

Paleocene calcareous nannofossils from East Coast, New Zealand: biostratigraphy and palaeoecology

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Abstract Three outcrop sections (Angora Road, Tawanui and Pahaoa) and one stratigraphic core (Toi Flat-1) from the East Coast of North Island, New Zealand contain moderately-preserved Paleocene calcareous nannofossil assemblages. Lower Paleocene intervals in the New Zealand region are often barren, or contain very sparse and often poorly-preserved nannofossil assemblages, making correlation to the geologic time-scale difficult. Despite this, the oldest fossiliferous rocks from the Angora Road outcrop and the Toi Flat-1 core contain *Chiasmolithus bidens* and *Toweius pertusus*, indicating nannofossil zone NP4. In these sections, the first occurrence of *Fasciculolithus tympaniformis* marks an increase in the abundance and preservation of nannofossils, and allows assignment of NP5. The oldest samples examined that contain discernable nannofossils from the Tawanui and Pahaoa outcrop sections also contain *F. tympaniformis*. The Angora Road section contains a thick sequence (~40m) of typical Waipawa Formation, an organic-rich, often non-calcareous, Upper Paleocene dark mudstone unit that exhibits a positive $\delta^{13}\text{C}$ excursion. Although the type facies is dark mudstone, a correlative facies (termed the Waipawa organofacies), that is also enriched in $\delta^{13}\text{C}$ and total organic carbon, occurs at the other sites. The presence of *Heliolithus kleinpellii* in most sections indicates correlation of this unit to NP6, with the first appearance of the genus *Discoaster* (*D. mohleri*; NP7) occurring near the top of the section at Angora Road and questionably just above the equivalent interval at Pahaoa. At Tawanui and Toi Flat-1, an unconformity separates the NP6 sediments of the Waipawa organofacies from overlying sediments of Late Paleocene age, belonging to NP8 (Tawanui) and NP9 (Toi Flat-1). Recent work shows that the Waipawa organofacies is associated with climatic cooling and sea-level fall, which may have resulted from the development of small, ephemeral ice-sheets on Antarctica. Nannofossil assemblages at all studied sections support cooler sea-surface temperatures before and during deposition of the Waipawa organofacies, with abundant *Chiasmolithus* spp. and very rare or absent warm-water taxa, including the fasciculith group and *Sphenolithus*. In fact, the first appearance of the genus *Sphenolithus* is delayed in the New Zealand region, where it is not consistently present until the Late Paleocene, after sea-surface temperatures increased, following the brief interval of cooling associated with deposition of the Waipawa organofacies.

Keywords calcareous nannofossils, Paleocene, New Zealand, Waipawa, biostratigraphy, sea-surface temperature

1. Introduction

Calcareous nannofossils are nearly ubiquitous in Jurassic to Recent marine sediments deposited above the calcite compensation depth. Their small size, rapid evolution and generally cosmopolitan nature make them excellent biostratigraphic indicators. As phytoplankton, they also record surface-water conditions, with some species particularly sensitive to temperature and nutrient conditions in the photic zone (e.g. Okada & Honjo, 1973; Molino & McIntyre, 1990; Winter *et al.*, 1994; Ziveri *et al.*, 2004). Thus, this group of marine microfossils is crucial for biostratigraphic and palaeoclimatic studies in many settings.

Today nanoplankton are excluded from the region south of the Antarctic Polar Front (~65°S; Findlay & Giraudeau, 2000); however, during the greenhouse climate of the Palaeogene, nannofossils were more widely distributed and are commonly found in Paleocene to Oligocene sediments deposited in the high southern latitudes (e.g. Wise, 1983; Wei, 1991, 1992; Watkins *et al.*, 2001; Bralower, 2002; Persico & Villa, 2004; Fioroni *et al.*, 2012; Persico *et al.*, 2012).

Calcareous nannofossils reached their greatest diversity in the calcite seas of the Late Cretaceous (Bown *et al.*, 2004) and, like many other groups, suffered high ex-

tion rates at the Cretaceous /Palaeogene boundary (*e.g.* Bramlette & Martini, 1964; Pospichal, 1996; Bown *et al.*, 2004). The small number of taxa that survived the mass extinction rapidly diversified during the Paleocene (Pospichal, 1996; Bown *et al.*, 2004). This period is interesting, not only for high-resolution nannofossil biostratigraphy, but also for the study of evolutionary processes, as various groups speciated to fill the niches left by the mass extinction. Although many nannofossil taxa are cosmopolitan, the provincialism seen in Maastrichtian high latitudes (Watkins *et al.*, 1996; Lees, 2002) continued into the Paleocene, with some taxa migrating into the high southern latitudes well after their first appearance in low and mid-latitudes (Edwards, 1971).

During the Paleocene, New Zealand was situated further south than today (Cande & Stock, 2004; Figure 1A), yet nannofossils are reasonably common in calcareous Paleocene sediments deposited in the region (*e.g.* Edwards, 1971; Edwards & Perch-Nielsen, 1974; Edwards, 1982; Morgans *et al.*, 2004). Although some taxa clearly have diachronous first occurrences, most seem to have synchronous first appearances between this region and lower latitudes (*e.g.* Edwards, 1971). Thus, New Zealand is an excellent location for correlating biostratigraphic events from the low and mid-latitudes into the high southern latitudes. The sensitivity of some taxa to sea-surface temperatures (SSTs) also allows us to track changes in climate, as certain species are only found in the New Zealand region during intervals of warmer SST.

This study documents the calcareous nannofossil assemblages from three outcrop sections (Angora Road, Tawanui and Pahaoa) and one stratigraphic core (Toi Flat-1) from the East Coast of North Island, New Zealand (Figure 1B). The three outcrop sections were originally studied to provide age control for a sedimentological and palaeoclimatic study undertaken by a graduate student at the University of Waikato (Tayler, 2011). Additional work was later completed for Tawanui, and also for the Toi Flat-1 core, to improve the Paleocene biostratigraphy in the New Zealand region (Crouch *et al.*, 2014) and to examine

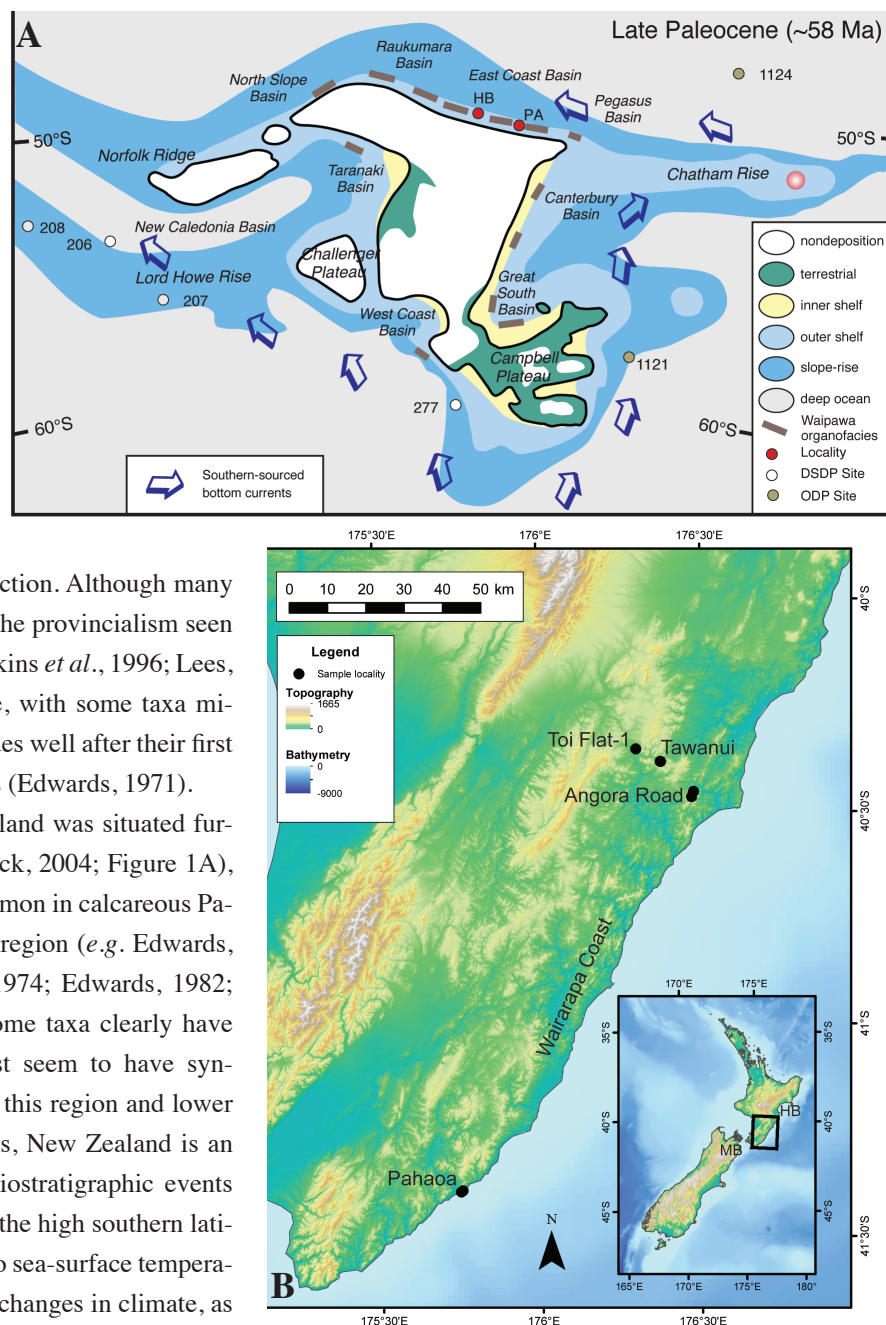


Figure 1: (A) Late Paleocene (~58Ma) palaeogeographic reconstruction of New Zealand region, with approximate locations of studied sections indicated by red circles (adapted from King *et al.*, 1999, modified from Hollis *et al.*, 2014). HB = Hawke's Bay (Angora Road, Tawanui, Toi Flat-1), PA = Pahaoa. (B) Topographic and bathymetric map, East Coast, New Zealand, showing location of studied sections. Samples taken from two different localities at Angora Road and Pahaoa. MB = Marlborough

Middle to Late Paleocene climate conditions associated with deposition of the organic-rich rocks of the Waipawa Formation (Hollis *et al.*, 2014). Data presented here document the nannofossil biostratigraphy for each section and examine the sea-surface conditions inferred from changes

in the calcareous nannofossil assemblages.

