. ripply, forms gentle slope.
3-3426	
3-3425	Pebb. band 7.6-20 cm wide, pebbs. to 2.5 cm, gen. sm., sl. glauc., in mass. s. lst., tends fritt. 19-20 m - 2.5-5 cm flags and more mass. 18.3-19 m , pebbs. scatt. throughout, 10 cm pebb. band at base, pebbs to 4 cm.
3-3424	
3-3423	Bl/gr. calc. mst., mass.
3-3422	Sl. pebbly calc. mst.
3-3421	Rippled surf. lst., pyrite.
	Poorly exposed mst., suggested Mangakotuku affinities.
	Interbedded coal and carb. msts.
	Mesozoic basement rocks.

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Ngapaenga Zst
Awaroa Lst
Dunphail Zst
Elgood Lst
Mangakotuku Fm
WCM
Basement

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Stratigraphic Column No: *C-78*
Region: King Country/Waitomo
Location: Between Mangaohae and Waitanguru
NZMS 1 Sheet: R16

Grid Reference:
E: 2672653
N: 6313773

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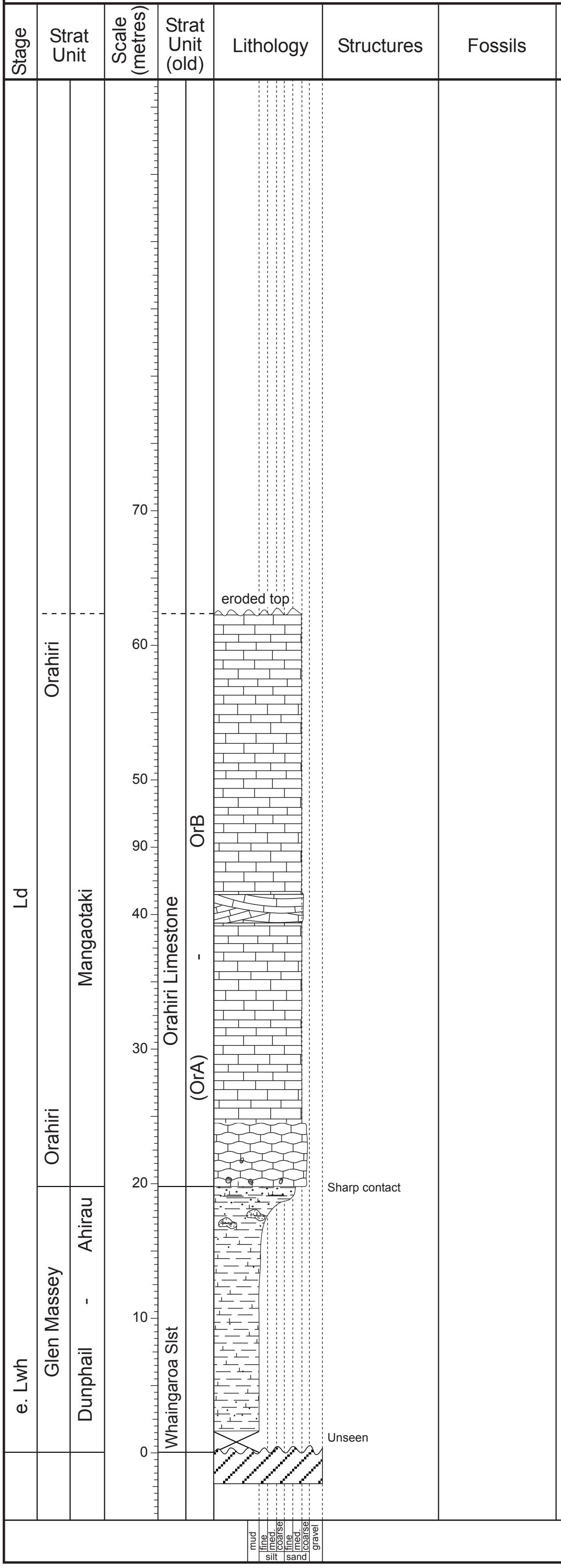
Author: C. Nelson
Modified: A. Tripathi



Facies	Photo No.	WO No.	Description
L3			Mod.-well dev. flaggy 2.5-7.6 cm lst., common gritty surface feel.
L2			Incip.-mod. seams, av. 4-7.6 cm apart, very occ. veining.
L3-L4			Cross beds, dip 5° E.
			Incip. flaggy lst., weath. out to show seams only 1.3-2.5 cm apart.
L1			Incipient-mod. flaggy lst., gritty surface.
L6			Mass. pure lst., with very occ. pebbles to 5 cm near base, over basal 30 cm scatt. pebbs. in white c/gr. knobbly lst.
S4			Bl/gr. muddy calc. sst., weathering fritt. with iron-stained concret. horizon some 15-60 cm thick.
S6			Bl/gr. frittery calc. mst.
			Slightly sandy calc. mst.
			Mesozoic basement rocks.

Stratigraphic Column No: *C-8* **Grid Reference:**

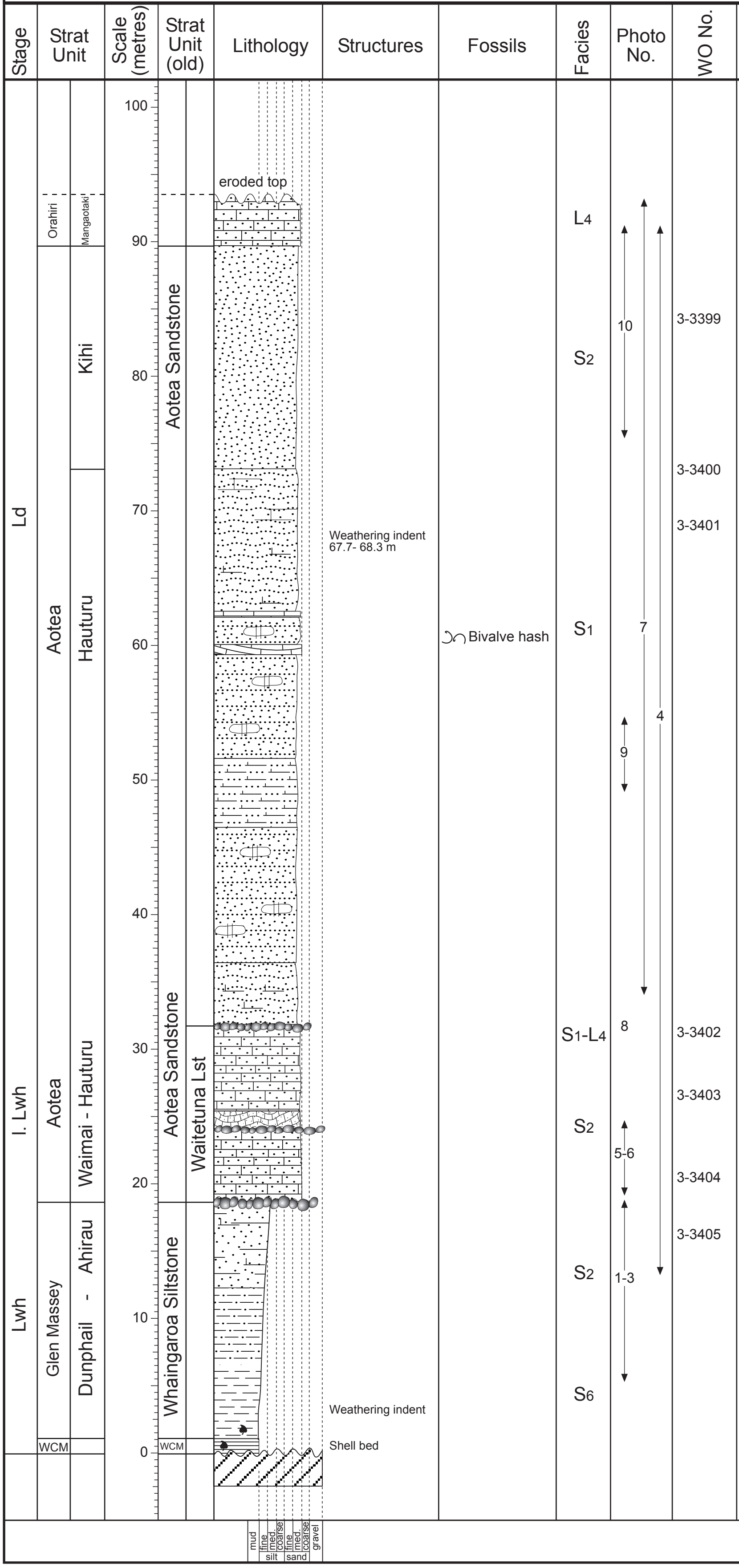
Region: King Country/Waitomo

Location: Paparoa Stream, Kaimango Road

E:	2683738	-	2683548
N:	6337056	-	6337073

NZMS 1 Sheet: R16

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



Description

1.2 km south "The Dome" shows at least 24 m of purer flaggy lst. above top

Very incip. seamed - mass. ripply s. lst.

Highly weath. yellow sands, no "hard" outcrops present. Leaching severe, outcrops poor

Mass. incip. ripply s. lst.-calc. sst.

W. Br ~65-65.5 m, prod. by sl. muddier ssts. Mass., sandy, sl. fritt.

Sharp contact 62.5 m w. 0.3 m hard lst. Bded. ssts. below.
59.5 - 60 m - mod. flagged, av. 5-7.5 cm lst., x-beds and laminations evid., also bivalve hash

Bded ssts., hard to soft "concret.", soft shows occ. ff.-debris

45° shelf, poor expos., mass.-incip. seams calc. ssts

Bded. ssts., hard comm. almost obl. leaving yellow sands, hard bands app. as thin irreg. platy lenses

Calc. sst. w.v. "rippled" surf., each ripple somewhat less sandy and gives shelving app. flags

Pebb. lst. forming 20 cm band, pebbs. scatt. to mod. packed, av. 0.3 cm, max 1.5 cm, scatt. ff-debris, thickn. varies, occ. weath. in. below band. Lst. below av. 5-15 cm flagged s. lst. w . vert. joints, sl. bded app. in weath. indent

Sand seams in lst. wide and lst. comm. has slabby bded app.

Highly irreg. narrow sand seams sep. purer sl. gl. s. lst., vari. thick. along strike, 4 cm pebb. band at base, pebbs. av. 0.3, max 2 cm, and packed

Slabby s. lst., prom. seams and weath. to give bedded app.

Pebble band 22 cm thick, packed, av. 0.3 cm, max ~2 cm, pebbs. weath. Occurs on sm. cliff face below swampy ledge

Mass. ripply muddy calc. ssts, occ. pseudobded, poorly exposed

Small cliff in mass. ripply muddy calc. ssts

Around 6.7 m incr. in sand content of sandy msts

Bl/gr. fritt. s.mst., 45° slopes, common forms lge. ; char. pyrite concrets. - limon. tubules and ellipsoids, leaves, concentric weath. casts

Carb. msts. occur locally at base; pale grey msts and concets. w. ff., coaly layers, leached clays on Mesozoic basement rocks

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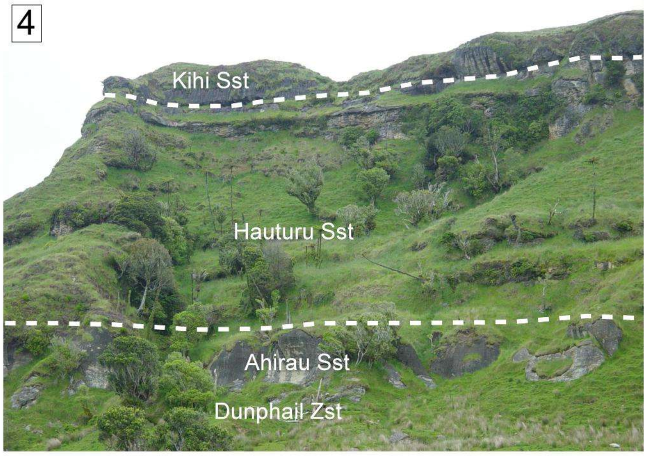

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Stratigraphic Column No: *C-85*

Region: King Country/Waitomo

Location: North of Mangaotaki

NZMS 1 Sheet: R16

Grid Reference:

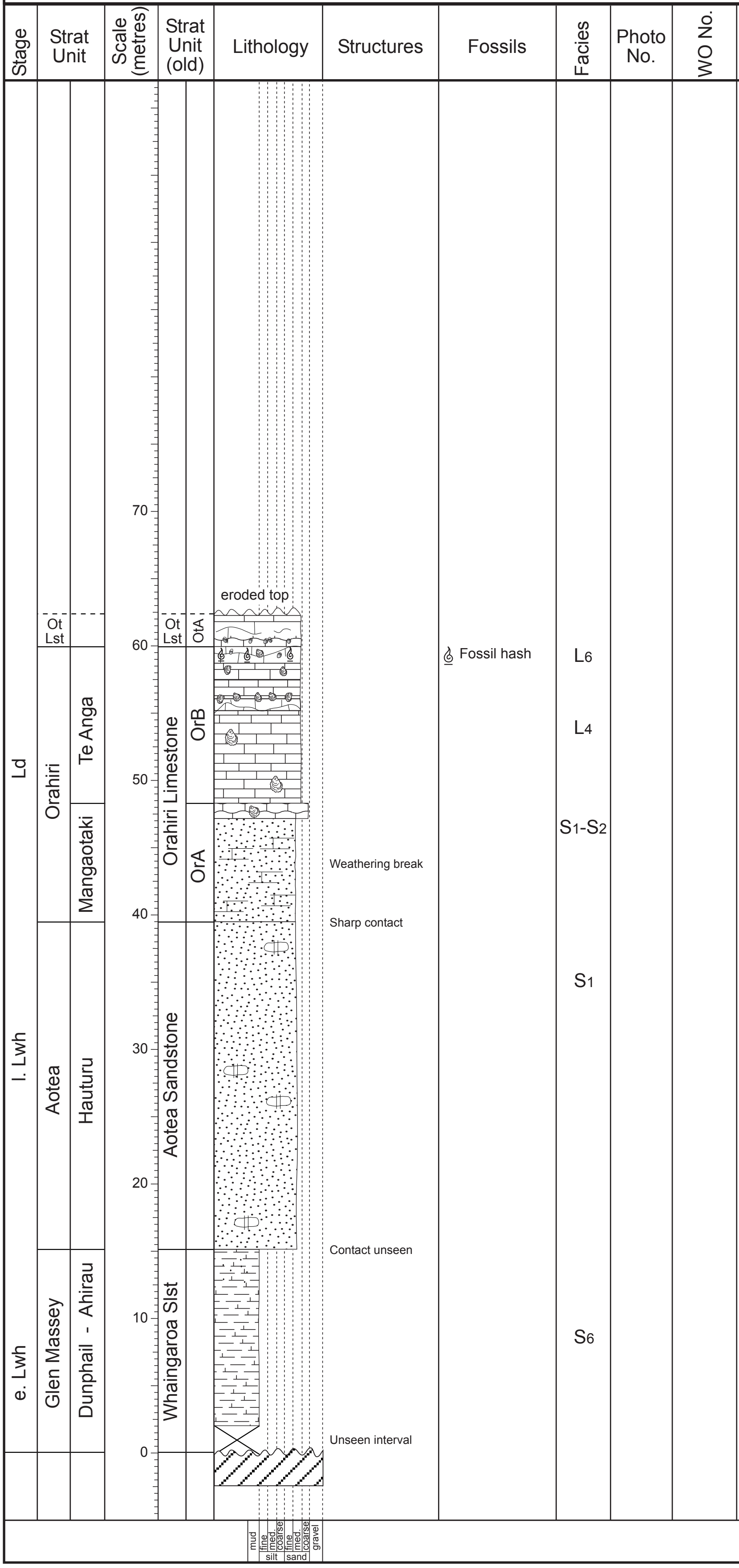
E: 2674561

N: 6310061

Page 1 *of* 1

Author: C. Nelson

Modified: A. Tripathi



Description

Pure flaggy 2.5-5 cm lst., slightly wavy seams.

Mass.-incip. seams, incip. knobbly lst., scatt. pebbs. av. 1.3 cm, max 2.5 cm.

Fossiliferous-hash zone, iron-stained, occ. tiny pebbs., v. incip. seams, occ. veining, oysters and pectins.

56.4-57.6 m reg. 2.5-5 cm flags, occ. oysters.

56.1-56.4 m oyst. band, gen. oysters < matrix, oysters artic., haphaz., grad. contacts.55.2-56.1 m irregularly seamed lst.

Flaggy 2.5-5 cm lst., occ. inv. seams and oysters, smooth surface feel, reg. seams.

Pronounced strat. break, below seams v. irreg., semiknobbly app., v. occ. oysters.

Mass., incip. seamed s. lst.

Mass.-ripply sandy lst., smooth surf., sand grain par. bed.

Mass.-rippled surf. calc. sst., gen. very weathered.

Evid. of banded calc. sst. at various levels, hard bands protrude as elongated slabs from soft sandy zones, var. exposures.

Bl/gr. calc. mst., mass., fritt. surface as smooth slippery slope.

Mesozoic basement rocks.

Stratigraphic Column No: *C-94*

Region: King Country/Waitomo

Location: Pungarehu Road, west of Mairoa

Grid Reference:

E: 2680521

N: 6310624

NZMS 1 Sheet: R16

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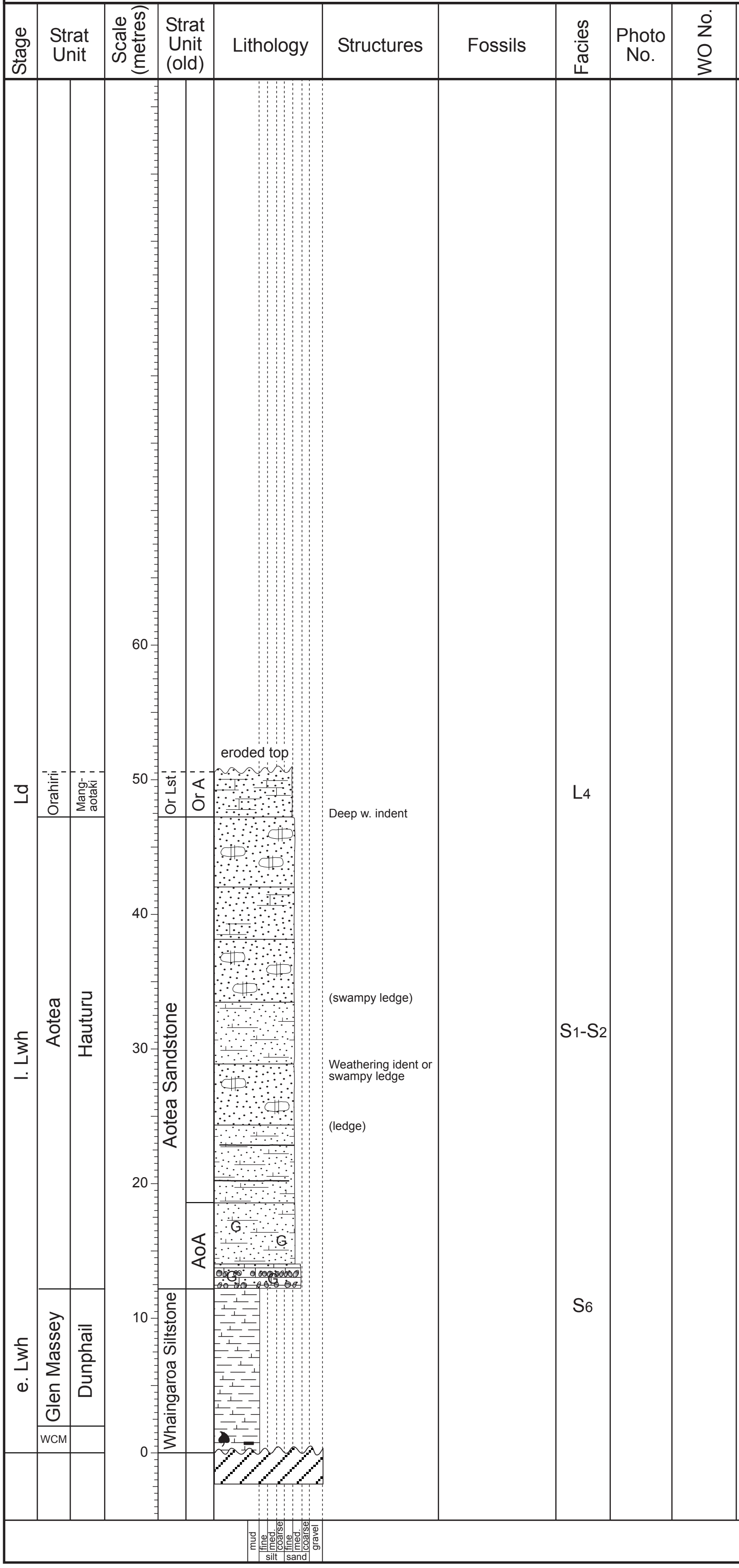
Author: C. Nelson

Modified: A. Tripathi



Description

Mass. sandy lst., ripply surface, non-seamed.

Bded. sst., var. appearance along strike where only incip. bded.-mass.

Contin. bands of better cem. calc. sst. separated by soft 2.5 cm wide sand seams (cf. flags and seams). Mass.-ripply near base.

Banded sst.

Frittery weath. massive calc. sst., sl. glauc., forms smooth mossy slope.

Incip.-mod. developed bedded. sst.

Incipient seamed, 10-15 cm apart, calc. sst.

Bl/gr. slightly glauc. calc. sst., forms swampy slope, poorly exposed.

1.8 m shoulder of glauc. s. lst., pebbs. th/out. to 3.8 cm seen, pebb. bands at 13.25 -13.42 m & 12.2-12.5 m, pebbs. packed but sm. and comm. weath., lst. mass. w. rippled surf.

Bl/gr. calc. mst.

Poorly exposed leached red to white puggy clays.

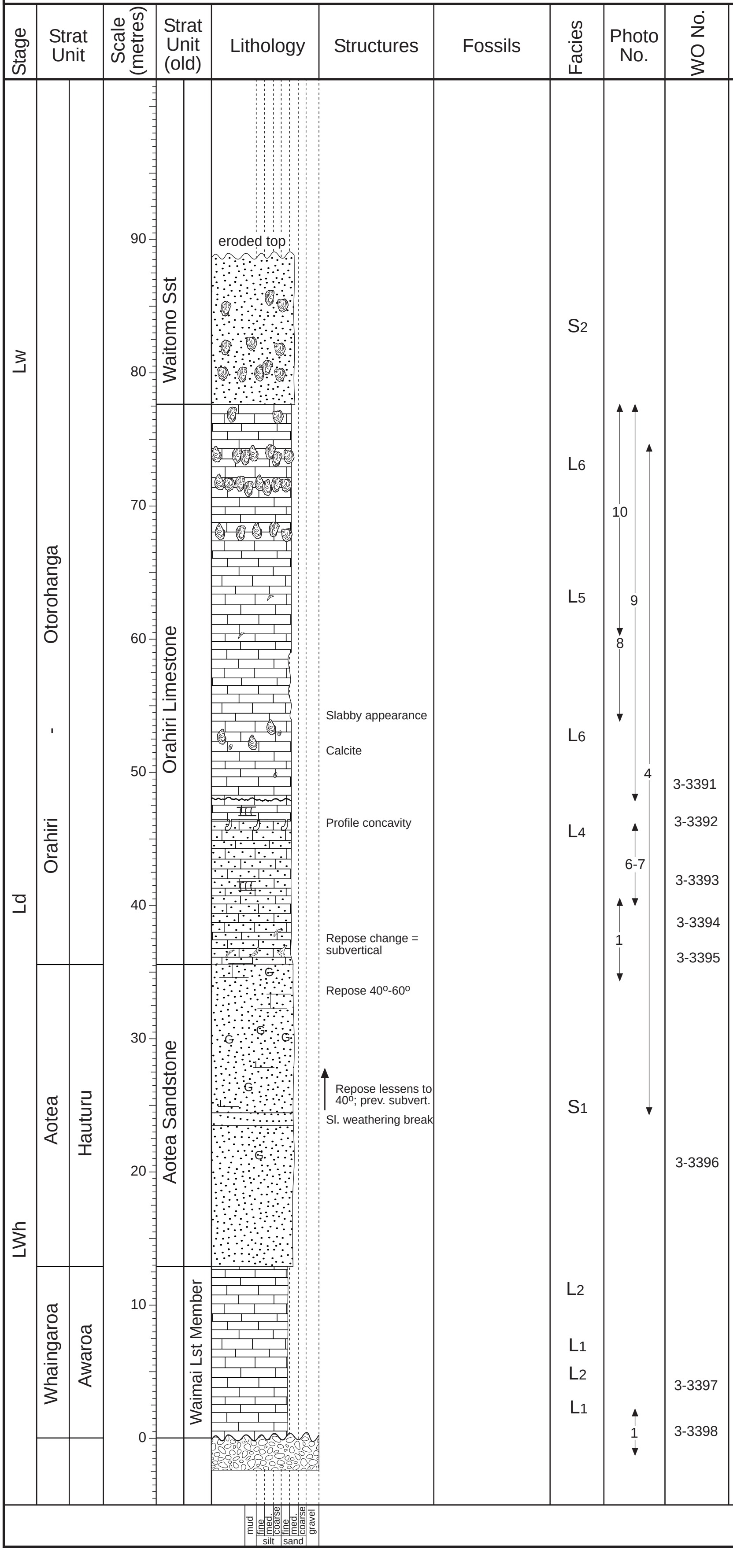
Mesozoic basement close by.

Stratigraphic Column No: *S11*
Region: Aotea - Kawhia
Location: ca. 2km south of Pukenoi

NZMS 260 Sheet: R16/ 755379

Grid Reference:
E: 2675500 - 2675339
N: 6337900 - 6337911

Page 1 *of* 4 **Author:** D. Fergusson



Description

Massive, frittery.

Bands of whole, loose oysters, loosely packed, no pref. orientation.

Loosely-mod. packed oyst. and fossil impressions.

Mod. packed oyst. band. Micritic matrix.

Wavy flags.

Well flagged; flags variable thickness 4-12 cm. Seams well devel. Vertical joints in flags impart blocky app. to outcrop.

Disartic. oyst. valves. Cr.-white, bioclastic pure lst with v. rare grans. Incip. flaggy - seams sl. developed.

Lt. or.-gr., mod. ind., sl. gran. bioclastic lst. terrig.-rich seams. Ripply-incip. flaggy.

Reddish-or. lst, prob. endolithic algae. Ripply/smooth surface, reflects poorly dev. seams.

Crys. sl. s. bioclastic lst.

Mod. in., m-crs S. lst. massive-ripply, occ. erosional pockets. Pink discolouration in o/c - prob. caused by presence of endolithic red alagae. Incip. flaggy-ripply.

Flaggy; flags 8-10 cm, seams 3-5 cm.

Conspic. shell frags; oyst? Pronounced erosional seam.

Lt. or.-gr., mod. ind., m-crs S lst?-v.c. sst. Flaggy, seams deeply weathered.

Or.-br., wk.-mod. ind., sl. glauc., calc (f-m) sst with rare small pebbles. Horizontal burrow noted. Pocked outcrop surface, massive-ripply (form somewhat aspect dependent).

Lt. or.-br., mod. ind.,m sl. glauc., m (crs S) clacl. sst. Massive-ripply.

Lt. or.-cr., mod. ind., v. sl. glauc., (qtz. s) calc. sst. Rare inverted seams.

Low ang. x-beds (14º app. dip E); sets differentially cemented as with bedded
lithofacies.

See pg 2 for detailed column 0-20 m

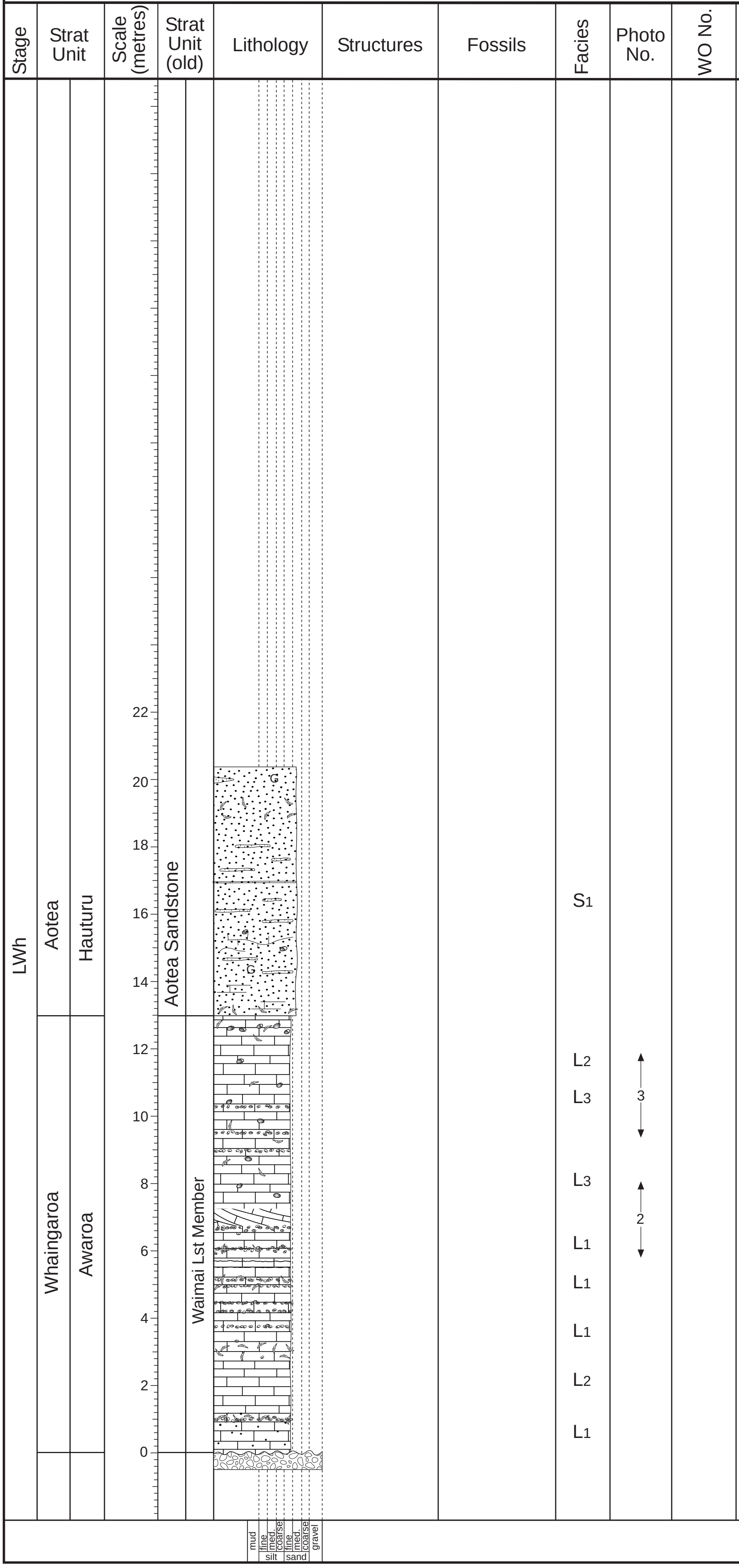
Waiharakeke Conglomerate, Late Jurassic. Contact sharp; has relief, effects of compaction evident in Waimai Lst.

Stratigraphic Column No: *S11*
Region: Aotea - Kawhia
Location: ca. 2km south of Pukenoi

NZMS 260 Sheet: R16

Grid Reference:
E: 2675500 - 2675339
N: 6337900 - 6337911

Page 2 *of* 4 **Author:** D. Fergusson



Description

Yellow gr., mod. ind., v. sl. glauc., c. sst. massive - ripply.

Oyster frags.

Poorly devloped (= greatly weath?) bands.

Scattered m. pbls., ripply s. lst-c sst. Massive.

Band: yell. gr., mod. ind., v. sl. glauc., f.s. lst - v. calc. sst, otherwise leached c. sst. Knobbly-banded.

Seams av. 13 cm well dev. 162.5-165.6 m.

Seams av. 8 cm, freq. anastomose.

Scattered pbls., rare oyst. frags. ripply, seams < 1 cm, beds 2-3 cm

Pectinid frags., crs S. and shell frags. Weathering break.

Seams < 1 cm, spaced 2-3 cm. Thinnly flagged-ripply.

Gr.-cr., well ind., gran.-pebbly lst. with rare sharks teeth, oyster frags. Occ. pebble lenses.

Low ang. x-beds (12-16^{o} (app.) dip, NE).

Beds of grans.-sm./med. pbl. interbedded with mod. pbl. creamy cryst. lst.

L. or.-cr., mod. ind., pbl. band (cobbles-grans.) with lst matrix cemeting clasts. Largest clast = 12x15 cm.

Very thin, sl. inverted shallow seams.

Ol. gr., well ind., f-m s. lst, with conspic. shell frags. and rare SRF grains. Massive-ripply appearance.

Sm.-med.pebb. band; gran’s., oyst. frags. Lenses out laterally. Pebble band weath. pref. - sl. profile concavity.

Lt. ol. gr., well ind., slightly gravelly-pebbly sandy lst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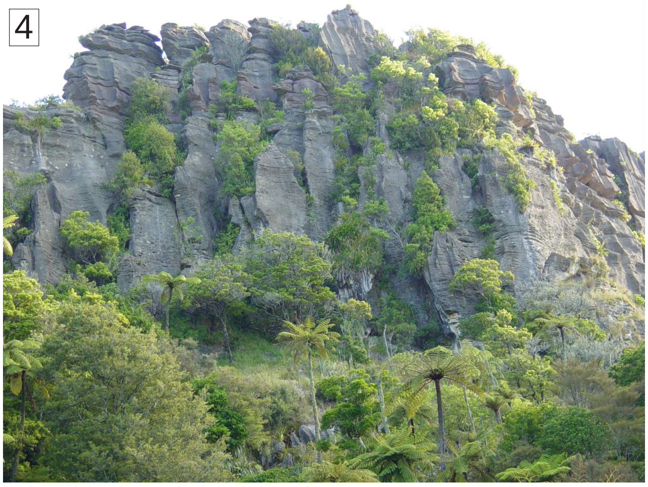
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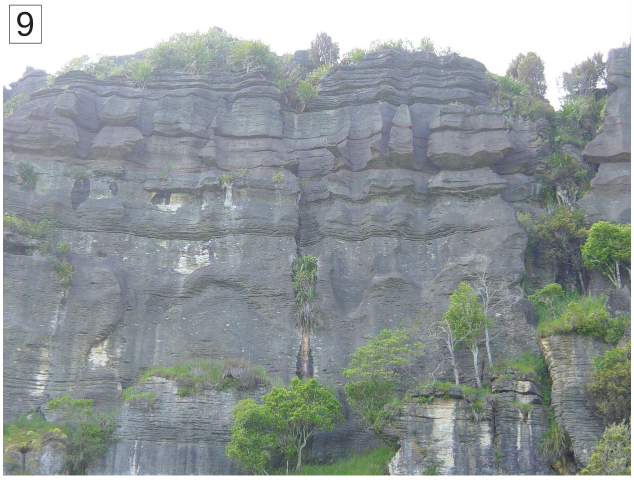

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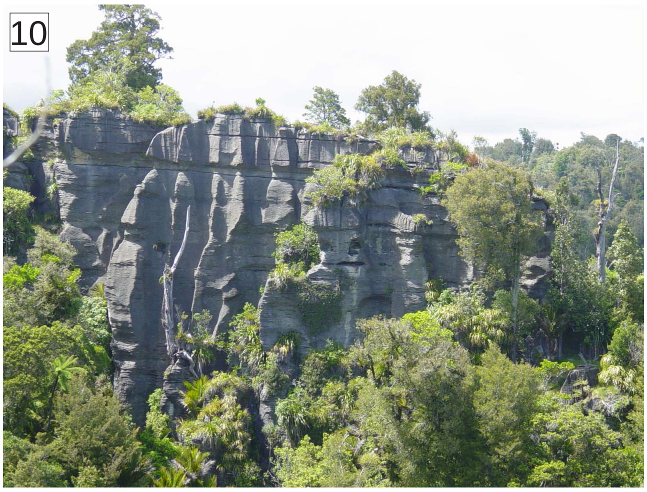
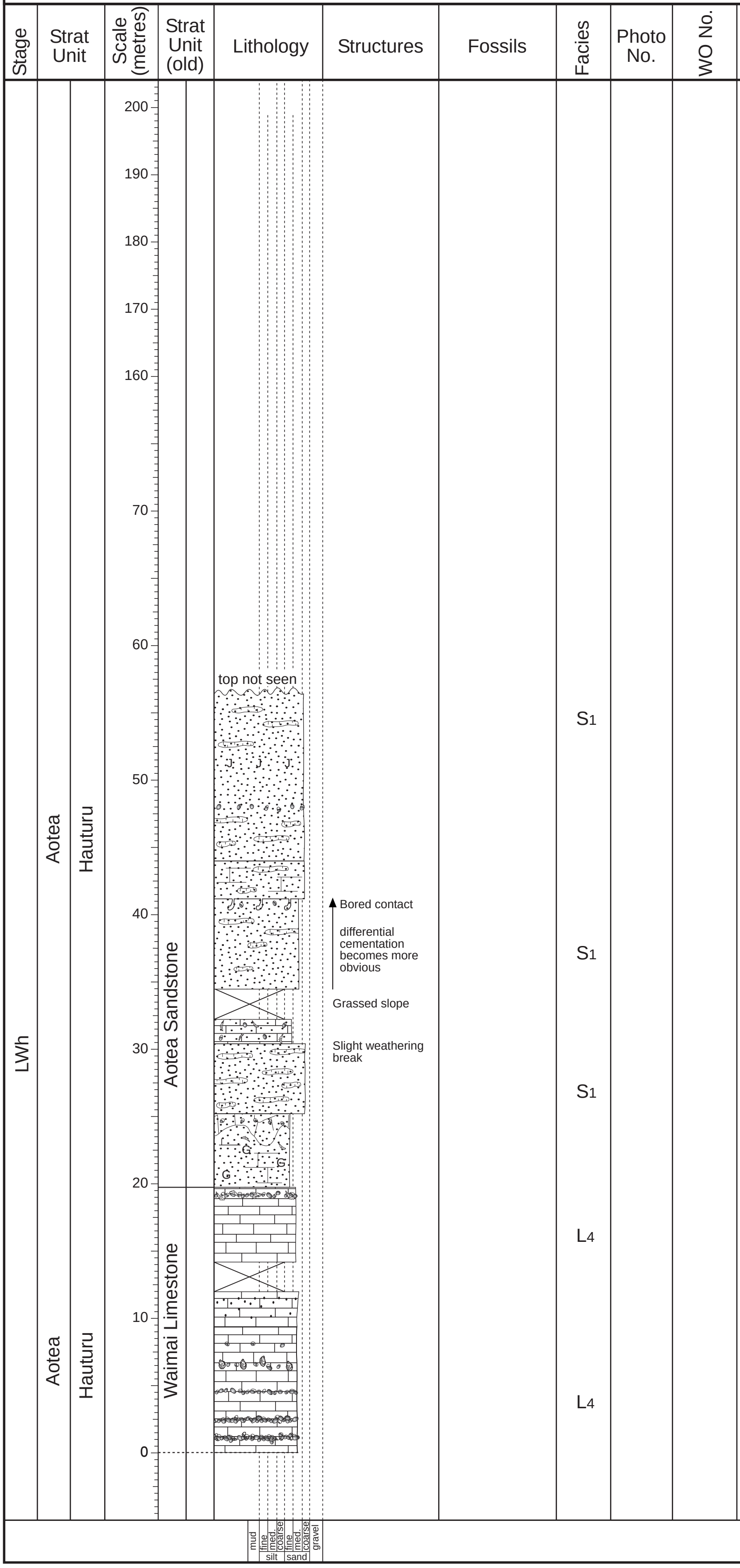


Stratigraphic Column No: S3; Greens **Grid Reference:**
Region: Aotea-Kawhia
E: 2676300
Location: Approx. 100 m north of Toi Road/bush line intercept
N: 6339700
NZMS 260 Sheet: R16/763397
Page 1 *of* 1 **Author:** D. Fergusson



Description

Lt. br.-gr., mod. ind., sl. glauc., v. calc. sst.

