Foraminiferal Biostratigraphy of the Caversham Formation and Its Implication For Stratigraphy and Sedimentation Study, Northeast Otago, New Zealand

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Abstract

Foraminifera play an important role in stratigraphy and sedimentation analysis of the Caversham Formation. Foraminiferal biostratigraphy has allowed definition of the stratigraphic relationship between three sections studied, i.e. Puketeraki, Karitane Peninsula, and Matanaka Farm respectively. Additionally, foraminiferal assemblages satisfactorily determined New Zealand Stages and Substages of the Otaian and Altonian Stages of the lower Miocene (Burdigalian) age, as well as the depositional environment. Paleoecology of some particular foraminifera (e.g. *Globoquadrina dehiscens* and *Ehrenbergina marwicki*) has been utilized successfully to examine the depositional process.

Introduction

Caversham Formation, which previously called Caversham Sandstone (Benson, 1969) of early Miocene age, is part of the Miocene regressive sequence of East Otago (Figure 1). This formation is underlain by marginal-marine mainly transgressive sequence of late Cretaceous to Oligocene age (Suggate et al, 1978), which is terminated by a regional break, the middle to late Oligocene Marshall Paraconformity (Carter and Landis, 1972; Carter, 1985; and Fulthrope and Carter, 1991). These transgressive and regressive sequences were deposited unconformably on a regionally extensive basement of quartzo-feldspathic schists of the Haast Schist Group of Mesozoic age.

The Caversham Formation (Figure 1) is characteristically a uniform bedded greyish-white mixed carbonate-siliciclastic rock, which becomes yellowish when weathered. This bioclastic- and quartz-rich formation rests on Concord Greensand, and overlain by Goodwood Limestone. Three measured sections, i.e. Puketeraki, Karitane, and Matanaka Farm, totally 95 meters in thickness are considered to represent a complete section through the onland stratigraphy of the Caversham Formation of East Otago (Toha, 1993). Terrigenous sands are quite low in amount throughout all sections compared to the carbonate fractions, however, it is apparent that Karitane contained slightly higher amount s of terrigenous sand than at Puketeraki and Matanaka Farm. The lower member (Puketeraki section) is made up of high frequency cyclothems dominated by "hard-soft" beds of muddy allochemic limestone and intercalated allochemic mudrock. The middle member (Karitane section) consists of heterolithic bedded allochemic sandstone, muddy allochemic sandstone, sandy allochem limestone, and muddy allochem limestone. The upper member (Matanaka Farm section) composes of a poorly bedded muddy allochem limestone, muddy micrite, and carbonaceous micritic shale.

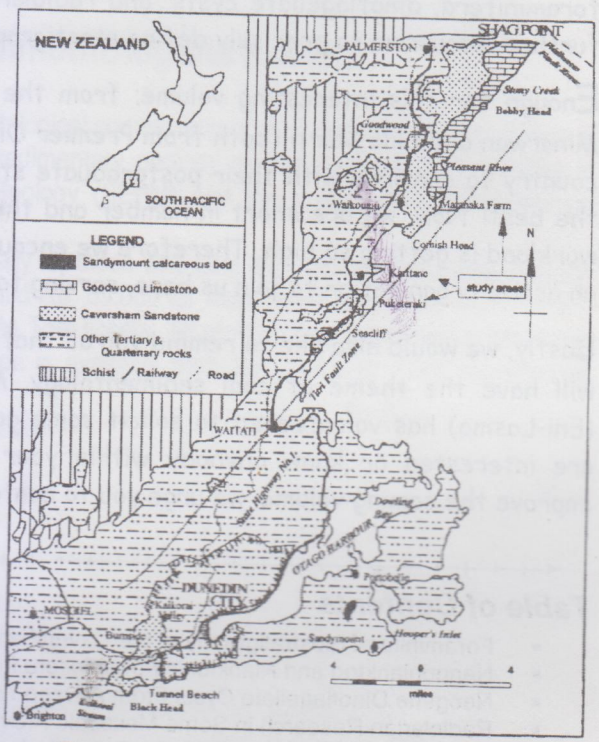


Figure 1: Location map of the study area

The Caversham Formation provides very good lithologies for foraminiferal study. It seems that the amount of terrigenous sediments in the sedimentary environment relate to the fossils occurrence. Ostracoda in limited number were found scattered throughout the sections. Articulated brachiopods and echionoids are only encountered sparsely in the lower member, but their bioclasts are very abundant, and form the major component of the carbonate skeletal grains in the formation. Other macrofossils such as bivalves, *Turritella spp.*, and barnacles formed shell beds in few localities. Moreover, there are significant carbon flakes in the washed residue across the boundary of the Caversham Formation and the Goodwood Limestone, which were never found in the older member.

The purpose of this article is to develop foraminiferal biostratigraphy with respect to the age determination of the Caversham Formation and its sedimentary environment.

Method Of Study

Twenty-one samples (Figure 2) were selected for foraminiferal analysis, i.e. eleven samples from Puketeraki, eight samples from northern Karitane Peninsula, and two samples from Matanaka Farm. Foraminifera are very well preserved in most members of the Caversham Formation, except in the upper member (KN9, 13 and 16) of the Karitane Peninsula section (Table1). Two samples from the underlying strata (Concord Greensand, PL 2 and PL 4) were analyzed, but only the PL 4 provided good foraminiferal preservation. Sample PL 2 is loose greensand and the washed residue contained mainly glauconite sands with a small amount of phosphatic grains, shark teeth, and extremely rare benthonic and planktonic foraminifera. This fact may be due to a subreducing or reducing environment (Odin and Matter, 1981), which was not favorable for living benthonic organisms and in which the settling planktonic foraminifera may dissolve partly.