2. Geological Setting

The New Zealand microcontinent (Zealandia) began separating from Australia and Antarctica during the Late Cretaceous. By the Paleocene, Zealandia was isolated and tectonically quiescent. Sedimentation around the margins of the microcontinent was dominated by passive margin transgressive sediments (Ballance, 1993; King *et al.*, 1999), interrupted briefly during the Late Paleocene by a short-lived regression and climatic cooling, possibly related to the development of ephemeral ice-sheets on Antarctica (Hollis *et al.*, 2014).

Paleocene outcrop sections preserved on the East Coast of North Island are characterised by shelf to slope deposition dominated by mudstone. Lower Paleocene sediments in the region are often non-, or weakly, calcareous, making correlation based on calcareous microfossils (nannofossils and foraminifera) difficult (*e.g.* Moore, 1988; Morgans *et al.*, 2004). Carbonate content generally increases in the Middle and Upper Paleocene, although the high-latitude location of Zealandia limited the distribution of low- to mid-latitude plankton (Edwards, 1971; Hornibrook & Edwards, 1971; Morgans *et al.*, 2004).

The Upper Cretaceous to Lower Palaeogene East Coast stratigraphy comprises three primary formations: the Whangai, Waipawa and Wanstead. The Upper Cretaceous to Middle Paleocene Whangai Formation is dominantly composed of fine-grained mudstone, often non- to weakly calcareous (Moore, 1988). The Whangai Formation is divided into five localised members; the Upper Calcareous Member (uppermost Cretaceous to Paleocene) and the Te Uri Member (Paleocene) were sampled for this study. The Upper Calcareous Member consists of 50–200m of calcareous mudstone, sometimes grading into sandstone, especially where it is overlain by the sandy mudstone and glauconitic sandstone of the Te Uri Member, which is up to 70m thick (Moore, 1988; Rogers *et al.*, 2001). The Kaiwhata Limestone, which occurs at the southernmost studied locality, Pahaoa (Figure 1B), is age-equivalent to the upper part of the Whangai Formation, and appears to be a northward extension of the Amuri Limestone of the Marlborough region on South Island (van den Heuvel, 1960).

In some East Coast sections, the Whangai Formation is overlain by a dark, organic-rich mudstone, known as the Waipawa Formation (Moore, 1989), with similar depos-

its found in other areas around New Zealand (*e.g.* Tartan Formation: Cook *et al.*, 1999; Schiøler *et al.*, 2010). Although often referred to as shale, these Upper Paleocene mudstones are usually poorly bedded, with a distinctive geochemical signature that includes high total organic carbon (TOC) and enriched $\delta^{13}\text{C}_{\text{TOC}}$ (Moore, 1988, 1989). A number of coeval Waipawa Formation-equivalent facies occur in the New Zealand region. Designated the ‘Waipawa organofacies’ by Hollis *et al.* (2014), these likely-correlative units show some enrichment of the TOC and $\delta^{13}\text{C}_{\text{TOC}}$ signals characteristic of the Waipawa Formation *sensu stricto*, but are composed of lithologies other than dark mudstone (*e.g.* Killops *et al.*, 2000; Rogers *et al.*, 2001; Hollis *et al.*, 2005a). At several localities in the East Coast region (*e.g.* Tawanui: Rogers *et al.*, 2001; Hollis *et al.*, 2014 and Toi Flat-1: Crouch *et al.*, 2014), this organofacies occurs in the uppermost part of the Te Uri Member of the Whangai Formation.

The uppermost Paleocene to Eocene Wanstead Formation overlies the Whangai or Waipawa Formations and is composed of poorly-bedded, calcareous mudstone (Moore & Morgans, 1987). This study includes samples from the Whangai, Waipawa and Wanstead Formations from three outcrop localities (Angora Road, Tawanui and Pahaoa) and one onshore stratigraphic core (Toi Flat-1; Figure 1B).

2.1 Angora Road outcrop

The Angora Road section is located in southern Hawke’s Bay, approximately 2km west of Wimbledon township (Figure 1B). The examined section includes ~60m of the Upper Calcareous Member of the Whangai Formation, overlain by 40m of typical Waipawa Formation. An unconformity separates the Waipawa Formation from the overlying Wanstead Formation (Figure 2). The Upper Calcareous Member of the Whangai Formation is composed of calcareous siltstone. The Waipawa Formation at this location is quite thick, with TOC generally increasing up-section, from ~1% to 6% (Tayler, 2011). The $\delta^{13}\text{C}$ increases from approximately -26‰ to around -20‰, and shows less variation than the TOC, although both records show a decrease approximately 30m above the base of the formation, before increasing again in the uppermost part (Figure 2; Tayler, 2011; Hollis *et al.*, 2014). The dark grey to black mudstone of the Waipawa Formation is generally low in carbonate, although there are intervals where carbonate material is preserved. This study includes 10 samples

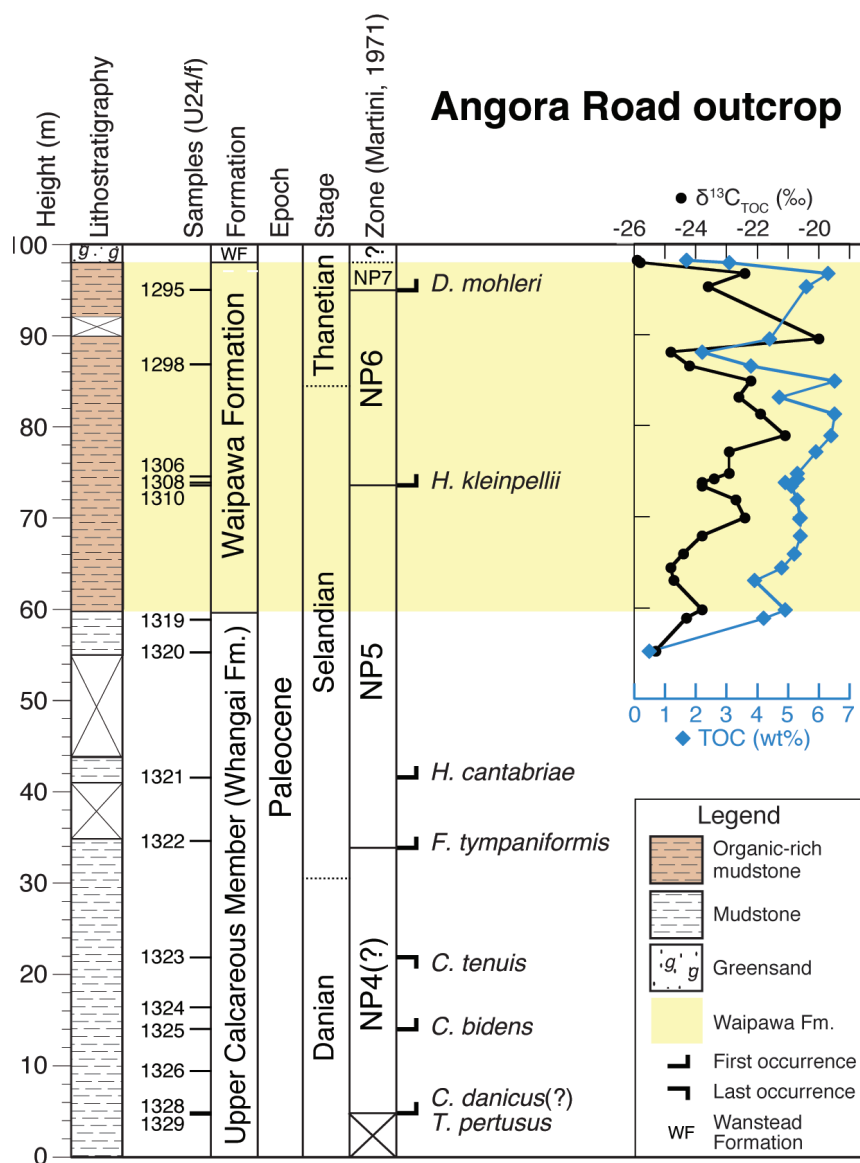


Figure 2: Angora Road section, showing first and last occurrences of key nannofossil taxa and biostratigraphic interpretation. Waipawa Formation TOC and $\delta^{13}\text{C}_{\text{TOC}}$ after Hollis *et al.* (2014). Dashed lines at ~98m indicate inferred unconformity between Waipawa and overlying Wanstead Formations. Waipawa Formation interval after Tayler (2011)

from the Whangai Formation and five from the Waipawa Formation taken from two localities (Table 1, Figure 2).