Massive ripply-incip. flags.

Diffuse pebb. band.

Lt. br-cr., mod. ind., sl. cryst. v.s. lst?-v.c. sst with some shell frags. conspic. on surface of o/crop. Banded; 2-4 cm.

Rare pebbs., worm tubes.Lt. brown, wkly ind., sl. glauc. c. sst., leached? Knobbly-banded concave slope profile.

Cr.gr., mod. ind. sl. s. Massive-ripply; sl. pocked outcrop surface.

Lt. or.-cr. gr., mod. ind., sl. pebbly, s. bioclastic? lst. Banded (3-5 cm); wavy terrig. rich seams.

Lt. or.-gr., wkly (matrix)-mod ('band') ind., sl. glauc, (qtz.s. cryst. lst-) v.c. sst. Calcite prom. on surface. Knobbly-banded, beds 10-15 cm, seams not lat. contin., enclose beds?

Diffuse pebb. band. Incip. flags., seams wavy 1-2 cm.

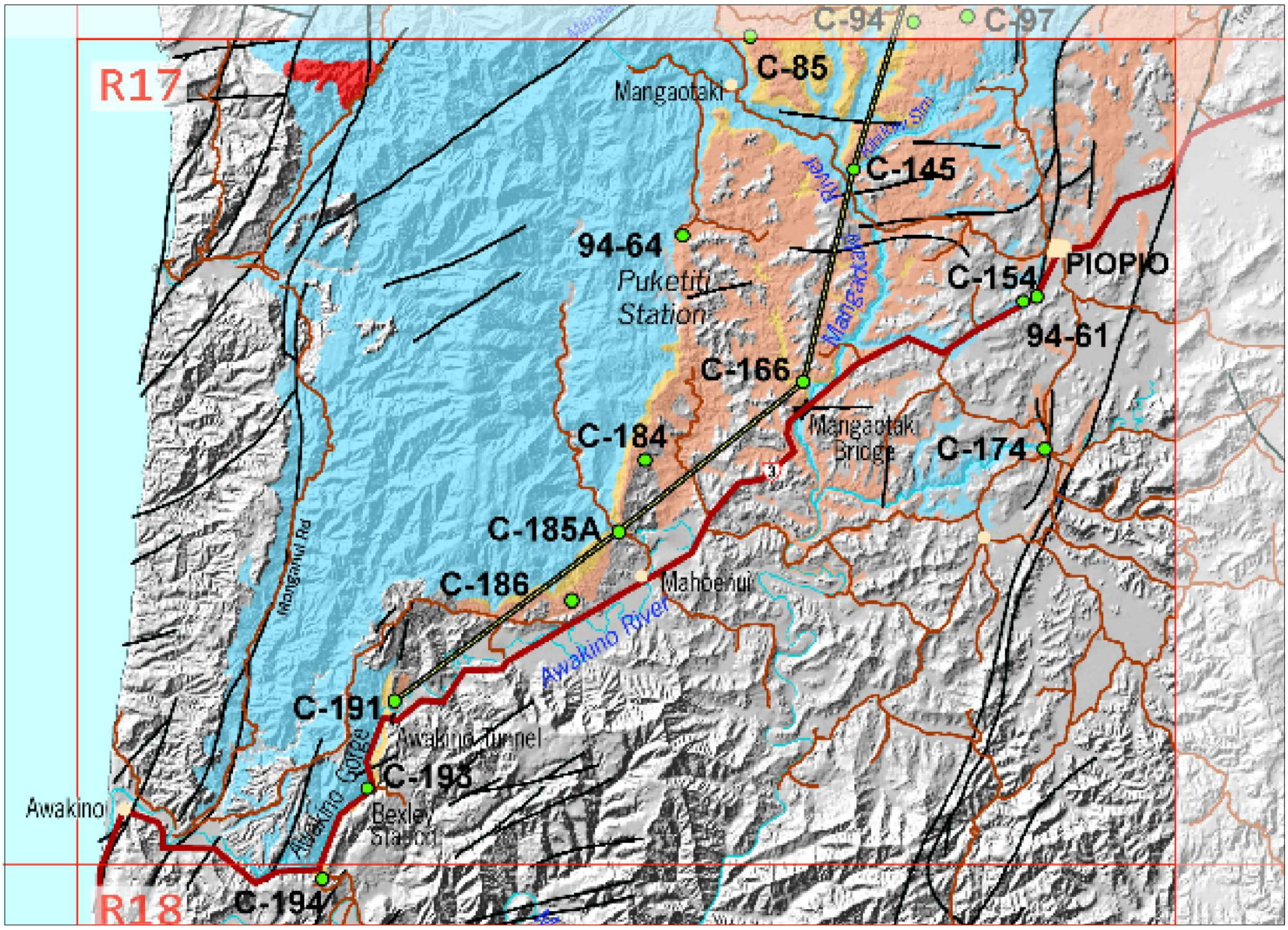
Or.-gr?; mod. ind., mod. glauc., (v.s lst?-) v. calc. f. sst with rare shell frags on outcrop surface. Crude, disorg. banding, blocky appearance in places.
Pebb. band with oyst. frags; occ. calcite pebb. Mod. ind., sl. glauc. s. lst matrix.

Lt. or.-gr., mod. ind., f.s. lst. Incip. flaggy; flags 3-5 cm, sl. wavy seams.

Lt. or.-gr., mod. ind., sl. glauc., f.s. lst. Inc. sand content upwards.

Occ. pebb. lenses. Inverted and deep incised seams. Sl. wavy.
Oyst. frags in cr. , well ind. cryst. lst. Diffuse sm.-med. pebble band.
Diffuse, sm.-med. pebb. band. Or.-gr., mod. ind., cryst., bioclastic lst; laminae & v. thin beds of s.; lenses of sm.-med pebbs. Flaggy (3-5 cm); seams sl. wavy.
Creamy (pure) well ind., cryst. biocl. lst. with inverted, terrig. rich, wavy laterally discont.seams.
Clasts up to 8 x 5 cm; intraclasted, enclosed in cryst. lst. matrix. Some cobbles/pebbs. = aggs. of cemented (SRF) pebbles.

Base not seen.


C-94
C-97
R17
C-85
Mangaotaki
C-145
Mangaotaki River
94-64
Puketiti Station
PIOPIO
C-154
94-61
C-166
Mangaotaki Bridge
C-174
C-184
3
C-185A
C-186
Mahoenui
Awakino River
Manganui Rd
C-191
Awakino Tunnel
C-193
Bexley Station
Awakino
Awakino Gorge
R18
C-194

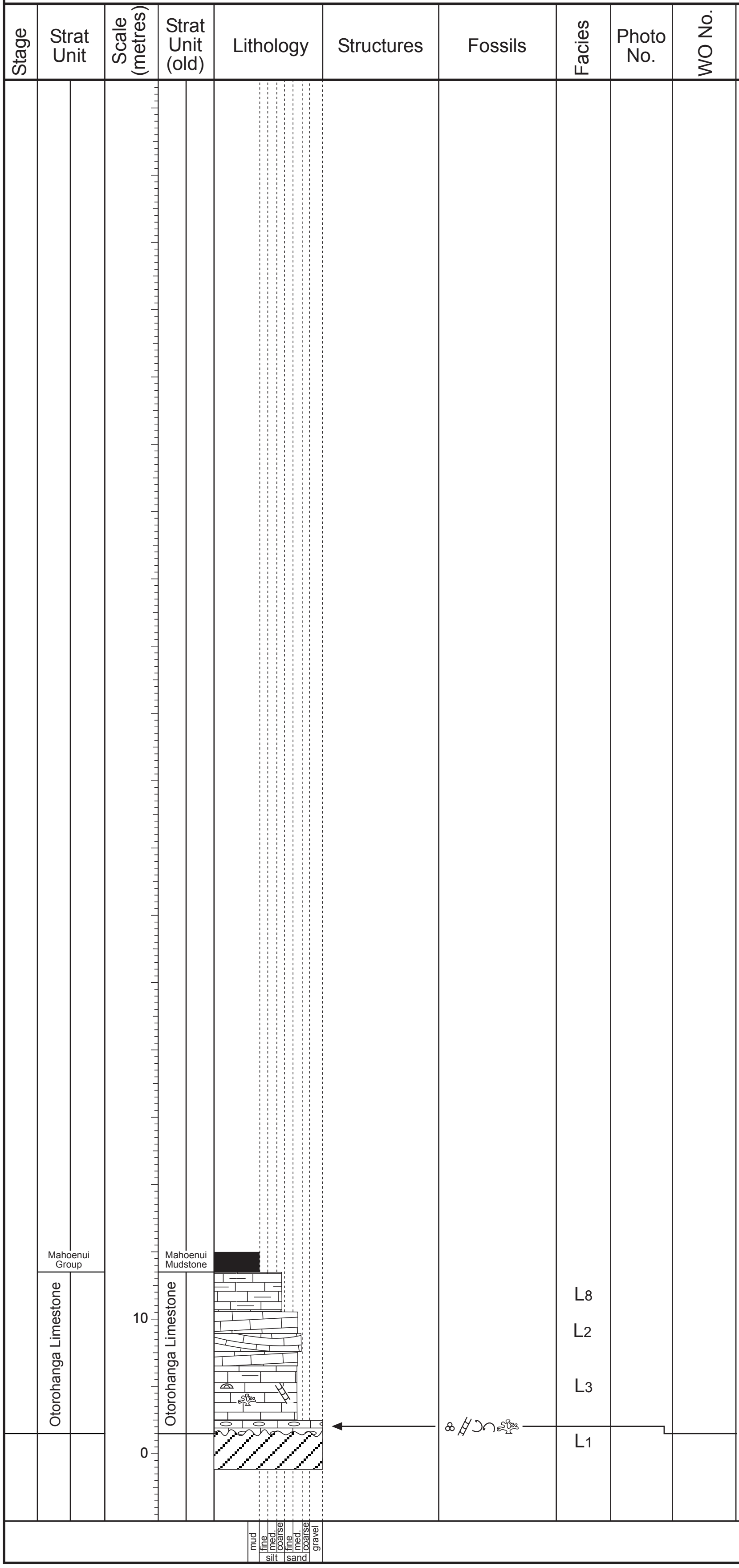
Stratigraphic Column No: *94-61*
Region: Te Kuiti
Location: Pio Pio Greywacke Quarry

Grid Reference: ***Top*** ***Bottom***
E: 2685000 -
N: 6294900 -

NZMS 260 Sheet: R17/850949

Page 1 *of* 2

Author: A.S. Anastas
Modified: A. Tripathi



Description

Horizontally bedded grainstone, argillaceous bding planes, undulatory beds

Cross-bedded lst.

Gently inclined bedded lst., cross-bedded

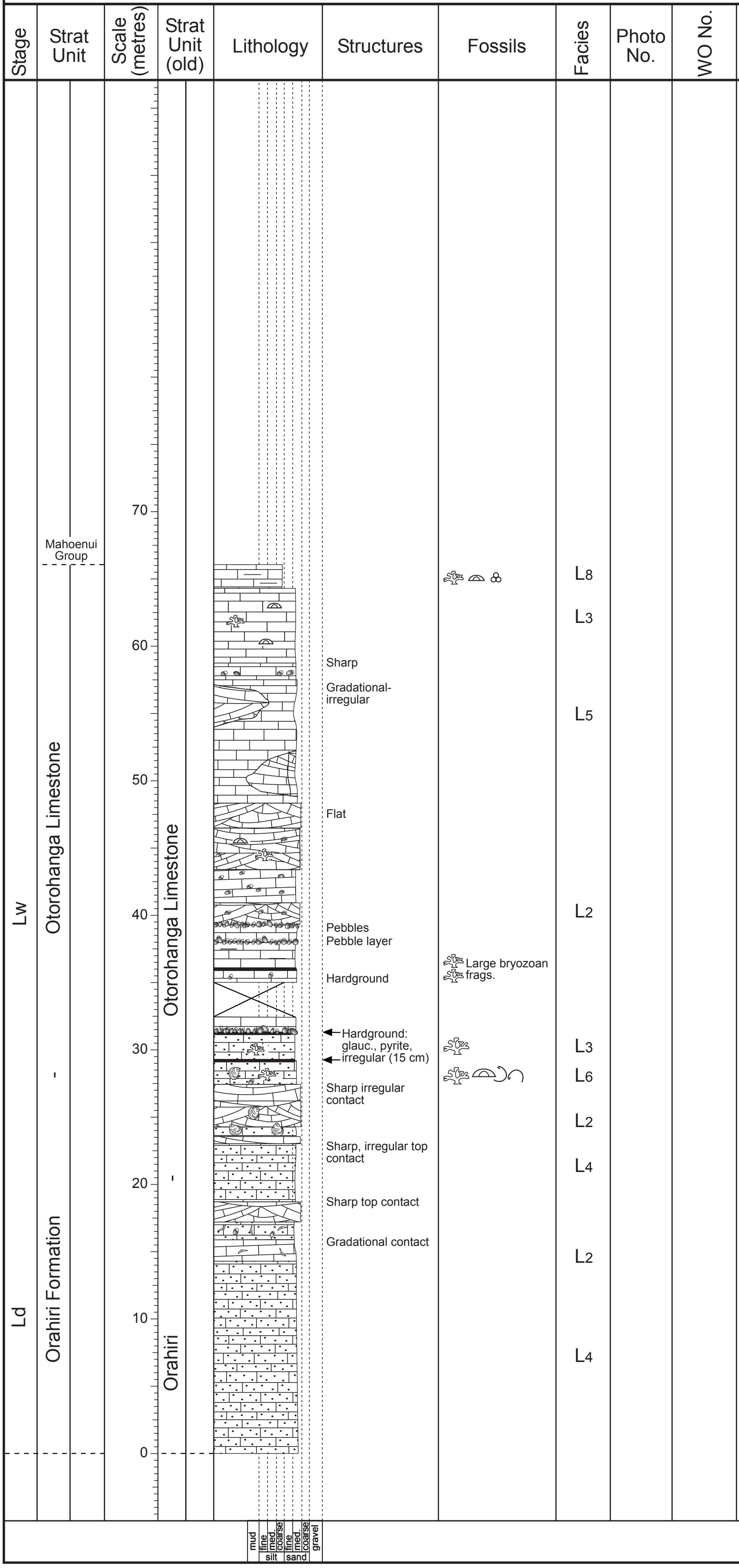
Mass.-thick bedded bryozoan, echinoderm, algal, grainstone/rudstone (biostrome?), copper mineralization, sub-horizontal sheets, rhodolites 10 cm, argillaceous top contact

Lst. with greywacke boulders, goethite staining, calc. algae, bryozoan, bivalves, foram grainstone, fissures into basement

Deformed greywacke (basement)

Stratigraphic Column No: *94-64* ***Grid Reference:***
Region: Te Kuiti
Location: Puketiti Station, south of Mangaotaki
E: 2672100
N: 6302800

NZMS 260 Sheet: R17/721028
Page 1 *of* 1
Author:A.S. Anastas
Modified: A. Tripathi



Description

Argillaceous lst., horizontal bedding, foram-ech.-bryozoan, mud clots.

Gently inclined beds, lst., packaged (30 cm), fine grainstone, well sorted.

Massive lst., pebbles common.

Deeply weath., cavernous, bry.-ech. grainstone, diff. to see x-bedding, amal. sets, bed-parallel lamin., 5-20 cm.

Cross-bdd lst., 2 lge. sets, basal set coarser, grain-rudstone, coarsening upward, 2% non-bioclasts, brys. and echs. <4 mm, lithic frag. pebbs. rare, appears compound.

Low an. incl. beds, 30-50 cm , styl. beds, x-bdd?, pebbly, large bul. bry., grain-packstone.

Pebbly cross-bedded packstone, 1 set, bryozoans, 10-20 cm beds.

Horizontally bedded grainstone, sandy, basement pebbles.

Mass. fossiliferous bryozoan wackestone floatstone, seams, pebbly, pyritic.

Horizontally bedded lst., no packages, basement pebbles.

Bro. packstone-floatstone, mass.-thick bdd, pyritic seams, cellapora, spar-filled cavities.

Bryozoan-oyster floatstone, basement pebbles, rare articulated oysters, large fossils.

X-bedded rudstone, tabular shape, fossilif., ech., bivalve , oyst., internal erosion surfaces.

Fossiliferous sandy grainstone.

Thick bedded sandy grainstone, 50-70 cm partings, thick bedding plane zones.

Cross-bedded lst.

Thick bedded sandy grainstone, pebbles, rare large oyster frags.

Sandy grainstone, low ang. inclin. beds, moll. frags., possibly x-bdd, echs., bryozoan.

Sandy grainstone, massive to thin seamed (pyritic), seams 2-3 cm, 10% non-bioclasts.

Stratigraphic Column No: *C-145*

Region: King Country/Waitomo

Location: Mangaotaki Road, west of Piopio

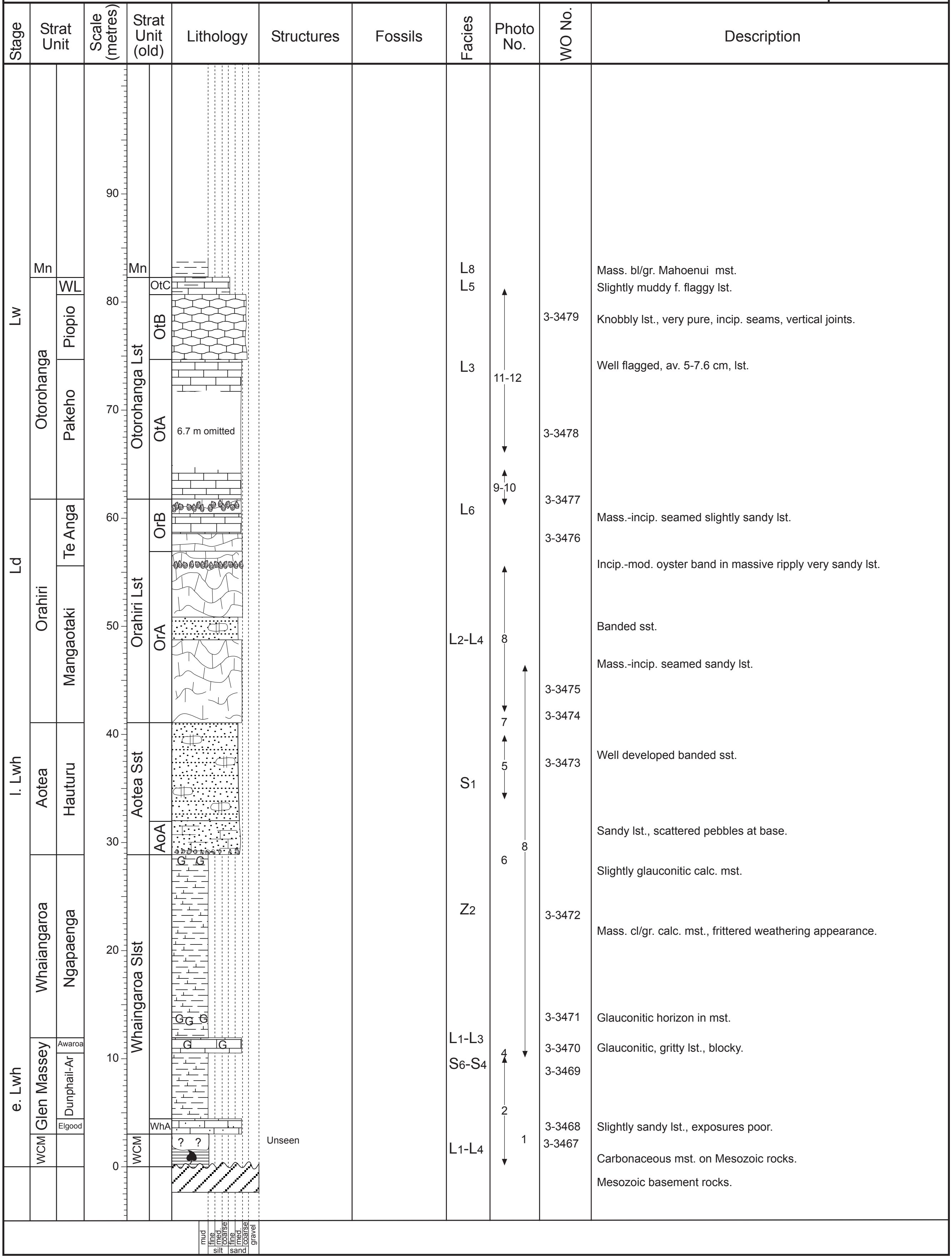
NZMS 1 Sheet: R17

Grid Reference:

E:	2678434	-	2678356
N:	6304738	-	6305198

Page 1 *of* 1

Author: C. Nelson
Modified: A. Tripathi

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Stratigraphic Column No: *C-154*

Region: Te Kuiti

Location: Pio Pio Quarry, SH3

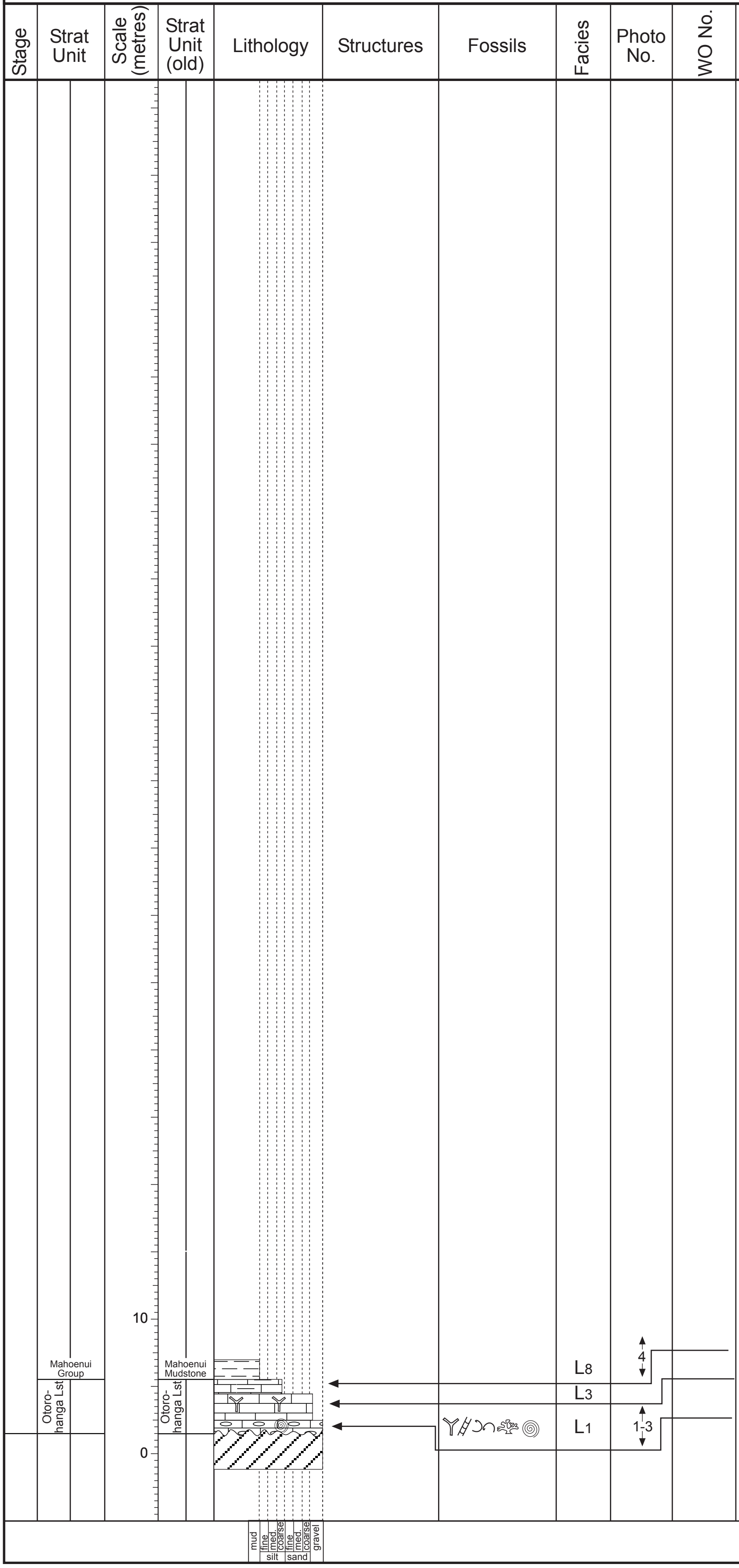
Grid Reference:

E: 2684500 -

N: 6300400 -

NZMS 260 Sheet: R17/845004

Page 1 *of* 1 **Author:** C.S. Nelson



Description

Horizontally bedded sandy silty grainstone, argillaceous bedding planes, glauconitic.

Mass.-thick bedded bryozoan grainstone, sub-horizontal bedding, well rounded fragments of bryozoan colonies.

Lst. with greywacke angular to subangular pebbles and boulders up to 50 cm in size floating in skeletal grainstone, clasts are frequently encrusted by calc. algae, scattered rhodoliths, bryozoan, and bivalves.

Deformed greywacke (basement).

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

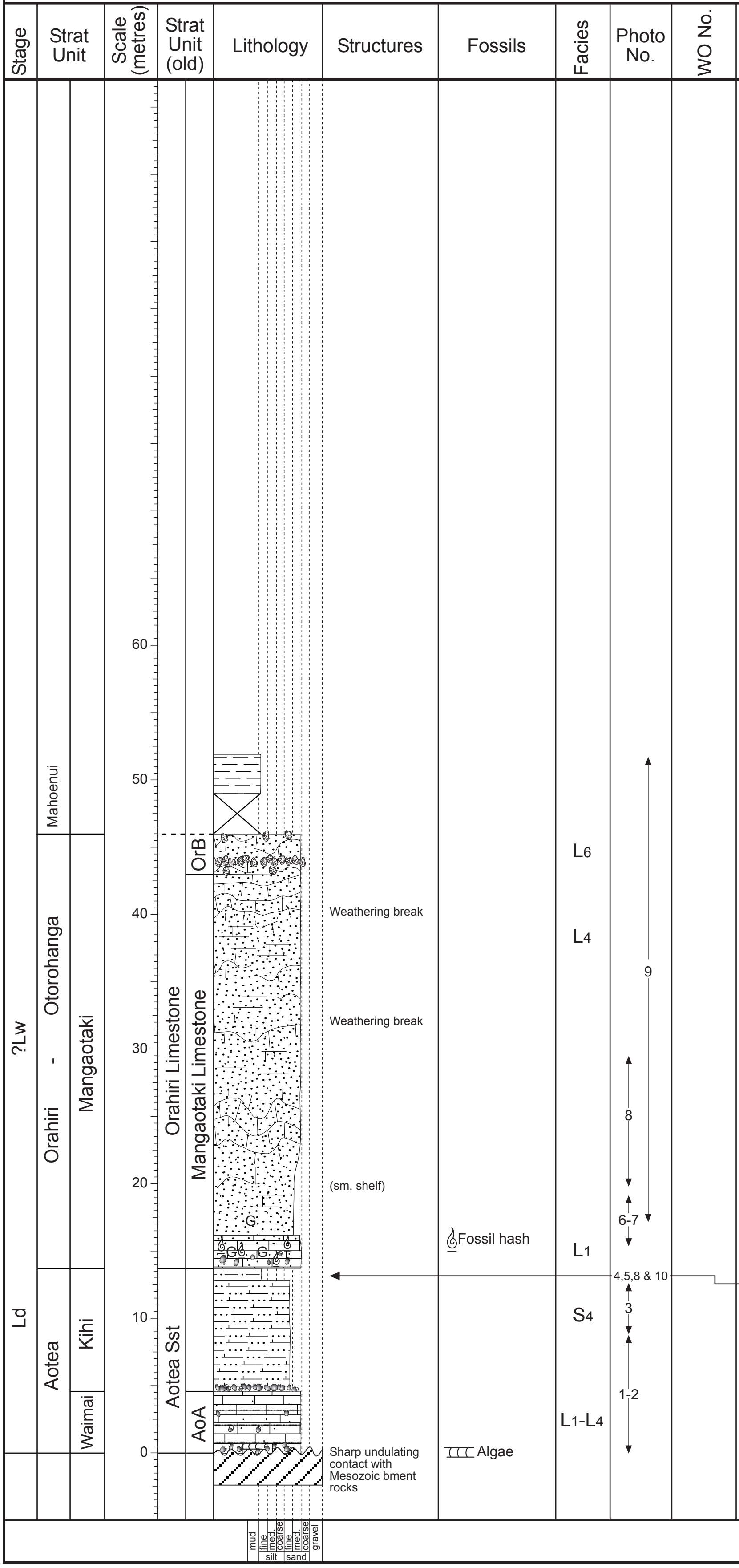
NZMS 1 Sheet: R17

Grid Reference:

E:	2676491	-	2676546
N:	6297477	-	6296195

Page 1 *of* 1

Author: C. Nelson
Modified: A. Tripathi



Description

Mn mst. within 1.5 m of top.

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

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

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

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

Sandy lst. with enlarged seams with sinuous trends.

Mass. slightly ripply sandy lst.

Sandy lst. has frittery weathered appearance.

Mass. frittery sandy lst., slightly ripply surface.

Fossiliferous-hash streaks apparent in c/gr. s. lst., slightly glauc.
Mass. sandy pebbly lst., pebbs. av. 0.6 cm, max 3.8 cm, glauc., fossil-hash, ?carb.; pebble band at base, pebbles av. 0.6 cm, max 5 cm, gwk. comp.

Blue-grey s. mst.

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

Rel. mass. lst. - calc. sst interbeds, beds 15 cm+ thick with pebbly bases, pebbles av. 0.15 cm; occ. intervening sandy mst., algae app. at base plus com. pebbles and ff. mat. over basal 15 cm; unit has var. width (1.5-4.5 m).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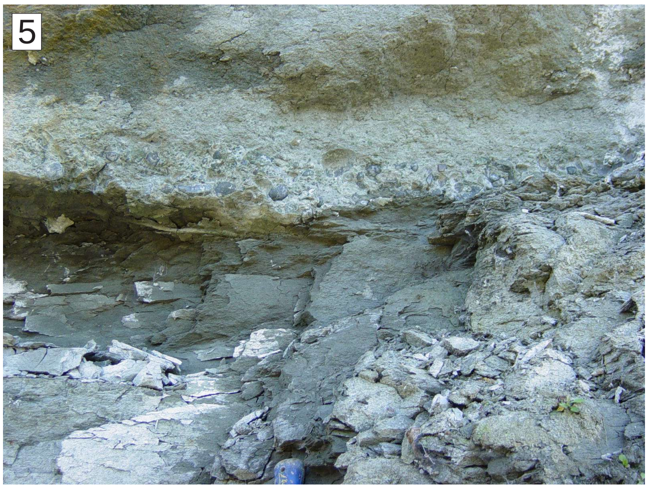
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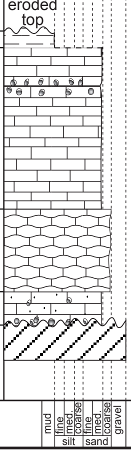
Stratigraphic Column No: *C-174*
Region: King Country/Waitomo
Location: Near Wairere Falls, Aria

Grid Reference:
E: 2685293
N: 6295033

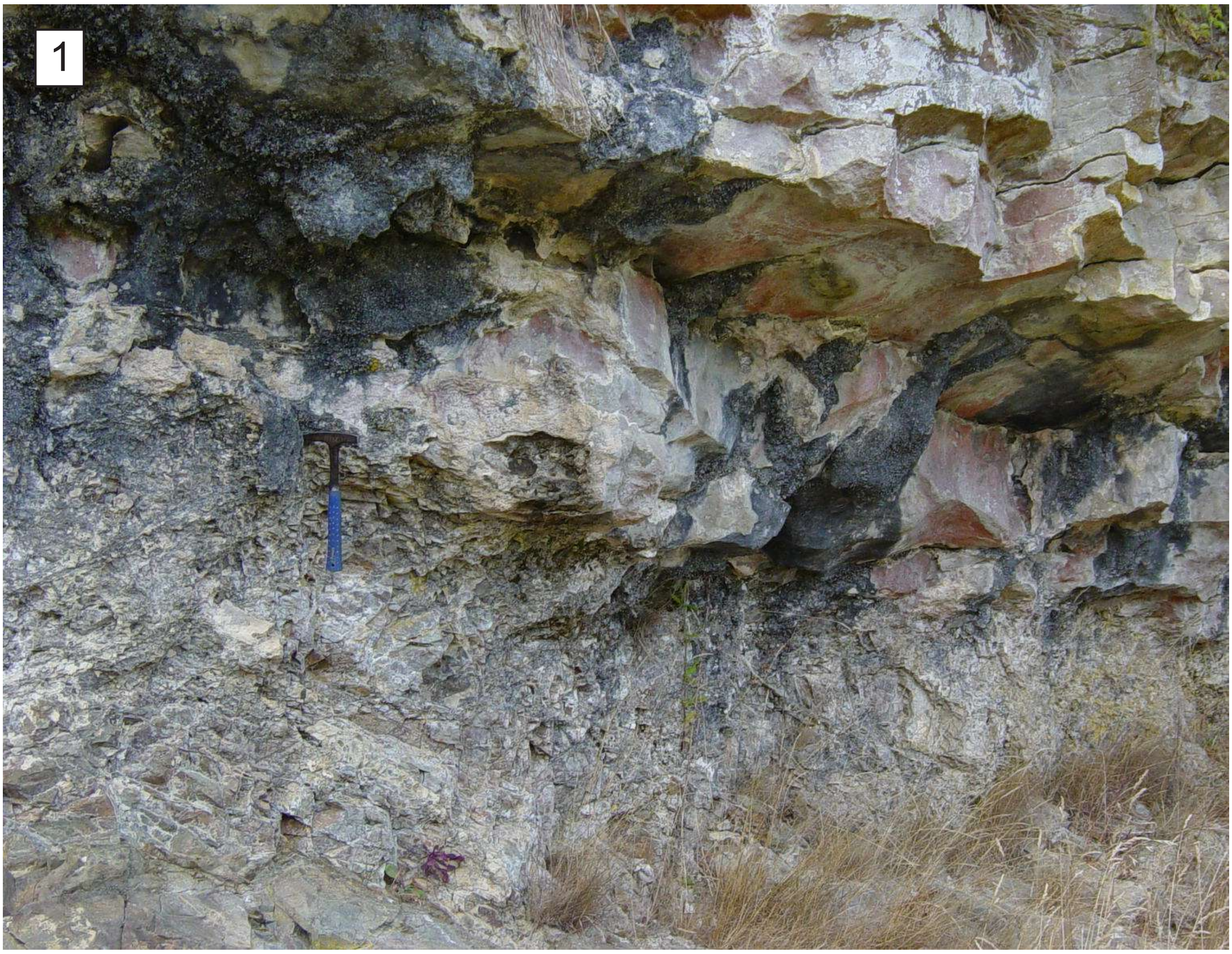
NZMS 1 Sheet: R17

Page 1 *of* 1

Author: C. Nelson
Modified: A. Tripathi



Stage	Strat Unit	Scale (metres)	Strat Unit (old)	Lithology	Structures	Fossils	Facies	Photo No.	WO No.	Description
	Mn	20	Mn		Contact unseen					Blue-grey mst. of Mn Group.
Lw	Otorohanga		Otorohanga Limestone OtC							Well flagged 2.5-5 cm pure lst.
					Weathering break					Scattered pebbles. av 0.6 cm above and below Weathering break.
		10					L_3			Pure well flagged av. 5-7.6 cm lst., smooth regular seams.
			OtB				L_5			Massive, irreg. weath. lst. equivalent to knobbly weathering type.
		0	OtA				L_1	1		Slightly pebbly well flagged av. 12.7 cm, but var., lst., small sand content.
										Scatt. pebbles av. 1.3, max 12.7 cm in basal 15 cm, sharp contact on irregular Mesozoic basement surface; along the contact basal pocket congloms. 0-1.5 m thick appear with pebbles av. 2.5 cm, max. 18 cm.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Stratigraphic Column No: *C-184*

Region: King Country/Waitomo

Location: Mangaorongo Road, north of Mahoenui

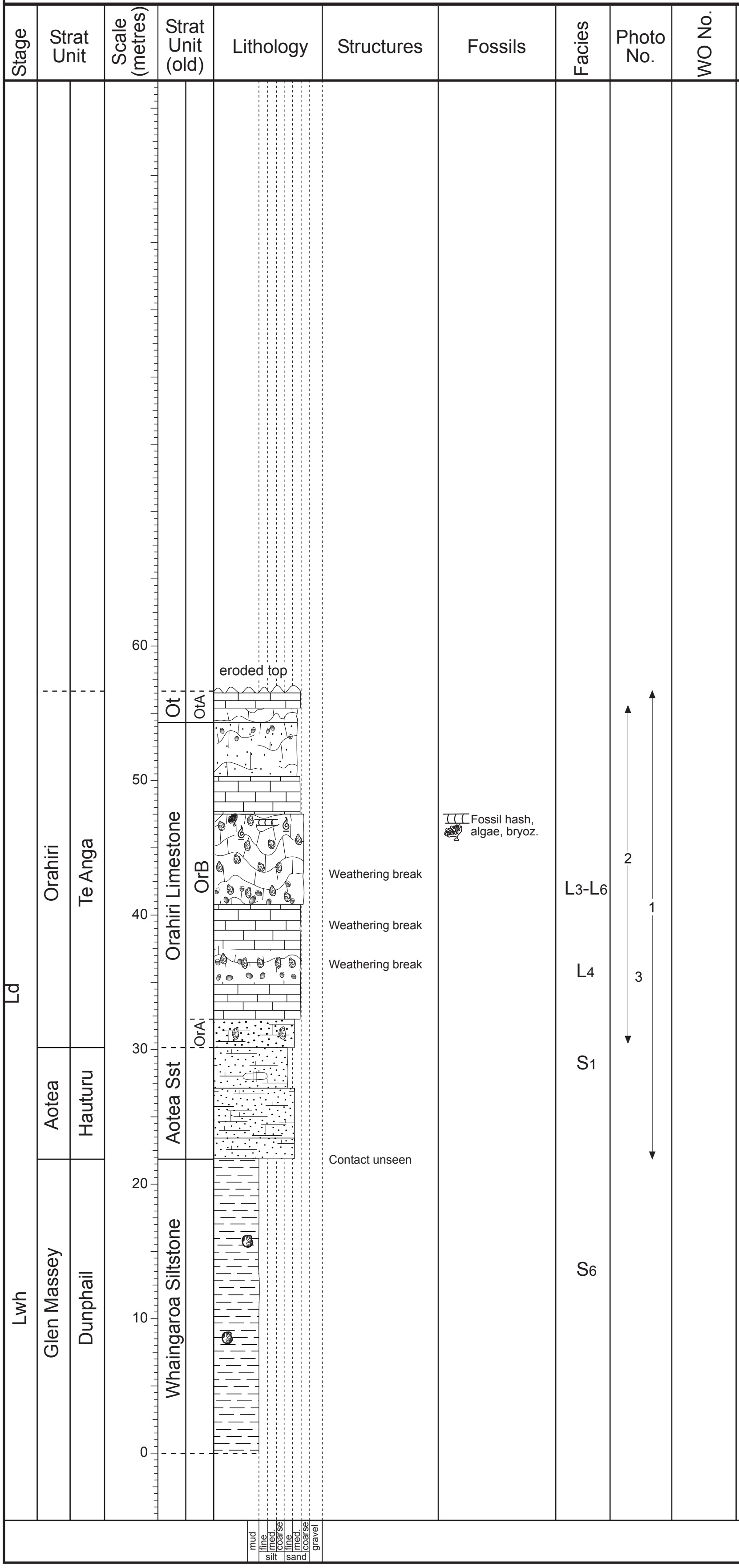
NZMS 1 Sheet: R17

Grid Reference:

E:	2670672	-	2670700
N:	6295446	-	6294600

Page 1 *of* 1

Author: C. Nelson
Modified: A. Tripathi



Description

Well flagged 2.5-5 cm lst.

