NEW ZEALAND OLIGOCENE LAND CRISIS:
INTEGRATED MICROPALEONTOLOGY OF WAIKATO COAL MEASURES AND ASSOCIATED SEDIMENTS IN CENTRAL NORTH ISLAND, NEW ZEALAND

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ABSTRACT

The topic of complete inundation of the New Zealand landmass during the Oligocene is a contentious one, with some proponents arguing the possibility that Zealandia became completely submerged during this time, and others contesting the persistence of small islands. The outcome of this debate has significant implications for the way in which modern New Zealand flora and fauna have evolved. This research project addresses the topic from a geological point of view by analysing late Oligocene–early Miocene sediments in the Benneydale region, in order to establish the timing of marine transgression in this area.

Samples from two cores drilled in the Mangapehi Coalfield were analysed for palynological and calcareous nannofossil content, and these data were used to determine the age and paleoenvironment of Waikato Coal Measures, Aotea Formation and Mahoenui Group. Additionally, data from 28 boreholes in the coalfield were utilized to construct a series of isopach maps to elucidate changes in the paleostructure through time. All data were combined to develop a series of paleogeographic maps illustrating the development of coal measures and associated sediments across the Benneydale region.

The results of this study indicate a Waitakian (late Oligocene-early Miocene) age for Waikato Coal Measures in the Benneydale region. Although this finding is consistent with the idea that Waikato Coal Measures young to the south, it appears that deposition occurred later than previously thought. Additionally, palynological data signify the persistence of a well vegetated pollen source throughout the late Oligocene–early Miocene sequence. Isopach analysis reveals the presence of paleohighs in the eastern and southern regions of the coalfield. While there is no direct evidence of land persisting in the Benneydale region, the pollen and isopach results support the hypothesis that some land remained above sea level during the Oligocene.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF PLATES

LIST OF TABLES

CHAPTER 1 - INTRODUCTION

1.1 BACKGROUND

1.1.1 The Oligocene land crisis

The Oligocene covers the period of time between 33.7 and 23.8 Ma, and along with the Paleocene and Eocene epochs constitutes the Paleogene period. Following the separation from Gondwanaland approximately 85 Ma, Zealandia began to sink below the sea and it is now widely accepted that by early Oligocene (~25 Ma) the land area had become substantially reduced. The degree to which Zealandia became submerged during the Oligocene is however, still a topic of much debate.

The two sides of this argument stem largely from the way in which the modern New Zealand flora and fauna are perceived to have evolved. The first hypothesis supports the idea that Zealandia was not entirely submerged during the Oligocene, but instead there were pockets of land that remained above the ocean, providing island refugia in which terrestrial biota persevered (Tennyson et al., 2010; Worthy et al., 2006). This upholds the long-standing belief that a significant proportion of the present day flora and fauna has evolved from biota that were present around 85 million years ago, when Zealandia separated from Gondwanaland.

The competing hypothesis argues the possibility that by or during the Oligocene, Zealandia had become entirely submerged (Campbell & Landis, 2001; Landis et al., 2008; Trewick et al., 2007). Under this hypothesis, New Zealand rose from the sea during the early Miocene (Trewick et al., 2007) and all native flora and fauna have appeared and evolved since that time (Landis et al., 2008). This could help to explain why today the diversity of animals in New Zealand is perhaps not as great as might be expected. It is believed that when Zealandia split from Gondwana, a whole raft of terrestrial animals where carried along with it. Somewhere along the way, these animals disappeared from Zealandia, and consequently New Zealand. The idea of complete submergence could offer an explanation for how this occurred (Campbell & Landis, 2001).

1.1.2 Importance of Coal Measures and their associated sediments

One of the ways in which the submergence debate can be addressed is to look at the coal measures that were deposited during the Oligocene, and the sediments that are associated with them. Coal is an organic sedimentary rock derived from the remains of degraded plant material. As such, we can infer that in areas where coal occurs, a landmass must have been present at the time of deposition in order to support the vegetation that would later constitute the debris needed for peat formation. By studying the fossil pollens of these coal and associated deposits we can attribute an age to their initial deposition, and by association approximate a time when land was present in the area. In addition, we can examine the sediments directly above the coal measures to build up a bigger picture of the timing of events and changes in paleoenvironment through time.

1.2 PURPOSE AND SCOPE OF STUDY

This research project focuses on the analysis of late Eocene–early/mid Miocene sediments (Figure 1.1) located in the Benneydale region (Figure 1.2) of the central North Island, in particular, Waikato Coal Measures and the shallow marine sediments associated with them. The objective of the project is to establish the age of the coal measures and determine the nature of the overlying and underlying units, including paleoenvironment and age.

An integrated approach was used in this project to increase the biostratigraphic resolution of the stratigraphic sequences. Samples were analysed for calcareous nannofossil and palynological content, and these data were combined to determine age and paleoenvironment. Additionally, data from drillholes in the Mangapehi Coalfield were used to create a series of isopach maps, which were used to reconstruct the paleostructure of the region. All available data have been collated and used to construct a series of paleogeographic maps illustrating the development of coal measures and associated sediments across the Benneydale region of the central North Island.

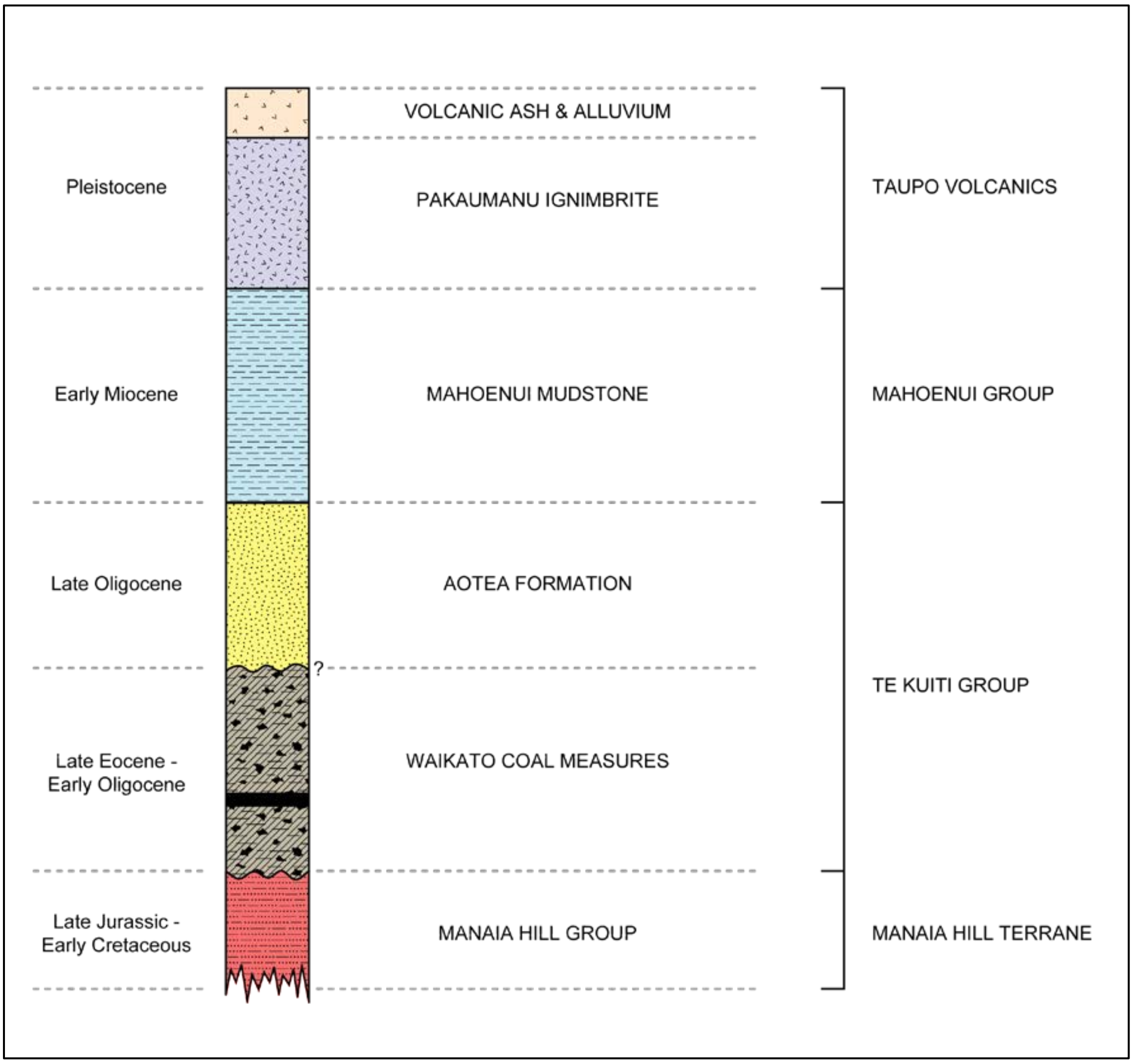

Figure 1.1: Simplified diagram showing the stratigraphic relationships of the major lithological units focused on in this study. Age ranges are given for units across the Waikato region, taken from Edbrooke et al., 2005.

1.3 PREVIOUS WORK

1.3.1 Geology and mining - Mangapehi Coalfield

Early work in the Mangapehi Coalfield (Figure 1.2) was carried out by Gage (1942), who provided a summary of the general geology and structure of the Mangapehi area. In an unpublished coal report in 1940, Gage proposed a number of sites that would be suitable for surface holes and many of these were subsequently drilled in the 1940's and 1950's (Gage, 1940).

Several unpublished reports by Fyfe (1942, 1943, 1944) followed the work undertaken by Gage. The first two reports provide details of five boreholes drilled in the Mangapehi Coalfield, subsequently re-numbered as 5521 to 5525. No coal was observed in any of these holes, suggesting at the time that there was no workable coal to the west of the Mangapehi mine. However, Fyfe acknowledged that hole 5 did not reach the greywacke basement, and therefore may not have been drilled deep enough to encounter the coal seam (Fyfe, 1942, 1943). Four bores were also drilled from underground in the Mangapehi Mine (Figure 1.3), and these are discussed by Fyfe (1944) along with details of faulting encountered at this location.

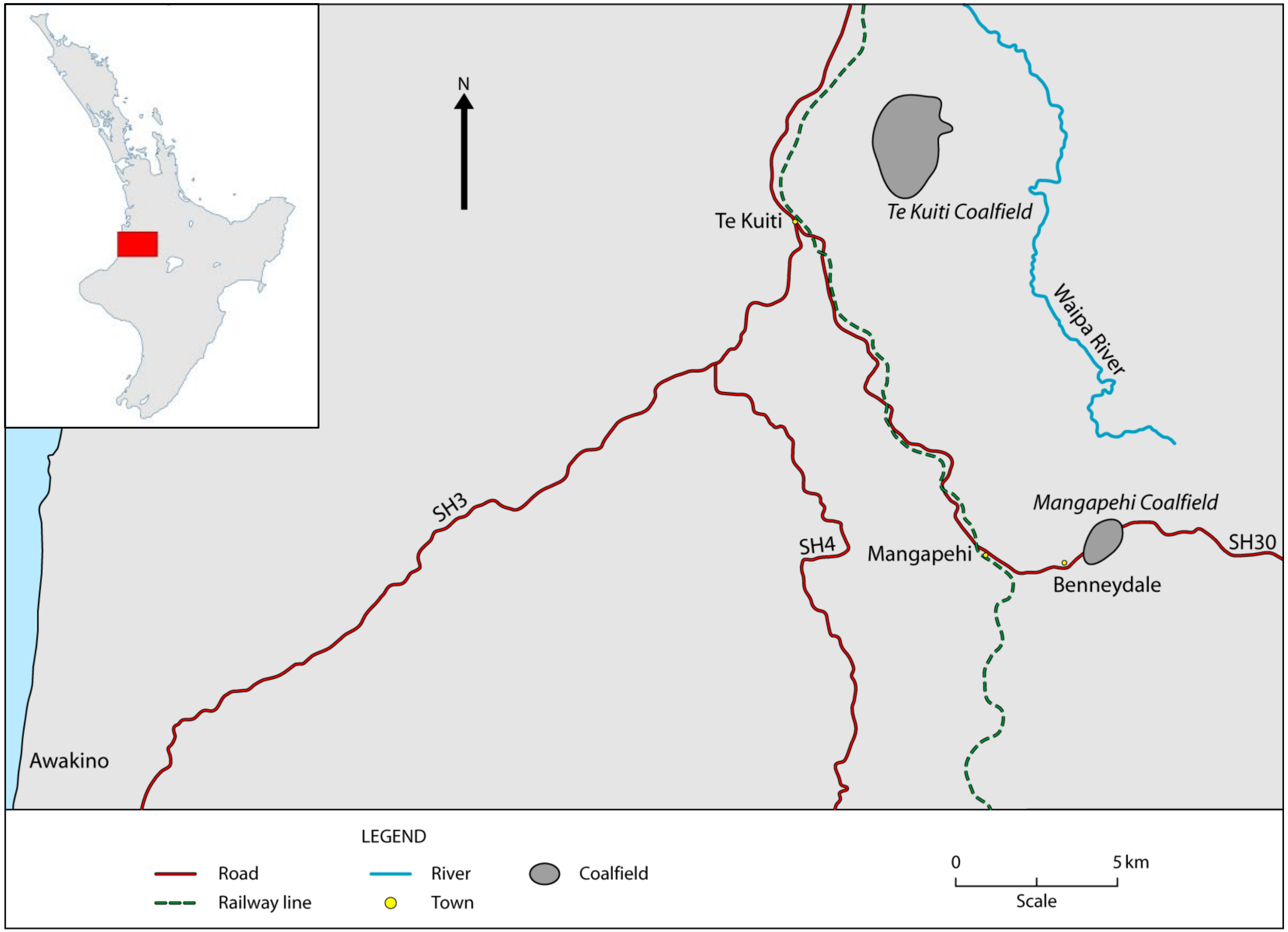

Figure 1.2: Map showing the location of Benneydale and the Mangapehi Coalfield, North Island, New Zealand. Inset map shows the location and size of the area presented in the enlarged map.

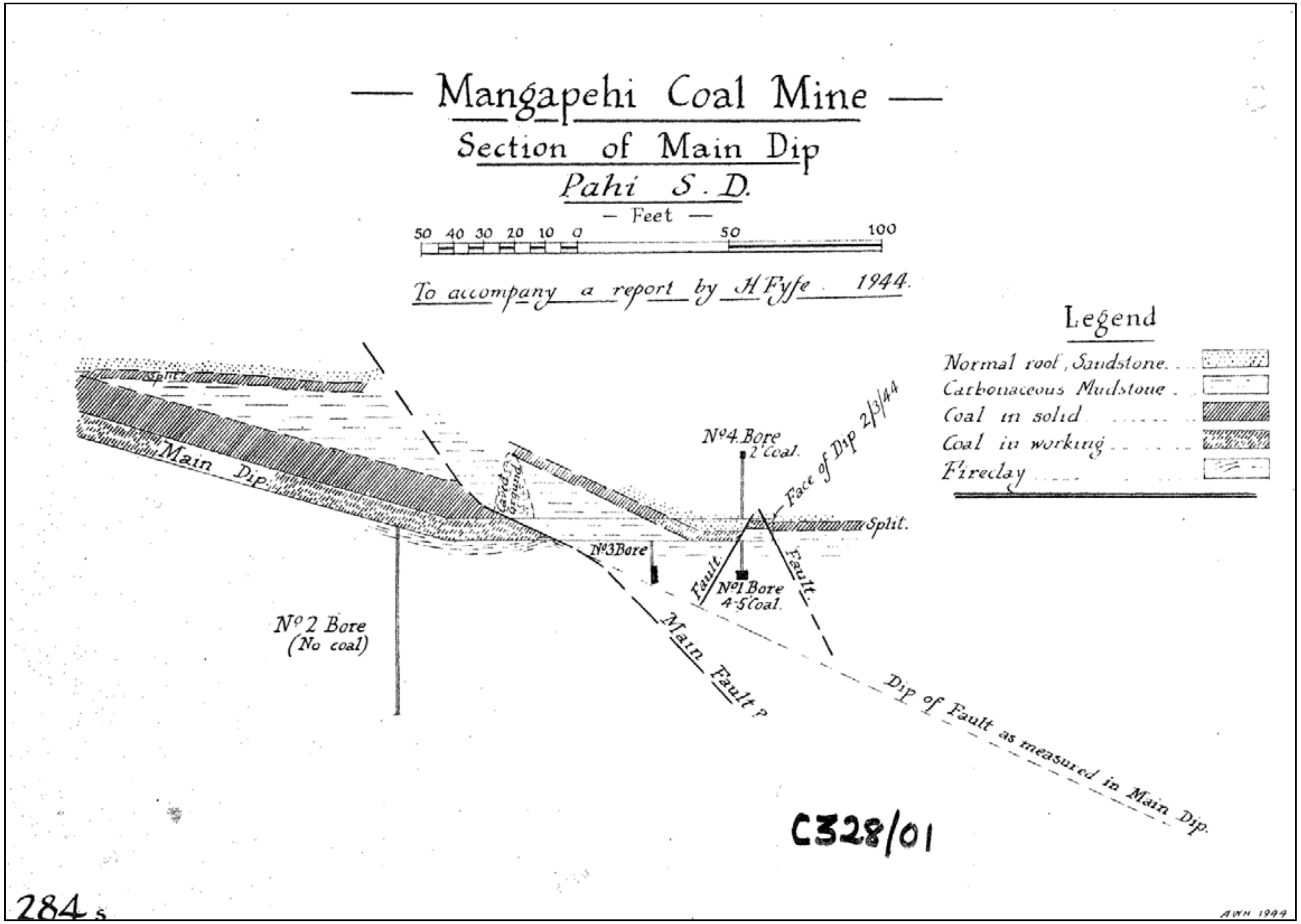

Figure 1.3: Diagram showing the location of four bores drilled underground at the Mangapehi Coal Mine (Fyfe, 1944).

A general description of the geology of the Mangapehi Coalfield is included in the bulletin on the geology of the Te Kuiti Subdivision (Marwick, 1946). This bulletin also provides brief details of mining history to that date, along with discussion of coal analysis carried out on eight samples collected in 1933 and 1936. A point of interest in this bulletin was the discussion on the original age ascribed to the coal seam in the Mangapehi region. Fauna from a shell-bed closely associated with the coal seam led to the inclusion of the coal bed in the Mokau Series (Marwick, 1946). Later work by Finlay on foraminifera identified in glauconitic sandstone overlying the coal seam, collected by Gage (1942) from the eastern boundary of the Mangapehi coal mine, provided a Duntroonian age (late Oligocene). This led to the conclusion that the coal must therefore lie below beds of the Te Kuiti Series, in the Whaingaroa Series, as defined by Marwick (1946)[1].

In the early 1950's Kear produced two unpublished reports on various aspects of the geology of the Mangapehi coalfield. The first report provides a summary of the general geology of the coalfield, along with a detailed description of the ignimbrite deposits blanketing the region and their suitability as mine stowage material (Kear, 1950). Kear's later report in 1954 provides analyses of samples taken from the Mangapehi Mine, as well as notes on the general stratigraphy (Kear, 1954).

A further report was written by Kear in 1959, relating the state of the drilling programme in Mangapehi Mine at that time. This report provides an updated summary of the stratigraphy in the coalfield, incorporating data retrieved from drillholes completed after 1957. A sketch map is also included in the report showing the location of drillholes, coal thickness in each drillhole, possible sites for future drillholes, the limits of workable coal, and updates the location of the Benneydale fault (Kear, 1959b).

[1] Te Kuiti Series referred to marine limestone and glauconitic sandstone of Waitakian–Duntroonian age (late Oligocene). Coal measures were included in the Whaingaroa Series, below the Te Kuiti Series (Marwick, 1946).

Several other works have built on the early contributions of Gage, Fyfe, Marwick, and Kear. An assessment of the geology and coal resources, including quality and quantity of the Mangapehi Coalfield, was presented by Schofield (1974) in an unpublished NZ Geological Survey Report. This report also provides a history of mining undertaken in the coalfield up until that time. The Tertiary geology of the coalfield was recounted by Armstrong (1987), giving a detailed description of coal measure sediments and discussion of possible paleoenvironments. Stratigraphic columns are also presented for 18 holes drilled in the Mangapehi Coalfield from 1940 to 1960.

In 1989 and 1990 two reports were prepared by Edbrooke on behalf of Pike River Coal Company (NZ Oil & Gas), which held coal prospecting licences between 1987 and 1995 over the northern section of the coalfield (Fowke, 1997). The first of these reports presents a summary of the geography, history, geology, and coal quality of the Mangapehi Coalfield. It also provides recommendations for future prospecting locations, along with a number of isopach and structure contour maps (Edbrooke, 1989). Edbrooke's later report also summarises coalfield stratigraphy, and includes a generalised stratigraphic column for the area (Figure 1.4). Results of prospecting in the Coal Prospecting Licence (CPL) areas are also presented and recommendations for future drilling are given (Edbrooke, 1990).

Edbrooke, Sykes & Pocknall (1994) compiled a detailed monograph on the Waikato Coal Region. This report includes work by previous authors on the geology and mining history, and also discusses aspects of palaeobotany, coal petrology, and depositional environments. Two points of interest made in this monograph are that coal in the Mangapehi Coalfield is younger than that in coalfields of North Waikato, but still forms part of the Waikato Coal Measures, and the seam found in the Mangapehi Coalfield is named as Mangapehi Seam.

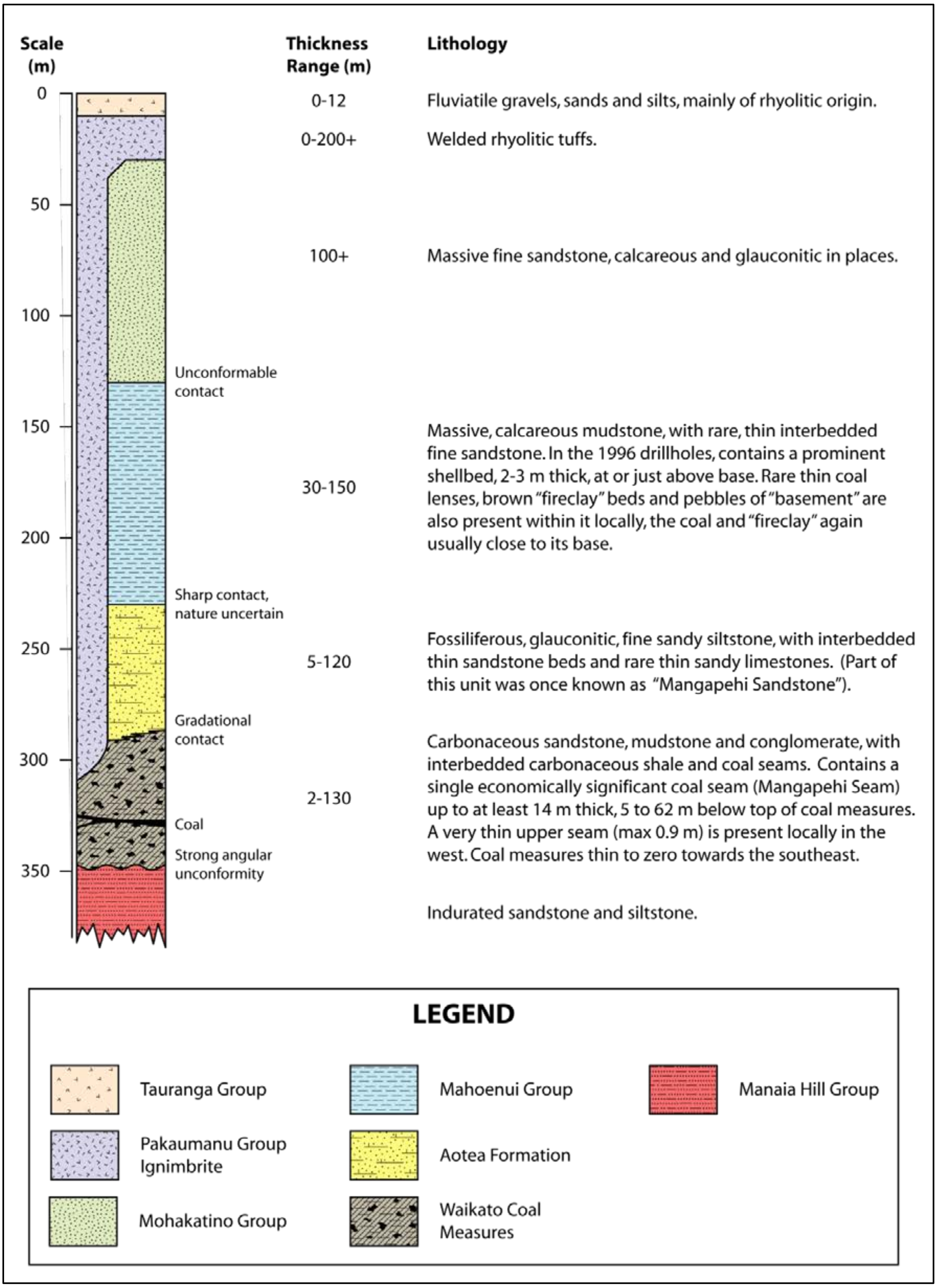

Figure 1.4: Stratigraphic column for the Mangapehi Coalfield area. This diagram was based on the original column presented by Edbrooke (1990), and modified by Fowke (1997) to include results from the 1996 drillholes, such as increases to maximum known thicknesses. (Figure redrawn from Fowke, 1997).

A number of reports were written by Fowke in the mid- to late 1990's. The first of these provides a brief mining history of the Mangapehi and Benneydale mines, and summarises coal quality within Mangapehi Coalfield (Fowke, 1995). Fowke's second report (1996) presents a pictorial history of mining in the coalfield, and includes maps and plans of the two mines, along with technical plans for methods of extraction and stowage. The final report produced by Fowke (1997) gives a comprehensive geological assessment of Mangapehi Coalfield. In addition to presenting the results of a five hole drilling programme undertaken in 1996, the report also discusses the geology and mining history of the area, provides coal estimates, and gives recommendations for a further ten drillhole locations. A number of maps supplement this report including the geography and surface geology of the coalfield, and isopachs of Waikato Coal Measures and Mangapehi Seam.

A technical report was prepared by Bateman (2006), providing a summary of work carried out under Prospecting Permit 39 275 in the Mangapehi Coalfield. This report also contains updated copies of the maps produced by Fowke (1997), along with additional maps incorporating data from the GNS QMAP project.

1.3.2 Palynology of Waikato Coal Measures

The earliest palynological work on the Waikato Coal Measures (Couper, 1953) ascribes sub-Whaingaroan ages (Figure 1.5) to samples obtained from Maramarua State Forest and Pukemiro Colliery in the Rotowaro Coalfield (Table 1.1). An account of Drury Coalfield (Kear, 1959a), included a palynological analysis of Waikato Coal Measures by Couper and MacIntyre. They found that samples collected from different areas of the coalfield varied slightly in age from upper Arnold (late Eocene) to Landon (Oligocene), and attributed this variation to the irregular topography that was present pre-coal measure deposition. Kear and Schofield (1959) reported ages for the Waikato Coal Measures ranging from lower Arnold (mid Eocene) to Whaingaroan (late Eocene – late Oligocene).

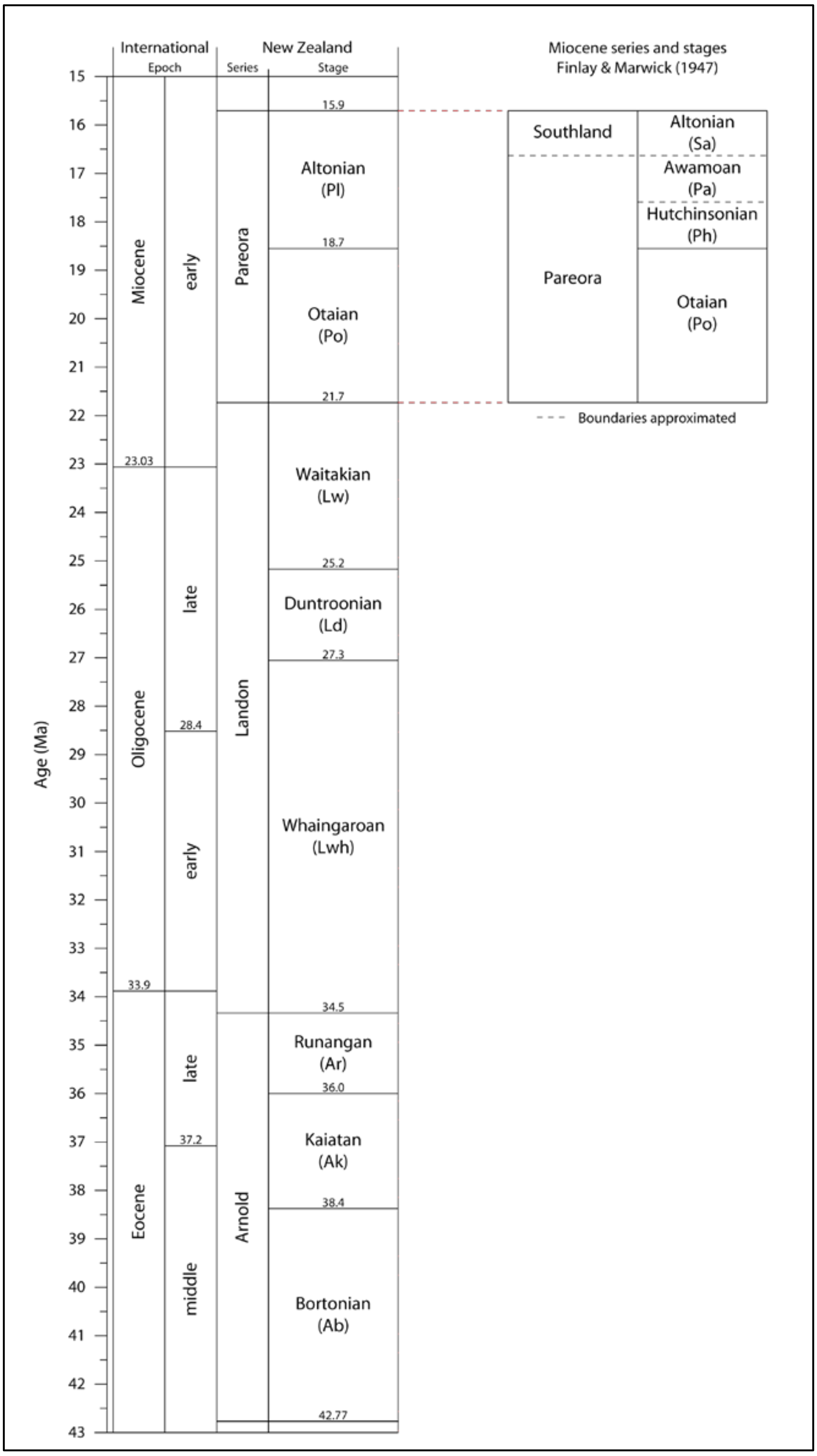

Figure 1.5: Geological timescale showing international epochs and New Zealand stages and series. Diagram to the right of the timescale illustrates the approximate position of the now obsolete Hutchinsonian and Awamoan stages.

Couper (1960) published ages for Rotowaro, Huntly and Whatawhata Coal Measures. These names were subsequently abandoned by Kear and Schofield (1964), and instead the terms Lower Waikato Coal Measures (=Rotowaro Coal Measures) and Upper Waikato Coal Measures (=Huntly and Whatawhata Coal Measures) were used. Couper (1960) assigned a Bortonian to Kaiatan (mid- to late Eocene) age to Rotowaro Coal Measures based on comparisons with floras from Arnold sequences found elsewhere (e.g. Middle Waipara Section, Beaumont Coal Measures, Quartzose Coal Measures of Westland and Nelson). A Runangan (late Eocene) age was ascribed to Huntly Coal Measures, based on their similarity to the Beaumont Coal Measures *Nothofagus matauraensis* zone of Couper (1960). The flora of Whatawhata Coal Measures was indistinguishable from that of Huntly Coal Measures and consequently a Runangan age was also assigned to this unit (Couper, 1960).

Later studies focused on the distinction between Lower and Upper Waikato Coal Measures, as previously defined by Kear and Schofield (1964). Palynological analysis of samples collected from locations within the Ngaruawahia Subdivision was carried out by Couper, providing a Bortonian–Kaiatan age for the lower Waikato Coal Measures and a Runungan age for the upper Waikato Coal Measures (Kear & Schofield, 1978). Fowke & Raine (1984) identified an occurrence of Lower Coal Measures in the northeast of the Huntly Coalfield, which show a similar microfloral assemblage to that seen in the Lower Waikato Coal Measures of Rotowaro (Couper, 1960). A slightly younger Kaiatan age was given by Fowke & Raine (1984), than the Bortonian age previously assigned by Couper (1960).

In a study by Pocknall (1985), samples taken from Waikato Coal Measures at three locations in the Raglan area (Wharauroa Plateau, Te-Mata-Kawhia road, and Karamu District), showed assemblages consistent with the late Oligocene Upper *Nothofagidites matauraensis* zone of Pocknall & Mildenhall (1984). Re-examination of collections from Old Mountain Road, Raglan (Pocknall, 1985), indicate an early Oligocene age consistent with the Lower *Nothofagidites matauraensis* zone of Pocknall & Mildenhall (1984). This difference in age between northern and southern locations within the Raglan area suggests that the coal measures young in a southwesterly direction (Pocknall, 1985).

Additionally, Pocknall (1985) compared the assemblages described from the Wharauroa Plateau, Te-Mata-Kawhia road, and Karamu District with those found in the Waikato Coal Measures at Mangapehi. Previous age estimations of coal measures to the west of Mangapehi were given as late Eocene–early Miocene, possibly Whaingaroan, however, there were few stratigraphically useful taxa present to make accurate determinations (Nelson, 1973, 1978). Re-examination of Mangapehi assemblages by Pocknall (1985) found that palynofloras from the Raglan and Mangapehi regions were very similar, leading to the assertion that coal measures in the Mangapehi Coalfield are also of Oligocene age, and most likely late Oligocene.

A detailed account of the palynostratigraphy of the Te Kuiti Group in the Waikato Basin was provided by Pocknall (1991). Four biozones covering late Eocene–Oligocene, were proposed by Pocknall for the Te Kuiti Group. The biozones are based on changes in palynofloras identified in a composite section from Rotowaro and Huntly. These data were later utilised in the monograph of the Geology of the Waikato Coal Measures (Edbrooke et al., 1994), to assist with age correlation within and between the coalfields of the Waikato region (Figure 1.6).

Table 1.1: Summary of ages determined for Waikato Coal Measures by previous studies.

Author	Locality	Stratigraphic Unit	Inferred Age
Couper (1953)	Maramarua State Forest & Pukemiro Colliery	Waikato Coal Measures	Sub–Whaingaroan
Kear (1959)	Drury Coalfield	Waikato Coal Measures	Upper Arnold to Landon
Kear & Schofield (1959)	Papakura to Piriaka	Waikato Coal Measures	Lower Arnold to Whaingaroan
Couper (1960)		lower Waikato Coal Measures	Bortonian to Kaiatan
		upper Waikato Coal Measures	Runangan
Nelson (1973), (1978)	west of Mangapehi	Waikato Coal Measures	late Eocene–early Miocene, possibly Whaingaroan
Kear & Schofield (1978)	Ngaruawahia Subdivision	lower Waikato Coal Measures	Bortonina to Kaiatan
		upper Waikato Coal Measures	Runangan
Fowke & Raine (1984)	Huntly Coalfield	lower Waikato Coal Measures	Kaiatan
Pocknall (1985)	Raglan	Waikato Coal Measures	early Oligocene to late Oligocene
	Mangapehi	Waikato Coal Measures	late Oligocene

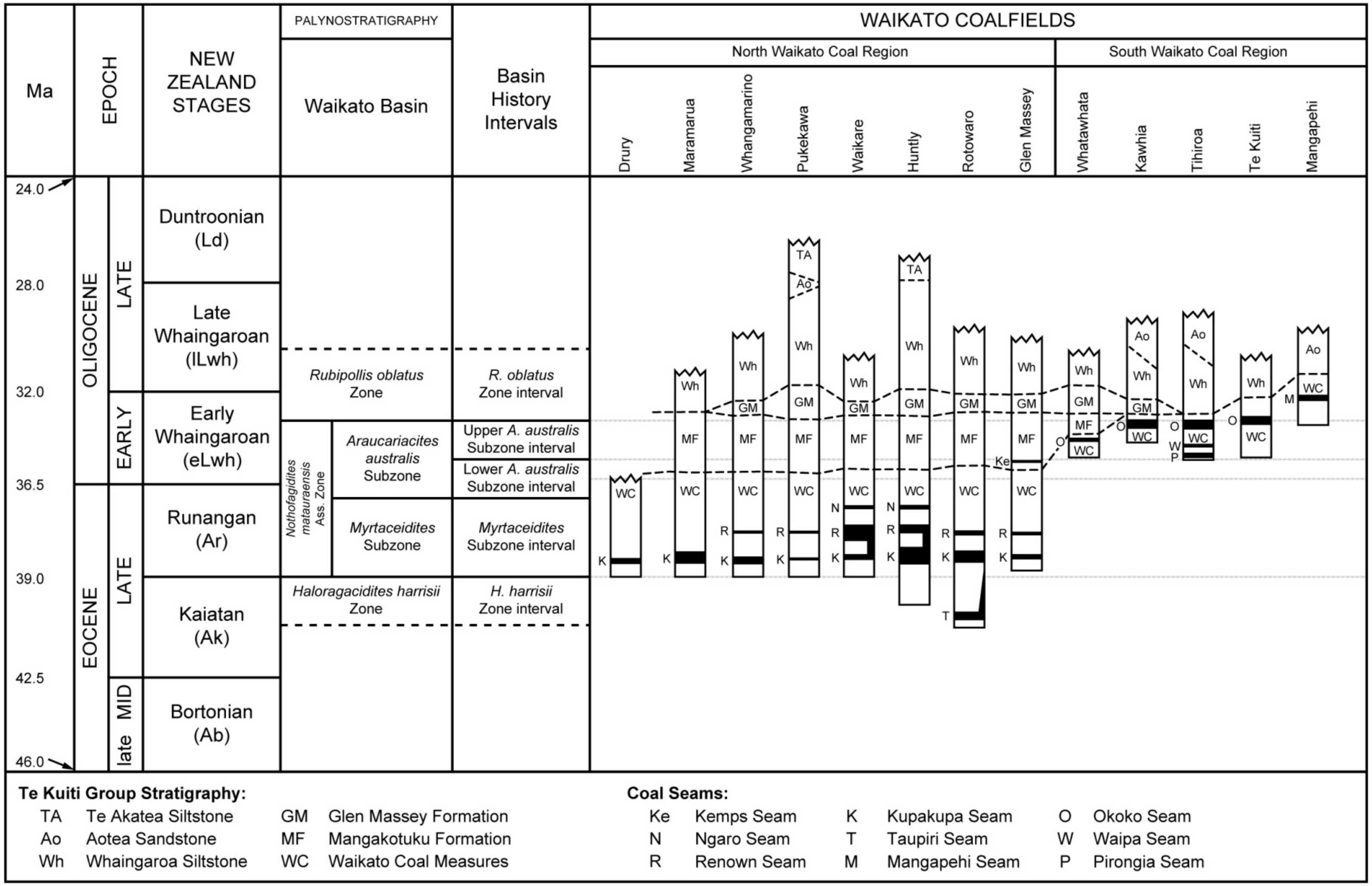

Figure 1.6: Diagram illustrating the four biozones proposed by Pocknall (1991) for the Waikato Basin, and their application in correlating stratigraphic sections across the Waikato Coal Region (Figure redrawn from Edbrooke, et al., 1994).

