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Integrated stratigraphy of the Waitakian-Otaian Stage boundary stratotype, Early Miocene, New Zealand

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Abstract The base of the type section of the Otaian Stage at Bluecliffs, South Canterbury, is recognised as the stratotype for the boundary between the Waitakian and Otaian Stages. Principal problems with the boundary are the restriction of existing bioevent proxies to shelf and upper slope environments and its uncertain age. These topics are addressed by a multidisplinary study of a 125 m section about the boundary, which examines its lithostratigraphy, depositional setting, biostratigraphy, correlation, and geochronology.

The lower siltstone lithofacies (0–38.5 m) was deposited at upper bathyal depths (200–600 m) in a marginal basin which was partially sheltered from fully oceanic circulation by a submarine high and islands. The site was covered by cool-temperate water and was probably adjacent to the Subtropical Convergence. This unit is succeeded by the banded lithofacies (38.5–106 m) and the upper siltstone lithofacies (basal 19 m studied). Paleodepth probably declined up-sequence, but deposition at shelf depths is not definitely indicated. A cyclic pattern of abundance spikes in benthic and planktonic foraminifera commences 9 m above base and extends to 73 m in the banded lithofacies. Oxygen isotope excursions (up to 2.08‰) in *Euuvigerina miozea* and *Cibicides novozelandicus* are greatest within the interval containing the abundance spikes. The stage boundary occurs in the banded lithofacies at the highest abundance spike (73 m). Although condensed intervals might affect the completeness of the section, they are not associated with sedimentary discontinuities, and we consider that the section is suitable as a biostratigraphic reference.

Spores, pollens, dinoflagellates, calcareous nannofossils, foraminifera, bryozoans, and ostracods are preserved near the boundary, but molluscs principally occur higher, in the shallower upper siltstone lithofacies. Siliceous microfossils are rare. There is considerable scope for further biostratigraphic research.

The primary event marking the boundary at 73 m is the appearance of the benthic foraminifer *Ehrenbergina marwicki*. This is a distinctive and widely distributed event but is restricted to shelf and upper bathyal environments. Supplementary events in planktonic foraminifera and calcareous nannofossils were researched. Highest occurrences of *Globigerina brazieri* and *G. euapertura* are recorded at 47 and 58 m. There is a marked decline in relative abundance of *Paragloborotalia* spp. at 62 m. *Helicosphaera carteri* becomes more abundant than *H. euphratis* between 56 and 87 m. These events are not exact proxies for the boundary but they may usefully indicate proximity to it. They occur in the interval of prominent spikes in foraminiferal abundance.

The Waitakian-Otaian boundary is dated at 21.7 Ma by strontium isotopes. Stable primary remanence could not be determined in a pilot paleomagnetic study of Bluecliffs specimens. However, specimens trended towards reversed polarity, and remagnetisation great circle analysis will allow directions to be calculated in future collections.

Keywords Oligocene; Miocene; Waitakian; Otaian; stage boundary stratotype; lithostratigraphy; biostratigraphy; geochronology; integrated stratigraphy; Bluecliffs Silt; Otekaike Limestone; planktonic foraminifera; benthic foraminifera; calcareous nannofossils; Mollusca; palynoflora; dinoflagellates; Radiolaria; oxygen isotopes; carbon isotopes; strontium isotopes

INTRODUCTION

New Zealand Cenozoic stages were developed as biostratigraphic units based on local bioevents to overcome problems in recognising European stages in a distant biogeographic province. Pioneering work by Thomson (1916) and Allan

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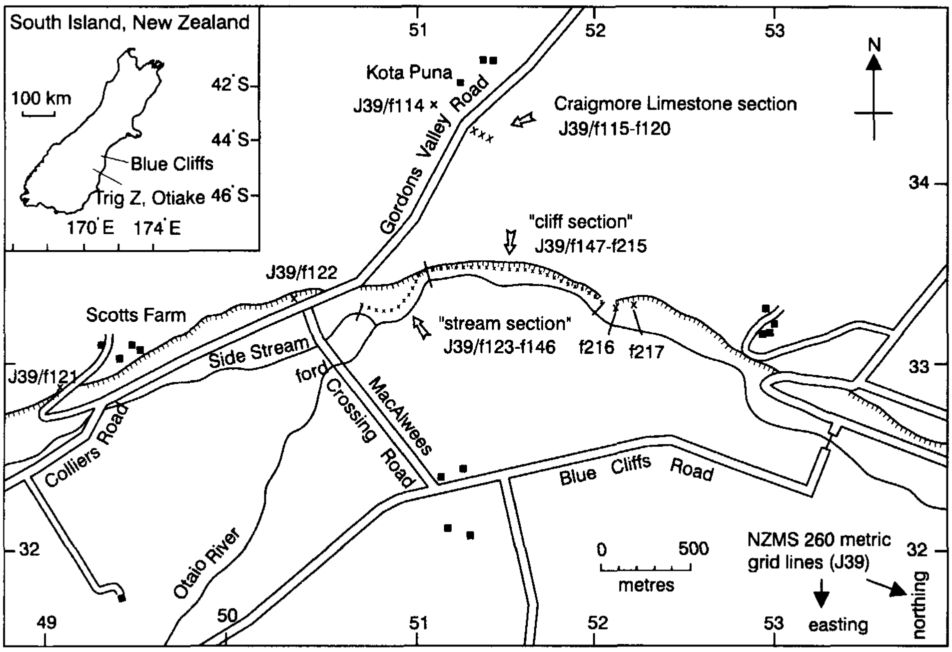


Fig. 1 Location of Bluecliffs exposures, Otaio River, showing sections sampled: "stream section", "cliff section", Craigmore Limestone section, and location of isolated samples. Access to Bluecliffs is from MacAlwees Crossing Road. NZMS 260 co-ordinates for the base of "stream section": J39/507333.

(1933) used brachiopod and mollusc distributions, but the resolution and biofacies coverage of the classification were considerably enhanced by inclusion of foraminiferal events (Finlay & Marwick 1940, 1947). Following the latter work, the classification stabilised and became the standard stratigraphic reference in New Zealand Cenozoic geology. A large amount of earth science research has been reported using local stages (e.g., Suggate et al. 1978; Field et al. 1989). As well, the classification provides a framework for single-group biostratigraphies (e.g., Edwards 1971; Wilson 1984). Significantly, the local stages now act as a *de facto* chronostratigraphic classification for Cenozoic time in New Zealand (Edwards et al. 1988; Morgans et al. 1996). For stages to perform this role effectively it is necessary to define, evaluate, and calibrate boundaries, and to identify bioevents that are suitable time proxies. The Waitakian-Otaian boundary has high priority for early review. Biostratigraphically, it is defined by benthic foraminiferal events that occur primarily in shelf and upper bathyal sequences. More widely dispersed substitutes are needed. Currently, poor biostratigraphic resolution constrains studies of the evolution of deep-water Early Miocene basins that are prospective for hydrocarbons. Chronostratigraphically, the age of the boundary is poorly constrained because of the absence of geomagnetic polarity, isotopic or bioevent proxy data; this impacts on geohistory modelling. Edwards et al. (1988) rather arbitrarily located the boundary at 22 Ma, a moderately close assignment in the light of the present research.

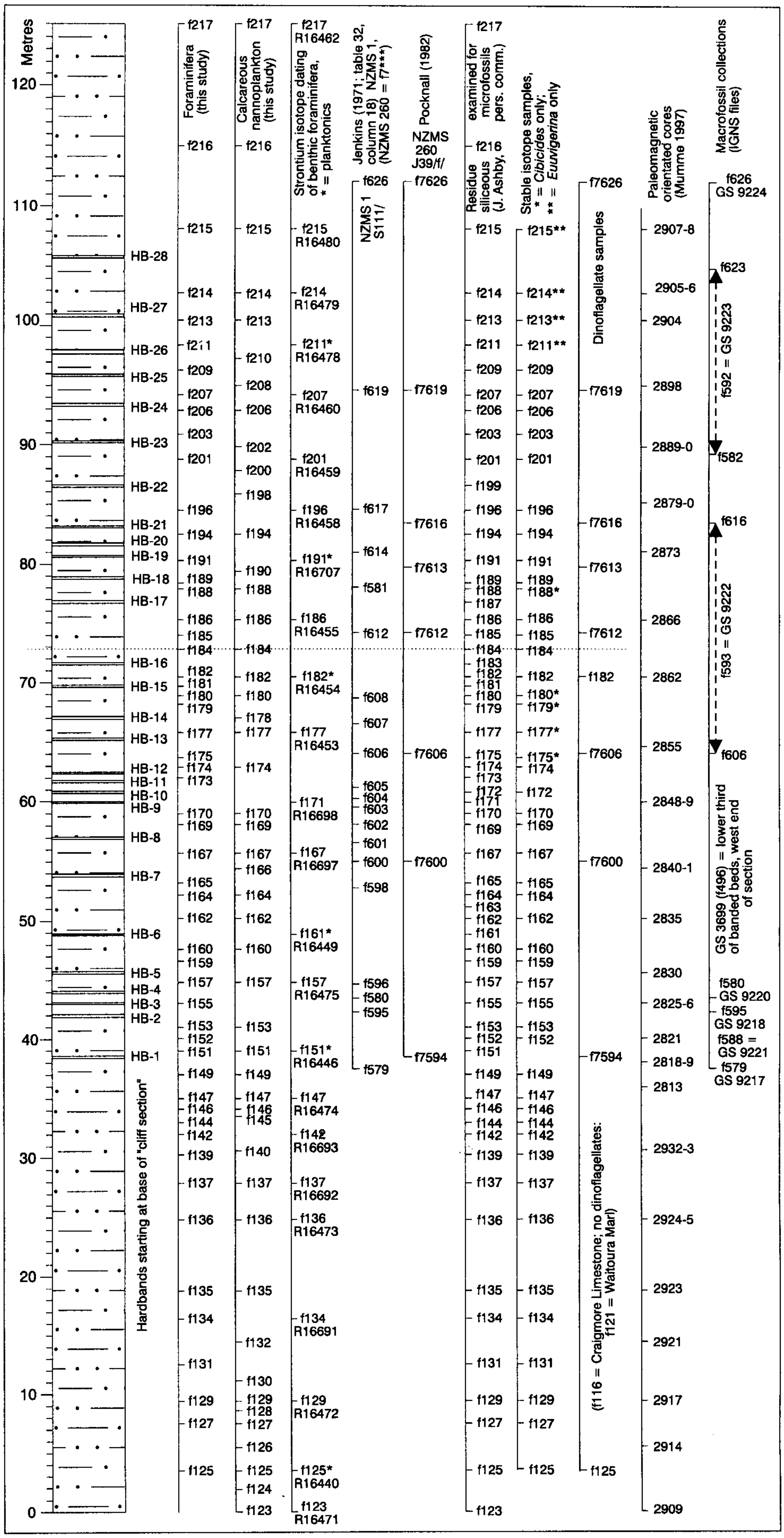
In this study we integrate data relevant to these problems. The boundary stratotype section is studied to identify its depositional setting, completeness, and suitability as a chronostratigraphic and biostratigraphic reference. The position of the boundary within the section and its environmental history are examined. Dating is attempted using strontium isotopes, oxygen isotopes, and magnetostratigraphy. Major fossil groups present are reviewed with special attention to nannofossils and planktonic foraminifera. The performance of the present boundary events is evaluated. We describe changes in planktonic taxa close to the present boundary that might serve as proximity events and extend its utility. The boundary is correlated with other regional and global biostratigraphic classifications.

Waitakian and Otaian Stages

Allan (1933) showed that Park's (1918) original usage of Waitakian was ambiguous, biostratigraphically. He resolved the problem by proposing that Waitakian should refer to "...the period of time represented by the deposition of the Waitaki Limestone and the Otiake beds of Waitaki Valley...". He cited the Trig Z section (Fig. 1) as the most complete reference, but noted that Waitakian, as redefined, might not be contiguous with the overlying Hutchinsonian Stage. Gage (1957) revised the lithostratigraphy of the Waitaki valley and proposed Otekaike Limestone for Waitaki Limestone. Four members were recognised, the uppermost (Waitoura Marl) having its type section at Trig Z.

The origin of the Otaian Stage dates from Allan's (1933) surmise that there might be a gap in the biostratigraphic classification between Waitakian and Hutchinsonian Stages. Finlay (1939) cited supporting brachiopod evidence, and Finlay & Marwick (1940) gave criteria that distinguished lower Hutchinsonian from Hutchinsonian *s.s.* Finlay & Marwick (1947) proposed the Otaian Stage for the informal lower Hutchinsonian of Finlay & Marwick (1940) and cited Bluecliffs as type locality (Otaio River, South Canterbury, Fig. 1). They stated that the "...lower limit is marked by the lowest occurrence of (primarily) *Ehrenbergina* and (secondarily) *Spiroloculina novo-zealandica* (Cush. and Todd)" and noted that the stage extends from "...somewhat below the middle of the banded unit at Blue Cliffs...up to the 'Brown Sandstone' which is Hutchinsonian." Importantly, Finlay & Marwick (1947) stated that "...the lower part of the banded beds is Waitakian." Gair (1959) proposed Bluecliffs Silt and Southburn Sand for the lithostratigraphic units referred to by Finlay & Marwick

Fig. 2 Location of biostratigraphic, magnetostratigraphic, and isotopic samples from a 125 m interval across the Waitakian-Otaian boundary, Bluecliffs.



(1947). Hutchinsonian Stage was incorporated in Altonian Stage by Scott (1972).

The stratotypes for Waitakian and Otaian Stages are components of the same sedimentary sequence (Carter 1988; Field et al. 1989) but are 60 km apart in Canterbury Basin (Fig. 1). However, there is no ambiguity as to the location of the boundary stratotype. Waitoura Marl, the highest Waitakian unit at Trig Z, lacks Otaian fossils and correlates with strata near Bluecliffs that are significantly below the Waitakian-Otaian boundary. At Bluecliffs, the boundary, following Finlay & Marwick (1947), is well defined and the surrounding section is well exposed. We recognise the boundary stratotype for the Waitakian and Otaian Stages as the horizon at 73 m (Fig. 2) defined by the primary event for the base of the Otaian Stage, namely, the first appearance datum (FAD) of the benthic foraminifer *Ehrenbergina marwicki*.

The Waitakian and Otaian Stages are regarded as biostratigraphic units, defined by homotaxial biostratigraphic events whose chronostratigraphic value is yet to be established. Therefore, we use "lower", "middle", and "upper" for their informal subdivisions.

MATERIAL AND METHODS

Collections

Samples were taken for biostratigraphic, oxygen, carbon, and strontium isotope analysis, and for a pilot study of paleomagnetism (Fig. 2). We focused on the section spanning the Waitakian-Otaian boundary ("cliff section", Fig. 1), the preceding "stream section", and isolated exposures down to Otekaike Limestone (Fig. 3). A further 220 m of Bluecliff Silt overlies the cliff section, although much of it is poorly exposed. Previous collectors (e.g., Scott 1965; Shelley 1974) commenced at the base of the cliff section (Fig. 1; NZMS 260 grid ref. J39/5108–3351). We extended our sampling further upstream and into a tributary stream ("stream section") and included a further 35 m of strata below the cliff section. Sample density varied between 1 and 2 m; 35 magnetostratigraphic samples and 94 biostratigraphic samples (J39/f123–217) were taken. Material from the foraminiferal samples was used for isotope studies.

Collections were also made for biostratigraphic control through Craigmore Limestone (J39/f114–120) and within Waitoura Marl between Craigmore Limestone and the base of the Bluecliffs section (J39/f121–122).

Fossil groups examined and previous studies

Foraminifera

The section is highly fossiliferous and especially rich in calcareous groups. Planktonic taxa (Table 1) are consistently more abundant than benthic taxa (Table 2), typically ranging between c. 45 and 85% of total foraminiferal fauna. Benthic foraminifera become more abundant in the upper part of the section. Previous foraminiferal studies by Finlay & Marwick (1947), Scott (1958, 1965, 1973), Jenkins (1971), and Shelley (1974) underpin our present understanding of the Waitakian-Otaian boundary and its position at Bluecliffs.

Nannofossils

Coccoliths, and associated calcareous nannofossils, constitute a small and variable part of the samples. Their

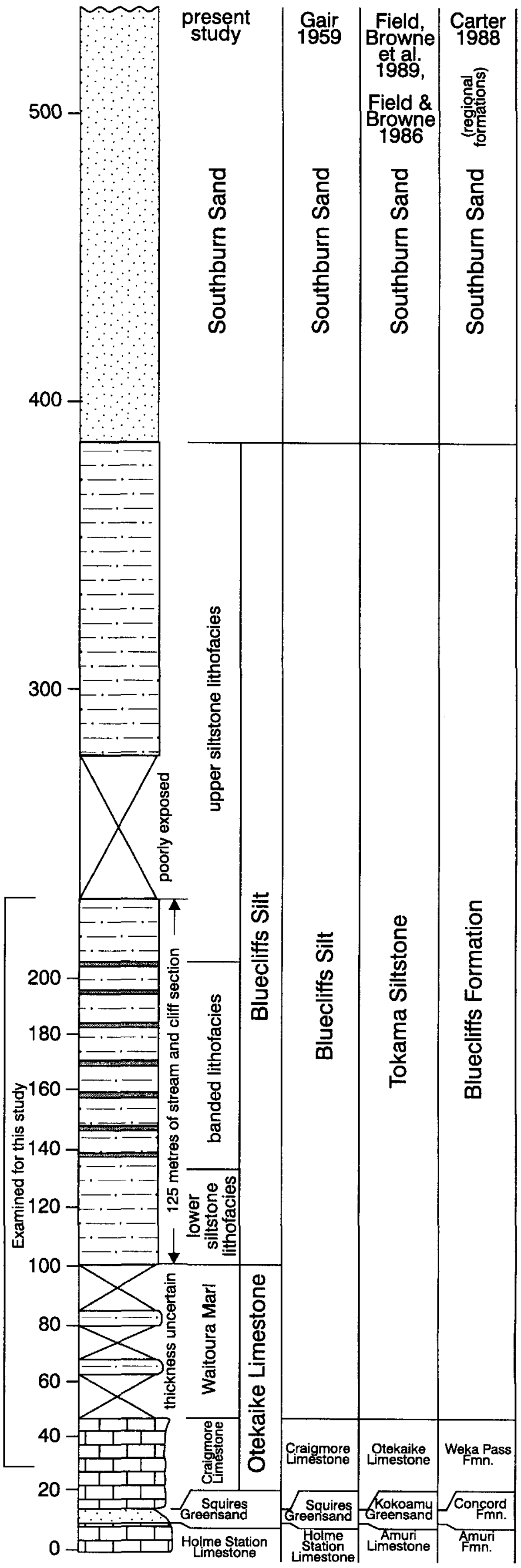


Fig. 3 Lithostratigraphic nomenclature for section at Bluecliffs and for underlying units.