C/gr. cavernously weathered, irregularly seamed lst.

Rel. massive irregular incipient seams with scattered pebbles at top av. 1.9 cm, max. 7.6 cm.

Rel. mass lst. with highly irregular seams.

Narrow undulating incipient seams 2.5-5 cm apart, occ. bryozoan heads to 6.3 cm diameter.

Highly irregular seams with common oysters, fossiliferous-hash, bryozoan heads and calc. algae.

Incipient slightly irregular sandy seams with scattered oysters.

Incip. highly irregular seams, occ. tiny pebbles, com. scattered oysters haphaz., vertical veining.

Incip.-mod. flags, 5-7.6 cm thick.

Mod.-well developed flags av. 10-13 cm thick with incipient. seams within; occ. scattered oysters and tiny pebbles, irregular seams at 36.6 m; 15 cm zone of scattered-common pebbles av. 0.6 cm, max. 1.8 cm, rare oysters, shark teeth at 35. 4 m.

Mass.-incipient seamed, av. 7.6-10 cm apart, sandy lst.

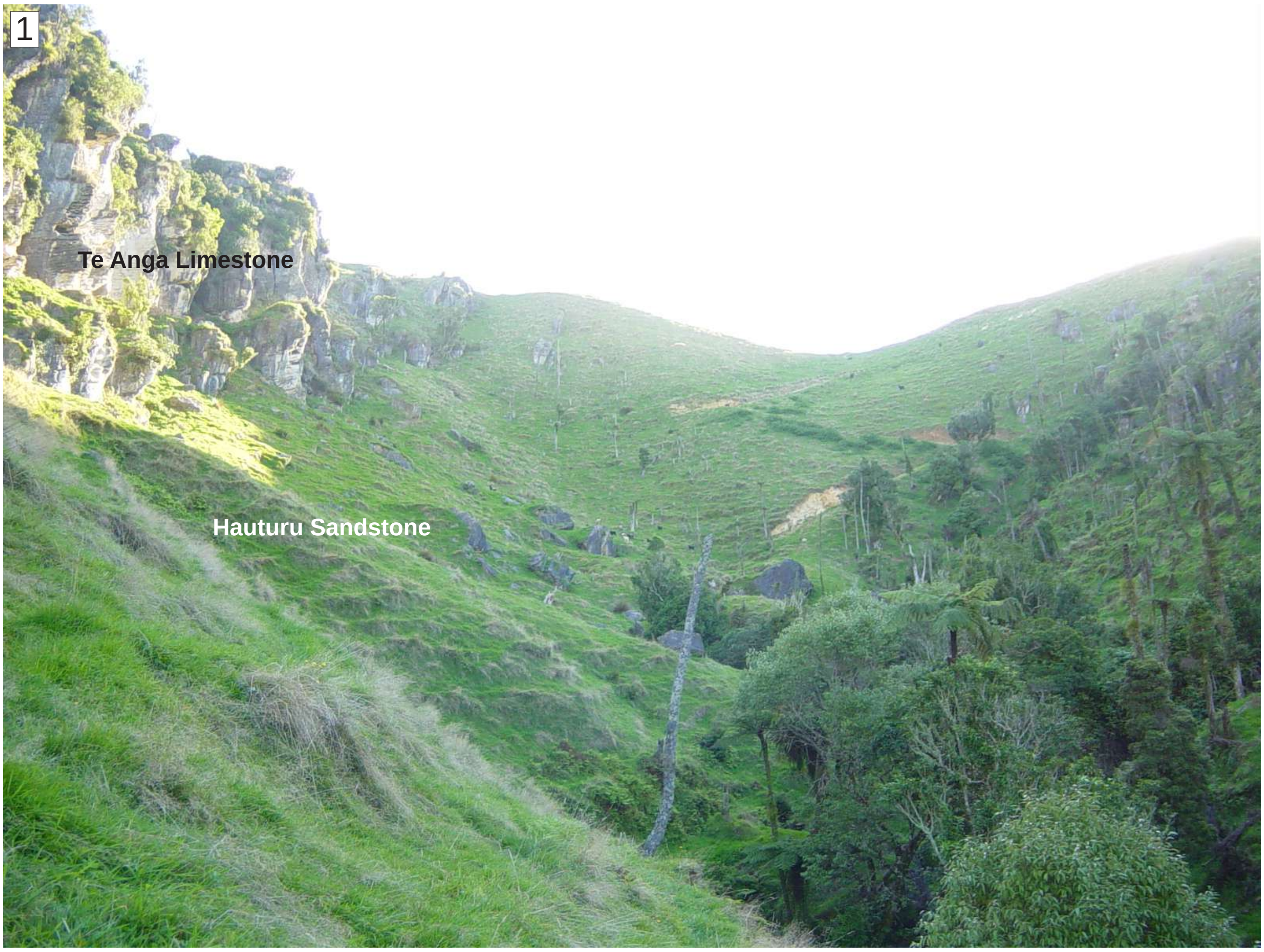
Var. developed bedded calc. fine sst., grassed ledge 21.1-28.7 m.

Massive-incipient ripply calc. sst. - sandy lst., some incipient seams.

Massive-incipient seamed, slightly red calc. sst.

Massive bl/gr. frittery calc. mst., scattered bivalves eg. *Nuclua* sp.

Base in stream with exposures over waterfall.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Te Anga Limestone
Hauturu Sandstone


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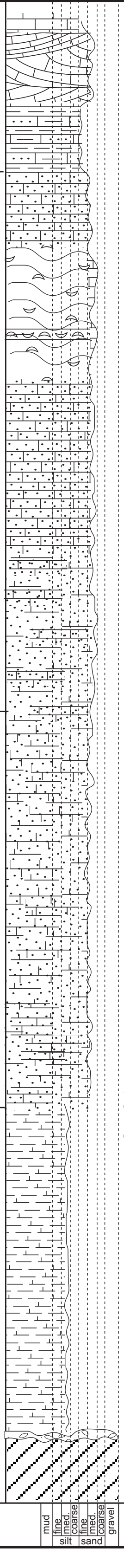
Stratigraphic Column No: C 185A **Grid Reference:**
Region: King Country/Waitomo
Location: Awakino River Gorge, Gribbon Road
E: 2670300 - 2669752
N: 6292000 - 6291997

NZMS 1 Sheet: R17

Page 1 of 2

Author: C. Nelson
Modified: A. Tripathi

Stage	Strat Unit	Scale (metres)	Strat Unit (old)	Structures	Fossils	Facies	Photo No.	WO No.	Description
	Mahoenui Gp		Mahoenui Gp						Cross bedded limestone 0.8-1.6 m thick in flaggy limestone
									Interbeds of calcareous sandstone and calc mudstone
		90							
Lw					Scattered oysters				Relatively massive, irregular seamed limestone, occas scattered oysters
	Otorohanga	80			Occas pectin	L6			Oyster band, generally disarticulated, haphazard, occas pectins
					Scattered oysters and bands				Scattered oysters, slightly irregular seamed limestone
-							4		
		70	Orahiri Limestone			L3-L4			Incipient seamed slightly sandy limestone, seams 5-7 cm apart
	-								
		60							
						L4			Relatively massive, ripply sandy limestone
Ld	Orahiri								
		50		Sharp contact					
	Aotea / Hauturu	40	Aotea Sandstone			S1			Bedded calc sandstone, hard bands forms continuous bands with soft interbeds
		30				L4	3		Slightly flaggy limestone, flags av 10-12 cm, slight cross-bedding evident
-				Sharp possibly a erosional contact, prominent overhang			1-2		
		20							
	Glen Massey / Dunphail	10	Whaingaroa Siltstone			S6			Massive, blue-grey slightly sandy mudstone, frittery weathering, poorly exposed
Lwh		0				S1			Basal few scattered basement pebbles, burrows, slightly glauconite and sandy



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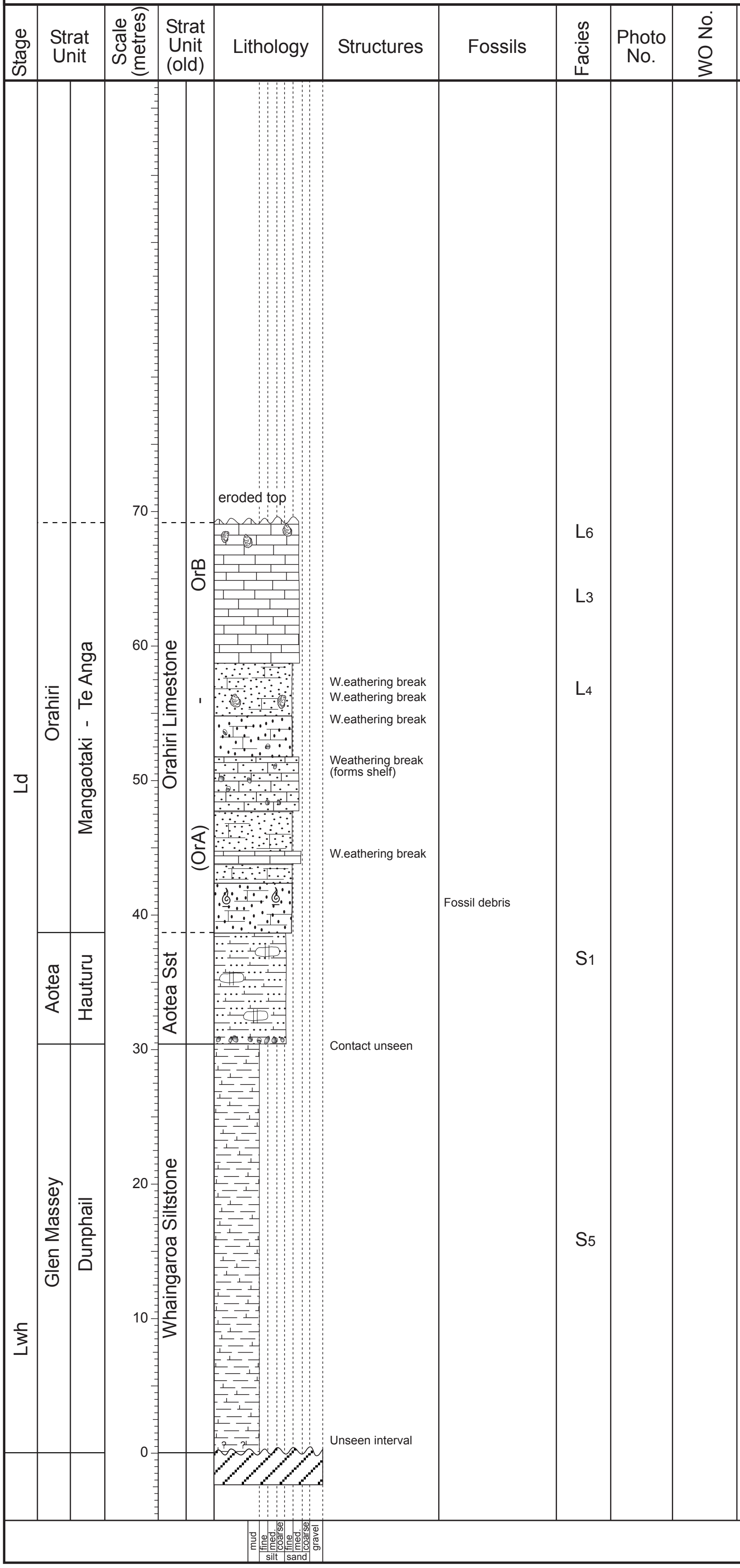
Stratigraphic Column No: *C-186*
Region: King Country/Waitomo
Location: West of Mahoenui

Grid Reference:
E: 2668034
N: 6289485

NZMS 1 Sheet: R17

Page 1 *of* 1

Author: C. Nelson
Modified: A. Tripathi



Description

Mn mst. nearby.

Mod.-well developed flaggy av. 5-7.6 cm lst., occ. scattered oysters near top.

Incip.-mod seams, av. 5-10 cm apart.

Mass., incipient seamed, slightly ripply surface sandy lsts. with scattered oysters.

Mass. ripply sandy lst. with occ. limonitised av. 0.3 cm scattered pebbles.

Mass., incip. seamed sandy lst., very occ. scattered lim. pebbles av. 0.95 cm, max. 2.5 cm.

Incip. seams - ripply surface, seams av. 10 cm apart.

Well flagged 2.5-5 cm lst.

Massive slightly frittery sandy lst., very incipient seams.

Mass. sandy non-seamed lst. with scattered ff-debris, incipient seams dev. below to 38.7 m.

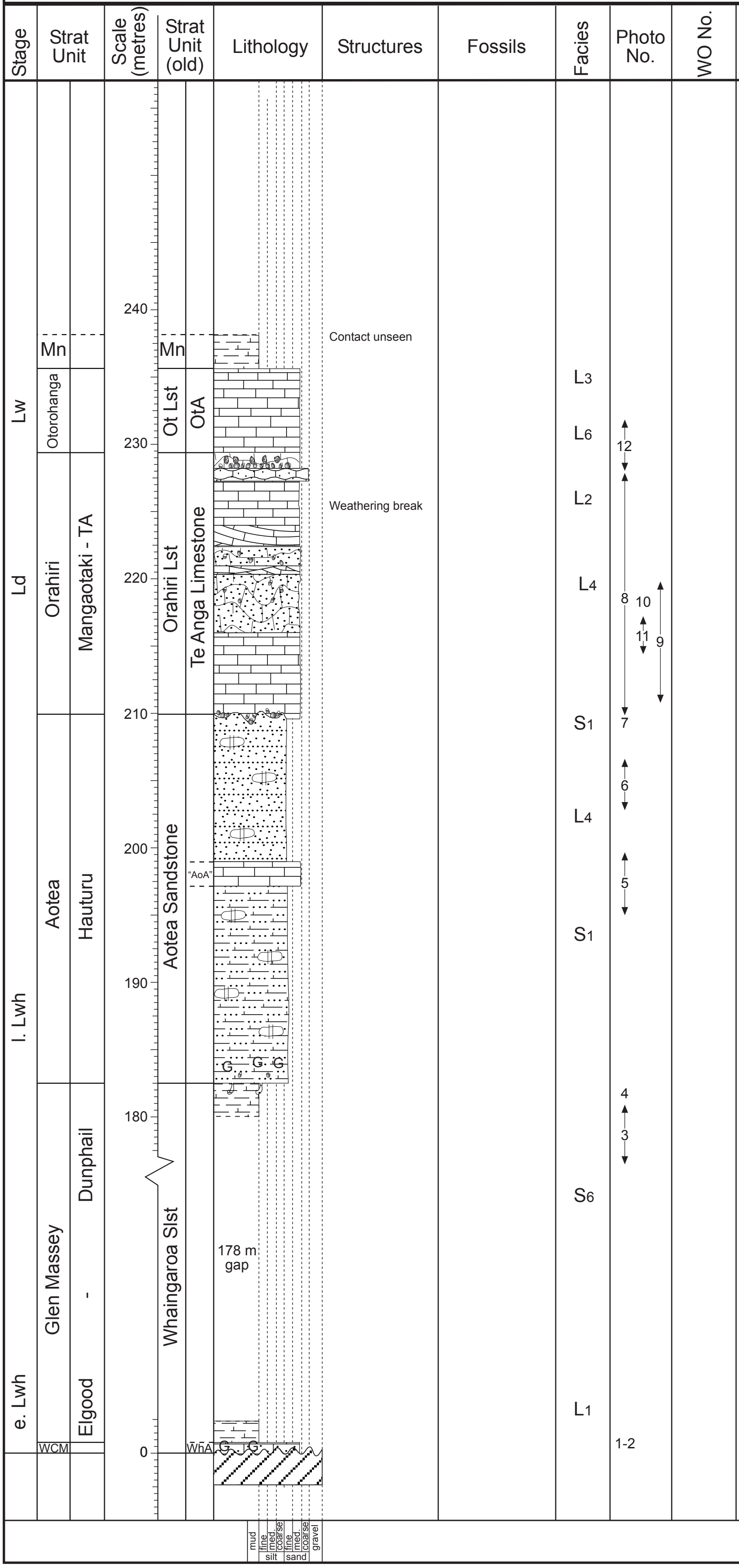
Banded calc. f. sst., variably weathered and commonly loose sand, scattered pebbles at base.

Mass. bl/gr. calc. mst., frittered weathering appearance, very poor exposures.

Mesozoic basement rocks.

Stratigraphic Column No: *C-191* **Grid Reference:**
Region: King Country/Waitomo **E:** 2661620
Location: Awakino tunnel (approx.), SH3 **N:** 6285825

NZMS 1 Sheet: R17 *Page* 1 *of* 1 **Author:** C. Nelson
Modified: A. Tripathi



Description

Mn calc. mst. against dip slope.

Pure well flagged av. 5-7.6 cm lst.

Common oysts., scatt. pebbs., highly irreg. seams, basal pebble. band of bored calc. sst., pebbles to 22.5 cm size, av. 1.3 cm (gwk.); 227.8-228.75 m of massive very irregularly weathered lst., knobbly-like.

Crossbedded ‘ellopsoids’, flaggy lst.

Mass.-ripply pebbly, av. 1.9 cm, lst.
Pseudoflaggy cross bedded lst.

Mass. lst. with common scattered sst. pebbles to 7.6 cm, av. 1.9 cm.

Mass. ripply sandy lst., fluted weathering appearance.

Mod.-well developed flags with slightly undulating surfaces, slabby app., wide seams nearer base.

Scoured undul. contact with abund. pebbles to 15 cm size, av. 0.95 cm, of bored calc. sst. and greywacke liths., scour pockets, along strike the pebble band divides with one 0.9 cm above.

Highly weathered bedded. sst., developed by lateral enlargement of seams followed by vertical enlargement along vertical calcite joints, commonly appear as loose friable quartzofeldspathic sand.

Well flagged av. 2.5 cm lst.

Bedded. calc sst. entirely similar to above.

Mass. glauc. calc sst. with tiny pebbles, strongly churned at contact, large borings into mst.

Mass. bl/gr. calc. mst., fritt. weath. app., 178.12 m omitted from column.

Basal 0.9 m - sandy glauconitic lst. and/or C.M.

Mesozoic basement rocks.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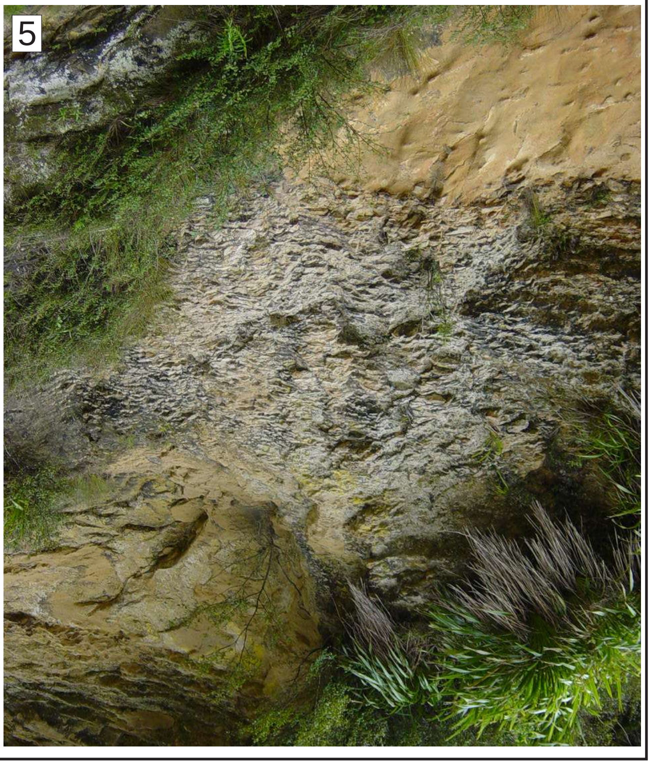
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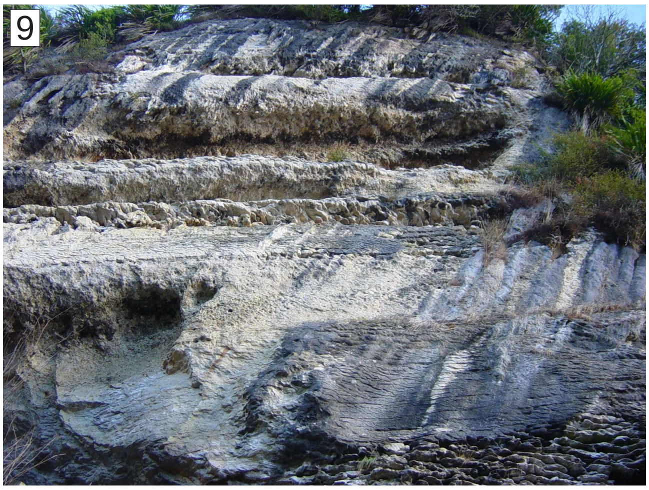
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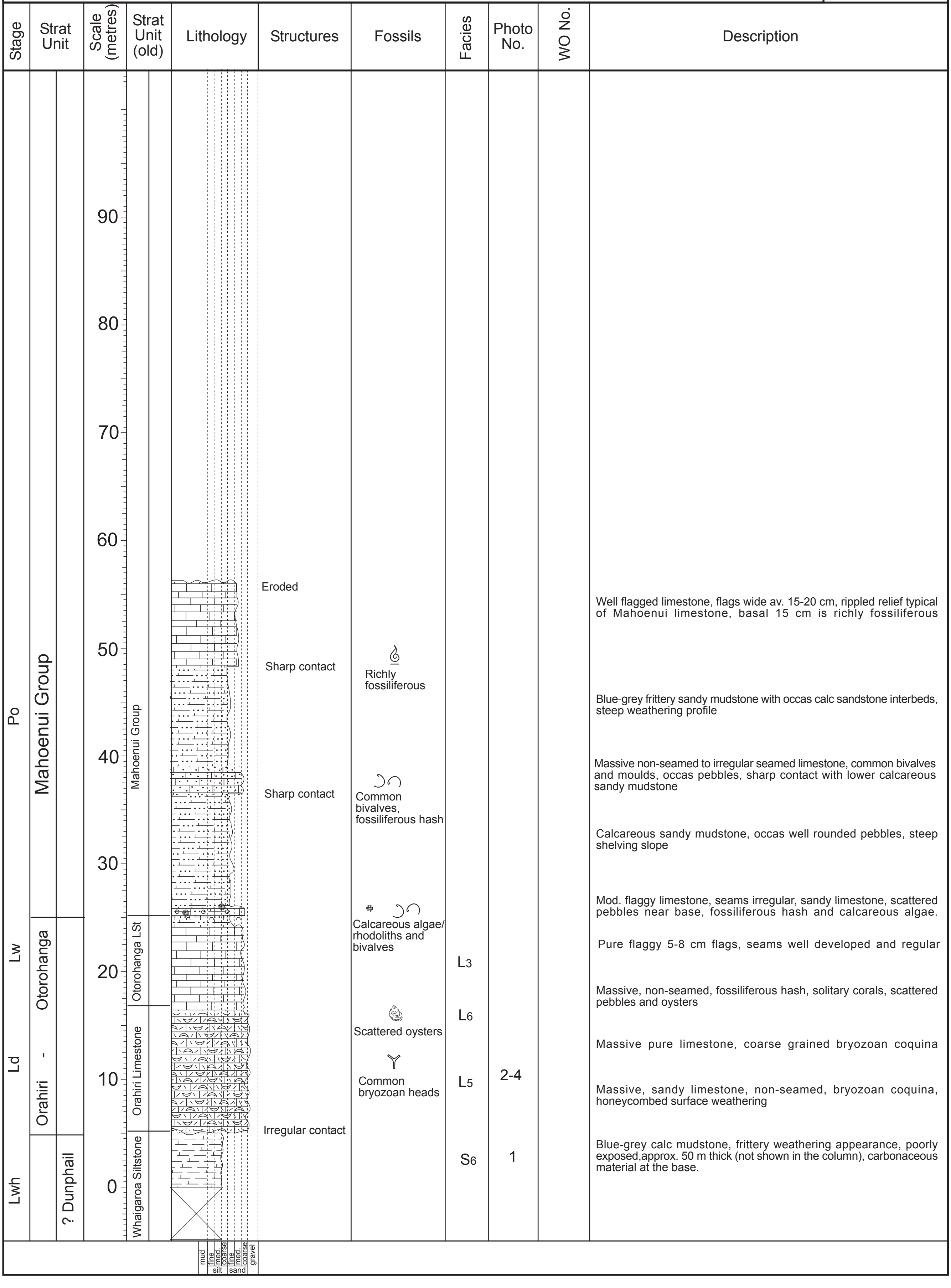
Stratigraphic Column No: C 193 **Grid Reference:**

Region: Waitomo/King Country **E:** 2660616

Location: Bexley Tunnel, Awakino Gorge **N:** 6282653

NZMS 260 Sheet: R18 *Page* 1 of 2

Author: C. Nelson
Modified: A. Tripathi



Well flagged limestone, flags wide av. 15-20 cm, rippled relief typical of Mahoenui limestone, basal 15 cm is richly fossiliferous

Blue-grey frittery sandy mudstone with occas calc sandstone interbeds, steep weathering profile

Massive non-seamed to irregular seamed limestone, common bivalves and moulds, occas pebbles, sharp contact with lower calcareous sandy mudstone

Calcareous sandy mudstone, occas well rounded pebbles, steep shelving slope

Mod. flaggy limestone, seams irregular, sandy limestone, scattered pebbles near base, fossiliferous hash and calcareous algae.

Pure flaggy 5-8 cm flags, seams well developed and regular

Massive, non-seamed, fossiliferous hash, solitary corals, scattered pebbles and oysters

Massive pure limestone, coarse grained bryozoan coquina

Massive, sandy limestone, non-seamed, bryozoan coquina, honeycombed surface weathering

Blue-grey calc mudstone, frittery weathering appearance, poorly exposed,approx. 50 m thick (not shown in the column), carbonaceous material at the base.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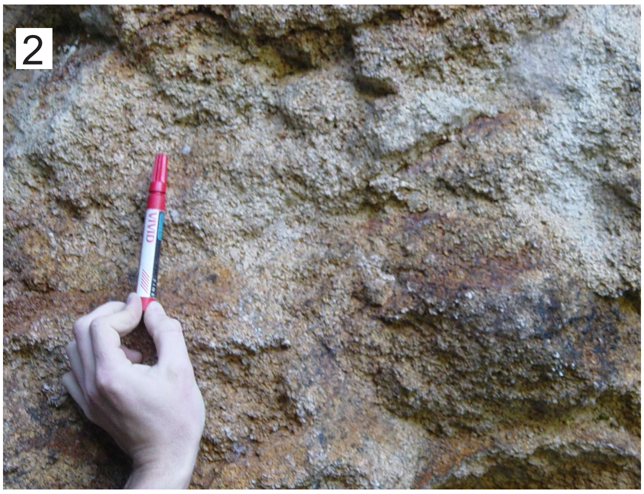
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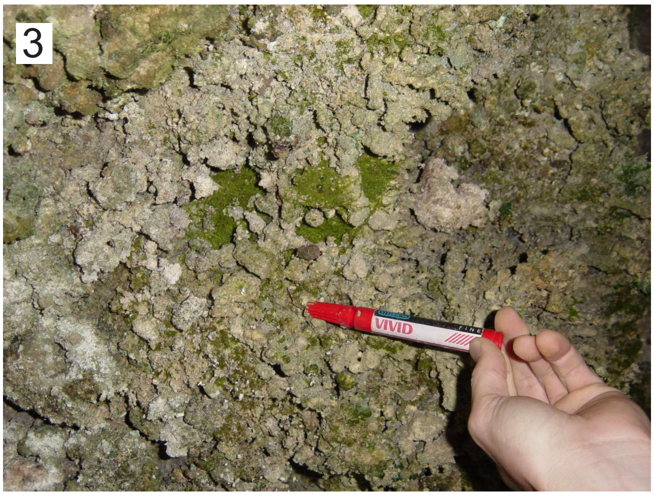

3


4

Stratigraphic Column No: *C-194*

Grid Reference:

Region: King Country/Waitomo

E: 2658967

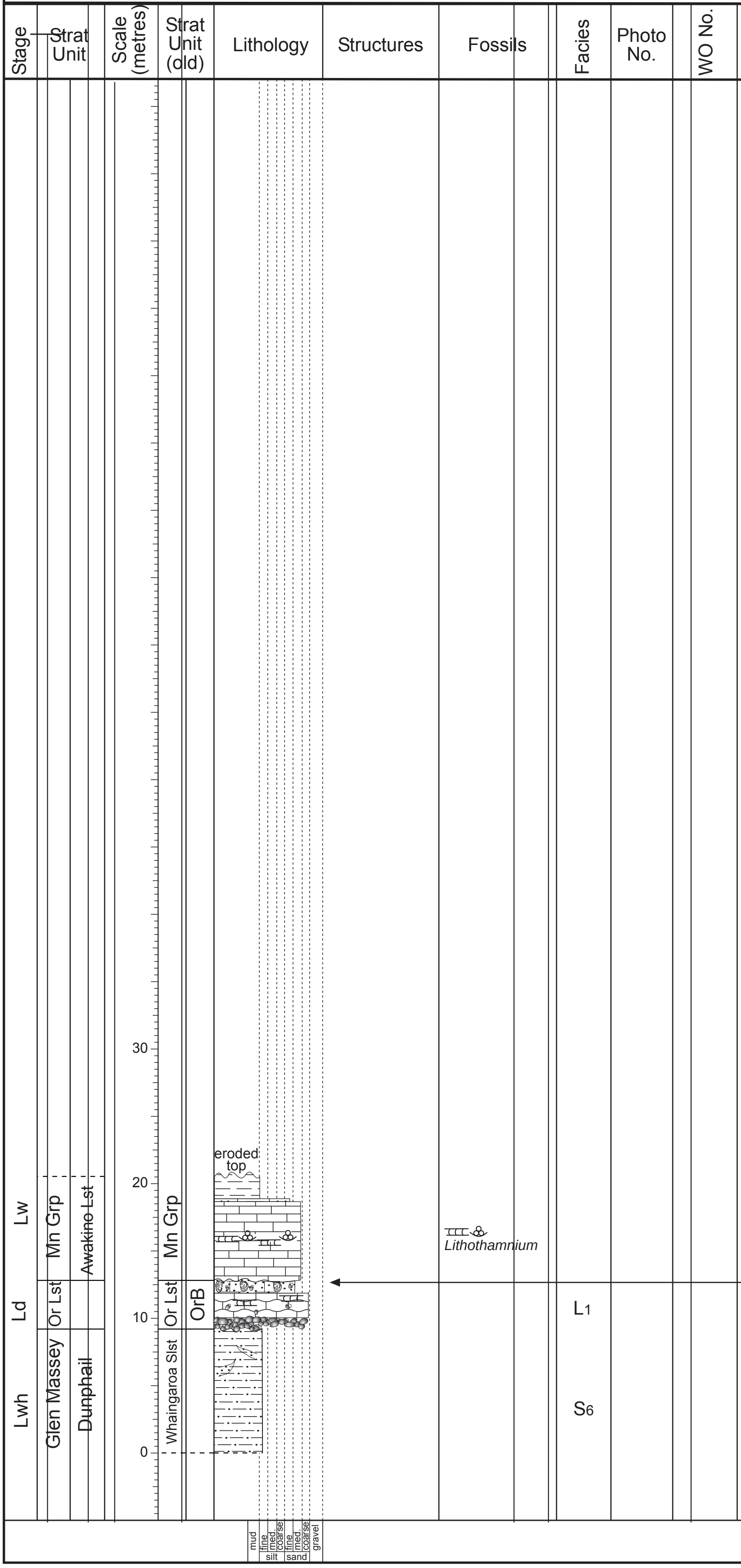
Location: Awakau Road, southeast of Awakino

N: 6279315

NZMS 1 Sheet: R18

Page 1 *of* 1

Author: C. Nelson
Modified: A. Tripathi



Description

Blue-grey calc. mst., Mn Group.

Muddy sandy lst.

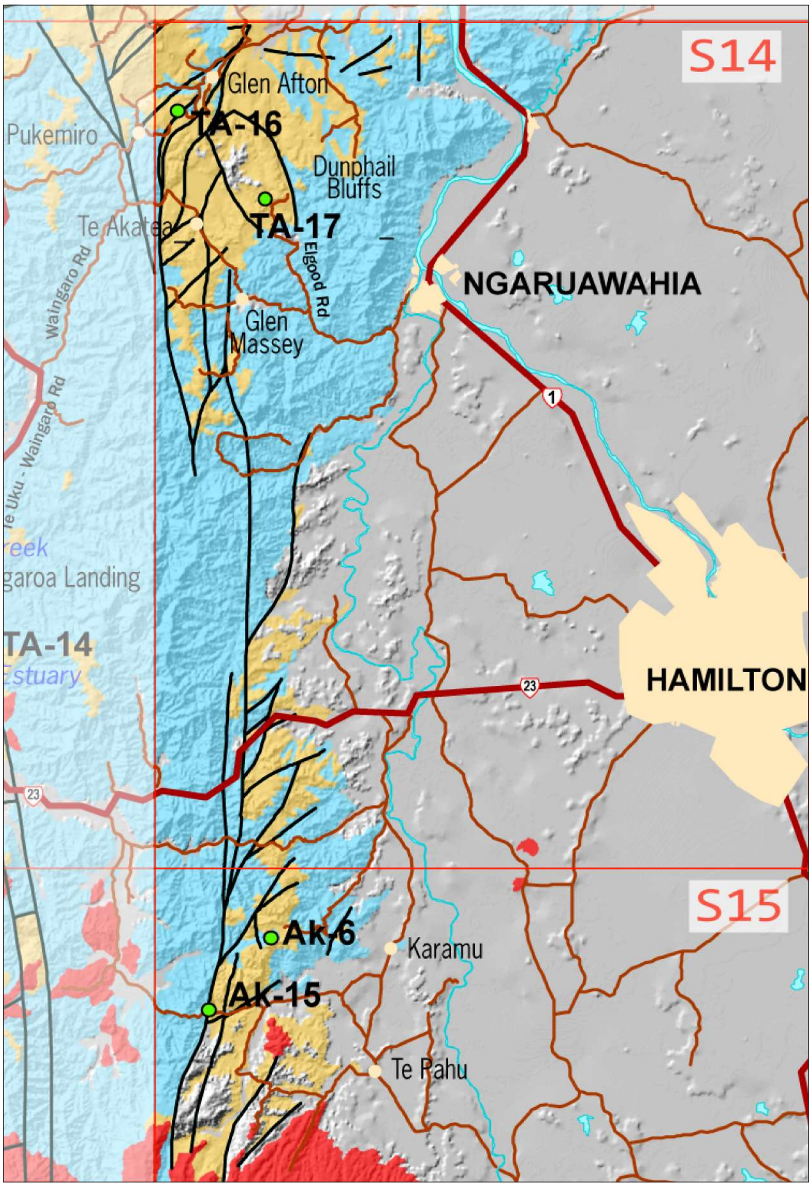
Mass.-mod. dev. flaggy lst., flags char. wide 15-30 cm, slightly irregular seams, conspic. algal heads thro/out, scatt. pebbles. to 15 cm size thro/out, common algal encrusted, seams to 2.5 cm thick and marked by *Amphistegina* forams., nearer top seams muddy and sandy, lensoid.

Undulating contact, below mass. lst. w. occ. mod. seams, blocky app., honeycomb weath., scatt. oysters and pebbles, occ. veining, irreg. base 15 cm concen. pebb. band as W. indent.

Knobbly-like non-seamed lst., var. thickn., scatt. pebbles to 13 cm size. 0.6-0.9 cm conglom., gen. pebbles >matrix, pebbles to 0.9 cm, av. 7.6 cm, subrounded.-rounded., gwk. mst. and calc. sst. pebbles., sharp undulating contact at 9.15 m.

Poorly exposed blue-grey calc. mst.