2.2 Tawanui outcrop

The Tawanui section includes outcrops along the upper Akitio River in southern Hawke's Bay (Figure 1). At Tawanui, the Wanstead Formation overlies the Te Uri Member of the Whangai Formation (Figure 3). The uppermost part of the Te Uri Member correlates to the Waipawa Formation, although it is composed of bioturbated greensand, rather than the dark mudstone typical of the Waipawa Formation (Rogers *et al.*, 2001). Both TOC and $\delta^{13}\text{C}$ increase

up-section throughout the interval correlated with the Waipawa Formation; however, TOC values only reach ~1.2%, even though the $\delta^{13}\text{C}$ shows ~6‰ enrichment over the same interval (Figure 3; Hollis *et al.*, 2014). Below the organic-rich greensand, the Te Uri Member consists of sandstone (Moore, 1988). The overlying Wanstead Formation is calcareous mudstone (Moore & Morgans, 1987). The contact between the Whangai and Wanstead Formation is obscured, but inferred to be unconformable (Tayler, 2011; Crouch *et al.*, 2014). Initially, three samples, collected in 2009 (Tayler, 2011), were examined for calcareous nannofossils to confirm correlation of the uppermost Te Uri Member to the Waipawa organofacies. Additional samples were later examined from ~65m of section. This study includes results for six samples from the Te Uri Member of the Whangai Formation (including two from the Waipawa organofacies) and 12 samples from the Wanstead Formation (Table 2, Figure 3).

2.3 Toi Flat-1 core

The Toi Flat-1 core was drilled to a total depth of 55.37m in 1991, on the flank of the Toi Flat Anticline

in southern Hawke's Bay (Figure 1; Laing, 1991). Rocks cored include mudstone from the Wanstead Formation, green, glauconitic, silty sandstone from the Te Uri Member of the Whangai Formation, as well as a few metres of undifferentiated Whangai Formation below the Te Uri Member (Figure 4). The uppermost part of the Te Uri Member is likely correlative to the Waipawa Formation; however, similarly to the Te Uri Member at Tawanui, TOC values are lower than other Waipawa organofacies, but increase from 0.67% to 0.9% at the top of the Te Uri Member. The $\delta^{13}\text{C}$ record is also more enriched in the Te Uri Member

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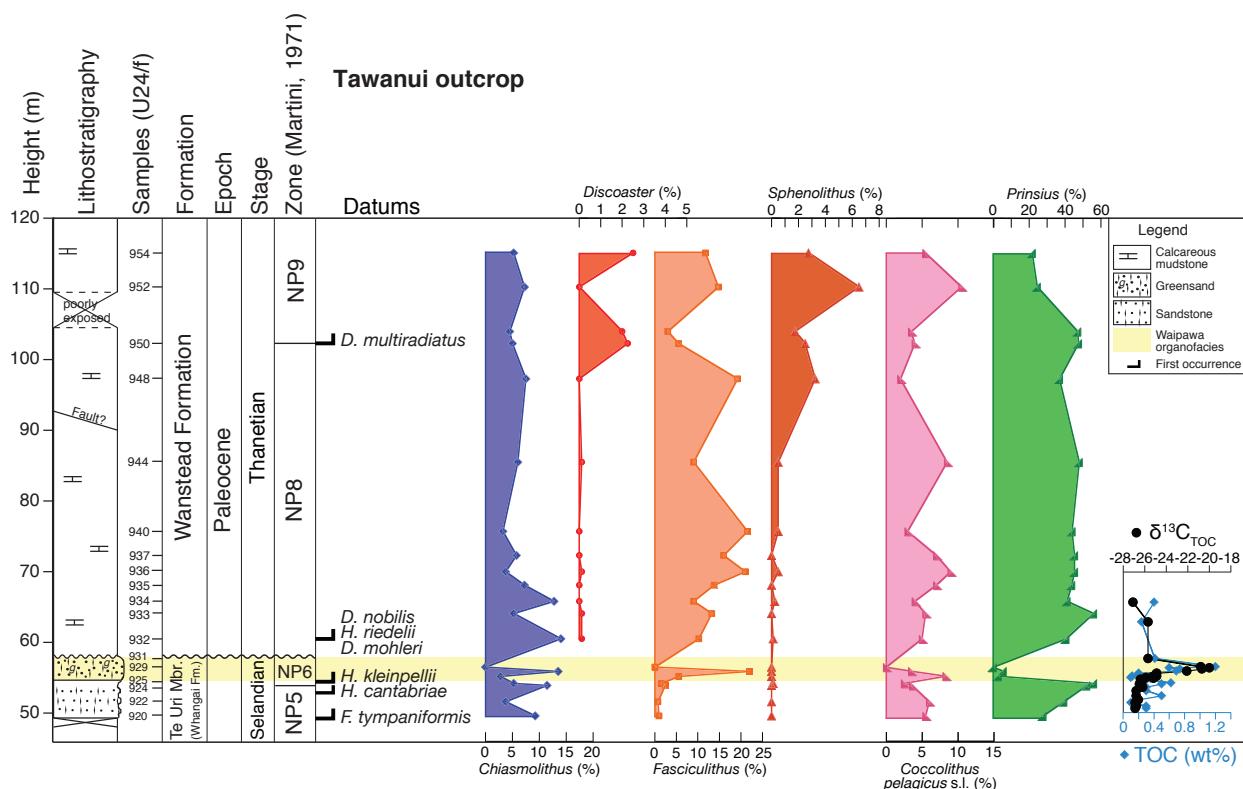


Figure 3: Tawanui section, showing first occurrences of key nannofossil taxa and biostratigraphic interpretation. TOC and $\delta^{13}\text{C}_{\text{TOC}}$ for lower part of section after Hollis *et al.* (2014). Wavy lines at ~58m indicate inferred unconformity between Te Uri Member and Wanstead Formation. Percent abundance variations for cold-water (blue) and warm-water (red/orange) taxa are shown. Yellow box = Waipawa organofacies (after Crouch *et al.*, 2014; Hollis *et al.*, 2014)

section and Toi Flat-1 core were collected on an Olympus BX-51 microscope at 1250 \times by counting 400 specimens in random FOV, followed by a scan of a minimum of 400 additional FOV for rare taxa. For samples with very sparse assemblages, all specimens encountered in 200 FOV (Tawanui) or 400 FOV (Toi Flat-1) were counted. Photomicrographs were taken using a Spot camera on a Zeiss universal microscope. The data are interpreted using the NP biozonation scheme of Martini (1970, 1971) and tied in to the chronostratigraphy of the Geologic Time Scale of Gradstein *et al.* (2012). Taxonomic concepts for species are those given in Perch-Nielsen (1985), Bown (1998, 2005), Self-Trail (2011) and Shamrock & Watkins (2012).

4. Results

The abundance and preservation of calcareous nannofossils generally increase up-section at each locality, as the sediments from the Lower Paleocene are either non- or weakly calcareous. The main biostratigraphic results and assemblage variations from the four sections examined are discussed below.

4.1 Angora Road outcrop

The upper 55m of the Upper Calcareous Member of the Whangai Formation at Angora Road generally contains few to common calcareous nannofossils, although some samples are barren (Table 1). The sparse assemblage in the lowest sample examined (U24/f1329) contains questionable *Chiasmolithus danicus* and *Toweius pertusus* and is tentatively assigned to NP4 (Figure 2, Table 1). The delayed first appearance of *Ellipsolithus macellus* in the New Zealand region (Edwards, 1971) makes it impossible to identify the base of NP4; however, a newly developed low- and mid-latitude nannofossil biozonation scheme shows that the first appearance of round *T. pertusus* falls within NP4 (Agnini *et al.*, 2014). Thus, we use the presence of *T. pertusus* in the assemblage as a secondary bio-event to identify NP4. The first occurrence (FO) of *Chiasmolithus bidens* is in U24/f1325, which is the first sample examined that contains a reasonably abundant and diverse assemblage. The presence of this species, together with the absence of other taxa typical of earliest Paleocene assemblages (*e.g.* *Futyania* spp., *Neobiscutum* spp., *Prinsius*