1.3.3 *Paleontology of shallow marine sediments associated with the Waikato Coal Measures in the Mangapehi Region*

The shallow marine sediments overlying Waikato Coal Measures in the Mangapehi region were described in detail by Gage (1942). Ages were given for the sandstone and mudstone units overlying the basal unit of the Te Kuiti Group, based on molluscan and foraminiferal assemblages. Mollusca from within the massive glauconitic sandstone overlying the basal member of the Te Kuiti were too poor for precise determination, but generally indicated a Waitakian (late Oligocene–early Miocene) or lower Altonian[2] (early Miocene) age. However, foraminifera within the sandstone unit provided strong evidence for a Duntroonian (late Oligocene) age. Sandy mudstone overlying the lower glauconotic sandstone also contained foraminifera, and these provided a Waitakian age for the basal portion of the mudstone unit. The faunal assemblage of the upper portion of the sandy mudstone suggests a similarity with both Waitakian and lower Altonian stages. Faunal assemblages for the Mahoenui Group overlying the Te Kuiti Group sediments were unable to be obtained from the samples collected. The lower Altonian age given by Gage is derived from lithological correlation of strata with Mahoenui beds in the adjoining Ohura-Tongaporutu Subdivision.

An estimated age for glauconitic sandstone was given by Finlay for samples obtained from the Mapara Survey District, on the eastern boundary of the Mangapehi coal mine. The faunal assemblage was suggestive of a Duntroonian age, and quite close to Whaingaroan (late Eocene–late Oligocene). However, species of *Guttulina*, *Notorotalia* and *Gyroidina*, allow a distinction between the two stages (Marwick, 1946). This glauconitic sandstone was later identified by Nelson (1973) as Aotea Sandstone. Details of foraminiferal assemblages of the overlying Mahoenui Formation are also given in Marwick (1946). Although no samples were collected from the Mangapehi region, analysis of material collected from the Tortoro Survey District, to the west of Mangapehi, show a lower Altonian assemblage.

[2] Note that Gage (1942) refers to the now obsolete Hutchinsonian Stage, refer to Figure 1.5.

The graded sediments of the Mahoenui Formation in the King Country were discussed by Glennie (1959). Foraminifera in the graded beds were rare but provided an age range from Waitakian to Otaian (late Oligocene to early Miocene), and possibly lower Altonian. Dating on the massive mudstones of the Mahoenui Formation proved to be more accurate and an age range from Upper Waitakian to Otaian was given over most of the basin, with lower Altonian faunas being recognized in the north.

Nelson (1973, 1978) provided a detailed study of the stratigraphy and paleontology of the Te Kuiti Group in Waitomo County. As previously mentioned, analysis of material from the Mangapehi coalfield (Marwick, 1946) was incorporated into the section on Aotea Sandstone. Based on foraminiferal analyses, Nelson (1973, 1978) provided an age range for Aotea Sandstone in Waitomo County from lower/middle Whaingaroan to Duntroonian. A similar age was suggested by Armstrong (1987) for Aotea Sandstone in the Mangapehi Coalfield. In a sample collected at this locality, a foraminiferal specimen was identified as *Notorotalia,* possibly *N. stachei*, which is known to occur in the Whaingaroan (Morgans et al., 2004).

The foraminifera of the Mahoenui Group were extensively studied by Topping (1978) who examined assemblages to the west and south of the Benneydale region, as well as from a site located near the Benneydale township. The results of his study provided a broad age range for the Mahoenui Group from Waitakian to Otaian. Samples taken closest to the Mangapehi coalfield (location 16 on Figure 1.7) inferred an Otaian age.

1.3.4 The Fossil Record Electronic Database (FRED)

Investigation of the Fossil Record Electronic Database (GNS Science, 2009) shows a number of samples have been collected in the Mangapehi/Benneydale area. Many of these pertain to the studies discussed in the previous sections. The locations of samples that have relevance to this study are shown in Figure 1.7 and a summary of the samples is presented in Appendix 1.

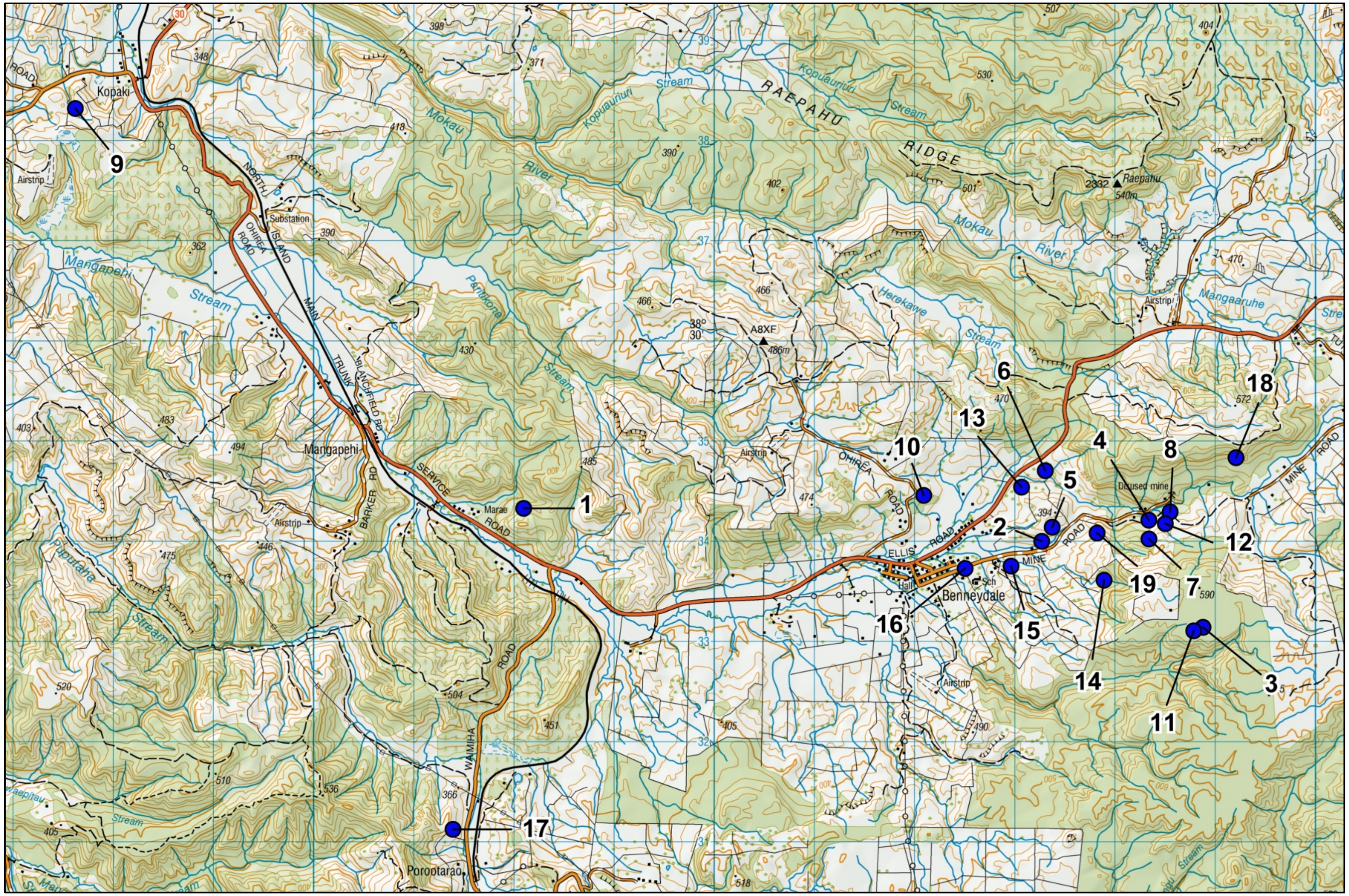

Figure 1.7: Location map for samples collected in the Mangapehi/Benneydale region. Adapted from the Fossil Record Electronic Database (GNS Science, 2009).

CHAPTER 2 - WAIKATO COAL REGION

2.1 INTRODUCTION

The Waikato Coal Region is described in detail by Edbrooke et al. (1994), and the following summary of the geographical setting of the area is based primarily on their observations.

2.1.1 Extent of Waikato Coal Region

The Waikato Coal Region refers to the area in which Waikato Coal Measures occur and it encompasses 13 coalfields (Figure 2.1). The northernmost extent of the region is found in Ardmore, where 5 m of coal measures were recorded from a drillhole. Coal measures extend to King Country in the south, and only limited occurrences of coal measures are recorded to the south of Benneydale. The relationship of these restricted deposits to Waikato Coal Measures is uncertain, and as such, the southern boundary for the Waikato Coal Region is marked by Benneydale in the east and Awakino Gorge in the west (Edbrooke et al., 1994).

To the east, Waikato Coal Measures thin and disappear against the basement of the Waipapa Terrane, marked by the Hunua Ranges in the north and the Hauhungaroa Range in the south (Figure 2.2). These ranges were uplifted during the Neogene, and as a consequence coal measures have been eroded from their flanks in many locations. Coal measures also become progressively thinner and disappear to the west, with thin coal measures located on the eastern side of Kaketu Range in the north and Herangi Range in the south. It is likely that late Neogene uplift and erosion has removed the majority of coal measures that may once have been present east of the highest ranges. To the north of the Waikato River the absence of basement outcrop and thick cover of late Neogene coverbeds (Tauranga Group and Kaihu Group) make it difficult to determine the western boundary of the coal region (Edbrooke et al., 1994).

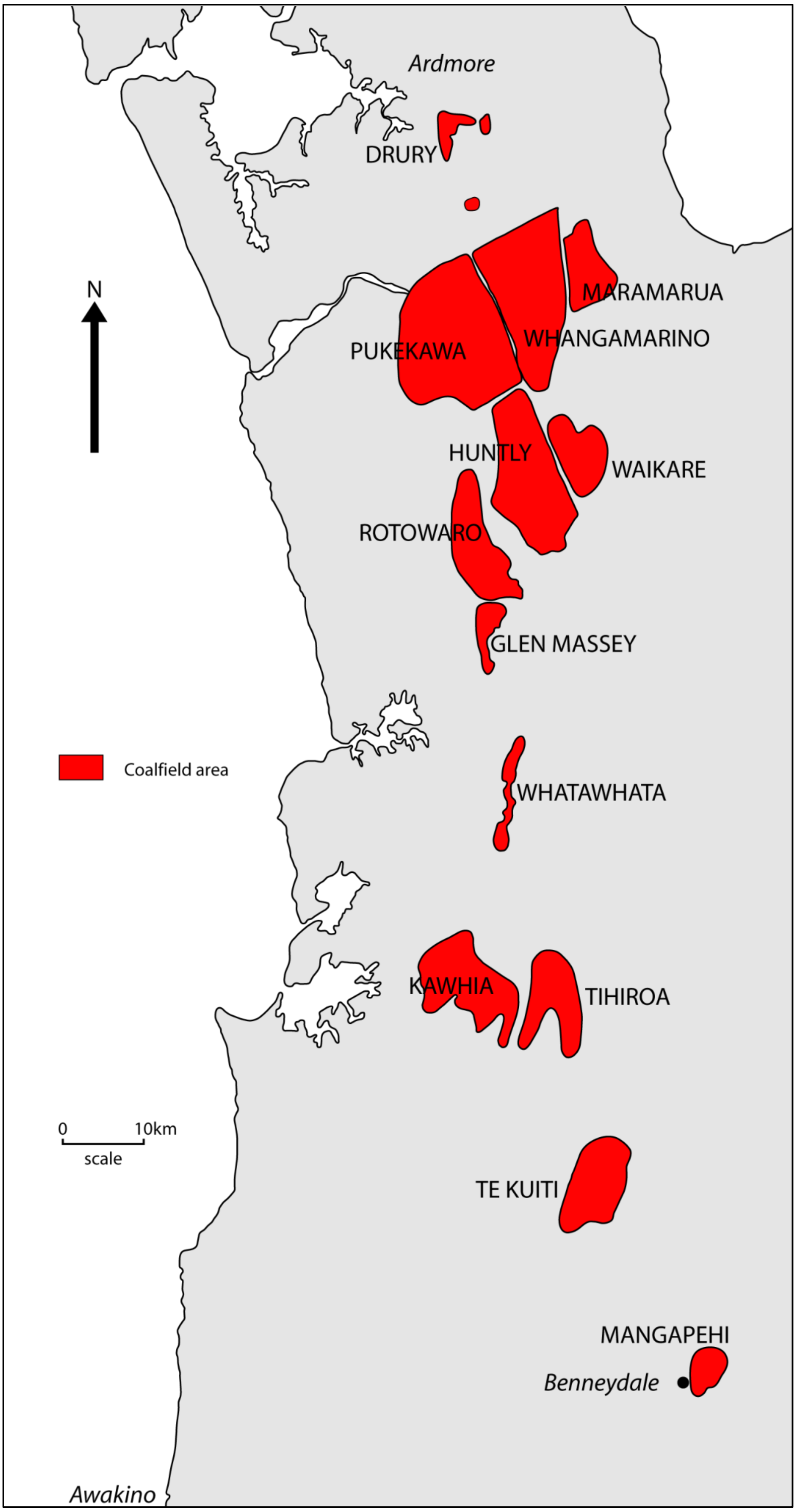

Figure 2.1: Coalfields within the Waikato Coal Region. (Figure redrawn from Edbrooke et al., 1994).

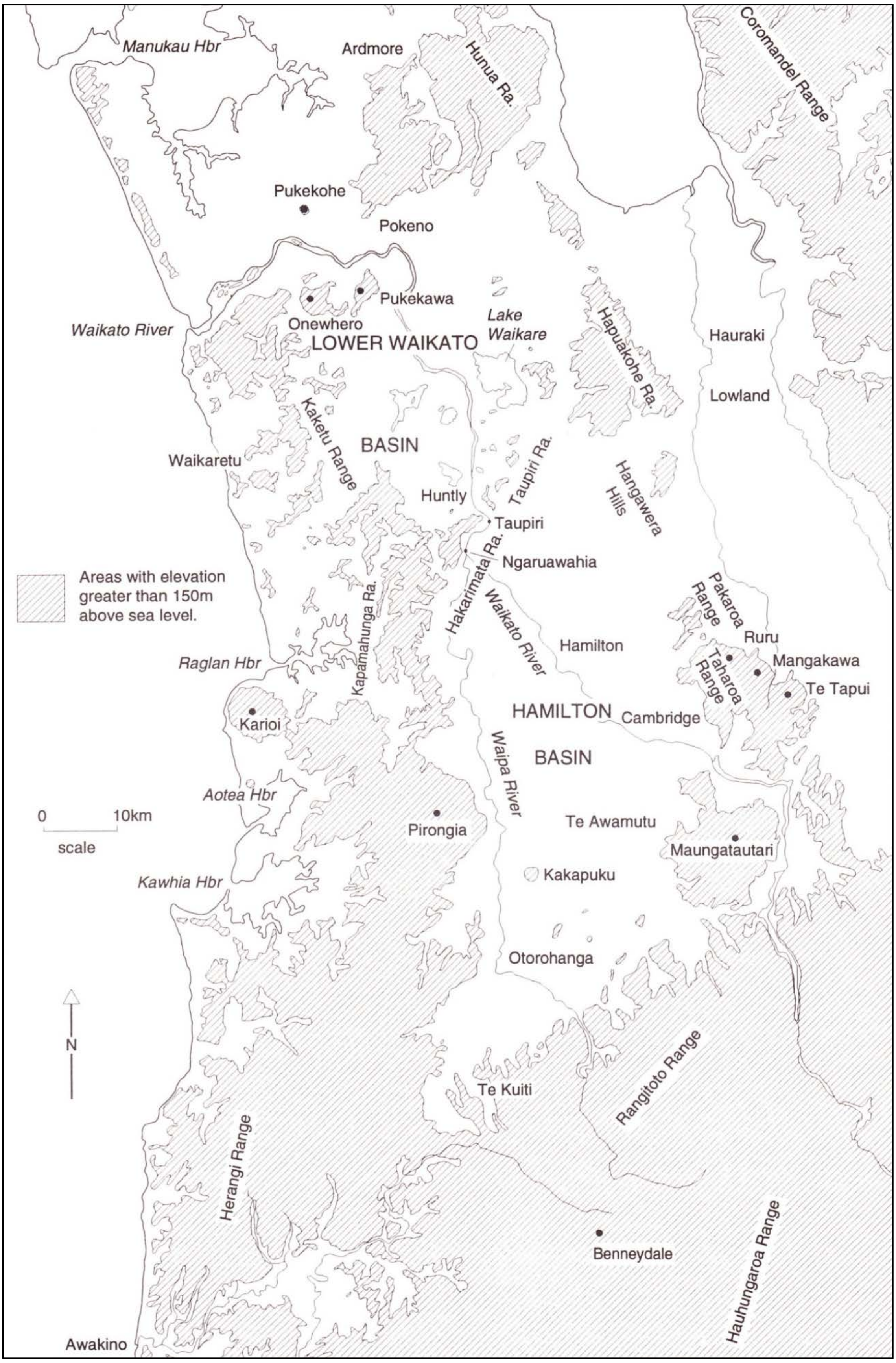

Figure 2.2: Physiographic features of the Waikato Coal Region (Edbrooke et al., 1994).

2.1.2 Physiography

The Waikato Coal Region consists of a long central lowland area that is divided by Hakarimata and Taupiri Ranges (Figure 2.2). These ranges are positioned across the trend of coal measure deposition, effectively splitting the Waikato Coal Region into North and South Waikato Coal Subregions. The presence of thin coal measures lapping onto these ranges suggests that they were substantial topographic structures during the late Eocene and early Oligocene, when coal measures were deposited (Edbrooke et al., 1994).

The central lowland area comprises two basins: Lower Waikato Basin in the north, and Hamilton Basin in the south. Lower Waikato Basin is primarily the flood basin for Waikato River and covers the area from Pokeno to Taupiri Gorge. Hamilton Basin encompasses the flood plains of both Waikato and Waipa rivers. It is considerably larger than Lower Waikato Basin, and extends from Taupiri Gorge to just south of Te Kuiti (Edbrooke et al., 1994).

Lowland areas are flanked to the east by hills and ranges that become increasingly higher towards the south, with Hauhungaroa Range reaching heights of more than 1000 m. To the west, lowland areas are bordered by high volcanic centres, in particular Pirongia and Karioi mountains, and by coastal ranges of Mesozoic sedimentary rocks. Volcanic centres to the north include Pukekohe, Pukekawa, Onewhero and Waikaretu and these represent more subdued areas of elevated topography (Edbrooke et al., 1994).

2.2 REGIONAL GEOLOGICAL SETTING

2.2.1 Tectonic history and structural development

The initial phase of deformation in the Waikato Region was associated with the Rangitata Orogeny, which occurred during the early Cretaceous. Mesozoic strata were strongly deformed during this time and the New Zealand continental block was uplifted, leading to the formation of the basement for the Cenozoic sedimentary sequence (Edbrooke et al., 1994). Following this phase of uplift and deformation, and the cessation of subduction along the Pacific margin of Gondwana, extensive erosion of basement terranes took place (Edbrooke, 2005).

The deposition of terrestrial and marine sediments to the west of present-day North Island occurred during the late Cretaceous and early Paleogene as a result of rifting and subsidence associated with the opening of the Tasman Sea. Extensional faulting resulting from this period of rifting, led to the development of a number of NNW- to NNE-trending normal faults and less common ENE-trending faults (Edbrooke, 2005).

A phase of strike-slip faulting occurred prior to normal block faulting, as evidenced by the tectonic rotation of a northeastward trending block of Murihiku Terrane, comprising the Hakarimata-Taupiri ranges (H-T Block) (Figure 2.3). The strike of the Hakarimata-Taupiri block contrasts with that of other Murihiku and Waipapa strata in the area. To the west of the H-T block, beds strike N-NNW, suggesting that the block has rotated 50° clockwise. The timing of this period of strike-slip faulting has not been precisely determined but is confined to late early Cretaceous to latest Eocene (before deposition of Te Kuiti Group sediments) (Kirk, 1991).

Late Paleogene saw a period of tectonic stability during which widespread regional subsidence occurred, accompanied by very minor localized faulting. Palmer and Andrews (1993) suggest a period of tectonic quiescence for the Taranaki Basin during late Oligocene, when sediments of the upper Otaraoa Formation and Tikorangi Limestone accumulated across much of the basin. In the north of the Waikato area, uplift and westward tilting occurred during latest Oligocene, the first sign that an evolving convergent plate margin in northern New Zealand was developing (Edbrooke, 2005).

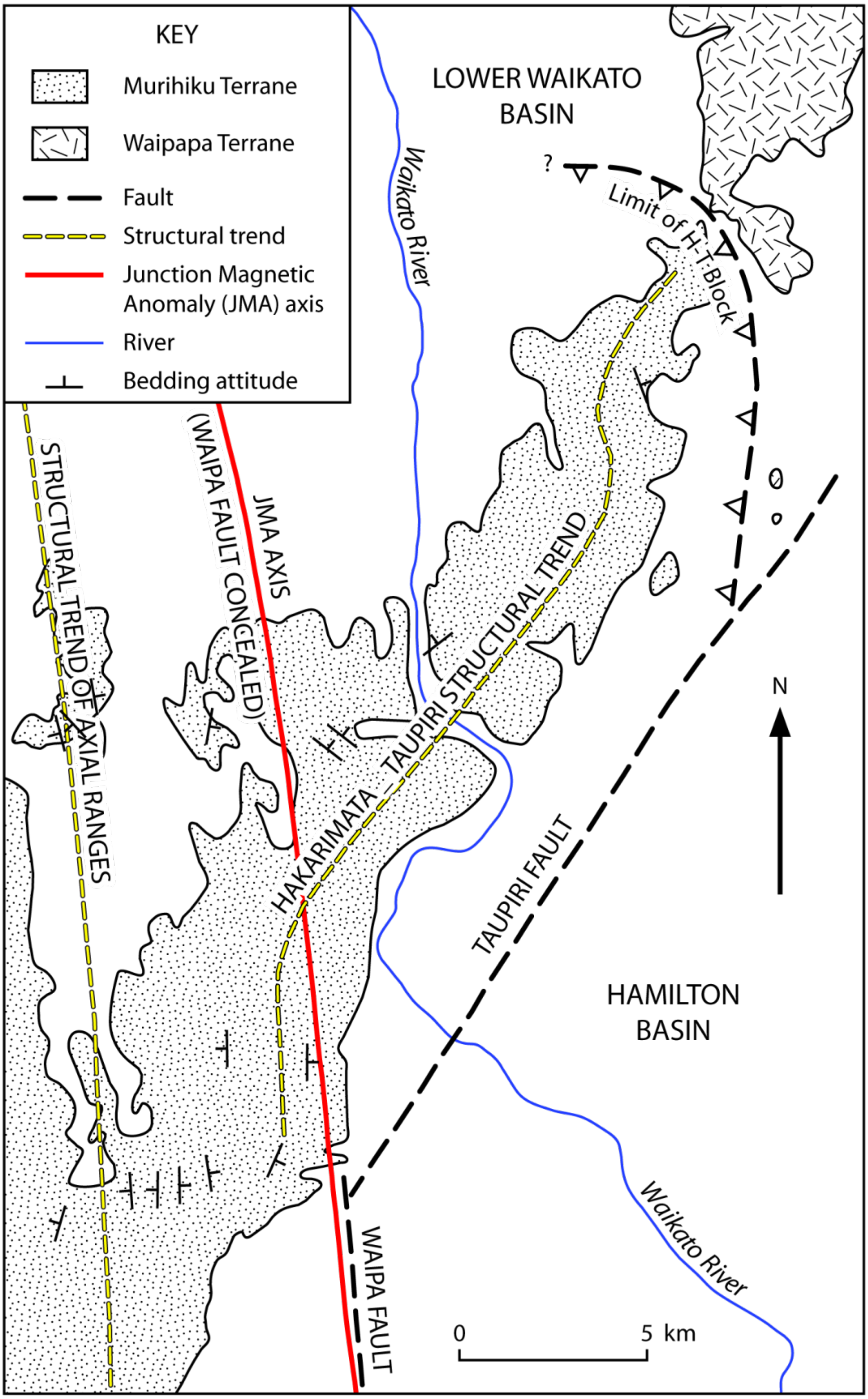

Figure 2.3: Diagram showing the structure of the Hakarimata-Taupiri (H-T) block and surrounding area. (Figure redrawn from Kirk, 1991).

There seems to be some controversy as to when the plate boundary propagated through New Zealand with estimates varying from late Eocene–early Oligocene (Palmer & Andrews, 1993), to early Miocene (Kamp, 1986). Edbrooke (2005) states that the convergent Australian-Pacific plate boundary began to propagate through northern New Zealand during early Miocene, leading to compression and basement overthrusting on the Taranaki Fault.

Changes in the deposition from carbonate-rich sediments to terrigenous clastic sediments occurred in the Taranaki Basin during the early Miocene, coinciding with a tectonic change to the plate boundary in the Southwest Pacific (Palmer & Andrews, 1993). The instantaneous pole began moving away from New Zealand between 10 to 20 Ma, and a faster rate of rotation accompanied the increase in distance. This resulted in an increase in the rate of relative plate motion along the plate boundary in the vicinity of New Zealand (Walcott, 1987).

Regional subsidence continued in the south of the Waikato area during middle to late Miocene, leading to the deposition of a transgressive sequence of sediments. In the north, subsidence did not recommence and instead the area experienced the effects of westward tilting, open folding, and normal faulting (Edbrooke, 2005).

2.2.2 Stratigraphy

Sedimentary rocks of the Waikato Region are separated into four general lithostratigraphic groups; a brief description of each is given in the following sections.

2.2.2.1 Mesozoic basement rocks

The oldest rocks within the Waikato Coal Region are indurated late Triassic to late Jurassic sediments. These basement rocks belong to two distinct terranes: the Waipapa terrane in the east and the Murihiku terrane in the west. In the South Waikato Coal Subregion these two terranes converge along the Aria-Waipa fault zone, and in the northern subregion the boundary between the two terranes follows the Junction Magnetic Anomaly (Figure 2.3) (Edbrooke et al., 1994).

The Waipapa composite terrane consists of three tectonostratigraphic units: Omahuta, Bay of Islands and Manaia Hill terranes (Black, 1996). In the Waikato region, Waipapa rocks belong to the Manaia Hill terrane, and these are further divided into the Hunua and Morrinsville lithofacies (Kear, 1971). Of these two lithofacies, only the Morrinsville facies is represented in the Waikato region and is referred to as the Manaia Hill Group. This group is late Jurassic to early Cretaceous and consists of well indurated, volcaniclastic sandstone with some thin siltstone and conglomerate (Edbrooke, 2005).

The Murihiku terrane is of Triassic and Jurassic age and consists of a thick sequence of volcanogenic sediments (Coombs et al., 1976). It is subdivided into five groups (Newcastle, Rengarenga, Kirikiri, Apotu and Huriwai), based on lithology and fossil content (Edbrooke, 2005; Edbrooke et al., 1994). The sediments of the Murihiku terrane are inferred to have been deposited in a forearc basin setting (Briggs et al., 2004; Coombs et al., 1976).

Kear and Mortimer (2003) proposed a new subdivision of the central North Island tectonostratigraphic terranes, under which the Manaia Hill Group (Waipapa terrane) and Apotu and Huriwai groups (Murihiku terrane) are incoporated into a single unit, along with rocks of the Waioeka petrofacies (Torlesse terrane). This unit is referred to as the Waipa Supergroup and is described as a late Jurassic overlap assemblage.

2.2.2.2 Late Paleogene rocks - Te Kuiti Group

Sediments of the Te Kuiti Group represent a predominantly transgressive sequence which was deposited throughout the Waikato region between late Eocene and early Miocene. It comprises basal coal measures overlain by calcareous sandstones, calcareous mudstones and limestones. Deposition took place during a period of tectonic quiescence, when extensive regional subsidence and minimal localized faulting occurred (Edbrooke, 2005; Edbrooke et al., 1994).

Nelson (1978) reviewed the earlier definition of the Te Kuiti Group, published by Kear & Schofield (1959), and suggested that:

> The Te Kuiti Group includes all those sedimentary lithologies in the South Auckland area lying above the regional unconformity developed on rocks of the Murihiku Supergroup and Manaia Hill Group, loosely named the Mesozoic basement rocks, and below the Mahoenui Group or its more northerly counterpart, the Waitemata Group. (p. 561)

In the Waikato region the Te Kuiti Group comprises nine units: Waikato Coal Measures, Mangakotuku Formation, Glen Massey Formation, Whaingaroa Formation, Aotea Formation, Te Akatea Formation, Orahiri Limestone, Waitomo Sandstone and Otorohanga Limestone. A detailed description of each of these formations is given by Edbrooke et al. (2005), and the generalised distribution of each is shown in Figure 2.4.

2.2.2.3 Miocene Rocks

Marine sediments of Miocene age overlie the Te Kuiti Group, and consist of Waitemata Group in the north and Mahoenui Group in the south (Kirk et al., 1988). Waitemata Group extends from the North Waikato Coal Subregion to the northern flank of Pirongia Mountain in the south. A boundary between Waitemata Group and Mahoenui Group can be drawn where a gap occurs in outcrop at Pirongia Mountain. Mahoenui Group occurs south of Pirongia Mountain and into the South Waikato Coal Subregion (Edbrooke et al., 1994).

2.2.2.4 Late Neogene Rocks - Tauranga Group

Tauranga Group includes all sediments of post-Miocene age and is comprised mainly of terrestrial sediments, which are dominated by pumiceous and rhyolitic sands, clays and gravels, and interbedded peat. It is extensive within the Waikato Coal Region, and unconformably overlies Te Kuiti, Waitemata, Mahoenui and Mohakatino groups (Edbrooke et al., 1994; Kirk et al., 1988).

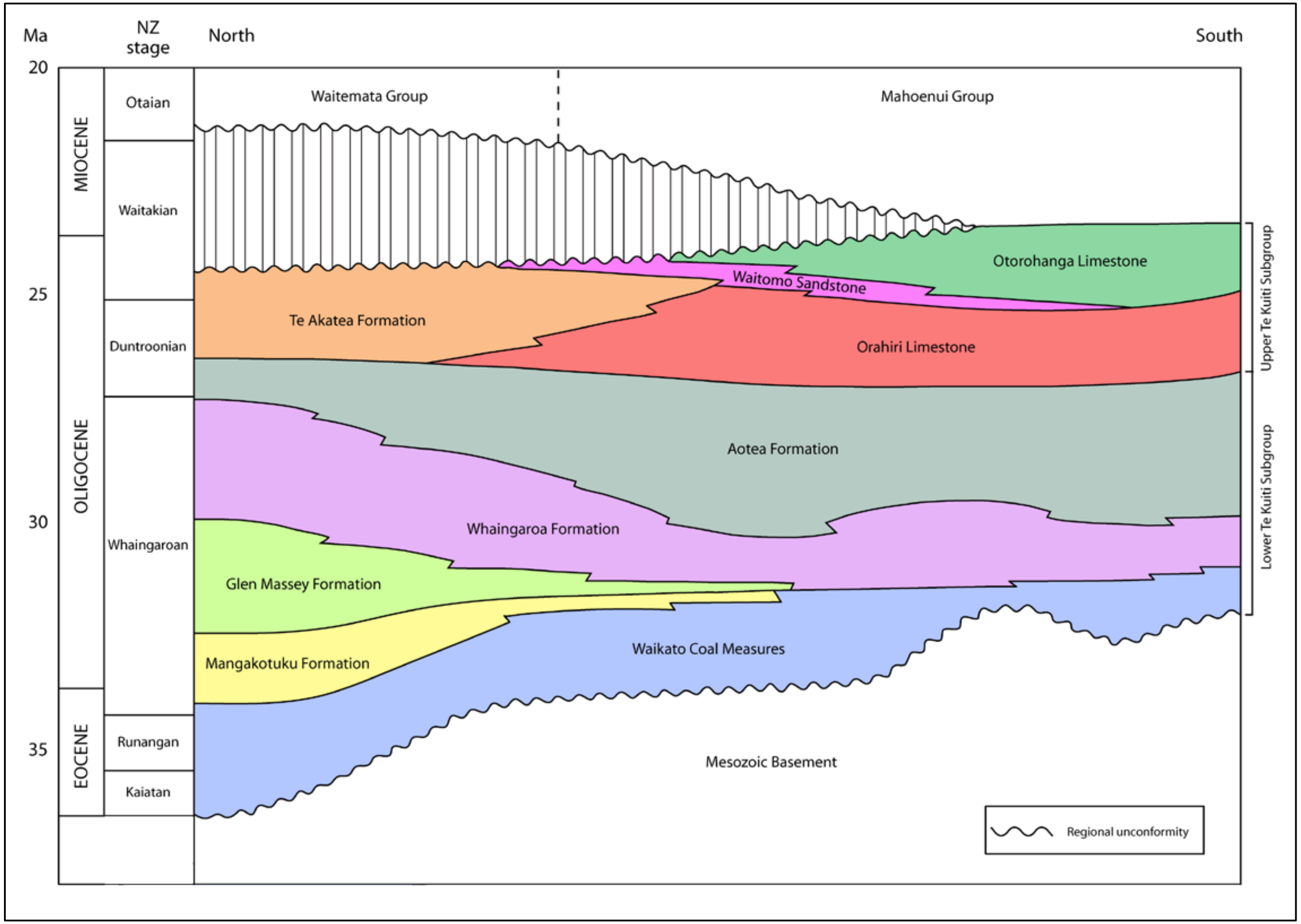

Figure 2.4: Generalised section through the Waikato region (North to South) showing the distribution of Te Kuiti Group formations. (Figure redrawn from Edbrooke, 2005)

2.3 MANGAPEHI COALFIELD

2.3.1 Introduction

Mangapehi Coalfield is the southernmost-known coalfield in the Waikato Coal Region and is located in the Waitomo District approximately 240 km south of Auckland and 40 km south-east of Te Kuiti by road (Edbrooke, 1989; Fowke, 1997; Kirk et al., 1988). The entrances to the underground mine shafts are located at the end of Mine Road, approximately 3 km east of Benneydale township (Edbrooke, 1989). Coal was not discovered in the Mangapehi region until 1931–1932, when a 3.7 to 4.5m-thick seam was discovered in Mangapehi Stream valley (Edbrooke, 1989; Fowke, 1997). Mining commenced in 1933, and by 1940 the Mangapehi Mine had produced almost 30,000 tonnes of coal. New Zealand State Coal Mines took over operation of the mine in 1940 and a further 820,000 tonnes of coal were produced. The mine was allowed to flood following an explosion and fire, and was sealed off in 1962 (Edbrooke et al., 1994; Fowke, 1995).

A new mine was established by Hughes Brothers, a small private mining operation, in 1978. This mine, known as the Benneydale Mine, was developed from a second outcrop in the Mangapehi Stream located approximately 150 m east of where the Mangapehi Mine operation commenced. In late 1990 Coalcorp become the outright owners of the mine and related mining licences, and an estimate of coal production between 1978 to 1995 is given at 150,000 tonnes (Fowke, 1995).

2.3.2 Geological structure

The Mangapehi Coalfield lies near the southernmost limit of the Hamilton Basin, and is included in the King Country Basin, formerly known as the North Wanganui Basin. The King Country Basin extends from the Marokopa Fault in the north to the latitude of Stratford in the south (Figure 2.5), with the western and eastern boundaries being marked by the Strathmore Fault and the Hauhungaroa Fault respectively (Crosdale & Regenauer-Lieb, 1995; Nelson & Hume, 1977). Structural highs of Mesozoic basement rocks border the basin, comprising the Herangi Range (Figure 2.2) to the west and the Rangitoto-Hauhungaroa-Kaimanawa Ranges to the east (Nelson & Hume, 1977).

The major faults located within the King Country Basin strike from 000° to 020°, and most of these appear to be normal faults (Figure 2.5). However, there is evidence that many may have undergone transcurrent movement in the past. Laird (1967) proposed transcurrent movement on the Kapamahunga Fault, in the Whatawhata District (to the north of Figure 2.5), based on the absence of a prominent conglomerate band on the eastern side of the fault, which appears *in situ* in a number of localities on the western side of the fault. The Waipa Fault lies to the east of the Kapamahunga Fault and was also inferred to be transcurrent (Kear, 1960).

