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FORAMINIFERAL BIOFACIES OF THE MIOCENE WARM TO COOL CLIMATIC TRANSITION IN THE PORT PHILLIP BASIN, SOUTHEASTERN AUSTRALIA

TIFFANY L. GOURLEY AND STEPHEN J. GALLAGHER*

School of Earth Sciences, The University of Melbourne, Victoria 3010, Australia

ABSTRACT

The Miocene marine sediments of the Torquay Group in the Port Phillip Basin of southeast Australia were deposited at a paleolatitude of at least 45°S. Nevertheless, the presence of subtropical larger foraminifers, plankton of the ''*Orbulina*'' bioseries and other biofacies signals testify to a time of global warmth and correspond to the ''Miocene Climatic Optimum''. Throughout the Early Miocene to early Middle Miocene, bioclastic calcarenite of the Batesford Limestone was deposited in warm, subtropical and oligotrophic marine conditions in a high-energy inner-shelf (<70 m depth) environment. During the early Middle Miocene, a distinct change in foraminiferal assemblage accompanied the transition to deposition of finer-grained marl and silty clay of the Fyansford Formation. At this level, a significant increase in the abundance of infaunal and planktonic taxa indicates a shift to a low-energy, middle- to outer-shelf environment (50–100 m depth). The disappearance of the larger subtropical foraminifera and the shift to a foraminiferal assemblage dominated by cool-water upwelling indices later in the Middle Miocene, signal the onset of oceanic upwelling and climatic cooling as identified in other southern Australian Tertiary basins. This event can be correlated to a period of global climatic cooling and intensified oceanic circulation that occurred in response to expansion of the East and West Antarctic ice sheets during the Middle to Late Miocene.

INTRODUCTION AND GEOLOGICAL SETTING

Evidence for global climatic change during the Miocene is preserved within the sedimentary successions of the southern Australian Tertiary basins. Although these ''cool-water'' carbonate sequences (*sensu* James, 1997) were deposited at a paleolatitude of at least 45°S (Veevers and others, 1991, Fig. 1a), foraminiferal analysis of Miocene strata in the Port Phillip Basin has uncovered evidence for a period of global warmth corresponding to the ''Miocene Climatic Optimum''.

The Port Phillip Basin is one of a number of Tertiary basins situated along the southern margin of Australia (Fig. 1b). The basin covers an area of approximately 40,000 km^2 and is bound by the Selwyn Fault, the Rowsley Fault and the Melbourne Monocline, and merges to the south with the Sorrento Graben (Fig. 1c). All basins along the southern Australian coastline have a common basin filling history that is related to the Late Cretaceous rifting of Gondwana, separation of Australia and Antarctica and the subsequent opening of the Southern Ocean. As a result, the transition from non marine early Cretaceous sedimentation to marine Tertiary conditions can be observed in almost all of these basins.

From Late Oligocene to Miocene times, predominantly marine siliciclastics and carbonates were deposited in the Port Phillip Basin. These units belong to the Torquay Group and they overlie near-shore terrestrial Tertiary sediments of the Werribee Formation (Fig. 2; Abele, 1988). The Torquay Group sediments attain a thickness of over 240 m in the deeper southwestern section of the basin, where the lowermost strata are late Oligocene (Janjukian) in age (Abele, 1988). To the northwest, late middle Miocene (Bairnsdalian) strata of the Torquay Group wedge out against Paleozoic basement rock (Abele, 1988).

The studied section outcrops at Batesford (Fig. 1) in the southwestern section of the Port Phillip Basin. Here, the Torquay Group can be subdivided into the Batesford Limestone and the overlying, or part laterally equivalent, Fyansford Formation (Fig. 2). The Batesford Limestone is a bioclastic calcarenite unit that can attain thicknesses greater than 100 m (Abele, 1988) and is interpreted to represent a fringing 'reef' and talus-slope deposit around a granitic island known as Dog Rocks (Bowler, 1963, Fig. 1). The lower section of the Batesford Limestone at the type locality (Batesford Quarry, Fig. 1) has been assigned an Early Miocene Longfordian age, although the Batesford Limestone in the southwestern part of the basin may be as old as Janjukian (Late Oligocene to Early Miocene; Abele, 1988). The upper section of the Batesford Limestone in the Batesford Quarry represents the type section for the early Middle Miocene Batesfordian stage of southeastern Australia (Carter, 1964; Bowler, 1963; Singleton, 1941).

The Batesford Limestone and the overlying Fyansford Formation have conformable but strongly diachronous formation boundaries. The Fyansford Formation is the most widespread unit within the Torquay Group of the Port Phillip Basin and consists predominantly of silty clay and marl. The Fyansford Formation attains a maximum thickness of around 230 m in the southwestern section of the Port Phillip Basin, where it ranges in age from Longfordian to Bairnsdalian (late Early to early Middle Miocene; Abele, 1988). To the west and south, the Fyansford Formation grades laterally into clay of the Puebla Formation (Torquay Basin) and the Newport Formation towards the east.

Marine and terrestrial siliciclastic sediments of the Brighton Group unconformably overlie the marine Torquay Group sediments. In the Batesford region, Brighton Group sediments are represented by thin and discontinuous sand and silty sand of the Moorabool Viaduct Sand (Fig. 2). The age of the Moorabool Viaduct Sand is poorly constrained due to the poor preservation of foraminifera, although, based on the molluscan assemblage (Abele, 1988; Singleton, 1941)

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* Corresponding author
E-mail: t.gourley@pgrad.unimelb.edu.au; sjgall@unimelb.edu.au

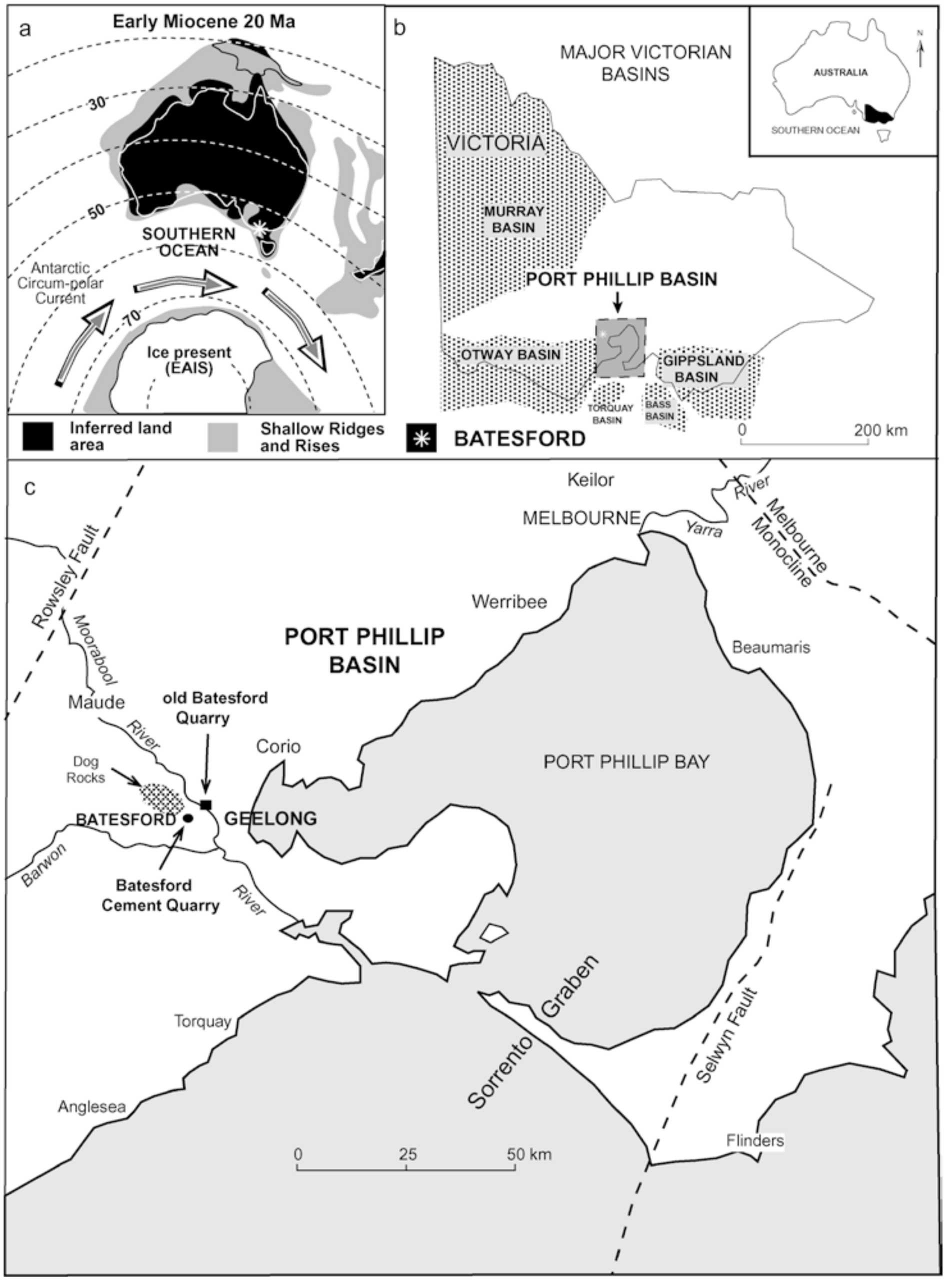

FIGURE 1. (a) Early Miocene oceanic circulation around Australia (adapted from Gallagher and others, 2001). (b) Location of major Tertiary basins within Victoria. (c) The Port Phillip Basin showing bounding structural features and a map of the Batesford region, including location of the outcropping succession (black square) under investigation within this study (adapted from Abele, 1988).

and a strontium isotope date of 4.5 ± 0.5 Ma obtained from marine molluscs (Dickinson and others, 2002), a Late Miocene to Early Pliocene age has been assigned.