Collecting foraminifera from washed residue was carried out using subjective criteria, e.g. if fewer than 5 of the same species in the sample were recognized, the term "present" is then used. Similarly, "common" is used for 6 to 10, and "abundant" for more than 10 of the same species present in the same sample. As a result, a list of distributions of the major foraminifera from the Caversham Formation in the study areas was provided (Table 1). The list was then utilized for stratigraphic analysis, i.e. Figure-2. Thus all age determination and sedimentary environment interpretations should be made in consultation with Table-1 and Figure-2

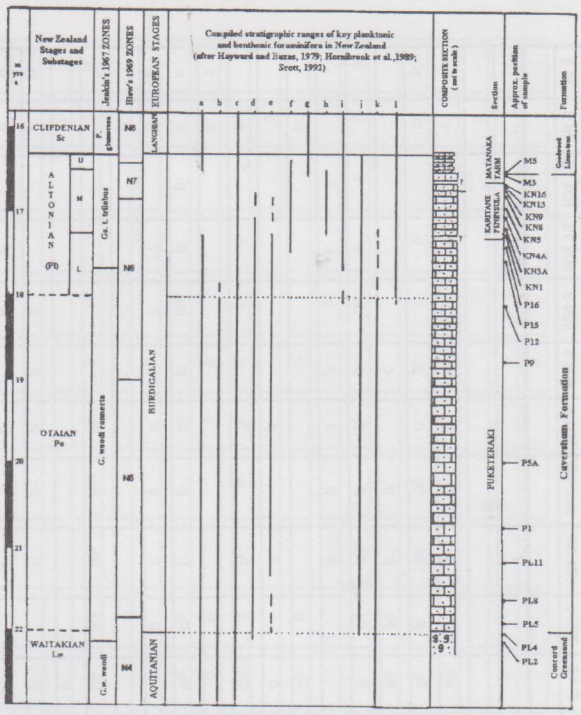


Figure 2: Age and stratigraphic position of the Caversham Formation based on key species of foraminiferal biostratigraphy in New Zealand. The key species are: a) *Globoquadrina dehiscens* (Chapman, Parr & Collins); b) *Catapsidrax dissimilis* (Cushman and Bermudez); c) *G. woodi woodi* Jenkins; d) *G.w. connecta* Jenkins, e) *Globorotalia incognita* Walters; f) *Globorotalia praescitula* Blow; g) *G. miozea* Finlay; h) *Globorotalia zealandica Hornibrook;* i) *Globigerinoides trilobus* (Reuss); j) *Ehrenbergina marwicki* Finlay; k) *Haeuslerella hectori* Finlay; l) *Haeuslerella. pukeuriensis* Parr

It was recognized that the washed residue from Puketeraki contained about fifty percent of planktonic well as the benthonic foraminifera, and it was noticeable that planktonic foraminifera decreased significantly from Puketeraki to Karitane sections. Planktonic – benthonic ratio also decreased upward in the Karitane section, where they were estimated at about 15% to 30% of planktonic foraminifera up to KN 8, and only 4% to 1% from KN 9 to KN 16. Despite the lack of quantitative data, the gradual change in the ratio is apparent. In the top of three samples from Karitane, the benthonic foraminifera are bigger and more robust compared to those from lower stratigraphic positions. Such benthonic foraminifera are *Nonionella novozealandica* Cushman, *Milonis simplex* (Karrer), *Notorotalia spinosa* (Chapman), *Cibicides novozelandicus* (Karrer), *Zeaflorius stachei* (Cushman). Some of these specimens showed abrasion features and were a little bit weathered to form a "milky" test; therefore, some winnowed specimens were suspected.

Table 1 : Distribution of the major foraminifera of the Caversham Fm. in the study area

No of samples / Foraminifera	PL 4	PL 5	PL 8	PL 11	P 1	P 5A	P 9	P 12	P 15	P 16	KN 1	KN 3A	KN 4A	KN 5	KN 8	KN 9	KN 13	KN 16	M 3	M 5
Catapsidrax dissimilis (Cushman & Bermudez)	?	p		?	?	p	p													
Globigerina bulloides d'Orbigny	p	p	c	c	a	a	p	c	p	p	p	p	p	p	p	p	p		c	c
Globigerina c.ciperoensis Bolli				p	p	p	p	p	p	c	p	p	p	c	p				c	p
Globigerina w. connecta Jenkins	p	p	c	p		c	c	c	p	p	p	p	p		c					
Globigerina w. woodi Jenkins	p	p	c	c	a	a	p	p	p	p	c	p	p	p	p	p	p			
Globigerinoides trilobus (Reuss)								p	p			p	p	a	p			?		
Globoquadrina dehiscens Chapman, Parr & Collins	p	p	c	c	a	a	c	c	p	c									p	
Globorotalia incognita Walters	p	p	c	p	a	a	a	a	c	c		?		p						
Globorotalia mayeri semivera (Hornibrook)	p	p	p		c	c	p	p	p	c		p		?					p	
Globorotalia miozea Finlay																			p	p
Globorotalia praescitula Blow										p	c	p	p	c	p	p	p	p	c	c
Globorotalia zealandica Hornibrook											p	c	p	c	p	?	?		p	p
Alabamina tenuimarginata Chapman, Parr & Collins	p		p	p	p	c													p	
Angulogerina costornata Hornibrook						p	p		p	p	p	p	p	p						
Angulogerina juniornata Hornibrook									p	p										
Anomalinoides macraglabra Finlay	p	p	c	c	c	p	p	p	p	p		p	p	p	p	p			p	p
Anomalinoides parvumbilia (Finlay)	p	p	c	c	p	p	p	p		p		p		p		p	p		p	p
Anomalinoides penguiglabra (Finlay)	p	p	p	c	p		c	p	p		p	p	p		p	p			p	p
Anomalinoides subnonionides (Finlay)				p	p		c			p			p			p				
Baggina ampla (Finlay)										p		p								
Bolivina finlayi Hornibrook							p				p	p	p	p	p	p	c	p	p	p
Bolivina lapsus Finlay	p	p	c	p		p				p						p				
Bolivina mahoenuica Hornibrook											p					p	c	p		
Bolivina reticulata Hantken		p				p	p		p		p	p	p	p	p		c	p	p	p
Bolivina zedirecta Finlay									p	p	p						c	p		
Bulimina pupula Stache			p	p	p	p	p		p	p	p									
Cancris laevinflatus Hornibrook				p	p		p										p		p	
Cassidulina cuneata Finlay		?			p	p	p	p	p	p						p		p	p	p
Cibicides mediocris Finlay		p	p	c	p	p	p		p	p		p	p	p	p	p			p	p
Cibicides molestus Hornibrook	p	p	c	c		p	p	p	p			p	p	p	p	p	p			
Cibicides novozealandicus (Karrer)	c	c	a	a	a	c	p	c	p	c	p	p	p	p	p	c		c	c	p
Cibicides temperata Vella	c	c	c	c																
Discopulvinulina bertheloti (d'Orbigny)							p	p	p	p		p	p	p	p	p	p		p	
Discorotalia aranea (Hornibrook)							p		p		p			p	p	p	p	p	p	p
Discorotalia tenuissima (Karrer)		p		p		p	p	p				p	p	p				p	p	p
Ehrenbergina marwicki Finlay	c	c	c	c	a	c	p	p	p	a		c	c	p	c	p	p		p	p
Elphidium cf. subrotatum Hornibrook															p		p	p		
Eponides broeckhianus (Karrer)							p	p								p				
Gaudryina quadrazea Hornibrook						?					p									
Glandulina symmetrica Stache	p	p	p			p	c	p	p	p		p	p		p					