Table 1 Planktonic foraminiferal census chart, Bluecliffs Silt. Stratigraphic position is measured relative to the base of the "stream section". Species abundances are given as percentages of total planktonic specimens. Also enumerated are sample weights, number of benthic specimens, planktonic species diversity, and the percentage of planktonic specimens. Observed occurrences of *Globigerina brazieri* and *Globigerina euapertura*, not recorded in the census, are plotted as x.

Fossil record number J39/	f121	f122	f125	f127	f129	f131	f134	f135	f136	f137	f139	f142	f144	f146	f147	f149	f151	f152	f153
New Zealand stage	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw
Stratigraphic position (m)	–50	–25	3.5	7.5	9.4	12.5	16.4	18.8	24.9	28	30.3	32	33	34.1	35	37	39	40	41
%*Globigerina brazieri*	1.7	1.6	0.4	2.3	x		1.2		0.4	0.9	2.0	2.0	x	1.1	1.0	x			
%*Globigerina bulloides*	3.3	5.7	0.1	4.3	0.5		0.3	0.8	1.1				0.5	1.1	2.7		0.5	0.9	
%*Globigerina falconensis*			0.3	1.3	2.5		0.3												
%*Globigerina euapertura*	1.4	0.8	0.6	2.3	4.9	1.1	1.2	3.1	0.7	1.3	0.7	2.0	0.5	0.5	0.7		2.0		1.2
%*Globigerina ciperoensis*	14.2	21.3	18.0	18.0	9.4	23.7	13.6	13.0	26.2	21.8	14.7	19.4	21.2	10.9	12.7	14.6	13.8	14.2	12.0
%*Globigerina connecta*	3.1	9.0	4.4	3.0	4.4	6.1	0.9	4.6	3.9	11.5	12.7	9.5	17.4	7.7	3.8	5.3	7.9	3.4	7.2
%*Globigerina praebulloides*	7.0	6.6	7.0	8.5	6.4	4.2	3.2	4.6	2.8	2.6	1.3	1.5	2.2	3.8	10.3	6.6	7.9	4.3	1.6
%*Globigerina* sp.A	9.5	5.7	10.7	19.0	21.7	13.7	16.8	17.6	10.6	6.0	8.7	11.9	3.3	13.7	5.8	7.3	9.4	13.7	7.2
%*Globigerina* sp.B	7.0	6.6	21.2	6.9	5.9	11.1	7.8	8.4	8.9	11.5	18.0	6.5	13.0	17.5	28.8	20.5	23.6	15.0	23.5
%*Globigerina* sp.misc			0.3		1.0								0.5					0.4	0.4
%*Globigerina woodi*	18.1	13.9	6.6	10.5	12.3	11.5	24.0	20.6	19.1	15.8	8.7	16.9	10.9	13.7	9.2	11.3	8.4	22.3	17.9
%*Globigerina juvenilis*	0.6	0.8	0.1	0.7	3.0	1.9	0.3	3.1	1.1	0.4	1.3	0.5		0.5	0.3		1.0	0.9	2.0
%*Globoquadrina dehiscens*	1.4		1.6	2.0	1.5	1.1	2.0	1.5	1.8	1.7	2.0	1.5	2.2	1.6	1.7	2.6	2.0	1.3	2.4
%*Globorotaloides* sp.	1.4	0.8	0.1	0.7	0.5						2.0	1.0		1.1	0.3	2.6	0.5		2.0
%*Paragloborotalia* sp.	11.7	16.4	8.3	6.9	8.9	4.2	13.0	7.6	16.7	11.5	11.3	17.9	13.6	18.6	8.9	14.6	7.9	13.3	8.0
%Planktic indeterminable	19.8	10.7	20.2	13.8	17.2	21.4	15.6	15.3	6.7	15.0	16.7	9.5	14.7	8.2	13.7	14.6	15.3	10.3	14.7
% Total planktonics	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Total planktonic count	359	122	699	305	203	262	346	131	282	234	150	201	184	183	292	151	203	233	251
Total planktonic taxa	11	11	14	15	13	12	12	12	12	12	14	11	10	12	11	10	10	11	13
Benthics (in planktic census)	171	83	108	62	72	59	139	99	186	170	86	82	100	146	80	74	52	69	130
Total planktonic abundance %	67.7	59.5	86.6	83.1	73.8	81.6	71.3	56.9	60.2	57.9	63.5	71	64.8	55.6	78.5	67.1	79.6	57.9	68.8
Original weight (grams)	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Residue weight (grams)	19.9	27.8	120	17	13.7	63.6	15	21.9	26.9	25	16.9	45.8	34.4	11.9	17.4	20.7	74.7	28.4	20.8
Weight of picked split (g)	0.04	0.03	0.06	0.02	0.01	0.03	0.03	0.02	0.05	0.05	0.02	0.04	0.03	0.02	0.02	0.02	0.04	0.03	0.04

Table 1 (*continued*)

Fossil record number J39/	f155	f157	f159	f160	f162	f164	f165	f167	f169	f170	f173	f174	f175	f177	f179	f180	f181	f182
New Zealand stage	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw
Stratigraphic position (m)	43	44.8	46.7	47.7	50.2	52.3	53.2	55.7	58.1	59	62	62.9	63.7	65.9	68.2	68.9	69.7	70.6
%*Globigerina brazieri*	0.6	1.8	1.9															
%*Globigerina bulloides*			0.5	0.5	1.0	1.1				0.5	4.0		0.7		0.8	3.4		0.4
%*Globigerina falconensis*							1.4		0.6			0.6				2.1		2.6
%*Globigerina euapertura*	x	x	0.5	x	x				x									
%*Globigerina ciperoensis*	13.7	4.5	7.7	18.3	10.5	9.7	17.7	6.6	10.3	18.1	16.4	14.9	10.5	14.0	21.3	17.0	10.8	14.6
%*Globigerina connecta*	13.7	16.2	13.5	10.4	7.9	8.0	6.8	10.8	5.1	8.0	7.0	3.2	6.6	7.0	5.0	1.8	5.4	6.9
%*Globigerina praebulloides*	1.2	5.4	1.4	2.0	3.1	6.3	2.3	4.2	4.5	0.5		6.5	5.3	4.2	0.8	3.2	7.2	9.9
%*Globigerina* sp.A	3.7	4.5	4.8	18.3	23.6	23.9	10.5	8.4	9.0	19.7	7.5	22.1	12.5	10.5	19.2	9.2	9.0	10.7
%*Globigerina* sp.B	9.9	9.0	11.1	5.9	12.6	12.5	8.2	9.6	13.5	11.2	29.9	19.5	22.4	25.2	16.7	33.5	34.7	28.8
%*Globigerina* sp.misc				0.5			0.9		0.6	0.5	0.5	0.6		0.7	0.4	0.7		
%*Globigerina woodi*	12.4	18.9	31.4	24.3	11.0	14.2	21.4	25.1	21.2	9.0	7.5	11.0	10.5	18.9	18.4	11.2	7.8	7.7
%*Globigerina juvenilis*	1.2	0.9	1.0	1.5	0.5	2.3	4.1	1.2	3.8		1.5	1.3	2.6	0.7	0.8	2.8	3.0	1.3
%*Globoquadrina dehiscens*	2.5	2.7	3.4	1.0	1.0		2.3	4.8	1.9	0.5	1.5	0.6	0.7	1.4		0.7	0.6	
%*Globorotaloides* sp.	2.5	0.9	3.4		0.5		1.8	1.8	1.9	0.5	0.5			1.4	0.8	0.4		
%*Paragloborotalia* sp.	23.6	24.3	10.6	9.9	21.5	8.5	15.0	20.4	16.7	12.8	1.0	3.9	5.9	7.0	2.5	2.3	2.4	2.6
%Planktic indeterminable	14.9	10.8	8.7	7.4	6.8	13.6	7.7	7.2	10.9	18.6	22.9	15.6	22.4	9.1	13.0	11.9	19.2	14.6
% Total planktonics	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Total planktonic count	161	111	207	202	191	176	220	167	156	188	201	154	152	143	239	565	167	233
Total planktonic taxa	10	8	10	10	10	9	11	11	12	11	12	11	10	12	11	12	10	10
Benthics (in planktic census)	192	214	241	129	58	100	74	127	143	70	143	67	167	80	119	158	27	34
Total planktonic abundance %	45.6	51.8	46.2	61	76.7	63.7	74.8	56.8	52.2	72.8	58.4	69.6	47.6	64.1	66.7	78.1	86	87.3
Original weight (grams)	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Residue weight (grams)	15.4	9.6	5.81	10.8	20.5	48.3	44.5	6.39	21.3	81.2	59.2	62.6	22	31.1	35.2	61	145	138
Weight of picked split (g)	0.06	0.04	0.02	0.02	0.02	0.05	0.04	0.03	0.04	0.04	0.06	0.03	0.04	0.03	0.07	0.12	0.04	0.03

(*continued over page*)

Table 1 (*continued*)

Fossil record number J39/ New Zealand stage Stratigraphic position (m)	f184 Po 72.8	f185 Po 74	f186 Po 75.3	f188 Po 77.9	f189 Po 78.4	f191 Po 80.3	f194 Po 82.5	f196 Po 84.5	f201 Po 88.8	f203 Po 90.9	f206 Po 92.9	f207 Po 94.2	f209 Po 96.3	f211 Po 98.4	f213 Po 100	f214 Po 103	f215 Po 108	f216 Po 115	f217 Po 125
%*Globigerina brazieri*																			
%*Globigerina bulloides*	0.7	0.8	0.7			0.4					0.6			0.7			1.2		
%*Globigerina falconensis*	2.5	1.6	1.8	1.3	0.7	3.1	1.5		1.1	1.0		0.6			1.2		1.2	1.2	3.1
%*Globigerina euapertura*																			
%*Globigerina ciperoemsis*	14.4	17.2	13.9	11.9	16.1	10.9	8.0	1.9	24.7	12.3	17.1	24.9	27.7	18.2	7.5	8.2	19.7	5.8	32.7
%*Globigerina connecta*	4.2	6.3	9.1	8.6	8.7	3.1	5.1	4.5	11.6	8.4	17.1	6.5	8.2	9.5	9.8	10.3	5.2	4.7	4.1
%*Globigerina praebulloides*	4.9	10.2	5.5	2.6	3.4	6.2	4.4	3.8	2.1	5.9	5.7	3.6	4.4	3.6	8.1	7.6	8.7	4.7	3.1
%*Globigerina* sp.A	3.9	6.3	5.5	17.9	7.4	10.9	8.8	9.6	6.3	18.7	8.2	4.7	10.1	8.8	12.1	8.7	8.7	12.8	9.2
%*Globigerina* sp.B	34.5	17.2	15.3	13.2	23.5	31.4	24.1	36.9	20.5	12.3	12.0	17.8	16.4	20.4	21.4	19.0	22.0	35.5	23.5
%*Globigerina* sp.misc	0.4		0.4		0.7	0.4		0.6	0.5	0.5	0.6		0.6		1.7			0.6	1.0
%*Globigerina woodi*	15.1	14.1	21.5	16.6	12.1	15.5	29.2	21.7	21.6	27.6	20.9	16.0	19.5	22.6	17.9	25.5	12.1	18.0	11.2
%*Globigerina juvenilis*	4.2	3.9	4.0	2.6	2.7	0.8	0.7			0.5			1.9				0.6		2.0
%*Globoquadrina dehiscens*	2.1	1.6	0.4			0.4	1.5	1.9	2.6	2.0	1.9	1.2	1.3	0.7				0.6	
%*Globorotaloides* sp	1.1	0.8	0.7		0.7	1.6				0.5	0.6	1.8		1.5	0.6	2.2	2.3		2.0
%*Paragloborotalia* sp	1.8	3.9	8.0	14.6	11.4	1.6	7.3	4.5		2.0	2.5	4.7	0.6	3.6	5.2	7.1	4.0	5.8	3.1
%Planktic indeterminable.	10.2	16.4	13.1	10.6	12.8	14.0	9.5	14.6	8.9	8.4	12.7	18.3	9.4	10.2	14.5	11.4	14.5	10.5	5.1
% Total planktonics	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Total planktonic count	284	128	274	151	149	258	137	157	190	203	158	169	159	137	173	184	173	172	98
Total planktonic taxa	11	10	10	9	10	11	9	10	8	12	10	9	11	9	9	9	10	10	10
Benthics (in planktic census)	201	90	180	57	62	54	108	63	107	121	85	57	37	26	79	124	85	210	356
Total planktonic abundance %	58.5	58.7	60.3	72.6	70.6	82.7	55.9	71.4	63.9	62.9	65	74.8	81.1	84	68.6	59.7	67	45	21.6
Original weight (grams)	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Residue weight (grams)	32	55.2	60.2	76.2	95.1	277	79.3	119	84.5	54.2	75.2	137	218	204	145	39.5	90	127	70.6
Weight of picked split (g)	0.06	0.05	0.12	0.04	0.05	0.07	0.08	0.06	0.04	0.05	0.04	0.03	0.05	0.03	0.04	0.04	0.02	0.12	0.14

abundance (Table 3) is expressed in terms of their estimated relative proportion of the sediment matrix strewn over a slide. Nannofossils are a minor constituent of Craigmore Limestone, always being <1% of the strew. They form a more significant part of the Waitoura Marl and Bluecliffs Silt, averaging 10% of the strew but ranging from c. 1% to almost 50% and tending to lower values in the upper part of the section. There are no published studies on the nannofossils of this section, but Kadar (1983, pp. 108–9) listed the content of a collection from about the same horizon as our highest sample.

Pollens, spores, dinoflagellates

Pollen and spore assemblages from the Bluecliffs section have been studied by Pocknall (1982, 1988). Palynofloras from the Bluecliffs Silt are dominated by pollen of the *Nothofagus brassii* group and are indicative of a forest vegetation in which beech of the *Nothofagus brassii* group was dominant growing under a warm-temperate climate with moderately high rainfall. Palynomorph assemblages closely resemble those of similar age from Southland and Otago.

Dinoflagellate cysts were reported from three collections from the Bluecliffs Silt by Wilson (1996). They are reasonably diverse and are typical of the Oligocene–Early Miocene. Dinoflagellates were absent from a sample from the Craigmore Limestone.

Siliceous microfossils

Sixty-four of the foraminiferal residues were examined for their siliceous microfossil content. Jeff Ashby (pers. comm. 1995) found no radiolarians, sponge sterrasters, or diatoms but did observe the intermittent presence of rare, highly etched sponge spicules.

Bryozoans

Jeff Ashby (pers. comm 1995) noted that bryozoan fragments are consistently present in variable numbers through the whole section. Abundances vary from rare to fairly common, with no obvious stratigraphic pattern.

Ostracods

These benthic crustaceans are a common component of the microfossil assemblage but have not been examined in detail.

Molluscs

The section has long been famous for its diverse, beautifully preserved molluscs, and a large number of collections have been made at Bluecliffs over the past 130 years. Some of the fauna have been reported by Gudex (1914, 1918), Laws (1934), Maxwell (1969), Marwick (1971), and Beu & Maxwell (1990). Examination of foraminiferal residues shows that shell debris and micro-molluscs occur throughout the section but are more abundant in the upper part of the section.

Methods

Foraminiferal preparation

For each sample an amount in excess of 1.2 kg was air-dried at 35°C. When the dried weight had stabilised, 1 kg was placed in water and left for 1–2 days. This was washed over a 75 μm screen and the residue again air-dried at 35°C and then weighed. This treatment provided material suitable for stable isotope studies. Most of the material was in good condition. Only at the base of the section and from within or near the hard bands in the cliff section were there problems with preservation of the foraminifera. Where these problems were severe, extra samples were prepared.

For the biostratigraphic study, a small statistical sample was prepared from each bulk sample using a Carpco microsplitter, the sample being split repeatedly until a fauna of 100–200 specimens remained on a 150 μm screen. The splits were manipulated so that both planktonic and benthic splits each contained 100–200 specimens, although for some benthic splits, the final counts had fewer than 100 specimens. The number of benthic specimens in the final >150 μm split, and its weight, are given in Table 2. Planktonic foraminifera are recorded as percentages in Table 1. All other fossil material in the sample encountered during the census was retained. This material consisted mainly of ostracods, which were counted in the census, as well as broken molluscs, which were not examined further.

One-half of all residues has been kept intact for further studies. The remainder of the other splits, from which the statistical samples were counted, were utilised for the isotope studies. All calcareous benthic material in each sample above 500 μm was taken for strontium isotope analysis, including some selected planktonic specimens. For oxygen and carbon isotope studies, undertaken at University of Waikato, we used the benthic foraminifera *Euuvigerina* spp. (Fig. 4J, K) and *Cibicides novozelandicus* (Fig. 4M). Acquisition of this material provided a more extensive conspectus of assemblages than was gained during the census.

Nannofossil preparation

The suite of samples examined included 7 collected from Craigmore Limestone and 50 from Waitoura Marl and Bluecliff Silt (Fig. 2). The latter are evenly spaced stratigraphically but have a bias against the hard bands and towards the lower and upper limits of the section. Despite this, they are considered to be representative of the range of environmental and stratigraphic changes occurring in this section.

Standard methods were used to prepare and examine samples selected for calcareous nannofossil analysis. A thin representative slurry of the sample matrix was spread over a 22 × 32 mm coverglass, dried, and attached to a glass slide using the permanent mounting medium Petropoxy 154. Examination was undertaken using a polarising microscope equipped with a lambda plate to traverse the coverglass at magnifications of 1500× (detail) and then, as appropriate, at either 900× or 750× (survey). As a minimum, each slide examined was traversed twice at 1500×. The nature of each assemblage was documented (Table 3) in terms of its abundance (estimated relative cover of the smear), diversity (species number, both observed and adjusted), preservation (overall plus breakage, etching and plating), inferred environmental conditions (living and depositional), and biostratigraphic position (datums and zones). Also documented was the estimated abundance of each species or operational taxonomic unit and, as appropriate, other relevant information such as the nature, preservation, size, location, and inferred origin of individual specimens.