This paper describes an outcropping succession of Miocene marine Torquay Group sediments, situated within the Batesford region and on the northern side of the Moorabool River at the 'old' Batesford Quarry (Fig. 1). The marine sediments at this locality preserve biofacies evidence for the environmental evolution of the Batesford region during the Miocene, which can be directly correlated to events associated with the evolution of the Southern Ocean.

MATERIALS AND METHODS

The outcropping succession was sampled and logged in a well-exposed quarry near Batesford. A Gamma Log for the section was compiled and the carbonate content of samples was measured to enable correlation with subsurface data and to enhance facies interpretations (Fig. 3). Percentage carbonate data were obtained from Chan (2000).

Based upon facies and carbonate analyses and the gamma log, 21 representative samples were chosen for micropaleontological analyses. Nineteen of these samples were used

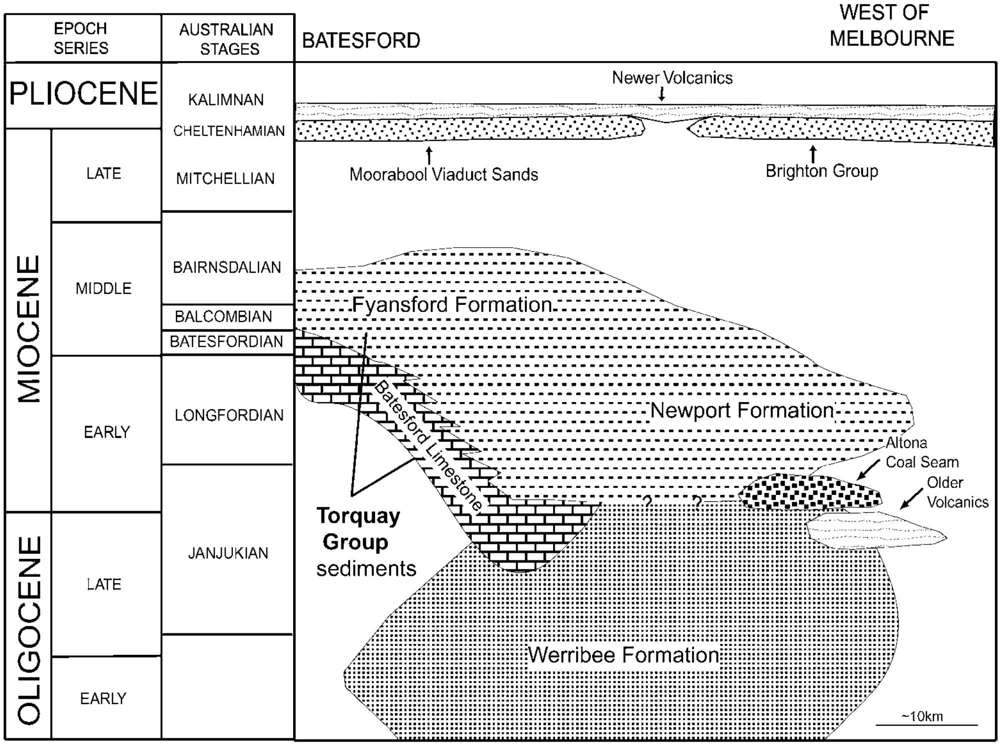

FIGURE 2. Port Phillip Basin (Melbourne-Batesford) stratigraphy with Australian stages (adapted from Abele, 1988).

for quantitative foraminiferal analyses and the remainder for qualitative paleoenvironmental purposes. Facies analyses involved recording the composition, color, texture, grain size, sorting, rounding, cementation, bioclast type, preservation and other lithological features for each sample.

Quantitative analysis of each sample involved systematically picking, sorting and identifying around 300 foraminifera for each sample. One hundred and twenty-six benthic species and 18 planktonic species were identified from the section (Table 1). The computer program Microsoft Excel™ was then used for the statistical analyses of foraminiferal data. Identification of foraminifera was carried out using the taxonomy of Carter (1964), Hornibrook and others (1989) and Li and McGowran (2000). The biostratigraphic datums used in this work are based on the zonation schemes of Holdgate and Gallagher (1997), McGowran and others (1997) and Gallagher and others (2001).

Paleoenvironmental interpretations are based upon direct comparison between fossil foraminifera and the ecological studies of recent foraminifera such as those by Vella (1962), Hayward (1990), Yassini and Jones (1995), Sen Gupta and Machain-Castillo (1993), Jorissen and others (1994), Van der Zwaan and others (1999), Murray (1991), Hohenegger (1995), Hallock and Glenn (1986), Gupta and Srinivasan (1992) and Smith and others (2001), following the methodology in Gallagher and Holdgate (2000) and Gallagher and others (1999, 2001). Table 1 provides interpreted paleoenvironmental and paleobathymetric information for identified taxa that were used to make paleoenvironmental interpretations of the Batesford Quarry succession.

RESULTS

BIOSTRATIGRAPHY

Planktonic foraminifera comprise up to 30% of the total fauna in the Batesford succession. The identification of age-diagnostic taxa, in particular, species of the *Globigerinoides-Praeorbulina-Orbulina* bioseries, has constrained the age of the sequence. In the lower section of the Batesford Limestone, the appearance of *Globigerinoides bisphericus* and first appearance datum (FAD) of *Globigerinoides sicanus* places the N7/N8a zonal boundary at the Early-Middle Miocene boundary at log level 5.0 m (Fig. 3). In the lower section of the Fyansford Formation, at log level 19.5 m, the FAD of *Praeorbulina glomerosa* defines the N8a/N8b zonal boundary and indicates an early Middle Miocene age. The FAD of *Orbulina suturalis* defines the N8b/N9 zonal boundary at approximately 24.5 m (log level). Age-diagnostic planktonic taxa could not be identified to define the N9-N10 zonal boundary. A study of equivalent strata in the Gippsland basin (Gallagher and others, 2001) has revealed that the concurrent LADs of the larger foraminifers and warmer water planktonic taxa, associated with a shift to foraminiferal assemblages dominated by cool-water upwelling indices in Middle Miocene strata, may be ecostratigraphically significant. It is suggested that this association can be used as a regional ecostratigraphic proxy for the N9-N10 zonal boundary in southeastern Australia (see Discussion). Planktonic taxa of N11 zonal age or younger are absent from the Fyansford Formation.

Based on the identification of planktonic taxa and an ecostratigraphic proxy for the N9-N10 zonal boundary, it is

TABLE 1. **Faunal List:** Foraminiferal species identified in this study with paleoenvironmental interpretations after Gallagher and others (2001).

BENTHIC ROTALIIDS:

			Plate 1-Fig.			inner shelf	middle shelf	outer shelf	upper slope	middle slope
Alabamina	*tenuimarginata*	(Chapman, Parr & Collins)					3	2		
Ammonia	*beccarii*	(Linne)	11	I		3				
Amphistegina	*lessonii*	(d'Orbigny)	5							
Anomalinoides	*awamoana*	Hornibrook					2	3	2	1
Anomalinoides	*macroglabra*	(Finlay)					2	3	2	1
Anomalinoides	*pinguiglabra*	(Finlay)					2	3	2	1
Anomalinoides	*planulata*	Carter					2	3	2	1
Astacolus	spp.			I						
Astrononion	*centroplax*	Carter				1	2	3	2	1
Astrononion	*stelligerum*	(d'Orbigny)		I		1	2	3	2	1
Astrononion	*tasmanensis*	(Carter)	10	I		1	2	3	2	1
Baggina	spp.									
Bolivina	*alata*	(Seguenza)	15	I	O	2	1	2	2	2
Bolivina	*albatrossi*	Cushman		I	O	2	1	2	2	2
Bolivina	*aenariensis*	(Costa)		I	O	2	1	2	2	2
Bolivina	*moodysensis*	Cushman & Todd		I	O	2	1	2	2	2
Bolivina	*pseudopissa*	Kleinpell		I	O	2	1	2	2	2
Bolivina	*reticulata*	Hantken		I	O	2	1	2	2	2
Bolivina	*retiformis*	Cushman		I	O	2	1	2	2	2
Bolivina	*victoriana*	(Cushman)		I	O	2	1	2	2	2
Bolivina	*watti*	Gibson		I	O	2	1	2	2	2
Bolivinella	spp.				O					
Buchnerina	spp.									
Buliminella	*missilis*	Vella								
Cancris	*auriculus*	(Fichtel and Moll)			O					
Cassidulina	*cuneata*	Finlay		I	O	1	1	3	3	3
Cassidulina	*crassa*	d'Orbigny		I	O	1	1	3	3	3
Cassidulina	*laevigata*	(d'Orbigny)	7	I	O	1	1	3	3	3
Cassidulinoides	*aequilatera*	Carter		I	O	1	1	3	3	3
Cassidulinoides	*chapmani*	Parr	8	I	O	1	1	3	3	3
Ceratobulimina	spp.									
Cerobertina	*bartrumi*	Finlay								
Cerobertina	*dehiscens*	(Heron-Allen and Earland)								
Cibicides	*amoenus*	Finlay				1	3	3	2	1
Cibicides	*boueana*	(d'Orbigny)				1	3	3	2	1
Cibicides	*catillus*	Finlay				1	3	3	2	1
Cibicides	*ihungia*	Finlay				1	3	3	2	1
Cibicides	*lobatulus*	(Walker & Jacob)				1	3	3	2	1
Cibicides	*mediocris*	Finlay	17			1	3	3	2	1
Cibicides	*thiara*	(Stache)				1	3	3	2	1
Cibicides	*vortex*	Dorreen				1	3	3	2	1
Cibicidoides	*perforatus*	(Karrer)	18				3	3	3	3
Dentalina	spp.			I						
Discorbinella	*bertheloti*	(d'Orbigny)				1	2	2	1	
Discorbinella	*biconcava*	(Jones and Parker)				1	2	2	1	
Discorbinella	*planoconcava*	(Chapman, Parr & Collins)				1	2	2	1	
Discorbinella	*scopos*	(Finlay)				1	2	2	1	
Discorbis	*balcombensis*	(Karrer)	19			3	2			
Discorbis	*dimidiatus*	(Jones and Parker)				3	2			
Discorbis	*zealandica*	(Vella)				3	2			
Dyocibicides	*biserialis*	Cushman & Valentine				1	2	1		
Dyocibicides	*uniserialis*	Thalmann				1	2	1		
Ehrenbergina	*marwicki*	(Finlay)	20	I					3	
Elphidium	*centrifugalis*	Carter		I		3	2	1		
Elphidium	*chapmanni*	Cushman		I		3	2	1		
Elphidium	*crassatum*	Cushman		I		3	2	1		
Elphidium	*crispum*	(Linne)		I		3	2	1		
Elphidium	*parri*	Cushman		I		3	2	1		
Elphidium	*pseudoinflatum*	(Cushman)		I		3	2	1		
Epistominella	*cassidulinoides*	Hornibrook			O				2	1
Epistominella	*iota*	Hornibrook			O				2	1
Eponides	*repandus*	(Fichtel and Moll)				1	1	2	2	
Evolvocassidulina	*orientalis*	(Cushman)		I						

TABLE 1. Continued.

Favulina	*hexagona*	(Williamson)		I						
Fissurina	*crassiannulata*	Collins		I						
Fissurina	*densifosciataformis*	Albani & Yassini		I						
Glabratella	spp.					2	1	1		
Glabratella	*crassa*	Dorreen				2	1	1		
Glabratella	*patelliformis*	(Brady)				2	1	1		
Glabratellina	*sigali*	(Siegle and Bermudez)	12&13							
Globocassidulina	*pseudocrassa*	(Hornibrook)		I	O		1	3	3	
Globocassidulina	*subglobosa*	(Brady)	6	I	O		1	3	3	1
Globulina	*gibba*	(d'Orbigny)		I						
Guttilina	*problema*	d'Orbigny		I			1	1	1	1
Guttilina	*regina*	(Brady, Parker & Jones)		I			1	1	1	1
Gypsina	*howchini*	(Chapman and Crespin)	1							
Gyroidinoides	spp.							2	2	1
Heronallenia	*howitti*	Carter								
Heronallenia	*lingulata*	(Burrows & Holland)								
Heronallenia	*parri*	Carter								
Heterolepa	*brevoralis*	(Carter)	16				1	2	2	1
Heterolepa	*novozelandica*	(Karrer)					1	2	2	1
Heterolepa	*opaca*	(Carter)					1	2	2	1
Heterolepa	*subhaidingeri*	(Parr)					1	2	2	1
Lagena	*cultrata*	(Montfort)		I						
Lagena	*distoma*	Parker & Jones		I						
Lagena	*perlucida*	(Montagu)		I						
Lenticulina	*foliata*	(Stache)				1	1	2	3	2
Lenticulina	*gyroscalpra*	(Stache)				1	1	2	3	2
Lenticulina	*lenticula*	(Stache)				1	1	2	3	2
Lenticulina	*lucida*	(Cushman)				1	1	2	3	2
Lenticulina	*reginus*	(Karrer)				1	1	2	3	2
Lepidocyclina	*howchini*	(Chapman and Crespin)	2							
Mississippina	*concentrica*	(Parker & Jones)								
Notorotalia	*howchini*	(Chapman, Parr & Collins)				3	2	1		
Notorotalia	*miocenica*	(Cushman)				3	2	1		
Notorotalia	*targetensis*	Hornibrook				3	2	1		
Operculina	*victoriensis*	Chapman & Parr								
Palliolatella	*laevis*	(Seguenza)								
Palliolatella	*pterocephala*	(Seguenza)								
Pararotalia	*mackayi*	(Karrer)	3&4							
Parrellina	*crespinae*	(Cushman)		I		1	3	2	1	
Parrellina	*imperatrix*	(Brady)		I		1	3	2	1	
Planodiscorbis	*irregularis*	Carter								
Planularia	*planulata*	(Galloway & Wissler)								
Planulina	*biconcava*	(Jones and Parker)								
Planulina	*papillata*	(Chapman, Parr & Collins)								
Pleurostomella	*tenuis*	Hantken								
Polysigmoidella	*kaegaensis*	Cushman & Ozawa								
Pseudofissurina	*obscurocostata*	(Galloway & Wissler)		I						
Pullenia	*bulloides*	(d'Orbigny)		I				2	2	2
Pullenia	*quinqueloba*	(Reuss)		I			1	1		
Pygmaeoseistron	*hispidula*	(Cushman)		I						
Pyrulina	spp.			I						
Reussella	*ensiformis*	(Chapman)		I						
Reussella	*spinulosa*	(Reuss)		I						
Rosalina	*australis*	Parr				3	2	1		
Sigmoidella	*pacifica*	Cushman & Ozawa		I		1	1			
Siphonina	*australis*	(Cushman)								
Sphaeroidina	*bulloides*	(d'Orbigny)	9	I			1	2	2	2
Trifarina	*bradyi*	Cushman		I		2	1	2	2	1
Uvigerina	*miozea*	Finlay		I		1	2	3	2	1
Uvigerina	*proboscidea*	(Shwager)	14	I				1	3	3
TEXTULARIIDS:										
Dorothia	*minima*	(Karrer)								
Guadryina	*crespinae*	Cushman								
Textularia	*hayi*	(Karrer)								
Turbulogenerina	spp.									
PLANKTONIC TAXA:										
Catapsydrax	*unicavus*	Bolli, Loeblich & Tappan		CT	D					
Globigerinoides	*bisphericus*	Todd		W	S					
Globigerina	*bulloides*	d'Orbigny	23	CT	D					
Globigerina	*falconensis*	Blow		W						

TABLE 1. Continued.

Globigerinella	*aequilateralis*	Brady			
Globigerinoides	*trilobus*	(Reuss)	24	W	S
Globoquadrina	*alstispira*	(Cushman & Jarvis)			
Globoquadrina	*dehiscens*	(Chapman, Parr & Collins)		W	
Globorotalia	*mayeri bella*	Jenkins		W	S
Globorotalia	*mayeri mayeri*	Cushman & Ellisor		W	S
Globoturborotalia	*woodi woodi*	(Jenkins)	21	CT	S
Orbulina suturalis	*suturalis*	Bronnimann		W	S
Orbulina universa	*universa*	d'Orbigny		W	S
Praeorbulina	*glomerosa*	(Blow)		W	S
Praeorbulina	*sicana*	(De Stefani)		W	S
Sphaeroidinellopsis	*disjuncta*	(Finlay)	22	W	D
Tenuitella	*minutissima*	(Bolli)		W	S
Tenuitellinata	*juvenilis/munda*	(Bolli)/(Jenkins)			S

Benthic symbol key:	
1	Rare
2	Common
3	Abundant
O	Taxon of dysoxic environment
I	Infaunal taxon
Planktonic symbol key:	
D	Deep dwellers (>50m)
S	Surface dwellers (0-50m)
CT	Cool-temperate indices (15-18°C)
W	Warm indices (19-22°C)

suggested that the marine Torquay Group sediments exposed at the Batesford Quarry section range in age from the late Early Miocene, N7 Zone, through to the Middle Miocene, N10 Zone (Fig. 3). In samples of the lower Moorabool Viaduct Sand, the presence of *Globigerinella aequilateralis,* a Late Miocene to Recent taxon, along with Early Pliocene molluscan fauna identified by Singleton (1941) and a strontium isotope date of 4.5 ± 0.5 Ma obtained by Dickinson and others (2002), suggest a Late Miocene to Early Pliocene age for these sediments.

LITHO- AND BIOFACIES

Biofacies (1): Foraminiferal and Bryozoan Calcarenite (0–7.5 m log level, Fig. 4)

This interval consists of coarse-grained cream to white calcarenite (clean carbonate sand)/grainstone and is composed almost entirely of bioclastic skeletal fragments. The calcarenite is predominantly grain-supported with medium to strong sparite cementation. Bioclasts include common stick and encrusting bryozoans, regular and irregular echinoid plates and spines, bivalves and abundant larger subtropical foraminifera (Fig. 3). Rounding and sorting of bioclasts occurs in all samples. Burrow infill alignment and cross-beds lined with large foraminifera typify the calcarenite. This interval is also characterized by a high carbonate content (80–100% $CaCO_3$) and low gamma values (70–120cps)(Fig. 3).