Guttulina sequenzana (Brady)		p	p	p									p								p
Gyroidinoides neosoldanii (Brotzen)			p	p	p	p	c	p	p	p	p		p	p	p	p			p	p
Gyroinoides subzealandica Hornibrook				p			p				p	c		p			p		p	p
Gyroinoides zealandica (Finlay)	p	p	p	p	p	p	c		p			c	p	p	p	p	p		p	p
Haeuslerella decepta Hornibrook	p	p	p	?	p					c	p	p	p	p	p				p	
Haeuslerella hectori Finlay		c	p		p	p	p	c	p	p	p	p		?						
Haeuslerella pukeuriensis Parr									p	p	p	c	p	p	p					
Lagenoglandulina annulata (Stache)						p														
Lenticulina / Robulus spp.	c	p	p	c	c	c	p	p	c	c	p	p	p	p		p		p	p	p
Melonis maorica (Stache)	c	c								p									p	p
Melonis simplex (Karrer)	p		c	a	p	p	p	p	p	p		p		p	p	p	p	p		
Nonion deceptrix Hornibrook		p		p	p	c	p	p	p	p										
Nonion dorreeni Hornibrook									p	p										
Nonionella magnalingula Finlay		p	p	p	p	c		c	p	p		p	p	p			p			
Nonionella novozealandica Cushman		p				p	p	p	p	p	p	c	a	c	c	a	a	a	p	p
Nonionella satiata Finlay					p	p		p	p	p				p			p			
Notorotalia serrata Finlay					c			p	p											
Notorotalia spinosa (Chapman)					c		p	p	p	p		p	p	p	p	p	p	c		
Notorotalia spp.		c	c	c		a				p	p	p							p	p
Plectofrondicularia awamoana Finlay			p	p		p	p		p	c		p								
Plectofrondicularia parri Finlay					p		p				p	p								
Parvicarinina altocamerata (Heron-Allen & Earland)	p		p	p	p	p	p		p	p		p			p		p		p	
Pleurostomella tenuis Hantken		?	p		?					p										
Pullenia bulloides (d'Orbigny)		p		p	p	p	p		p											
Pullenia quinqueloba (Reuss)		p			p			p											p	
Sphaeroidina bulloides d'Orbigny	p	c	c	c	p	c	p	p	c	p	p	p	p	p	p	p	p		p	p
Stilostomella antipoda (Stache)		p																		
Stilostomella spp.			p	p	c	p	p								p					
Siphotextularia awamoana Finlay					p			p	p	p	p			p		p				
Textularia wamoana Hornibrook				p	p	p		p	p	p	p			p	p					
Textularia miozea Finlay	p	p	p		c	p		p		p	p	p	p	p	p	p	p			
Textularia ototara Hornibrook			p		p			p	p										p	
Textularia spp.	p	p			p	p		p	p	p	p				p					
Trifarina bardyi Cushman		?					p									p				
Trifarina parva Hornibrook	p		c	p	a	c	p				p	p		p		p		p	p	p
Uvigerina canariensis d'Orbigny	p	c	p		p				p	p	p									
Uvigerina miozea Finlay	c	p	c	c	p	c	a	p	p	p		c	c		p	p	p		p	p
Vaginulina awamoana Hornibrook					p				p	p							p			
Vaginulinopsis mokauensis Hornibrook			p	p															p	
Virgulina schreibersiana Czjzek					p				p	p										
Zeaflorilus stachei (Cushman)							p	p							p	c	c	a		

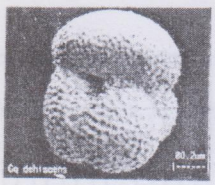
Note :

p : present (< 5 specimens) a : abundant (> 10 specimens)

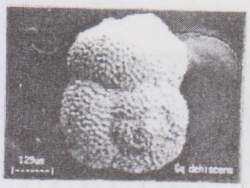
c : common (6 - 10 specimens) ? : not sure



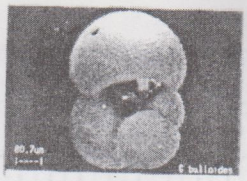
1. Ehrenbergina marwicki Finlay (PL11)



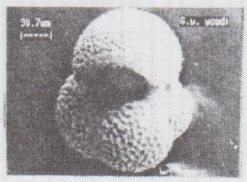
2. Globoquadrina dehiscens Chapman, Parr & Collins (P1)



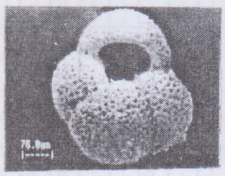
3. Globoquadrina dehiscens Chapman, Parr & Collins (P1)



