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Title **Te Kuiti Group (Late Eocene - Oligocene) lithostratigraphy east of Taranaki Basin in central-western North Island, New Zealand**

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Author Tripathi, A.R.P., Kamp, P.J.J. and Nelson, C.S.

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Summary This report presents a lithostratigraphy for the Late Eocene - Oligocene Te Kuiti Group that crops out in central-western North Island, New Zealand, between Port Waikato in the north and Awakino in the south. The Te Kuiti Group is a mixed carbonate-siliciclastic succession and includes extensive limestone development in its upper parts. The group is up to several hundred metres thick, and accumulated unconformably above indurated Triassic and Jurassic sedimentary basement. The Te Kuiti Group accumulated east of Taranaki Fault and contains a record of sequence and unconformity development that helps constrain the tectonic development of eastern Taranaki Basin. In particular, it records the timing of the mid-Oligocene transition from extension to crustal shortening. Most of the report is however concerned with rationalisation of the group's lithostratigraphy to enable the geological signals within it to be inferred.

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Te Kuiti Group (Late Eocene - Oligocene) Lithostratigraphy

east of taranaki Basin in central-western North Island, New Zealand

by

Peter J.J. Kamp, Anand Tripathi & Campbell S. Nelson
Department of Earth and Ocean Sciences
The University of Waikato,
Private Bag 3105
Hamilton, New Zealand

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Executive Summary

This report presents a lithostratigraphy for the Late Eocene - Oligocene Te Kuiti Group that crops out in central-western North Island, New Zealand, between Port Waikato in the north and Awakino in the south. The Te Kuiti Group is a mixed carbonate-siliciclastic succession and includes extensive limestone development in its upper parts. The group is up to several hundred metres thick, and unconformably overlies indurated Triassic and Jurassic sedimentary basement.

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. In the revised stratigraphic scheme reported here, seven formations and 24 members of Kaiatian to Waitakian (Late Oligocene to Early Miocene) age are identified. The group has also been classified into six unconformity-bound sequences (TK1 – TK6) using sequence stratigraphic principles, although details of the definition and characteristics of these sequences have not been developed here and will be reported elsewhere.

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 relation to the Glen Massey Formation and the Whaingaroa Formation. 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 (Kear & Schofield 1959; Nelson 1973, 1978), be demoted to member status and become incorporated into a combined Orahiri Formation/Otorohanga Limestone. The Orahiri Formation and Otorohanga Limestone can be difficult to distinguish from each other over extensive areas, especially in the vicinity of Kawhia Harbour, Te Kuiti and Awakino Gorge. The approach taken here is to assign them to an undifferentiated formation loosely referred to as the Orahiri Formation/Otorohanga Limestone. In areas north of Raglan Harbour, units mapped by Kear (1963) and Waterhouse and White (1994) as Waitomo Sandstone and Otorohanga Limestone above Carter Siltstone are now included as basal units within the Waitemata Group.

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

The Waikato Coal Measures of Late Eocene to earliest Oligocene age accumulated in paleovalleys concurrent with minor extensional faulting. The upper beds are marginal marine and consist primarily of estuarine and shallow shelfal mudstone (Mangakotuku Formation). The Early Oligocene (lower Whaingaroan) Glen Massey Formation 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 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 and Aotea Formation, combined with a basinward shift in the position of onlap with accumulation of Aotea Formation, 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, reflect a second phase of inversion along the southwestern margin of the basin associated with the start of 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/Otorohanga Limestone). These formations pass northward into outer shelf-upper bathyal micritic limestone (Raglan Limestone Member) and calcareous siltstone (Carter Siltstone). Several additional phases of unconformity development are recorded in the Castle Craig Subgroup, but these unconformities had limited extent in the basin, being mainly restricted to the area immediately west of the Herangi High.

A companion PR report (Kamp et al. 2008) contains numerous stratigraphic column descriptions for sites spread widely throughout the outcrop extent of the Te Kuiti Group. The columns are the primary dataset upon which our rationalisation of Te Kuiti lithostratigraphy has been based.

Introduction

During the Late Eocene and Oligocene a sedimentary succession up to several hundred metres thick accumulated above basement east of Taranaki Fault in central-western parts of North Island. Known as the Te Kuiti Group, the various formations and members are moderately high in carbonate content, some forming limestone. The group started to accumulate during a phase of continental extension that affected western parts of New Zealand. During the mid-Oligocene the tectonic regime changed to one of crustal shortening, expressed as overthrusting of basement westward into Taranaki Basin on the Taranaki Fault (King & Thrasher 1996; Tripathi & Kamp 2008). To date the stratigraphic record east of Taranaki Fault in central-western North Island has not been extensively used to help constrain the development of Taranaki Basin, largely because there has been a certain lack of clarity around the lithostratigraphy, and a unified scheme that includes the succession along the whole of the outcrop belt from Port Waikato to Awakino has not been robustly developed.

This report develops 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.

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 this was primarily an extension of Kear & Schofield's (1959) original scheme. This report 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. A direct comparison of the White & Waterhouse (1993) scheme and the one proposed in this study is shown in Fig. 1.

The Te Kuiti Group lithostratigraphy, as rationalised here, is supported by numerous descriptions of stratigraphic columns for sites throughout the outcrop belt in central-western North Island. These stratigraphic columns have been assembled into a separate report (Kamp et al. 2008). The outcrop distribution of the Te Kuiti Group is shown on the 1:250,000 Auckland and Waikato geology maps in Edbrooke (2001, 2004). Enclosure 1 shows the outcrop distribution for each of the two subgroups (Okoko Subgroup, Castle Craig Subgroup) of the Te Kuiti Group in relation to basement units, Neogene strata and the Pliocene-Pleistocene Alexandra Volcanic Group. It also shows the position of the stratigraphic columns for the Te Kuiti Group reported in Kamp et al. (2008).

Mesozoic basement

The Oligocene Te Kuiti Group directly overlies basement, usually with a pronounced angular unconformity. The top basement structure in central-

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

Fig. 1: 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.

western North Island is strongly influenced by pre-Te Kuiti Group paleotopography, synsedimentary basement uplift, particularly along the western margin, and post-depositional faulting.

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 & 3). A small mass of serpentinite 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 crop 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 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 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 crops 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) 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

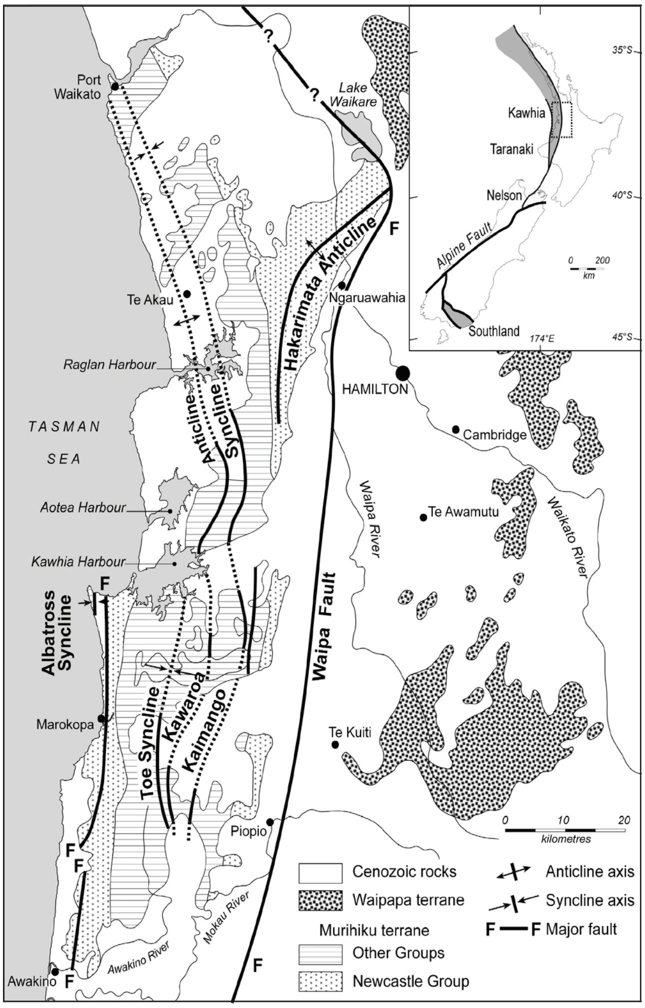


Fig. 2: Map of central-western North Island showing the distribution of Murihiku succession and the main structural features. Inset map indicates the present-day distribution (shaded) of the Murihiku succession in New Zealand. From Briggs et al. (2004).

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 (100 m) of sheared serpentinite extending for about 500 m along the Waipa Fault at Wairere, south of Piopio. 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 Serpentinite 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. 3) (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 Morrisville 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).

Te Kuiti Lithostratigraphy

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 (Enclosure 1). However, most surface exposures of the group lie between Port Waikato and Awakino, the area that has been the 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

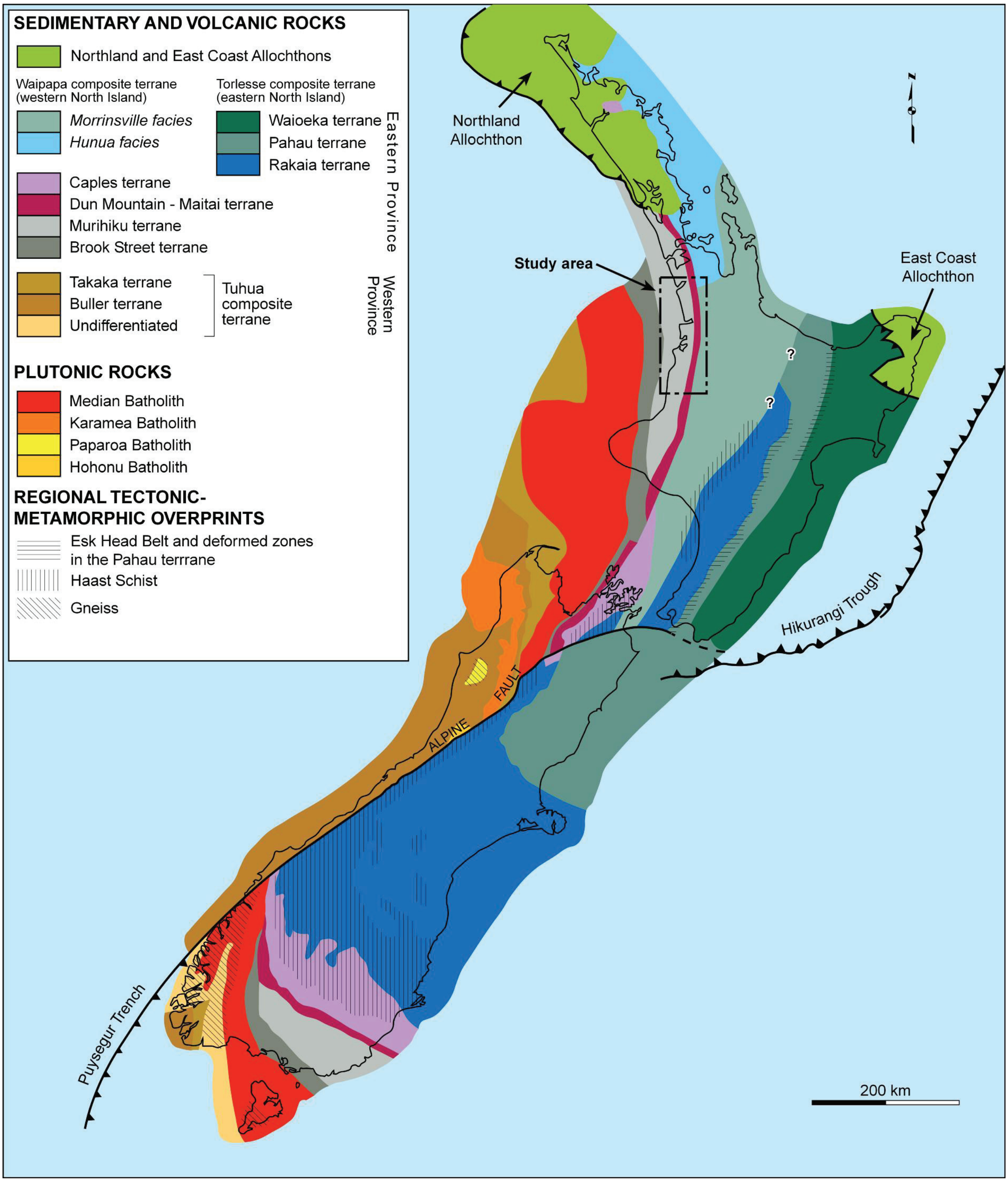


Fig. 3: Pre-Cenozoic basement rocks of New Zealand, subdivided into tectonostratigraphic terranes and batholiths, after Mortimer (2004), adapted from Rattenbury et al. (1997). Basement rocks of the study area comprise Murihiku terrane, Dun Mountain - Maitai terrane and Waipapa (composite) terrane (Morrinsville facies).

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 1977; 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).

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. 4.

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.

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 basement 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 (Kamp et al. 2008). 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. 5 and 6). 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 (Fig. 7). The region boundaries coincide with points of change in the stratigraphy.

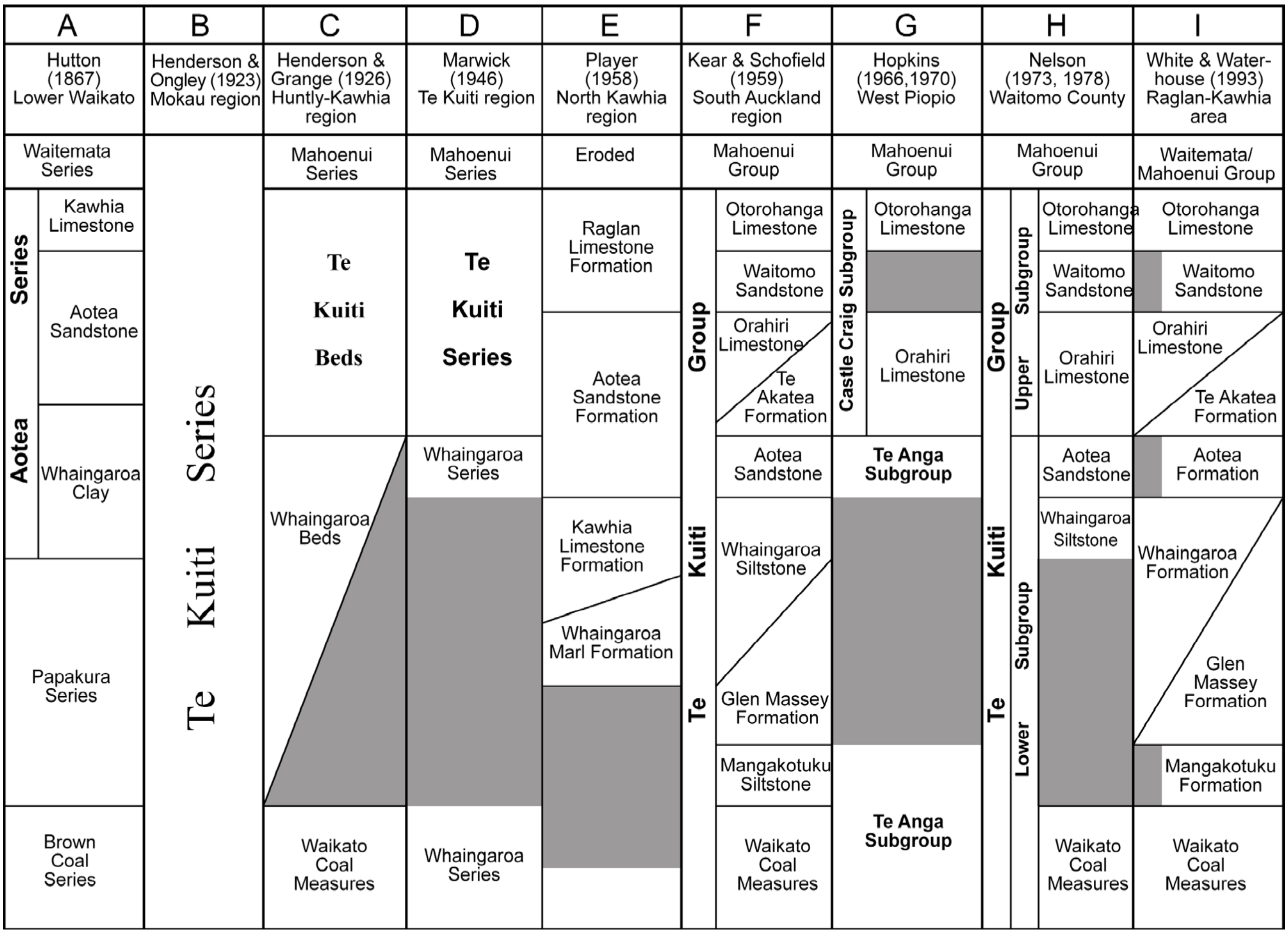


Fig. 4: Historic development of stratigraphic terminology for Te Kuiti Group modified and extended from Nelson (1978a). NB: The grey boxes indicate stratigraphy inferred by the respective authors to be absent in particular areas.

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. 1 with the subdivision and nomenclature proposed by White & Waterhouse (1993).