The microfauna within this interval are abraded and poorly preserved with microboring of some of the larger foraminifera. Large, robust and spheroidal to discoidal benthic rotaliids dominate the assemblage and the presence of the larger benthic foraminifera such as *Lepidocyclina howchini (*Pl. 1, Fig. 2) and *Pararotalia mackayi (*Pl. 1, Figs. 3,4), characterizes this interval. The foraminiferal assemblage consists predominantly of benthic *Cibicidoides perforatus (*Pl. 1, Fig. 18), elphidiids (e.g., *Elphidium crispum*) and discorbids (e.g., *Discorbis balcombensis,* Pl. 1, Fig. 19). A minor increase in abundance of planktonic foraminifera and the bolivinids (e.g., *Bolivina victoriana*), with a peak in abundance of the planktonic species *Globigerinoides trilobus (*Pl. 1, Fig. 24), occurs towards the top of the interval. Both planktonic percentage and total species diversity (10 to 19) are relatively low.

Biofacies (2): Bryozoal Calcarenite (7.5–16.1m log level, Fig. 4)

At log level 7.5 m, an erosional surface defines the boundary between Biofacies 1 and 2 (Fig. 4). This limonite stained surface shows evidence of bioturbation, with the underlying sediments having a hummocky, irregular nodular like texture.

The cream-colored calcarenite/packstone of this interval is similar to the facies of Biofacies 1, although fragments of both rigid and encrusting Bryozoa are the dominant bioclasts. Bioclasts also include both regular and irregular echinoid spines and the first occurrence of sponge spicules (Fig. 3). Relative to Biofacies 1, this facies is less cemented and sorted. The overall carbonate content is also less than Biofacies 1, being reduced to around 45% $CaCO_3$ just above the base of this unit at log level 7.5 m, although increasing to around 80–100% $CaCO_3$ above this level. Gamma values are relatively low (80–170cps) for this interval, yet slightly higher than Biofacies 1 (Fig. 4).

This interval is dominated by the benthic rotaliids and is plankton-poor. Benthic rotaliids comprise over 90% of the total foraminiferal assemblage, with epifaunal forms dominant. The poor preservation of foraminifera and other microfauna is similar to Biofacies 1. The larger benthic foraminifera are also an important group within this biofacies, but decrease in abundance above 8.5 m log level. The abundance of *Pararotalia mackayi* and *Lepidocyclina howchini* decrease significantly compared to Biofacies 1, being replaced by the large foraminiferid *Amphistegina lessonii (*Pl. 1, Fig. 5). Near the top of this interval, *Pararotalia mackayi* re-occurs in the absence of *A.lessonii.* Similar to Biofacies 1, the benthic discorbids, elphidiids and cibicidids comprise the major part of the assemblage. The relative percentage of *Glabratella* (e.g., *Glabratella sigali,* Pl. 1, Fig's.12&13), *Ehrenbergina marwicki (*Pl. 1, Fig. 20) and the cassidulinids (e.g., *Evolvocassidulina orientalis*) increases in Biofacies 2. With the exception of bolivinids and *Globocassidulina subglobosa (*Pl. 1, Fig. 6), infaunal taxa are rare. Planktonic percentages are low, and overall, species diversity is slightly higher than in Biofacies 1.

Biofacies (3): Calcisiltite, Bryozoan Silt and Calcareous Silty-clay (16.1–23 m log level, Fig. 5)

This interval consists predominantly of fine-grained grey bryozoan marl (wackestone) and calcareous silty sand, with

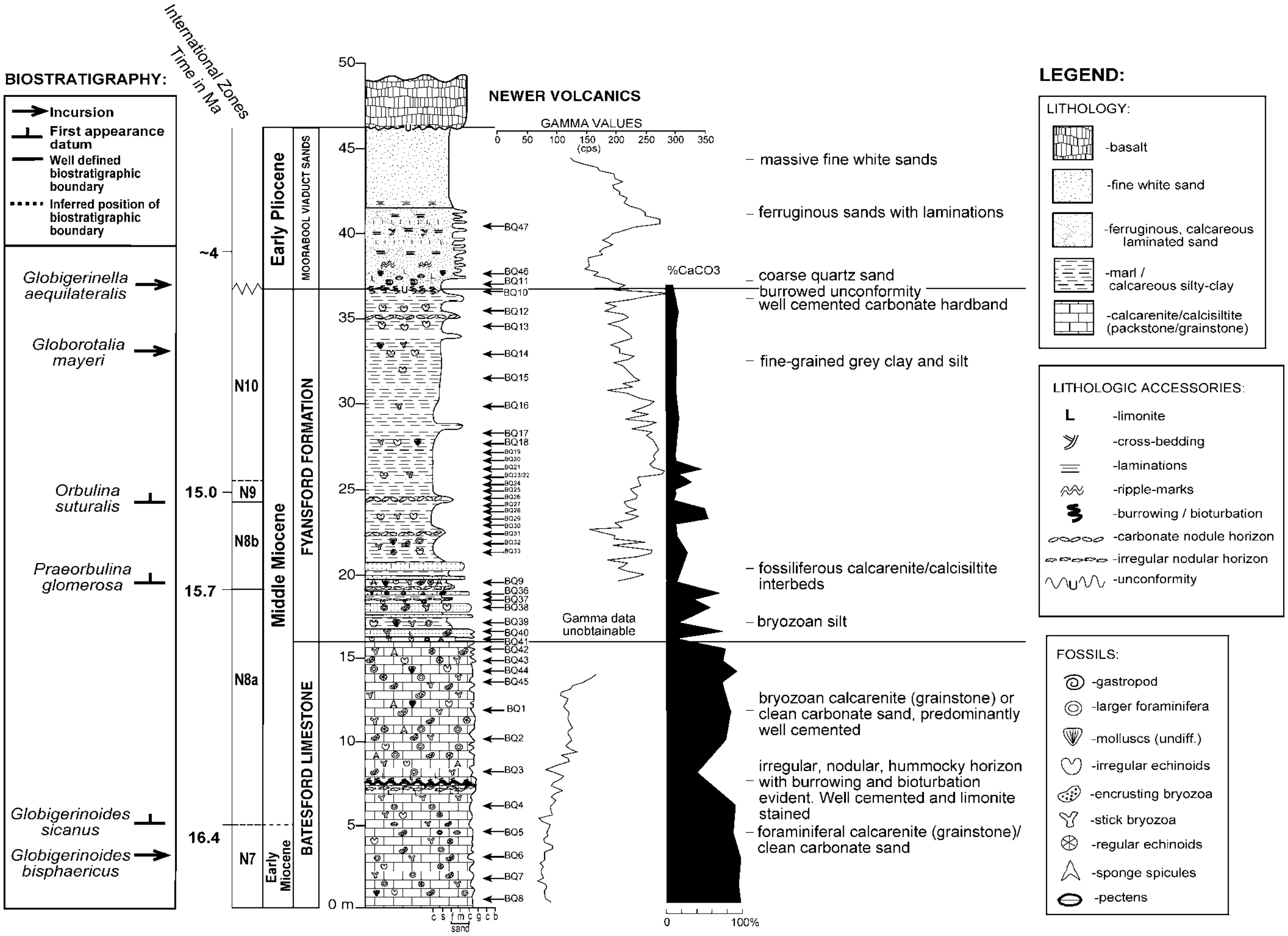

FIGURE 3. Detailed lithology of the Batesford Quarry succession and datum planes of biostratigraphically significant planktonic foraminifera (using the zonation schemes of Gallagher and others (2001), Holdgate and Gallagher (1997) and McGowran and others (1997a) with chronology from Berggren and others (1995)) with faunal components, gamma values, carbonate values, position of samples and facies comments. Note: The legend is for all logs of the Batesford Quarry in the following figures.

occasional organic material present. In the lower part of this interval, yellow/cream cemented calcisiltite (packstone) bands (0.5–0.15 m thick), similar in composition to Biofacies 2, are interbedded with bryozoan-rich silt that has a significant bioclastic component of both stick and encrusting Bryozoa and regular echinoid spines (Fig. 3). Bioclasts also include sponge spicules and ostracods. Above this transitional interval, bioclastic content decreases. Well-cemented carbonate hardbands and nodular carbonate horizons (0.1–0.2 m thick) occur throughout this interval (Fig. 3). With the exception of these carbonate hardbands and nodular horizons (which have a very high % $CaCO_3$), the carbonate content of this interval is lower than in Biofacies 1 and 2, with values 6–30% $CaCO_3$. Gamma values can be seen to increase markedly to around 150 to 260cps moving into this biofacies (Fig. 5).