The Herangi Range and subsurface Patea-Tongaporutu High together represent an uplifted basement block that dips to the south and constitutes the western boundary of the basin (Nelson & Hume, 1977). The Waipa Fault is a major north-south feature that lies to the east of the Taranaki-Manganui-Whareorino Fault system (Figure 2.5) and separates Mesozoic basement rocks into Waipapa and Murihiku terranes (Kear, 1971). It is likely that the Waipa Fault represents the eastern boundary of the Herangi-Patea-Tongaporutu block (Nelson & Hume, 1977).

Following the end of Paleogene–Neogene sedimentation, uplift occurred along the Hauhungaroa Fault, and relative subsidence of the Central Volcanic Region occurred to the east. The timing of movement on the Hauhungaroa Fault is not precisely known, however, Villamor and Berryman (2006) suggest that activity occurred prior to c. 340 ka. This date is based on the observation that Ongatiti Ignimbrite, with an estimated age of 1.25 Ma (Houghton et al., 1995), is displaced by the Hauhungaroa Fault, yet at the northern end Whakamaru Ignimbrite, with an estimated age of 0.32 Ma (Houghton et al., 1995), laps over the fault scarp.

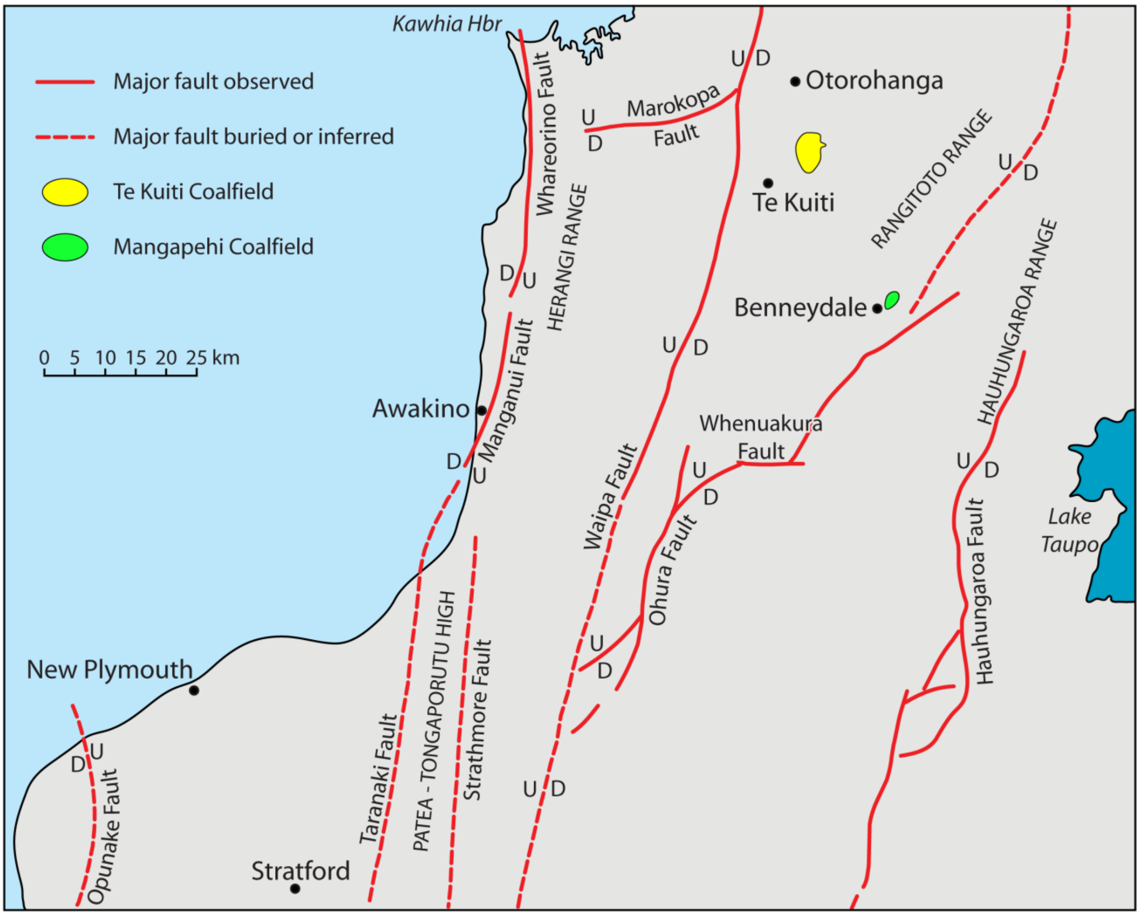

Figure 2.5: Location of major faults within the King Country Basin. (Figure redrawn from Crosdale & Regenauer-Lieb, 1995; Nelson & Hume, 1977).

The Ohura Fault occurs to the south of Mangapehi, is downthrown to the east and displays vertical displacement in the range of 400–490 m (Crosdale & Regenauer-Lieb, 1995). Early mapping of the Ohura Fault suggested that to the north of Ohura, it swung to the east for some distance, before swinging back to a NNE direction. However, this ENE-trending fault was later renamed as Whenuakura Fault (Figure 2.5) and the Ohura Fault was found to continue in a NNE direction into the Hapurua Valley for a short distance (Crosdale & Regenauer-Lieb, 1995). NNE faults within the basin are believed to have been active since late Oligocene and the Ohura Fault experienced a reversal in movement during the Altonian (early – mid Miocene), resulting in erosion of sediments on the uplifted eastern block and a reduction in the thickness of Mahoenui Group in that area (Crosdale & Regenauer-Lieb, 1995; McQuillan, 1977) .

Locally, the Mangapehi Coalfield is divided into two sectors by the NNE-trending Benneydale Fault (Figure 2.6). Old mine workings were limited to the western sector and current workings are located to the east (Kirk et al., 1988). The Benneydale Fault downthrows beds to the southeast and represents a zone of faulting. Two faults are identified in Mangapehi Stream Valley, each with throws of 3–6 m (Kear, 1959b). Gage (1942) also discussed two dislocations in the Mangapehi Valley, upstream of the Mangapehi mine. The first, located approximately 241 m from the mouth of the mine, displaces the coal seam about 11 m. A second fault running parallel to the first, 80 m to the east, exhibits a throw of approximately 15 m.

Tiroa Fault (Figure 2.6) lies towards the eastern boundary of the coalfield and differs from the majority of faults in the region by trending in a north-westerly direction. Fowke (1997) suggests that this fault may be a remnant of an earlier period of faulting. The "Double Step" Fault located in the Mangapehi Mine is one of a few smaller faults identified in the coalfield that do not follow the typical north-east orientation. It is likely that these smaller NW-trending faults developed locally as synthetic faults to the major NE-trending faults in response to local stresses (Fowke, 1997).

2.3.3 Stratigraphy

The oldest rocks in the Mangapehi coalfield are those of Mesozoic age belonging to the Manaia Hill Group (Edbrooke, 1990). These are comprised of well-indurated greywacke and argillite that has been heavily fractured and faulted (Gage, 1942). Basement rock crops out in the southeast of the area and the Paleogene–Neogene sedimentary sequence above it dips at 10–20° to the northwest. The southeastern exposure of Mesozoic rock was higher-standing at the time that younger sediments began to accumulate, and as a result all of the Paleogene–Neogene units in the Mangapehi coalfield thin towards this area (Fowke, 1997). Gage (1940) referred to the basement surface as "generally undulating" and "locally irregular" (p. 3).

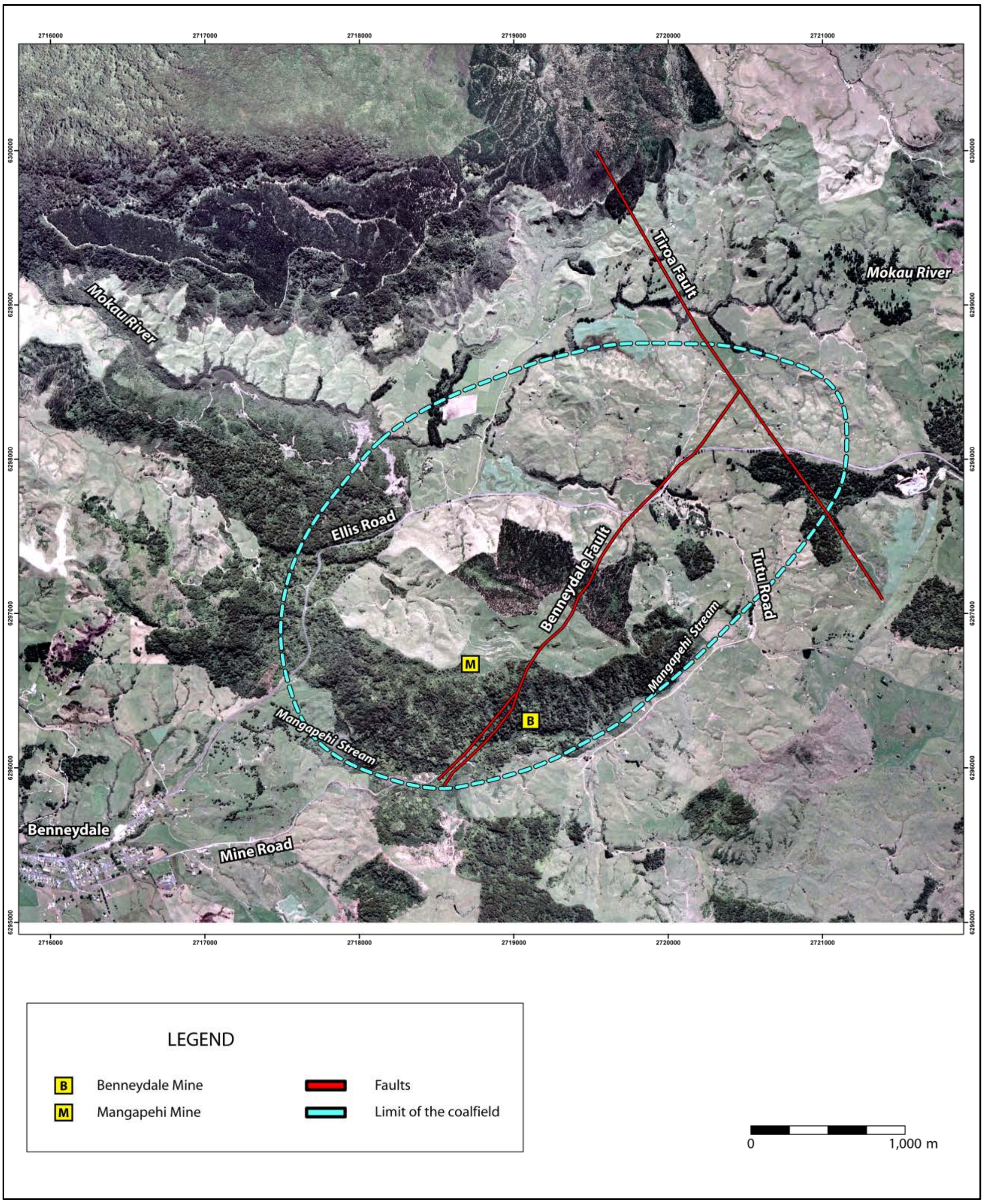

Figure 2.6: Map of Mangapehi Coalfield showing the location of main faults and mine entrances. (Figure redrawn from Bateman, 2006; Fowke, 1997).

Waikato Coal Measures represent the basal formation of the Te Kuiti Group in the Mangapehi region. This unit unconformably overlies the Manaia Hill Group. The Waikato Coal Measures consist of approximately 106 m of carbonaceous sandstone and mudstone, with some carbonaceous shale, conglomerate and coal (Edbrooke, 1989, 1990). The primary coal seam is up to 10 m thick and is located in the lower half of the coal measures. A much thinner upper seam may be observed locally, approximately 25 m above the main seam, and is usually less than 2 m thick (Edbrooke, 1989).

An interesting feature of the coal measure sequence in the Mangapehi Coalfield is the evidence of sea water invasion during the time that coal measures were accumulating (Fowke, 1997). Some of the old drillhole logs record beds that contain shell fragments or pipi shell beds, and this characteristic is also noted in a few of the newer drillholes. Drillhole 8794 contains a sandstone bed 20 m above the Mangapehi coal seam that contains macrofossils (Figure 2.7), and two shelly sandstone beds are observed 2 m above the coal seam in drillhole 8798 (Appendix 2).

Above the basal coal measures lies up to 107 m of fossiliferous, glauconitic sandstone, and this is correlated with the Aotea Formation, which constitutes the upper formation of the Te Kuiti Group in the Mangapehi coalfield (Edbrooke, 1989). The nature of the contact between the Aotea Formation and the underlying coal measures has been recognised as a probable disconformity (Edbrooke et al., 1994), but in some cases a gradation between the two formations is observed (Edbrooke, 1989, 1990; Kirk et al., 1988).

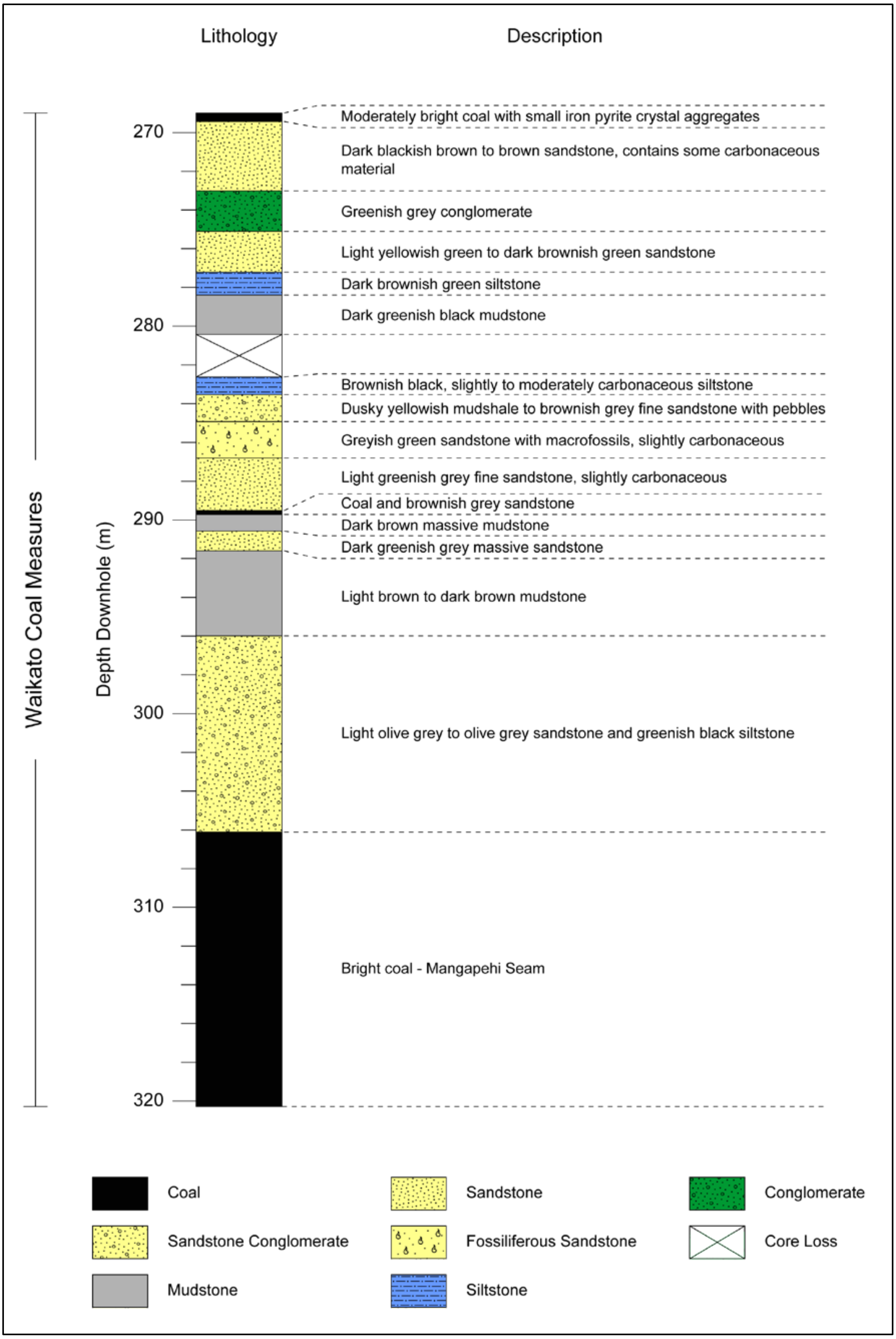

Figure 2.7: Stratigraphic column for drillhole 8794 showing the section of the Waikato Coal Measures that includes a fossiliferous sandstone bed 20 m above the Mangapehi Seam.

Fowke (1997) raised the possibility that in some areas of the coalfield, the marine Te Kuiti Group rock that has previously been correlated with the Aotea Formation, may actually be the older Whaingaroa Formation of White and Waterhouse (1993). Sequences in drillholes 8790 and 8792–8794 consist of a rock that is dominantly siltstone and is much finer grained than earlier descriptions indicate. Chips drilled from marine Te Kuiti Group in 1996 appear to be more like the Whaingaroa Formation in the northern coalfields (Fowke, 1997). For the purpose of this study, the name Aotea Formation will be retained for marine Te Kuiti Group units in the Mangapehi region.

Overlying the Aotea Formation is the massive, calcareous, sandy mudstone of the Mahoenui Group, which reaches a maximum thickness of approximately 150 m (Edbrooke, 1989). The nature of the contact between the Mahoenui Group and the underlying Aotea Formation is uncertain but has been reported as being sharp and conformable (Armstrong, 1987; Fowke, 1997). Mahoenui Group crops out in the lower parts of the hills that surround the Benneydale township (Edbrooke, 1990).

The Mohakatino Group unconformably overlies the Mahoenui Group and is comprised of massive, fine sandstone, with some glauconitic and calcareous horizons, and thin, fine sandy limestone near the base (Edbrooke, 1990). Although this group is absent from many of the holes drilled in the Mangapehi Coalfield, it is known to crop out extensively in the northern and western areas of the coalfield, and can reach thicknesses of up to 100 m (Edbrooke, 1989, 1990).

The volcanic rocks of the Pakaumanu Group overlie much of the Mangapehi Coalfield and the extensive ignimbrite sheet may be found overlying any of the sedimentary units previously described. The ignimbrite sheet ranges in thickness from less than 10 m to 200 m and this variability reflects the pre-existing topography of the region, which resulted from erosion of the underlying sedimentary rocks (Edbrooke, 1990). Ignimbrites of the Pakaumanu Group are comprised of welded rhyolitic tuffs (Fowke, 1997).

The lowest parts of stream valleys in the Mangapehi area are infilled by thin Tauranga Group deposits, which include fluviatile, pumiceous gravels, sands and silts, mainly of rhyolitic origin. The thickness of these deposits ranges from 0–12 m (Edbrooke, 1990; Fowke, 1997).

CHAPTER 3 - STUDY AREA

3.1 INTRODUCTION

A total of 28 boreholes have been drilled in the Mangapehi Coalfield from 1940 to 2007 (Figure 3.1). The eighteen holes drilled prior to 1996 (grouped together as the 5000 series) have been discussed by Armstrong (1987) and will not be described again in this study. Ten boreholes were drilled by Solid Energy NZ Limited from 1996 to 2007 and these constitute the 8000 series. Data has been provided by Solid Energy NZ Limited for all of these later boreholes, in the form of geological logs, core photos and some geophysical data. In addition, core extracted from two of these drillholes (ID 8795 and 8798) was made available for sampling. Summarised stratigraphic columns for drillholes 8795 and 8798 are presented in this chapter, and detailed stratigraphic columns, covering the sequence between Mahoenui Group to Manaia Hill Group, are included in Appendix 2. All columns are based on the original logging carried out by Solid Energy and no attempt has been made to reinterpret the lithological sequences of these drillholes.

3.2 DRILLHOLE DESCRIPTIONS

3.2.1 Drillhole 8790

Early boreholes of the 5000 series are located mainly in the western or southern areas of the Mangapehi coalfield (Figure 3.1). Borehole 8790 was drilled in early 1996 and is located further north than the 5000 series holes, in the eastern region of the coalfield between Ellis Road and Mokau River. It covers the sequence between Taupo Volcanic Group to Mesozoic basement rocks and reaches a depth of 302.60 m.

3.2.2 Drillhole 8791

Drillhole 8791 is the most eastern of the ten boreholes and is the only hole located on the upthrown side of the Tiroa Fault. It reaches a depth of 143.20 m, and differs from the other nine holes by the fact that volcanic rocks, identified as Whakamaru Ignimbrite, directly overlie basement rocks of the Manaia Hill Group. Sediments of late Paleogene to Miocene age are absent from the sequence.

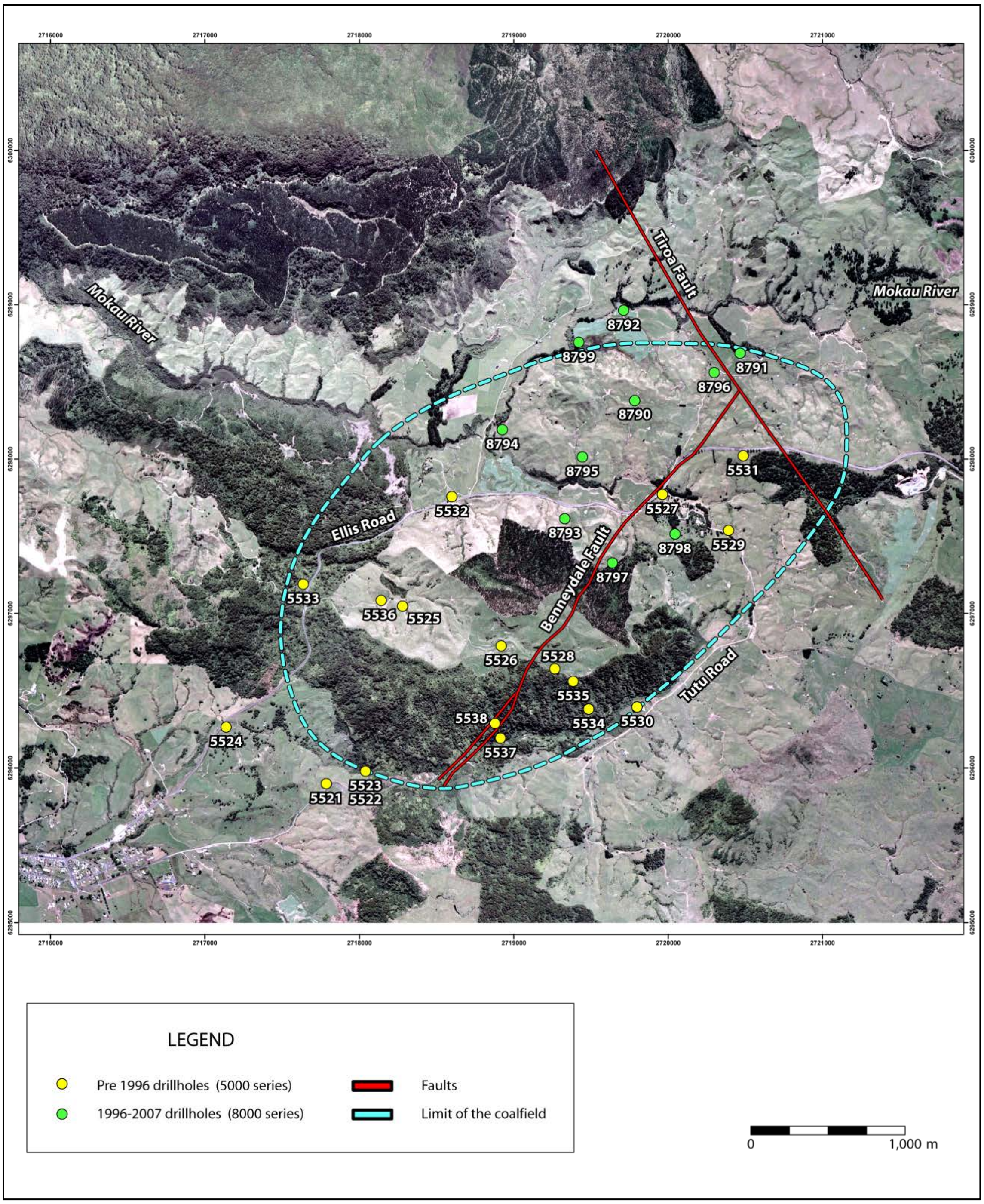

Figure 3.1: Location of all holes drilled in the Mangapehi Coalfield up to 2007. (Figure redrawn from Bateman, 2006).

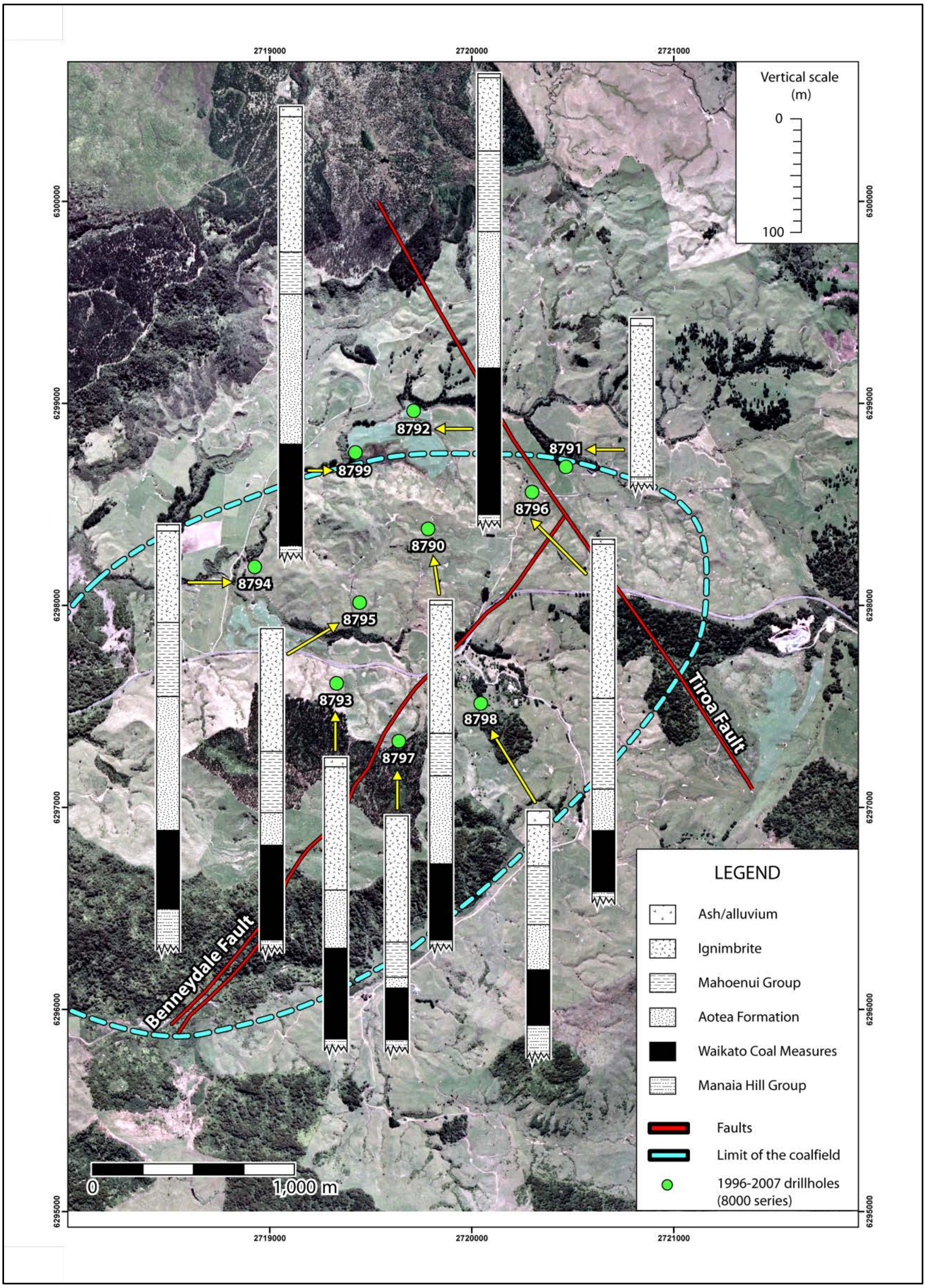

Figure 3.2: Map showing simplified stratigraphy for holes drilled in the Mangapehi Coalfield between 1996 to 2007.

3.2.3 Drillhole 8792

This is the northern-most borehole in the Mangapehi coalfield, located around 800 m north-west of drillhole 8791 on the downthrown side of the Tiroa Fault. It spans the same sequence seen in drillhole 8790 and extends to a depth of 393.50 m. Waikato Coal Measures at this location reach a thickness of 129 m, which is the thickest sequence seen in any of the 8000 series holes.

3.2.4 Drillhole 8793

Drillhole 8793 is located on the south side of Ellis Road, and lies on the upthrown side of the Benneydale Fault. It reaches a depth of 251.30 m, and passes from Taupo Volcanic Group through to Manaia Hill Group. Sediments of the Mahoenui Group are not seen in this drillhole however, with ignimbrite directly overlying Aotea Formation.

3.2.5 Drillhole 8794

This is the western-most drillhole of the 8000 series but is still located east of a number of the pre-1996 holes. It lies approximately 700 m northwest of drillhole 8793 reaches a depth of 370.5 m. It spans the same sequence seen in borehole 8790.

3.2.6 Drillhole 8795

Drillhole 8795 is located around 410 m NNE of drillhole 8793. It reaches a depth of 275.40 m and spans the sequence between Taupo Volcanic Group to Manaia Hill Group (Figure 3.3). The majority of drillhole 8795 was wash-drilled and as a result core was only extracted from sections within Aotea Formation and Waikato Coal Measures.

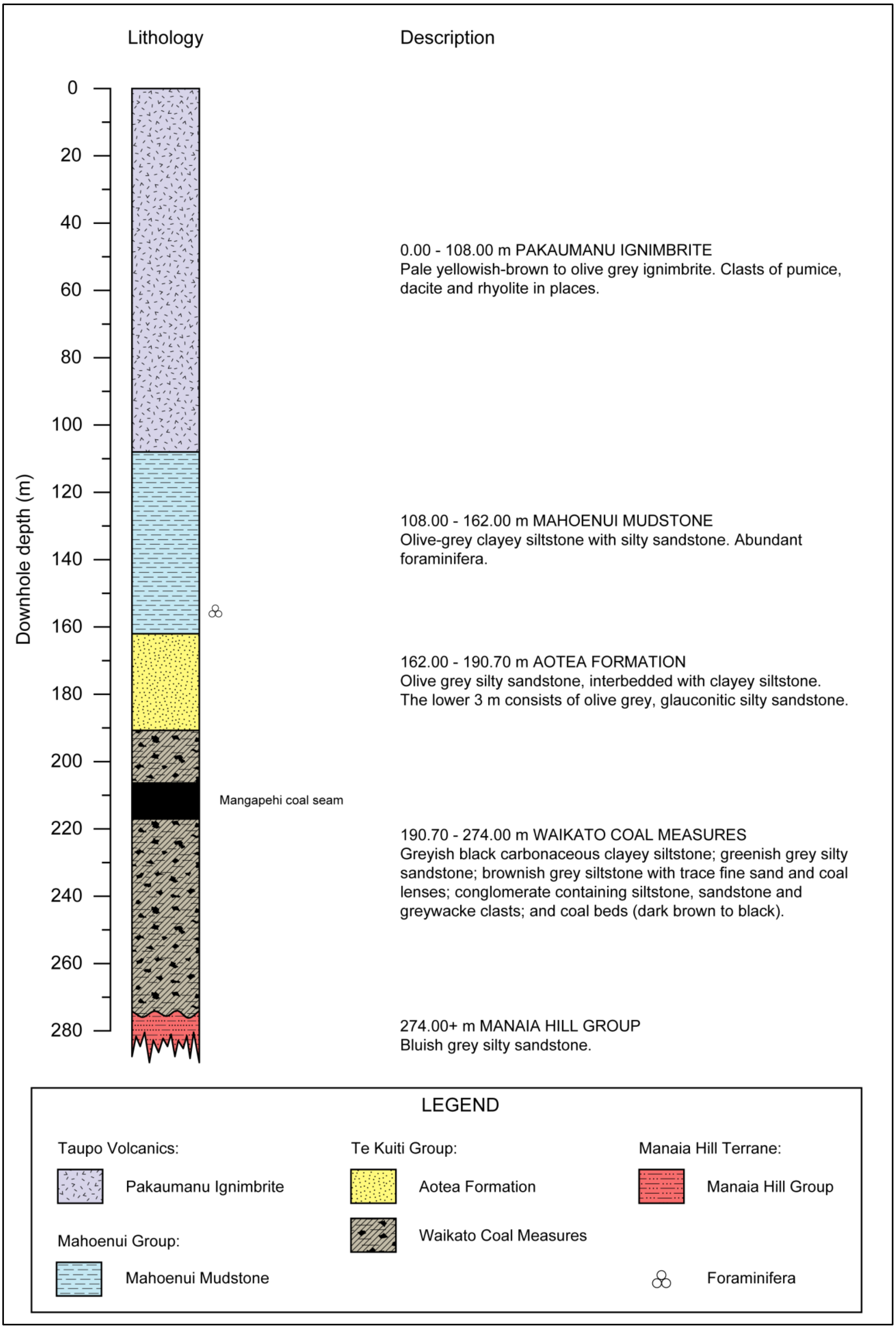

Figure 3.3: Summarised stratigraphic column for drillhole 8795 showing the thicknesses of major units and placement of the Mangapehi coal seam within the Waikato Coal Measures.

3.2.7 Drillhole 8796

This drillhole lies on the downthrown side of the Tiroa Fault, 205 m southwest of drillhole 8791. It extends to a depth of 313.50 m and covers the same sequence seen in drillhole 8795.

3.2.8 Drillhole 8797

This is the southern-most drillhole of the series, lying approximately 410 m southeast of drillhole 8793 and is one of two holes located on the downthrown side of the Benneydale Fault. It extends down to Mesozoic basement but is the second shallowest hole of the 8000 series, reaching a depth of 204 m. It also has the thinnest sequence of Waikato Coal Measures, which measure 45.50 m.

3.2.9 Drillhole 8798

Drillhole 8798 is located approximately 760 m southeast of drillhole 8795, and like drillhole 8797, lies on the downthrown side of the Benneydale Fault. It extends to a depth of 212.60 m and like many of the previous holes it spans the sequence between Taupo Volcanic Group to Manaia Hill Group (Figure 3.4). Core was extracted from this drillhole in its entirety, providing a full range of lithologies for biostratigraphic analysis.

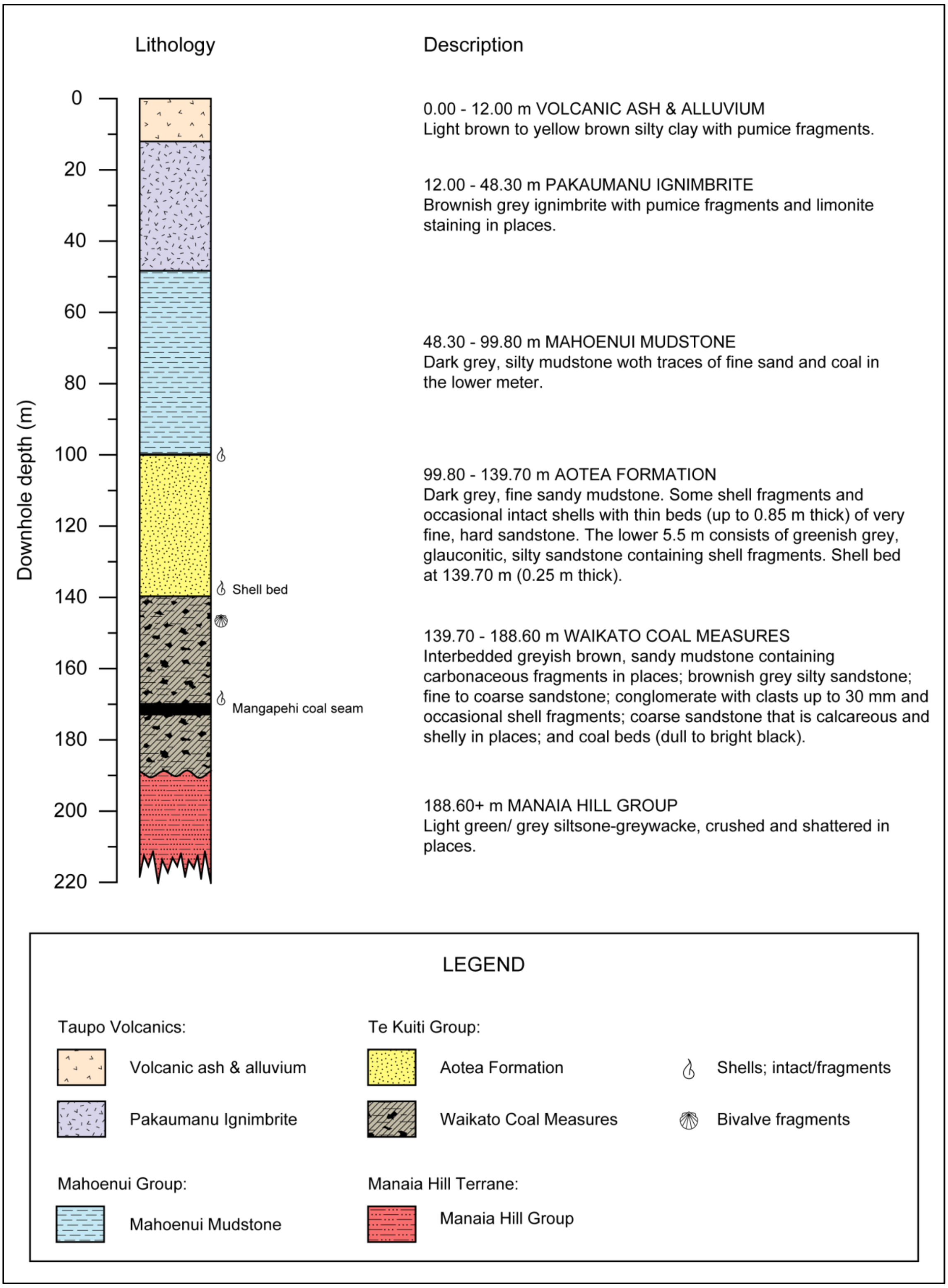

Figure 3.4: Summarised stratigraphic column for drillhole 8798 showing the thicknesses of major units and placement of the Mangapehi coal seam within the Waikato Coal Measures.