The age and facies distribution of stratigraphic units proposed in this study are also illustrated in a litho-chronostratigraphic panel (Fig. 5). 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, and 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

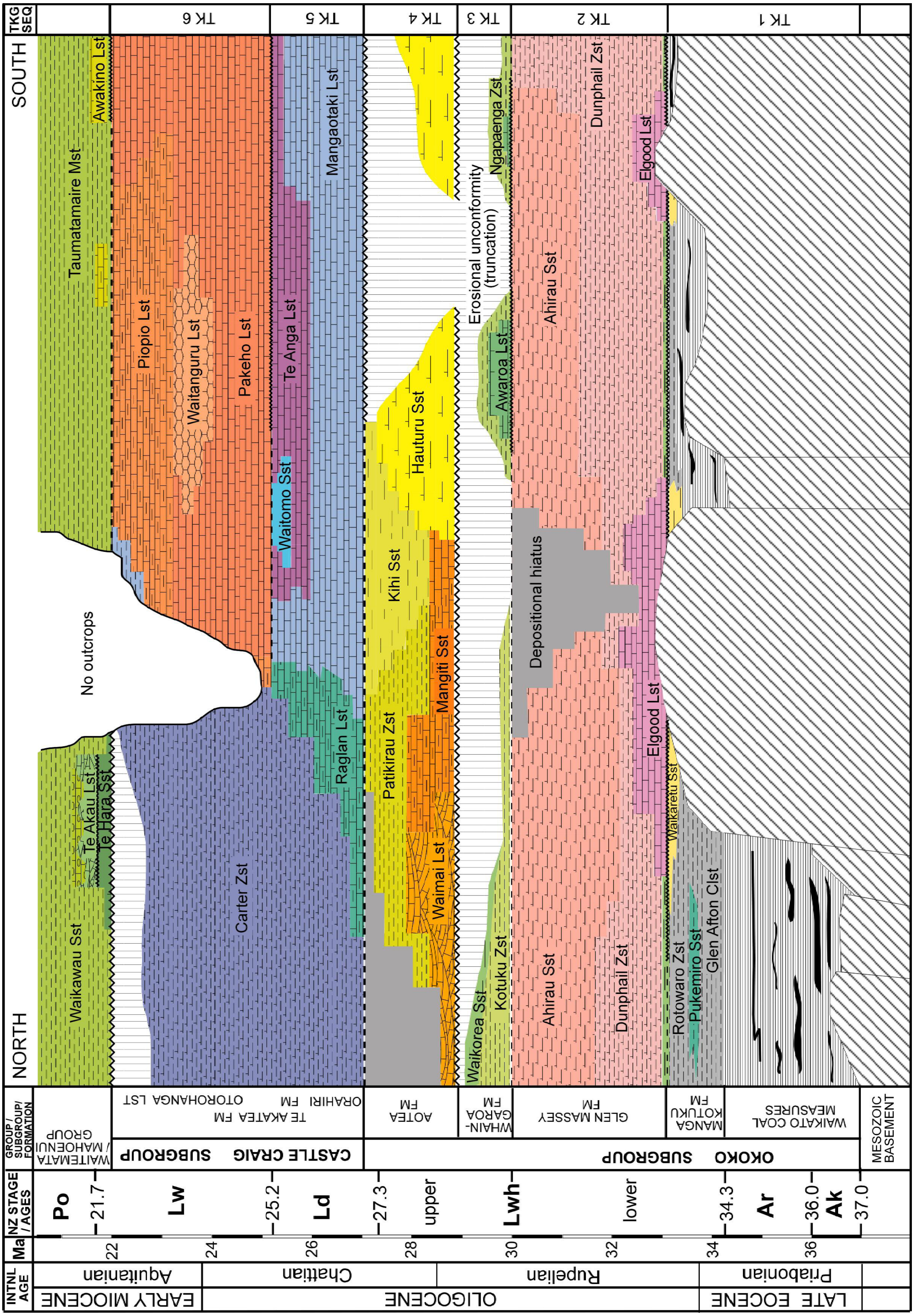


Fig. 5: *New chronostratigraphic scheme for the Te Kuiti Group, and its transition to Waitemata and Mahoenui groups, showing the relationship between formations and members, their age, and the extent of sequences.*

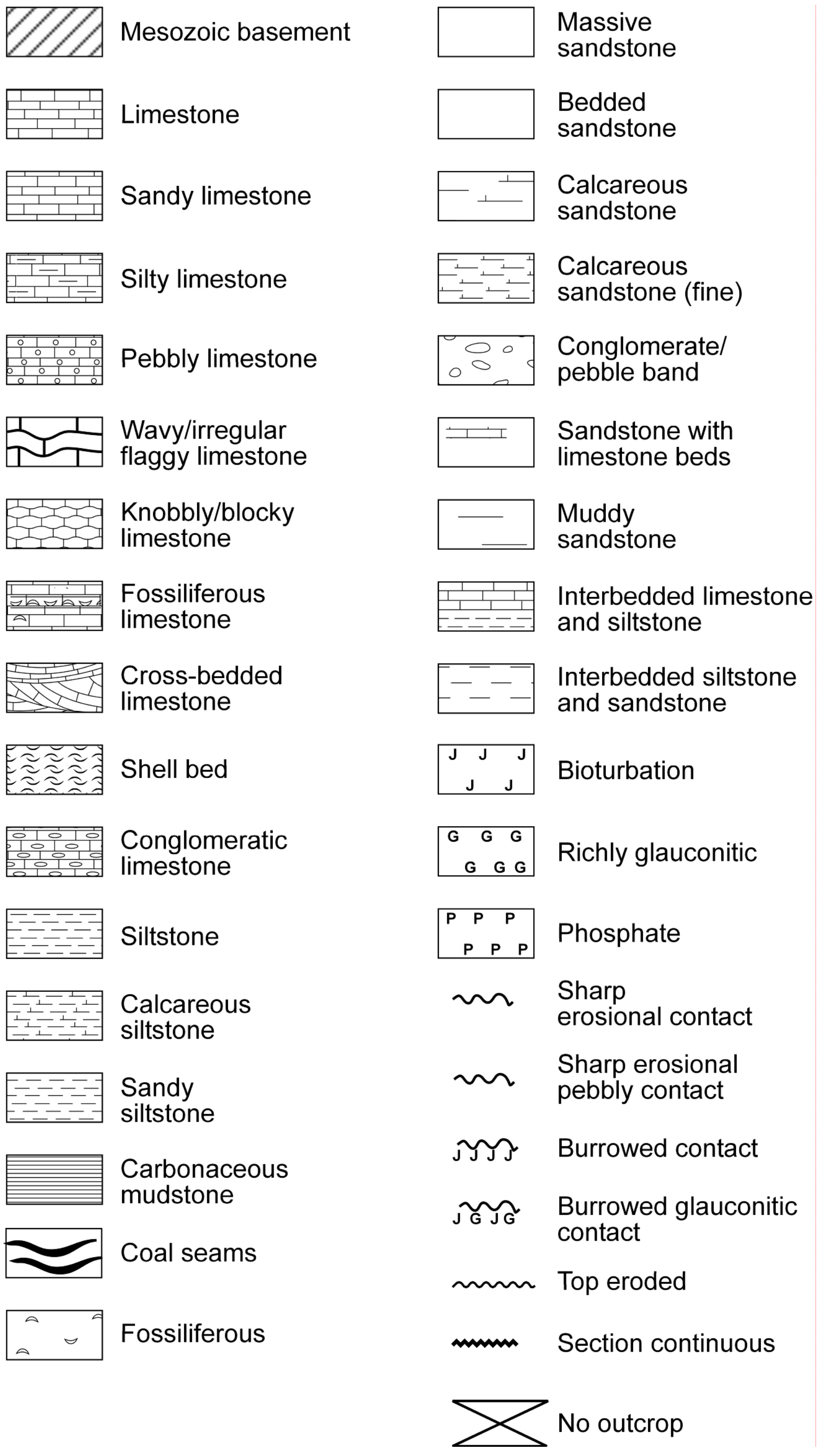


Fig. 6: Figure showing the standard symbols used in the chrono- and lithostratigraphic correlation panel (Fig. 5) and the stratigraphic column correlations.

the division into subgroups. This subdivision and its lithological basis have been acknowledged in most previous classifications of the Te Kuiti Group (Fig. 4). 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. 1).

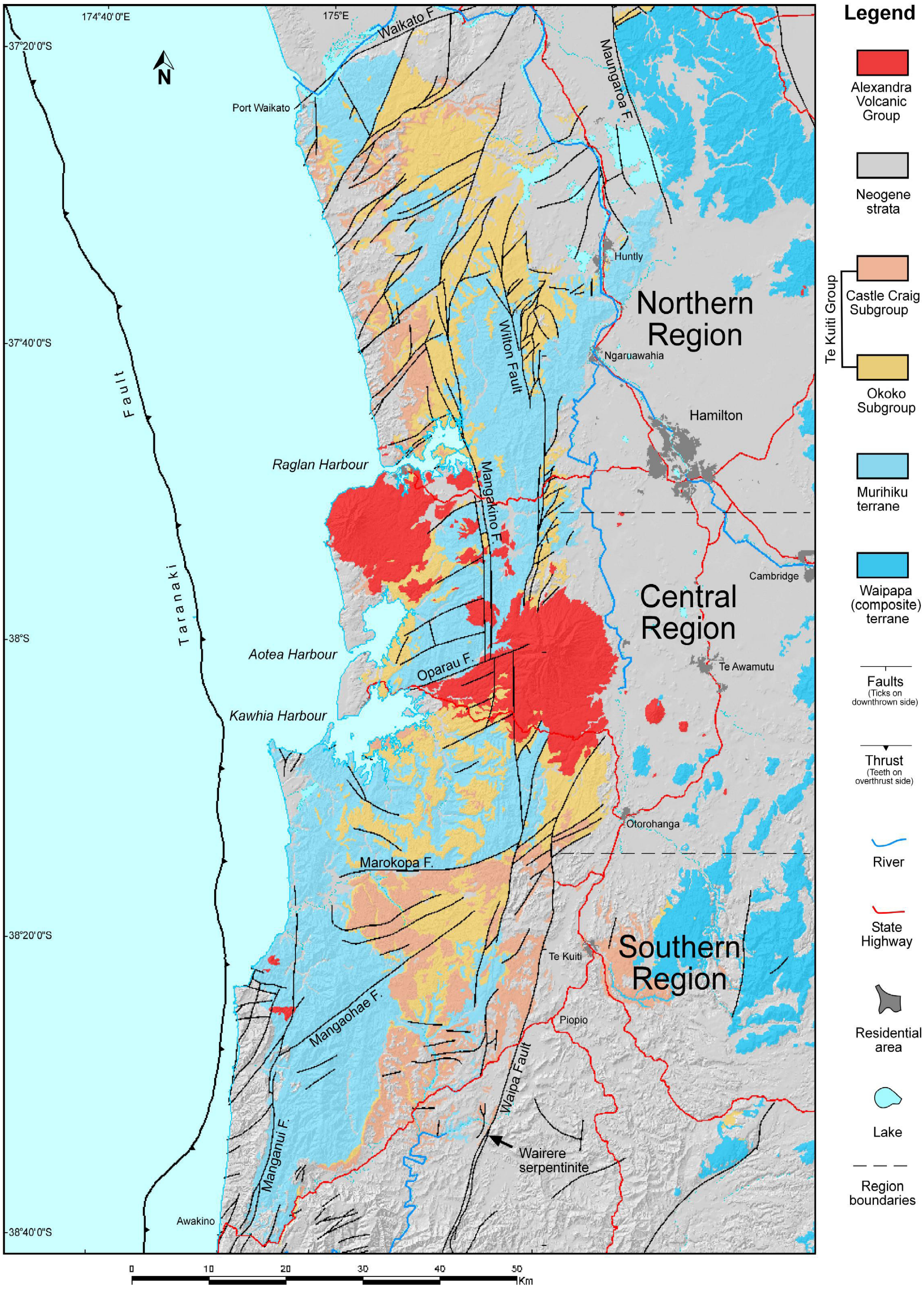


Fig. 7: *Simplified map of the outcrop geology of the Waikato and King Country regions showing the distribution of Pliocene-Pleistocene volcanics, mid-Cenozoic Te Kuiti Group (Okoko and Castle Craig subgroups) and Mesozoic basement rocks in central-western North Island. Also shown are the major structural features. Map compiled from Edbrooke 2001 and 2005 QMAP Auckland & Waikato).*

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 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. 8).

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. 9 a). 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 the WCM. Edbrooke et al. (1994) nominated two reference sections for the northern region, one at the Huntly Brickworks Section (S13/012016) (Fig. 9 a & 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. 9 e & f)) are retained here.

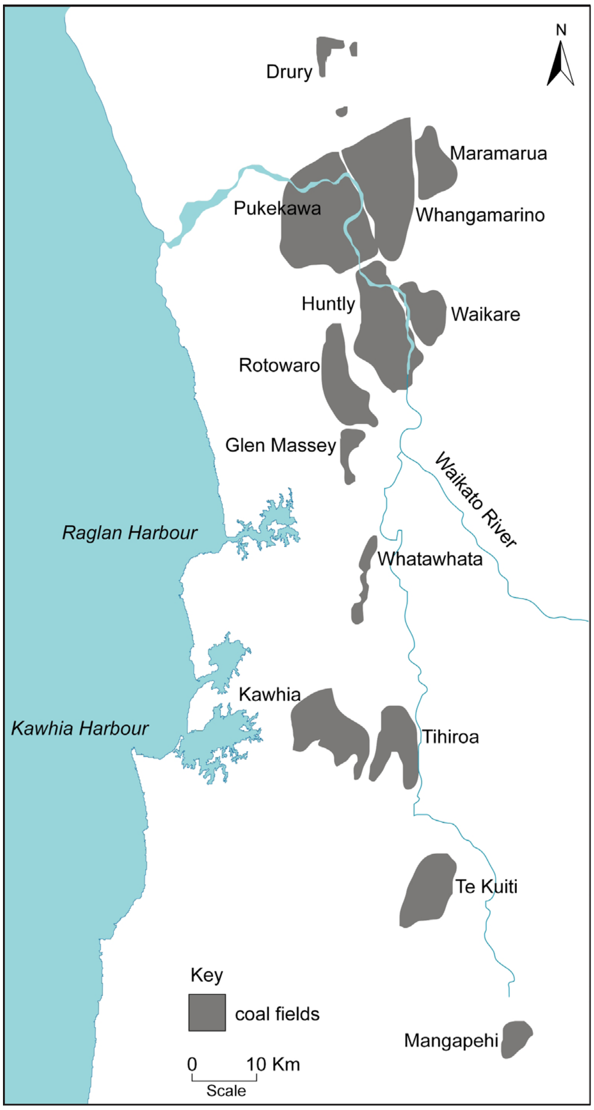


Fig. 8: *Distribution of coalfields within the study area. (Adapted from Edbrooke et al. 1994).*

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. 8). 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. 11). 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 1). The most striking feature of WCM distribution is its absence over virtually the entire western part of the study area.

Table 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	

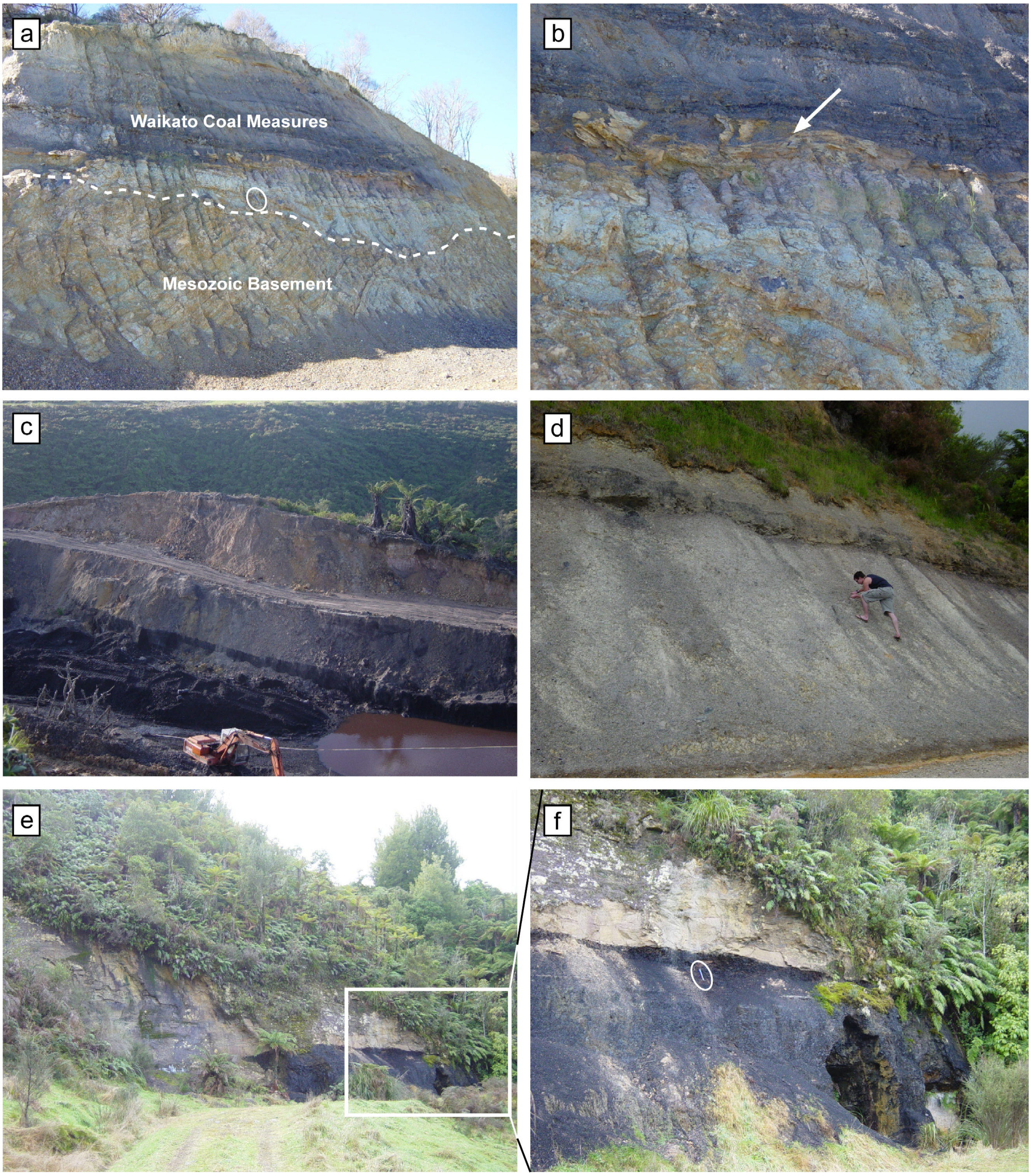


Fig. 9: *Examples of Waikato Coal Measures in the field. (a) Strong angular unconformity between highly weathered basement and WCM at Huntly Brickworks Quarry (S13/012016). Note the irregular Late Eocene relief upon basement rocks. (b) Close-up of claystone with a siderite concretion band (pointed by 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.*

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. 9 b). 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. The 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 and 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 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. 10 c), 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 10 a). This study retains the Dunphail Bluffs type locality and nominates Waikoha Road, Te Pahu (AK-6, S15/941674) (Fig. 10 d), 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

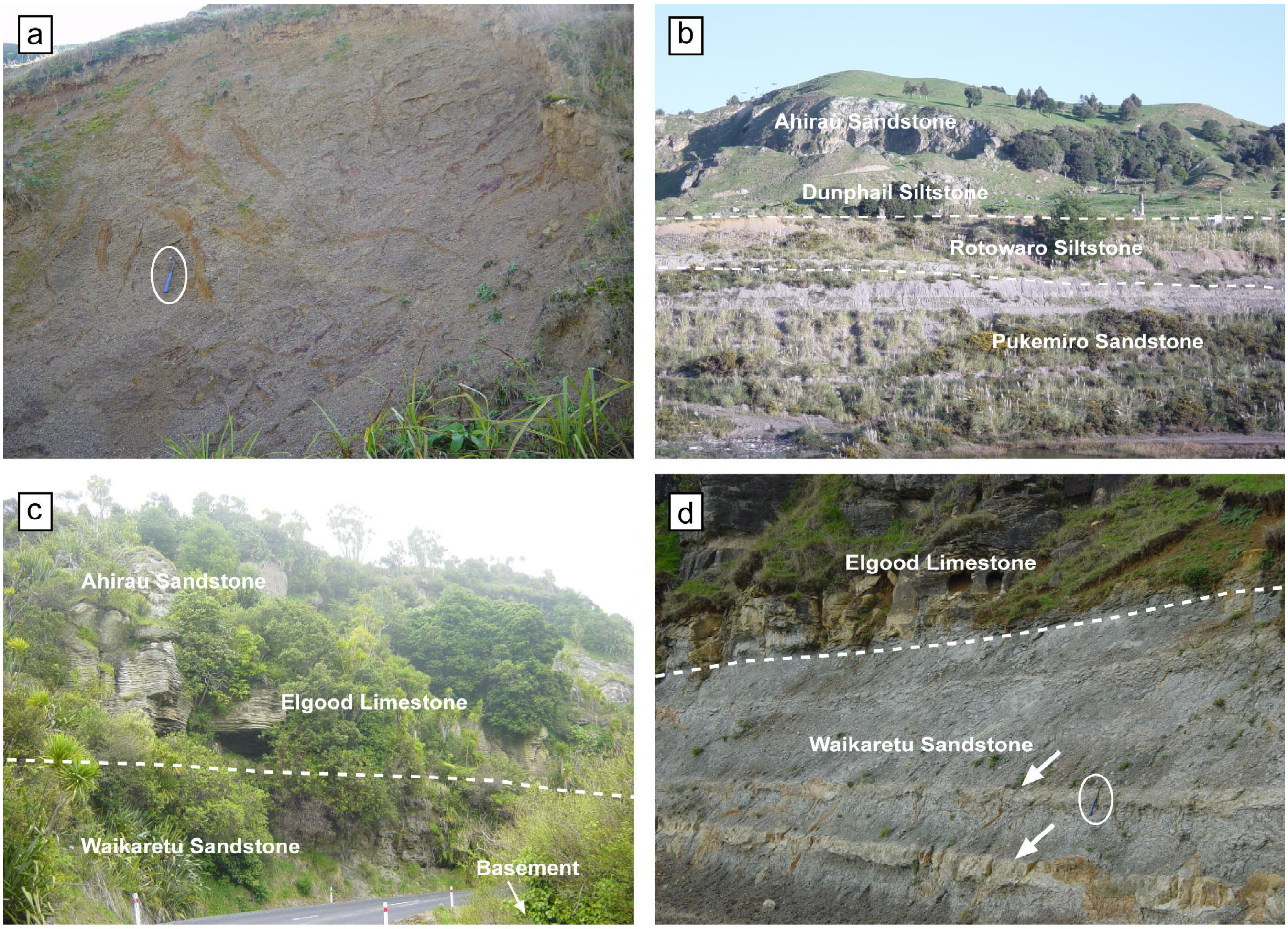


Fig. 10: *Examples of Mangakotuku Formation in the field. (a) Rotowaro Siltstone exposed along the bank of Mangakotuku Stream at its type locality at Dunphail Bluffs (TA-17, S14/946933). Note the massive appearance of typical ochre brown to purplish weathering crumbling surface. (b) Pukemiro Sandstone 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.*