Stable isotopes

Analyses were carried out on the benthic foraminifera *Cibicides novozealandicus* and *Euuvigerina* spp. Specimens were cleaned in an ultrasonic bath, vacuum roasted, and reacted with 100% orthophosphoric acid at 70°C for 20 min under vacuum. The evolved CO_2 was separated, purified, and isotopically analysed in a VG Micromass 602E mass spectrometer at University of Waikato. The reference gas was calibrated daily against the international standard NBS-19. The ^{13}C and ^{18}O isotope values are presented (Fig. 5) in conventional per mille deviations from the PDB standard, and the analytical precision is better than ±0.05‰.

Paleomagnetism

Standard paleomagnetic samples (25 mm diameter × 22 mm height) were collected from 5 m intervals throughout the sequence using a portable Tas drill (Mumme 1997). After collection, samples were shielded until they were measured on a two-axis ScT cryogenic magnetometer at Victoria University of Wellington (VUW). The NRM was routinely measured on all samples and found to be weak $<2 \times 10^{-4}$ A/m. Six sample pairs were selected to evaluate behaviour and applicability of thermal and alternating field (AF) demagnetisation methods. AF demagnetisation was conducted in a Molspin AF demagnetiser, and samples were measured at peak fields of 5 mT to a maximum of 40 mT. Thermal demagnetisation was conducted at 50° increments from 100°C to 400°C in the VUW purpose-built zero-field oven. All other samples were subjected to thermal demagnetisation only. After each thermal demagnetisation step, the magnetic susceptibility was measured to monitor for thermal alteration. In all measurements, susceptibility and remanence increased markedly by 400°C of heating and, in several, increases occurred by the 350°C step of heating. Measurements after these heating steps were not used in further analysis.

LITHOSTRATIGRAPHY

The lithostratigraphic classification adopted (Fig. 3) is based on Gair (1959) and Field & Browne (1986). The following units are recognised in upward sequence.

Craigmore Limestone Member, Otekaike Limestone

Craigmore Limestone is exposed beside Gordons Valley Road (Fig. 1), where it consists of 16 m of well-bedded, pale cream-grey, slightly glauconitic limestone. The lower 4 m is concretionary and nodular and is overlain by 12 m of a softer, well-bedded unit with a hard band near the top. Although the position of this sequence relative to the >80 ft (>25 m) of Craigmore Limestone recorded by Gair (1959) is unknown, the bedding suggests that it correlates with the middle to upper parts. A basal greensand was not observed.

Waitoura Marl Member, Otekaike Limestone

Pale brown-grey, soft, marly mudstone is poorly exposed in weathered hillside exposures (old cliffs) to the west of the Bluecliffs section (Fig. 1, J39/f121, 122). This unit lies between Craigmore Limestone and Bluecliffs Silt. Its identification as Waitoura Marl is tentative and cores are needed to establish its content and relationships.

Table 2 Benthic foraminiferal census chart, Bluecliffs Silt. Stratigraphic position is measured relative to the base of the "stream section". Species abundances are given as raw numbers found in the split used for the census. Also enumerated for each sample are the diversity of benthic foraminiferal species, number of ostracods, weights of the census split, and the >75 μm residue from which it was obtained. Some taxa are aggregated in the table and the listed species diversity may exceed the number of taxa listed. Observed occurrences of *Ehrenbergina marwicki* and *Spiroloculina novozealandica*, not recorded in the census, are plotted as x.

Benthic foraminiferal distribution chart; Bluecliffs																																																								
Fossil record number J39/	f121	f122	f125	f127	f129	f131	f134	f135	f136	f137	f139	f142	f144	f146	f147	f149	f151	f152	f153	f155	f157	f159	f160	f162	f164	f165	f167	f169	f170	f173	f174	f175	f177	f179	f180	f181	f182	f184	f185	f186	f188	f189	f191	f194	f196	f201	f203	f206	f207	f209	f211	f213	f214	f215	f216	f217
Stratigraphic position (m)	-50	-25	3.5	7.5	9.4	13	16	19	25	28	30	32	33	34	35	37	39	40	41	43	45	47	48	50	52	53	56	58	59	62	63	64	66	68	69	70	71	73	74	75	78	78	80	83	85	89	91	93	94	96	98	100	103	108	115	125
New Zealand Stage	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Lw	Po	Po	Po	Po	Po	Po	Po	Po	Po	Po	Po	Po	Po	Po	Po	Po	Po	Po	Po	Po
Alabamina tenuimarginata		1						1	1	1		1	3	1		2																1						1			1						1				1					1	
Amphicoryne hirsuta	1		2	3	3			1				1		1	3							4	2		4		4		1			1			7	3	7	10	4	4	1	1	1				1			1			2	9	1	
Amphicoryne scalaris							2	3		1	2																	2																			1													
Amphistegina sp.																																														1											
Anomalina aotea																												1																											
Anomalinoides fasciatus	9			3	2									5							1	1					1				2			1		1	3	1	8				1	4		1					1	1		1		
Anomalinoides macroglabra	16	2	3				1							6	9	10		1	3	6		1	3	2	4	4	3	5	3	5	4	5		4	8	1	5	2	4	5		2	2	2	4	3	5	6	4	5	1	4	2			6
Anomalinoides orbiculus		4		3	2	1	4	1			5	3	1	4	7	1		5		3		12																										2	7						16	8
Anomalinoides parvumbilia		8	3	6	4	4	4	6	12	6	6	6	7	6		5	1	10		4	7	2	1	6	7	11	5	3	8	1	5	4	5	5	4	6	2	3	11	10	11	7	9	9	13	5	10	15	13	19	7	13	7	22	19	8
Anomalinoides spherica	4	13		10	8	7	10	9	8	5	6	6	4	3	4	4	1	5	8	21	2	4	4	4	11	3	4	9	2	4	4	2	3	6	4	4	6	6	8	9	7	7	3		4	4	5	2	4	10		1	1		2	
Arenodosaria antipoda																									1								1		1			1	1	6	4		1	3	2					1		1				
Astrononion parki									2	1							1			1					4				1	1					1	1	1	1				3				1	2	2		4	2	2	1		7	3
Astrononion pusillum				2	1		7		3			2		1		1																																									1				3
Astrononion sp.A	2	2	1	3	1	1	2		3	5	4	2	3	2	4		3	2	2	1		1	2		6	3			4	1	2			1	5	5		1	2	2				2	2		1			1	1		2	1	1	
Astrononion spp.	2																																																						
Baggina sp.																																						1										1									1
Bolivina lapsus					1																1				1								1					1						1											
Bolivina mahoenuica													1																																										
Bolivina reticulata	6	2	12	5	7	3	6	3	3	2	6		1	2	7	5	4		4	3		3	1	1	3	3	1		2		1			3	9	2		2	1	1	4	4	6	2	3	1	1				2				
Bolivina spp.																	1							1				1		2							1				1	1												1	1	2
Bulimina pupula				1	1	1									1		1	1						1		1				2		1				2	1	1				1			1											1	2
Buliminella spicata																																	1					2	7	2	1	2				1	2		1		1				
Cassidulina carinata	6	11		1	1	13	1	1	8	17	2	9	2	3	3	1	9	3	1	3		2	1	1	16	6	1		2	6	3	4	3	5	4	8	4	16	10	1	4	5	3	1		4	5		2		2	3	12	10	1	
Cassidulina cuneata															2						1			1						2	1	2		1			1																		1	
Cassidulina laevigata		5		3	4	1		1	6	2	1	2		1	3	1		1	1	1	4	3	4	1	4		2		2	2	1		4			1		5	3		1	1	1		1					1			2		5	2
Ceratobulimina sp.																																			1																				
Cibicides cf. *ihungia*	1	20		3	2																																																			
Cibicides mediocris		2					5										1		3	2	3	2	3				1		2	3														1												2	
Cibicides molestus	12	13	13	7	5	9	11	7	19	19	29	22	9	20	5	13	4	12	13	19	17	24	21	6	11	8	23	25	15	8	8	16	25	13	10	8	12	24	18	19	12	16	12	19	8	17	9	6	10	14	9	8	7	15	35	18
Cibicides novozelandicus		2	1		3	1	2			2	1		2	5		4	2		1			1	3	2		1	1	1	2		2	1			1		1		1			1				2								
Cibicides perforatus					2	1	1			3		1		2	2				3	2	1								3			1									2					1	1		1				1			
Cibicides spp.	5					3	2	2			1	2	2			2	2		1	6	4	4			1	1				3	1	2			2			1		1			3	5		1		3				1			5	
Cibicides cf. *pseudoungerianus*	21		8	3	8	10	20	7	8	12	23	15	9	19	17	9	7	21	29	4	4	19	6	12	16	14	17	12	8	9	10	15	21	12	8	3	7	10	16	16	6	13	3	22	18	10	7	13	11	21	7	22	3	12	18	31
Cibicides vortex				3	1	1		2					1																																										
Cribrorotalia dorreeni									1			1	1		1		1	1						3				1															1				1								
Dentalina sp.	1		1	1	1				2	1		2			2						3	1	2	3																														
Discorbinella complanata																									2																														
Discorbinella scopos	1		1	1									1			1	1	1				1						1	1	9	8	14	12	15	3	7	15						2	1	2	2	2		1			9	1	1	1	3
Discorbinella sp.																																	1			1	1		2			1	1				2									
Dyocibicides primitiva																						1		1														2		4																			
Ehrenbergina marwicki																																						x	x	x	1	2	x	x	x	1	6	1	x	x	x	x	x	6		
Elphidium charlottense																																													1										
Eponides broeckhianus											1										1										1																										
Euuvigerina mioschwageri			2				1	1	1			3							1		1		1				1																														
Euuvigerina miozea													1			2						1		1	1	1	1		2						1										2	1	1	3		1	5	14	1			
Evolvocassidulina sp.	2																																																						
Fissurina spp.	3	1		2	3	4	2	4	4	2	3	3	1	1	1	3	7	1	1	4	5	2	2	1	6		3	2	3	1	7	3		4	4	1		4	1	7	2	4		1	1	1	1									1
Florilus stachei	1			1					1					1															1					1	1	1														1				2		1
Globocassidulina subglobosa	6		5	9	15		1	3	2	1	2	1	1	21	10	3	4	1	1	2	2	24	14	2	1		6	1										1																	
Guttulina spp.				1										1							1																7	2										2				1			1	
Gyroidina prominula	3		12	1	4	9	1		1	2	5	10	7	7	4		7	6	1	4			1	3	4	2			4	1		2	1	7	9	3	3	1	3	10	5	11	9	1	6	5	6	14	9	5	5	19	9	20	2	
Gyroidinoides zelandica	2			3	3	3	1		1				2		3	15		2				1	11	10	7	5	5	3	14	6	3	16											1			4									2	
Haeuslerella decepta																					1									1																										
Haeuslerella hectori	13	10	7	5	8	10	9	10	20	22	18	14	7		8	16	9	8	8	21	11	23	10	17	14	17	6	7	6	12	11	8	12	7	17	3	17	27	16	18	10	4	6	5	6	9	10	1	3	5	11	15	9	14	7	16
Hoeglundina elegans			6																1			1																																		
Karreria maoria																																																							
Lagena spp.	5	7	1	5	1	3	5	3	1		6	3	2	3	3	3	3	3	6	3	1	2	1	3	6	3	21			4	4	1	1		6	1	2	4	2	2	1	6	2		1	2	1	3			1	2		2	1	
Laticarinina altocamerata	1	3	1		3	2	3			4		2	4			2		2	1	1		1			2	1		2	2			3			3	1	1	1	2	2		1						1			1			1	1	

(*continued*)

Table 2 (*continued*)

Laticarinina pauperata	2	1		3								1	1	1				1			1	7	1							1																										
Lenticulina cultratus	9		2	4	7	3	6	7	12	7	8	5	6	5	9	6	4			10	2	10	5	4	1	6	4	11	6	4	3	1	8	3	4	3	3	2	7	3		6	2	2	2	1	2	6	4	1		1	7	1		2
Lenticulina dicampylus		8			1	1	4		2	1	5	4	2		1		3	5	9	2		8	1		7		7	7	2			2	1	1							2			1	2	1									2	
Lenticulina gibba		1		1			1						2		1			2		1		2					1	1	2						1				1		1				2	1					1					
Lenticulina loculosus																													1			2		1													1								3	
Lenticulina mamilligera																																																		1						
Lenticulina spp.	4		1	2	2	1	2	2		2	4	2	1	5	4	1	1	10	1	5	10	6	5		2	2	4		1		2	2	3	1	1		3	2	1		7		5		3	1	5	6	2	10	9	2	3		3	4
Marginulina subbullata																						2						1																												
Martinottiella communis	6	2	6	5	1	2	2	1	7	7	1	2	5		9	4	1		1	5	1	3	1	6	1	2	1	5	2	3	2	3	1	1	2	1	2	11	3		2		3	1	8	7	1	9	3	5	4	6	15	11	11	7
Melonis cassidulinoides	1	4	1			1						2		1	1					1	2	1				1	2				1	1			1	2	1			1				1		1					1					
Melonis maorica		1														1							6	1	1			1		1	1									2		1	4	3	2	4	2		6	2						
Melonis spp.	1										1				1	1	1						2	2		1			2	1										3	4	3	6	8	8	3			1	15	2	2				
Nodosaria longiscata	1	1							1			1		2	1	1		4				5			1	1			1	2	1					1				1												1			1	
Nodosaria pyrula				1	1		1															2					1											1																1		
Nodosaria semirugosa	2										2	1			2	1		2	4			2	1																																	
Nodosaria sp.	3	1												1																1																									
Nonionella sp.		1		1										1						1																																			
Notorotalia serrata		1	1	2		1	1	1		12	2	4	1					2	7			12	3	3	6			5	5	9	2	4	6	4	4		5	1	4	7	5	5	6	6	4		4	13	5	2	4	2		7	3	7
Notorotalia sp.														1																																								9	
Notorotalia spinosa	8	8	2	4	10		3	3	13	2	3	1	1	2	5	2	6	1	1	12	9	1	5	3	5	5	3	9	5	8	4	20		2											5	2	2	3	3		2	2	2		19	
Notorotalia sp.C		6	7			5	5	6	12	7	8	6	4	5	3	12		4	3	22	11	5	6		13	7	8	8	6	7	5	14	5	8	3	2	4	5	2	7	3	1	2	5		7	9	16	8	10	5	4	14	2	17	2
Oridorsalis sp.A		2	2	1	1	1			6	4		1			2		2	1		1		1	2	5	2	1			7		4		3	1	4	7	3	2	4	3	1	1														
Orthomorphina cf. *challengeriana*																			2																																				
Plectofrondicularia proparri				1		1																1																							1			1					1			1
Plectofrondicularia sp.	1																																																							
Polymorphina sp.							1																																																	
Pseudonodosaria aperta	1			1	1		3							2	4			1	1			1	1		1	1																														
Pseudonodosaria symmetrica		2																						1											1	1	1	2										1								
Pullenia bulloides																						1	1																																	
Pullenia quinqueloba								1													1		1																1		1		1					1	2							
Pullenia sp.												1								2																																			
Quinqueloculina spp.			1	4	2	2		1	2	1					1	2			1			2									2			1	3			7	5	5	2	1			1						3		1	2		
Ramulina sp.																	1																																						
Rosalina sp.																																							1																	
Saracenaria sp.																											1																													
Sigmoilina tenuis																																			1		1	1																		
Siphonina australis																		1										2					1		1								2		1		1	7	4	2	1					
Siphotextularia awamoana					1							4					4								1				1				1			1	6						4		2				1		2	2		2		2
Siphotextularia emaciata												1																									2																2		
Siphotextularia sp.		1					1							1																																									
Siphouvigerina proboscidea		1			1	1			2		1					1	4		1			3	1	1					1		1		1	1	1	2			1				1								1					
Siphouvigerina sp.																1																																							
Sphaeroidina bulloides	8	11	2	2	7	4	4	5	10	8	7	7		3	2	2	1	4	6	3	6	7	1	3	11	11	3	2	7	6	9	9	8	4	11	19	7	14	18	11	8	6	2		3	2	3	13	6	6	4	11	6	18	5	2
Spiroloculina novozealandica																																														x	x	2	x	x	x	1	x	x	x	x
Stilostomella pomuligera		2			1											3		1		3		1	1			1		3										1																		
Stilostomella sp.							1		1	1										1																																			
Textularia miozea											1																												1																	
Textularia sp.																			1																				1																	
Trifarina bradyi		3	1		7	3		1	5		4	2	1		3	2	4	2		1		8	3	3	6	1	1	6	7		9	16	13	3	10	3	4	12	11	6	8	5														
Trifarina esuriens						2			1	2																																														
Trifarina spp.		2		4														1		1		1				5									1	1				1	1	1					5	10	6	4	5	5		5		44
Vaginulina elegans				1	2		1					1		4	1	2	1	1			1	1				1	1	2	2		1									1		1	1	2								2			
Vaginulina spp.	1			1	1	1					2	2						1		1		2					1	1							1	2						1														
Vaginulina vagina		1														1			2		1	1					3											1															1	1	
Vaginulinopsis sp.																																												1												
specimens indet.			3	1	3	2	2	6	7	1	2	4	4	3	4	1	2	6	4	5				3	4	7	1		5		4	1	2	3		3	3		3				1	1	2	5	1	1	1			1			2	2
Benthic diversity (species/sample	43	41	29	48	45	39	42	33	36	35	40	47	36	37	43	42	38	44	36	47	30	57	42	36	38	30	26	34	44	35	44	36	28	32	44	35	35	45	41	39	30	36	36	29	34	34	38	35	29	26	31	31	24	28	36	25
Benthic specimens per sample	171	165	108	123	143	118	139	99	186	170	173	164	100	146	160	147	104	139	130	192	107	241	129	117	201	148	127	143	140	143	135	167	159	119	158	109	135	201	179	180	115	124	108	108	126	107	121	170	113	147	101	157	124	170	210	178
Ostracoda per sample	29	24	26	54	28	28	14	17	18	29	36	36	12	17	24	41	20	40	56	22	20	36	13	34	26	72	44	54	24	46	64	60	96	50	59	88	128	58	68	55	36	58	48	48	46	40	18	22	36	104	52	28	10	48	40	50
Bulk weight all samples = 1000g. Residue weight (grams) =	19.91	27.82	120.38	16.98	13.70	63.58	14.96	21.95	26.90	24.97	16.94	45.81	34.41	11.89	17.38	20.73	74.72	28.42	20.77	15.38	9.60	5.81	10.76	20.52	48.30	44.50	6.39	21.31	81.16	59.19	62.61	21.96	31.07	35.17	60.97	144.71	137.74	32.02	55.19	60.17	76.22	95.09	276.55	79.27	118.52	84.47	54.42	75.15	136.74	217.56	204.33	144.60	39.47	90.00	126.97	70.57
Weight of picked split (grams)	0.038	0.054	0.058	0.033	0.026	0.062	0.029	0.021	0.052	0.048	0.033	0.089	0.033	0.023	0.033	0.040	0.072	0.055	0.040	0.060	0.018	0.022	0.021	0.040	0.094	0.086	0.025	0.042	0.079	0.057	0.061	0.043	0.060	0.068	0.119	0.141	0.134	0.062	0.108	0.117	0.074	0.092	0.135	0.077	0.116	0.041	0.053	0.073	0.067	0.212	0.100	0.071	0.038	0.044	0.124	0.069

Table 3 Nannofossil distribution chart, Craigmore Limestone, Waitoura Marl, and Bluecliff Silt. Stratigraphic position is measured relative to the base of the "stream section". Data categories are shown in bold and codes used for each category are shown in the footnotes. In category 6 abundance data are qualitative estimates of numbers observed during examination of smear slides. Numbers 1–4 are actual specimens observed.