Swamp; Mesozoic basement rocks within 3 m.


S14
Glen Afton
TA-16
Pukemiro
Dunphail
Bluffs
TA-17
Te Akatea
Elgood Rd
NGARUAWAHIA
Waingaro Rd
Glen
Massey
Te Uku - Waingaro Rd
1
eek
garoa Landing
TA-14
stuary
23
HAMILTON
23
S15
Ak-6
Karamu
Ak-15
Te Pahu

Stratigraphic Column No: *Ak-6*

Grid Reference:

	Top	***Bottom***
E:	2694164	
N:	6367423	

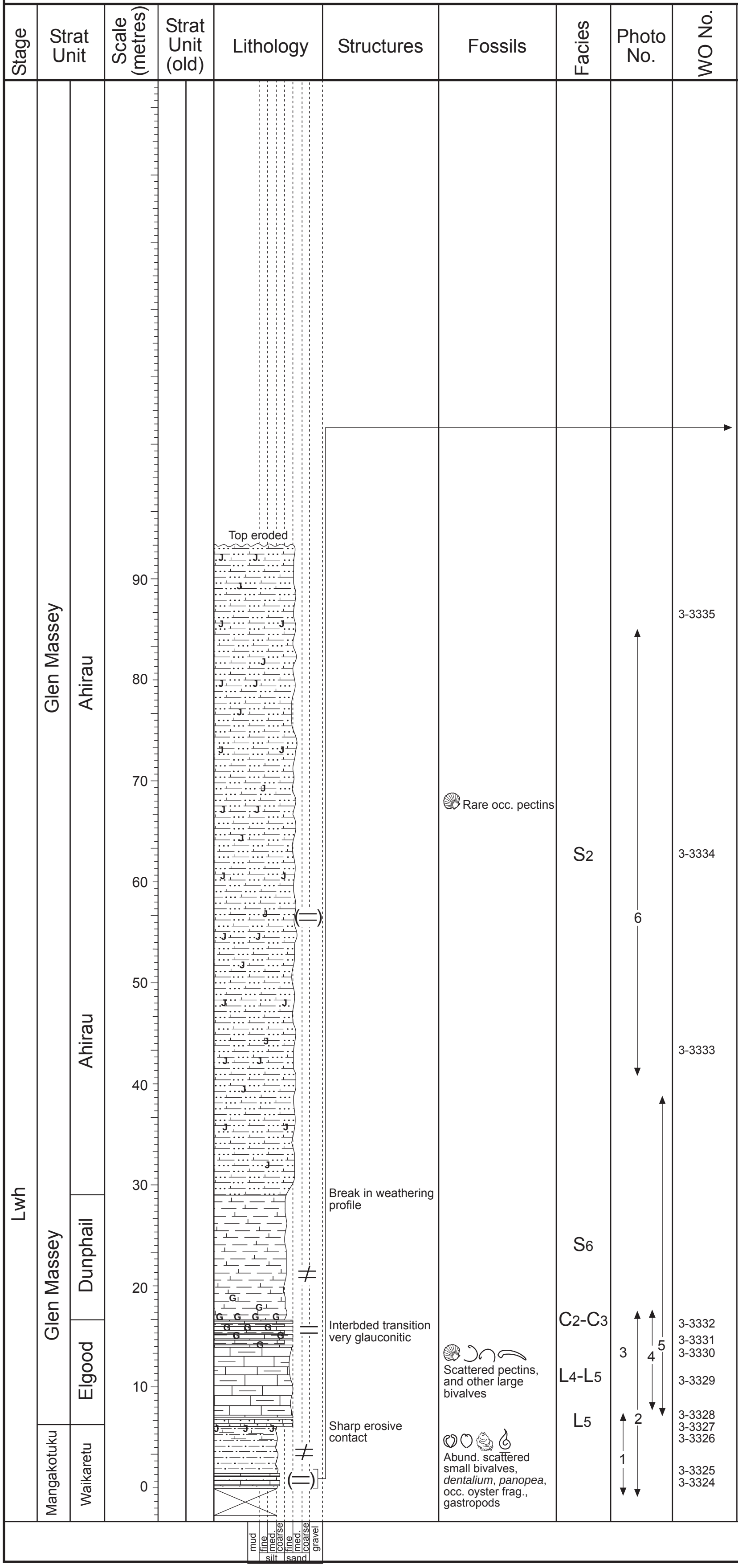
Region: Aotea-Kawhia

Location: Johnstone's farm, Waikhowa Road,
Te Pahu-Karamu, Whatawhata

NZMS 260 Sheet: S15/941674

Page 1 *of* 2

Author: A. Tripathi



Description

INTERBEDDED SANDY MUDSTONE AND CALC. MUDDY SANDSTONE: Medium dull greyish, alteration of weakly cemented massive sandy mudstone and 15-20 cm mod. cemented calcareous muddy sandstone, fossiliferous with abundant often leached bivalves, dentalium, oyster fragments and gastropod.

CALC. SILTY SANDSTONE: Light brownish to bluish grey, well cemented, overall massive in appearance, however over massive interval faint horizontal bedding is often discernible from weathering breaks and ocassional honey-combed intervals, bluffy near vertical weathering profile, highly calcareous very fine to fine sandstone grading into silty sandstone, bioturbated, rare scattered bivalves.

MASSIVE CALC. SILTSTONE: Light greyish to bluish grey, massive, fine siltstone, highly calcareous, mod. glauconitic in places.

GLAUC. CALC. SILTSTONE: Dull greenish grey, mod. cemented, massive often with frittered surface, fine calc. siltstone with high concentration of glauconite, grades above into weakly to mod. glauconitic calc. siltstone.

INTERBEDDED GLAUCONITIC LIMESTONE & MASSIVE CALC. SILTSTONE: Dull brownish grey to greenish grey, alteration of 20-30 cm highly glauconitic limestone and massive glauconitic siltstone, common scattered pectins.

FLAGGY LIMESTONE: Light brownish to greyish white, lowermost 1-1.2 m interval above the contact is mass., grades upsection into poorly to mod. flaggy, flags 6-10 cm separated by thin recessive seams, horizontally bedded fine to medium sparry grainstone to packstone, common scattered whole bivalves and coarse shell hash mainly of pectins, especially in the upper transition to interbedded calc. siltstone and lst, common disseminated glauconite pellets.

MASSIVE SANDY MUDSTONE: Dull medium greyish, weakly to mod. cemented often crumbly and sticky when wet, massive with only faint horizontal bedding apparent in places, scattered leached bivalves, gastropod and *dentalium.*

Lower contact of the unit not exposed.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Stratigraphic Column No: *Ak-15* ***Grid Reference:*** ***Top*** ***Bottom***

Region: Whatawhata

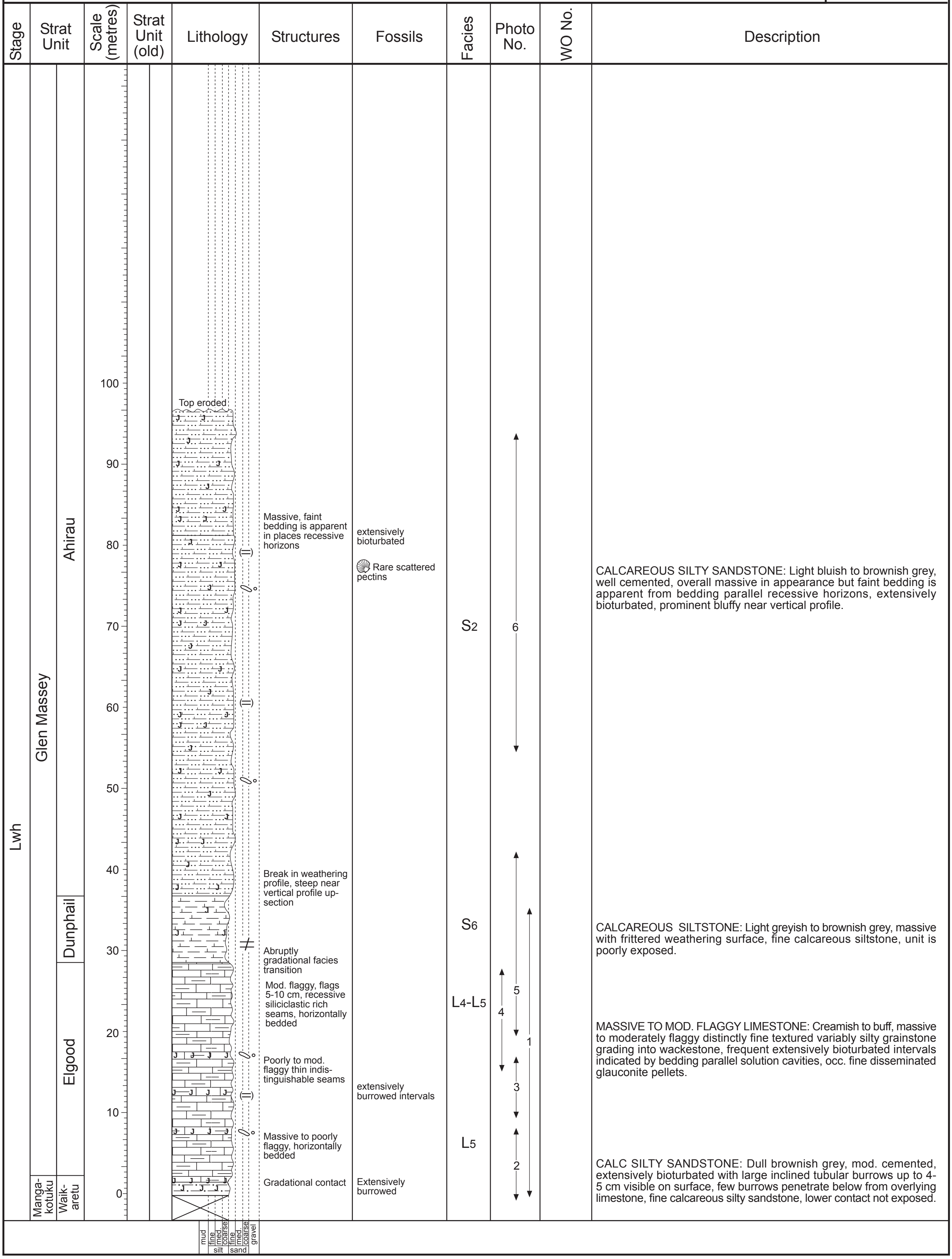
Location: Quarry Road, Te Pahu-Karamu, Whatawhata

E: 2691961

N: 6364878

NZMS 260 Sheet: S15/919648

Page 1 *of* 2 **Author:** A. Tripathi



CALCAREOUS SILTY SANDSTONE: Light bluish to brownish grey, well cemented, overall massive in appearance but faint bedding is apparent from bedding parallel recessive horizons, extensively bioturbated, prominent bluffy near vertical profile.

CALCAREOUS SILTSTONE: Light greyish to brownish grey, massive with frittered weathering surface, fine calcareous siltstone, unit is poorly exposed.

MASSIVE TO MOD. FLAGGY LIMESTONE: Creamish to buff, massive to moderately flaggy distinctly fine textured variably silty grainstone grading into wackestone, frequent extensively bioturbated intervals indicated by bedding parallel solution cavities, occ. fine disseminated glauconite pellets.

CALC SILTY SANDSTONE: Dull brownish grey, mod. cemented, extensively bioturbated with large inclined tubular burrows up to 4-5 cm visible on surface, few burrows penetrate below from overlying limestone, fine calcareous silty sandstone, lower contact not exposed.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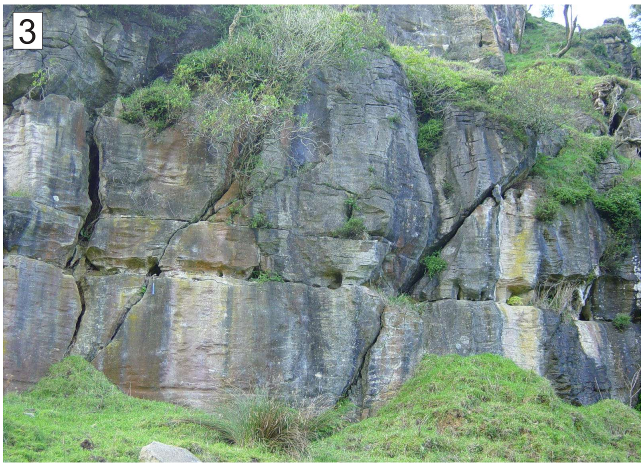
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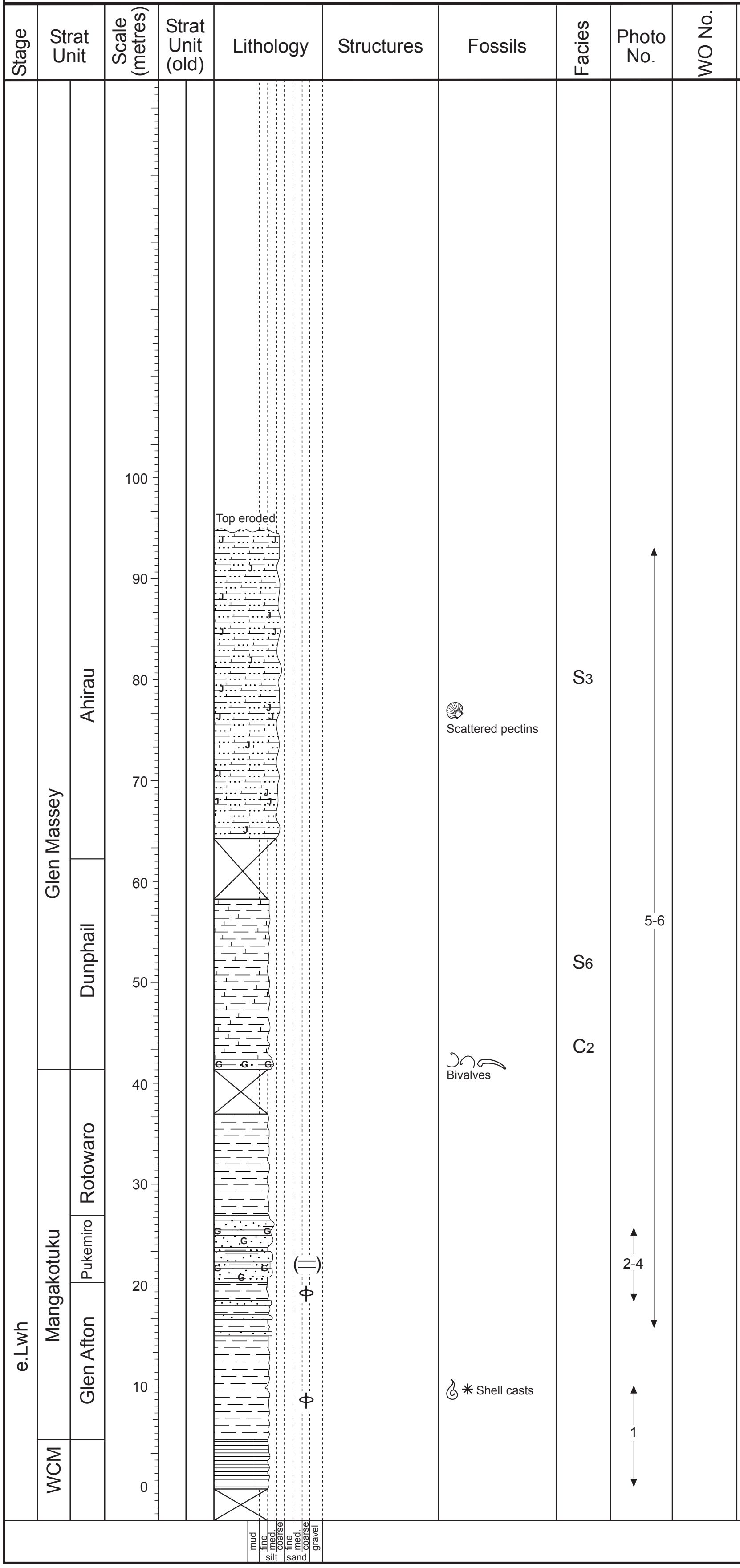
Stratigraphic Column No: *TA-16*
Grid Reference:
Region: Te Akau
E: 2690825
Location: Hangapipi abandoned coal mine, Glen Afton Road
N: 6396795
NZMS 260 Sheet: S14/908967
Page 1 *of* 2
Author: A. Tripathi



Description

CALCAREOUS SILTY SANDSTONE: Light brownish grey, mod. well cemented, massive in appearance, very fine to fine calcareous sandstone grading into silty sandstone, bioturbated, bluffy near vertical weathering profile.

CALCAREOUS SILTSTONE: Light blue-grey, massive, mod. well cemented, typical frittered weathering surface, unit is poorly exposed.

GLAUCONITIC SANDY SILTSTONE: Dull greenish grey, mod. cemented, bioturbated, high concentration of glauconite pellets and glauconitised bivalves.

MASSIVE SILTSTONE: Medium to dark grey, frequently weathers to purplish brown, soft and crumbly, non-calcareous, common thin iron stained veinlets.

GLAUCONITIC SANDSTONE: Dull greenish grey, weakly to mod. cemented, fine glauconitic sandstone often interbedded with purplish grey mudstone, common iron stone concretions, rare burrows infilled with glauconitic sst.

MASSIVE MUDSTONE WITH GLAUCONITIC SANDSTONE INTERBEDS: Thin interbeds of dull greenish grey sandstone within massive medium grey slst, poorly exposed.

MASSIVE MUDSTONE: Medium grey weathering into light yellow florescence, occ. with slight greenish tinge, soft and sticky, non-calc., occ. carbonaceous streaks and ironstone concretions, shell casts seen in places, slumping com.

WAIKATO COAL MEASURES: Sub-bituminous coal seams grading into impure coal interbedded with purplish black faintly bedded to massive carbonaceous mudstone, rare resistant ironstone lenses and concretions.

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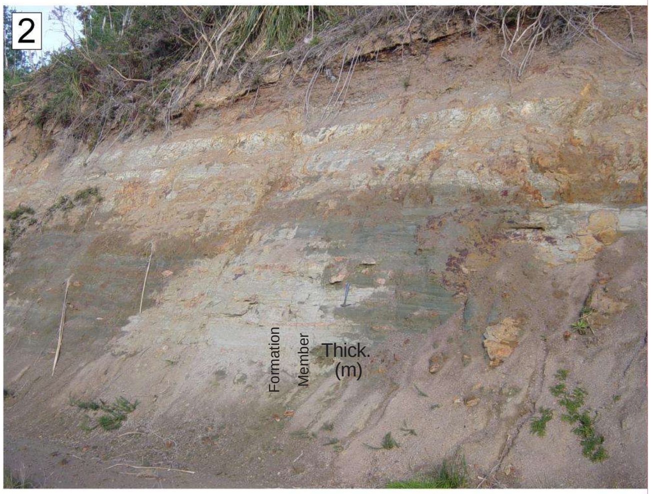

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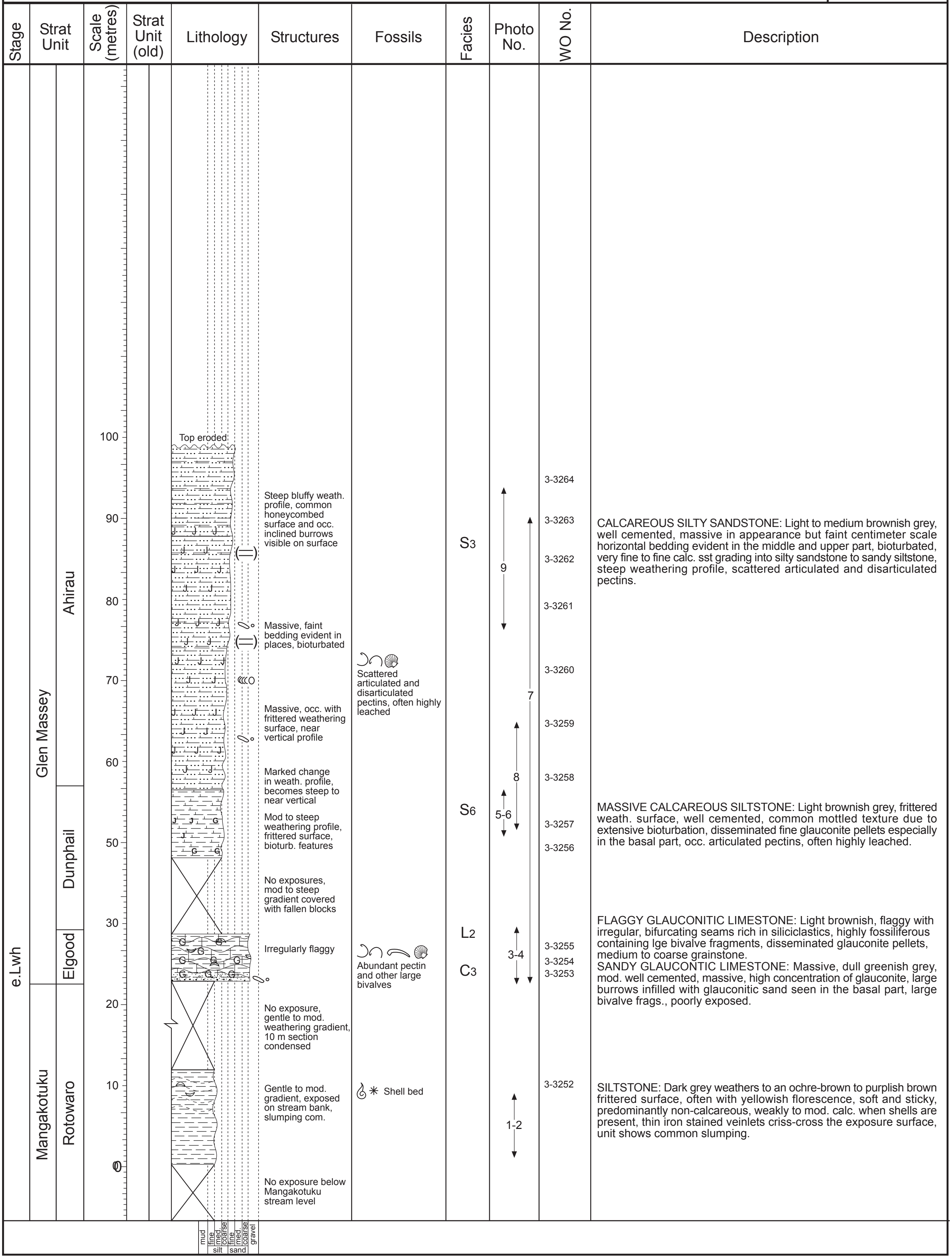
Stratigraphic Column No: *TA-17*
Region: Te Akau
Location: Dunphail Bluff, Elgood Road

Grid Reference:
E: 2693952
N: 6393645

NZMS 260 Sheet: S14/939936

Page 1 *of* 3 **Author:** A. Tripathi



Steep bluffy weath. profile, common honeycombed surface and occ. inclined burrows visible on surface

Massive, faint bedding evident in places, bioturbated

Massive, occ. with frittered weathering surface, near vertical profile

Marked change in weath. profile, becomes steep to near vertical

Mod to steep weathering profile, frittered surface, bioturb. features

No exposures, mod to steep gradient covered with fallen blocks

Irregularly flaggy

No exposure, gentle to mod. weathering gradient, 10 m section condensed

Gentle to mod. gradient, exposed on stream bank, slumping com.

No exposure below Mangakotuku stream level

Scattered articulated and disarticulated pectins, often highly leached

Abundant pectin and other large bivalves

Shell bed

CALCAREOUS SILTY SANDSTONE: Light to medium brownish grey, well cemented, massive in appearance but faint centimeter scale horizontal bedding evident in the middle and upper part, bioturbated, very fine to fine calc. sst grading into silty sandstone to sandy siltstone, steep weathering profile, scattered articulated and disarticulated pectins.

MASSIVE CALCAREOUS SILTSTONE: Light brownish grey, frittered weath. surface, well cemented, common mottled texture due to extensive bioturbation, disseminated fine glauconite pellets especially in the basal part, occ. articulated pectins, often highly leached.

FLAGGY GLAUCONITIC LIMESTONE: Light brownish, flaggy with irregular, bifurcating seams rich in siliciclastics, highly fossiliferous containing lge bivalve fragments, disseminated glauconite pellets, medium to coarse grainstone.

SANDY GLAUCONTIC LIMESTONE: Massive, dull greenish grey, mod. well cemented, massive, high concentration of glauconite, large burrows infilled with glauconitic sand seen in the basal part, large bivalve frags., poorly exposed.

SILTSTONE: Dark grey weathers to an ochre-brown to purplish brown frittered surface, often with yellowish florescence, soft and sticky, predominantly non-calcareous, weakly to mod. calc. when shells are present, thin iron stained veinlets criss-cross the exposure surface, unit shows common slumping.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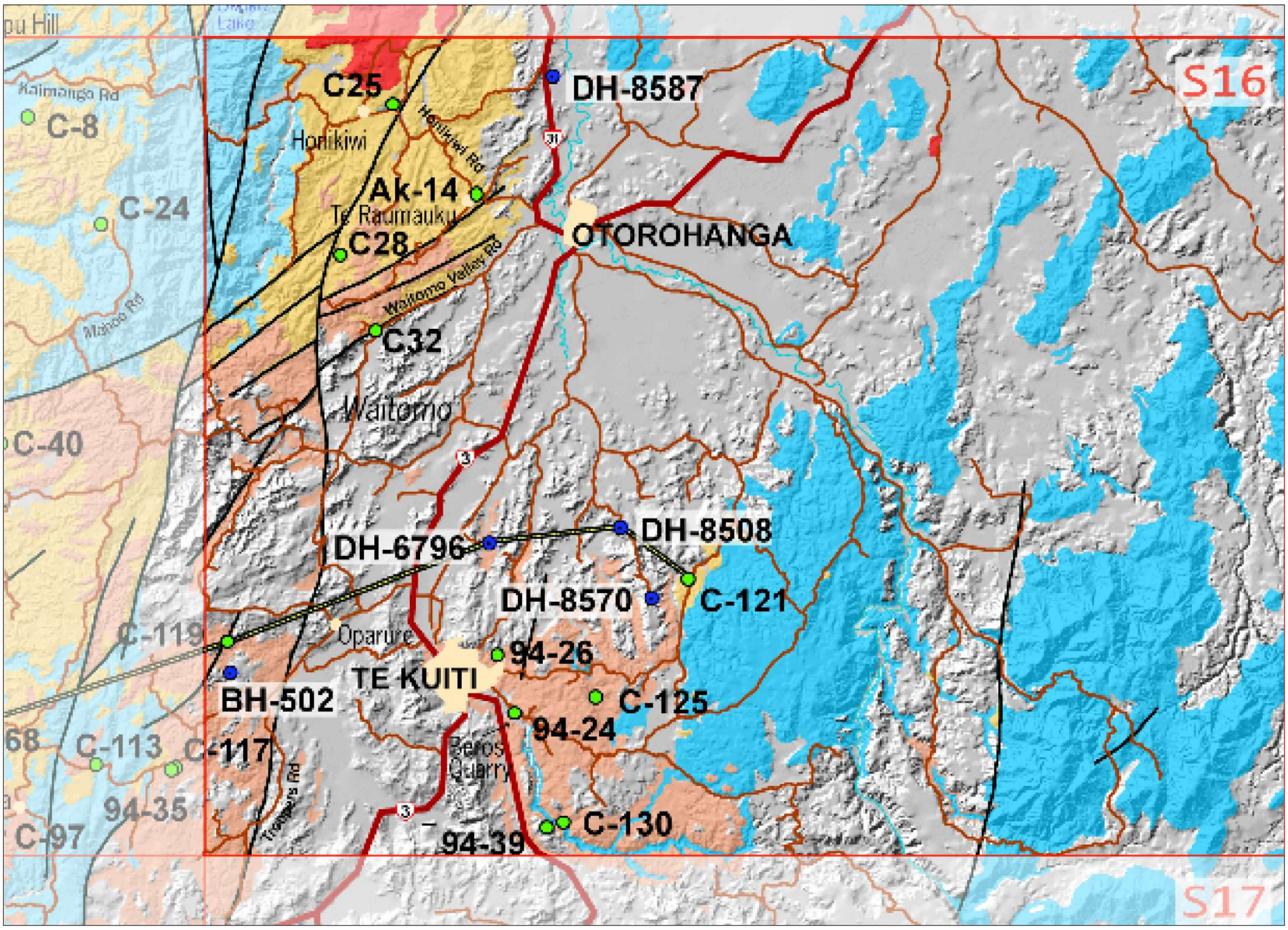
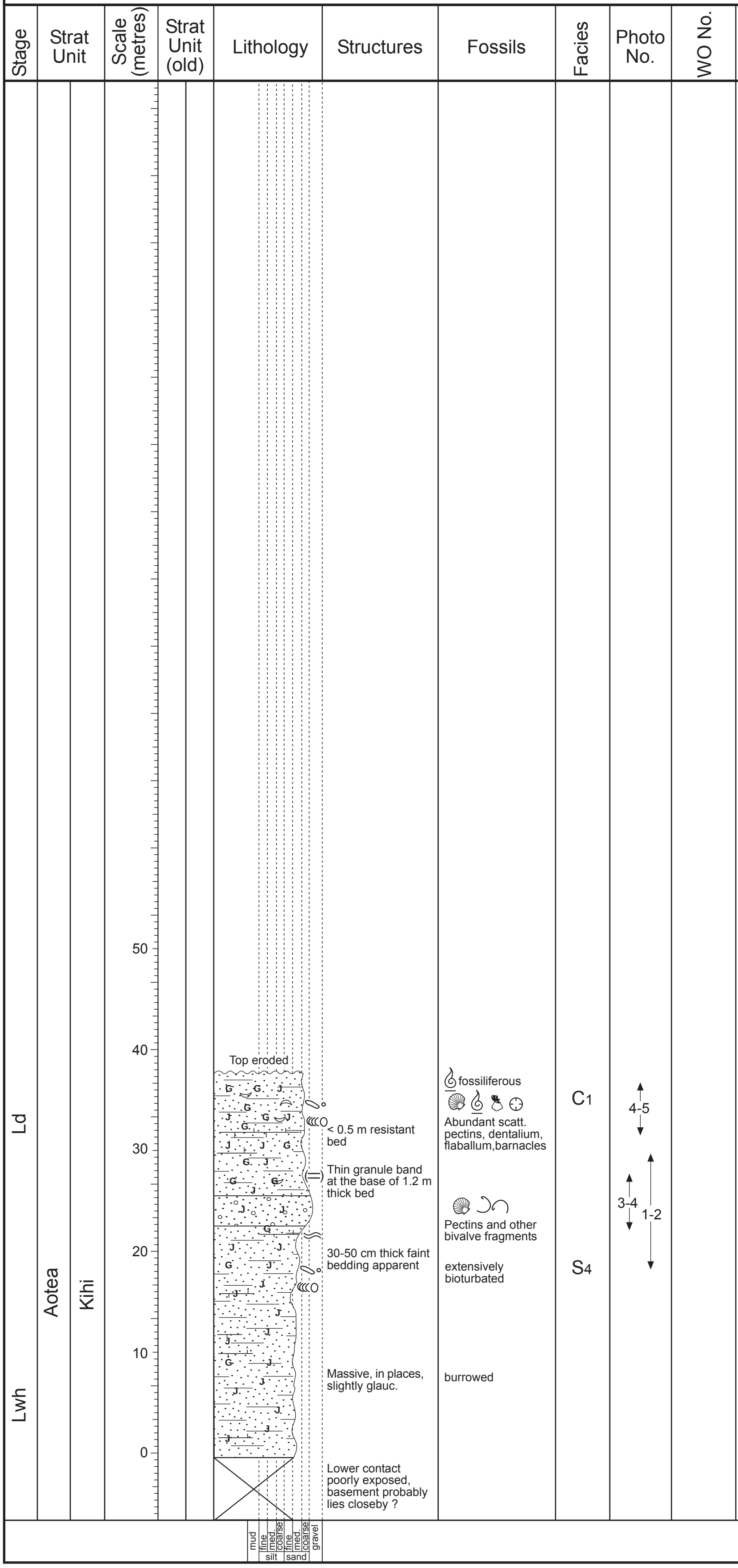

S16
C25
DH-8587
Kaimanga Rd
C-8
Honikiwi
Honikiwi Rd
31
Ak-14
C-24
Te Raumauku
OTOROHANGA
C28
Waitomo Valley Rd
Mahoe Rd
C32
Waitomo
C-40
3
DH-8508
DH-6796
C-121
DH-8570
C-119
Oparure
94-26
TE KUITI
BH-502
C-125
94-24
68
C-113
C-117
Beros Quarry
94-35
Troopers Rd
3
C-97
C-130
94-39
S17

Stratigraphic Column No: *Ak-14*
Region: Aotea-Kawhia
Location: Honikiwi Road side exposure

Grid Reference: **Top** **Bottom**
E: 2700010
N: 6334249

NZMS 260 Sheet: S16/000342
Page 1 *of* 2
Author: A. Tripathi



Description

GLAUCONITIC SANDSTONE: Dark greenish-grey, weakly to mod. cemented, fine to medium variably calc. muddy fine to medium sandstone with abundant glauconite (content > 50%), fossiliferous, burrowed, abundant scattered pectins, barnacles, solitary corals and dentalium.

GRITTY SANDSTONE: Greenish grey, mod. cemented. 0.3-1.2 m crude bding apparent from relatively resistant beds, scattered rounded-subrounded granule size clasts in places concentrated in thin beds and occ. infilling the burrows, extensively bioturbated evident from mottled texture, abun. glauconite pellets of fine to medium sand grade.

MUDDY SANDSTONE: Dull blue-grey, mod. cemented, massive to faint horizontal bedding discernible in places, common exfoliation weathering, muddy fine sandstone, extensively bioturbated, disseminated glauconite pellets.

CALCAREOUS SILTY SANDSTONE: Dull grey to bl-grey, mod. well cemented massive, slightly frittery in places, fine calcareous silty sandstone, bioturbated, grades upsection into muddy sandstone.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Stratigraphic Column No: *94-24* **Grid Reference:**

Region: Te Kuiti **E:** 2701400

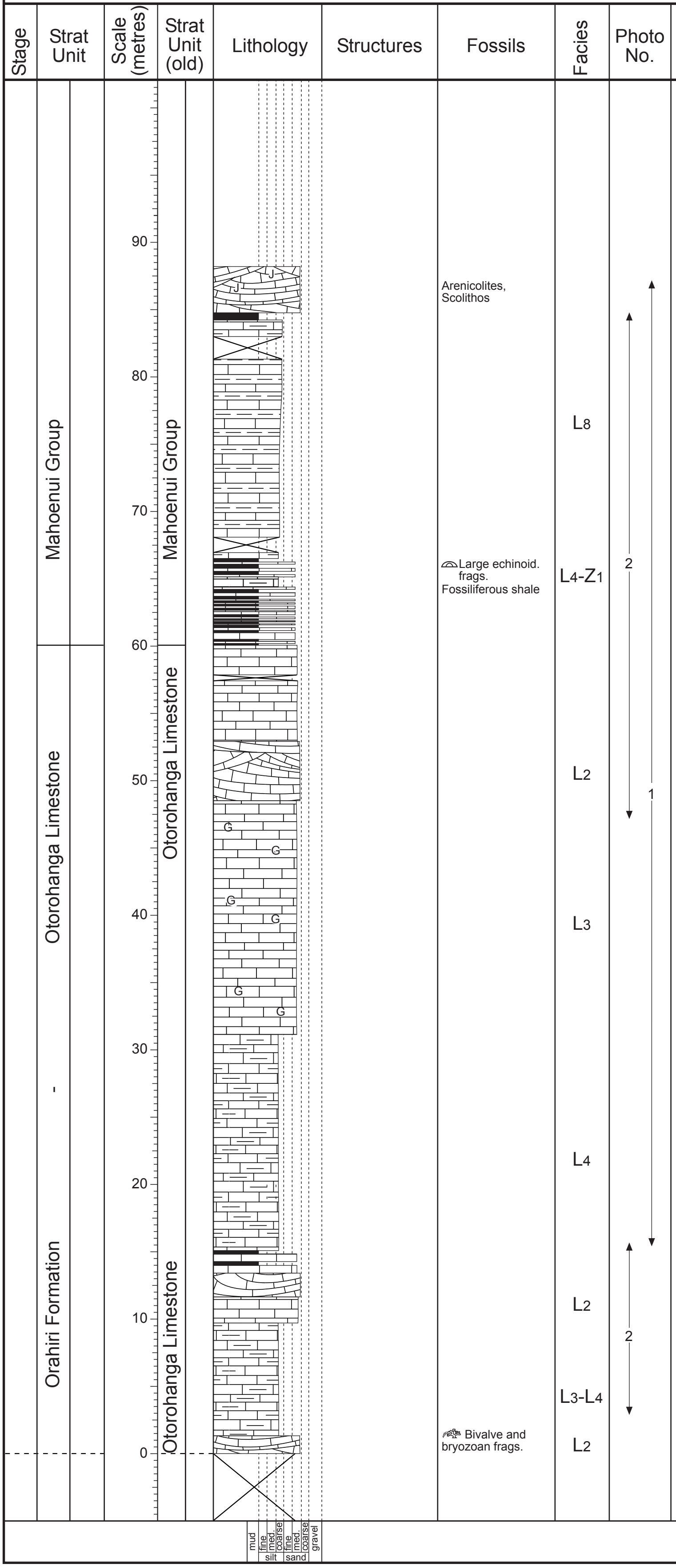
Location: Old Beros quarry, Te Kuiti **N:** 6315200

NZMS 260 Sheet: S16/014152

Page 1 *of* 2

Author: A.S. Anastas

Modified: A. Tripathi



Description

Vertical burrows containing pellets.

Cross-bedded lst.

Laminated grey-green shale.

Argillaceous lst./interbedded shale and lst., shale % decreases upwards, beds undulatory, shales 1-1.5 cm, lsts. 7-12 cm.

Tempestite, sharp base.

Cross-bedded lst., formset preservation, 7-10 cm beds.

Horizontally bedded lst., glauconite common.

Massive argillaceous lst.

Horizontal bedding.

Massive lst., argillaceous, poorly developed bedding.

Cross-bedded lst., one large set, obscure, north.