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 are depicted in Fig. 11. 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 10 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. 11). Although all three members are retained here (Table 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

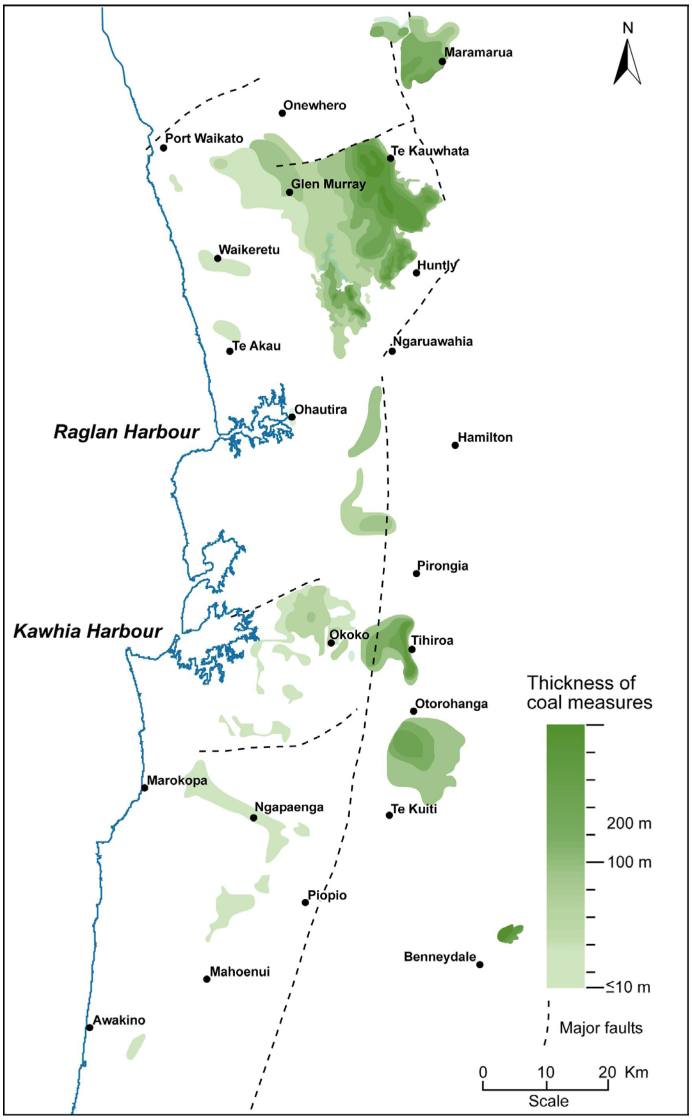


Fig. 11: Generalised distribution and thickness of Waikato Coal Measures and Mangakotuku Formation.

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, 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. 10 b). 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.

Table 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

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. 10 c). 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. 10 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 other 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. 12, 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).

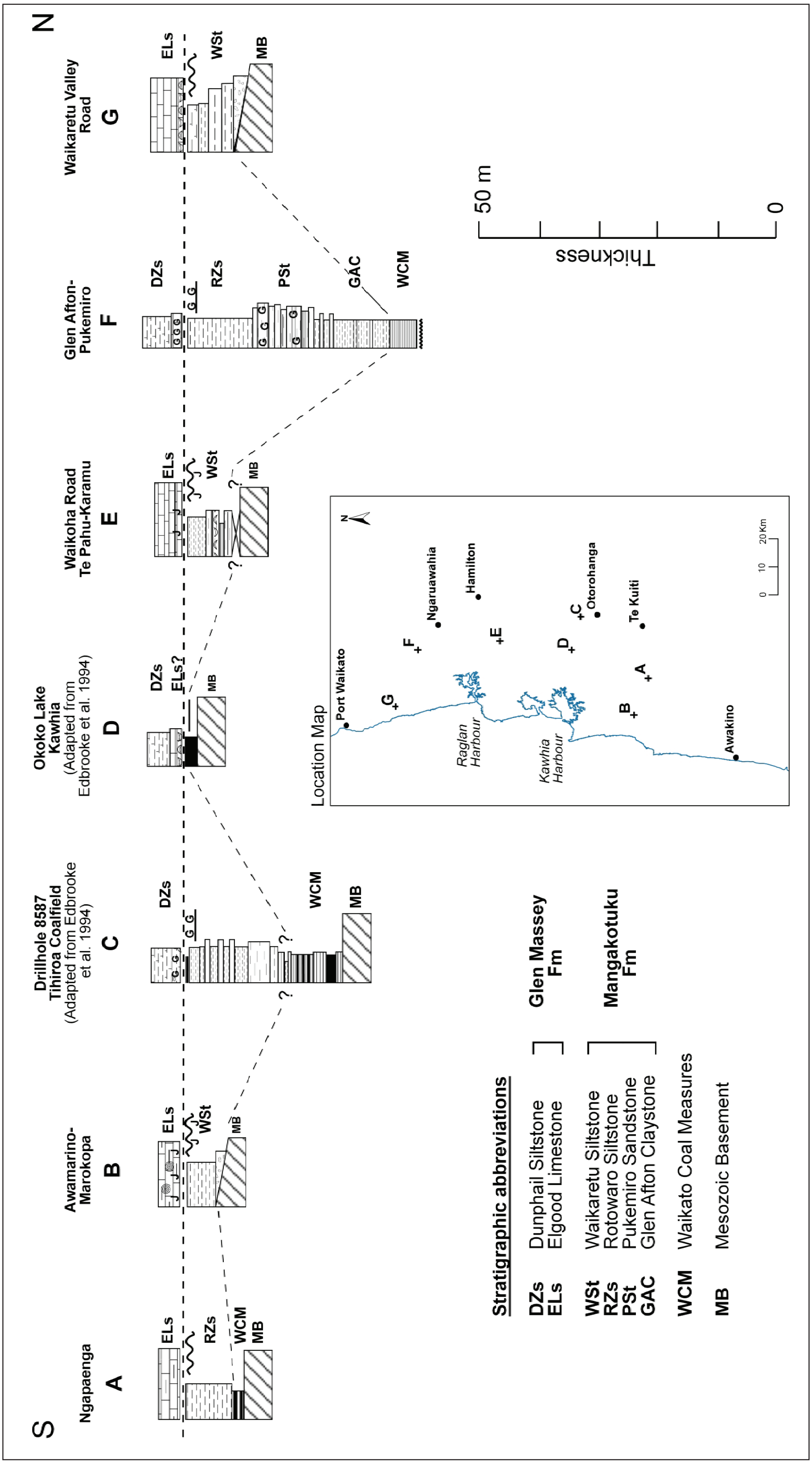


Fig. 12: Correlation of Mangakotuku Formation members from their type locality at Glen Afton-Pukemiro (column F) to the north at Waikaretu Valley Road (column G) and to the south at Ngapaenga (column A). Note the Mangakotuku Formation is inferred to be more sandy (Waikaretu Sandstone) and/or carbonaceous 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. 4 for lithology symbols.

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. 13 a). Elgood Limestone Member is the lowermost unit in the formation and comprises flaggy bioclastic limestone. Dunphail Siltstone Member is the middle 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) and Waterhouse & White (1994) (Fig. 13 e) 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 14 & 15).

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. 13 a). 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. 13 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. 13 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 inland of the west coast (Fig. 16). 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. 16). 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;

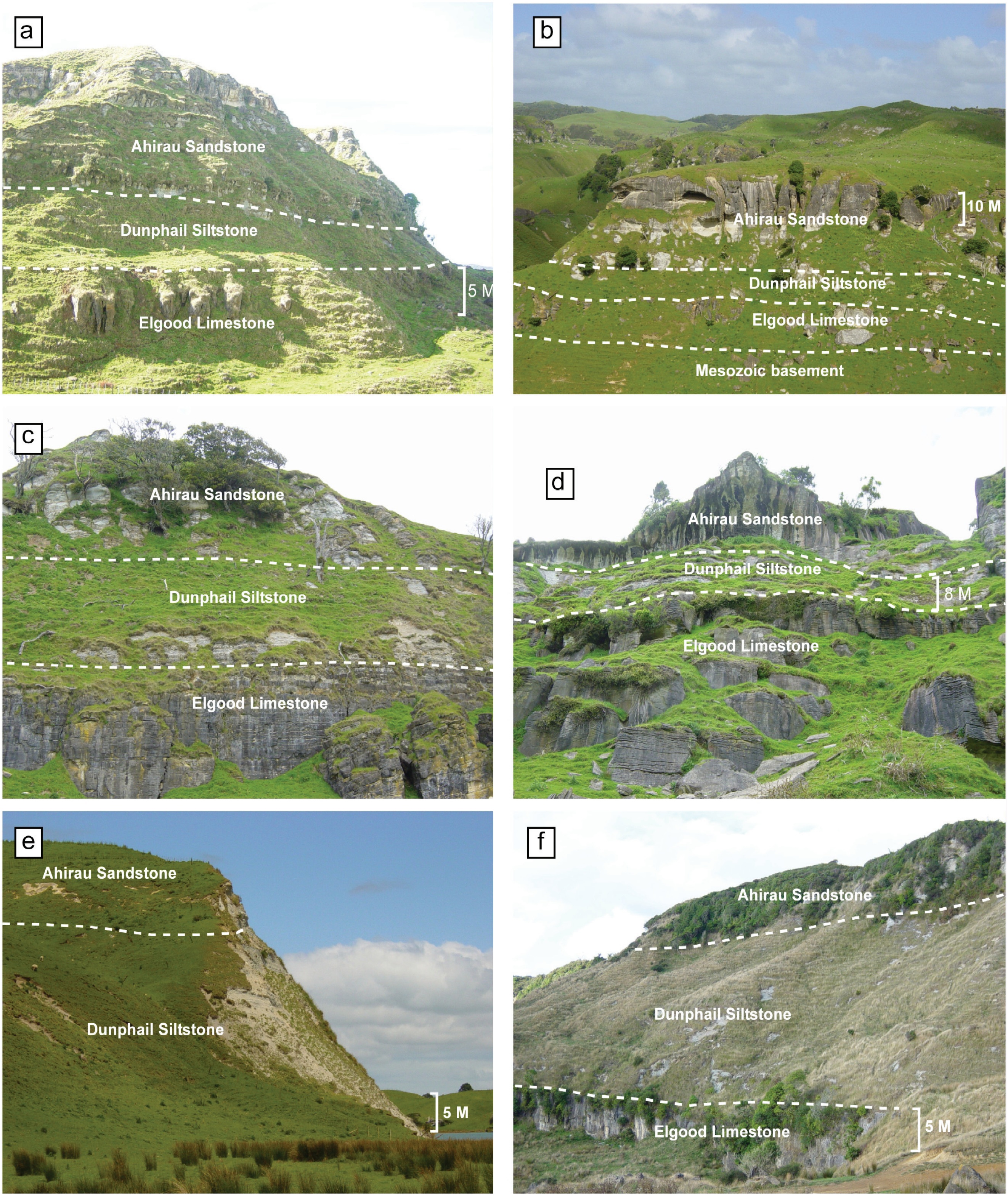


Fig. 13: Examples of Glen Massey Formation in the field. (a) Type locality at Dunphail Bluffs (TA-17, S14/943937). Note the distinct break in gradient defining the boundaries of members. (b) View looking to the east across Waimai Stream Valley from Port Waikato-Waikaretu Road (R13/643185). Here Glen 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.

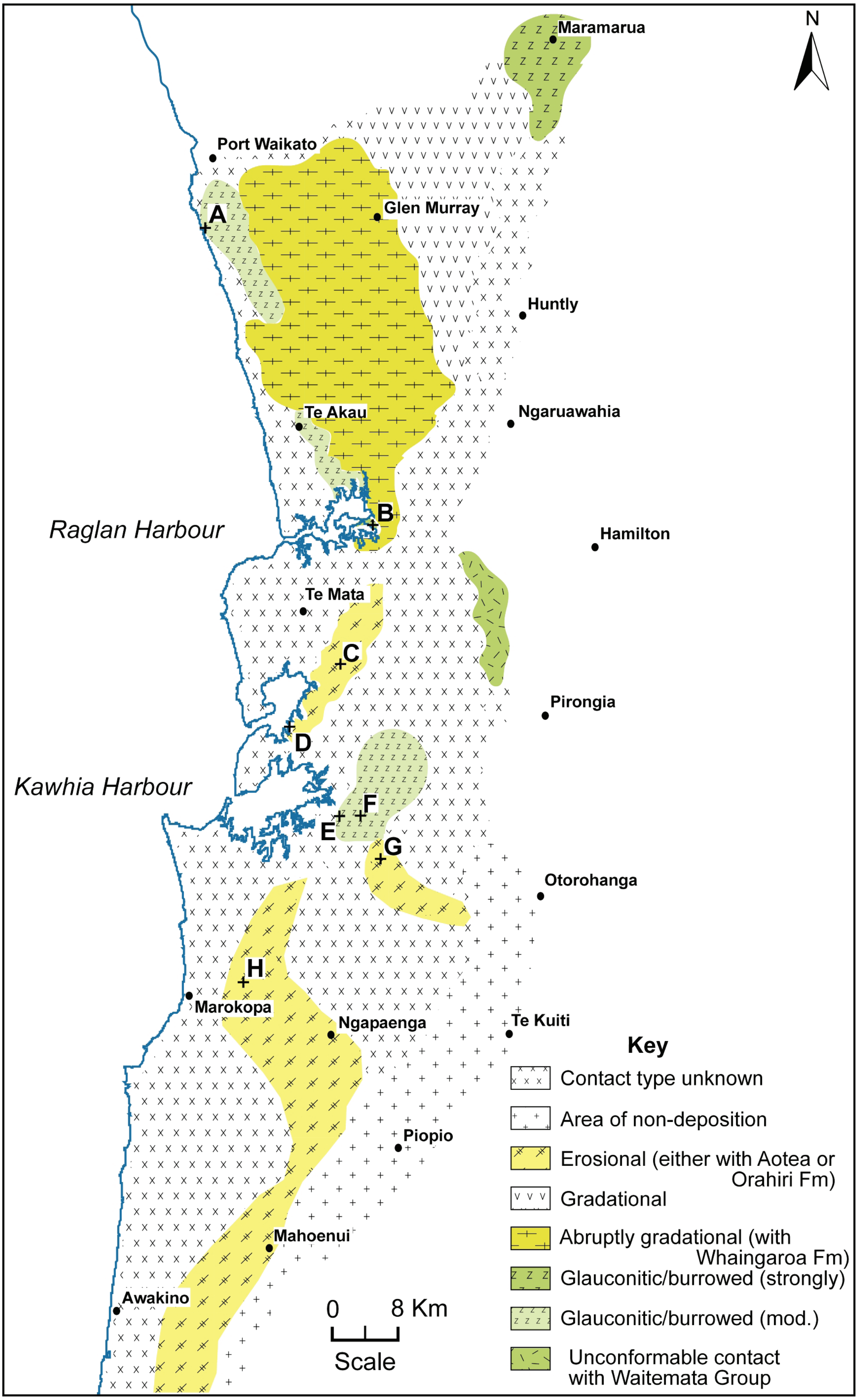
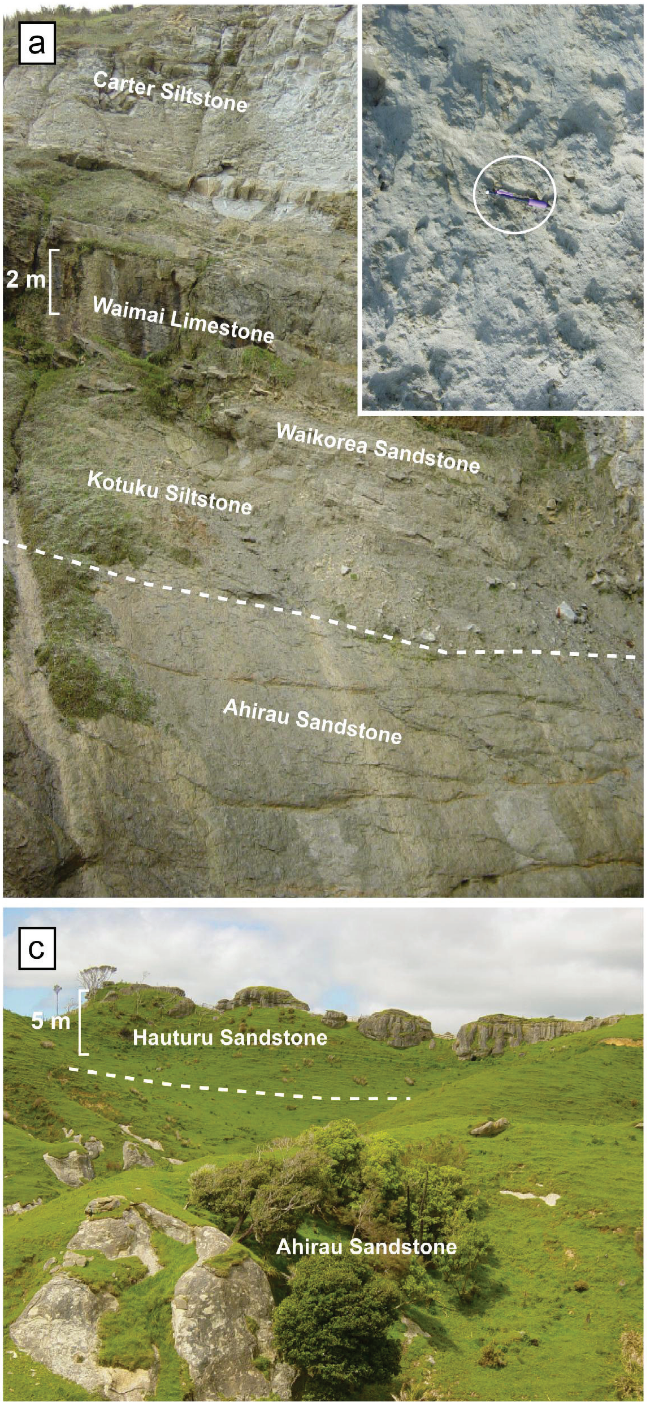


Fig. 14: Extent of Glen Massey Formation upper contact types within the study area and their extrapolation to neighbouring areas. A, Waikawau Beach; B, Waitetuna Estuary; C, Shea Road; D, Orotangi Cliff; E, Hautapu Hill; F, Kihi Road; G, Kaimango Road; H, Awamarino.