3.2.10 Drillhole 8799

Drilled in 2007, this is the most recent drillhole of the 8000 series and is located about 350 m southwest of drillhole 8792. It is the second deepest hole of the 8000 series, reaching a depth of 393 m, only half a metre shorter than borehole 8792. It spans the same sequence seen in most of the other holes, although the basement rocks in this borehole have been identified as Newcastle Group.

CHAPTER 4 - METHODOLOGY

4.1 CORE SAMPLING

4.1.1 Introduction

All of the material used for analysis in this study was obtained from cores extracted from drillholes 8795 and 8798, and stored by Solid Energy NZ Limited at their core shed in Huntly, New Zealand. Both cores had been cut into 1 metre lengths, and each length was packaged in a split round covered by a plastic sleeve and stored in a standard core box. Core depth for each length was recorded at the top and bottom of the box. In some cases, core was packaged in a plastic tube rather than a split round, which made sampling more difficult for these sections.

4.1.2 Sample collection and preparation

Sampling was carried out in two stages using the facilities at the Huntly core shed. During the first stage, core boxes were laid out in sequential order on the rolling core tables and each core was examined in order to determine its condition and to establish which sections would be the most useful to sample from. Samples during this initial phase were selected from lithologies that would prove most useful for biostratigraphic analysis. Each sample was placed in a clean sample bag, which was labeled with drillhole number, depth of sample, thickness of sample and sample number. An additional label containing the same information was also placed inside the bag.

The second stage of sampling involved a more detailed sampling of core 8798. Samples were taken at regular intervals, so that when combined with the first batch of samples, the core had been sampled every 5 metres. Additional samples were also taken for core 8795, but due to the restricted sections available, regular spacing of samples was not possible. Stratigraphic logs were prepared for both cores using the software program Strater 1.02.27, and sample locations were updated onto each log (Appendix 2).

Each sample was cut into two or more pieces using the rock saw in the Massey University Earth Science laboratory. Individual pieces of each sample were placed into separately labelled bags for palynological or nannofossil analysis, and any remaining pieces were retained in the event that additional sampling was required. Samples of Manaia Hill Group were analysed even though this unit falls outside of the age range focus of this study. The appearance of this lithology is atypical of basement greywacke, suggesting that it may not be Manaia Hill Group as previously logged by Soild Energy NZ Limited.

4.2 NANNOFOSSIL ANALYSIS

4.2.1 Introduction

Calcareous nannofossils comprise nannoliths, which are small calcite bodies of organic origin, and coccoliths, which are small calcite plates produced by haptophyte algae. They are abundant in marine sediments above the calcite compensation depth and are particularly useful in biostratigraphy, providing a fossil record that is continuous from their first appearance in the late Triassic through to the present day. In addition to their abundance and rapid evolution, the small size of nannofossils (less than 30 microns) means that they can be analysed from very small samples, making them a valuable tool for biostratigraphic studies (Bown & Young, 1998; Perch-Nielson, 1985).

4.2.2 Sampling

37 samples were taken from core 8798 at 5m intervals, from the top of the Manaia Hill Group to the top of the Mahoenui Group. As previously mentioned, sampling from the second core was far more limited, owing to the fact that much of drillhole 8795 was wash-drilled. Subsequently sampling was restricted to sections of core retrieved from within the Aotea Formation and the Waikato Coal Measures. Twenty samples were taken from core 8795 for nannofossil analysis.

4.2.3 Slide preparation

Smear slides were prepared directly from raw samples using the following standard technique. Each sample was first cleaned using a razor blade to scratch the outer surface off. A small amount of the sample was then scraped off onto a clean cover slip and a drop of distilled water was added. This mixture of sediment and water was spread evenly across the cover slide using the long side of a wooden toothpick. Once uniform coverage was achieved, the cover slip was placed on a hot plate to dry. While the cover slips were drying, two slides were labelled with sample number, and three drops of Norland optical adhesive were applied to each slide. The slides were then inverted over the dry cover slips on the hot plate and lowered on an angle, just until contact was made with the cover slip. Once the slide and cover slip were affixed, the slides were turned over and briefly placed on the hot plate until the adhesive spread to all edges of the cover slip. Slides were then removed from the hot plate and placed for 10 to 15 minutes under UV light to cure.

4.2.4 Data collection

Calcareous nannofossils were examined under plain-transmitted light and cross-polarised light at a magnification of 1000x. Relative abundance of individual species and overall abundance of nannofossils were recorded for each sample by making random traverses across the smear slide. The following abbreviations are used to denote individual species and total nannofossil assemblage abundance:

V	=	very abundant (more than 100 specimens per 10 fields of view (FOV))
A	=	abundant (11–100 specimens per 10 FOV)
C	=	common (6–10 specimens per 10 FOV)
F	=	few (1–5 specimens per 10 FOV)
R	=	rare (1 specimen per > 10 FOV)

In addition, B (barren) was used to indicate samples completely devoid of nannofossils.

4.2.5 Taxonomy

Concepts for species identified in this study are those given in Perch-Nielsen (1985), Varol (1998) and Young (1998). The following section provides additional criteria used for identifying taxa within groups. A complete list of calcareous nannofossil species considered in this study is presented in Appendix 3.

4.2.5.1 *Cyclicargolithus*

Differentiation between *Cyclicargolithus abisectus* and *Cyclicargolithus floridanus* is often difficult to achieve consistently (Wei & Wise, 1990). For the purpose of this study, *C. abisectus* were counted as those forms larger than 11 μm, and *C. floridanus* as those smaller than 11 μm.

4.2.5.2 *Helicosphaera*

Differentiation of *Helicosphaera* species is difficult to achieve due to the subtle differences in their structure (Wei & Wise, 1990). While it was possible to identify some specimens as *H. euphratis,* consistency of identification was hard to accomplish and therefore all species were grouped together as *Helicosphaera* spp.

4.2.5.5 *Reticulofenestra*

Many species of *Reticulofenestra* have been previously described and a number of these are very similar to each other. Additionally, there is a degree of inconsistency in the way that names are used by different researchers. In this study, *Reticulofenestra* were differentiated on the basis of rim structure, central area and overall size, as described below.

Reticulofenestra daviesii: Medium sized coccolith, 5–8 μm in length with a plug in the central area, surrounded by a ring of pores.

Reticulofenestra dictyoda: Elliptical reticulofenestrids between 8–10 μm in length with a wide, vacant central area.

Reticulofenestra filewiczii: Medium to large (>5 μm) coccolith with a narrow, elongated central area. A weakly birefringent net can be observed in the central area.

Reticulofenestra gelida: Large (>8 μm) elliptical coccolith with a restricted centre and vacant central area.

Reticulofenestra haqii: Medium (5–8 μm) reticulofenestrids with a restricted centre.

Reticulofenestra lockeri: Medium to large (>5 μm) reticulofenestrids with a lattice in central area.

Note that specimens of *Reticulofenestra* that could not be identified to species level have been grouped by size.

4.2.6 Biostratigraphic zonation

A number of biostratigraphic zonation schemes have been established for calcareous nannofossils, based primarily on the first and last occurrences of species, along with shifts in abundance of specific species. The standard zonation schemes of Martini (1971) and Bukry (1973, 1975; Okada & Bukry, 1980) are used in this study (Figure 4.1). The abbreviations NP (Nannoplankton Paleogene) and NN (Nannoplankton Neogene), followed by a number, are used by Martini (1971) to define the zones of his scheme. A similar system was adopted by Okada & Bukry (1980) to define their zones, opting instead for the abbreviations CP and CN (Coccoliths Paleogene and Coccoliths Neogene). Nannofossil subdivision of the Oligocene is mainly based on the lineage of *Sphenolithus predistentus*, *Sphenolithus distentus* and *Sphenolithus ciperoensis* (McMonagle et al., 2011).

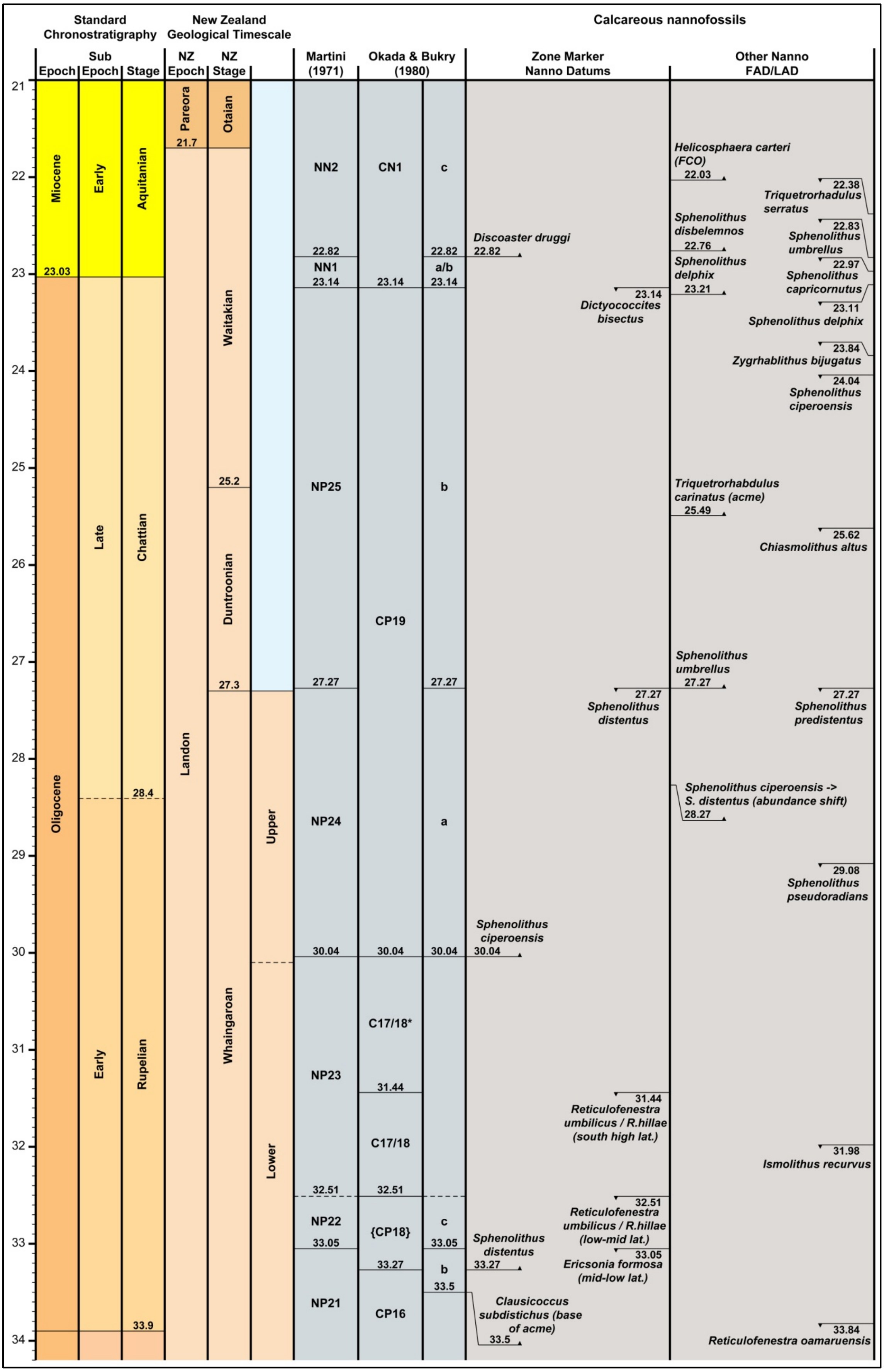

Figure 4.1: Chart showing the zones used by Martini (1971) and Okada & Bukry (1980) correlated with the New Zealand geological time scale. Adapted from Paleogene Microfossil Chart (GNS Science, 2010).

4.3 PALYNOLOGICAL ANALYSIS

4.3.1 Introduction

Two days were spent at GNS Science observing the procedures used for fossil pollen extraction. A protocol for fossil pollen extraction at the Massey University pollen laboratory was developed based on the methods used at GNS Science and those used by Massey University.

4.3.2 Pollen extraction and slide preparation

One gram (dry weight) of each sample was weighed and placed in a clean empty tube and 10% Hydrochloric acid (HCl) was added and stirred gently. Following any initial reaction, tubes were topped up with HCl, leaving 1 cm at top. Samples were then placed in the centrifuge and spun at 3000 rpm for 3 minutes and excess liquid was decanted off. This stage was repeated until all calcium carbonate ($CaCO_3$) matter was removed. Three ml of 30% hydrofluoric (HF) acid was then added to each sample and tubes were placed in a water bath to dissolve siliceous matter. Tubes were removed from the water bath after 30 minutes and HCl was added to neutralize the reaction. Samples were centrifuged again and the supernatant was decanted off. This step was repeated until all siliceous content had dissolved. The final samples were rinsed in HCl, centrifuged and decanted, then rinsed with distilled water. Excess water was spun off and the samples were dehydrated using progressive strengths of ethanol and tertiary butyl alcohol (TBA). After the final treatment of ethanol and TBA, the remaining pollen extract was transferred to a small tube, treated with another round of TBA, centrifuged and decanted. Silicon oil and TBA were then added to the sample, stirred, centrifuged and placed overnight in an oven at 50° C. Dried samples were mounted on glass slides, covered with a cover slip and sealed with paraffin wax.

Slides were examined under normal light at a magnification of 1000x. The samples yielded very few pollens and spores however, and the extraction process was repeated across eight samples, varying different stages of the process to try and achieve better results. Unfortunately these samples also showed a low abundance of pollen grains, even though the samples selected were believed to contain significant palynological content. One of the reasons that extraction was unsuccessful may have been due to the fact that the Massey University pollen laboratory was set up to run smaller samples (1 g), rather than the much larger samples (20 g) that are required for this study. In the interest of achieving better results, it was decided to send samples to GNS Science for pollen analysis as they are set up to handle the larger sized samples.

24 samples were taken from the Mangapehi cores and sent to GNS Science for pollen analysis (Table 4.1; Appendix 2). The amount of material processed for pollen analysis varied between 11.9–26.6 g (dry weight). Samples were treated in the conventional way with HCl, 50% HF, oxidation in Schulze solution, 5% ammonium hydroxide (NH_4OH), and heavy liquid flotation for some samples. The organic fraction was filtered through a 6 μm filter and mounted in glycerine jelly on one or two slides, depending on the amount of residue recovered.

Identification and counts of palynological content was undertaken by Dr Dallas Mildenhall. All samples were counted to 300 grains, except where indicated otherwise. The binomial *Haloragacidites harrisii* has been used for all similar appearing triorate Casuarina-type pollen; the name also covers the presence of *Casuarinidites cainozoicus* and *Haloragacidites canacomyricoides*. Brief information of the content, age and environmental significance of each sample was provided by way of a summary report, along with raw count data (Dallas Mildenhall, personal communication, April, 2012).

Table 4.1: Summary of samples collected from the Mangapehi cores for pollen analysis by GNS Science.

Sample number	Slide number	Depth (m)	Formation	Lithology
Drillhole 8795				
27B	L26419	180.90	Aotea Formation	Silty sandstone
28B	L26420	201.13	Waikato Coal Measures	Siltstone, traces of sand & coal
41B	L26421	203.80	Waikato Coal Measures	Conglomerate
30B	L26422	206.30	Waikato Coal Measures	Clayey siltstone
31B	L26423	207.00	Waikato Coal Measures	Coal
32B	L26424	218.05	Waikato Coal Measures	Carbonaceous siltstone, some sand & coal
34B	L26425	218.96	Waikato Coal Measures	Carbonaceous siltstone, some sand & coal
36B	L26426	220.07	Waikato Coal Measures	Carbonaceous siltstone, some sand & coal
38B	L26427	220.71	Waikato Coal Measures	Carbonaceous siltstone, some sand & coal
39B	L26428	221.90	Waikato Coal Measures	Carbonaceous siltstone, some sand & coal
Drillhole 8798				
26B	L26429	52.85	Mahoenui Group	Silty mudstone
23B	L26430	65.78	Mahoenui Group	Silty mudstone
5A	L26431	99.40	Mahoenui Group	Silty mudstone, traces of sand and coal
6A	L26432	100.40	Aotea Formation	Sandy mudstone, shell fragments
12B	L26433	125.04	Aotea Formation	Sandy mudstone
1A	L26434	141.90	Waikato Coal Measures	Sandy mudstone
9B	L26345	155.80	Waikato Coal Measures	Silty sandstone
9A	L26346	169.67	Waikato Coal Measures	Carbonaceous conglomerate
7B	L26347	175.73	Waikato Coal Measures	Mudstone
5B	L26348	185.07	Waikato Coal Measures	Silty sandstone, coal fragments
10A	L26349	189.53	Manaia Hill Group	Siltstone
4B	L26350	195.60	Manaia Hill Group	Siltstone
2B	L26351	205.60	Manaia Hill Group	Siltstone
1B	L26352	210.60	Manaia Hill Group	Siltstone

4.3.3 Interpretation of palynological data

Palynological count data were collated and pollen diagrams were constructed using a combination of the software programs Tilia (version 1.7.16) and Adobe Illustrator. Age data was correlated with the biozones of previous workers (Couper, 1960; Pocknall, 1991; Pocknall & Mildenhall, 1984; Raine, 1984) and integrated with calcareous nannofossil results (this study) to determine the timing of events in the Mangapehi region. Information provided on the environmental significance of palynological taxa was used in conjunction with calcareous nannofossil evidence to ascertain the paleoclimate and paleoenvironment of the Mangapehi area during late Oligocene - early Miocene.

4.4 ISOPACH ANALYSIS

4.4.1 Introduction

A series of isopach maps were compiled for the Mangapehi Coalfield using data for all 28 boreholes drilled between 1940 and 2007. Data for the pre-1996 holes are based on estimation of thicknesses made by Fowke (1997), in conjunction with the original drill logs obtained from NZ Petroleum and Minerals (2007). Data for the 1996–2007 holes are based on the drill logs provided by Solid Energy NZ Limited. Appendix 4 provides a full list of the thicknesses used for isopach constructions. Contour lines were not offset across the Benneydale Fault, given that the amount of throw is reported to be less than 15 m and such detail would not be noticeable due to scale. All maps were constructed by hand using Adobe Illustrator.

4.5 PALEOGEOGRAPHIC MAPS

4.5.1 Introduction

The paleogeography of the Mangapehi Coalfield was reconstructed in a series of maps illustrating the timing of marine transgression across the region between early Waitakian to mid/late Waitakian. Maps were constructed using Adobe Illustrator and were based on the synthesis of age, paleoenvironment and paleostructure interpretations. Drillhole locations are shown on each map in order to provide reference points.

CHAPTER 5 - RESULTS

5.1 NANNOFOSSIL ANALYSIS

5.1.1 Drillhole 8795

Of the 20 samples analysed from core 8795, only two contained nannofossils (Table 5.1). Both of these were located within the Aotea Formation and a summary of taxa identified in each sample is presented below.

5.1.1.1 Aotea Formation

180.90 mDH[3] (27B)[4]

Dominated by *Reticulofenestra* spp., particularly those smaller than 5 µm. Less common species include *Coccolithus pelagicus*, *Cyclicargolithus floridanus, Dictyococcites bisectus, Pontosphaera multipora*, *Reticulofenestra filewiczii, Sphenolithus moriformis*, and *Zygrhablithus bijugatus*, along with rare *Chiasmolithus altus*, *Reticulofenestra daviesii* and *Sphenolithus* spp.

182.90 mDH (15A)

Reticulofenestra spp. (2–5 µm) and *R. daviesii* dominate, with common *Reticulofenestra* spp. (<2 µm) and *C. pelagicus.* Less common taxa include *C. altus, Clausicoccus fenestratus, Cyclicargolithus abisectus, C. floridanus, D. bisectus*, *Discoaster deflandrei, P. multipora*, *R. filewiczii, S. moriformis, Sphenolithus* spp., *Umbilicosphaera jafarii* and *Z. bijugatus*. The sample also contains rare *Braarudosphaera bigelowii, Helicosphaera* spp*., Sphenolithus ciperoensis* and *Sphenolithus distentus.*

[3] DH denotes downhole depth.
[4] The number in brackets refers to the sample number. The location of each sample is recorded on the stratigraphic columns in Appendix 2.

5.1.1.2 Summary of assemblage

Aotea Formation is dominated by small specimens (<5 µm) of *Reticulofenestra* spp*.* The lower sample at 182.90 mDH has higher diversity and higher abundances of *C. pelagicus* and *R. daviesii***.** The assemblage includes *C. altus*, *S. ciperoensis* and *S. distentus*, all of which are key biostratigraphic species within the Oligocene. Light microscope images of representative nannofossil specimens from Aotea Formation (core 8795) are presented in Plate 5.1.

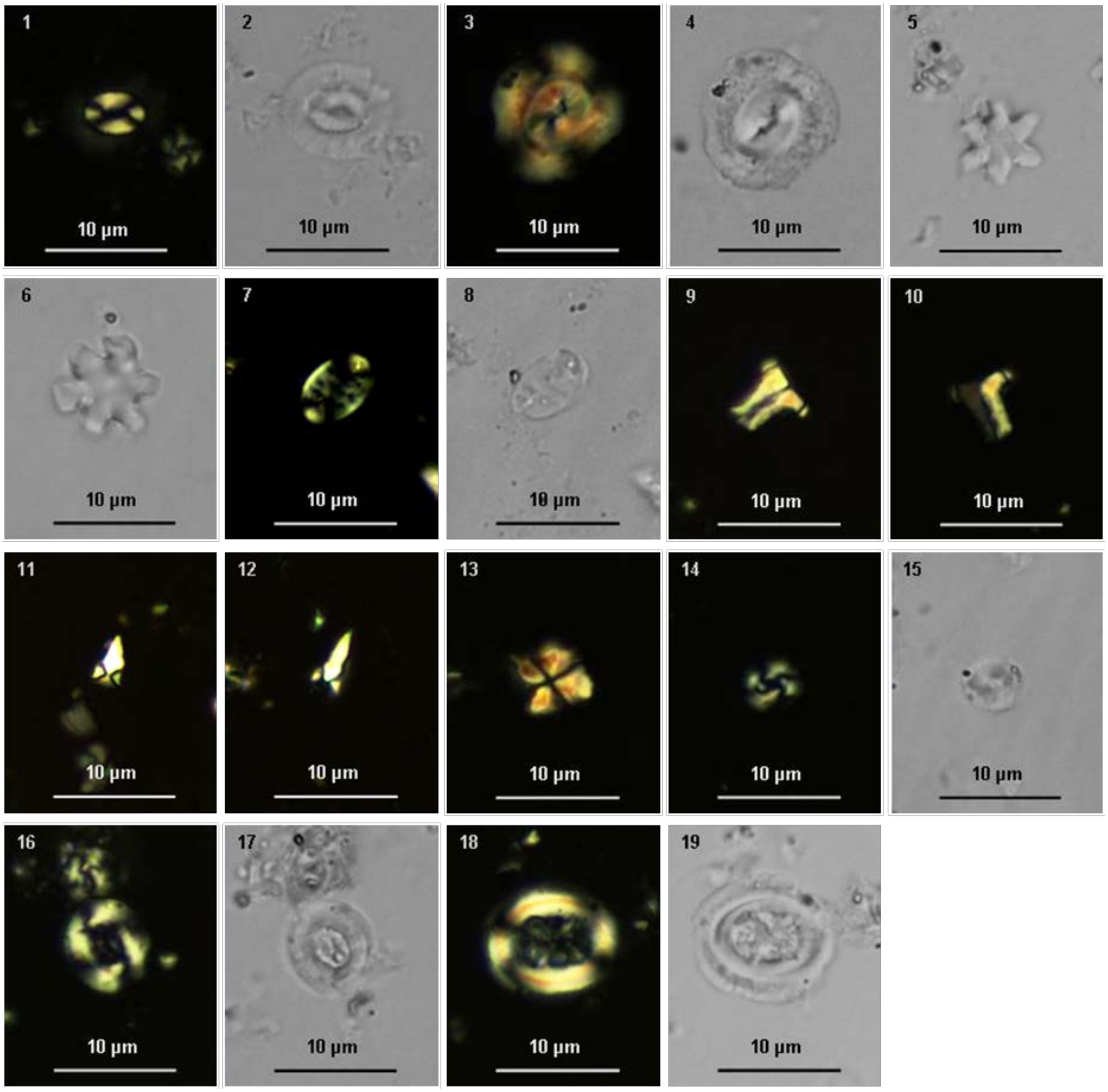

Plate 5.1: LM images of representative nannofossil specimens from Aotea Formation, core 8795:
XP = Cross-polarised light, PL = Plain transmitted light. All images at 1000x magnification. **1, 2.** Coccolithus pelagicus; (1) XP and (2) PL. **3, 4.** *Dictyococcites bisectus*; (3) XP and (4) PL. **5, 6.** *Discoaster deflandrei*; (5) PL and (6) PL. **7, 8.** *Pontosphaera multipora*.; (7) XP and (8) PL. **9, 10.** *Zygrhablithus bijugatus*; (9) XP and (10) PL. **11.** *Sphenolithus ciperoensis*; XP. **12.** *Sphenolithus distentus*; XP. **13**. *Spenolithus moriformis*; XP. **14, 15.** *Reticulofenestra haqii*; (14) XP and (15) PL. **16, 17.** *Reticulofenestra daviesii*; (16) XP and (17) PL. **18, 19.** *Chiasmolithus altus;* (18) XP and (19) PL.

Table 5.1: Relative abundance of individual species and overall abundance of nannofossils in samples taken from core 8795.

	Downhole depth (m)	Sample number	Overall abundance	*Braarudosphaera bigelowii*	*Chiasmolithus altus*	*Clausicoccus fenestratus*	*Coccolithus pelagicus*	*Cyclicargolithus abisectus*	*Cyclicargolithus floridanus*	*Dictyococcites bisectus*	*Discoaster deflandrei*	*Helicosphaera* spp.	*Pontosphaera multipora*	*Reticulofenestra daviesii*	*Reticulofenestra filewiczii*	*Reticulofenestra* spp. <2 µm	*Reticulofenestra* spp. 2–5 µm	*Sphenolithus ciperoensis*	*Sphenolithus distentus*	*Sphenolithus moriformis*	*Sphenolithus* spp.	*Umbilicosphaera jafarii*	*Zygrhablithus bijugatus*
Aotea Formation	180.90	27B	A		R		F		F	F			F	R	F	C	A			F	R		F
	182.82	40B	B																				
	182.90	15A	V	R	F	F	C	F	F	F	F	R	F	A	F	C	V	R	R	F	F	F	F
Waikato Coal Measures	201.13	28B	B																				
	201.29	29B	B																				
	202.66	14A	B																				
	203.80	41B	B																				
	204.90	12A	B																				
	206.30	30B	B																				
	207.00	31B	B																				
	217.90	13A	B																				
	218.05	32B	B																				
	218.90	33B	B																				
	218.96	34B	B																				
	219.34	42B	B																				
	219.95	35B	B																				
	220.07	36B	B																				
	220.41	37B	B																				
	220.71	38B	B																				
	221.90	39B	B																				

5.1.2 Drillhole 8798

The first three samples taken from Mahoenui Group (26B, 52.85 mDH; 25B, 54.00 mDH; 24B, 60.15 mDH) were barren of nannofossils (Table 5.2), as were the four samples taken from the base of Aotea Formation and top of Waikato Coal Measures (11B, 134.00 mDH; 2A, 139.00 mDH; 1A, 141.90 mDH; 3A, 143.44 mDH). Three samples taken at the base of Waikato Coal Measures (7B, 175.73 mDH; 6B, 180.20 mDH; 5B, 185.07 mDH) also showed no evidence of nannofossil content. All other samples proved to be productive and are summarised below.

5.1.2.1 Mahoenui Group

65.78 mDH (23B)

Dominated by *Reticulofenestra* spp. (2–5 µm), with common *Reticulofenestra* spp. (<2 µm), *C. pelagicus,* and *C. floridanus*. *Reticulofenestra daviesii, Reticulofenestra haqii, S. moriformis, Thoracosphaera* spp., and *Umbilicosphaera jafarii* are also present, with rare *Helicosphaera* spp., 'Pyrocyclus' spp., *Reticulofenestra pseudoumbilicus* and *Z. bijugatus.*

69.60 mDH (22B)

Dominated once again by *Reticulofenestra* spp. (2–5 µm) with common *C. pelagicus* and *S. moriformis*. Less common taxa include *C. floridanus, Discoaster* spp., *Helicosphaera* spp., *R. daviesii, R. filewiczii, R. haqii* and *Reticulofenestra* spp. (<2 µm).

74.60 mDH (21B)

Reticulofenestra spp. (2–5 µm) dominates this sample, with *C. pelagicus, C. floridanus, R. daviesii, R. haqii, Reticulofenestra* spp. (<2 µm) and *S. moriformis* present in low abundances. Rare taxa include *C. abisectus, D. deflandrei, Helicosphaera* spp. and *U. jafarii.*

78.98 mDH (20B)

This sample contains common *C. floridanus* and *Reticulofenestra* spp. (2–5 µm). *Coccolithus pelagicus, Reticulofenestra* spp. (<2 µm), *S. moriformis* and *U. jafarii* are less common. Rare *C. fenestratus*, *Helicosphaera* spp., *R. daviesii, R. filewiczii, Reticulofenestra lockeri,* and *Z. bijugatus* are also observed.

83.70 mDH (19B)

This sample is dominated by *Reticulofenestra* spp. (2–5 µm), with common *Reticulofenestra* spp. (<2 µm) and *C. floridanus*. Less common taxa include *C. pelagicus, D. bisectus, Helicosphaera* spp., *R. haqii, S. moriformis, Thoracosphaera* spp. and *U. jafarii.*

90.77 mDH (18B)

Coccolithus pelagicus, C. floridanus, Reticulofenestra spp. (<2 µm) and *Reticulofenestra* spp. (2–5 µm) are all abundant in this sample, with common *U. jafarii*. *Chiasmolithus altus*, *R. daviesii, R. filewiczii, R. haqii, S. moriformis* and *Z. bijugatus* are less common. Rare *D. deflandrei* is also observed.

94.87 mDH (17B)

This sample is similar to 18B (90.77 mDH) with abundant *C. pelagicus, C. floridanus, Reticulofenestra* spp. (<2 µm) and *Reticulofenestra* spp. (2–5 µm). *Dictyococcites bisectus, R. daviesii, R. filewiczii, S. moriformis, U. jafarii* and *Z. bijugatus* are present in low abundances.

99.40 mDH (5A)

The assemblage is dominated by *Reticulofenestra* spp. (2–5 µm), which is very abundant in this sample. *Coccolithus pelagicus, C. floridanus* and *Reticulofenestra* spp. (<2 µm) are abundant, along with *U. jafarii*. Less common taxa include *C. fenestratus, Coronocyclus nitescens, D. deflandrei, Helicosphaera* spp., *P. multipora*, 'Pyrocyclus' spp., *R. daviesii, R. filewiczii, Reticulofenestra* spp. (5–8 µm) and *S. moriformis.*

5.1.2.2 Summary of assemblage

Coccolithus pelagicus, C. floridanus, and *Reticulofenestra* spp. (<2 µm) are abundant in the lower portion of the Mahoenui Group. *Dictyococcites bisectus* is also observed in the lower portion of the Mahoenui Group and its absence in the upper section is of biostratigraphic importance. The upper sequence of Mahoenui Group is dominated by small specimens of *Reticulofenestra* spp., particularly those between 2–5 µm. A number of less common to rare taxa are observed throughout the unit. Light microscope images of representative nannofossil specimens from Mahoenui Group (core 8798) are presented in Plate 5.2.

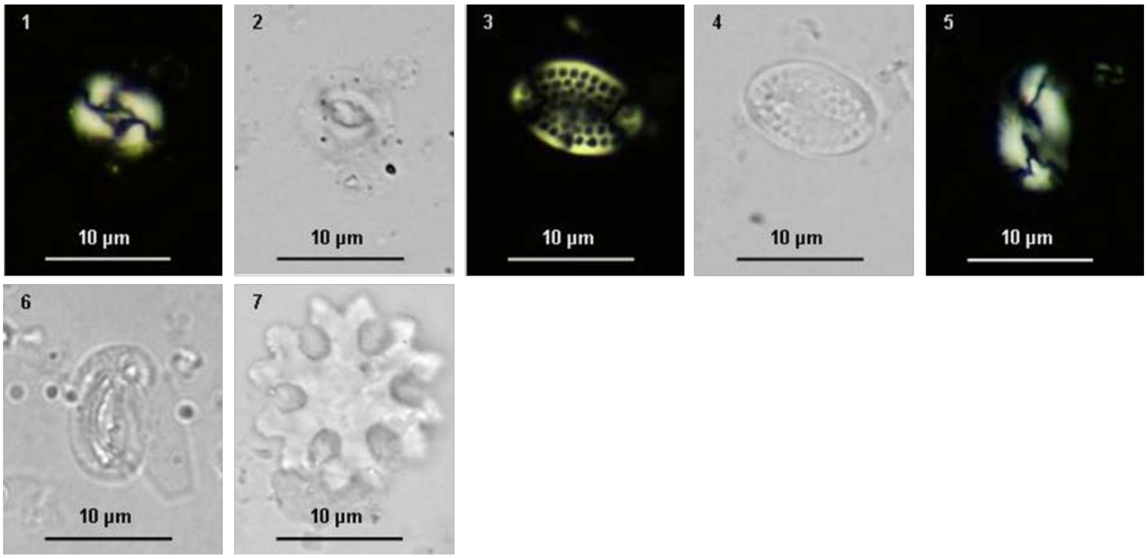

Plate 5.2: LM images of representative nannofossil specimens from Mahoenui Group, core 8798:
XP = Cross-polarised light, PL = Plain transmitted light. All images at 1000x magnification. **1, 2.** *Reticulofenestra daviesii*; (1) XP and (2) PL. **3, 4.** *Pontosphaera multipora*; (3) XP and (4) PL. **5, 6.** *Helicosphaera* spp.; (5) XP and (6) PL. **7.** *Discoaster deflandrei*; (7) PL.

5.1.2.3 Aotea Formation

<u>100.40 mDH (6A)</u>

This sample contains abundant *C. floridanus, Reticulofenestra* spp. (<2 µm) and *Reticulofenestra* spp. (2–5 µm), with common *C. pelagicus. Chiasmolithus altus, C. nitescens, D. deflandrei, Helicosphaera* spp., *P. multipora*, *R. filewiczii, S. moriformis* and *Z. bijugatus* are less common.

<u>105.38 mDH (16B)</u>

Reticulofenestra spp. (2–5 μm) dominates the assemblage in this sample, with common *C. floridanus.* Less common taxa include *C. pelagicus, D. bisectus, D. deflandrei, Helicosphaera* spp., *R. filewiczii, Reticulofenestra* spp. (<2 μm), *S. moriformis* and *U. jafarii*.

<u>110.20 mDH (15B)</u>

Like sample 16B (105.38 mDH), *Reticulofenestra* spp. (2–5 μm) dominates the assemblage, with common *C. floridanus.* Less common are *C. pelagicus, Helicosphaera* spp., *R. daviesii, Reticulofenestra* spp. (<2 μm) and *S. moriformis. Reticulofenestra filewiczii, R. haqii* and *U. jafarii* also rarely occur.

<u>115.85 mDH (14B)</u>

Abundant *Reticulofenestra* spp. (2–5 μm), with common *Reticulofenestra* spp. (<2 μm) characterizes this sample. *Clausicoccus fenestratus, C. pelagicus, C. floridanus, R. daviesii, R. filewiczii* and *U. jafarii* are present in low abundances.

<u>120.37 mDH (13B)</u>

This sample is dominated by *Reticulofenestra* spp., particularly those smaller than 5 μm, with common *C. pelagicus.* Less common taxa include *C. floridanus, D. bisectus, Helicosphaera* spp., *P. multipora*, *R. daviesii, R. filewiczii, R. lockeri, S. moriformis* and *Z. bijugatus.* Rare *C. fenestratus, D. deflandrei* and *Thoracosphaera* spp. also occur.

<u>125.04 mDH (12B)</u>

The assemblage is similar to that in sample 13B (120.37 mDH) with *Reticulofenestra* spp. dominating once again, with specimens smaller than 5 μm being the most abundant. Common taxa include *C. pelagicus* and *C. floridanus. Dictyococcites bisectus, R. daviesii, R. filewiczii, R. lockeri, S. moriformis* and *U. jafarii* are less common. *Chiasmolithus* spp., *C. fenestratus, P. multipora* and *Thoracosphaera* spp. are rare.

129.70 mDH (4B)

No one taxon dominates this sample with *C. floridanus, R. daviesii, Reticulofenestra dictyoda, Reticulofenestra* spp. (2–5 µm) and *Thoracosphaera* spp. all present in low abundances. Rare taxa include *C. abisectus, D. deflandrei* and *Reticulofenestra gelida.*

5.1.2.4 Summary of assemblage

As in core 8795, Aotea Formation is dominated by *Reticulofenestra* spp. (<5 µm). The abundance of *C. floridanus* and *U. jafarii* increases upwards, but overall diversity remains fairly constant. The basal section of the Aotea Formation in core 8798 is barren of nannofossils. Light microscope images of representative nannofossil specimens from Aotea Formation (core 8798) are presented in Plate 5.3.