Fossil Record File No.	Height (m)	<i>Neochiastozygus rosenkrantzii</i>	<i>Prinsius bisulcus</i>	<i>Prinsius martinii</i>	<i>Sphenolithus primus</i>	<i>Towelus callosus</i>	<i>Towelus emihens</i>	<i>Towelus pertusus</i>	<i>Towelus pertusus</i> (large)	<i>Towelus rotundus</i>	<i>Towelus sp. 1</i> (after Bown, 2005)	<i>Towelus tovae</i>	<i>Towelus? magnicrassus</i>	<i>Zeughabdolus sigmoides</i>	<i>Zygodiscus adamsi</i>	<i>Zygodiscus bryanlei</i>	<i>Zygodiscus sheldoniae</i>	<i>Zygnatholithus djugatae</i>	Fragments/Unidentifiable	Notes
U24/1954	115.10	x	27	60	11	61	11	79	31	1	9								5	<i>Thoracosphaera</i> spp.
U24/1952	110.30		24	75	26	13	86	42						1					x	Possible discoasters, but very poor preservation
U24/1957	104.00		76	113	7	2	123	23	2										1	
U24/1950	102.30		58	132	10	3	5	117	6				x						x	
U24/1948	97.30		18	130	x	13	x	119	3										x	NP6 reworking
U24/1944	85.50	1	x	90	102	2	x	19	71	20				x						
U24/1940	75.70		58	118	2	1	55	55										?	x	
U24/1937	72.30		60	122	x	1	9	50	41	1									1	
U24/1936	70.00		56	126	2	11	46	23										?		
U24/1935	68.10	1	1	52	123	8	69	24						1				x	1	R. haqii (5-8µm) as contamination
U24/1934	65.80	1	x	40	125	1	5	11	90	16			x							
U24/1933	64.10		83	141		4	55	17	2					1					1	
U24/1932	60.50	x	46	117	x	3	9	100	8							x			x	
U24/1931	56.50																			
U24/1929	55.90		11	12		8	120	15	43										29	Glauconite
U24/1928	55.20		1			2	5	2											20	Glauconite
U24/1925	54.20		39	185	x			100	33	2				x					3	Glauconite
U24/1924	53.90		1	50	164		9	92	18											
U24/1922	51.60		46	112		6	135	8						1					6	
U24/1909	49.60		x	51	60	5	177	1											4	<i>D. arctostaphylos</i> , <i>D. baculi</i> contamination

dimorphosus), confirms NP4. These two samples also contain various *Crucioplacolithus* species.

Fasciculithus tympaniformis, together with other species of *Fasciculithus*, first occurs in U24/f1322 (Figure 2, Table 1). The FO of the former species marks the base of NP5 (61.51Ma). This sample also marks a change in the assemblage, with *Cruciplacolithus* species becoming very rare or absent and radiation of the *Toweius* lineage. Carbonate content is also generally higher above this sample, with the exception of intervals of the overlying Waipawa Formation. An upper NP5 event, the FO of *Heliolithus cantabriae* (59.60Ma), was found ~13m above *F. tympaniformis* (and ~25m below the base of the Waipawa Formation) in U24/f1321.

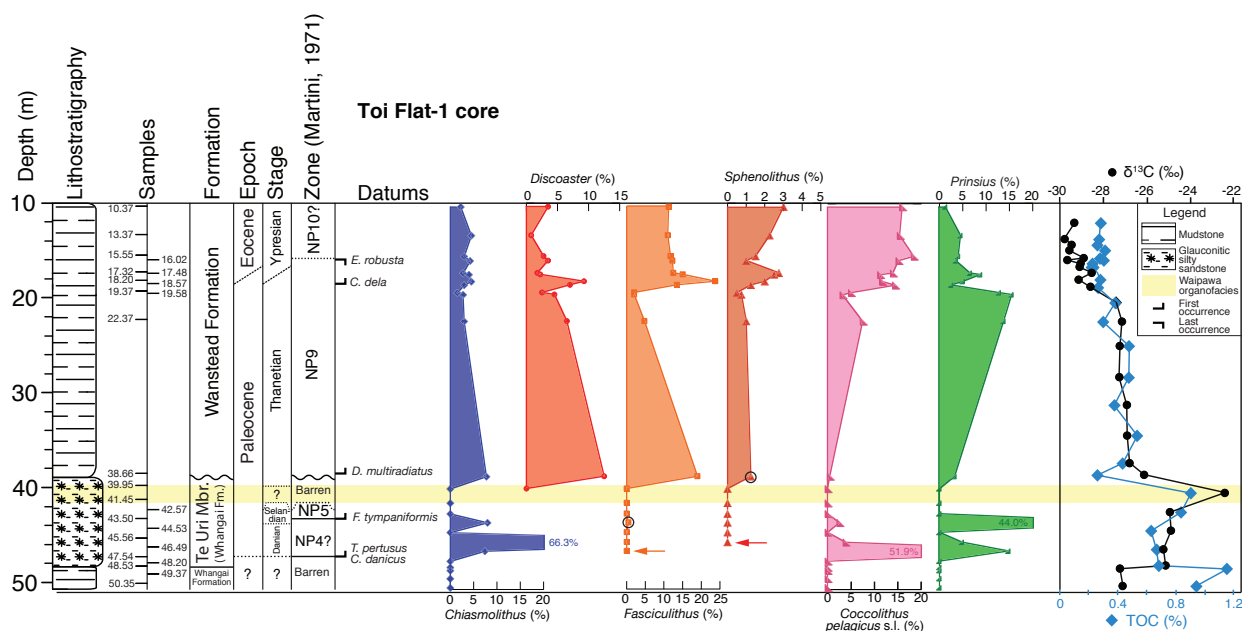


Figure 4: Toi Flat-1 core, showing first and last occurrences of key nannofossil taxa and biostratigraphic interpretation. TOC and $\delta^{13}\text{C}_{\text{TOC}}$ after Crouch *et al.* (2014). Wavy lines at ~39m indicate inferred unconformity between Te Uri Member and Wanstead Formation. Dashed lines in the age and zone columns indicate tentative interpretations. Percent abundance variations for cold-water (blue) and warm-water (red/orange) taxa shown. Shaded yellow box = Waipawa organofacies (Crouch *et al.*, 2014). Red/orange arrows on warm-water taxa indicate approximate interpolated position of first appearance datums of each genus at lower latitudes; black circle shows first occurrence in the Toi Flat-1 section

Samples from the base of the uppermost Upper Calcareous Member and basal Waipawa Formation contain relatively sparse nannofossil assemblages. Nevertheless, the FO of *Heliolithus kleinpellii*, which marks the base of NP6 (59.54Ma), is in the lowest sample examined from the Waipawa Formation (U24/f1310). The preservation is poor to moderate in this sample, probably due to the high organic content in this interval (Hollis *et al.*, 2014). Preservation and abundance of nannofossils increases up-section through the Waipawa Formation. The stratigraphically highest sample examined (3m below the top of the Waipawa Formation) contains the FO of *Discoaster mohleri* (base of NP7, 58.97Ma), which marks the evolution of this significant genus. Thus, nannofossil biostratigraphy indicates that the bulk of the Waipawa Formation was deposited during NP6 (Figure 2).

4.2 Tawanui outcrop

The Te Uri Member of the Whangai Formation at Tawanui is calcareous, with relatively-abundant, moderately-preserved calcareous nannofossils (Table 2). The lowest sample examined, U24/f920, contains *F. tympaniformis*, indicating that the Te Uri Member is in NP5 (Figure 3, Table 2). The FO of *H. cantabrigiae* (an upper NP5 event, 59.76Ma) is in U24/f924, with the FO of *H. kleinpellii*

(NP6, 59.17Ma) found approximately 30cm higher, in U24/f925. The FO of *Sphenolithus primus* also occurs at this level, well after its first appearance datum in lower and mid-latitudes in mid-NP4 (61.98Ma), which is typical of New Zealand assemblages (Edwards, 1971). Two of the three samples from the uppermost Te Uri Member are calcareous at this site and indicate the Waipawa organofacies falls in NP6 (Figure 3). Assemblages in the Te Uri Member are dominated by *Prinsius martinii*, *P. bisulcus* and *T. pertusus*. Members of the genus *Fasciculithus* increase in abundance in the uppermost part of the Te Uri Member (U24/f929).

The contact between the Te Uri Member and the overlying Wanstead Formation is unconformable, with the first sample examined above the unconformity (U24/f932) containing *Heliolithus riedelii* and *Discoaster nobilis*, indicating mid-NP8 (Figure 3, Table 2). The FO of *Discoaster multiradiatus* in U24/f950 indicates the base of NP9 (57.21Ma). The NP8 assemblage continues to be dominated by *Prinsius* spp. and *T. pertusus*, with common *Fasciculithus*. Although the NP9 assemblage is similar near the FO of *D. multiradiatus*, the abundance of *Prinsius* begins to decrease in the lower part of NP9. *Toweius pertusus* remains an important part of the assemblage, but *Toweius callosus* starts to replace it in U24/f954. The