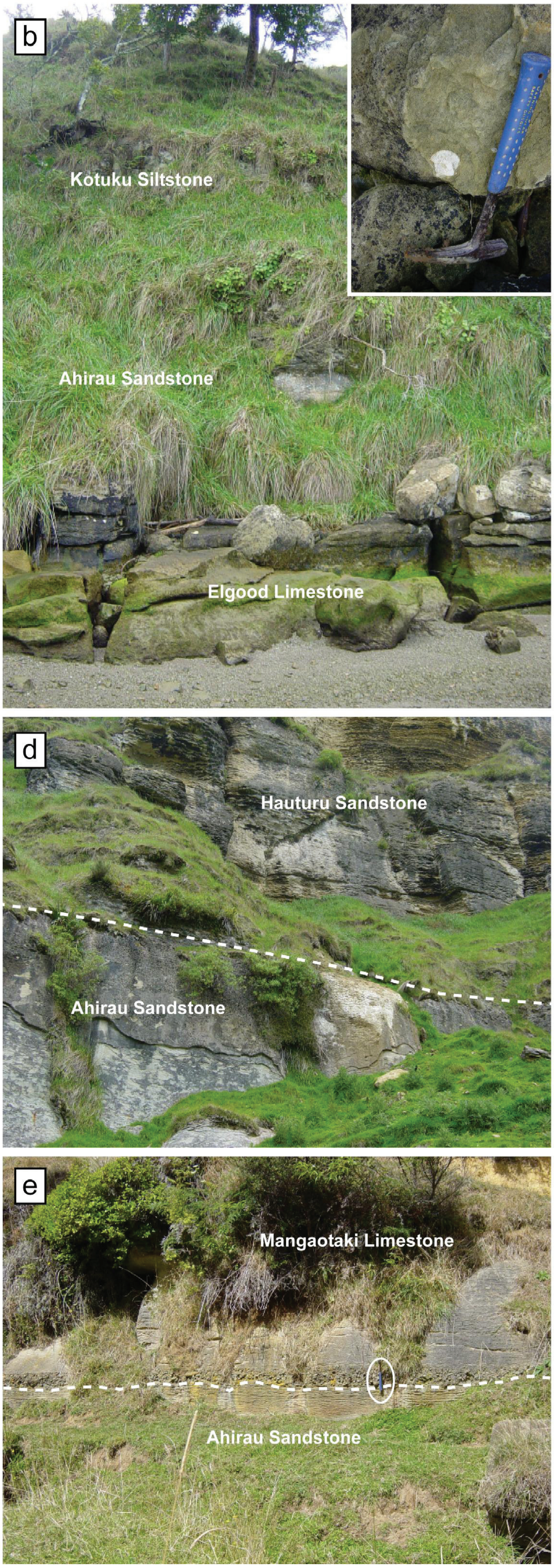


Fig. 15: Examples of Glen Massey Formation contacts. (a) Ahirau Sandstone abruptly grading into Kotuku Siltstone at Waikawau Beach (PW-11, R13/625138). Inset: intense bioturbation and scattered phosphate nodules on top of Ahirau Sandstone. (b) Highly glauconitic and bioturbated Ahirau Sandstone sharply 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).

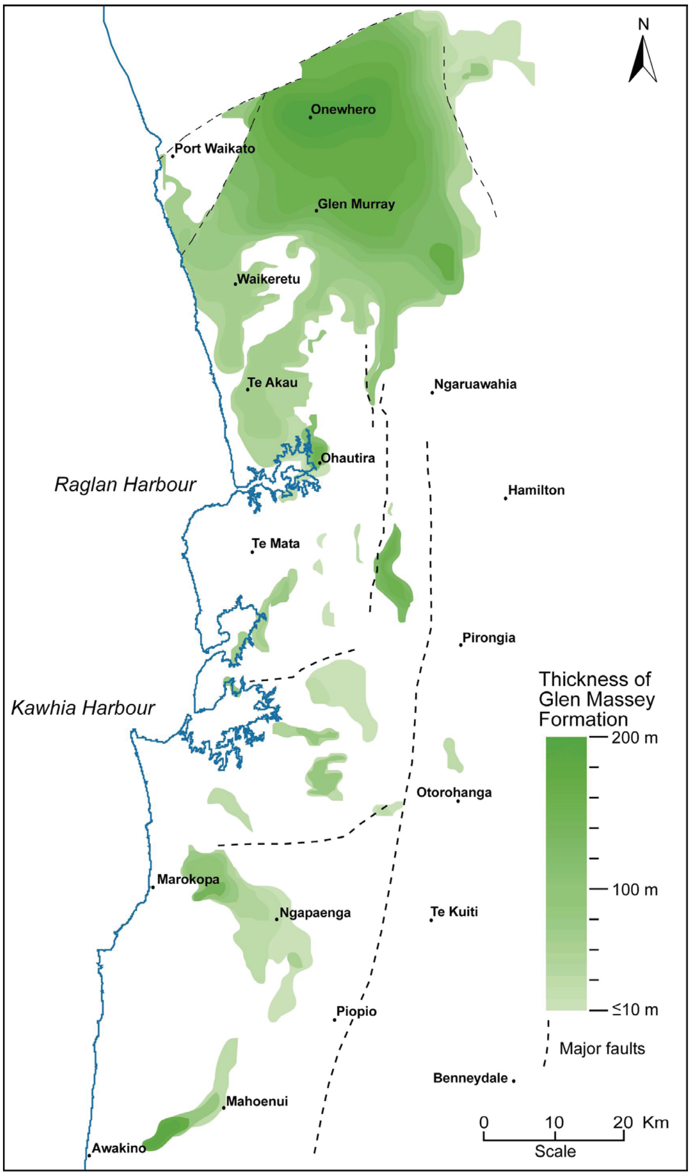


Fig. 16: Existing distribution and thickness of Glen Massey Formation

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. 13 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-planed 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 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. 15 b). 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. 15 a).

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. 14). 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. 15 e). Whaingaroa and Aotea Formations are missing in the Awamarino area and 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. 13 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. 10 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 from 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 from 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 shelf 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. 17a. 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. 17 b.

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 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. 18 depicts correlation of Glen Massey Formation between its type section at Dunphail Bluffs and Awamarino.

The Te Kotuku Creek section (Fig. 18, 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. 13 e & Fig. 18, 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.

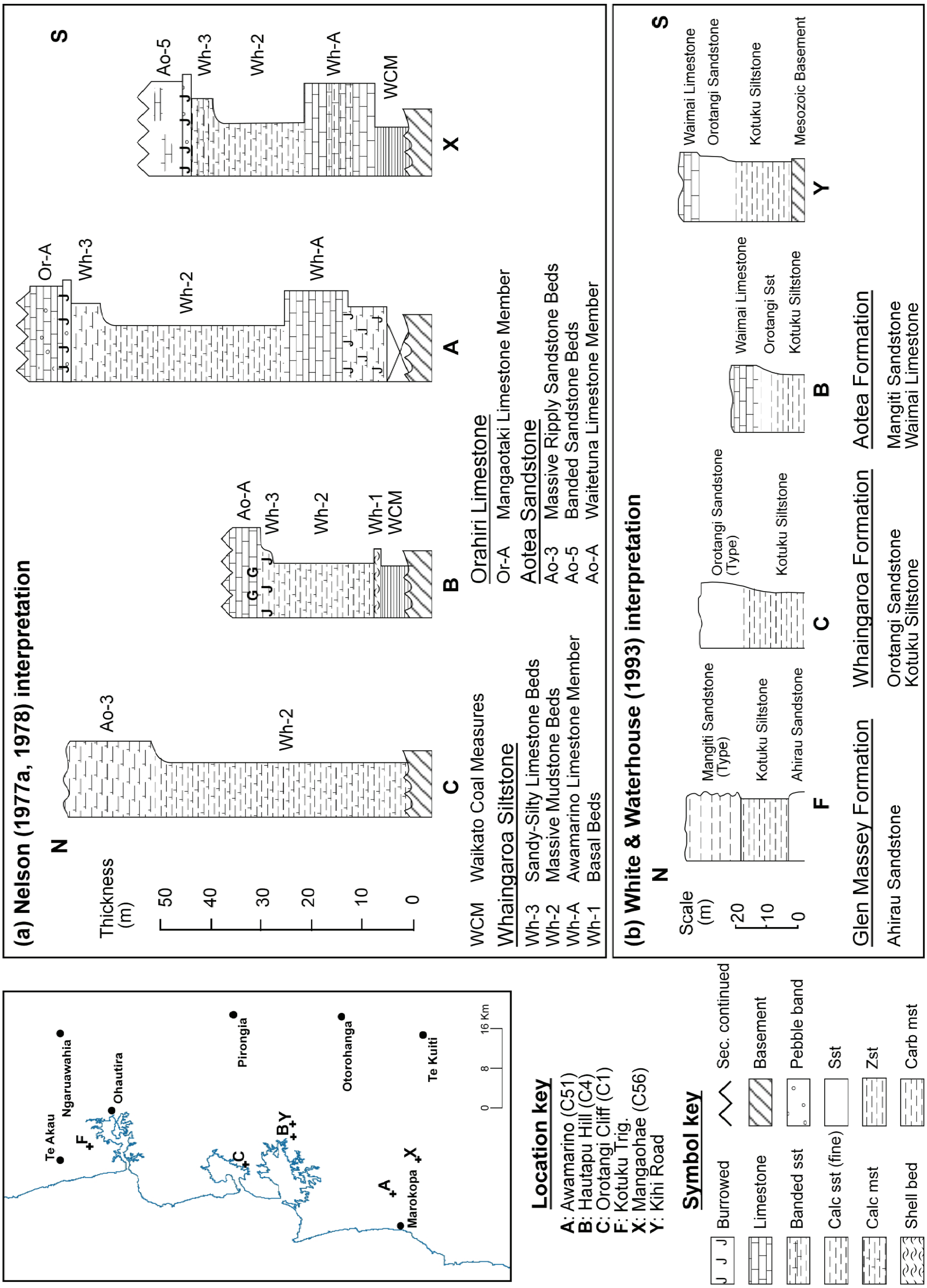


Fig. 17: (a) Stratigraphic correlation suggested by Nelson (1977, 1978a) compared with that of White & Waterhouse (1993) in (b). Column numbers within brackets in the location key refer to Nelson's (1977) stratigraphic columns.

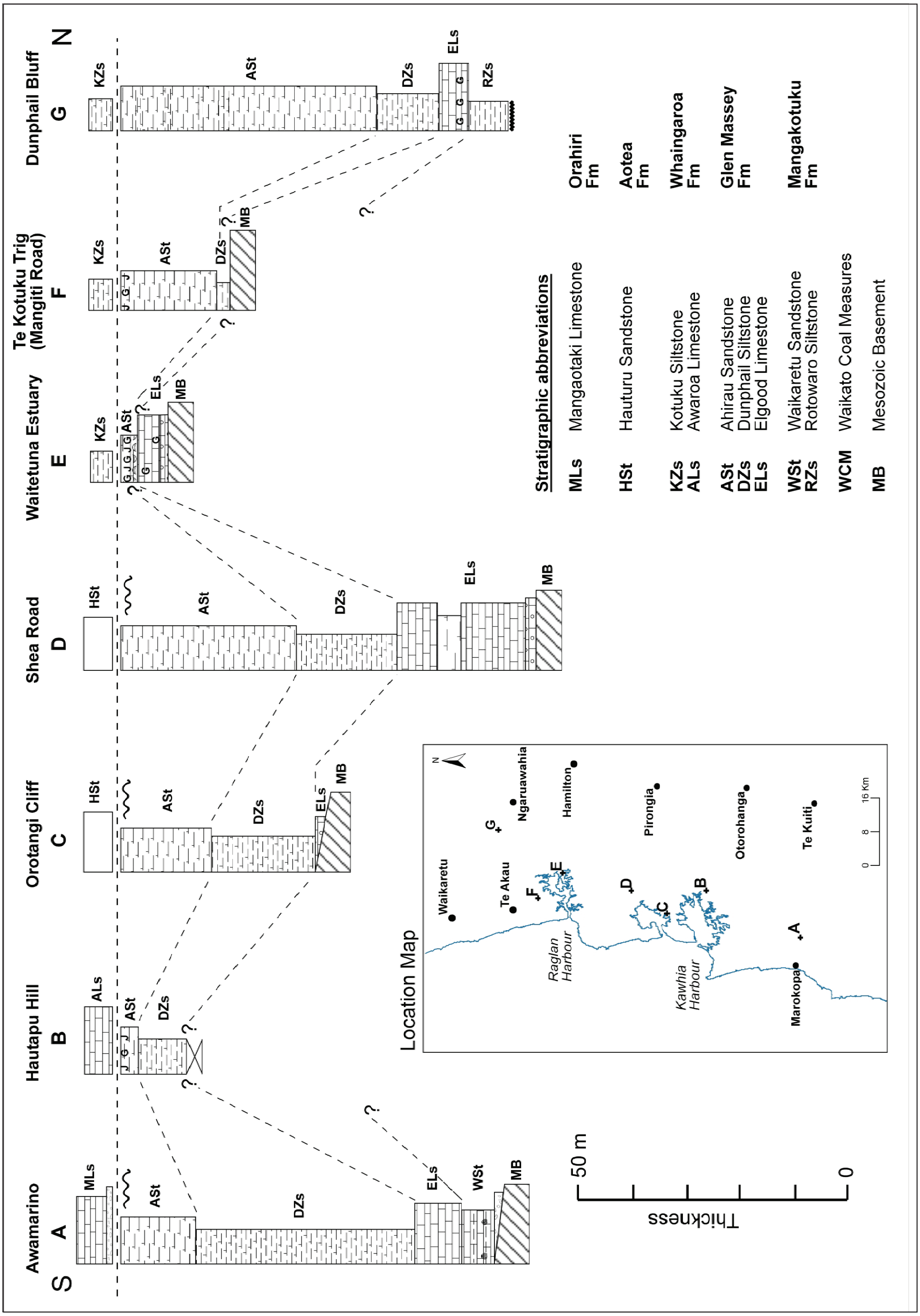


Fig. 18: Correlation of Glen Massey Formation members from the type section at Dunphail Bluffs (column G), to Awamarino in the south (column A). The datum used in this correlation is the top of the Ahirau Sandstone Member. No horizontal scale is implied. Refer Fig. 6 for lithology symbols.

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. 19 a). 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 (1994) formalised Nelson's (1973, 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).

Definition

All of the units south of Raglan Harbour previously regarded as Whaingaroa Siltstone are 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).

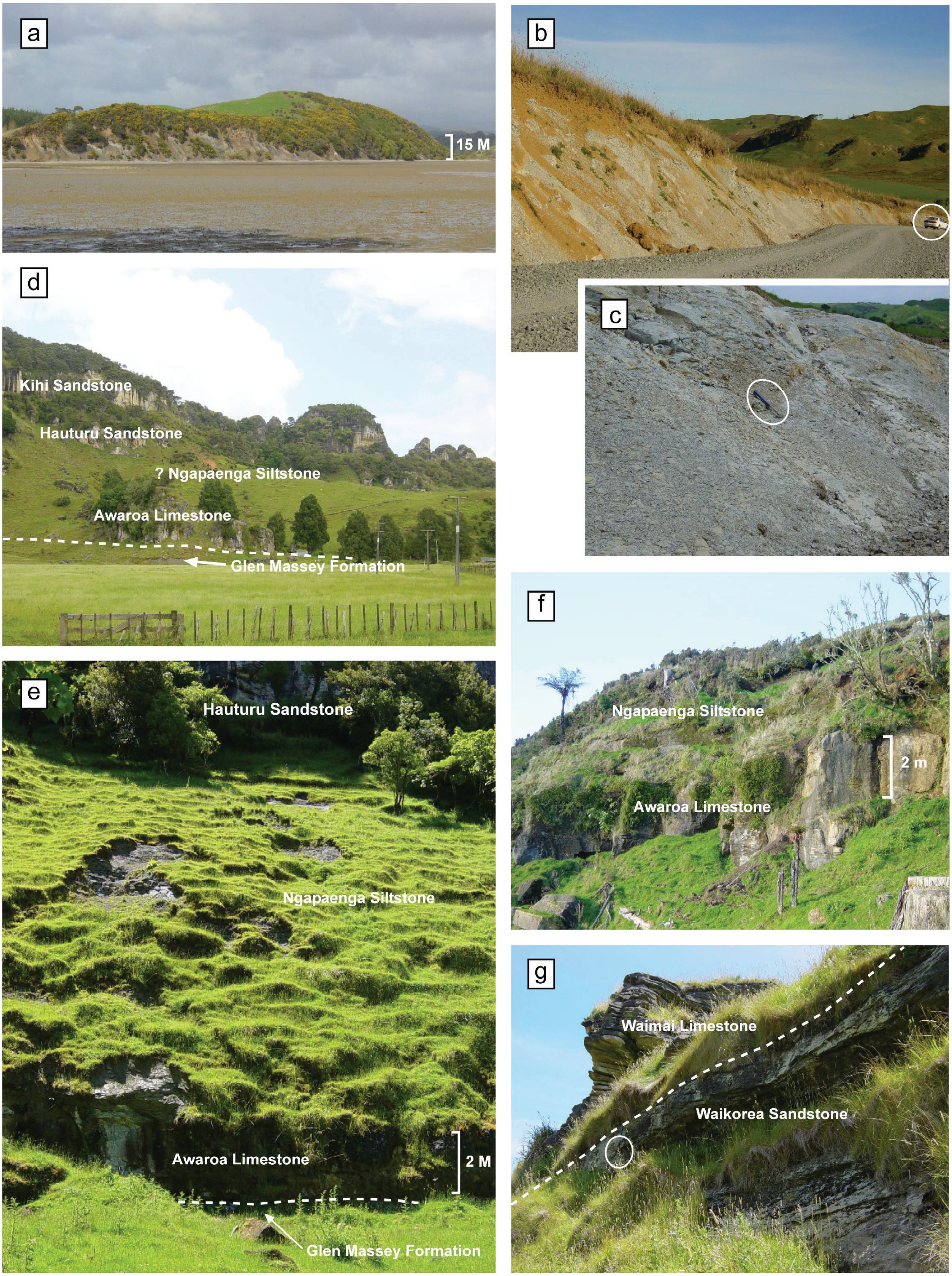
Type and reference sections

Kear & Schofield (1959) designated the type locality of Whaingaroa Siltstone to be at Waitetuna Creek (TA-14, R14/836775) (Fig. 19 a) 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 uplifted block about 400 m along the shoreline to the west of the main section. Although the stratigraphic relationship of Whaingaroa

Table 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	now included in the Elgood Limestone Member of the Glen Massey Formation	

Fig.19 facing page: *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).