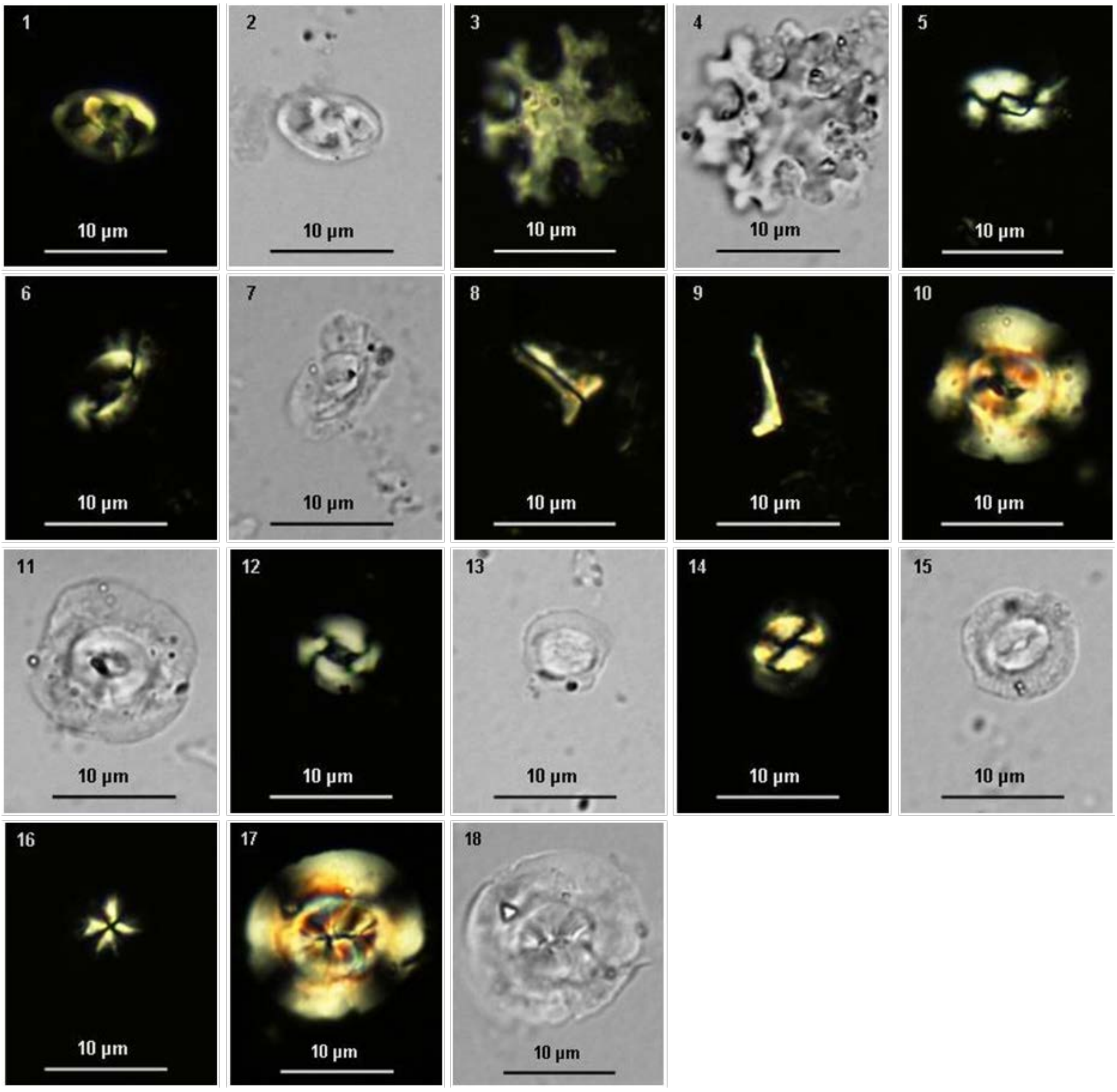

Plate 5.3: LM images of representative nannofossil specimens from Aotea Formation, core 8798:
XP = Cross-polarised light, PL = Plain transmitted light. All images at 1000x magnification. **1, 2.** *Neococcolithes dubius*; (1) XP and (2) PL. **3, 4.** *Discoaster deflandrei*; (3) XP and (4) PL. **5, 6, 7.** *Helicosphaera* sp.; (5), (6) XP and (7) PL. **8, 9.** *Zygrhablithus bijugatus*; (8) and (9) XP. **10, 11.** *Reticulofenestra filewiczi*; (10) XP and (11) PL. **12, 13.** *Reticulofenestra daviesii*; (12) XP and (13) PL. **14, 15.** *Coccolithus pelagicus;* (14) XP and (15) PL. **16.** *Sphenolithus moriformis;* (16) XP. **17, 18.** *Dictyococcites bisectus;* (17) XP and (18) PL.

5.1.2.5 Waikato Coal Measures

150.65 mDH (10B)

Coccolithus pelagicus and *Reticulofenestra* spp. (2–5 μm) are abundant in this sample. Common *C. floridanus* and *Reticulofenestra* spp. (<2 μm), with less common *D. bisectus, P. multipora, R. daviesii, R. filewiczii, S. moriformis* and *Z. bijugatus* also occur. Rare taxa include *C. abisectus* and *S. ciperoensis.*

155.80 mDH (9B)

This sample is dominated by *Reticulofenestra* spp. (2–5 μm), with common *C. pelagicus* and *Reticulofenestra* spp. (<2 μm). A number of other taxa are present in low abundances including *Coccolithus* spp., *C. floridanus, D. bisectus, Helicosphaera* spp., *P. multipora, R. daviesii, R. filewiczii, Reticulofenestra* spp. (5–8 μm), *S. moriformis* and *Sphenolithus* spp.

160.60 mDH (8B)

Reticulofenestra spp. (2–5 μm) dominates this sample, with *C. altus, C. pelagicus, C. floridanus, D. bisectus, R. filewiczii, Reticulofenestra* spp. (<2 μm), *S. moriformis* and *Z. bijugatus* observed in low abundances. A number of taxa are present in rare numbers including, *C. fenestratus, P. multipora, R. daviesii, Reticulofenestra* spp. (8–10 μm) and *U. jafarii*.

165.40 mDH (7A)

Reticulofenestra spp. (2–5 μm) is very abundant and dominates this sample. *Coccolithus pelagicus* and *Reticulofenestra* spp. (<2 μm) are common, with *C. fenestratus, C. floridanus, D. bisectus, P. multipora, R. daviesii, R. filewiczii, Reticulofenestra* spp. (5–8 μm), *S. moriformis* and *Z. bijugatus* less common. *Discoaster deflandrei*, *Helicosphaera* spp., *R. gelida, S. ciperoensis* and *S. distentus* occur sporadically.

<u>168.00 mDH (8A)</u>

Reticulofenestra spp. (<5 μm) dominates the assemblage once again, along with common *C. pelagicus, C. floridanus* and *Reticulofenestra* spp. (5–8 μm). Less common taxa include *C. altus*, *C. fenestratus, D. bisectus, Discoaster* spp., *Helicosphaera* spp., *P. multipora, R. daviesii, R. lockeri, Reticulofenestra* spp. (8–10 μm), *S. moriformis* and *U. jafarii.*

<u>169.67 mDH (9A)</u>

This sample contains very abundant *Reticulofenestra* spp. (2–5 μm), along with abundant *C. pelagicus, C. floridanus* and *Reticulofenestra* spp. (<2 μm). A number of other taxa are present in low abundances including *C. altus*, *C.fenestratus, D. bisectus, P. multipora, R. daviesii, R. filewiczii, R. haqii, S. distentus, S. moriformis* and *Z. bijugatus*. Rare taxa include *C. nitescens*, *D. deflandrei*, *Helicosphaera* spp., *Reticulofenestra* spp. (5–8 μm) and *U. jafarii.*

5.1.2.6 Summary of assemblage

Nannofossil assemblages from Waikato Coal Measures are dominated by *Reticulofenestra* spp., particularly those 2–5 μm. *Coccolithus pelagicus, C. floridanus* and *Reticulofenestra* spp. (<2 μm) are common to abundant throughout. Diversity increases with depth, with a number of additional taxa observed in the lower section. The key biostratigraphic species *C. altus, S. ciperoensis* and *S. distentus* all occur in Waikato Coal Measures. The upper section of the unit is barren of nannofossils. Light microscope images of representative nannofossil specimens from Waikato Coal Measures (core 8798) are presented in Plate 5.4.

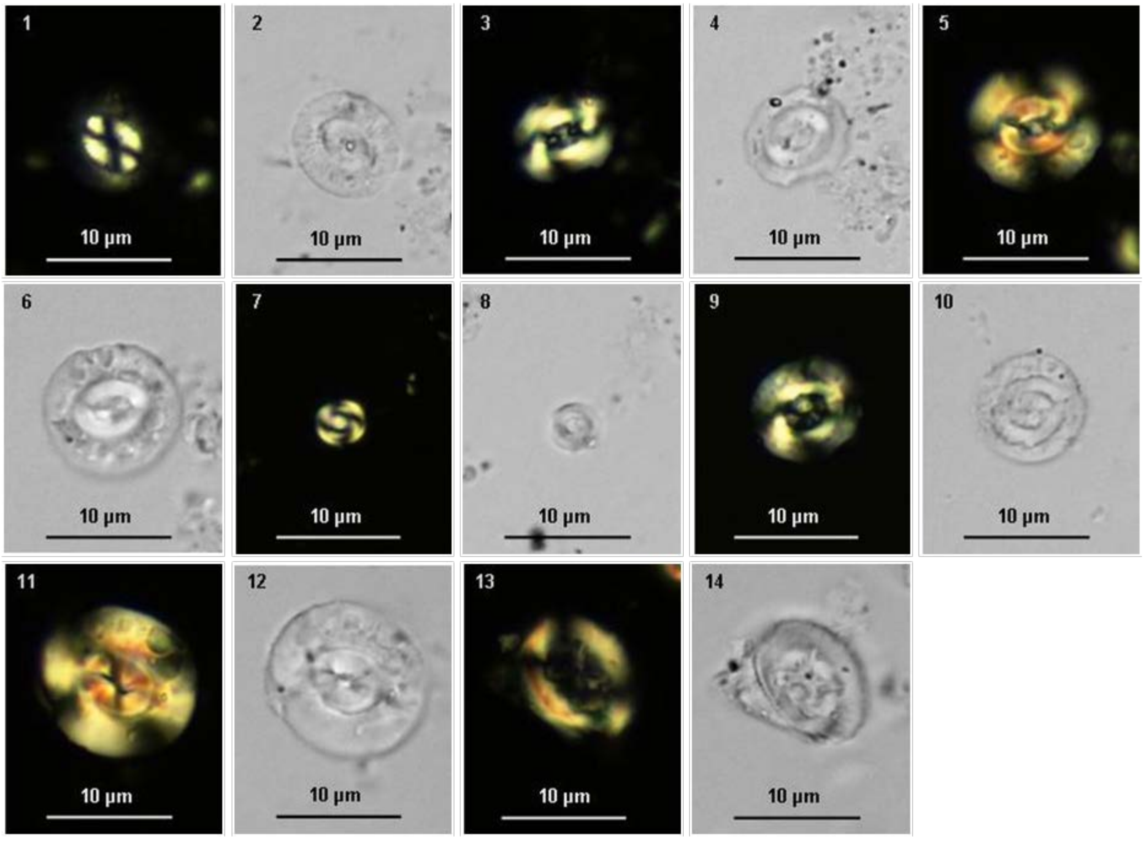

Plate 5.4: LM images of representative nannofossil specimens from Waikato Coal Measures, core 8798:
XP = Cross-polarised light, PL = Plain transmitted light. All images at 1000x magnification. **1, 2.** *Coccolithus pelagicus*; (1) XP and (2) PL. **3, 4.** *Reticulofenesra daviesii*; (3) XP and (4) PL. **5, 6.** *Reticulofenestra filewiczii*; (5) XP and (6) PL. **7, 8.** 'Pyrocyclus' sp.; (7) XP and (8) PL. **9, 10.** *Reticulofenestra lockeri*; (9) XP and (10) PL. **11, 12.** *Dictyococcites bisectus*; (11) XP and (12) PL. **13, 14.** *Chiasmolithus altus;* (13) XP and (14) PL.

Table 5.2: Relative abundance of individual species and overall abundance of nannofossils in samples taken from core 8798.

	Downhole depth (m)	Sample number	Overall abundance	*Chiasmolithus altus*	*Chiasmolithus* spp.	*Clausicoccus fenestratus*	*Coccolithus pelagicus*	*Coccolithus* spp.	*Coronocyclus nitescens*	*Cyclicargolithus abisectus*	*Cyclicargolithus floridanus*	*Dictyococcites bisectus*	*Discoaster deflandrei*	*Discoaster* spp.	*Helicosphaera* spp.	*Pontosphaera multipora*	'*Pyrocyclus*' spp.	*Reticulofenestra daviesii*	*Reticulofenestra dictyoda*	*Reticulofenestra filewiczii*	*Reticulofenestra gelida*	*Reticulofenestra haqii*	*Reticulofenestra lockeri*	*Reticulofenestra pseudoumbilica*	*Reticulofenestra* spp. <2 µm	*Reticulofenestra* spp. 2–5 µm	*Reticulofenestra* spp. 5–8 µm	*Reticulofenestra* spp. 8–10 µm	*Sphenolithus ciperoensis*	*Sphenolithus distentus*	*Sphenolithus moriformis*	*Sphenolithus predistentus*	*Sphenolithus* spp.	*Thoracosphaera* spp.	*Umbilicosphaera jafarii*	*Zygrhablithus bijugatus*
Mahoenui Group	52.85	26B	B																																	
	54.70	25B	B																																	
	60.15	24B	B																																	
	65.78	23B	A				C				C				R		R	F				F		R	C	A					F			F	F	R
	69.60	22B	A				C				F			F	F			F		F		F			F	A					C					
	74.60	21B	A				F			R	F		R		R			F				F			F	A					F				R	
	78.98	20B	A			R	F				C				R			R		R			R		F	C					F				F	R
	83.70	19B	A				F				C	F			F							F			C	A					F			F	F	
	90.77	18B	A	F			A				A		R					F		F		F			A	A					F				C	F
	94.87	17B	V				A				A	F						F		F					A	A					F				F	F
	99.40	5A	V			F	A		F		A		F		F	F	F	F		F					A	V	F				F				A	
Aotea Formation	100.40	6A	V	F			C		F		A		F		F	F				F					A	A					F				A	F
	105.38	16B	A				F				C	F	F		F					F					F	A					F				F	
	110.20	15B	A				F				C				F			F		R		R			F	A					F				R	
	115.85	14B	A			F	F				F							F		F					C	A									F	
	120.37	13B	V			R	C				F	F	R		F	F		F		F			F		A	A					F			R	F	F
	125.04	12B	A		R	R	C				C	F				R		F		F			F		A	A					F			R	F	
	129.70	4A	A							R	F		R					F	F		R					F								F		
	134.00	11B	B																																	

	Downhole depth (m)	Sample number	Overall abundance	*Chiasmolithus altus*	*Chiasmolithus* spp.	*Clausicoccus fenestratus*	*Coccolithus pelagicus*	*Coccolithus* spp.	*Coronocyclus nitescens*	*Cyclicargolithus abisectus*	*Cyclicargolithus floridanus*	*Dictyococcites bisectus*	*Discoaster deflandrei*	*Discoaster* spp.	*Helicosphaera* spp.	*Pontosphaera multipora*	'Pyrocyclus' spp.	*Reticulofenestra daviesii*	*Reticulofenestra dictyoda*	*Reticulofenestra filewiczii*	*Reticulofenestra gelida*	*Reticulofenestra hagii*	*Reticulofenestra lockeri*	*Reticulofenestra pseudoumbilica*	*Reticulofenestra* spp. <2 µm	*Reticulofenestra* spp. 2–5 µm	*Reticulofenestra* spp. 5–8 µm	*Reticulofenestra* spp. 8–10 µm	*Sphenolithus ciperoensis*	*Sphenolithus distentus*	*Sphenolithus moriformis*	*Sphenolithus predistentus*	*Sphenolithus* spp.	*Thoracosphaera* spp.	*Umbilicosphaera jafarii*	*Zygrhablithus bijugatus*
	139.00	2A	B																																	
Waikato Coal Measures	141.90	1A	B																																	
	143.44	3A	B																																	
	150.65	10B	V				A			R	C	F				F		F		F					C	A			R		F		R			F
	155.80	9B	A				C	F			F	F			F	F		F		F					C	A	F				F		F			
	160.60	8B	A	F		R	F				F	F				R		R		F					F	A		R			F				R	F
	165.40	7A	V			F	C				F	F	R		R	F	R	F		F	R				C	V	F		R	R	F					F
	168.00	8A	V	F		F	C				C	F		F	F	F		F					F		A	A	C	F			F				F	
	169.67	9A	V	F		F	A		R		A	F	R		R	F		F		F		F			A	V	R			F	F				R	F
	175.73	7B	B																																	
	180.20	6B	B																																	
	185.07	5B	B																																	

5.2 PALYNOLOGICAL ANALYSIS

5.2.1 Drillhole 8795

Ten core samples were analysed from drillhole 8795, but due to the fragmentary nature of this core, samples were restricted to sections within the Aotea Formation and Waikato Coal Measures and did not cover the complete stratigraphic succession. Figure 5.1 shows the dominant spore and pollen taxa for each sample and a full record of spores and pollen identified from core 8795 is provided in Appendix 5. Photomicrographs of key taxa identified in samples from both cores are presented in Plate 5.5 and Plate 5.6.

5.2.1.1 Aotea Formation

<u>180.90 mDH (27B)</u>

This sample contains abundant dinoflagellates but spores and pollen are few and not enough to count.

5.2.1.2 Waikato Coal Measures

<u>201.13 mDH (28B)</u>

Myrtaceae pollen dominates with *Myrtaceidites parvus* representing 30% of the sample. *Laevigatosporites* spp. and *Nothofagidites cranwelliae* are common, along with a number of different tricolpate and tricolporate pollens.

<u>203.80 mDH (41B)</u>

This sample contains abundant charcoal but very rare, poorly preserved spores and pollen. There is insufficient pollen to count.

<u>206.30 mDH (30B)</u>

The assemblage is dominated by *Cyathidites* spp. and smooth monolete spores (*Laevigatosporites* spp.), which account for 24.7% and 21.7% of the sample respectively. *N. cranwelliae* and *Rhoipites sphaerica* are also common.

<u>207.00 mDH (31B)</u>

Haloragacidites harrisii (*Casuarina*) is the dominant taxa, constituting 41% of the assemblage, with common *M. parvus*.

218.05 mDH (32B)

This sample is dominated by *N. cranwelliae*, with common *Nothofagidites matauraensis*, *M. parvus*, *H. harrisii*, *Cyathidites* spp. and smooth monolete spores (*Laevigatosporites* spp.).

218.96 mDH (34B)

The assemblage is similar to that in sample 32B (218.05 mDH), with *N. cranwelliae* dominating (22%) and common *N. matauraensis*, *M. parvus*, *Cyathidites* spp. and *Laevigatosporites* spp. The sample also contains common *Rhoipites karamuensis*.

220.07 mDH (36B)

No one taxon dominates this sample, but *N. cranwelliae, H. harrisii and Laevigatosporites* spp. are common. Other common taxa include *Myrtaceidites mesonesus* and *Stephanocolpites sphericus*.

220.71 mDH (38B)

All previous samples contain rare *Podocarpidites puteus* but in this sample it becomes the dominant taxon, accounting for 44% of the assemblage. *N. cranwelliae* is also common.

221.90 mDH (39B)

This sample is very similar to 34B (218.96 mDH), with *N. cranwelliae* being the dominant taxon once again. Also common are *N. matauraensis*, *M. parvus*, *Cyathidites* spp. and *Laevigatosporites* spp.

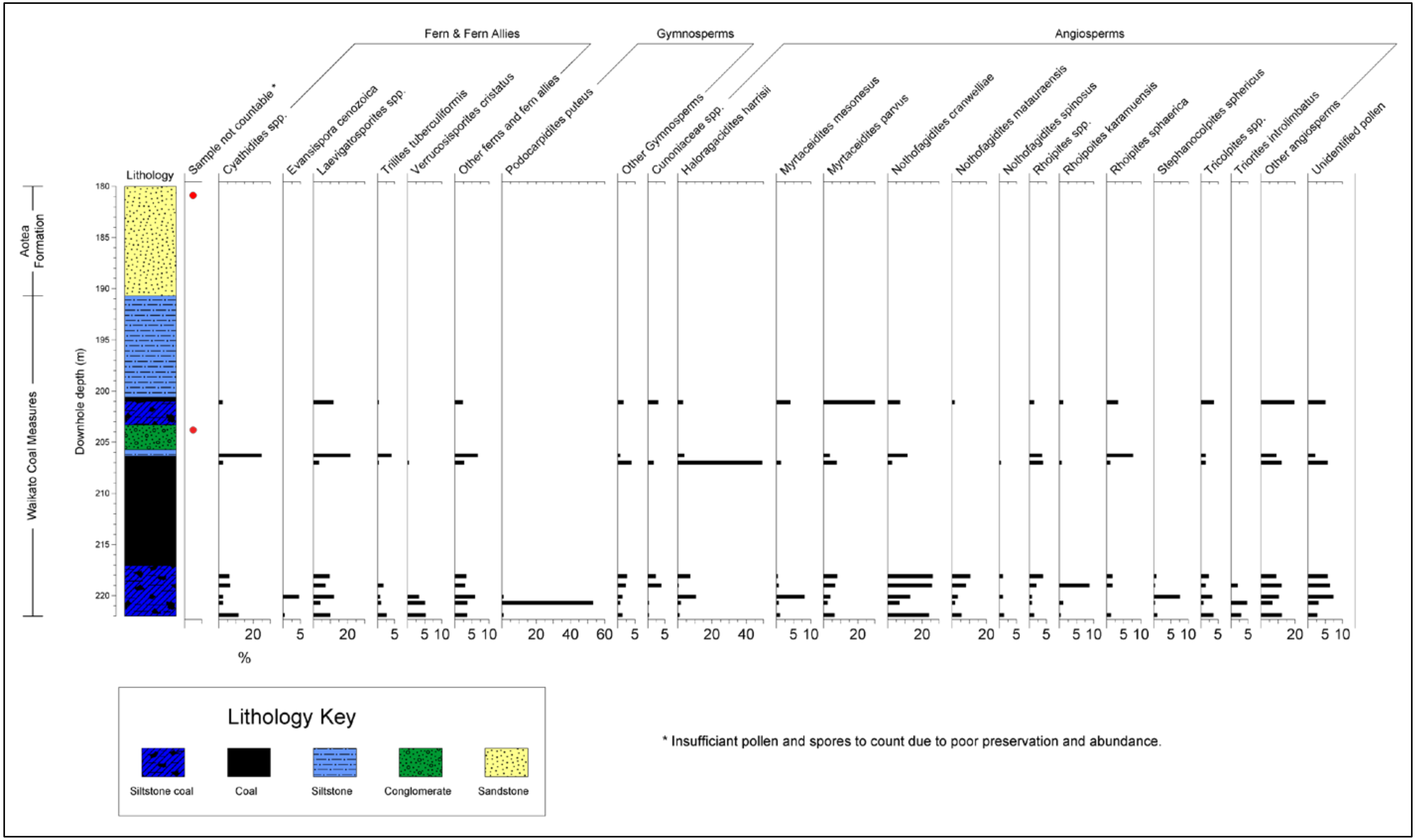

Figure 5.1: Relative pollen diagram for Drillhole 8795 showing dominant spore and pollen types.

5.2.2 Drillhole 8798

Fourteen samples were analysed from core extracted from drillhole 8798, and these span the section between Mahoenui Group to Manaia Hill Group. Dominant spore and pollen taxa for each sample are shown in Figure 5.2 and a full record of spores and pollen identified from core 8798 is presented in Appendix 5.

5.2.2.1 Mahoenui Group

52.85 mDH (26B), 65.78 mDH (23B), 99.40 mDH (5A)

The preservation and abundance of spores and pollens in these three samples was very poor and as a result no counts were made. Charcoal was present in two of the samples and is probably recycled or concentrated at shorelines. Sample 5A contained rare *Clavastephanocolporites meleosus*, a pollen type that has not been identified in any other region of New Zealand. It does occur in Australia however, and has a wide age range. Dinoflagellates are present in both samples.

5.2.2.2 Aotea Formation

100.40 mDH (6A)

This sample contains abundant dinoflagellates and some charcoal but spores and pollen were insufficient to count.

125.04 mDH (12B)

Pollens and spores in this sample are sparse and poorly preserved. The assemblage is dominated by *N. cranwelliae*, with common *Nothofagidites spinosus*, *Cyathidites* spp. and *Laevigatosporites* spp. The sample also contains abundant dinoflagellates.

5.2.2.3 Waikato Coal Measures

141.90 mDH (1A)

This sample is dominated by *N. cranwelliae* and *M. parvus*, which account for 44% and 21% of the sample, respectively. Conifer pollen is more prominent in this sample than in any previous sample from this drillhole. Dinoflagellates do not occur but charcoal is present.

155.80 mDH (9B), 169.67 mDH (9A)

Preservation in these samples is poor with many fragments present and insufficient spores and pollen to count. Dinoflagellates and charcoal occur in both samples.

175.73 mDH (7B)

Like sample 1A (141.90 mDH), *N. cranwelliae* and *M. parvus* dominate the assemblage. There are no dinoflagellates or charcoal present.

185.07 mDH (5B)

The assemblage is dominated by *Cyathidites* spp. and smooth monolete spores (*Laevigatosporites* spp.), with common *Trilites tuberculiformis* and *N. cranwelliae*. Like sample 7B, dinoflagellates and charcoal do not occur in this sample.

5.2.2.4 Manaia Hill Group

189.50 mDH (10A), 195.60 mDH (4B), 205.60 mDH (2B), 210.60 mDH (1B)

All four samples contain very few *in situ* spores or pollen and a lot of modern contaminants. Charcoal occurs in the three oldest samples and the presence of the fresh- to brackish-water colonial alga *Botryococcus* is noted in samples 10A (189.50 mDH) and 2B (205.60 mDH).

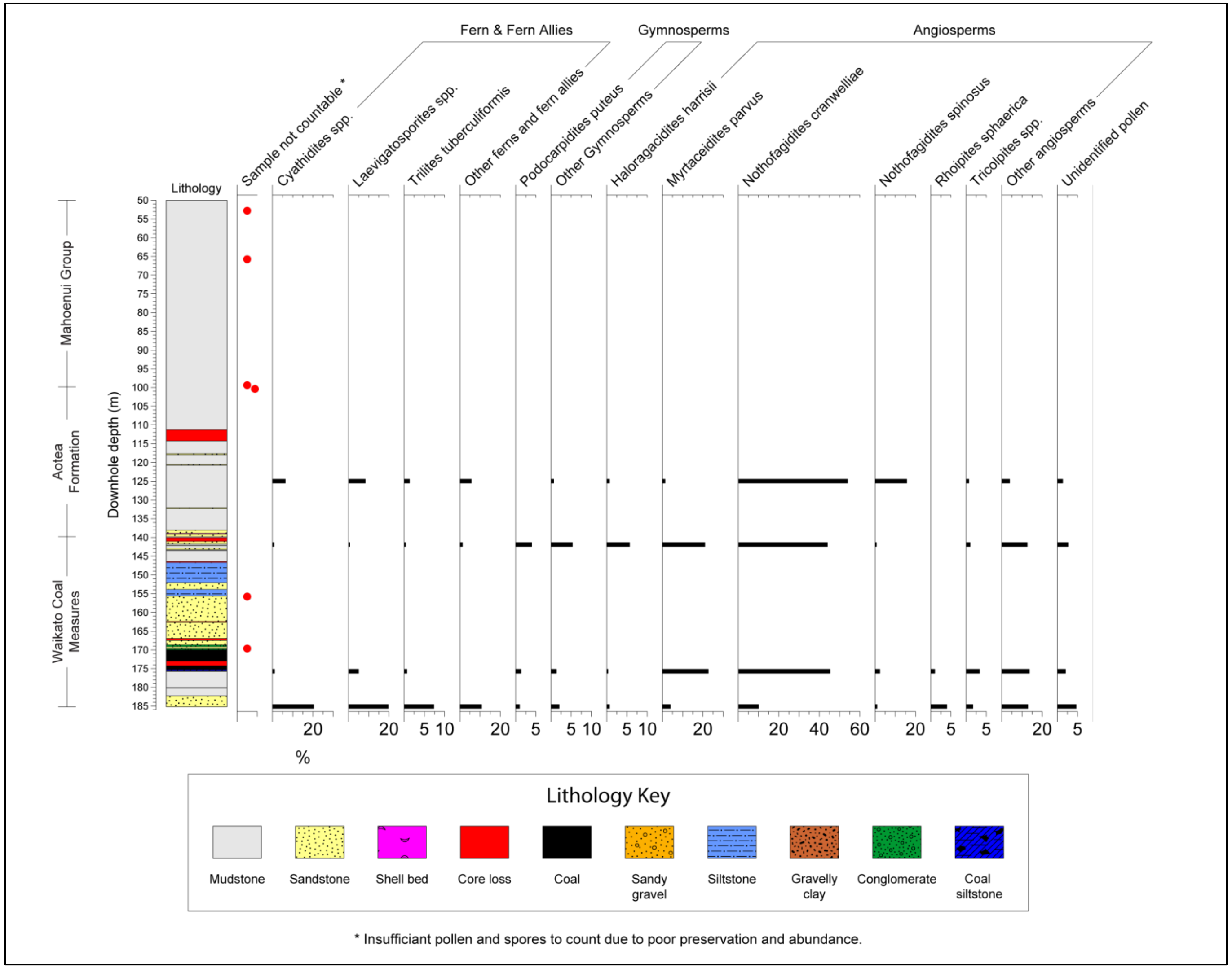

Figure 5.2: Relative pollen diagram for Drillhole 8798 showing dominant spore and pollen types.

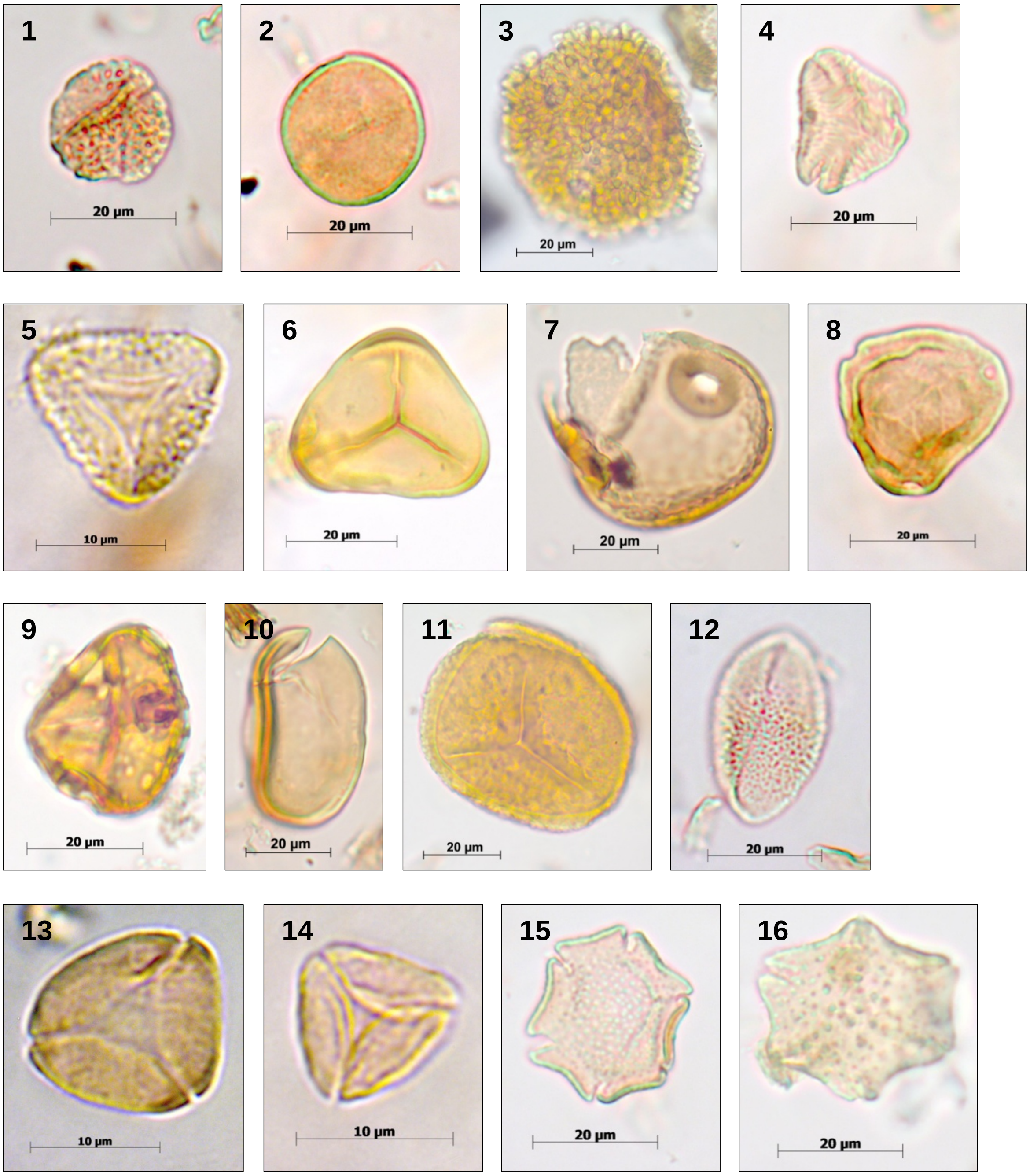

Plate 5.5: Photomicrographs of representative palynomorphs from Mangapehi cores 8795 and 8798: **1.** *Anisotricolporites truncatus*. **2.** *Assamiapollenites incognitus*. **3.** *Clavastephanocolporites meleosus*. **4.** *Cranwellia striata*. **5.** *Cupanieidites insularis*. **6.** *Cyathidites* sp. **7.** *Diporites* n.sp. **8.** *Haloragacidites harrisii*. **9.** *Kuylisporites waterbolkii*. **10.** *Laevigatosporites* sp. **11.** *Latrobosporites marginis*. **12.** *Liliacidites variegatus*. **13.** *Myrtaceidites mesonesus*. **14.** *Myrtaceidites parvus*. **15.** *Nothofagidites cranwelliae*. **16.** *Nothofagidites matauraensis*. Images courtesy of Liz Kennedy, GNS Science.

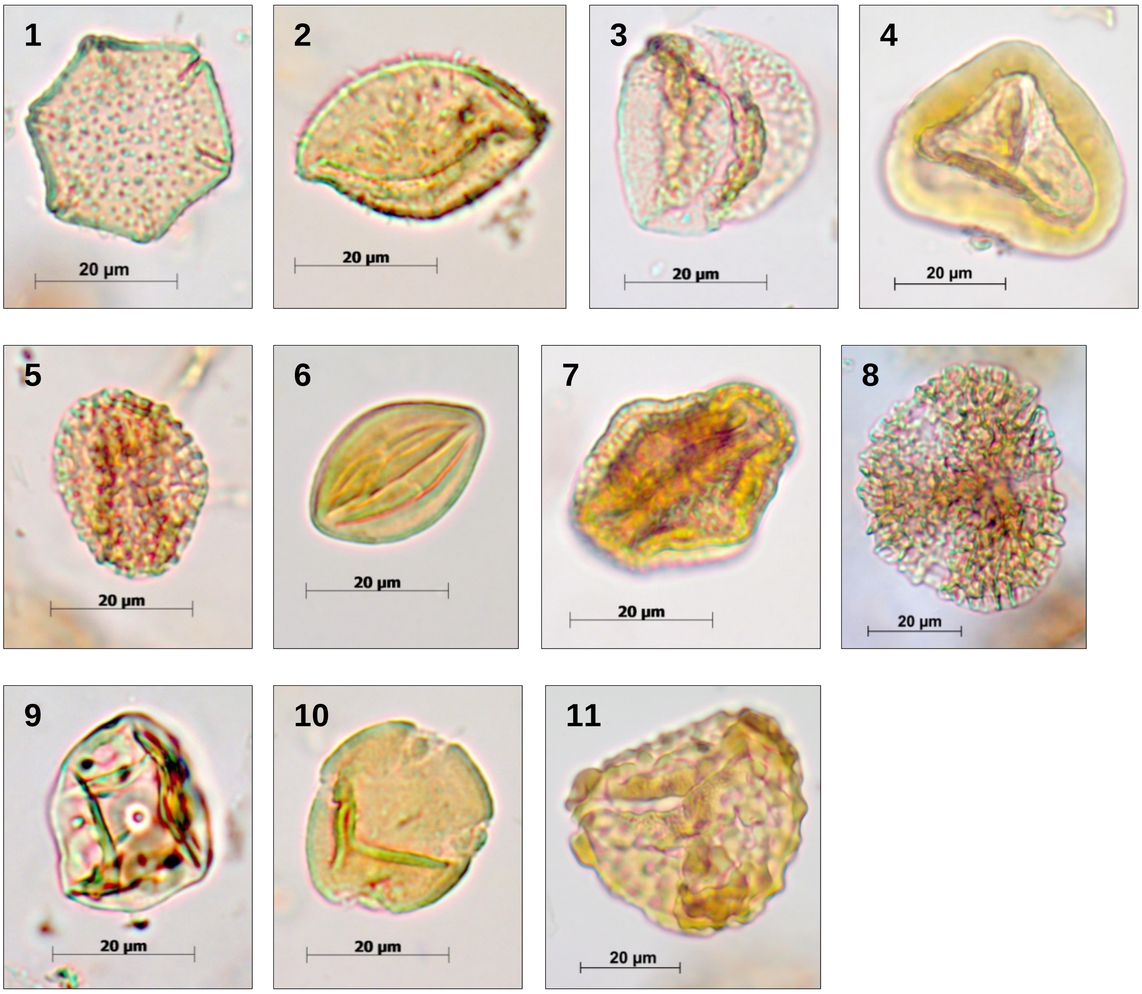

Plate 5.6: Photomicrographs of representative palynomorphs from Mangapehi cores 8795 and 8798: **1.** *Nothofagidites spinosus*. **2.** *Nupharipollis mortenensis*. **3.** *Podocarpidites puteus*. **4.** *Polypodiaceoisporites papuanus*. **5.** *Rhoipites aequatorius*. **6.** *Rhoipites karamuensis*. **7.** *Rhoipites sphaerica*. **8.** *Rubipollis oblatus*. **9**. *Sparsipollis papillatus*. **10.** *Stephanocolpites sphericus*. **11.** *Trilites tuberculiformis*. Images courtesy of Liz Kennedy, GNS Science.