Sample # (J39/f...)	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128	129	130	132	135
Stratigraphic unit	Craigmore Limestone							Waitoura		Bluecliffs Silt (stream section)									
Stratigraphic position (metres)	<f115	0.5	5.2	8	11	15.5	15.9	>f120	>f121	0	1.9	3.5	5.5	7.5	8.6	9.4	11.1	14.4	18.8
Overall abundance [1]	S	S	T	T	T	T	S	C	A	R	R	R	F	C	A	C	F	C	C
Overall preservation [2]	M	P	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
Overall nannosize [3]	S	S					S	S	S	S	S	S	S	S	T	S	S	S	S
Other microfossils [4]															b	f			f
Lithofacies (on microslide) [5]	LM	LM	LM	LM	LM	LM	LM	M	Z	LM	LM	LM	LM	Z	M	M	M	LM	LM
Taxa: [1,6] (see caption)																			
Braarudosphaera bigelowi													1						
Calcidiscus leptoporus														1					
Chiasmolithus altus																			
Chiasmolithus oamaruensis																			
Coccolithus miopelagicus	2						T	T	S	T	T	T	T	S	S	S	T	S	**R**
Coccolithus ovalis	T	3	3	T	T	2*	S	C	C	S	R	R	**F**	C	C	F	**F**	C	C
Cyclicargolithus floridanus	S	S	T	T	T	3	S	S	R	S	S	S	R	R	S	T	S	R	S
Cystodytes sp. indeterminate																			
Discoaster deflandrei									1*				3*	T*	4*	1.5*		3	1
Helicosphaera carteri								3	4			1	3	2	2	1	4	T	2
Helicosphaera euphratis					1		1	S	S	**S**	3	**T**	**T**	**T**	**S**	1	T	1	3
Helicosphaera obliqua																			
Holodiscolithus macroporus																			
Micrascidites vulgaris								T	4			T	**T**	T		T	**S**	**T**	**T**
Pontosphaera multipora								2	1	1	1	3	2				1		1
Pontosphaera sp. (punctate)													1						
Prinsiaceae indet. (small)	T						3	F	A	R	R	R	F	C	C	C	R	F	F
Reticulofenestra bisecta				1*				1*	3*	2			2*			2			2
Reticulofenestra "clifdenensis" MS									1										
Reticulofenestra gartnerii											1	2	2		3		1		3
Reticulofenestra placomorpha												1?*							
Sphenolithus moriformis								3	1				3	2	T	1	2	1	1
Syracosphaera clathrata																			

Table 3 (*continued*)

Sample # (J39/f...)	136	137	140	145	146	147	149	151	153	157	160	162	164	166	167	169	170	174	17
Stratigraphic unit	Bluecliffs Silt (stream section)					Bluecliffs Silt (cliff section; Waitakian part)													
Stratigraphic position (metres)	24.9	28	30.7	33.5	34.1	35	37	39	41	44.8	47.7	50.2	52.2	54.4	55.7	58.1	59	62.9	65
Overall abundance [1]	F	C	C	C	F	C	A	C	F	F	C	A	C	A	C	F	C	C	C
Overall preservation [2]	M	M	M	M	M	M	M	P	M	M	M	P	M	M	M	M	P	P	M
Overall nannosize [3]						S	M	S	S	S	S	M	M	S	M	M	S	S	M
Other microfossils			f		b						f	f		f	f,s	f		f	
Lithofacies (on microslide) [5]	LM	LM	LM	M	M	M	LM	LM	M	LM	M	Z	M	M	LM	M	LM	LM	L
Taxa: [1,6] (see caption)																			
Braarudosphaera bigelowi						1								1					
Calcidiscus leptoporus																			
Chiasmolithus altus				4															
Chiasmolithus oamaruensis		1																	
Coccolithus miopelagicus	T	S	S	F	T	S	S	S	T	T	T	T	S		T				3
Coccolithus ovalis	F	F	F	C	F	C	C	C	R	R	F	F	C	F	F	R	F	F	R
Cyclicargolithus floridanus	S	S	S	S	S	R	T	R	S	3	S	T	S	T	R	S	S	S	S
Cystodytes sp. indeterminate														1					
Discoaster deflandrei			T*		2	T	1*				1		1	T	T*	2*	1		T
Helicosphaera carteri		1	3	2		T	1	3	2	1			4	2	2	2		2	[illegible]
Helicosphaera euphratis	2	4	1	2		T	**T**	T	4	**T**	2	2?	T	4	**T**			3	
Helicosphaera obliqua						1													
Holodiscolithus macroporus																			
Micrascidites vulgaris		3	**S**	T	**T**	**S**	T	3	T	3	**T**	**T**	**S**	T	S	**T**		**S**	T
Pontosphaera multipora	1	1	3					1	2	2		2	4	T			1	1	1
Pontosphaera sp. (punctate)																			
Prinsiaceae indet. (small)	R	C	C	R	F	C	A	F	F	F	C	A	F	A	C	F	C	C	C
Reticulofenestra bisecta		2*		1			2*		1*				3*	1?				1	1*
Reticulofenestra "clifdenensis" MS						1													
Reticulofenestra gartnerii						2		1	2	1		2	T	T	T		2	1	
Reticulofenestra placomorpha																			
Sphenolithus moriformis	1		3			T	2	1	T	1	2		3	T	S	1			
Syracosphaera clathrata																		1	

(*continued*)

Table 3 (*continued*)

Sample # (J39/f...)	178	180	182	184	186	188	190	194	198	200	202	206	208	210	213	214	215	216	217
Stratigraphic unit	Bluecliffs Silt (cliff section;Waitakian part)			Bluecliffs Silt (main section; Otaian part)															
Stratigraphic position (metres)	67	68.9	70.6	72.8	75.3	77.9	79.4	82.5	85.8	87.8	89.8	92.9	95	97.3	101	103	108	115	125
Overall abundance [1]	T	F	R	C	F	C	C	C	R	F	F	F	R	F	R	R	C	F	F
Overall preservation [2]	P	M	P	M	P	M	P	P	P	M	P	P	P	P	M	M	P	P	P
Overall nannosize [3]	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S
Other microfossils						f											f		
Lithofacies (on microslide) [5]	LM	LM	LM	LZ	Z	Z	M	LM	LM	LM	LM	LZ	LM	LZ	LM	M	LZ	Z	Z
Taxa: [1, 6] (see caption)																			
Braarudosphaera bigelowi																			
Calcidiscus leptoporus									1										
Chiasmolithus altus																			
Chiasmolithus oamaruensis				1															
Coccolithus miopelagicus			1	1		1			1	2	1	4	4		5	T	T		
Coccolithus ovalis	T	R	R	R	R	F	C	F	R	F	F	R	S	F	S	S	F	F	R
Cyclicargolithus floridanus	2	T	T*	R	S	S	S	T	1	4	1	3	T	1	3	3	T	T	T*
Cystodytes sp. indeterminate							1				1								
Discoaster deflandrei		1	1	T	T	2	4	1*		2	3		1*	3*	4	3	1	3*	1*
Helicosphaera carteri		1	2		4	3	1	1	2	**T**	2	3	**T**	3	**T**	**T**	**R**	1	3
Helicosphaera euphratis		**T**	1		2							4	1	1	1				1
Helicosphaera obliqua											2								
Holodiscolithus macroporus														3					
Micrascidites vulgaris		**T**	T	**T**	**1**	**T**		1	**T**	**T**	3	**T**	**T**	**T**	**1**	2	**S**	3	**S**
Pontosphaera multipora	1	T	2	S				3	1	2	1	T	T	1	T	T	T		T
Pontosphaera sp. (punctate)				2														T	
Prinsiaceae indet. (small)	T	F	S	A	F	C	C	F	R	R	F	R	R	F	R	R	C	R	F
Reticulofenestra bisecta		2		1							2?	1	1	1	3			1	
Reticulofenestra "clifdenensis" MS											1								
Reticulofenestra gartnerii		1		1	1	4		T	2	4	1		2	1	2*			2	3*
Reticulofenestra placomorpha		2											1						
Sphenolithus moriformis		1	3	T	2	1		1			1		1		1			1	
Syracosphaera clathrata				1								1							

[1] A = abundant (>5000), C = common (2500–5000), F = few (1000–2500), R = rare (500–1000), S = sparse (100–500), T = trace (5–100). [2] M = moderate, P = poor. [3] T = tiny, S = small, M = medium. [4] b = bryozoan, f = foraminifera, s = calcareous sponge spicules. [5] L = lime, M = mud, Z = silt. [6] * = battered, bold = complete.

Bluecliffs Silt

Gair (1959) originally described Bluecliffs Silt as "...a blue sandy silt ('Blue clay' of Gudex) in which hard sandstone layers 5 ft to 6 ft apart and about 1 ft thick give a very regularly banded appearance. The silt is fossiliferous throughout, but more so in the middle and upper portions, the macrofossils being chiefly Mollusca with a few brachiopods near the base. Pyritic concretions occur irregularly throughout, and gypsum in small films is widely distributed." This description refers to the cliff section (Fig. 1) which contains the boundary stratotype. Although Field & Browne (1986) synonymised Bluecliffs Silt with Tokama Siltstone, we consider the latter to be restricted to North Canterbury (Andrews et al. 1987). It was not deposited contiguously with Bluecliffs Silt (Field et al. 1989, sheet 4, map 28).

From outcrop data we estimate that there is c. 100 m of section between Craigmore Limestone and the base of the cliff section. The upper 35 m (stream section, Fig. 1) is massive blue-grey siltstone which is exposed in the riverbed and banks. It is in conformable contact with strata at the base of the cliff section. For descriptive convenience we distinguish three informal lithofacies in upward succession at Bluecliffs.

1. *Lower siltstone lithofacies*

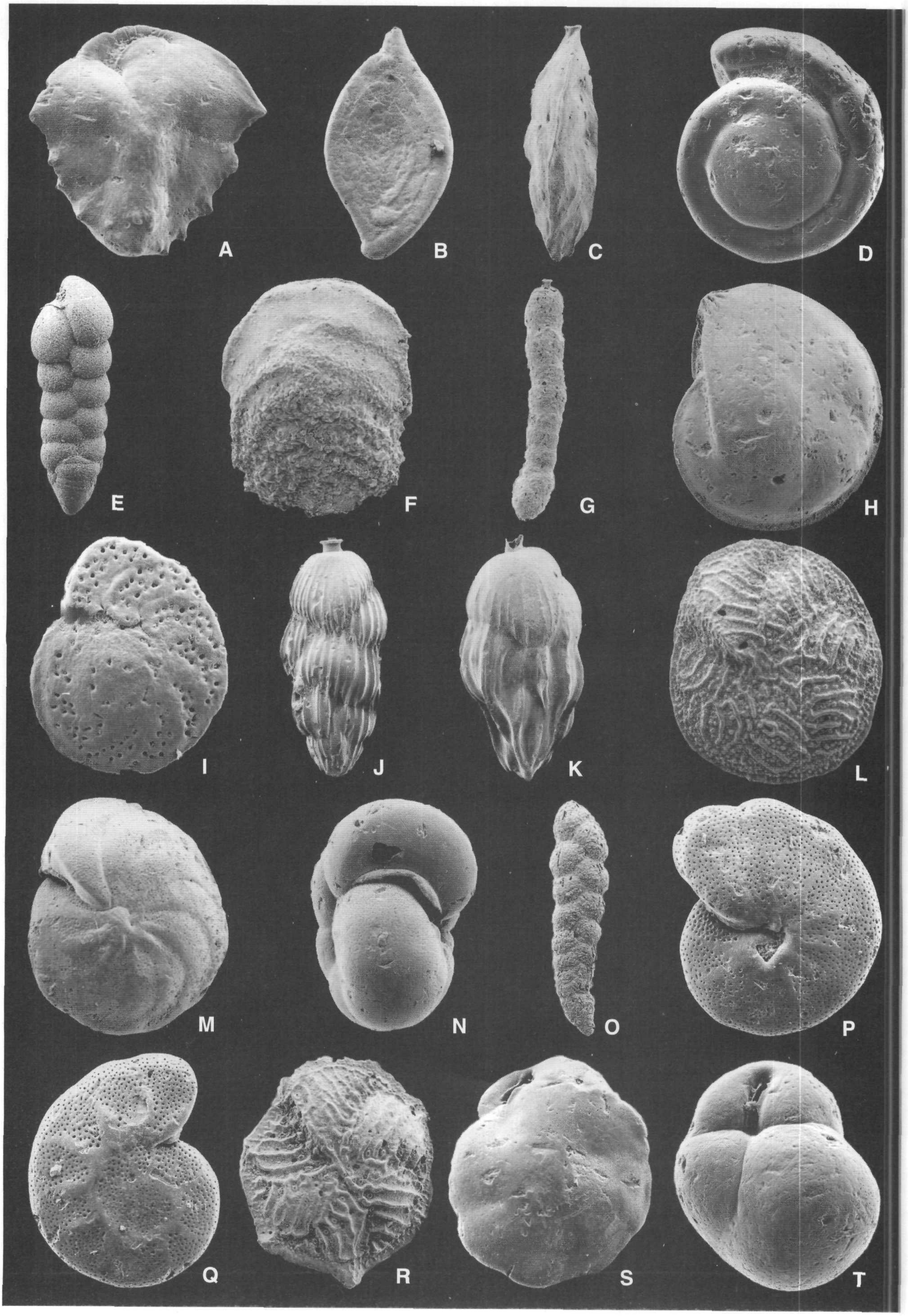
The lower siltstone lithofacies (0–38.5 m) is a massive, soft to moderately hard, medium blue-grey calcareous siltstone with no obvious bedding. It is exposed in low banks and in channels starting in a side stream 400 m to the west of the Bluecliffs cliff section, and continues along the north bank of the Otaio River to the base of the latter.

2. *Banded lithofacies*

The banded lithofacies (38.5–106 m) is a bedded, moderately soft, blue-grey, calcareous siltstone. Bedding varies from indistinct to well defined and reflects variation in lithification. Cemented beds, which appear to be more calcareous than the surrounding siltstone, are termed hard bands. The base of the lithofacies is defined by the lowest hard band, and the top of the lithofacies is the topmost hard band. We recognise 28 hard bands (Fig. 2). They vary considerably in prominence; some are most obvious at a distance from the exposure. The banded lithofacies is exposed in the cliff section for 1 km along the north bank of the Otaio River.

3. *Upper siltstone lithofacies*

The upper siltstone lithofacies (base at 106 m) is a massive, soft, blue-grey calcareous siltstone without obvious bedding.


A
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T

It overlies the highest hard band; only the lower part at the eastern end of the cliff exposure was examined in this study. Macrofossils become more abundant higher in the upper siltstone lithofacies.

Southburn Sand

Bluecliffs Silt grades up into the brown sands of Southburn Sand, which is characterised by fossiliferous sandstone and concretions.

Sedimentary cycles

Carter (1988) included Bluecliffs Silt in Otakou Group, regarded by Carter et al. (1991) as a progradational highstand systems tract that developed as sediment supply into Canterbury Basin increased in the Early Miocene. In their interpretation, the condensed interval (not exposed in our sections) underlying Otekaike Limestone marks the maximum flooding surface between the highstand systems tract and the preceding transgressive systems tract in a second order cycle of thermo-tectonic subsidence at a passive margin. They did not resolve higher order cycles embracing Bluecliffs Silt.

Maximum flooding surfaces separating transgressive systems tract and highstand systems tract sequence units can be characterised by microfossil abundance and diversity peaks (Armentrout 1996; Mancini & Tew 1997) which, given stable biotic productivity, reflect decreases in sediment flux at highstands. At Bluecliffs there is a well-defined series of foraminiferal abundance peaks (Fig. 5), between 9 and 73 m in the lower siltstone and banded siltstone lithofacies. Spikes in benthic abundance form a waxing series up to 47 m and then wane to 73 m. The turning point at 47 m coincides with maximum species diversity (57 taxa). The spikes occur in, or near, minima in the coarse fraction signature. Spikes in the planktonic abundance signature coincide with benthic spikes at 9 m and 30 m but are slightly offset at 34–36 m and 70–73 m. Overall, spikes in planktonic abundance decline up-sequence from the major excursion at 9 m.

◀ **Fig. 4** Benthic foraminifera from Bluecliffs, SEM micrographs. J39/fxxx = locality (see Fig. 2). FPxxxxx = catalogue number of specimen in foraminiferal collections at Institute of Geological & Nuclear Sciences, Lower Hutt. md = maximum dimension. **A**, *Ehrenbergina marwicki* Finlay (J39/f184; FP4566; md = 0.41 mm). **B**, *Spiroloculina novozealandica* Cushman & Todd (J39/f215; FP4567; md = 1.02 mm). **C**, *Trifarina bradyi* Cushman (J39/f134; FP4568; md = 0.34 mm). **D**, *Gyroidinoides zelandica* (Finlay) (J39/f164; FP45469; md = 0.50 mm). **E**, *Karreriella* cf. *chilostoma* (Reuss) (J39/f127; FP4570; md = 1.35 mm). **F**, *Vulvulina pennatula* (Batsch) (J39/f146; FP4571; md = 0.79 mm). **G**, *Martinottiella communis* (d'Orbigny) (J39/f7597; FP4572; md = 1.63 mm). **H**, *Lenticulina* sp. (J39/f135; FP4573; md = 0.75 mm). **I**, *Cibicides* cf. *pseudoungerianus* (Cushman) (J39/f134; FP4574; md = 0.40 mm). **J**, *Euuvigerina miozea* (Finlay) (J39/f213; FP4575; md = 0.76 mm). **K**, *Euuvigerina maynei* (Chapman) (J39/f135; FP4576; md = 0.81 mm). **L**, *Notorotalia spinosa* (Chapman) (J39/f164; FP4577; md = 0.47 mm). **M**, *Cibicides novozelandicus* (Karrer) (J39/f170; FP4578; md = 1.05 mm). **N**, *Anomalinoides sphericus* (Finlay) (J39/f185; FP4579; md = 0.41 mm). **O**, *Haeuslerella hectori* Finlay (J39/f7603; FP4580; md = 1.56 mm). **P, Q**, *Anomalinoides parvumbilia* (Finlay). P (J39/f209; FP4581; md = 45 mm). Q (J39/f209; FP4582; md = 0.44 mm). **R**, *Notorotalia serrata* Finlay (J39/f206; FP4583; md = 0.53 mm). **S**, *Cassidulina carinata* Silvestri (J39/f185; FP4584; md = 0.29 mm). **T**, *Globocassidulina subglobosa* (Brady) (J39/f129; FP4585; md = 0.28 mm).