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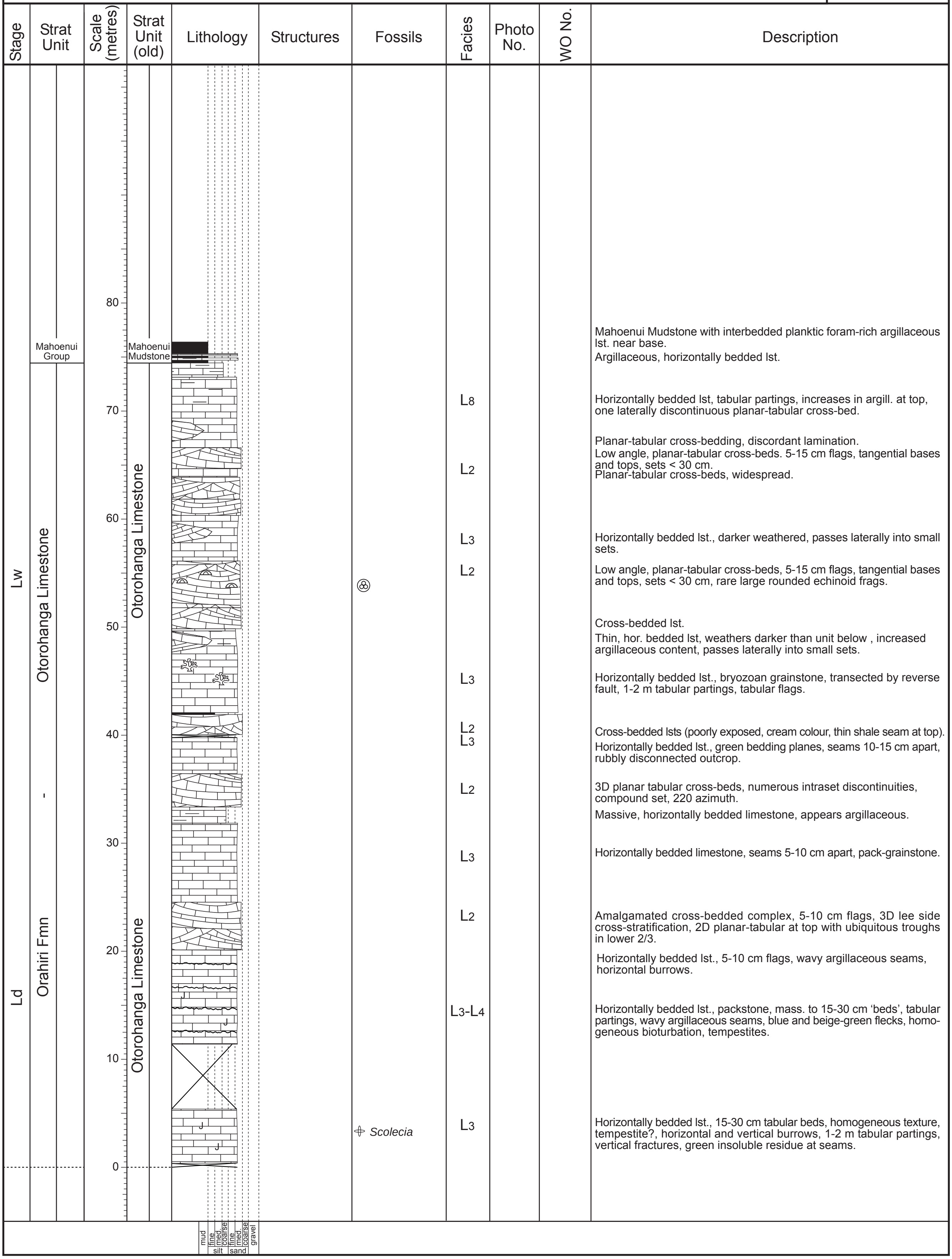
Stratigraphic Column No: *94-26*
Region: Te Kuiti
Location: Rangitoto Quarry

Grid Reference:
E: 2700800
N: 6317300

NZMS 260 Sheet: S16/008173

Page 1 *of* 1
Author: A.S. Anastas
Modified: A. Tripathi



Mahoenui Mudstone with interbedded planktic foram-rich argillaceous lst. near base.

Argillaceous, horizontally bedded lst.

Horizontally bedded lst, tabular partings, increases in argill. at top, one laterally discontinuous planar-tabular cross-bed.

Planar-tabular cross-bedding, discordant lamination.

Low angle, planar-tabular cross-beds. 5-15 cm flags, tangential bases and tops, sets < 30 cm.

Planar-tabular cross-beds, widespread.

Horizontally bedded lst., darker weathered, passes laterally into small sets.

Low angle, planar-tabular cross-beds, 5-15 cm flags, tangential bases and tops, sets < 30 cm, rare large rounded echinoid frags.

Cross-bedded lst.

Thin, hor. bedded lst, weathers darker than unit below , increased argillaceous content, passes laterally into small sets.

Horizontally bedded lst., bryozoan grainstone, transected by reverse fault, 1-2 m tabular partings, tabular flags.

Cross-bedded lsts (poorly exposed, cream colour, thin shale seam at top).

Horizontally bedded lst., green bedding planes, seams 10-15 cm apart, rubbly disconnected outcrop.

3D planar tabular cross-beds, numerous intraset discontinuities, compound set, 220 azimuth.

Massive, horizontally bedded limestone, appears argillaceous.

Horizontally bedded limestone, seams 5-10 cm apart, pack-grainstone.

Amalgamated cross-bedded complex, 5-10 cm flags, 3D lee side cross-stratification, 2D planar-tabular at top with ubiquitous troughs in lower 2/3.

Horizontally bedded lst., 5-10 cm flags, wavy argillaceous seams, horizontal burrows.

Horizontally bedded lst., packstone, mass. to 15-30 cm ‘beds’, tabular partings, wavy argillaceous seams, blue and beige-green flecks, homogeneous bioturbation, tempestites.

Horizontally bedded lst., 15-30 cm tabular beds, homogeneous texture, tempestite?, horizontal and vertical burrows, 1-2 m tabular partings, vertical fractures, green insoluble residue at seams.

Stratigraphic Column No: *94-39*

Grid Reference:

Region: Te Kuiti

E: 2703200

Location: 'CSN' 135, Mangaokewa Stream,
south of Te Kuiti

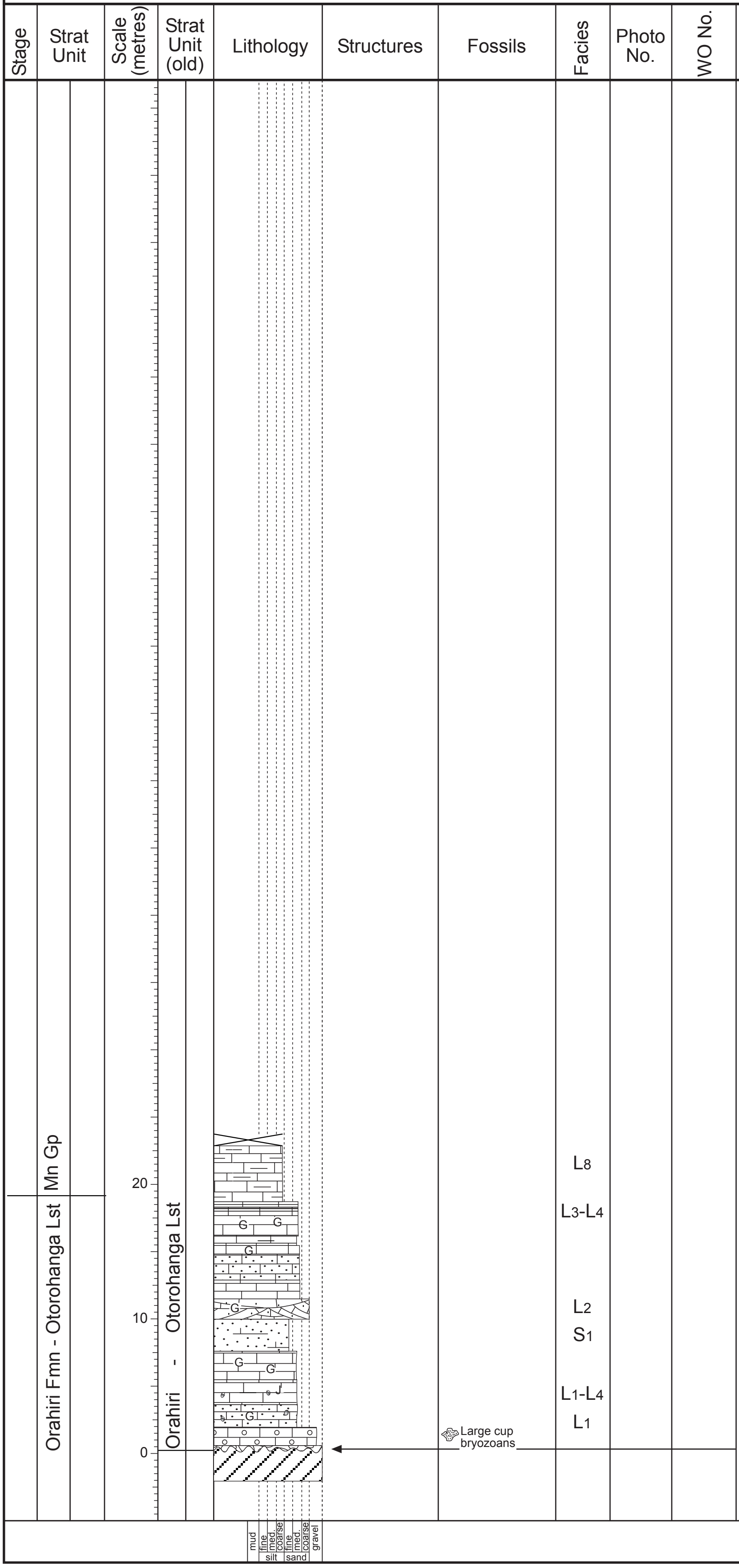
N: 6311200

NZMS 260 Sheet: S16/032112

Page 1 *of* 1

Author: A.S. Anastas

Modified: A. Tripathi



Description

Argillaceous, horizontally bedded lst., glauconitic (?) lamination. Tabular beds 15-20 cm, rare vertical burrows.

Interbedded brown friable and glauc. lst., cross-bedded?

Glauconitic lst.

Massive to thick bedded lst., sandy.

Sandy glauc. lst., cross-set, lamination.

Massive calc. sst., dark green-brown.

Massive to thick bedded lst., horizontally bedded, glauconitic.

Rhodolite-pebble lst., borings, massive, mud chips.

Massive sandy glauc. lst., rare pebbles.

Pebbly lst.

Boulder conglomerate, carbonate cemented, pebbly.

Basement.

Stratigraphic Column No: *C-25* **Grid Reference:**

Region: King Country/Waitomo

E: 2696921

Location: Abandoned basement quarry, East of Honikiwi

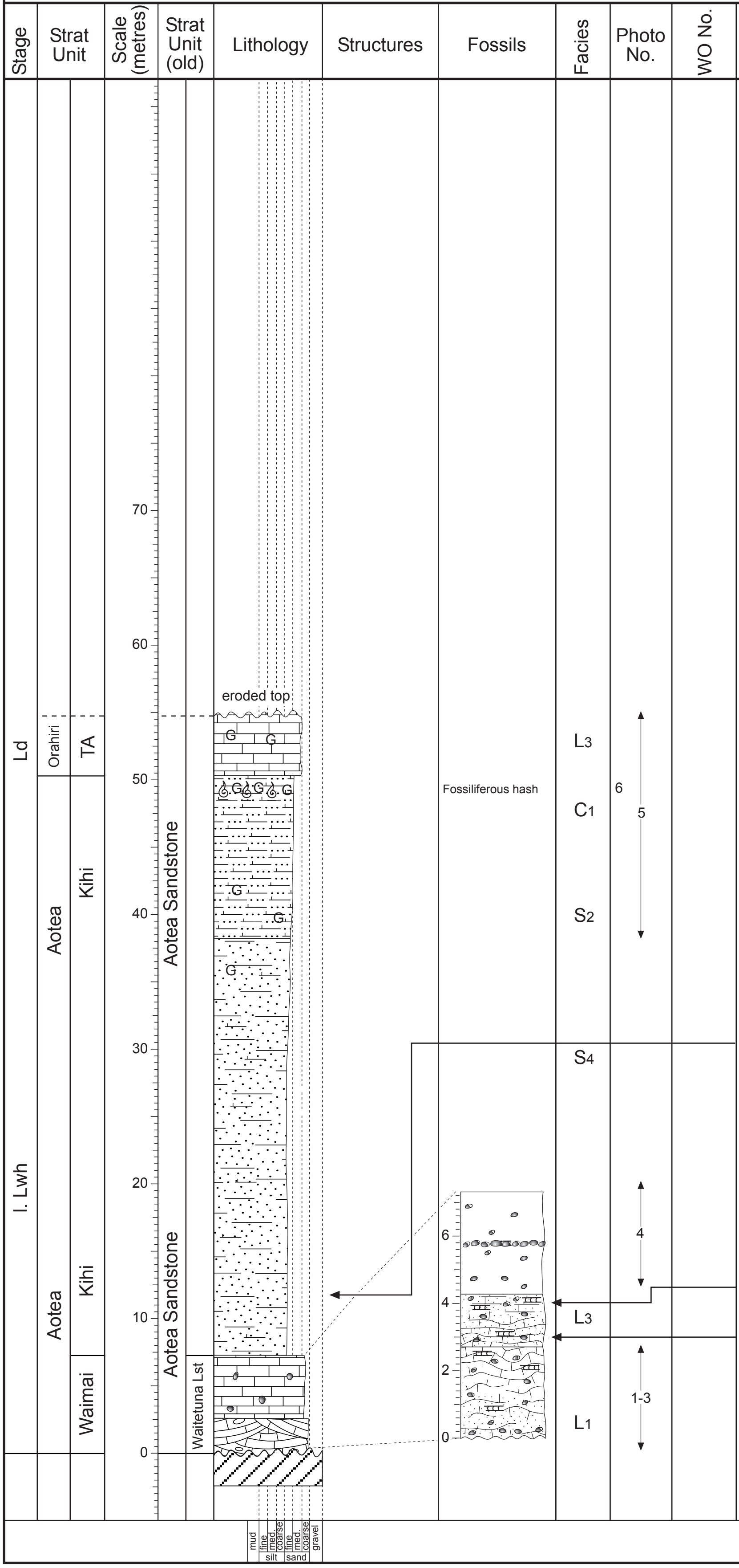
N: 6337506

NZMS 1 Sheet: S16

Page 1 *of* 1

Author: C. Nelson

Modified: A. Tripathi



Description

C/gr. glauc. slabby lst. showing pseudobded. app. where weathered.

Weath. indent., ff-hash in well cem. glauc. s. lst. for 15-22 cm grad. down into horiz. of limonite pyrite concrets. and tubules.

Fine glauc. calc. sst.

Muddy sl. glauc. f. calc. sst.

Blue/grey muddy v.f. calc. ssts., mst. horizons, frittered surf., poorly exposed.

Mass.-incip. seams, 5-7.5 cm flags, v. occ. sm. pebbs. to 1.3 cm seen.

15 cm pebb. band as w. ind., pebbs. av. 2.5 cm, max. 10 cm, algae present.

Incip.-mod. seams, slabby app., scatt. pebbs. av. 2 cm, v. poorly sorted.

Pebbs. to 15 cm common in mass., irreg. surf. s. lst., algae, grit-f. pebbs. typical.

Mass.-sl. incip. seams.

Incip.-mod. seams, flags av. 7.5 cm, lge. pebbs. rare, common grit and v.c. sand.

Pebbs. av. 7.5 cm in irreg. incip. seamed lst., flags av. 5 cm, algal encrustn. common.

Rel. mass., irreg. surf. pebbly lsts. w. pebbs. to 10 cm near base becoming less abund. upwrds, algal encrustaceans.

Mesozoic basement rocks - a conglom.; basal lst. dips 11°E/342° against old hill of conglomerate.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Orahiri Fm
Kihi Sst


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Stratigraphic Column No: *C-28*

Grid Reference:

Region: King Country/Waitomo

E: 2695027

Location: Te Raumauku, south of Honikiwi

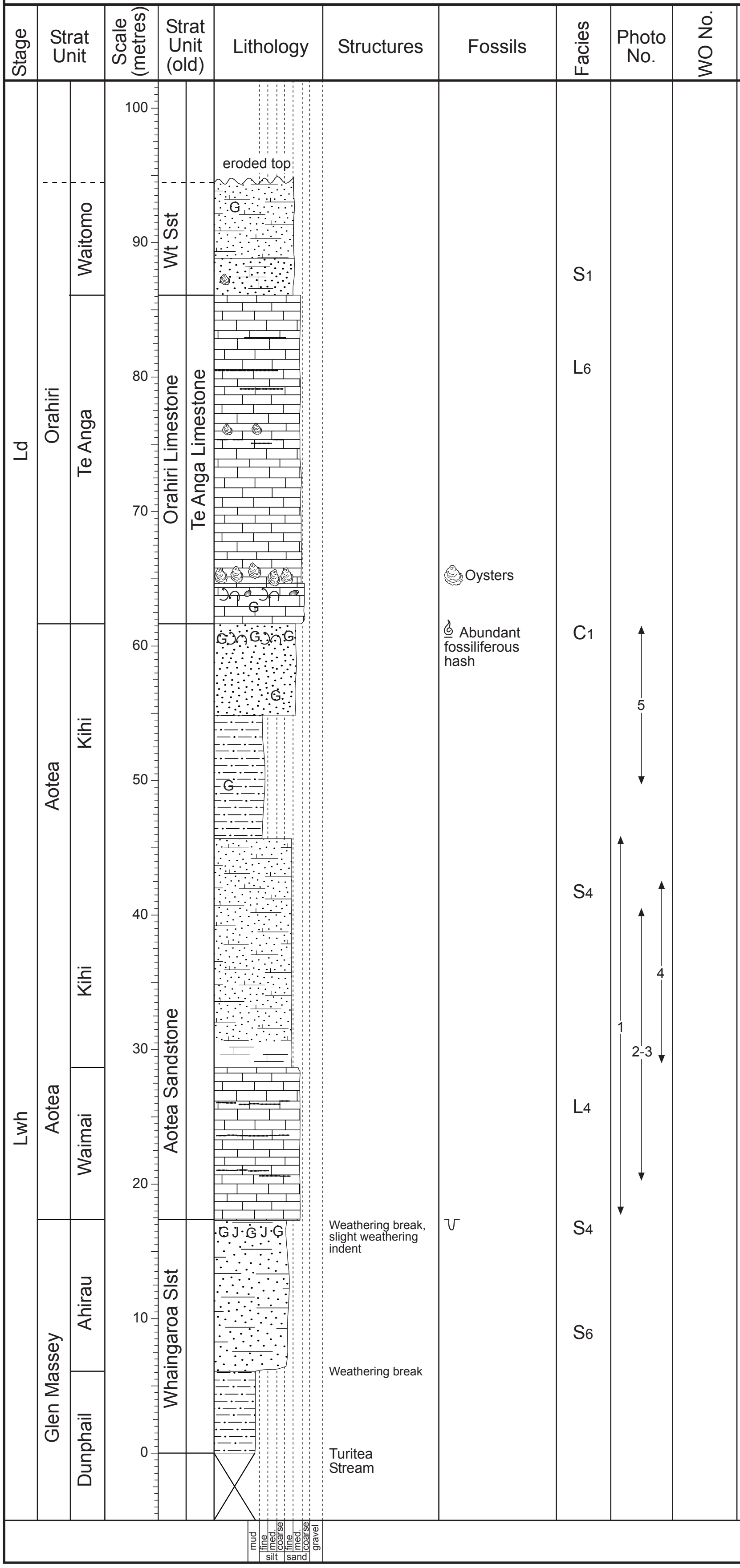
N: 6331981

NZMS 1 Sheet: S16

Page 1 *of* 1

Author: C. Nelson

Modified: A. Tripathi



Sl. glauc. calc. sst., green-grey colour, smooth, tends frittery.

Mass. ripply-incip. seamed calc. sst. (s.lst.), rare oyst., grad. contacts.

Wide flagged, av. 10-15 cm, lst. with rel. prominent sand seams.

~76 m, incip. oyst. plus ff-material.
75-76 m - highly irreg. and thick mod. dev. seams, vert. jointing, pseudo-knobbly appearance.

Flaggy lst., flags av. 10-13 cm w. incip. sand seams above 65.5 m becoming mod.-well developed, sl. wavy higher with var. flags 5-10 cm.

64.5-65 m - incip.- well dev., sl. irreg. seams, non-glauc. ~ 65 m, mod. packed oyst. band, oyst. haphaz., disart. and art., rel. sharp top and bottom.

61.6-64.6 m - sl. glauc. slabby lst., flags av. 7.5 cm, occ. pseudobded., after 64.3 m, ff-hash zone with abund. fine bivalve debris, occ. pebbs. av. 1 cm, bone.

55-61.6 m - glauc. calc. sst. as smooth faced “cliff”, occ. bivalve mat. and limonite borings at top, sst. bl./gr., fritt., occ. limonite (pyrite) concrets. to 7.5 cm size, elliptical shapes.

45.75-55 m - poorly exposed, app. sl. glauc. s. msts.

B/gr. fine calc. ssts., muddy, fritt. surface., weath., poorly exposed.

Slabby, mod.-well dev. seams, flags gen. wide, av. 12.5 cm, mod. glauc., seams wide and sandy and slightly irregular.

16-17 m, tends frittery in fine glauc. sst., occ. borings evid., top 2.5 cm better cemented.

Mass.-incip. ripply smooth sl. glauc. calc. muddy sst. (s. lst.) as small bluff.

Bl/gr. sandy mst., frittery weathering.

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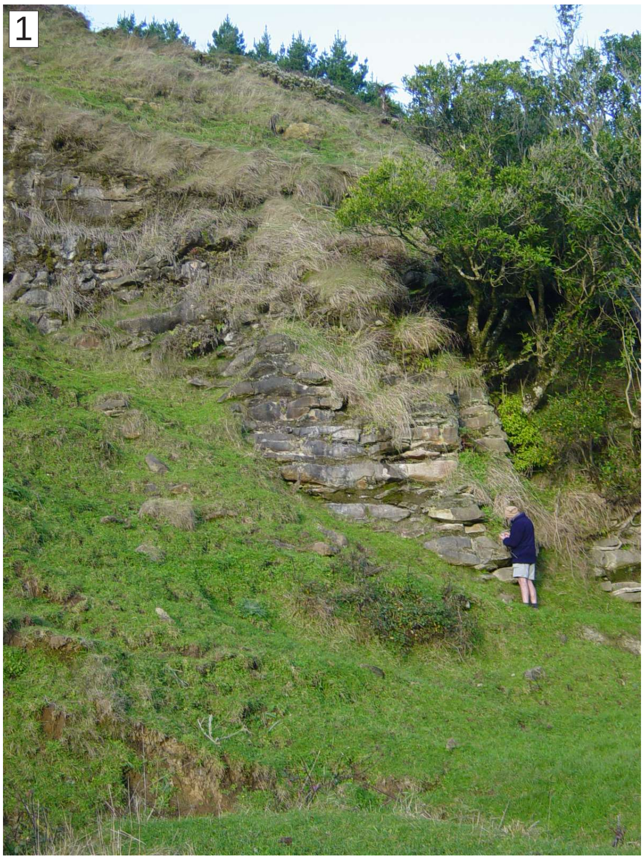

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Stratigraphic Column No: *C32*

Grid Reference:

Region: King Country/Waitomo

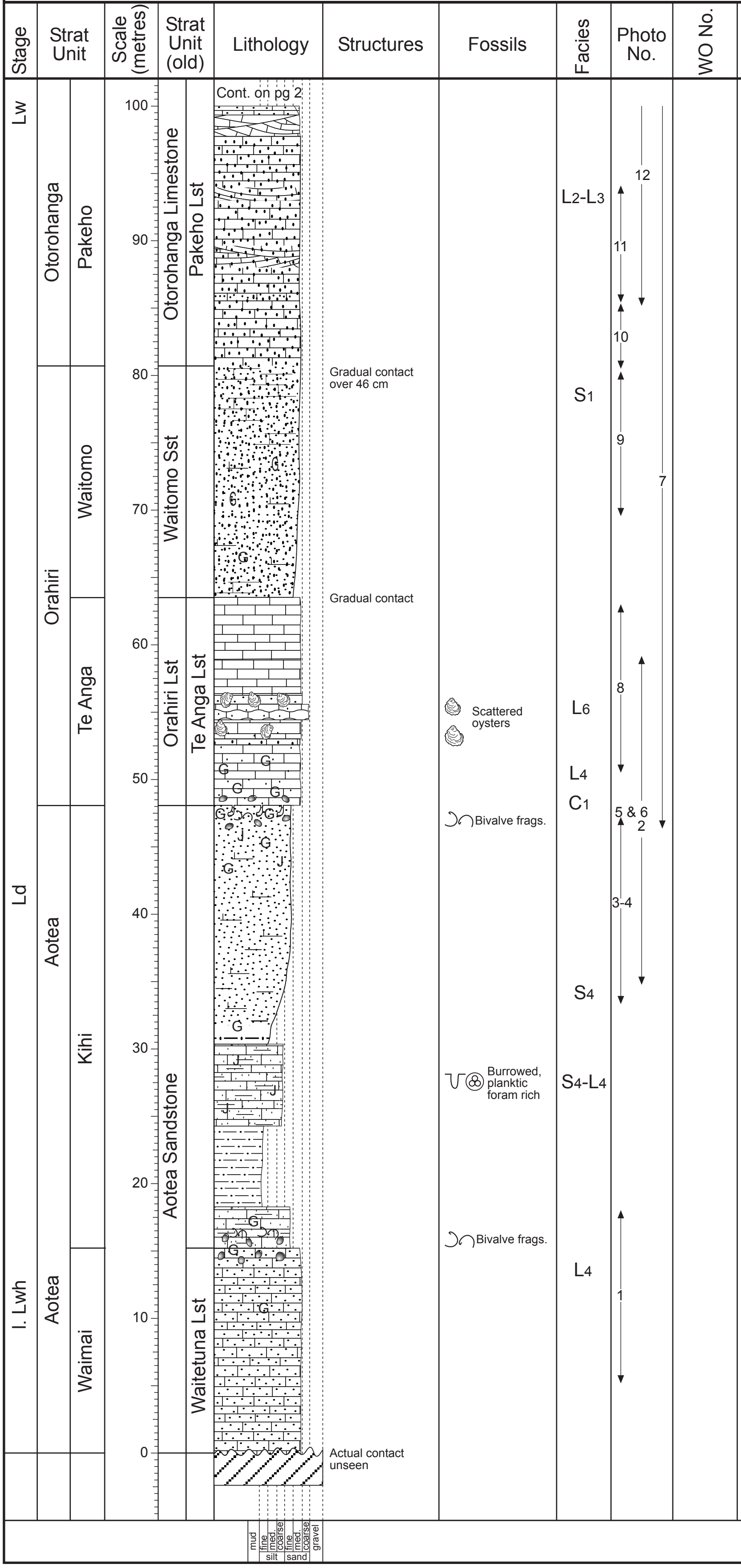
E: 2696320 - 2696142

Location: Abandoned limestone quarry,
northeast of Waitomo

N: 6329200 - 6329388

NZMS 1 Sheet: S16

Page 1 *of* 2 **Author:** C. Nelson
Modified: A. Tripathi



Description

Mass.-incip. seamed lst., sl. sandy.
Crossbed 12° to ENE, well dev. flags 5-10 cm.

Flaggy lst., flags mod.-well dev., 5-15 cm wide, sep. by wide (to 1.3 cm) seams Complexly cross-bedded at a no. of levels, is on a lge. scale and shows both planar and trough vars., var. current dir., cosets of 5-15 cm , sep. by horiz. flags minor channeling.

12° to NE seen.

Mass. s. lst. as 40.5 cm indent.

Inv. seams 2.5-7.6 cm apart, sl. irreg., seams wide near base, weath. in, to 2.5 cm wide.

Calc. sst. - s. lst.

Mass. calc. sst., com. leached and w., forms smooth connecting slope between two lst. Glauc. content mod., decr. upwards as does sand content. Ssts. fine throughout.

25 cm hard s. lst., 10 cm calc. sst., passes into flaggy lst.

7.6-15.2 cm flaggy lst., irreg. seams, sl. sandy, glauc. nearer top.

Pure micritic lst., irreg. seams 7.6-15.2 cm.

Oyster band, disartic., haphaz., 10 cm frags., incip. irreg. seams.

Scatt. oyst. horizon, 45.7 cm scatt. frags., 53.5 cm occ. lge. frags, 38 cm scatt. oysts.
Sl. glauc. lst., mass.
Mass.-incip. lge. flagged lst., sl.-mod. glauc., occ. pebbs. near base, borings infilled w. glauc. lst. into underlying gsd.

Immed. below 48.2 m have calc. gsd., mass., well cem. for 30.5 cm, less cem. and forms strong w. indent. 47-48 m, base marked by 5-7.6 m band of biv., par. bed., trace ff., pebbs. to 5 cm av., 0.95 cm scatt. thr.out, biv. frags. scatt., com. in streaks & lenses, calc. worm tubes, cem. top shows lge. borings infil. w. overlying lst., biv. band varies in dist. below contact along strike, also glauc. content, overlying lst. shows marked overhang. Grad. down into w. mod. gl. calc. muddy sst., less ff. mat., sl. fritt., occ. borings, glauc. content decreases. dnwd. Passes down into bl/gr fritt. m. v.f. sst. and v. s. msts, burrowed, sl. glauc.

Sl. s. burrowed muddy lst., plnk. foram. rich.

Blue/grey s. mst.

Sl.-v.s. lst., muddy, glauc. and pebbly (av. 0.6 cm) at base, bivalve frags. common.

Mass. ripply-incip. seamed, av. 7.5 cm apart sandy lst., sl. glauc. Sand content incr. upwards w. mod. glauc. and pebbs. av. 0.15 cm, max. 0.95 cm at top. Waterfall over lst.

Mesozoic basement rocks.

Stratigraphic Column No: *C32*

Region: King Country/Waitomo

Location: Abandoned limestone quarry,
northeast of Waitomo

NZMS 1 Sheet: S16

Grid Reference:

E: 2696320 - 2696142

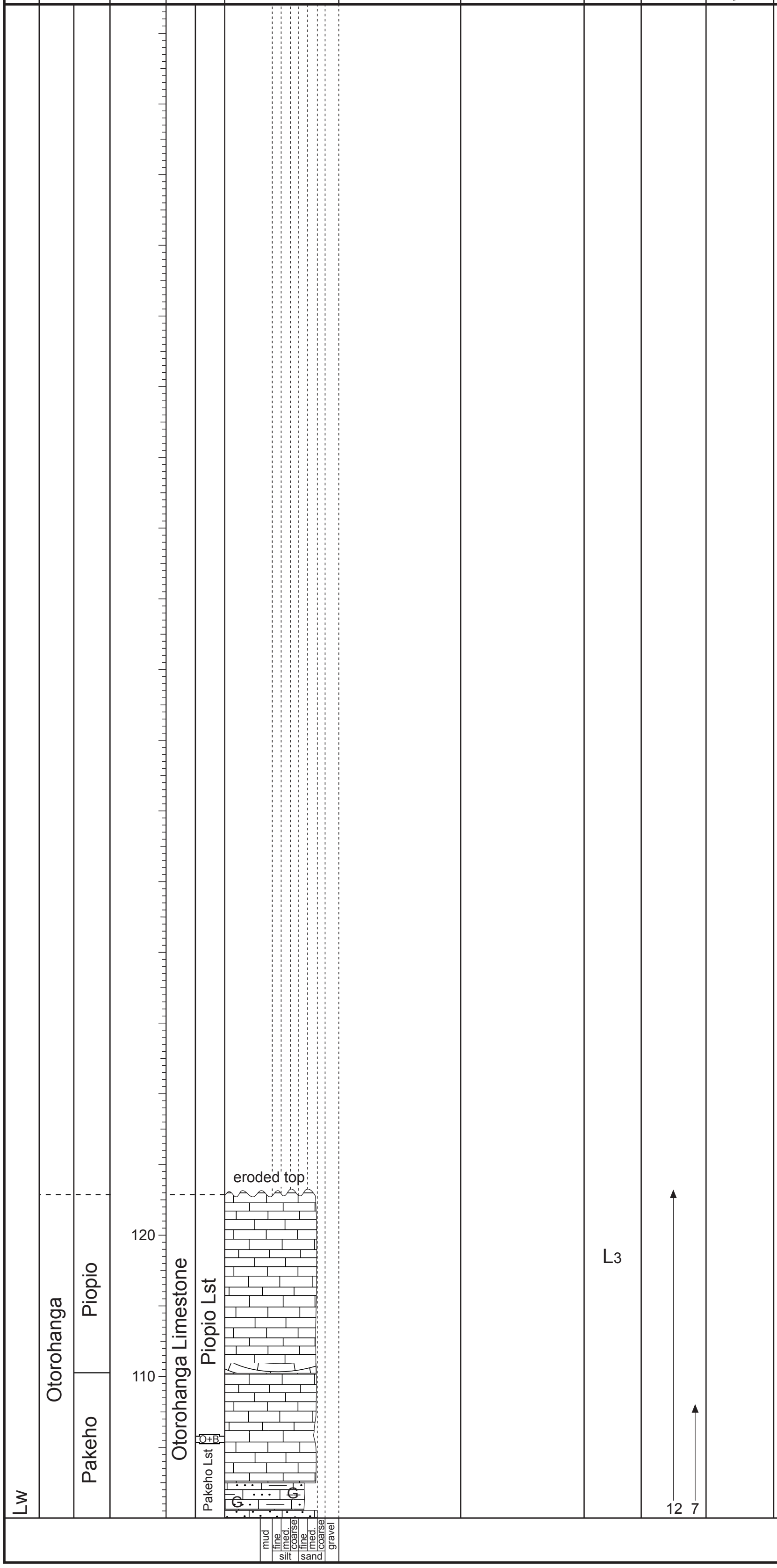
N: 6329200 - 6329388

Page 2 *of* 2

Author: C. Nelson

Modified: A. Tripathi

Stage | Strat Unit | Scale (metres) | Strat Unit (old) | Lithology | Structures | Fossils | Facies | Photo No. | WO No. | Description



Well flagged 15-20 cm lst.

Seams 2.5-7.6 cm apart, seams typ. wide, to 1.2 cm, sl. cavernous w.

Flags 2.5-7.6 cm, wide seams, c. shell mat. appar.

1.22 m more mass. micritic lst., dense, contacts not well flagged
Cross-bedded, flaggy, 10o to NW.

Flaggy lst., 5-7.6 cm.

Irreg. cav. weath., high cement content.

Wide seamed, lamin., flaggy lst.

Muddy glauc. unit, 12.7 cm glauc. lst., 3.8 cm slst., 15 cm glauc. lst.
1.2 cm slst.