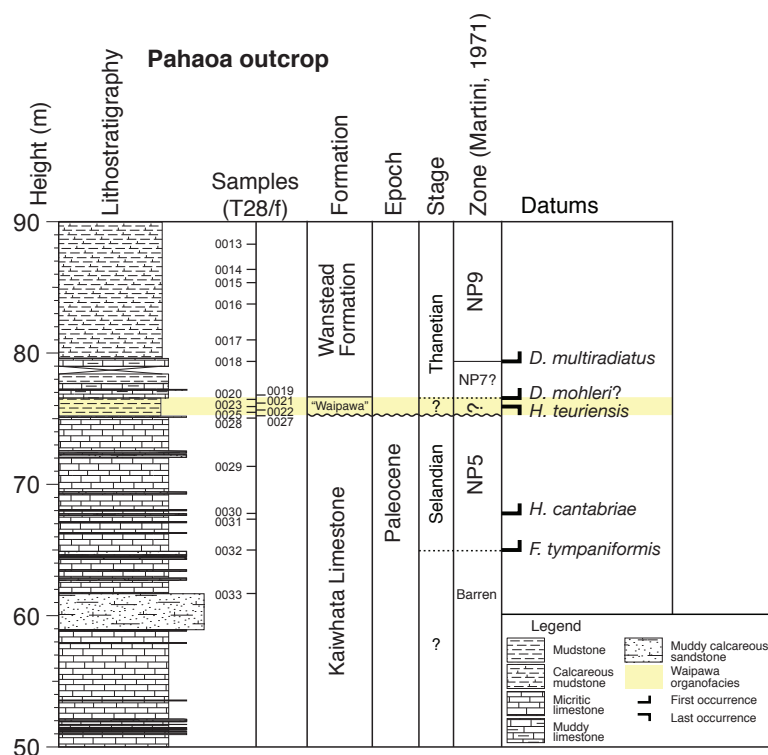


Figure 5: Pahaoa section, showing first and last occurrences of key nannofossil taxa and interpreted biostratigraphy. Wavy line at ~75m indicates inferred unconformity between Kaiwhata Limestone and Waipawa organofacies (Tayler, 2011). Dashed lines in age and zone columns indicate tentative interpretations. Shaded yellow box = Waipawa organofacies (Tayler, 2011)

abundance of *S. primus* also increases in uppermost NP8 and into NP9 (Figure 3, Table 2).

4.3 Toi Flat-1 core

Samples below 47m, from the undifferentiated Whangai Formation, are barren of calcareous nannofossils, although a single arkhangelskiellid rim was found in the sample from 49.37m (Table 3). Whether it is reworked or *in situ* cannot be determined. Three of the nine samples examined from the Te Uri Member contain poorly- to moderately-preserved, sparse to common calcareous nannofossil assemblages. The sample at 46.49m is questionably assigned to NP4, based on the presence of *C. danicus* and *C. bidens* (Figure 4, Table 3). *Ellipsolithus macellus*, the marker for the base of NP4, is absent from the New Zealand region until NP8–NP9 (Late Paleocene) or NP10 (Early Eocene) (e.g. Edwards, 1971). The FO of *F. tympaniformis* occurs in the sample at 43.50m, indicating NP5 (61.51Ma). The three samples examined from the uppermost part of the Te Uri Member, which appears to be correlative to the Waipawa Formation, are barren of calcareous nannofossils.

Calcareous nannofossils from the Wanstead Formation are relatively abundant and moderately preserved (Table 3). The contact between the Te Uri Member and the Wanstead Formation is unconformable, with the first sample examined from the base of the Wanstead (38.66m) containing *D. multiradiatus*, indicating NP9 (Figure 4). The NP9 sediments are dominated by *Toweius* (mostly *T. callosus* and *T. pertusus*), as well as *Coccolithus pelagicus*.

A few samples from the Paleocene/Eocene boundary interval were also examined and the results briefly described here. The section lacks members of the *Rhomboaster* and *Tribrachiatus* genera, making it impossible to confidently identify the NP9/NP10 boundary. Common *Fasciculithus* specimens are still present in the stratigraphically youngest sample examined (10.37m), indicating that the top of the section is lower NP10 or older. The last occurrence of *Ericsonia robusta* is found in the sample at 17.32m (Figure 4, Table 3). This event occurs in NP9 (Agnini *et al.*,

2014) and is dated to ~56.78Ma (Gradstein *et al.*, 2012). The NP9/NP10 boundary is tentatively placed above this sample and below the sample at 16.02m, in part based on the identification of the Paleocene/Eocene boundary interval between ~19 and 16m from dinoflagellate biostratigraphy (Crouch *et al.*, 2014). This interval (above 19m) is characterised by increased abundances of *Fasciculithus*, *Sphenolithus* and *C. pelagicus*; a similar assemblage occurs in the Paleocene/Eocene Thermal Maximum interval documented at DSDP Site 277 on Campbell Plateau, south of New Zealand (Hollis *et al.*, 2015).

4.4 Pahaoa outcrop

The lowest sample examined (T28/f0033) contains very rare, poorly-preserved nannofossils and cannot be assigned to a zone (Table 4). Nannofossil abundance increases up-section, although preservation is generally poor at Pahaoa. Sample T28/f0032 contains *F. tympaniformis*, indicating NP5 (Figure 5, Table 4). These mid-Paleocene assemblages are characterised by *P. martinii*, *P. bisulcus*, *T. pertusus*

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(Martini, 1970, 1971) and CP3 (Okada & Bukry, 1980), *E. macellus*, is not recorded in the New Zealand region until the uppermost Paleocene (NP8–NP9) or Lower Eocene (NP10; *e.g.* Edwards, 1971). Similarly, the first two species to evolve in the *Sphenolithus* genus migrated to the New Zealand region much later than at lower latitudes. The first appearance datum of *S. primus* is a mid-NP4 event in lower latitudes (Gradstein et al., 2012), but is generally absent in New Zealand sections until the Upper Paleocene or Lower Eocene (*e.g.* Edwards, 1971; Edwards & Perch-Nielsen, 1974). *Sphenolithus anarrhopus* is rarely recorded in New Zealand sections, although it is occasionally found in uppermost Paleocene to lowermost Eocene intervals, significantly later than its NP6 appearance at lower latitudes (Perch-Nielsen, 1985; Agnini et al., 2014).

Ellipsolithus macellus is only recorded in one Tawanui sample, assigned to NP8 (Table 2), although it does occur in lowermost Eocene samples from the same section that are not part of the present study. Specimens of *Sphenolithus* are also present in the uppermost Paleocene sections at Tawanui (Figure 3, Table 2) and Toi Flat-1 (Figure 4, Table 3), but only a single specimen of *S. primus* was observed in a sample from just below the Waipawa organofacies interval (uppermost Te Uri Member), which is assigned to NP6 at Tawanui. Above the Waipawa organofacies, *S. primus* is present in low numbers through NP8 at Tawanui, and increases significantly in abundance near the NP8/NP9 boundary (Figure 3). In the Toi Flat-1 core, where sediment above the unconformity is assigned to NP9, *S. primus* is present, although in few numbers (Figure 4). It is notable that *Sphenolithus* is considered

sites is on the order of a couple of metres thick. Unfortunately, the duration of the hiatus at the top of the Waipawa Formation at Angora Road cannot be calculated, as no samples were collected from above the top of the formation. The estimated Eocene age of the overlying Wanstead Formation (Tayler, 2011; Hollis *et al.*, 2014) would mean that the hiatus was at least of 3Myr duration.

A Late Paleocene hiatus is recorded at other localities around New Zealand and the SW Pacific. Edwards (1973) discussed a Paleocene–Eocene unconformity recovered at three Deep Sea Drilling Project (DSDP) sites (206, 207, 208) on Lord Howe Rise, NW of New Zealand. At Sites 206 and 208, the ages above and below the unconformity are reasonably well constrained, whereas at Site 207, the interval is strongly affected by drilling disturbance. At Site 206, the sediment underlying the unconformity contains *F. tympaniformis* (NP5) and at Site 208, the sediment contains *H. kleinpellii* (NP6), very similar to sections from the present study. The hiatus is longer in the Lord Howe Rise region, with sediment above the unconformity of Early Eocene (NP12; Site 206) or Middle Eocene (NP14; Site 208) age. At DSDP Site 277 on Campbell Plateau, south of New Zealand, NP9 sediments overlie NP6 sediments (Hollis *et al.*, 2014). This succession has also been recorded at other localities on or near South Island, New Zealand, including Mead Stream (Hollis *et al.*, 2005a), Muzzle Stream (Hollis *et al.*, 2005b), Kaikoura Peninsula (Crampton *et al.*, 2003) and in the Great South Basin (Schiøler *et al.*, 2010).

The regional nature of this unconformity, which can be compared to that of the Oligocene Marshall Paraconformity that is linked to the onset of major continental-scale ice-sheets on Antarctica and associated ocean circulation changes (*e.g.* Kennett *et al.*, 1975; Carter, 1985; Fulthorpe *et al.*, 1996), together with evidence for an associated sea-level fall (Schiøler *et al.*, 2010) and climatic cooling (Hollis *et al.*, 2012; Pancost *et al.*, 2013), led Hollis *et al.* (2014) to hypothesise that the origin of the Late Paleocene unconformity may also be related to growth of ice-sheets on Antarctica.

5.3 Late Paleocene SW Pacific sea-surface temperatures

Calcareous nannoplankton are sensitive to surface-water conditions, including SST and nutrient availability, and their rapid transport to the sea-floor via the sinking of fecal pellets allows assemblages to be used to decipher local

sea-surface conditions (*e.g.* McIntyre & Bé, 1967; Okada & Honjo, 1973). Numerous studies have demonstrated that nannofossil assemblages can be used to reconstruct palaeoclimate (*e.g.* Wei, 1991; Watkins *et al.*, 1996; Aubry, 1998; Bralower, 2002). Deposition of the Waipawa organofacies around the New Zealand region during the Late Paleocene correlates with a decrease in SSTs, based on foraminiferal Mg/Ca and $\delta^{18}\text{O}$, as well as TEX_{86} (*e.g.* Hollis *et al.*, 2014). Thus, changes in calcareous nannofossil assemblages may also record this event.