The generally inverse relation between the foraminiferal specimen abundance and coarse fraction signatures is consistent with a cyclic record of highstands which produced condensed intervals due to decreases in sediment flux. Most of the abundance peaks (e.g., 9, 47, 56, 64 m) occur close to minima in the relative abundance of spinose planktonic taxa (Fig. 5). The latter signature is possibly a climate proxy in which maxima occur in cool episodes, while minima represent warm near-surface water (Li & McGowran 1994). These data support the interpretation of the benthic abundance spikes as marking highstands, possibly representing higher order maximum flooding surfaces. The ^{18}O signatures for two benthic foraminiferal species (Fig. 5) show inconsistent relationships with the sedimentary and faunal signatures, except that excursions are largest within the interval containing the abundance spikes.

Significantly, the abundance spikes are not well defined in the exposure, and there is little evidence that the inferred condensed intervals affect the completeness of the stratotype section. They are not associated with prominent bedding planes or concentrations of glauconite. The connection between the spikes and cemented beds in the banded lithofacies is not resolved by our data because sampling is restricted to the less cemented interbeds. Marked changes in the composition of benthic foraminiferal assemblages at the spikes is not observed. The principal macroscopic evidence suggesting slow sedimentation in the vicinity of the major benthic spike at 47 m is a significant increase in the number of pyritised burrows. These considerations indicate that, while the spikes probably represent condensed intervals, they may not significantly affect the completeness of the section. Particularly, the condensed interval at 73 m (boundary horizon) is minor as judged by the coarse fraction and benthic abundance signatures.

DEPOSITIONAL SETTING

Paleogeography

The interval studied covers a period in which the earliest Miocene carbonate facies changed to predominantly clastic sedimentation, derived from uplift initiated by movement on the Alpine Fault (Kamp 1986). A lower Otaian reconstruction of Canterbury (Field et al. 1989, sheet 4, map 28) showed Bluecliffs at shelf depths in a shallow basin bordered by land to the north and west, and by the submarine Endeavour High to the east. Fine clastic sediments in the vicinity of Bluecliffs lay seaward of a sand wedge prograding out from the western landmass. Peter King's (pers comm. 1997) reconstruction (Fig. 6) suggests that the Bluecliffs site was at upper bathyal depths below the Waitakian-Otaian boundary. The relative abundance of planktonic foraminifera, discussed later, indicates that, near the stage boundary, the basin was not closed to the extent shown by Field et al. (1989).

Paleodepth

Karreriella cf. *chilostoma* (Fig. 4E) and *Vulvulina pennatula* (Fig. 4F) occur in the lower siltstone lithofacies but

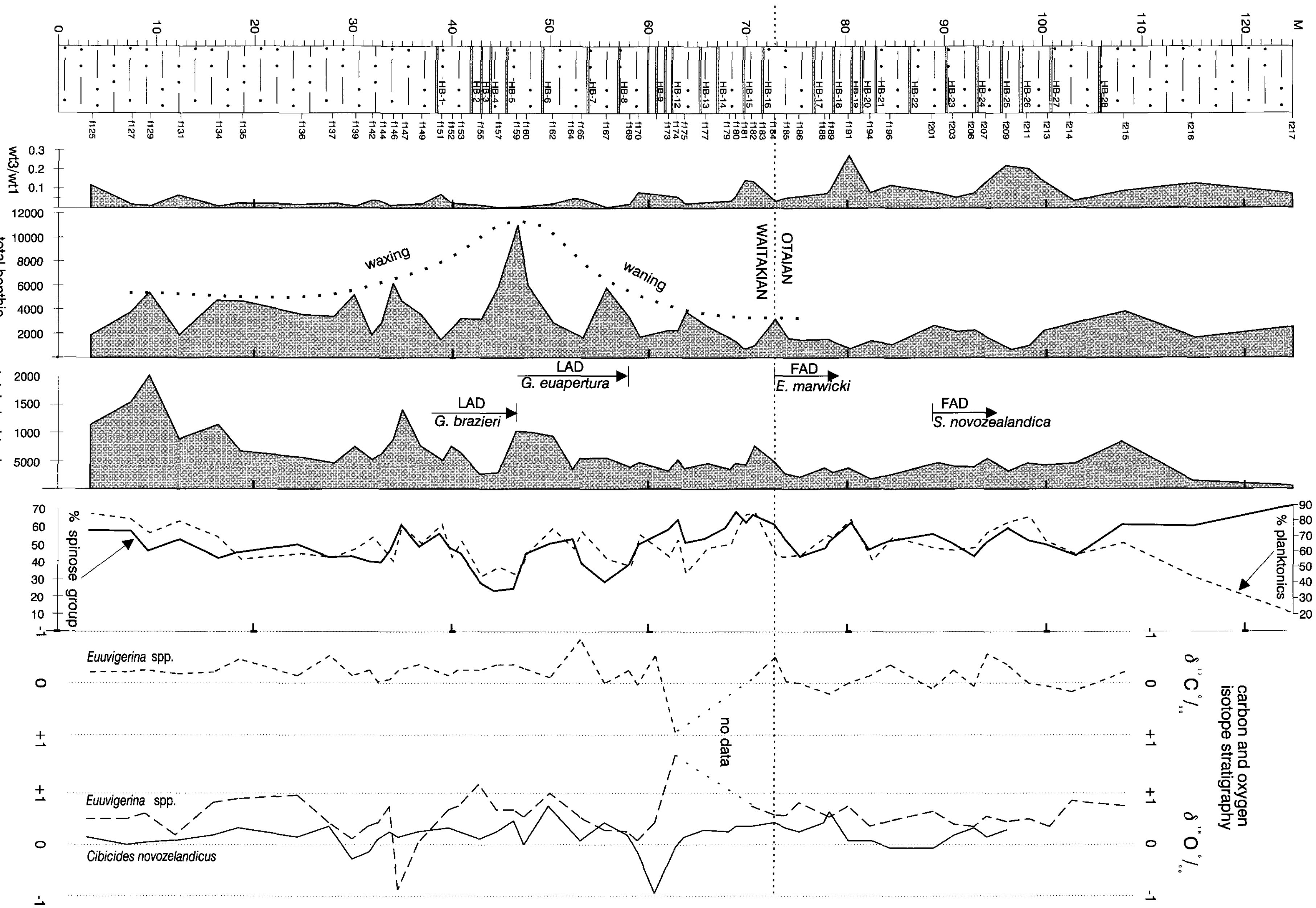


Fig. 5 Sedimentary, foraminiferal, and isotope signatures for a section across the Waitakian-Otaian boundary at Bluecliffs. wt3/wt1: wt3 is the dry weight of >75 μm fraction; wt1 is the dry weight of the bulk sample. Total benthic specimens/g, total planktic specimens/g: = the number of (benthic or planktonic) foraminifera in a weighed split of >150 μm fraction, recalculated to specimens per gram of >150 μm fraction. % spinose group = the spinose group includes *Globigerina bulloides*, *G. praebulloides* and variants, *G. falconensis*, and *G. ciperoensis*; reported as a percentage of total planktonic specimens in the >150 μm fraction. Carbon and oxygen isotopes are reported as per mille deviations from the PDB standard.

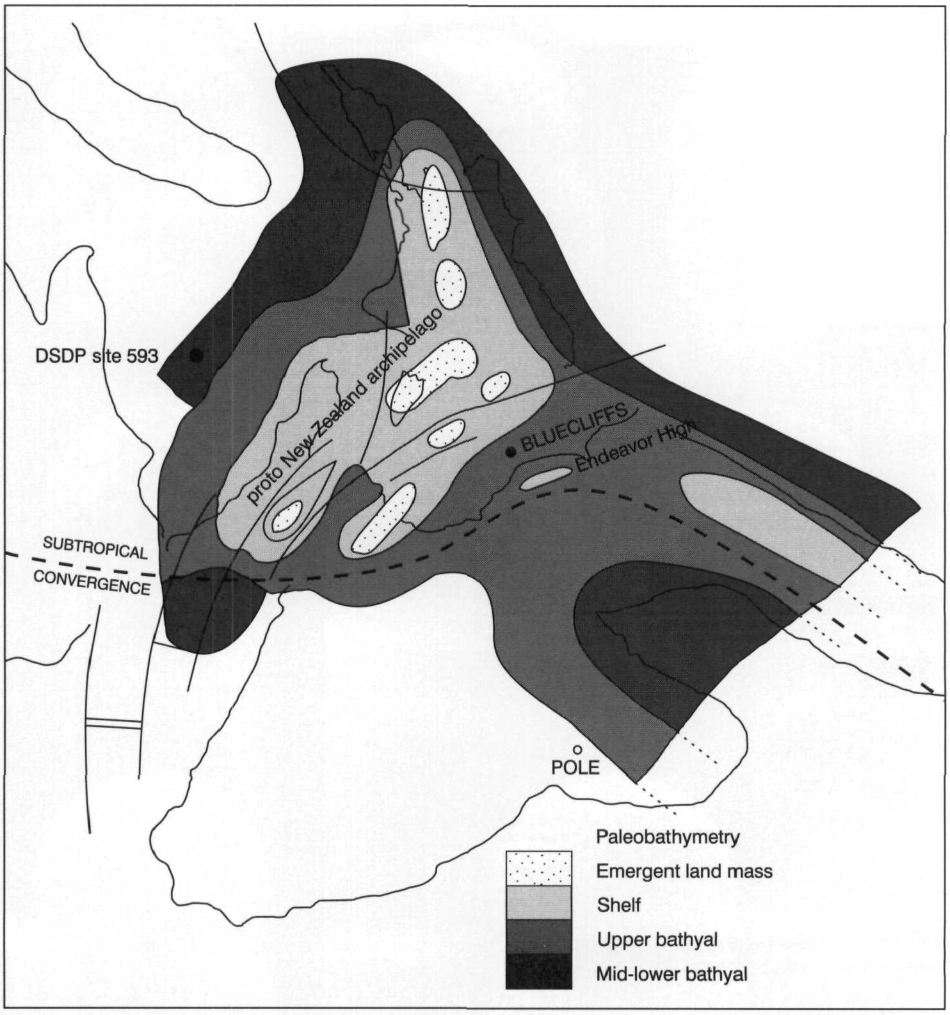


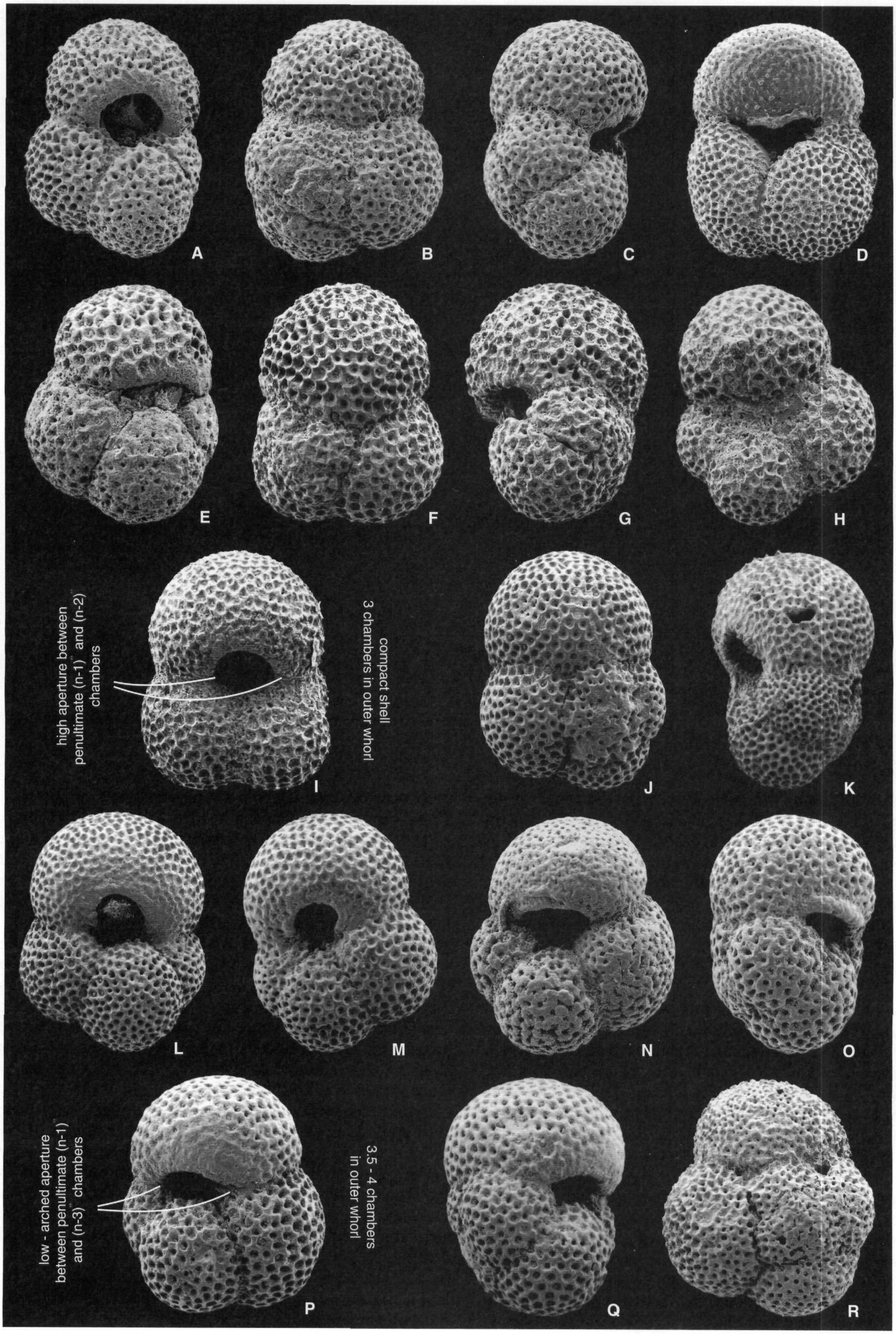
Fig. 6 Paleogeography and paleobathymetry of the New Zealand region at 22 Ma (after P. R. King pers. comm. July 1997). Position of Subtropical Convergence after Edwards (1975).

populations are very small and they do not appear in the census (Table 2). Both are restricted to slope and deep-sea environments (Hayward 1986). Crundwell et al. (1994) found that *Vulvulina pennatula* occurred below 600 m in a Taranaki Basin Pliocene sequence. The rarity of these taxa, with the absence of other typical slope taxa (e.g., *Gyroidinoides neosoldanii*, *Planulina catilla*, *Sigmoilopsis schlumbergeri*), suggests that the lower siltstone lithofacies was deposited in the upper bathyal zone (200–600 m).

Apart from the absence of deeper water taxa, the taxonomic composition of assemblages in the banded and upper siltstone lithofacies resembles that of the lower siltstone lithofacies. Dominant or common taxa (Table 2) include *Anomalinoides* spp. (Fig. 4N, P, Q), *Cassidulina* spp., and *Globocassidulina subglobosa* (Fig. 4S, T), *Cibicides* spp. (Fig. 4I, M), *Gyroidinoides* spp. (Fig. 4D), *Haeuslerella hectori* (Fig. 4O), *Lenticulina* spp. (Fig. 4H), *Martinottiella communis* (Fig. 4G), *Notorotalia* spp. (Fig. 4L, R), *Sphaeroidina bulloides*, and *Trifarina* spp. (Fig. 4C). Many species persist throughout the interval sampled. Distinctive shallow shelf and shoal species (e.g., *Amphistegina* sp., *Cribrorotalia ornatissima*, *Elphidium crispum*, *E. kanoum*) are almost absent, although they are major constituents of a Waitakian assemblage (I38/f7607) from the prograding sand wedge to the west near Fairlie. Of these taxa, only two specimens of *Amphistegina* are present in our collections. These data suggest that the banded lithofacies and lower part of the upper siltstone lithofacies were deposited at outer shelf to uppermost bathyal depths (c. 150–300 m). The similarity in taxonomic composition of assemblages is evidence that changes in depth during deposition of the three lithofacies were relatively small.

Planktonic foraminifera live at preferred positions in the water column during growth (Bé 1977) and, insofar as the oxygen and carbon isotope compositions of their shells record environmental parameters (Hemleben et al. 1989), fossil taxa provide some information about relative paleodepth. Of relevance here is the persistent presence in Bluecliffs assemblages of small but typical populations of *Globoquadrina dehiscens* (Fig. 7D). In stable isotope studies of Miocene material (Corfield & Cartlidge 1991; Gasperi & Kennett 1992) this species ranks as one of the deepest dwelling planktonic taxa. Although this relative ranking cannot be converted reliably to absolute depth in the water column, the data show that *Globoquadrina dehiscens* calcified significantly below the 0–50 m photic zone and that the Bluecliffs sea probably exceeded shelf depths.

Molluscs are rare in the lower siltstone and banded lithofacies but are common and diverse in the upper siltstone. Assemblages include outer shelf and upper bathyal taxa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high aperture between penultimate (n-1) and (n-2) chambers
compact shell
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O
low - arched aperture between penultimate (n-1) and (n-3) chambers
3.5 - 4 chambers in outer whorl
P
Q
R

(Alan Beu pers. comm. 1997). Nannofossil abundance and diversity begins to decrease in the banded lithofacies (c. 57 m) and indicate the onset of gradual shoaling.