5.3 ISOPACH ANALYSIS

The isopach maps presented in this section are restricted to the area of the Mangapehi Coalfield, however the same units occur widely across the King Country and Waikato areas. The density of drillholes within the Mangapehi Coalfield is reasonably low and as a result the isopach maps provide a rather broad profile of the distribution of each lithological unit. Despite this, a number of trends can be observed.

5.3.1 Mahoenui Group

The isopach map of the Mahoenui Group (Figure 5.3) shows that maximum thickness occurs in the northwest of the coalfield, where it reaches up to 140 m. Thickness of the unit decreases to the south and also in an easterly direction, towards the centre of the coalfield. Mahoenui Group appears to pinch out in this central area before thickening in a northeasterly direction into the Tiroa Fault.

5.3.2 Aotea Formation

The Aotea Formation reaches a maximum thickness of approximately 130 m, along the northwestern boundary of the Mangapehi Coalfield (Figure 5.4). Like the Mahoenui Group, a general decrease in thickness occurs in a southerly direction. In the eastern region of the coalfield an area of thinner sediments extends up into the coalfield. Aotea Formation on the eastern side of this area increases in thickness and then thins again to the southeast. Sediments along the eastern boundary are truncated by the Tiroa Fault.

5.3.3 Waikato Coal Measures

Isopachs of Waikato Coal Measures show similar trends to those seen in the two previous maps, with maximum thickness seen in the northwest and a thinning towards the southern region of the coalfield (Figure 5.5). An area of thicker sediments extends down into the coalfield in the eastern region of the coalfield. Waikato Coal Measures thin out to the east of the coalfield, as they abut the Tiroa Fault.

Analysis of coal seam thickness shows a thinning of the Mangapehi seam to the south of the coalfield and maximum thickness in the northern area (Figure 5.6), which follows the same trends seen in the thickness of the coal measures themselves. To the west, the coal seam pinches out and is not observed in the four drillholes located in the southwest region of the coalfield. However, these holes do contain beds of black/brown shale which may correlate with the Mangapehi seam.

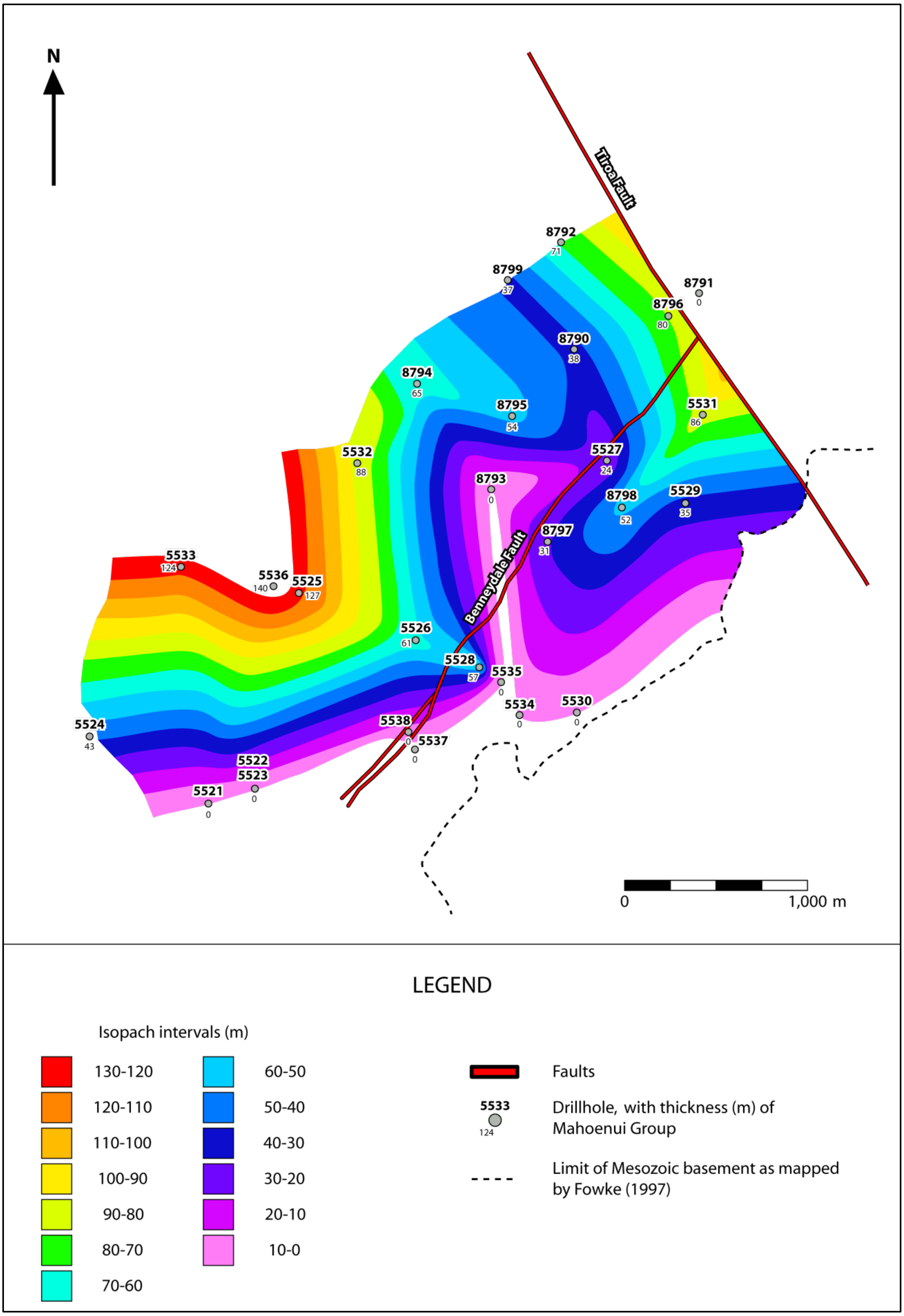

Figure 5.3: Isopach map showing the thickness of Mahoenui Group in the Mangapehi Coalfield. Isopachs are shown in 10 metre intervals.

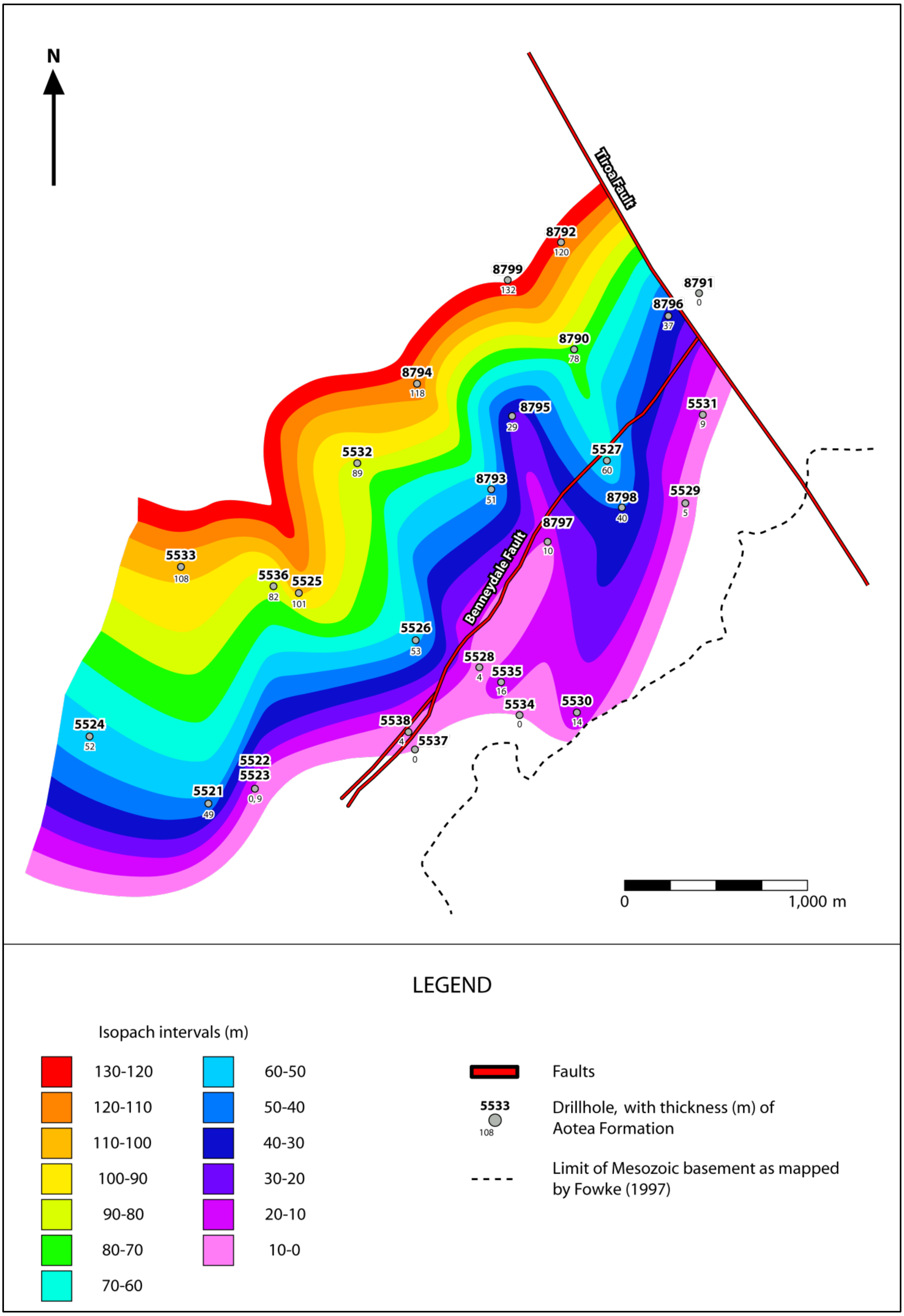

Figure 5.4: Isopach map showing the thickness of Aotea Formation in the Mangapehi Coalfield. Isopachs are shown in 10 metre intervals.

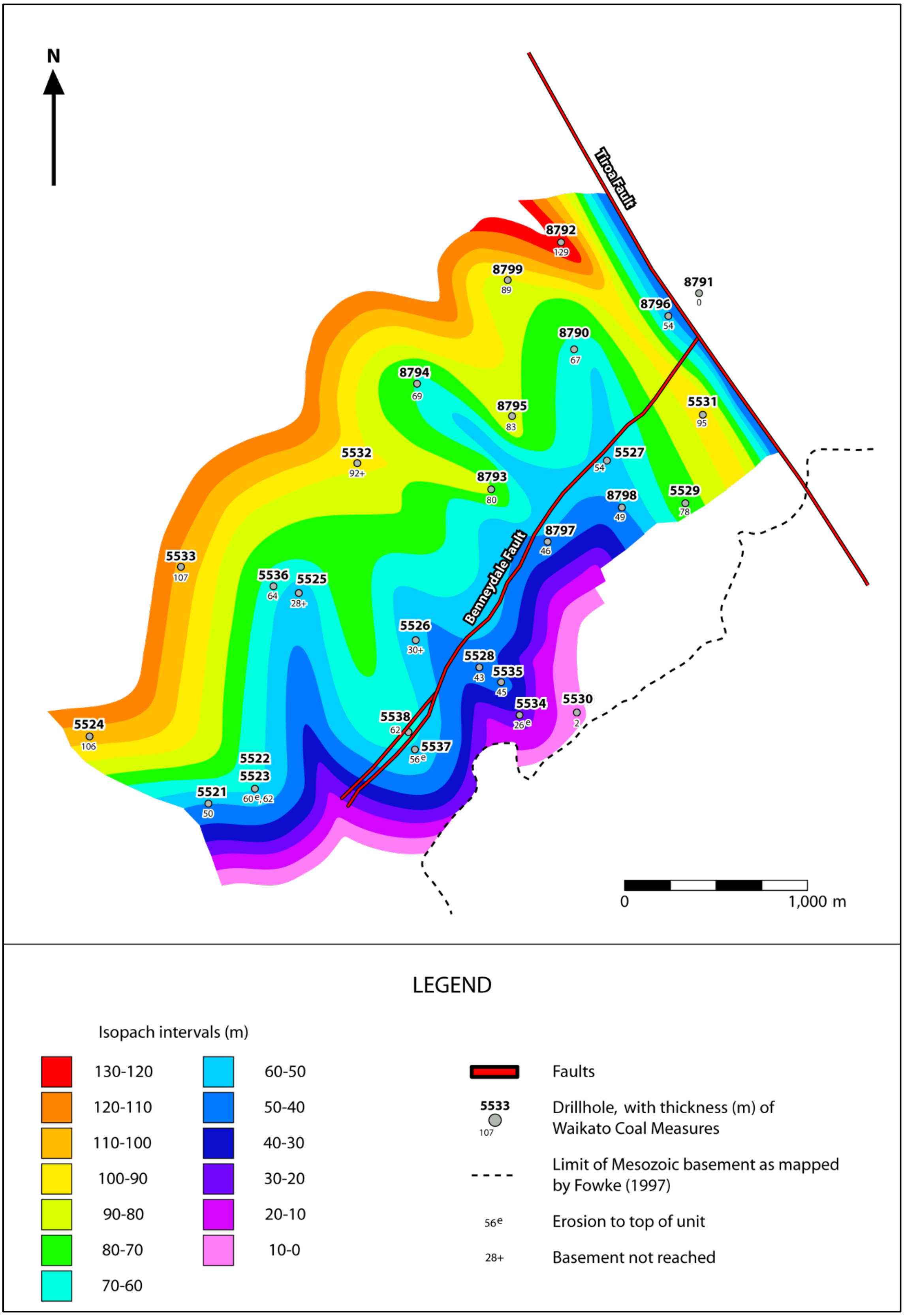

Figure 5.5: Isopach map showing the thickness of Waikato Coal Measures in the Mangapehi Coalfield. Isopachs are shown in 10 metre intervals.

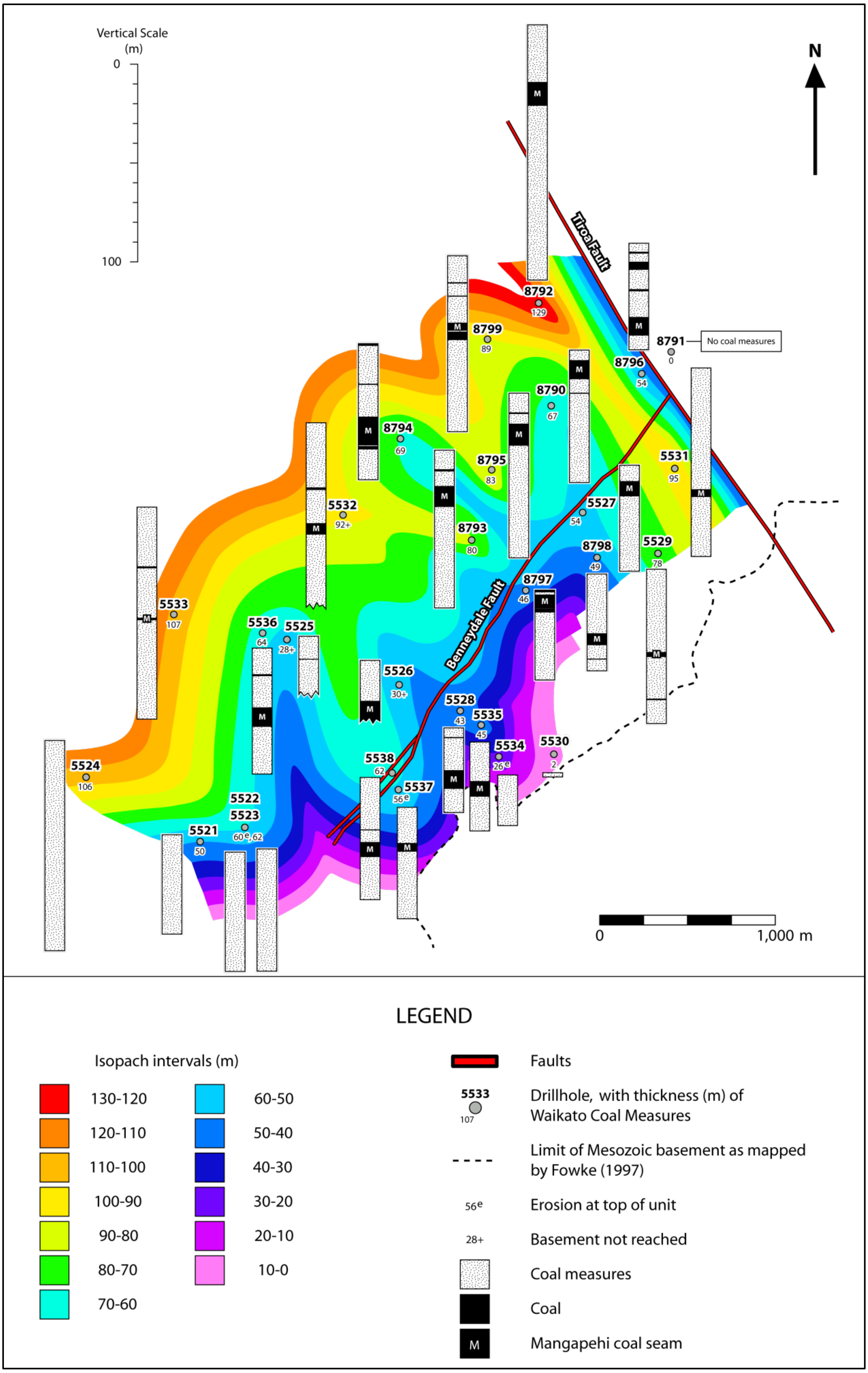

Figure 5.6: Simplified stratigraphic columns showing the thickness of coal measures and coal seams for boreholes in the Mangapehi Coalfield, superimposed on isopachs of Waikato Coal Measures.

CHAPTER 6 - DISCUSSION

6.1 DETERMINATION OF AGES

6.1.1 Palynological analysis

No definite age determination was made for the Mahoenui Group from palynological data due to the poor preservation and low abundance of taxa in samples retrieved from core 8798. *Polypodiaceoisporites papuanus* was recorded in sample 5A (99.40 mDH) and may be suggestive of a Waitakian (late Oligocene–early Miocene) age but more counts are needed to validate this. A pollen type identified as *Clavastephanocolporites meleosus*, also occurs in sample 5A. As previously mentioned, this species is not known to occur anywhere else in New Zealand but is present in Australia and has a wide age range.

Microflora identified in the sample taken from core 8795 at 180.90 m (27B) suggest an early Miocene age for Aotea Formation. *Podocarpidites rugulatus* is observed and this taxon has previously been found in Southland sequences of late Oligocene–early Miocene age (Table 6.1). Rare *P. papuanus* and *Nothofagidites cranwelliae* are also recorded in sample 27B. *Nyssapollenites endobalteus* is found in both samples taken from core 8798. This species is present throughout early to late Miocene sequences in Central Otago (Mildenhall & Pocknall, 1989), and throughout the Oligocene and Miocene in other areas of New Zealand.

Table 6.1: Age ranges of selected spore-pollen species in Southland and Central Otago, New Zealand (Mildenhall & Pocknall, 1989; Pocknall & Mildenhall, 1984).

INTERNATIONAL EPOCH	OLIGOCENE			MIOCENE		
	EARLY	LATE		EARLY	MIDDLE	
NEW ZEALAND STAGE	Whaingaroan	Duntroonian	Waitakian	Otaian	Altonian / Clifdenian	
SPORE-POLLEN SPECIES (Stratigraphical listing)	Lower *Nothofagidites matauraensis* Zone	Upper *Nothofagidites matauraensis* Zone	*Rhoipites waimumuensis* Zone	*Proteacidites isopogiformis* Zone	*Spinitricolpites latispinosus* Zone*	SPORE-POLLEN SPECIES (Alphabetical listing)
K. waterbolkii (1)	← 1					*Anisotricolporites truncatus* (8)
N. cranwelliae (2)	2				→	*Assamiapollenites incognitus* (9)
T. orbiculatus (3)		3			→	*Cupanieidites insularis* (6)
P. rugulatus (4)		4				*Kuylisporites waterbolkii* (1)
P. tenuiexinus (5)		5				*Latrobosporites marginis* (7)
C. insularis (6)				←		*Nothofagidites cranwelliae* (2)
L. marginis (7)			7			*Podocarpidites puteus* (10)
A. truncatus (8)				8		*Podocarpidites rugulatus* (4)
A. incognitus (9)				9	→	*Proteacidites tenuiexinus* (5)
P. puteus (10)				10		*Triorites orbiculatus* (3)

* Previously defined as *Tricolpites latispinosus* Zone

Palynological samples taken from core 8795 contained very few key taxa and a Waitakian to Altonian (late Oligocene to early Miocene) age is determined for Waikato Coal Measures based on the following observations. *Assamiapollenites incognitus* was identified in sample 28B (201.13 mDH) and is not known to be older than early Miocene (Table 6.1) This species has previously been found at a number of central Otago localities, ranging from early to late Miocene (Mildenhall & Pocknall, 1989), and has also been recorded in lower Miocene sequences in Southland (Pocknall & Mildenhall, 1984). *Rhoipites aequatorius* is also present in 28B and this species has originally only been found in the Oligocene in the Waikato region (Pocknall, 1991). *Podocarpidites rugulatus* was observed in 28B and the age range of this taxon has been previously discussed. Rare *Kuylisporites waterbolkii* is seen in four samples (28B, 201.13 mDH; 30B, 206.30 mDH; 32B, 218.05 mDH; 39B, 221.90) and this taxon was thought to be Waitakian or older, although it has now been found infrequently in younger sediments. It has previously been recorded in two Southland sequences with an age range of late Oligocene–early Miocene, and is also known to be present in Eocene sequences elsewhere in New Zealand (Pocknall & Mildenhall, 1984).

Latrobosporites marginis is identified in sample 36B (220.07 mDH in core 8795), which has been recorded in sequences in Southland where it was given an age range of early to middle Miocene. However, despite this, the age range of *L. marginis* is poorly constrained (Mildenhall & Pocknall, 1989) and spans the range from Waitakian to Altonian. *Cupanieidites insularis* is observed in 31B (217.00 mDH); this species has been recorded from a number of locations in New Zealand. In Central Otago sequences it is assigned an early to middle Miocene age range (Mildenhall & Pocknall, 1989), elsewhere it has been recorded from the late Eocene (Couper, 1960) and throughout the Oligocene and early Miocene (Pocknall, 1985). *Triorites orbiculatus* is present in 36B and 39B (221.90 mDH), and has been recorded in sequences in Southland where it has an age range of late Oligocene to early Miocene. It is also known to occur in the middle Miocene (Pocknall & Mildenhall, 1984).

Samples from core 8798 provide a similar age range for the Waikato Coal Measures, with a Waitakian–Altonian range assigned to all productive samples. The presence of *Anisotricolporites truncatus* is noted in samples 7B (15.73 mDH) and 5B (185.07 mDH) and this species has previously been assigned an early Miocene age range in Southland sequences (Pocknall & Mildenhall, 1984). *Proteacidites tenuiexinus* is seen in sample 1A (141.90 mDH) and previous observations from Southland locations indicate a late Oligocene–early Miocene range. *Rhoipites aequatorius*, previously recorded in sequences in the Raglan area and ascribed a late Oligocene age (Pocknall, 1985), is identified in sample 5B.

6.1.2 Integration of nannofossil data

Assemblages are dominated primarily *Reticulofenestra* spp., particularly those 2–5 µm. Other less abundant taxa include *Coccolithus pelagicus*, *Zygrhablithus bijugatus*, *Discoaster deflandrei*, *Sphenolithus moriformis*, *Pontosphaera multipora* and *Cyclicargolithus floridanus*, all of which are known to occur during the Oligocene. A number of inferences can be drawn from the first occurrence (FO), last occurrence (LO), and to a lesser extent the absence of specific nannofossil taxa.

In a study of calcareous nannofossils from the southwest Pacific, Edwards (1973) suggested that the best approximation of the Oligocene/Miocene boundary is the extinction level of *Dictyococcites bisectus* (=*Reticulofenestra bisecta*). This datum level occurs at approximately 23 Ma and was also used as a secondary marker by Bukry (1973) to recognize the base of Subzone CN1a (Figure 4.1). In samples taken from core 8798, the LO of *D. bisectus* is noted within Mahoenui Group at a depth of 83.70 mDH, indicating that the Oligocene/Miocene boundary occurs within this unit. This suggests a late Waitakian (late Oligocene–early Miocene) age for Mahoenui Group. Although pollen data for this unit were poor, there is a suggestion of a Waitakian age, which supports the nannofossil data.

As previously mentioned, sphenoliths are an important taxon for subdividing the Oligocene (Fornaciari et al., 1990) and the following events are commonly used: FO of *Sphenolithus ciperoensis*, LO of *Sphenolithus distentus* and LO of *S. ciperoensis* (McMonagle et al., 2011). The occurrence of *S. ciperoensis* within upper Waikato

Coal Measures (core 8798: 165.40 mDH and 150.65 mDH) and lower Aotea Formation (core 8795: 182.90 mDH) indicates that these formations were deposited prior to the LO of *S. ciperoensis* (~24 Ma). This finding is consistent with the palynological results for Waikato Coal Measures, which suggest a Waitakian (late Oligocene–early Miocene) age.

Although an age for the base of the Waikato Coal Measures cannot be precisely determined, presence and absence of specific species can help to refine the interval during which deposition occurred. *Reticulofenestra umbilicus* has a LO at ~31 Ma, and its absence in assemblages from Waikato Coal Measures suggests that deposition in the Mangapehi Coalfield began sometime after this. The presence of *S. ciperoensis* within Waikato Coal Measures (core 8798: 165.40 mDH and 150.65 mDH) provides additional support for this finding. *S. ciperoensis* has a FO of ~30 Ma, and is used by Martini (1971) and Okada & Bukry (1980) to define the bases of Zone NP24 and Zone CP19, respectively. Its presence within assemblages of the Waikato Coal Measures suggests that deposition occurred subsequent to 30 Ma.

6.1.3 Comparison with previous studies

A number of spore-pollen zonation schemes have been proposed for the New Zealand Tertiary (Figure 6.1). In one of the earliest schemes, Couper (1960) proposed the *Nothofagus flemingii* and *Nothofagus matauraensis* Zones as a means of subdividing middle–late Eocene Beaumont Coal Measures. Later zonation schemes became more detailed due to the development of concepts and successful application to sequences overseas. Raine (1984) developed a scheme for Cretaceous and Paleogene terrestrial sediments in Westland; Pocknall & Mildenhall (1984) for late Oligocene–early Miocene Southland sequences; Mildenhall & Pocknall (1989) for Miocene–Pleistocene sequences in Central Otago; and Pocknall (1991) for Te Kuiti Group in the Waikato Basin.

The determination of an early Waitakian (late Oligocene) age for Waikato Coal Measures in the Mangapehi Coalfield is consistent with the late Oligocene age proposed by Pocknall (1985), who places spore-pollen assemblages in the Mangapehi region within the Upper *Nothofagidites matauraensis* Zone of Pocknall

& Mildenhall (1984). Analysis of palynological data in this study suggest they fall within the younger *Rhoipites waimumuensis* Zone of Pocknall and Mildenhall (1984). As with sequences in Southland, many of the assemblages are dominated by *N. cranwelliae* or *Haloragacidites harrisii. Myrtaceidites* sp. is common throughout, with *Myrtaceidites parvus* dominating some samples. A number of other taxa common in the *Rhoipites waimumuensis* Zone are seen in the Mangapehi assemblages including *Cranwellia striata, Pseudowinterapollis couperi*, *Liliacidites variegatus, Malvacipollis* sp., *Monogemmites gemmatus*, *Triporopollenites ambiguus*, *Rhoipites waimumuensis*, and *Verrucosisporites kopukuensis*.

It is possible however, that the Waikato Coal Measures span the Upper *Nothofagidites matauraensis* and *Rhoipites waimumuensis* Zones of Pocknall and Mildenhall (1984) (Figure 6.2). Sampling of core 8795 was restricted to the middle to upper sequence of the Waikato Coal Measures and as such the palynological assemblage of the basal section is unknown. It would have been interesting to see whether a change of assemblage occurs in the Waikato Coal Measures of core 8795.

In considering the biozones of Pocknall (1991), the assemblages recorded from the Mangapehi coalfield show similarities with the *Rubipollis oblatus* Zone, with *N. cranwelliae* dominating the assemblage and *Nothofagidites matauraensis* recorded at much lower levels. Rare occurrences of *Rubipollis oblatus* were recorded from core 8795 samples, as were *Tetracolporopollenites costatus, Foveotriletes crater,* and *Periporopollenites vesicus,* all of which are known to occur within the *Rubipollis oblatus* Zone (Edbrooke et al., 1994). However, the combined palynological and nannofossil data of this study suggest a younger Waitakian age for Waikato Coal Measures in the Mangapehi area, rather than the Whaingaroan (late Eocene–late Oligocene) age range attributed to the *Rubipollis oblatus* Zone.

Previous dating of Aotea Formation in Waitomo County by Nelson (1973, 1978) provided an age range of lower/middle Whaingaroan age to Duntroonian (late Eocene to late Oligocene). A similar age was also proposed by Armstrong (1987) based on foraminiferal analysis. The results of this study suggest a Waitakian age for the Aotea Formation, which is younger than previously thought, with the basal portion being constrained to an age of deposition prior to around 24 Ma.

The late Waitakian age inferred for Mahoenui Group coincides with the Upper Waitakian to Otaian (early Miocene) age range proposed by Glennie (1959) for massive mudstones of the Mahoenui Group in the King Country. Study of foraminifera by Topping (1978) in the Benneydale region inferred an Otaian age for the Mahoenui Group. However, the results of this study do not enable an age to be determined for the top of the Mahoenui Group and it is possible that this unit extends into the Otaian.

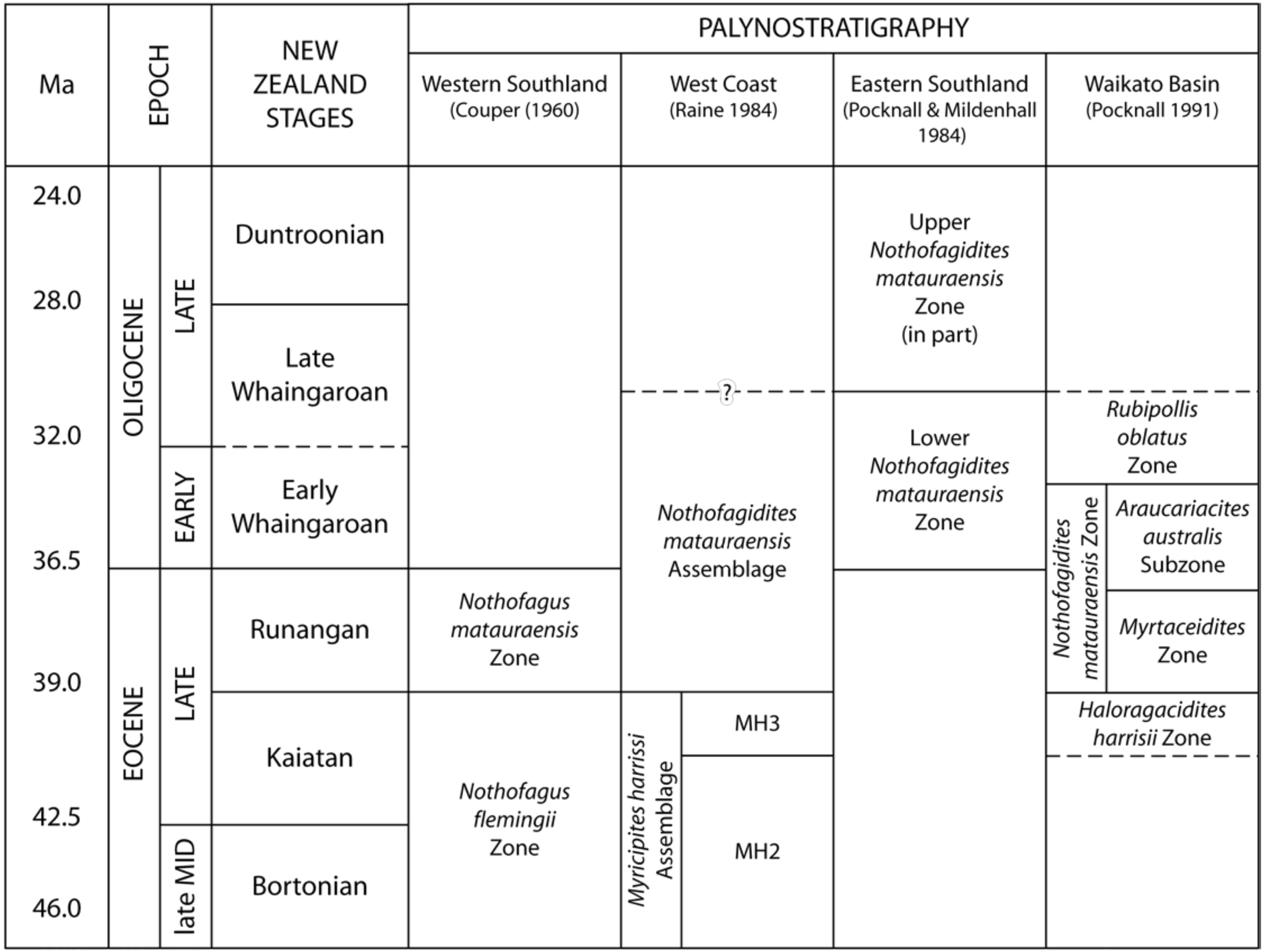

Figure 6.1: Pollen zonation schemes for the Tertiary of New Zealand. (Figure redrawn from Pocknall, 1991).

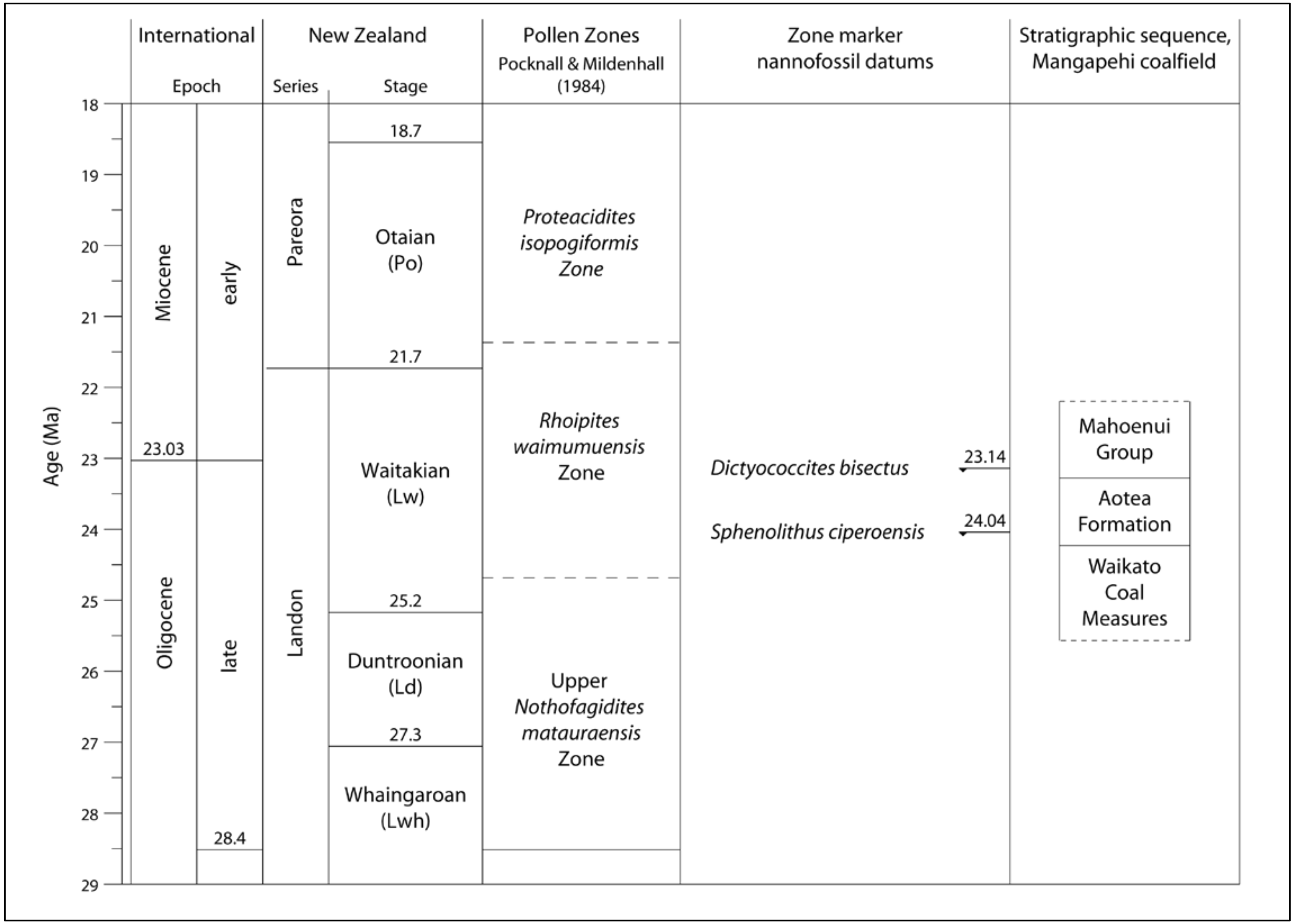

Figure 6.2: Representative stratigraphic section for Mangapehi Coalfield correlated with the New Zealand timescale, palynology zones, and key nannofossil datums.