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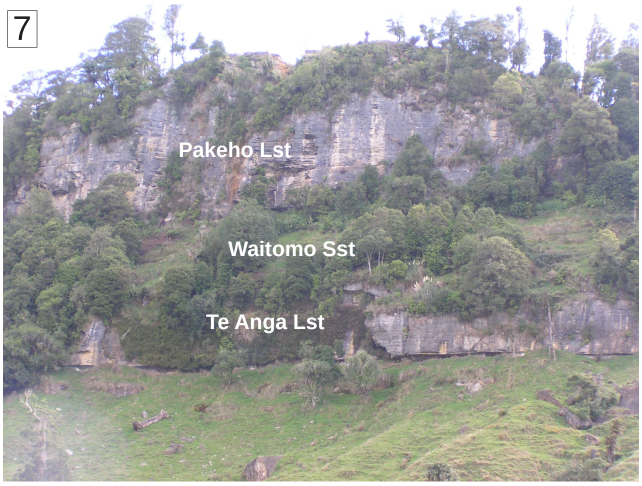


8

9

11

10

12

Stratigraphic Column No: *C-121* ***Grid Reference:***

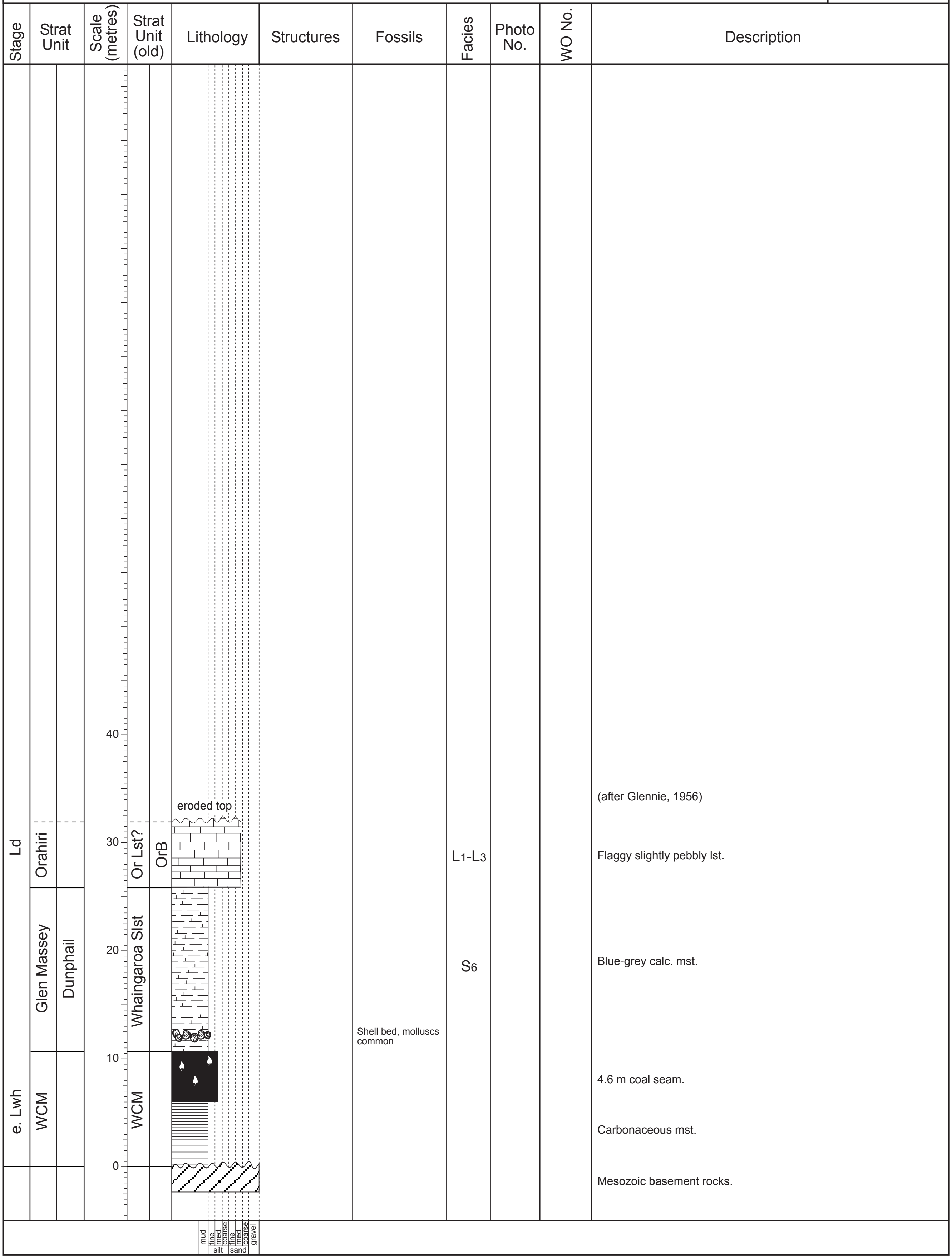
Region: King Country/Waitomo **E:** 2707769

Location: Ngapeke Road, north of Rangitoto **N:** 6320097

Author: C. Nelson (after Glennie 1956)

NZMS 1 Sheet: S16 *Page* 1 *of* 1

Modified: A. Tripathi



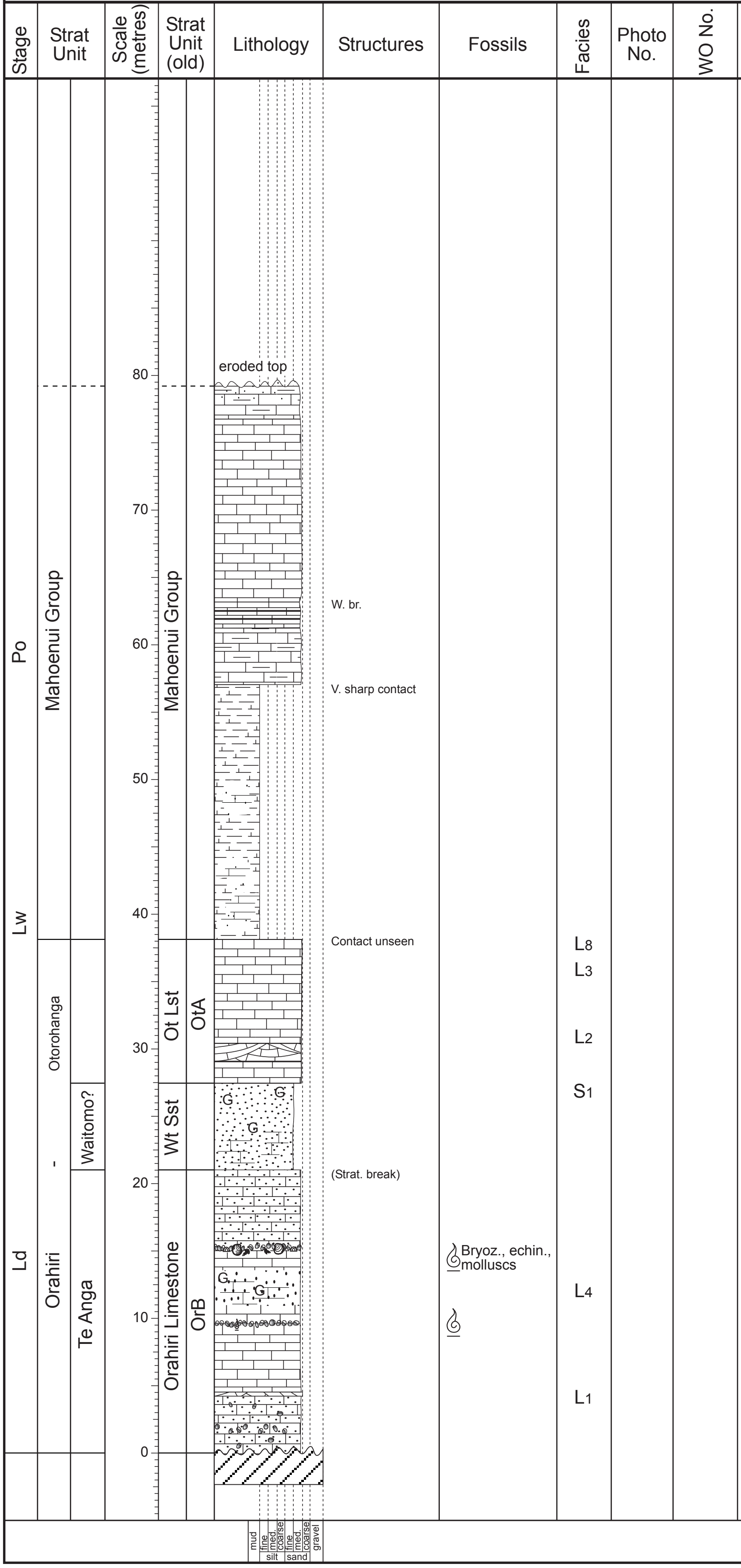
Stratigraphic Column No: *C-125*
Region: King Country/Waitomo
Location: Walker Road, east of Te Kuiti

NZMS 1 Sheet: S16

Grid Reference:
E: 2704355
N: 6315803

Page 1 *of* 1

Author: C. Nelson
Modified: A. Tripathi



Description

Top sample muddy lst. in paddock.
Variable sandy-muddy lst., incipient-mod. flags 2.5-20 cm with shaley seams.

Mod.-well flagged, var. 5-23 cm, av. 13 cm thick lst., seams common, wavy and occ. thick, topog. shelves develop at a no. of heights.

Flags 5-25 cm thick.

Prominent sandy mst. seams to 2.5 cm thick between var. thickness flags.

40° connecting slope of sandy muddy lst. and interbedded mst., lst. beds 15-20 cm thick, nearer base mst. beds up to 23 cm thick.

Bl/gr. calc. mst., weaths. brown, very frittery appearance, contains interbedded smooth mass. slightly sandy muddy lst., non-seamed. Msts. burrowed.

Well flagged 5-15 cm pure lst., seams slightly wavy.

Cross-beds dip 15°, flags 5-15 cm.

Reg. seams 5-7.6 cm apart, sl. glauc. at base.

Mass. calc. glauc. fine sst., fluted outcrop.

Incip. seams 10-20 cm apart nearer base.

Flaggy lst., 7.6-20 cm flags, av. 15 cm.

Gritty sandy lst.

Gritty-pebbly band 10 cm wide, non-seamed, fossiliferous material.

Incip.-mod. flaggy lst., flags av. 7.6 cm, slightly glauc., slightly gritty.

Ff-gritty base, with pebble band 9.5-9.8 m, pebbs. av. 0.3-1.3 cm, sharp base, grad. top, slightly glauconitic.

Flaggy 5-10 cm lst., occ. grit.

30.5 cm cross-bedded unit.

Incip. seams 5-10 cm apart, slightly gritty, pebbs. av. 0.3-0.6 cm, common 1.5-2.1 m, no basal conglom., sharp irregular contact.

Mesozoic basement rocks.

Stratigraphic Column No: *C-130*

Grid Reference:

Region: King Country/Waitomo

E: 2702573

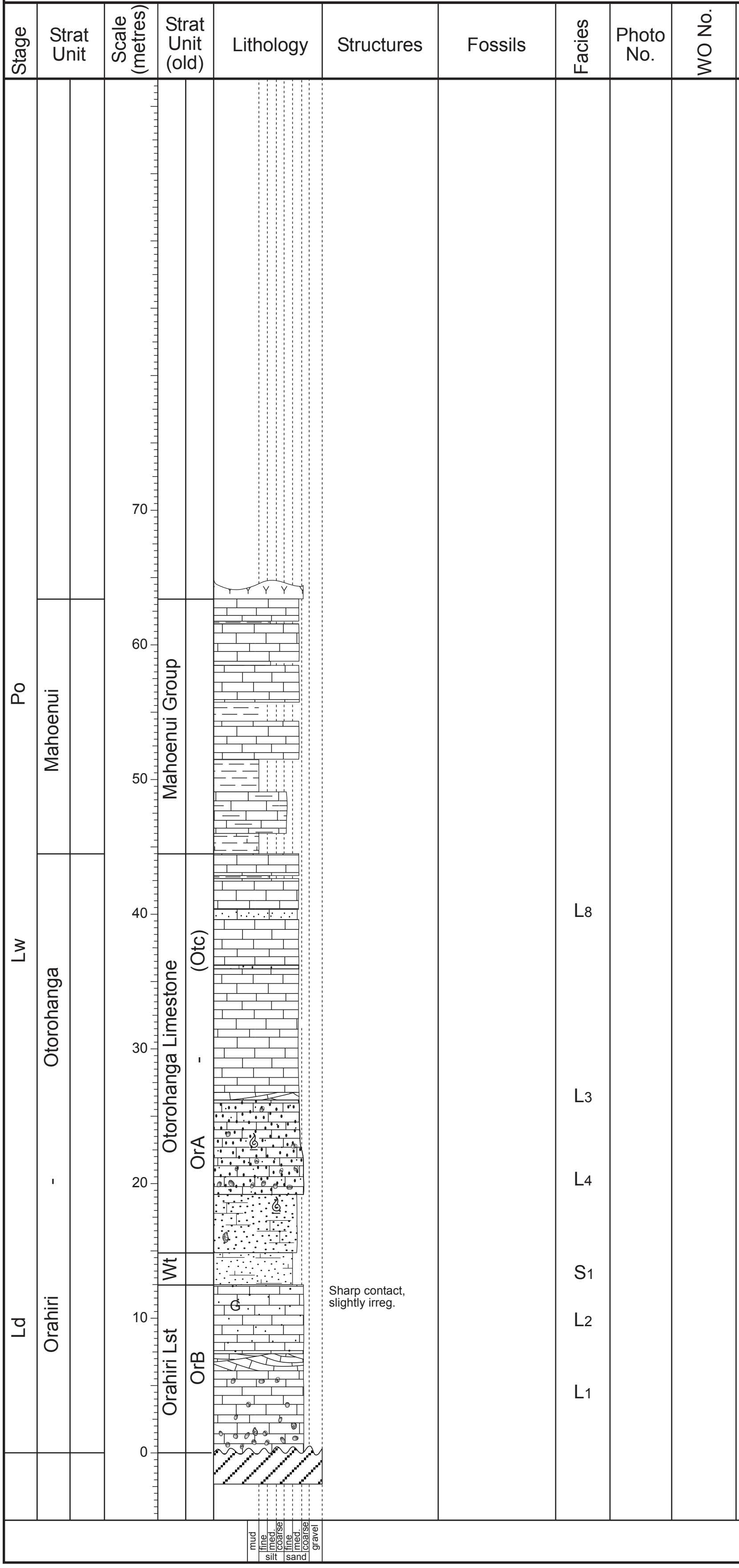
Location: Mangaokewa Stream, SH30, south of Te Kuiti

N: 6311007

NZMS 1Sheet: S16

Page 1 *of* 1

Author: C. Nelson
Modified: A. Tripathi



Description

Ignimbrites.

Flaggy 10-13 cm lst.

18 cm shale unit.

Flaggy 5-10 cm lst.

23 cm shale unit.

Flaggy 5-10 cm lst., well developed flags.

1.5 m blue-grey mst., frittery weathered appearance.

Pure 5-10 cm flagged lst.

Blue-grey. mst.

Muddy lst., var. appearance, top 30.5 cm very hard.

1.5 m blue-grey massive calc. mst.

Pure flaggy 7.6-15 cm lst.

Narrow shale band.

Flags 7.6-15 cm.

60 cm sandy lsts. band, sharp contacts.

Flaggy 2.5-10 cm lst.

Massive sandy lst. band, sharp contacts.

Pure 2.5-7.6 cm flaggy lst., very scattered pebbles, occ. iron-stained pyrite concretions.

Cross-beds, dip 10° N.

Incip. seamed 2.5-7.6 cm lst., occ. ff., v. occ. gwk pebbs. 1.3-12.7 cm size.

Incip.-mod. flaggy av. 5 cm lst., gritty-pebbly, esp. 19.5-20.7 m, pebbles to 5 cm size, no def. pebble bands, pebbles av. 0.6 cm.

Mass. sandy lst., occ. incip. bedded. app., ff in parts, rare large. oysters.

Weathered, smooth sloping (40°) calc. fine sst., var. width along strike (e.g., to 30 cm).

Sparsely gritty 7.6-10 cm flaggy lst., seams to 1.3 cm thick with sand and glauc., incipient-mod. seam development, limonite pyrite.

Cross-beds, dip 10° N.

Sl. pebbly lst., pebbs. 0.3-0.6 cm size, occ. lger. in mass.-incip. seamed s. lst.

V. pebbly basal portions, pebbles subrounded.-rounded. gwk., pebbs. 0.32-60 cm+, pebbles >matrix at base, ff-oysters to 30 x 23 cm size, art. and disart., sharp irregular contact.

Mesozoic basement rocks.

Stratigraphic Column No: *S1* ***Grid Reference:***

Region: Aotea - Kawhia

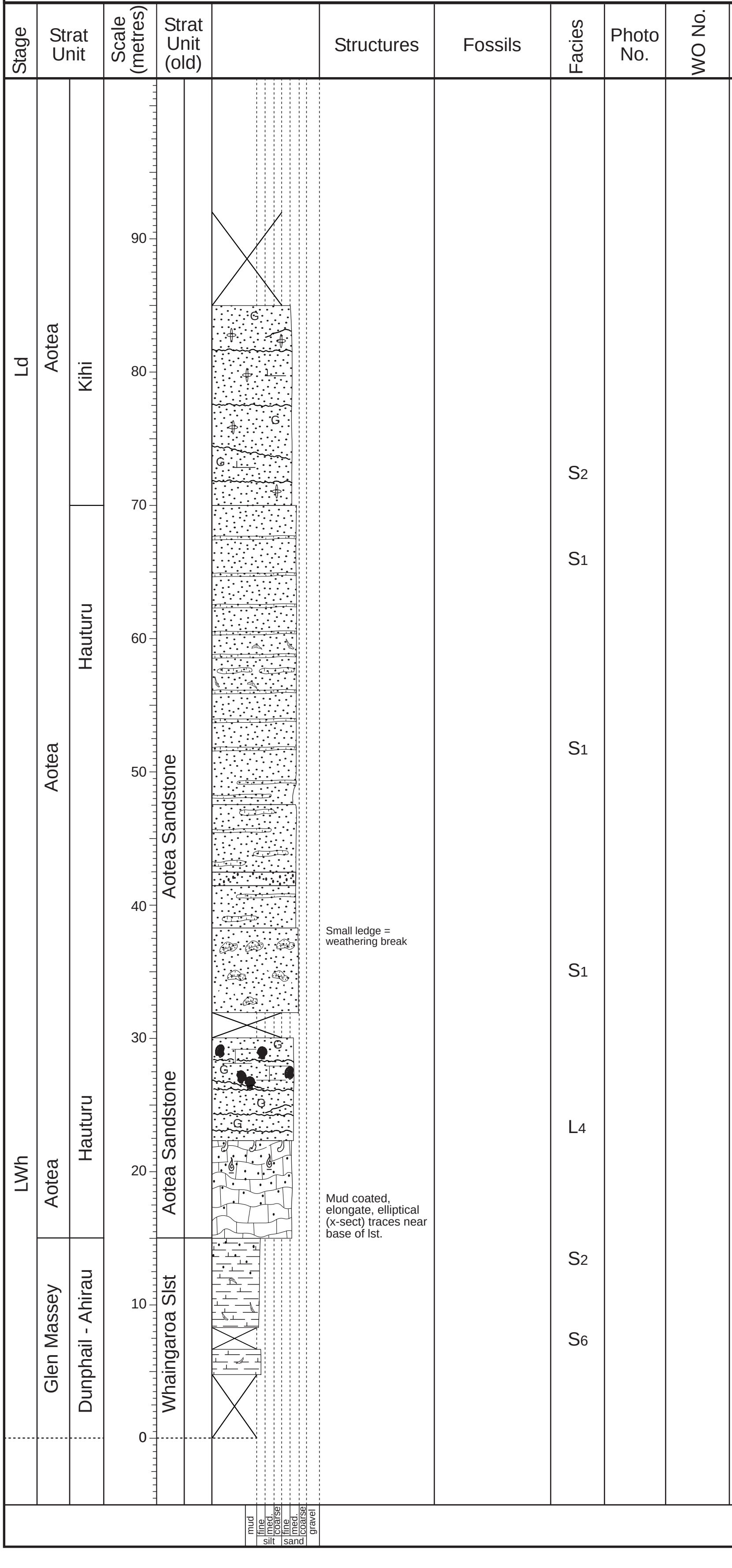
E: 2681981

Location: "Southern Bluffs"; ca. 1.5 km NW of "The Dome"

N: 6336374

NZMS 1 Sheet: S16

Page 1 *of* 2 **Author:** D. Fergusson



Small ledge = weathering break

Mud coated, elongate, elliptical (x-sect) traces near base of lst.

Description

Vegetation (sl. coarsening upwards).

Lt. or. gr., mod. ind., sl.-glauc., calc f. sst. with small concret. or better cemented sst. Bioturbation evident throughout. Grades up to massive-ripply-bulbous profile. Finely banded at lower zone - irreg. shaped 'ripply' bands.

Profile changes - oversteep, 'bulbous'.

Lt. or. gr., mod. ind., sl.-mod. calc., f. sst. with rare-some shell frags. Banded, uniform 12-15 cm thick bands.

1.5 m overhang.
Erosional concavity.

Lt. or.-gr., wk. ind., sl.-mod. glauc., clc. f.m. (qtzose) sst. Leached zone.

Cross-bedded; 16^{o} app. dip, foresets planar. Foresets preserved as alt. well/poorly cemented sets; 4-6 cm spacing.

Lt. or.-gr., wk. ind., sl. glauc., sl. calc., f-m sst. with shell frags enclosed by matrix of friable, shelly sand. Knobbly; leached-unevenly distrib. Knobs 8-12 cm width. Matrix weath. back into outcrop up to 10-15 cm (banded app. becomes obv. up section).

Proportion of terrig. clastics increases.

Pectinid frags. conspic.

Br.gr., mod. ind., sl. glauc., v. calc. f.m. sst (-v. s. lst?) with shell frags. Dev. of inver. seams inc. upward, as does. irreg.

Inverted seams.

Lt. br., mod. ind., sl. glauc., v. calc. f. sst - v.s. lst. with conspic. shell frags. Seams (2 cm) more persistent laterally but wavy.

Lt. or., mod. ind., v.sl. glauc. sl. cryst., f.s. lst. Incip. flaggy, flags 3 - 8 cm, seams <1cm and wavy.

Br-gr. (sl. Fe-staining), mod. ind., sl. glauc., calc. m.f. sst-fs. mst. Muddy lenses and up to grain sized shell fragments visible. Coarsening upwards discern. to incoming lst. above. Massive, fritt.-incip. fine bedding.

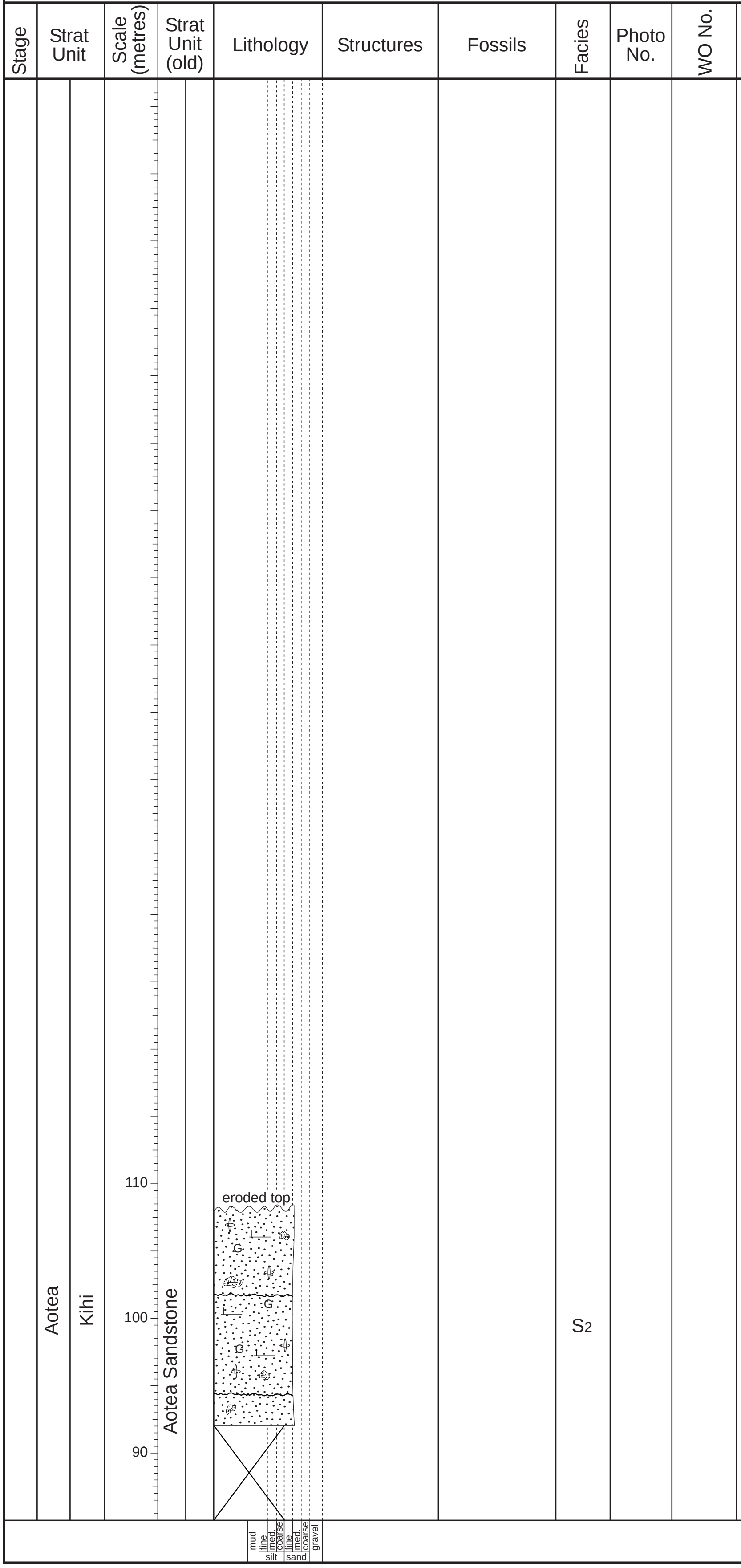
Grassed.

Bl./gr., wk. ind., sl. glauc., sl.f.s. calc. mst. with rare shell frags, serpulids. Massive, fritt. and exfoliated. Fe-stained joint traces. Active water seepage.

Grassed slope; occ. showings of above lith. 40^{o} repose angle.

Basal contact not seen. WCM?

Stratigraphic Column No: *S1*
Grid Reference:
Region: Aotea - Kawhia
E: 2681981
Location: “Southern Bluffs”; ca. 1.5 km NW of “The Dome”
N: 6336374
NZMS 260 Sheet: S16
Page 2 *of* 2 **Author:** D. Fergusson



Description

Or. g. (sl. Fe-staining), sl.-mod. ind. calc. sst. Massive-ripply with scattered knobs and hollows.

Sl. or.-yell. gr., mod. ind., sl. glauc., mod. calc., m. sst. Massive, occ. rounded protuberance.

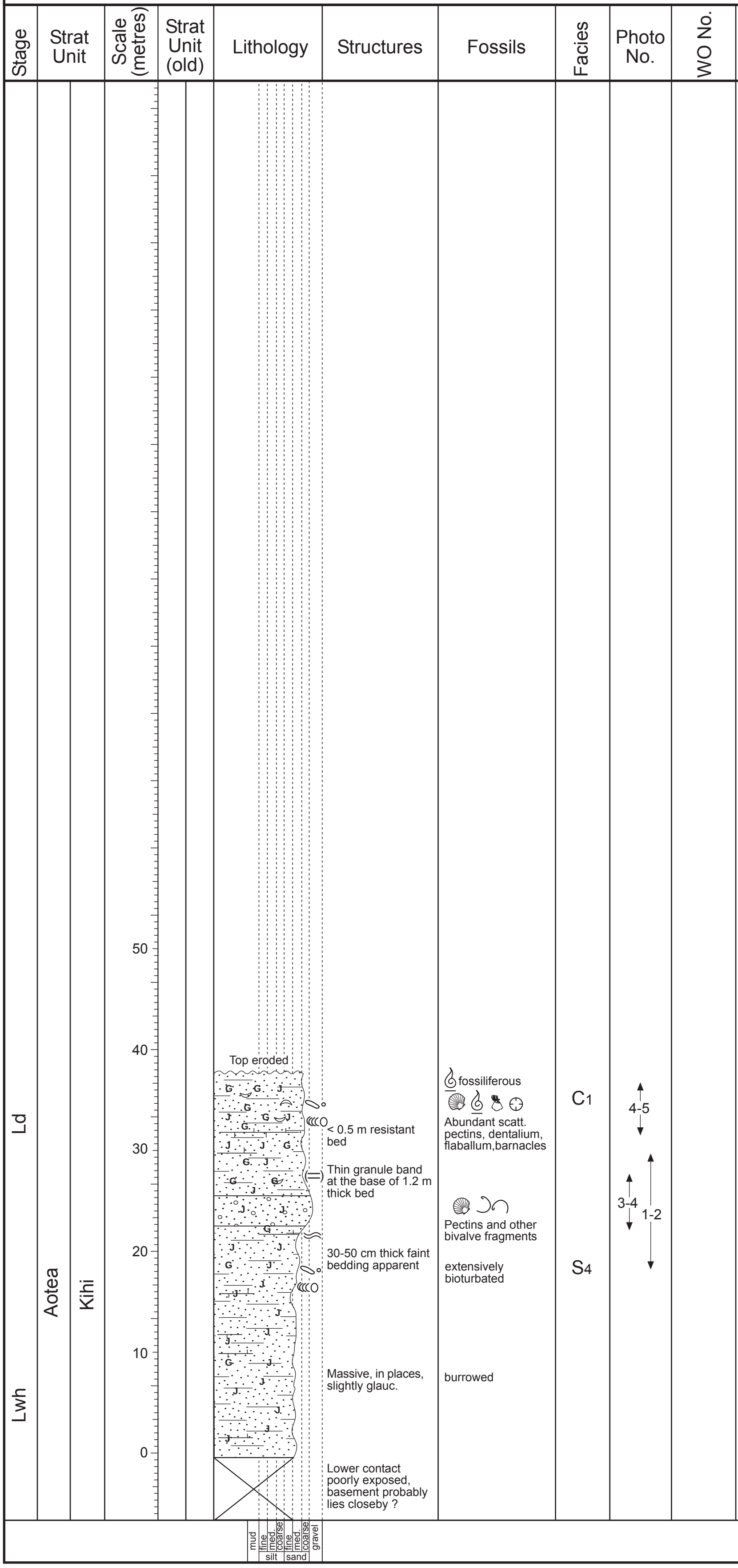
Stratigraphic Column No: *Ak-14*
Region: Aotea-Kawhia
Location: Honikiwi Road side exposure

Grid Reference:

	Top	Bottom
E:	2700010	
N:	6334249	

NZMS 260 Sheet: S16/000342

Page 1 *of* 2 **Author:** A. Tripathi



Description

GLAUCONITIC SANDSTONE: Dark greenish-grey, weakly to mod. cemented, fine to medium variably calc. muddy fine to medium sandstone with abundant glauconite (content > 50%), fossiliferous, burrowed, abundant scattered pectins, barnacles, solitary corals and dentalium.

GRITTY SANDSTONE: Greenish grey, mod. cemented. 0.3-1.2 m crude bding apparent from relatively resistant beds, scattered rounded-subrounded granule size clasts in places concentrated in thin beds and occ. infilling the burrows, extensively bioturbated evident from mottled texture, abun. glauconite pellets of fine to medium sand grade.

MUDDY SANDSTONE: Dull blue-grey, mod. cemented, massive to faint horizontal bedding discernible in places, common exfoliation weathering, muddy fine sandstone, extensively bioturbated, disseminated glauconite pellets.

CALCAREOUS SILTY SANDSTONE: Dull grey to bl-grey, mod. well cemented massive, slightly frittery in places, fine calcareous silty sandstone, bioturbated, grades upsection into muddy sandstone.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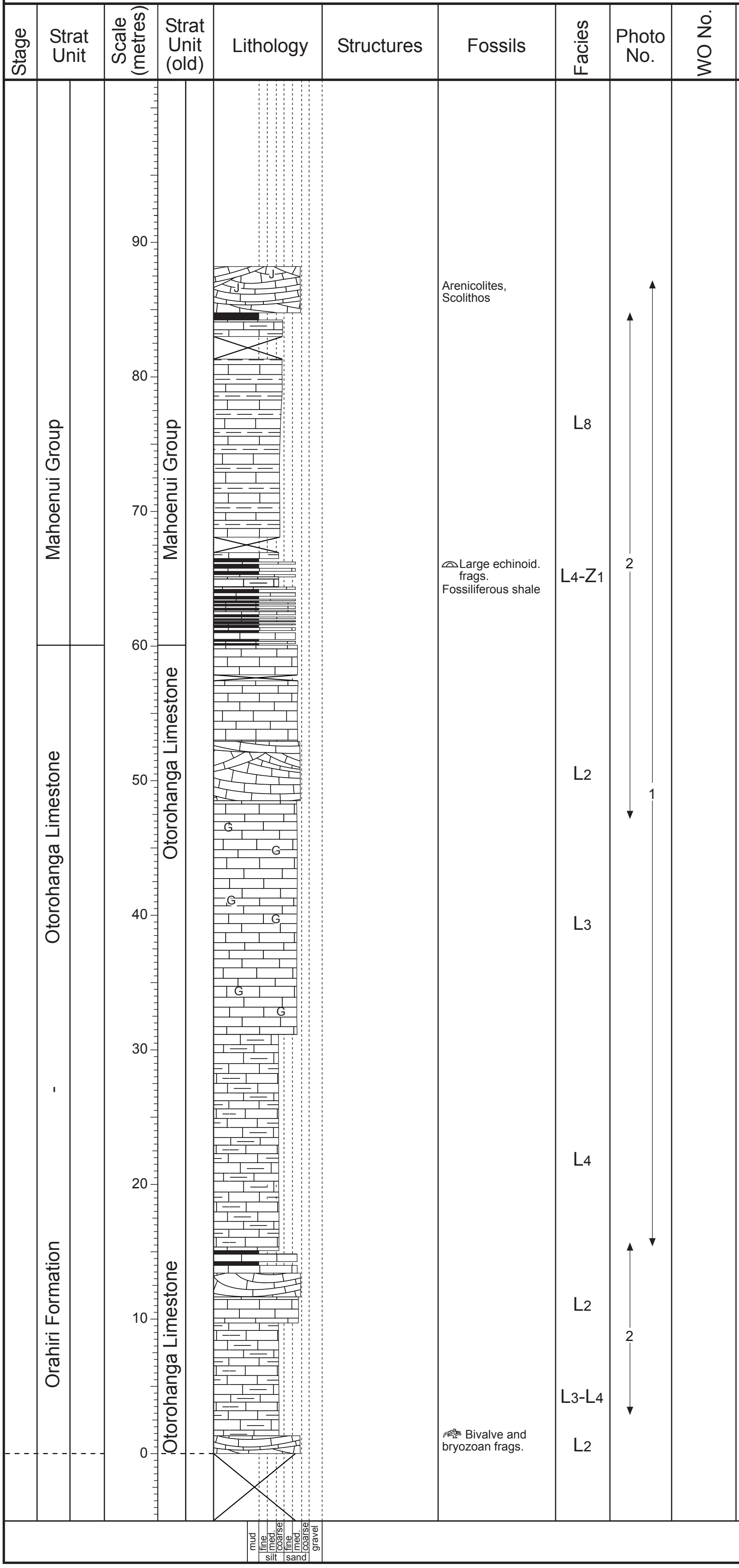
Stratigraphic Column No: *94-24*
Region: Te Kuiti
Location: Old Beros quarry, Te Kuiti

Grid Reference:
E: 2701400
N: 6315200

NZMS 260 Sheet: S16/014152

Page 1 *of* 2

Author: A.S. Anastas
Modified: A. Tripathi



Description
Vertical burrows containing pellets.
Cross-bedded lst.
Laminated grey-green shale.
Argillaceous lst./interbedded shale and lst., shale % decreases upwards, beds undulatory, shales 1-1.5 cm, lsts. 7-12 cm.
Tempestite, sharp base.
Cross-bedded lst., formset preservation, 7-10 cm beds.
Horizontally bedded lst., glauconite common.
Massive argillaceous lst.
Horizontal bedding.
Massive lst., argillaceous, poorly developed bedding.
Cross-bedded lst., one large set, obscure, north.

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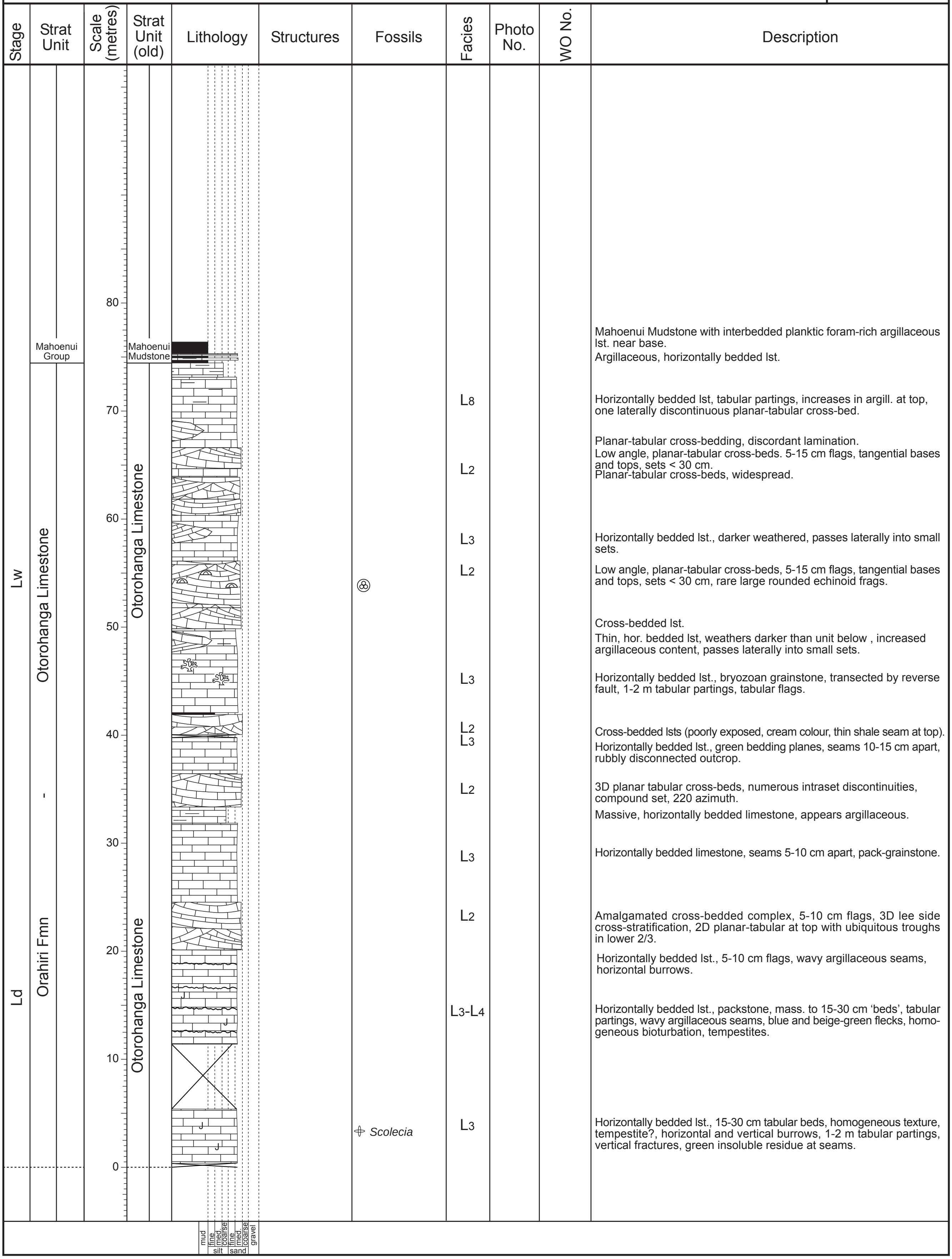
Stratigraphic Column No: *94-26*
Region: Te Kuiti
Location: Rangitoto Quarry

NZMS 260 Sheet: S16/008173

Grid Reference:
E: 2700800
N: 6317300

Page 1 *of* 1
Author: A.S. Anastas
Modified: A. Tripathi



Mahoenui Mudstone with interbedded planktic foram-rich argillaceous lst. near base.

Argillaceous, horizontally bedded lst.

Horizontally bedded lst, tabular partings, increases in argill. at top, one laterally discontinuous planar-tabular cross-bed.

Planar-tabular cross-bedding, discordant lamination.

Low angle, planar-tabular cross-beds. 5-15 cm flags, tangential bases and tops, sets < 30 cm.

Planar-tabular cross-beds, widespread.

Horizontally bedded lst., darker weathered, passes laterally into small sets.

Low angle, planar-tabular cross-beds, 5-15 cm flags, tangential bases and tops, sets < 30 cm, rare large rounded echinoid frags.

Cross-bedded lst.

Thin, hor. bedded lst, weathers darker than unit below , increased argillaceous content, passes laterally into small sets.

Horizontally bedded lst., bryozoan grainstone, transected by reverse fault, 1-2 m tabular partings, tabular flags.

Cross-bedded lsts (poorly exposed, cream colour, thin shale seam at top).

Horizontally bedded lst., green bedding planes, seams 10-15 cm apart, rubbly disconnected outcrop.

3D planar tabular cross-beds, numerous intraset discontinuities, compound set, 220 azimuth.

Massive, horizontally bedded limestone, appears argillaceous.

Horizontally bedded limestone, seams 5-10 cm apart, pack-grainstone.

Amalgamated cross-bedded complex, 5-10 cm flags, 3D lee side cross-stratification, 2D planar-tabular at top with ubiquitous troughs in lower 2/3.

Horizontally bedded lst., 5-10 cm flags, wavy argillaceous seams, horizontal burrows.

Horizontally bedded lst., packstone, mass. to 15-30 cm 'beds', tabular partings, wavy argillaceous seams, blue and beige-green flecks, homogeneous bioturbation, tempestites.

Horizontally bedded lst., 15-30 cm tabular beds, homogeneous texture, tempestite?, horizontal and vertical burrows, 1-2 m tabular partings, vertical fractures, green insoluble residue at seams.