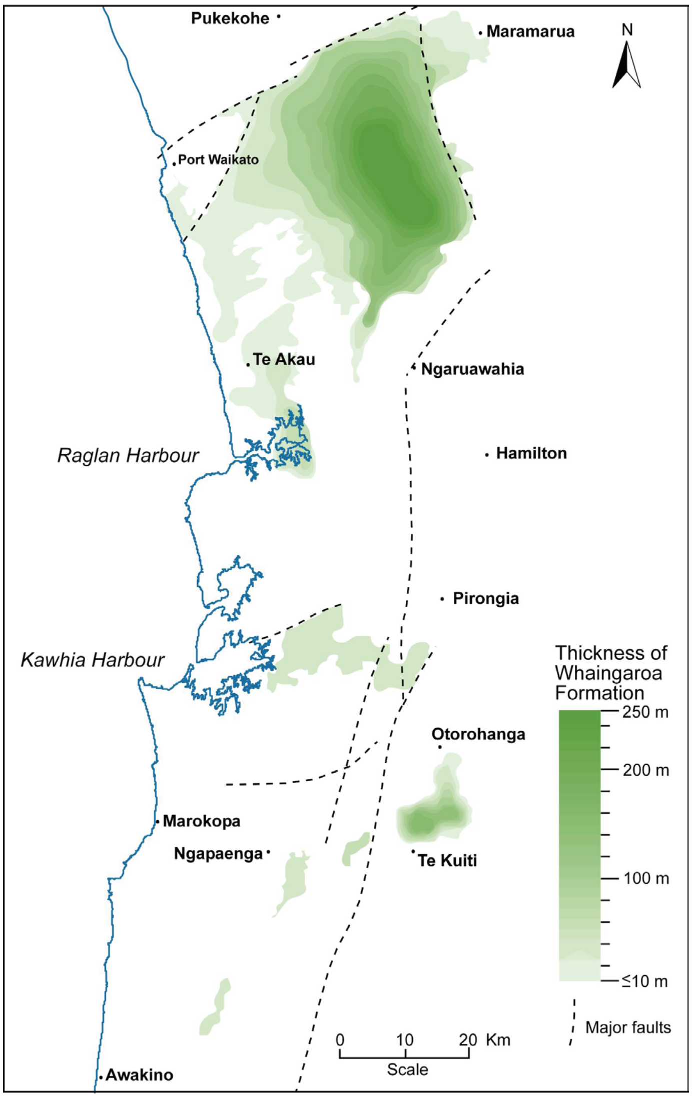


Fig. 20: Generalised distribution and thickness of Whaingaroa Formation.

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. 19 b & c). A Mangaotaki River reference section (C-145, R16/787385) west of Piopio (Fig. 19 e) 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. 20) 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 observed in several coal exploration drill holesand difficult to distinguish from the Kotuku Siltstone Member of the Glen Massey Formation (Kear & Schofield 1978; White & Waterhouse 1993) (Fig. 20). 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. 20).

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. 21, column A & B) and at Mangaotaki, and inland at Kawhia Harbour (Hautapu Hill, Kihi Road) (Fig. 21, column C). In a few coal exploration drill holes in the West Kawhia Coalfield, a thick siltstone interval intersected below Aotea Formation is included here within Whaingaroa Formation (Fig. 21, 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

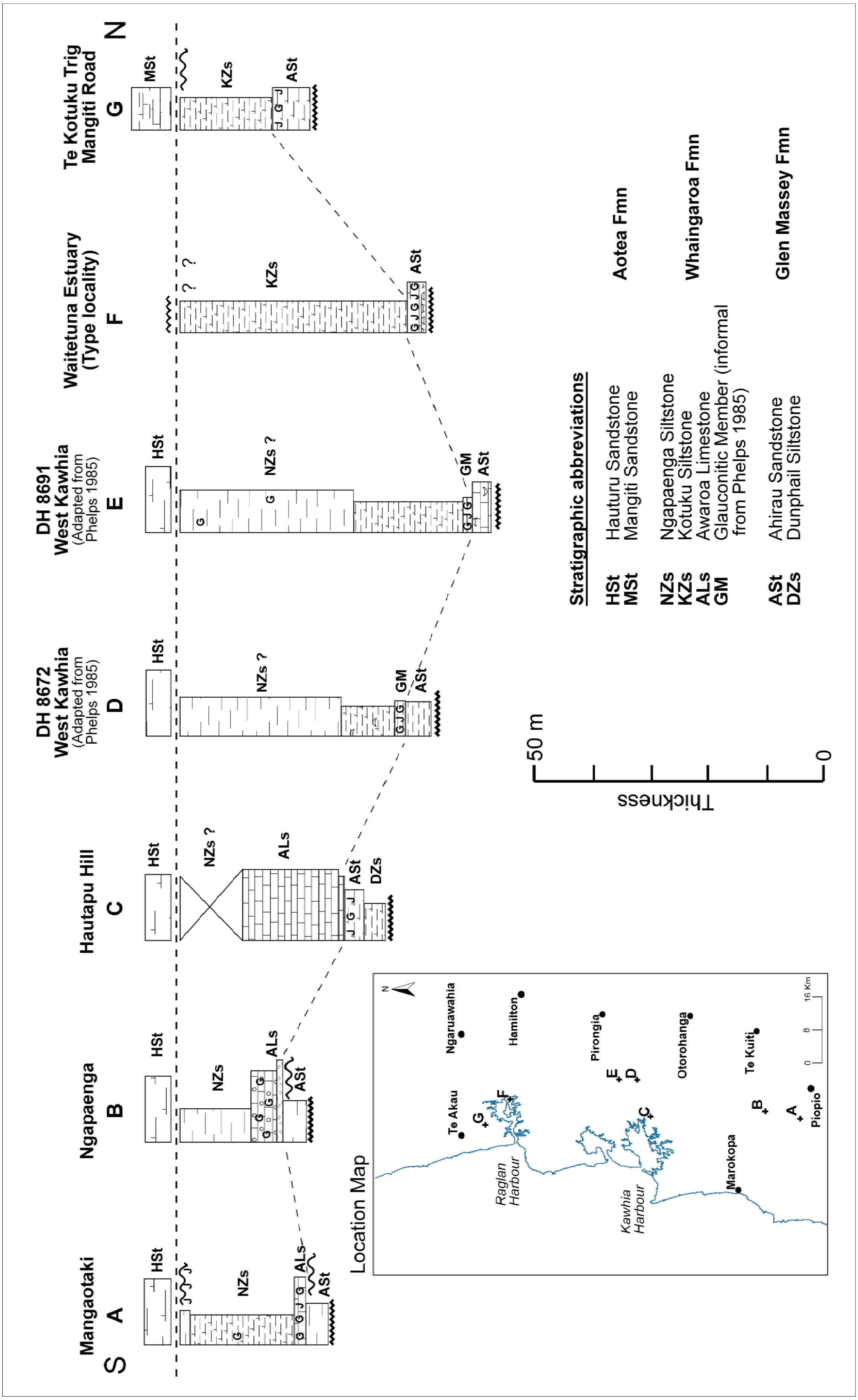


Fig. 21: Correlation of Whaingaroa Formation members between the type locality at Waitetuna Estuary and sections to the north (Mangiti Road, column G) and south (columns E to A). Datum is the base of Hauturu Sandstone Member of Aotea Formation, or its lateral equivalent, the Mangiti Sandstone Member. No horizontal scale is implied. Refer to Fig. 6 for lithology symbols.

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. 15 a). 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 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. 19 d). 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. 19 d). 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. 21, 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. 19 f). Less well-developed Awaroa Limestone extends southward as far as Kihikihi Stream Valley near Mangaotaki (Fig. 19 e).

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, C-68) 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. 19 f) 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. 21, 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. 19 g). The member is easily distinguished by its 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. 19 g).

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. 5). Table 4 shows the distribution of Aotea Formation members in the various parts of the study 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. 13 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. 15 c). 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. 22 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)

This section crops out as a prominent bluff at the end of Shea Road and across a stream flat (Fig. 22 d). 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 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

Table 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 (e.g. 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 areas (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.

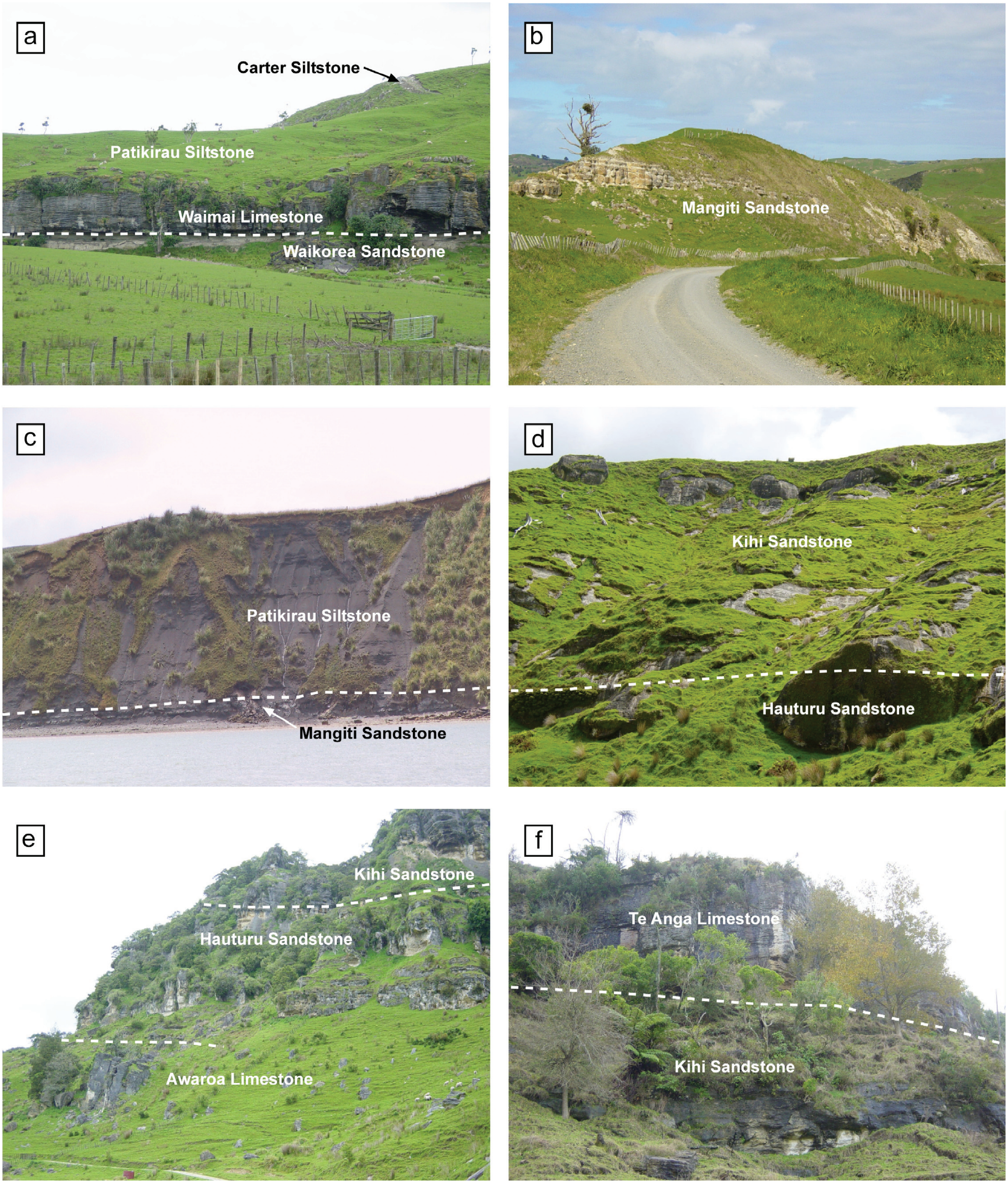


Fig. 22: Field examples of Aotea Formation. (a) Waimai Limestone with prominent cross-bedding sharply overlying Waikorea Sandstone along Waimai Stream (TA-3, R13/707943). (b) Mangiti Sandstone exposed along Mangiti Road (TA-12, R14/785835). Note the distinct bedding development within the sandstone. (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).

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. 23). 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.

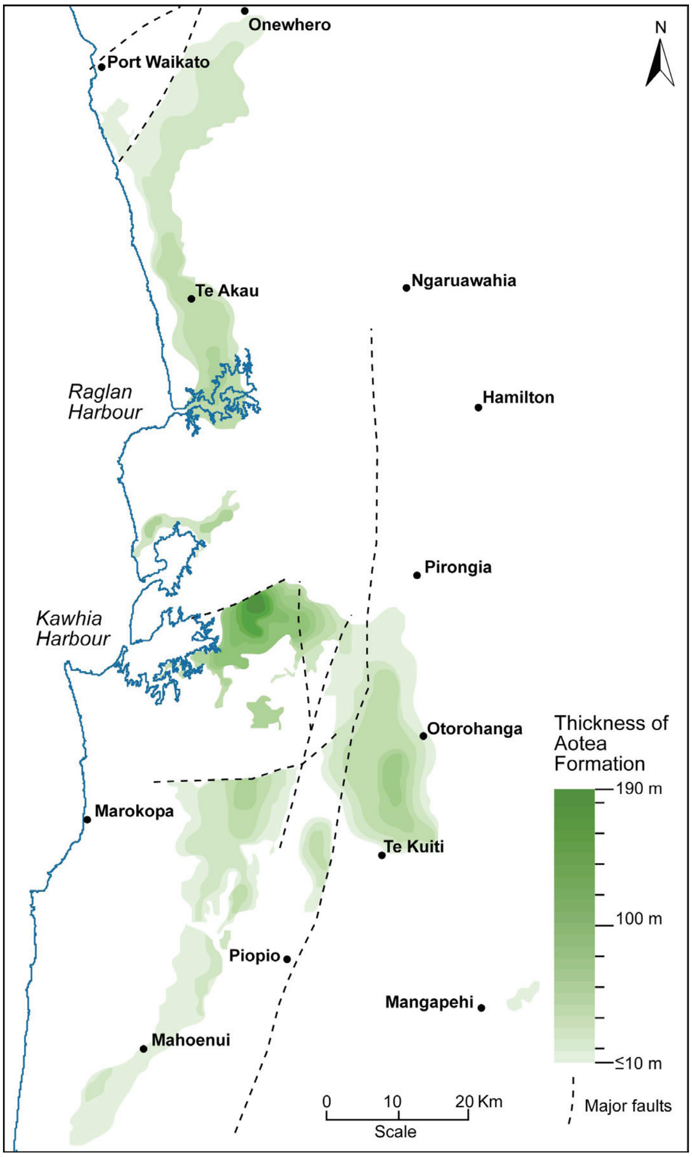


Fig. 23: General extent and thickness distribution of Aotea Formation.

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. 22 c). 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 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. 15 d).

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. 22 f). 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. 24 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. 22 b). 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. 22 c). 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.

Between Te Akau and Port Waikato the formation consists of prominently cross-stratified, variably sandy limestone (Waimai Limestone Member) (Fig. 22 a). 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 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

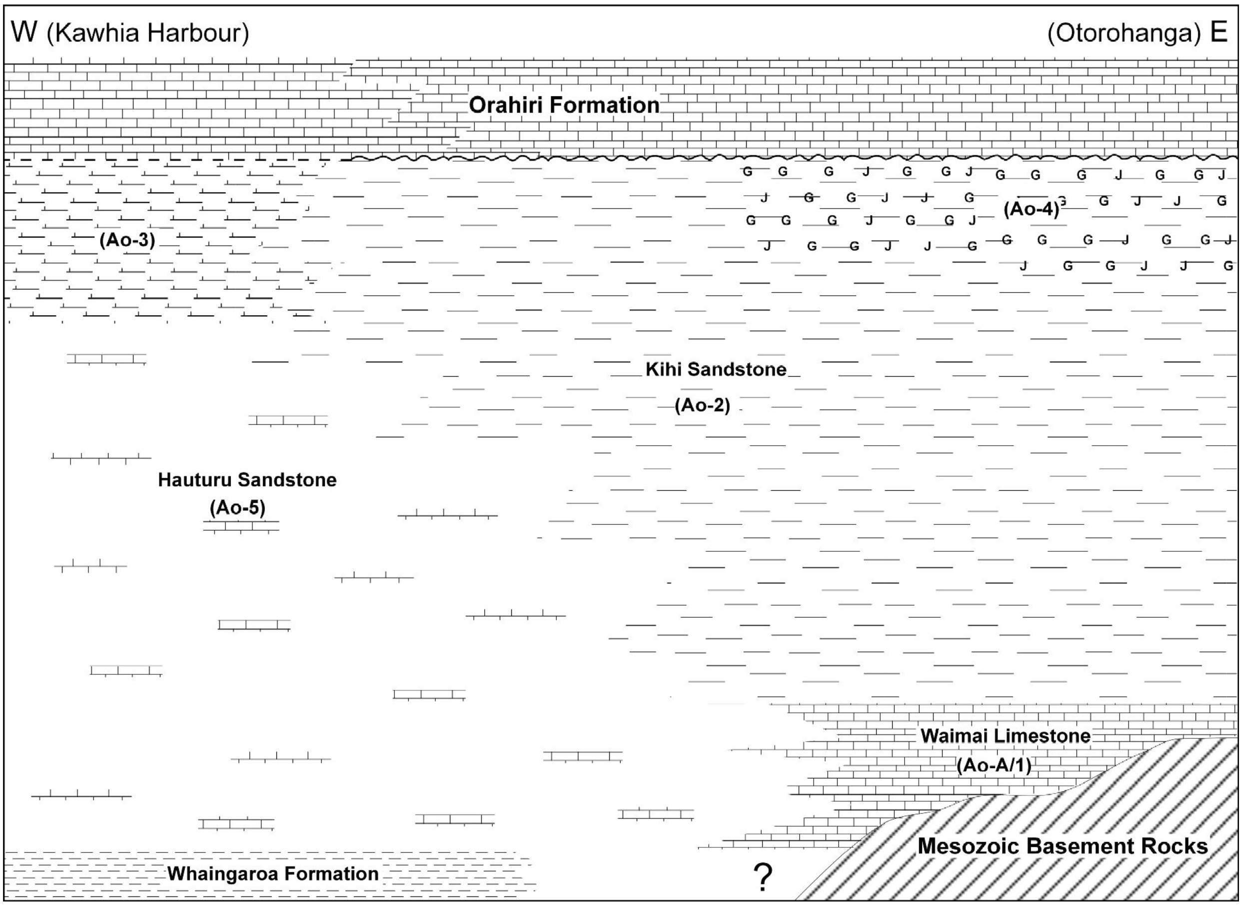


Fig. 24: Schematic cross-section from Kawhia Harbour (Hautapu Hill, Kihi Road) to west of Otorohanga (Honikiwi, Waitomo Valley Road) illustrating a complex relationship amongst the members of the Aotea Formation. Abbreviations within brackets represent Nelson's (1978a) lithofacies within Aotea Sandstone. Wavy line corresponds to Aotea-Orahiri unconformable contact. No distance or thickness scale implied

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. 25, 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. 25, column I).