6.2 PALEOENVIRONMENT INTERPRETATION

The absence of nannofossil and dinoflagellates in the lower part of the Waikato Coal Measures indicates a fully terrestrial environment in the Mangapehi Coalfield at the time of deposition. Palynological assemblages in this basal section are dominated by *Nothofagidites cranwelliae* and *Myrtaceidites parvus*, suggesting the presence of a lowland subtropical beech/myrtle forest in the area. The lowest sample taken from the coal measure sequence (core 8798: 185.07 mDH) is dominated by the fern types *Cyathidites* spp. and *Laevigatosporites* spp., which may be indicative of an early fernland. The "*brassi*" beech group, to which *N. cranwelliae* belongs, is recognized as an indicator of humid, sub-tropical conditions (Mildenhall, 1980). The abundance of *N. cranwelliae,* along with lower levels of other *"brassi"* beech (*Nothofagidites matauraensis, Nothofagidites spinosus*), suggests a similar climatic regime for the Mangapehi region during the late Oligocene.

There is general agreement that some nannofossil species signify distinct paleoecological conditions and as such they can be used for interpreting oceanographic and climatic changes (Villa et al., 2008). Of the taxa observed in the Mangapehi assemblages, *Discoaster* spp., *Helicosphaera* spp. and *Sphenolithus* spp., are considered warm-water taxa (Villa et al., 2008; Wei et al., 1992; Wei & Wise, 1990); *Cyclicargolithus floridanus*, *Zygrhablithus bijugatus,* and *C. pelagicus* are considered to prefer temperate waters (Villa et al., 2008; Wei & Wise, 1990); and *D. bisectus* prefers warm to temperate waters (Villa & Persico, 2006; Wei et al., 1992). *Reticulofenestra daviesii* and *Chiasmolithus* spp. have both been described as cool-water taxa (Persico & Villa, 2004; Villa et al., 2008; Wei & Wise, 1990). Based on these classifications, the Mangapehi assemblages are dominated by those taxa that have a preference for warm to temperate waters.

There has been some debate in reconstructing the climate for the New Zealand Cenozoic, depending on whether terrestrial or marine paleontological data are considered (Pocknall, 1990). However, there is a general consensus that temperatures within the Oligocene were fairly stable, other than a drop at the beginning of the epoch (Mildenhall, 1980). Temperature continued to rise during the early Miocene to warm subtropical conditions (Nelson & Cooke, 2001). Comparison of the Mangapehi palynological and nannofossil evidence with climate curves for the New Zealand Cenozoic shows that the interpretation of a warm-temperate to subtropical climate regime during the Waitakian (late Oligocene–early Miocene) is consistent with published climate curves (Figure 6.3). This also correlates with the findings of Villa, et al., (2008), who interpreted a warming episode in Southern Ocean sea-surface temperature during the late Oligocene.

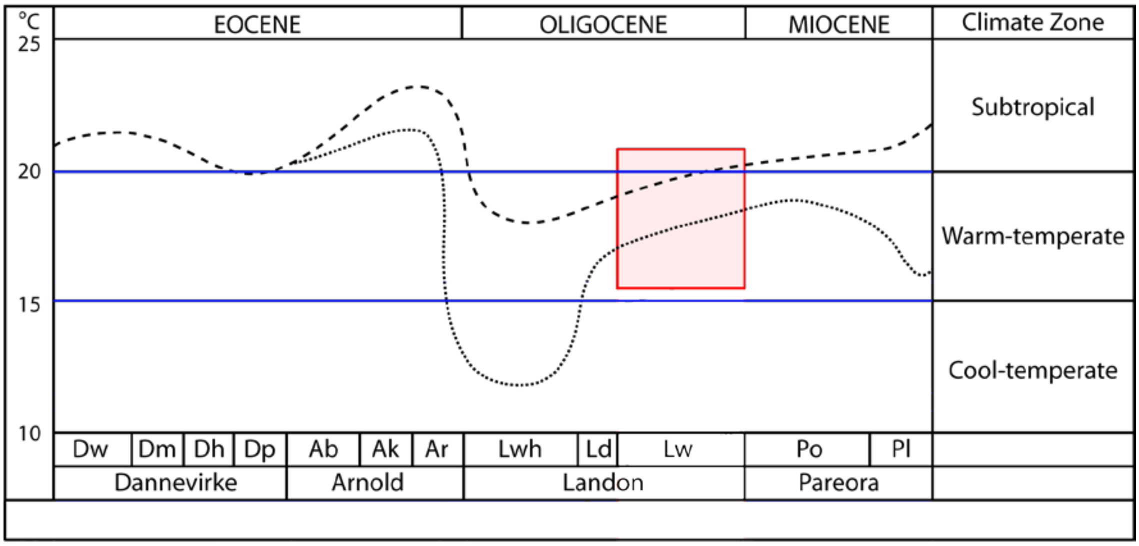

Figure 6.3: Climate curves for the New Zealand Cenozoic. The dashed line is based on paleontological data and the dotted line is based on oxygen isotope data of Devereux (1968). (Figure redrawn from Pocknall, 1990, where it was modified from Hornibrook, 1978).

Samples taken from above the Mangapehi Seam (~170 mDH) in core 8798 show marine incursions at the time of coal measure deposition, as evidenced by the presence of dinoflagellates[5] and nannofossil taxa. The poor preservation of spores and pollen in these younger samples, combined with the evidence of sea-water invasion, infers a near-shore, turbulent marine setting for this section of the coal measure sequence. Interestingly, the sample (1A, 141.0 mDH) taken from the top of the coal measures in core 8798 contained no dinoflagellate or nannofossil taxa, and palynoflora were more abundant than those of the aforementioned section. *Nothofagidites cranwelliae* and *M. parvus* remain the dominant palynofloras, indicating the presence of a nearby lowland beech/myrtle forest pollen source. The

[5] Refer to Appendix 5.

transition from a marine influenced setting to a terrestrial influenced one could be suggestive of a brief transgressive-regressive cycle. Charcoal[6] is present in most of the samples taken from the upper part of the coal measure sequence, indicating that fires occurred at this time. In many of the drillholes in the Mangapehi coalfield a conglomerate bed containing sub-rounded to mostly sub-angular pebbles is observed within Waikato Coal Measures, suggesting proximity to an elevated land source.

A nearshore, marine environment is interpreted for the Aotea Formation, based on the presence of dinoflagellates and nannofossils in most of the samples analysed. Interestingly, the basal section of the formation proved barren of nannofossil taxa but it is difficult to draw any conclusions about this, as part of the formation was not analysed for palynological content. The oldest sample analysed from core 8798 (125.00 mDH) was dominated by *N. cranwelliae,* with common *Cyathidites* spp. and *Laevigatosporites* spp., suggesting a nearby pollen source still prevailed. The scarcity and poor preservation of spores and pollen in the younger samples implies a turbulent depositional environment. Conglomerate beds are present within the basal section of Aotea Formation in some areas of the coalfield, suggesting the persistence of an elevated landscape nearby.

Calcareous nannofossils and dinoflagellates are abundant in most of the Mahoenui Group samples analysed, disappearing towards the top of unit (core 8798: 60.15 mDH). Spores and pollen were sparse and poorly preserved, and as a consequence no dominant taxa were identified. *Nothofagidites cranwelliae, Haloragacidites harrisii*, *Cyathidites* spp. and *Laevigatosporites* spp. were observed, again supporting the idea of a nearby pollen source. A nearshore, marine environment is interpreted for the Mahoenui Group, transitioning to a deeper marine environment during early Miocene.

[6] Refer to Appendix 5.

6.3 PALEOSTRUCTURE INTERPRETATION

Isopachs of the Mahoenui Group indicate a thinning of the unit in the central part of the coalfield (Figure 5.3). One interpretation for this is the existence of a paleohigh located in this area at the time of deposition. Under this scenario, the pattern of thickening of the unit towards the northwest suggests the presence of a paleovalley, which may have acted as a drainage channel transporting sediments eroded from the paleohigh. In the eastern region of the coalfield a similar pattern is seen, with Mahoenui Group sediments thickening in a north easterly direction, into the Tiroa Fault. A second interpretation is that sediments of the Mahoenui Group have been eroded from this central area of the coalfield subsequent to deposition, and the thickness observed in drillhole 8793 is incomplete in this region of the coalfield.

Mahoenui Group is absent on the upthrown side of the Tiroa Fault, which suggests that this area was also a paleohigh at the time of deposition. Of course, the absence of Mahoenui Group to the east of the Tiroa Fault may also be a consequence of subsequent erosion resulting from movement on the Tiroa Fault. However, based on the examination of only one drillhole in this area it is difficult to determine which of these two scenarios is correct. An overall trend of thinning to the south is observed, reflecting the fact that Mesozoic basement exposed in the southeast region of the coalfield was a paleohigh at the time of Tertiary deposition (Fowke, 1997).

The structure of the area during deposition of Aotea Formation shows similar trends with the suggestion of a paleohigh towards the centre of the coalfield and paleovalleys on either side (Figure 5.4), although these are not quite as pronounced as those seen in the Mahoenui Group. A general thinning of Aotea Formation occurs in a southerly direction towards exposed Mesozoic rocks and again, the absence of sediments to the east of the Tiroa Fault suggests a paleohigh. Again the thinning of sediments in the centre of the coalfield and to the east of the Tiroa Fault may simply represent periods of subsequent erosion.

The isopach map of the Waikato Coal Measures (Figure 5.5) reveals a more complex structure in the area than that seen for the overlying two units, possibly reflecting the undulating nature of the basement rocks onto which Waikato Coal Measures were deposited (Gage, 1940). A couple of general trends are recognized; the thickness of sediment gradually thins from the north to the south, and no sediments are observed on the upthrown side of the Tiroa Fault. There is a narrow thick sequence of Waikato Coal Measure sediments in the east of the coal field adjacent to the Tiroa Fault, perhaps suggesting a depression or depocentre in that area at the time of deposition. The isopach map supports the suggestion by Fowke (1997) that a basement valley was present directly to the west of the Tiroa Fault. Fowke based this observation on the fact that in three of the four 1996 drillholes located closest to the Tiroa Fault, Waikato Coal Measures appear to rest on virtually fresh basement. In contrast, a leached basement zone is seen in the fourth drillhole (8794) further to the west. Fowke proposed that in those areas where fresh basement is observed directly below coal measures, deposition occurred within the valley bottoms of an old drainage system.

In addition to the depocentre seen in the eastern section of the coalfield, the ispoachs indicate at least two other depocentres, one in the centre, and one to the west. Interestingly, no coal seams were observed in drillholes in the westernmost region of the coalfield. However, several of these drillholes do show traces of coal, coalified leaf and twig matter, and/or dark shale beds, which may correlate with coal seams elsewhere in the coalfield. Coal seam thickness increases in a northwesterly direction indicating that thicker seams may lie, as yet undiscovered, in this direction.

Although further investigation to the west and south of the coalfield has previously been disregarded, it is worth speculating that coal measures may continue in either or both of these directions. To the south it is interpreted that Mesozoic basement rocks were upstanding at the time of coal measure formation and as such coal measures thinned in this direction. It is possible that coal measures lapped onto basement in this area but sediments have subsequently been eroded.

In the west coal seams are absent, although brown/black shales encountered in boreholes in this region may be their lateral equivalent. This could be interpreted as a facies change reflecting a shift from peat mire conditions in the east, to a fluvial channel environment in the west. A paleodepression might have existed to the west of the paleochannel, in which coal measures may have accumulated.

6.4 SYNTHESIS OF AGE, PALEOENVIRONMENT AND PALEOSTRUCTURE

Deposition of coal measures in the Mangapehi coalfield began in the late Oligocene, sometime after 30 Ma. At that time a lowland beech/myrtle forest existed in the region, and a humid, warm-temperate climatic regime was in effect. Coal measures accumulated in depressions on the underlying basement rocks, resulting in a number of depocentres and variations in thickness across the coalfield (Figure 6.4). Edbrooke et al. (1994) suggests that early low-lying topogenous mires developed in the Benneydale region from paludification of a fluvial coastal plain. Paleohighs to the east of the Tiroa Fault and in the southwest region of the coalfield constrained deposition to small "subbasins" or depocentres. Overall there is a thinning of sediments southwards and Waikato Coal Measures are absent to the east of the Tiroa Fault, suggesting the eastern margin of the sedimentary basin was fault controlled.

Environmental conditions began to change from terrestrial to marine, with transgressive/regressive marine cycles occurring as coal measure deposition continued. Erosion of elevated basement rocks to the south and east of the coalfield, contributed coarse sediments to the Waikato Coal Measures sequence. Armstrong (1987) suggests that the conglomerate beds seen in the Waikato Coal Measures represent periods of episodic flooding, resulting in the erosion of peat deposits and deposition of lag gravels and sands. Investigation of drillhole logs reveals a general pattern across the coalfield, with conglomerate beds present in the east and disappearing to the southwest, supporting the idea of an elevated landscape to the east.

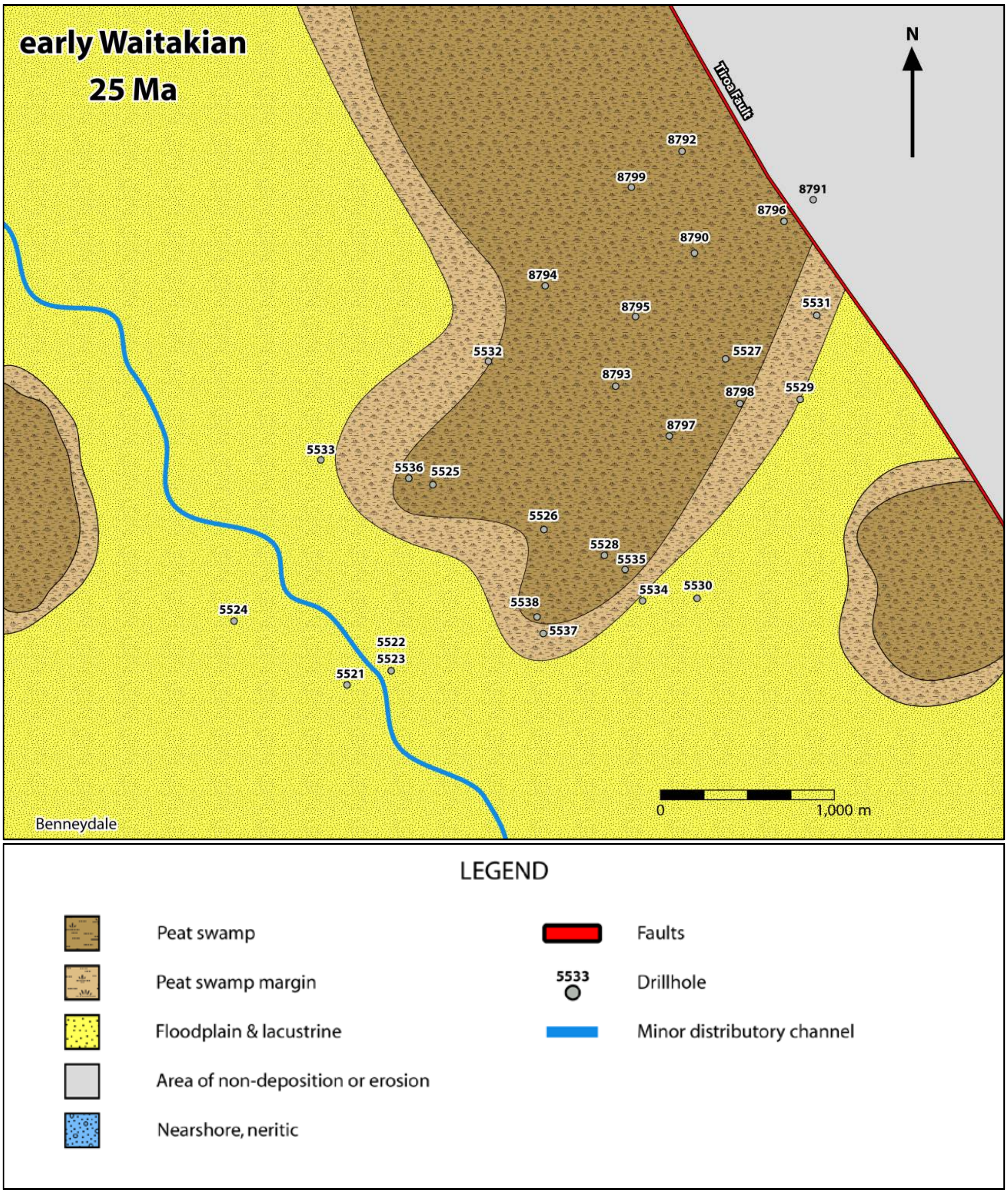

Figure 6.4: Paleogeographic reconstruction during the early Waitakian showing the development of an extensive peat swamp in the Mangapehi Coalfield.

The shift to a nearshore, turbulent marine environment during early to middle Waitakian (Figure 6.5) marked the onset of the deposition of Aotea Formation in the region. A lowland beech forest with a strong fern component still persisted nearby. The paleohigh to the east continued to constrain deposition and sediments are seen to thin against basement rocks to the south. A new paleohigh began to emerge towards the centre of the coalfield, resulting in paleovalleys on either side which acted as drainage channels.

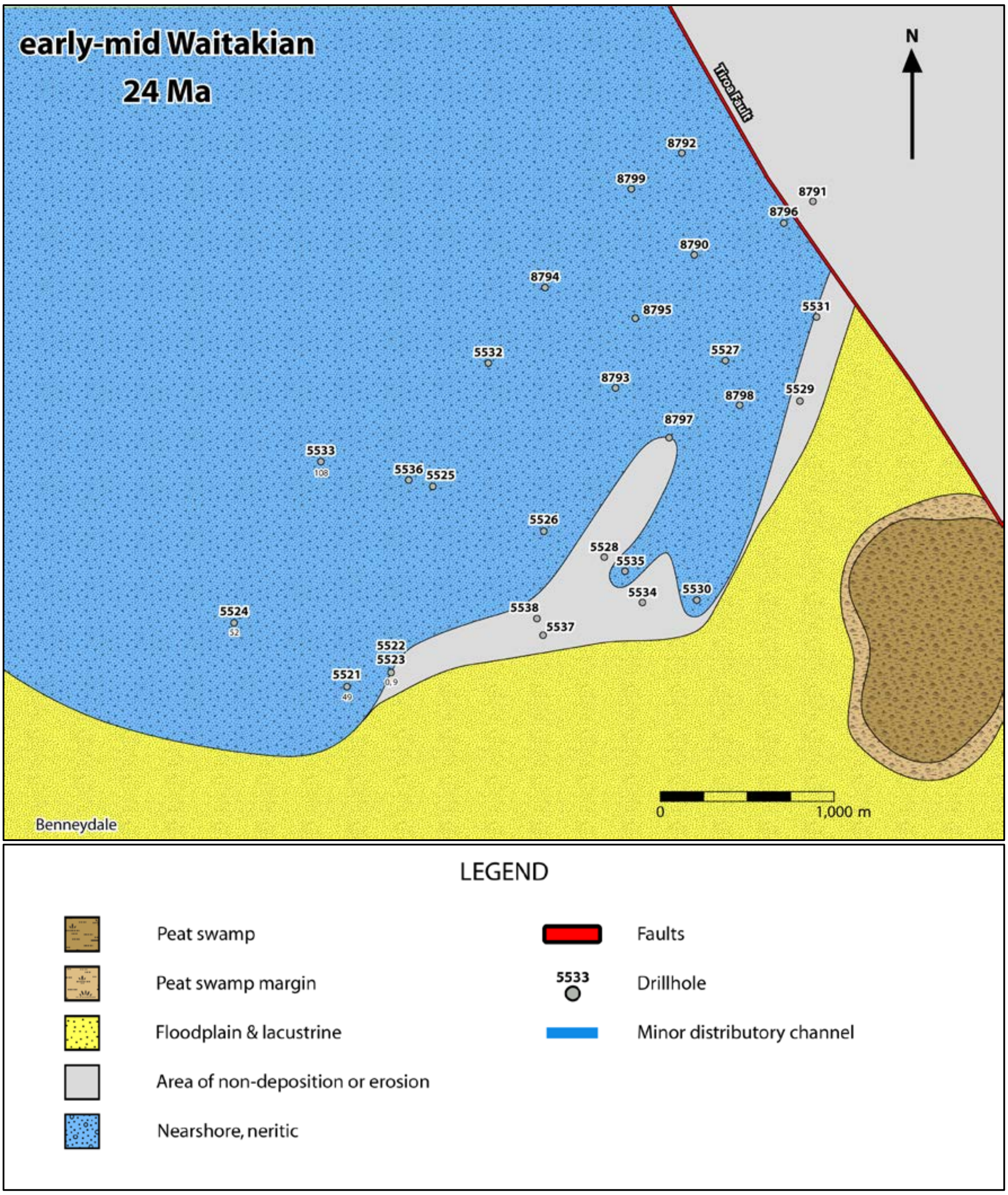

Figure 6.5: Paleogeographic reconstruction of the Mangapehi Coalfield during early-mid Waitakian, illustrating marine transgression across the area and the deposition of Aotea Formation.

Deposition of Mahoenui Group began by middle to late Waitakian (Figure 6.6), as nearshore marine conditions persevered. Vegetation persisted nearby, and was composed predominantly of beech, casuarina and ferns. Paleohighs to the east and south continued to limit deposition, and the paleohigh in the centre of the coalfield resulted in a shallowing of sediments in that area. As transgression across the area continued, water depths began to increase, eventually leading to fully marine conditions.

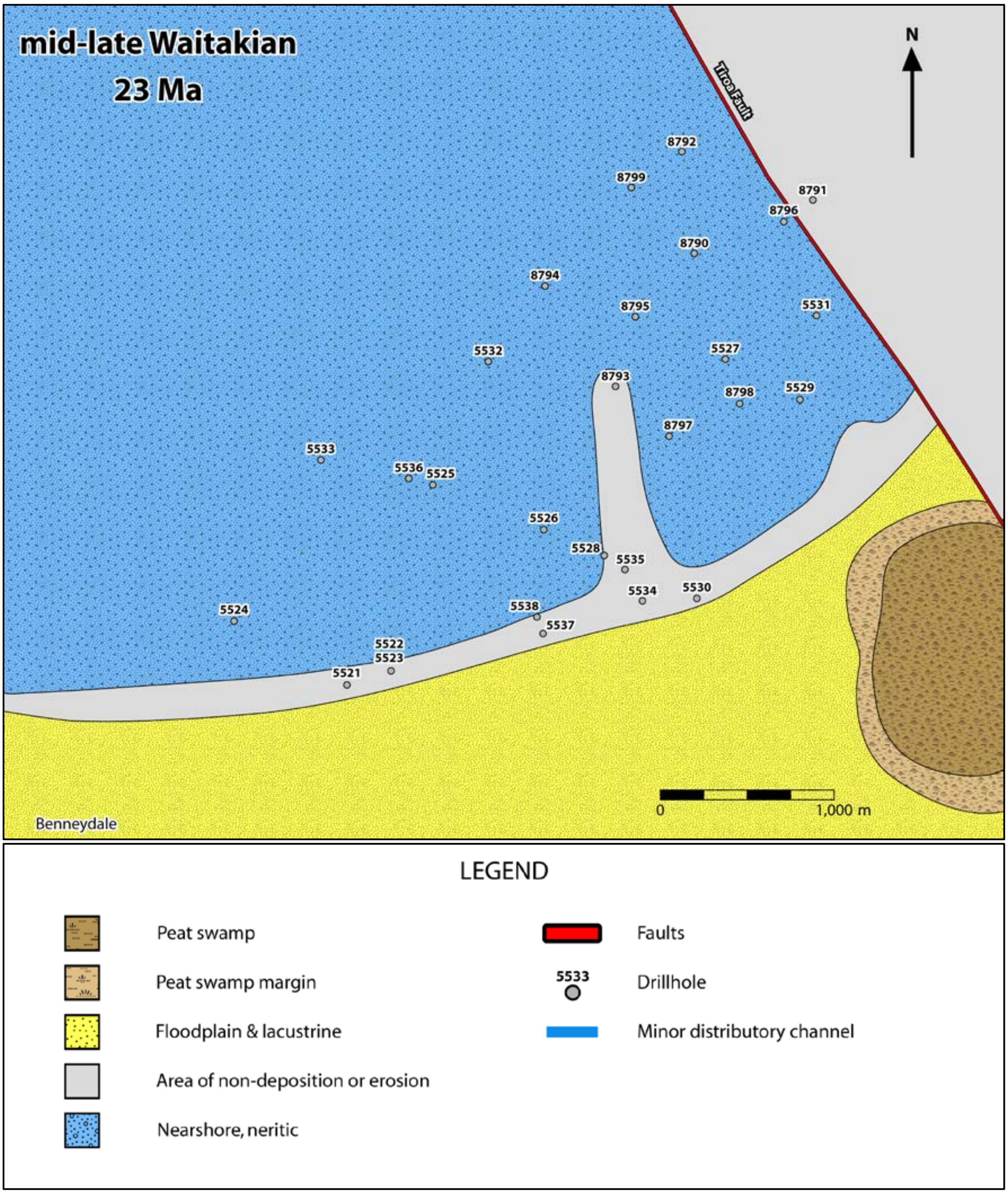

Figure 6.6: Paleogeographic reconstruction of the Mangapehi Coalfield during mid–late Waitakian, illustrating marine transgression across the area and the deposition of Mahoenui Group.

CHAPTER 7 - CONCLUSIONS

The objective of this research project was to analyse Waikato Coal Measures and the shallow marine sediments associated with them, in order to determine the age of these units and establish changes in paleoenvironment through time. This was achieved using the integration of palynological and calcareous nannofossil data, along with analysis of drillhole data.

The main conclusions of this study are:

- Waikato Coal Measures in the Mangapehi Coalfield could be as young as Waitakian (late Oligocene–early Miocene) in age, which is younger than previously thought. This finding is consistent with the idea that coal measures in the Waikato Coal Region become progressively younger to the south.

- A well vegetated pollen source persisted in the area throughout the late Oligocene–early Miocene sequence, supporting the hypothesis that some land remained above sea level during the Oligocene and continued into early Miocene.

- Thinning and/or absence of sediments to the east and south of the coalfield suggest the presence of paleohighs at the time of deposition. Conglomerate beds within the coal measure sequence provide further evidence of elevated hinterland, probably to the east of the coalfield.

- In the Mangapehi Coalfield, initial deposition of the Mahoenui Group began in a nearshore setting, gradually transitioning to deeper marine conditions during early Miocene.

- A Waitakian age is inferred for Aotea Formation in the Mangapehi region.

In addressing the bigger question of total or partial submergence of Zealandia during the Oligocene, it can be concluded that although we do not see direct evidence of land persisting in the Benneydale region, the indirect evidence of a continuous pollen source and thinning of sediments to the south and east of the coalfield supports the idea of elevated land nearby.

The results of this study could be enhanced further by conducting foraminiferal, petrological and sedimentological analyses of samples from cores 8795 and 8798. The integration of foraminiferal data with the palynological and nannofossil data collected for this study would refine the biostratigraphic resolution of the stratigraphic sequences. Examination of the petrological and sedimentological characteristics of the sediments would assist in reconstructing changes to the paleoenvironment through time, and could also determine provenance of the sandstone and conglomerate beds present within Waikato Coal Measures.

From an exploration point of view, further surveying to the northwest of the coalfield is warranted, given that coal seam thickness increases in this general direction. Exploration south of the Mesozoic basement rocks in the southern region of the coalfield has previously been disregarded. However, based on the possibility that erosion rather than non-deposition is responsible for the absence of sediments in this area, investigation further south could be justified. Additionally, further exploration to the west of the Mangapehi Coalfield to investigate the possibility of a paleovalley in this area should be considered.

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APPENDIX 1 - SUMMARY OF PREVIOUS SAMPLING

Summary of samples collected in the Mangapehi/ Benneydale region. Data obtained from the Fossil Record Electronic Database (GNS Science, 2009).

Fossil Type	FRED ID	Collected by	Date	Stratigraphic location	Inferred Age	Location*
Macrofauna	S17/f8015	Williamson, J	1933	Between coal seams	Awamoan 19.0–15.9 Ma	1 (1)
	S17/f0011	Richardson, L.R., Schofield, J.C., & Kear, D.	1950	3m above basement	Whaingaroan 34.3–27.3 Ma	14 (36)
	S17/f0060	Bland, G., & Nelson, C	1997	Between the Waikato Coal Measures and Aotea Formation	Whaingaroan–Duntroonian 34.3–25.2 Ma	8 (15)
Microfauna	S17/f8505	Schofield, J.C., & Kear, D	1951	Upper Te Kuiti Formation	Waitakian–Otaian 25.2–19.0 Ma	13 (27)
	S17/f8506	Schofield, J.C., & Kear, D	1951	Upper Te Kuiti Formation	Waitakian 25.2–21.7 Ma	2 (5)
	S17/f8507	Schofield, J.C., & Kear, D	1951	Upper Te Kuiti Formation	Waitakian–Otaian 25.2–19.0 Ma	10 (19)
	S17/f8508	Schofield, J.C., & Kear, D	1951	Mahoenui Group	Waitakian–Otaian 25.2–19.0 Ma	17 (43)
	S17/f8511	Kear, D	1951	Te Kuiti Formation	Duntroonian 27.1–25.2 Ma	11 (20)
	S17/f8512	Kear, D	1951	Basal Mahoenui Group	Waitakian 25.2–21.7 Ma	3 (6)
	S17/f8514	Kear, D	1954	Lower Te Kuiti	Duntroonian 27.1–25.2 Ma	19 (59)
	S17/f8515	Kear, D	1954	Lower Te Kuiti	Duntroonian 27.1–25.2 Ma	19(67)
	S17/f8518	Brown Brothers	1959	25m above top coal	Whaingaroan–Duntroonian 34.3–25.2 Ma	18 (44)
	S17/f0008	Topping, R.M	1975	Mokau Group	Otaian–Altonian 21.7–15.9 Ma	9 (29)
	S17/f0009	Topping, R.M	1975	Mahoenui Group	Otaian 21.7–19.0 Ma	9 (41)
Microfauna	S17/f0010	Topping, R.M	1975	Mahoenui Group	Waitakian–Altonian 25.2–15.9 Ma	9 (17)

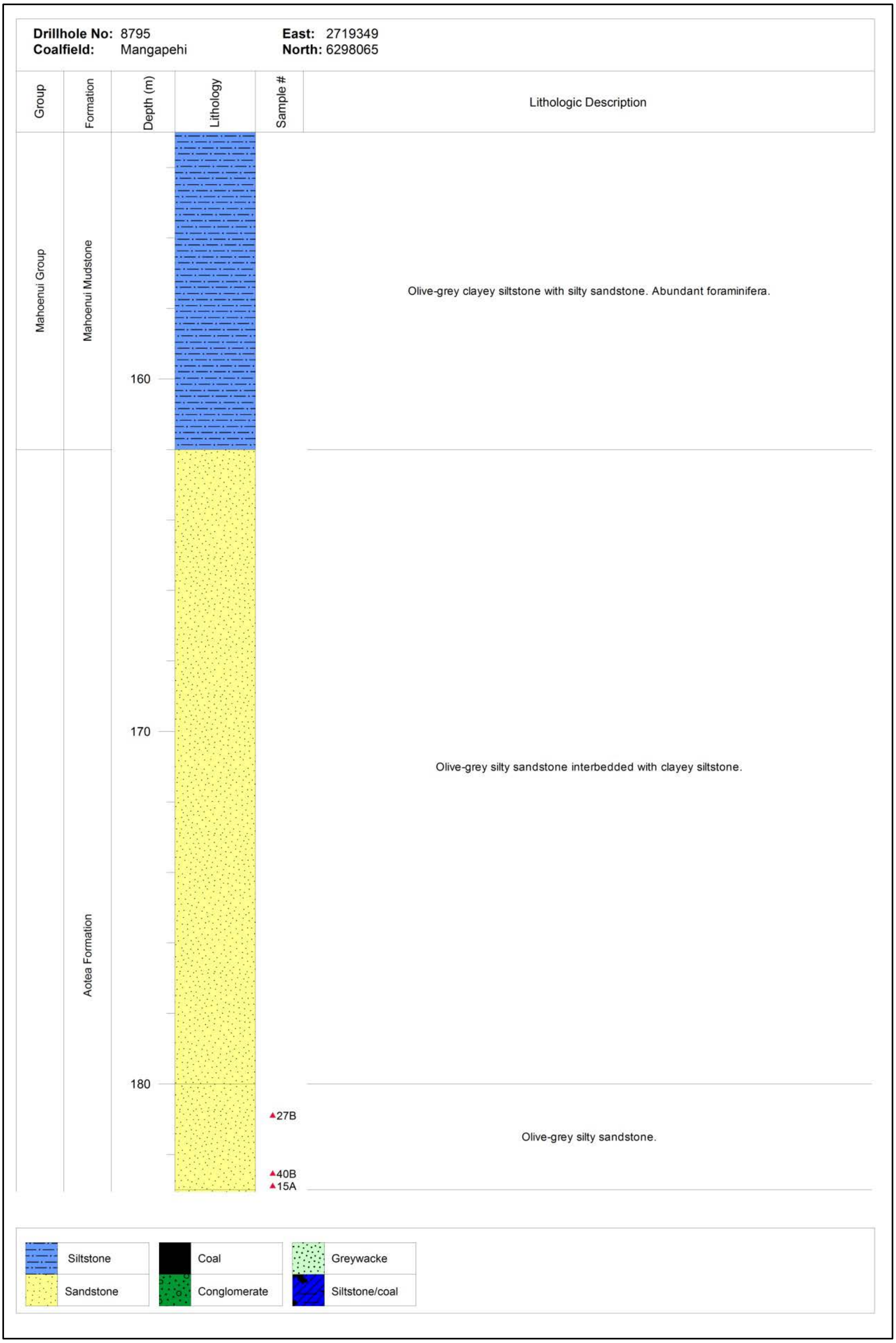
Fossil Type	FRED ID	Collected by	Date	Stratigraphic location	Inferred Age	Location*
	S17/f0011	Topping, R.M	1975	Mahoenui Group	Otaian–Clifdenian 21.7–15.1 Ma	9 (38)
	S17/f0015	Topping, R.M	1975	Mahoenui Group	Otaian 21.7–19.0 Ma	16 (42)
	S17/f0053	Armstrong, B.D., & Vella, P	1987	Mahoenui Group	Whaingaroan–Waitakian 34.3–21.7 Ma	5 (9)
	S17/f0058	Bland, G., & Nelson, C	1997	Base of Mahoenui Group	Waitakian–Otaian 25.2–19.0 Ma	6 (10)
	S17/f0059	Bland, G	1997	Mahoenui Group	Duntroonian–Otaian 27.3–19.0 Ma	15 (40)
Microflora	S17/f0001	King, P.R	1976	Waikato Coal Measures	Runangan–Duntroonian 36.0–25.2 Ma	7 (12)
	S17/f0002	King, P.R	1976	Waikato Coal Measures	Whaingaroan–Waitakian 34.3–21.7 Ma	7 (56)
	S17/f0043	Pocknall, D., & Kirk, P.A.	1987	Waikato Coal Measures	Duntroonian 27.1–25.2 Ma	4 (16)
	S17/f0044	Pocknall, D., & Kirk, P.A.	1987	Waikato Coal Measures	Duntroonian 27.1–25.2 Ma	4 (34)
	S17/f0045	Pocknall, D., & Kirk, P.A.	1987	Waikato Coal Measures	Duntroonian 27.1–25.2 Ma	4 (51)
	S17/f0046	Pocknall, D., & Kirk, P.A.	1987	Waikato Coal Measures	Duntroonian 27.1–25.2 Ma	4 (13)
	S17/f0047	Pocknall, D., & Kirk, P.A.	1987	Waikato Coal Measures	Duntroonian 27.1–25.2 Ma	4 (47)
	S17/f0048	Pocknall, D., & Kirk, P.A.	1987	Waikato Coal Measures	Duntroonian 27.1–25.2 Ma	4 (7)
Microflora	S17/f0049	Pocknall, D., & Kirk, P.A.	1987	Waikato Coal Measures	Duntroonian 27.1–25.2 Ma	4 (52)
	S17/f0055	Sykes, R	1988	Waikato Coal Measures	Whaingaroan–Duntroonian 34.3–25.2 Ma	12 (57)

Fossil Type	FRED ID	Collected by	Date	Stratigraphic location	Inferred Age	Location*
	S17/f0056	Sykes, R	1988	Waikato Coal Measures	Whaingaroan–Duntroonian 34.3–25.2 Ma	12 (24)