Stratigraphic Column No: *94-39*

Region: Te Kuiti

Location: 'CSN' 135, Mangaokewa Stream,
south of Te Kuiti

NZMS 260 Sheet: S16/032112

Grid Reference:

E: 2703200

N: 6311200

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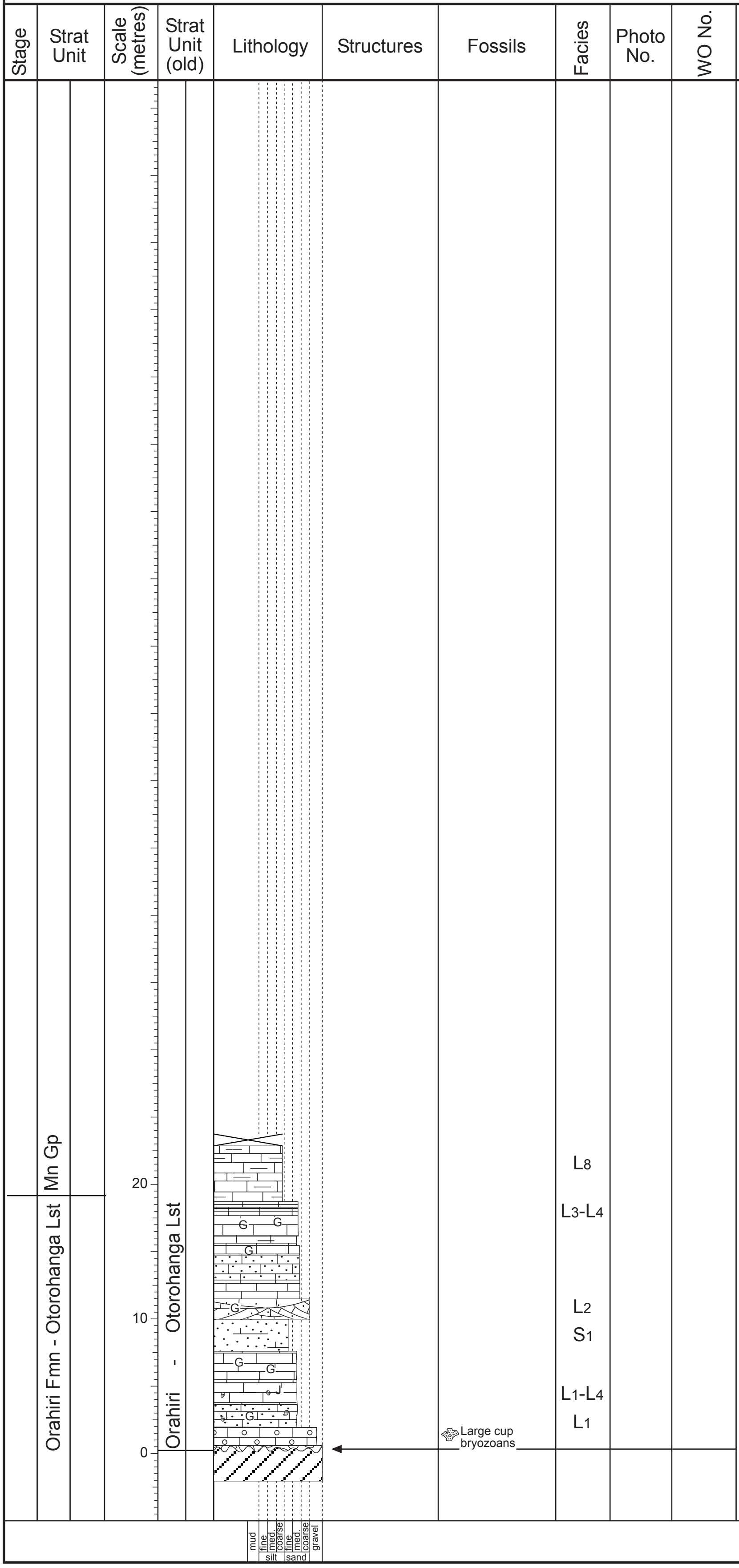
Author: A.S. Anastas

Modified: A. Tripathi



Description

Argillaceous, horizontally bedded lst., glauconitic (?) lamination. Tabular beds 15-20 cm, rare vertical burrows.

Interbedded brown friable and glauc. lst., cross-bedded?

Glauconitic lst.

Massive to thick bedded lst., sandy.

Sandy glauc. lst., cross-set, lamination.

Massive calc. sst., dark green-brown.

Massive to thick bedded lst., horizontally bedded, glauconitic.

Rhodolite-pebble lst., borings, massive, mud chips.

Massive sandy glauc. lst., rare pebbles.

Pebbly lst.

Boulder conglomerate, carbonate cemented, pebbly.

Basement.

Stratigraphic Column No: *C-121*
Region: King Country/Waitomo
Location: Ngapeke Road, north of Rangitoto

NZMS 1 Sheet: S16

Grid Reference:
E: 2707769
N: 6320097

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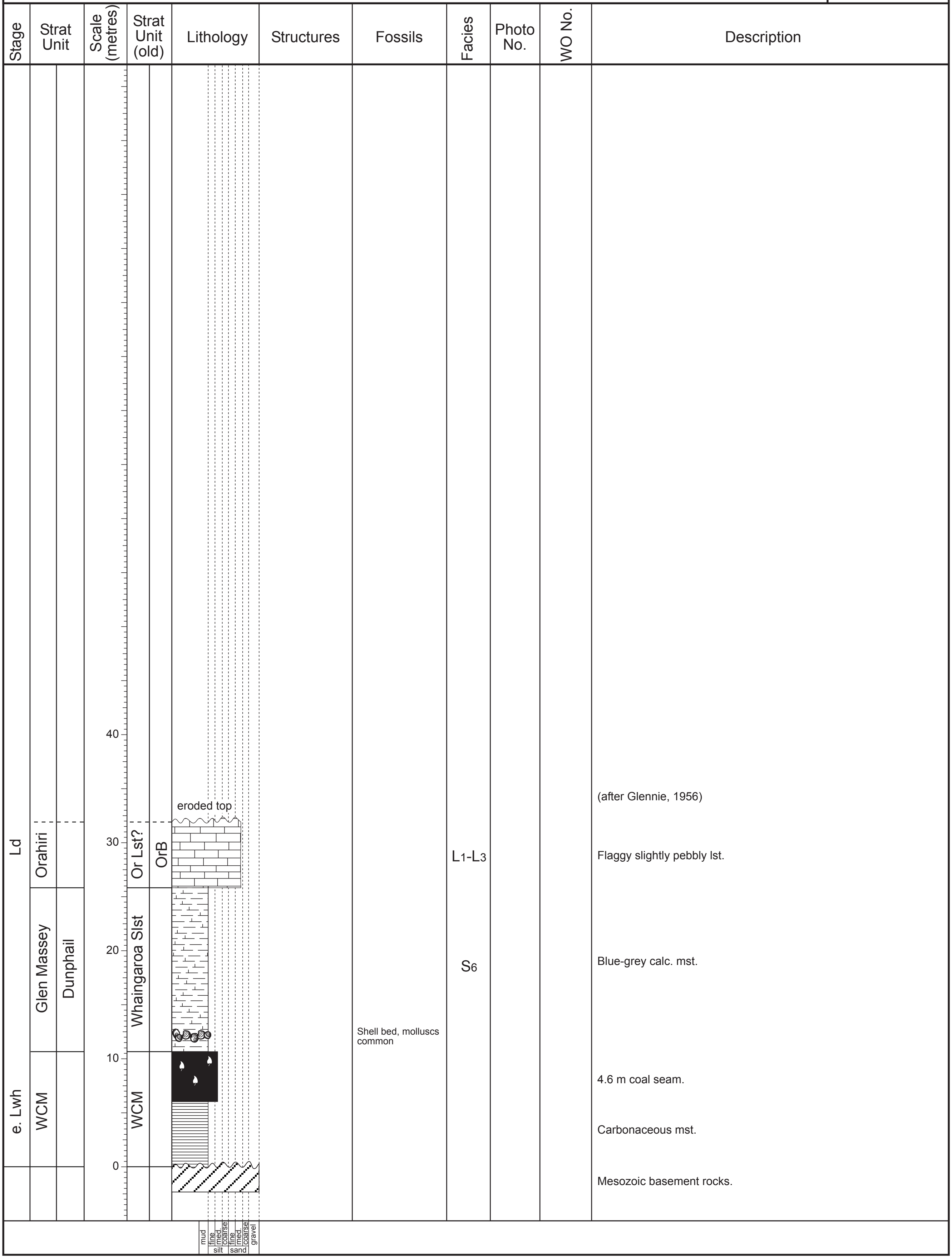
Author: C. Nelson (after Glennie 1956)
Modified: A. Tripathi



Stage	Strat Unit		Scale (metres)	Strat Unit (old)		Lithology	Structures	Fossils	Facies	Photo No.	WO No.	Description
						eroded top						(after Glennie, 1956)
Ld	Orahiri		30	Or Lst?	OrB				L1-L3			Flaggy slightly pebbly lst.
	Glen Massey	Dunphail	20	Whaingaroa Slst					S6			Blue-grey calc. mst.
								Shell bed, molluscs common				
e. Lwh	WCM		10	WCM								4.6 m coal seam.
												Carbonaceous mst.
			0									Mesozoic basement rocks.

Stratigraphic Column No: *C-125*
Region: King Country/Waitomo
Location: Walker Road, east of Te Kuiti

Grid Reference:
E: 2704355
N: 6315803

NZMS 1 Sheet: S16

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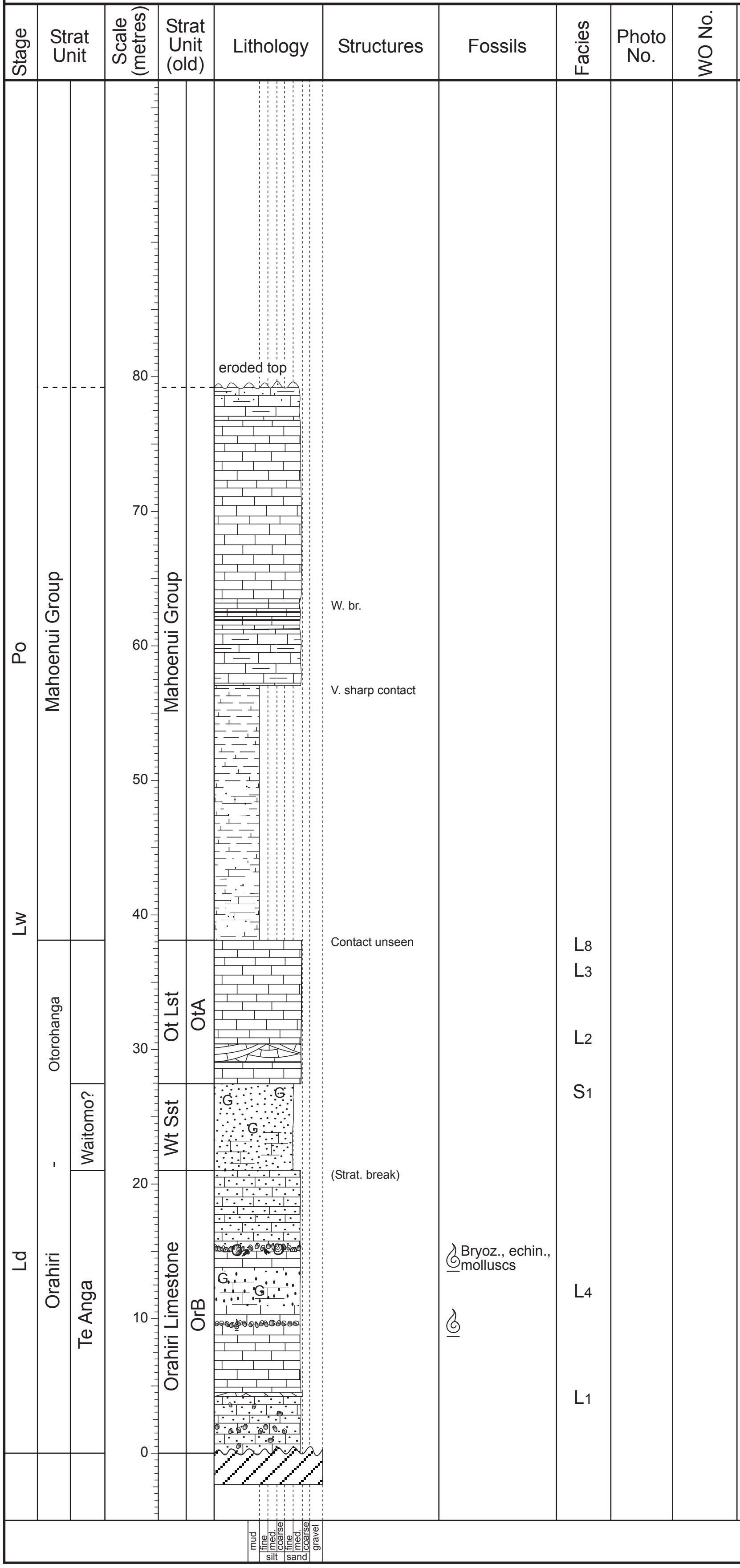
Author: C. Nelson
Modified: A. Tripathi



Description

Top sample muddy lst. in paddock.
Variable sandy-muddy lst., incipient-mod. flags 2.5-20 cm with shaley seams.

Mod.-well flagged, var. 5-23 cm, av. 13 cm thick lst., seams common, wavy and occ. thick, topog. shelves develop at a no. of heights.

Flags 5-25 cm thick.

Prominent sandy mst. seams to 2.5 cm thick between var. thickness flags.

40° connecting slope of sandy muddy lst. and interbedded mst., lst. beds 15-20 cm thick, nearer base mst. beds up to 23 cm thick.

Bl/gr. calc. mst., weaths. brown, very frittery appearance, contains interbedded smooth mass. slightly sandy muddy lst., non-seamed. Msts. burrowed.

Well flagged 5-15 cm pure lst., seams slightly wavy.

Cross-beds dip 15°, flags 5-15 cm.

Reg. seams 5-7.6 cm apart, sl. glauc. at base.

Mass. calc. glauc. fine sst., fluted outcrop.

Incip. seams 10-20 cm apart nearer base.

Flaggy lst., 7.6-20 cm flags, av. 15 cm.

Gritty sandy lst.

Gritty-pebbly band 10 cm wide, non-seamed, fossiliferous material.

Incip.-mod. flaggy lst., flags av. 7.6 cm, slightly glauc., slightly gritty.

Ff-gritty base, with pebble band 9.5-9.8 m, pebbs. av. 0.3-1.3 cm, sharp base, grad. top, slightly glauconitic.

Flaggy 5-10 cm lst., occ. grit.

30.5 cm cross-bedded unit.

Incip. seams 5-10 cm apart, slightly gritty, pebbs. av. 0.3-0.6 cm, common 1.5-2.1 m, no basal conglom., sharp irregular contact.

Mesozoic basement rocks.

Stratigraphic Column No: *C-130*
Region: King Country/Waitomo
Location: Mangaokewa Stream, SH30, south of Te Kuiti
NZMS 1Sheet: S16

Grid Reference:
E: 2702573
N: 6311007

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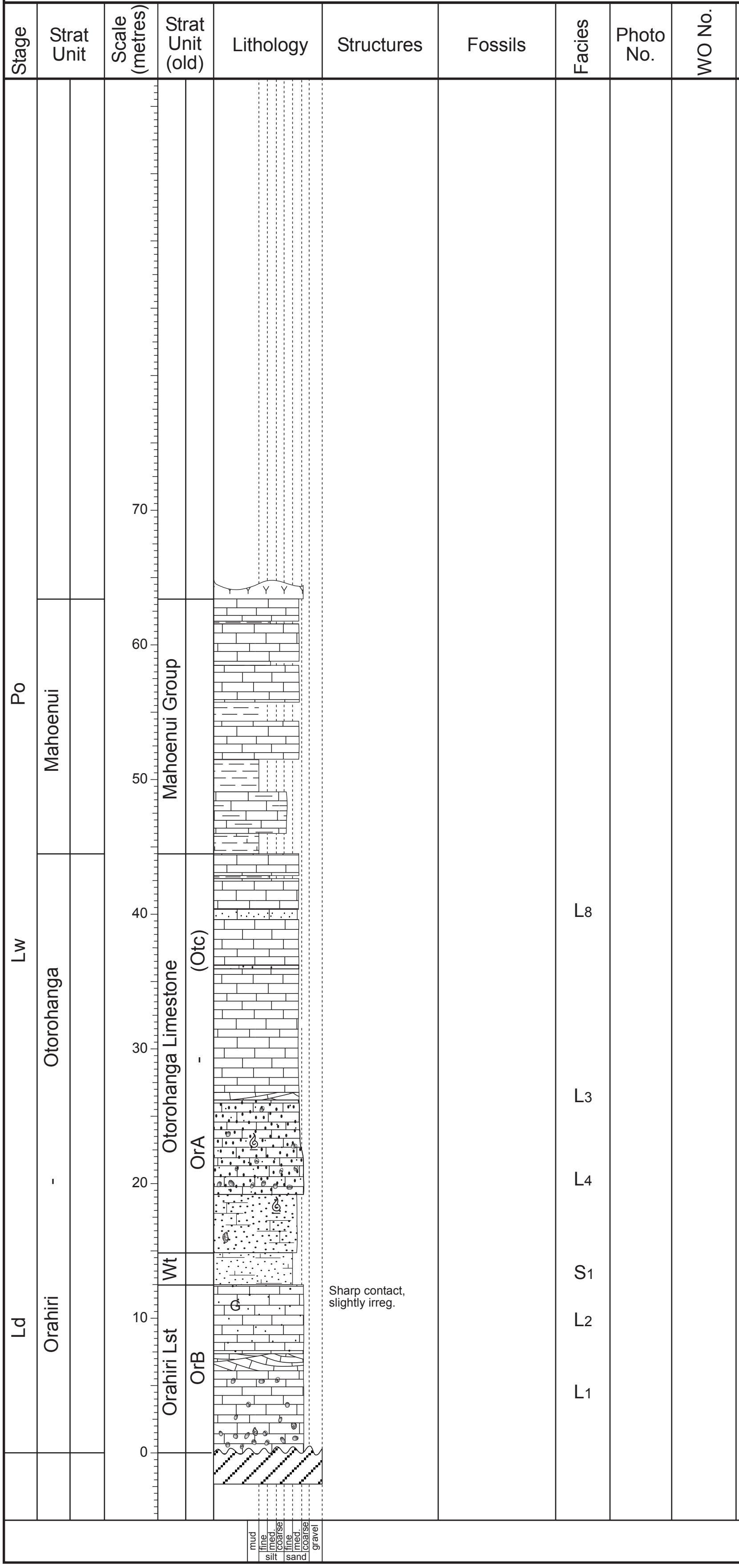
Author: C. Nelson
Modified: A. Tripathi



Description

Ignimbrites.
Flaggy 10-13 cm lst.
18 cm shale unit.
Flaggy 5-10 cm lst.
23 cm shale unit.
Flaggy 5-10 cm lst., well developed flags.
1.5 m blue-grey mst., frittery weathered appearance.
Pure 5-10 cm flagged lst.
Blue-grey. mst.
Muddy lst., var. appearance, top 30.5 cm very hard.
1.5 m blue-grey massive calc. mst.
Pure flaggy 7.6-15 cm lst.
Narrow shale band.
Flags 7.6-15 cm.
60 cm sandy lsts. band, sharp contacts.
Flaggy 2.5-10 cm lst.
Massive sandy lst. band, sharp contacts.
Pure 2.5-7.6 cm flaggy lst., very scattered pebbles, occ. iron-stained pyrite concretions.
Cross-beds, dip 10° N.
Incip. seamed 2.5-7.6 cm lst., occ. ff., v. occ. gwk pebbs. 1.3-12.7 cm size.
Incip.-mod. flaggy av. 5 cm lst., gritty-pebbly, esp. 19.5-20.7 m, pebbles to 5 cm size, no def. pebble bands, pebbles av. 0.6 cm.
Mass. sandy lst., occ. incip. bedded. app., ff in parts, rare large. oysters.
Weathered, smooth sloping (40°) calc. fine sst., var. width along strike (e.g., to 30 cm).
Sparsely gritty 7.6-10 cm flaggy lst., seams to 1.3 cm thick with sand and glauc., incipient-mod. seam development, limonite pyrite.
Cross-beds, dip 10° N.
Sl. pebbly lst., pebbs. 0.3-0.6 cm size, occ. lger. in mass.-incip. seamed s. lst.
V. pebbly basal portions, pebbles subrounded.-rounded. gwk., pebbs. 0.32-60 cm+, pebbles >matrix at base, ff-oysters to 30 x 23 cm size, art. and disart., sharp irregular contact.
Mesozoic basement rocks.

Stratigraphic Column No: *C-25* **Grid Reference:**

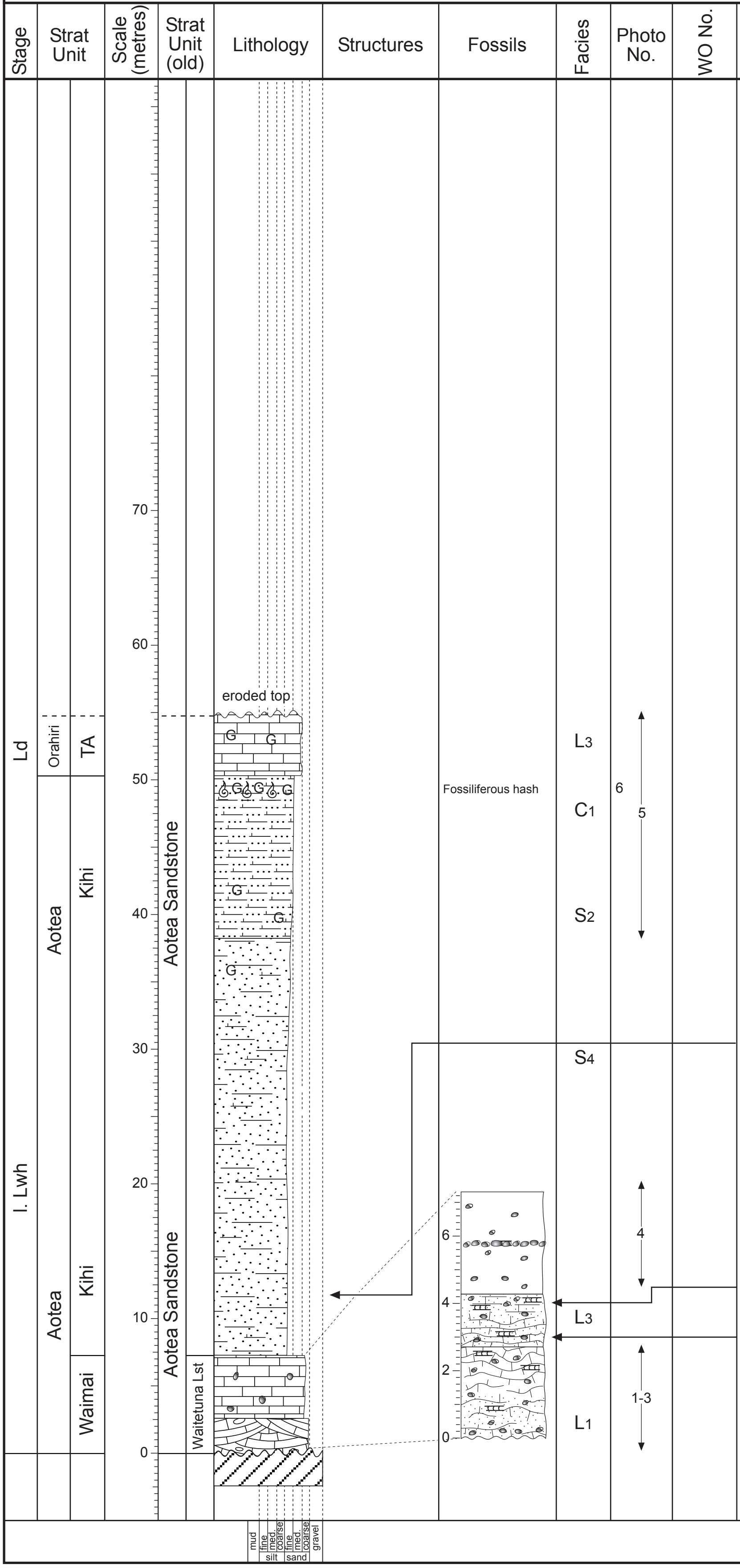
Region: King Country/Waitomo **E:** 2696921

Location: Abandoned basement quarry, East of Honikiwi **N:** 6337506

NZMS 1 Sheet: S16

Page 1 *of* 1 **Author:** C. Nelson

Modified: A. Tripathi



Description

C/gr. glauc. slabby lst. showing pseudobded. app. where weathered.

Weath. indent., ff-hash in well cem. glauc. s. lst. for 15-22 cm grad. down into horiz. of limonite pyrite concrets. and tubules.

Fine glauc. calc. sst.

Muddy sl. glauc. f. calc. sst.

Blue/grey muddy v.f. calc. ssts., mst. horizons, frittered surf., poorly exposed.

Mass.-incip. seams, 5-7.5 cm flags, v. occ. sm. pebbs. to 1.3 cm seen.

15 cm pebb. band as w. ind., pebbs. av. 2.5 cm, max. 10 cm, algae present.

Incip.-mod. seams, slabby app., scatt. pebbs. av. 2 cm, v. poorly sorted.

Pebbs. to 15 cm common in mass., irreg. surf. s. lst., algae, grit-f. pebbs. typical.

Mass.-sl. incip. seams.

Incip.-mod. seams, flags av. 7.5 cm, lge. pebbs. rare, common grit and v.c. sand.

Pebbs. av. 7.5 cm in irreg. incip. seamed lst., flags av. 5 cm, algal encrustn. common.

Rel. mass., irreg. surf. pebbly lsts. w. pebbs. to 10 cm near base becoming less abund. upwrds, algal encrustaceans.

Mesozoic basement rocks - a conglom.; basal lst. dips 11^{o}E/342^{o} against old hill of conglomerate.

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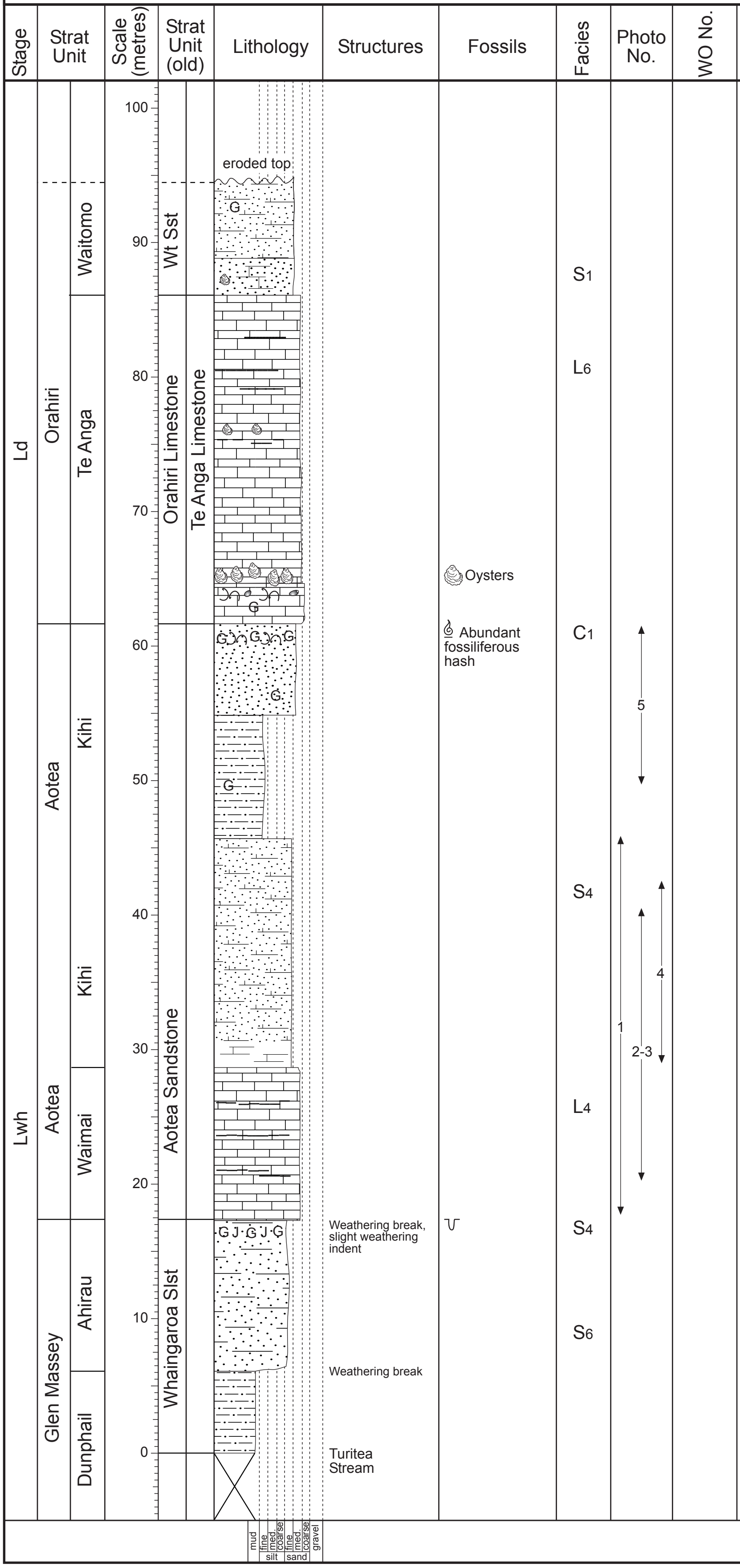
Stratigraphic Column No: *C-28*
Region: King Country/Waitomo
Location: Te Raumauku, south of Honikiwi

Grid Reference:
E: 2695027
N: 6331981

NZMS 1 Sheet: S16

Page 1 *of* 1

Author: C. Nelson
Modified: A. Tripathi



Description

Sl. glauc. calc. sst., green-grey colour, smooth, tends frittery.

Mass. ripply-incip. seamed calc. sst. (s.lst.), rare oyst., grad. contacts.

Wide flagged, av. 10-15 cm, lst. with rel. prominent sand seams.

~76 m, incip. oyst. plus ff-material.
75-76 m - highly irreg. and thick mod. dev. seams, vert. jointing, pseudo-knobbly appearance.

Flaggy lst., flags av. 10-13 cm w. incip. sand seams above 65.5 m becoming mod.-well developed, sl. wavy higher with var. flags 5-10 cm.

64.5-65 m - incip.- well dev., sl. irreg. seams, non-glauc. ~ 65 m, mod. packed oyst. band, oyst. haphaz., disart. and art., rel. sharp top and bottom.
61.6-64.6 m - sl. glauc. slabby lst., flags av. 7.5 cm, occ. pseudobded., after 64.3 m, ff-hash zone with abund. fine bivalve debris, occ. pebbs. av. 1 cm, bone.

55-61.6 m - glauc. calc. sst. as smooth faced “cliff”, occ. bivalve mat. and limonite borings at top, sst. bl./gr., fritt., occ. limonite (pyrite) concrets. to 7.5 cm size, elliptical shapes.

45.75-55 m - poorly exposed, app. sl. glauc. s. msts.

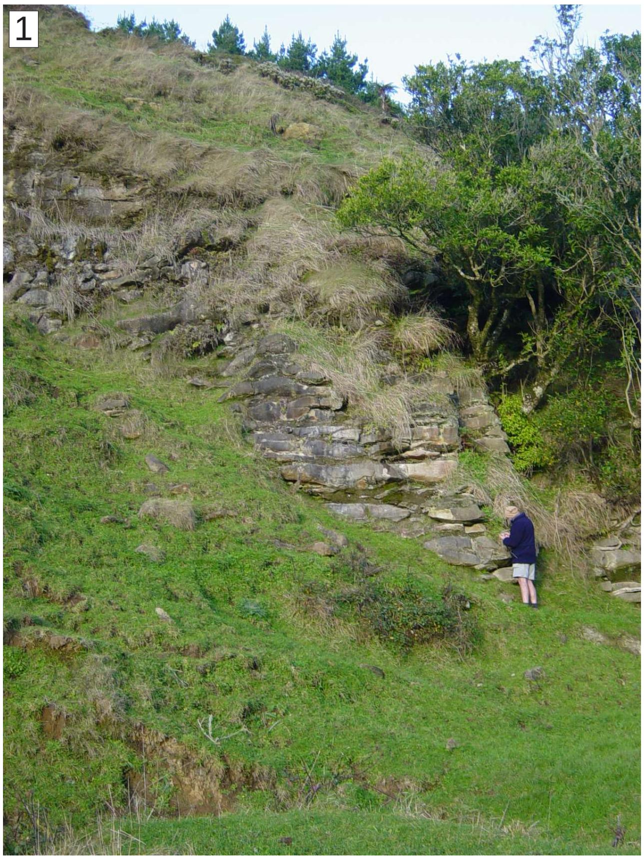
B/gr. fine calc. ssts., muddy, fritt. surface., weath., poorly exposed.

Slabby, mod.-well dev. seams, flags gen. wide, av. 12.5 cm, mod. glauc., seams wide and sandy and slightly irregular.

16-17 m, tends frittery in fine glauc. sst., occ. borings evid., top 2.5 cm better cemented.

Mass.-incip. ripply smooth sl. glauc. calc. muddy sst. (s. lst.) as small bluff.

Bl/gr. sandy mst., frittery weathering.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Stratigraphic Column No: *C32*

Region: King Country/Waitomo

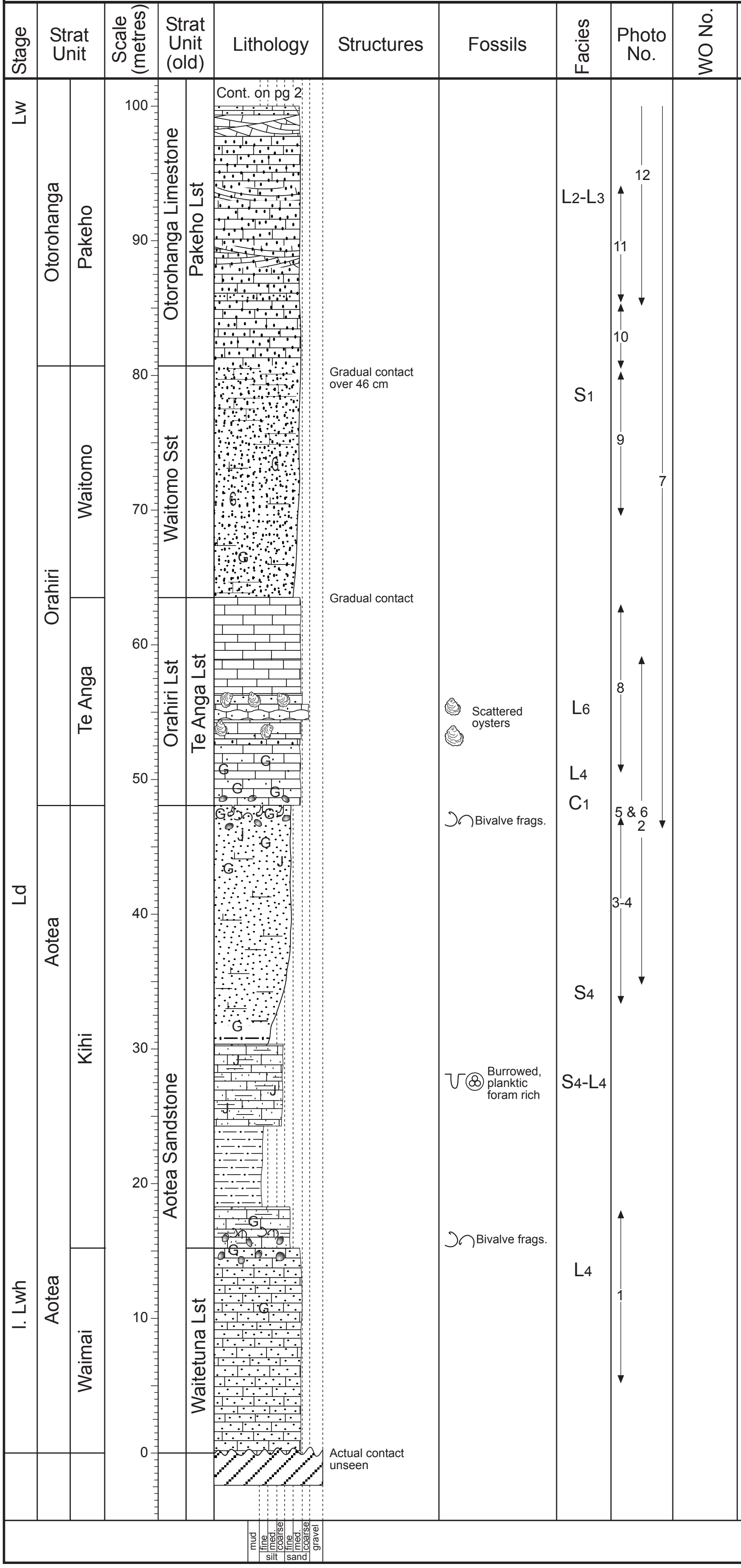
Location: Abandoned limestone quarry,
northeast of Waitomo

NZMS 1 Sheet: S16

Grid Reference:

E:	2696320	-	2696142
N:	6329200	-	6329388

Page 1 *of* 2 **Author:** C. Nelson
Modified: A. Tripathi



Description

Mass.-incip. seamed lst., sl. sandy.
Crossbed 12° to ENE, well dev. flags 5-10 cm.

Flaggy lst., flags mod.-well dev., 5-15 cm wide, sep. by wide (to 1.3 cm) seams Complexly cross-bedded at a no. of levels, is on a lge. scale and shows both planar and trough vars., var. current dir., cosets of 5-15 cm , sep. by horiz. flags minor channeling.

12° to NE seen.

Mass. s. lst. as 40.5 cm indent.

Inv. seams 2.5-7.6 cm apart, sl. irreg., seams wide near base, weath. in, to 2.5 cm wide.

Calc. sst. - s. lst.

Mass. calc. sst., com. leached and w., forms smooth connecting slope between two lst. Glauc. content mod., decr. upwards as does sand content. Ssts. fine throughout.

25 cm hard s. lst., 10 cm calc. sst., passes into flaggy lst.

7.6-15.2 cm flaggy lst., irreg. seams, sl. sandy, glauc. nearer top.

Pure micritic lst., irreg. seams 7.6-15.2 cm.

Oyster band, disartic., haphaz., 10 cm frags., incip. irreg. seams.

Scatt. oyst. horizon, 45.7 cm scatt. frags., 53.5 cm occ. lge. frags, 38 cm scatt. oysts.
Sl. glauc. lst., mass.
Mass.-incip. lge. flagged lst., sl.-mod. glauc., occ. pebbs. near base, borings infilled w. glauc. lst. into underlying gsd.