Mangiti Sandstone is a correlative of Hauturu Sandstone (Plateau Road, AK-3; Shea Road, AK-4; and Ruaweke Point, C-32; Fig. 25, column H). 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 Hauturu Sandstone, Mangiti Sandstone and Waimai Limestone occurs at Makaka (AK-1) to the north of Aotea Harbour (Fig. 25, column G). At this section, about 70 m of moderately flaggy sandy limestone, calcareous sandstone, and flaggy limestone crops out along the

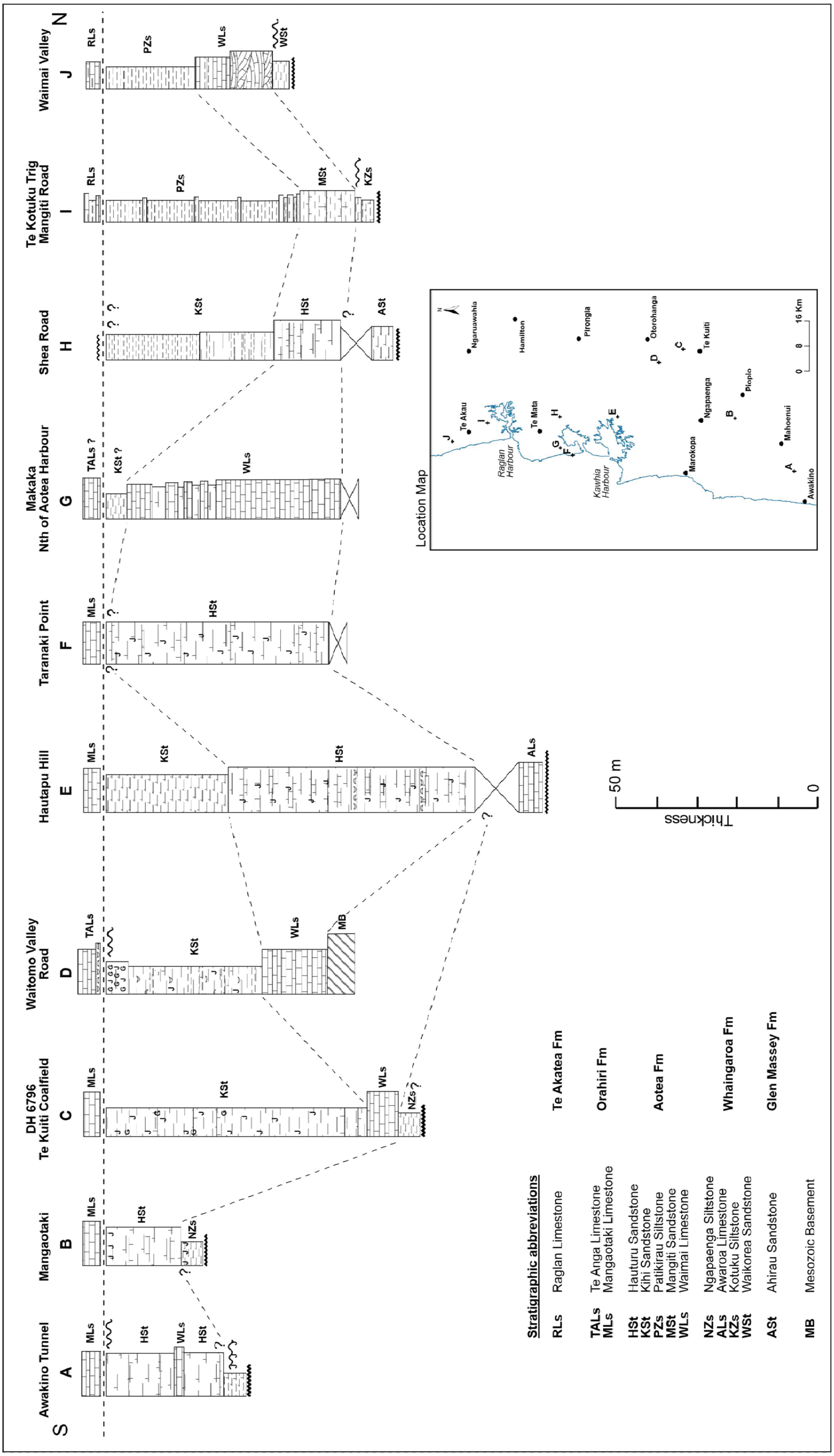


Fig. 25: *Correlation of Aotea Formation members from Waimai Valley in the north (column J) to Awakino Tunnel (column A) in the south. The datum is the base of Orahiri Formation or its correlative (Te Akatea Formation) in the north. Refer to Fig. 6 for lithology symbols.*

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. 25, 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. 25, 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. 25, 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. 25, column C) intersected at depth 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. 25, 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. 26 a). 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. 26 b). 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. 26 d). 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. 27). 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 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. 26 f). 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. 28). 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

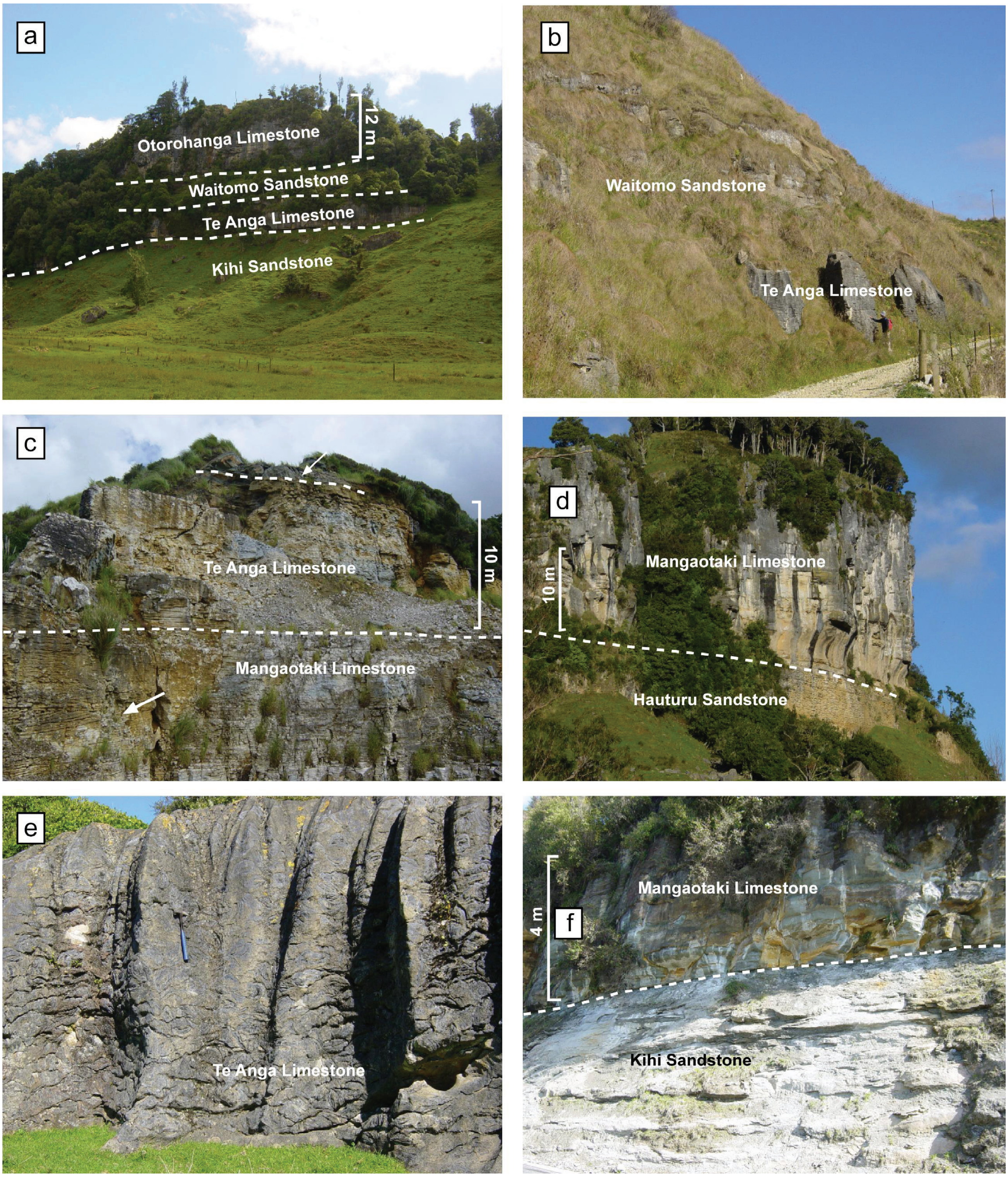


Fig. 26: Examples of Orahiri Formation in the field. (a) Cliff on the backside of the now disused limestone quarry facing Waitomo Valley Road (C-32, S16/961292), the type locality of Orahiri Formation and Otorohanga Limestone. Note the sharp contact between the Kihi Sandstone Member and overlying Te 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).

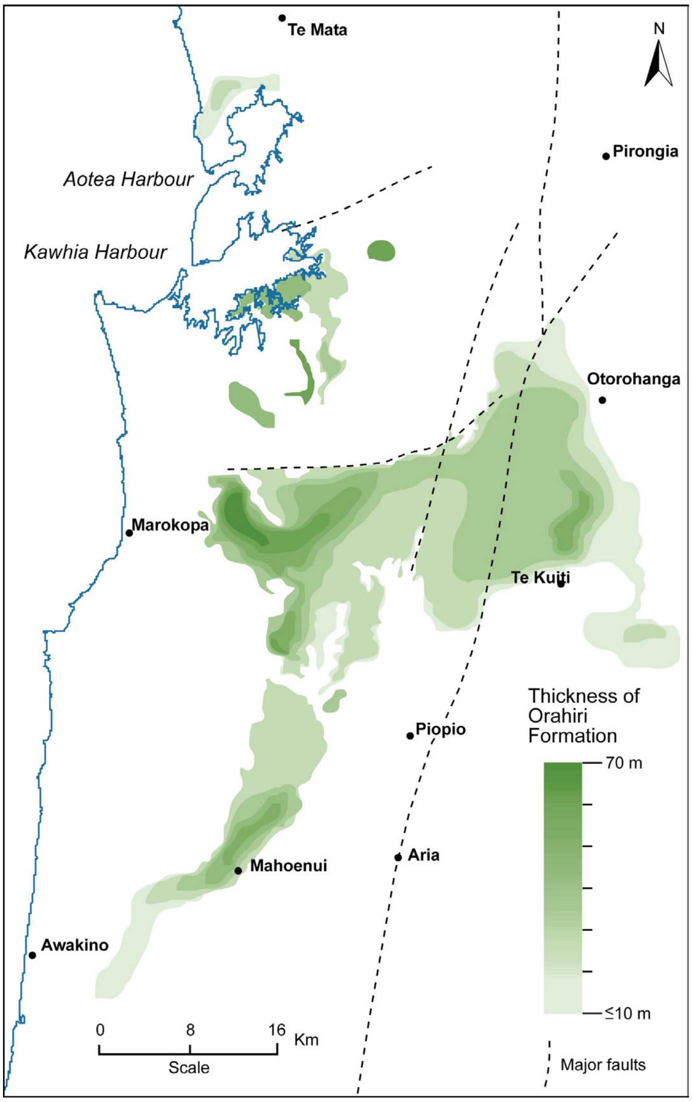


Fig. 27: Generalised distribution and thickness of Orahiri Formation, as defined by Nelson (1978a).

type 'B', Fig. 28). 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. 28). 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 an (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 across, 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 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. 26 e) (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

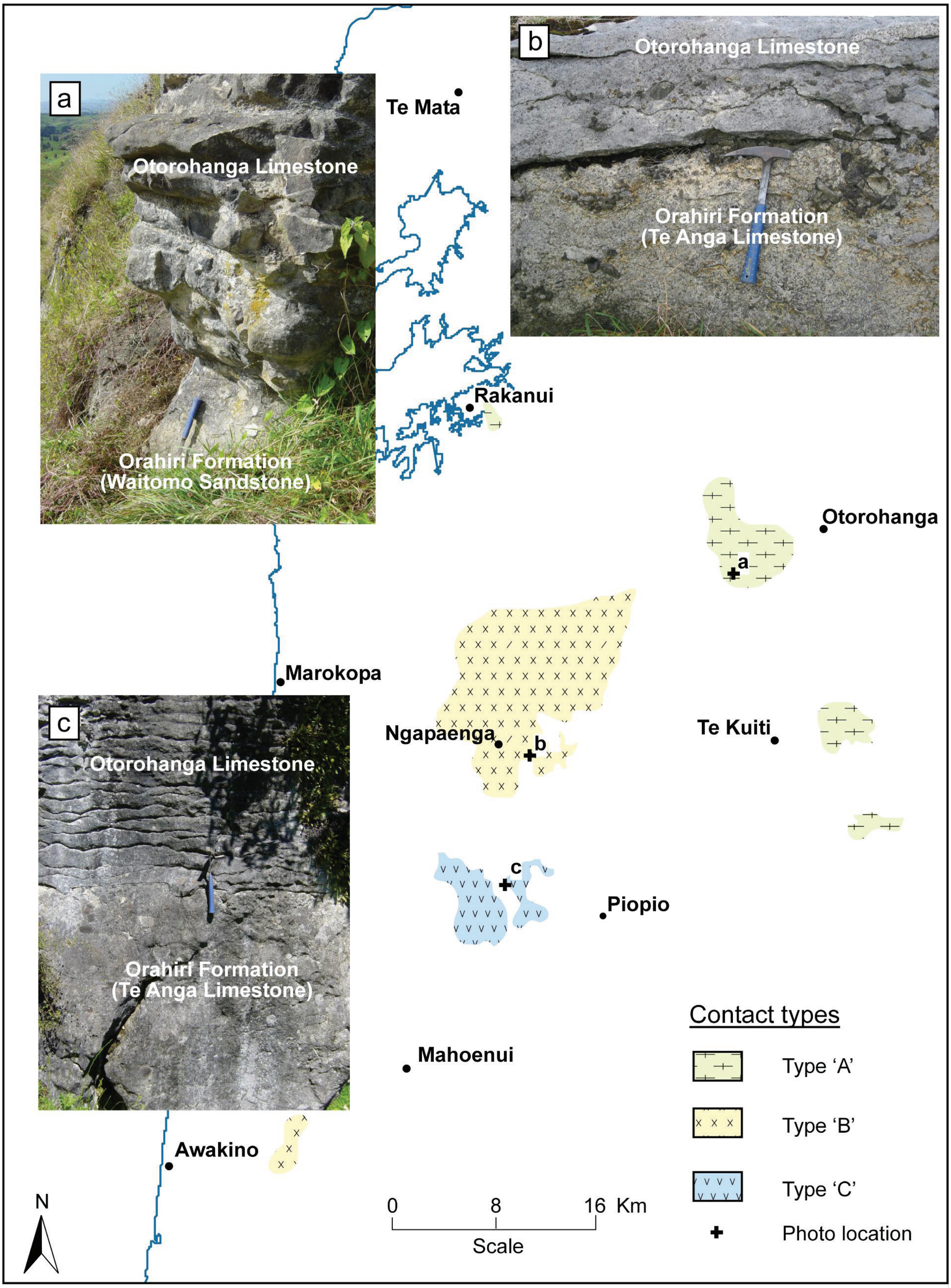


Fig. 28: *Extent and distribution of different types of Orahiri Formation – Otorohanga Limestone contact. Type 'A' is defined by a gradational contact between Otorohanga Limestone and underlying Waitomo Sandstone Member. See photo (a) Waitomo Valley Road Limestone Quarry (C-32, S16/960295). Type 'B' 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).*

type Waitomo area (C-32) is a muddy, 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. 26 a & 29 a). 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. 29 b). 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 accumulation is apparent when compared with the Orahiri Formation thickness trend (Figs. 27 & 30). The formation is

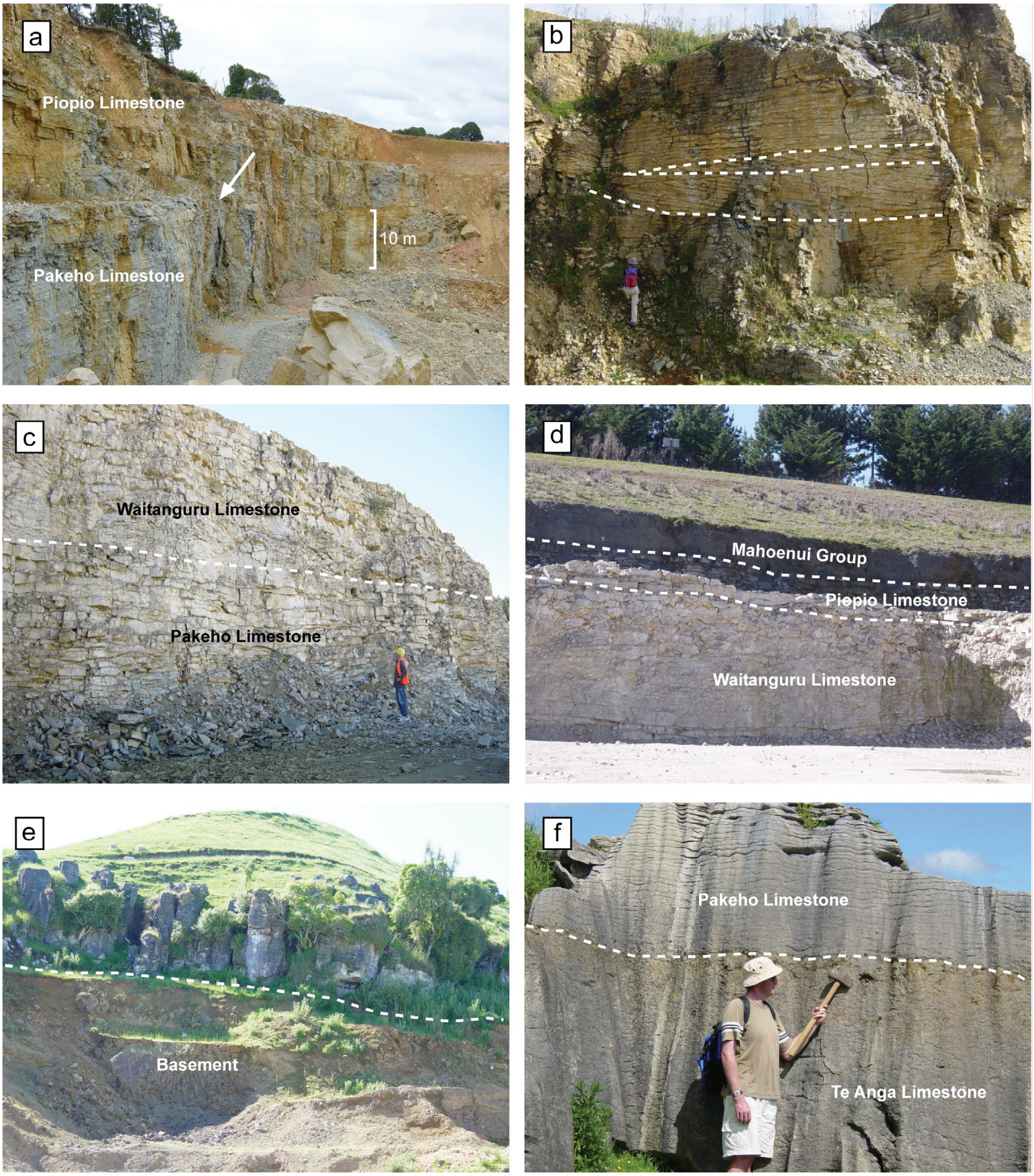


Fig. 29: Examples of Otorohanga Limestone in the field. (a) View of Otorohanga Limestone type locality at Waitomo Valley Road limestone quarry (C-32, S16/963291). Note the prominent ledge in the middle of the quarry face marking the contact between the lower cross-bedded Pakeho Limestone Member and the 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).