The preservation of foraminifera within this interval is much better than in Biofacies 1 and 2, and a distinct change in the faunal assemblage is preserved. Larger foraminifera include *Gypsina howchini (*Pl. 1, Fig. 1) and *Amphistegina lessonii,* which occur at log level 18.8 m with a flatter and thinner test compared with those in Biofacies 2. The last occurrence of *A.lessonii* occurs towards the top of Biofacies 3 at log level 22.5 m and coincides with the disappearance of the larger foraminifera from the succession. The foraminiferal assemblage contains abundant small, delicate infaunal taxa such as *Astrononion tasmanensis (*Pl. 1, Fig. 10) and the cassidulinids (e.g., *Cassidulinoides chapmanni,* Pl. 1, Fig. 8). *Sphaeroidina bulloides (*Pl. 1, Fig. 9) and *Globocassidulina subglobosa* are abundant throughout and the epifaunal *Lenticulina cultrata* and heterolepids (e.g., *Heterolepa brevoralis,* Pl. 1, Fig. 16) are common at log level 19.5 m. At log level 18.8 m, abundant agglutinated species occur (e.g., *Dorothia minima*) and are associated with the rotaliids, *Notorotalia* and *Eponides.* The relative abundance of *Siphonina australis* and the plankton percentage (up to 15%) increases towards the top of Biofacies 3. The taxon *Discorbinella bertheloti* is common throughout, and the last occurrence in the succession of the glabratellids and the species *Discorbis balcombensis* occurs in this interval. The planktonic species *Sphaeroidinellopsis disjuncta* and *Globoturborotalia woodi (*Pl. 1, Fig. 21) are abundant near the base of this biofacies, decreasing in abundance towards the top. Common *Orbulina* bioseries taxa such as *Praeorbulina glomerosus* (first appearance) and *Praeorbulina sicana* occur at the base of this interval.

Biofacies (4): Plankton-rich Calcareous Clay and Silt (23.0–31.0 m log level, Fig. 5)

This interval consists of grey silt and calcareous clay with common organic material. Apart from foraminifera, bioclastic material such as irregular echinoid spines and delicate branching Bryozoa are rare. Similar to Biofacies 3, carbonate cemented hardbands and carbonate nodule horizons are present but not as common. With the exception of hardbands and nodular horizons, the carbonate content of this biofacies is low, 5–30% $CaCO_3$. High gamma values of around 250–270cps characterize this interval (Fig. 5).

Foraminifera are abundant and well preserved in this biofacies and a distinctive faunal assemblage dominated by the benthic infaunal taxa and with a higher planktonic percentage than Biofacies 3 is preserved. Plankton (comprising 28.5% of the foraminiferal assemblage) and the delicate infaunal uvigerinids (e.g., *Uvigerina proboscidea*, Pl. 1, Fig. 14*)* are abundant at log level 27.5 m. A close relationship between gamma values and planktonic abundance has been observed in this sequence (Fig. 5) and an increase in the relative size of planktonic tests occurs from Biofacies 1 and 2 to Biofacies 3. The infaunal taxa *Astrononion tasmanensis* and *Ehrenbergina marwicki* are abundant at the base of the interval although these taxa become rare towards the top. The infaunal cassidulinids are also common and the larger subtropical foraminifera are absent throughout. The epifaunal cibicidids (e.g., *Cibicidoides perforatus*), heterolepids (e.g., *Anomalinoides macroglabra, Heterolepa*) and *Lenticulina* spp. are abundant in this interval. *Globigerina bulloides (*Pl. 1, Fig. 23) and *Globoturborotalia woodi* dominate the planktonic assemblage. These taxa are most common at log level 27.5 m and associated with common tenuitinellids and *Sphaeroidinellopsis disjuncta (*Pl. 1, Fig. 22). A relatively high percentage of plankton and high total species diversity (35–61 species) characterize this interval (Fig. 4).

Biofacies (5): Calcareous Silt and Silty-clay (31.0–36.5 m log level, Fig. 5)

The facies of this interval is similar to the upper section of Biofacies 3 and consists of calcareous silt and silty clay which occasionally contain organic material. In addition to foraminifera, bioclastic material such as stick Bryozoa, irregular echinoid spines and ostracods are rare. Carbonate cemented hardbands and nodular carbonate horizons are common towards the upper part of the interval (Fig. 3). Biofacies 5 is characterized by lower carbonate values (5–20% $CaCO_3$) and lower gamma values (180–230cps) than in Biofacies 3 and 4 (Fig. 5).

This interval contains abundant infaunal bolivinids (e.g., *Bolivina alata,* Pl. 1, Fig. 15) at log level 32.5 m and the infaunal cassidulinids throughout. *Siphonina australis* and *Ehrenbergina marwicki* are common at log level 35.5 m. *Lenticulina* spp., *Anomalinoides* spp. and plankton decrease in abundance compared to Biofacies 4. The epifaunal discorbids (*e.g., Discorbinella bertheloti)* are abundant at log level 32.5 m where the planktonic species *Globorotalia mayeri* is common. The planktonic percentage of this interval is relatively high (~10%) yet lower than Biofacies 4. Species diversity decreases to 9 towards the top of the interval (Fig. 4).

DISCUSSION

PALEOENVIRONMENTAL INTERPRETATION

Paleoenvironment of Biofacies 1 and 2

The 'larger foraminifera' are important paleoenvironmental indices; today these taxa are principally restricted to oligotrophic, shallow waters (most <70 m depth) in the subtropics and tropics (Murray, 1987, 1991; Li and others, 1996a). The abundance of these robust, discoidal larger foraminifera, with the presence of other shallow-water indices (e.g., *Elphidium)* and a low plankton percentage in these two biofacies, suggests that the bryozoan and foraminiferal calcarenite (clean carbonate sand) of the Batesford Limestone was deposited in a shallow inner-shelf (neritic) environment (Fig. 6C) within the euphotic zone. Conditions were probably subtropical and oligotrophic (low-nutrient and oxygenated, ~8.0–2.0 ml/l O_2) and the presence of echinoderms and bryozoans indicates that unrestricted, normal marine, stenohaline salinities of around 30–45‰ prevailed.

Modern ecological studies of the larger foraminifera, in particular *Amphistegina* and taxa similar to *Lepidocyclina*, by Chaproniere (1975), Murray (1991), Hallock (1986) and Hohenegger (1995), can be used to interpret the paleodepth of Biofacies 1 and 2. The calcarenite (bioclastic sand) of Biofacies 1, with abundant *L.howchini* and *Pararotalia mackayi*, was most likely deposited as carbonate shoal sand at depths from 10 to 50 m. The switch to more abundant *A.lessonii* in Biofacies 2 may indicate a change to a slightly deeper and quieter environment at depths from 40–70 m. The interpreted deepening from Biofacies 1 to 2 is also associated with a slight increase in gamma values, most likely directly related to an increasing clay content up section. The reappearance of highly abraded *P.mackayi* specimens at log level ~15.8 m, further up section within Biofacies 2, may represent the bioclast reworking and redeposition of coarser, underlying sediments during this transgressive phase.

The dominance of warm-water planktonic indices such as the *Orbulina* lineage (Fig. 6D) and the presence of larger foraminifera, especially *Amphistegina,* which is known to have a relatively lower temperature tolerance limit of around 20°C (Hornibrook, 1968), suggests that warm temperate conditions (~19 to 22°C) prevailed during the late Early Miocene to early Middle Miocene in the Batesford region. The low diversity (4 species) of the larger foraminifera probably indicates that warm temperate conditions rather than subtropical conditions prevailed (cf., Murray, 1987). This may also reflect the southernmost latitudinal limit of distribution of these subtropical, migratory species (cf., Murray, 1987).

Previous studies carried out by Bowler (1963) and Foster (1970) have suggested that the sediments of the Batesford Limestone were derived from a ''reefal'' community that fringed the nearby Dog Rocks (a granite massif), which was thought to have existed as a topographical high in the Early