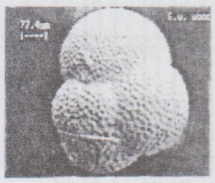
4. Globigerina bulloides d'Orbigny (P9)



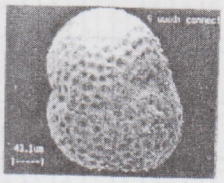
5. Globigerina w. woodi Jenkins (P1)



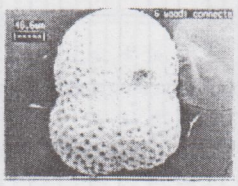
6. Globigerina w. woodi Jenkins (P12)



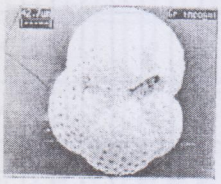
7. Globigerina w.woodi Jenkins (P12)



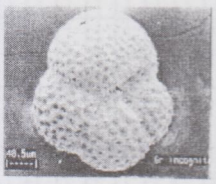
8. Globigerina w. connecta Jenkins (P11)



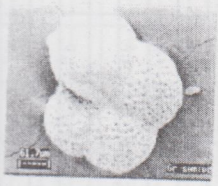
9. Globigerina w. connecta Jenkins (P15)



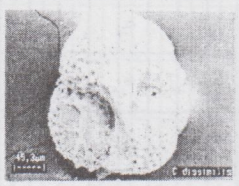
10. Globorotalia incognita Walters (P1)



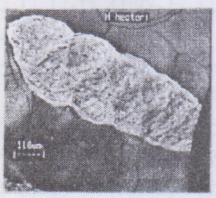
11. Globorotalia incognita Walters (P9)



12. Globorotalia mayeri semivera (Hornibrook) (PL8)



13. Catapsydrax dissimilis (Cushman & Bermudez) (P5A)



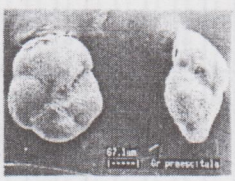
14. Haeuslerella hectori Finlay (P15)



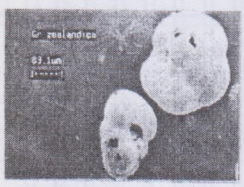
15. Haeuslerella pukeuriensis Parr (P15)



16. Haeuslerella decepta Hornibrook (P1)



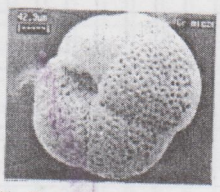
17. Globorotalia praescitula Blow (KN1)



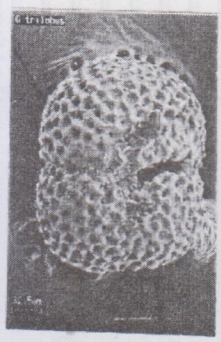
18. Globorotalia zealandica Hornibrook (KN1)



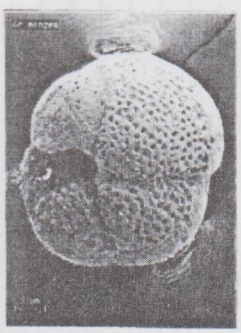
19. Globigerinoides trilobus (Reuss) (KN3A)



21. Globorotalia miozea Finlay (M3)



20. Globigerinoides trilobus (Reuss) (KN4A)



22. Globorotalia miozea Finlay (M5)

PLATE 1 :

SEM photos of representative foraminifera from the Caversham Formation

All samples used in this study suggest an early Miocene age, and can be allocated to the local New Zealand stages of Otaian (Po) up to middle Altonian (Pl). A distinctive benthonic foraminifera, Ehrenbergina marwicki Finlay (Plate I fig. 1) that was found throughout the samples, is the best key species for designating the base of Otaian and the top of the Altonian stages (Hornibrook et al, 1989). These stages are comparable to the Burdigalian stage of the European Stages (Hornibrook et al, 1989 fig. 6). The stage determinations have been made mostly using the planktonic and benthonic foraminiferal stratigraphic framework established by Hornibrook et al (1989). However, some very useful biostratigraphic references including Hornibrook (1961), Hornibrook and Brazier (1968), Jenkins (1971), and Scott (1972,1992), were also applied.

Otaian Stage

The oldest samples from the Caversham Formation contain typical Otaian planktonic foraminifera (Jenkins, 1971; Hornibrook et al, 1989) with abundant *Globoquadrina dehiscens* Chapman, Parr & Collins (Plate I fig. 2,3); *Globigerina bulloides* d'Orbigny (Plate I fig. 4); *G. woodi woodi* Jenkins (Plate I fig. 5,6,7); *G.w. connecta* Jenkins (Plate I fig. 8,9); and *Globorotalia incognita* Walters (Plate I fig. 10, 11). *Globorotalia mayeri semivera* Hornibrook (Plate I fig. 12) is also quite common, while *Catapsidrax dissimilis* (Cushman and Bermudez) (Plate I fig. 13) is rare. This stage coincides with *Globigerina woodi connecta* Zone in biostratigraphy (Hornibrook et al, 1989).

The boundary between the Otaian and the underlying Waitakian strata cannot be determined in this study. This is because: firstly, in the lowest sample (PL 2) from loose greensand of the Concord, foraminifera are extremely rare; and secondly, the uppermost sample (PL 4) from the Concord Greensand also indicates lower Otaian with an assemblage of *Ehrenbergina marwicki* (common), *Globorotalia incognita*, *G. mayeri semivera*, *Globigerina w. Woodi*, *G.w. connecta*, *G. bulloides*, and *Globoquadrina dehiscens* (Table 1). Since the age of the Concord Greensand has been determined as Waitakian (McKellar, 1990) and up to early Otaian (Field and Brown, 1992), the result of this study is in accord with the established regional data. Accordingly, a provisional Waitakian – Otaian boundary is located just below PL 4.