Members of the discoaster, sphecolith and fasciculith groups (including those species now included in the genera *Gomphiolithus*, *Diantholitha* and *Lithoptychius* of Aubry *et al.*, 2011) have been correlated to warm, oligotrophic surface-waters (*e.g.* Aubry, 1998; Bralower, 2002; Gibbs *et al.*, 2006; Kalb & Bralower, 2012; Monechi *et al.*, 2013). Conversely, the *Chiasmolithus* genus is interpreted as a cool-water taxon, although different studies indicate that it prefers mesotrophic (Aubry, 1998; Bralower, 2002; Kalb & Bralower, 2012) or oligotrophic (Gibbs *et al.*, 2006) conditions. These warm-water genera evolved during the Middle to Late Paleocene, corresponding to the interval of interest in this study. This could make it difficult to distinguish between an increase in abundance due to evolutionary mechanisms, and one due to changes in palaeoenvironment.

The first appearance of the fasciculith group (*Gomphiolithus magnus* and *G. magnicordis*), first appearance of *S. primus* and first radiation of fasciculiths (*Lithoptychius*) all occurred in NP4 (Gradstein *et al.*, 2012; Monechi *et al.*, 2013); however, these events are not recorded in the New Zealand region. *Fasciculithus tympaniformis* is the first member of this group to appear in the studied interval. This species has a first appearance datum at the end of the second radiation of fasciculiths (Bernaola *et al.*, 2009; Monechi *et al.*, 2013) and approximately 650kyr after the evolution of *G. magnus*/*G. magnicordis* (Gradstein *et al.*, 2012). The diversity of fasciculiths shortly after they evolved in the Middle Paleocene is also much higher at lower latitudes (*e.g.* Romein, 1979; Perch-Nielsen, 1985; Monechi *et al.*, 2013), whereas in the New Zealand sections, only two to four species occur in the older part of the section (*i.e.* Waipawa organofacies and older; Tables 1–4). A greater range of morphologies is found in the Upper Paleocene sediment of the Wanstead Formation. A single sphecolith specimen was found in one sample, just below

the base of the Waipawa Formation at Tawanui (Table 2). Otherwise, sphenoliths are not recorded in the New Zealand sections until the interval deposited in the Late Paleocene that corresponds to NP8 and NP9, when SSTs were warmer (*e.g.* Hollis *et al.*, 2012).

The warm-water genus *Discoaster* first evolved in the Late Paleocene, its evolution marking the base of NP7 (Martini, 1970, 1971), which is correlated to the top of the Waipawa Formation at Angora Road (Figure 2), and questionably just above the equivalent interval at Pahaoa (Figure 5). This event is missing at Tawanui and Toi Flat-1, due to the unconformity at the top of the Waipawa organofacies (Figures 3 and 4). It is notable that this genus appears to have evolved near the very end of deposition of this organic-rich facies, at a time when climatic conditions were beginning to ameliorate (Hollis *et al.*, 2014). Furthermore, semi-quantitative data from Tawanui and Toi Flat-1 show a decrease in the relative abundance of the cool-water genus *Chiasmolithus* above the Waipawa organofacies (Figures 3, 4; Tables 2, 3). These assemblage changes through the studied sections support cooler SSTs during the Middle Paleocene, with the warming trend beginning at, or near the end of, deposition of the Waipawa organofacies.

6. Conclusions

Middle and Upper Paleocene rocks in the New Zealand region generally contain moderately-preserved calcareous nannofossil assemblages, whereas Lower Paleocene intervals are often barren, or contain very sparse and poorly-preserved assemblages, making correlation to the geological time-scale difficult. On the East Coast of North Island, three outcrop sections (Angora Road, Tawanui and Pahaoa) and one stratigraphic core (Toi Flat-1) contain Paleocene nannofossil assemblages that can be calibrated with the geological time-scale (Gradstein *et al.*, 2012) and are also useful for making palaeoenvironmental interpretations from. Although some first appearances are clearly diachronous relative to those in lower latitudes, many appear to be synchronous, thus making this an excellent region for correlating biostratigraphic events from the low and mid-latitudes into the high southern latitudes. In the studied sections, samples from the lowermost Paleocene are barren or contain very poorly-preserved and sparse assemblages. The oldest fossiliferous rocks from the Angora Road outcrop and the Toi Flat-1 core can be correlated to

NP4, based on the presence of *C. bidens* and *T. pertusus*. The FO of *F. tympaniformis* in these sections marks an increase in both the abundance and preservation of nannofossils and correlates to NP5. At Tawanui and Pahaoa, the oldest samples examined containing discernable nannofossils also contain *F. tympaniformis*, suggesting that this interval marks a general increase in either deposition or preservation of carbonate in the New Zealand region.

During the Late Paleocene, an organic-rich, dark mudstone unit (Waipawa organofacies) enriched in $\delta^{13}\text{C}$ was deposited in many regions around New Zealand. The Angora Road section contains a thick sequence (~40m) of typical Waipawa facies. Although the type facies is dark mudstone, correlative units that are also enriched in $\delta^{13}\text{C}$ and TOC occur at the other sites. The presence of *H. kleinpellii* at, or near the base of, the Waipawa organofacies at Angora Road and Tawanui indicates correlation of this unit to NP6, with the first appearance of *Discoaster* (NP7) occurring near the top of the section at Angora Road and questionably just above the equivalent interval at Pahaoa. In the Toi Flat-1 core, the Waipawa organofacies is nearly devoid of nannofossils, making it difficult to make a precise correlation, although the base of the interval is dated as NP5 or younger, based on the presence of *F. tympaniformis* in samples from below it. At Tawanui and Toi Flat-1, an unconformity separates the NP5/NP6 sediments of the organofacies from overlying sediments of Late Paleocene age correlated to NP8 (Tawanui) and NP9 (Toi Flat-1). At Pahaoa, the uppermost part of the Waipawa organofacies is barren, or contains only few nannofossils, making it difficult to discern if there is an unconformity or if the interval is condensed.

Recent work by Hollis *et al.* (2014) shows that the Waipawa organofacies is associated with climatic cooling and sea-level fall, which may have resulted from the development of small, ephemeral ice-sheets on Antarctica. Nannofossil assemblages at all studied sections support cooler SSTs before and during deposition of the organofacies, with abundant *Chiasmolithus* spp., lower abundances of *C. pelagicus* and very rare or absent warm-water taxa, including *Fasciculithus* and *Sphenolithus*. The first appearances of a number of taxa were delayed in the New Zealand region, including *E. macellus* and *S. primus*. These taxa are not consistently present until uppermost Paleocene or even lowermost Eocene sediments, which were deposited after SSTs increased, following the

brief interval of cooling associated with deposition of the Waipawa organofacies.

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Appendix - Systematic palaeontology

A taxonomic review of calcareous nannofossils identified in this study follows, with descriptions included to explain variability seen in the SW Pacific region and for those taxa requiring clarification.

Order ISOCHRYSIDALES Pascher, 1910

Family **PRINSIACEAE** Hay & Mohler, 1967 emend. Young & Bown, 1997

Girgisia gammation (Bramlette & Sullivan, 1961) Varol, 1989

Hornibrookina australis Edwards & Perch-Nielsen, 1975

Hornibrookina edwardsii Perch-Nielsen, 1977

Hornibrookina teuriensis Edwards, 1973

Prinsius bisulcus (Stradner, 1963) Hay & Mohler, 1967

Pl.1, figs 1, 5

Some specimens have either two or four elongate pores, although these are likely due to dissolution. These specimens can be distinguished from *Toweius eminens* by the shape of the central-area, which is rounder in *T. eminens*, and the nature of the extinction lines.

Prinsius dimorphosus (Perch-Nielsen, 1969) Perch-Nielsen, 1977

Prinsius martinii (Perch-Nielsen, 1969) Haq, 1971

Used for small forms (typically $<5\mu\text{m}$) without distinct suture lines in the central-area. Some forms have one or more small openings in the central-area, although this is likely due to dissolution.

Toweius callosus Perch-Nielsen, 1971

Toweius eminens (Bramlette & Sullivan, 1961), Perch-Nielsen, 1971

Pl.1, Figs 9, 10, 13, 14

Forms with four distinct, large pores in the central-area that are formed by conjunct bars. Most specimens have a broadly elliptical central area.

Toweius? magnicrassus (Bukry, 1971) Romein, 1979

Toweius occultatus (Locker, 1967) Perch-Nielsen, 1971

Toweius pertusus (Sullivan, 1965) Romein, 1979

Pl.1, figs 2, 3, 6, 7

Small to medium-sized forms of *Toweius* with a central-area spanned by a grill with small, often indistinct, pores.

Toweius rotundus Perch-Nielsen in Perch-Nielsen *et al.*, 1978
Distinguished from *T. pertusus* by the small, circular form and

indistinct perforations in the central-area.