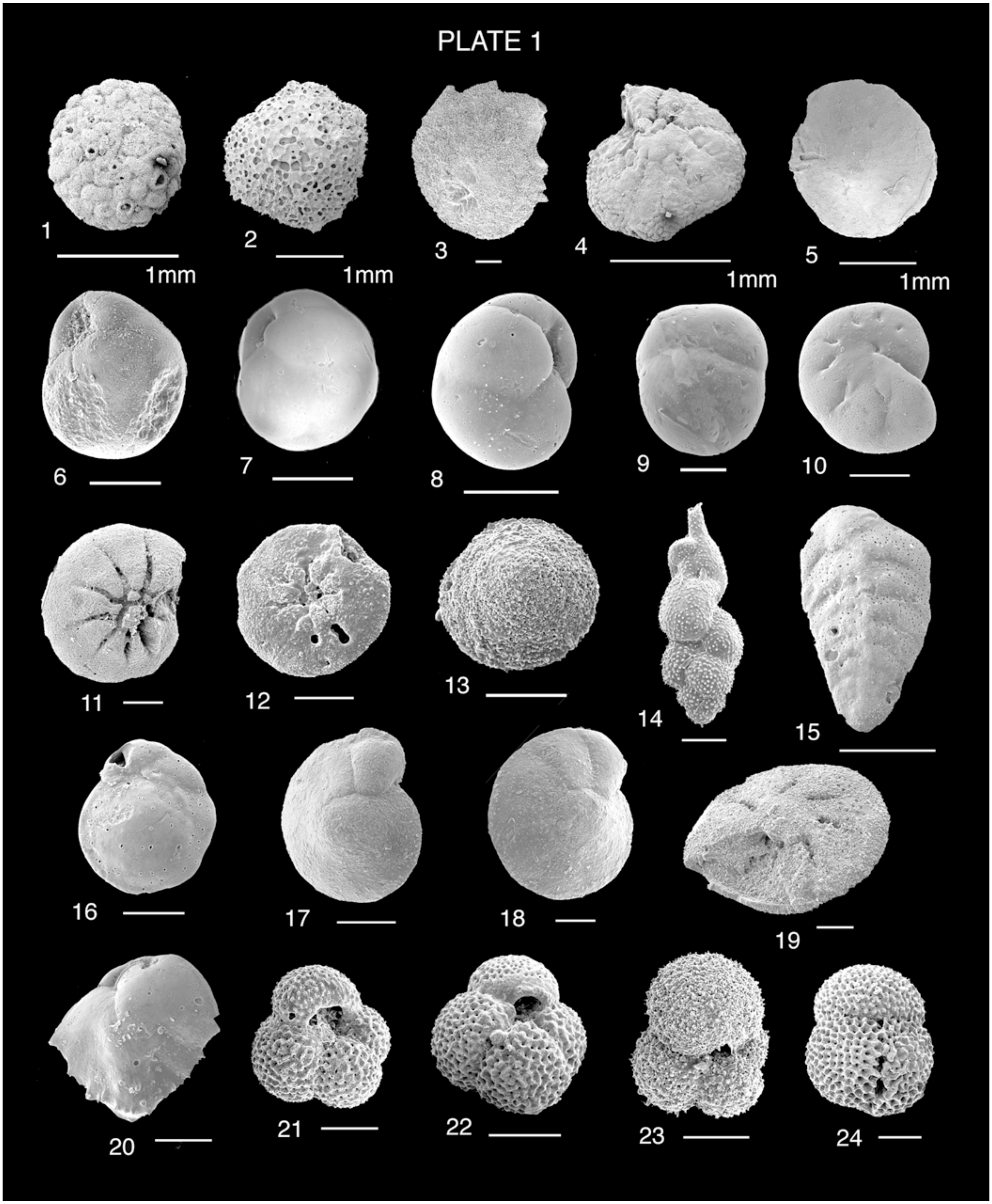

PLATE 1

SEM images of paleoenvironmentally and biostratigraphically significant foraminiferid taxa. Horizontal bar = 0.1mm unless otherwise stated. **1.** *Gypsina howchini* (Chapman & Crespin), 8.5m log level. **2.** *Lepidocyclina howchini* (Chapman & Crespin), 5.0m. **3–4.** *Pararotalia mackayi* (Karrer), 8.5m. **5.** *Amphistegina lessonii* (d'Orbigny), 8.5m. **6.** *Globocassidulina subglobosa* (Brady), 8.5m. **7.** *Cassidulina laevigata* (d'Orbigny), 27.5m. **8.** *Cassidulinoides chapmani* (Parr), 21.0m. **9.** *Sphaeroidina bulloides* (d'Orbigny), 19.5m. **10.** *Astrononion tasmaniensis* (Carter), 19.5m.

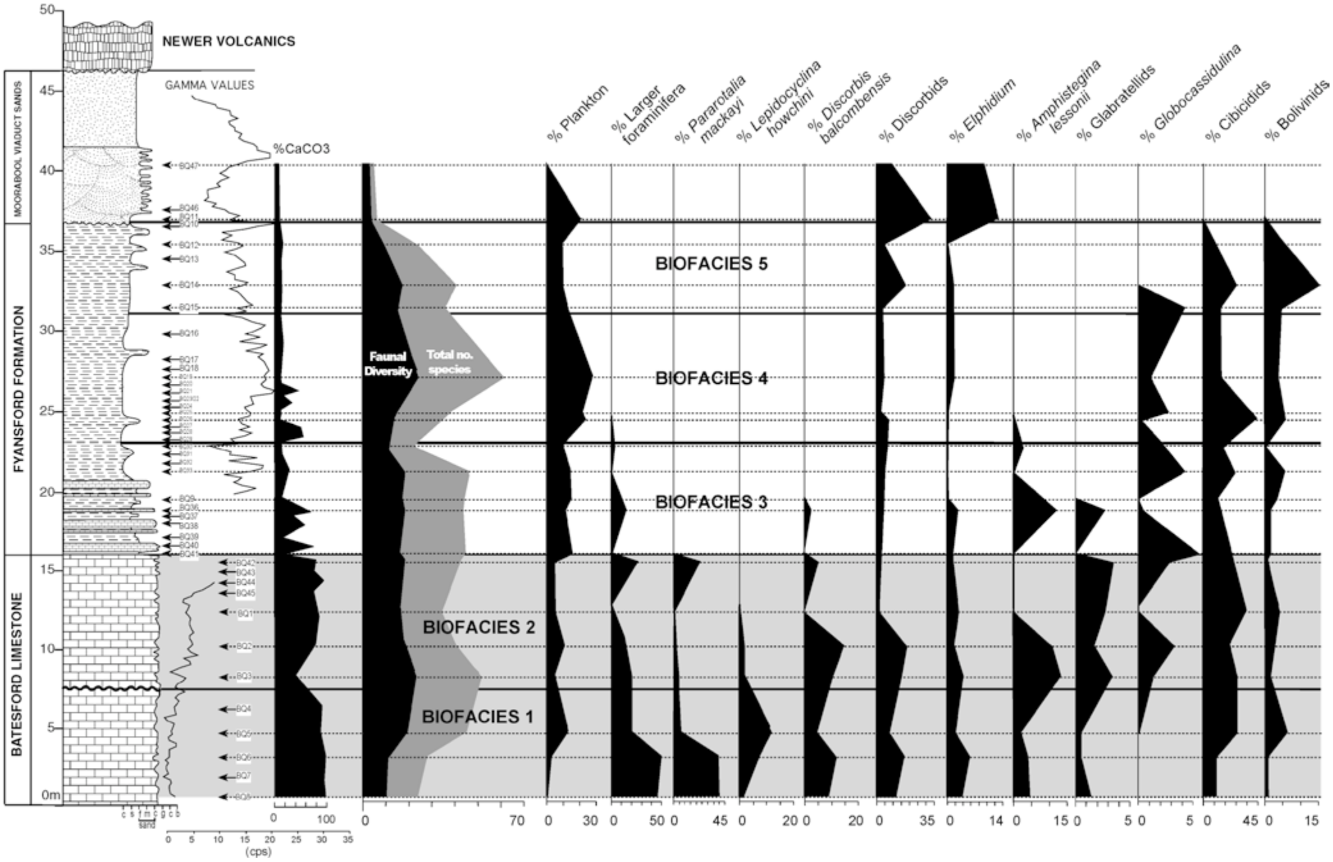

FIGURE 4. Gamma value, carbonate value, planktonic percentage (% of total fauna), faunal diversity and frequency of some benthic foraminifera (% of total benthic forms) for Biofacies 1 and 2. Standardized faunal diversities were calculated using the Margalef diversity calculation (from Brenchley & Harper, 1988): diversity = S-1/log$N$, where S = number of species and N = number of specimens.

Miocene ocean. In this study, the sorting, rounding, abrasion and current reworking and alignment of coarse skeletal debris, observed in samples taken from the Batesford Quarry, indicates that the calcarenite was probably deposited as a carbonate shoal, eroded from an encrusting community of organisms attached to the granite massif, in a high-energy, shallow-water environment. Moderate to strong currents and wave activity would have resulted in the post-mortem winnowing of finer grained material (including clay and organic matter) and smaller foraminifera from the Batesford Limestone sediments. Under these conditions, the relatively low-diversity assemblages of both Biofacies 1 and 2 and abundance of more resistant epifaunal foraminiferid tests is to be expected. The skeletal fragments observed within these biofacies suggest that the carbonate shoal around Dog Rocks had a diverse community of regular echinoids, encrusting and robust branching Bryozoa and a variety of Mollusca.

The presence of a limonite-stained, erosional, bioturbated hardground at log level 7.5 m is indicative of shallow-water conditions where either subaerial erosion or submarine cementation occurred, possibly caused by a small-scale sea-level change or lateral facies variation on the flank of the shoal. Burrowing of shallow marine organisms during this time (e.g., polychaete annelids, bivalves and sponges) resulted in the irregular nodular appearance of sediments just below this surface, and later pressure dissolution is likely to have accentuated this texture.

Paleoenvironment of Biofacies 3

The lower interval of Biofacies 3 represents the transition from the Batesford Limestone into the marl and silty clay of the Fyansford Formation. This coincides with an increase in the abundance of plankton, middle-shelf benthic indices (e.g., *Eponides repandus* and *Notorotalia*) and infaunal species (Fig. 6B) such as *Sphaeroidina bulloides*, *Siphonina australis* and *Astrononion* spp.. On the modern shelves of South Australia, similar faunal assemblages with *Cibicides*, *Heterolepa*, *Eponides* and *Notorotalia* are known to comprise the bulk of benthic assemblages from 50–100 m water

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11. *Ammonia beccarii* (Linne), 37.0m. **12–13.** *Glabratellina sigali* (Seigle and Bermudez), 8.5m. **14.** *Uvigerina proboscidea* (Shwager), 27.5m. **15.** *Bolivina alata* (Seguenza), 32.5m. **16.** *Heterolepa brevoralis* (Carter), 27.5m. **17.** *Cibicides mediocris* (Finlay), 8.5m. **18.** *Cibicidoides perforatus* (Karrer), 8.5m. **19.** *Discorbis balcombensis* (Karrer), 8.5m. **20.** *Ehrenbergina marwicki* (Finlay), 19.5m. **21.** *Globoturborotalia woodi* (Jenkins), 19.5m. **22.** *Sphaeroidinellopsis disjuncta* (Finlay), 27.5m. **23.** *Globigerina bulloides* (d'Orbigny), 19.5m. **24.** *Globigerinoides trilobus* (Reuss), 27.5m.