Immed. below 48.2 m have calc. gsd., mass., well cem. for 30.5 cm, less cem. and forms strong w. indent. 47-48 m, base marked by 5-7.6 m band of biv., par. bed., trace ff., pebbs. to 5 cm av., 0.95 cm scatt. thr.out, biv. frags. scatt., com. in streaks & lenses, calc. worm tubes, cem. top shows lge. borings infil. w. overlying lst., biv. band varies in dist. below contact along strike, also glauc. content, overlying lst. shows marked overhang. Grad. down into w. mod. gl. calc. muddy sst., less ff. mat., sl. fritt., occ. borings, glauc. content decreases. dnwd. Passes down into bl/gr fritt. m. v.f. sst. and v. s. msts, burrowed, sl. glauc.

Sl. s. burrowed muddy lst., plnk. foram. rich.

Blue/grey s. mst.

Sl.-v.s. lst., muddy, glauc. and pebbly (av. 0.6 cm) at base, bivalve frags. common.

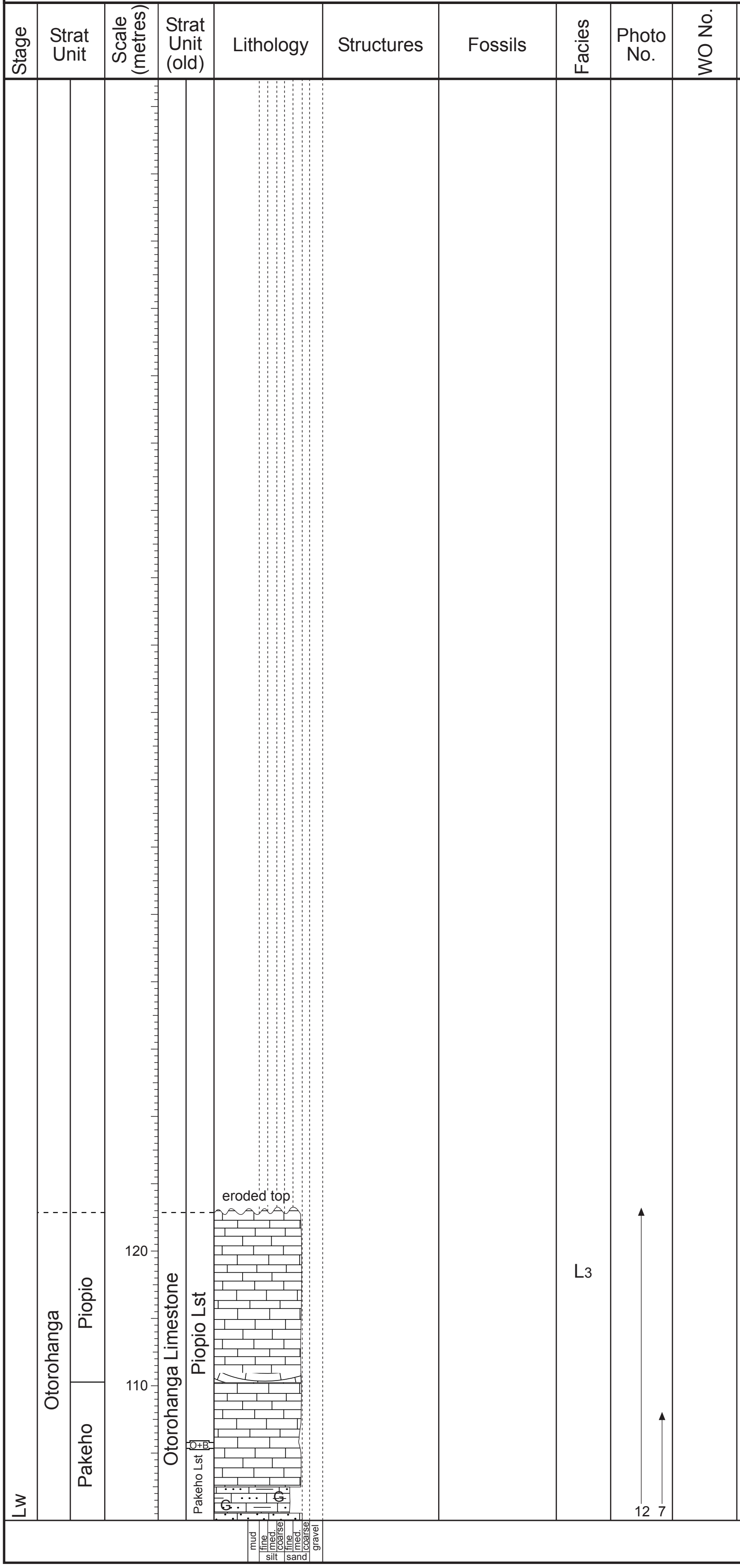
Mass. ripply-incip. seamed, av. 7.5 cm apart sandy lst., sl. glauc. Sand content incr. upwards w. mod. glauc. and pebbs. av. 0.15 cm, max. 0.95 cm at top. Waterfall over lst.

Mesozoic basement rocks.

Stratigraphic Column No: *C32*
Region: King Country/Waitomo
Location: Abandoned limestone quarry,
northeast of Waitomo
NZMS 1 Sheet: S16

Grid Reference:
E: 2696320 - 2696142
N: 6329200 - 6329388

Page 2 *of* 2
Author: C. Nelson
Modified: A. Tripathi



Description

Well flagged 15-20 cm lst.

Seams 2.5-7.6 cm apart, seams typ. wide, to 1.2 cm, sl. cavernous w.

Flags 2.5-7.6 cm, wide seams, c. shell mat. appar.

1.22 m more mass. micritic lst., dense, contacts not well flagged
Cross-bedded, flaggy, 10o to NW.

Flaggy lst., 5-7.6 cm.

Irreg. cav. weath., high cement content.

Wide seamed, lamin., flaggy lst.

Muddy glauc. unit, 12.7 cm glauc. lst., 3.8 cm slst., 15 cm glauc. lst.
1.2 cm slst.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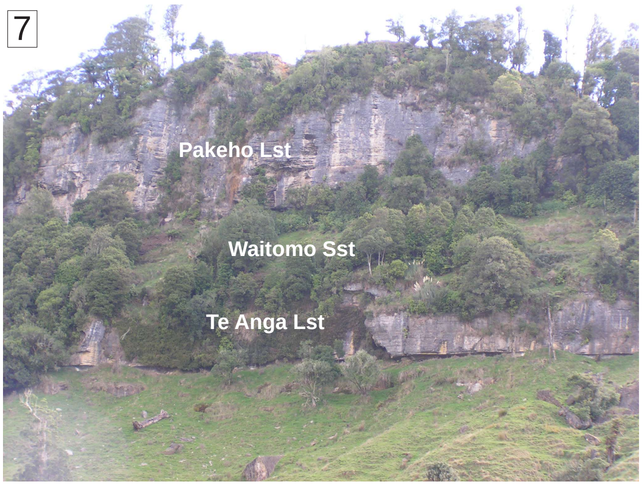

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Stratigraphic Column No: *S1*

Grid Reference:

Region: Aotea - Kawhia

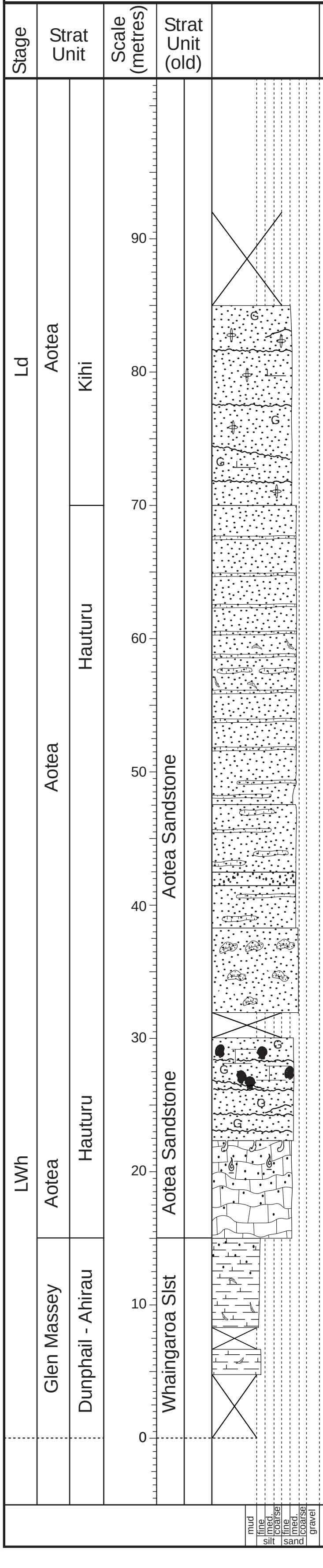
Location: "Southern Bluffs"; ca. 1.5 km NW of "The Dome"

E: 2681981

N: 6336374

NZMS 1 Sheet: S16

Page 1 *of* 2 **Author:** D. Fergusson

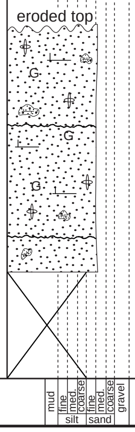


Structures	Fossils	Facies	Photo No.	WO No.	Description
					Vegetation (sl. coarsening upwards).
		S_2			Lt. or. gr., mod. ind., sl.-glauc., calc f. sst. with small concret. or better cemented sst. Bioturbation evident throughout. Grades up to massive-ripply-bulbous profile. Finely banded at lower zone - irreg. shaped 'ripply' bands.
					Profile changes - oversteep, 'bulbous'.
		S_1			
					Lt. or. gr., mod. ind., sl.-mod. calc., f. sst. with rare-some shell frags. Banded, uniform 12-15 cm thick bands.
		S_1			
					1.5 m overhang. Erosional concavity.
					Lt. or.-gr., wk. ind., sl.-mod. glauc., clc. f.m. (qtzose) sst. Leached zone.
					Cross-bedded; 16^{o} app. dip, foresets planar. Foresets preserved as alt. well/poorly cemented sets; 4-6 cm spacing.
Small ledge = weathering break		S_1			Lt. or.-gr., wk. ind., sl. glauc., sl. calc., f-m sst. with shell frags enclosed by matrix of friable, shelly sand. Knobbly; leached-unevenly distrib. Knobs 8-12 cm width. Matrix weath. back into outcrop up to 10-15 cm (banded app. becomes obv. up section).
					Proportion of terrig. clastics increases.
					Pectinid frags. conspic.
		L_4			Br.gr., mod. ind., sl. glauc., v. calc. f.m. sst (-v. s. lst?) with shell frags. Dev. of inver. seams inc. upward, as does. irreg.
					Inverted seams.
					Lt. br., mod. ind., sl. glauc., v. calc. f. sst - v.s. lst. with conspic. shell frags. Seams (2 cm) more persistent laterally but wavy.
Mud coated, elongate, elliptical (x-sect) traces near base of lst.					Lt. or., mod. ind., v.sl. glauc. sl. cryst., f.s. lst. Incip. flaggy, flags 3 - 8 cm, seams <1cm and wavy.
		S_2			Br-gr. (sl. Fe-staining), mod. ind., sl. glauc., calc. m.f. sst-fs. mst. Muddy lenses and up to grain sized shell fragments visible. Coarsening upwards discern. to incoming lst. above. Massive, fritt.-incip. fine bedding.
		S_6			Grassed.
					Bl./gr., wk. ind., sl. glauc., sl.f.s. calc. mst. with rare shell frags, serpulids. Massive, fritt. and exfoliated. Fe-stained joint traces. Active water seepage.
					Grassed slope; occ. showings of above lith. 40^{o} repose angle.
					Basal contact not seen. WCM?

Stratigraphic Column No: *S1*
Region: Aotea - Kawhia
Location: “Southern Bluffs”; ca. 1.5 km NW of “The Dome”
NZMS 260 Sheet: S16

Grid Reference:
E: 2681981
N: 6336374

Page 2 *of* 2 **Author:** D. Fergusson

Stage	Strat Unit		Scale (metres)	Strat Unit (old)	Lithology	Structures	Fossils	Facies	Photo No.	WO No.	Description
	Aotea	Kihi	110 100 90	Aotea Sandstone				S2			Or. g. (sl. Fe-staining), sl.-mod. ind. calc. sst. Massive-ripply with scattered knobs and hollows. Sl. or.-yell. gr., mod. ind., sl. glauc., mod. calc., m. sst. Massive, occ. rounded protuberance.

APPENDIX II

Sample catalogue

SAMPLE CATALOGUE (Appendix II)

Column. No.	Sample Reference	Running No.	Science Store No.
PW-1A	PW-1A-El-1	1	WO3 3001
	PW-1A-El-2	2	WO3 3002
	PW-1A-El-3	3	WO3 3003
	PW-1A-Dn-1	4	WO3 3004
	PW-1A-Dn-2	5	WO3 3005
	PW-1A-Ar-1	6	WO3 3006
	PW-1A-Wm-1	7	WO3 3007
	PW-1A-Wm-2	8	WO3 3008
	PW-1A-Ct-1	9	WO3 3009
	PW-1A-Ct-2	10	WO3 3010
	PW-1A-Ct-3	11	WO3 3011
	PW-1A-Ct-4	12	WO3 3012
PW-1	PW-1-Ar-8	13	WO3 3013
	PW-1-Ar-7	14	WO3 3014
	PW-1-Ar-6a	15	WO3 3015
	PW-1-Ar-6	16	WO3 3016
	PW-1-Ar-5	17	WO3 3017
	PW-1-Ar-4	18	WO3 3018
	PW-1-Ar-3	19	WO3 3019
	PW-1-Ar-2	20	WO3 3020
	PW-1-Ar-1	21	WO3 3021
	PW-1-Wm-1	22	WO3 3022
	PW-1-Wm-2	23	WO3 3023
	PW-1-Wm-3	24	WO3 3024
	PW-1-Wm-4	25	WO3 3025
	PW-1-Wm-5	26	WO3 3026
PW-1B	PW-1B-Ar-5	27	WO3 3027
	PW-1B-Ar-4	28	WO3 3028
	PW-1B-Ar-3	29	WO3 3029
	PW-1B-Ar-2	30	WO3 3030
	PW-1B-Ar-1	31	WO3 3031
PW-2	PW-2-Wt-1	32	WO3 3032
	PW-2-Wt-2	33	WO3 3033
	PW-2-El-1	34	WO3 3034
	PW-2-El-2	35	WO3 3035
	PW-2-El-3	36	WO3 3036
	PW-2-El-4	37	WO3 3037
	PW-2-El-5	38	WO3 3038
	PW-2-El-6	39	WO3 3039
	PW-2-El-7	40	WO3 3040

PW-2	PW-2-Kt-1	41	WO3 3041
	PW-2-Kt-2	42	WO3 3042
	PW-2-Wk-3	43	WO3 3043
PW-5	PW-5-Rt-1	44	WO3 3044
	PW-5-Rt-2	45	WO3 3045
	PW-5-El-1	46	WO3 3046
	PW-5-El-2	47	WO3 3047
	PW-5-El-3	48	WO3 3048
	PW-5-El-4	49	WO3 3049
	PW-5-El-5	50	WO3 3050
	PW-5-El-6	51	WO3 3051
	PW-5-El-7	52	WO3 3052
	PW-5-Dn-1	53	WO3 3053
	PW-5-Dn-2	54	WO3 3054
	PW-5-Dn-3	55	WO3 3055
	PW-5-Ar-1	56	WO3 3056
	PW-5-Ar-2	57	WO3 3057
	PW-5-Ar-3	58	WO3 3058
	PW-5-Ar-4	59	WO3 3059
	PW-5-Ar-5	60	WO3 3060
	PW-5-Kt-1	61	WO3 3061
	PW-5-Kt-2	62	WO3 3062
	PW-5-Kt-2a	63	WO3 3063
	PW-5-Kt-2b	64	WO3 3064
	PW-5-Kt-3	65	WO3 3065
	PW-5-Wm-1	66	WO3 3066
	PW-5-Wm-1a	67	WO3 3067
	PW-5-Wm-2	68	WO3 3068
	PW-5-Wm-3	69	WO3 3069
	PW-5-Wm-4	70	WO3 3070
	PW-5-Ct-1	71	WO3 3071
	PW-5-Ct-2	72	WO3 3072
PW-7	PW-7-Ar-1	73	WO3 3073
	PW-7-Ar-2	74	WO3 3074
	PW-7-Ar-3	75	WO3 3075
	PW-7-Ar-4	76	WO3 3076
	PW-7-Ar-5	77	WO3 3077
	PW-7-Dn-1	78	WO3 3078
	PW-7-Dn-2	79	WO3 3079
	PW-7-Dn-3	80	WO3 3080

PW-7	PW-7-Ct-4	81	WO3 3081
	PW-7-Ct-3	82	WO3 3082
	PW-7-Ct-2	83	WO3 3083
	PW-7-Ct-1	84	WO3 3084
PW-8	PW-8-Dn-4	85	WO3 3085
	PW-8-Dn-3	86	WO3 3086
	PW-8-Dn-2	87	WO3 3087
	PW-8-Dn-1	88	WO3 3088
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	PW-8-Mg-3	97	WO3 3097
	PW-8-Mg-4	98	WO3 3098
	PW-8-Mg-5	99	WO3 3099
	PW-8-Mg-6	100	WO3 3100
	PW-8-Mg-7	101	WO3 3101
PW-9	PW-9-Wt-1a	102	WO3 3102
	PW-9-Wt-1	103	WO3 3103
	PW-9-Wt-4	104	WO3 3104
	PW-9-Wt-2	105	WO3 3105
	PW-9-Wt-2b	107	WO3 3107
	PW-9-Wt-3	108	WO3 3108
	PW-9-Wt-3a	109	WO3 3109
	PW-9-Ar-1	110	WO3 3110
	PW-9-Ar-2	111	WO3 3111
	PW-9-Ar-3	112	WO3 3112
	PW-9-Ar-4	113	WO3 3113
	PW-9-Ar-5	114	WO3 3114
	PW-9-Ar-6	115	WO3 3115
	PW-9-Wk-3	116	WO3 3116
	PW-9-Wk-2	117	WO3 3117
	PW-9-Wk-1	118	WO3 3118
	PW-9-Wm-3	119	WO3 3119
	PW-9-Wm-2	120	WO3 3120
	PW-9-Wm-1	121	WO3 3121
	PW-9-Pt-2	122	WO3 3122
	PW-9-Pt-1	123	WO3 3123

PW-9	PW-9-Ct-9	124	WO3 3124
	PW-9-Ct-8	125	WO3 3125
	PW-9-Ct-7	126	WO3 3126
	PW-9-Ct-6	127	WO3 3127
	PW-9-Ct-5	128	WO3 3128
	PW-9-Ct-4	129	WO3 3129
	PW-9-Ct-3	130	WO3 3130
	PW-9-Ct-2	131	WO3 3131
	PW-9-Ct-1	132	WO3 3132
PW-11	PW-11-Ct-1a	133	WO3 3133
	PW-11-Ct -2b	134	WO3 3134
	PW-11-Ct-3c	135	WO3 3135
	PW-11-Ct -1	136	WO3 3136
	PW-11-Ct-2	137	WO3 3137
	PW-11-Ct-3	138	WO3 3138
	PW-11-Ct-4	139	WO3 3139
	PW-11-Ct-5	140	WO3 3140
	PW-11-Ct-6	141	WO3 3141
	PW-11-Ct-7	142	WO3 3142
	PW-11-Ct-8	143	WO3 3143
	PW-11-Ct-9	144	WO3 3144
	PW-11-Ct-10	145	WO3 3145
	PW-11-Ct-11	146	WO3 3146
	PW-11-Ct-12	147	WO3 3147
	PW-11-Ct-13	148	WO3 3148
PW-2	PW-2-Wk-4	149	WO3 3149 – No Information
TA-3a	TA-3a-El-1	160	WO3 3160
	TA-3a-El-1a	161	WO3 3161
	TA-3a-El-2	162	WO3 3162
	TA-3a-El-3	163	WO3 3163
	TA-3a-El-4	164	WO3 3164
	TA-3a-Ar-1	165	WO3 3165
	TA-3a-Ar-2	166	WO3 3166
	TA-3a-Ar-3	167	WO3 3167
	TA-3a-Ar-4	168	WO3 3168
	TA-3a-Ar-5	170	WO3 3170
TA-3	TA-3-Wk-1	171	WO3 3171
	TA-3-Wk-2	172	WO3 3172
	TA-3-Wk-3	173	WO3 3173
	TA-3-Wk-3a	174	WO3 3174
	TA-3-Wk-4	175	WO3 3175
	TA-3-Wm-1	176	WO3 3176
	TA-3-Wm-2	177	WO3 3177
	TA-3-Wm-3	178	WO3 3178

TA-3	TA-3-Wm-4	179	WO3 3179
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	TA-3-Wm-6	181	WO3 3181
	TA-3-Wm-7	182	WO3 3182
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TA-4	TA-4-Wt-1	193	WO3 3193
	TA-4-Wt-2	194	WO3 3194
TA-5	TA-5-Mg-1	195	WO3 3195
	TA-5-Mg-2	196	WO3 3196
	TA-5-Mg-3	197	WO3 3197
	TA-5-Mg-4	198	WO3 3198
TA-5	TA-5-Ct-1	199	WO3 3199
	TA-5-Ct-2	200	WO3 3200
	TA-5-Tu-1	201	WO3 3201
	TA-5-Tu-2	202	WO3 3202
	TA-5-Ct-3	203	WO3 3203
	TA-5-Ct-4	204	WO3 3204
	TA-5-Ct-5	205	WO3 3205
TA-12	TA-12-Dn-1	206	WO3 3206
	TA-12-Ar-2	207	WO3 3207
	TA-12-Ar-3	208	WO3 3208
	TA-12-Ar-4	209	WO3 3209
	TA-12-Kt-1	210	WO3 3210
	TA-12-Kt-2	211	WO3 3211
	TA-12-Kt-3	212	WO3 3212
	TA-12-Kt-4	213	WO3 3213
	TA-12-Kt-5	214	WO3 3214
	TA-12-Kt-6	215	WO3 3215
	TA-12-Mg-1	216	WO3 3216
	TA-12-Mg-2	217	WO3 3217
	TA-12-Mg-3	218	WO3 3218
	TA-12-Mg-4	219	WO3 3219
	TA-12-Mg-5	220	WO3 3220
	TA-12-Mg-6	221	WO3 3221
	TA-12-Mg-7	222	WO3 3222
	TA-12-Mg-8	223	WO3 3223

TA-12	TA-12-Pt-7	224	WO3 3224
	TA-12-Pt-6	225	WO3 3225
	TA-12-Pt-5	226	WO3 3226
	TA-12-Pt-4	227	WO3 3227
	TA-12-Pt-3	228	WO3 3228
	TA-12-Rg-7	229	WO3 3229
	TA-12-Rg-6	230	WO3 3230
	TA-12-Rg-4	231	WO3 3231
	TA-12-Rg-3	232	WO3 3232
	TA-12-Rg-2	233	WO3 3233
	TA-12-Ct-2	235	WO3 3235
	TA-12-Ct-1	236	WO3 3236
TA-13	TA-13-Rt-1	237	WO3 3237
	T-13-Rt-2	238	WO3 3238
	T-13-Rt-3	239	WO3 3239
	TA-13-El-5	241	WO3 3241
	TA-13-El-4	242	WO3 3242
	TA-13-El-3	243	WO3 3243
	TA-13-El-2	244	WO3 3244
	TA-13-El-1	245	WO3 3245
	TA-13-Ar-6	246	WO3 3246
	TA-13-Ar-5	247	WO3 3247
	TA-13-Ar-4	248	WO3 3248
	TA-13-Ar-3	249	WO3 3249
	TA-13-Ar-2	250	WO3 3250
	TA-13-Ar-1	251	WO3 3251
TA-17	TA-17-Rt-1	252	WO3 3252
	TA-17-El-1	253	WO3 3253
	TA-17-El-2	254	WO3 3254
	TA-17-El-3	255	WO3 3255
	TA-17-Ar-6	259	WO3 3259
	TA-17-Ar-5	260	WO3 3260
	TA-17-Ar-4	261	WO3 3261
	TA-17-Ar-3	262	WO3 3262
	TA-17-Ar-2	263	WO3 3263
	TA-17-Ar-1	264	WO3 3264
TA-18	TA-18-Th-3	265	WO3 3265
	TA-18-Th-2	266	WO3 3266
	TA-18-Th-1	267	WO3 3267
	TA-18-Tu-5	268	WO3 3268
	TA-18-Tu-4	269	WO3 3269
	TA-18-Tu-3	270	WO3 3270
	TA-18-Tu-2	271	WO3 3271
	TA-18-Tu-1	272	WO3 3272
	TA-18-Tu-1	273	WO3 3273

TA-19	TA-19-Pt-1	274	WO3 3274
	TA-19-Rg-1	275	WO3 3275
	TA-19-Rg-2	276	WO3 3276
	TA-19-Rg-3	277	WO3 3277
	TA-19-Rg-4	278	WO3 3278
	TA-19-Rg-5	279	WO3 3279
TA-11	TA-11-Rg-1	280	WO3 3280
	TA-11-Rg-2	281	WO3 3281
	TA-11-Rg-3	282	WO3 3282
	TA-11-Ct-1	283	WO3 3283
	TA-11-Ct-2	284	WO3 3284
	TA-11-Ct-3	285	WO3 3285
	TA-11-Ct-4	286	WO3 3286
	TA-11-Ct-5	287	WO3 3287
	TA-11-Ct-6	288	WO3 3288
	TA-11-B-1	289	WO3 3289
	TA-11-B-2	290	WO3 3290
	TA-11-B-3	291	WO3 3291
	TA-11-B-4	292	WO3 3292
	TA-11-Th-1	293	WO3 3293
	TA-11-Th-2	294	WO3 3294
	TA-11-Th-3	295	WO3 3295
: AK-4	AK-4-El-5	300	WO3 3300
	AK-4-El-4	301	WO3 3301
	AK-4-El-3	302	WO3 3302
	AK-4-El-2	303	WO3 3303
	AK-4-El-1	304	WO3 3304
	AK-4-Dn-1	305	WO3 3305
	AK-4-Ar-3	306	WO3 3306
	AK-4-Ar-2	307	WO3 3307
	AK-4-Ar-1	308	WO3 3308
	AK-4-Hu-5	309	WO3 3309
	AK-4-Ki-4	310	WO3 3310
	AK-4-Ki-3	311	WO3 3311
	AK-4-Ki-2	312	WO3 3312
	AK-4-Ki-1	313	WO3 3313
AK-5	AK-5-Dn-1	314	WO3 3314
	AK-5-Dn-2	315	WO3 3315
	AK-5-Dn-3	316	WO3 3316
	AK-5-Dn-4	317	WO3 3317
	AK-5-Ar-1	318	WO3 3318
	AK-5-Ar-2	319	WO3 3319
	AK-5-Ar-4	320	WO3 3320
	AK-5-Ar-3	321	WO3 3321
	AK-5-Hu-2	322	WO3 3322

	AK-5-Hu-1	323	WO3 3323
AK-6	AK-6-Wt-4	324	WO3 3324
	AK-6-Wt-3	325	WO3 3325
	AK-6-Wt-2	326	WO3 3326
	AK-6-Wt-1	327	WO3 3327
	AK-6-El-5	328	WO3 3328
	AK-6-El-4	329	WO3 3329
	AK-6-El-3	330	WO3 3330
	AK-6-El-2	331	WO3 3331
	AK-6-El-1	332	WO3 3332
	AK-6-Ar-3	333	WO3 3333
	AK-6-Ar-2	334	WO3 3334
	AK-6-Ar-1	335	WO3 3335
C-4	C-4-Dn-1	336	WO3 3336
	C-4-Ar-1	337	WO3 3337
	C-4-Aw-4	338	WO3 3338
	C-4-Aw-3	339	WO3 3339
	C-4-Aw-2	340	WO3 3340
	C-4-Aw-1	341	WO3 3341
	C-4-Hu-7	342	WO3 3342
	C-4-Hu-6	343	WO3 3343
	C-4-Hu-5	344	WO3 3344
	C-4-Hu-4	345	WO3 3345
	C-4-Hu-3	346	WO3 3346
	C-4-Hu-2	347	WO3 3347
	C-4-Hu-1	348	WO3 3348
AK-1	AK-1-Wm-1	349	WO3 3349
	AK-1-Wm-2	350	WO3 3350
	AK-1-Wm-3	351	WO3 3351
	AK-1-Wm-4	352	WO3 3352
	AK-1-Wm-5	353	WO3 3353
	AK-1-Wm-6	354	WO3 3354
	AK-1-Wm-7	355	WO3 3355
	AK-1-Ki-1	356	WO3 3356
	AK-1-Ki-2	357	WO3 3357
S-13	S-13-Hu-1	358	WO3 3358
	S-13-Hu-3	360	WO3 3360
	S-13-Hu-3a	361	WO3 3361
	S-13-Hu-4	362	WO3 3362
	S-13-Hu-5	363	WO3 3363 – No Information
	S-13-Ki-1	364	WO3 3364 – No Information
	S-13-Ki-2	365	WO3 3365 – No Information
AK-11	AK-11-Hu-1	366	WO3 3366
	AK-11-Or-2	367	WO3 3367
	AK-11-Or-3	368	WO3 3368

AK-11	AK-11-Or-4	369	WO3 3369
	AK-11-Or-5	370	WO3 3370
	AK-11-W-1	371	WO3 3371
	AK-11-W-2	372	WO3 3372
AK-7	AK-7-Dn-1	373	WO3 3373
	AK-7-Dn-2	374	WO3 3374
	AK-7-Ki-3	375	WO3 3375
	AK-7-Ki-2	376	WO3 3376
	AK-7-Ki -1	377	WO3 3377
AK-8	AK-8-El-2	378	WO3 3378
	AK-8-El-1	379	WO3 3379
	AK-8-Dn-2	380	WO3 3380
	AK-8-Ar-2	382	WO3 3382
	AK-8-Ar-1	383	WO3 3383
S-13	S-13-Aw-1	384	WO3 3384
	S-13-Aw-2	385	WO3 3385
	S-13-Aw-3	386	WO3 3386
AK-8a	AK-8A-Ar-1	387	WO3 3387
	AK-8A-Ar-2	388	WO3 3388
	AK-8A-Ar-3	389	WO3 3389
AK-8	AK-8-Dn-3	390	WO3 3390 – No Information
S-11	S-11-Or-1	391	WO3 3391
	S-11-Or-2	392	WO3 3392
	S-11-Or-3	393	WO3 3393
	S-11-Or-4	394	WO3 3394
	S-11-Or-5	395	WO3 3395
	S-11-Hu-1	396	WO3 3396
	S-11-Aw-1	397	WO3 3397
	S-11-Aw-2	398	WO3 3398
C-8	C-8-Ki-1	399	WO3 3399
	C-8-Hu-1	400	WO3 3400
	C-8-Hu-3	402	WO3 3402
	C-8-Hu-4	403	WO3 3403
	C-8-Ar-1	404	WO3 3404
	C-8-Ar-2	405	WO3 3405

C-68	C-68-El-1	421	WO3 3421
	C-68-Ar-1	422	WO3 3422
	C-68-Ar-2	423	WO3 3423
	C-68-Aw-1	424	WO3 3424
	C-68-Aw-2	425	WO3 3425
	C-68-Aw-3	426	WO3 3426
	C-68-Ng-1	427	WO3 3427
	C-68-Hu-2	428	WO3 3428
	C-68-Hu-3	429	WO3 3429
	C-68-Or-1	430	WO3 3430
	C-68-Or-2	431	WO3 3431
	C-68-Or-3	432	WO3 3432
	C-68-Ot-1	433	WO3 3433
	C-68-Ot-2	434	WO3 3434
C-56	C-56-El-1	435	WO3 3435
	C-56-Ar-1	436	WO3 3436
	C-56-Ar-2	437	WO3 3437
	C-56-Ar-3	438	WO3 3438
	C-56-Hu-1	439	WO3 3439
	C-56-Hu-2	440	WO3 3440
	C-56-Or-1	441	WO3 3441
	C-56-Or-2	442	WO3 3442
	C-56-Or-3	443	WO3 3443
	C-56-Or-4	444	WO3 3444
	C-56-Ot-1	445	WO3 3445
	C-56-Ot-2	446	WO3 3446
	C-56-Ot-3	447	WO3 3447
	C-56-Ot-4	448	WO3 3448
	C-56-Ot-5	449	WO3 3449
C-68	C-68-Or-1a	450	WO3 3450 – No Information
C-51	C-51-El-1	451	WO3 3451
	C-51-El-2	452	WO3 3452
	C-51-El-3	453	WO3 3453
	C-51-El-4	454	WO3 3454
	C-51-El-5	455	WO3 3455
	C-51-Ar-1	456	WO3 3456
	C-51-Ar-2	457	WO3 3457
	C-51-Dn-3	458	WO3 3458
	C-51-Dn-4	459	WO3 3459
	C-51-Dn-5	460	WO3 3460
	C-51-Dn-6	461	WO3 3461
	C-51-Dn-7	462	WO3 3462
	C-51-Or-1	463	WO3 3463
	C-51-Or-2	464	WO3 3464

C-51	C-51-Or-3	465	WO3 3465
	C-51-Or-4	466	WO3 3466
C-145	C-145-El-1	467	WO3 3467
	C-145-El-2	468	WO3 3468
	C-145-Ar-1	469	WO3 3469
	C-145-Aw-1	470	WO3 3470
	C-145-Ng-1	471	WO3 3471
	C-145-Ng-2	472	WO3 3472
	C-145-Hu-3	473	WO3 3473
	C-145-Hu-4	474	WO3 3474
	C-145-Or-1	475	WO3 3475
	C-145-Or-2	476	WO3 3476
	C-145-Ot-1	477	WO3 3477
	C-145-Ot-3	478	WO3 3478
	C-145-Ot-1	479	WO3 3479

Abbreviations:

Rt – Rotowaro Siltstone
Wt – Waikaretu Sandstone
El – Elgood Limestone
Dn – Dunphail Siltstone
Ar – Ahirau Sandstone
Kt – Kotuku Siltstone
Aw - Awaroa Limestone
Ng - Ngapaenga Siltstone
Wk – Waikorea Sandstone
Wm – Waimai Limestone
Mg - Mangiti Sandstone
Pt - Patikirau Siltstone
Hu - Hauturu Sandstone
Ki - Kihi Sandstone
Rg - Raglan Limestone
Ct - Carter Siltstone
Or - Orahiri Fm
Ot - Otorohanga Limestone
B - Basal Te Hara Sandstone
Th - Te Hara Sandstone
Tu - Te Akau Limestone

APPENDIX VII

Sr Isotope, O and C isotope data

Appendix VII - New Zealand Late Eocene to Early Miocene fossil $\delta^{13}C$, $\delta^{18}O$, and $^{87/86}Sr$ isotope data

* 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	Pectin		1.210	-0.549	0.707851	0.707867	32.72	
41	AU1090	N91/745	Whaingaroa Zst	Lwh	Pectin		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	Pectin		1.240	-0.469	0.707784	0.707800	34.13	
44	AU9529	R13 (7)	Elgood Lst	Lwh	Pectin		0.799	-0.832	0.707719	0.707735	38.77	
45	AU2468	R13 (13)	Elgood Lst	Lwh	Pectin		1.456	-1.286	0.707824	0.707840	33.23	
46	AU8998	N51/675	Dunphail Zst	Lwh	Pectin		1.877	-0.465	0.707865	0.707881	32.48	
47	AU2460	S14 (17)	Dunphail Zst	Lwh	Pectin		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	Pectin		0.881	-0.527	0.707912	0.707928	31.46	
50	AU1330	R13 (6)	Waimai Lst	Lwh	Pectin		2.385	0.822	0.707943	0.707959	30.65	
51	AU3037	N64/558	Aotea Sst	Lwh	Pectin		1.285	-0.447	0.707949	0.707965	30.49	
52	AU1974(a)	N73/936	Aotea Sst	Lwh-(?)	Pectin		2.931	-0.025	0.707885	0.707901	32.07	
53	AU1978	N74/609	Aotea Sst (Ao-2)	Lwh	Pectin		1.712	-0.374	0.707995	0.708011	29.32	
54	AU1979	N74/610	Aotea Sst	Lwh+	Pectin		1.621	-0.005	0.708038	0.708054	28.22	
55	AU1991	N74/613	Aotea Sst	Lwh	Pectin		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	Pectin		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	Pectin		1.634	-0.764	0.707755	0.707771	35.4	
60	M7	Mangaotaki	Orahiri Lst	Ld	Pectin		1.184	-0.809	0.707916	0.707932	31.37	
61	M5	Mangaotaki	Orahiri Lst	Ld	Pectin		1.413	-1.478	0.707858	0.707874	32.61	

62	M1	Mangaotaki	Orahiri Lst	Ld	Pectin		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	Pectin		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	26.7	
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	25.1	
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	Pectin		2.541	0.252	0.708218	0.708234	24.38	
75	AU2029	N83/558	Otorohanga Lst	Lw	Pectin		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	Pectin	Top	2.368	-0.247	0.708189	0.708205	24.8	
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	Pectin	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	Pectin	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	Pectin	Lower-middle	2.44	0.13	0.708035	0.708071	27.79	
6	WU06	R15/ Kawhia Road	Kihi Sst	Lwh-Ld	Pectin	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	Pectin	Near base	1.67	-0.53	0.707868	0.707904	32	
8	WU08	R14/ Waitetuna	Ahirau Sst	early Lwh	Pectin	Approx middle	1.75	-0.15	0.707922	0.707958	30.68	
9	WU09	R16/ Ngapaenga	Awaroa Lst	upper Lwh	Pectin	Near base	1.4	-0.49	0.707982	0.708018	29.14	
Repeat #1	WU09								0.707960	0.707984	29.99	

Repeat #2	WU09								0.707955	0.707989	29.86	29.66
10	WU010	R17/ Mangaotaki	Ngapaenga Zst	upper Lwh	Pectin	Near top	1.54	-0.69	0.708010	0.708046	28.43	
11	WU011	R13/ Kaawa Stream	Patikirau Zst	Ld	Pectin		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	Pectin	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	Pectin		1.37	-0.55	0.708042	0.708071	27.79	
15	WU015	R14/ Raglan Harbour	Raglan Lst	Ld	Pectin	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	Pectin	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	Pectin	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	Pectin		2.23	-0.24	0.707894	0.707923	31.58	
20	WU020	R15/ Rakanui Peninsula	Waitomo Sst	Ld-Lw	Pectin	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	21.8	
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	Pectin	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)