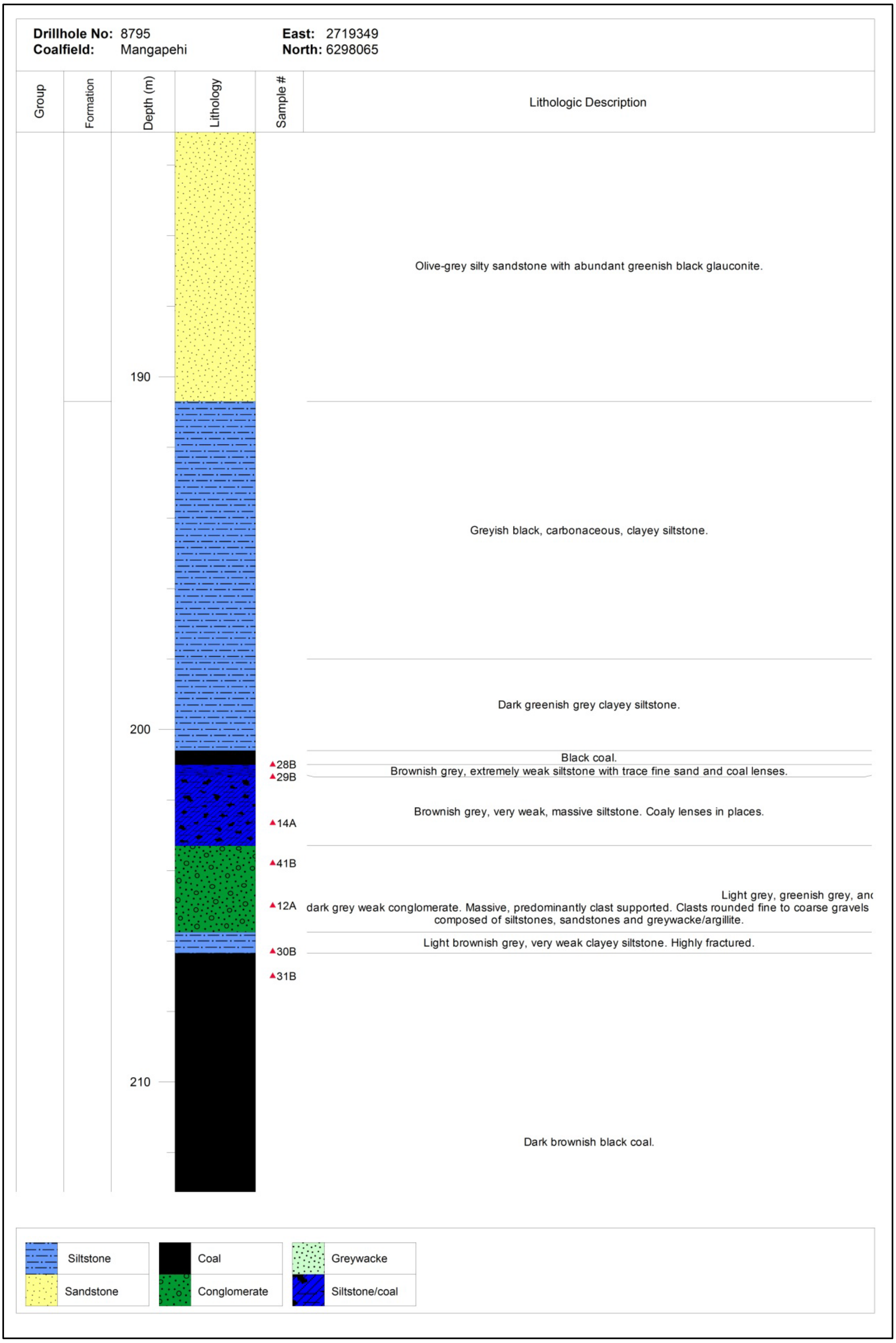
* No. in brackets refers to the Record number on FRED

APPENDIX 2 - DRILLHOLE LOGS

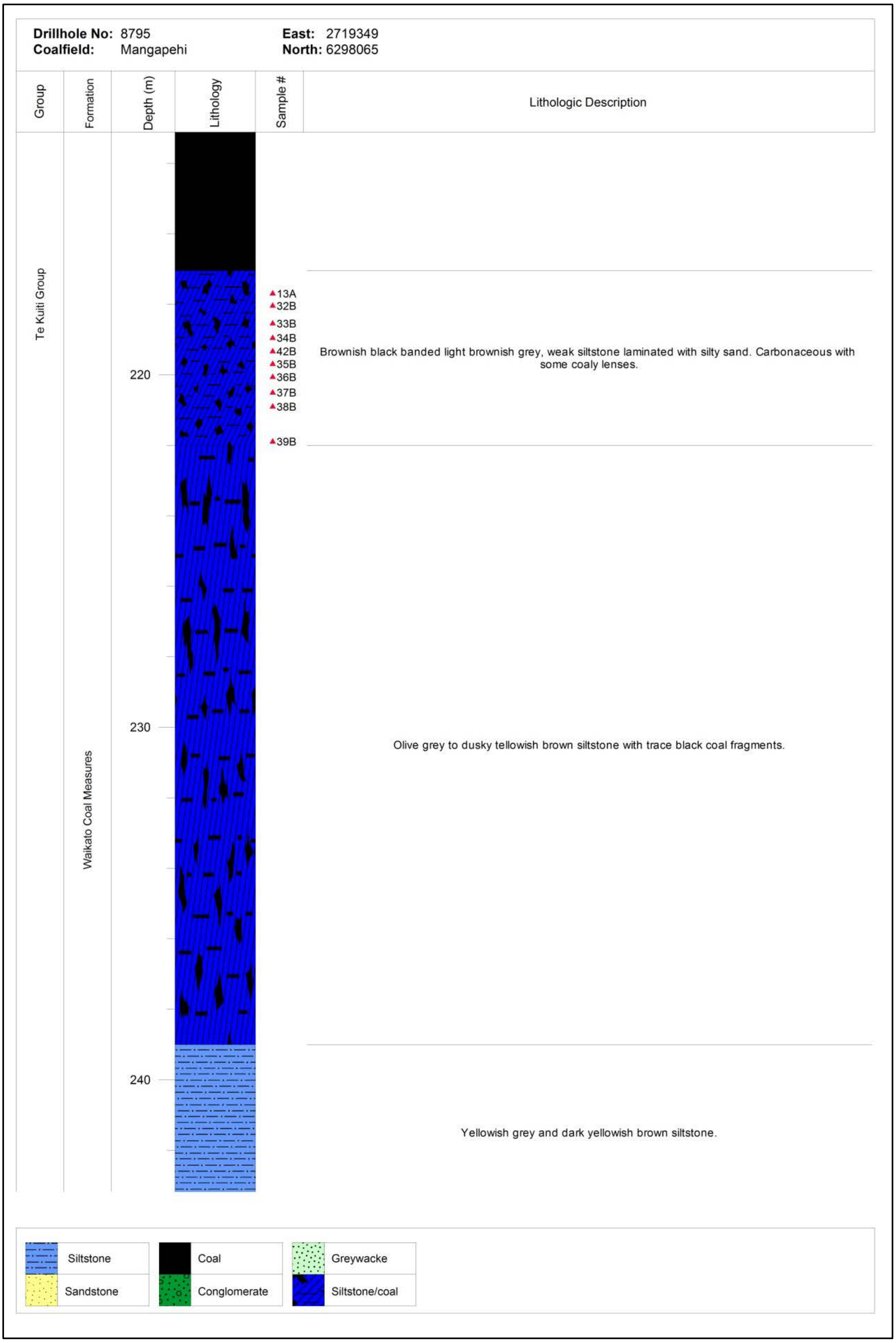
Drillhole 8795 - Page 1/5



Drillhole 8795 - Page 2/5



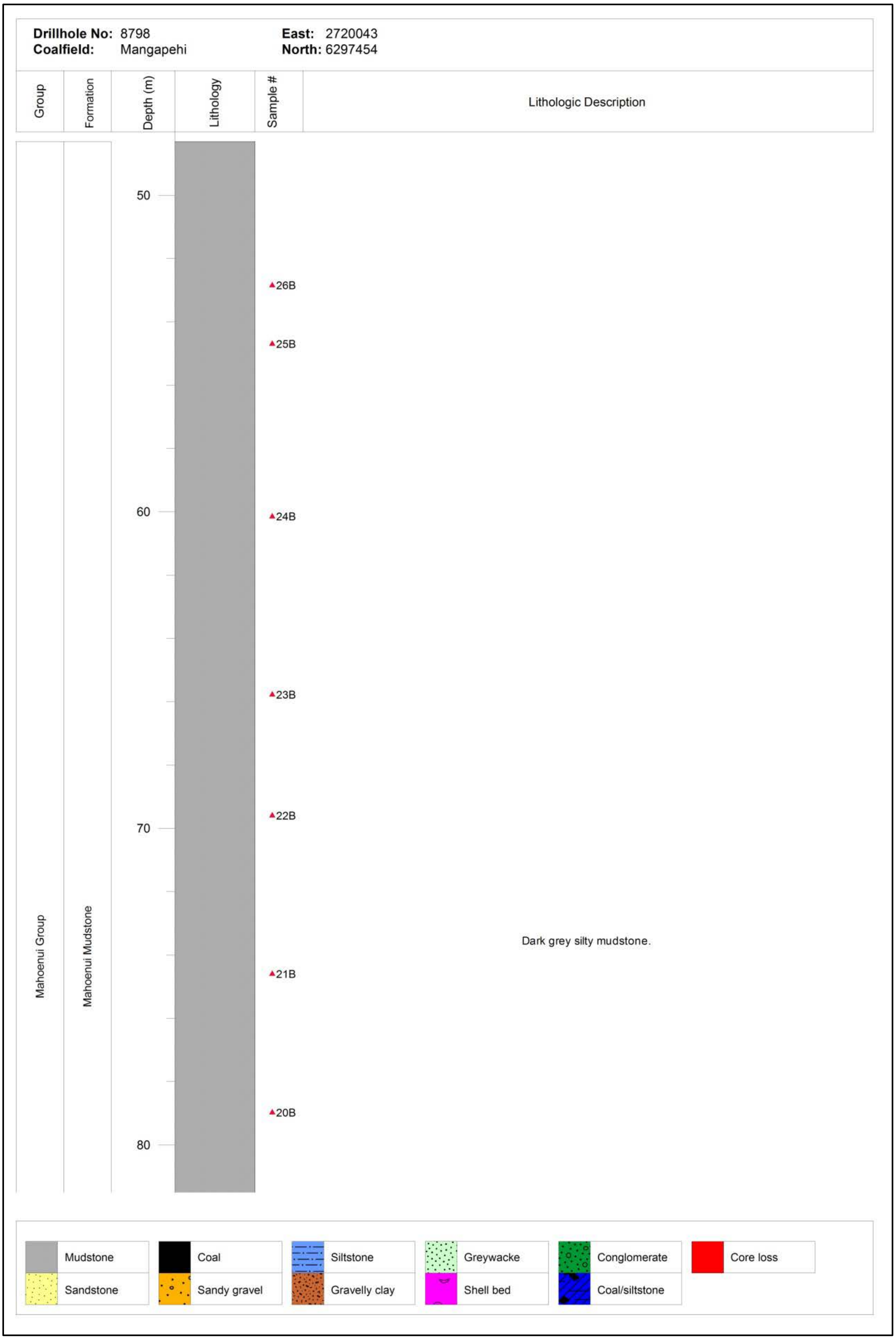
Drillhole 8795 - Page 3/5



Drillhole 8795 - Page 4/5

Drillhole 8795 - Page 5/5

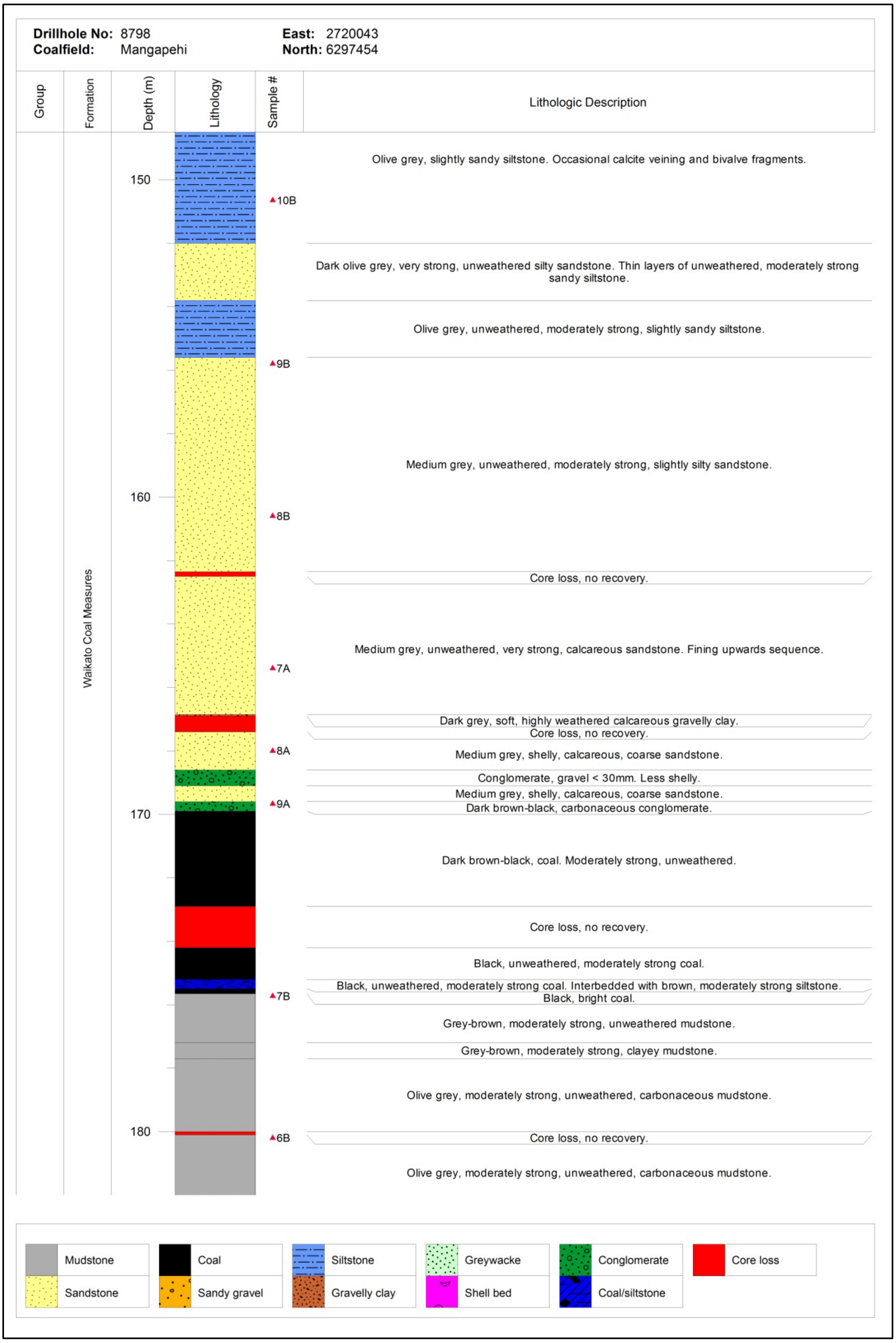
Drillhole 8798 - Page 1/5



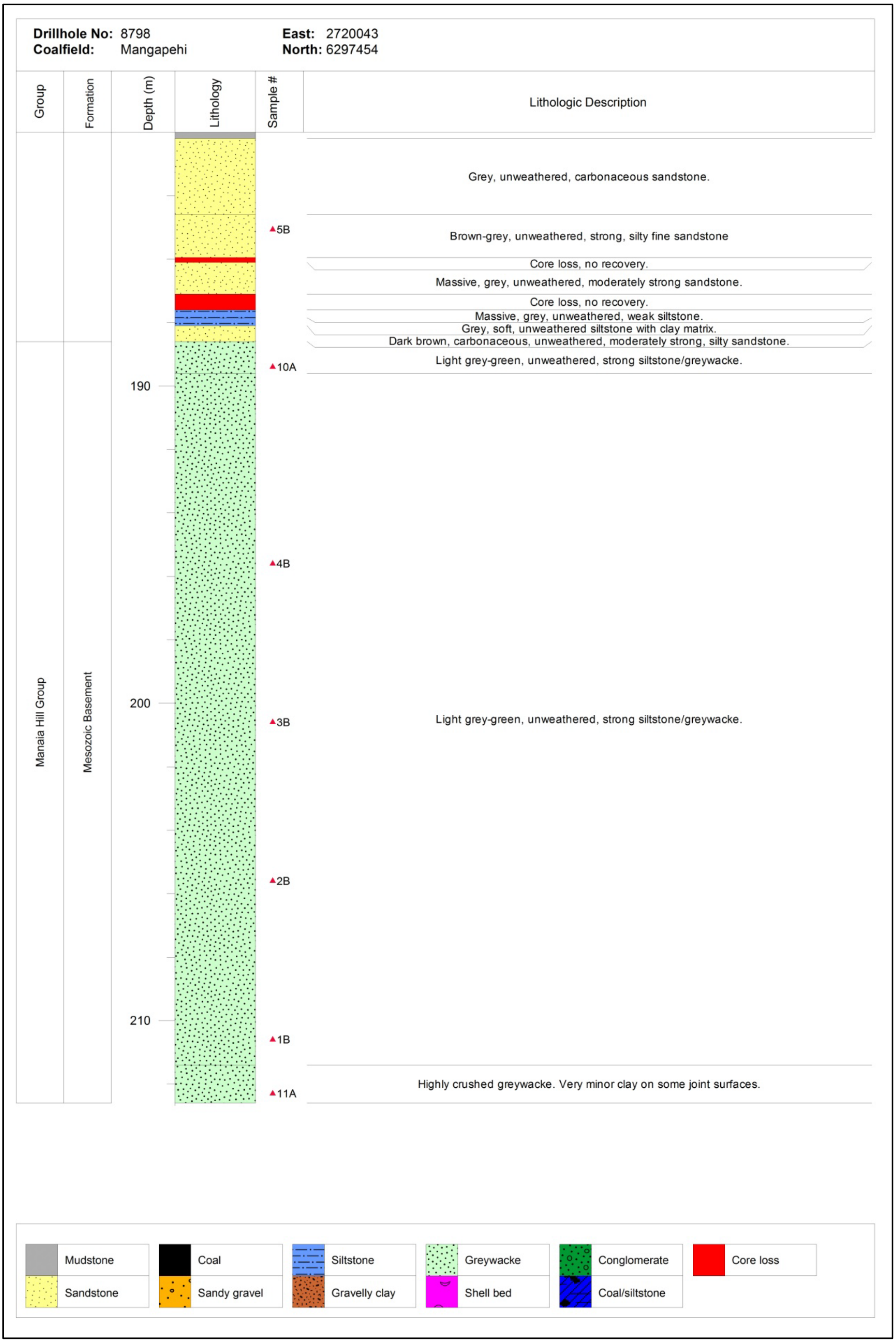
Drillhole 8798 - Page 2/5

Drillhole 8798 - Page 3/5

Drillhole 8798 - Page 4/5



Drillhole 8798 - Page 5/5



APPENDIX 3 - CALCAREOUS NANNOFOSSIL TAXONOMIC LIST

Calcareous nannofossil species considered in this study are listed alphabetically by generic epithet.

Braarudosphaera bigelowii (Gran & Braarud, 1935) Deflandre, 1947

Chiasmolithus altus Bukry & Percival, 1971

Clausicoccus fenestratus (Deflandre & Fert, 1954) Prins, 1979

Coccolithus pelagicus (Wallich, 1877) Schiller, 1930

Coronocyclus nitescens (Kamptner, 1963) Bramlette & Wilcoxon, 1967

Cyclicargolithus abisectus (Müller, 1970) Wei, 1973

Cyclicargolithus floridanus (Roth & Hay in Hay et al., 1967) Bukry, 1971

Dictyococcites bisectus (Hay, Mohler & Wade, 1966) Bukry & Percival, 1971

Discoaster deflandrei Bramlette & Riedel, 1954

Helicosphaera euphratis Haq, 1966

Pontosphaera multipora (Kamptner, 1948) Roth, 1970

Reticulofenestra daviesii (Haq, 1968) Haq, 1971

Reticulofenestra filewiczii (Wise and Wiegand in Wise 1983) Dunkley Jones et al., 2009

Reticulofenestra gelida (Geitzenauer, 1972) Backman, 1978

Reticulofenestra haqii Backman, 1978

Reticulofenestra pseudoumbilicus (Gartner, 1967) Gartner, 1969

Sphenolithus ciperoensis Bramlette & Wilcoxon, 1967

Sphenolithus distentus (Martini, 1965) Bramlette & Wilcoxon, 1967

Sphenolithus moriformis (Brönnimann & Stradner, 1960) Bramlette & Wilcoxon, 1967

Sphenolithus predistentus Bramlette & Wilcoxon, 1967

Umbilicosphaera jafari Müller, 1974

Zygrhablithus bijugatus (Deflandre in Deflandre & Fert, 1954) Deflandre, 1959

APPENDIX 4 - UNIT THICKNESSES FOR ISOPACH ANALYSIS

List of thicknesses used for the construction of isopach maps.

Drillhole Number	Thickness of units (m)		
	Waikato Coal Measures	Aotea Formation	Mahoenui Group
5521	50.29	48.77	0.00
5522	60.35[e]	0.00	0.00
5523	61.87	8.84	0.00
5524	106.38	51.51	42.98
5525	28.04[+]	101.19	127.10
5526	29.57[+]	53.04	60.96
5527	53.64	59.74	23.77
5528	42.82	4.42	57.30
5529	78.03	4.88	35.36
5530	2.13	13.72	0.00
5531	95.40	9.45	86.26
5532	91.74[+]	89.31	88.09
5533	107.29	107.90	124.05
5534	25.60[e]	0.00	0.00
5535	44.96	16.00	0.00
5536	63.70	81.99	139.90
5537	56.39[e]	0.00	0.00
5538	61.87	4.27	0.00
8790	67.00	77.50	37.50
8791	0.00	0.00	0.00
8792	129.00	120.00	71.00
8793	79.80	51.20	0.00
8794	69.00	117.80	65.20
8795	83.30	28.70	54.00
8796	53.90	36.50	80.00
8797	45.50	9.50	31.00
8798	48.90	39.70	51.70
8799	89.10	132.10	37.10

[e] = erosion to top of unit

[+] = basement not reached

APPENDIX 5 - PALYNOLOGY COUNTS

Species lists and counts for all samples examined by Dr Mildenhall during this study. The following abbreviations are used in the tables.

AF = Aotea Formation
MG = Mahoenui Group
MHG = Manaia Hill Group
WCM = Waikato Coal Measures

X = a lot present
x = a presence

Counts from samples taken from core 8795

Sample no. Formation Depth in m Slide no. Age	27B AF 180.9 L26419 n/d	28B WCM 201.13 L26420 Po-Pl	41B WCM 203.8 L26421 n/d	30B WCM 206.3 L26422 Lw-Pl	31B WCM 207 L26423 Lw-Pl	32B WCM 218.05 L26424 Lw-Pl	34B WCM 218.96 L26425 Lw-Pl	36B WCM 220.07 L26426 Lw-Pl	38B WCM 220.71 L26427 Lw-Pl	39B WCM 221.9 L26428 Lw-Pl
TAXA										
Charcoal			X	x						
Dinophyceae	X									
Botryococcus						x				
Microthyriaceous germlings	x								x	x
Baculatisporites disconformis		x		3	2	2		2	1	2
Bryophyta		x	x							
Cyathidites	x	6	x	74	7	18	19	7	7	35
Echinosporis				4		2				1
Evansispora cenozoica								14		1
Foveotriletes crater				x						
Foveotrilites lacunosus				1						
Gemmatriletes		x	x							
Hymenophyllaceae		2		5						
Kuylisporites waterbolkii		1		x		x				1
Laevigatosporites	x	35	x	65	10	29	21	36	12	30
Latrobosporites marginis								1		
Lycopodium scariosum		1								
Monolete (coarsely gemmate)								9	3	x
Peromonolites										1
Polypodiaceoisporites papuanus	x			1						
Polypodiisporites	x	1	x	2	x	1	3	1	3	x
Polypodiisporites histiopteroides									1	
Polypodiisporites inangahuensis				1	3	1	1			2
Polypodiisporites minimus				2	1	3	3			2
Polypodiisporites radiatus		1	x	x	1	x				
Polypodiisporites variscabratus	x	x				1	x	3	3	1
Rugulatisporites		1								
Stereisporites		x			x					
Triletes			x		x		2	1		1
Trilites tuberculiformis		1		12	1	x	5	2	3	8
Verrucosisporites cristatus					1			10	15	16
Verrucosisporites kopukuensis				1	1	x		1		

Sample no. Formation Depth in m Slide no. Age	27B AF 180.9 L26419 n/d	28B WCM 201.13 L26420 Po-Pl	41B WCM 203.8 L26421 n/d	30B WCM 206.3 L26422 Lw-Pl	31B WCM 207 L26423 Lw-Pl	32B WCM 218.05 L26424 Lw-Pl	34B WCM 218.96 L26425 Lw-Pl	36B WCM 220.07 L26426 Lw-Pl	38B WCM 220.71 L26427 Lw-Pl	39B WCM 221.9 L26428 Lw-Pl
Araucariacites australis	x	2						x		2
Cycadopitys?						1		1		
Dacrycarpites australiensis								1	x	
Dacrydiumites praecupressinoides		x		1	3	1	x	2	2	1
Equisetosporites notensis					1	x				
Microalatidites paleogenicus						1				
Phyllocladidites mawsonii									x	
Podocarpidites		3	x	x	8	5	7	x	x	1
Podocarpidites ellipticus				1	x					
Podocarpidites puteus		x			x		x	3	159	3
Podocarpidites rugulatus	x	x								
Podosporites		x								
Arecipites		4	x		3	1				1
Arecipites otagoensis		5		1	3	x	3		1	1
Arecipites subverrucatus		1								
Arecipites waitakiensis		3								
Assamiapollenites incognitus		x								
Astelia								1	x	
Bluffopollis maculatus										x
Bluffopollis scabratus					1	1			x	
Clavatipollenites ascarinoides		3			1	1				
Collospermum - type										1
Corsinipollenites oculus noctus		x								
Cranwellia striata		1				x	1	2	1	5
Cunoniaceae		9			5	7	12		1	1
Cupanieidites insularis					1					
Cupanieidites orthoteichus		x		x			2			
Cupanieidites reticularis		x					1			
Dryadopollis retequetrus					1					
Epacridaceae		4								
Ericipites crassiexinus		2					x		1	
Ericipites longisulcatus			x	2	x		x		3	1
Gemmapollis raglanensis				2	1	2	1	1	1	3
Gothanipollis perplexus		1			1		1	1	2	1
Haloragacidites harrisii		9		11	148	22	1	32	5	3
Ilexpollenites anguloclavatus						1				

Sample no. Formation Depth in m Slide no. Age	27B AF 180.9 L26419 n/d	28B WCM 201.13 L26420 Po-Pl	41B WCM 203.8 L26421 n/d	30B WCM 206.3 L26422 Lw-Pl	31B WCM 207 L26423 Lw-Pl	32B WCM 218.05 L26424 Lw-Pl	34B WCM 218.96 L26425 Lw-Pl	36B WCM 220.07 L26426 Lw-Pl	38B WCM 220.71 L26427 Lw-Pl	39B WCM 221.9 L26428 Lw-Pl
Lateropora glabra					?					
Liliacidites		3	x	x	2					1
Liliacidites variegatus					1					
Luminidites reticulatus								1		
Malvacipollis subtilis				2	1	2	3			3
Milfordia hypolaenoides					1					
Myrtaceidites mesonesus		12			4	1	2	25	2	3
Myrtaceidites parvus		90		11	23	24	20	12	7	19
Nothofagidites asperus				5		1				1
Nothofagidites cranwelliae	x	21	x	34	7	79	77	39	20	73
Nothofagidites lachlaniae	x	x				1	1			
Nothofagidites matauraensis		4				32	24	10	5	16
Nothofagidites spinosus					1	3	x	3		4
Nupharipollis mortenensis		2				x	7	2	x	2
Nuxpollenites varicosus					X					
Nyssapollenites endobalteus		1						x		
Palaeocoprosmadites zelandiae	x									
Periporopollenites vesicus							4	3		
Polycolporopollenites esobalteus										1
Proteacidites	x	2		5	8		2	2	x	
Proteacidites minimus		x		2	4	1		6	3	
Proteacidites pseudomoides		x			x	x			x	x
Proteacidites rectus				x		1				
Pseudowinterapollis couperi							x			
Quintiniapollis psilatispora					1		1			
Rhoipites		4		11	12	12	6	2	2	4
Rhoipites aequatorius		9	x	2	x	2			1	2
Rhoipites alveolatus				x	x	x				
Rhoipites aralioides					1					
Rhoipites couperi		x		x	x	5	3		x	1
Rhoipites hekelii		4								
Rhoipoites karamuensis		3			2		26	x	3	1
Rhoipites sphaerica		10		23	3	5	5			4
Rhoipites waimumuensis										2
Rubipollis oblatus		2			x	x				
Santalumidites cainozoicus									1	
Sapotaceoidaepollenites latizonatus		x			1					

Sample no. **Formation** **Depth in m** **Slide no.** **Age**	**27B** **AF** **180.9** **L26419** **n/d**	**28B** **WCM** **201.13** **L26420** **Po-Pl**	**41B** **WCM** **203.8** **L26421** **n/d**	**30B** **WCM** **206.3** **L26422** **Lw-Pl**	**31B** **WCM** **207** **L26423** **Lw-Pl**	**32B** **WCM** **218.05** **L26424** **Lw-Pl**	**34B** **WCM** **218.96** **L26425** **Lw-Pl**	**36B** **WCM** **220.07** **L26426** **Lw-Pl**	**38B** **WCM** **220.71** **L26427** **Lw-Pl**	**39B** **WCM** **221.9** **L26428** **Lw-Pl**
Sparganiaceaepollenites						3				
Sparsipollis papillatus		x								
Stephanocolpites sphericus					x	2	1	23	1	3
Tetracolporites										2
Tetracolporites ixerboides					x					
Tetracolporites spectabilis					1		1			
Tetracolporopollenites costatus		1			x					
Tricolpites	x	11		4	4	7	4	10	2	11
Tricolpites discus		2				1		7		1
Tricolpites perimarginatus									3	1
Triorites		1				1	2	1	3	2
Triorites introlimbatus							6		14	9
Triorites minisculus		2		1						
Triorites minor		5	x	5	2					
Triorites orbiculatus								1		1
Triporopollenites ambiguus					x					
Violaceae							3			
unidentified pollen	x	15		6	17	17	19	22	9	8
Total Count	**0**	**300**	**0**	**300**	**300**	**300**	**300**	**300**	**300**	**300**

Counts from samples taken from core 8798

Sample no. **Formation** **Depth in m** **Slide no.** **Age**	**26B** **MG** **52.85** **L26429** **n/d**	**23B** **MG** **65.78** **L26430** **n/d**	**5A** **MG** **99.4** **L26431** **Lw-Pl**	**6A** **AF** **100.4** **L26432** **n/d**	**12B** **AF** **125.04** **L26433** **Lw-Pl**	**1A** **WCM** **141.9** **L26434** **Lw-Pl**	**9B** **WCM** **155.8** **L26435** **n/d**	**9A** **WCM** **169.67** **L26436** **n/d**	**7B** **WCM** **175.73** **L26437** **Lw-Pl**	**5B** **WCM** **185.07** **L26438** **Lw-Pl**	**10A** **MHG** **189.53** **L26439** **n/d**	**4B** **MHG** **195.6** **L26440** **n/d**	**2B** **MHG** **205.6** **L26441** **n/d**	**1B** **MHG** **210.6** **L26442** **n/d**
TAXA	X		x	x	x	x	x	x				x	X	X
Charcoal		X	X	X	X		x	X						
Dinophyceae							x	x						
Tasmanitids											x		x	
Botryococcus			x											
Microthyriaceous germlings	X		x	x	x	x	x	x				x	X	X
Baculatisporites disconformis					1	x			x	7				
Bryophyta							x							
Cyathidites	x	x	x	x	19	2	x	x	3	61				
Echinosporis					1					8				
Evansispora cenozoica			x						x					
Foveotriletes verrucosus			x											
Ischyosporites gremius			x							1				
Kuylisporites waterbolkii								x						
Laevigatosporites	x	x	x	x	25	2		x	15	59			x	x
Lycopodium serpentinum					1									
Monolete (coarsely gemmate)									x	3				
Osmundaceae			x											
Peromonolites vellosus										x				
Polypodiaceoisporites papuanus			x					x						
Polypodiisporites			x	x	6	x	x	x	x	5				
Polypodiisporites histiopteroides						x				1				
Polypodiisporites inangahuensis			x		2					2				
Polypodiisporites minimus			x		2	1			x	3				
Polypodiisporites perverrucatus			x											
Polypodiisporites radiatus				x		3		x						
Polypodiisporites variscabratus				x		x			x	2				
Rugulatisporites mallatus			x											
Rugulatisporites trophus					1									
Triletes			x	x	1	x			x	x				
Trilites tuberculiformis		x	x	x	4	1			2	22				x
Verrucosisporites cristatus										x				
Verrucosisporites kopukuensis					2	x				x				

Sample no. **Formation** **Depth in m** **Slide no.** **Age**	**26B** **MG** **52.85** **L26429** **n/d**	**23B** **MG** **65.78** **L26430** **n/d**	**5A** **MG** **99.4** **L26431** **Lw-Pl**	**6A** **AF** **100.4** **L26432** **n/d**	**12B** **AF** **125.04** **L26433** **Lw-Pl**	**1A** **WCM** **141.9** **L26434** **Lw-Pl**	**9B** **WCM** **155.8** **L26435** **n/d**	**9A** **WCM** **169.67** **L26436** **n/d**	**7B** **WCM** **175.73** **L26437** **Lw-Pl**	**5B** **WCM** **185.07** **L26438** **Lw-Pl**	**10A** **MHG** **189.53** **L26439** **n/d**	**4B** **MHG** **195.6** **L26440** **n/d**	**2B** **MHG** **205.6** **L26441** **n/d**	**1B** **MHG** **210.6** **L26442** **n/d**
Araucariacites australis			x		x			x						
Cycadopitys?					x				1					
Dacrycarpites australiensis			x											
Dacrydiumites praecupressinoides			x	x	1	6		x	1	1				
Podocarpidites			x	x	1	8			1	4		x		x
Podocarpidites ellipticus					x	2				1				
Podocarpidites puteus			x			12	x		4	3				
Podosporites brevisaccatus									1					
Podosporites parvus								x						
Anisotricolporites truncatus									2	1				
Arecipites		x			1	1								
Arecipites otagoensis						5			x	5				
Arecipites subverrucatus						3								
Astelia									2					
Bluffopollis scabratus					x	x								
Bombacacidites bombaxoides				x										
Clavastephanocolporites meleosus			x											
Clavatipollenites ascarinoides		x				1		x	x	x				
Collospermum - type						1								
Cranwellia striata						3			1	2				
Cunoniaceae						x								
Cupanieidites orthoteichus									1	1				
Diporites n.sp.						x								
Ericipites crassiexinus										x				
Ericipites longisulcatus		x				1	x		1	x				
Gemmapollis raglanensis									2	3				
Gothanipollis bassensis									2	3				
Haloragacidites harrisii		x	x		2	17	x	x	1	2				
Liliacidites				x		1				1				
Liliacidites intermedius						x								
Liliacidites variegatus						2								
Malvacipollis subtilis		x	x		1		x		x	1				
Monogemmites gemmatus				x										
Myrtaceidites mesonesus					1	7			1	1				
Myrtaceidites parvus					4	63			68	12				
Nothofagidites asperus						1								

Sample no.	**26B**	**23B**	**5A**	**6A**	**12B**	**1A**	**9B**	**9A**	**7B**	**5B**	**10A**	**4B**	**2B**	**1B**
Formation	**MG**	**MG**	**MG**	**AF**	**AF**	**WCM**	**WCM**	**WCM**	**WCM**	**WCM**	**MHG**	**MHG**	**MHG**	**MHG**
Depth in m	**52.85**	**65.78**	**99.4**	**100.4**	**125.04**	**141.9**	**155.8**	**169.67**	**175.73**	**185.07**	**189.53**	**195.6**	**205.6**	**210.6**
Slide no.	**L26429**	**L26430**	**L26431**	**L26432**	**L26433**	**L26434**	**L26435**	**L26436**	**L26437**	**L26438**	**L26439**	**L26440**	**L26441**	**L26442**
Age	**n/d**	**n/d**	**Lw-Pl**	**n/d**	**Lw-Pl**	**Lw-Pl**	**n/d**	**n/d**	**Lw-Pl**	**Lw-Pl**	**n/d**	**n/d**	**n/d**	**n/d**
Nothofagidites cranwelliae		x	x	x	162	132	x	x	136	30				
Nothofagidites lachlaniae					4				1					
Nothofagidites matauraensis					x	1			6	x				
Nothofagidites spinosus			x	x	47	2			7	3				
Nupharipollis mortenensis					1				4					
Nyssapollenites endobalteus			x	x	x	x								
Proteacidites						1				1				
Proteacidites minimus						2	x		2	2				
Proteacidites pseudomoides					1				1	1				
Proteacidites tenuiexinus						x								
Proteacidites tuberculatus			x											
Rhoipites			x	x	3	2	x		3	6		x		
Rhoipites aequatorius										1				
Rhoipites alveolatus				x		x								
Rhoipites couperi		x	x			2				1				
Rhoipites pseudostriatus									x					
Rhoipites rhomboidaliformis										2				
Rhoipites sphaerica									3	12				
Rhoipites waimumuensis										1				
Santalumidites cainozoicus						x								
Sapotaceoidaepollenites latizonatus									x	2				
Stephanocolpites sphericus						1								
Tetracolporites spectabilis			x	x		x				x				
Tricolpites					2	3	x		10	5				
Tricolpites discus						1			1					
Tricolpites phillipsii									1					
Triorites			x			1			3					
Triorites minisculus									x	x				
Triorites minor									7	3				
Triorites orbiculatus						1			x	1				
Triporopollenites ambiguus														
Tubulifloridites	x													
Violaceae														
unidentified pollen		x	x	x	4	8		x	6	14				
Total Count	**0**	**0**	**0**	**0**	**300**	**300**	**0**	**0**	**300**	**300**	**0**	**0**	**0**	**0**