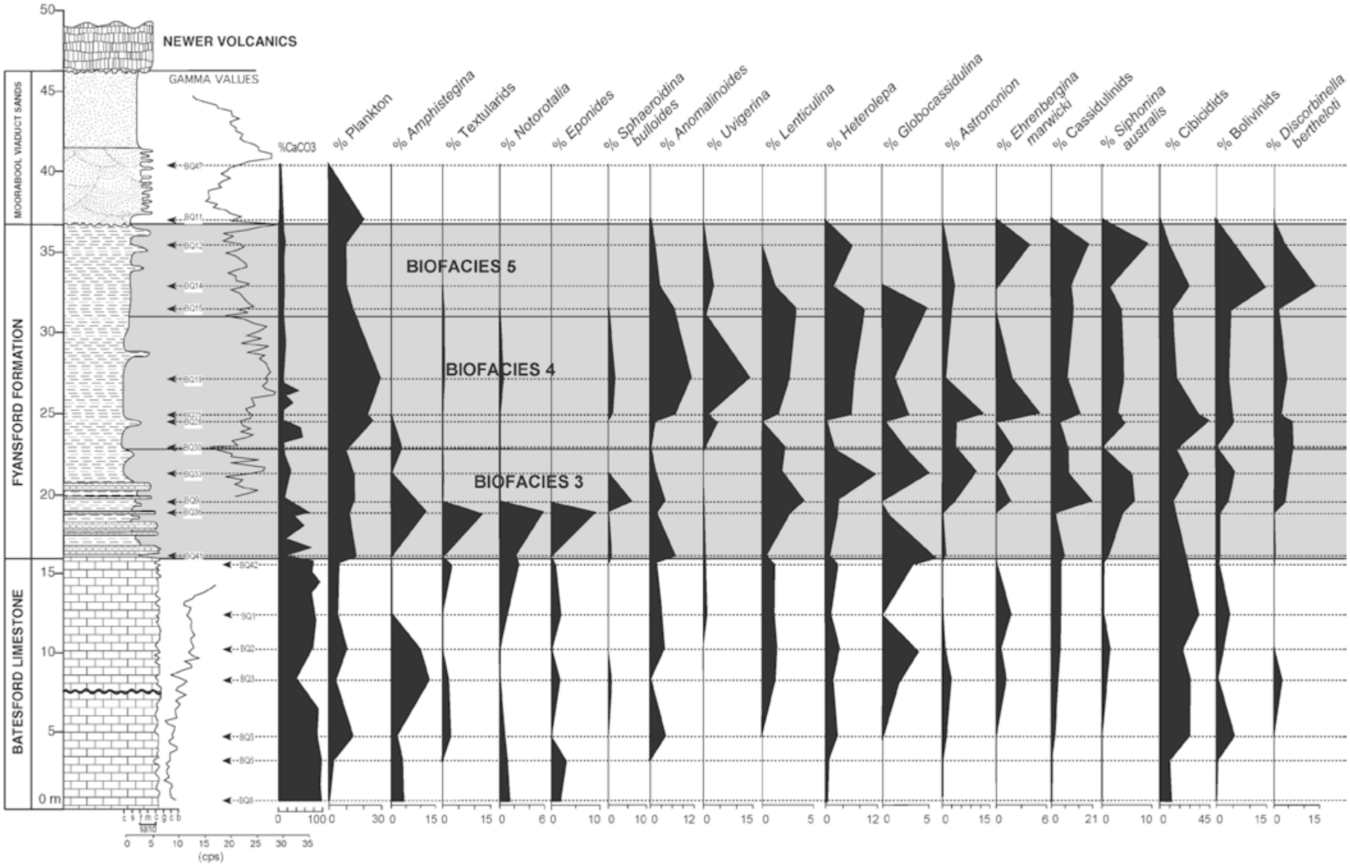

FIGURE 5. Gamma value, carbonate value, planktonic percentage (% of total fauna) and frequency of some benthic foraminifera (% of total benthic forms) for Biofacies 3, 4 and 5.

depth (Li and others, 1996a). This suggests a relative deepening of the marine environment by Biofacies 3 time to below wave-base, caused by an increased transgression of the ocean into the region. The re-appearance of *Amphistegina lessonii* with a flatter and thinner test is also likely to be indicative of a deepening from Biofacies 2 to 3, yet at depths still within the euphotic zone.

Minor sea-level change or autocyclic processes such as storm deposition during this transitional time created the alternations of calcarenite and calcisiltite in this biofacies. Transport and reworking of the underlying Batesford Limestone is interpreted to have contributed to the high bioclastic content of the calcisiltite units in the lower section of Biofacies 3 and contributed to a mixture of different shelfal depth indices. Calcarenite horizons contain a foraminiferal assemblage dominated by inner- to middle-shelf taxa, indicating a more oligotrophic and higher-energy environment, similar to that of Biofacies 2. The marl and silty clay near the top of the interval represents the onset of deeper, lower energy, middle- to outer-shelf conditions at depths from 60–100 m, and a more stable sea level following the initial transgressive waters representative of this biofacies.

Overall, this transitional interval is interpreted to have been deposited in a mesotrophic nutrient regime (relatively nutrient enriched and oxygenated) under normal marine salinities, in an inner- to middle-shelf environment at depths from 40–100 m. The presence of rare larger foraminifera such as *Gypsina* and *Amphistegina* and warm and cool-temperate planktonic indices (such as *Globoturborotalia woodi*) in this biofacies (Fig. 6D), indicates that oceanic conditions were cooling by Biofacies 3 time after the maximal temperatures achieved during Biofacies 1 and 2 times.

Paleoenvironment of Biofacies 4

The abundance of benthic taxa typical of dysoxic environments, such as the infaunal taxa *Ehrenbergina marwicki* and *Uvigerina proboscidea* (Fig. 6A), coinciding with an abundance of the cool-water planktonic species *Globigerina bulloides*, indicate that Biofacies 4 represents deposition in a cool, upwelling (eutrophic and dysoxic, low-oxygen ~2.0–0.2 ml/l O_2, Sen Gupta and Machain-Castillo, 1993) environment. An increase in abundance of the planktonic species *Tenuitinellinata juvenilis* in this biofacies may also be indicative of a eutrophic, cool-water upwelling environment (Li and McGowran, 2000). The abundance of organic matter within sediments of Biofacies 4 coincides with relatively high gamma values and an abundance of *Astrononion tasmanensis* and other infaunal species, indicating a muddy eutrophic substrate with a high organic flux. The shift to cooler oceanic conditions in this biofacies is also reflected in the absence of the larger subtropical foraminifera, an increase in abundance of cool to temperate plankton (Fig. 6D) such as *Globoturborotalia woodi*, and the occurrence of benthic infaunal species such as *Globocassidulina subglobosa*. The relative lack of photic indicators (e.g., larg-