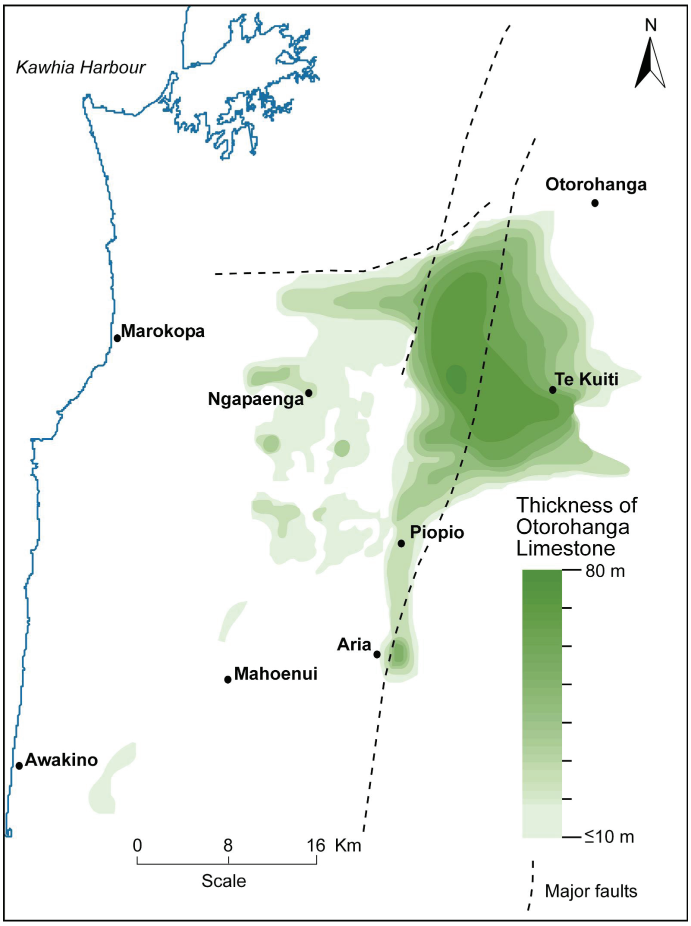


Fig. 30: Generalised distribution and thickness trends of Otorohanga Limestone, as defined by Nelson (1978a).

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 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. 28, 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. 29 d). 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. 29 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. 29 c). 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. 29 d).

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. 31). 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. 31) 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 gradational 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. 31). 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. 32, 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. 32, column C), and there is no evidence that Otorohanga Limestone was eroded in the Mangaotaki Bridge area 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. 32, 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. 27 compared with Fig. 30). 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,

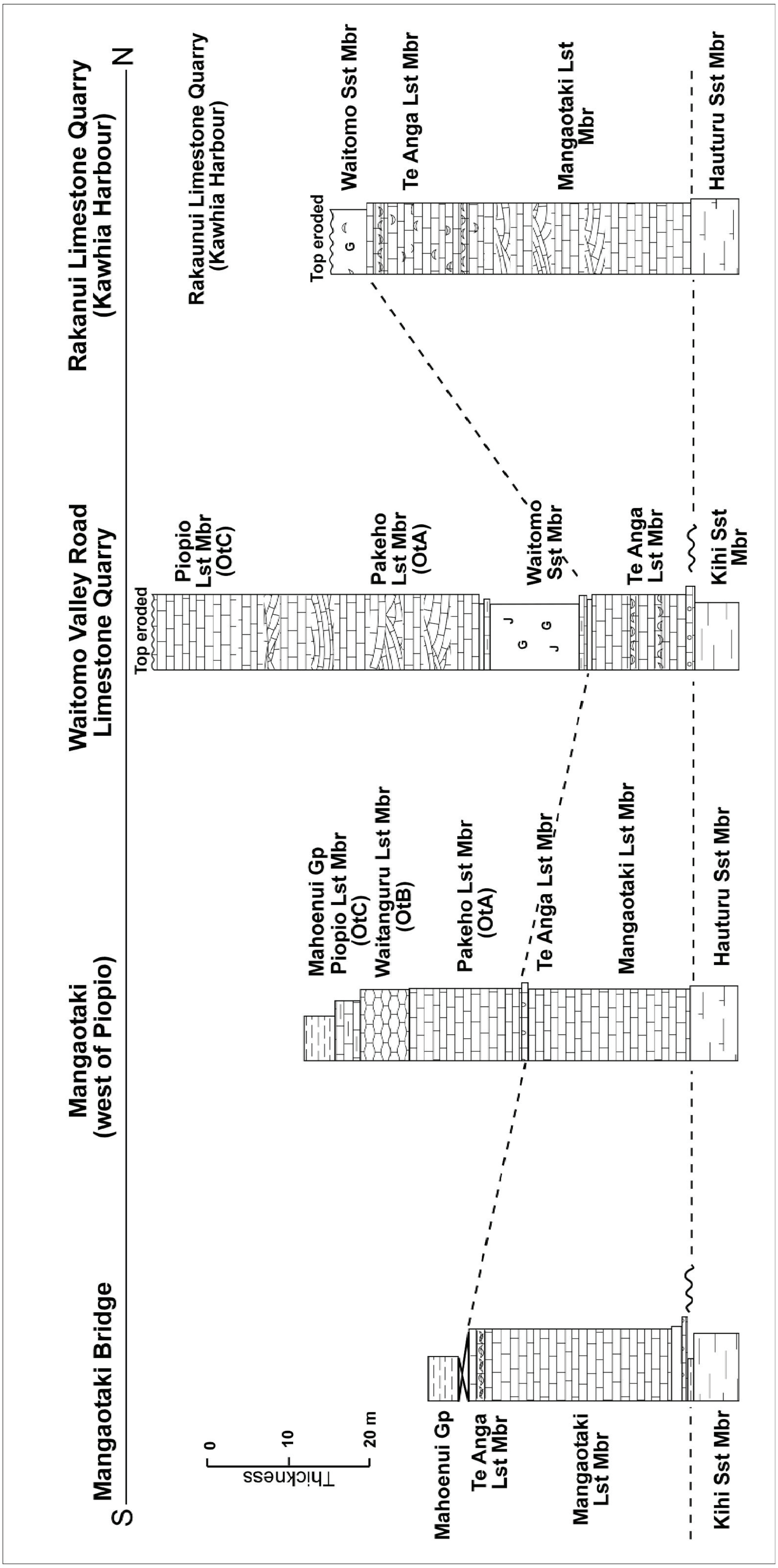
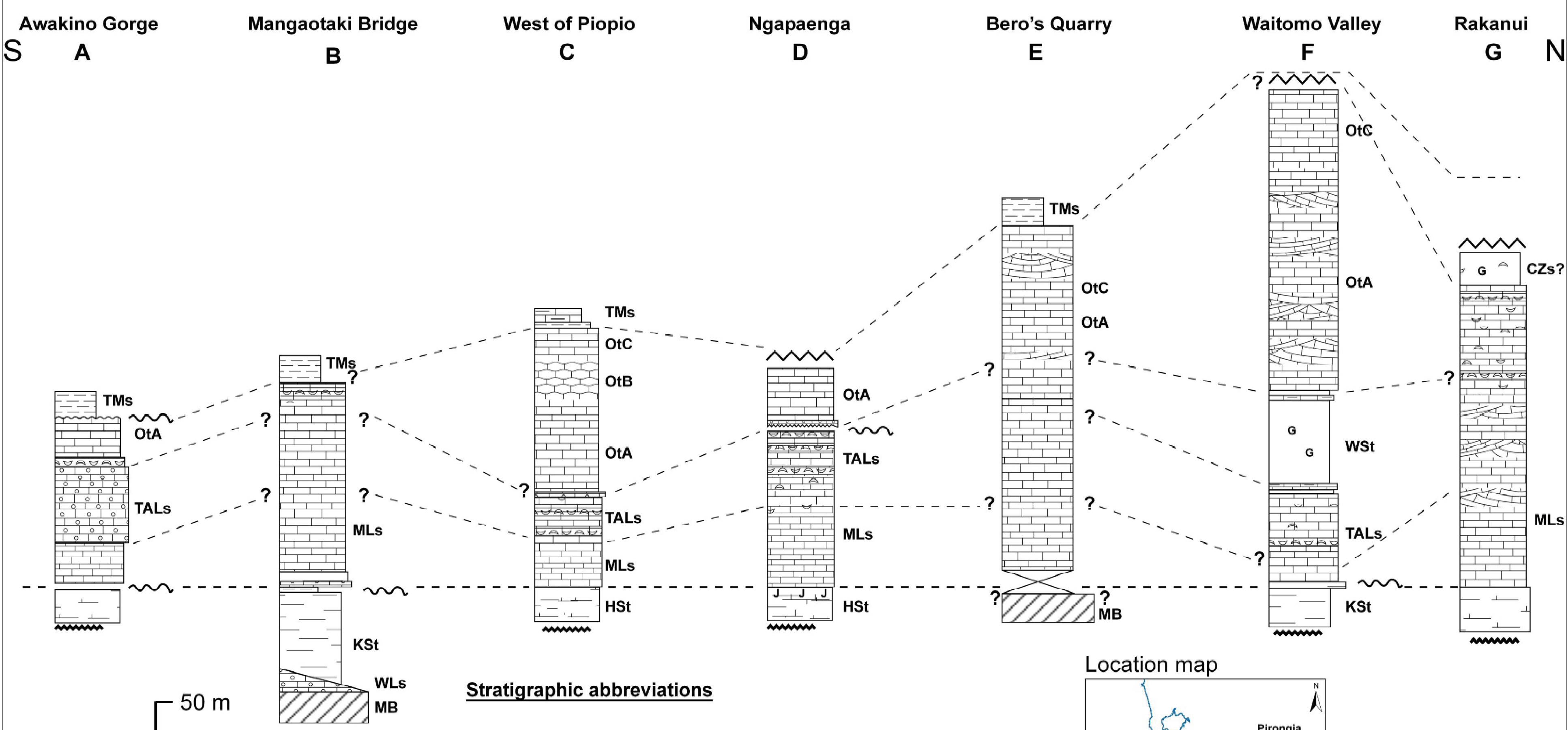
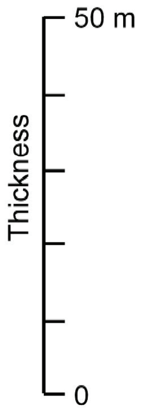


Fig. 31: Present understanding of the stratigraphic relationships between members of Orahiri Formation and Otorohanga Limestone, between Waitomo Valley Road Limestone Quarry (type locality), Rakaunui Limestone Quarry, Mangaotaki (west of Piopio), and Mangaotaki Bridge section, using the stratigraphic designations of previous workers. (See Fig. 32 for column locations). Refer to Fig. 6 for lithology symbols.

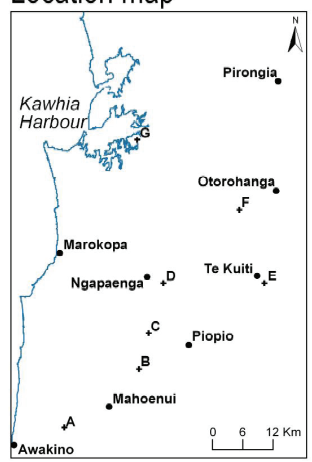




Stratigraphic abbreviations

TMs	Taumatamaire Mudstone	**Mahoenui Group**
CZs	Carter Siltstone Member	**Te Akatea Fm**
OtC **OtB** **OtA**	Piopio Limestone Waitanguru Limestone Pakeho Limestone	**Otorohanga Limestone**
TALs **MLs**	Te Anga Limestone Mangaotaki Limestone	**Orahiri Fm**
HSt **KSt** **WLs**	Hauturu Sandstone Kihi Sandstone Waimai Limestone	**Aotea Fm**
MB	Mesozoic Basement	

Location map



and west of Piopio) where there is a well-defined break between the two units, exemplified by columns C & D in Fig. 32. The absence of any apparent stratigraphic breaks within limestone occurring along the central-eastern and southwestern regions (exemplified by column E in Fig. 32), 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. 28, 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. 32). 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 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. 33). 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.

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. 34 a & 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

Fig. 32 (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. 6 for lithology symbols.*

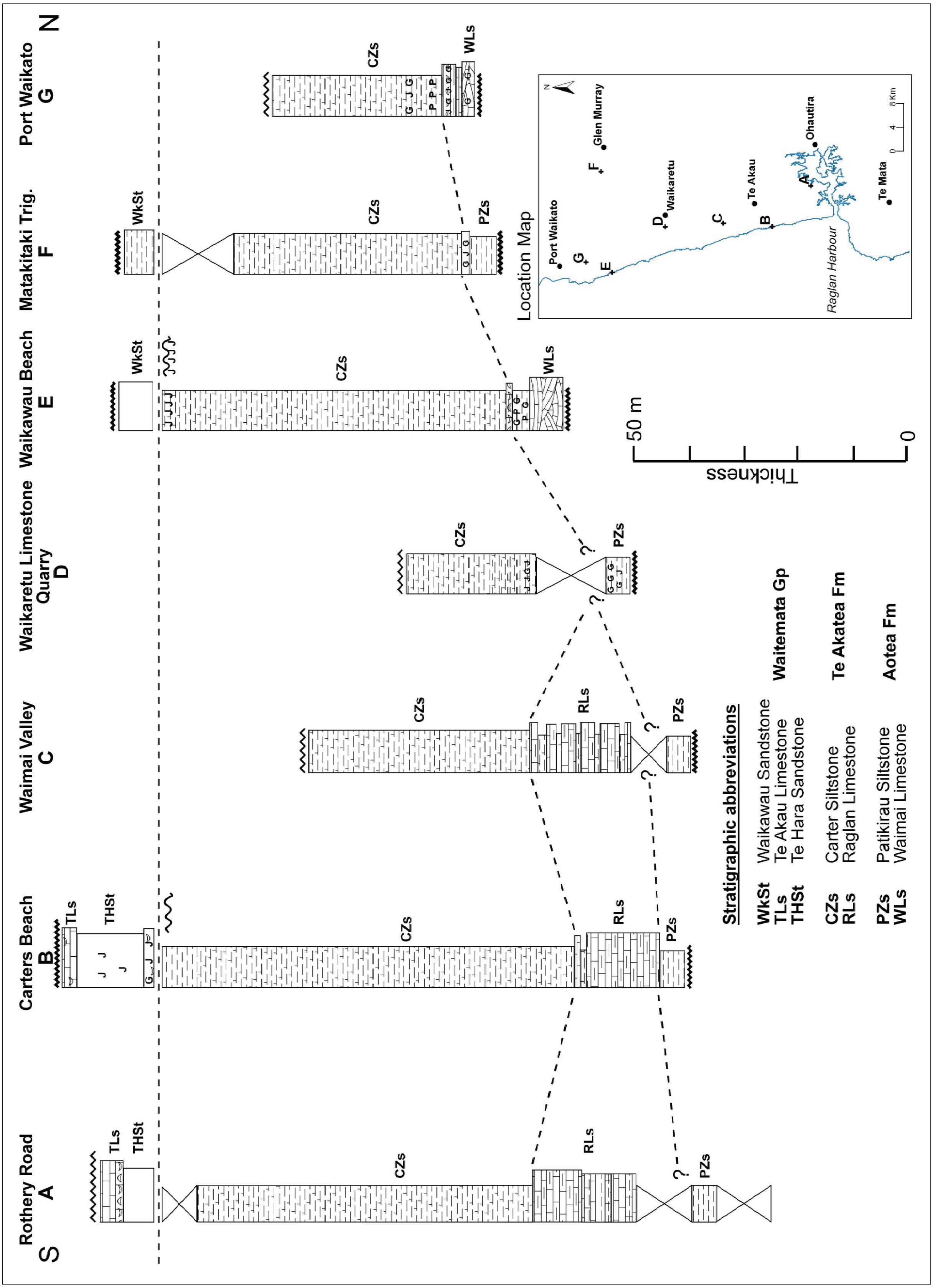


Fig. 33: Correlation of Te Akatea Formation members in selected locations from Raglan Harbour (Rothery Road, column A) to Port Waikato (column G). Datum is the top of Carter Siltstone Member. No horizontal scale is implied. Refer to Fig. 6 for lithology symbols.

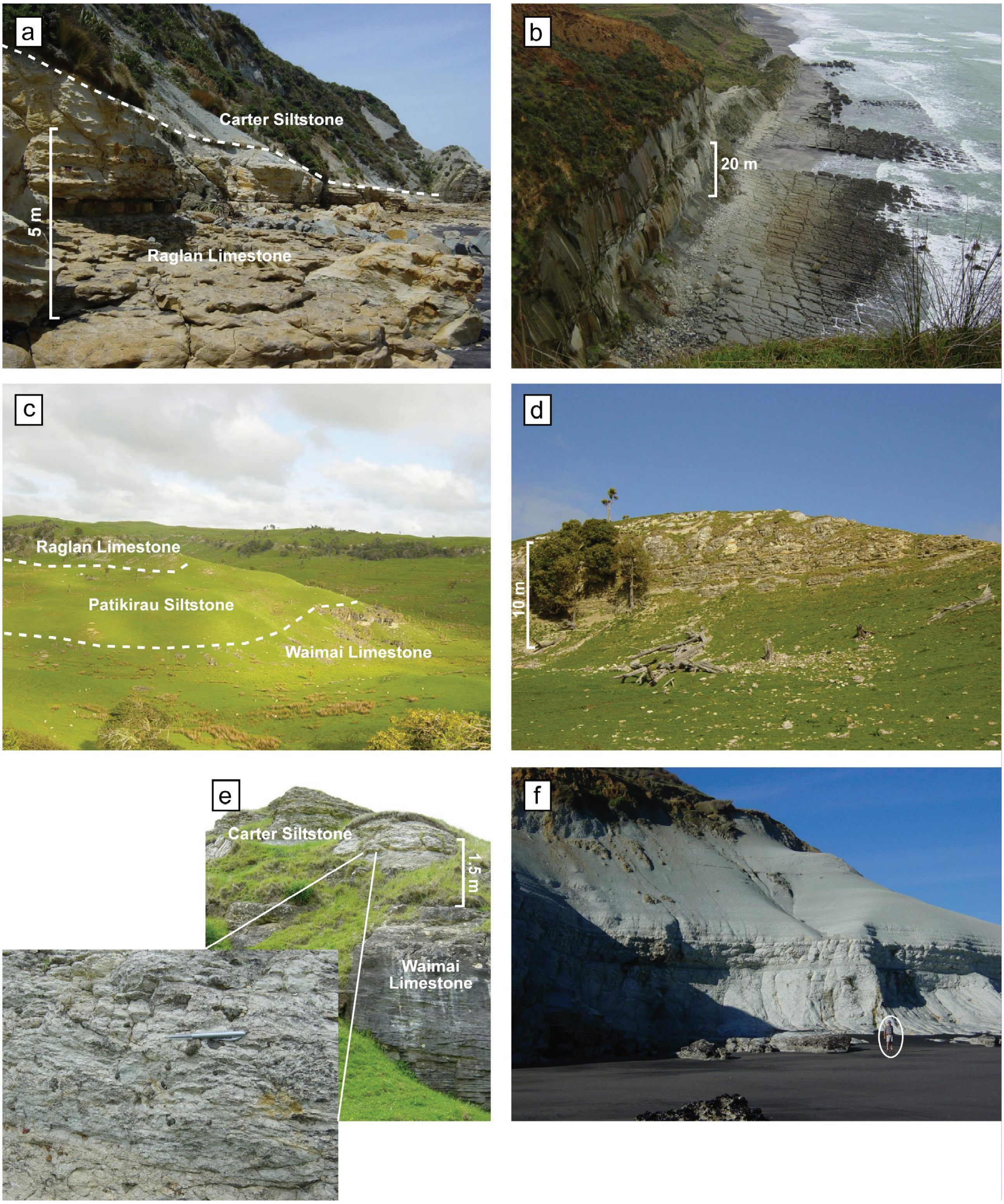


Fig. 34: Examples of Te Akatea Formation in the field. (a) View looking south from Tauterei Stream mouth, Carters Beach (TA-11, R14/707853), showing Raglan Limestone Member grading up-section into Carter Siltstone Member. (b) View looking south showing cliff of Carter Siltstone Member at Carters Beach. 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.