In overview, the lower siltstone lithofacies is identified as the deepest unit, estimated to have been deposited at upper bathyal depths (c. 200–600 m). Reduction in paleodepth is first detected within the banded lithofacies and continued into the upper siltstone. Whether the site had moved up to shelf depths at the top of the interval under study is uncertain. We consider that upper strata of the banded lithofacies and lower strata of the upper siltstone lithofacies were deposited at depths of 150–300 m in a regressive regime. These data are uniformitarian estimates of paleodepth that provide poor resolution and are not well constrained. Cyclic patterns in specimen abundance and sedimentation data discussed elsewhere suggest that eustatic oscillations in depth were superimposed on the long-term decline in depth.

Paleoclimate

The composition of nannofossil and planktonic foraminiferal assemblages indicate a cool-temperate water mass. An indication is the almost total absence of *Globigerinoides*, whose Early Miocene record in southeastern Australia is related to southward incursions of warm water (Chaproniere 1992). Oscillatory marine climate is indicated by the relative abundance signature of spinose globigerinids (Fig. 5), which Chaproniere (1992) took as a proxy for cool near-surface water. McGowran & Li (1993, 1996) and Li & McGowran (1994) noted the association of spinose taxa related to *Globigerina bulloides* with cool, nutrient-rich water (Weaver et al. 1997) and linked their abundance signature with northward fluctuations in the location of the Subtropical Convergence over southeastern Australian neritic sites in the Early Miocene. This signature, represented by *Globigerina bulloides* (Fig. 8O, P), *Globigerina praebulloides* (Fig. 8I–N), and variants *Globigerina* sp. A (Fig. 8Q, R) and *Globigerina* sp. B (Fig. 8S, T), and *Globigerina ciperoensis* (Fig. 8F–H), is cyclic at Bluecliffs with strong spikes between c. 35 and 70 m. The largest is at 70 m and immediately precedes the Waitakian-Otaian boundary.

Constraints on the interpretation of oxygen isotope data for two benthic foraminifera (Fig. 5) are the wide, variably spaced sample scheme, which may not reliably resolve periodic signals, and the weak, and sometimes negative, covariance between the signatures. However, the data are particularly variable between 25 and 63 m. The amplitude of the heavy excursion in ^{18}O‰ between 34 and 43 m in *Euuvigerina* spp. is large (2.08‰) and greatly exceeds amplitudes recorded by Zachos et al. (1997) for the basal Miocene Mi1a glacial maximum at an equatorial site. They considered that the increase might equate with a cooling of 6°C. Although the excursion between 34 and 43 m may not represent part of a single cycle, and may indicate change in ice volume as well as temperature, the data flag the likelihood of significant instability in climate before the Waitakian-Otaian Stage boundary at 73 m. While high amplitude excursions in ^{18}O‰ all occur within the 9–73 m section containing spikes in specimen abundance, the data often do not covary closely with the spinose globigerinid climatic proxy. If both contain climatic information, this suggests that near-surface and bottom water regimes differed significantly.

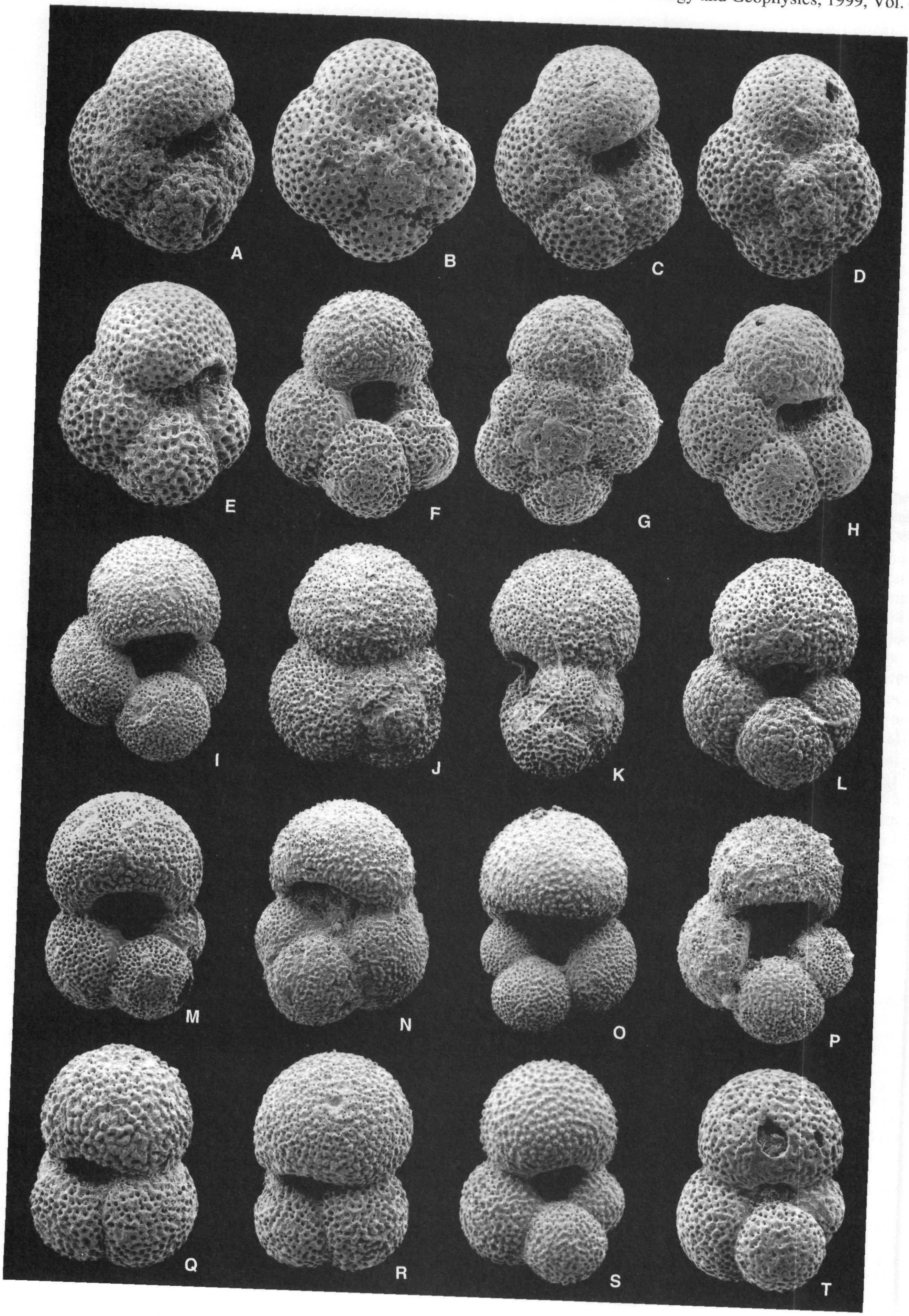
Whereas the marine signatures likely identify significant climatic change before the Waitakian-Otaian boundary, Pocknall (1982) did not observe comparable evidence in land floras. His data suggest that terrestrial climate was warm-temperate, with moderately high rainfall evenly distributed through the year. Landscapes were fully forested, with *brassi* beech as the dominant group. Montane taxa are absent (Dallas Mildenhall pers. comm. 1997). We have not resolved the discordance between marine and terrestrial climatic reconstructions. Southward in Canterbury Basin, Buening et al. (1998, fig. 7) analysed brachiopod carbonate and determined paleotemperatures of c. 11.2–14.5°C (corrected for depth) from a Waitakian locality and c. 9.5–11°C from an Otaian locality.

Oceanicity

Nannofossil assemblages in Bluecliff Silt and underlying Waitoura Marl have limited diversity (Table 3) and are numerically dominated by small or minute taxa. They often include specimens of *Coccolithus ovalis* (Fig. 9E–H) and *Cyclicargolithus floridanus* (Fig. 9T) that are smaller than normal. Taxa considered to prefer warmish water coastal, marginal sea, or oceanic conditions are either rare (e.g., *Braarudosphaera bigelowi*, *Discoaster deflandrei* (Fig. 9O), *Helicosphaera* spp. (Fig. 9I–N), *Pontosphaera multipora* (Fig. 9Q–S), and *Sphenolithus moriformis*) or absent (e.g., *Discoaster druggi*, high-spired *Sphenolithus* spp., *Thoracosphaera* spp., and *Triquetrorhabdulus carinatus*). *Coronocylus nitescens*, a ubiquitous oceanic species, is also absent. These rather featureless nannofloras imply deposition from a temperate, vertically well mixed, eutrophic water mass at a shallow offshore location, intermediate between neritic and fully oceanic.

Relative abundance of planktonic foraminifera (Fig. 5) varies between 45 and 87% of total specimens through the section but drops to 22% in the highest sample. The pattern is cyclical, possibly at several frequencies. Generally, planktonic species are open-ocean organisms and are scarce in low salinity, turbid coastal water (Hemleben et al. 1989), although the gross pattern is commonly perturbed by various physical and biotic factors. Gibson (1989) examined a large set of data from off northeastern United States and reported relative abundances comparable with Bluecliffs in the vicinity of the shelf break at depths between c. 90 and 500 m

◀ **Fig. 7** Planktonic foraminifera from Bluecliffs, SEM micrographs. J39/fxxx = locality (see Fig. 2). FPxxxxx = catalogue number of specimen in foraminiferal collections at Institute of Geological & Nuclear Sciences, Lower Hutt. md = maximum dimension. **A–C**, *Globigerina woodi woodi* Jenkins; J39/f185. A (FP4520; md = 0.40 mm). B (FP4521; md = 0.36 mm). C (FP4522; md = 0.34 mm). **D**, *Globoquadrina dehiscens* (Chapman, Parr & Collins) (J39/f185; FP4523; md = 0.39 mm). **E–G**, *Globigerina woodi connecta* Jenkins; J39/f185. E (FP4524; md = 27 mm). F (FP4525; md = 0.34 mm). G (FP4526; md = 0.34 mm). **H**, *Globorotaloides suteri* Bolli (J39/f134; FP4527; md = 0.32 mm). **I–M**, *Globigerina brazieri* Jenkins. I (J39/f134; FP4528; md = 0.35 mm). J (J39/f7602; FP4529; md = 0.33 mm). K (J39/f7602; FP4530; md = 0.35 mm). L (J39/f7602; FP4531; md = 0.37 mm). M (J39/f7602; FP4532; md = 0.33 mm). **N–R**, *Globigerina euapertura* Jenkins; J39/f7601 N (FP4533; md = 0.26 mm). O (FP4534; md = 0.26 mm). P (FP4535; md = 0.28 mm). Q (FP4536; md = 0.28 mm). R (FP4537; md = 0.37 mm).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in a zone separating neritic from oceanic water. In this region, the shelf break is usually >100 km from the shoreline. Although it is unlikely that Bluecliffs paleogeography was similar to that sampled by Gibson (1989), the comparison indicates that Bluecliffs was in an intermediate position between inshore neritic and fully oceanic water. The oscillatory pattern may have a climatic component. Generally, the planktonic representation is greatest when spinose taxa, possibly proxies for cool nutrient-rich water, are most abundant. This may be related to the position of the Subtropical Convergence, an important water mass boundary in the region in the Early Miocene (Edwards 1975; McGowran & Li 1996; Weaver et al. 1997).

Field et al. (1989, sheet 4, map 28) envisioned that the Bluecliffs basin was closed to the north and west. However, only at the top of our section, c. 50 m above the boundary between Waitakian and Otaian Stages, is there evidence of a neritic water mass over the site. Nannofossil and foraminiferal data from the lower siltstone, banded, and lower 15 m of the upper siltstone lithofacies suggest incomplete closure to the west. Figure 6 shows an archipelago scenario with a submarine ridge (Endeavour High) and isolated westward landmasses. These would partially deflect oceanic water yet provide insufficient shelter for neritic water to establish.

Bottom environment

Benthic foraminiferal assemblages are diverse and are primarily composed of shallow infaunal–epifaunal taxa. Species abundances tend to be equitably distributed. Particularly, abundance spikes of infaunal opportunist taxa (e.g., *Bolivina*, *Euuvigerina*) typical of nutrient-rich and/or oxygen-deficient environments (Sen Gupta & Machain-Castillo 1993) are absent. An overview of the data suggests that the sediment interface was well oxygenated, with moderate nutrient flux. Bottom energy was low. Laminated sediments are absent whereas bioturbation is commonly observed. An active metazoan infauna is suggested.

◀ **Fig. 8** Planktonic foraminifera from Bluecliffs, SEM micrographs. J39/fxxx = locality (see Fig. 2). FPxxxxx = catalogue number of specimen in foraminiferal collections at Institute of Geological & Nuclear Sciences, Lower Hutt. md = maximum dimension. **A, B,** *Paragloborotalia nana nana* Bolli; J39/f134. A (FP4538; md = 0.27 mm). B (FP4539; md = 0.26 mm). **C, D,** *Paragloborotalia nana semivera* Hornibrook; J39/f134. C (FP4540; md = 0.29 mm). D (FP4541; md = 0.30 mm). **E,** *Paragloborotalia nana pseudocontinuosa* Jenkins (J39/f134; FP4542; md = 0.34 mm). **F–H,** *Globigerina ciperoensis ciperoensis* Bolli; J39/f185. F (FP4543; md = 0.27 mm). G (FP4544; md = 0.26 mm). H (FP4545; md = 0.23 mm). **I–N,** *Globigerina praebulloides* Blow. I (J39/f185; FP4546; md = 0.48 mm). J (J39/f185; FP4547; md = 0.35 mm). K (J39/f185; FP4548; md = 0.37 mm). L (J39/f164; FP4549; md = 0.38 mm). M (J39/f164; FP4550; md = 0.39 mm). N (J39/f164; FP4551; md = 0.45 mm). **O, P,** *Globigerina bulloides* d'Orbigny. O (J39/f185; FP4552; md = 0.49 mm). P (J39/f164; FP4553; md = 0.47 mm). **Q, R,** *Globigerina* sp. A; J39/f185. Q (FP4554; md = 0.26 mm). R (FP4555; md = 0.28 mm). **S, T,** *Globigerina* sp. B; J39/f185. S (FP4556; md = 0.29 mm). T (FP4557; md = 0.25 mm).

BIOSTRATIGRAPHY

We evaluate the nature, distribution, and utility of selected bioevents in the vicinity of the Waitakian-Otaian boundary. Benthic foraminiferal taxa cited by Finlay & Marwick (1947) for the boundary are considered, as well as planktonic foraminiferal and nannofossil events that might potentially extend the range of environments in which the boundary can be recognised. Data from several other groups are reviewed briefly.

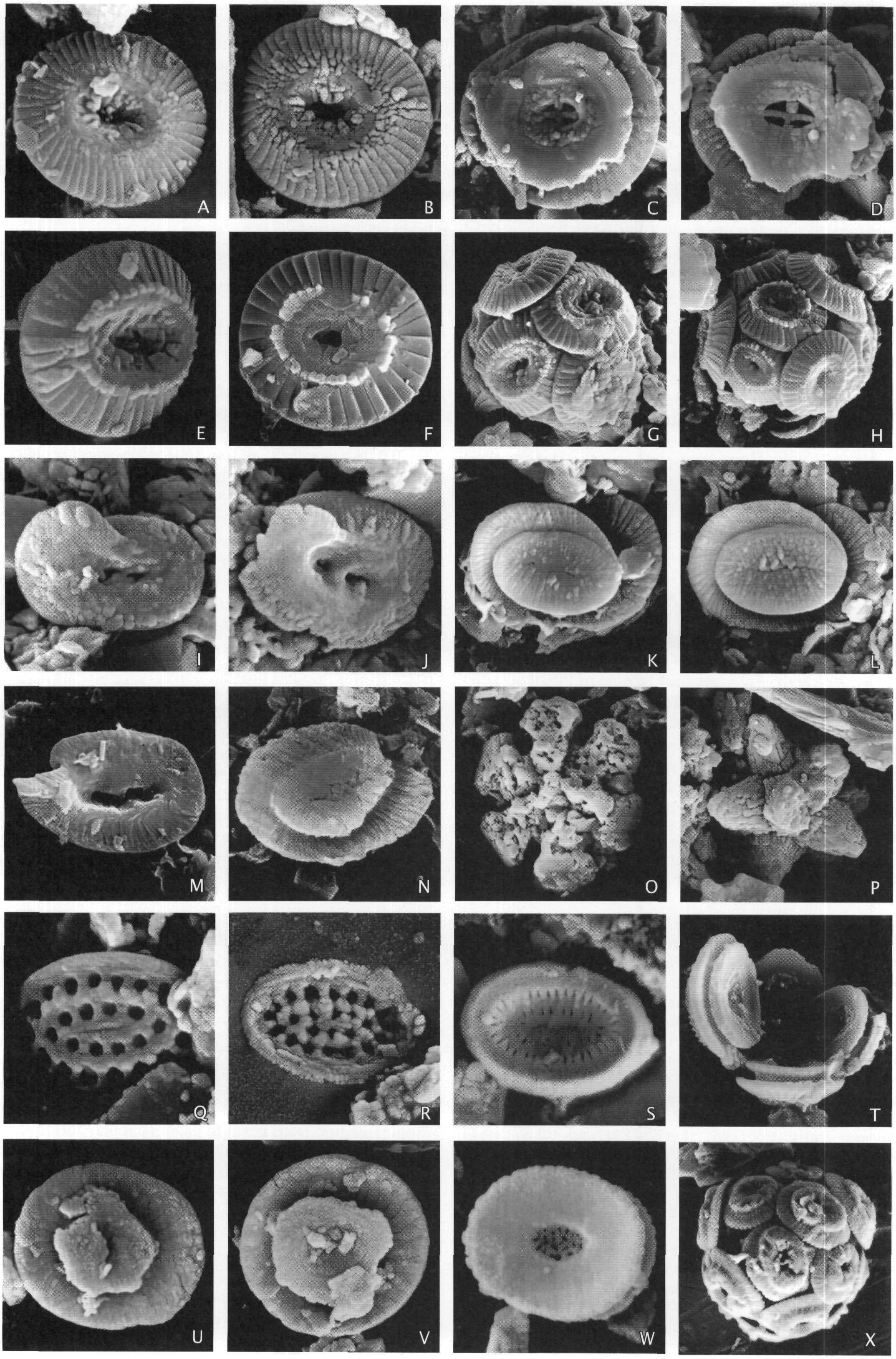
Benthic foraminifera

Ehrenbergina marwicki (Fig. 4A)

RECOGNITION: This species is highly distinctive (Scott 1973) and its occurrence is unlikely to be misidentified. *Ehrenbergina* cf. *bicornis* (FAD in Waitakian Stage) is tightly coiled whereas *E. marwicki* is largely uncoiled (Scott 1973).