Toweius serotinus Bybell & Self-Trail, 1995

Pl.1, figs 4, 8

Pores in central-area larger and more distinct than in *T. pertusus*, yet smaller and more numerous than in *T. tovae*.

Toweius sp.1 Bown, 2005

Toweius tovae Perch-Nielsen, 1971

Pl.1, figs 11, 15

Medium to large forms with five or more large holes formed by conjunct bars in the central-area.

Family **NOELAERHABDACEAE** Jerkovic, 1970 emend.

Young & Bown, 1997

Cyclicargolithus parvus Shamrock & Watkins, 2012

Order COCCOSPHAERALES Haeckel, 1894 emend. Young & Bown, 1997

Family **COCCOLITHACEAE** Poche, 1913 emend. Young & Bown, 1997

Camptosphaera dela (Bramlette & Sullivan, 1961) Hay & Mohler, 1967

Bown (2005) had difficulty distinguishing between *C. eodela* and *C. dela* and thus grouped those species together. This taxonomic concept is followed herein.

Coccolithus bownii Jiang & Wise, 2007

Elliptical species of *Coccolithus* with a wide central-area and narrow collar.

Coccolithus pelagicus (Wallich, 1877) Schiller, 1930

Pl.1, figs 12, 16

Ericsonia robusta (Bramlette & Sullivan, 1961) Edwards & Perch-Nielsen, 1975

Ericsonia subpertusa Hay & Mohler, 1967

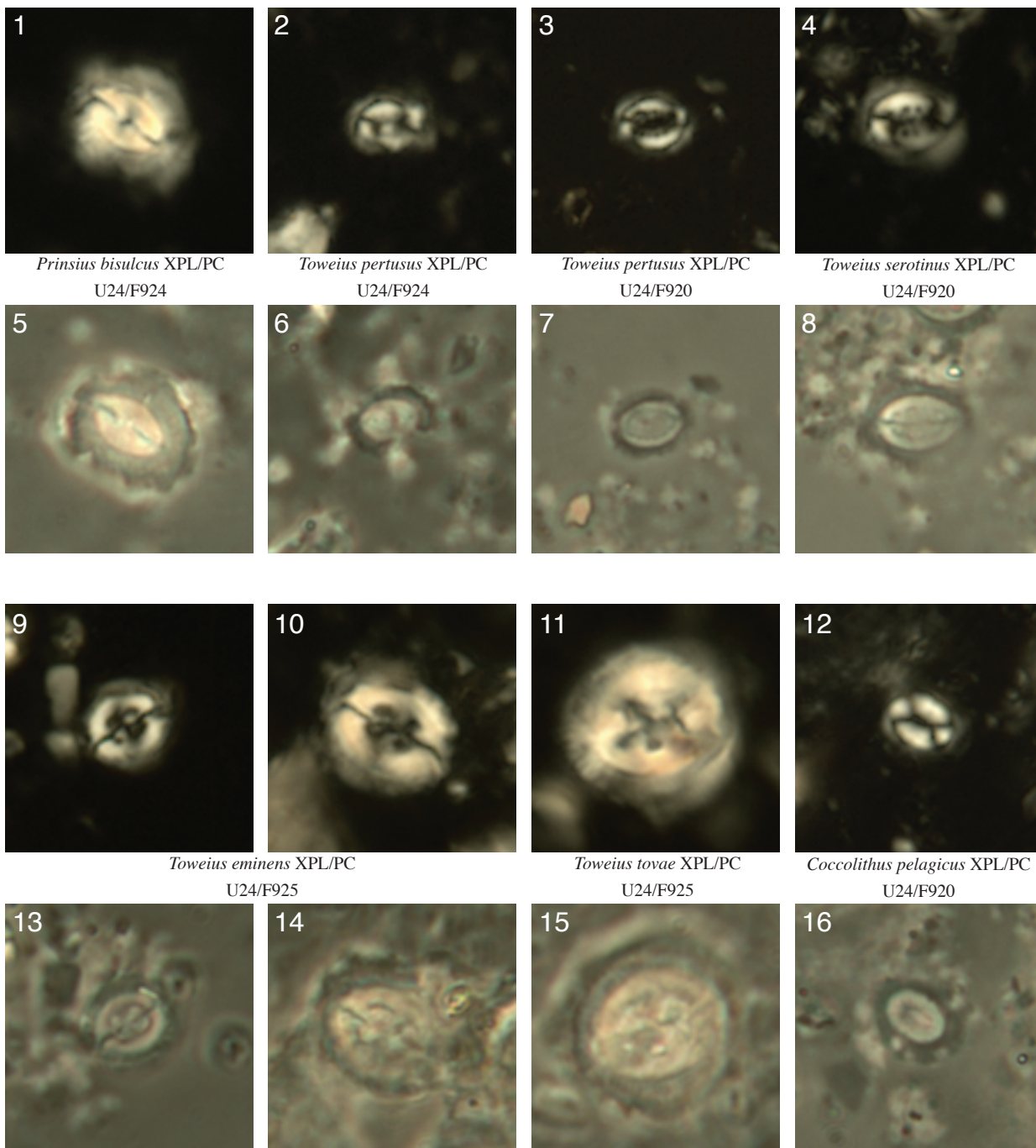
Chiasmolithus bidens (Bramlette & Sullivan, 1961) Hay & Mohler, 1967

Pl.2, figs 2, 6

Specimens of *Chiasmolithus* having a split cross with one curved and one straight arm. Distinct nodes or 'teeth' project from the proximal shield toward the central-area along the short axis of the placolith, distinguishing it from *C. danicus* and *C. solitus*. Some workers do not distinguish between *C. danicus* and *C. bidens* due to the difficulty in identifying these features as original (rather than diagenetic) in the light microscope.

Plate 1

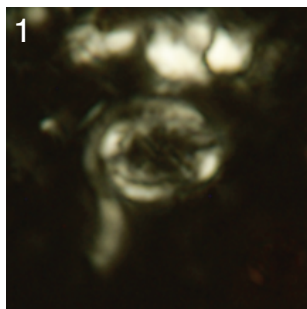
Tawanui section



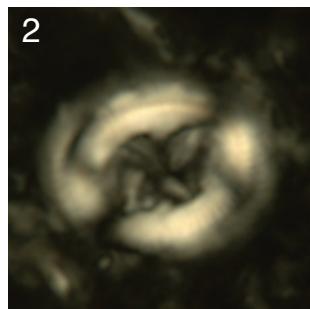
10 μm

Plate 2

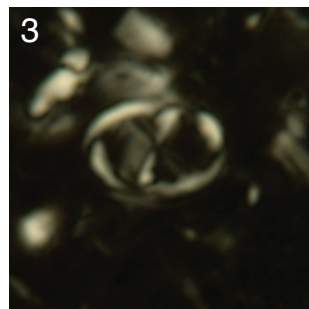
Tawanui section



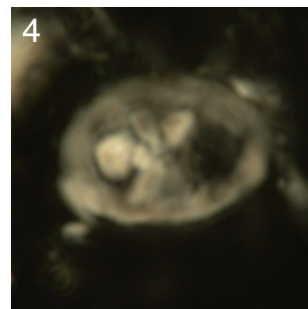
Chiasmolithus inconspicuus
XPL/PC U24/F925



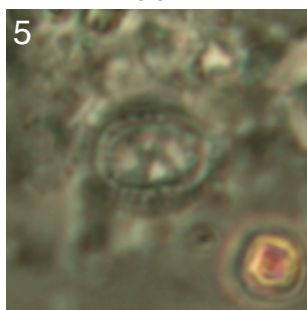
Chiasmolithus bidens XPL/PC
U24/F925



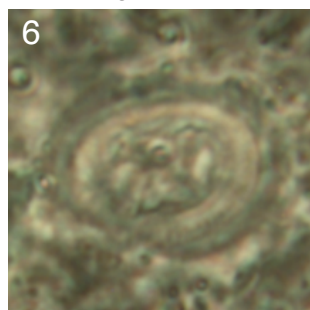
Neochiastozygus perfectus XPL/PC
U24/F925