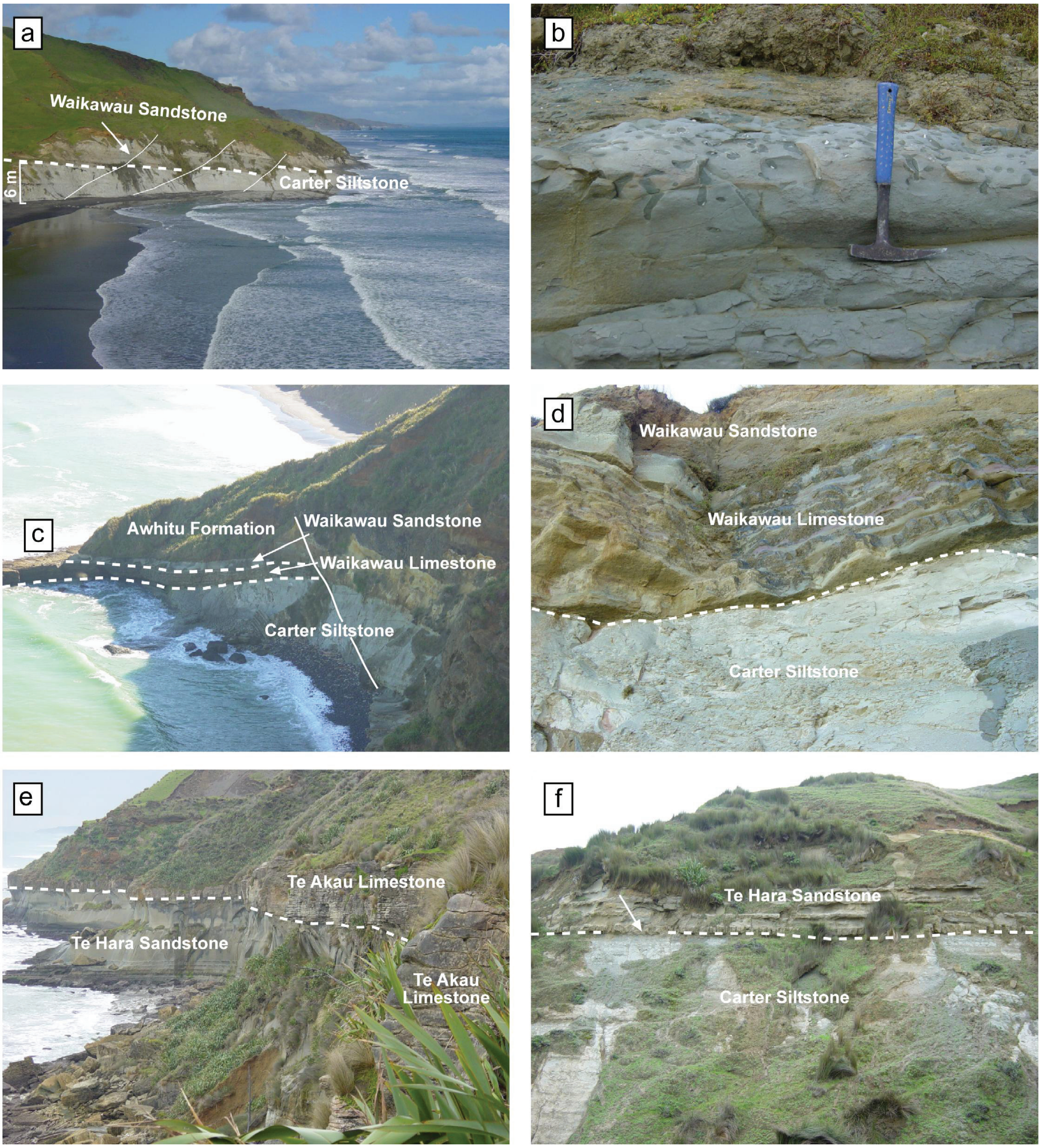


Fig. 35: *(a) View south from Waikawau Stream mouth (PW-11, R13/625138), showing sharp erosional contact between massive siltstone (Carter Siltstone) and thin-bedded Waikawau Sandstone. The base of the sandstone is the traditional Te Kuiti/Waitemata Group boundary in this section. (b) Close-up showing 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).*

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. 34 b). 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. 35 f). The Waitemata Group comprises thin horizontally bedded glauconitic fine sandstone that passes upward into massive, poorly cemented, very fine to fine sandstone beds.

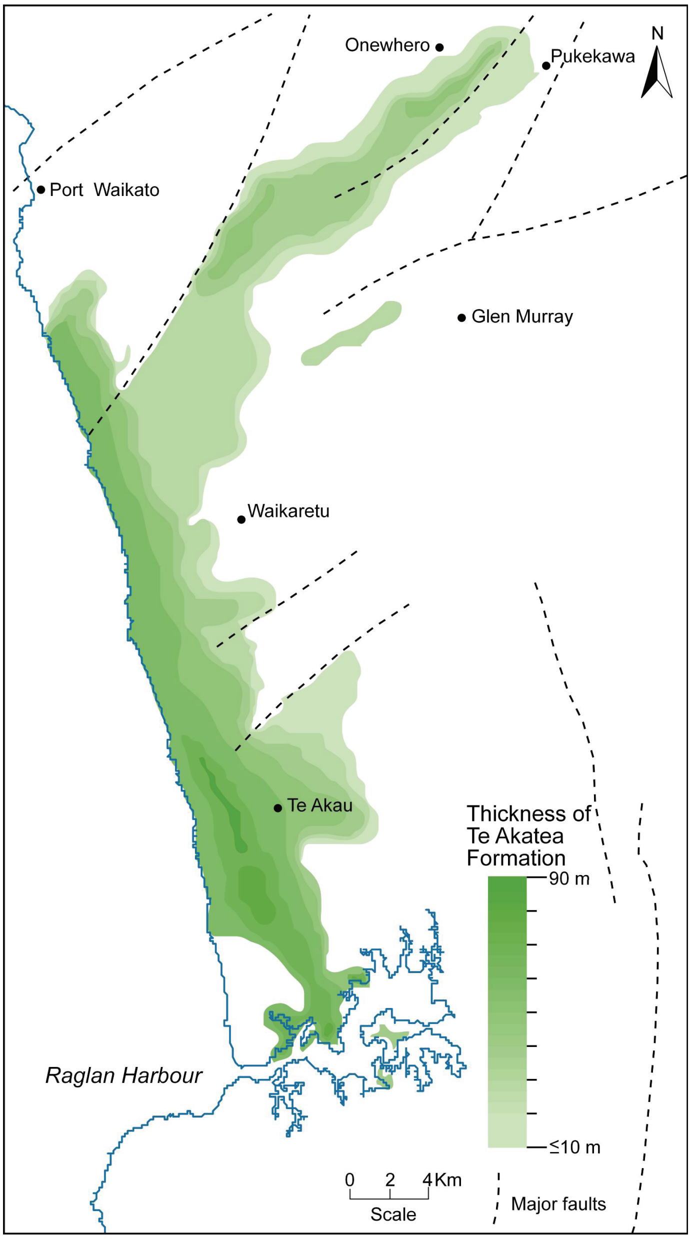


Fig. 36: Generalised distribution and thickness trends of Te Akatea Formation.

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. 36). 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. 33, 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 Formation is generally undifferentiated from underlying units.

Contacts

In the Raglan Harbour area there is an abrupt boundary between Raglan Limestone 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 (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. 34 e), 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. 34 a). 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. 34 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 35 a-d, f & 37), 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. 37, 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. 37, 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

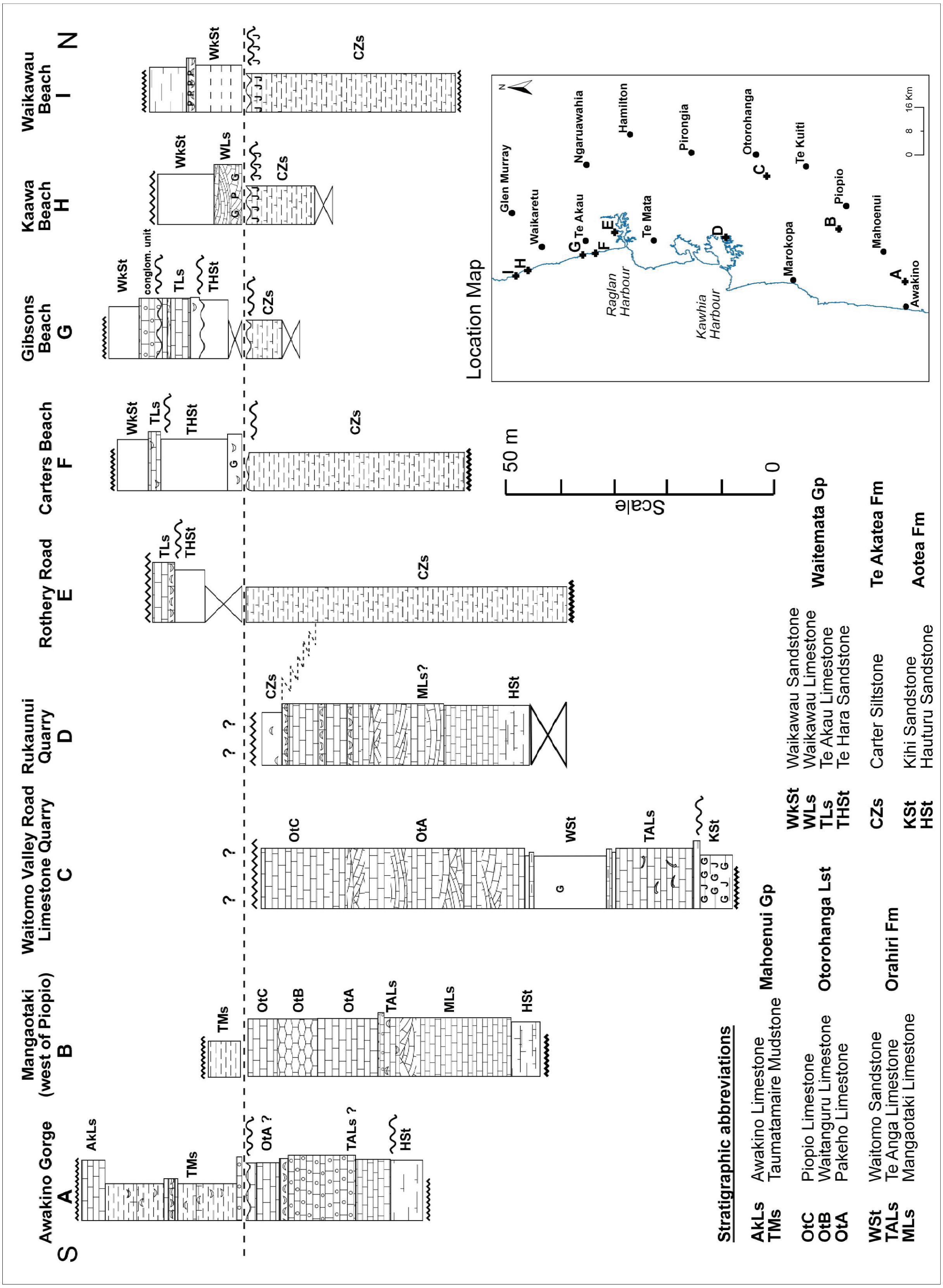


Fig. 37: Correlation of Orahiri Formation–Otorohanga Limestone/Te Akatea Formation members and their relationships to the Mahoenui and Waitemata groups in selected locations from Awakino Gorge (column A) to Port Waikato (Waikawau Beach, column I).

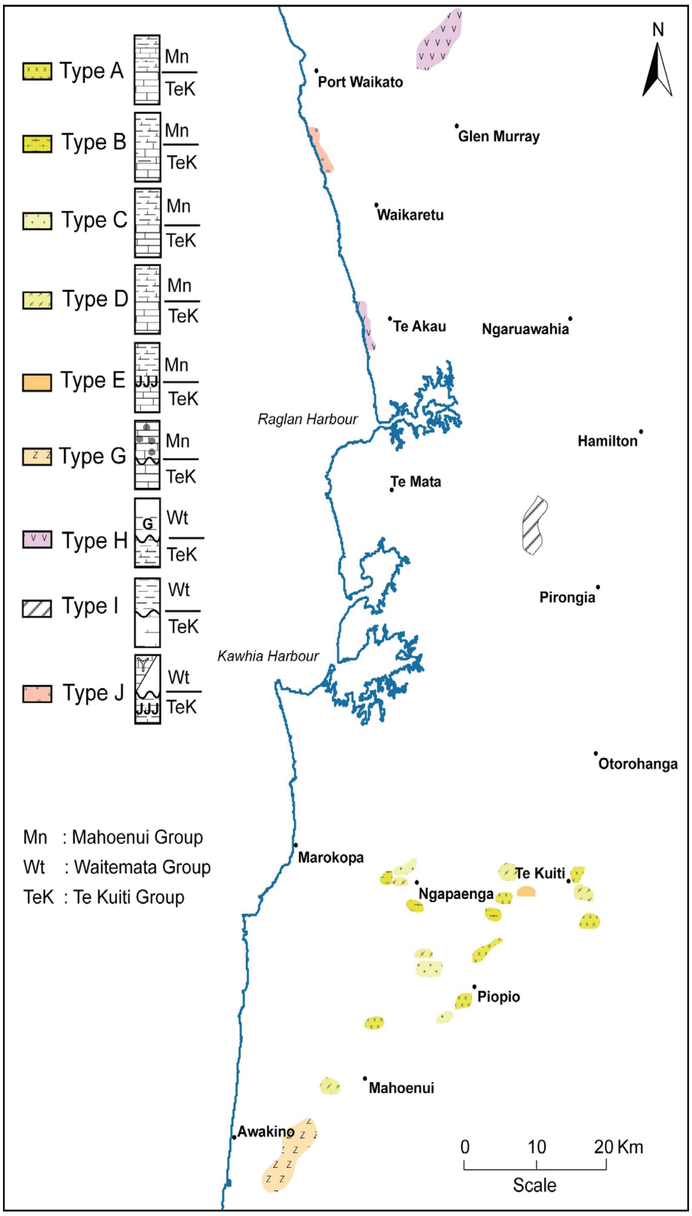


Fig. 38: *Te Kuiti Group - Mahoenui Group contact types, established by Nelson (1973), and Te Kuiti Group - Waitemata Group contact types established from outcrop observations in this investigation.*

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 is illustrated in Fig. 38. In most of the southern region, the transition from the Te Kuiti Group into the Mahoenui Group has been reported as gradational (Nelson 1978a) (Fig. 39). 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).

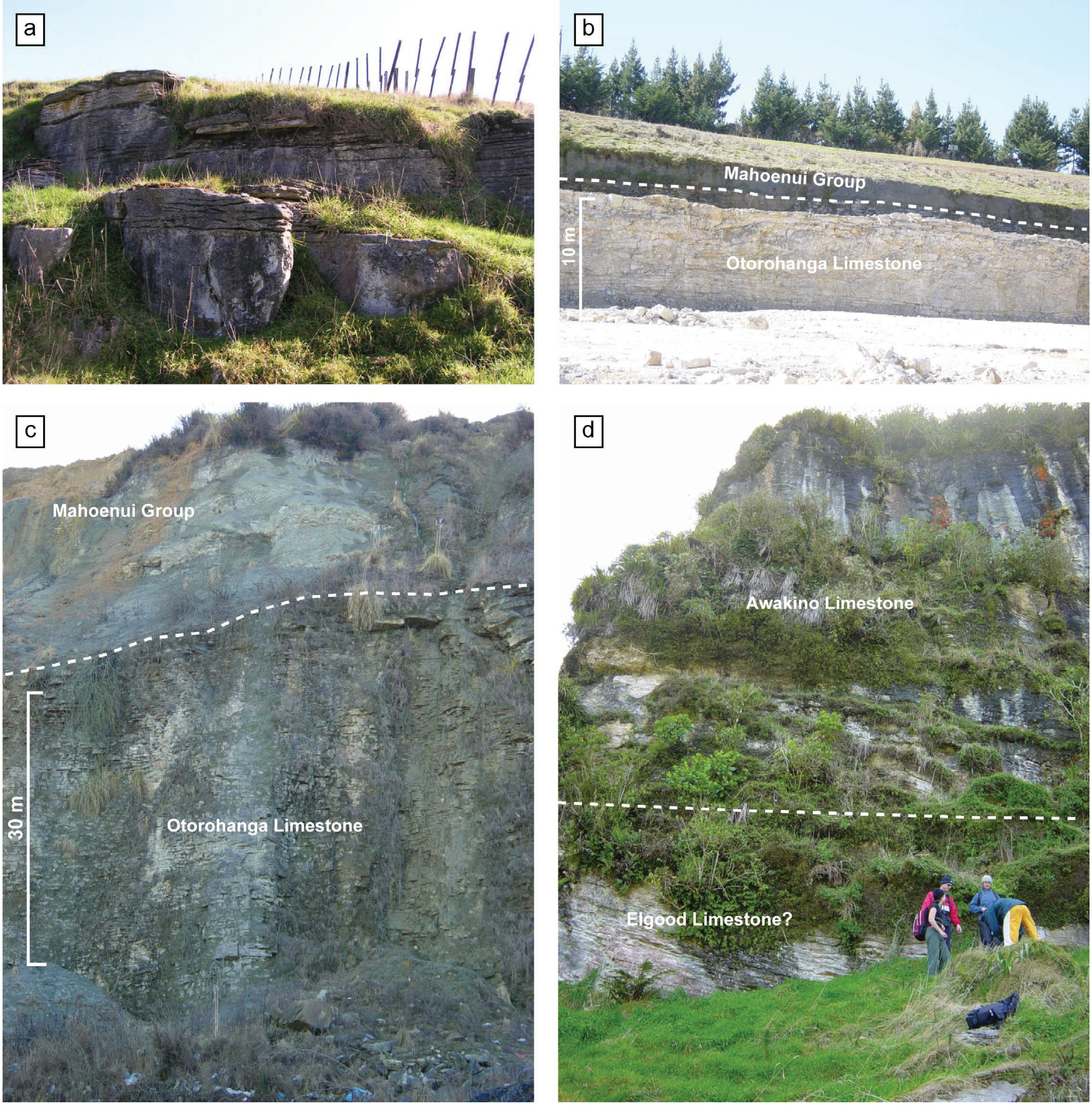


Fig. 39: *(a) Otorohanga Limestone at a quarry southwest of Piopio (C-154, R17/844005) becomes thinly flagged and argillaceous before passing upward into weathered mudstone of the Mahoenui Group (not seen in this photo). (b) Sharp contact between Otorohanga Limestone and Mahoenui Group mudstone at Oparure 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.*

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Enclosure 1: Distribution of Te Kuiti Group and location of stratigraphic columns and drill holes.