DISTRIBUTION: The FAD occurs at 73 m (J39/f184, Fig. 5). The event is widely recorded in shelf and upper bathyal sequences in South Island and western North Island (Fig. 10). It is generally absent from deep-water sequences in Northland, eastern North Island, and Taranaki. Hayward & Buzas (1979, fig. 15, 21) recorded the greatest abundance of *Ehrenbergina marwicki* in upper bathyal deposits from northern New Zealand. Conversely, a study by Hayward & Brook (1994) of inner–outer shelf Otaian sequences from Waiheke Island, Auckland, failed to recover any *Ehrenbergina marwicki*. Examination of collections higher in the section (Scott 1965) show *Ehrenbergina marwicki* is absent from the upper siltstone lithofacies and Southburn Sand at Bluecliffs. Early populations are small. At Bluecliffs, the species was not recorded in counts of <200 specimens until 5.1 m above its first occurrence in strews of several thousand specimens. Li & McGowran (1994) suggested that *Ehrenbergina marwicki* was a "deep-cold" species in the neritic Miocene assemblages at Lakes Entrance, Victoria; Li & McGowran (1997) placed it in their "outer neritic" group which inhabited depths of c. 150 m or more. At Bluecliffs, its FAD follows a spike in abundance of spinose globigerinids at 70 m, which possibly signals a cool-climate episode.

BIOSTRATIGRAPHIC UTILITY: No ancestral taxon has been identified in the New Zealand region, and the FAD is interpreted as a migration event. As such, it is sharply defined, although small population sizes may constrain precision in locating its exact position. The principal constraint on the use of the FAD is its restriction to shelf and upper slope sequences, although Hayward & Buzas (1979) documented its widespread but rare occurrence from a wide paleodepth range in Otaian strata of northern New Zealand. Whether the FAD maintains a consistent stratigraphic position from basin to basin is poorly tested. There are significantly different values of an index of evolutionary morphology in *Haeuslerella* near the FAD of *E. marwicki* in southeastern South Island sections (Scott 1973, fig. 16). If the FAD is related to the inferred cool-climate event with which it is associated at Bluecliffs, it may be useful in regional chronology. Data from the Lakes Entrance sequence in Victoria are ambiguous. There the FAD is closely above the LAD of *Globigerina euapertura* (Li & McGowran 1997), as at Bluecliffs (Fig. 5). However, they also position the FAD of *Ehrenbergina marwicki* below the FAD of *Globigerina*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woodi and FAD of *G. connecta*, whereas at Bluecliffs it is well above the latter events.

Spiroloculina novozealandica (Fig. 4B)

RECOGNITION: *Spiroloculina canaliculata* (Bortonian–Tongaporutuan) might be confused with *S. novozealandica*. In both taxa, chambers are rectangular in cross-section. Wall junctions are weakly rounded in *Spiroloculina novozealandica* but are usually angular in *S. canaliculata*. In some specimens of *Spiroloculina canaliculata*, side walls are slightly concave, with raised sutures. Commonly, specimens of *Spiroloculina novozealandica* are larger and more robust than *S. canaliculata*. If the material is well preserved and carefully observed, the two taxa can be discriminated reliably.

DISTRIBUTION: The FAD is at 89 m (J39/f201, Fig. 5) at Bluecliffs. This species is mainly confined to shelf and upper bathyal environments. It is widely distributed in these habitats throughout New Zealand (Fig. 10) although Hayward & Buzas (1979) and Hayward & Brook (1994) failed to record it from a variety of paleodepths from northern New Zealand. It is generally absent from deeper water assemblages in eastern North Island, Taranaki, and Northland. Populations are often small. For example, it occurs only twice in the benthic census (counts <200 specimens) at Bluecliffs. Examination of material stratigraphically higher in the section than examined for this study (earlier collections re. Scott 1965) show it to be a persistent component of the fauna. It is found throughout the upper siltstone lithofacies (Fig. 3) but is absent from the Southburn Sand.

BIOSTRATIGRAPHIC UTILITY: Provided that confusion with *Spiroloculina canaliculata* is avoided, the FAD is well defined morphologically. Small population sizes affect precision in locating the FAD which, commonly, is in the near vicinity of that for *Ehrenbergina marwicki*. Because the biofacies distribution of this species is similar to *Ehrenbergina marwicki*, it does not significantly extend the range of environments in which the Waitakian-Otaian boundary can be identified.

Planktonic foraminifera

Potentially, the wide distribution of planktonic foraminifera from middle neritic through oceanic environments might reduce the biogeographic limitations of benthic taxa used to define the stage boundary. However, there are few bioevents in the small cool-temperate assemblages, and none coincide with the stage boundary. We focus on the discrimination of several that occur in the vicinity of the boundary and should be useful in regional biostratigraphy.

Globigerina brazieri (Fig. 7I–M)

RECOGNITION Jenkins (1966), Topping (1978), Chaproniere (1988), and Hornibrook et al. (1989) all noted the close morphological similarity of this species to *Globigerina woodi* s.l., with which it usually occurs. Topping (1978) showed that variation in measured characters overlapped among *Globigerina woodi woodi* (Fig. 7A–C), *G. woodi connecta* (Fig. 7E–G), *G. apertura*, *G. labiacrassata*, and *G. brazieri*. However, *Globigerina brazieri* was discriminated from *G. woodi woodi* with only minor misclassification when 20 variates were jointly considered. Such analyses are impractical for routine biostratigraphy, and it is necessary to use qualitatively determined character states to discriminate *Globigerina brazieri* from *G. woodi* s.l. The most objective is a high primary aperture which spans the penultimate and antepenultimate chambers (Fig. 7I) (Jenkins 1966, fig. 6 #43, #49; Kennett & Srinivasan 1983, pl. 7 fig. 7; Chaproniere 1988, pl. 2 fig. 1, 4; not Berggren 1992, pl. 1, fig. 4, 5). Of the two characters, aperture attachment is considered to be more significant than aperture height. Usually, specimens with these features are compact, with 3–3.5 chambers in the outer whorl. Specimens in which the aperture spans the penultimate (*n*–1th) and *n*–3rd chambers typically are less compact as they include most of a fourth chamber in the outer whorl.

DISTRIBUTION: The LAD is placed at 47 m (J39/f159, Fig. 5) at Bluecliffs. Using the abundance of spinose globigerinids as a climate proxy, the LAD occurs at the close of a warm-climate episode associated with reduced sediment flux. The section may be condensed in the vicinity of the LAD. The event is recognised throughout New Zealand (Fig. 10) in Jenkins' (1966) *Globigerina woodi connecta* Zone. It is similarly placed in southeastern Australia (Chaproniere 1988). Northward, Jenkins & Srinivasan (1986) recorded the LAD in Zone N8 from DSDP Site 588 (26°S) and this position is also cited by Kennett & Srinivasan (1983). They regarded it as a warm-temperate to subtropical species.

BIOSTRATIGRAPHIC UTILITY: The principal merit of the LAD is its wide dispersal in the New Zealand region (Fig. 10), complementing the landward, shallow-water

◄ **Fig. 9** Calcareous nannofossils from Bluecliffs, SEM micrographs. J39/fxxx = locality (see Fig. 2). Gxxxx/xx = negative in collections of Stratigraphic Solutions Ltd, Waikanae. **A–D**, *Coccolithus miopelagicus* Bukry. A (J39/f215; ×2650; G1650/16; distal view). B (J39/f215; ×2850; G1651/14; distal view). C (J39/f147; ×2850; G1652/19; proximal view—with central cross). D (J39/f215; ×2800; G1651/34; proximal view—with cross). **E–H**, *Coccolithus ovalis* (Black); J39/f215. E (×4700; G1650/14; oblique distal view). F (×5500; G1655/22; distal view). G (×2800; G1650/4; coccosphere). H (×2500; G1650/19; coccosphere). Note prominent diagenetic ring of tube cycle laths. **I–L**, *Helicosphaera carteri* (Wallich); J39/f215. I (×3950; G1651/35; distal view, plated). J (×6100; G1651/31; distal view, plated). K (×3650; G1650/11; proximal view, flared flange). L (×4100; G1651/8; proximal view). **M**, *Helicosphaera obliqua* (Bramlette & Wilcoxon) (J39/f215; ×3550; G1655/24; distal view). **N**, *Helicosphaera euphratis* Haq (J39/f147; ×5000; G1655/16; proximal view). **O**, *Discoaster deflandrei* Bramlette & Reidel (J39/f215; ×3000; G1650/21; plan view—note corrosion pits). **P**, *Micrascidites vulgaris* Deflandre & Deflandre-Rigaud (J39/f215; ×2250; G1651/10; ascidian sclerite, aragonitic). **Q–S**, *Pontosphaera multipora* (Kamptner); J39/f215. Q (×5800; G1651/13; distal view). R (×4800; G1652/8; distal view, corroded). S (×5000; G1656/14; proximal view). **T**, *Cyclicargolithus floridanus* (Roth & Hay) (J39/f215; ×3200; G1650/15; damaged coccosphere). **U, V**, *Calcidiscus leptoporus* (Murray & Blackman); J39/f147. U (×6100; G1658/19; proximal view—note oval distal shield). V (×5900; G1658/20; proximal view). **W, X**, *Reticulofenestra* sp.; included in Table 3 as Prinsiaceae indet. (small). W (J39/f147; ×10 200; G1658/7; proximal view). X (J39/f215; ×2950; G1656/16; coccosphere).

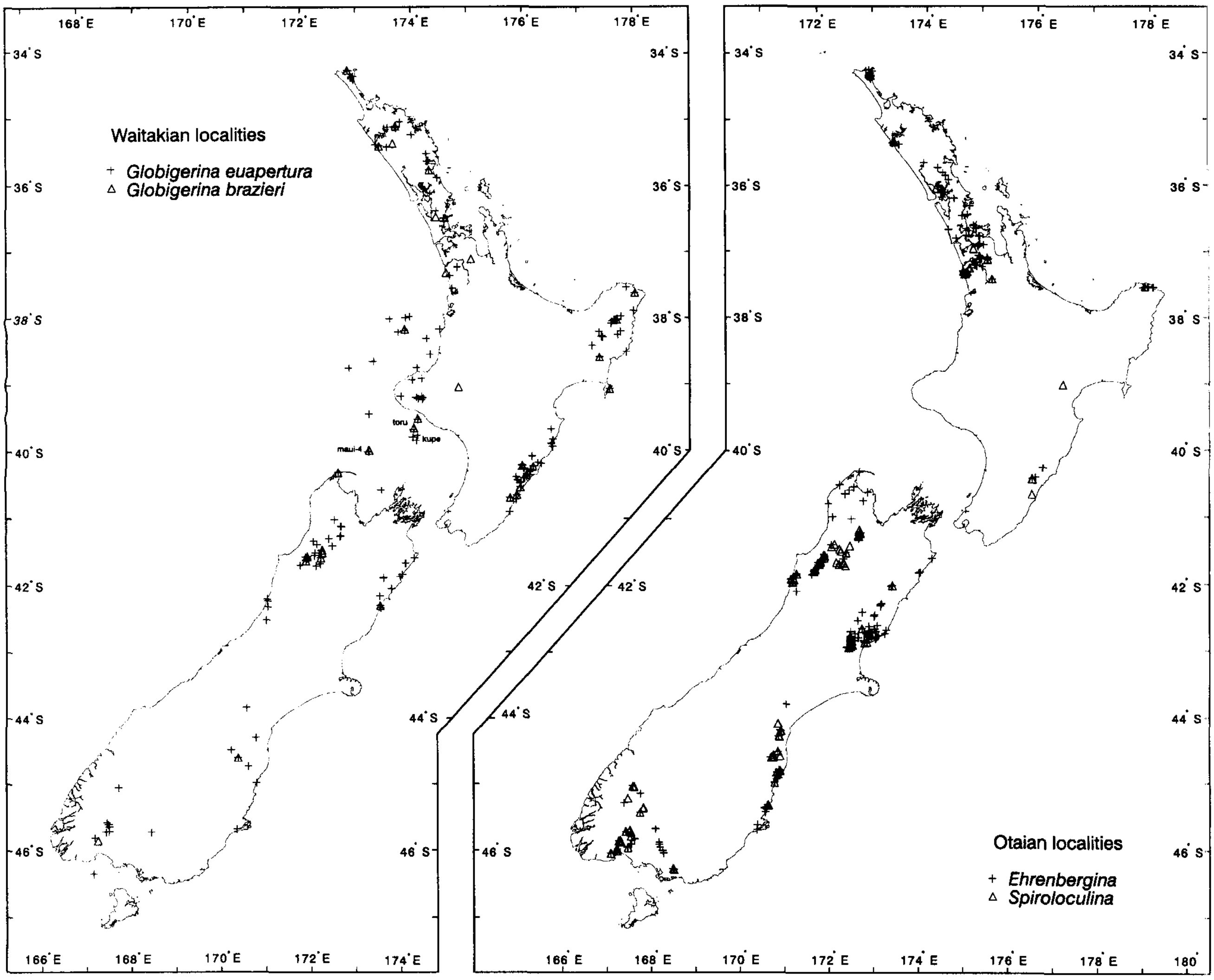

Fig. 10 (*Left*) Waitakian records of *Globigerina euapertura* and *G. brazieri*. (*Right*) Otaian records of *Ehrenbergina* and *Spiroloculina*. Both were extracted from New Zealand Fossil Record File database, July 1997. The data refer primarily to collections kept on open file at the Institute of Geological & Nuclear Sciences, Lower Hutt. A significant number of identifications made before 1950 are not in the database. Summary biostratigraphic data were inspected for each record but specimens were not examined. The records are not necessarily adjacent to the boundary between Waitakian and Otaian Stages. Only localities with eight-digit New Zealand Map Grid references are plotted. Due to these constraints, some subsurface records of *G. euapertura* from Taranaki Basin are not shown. However, for the generally deep water eastern North Island basin, the plots show the greater dispersal of *Globigerina euapertura* relative to *Ehrenbergina* and *Spiroloculina*.

distribution of the benthic foraminiferal events that define the Waitakian-Otaian boundary. While the LAD is less well defined, morphologically, than the benthic events, the criteria previously given enable it to be recognised objectively. Significant demerits as a boundary proxy are its 26 m displacement below the boundary at Bluecliffs, impersistence of populations (Fig. 11), and low abundance, even in offshore assemblages with abundant planktonic specimens. Although the event is apparently diachronous in the Southern Hemisphere, it may not be significantly so in New Zealand and southeastern Australian temperate water masses.

Globigerina euapertura (Fig. 7N–R)

RECOGNITION: Although *Globigerina euapertura* is readily identifiable for much of its history, discrimination of its latest populations from *G. woodi* is difficult. This problem has been largely ignored in the literature yet affects use of the event in biostratigraphy. Hornibrook et al. (1989, p. 126) commented that it was "Not a particularly distinctive taxon." Topping (1978) and Kennett & Srinivasan (1983) did not discuss *Globigerina euapertura*, whereas Chaproniere (1988, 1992) referred it to *Turborotalia*. Although the *Globigerina woodi* plexus may be phyletically distinct from *G. euapertura*, as is implicit in Chaproniere (1988, 1992), the taxa have some major characters in common. These include cancellate ("honeycomb") wall topography, low trochospiral shells with c. 3.5–4 chambers in the outer whorl, moderate rates of chamber expansion in the outer whorl, and apertures that span the *n*–1th and *n*–3rd chambers and principally face into the umbilicus. Variation in other characters overlap and do not provide a basis for simple categorical distinctions. In combination, several of the following are useful. In *Globigerina woodi* the aperture

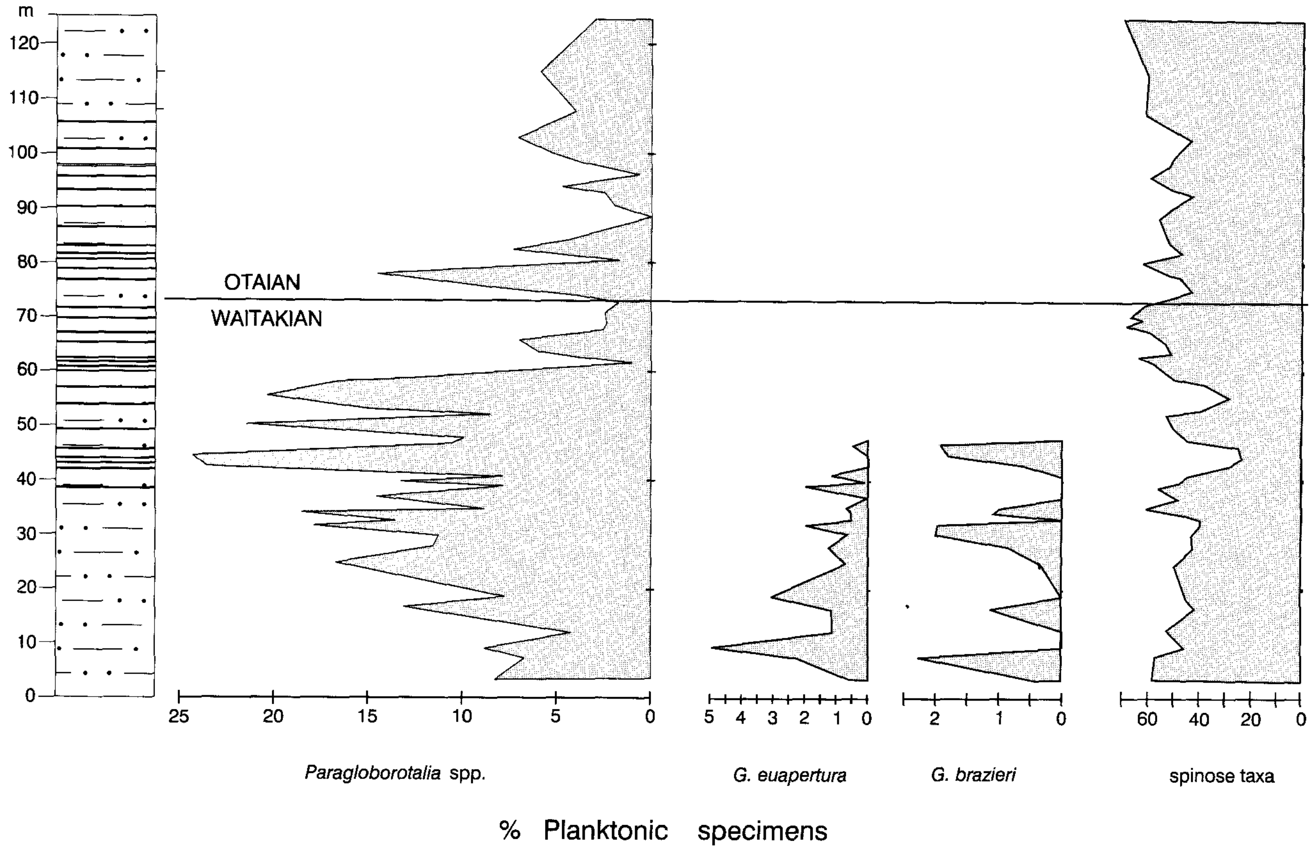

Fig. 11 Census data on potentially useful biostratigraphic events below the Waitakian-Otaian boundary. There is an abrupt decline in *Paragloborotalia* spp. above 55 m, which is interpreted as a population "crash". Populations of *Globigerina euapertura* decline up to their disappearance from the census at 47 m. There is one higher record at 58 m (not present in the census data). The pattern is consistent with niche contraction leading to extinction. *Globigerina brazieri* is rare and impersistent before its extinction. In the census data this coincides with an increase in spinose globigerinid specimens, possibly marking the inception of a cool-climate episode.

typically is high and the locus of maximum elevation faces directly into the umbilicus. It has a conspicuous poreless rim. The aperture forms a lower arch in most specimens of *Globigerina euapertura*. It faces directly into the umbilicus in some individuals, possibly including the holotype (Jenkins 1960, pl. 1 fig. 8b), but in others (Fig. 7Q) it is weakly oblique in axial orientation and very weakly extraumbilical. Often, the rim is narrow and sometimes concealed (Jenkins 1971, pl. 16, fig. 462), but there are specimens in which it is raised and prominent. Sutures are less depressed in *Globigerina euapertura* than in *G. woodi* and the shell outline is consequently less lobulate. Although chamber outlines are nearly hemispherical in *Globigerina woodi*, they are slightly elongated in the direction of coiling in *G. euapertura*, creating a weakly depressed outline. In some individuals the last chamber is set back farther from the umbilicus than in *Globigerina woodi.*

DISTRIBUTION: The number of specimens fluctuates (Fig. 11) but progressively declines through the lower siltstone lithofacies at Bluecliffs. The highest record in the census is with *Globigerina brazieri* at 47 m (J39/f159), at the end of a warm-climate episode as inferred by the relatively low abundance of spinose taxa (Fig. 5). From examination of much larger strews, we locate the LAD 11 m higher (J39/f169). This horizon is at the termination of the next warm-climate episode and is in the near vicinity of J39/7602 (S111/f602) from which Jenkins (1971, p. 147) recorded *Globigerina euapertura.* We have inspected his material and confirm the identification. *Globigerina euapertura* is widely distributed throughout New Zealand in Waitakian strata (Fig. 10).