There is an evidence of mixed taxa of *Haeuslerella hectori* Finlay (Plate I fig. 14) with slightly staggered *Haeuslerella* in P 12, but a definite entry of *H. pukeuriensis* Parr (Plate I fig. 15) is recognized in sample P 15. The occurrence of uniserial morphotypes of the benthonic foraminiferal *Haeuslerella* lineage defines the approximate boundary between Otaian and Altonian (Scott, 1972; Hornibrook et al, 1989 fig. 34). However, Hayward (1993, pers. comm.) believes that the first appearance of *H. pukeuriensis* indicates the exact boundary. Moreover, the first appearance of *Globorotalia praescitula* Blow (Plate I fig. 17) in sample in sample P 16 indicates the uppermost Otaian stage according to Scott (1972) and Hornibrook et al (1989). However, Scott (1992) and Hayward (1993, pers. comm.) regard it as within the early Altonian (i.e. slightly higher than Otaian-Altonian boundary). Therefore, it can be concluded that the Otaian-Altonian boundary occurs between P 12 and P 15, where the first appearance of definite *H. pukeuriensis* is recognized.

Altonian Stage

A numbers of workers (e.g. Walters, 1965; Wood, 1969; Scott, 1972; Hayward and Buzas, 1979; Hornibrook et al, 1989; and Scott, 1992) have noted that throughout New Zealand the Altonian stage can be readily be divided into three substages, i.e. lower, middle, and upper on the basis of planktonic foraminiferal biostratigraphy. Similarly, the Caversham Formation in the study areas can be divided into two substages based on vertical distribution of the key species of planktonic foraminifera as in the standard New Zealand planktonic biozonation (Hornibrook et al., 1989).

Lower Altonian

The lower Altonian is well defined as the interval between the first appearance of *Globorotalia praescitula* in sample P 16 and *Globorotalia zealandica Hornibrook* (Plate I fig. 18) in sample KN 1 (Table 1 and Figure 2; Hornibrook et al., 1989). This interval coincides exactly with the *Globorotalia zealandica incognita* Zone, whereas Scott (1992) informally defined it as a *Globorotalia incognita* Zone. Similar identification was reported by Walters (1965), Hayward (1975a), and Hayward and Buzas (1979). Other significant taxa in this interval are *Globorotalia incognita*, *Globoquadrina dehiscens*, *Globigerina woodi woodi* and *G.w. connecta* for the planktonic; and *Haeuslerella hectory* and *H. pukeuriensis* for the benthonic foraminifera. In sample KN 1 and throughout the rest of Karitane samples *Globoquadrina dehiscens* was absent.

The boundary between the lower and middle Altonian as used in this study is based on the entry of *Globorotalia zealandica* (Hornibrook et al., 1989; Scott, 1992) at interval in which *Globoquadrina dehiscens* temporarily disappears (Walters, 1965; Hayward, 1975a; Hayward and Buzas, 1979). Thus, the boundary is located between samples P 16 and KN 1.

Middle Altonian

The middle substage of the Altonian is well defined as the interval between the first appearance of *Globorotalia zealandica* and *G. miozea* Finlay (Hornibrook et al., 1989 ; Plate I fig. 21 and 22), and is considered as the *Globorotalia praescitula* Zone. Scott (1992) provisionally regarded this interval as an informal zone of *Globorotalia zealandica*. The absent of *Globoquadrina dehiscens* throughout the Karitane samples (Table 1) suggests that the section represents the middle Altonian substage. Other significant taxa are *Globorotalia praescitula*, *Globigerina woodi woodi*, *G. bulloides*, and *Globigerinoides trilobus* (Reuss)(Plate I fig. 19, 20). In the study area G. miozea was rare and only recognized in M3 and M5, samples from Matanaka Farm section. It is likely that this species may found in the lower samples.

Although quantitative data are not available, considerable changes from moderate to low planktonic-benthonic ratios were recognized. Sample KN 9, KN 13, and KN 16 had low numbers of planktonic foraminifera and KN 16 is almost nil. This ratio may be controlled by sedimentary environment.

The first appearance of *Globorotalia miozea* may indicate the beginning of the upper Altonian, where this species is rare (together with *Globorotalia zealandica*) with dominance of *Globorotalia praesticula* (Hayward, 1993 pers. comm.). In addition, the reappearance of *Globoquadrina dehiscens* in M3 (Table 1) may also indicate the end of the middle Altonian substage. The two samples of M3 and M5 which belong to different formation, the Caversham Formation and Goodwood Limestone respectively, are separated by a thin fossiliferous black clay / claystone which indicates a surface of maximum marine transgression (Toha, 1993) an event of relative sea change. Thus the formation boundary seems likely to represent the middle-upper Altonian boundary (Loutit and Kennett, 1981). In other words, the Caversham member at the Matanaka section represent the top of the middle Altonian substage, whereas the Goodwood Limestone is a part of upper Altonian age.

Sedimentary Environment

Paleoenvironmental assessment based on foraminifera was developed after their utilization for stratigraphic purposes. To employ foraminifera for that assessment, practitioners tend to develop their own, usually unwritten, personal criteria that have resulted in rather inconsistent analysis (Hayward, 1986). Because of that Hayward (1986) published a guide for paleoenvironmental assessment using a compilation of the New Zealand Cenozoic foraminiferal faunas. Since a wide variety of interrelated factors influence the life habit of foraminifera and their geographic distribution (e.g. temperature, salinity, turbidity, etc), most of these factors are still poorly understood. This study, therefore, tends to utilize foraminifera mainly for paleodepth estimation, based the percentage of planktonic and benthonic assemblages. Although depth itself is not regarded as a major factor controlling the benthonic foraminiferal pattern, many of the environmental factors, which exert a direct influence in this regard, are themselves broadly related to depth (Hayward, 1986; Haywick and Henderson, 1991).

Planktonic Foraminifera

The percentage of planktonic foraminifera in the Caversham Formation suggest that the formation was deposited on a marine shelf which underwent shallowing and subsequent deepening upward through Otaian to middle Altonian time.

The planktonic percentage of total foraminifera fauna can be used as a crude indicator of the water depth (Hayward, 1986). In general, the percentage increases with increasing water depth. This method has been recognized and utilize by several workers e.g. Phleger, 1960; Vella, 1962a; Boltovskoy and Wright, 1976.