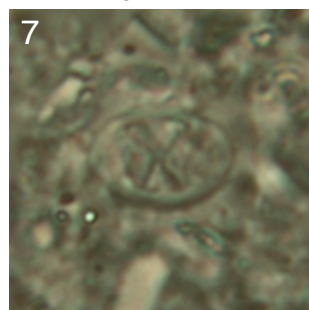
Neococcolithes protenus XPL/PC
U24/F925



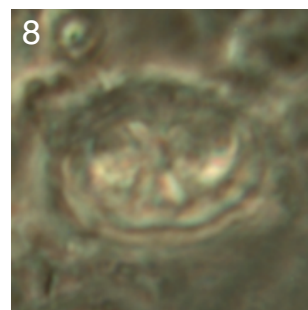
Markalius inversus XPL/PC
U24/F925



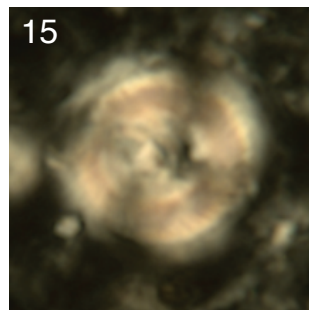
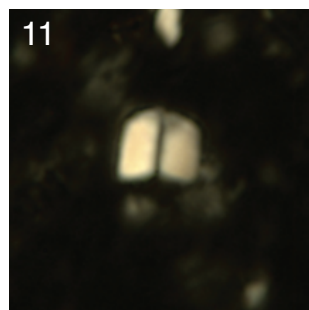
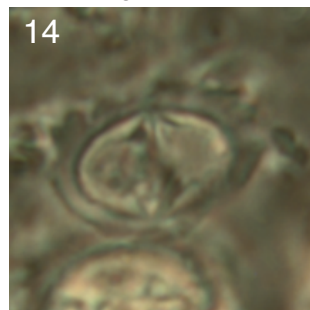
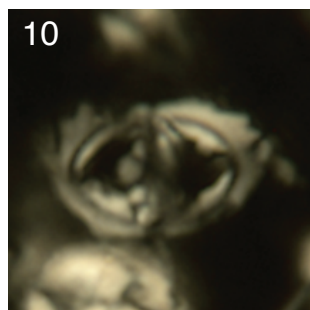
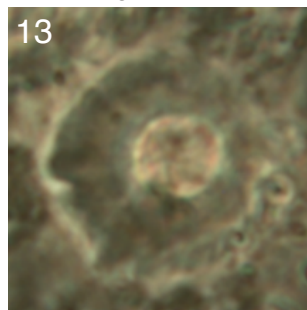
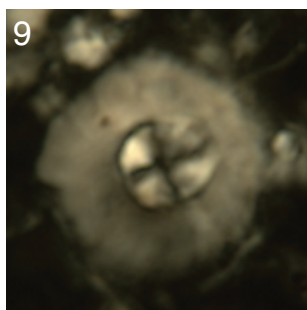
Zeugrhabdotus sigmoides XPL/PC
U24/F925



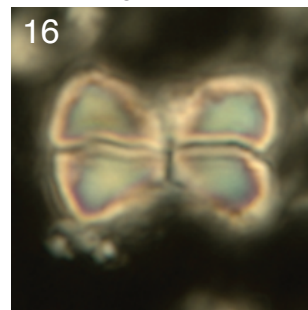
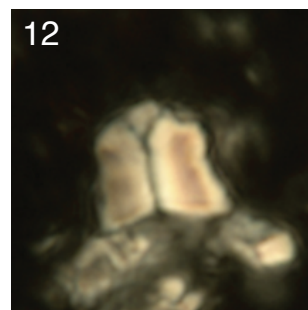
Fasciculithus tympaniformis XPL/PC
U24/F932



Fasciculithus thomasi XPL/PC
U24/F932



Heliolithus cantabrigiae XPL/PC
U24/F925



Heliolithus riedelii side view
XPL/PC U24/F932

10 μ m

Chiasmolithus consuetus (Bramlette & Sullivan, 1961) Hay & Mohler, 1967

Chiasmolithus danicus (Brotzen, 1959) Hay & Mohler, 1967
Generally smaller *Chiasmolithus* species with a central-area spanned by an offset cross with one straight arm and one curved arm.

Chiasmolithus inconspicuus van Heck & Prins, 1987
Pl.2, figs 1, 5

Similar to *C. danicus*, but with a weakly birefringent central-area structure.

Chiasmolithus solitus (Bramlette & Sullivan, 1961) Locker, 1968

Clausicoccus subdistichus (Roth & Hay in Hay *et al.*, 1967) Prins, 1979

Crucioplacolithus edwardsii Romein, 1979

Crucioplacolithus frequens (Perch-Nielsen, 1977) Romein, 1979

Crucioplacolithus intermedius van Heck & Prins, 1987

Crucioplacolithus latipons Romein, 1979

Crucioplacolithus primus Perch-Nielsen, 1977

Crucioplacolithus tenuis (Stradner, 1961) Hay & Mohler in Hay *et al.*, 1967

Family **CALCIDISCACEAE** Young & Bown, 1997

Calcidiscus? bicircus Bown, 2005

Calcidiscus? pacificanus (Bukry, 1971) Varol, 1989

Calcidiscus? protoannulus (Gartner, 1971) Loeblich & Tappan, 1978

Hughesius gizoensis Varol, 1989

A few specimens that appear similar to this species are found in the studied intervals, but additional work at higher magnification is needed to confirm identification.

PLACOLITHS INCERTAE SEDIS

Ellipsolithus distichus (Bramlette & Sullivan, 1961) Sullivan, 1964

Ellipsolithus macellus (Bramlette & Sullivan, 1961) Sullivan, 1964

Markalius apertus Perch-Nielsen, 1979

Markalius inversus (Deflandre in Deflandre & Fert, 1954) Bramlette & Martini, 1964
Pl.2, figs 9, 13

Order EIFFELLITHALES Rood *et al.*, 1971

Family **CHIASTOZYGACEAE** Rood *et al.*, 1973

Neocrepidolithus neocrassus (Perch-Nielsen, 1968) Romein,

1979

Zeughrabdotus sigmoides (Bramlette & Sullivan, 1961) Bown & Young, 1997
Pl.2, figs 10, 14

Order ZYGODISCALES Young & Bown, 1997

Family **ZYGODISCACEAE** Hay & Mohler, 1967

Neochiastozygus chiastus (Bramlette & Sullivan, 1961) Perch-Nielsen, 1971

Neochiastozygus concinnus (Martini, 1961) Perch-Nielsen, 1971

Neochiastozygus distentus (Bramlette & Sullivan, 1961) Perch-Nielsen, 1971

Neochiastozygus eosaepe Perch-Nielsen, 1981

Neochiastozygus imbriei Haq & Lohmann, 1975

Neochiastozygus junctus (Bramlette & Sullivan, 1961) Perch-Nielsen, 1971

Neochiastozygus macilentus Bown, 2005

Neochiastozygus modestus Perch-Nielsen, 1971

Neochiastozygus perfectus Perch-Nielsen, 1981
Pl.2, figs 3, 7

Neochiastozygus rosenkrantzii (Perch-Nielsen, 1971) Varol, 1989

Neochiastozygus substrictus Bown, 2005

Neococcolithes protenus (Bramlette & Sullivan, 1961) Black, 1967
Pl.2, figs 4, 8

Zygodiscus adamus Bramlette & Sullivan, 1961

Zygodiscus bramlettei Perch-Nielsen, 1981

Zygodiscus sheldoniae Bown, 2005

HOLOCOCCOLITHS *sensu* Young *et al.*, 2003

Lanternithus duocavus Locker, 1967

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

Order DISCOASTERALES Hay, 1977

Family **DISCOASTERACEAE** Tan, 1927

Discoaster kuepperi Stradner, 1959

Discoaster diastypus Bramlette & Sullivan, 1961

Discoaster falcatus Bramlette & Sullivan, 1961

Discoaster lenticularis Bramlette & Sullivan, 1961

Discoaster mediosus Bramlette & Sullivan, 1961

Discoaster megastypus (Bramlette & Sullivan, 1961) Perch-Nielsen, 1984

Discoaster mohleri Bramlette & Percival, 1971

Discoaster multiradiatus Bramlette & Riedel, 1954

Discoaster nobilis Martini, 1961

Discoaster salisburgensis Stradner, 1961

Discoaster wemmelensis Achuthan & Stradner, 1969

Family **FASCICULITHACEAE** Hay & Mohler, 1967

Fasciculithus aubertiae Hay & Aubry, 1981

Fasciculithus billii Perch-Nielsen, 1971

Fasciculithus clinatus Bukry, 1971

Fasciculithus involutus Bramlette & Sullivan, 1967

Fasciculithus lillianiae Perch-Nielsen, 1971

Fasciculithus pileatus Bukry, 1973

Fasciculithus richardii Perch-Nielsen, 1971

Fasciculithus thomasii Perch-Nielsen, 1981

Pl.2, fig.12

Fasciculithus tympaniformis Hay & Mohler in Hay et al., 1967

Pl.2, fig.11

Fasciculithus ulii Perch-Nielsen, 1971

Family **HELIOLITHACEAE** Hay & Mohler, 1967

Bomolithus elegans Roth, 1973

Bomolithus supremus Bown & Dunkley-Jones, 2006

Heliolithus cantabriae Perch-Nielsen, 1971

Pl.2, fig.15

Heliolithus kleinpellii Sullivan, 1964

Heliolithus riedelii Bramlette & Sullivan, 1961

Pl.2, fig.16

Family **SPHENOLITHACEAE** Deflandre, 1952

Sphenolithus anarrhopus Bukry & Bramlette, 1969

Sphenolithus primus Perch-Nielsen, 1971

INCERTAE SEDIS

Biantholithus flosculus Bown, 2005

Order **PODORHABDALES** Rood *et al.*, 1971 emend. Bown, 1987

Family **BISCUTACEAE** Black, 1971

Biscutum harrisonii Varol, 1989

Order **WATZNAUERIALES** Bown, 1987

Family **WATZNAUERiaceae** Rood *et al.*, 1971

Cyclagelosphaera alta Perch-Nielsen, 1979

Cyclagelosphaera reinhardtii (Perch-Nielsen, 1968) Romein, 1977

CALCAREOUS DINOFLAGELLATES

Thoracosphaera operculata Bramlette & Martini, 1964