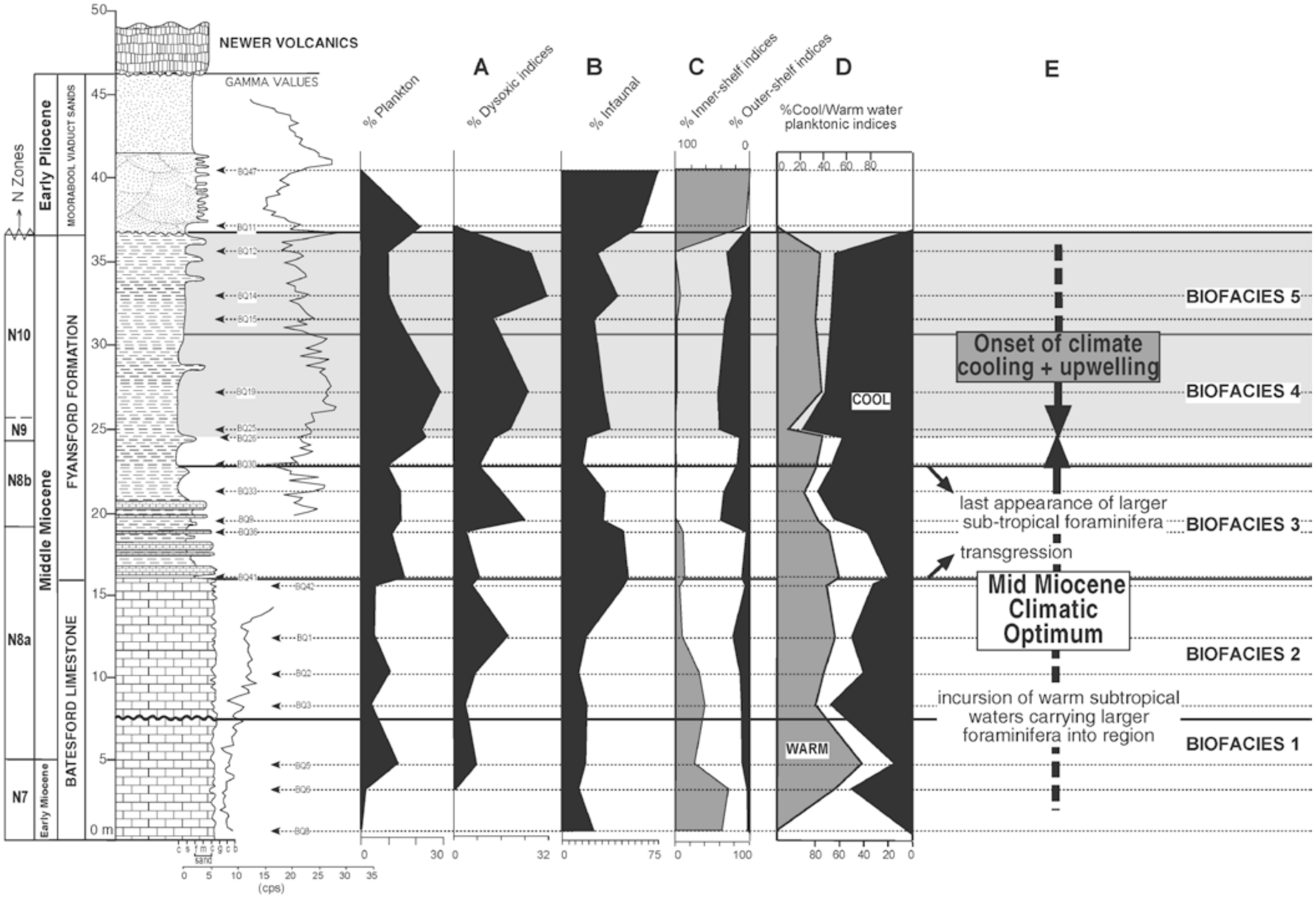

FIGURE 6 (A–E). Frequency of foraminiferal groups (see Table 1 for included taxa) that can be used for paleoenvironmental and paleoceanographic interpretation of the Batesford Quarry section. Cool/Warm planktonic indices are expressed as a percentage of total plankton and all other groups are expressed as a percentage of the total benthos.

er foraminifera) and an increase in abundance of plankton and well preserved deeper water benthic taxa (e.g., *Anomalinoides macroglabra, Lenticulina)*, suggests deposition below wave base in an outer-shelf environment (Fig. 6C) below or near the base of the euphotic zone.

Paleoenvironment of Biofacies 5

The fine-grained, silty clay and marl of Biofacies 5 contain a foraminiferal assemblage dominated by infaunal taxa (Fig. 6B) typical of a middle- to outer-shelf environment (Fig. 6C). Decreasing gamma values and the percentage plankton, together with an increase in the abundance of *Discorbinella bertheloti* in this biofacies, may indicate a slight shallowing of the environment compared to Biofacies 4. An abundance of infaunal taxa typical of dysoxic environments (Fig. 6A) suggests a period of eutrophy and benthic dysoxia (2.0–0.2 ml/l O_2) during the deposition of Biofacies 5. The decrease in abundance of upwelling indicators such as *Globigerina bulloides* and *Uvigerina proboscidea* in this interval indicates that upwelling may have ceased by Biofacies 5 time. Similar to Biofacies 4, the dominance of cool-temperate planktonic indices such as *G.woodi* in the absence of warmer water indices (Fig. 6D) indicates the continuation of relatively cooler oceanic conditions compared to Biofacies 1 to 3 time. The discontinuous nodular carbonate hardbands within this part of the Fyansford Formation are most likely a diagenetic feature caused by the segregation of carbonate and pressure solution.

REGIONAL STRATIGRAPHIC CORRELATION AND GLOBAL CONTEXT

Many of the biofacies signals preserved within the Batesford succession can be correlated regionally across the southern Australian Tertiary basins and provide evidence for a globally recognized, cool to warm paleoclimatic transition during the Miocene.

Li and McGowran (1994) have identified several third-order 'warm intervals' in southern Australia based on the presence of larger benthic foraminifera. One particular warm phase occurs at the Early/Middle Miocene boundary (within Zones N8-N9*)*. This is the 'Miocene Climatic Optimum' of Flower and Kennett (1994) and represents a period of maximum global warmth for the Neogene. The 'Miocene Climatic Optimum' is characterized by the presence of the migratory subtropical larger foraminifera, the first occurrence of the *Orbulina* bioseries and an abundance of warm-water cancellate-spinose planktonic species such as *Globigerinoides trilobus* (Li and McGowran, 2000). The preservation of this assemblage within Biofacies 1, 2 and 3 in the Batesford Quarry succession suggests deposition coincided with this 'Miocene Climatic Optimum' (Fig. 6E).

The late Early Miocene to early Middle Miocene (Zones N7-N9) limestone and marl of the Eucla (Li and others, 1996b), Murray (Li and McGowran, 1999), Port Phillip (this study) and Gippsland (Li and others, 2000; Gallagher and others, 2001) basins are characterized by the presence of the subtropical larger foraminifera (e.g., *Amphistegina lessonii*) and warm-water planktonic taxa (e.g., *Orbulina* and *Globigerinoides trilobus*). This illustrates the regional extent of evidence for the 'Miocene Climatic Optimum'. Sedimentary successions in New Zealand also preserve evidence (warm-water larger foraminifera and molluscs) for this period of warmth (McGowran and others, 1997; Flower and Kennett, 1994).

Modern ocean current systems cannot be extrapolated back to the early Middle Miocene (as interpreted by Li and McGowran, 1994) when the world's oceans were poorly stratified and much warmer than today (Gallagher and others, 2001). It is likely therefore, that during the early Early Miocene, the warm to subtropical waters bathed southern Australia including the Batesford region simply due to the more southerly latitudinal expansion of the subtropical and warm-temperate belts. This allowed the larger subtropical foraminifera such as *Lepidocyclina howchini* and *Amphistegina lessonii* to migrate to quite southerly latitudes. The more southerly distribution of the warm-water planktonic provinces during the Early to Middle Miocene has also been noted by Wright and Thunell (1988).

During the Middle Miocene, around the N9-N10 zonal boundary, strata in the Port Phillip, Gippsland and Murray Basins preserve similar biofacies signals for a shift to cool-water oceanic upwelling conditions (Fig. 6E). These signals include the disappearance of the subtropical larger foraminifera (Biofacies 3) and the shift to a foraminiferal assemblage dominated by upwelling indices (Biofacies 4) and cool-water planktonic taxa (Biofacies 4 and 5). This strongly suggests that the phase of cool-water upwelling identified within this study is not just a localized upwelling event, but rather a regional paleoclimatic change associated with the evolving Southern Ocean and recorded in the sedimentary successions across southern Australia. The disappearance of the larger foraminifera from the Miocene sedimentary successions of New Zealand has also been used to signal the onset of climatic cooling (Flower and Kennett,1994). This phase of cooling has been interpreted as a response to rapid glacial expansion of the East and West Antarctic Ice Sheets and a subsequent intensification of atmospheric and oceanic circulation.

CONCLUSIONS

The integration of both facies and foraminiferal data taken from an outcropping succession of Miocene sediments within the Batesford region, using facies changes and foraminifera as proxy for paleoenvironmental, paleoceanographical and biostratigraphic reconstruction, has allowed six separate biofacies to be identified and the following conclusions to be drawn:

(1) The Early Miocene to early Middle Miocene bryozoan and foraminiferal calcarenite of the Batesford Limestone (Biofacies 1 and 2), was deposited as talus-slope sand in a high-energy, inner-shelf environment under oligotrophic, normal marine conditions. High-intensity current and wave action resulted in the winnowing of smaller foraminifera from the sediment. Hence, the foraminiferal assemblage is dominated by larger and more robust epifaunal taxa. Based on the identification of subtropical larger benthic foraminifera such as *Amphistegina lessonii* and warm-water planktonic *Orbulina* bioseries taxa, Biofacies 1 and 2 of the Batesford Limestone can be correlated to an Early to Middle Miocene period of maximum warmth known as the 'Miocene Climatic Optimum'.

(2) The transition into finer-grained sedimentation of the Fyansford Formation during the early Middle Miocene, reflects a transgression of the warm Southern Ocean further into the Port Phillip Basin. The shift in Biofacies 3 from intercalated calcisiltite and bryozoan silt through to fine-grained calcareous silty clay, signals a marine deepening and the establishment of a lower-energy, middle- to outer-shelf environment. The persistence of the larger foraminifera and warm-water planktonic indices indicates the continuum of warm oceanic conditions during this transitional period.

(3) Biofacies 4 of the Fyansford Formation was deposited in a middle- to outer-shelf environment and preserves signals, including a marked change in foraminiferal assemblage, for an early Middle Miocene (N9-N10 Zonal) phase of intense cool-water upwelling and associated eutrophy and dysoxia in the Southern Ocean. This period of intensified oceanic circulation and climatic cooling can be correlated to a rapid glacial expansion of the East and West Antarctic ice sheets during the Middle Miocene.

(4) Biofacies 5 preserves facies and foraminiferal content suggestive of an outer-shelf environment under relatively dysoxic and eutrophic conditions. The foraminiferal assemblages also preserve evidence for a decline in oceanic upwelling but the continuum of cool oceanic conditions related to the global cooling event of the Middle Miocene.

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