Vella (1962a) proposed a biofacies scheme on the basis of the particular benthonic foraminiferal assemblages and the planktonic percentage. His scheme revealed a consistent increase in planktonic percentage with increasing water depth, i.e. 0% for 0-6 m; 10% for 67-130 m; 10-30% for 60-300 m; 30-50% for 300-900 m; 40-70% for 1200-2400 m; and 60-100% for a depth deeper than 2400 m. Hoskins (1978 vide Hornibrook et al, 1989) observed clear trends in the increasing percentage of planktonic versus

benthics oceanward as follows: inner shelf 10%; middle shelf 10-40%; outer shelf 40-70%; and upper slope 60%. Lewis (1979) found a less than 50% planktonic-benthonic ratio and a benthonic fauna of a fewer than 60 species on the marine shelf, but more than that on the continental slope. In their study in Gulf of Mexico, Pflum and Frerichs (1976) recognized fewer than 50% planktonics in neritic, 50-90% in upper bathyal, and more than 90% in the middle and lower bathyal.

In this study, samples from Puketeraki yielded about 50% planktonic foraminifera; Karitane about 15-30% up to KN8 and only 4-1% from KN9 to KN16; and 40-50% at Matanaka Farm. If the data of Vella (1962a), Hoskins (1978), Lewis (1979), and Pflum and Frerichs (1976) are utilized, it can be deduced that the Caversham Formation in the study area was deposited on a marine shelf environment which underwent shallowing and deepening upward through Otaian-middle Altonian time. The Puketeraki members suggests outer shelf to middle shelf; Karitane is middle shelf to inner shelf and possibly close to or around shoreface from KN9 to KN16; and perhaps mid-outer shelf for Matanaka member. Moreover, combined with field data (Toha, 1993) it seems that the change of environment from Puketeraki to lower Karitane is somewhat abrupt, as well as that from KN8 to KN9, and from Karitane to Matanaka.

Benthonic Foraminifera

Previous paleobathymetric studies based on depth range of benthonic foraminifera (e.g. Hayward, 1982; Culver and Buzas, 1981; Culver, 1988) can vary significantly between ocean basins through geological time. Compared to macrofossil utilization, however, patterns of the benthonic foraminiferal assemblage are generally more significant in determining paleobathymetry (Hornibrook et al, 1989; Van de Lingen and Pettinga, 1980; Harmsen, 1985). Additionally, many benthonic foraminifera from Neogene up to Pleistocene strata in New Zealand have proved very useful in such studies (Hayward and Buzas, 1979; Hayward 1986; Haywick and Henderson, 1991).

In this study, benthonic foraminifera have been listed on the basis of relative abundance (Table 1). Due to particular taxa may represent a wide range of depositional depth, interpretation on sedimentary environment was made based on assemblages of several taxa (Hayward, 1986; Hornibrook et al, 1989).

Ehrenbergina marwicki Finlay is found throughout the section and exhibits a variety of test-size and abundance. *E. marwicki* in Puketeraki is more abundant and the test-size is larger than of that in Karitane and Matanaka (Table 1 and 2). *Ehrenbergina* is commonly found today in upper bathyal environments (Hayward and Buzas, 1979), where it occurs together with *Anomalinoides, Cibicides, Sphaeroidina, Bolivina, Bulimina, Gyroidina*, and *Lenticulina*. The abundance of *E. marwicki* suggests middle to outer shelf marine environment (Hayward, 1992 pers. comm.). This species change gradually from common and abundant to present and common across the upper Puketeraki to the lower Karitane member (Table 1). The evidence possibly indicates a gradual change in the water depth from an outer shelf to mid-outer shelf from Puketeraki to Karitane. Scott's (1973) study on the variability of lower Miocene populations of Ehrenbergina based on detail morphometric techniques, led him to conclude that Finlay's three species could be reduced to two subspecies of *E. marwicki.* These subspecies were not separated in this present study. Moreover, different size within species was regarded by Scott as due to influence of the terrigenous sediment influx in the sedimentary environment, i.e. the larger specimens developed when terrigenous sediment influx is very low and the small specimens occur during the higher terrigenous input. Scott's prediction seems to be in accord with the relative terrigenous sediment influx in the sedimentary basin (Toha, 1993). The Puketeraki section shows lower sediment input compared to Karitane, and is similar to that in Matanaka.

The presence of *Anomalinoides, Plectofrondicularia, Lenticulina, Sphaeroidina bulloides* d'Orbigny, *Haeuslerella, Uvigerina, Gyroidina / Gyroidinoides*, and *Trifarina* at Puketeraki and at Karitane suggests middle shelf to bathyal depth (Table-3; Hayward, 1986 fig. 12, 13, 14). When lithological characteristics (i.e. mixed clastic-carbonate rocks) were applied, the combined data then suggest middle to outer shelf (Mount, 1984). However, deeper water genera are prominent at Puketeraki compared to Karitane, therefore Puketeraki may indicate outer to middle and Karitane middle to inner shelf marine environments (Table-3). Additionally, the (restricted) presence of minor *Cassudulina cuneata* Finlay, *Stilostomella, Pleurostomela tenuis* Hantken and *Pullenia bulloides* d'Orbigny at Puketeraki may strengthen the notion (Hayward, 1986). The greater abundance of *Cibicides mediocris* Finlay, *C. temperata* Vella, Melonis and Bolivina at Puketeraki (Table-1) suggest outer shelf in that section and shallower

to Karitane (Hayward, 1986 fig.19; Hayward and Buzas, 1979).

At upper Karitane, above the erosional surface (Toha, 1993), the foraminifera composition change considerably. Of three samples examined (KN9, KN13, and KN16), the lowest contains few planktonic foraminifera (i.e. < 4%) and they are extremely rare in KN16 (i.e. < 1%). On the other hand, the benthonic foraminifera in all samples decreases both in number and diversity compared to that available in the underlying strata. The dominant benthonic foraminifera recognized are *Nonionella novozealandica* Cushman, *Zeaflorilus stachei* (Cushman), *Notorotalia spinosa* (Chapman), *Cibicides temperata* Vella. These taxa are larger and more robust than in the older member. In term of its size and appearance, the assemblage depicts adaptation to high energy in a shallow marine setting (Hayward, 1982). Vella (1962a) classified such associations as the "Zeaflorilus biofacies" which indicates a shallow marine (0-6 m water depth) environment. However, considering the presence of other taxa such as *Bolivina reticulata* Hantken, *B. mahoenuica* Hornibrook, *B. finlayi* Hornibrook, *B. zedirecta* Finlay, and *Discorotalia aranea* (Hornibrook), it seems that inner shelf is more likely (Hayward, 1986).

Furthermore, on the basis of the benthonic assemblage and its appearance, the depth of deposition is probably not more than 20 meters (Hayward, 1993 pers. comm.). From their appearance, some of those taxa appear slightly oxidized and the test color has change into "milky reddish"; therefore submarine erosion (probably due wave base influence) might possibly have winnowed previously deposited specimens and mixed them with the younger specimens. The presence of the underlying erosional surface is confirmation of this evidence (Toha, 1993).

Two samples from Matanaka were examined and revealed mixing between foraminifera and carbon flakes. The benthonic foraminifera such as *Anomalinoides, Sphaeroidina bulloides, Cassidulina, Uvigerina*, and *Trifarina* suggest an outer shelf marine environment (Table-3; Hayward, 1986). However, considering their abundance, more muddy environment (Toha,1993; fig.26), and association with carbon-flakes this might be slightly shallower than Puketeraki. Accordingly, the Caversham Formation from Matanaka section indicate in mid outer shelf marine environment (Hayward, 1993 pers. comm.).

Discussion

The age of the Caversham Formation in the study areas is Otaian to middle Altonian. The assemblage taxa from Puketeraki suggest early Otaian to lower Altonian age ; whereas the northern Karitane Peninsula and Matanaka section indicate middle Altonian.

Foraminifera play an important role in determining stratigraphic position of the three main sections in the study areas, since all of the section revealed similar lithological characteristics. To fix the stratigraphic position between this three sections, the following considerations were taken into account. Firstly, overlap between *Haeuslerella hectori* and *H. pukeuriensis* in sample P15, P16, KN1, and KN3 (Table-1) suggests a continuing succession from upper Puketeraki to lower Karitane sections with respect to biostratigraphy. Secondly, based on established New Zealand foraminifera biostratigraphy (Hornibrook et al, 1989) and the *Haeuslerella bioseries* (Hornibrook et al, 1989; fig. 33), the occurrence of *Haeuslerella pukeuriensis* in P 15 (and in P 13 and P 14) and the *Globorotalia zealandica* in KN 1 which is preceded by *G. praescitula* in P 16 (Table-1) support this interpretation, and allow recognition of the stage boundary within these two sections. The Otaian-Altonian boundary is located between P12 and P 15 (most probably about 3 meters above P 12), and the lower-middle Altonian boundary is between P 16 and KN 1. Thirdly, the absence of *Globoquadrina dehiscens* throughout samples from Karitane Peninsula section suggests that the section is middle Altonian in age and a part of a continuous facies succession from Puketeraki. Finally, the first appearance of *Globorotalia mizoa* in M3 and M5 and the re-appearance of *Globoquadrina dehiscens* in M 3 from Matanaka Farm fit the middle-upper Altonian boundary, and a continuous facies succession from Karitane is assumed. Only a few meters of strata are inferred to be missing here, because most of the Caversham Formation is composed of fine sand-size mixed clastic-carbonate sediments, which indicate a very slow deposition rate (Mount, 1984).

The local absence of *Globoquadrina dehiscens* in the middle Altonian has been noted elsewhere by previous workers, i.e. Walters, 1965; Hayward and Buzas, 1979; Scott, 1992, There is no definite reason why this species is temporarily missing in the middle Altonian record, but it may relate to factors of the sedimentary environment. Based on its associated taxa , Hayward (1986 fig.6) suggested that *Gq. dehiscens* indicates tropical to temperate temperatures.

Table 2. Relative size of *Ehrenbergina marwicki* Finlay throughout the sections

No of sample	S	M	L
PL 4	p	c	p
PL 5	p	c	p
PL 8	p	c	-
PL 11	p	c	p
P 1	p	p	c
P 5A	p	-	-
P 9	p	-	p
P 12	p	-	-
P 15	p	-	p
P 16	-	p	-
KN 1	-	-	-
KN 3A	c	p	-
KN 4A	c	-	-
KN 5	p	-	-
KN 8	c	p	p
KN 9	p	p	-
KN 13	p	-	-
KN 16	-	-	-
M 3	p	-	-
M 5	p	-	-

Note :

S : Small
M : Medium
L : Large

p : present
c : common
- : not present

PL & P : Puketeraki
KN : Karitane
M : Matanaka

Downward indicates higher stratigraphic position

Table 3. Relative abundance of key selected genera in this study. The depth range is simplified from Hayward (1986).

Genera	Depht range	Puketeraki	Karitane	Matanaka
1. Cancris	i, m, o	p	p	p
2. Anomalinoides	m, o, ub	c	p	p
3. Pletofrondicularia	m, o, ub	c	p	-
4. Lenticulina	o, ub	c	p	-
5. Sphaeroidina	m, o, b	c	p	p
6. Cassidulina	o, b	c	-	p
7. Haeuslerella	m, o	c	p	-
8. Uvigerina	m, o, b	c	p	p
9. Gyroidina / Gyroidinoides	o, b	p	p	p
10. Trifarina	o, b	c	p	p
11. Stilostomella	o, b	p	-	-
12. Pleurostomela	o, b	p	-	-
13. Pullenia	o, b	p	-	-

Note :

i : inner shelf
o : outer shelf
m : middle shelf

ub : upper bathyal
b : bathyal

p : present
c : common
- : not present

The Altonian climate in New Zealand was described as warm temperate on the basis of paleontological evidence and oxygen isotope ratio (Hornibrook, 1978 in Suggate et al (Ed.) 1978 fig. 7.15) and approaching the highest temperatures at late Altonian (Hornibrook, 1992 fig. 1). Therefore, it is unlikely the absence of *Gq. dehiscens* was due to changing paleoclimate.

From data of Gisborne area, eastern North Island, New Zealand, Walters (1965 fig.3) considered that *Gq. deshiscens* which is ubiquitous from basal Waitakian became locally extinct in the *Globorotalia incognita* zone and re-appeared near the upper limit of the *Globorotalia zealandica* zone. Hayward (1975) and Hayward and Buzas (1979) reported that *Gq. dehiscens* disappeared from the middle Altonian foraminiferal record at Waitemata and Waitakere Groups, North Island. Scott (1992) recognized that the species is extremely rare in most samples from core 44-577 at DSDP site 593, Challenger Plateau, Tasman Sea. Moreover, the record at 593 suggests that the size of *Gq. dehiscens* was reduced markedly in the oceanic water assemblage in the *G. zealandica* zone. Because of this Scott (1992) suggested that its apparent absence from onshore sequences (Walters, 1965; Hayward, 1975; Hayward and Buzas, 1979), which usually deposited under neritic water or water immediate between neritic and oceanic is plausible. If Scott is correct, it implies that the absence of *Gq. dehiscens* in the middle Altonian foraminiferal record is due to the decrease in the water depth of the sedimentary environment at that time. In other words there was relative sea level fall across the lower-middle Altonian boundary and arise again from the middle to the upper Altonian. The re-appearance of *Globoquadrina dehiscens* in M 3, just below the middle-upper Altonian boundary and the maximum marine transgressive surface (Toha, 1993; p. 111), seem to confirm the influence of sea level fluctuation for the absence of this species in the middle Altonian.

Scott's notion seems to fit the planktonic-benthonic foraminifera ratio throughout the Caversham Formation in the study areas. At Puketeraki, the planktonic foraminifera form for about 50% of the fauna, decreasing at Karitane to become 15% - 30% up to KN 8 and 4% - 1% above the erosional surface from KN 9 to KN 16, and back again becoming 40% - 50% in Matanaka Farm sections. The data suggests shallowing upward in the sedimentary environment from Otaian/lower Altonian to middle Altonian, and deepening again from middle to upper Altonian. From the evidence, it was not clear whether the change was abrupt or gradational. In conjunction with that ratio and combining with sedimentological data (Toha, 1993 fig.26), it seems likely that gradational shallowing upward from outer to middle shelf occurred from Puketeraki to Karitane and fairly abrupt change occurred within inner shelf to shoreface from KN 8 to KN 9, and then rapid deepening occurred from inner to mid-outer shelf, toward the boundary between the Caversham Formation and Goodwood Limestone.

Globorotalia incognita has been generally used to define the substage of lower Altonian (Hornibrook et al., 1989; Scott, 1992), and its stratigraphic range is from middle Otaian to lower Altonian. Therefore, the species is very important in New Zealand biostratigraphy. However, this study has recognized that the stratigraphic range of this species may span from the basal of Otaian up to middle Altonian since it is present from sample number PL 4 up to P 16 and is scattered in KN 3A and KN 5 (Table –1). This statement needs confirmation with respect to biostratigraphy, but it is important to note such evidence for further study. In addition, other recent study of foraminiferal biostratigraphy in New Zealand indicates similar range to that in the Caversham Formation (Hayward, 1993 pers. comm.), but elsewhere the upper occurrence is limited to lower-middle Altonian.

Similarly, *Globigerinoides trilobus* has been identified in sample PL 12 and PL 15 mixing with *Globigereina woodi connecta*. Since the first appearance of this species is at the boundary between lower Altonian and middle Altonian (Hornibrook et al., 1989), the evidence from this study indicates earlier record than that, i.e. about the Otaian-Altonian boundary (Figure 2 sample # P 12). Scott (1992) indicated the first appearance of *Globigerinoides trilobus* is at the upper lower Altonian ; therefore, its occurrence in P 15 is not surprising. However, the presence of the species at the Otaian – Altonian boundary is uncommon (Hayward, 1993 pers. comm.). So this evidence is important for further study.

Based on foraminiferal study, the Caversham Formation in Puketeraki, Karitane , and Matanaka Farm provides a good basis for further study in taxonomy and phylogeny of taxa such as *Globorotalia incognita – G. zealandica* ; *G. praescitula – G. miozea*; *Ehrenbergina*; and *Haeuslerella*. The section is one of the most complete sections trough the Otaian – Altonian stages in New Zealand. Despite its important role in determining stratigraphy and sedimentation of the Caversham Formation, this study encountered several problems utilizing established New Zealand foraminiferal biostratigraphy due to different schemes

introduced by different workers. It is likely that local environmental conditions influenced the stratigraphic range of some particular species, e.g. *Globoquadrina dehiscens*, *Globorotalia incognita*, *Globigerinoides trilobus*. This evidence reveals that study on foraminiferal biostratigraphy still requires some further revision.

Conclusion

Foraminiferal biostratigraphy has played an important role in defining age of the Caversham Formation, and its depositional process and environment.

The Caversham Formation is typical mixed carbonate- siliciclastic rock, which records the dynamics of the shelf depositional environment. Based on foraminiferal biostratigraphy, the formation represents a regressive sequence during Otaian to middle Altonian, which underwent transgression in the late middle Altonian time

The lower member (Puketeraki section) was deposited during Otaian to early Altonian time, and corresponds to a period of gradual shallowing upward from outer shelf to mid-outer shelf. The middle member (Karitane section) was formed during middle Altonian time and coincided with ensuing shallowing upward from middle to inner shelf, possibly in a storm-dominated environment. The upper member (Matanaka Farm section) was deposited during late middle Altonian time in response to deepening water from inner to mid-outer shelf. This upper member is unconformably overlain by Goodwood Limestone, forming a gentle angular discordance surface.

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