BIOSTRATIGRAPHIC UTILITY: Although Hornibrook et al. (1989) stated that the LAD was a lower Waitakian event, our data show that it occurs 15 m below the FAD of *Ehrenbergina marwicki* and might be regarded more properly as a stratigraphically inferior proxy for the Waitakian-Otaian boundary. The LAD is more widely recorded than that of *Globigerina brazieri* (Fig. 10) but may not have been recognised consistently because of the problem of discriminating specimens from *G. woodi.* This is its principal demerit. Another is the indication of small, fluctuating populations immediately preceding the LAD at Bluecliffs (Fig. 11). The data suggest that specimen numbers may be climate related. The rarity of specimens, and likely impersistency of populations, indicates that the LAD is difficult to determine accurately.

Abundance of ***Paragloborotalia*** (Fig. 8A–E)

RECOGNITION: The principal taxa are *Paragloborotalia nana nana* (Fig. 8A, B), *P. nana semivera* (Fig. 8C, D), and *P. nana pseudocontinuosa* (Fig. 8E). Although these taxa have many similarities and are difficult to separate, the

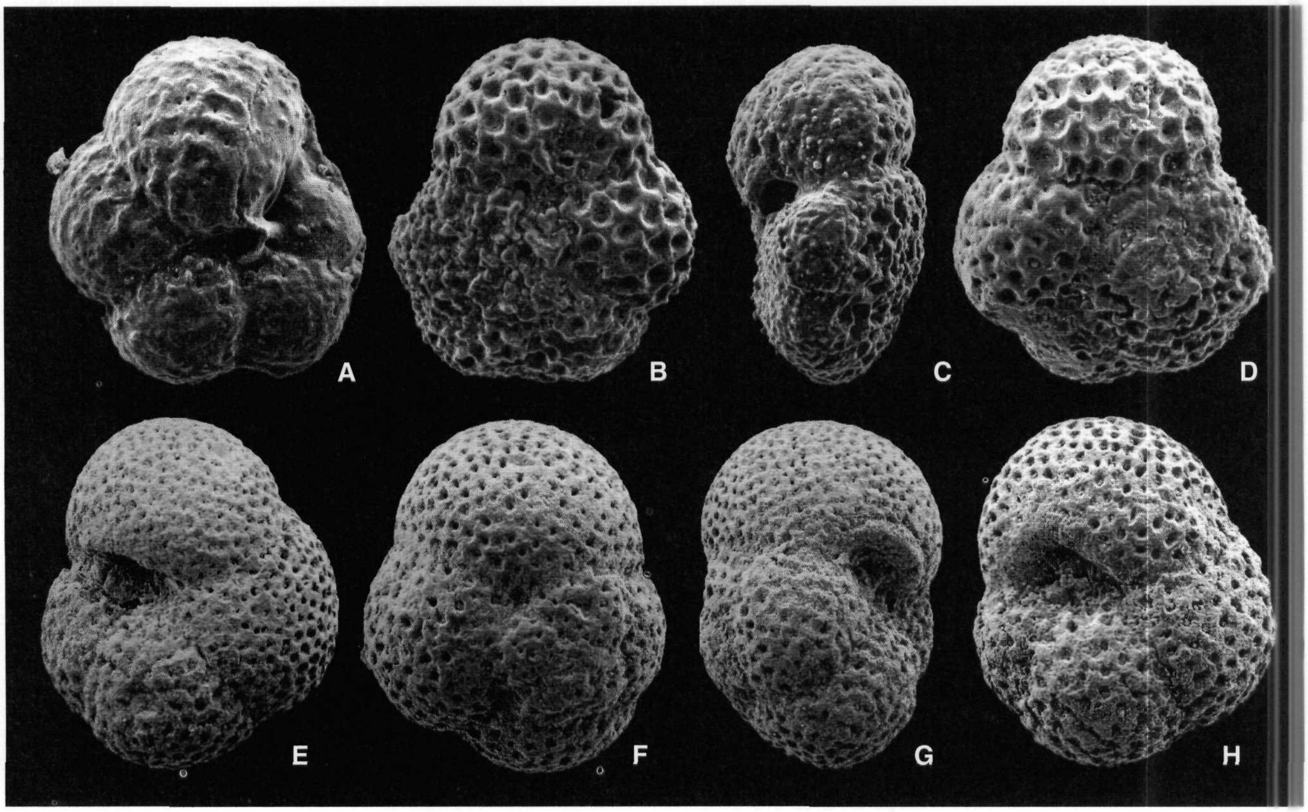

Fig. 12 Planktonic foraminifera from Bluecliffs, SEM micrographs. J39/fxxx = locality (see Fig. 2). FPxxxxx = catalogue number of specimen in foraminiferal collections at Institute of Geological & Nuclear Sciences, Lower Hutt. md = maximum dimension. **A–D**, *Globorotalia* cf. *kugleri* Bolli; J39/f7617. A (FP4558; md = 0.11 mm). B (FP4559; md = 0.14 mm). C (FP4560; md = 0.13 mm). D (FP4561; md = 0.14 mm). **E–H**, *Globorotalia* cf. *incognita* Walters; J39/f134. E (FP4562; md = 0.25 mm). F (FP4563; md = 0.27 mm). G (FP4564; md = 0.28 mm). H (FP4565; md = 0.26 mm).

abundance data (Fig. 11) refer to the generic representation, and discrimination is not a significant problem. Some forms are referred to *Globorotalia* cf. *incognita* (Fig. 12E–H) but are a minor part of the *Paragloborotalia* plexus. Although there are excursions, the relative abundance of *Paragloborotalia* climbs from 8% near the base of the section to 24% at 45 m. Larger excursions follow and abundance spikes decrease between 45 and 55 m. The latter position marks the inception of a steep decline in relative abundance to 1% at 62 m (J39/f172). There is a recovery to 15% at 78 m, but for most of the interval above the boundary values are <10%. In detail, the signature appears to be cyclic at frequencies <10 m, stratigraphically, but more closely spaced samples are needed to establish the pattern. Biostratigraphically, the most distinctive feature is the population crash at 62 m.

DISTRIBUTION: *Paragloborotalia* is widely distributed in Early Miocene planktonic foraminiferal assemblages but we lack comparable abundance data. The crash at 62 m is coincident with a small increase in spinose globigerinids (Fig. 11) and excursions in oxygen isotopes (Fig. 5). A climatic response is suggested.

BIOSTRATIGRAPHIC UTILITY: If confirmed elsewhere, the population event between 56 and 62 m is potentially useful because it is sharply defined, stratigraphically, and occurs in an easily recognised taxon. It is approximately coincident with the LAD of *Globigerina euapertura*. It usefully may indicate inferior proximity to the boundary.

Nannofossils

Overview

There are no published studies on the nannofossils of Bluecliffs other than Kadar's (1983, pp. 108–9) list of the taxa in a sample collected from about the same horizon as our highest sample. His list is similar to ours once nomenclatural changes and likely different taxonomic concepts are taken into account. The main differences are Kadar's records of *Coronocyclus nitescens* and *Triquetrorhabdulus milowii*. *Coronocyclus nitescens* is a distinctive taxon that preferred fully oceanic conditions (A.R.E. unpubl.), and its apparent complete absence from our samples at Bluecliffs was not anticipated. Conversely, *Triquetrorhabdulus milowii*, a stenothermal warm-water taxon, was not expected to occur at Bluecliffs, and the records may refer to specimens of *Micrascidites vulgaris* (Fig. 9P) in which some arms have been disarticulated.

Special mention should be made of the presence of *Reticulofenestra* sp. ("clifdenensis") (Table 3). This large, distinctive, unnamed taxon resembles the Late Eocene – Early Oligocene species *R. oamaruensis*. Always rare, it occurs sporadically in New Zealand in strata of upper Waitakian – lower Lillburnian (Early–Middle Miocene) age, including the Altonian of Clifden. Also worth noting is the occasional presence of specimens of *Calcidiscus leptoporus* (Fig. 9U, V). They represent one of the oldest known records of this long-ranging Neogene species.

Recycled nannofossils sporadically present at Bluecliffs, some as well-preserved specimens, include *Chiasmolithus altus*, *C. oamaruensis*, *Reticulofenestra bisecta*, *R. placomorpha*, and *Zygrhablithus bijugatus*. Their presence indicates the occurrence, somewhere along or upslope, of a fully marine sequence of Late Eocene and Oligocene age.

Craigmore Limestone

None of the Craigmore Limestone nannofloras are sufficiently diverse to allow them to be dated accurately or placed with any certainty in any particular zone (Table 3). However, their stratigraphic position indicates that they might be impoverished *Helicosphaera euphratis* Zone assemblages. Furthermore, it may be significant that the richest two assemblages lack *Reticulofenestra bisecta*, a robust and ubiquitous taxon that became extinct in the lower Waitakian. Thus, a middle or late Waitakian age is plausible for this part of the Craigmore Limestone.

Waitoura Marl, Bluecliffs Silt

The nannofloras of the Waitoura Marl and Bluecliffs Silt contain *Helicosphaera carteri*, and *Discoaster deflandrei* is the only discoaster present (Table 3). Thus, they can be placed in the *Helicosphaera euphratis* Zone of Edwards (1982). Although this zone was originally thought to range in age from earliest Otaian to middle Altonian (Edwards 1982), the results of the present study indicate that the base of the zone occurs within the upper Waitakian. Furthermore, *Calcidiscus macintyrei* s.l., *Discoaster variabilis*, and *Reticulofenestra pseudoumbilica*, all of which first appear in the younger (upper Otaian – mid Altonian) part of this zone, are not present. Also not observed, possibly due to cooler water temperatures, are several other biostratigraphically useful early Neogene nannofossils. They include *Discoaster druggi*, *Helicosphaera ampliaperta*, *H. recta*, *Ilselithina fusa*, *Sphenolithus belemnos*, *S. conicus*, and *Triquetrorhabdulus carinatus*.

Abundance of ***Helicosphaera***

The only biostratigraphically significant nannofossil event observed in the sequence at Bluecliffs is a reversal in the abundance of *Helicosphaera carteri* and *H. euphratis*. It occurs very close to the Waitakian-Otaian Stage boundary and probably is best characterised as the top of the acme of *H. euphratis* (Table 3). An important bioevent in the Mediterranean region (Fornaciari & Rio 1996), it may also be a useful correlation tool within the New Zealand region.

Dinoflagellates

Dinoflagellate cysts occur throughout the Bluecliffs Silt in reasonable diversity (Table 4), with assemblages typical of the Oligocene–Middle Miocene. It is difficult to assign a precise age because of the apparent lack of stratigraphically important taxa, and no obvious bioevents near the Waitakian-Otaian Stage boundary were observed. The relative lack of data on known ranges of Oligocene and Miocene dinoflagellates in New Zealand hinders the usefulness of this group in this part of the column.

Palynoflora

Pocknall (1982) recorded diverse floras of 30 spore, 8 gymnosperm, and 88 angiosperm taxa in 21 collections (Fig. 2) from Bluecliffs Silt and assigned them all to the

Table 4 Dinoflagellate distribution chart for selected samples (Fig. 2) from Bluecliffs.

Fossil record number J39/ Catalogue number	f116 L17626	f121 L17627	f125 L17628	f7594 L10142	f7600 L10143	f7606 L10144	f182 L17629	f7612 L10145	f7613 L10146	f7616 L10147	f7619 L10148	f7626 L10149
Chiropteridium lobospinosum		x										
Cassiculosphaeridia sp.		x										
Systematophora placacantha		x	x	x						x	x	
Operculodinium centrocarpum		x	x			x	x					
Deflandrea cf. *heterophlycta*		x			x							
Lejeunecysta sp.			x									
Phtanoperidinium sp.			x									
Cordosphaeridium sp.			x									
?*Pyxidinopsis* sp.			x									
Saturnodinium sp.			x									
Chiropteridium spp.			x				x					
Hystrichokolpoma rigaudiae			x									
Impagidinium cf. *victorianum*			x									
Nematosphaeropsis balcombiana			x									
Operculodinium tiara			x		x		x		x		x	x
Thalassiphora sp.			x				x					
Spiniferites ramosus			x				x	x	x			x
Hystrichokolpoma sp.			x				x			x		
?*Corrudinium* sp.				x								
Deflandrea phosphoritica				x		x			x	x	x	x
Cleistosphaeridium sp.				x				x			x	
Plerodinium cingulatum						x				x	x	
Membranilarnacia sp.							x					
Deflandrea leptodermata							x					
Polysphaeridium cf. *zoharyi*							x					
Operculodinium sp.												x
Thalassiphora pelagica												x

Proteacidites isopogiformis Zone (Pocknall & Mildenhall 1984). The palynofloras were notable for the consistency of dominant palynomorphs, and no significant events were seen near to the Waitakian-Otaian boundary.

Molluscs

The following data were supplied by Alan Beu (pers. comm. 1997).

The lowest localised collection (J39/f579), from the base of the banded lithofacies, includes *Limopsis*, *Globisinum miocaenicum*, *Proximitra rutidoloma*, *Spinomelon*, *Comitas fusiformis*, and *Zeacuminia*. It includes a specimen of *Notocorbula humerosa* whose size resembles small Otaian populations rather than the large specimens of Waitakian populations. Otherwise the collection is not age diagnostic.

A collection (GS3699, J39/f7496) from the lower third of the banded lithofacies has a typical Otaian assemblage, including *Spissatella trailli*, *Zeacolpus woodhouseae*, *Bathytoma haasti*, and *Austrotoma lawsi* and was assigned to Otaian Stage by Marwick (1971). Other collections from the banded siltstone lithofacies below the Otaian boundary lack diagnostic Waitakian taxa and resemble Otaian faunas from higher in the section.

Bluecliffs Silt assemblages are uniform in composition and compare with those from similar lithofacies in Mount Harris Beds and Rifle Butts Formation to the south. They contrast with the shallower assemblage in the Waitakian stratotype at Trig Z. This overview indicates that some molluscan FAD events cited for Otaian by Finlay & Marwick (1947) occur below the Waitakian-Otaian boundary stratotype as defined by the FAD of the foraminifer *Ehrenbergina marwicki*.

CORRELATION

New Zealand zones

Jenkins (1966) cited Bluecliffs section in his original proposal of the planktonic foraminiferal *Globigerina woodi connecta* Zone (Fig. 13). He noted that the LAD of *Globigerina brazieri* and LAD of *G. euapertura* occur in the lower part of the zone. *Globigerina woodi connecta* is present throughout the stream section and cliff section at Bluecliffs. The base of the zone probably lies in the unexposed interval above Waitoura Marl (Fig. 3). Craigmore Limestone and Waitoura Marl are correlated with the *Globigerina woodi woodi* Zone. Jenkins (1966) stated that the upper part of this zone is present in Otekaike Limestone in the Waitakian stratotype at Trig Z, Waitaki valley.

Exposures of Craigmore Limestone and Waitoura Marl and all of the stream section and cliff section sampled in this study lie in the lower part of the calcareous nannofossil *Helicosphaera euphratis* Zone (Edwards 1982).

Pocknall (1982) assigned Bluecliffs floras, including those from higher strata in the upper siltstone lithofacies (Fig. 2), to the *Proteacidites isopogiformis* Zone (Pocknall & Mildenhall 1984).

Tropical–subtropical zones

Jenkins (1971) recorded *Globorotalia* cf. *kugleri* in S111/f617, 619, and 626 from strata above the Waitakian-Otaian boundary at Bluecliffs. The material is tiny and atypical of *Globorotalia kugleri* (Fig. 12A–D). We consider that it is inadequate to identify reliably planktonic foraminiferal Zone M1 (Berggren et al. 1995), which is defined by the total range of the nominate species. Zone M2 refers to the interval between the LAD of *Globorotalia kugleri* and the FAD of *Globigerinatella insueta*. The only record of the latter in New Zealand is from V22/f6530, southern Hawke's Bay.

The Bluecliffs nannofloras lack the primary index species needed for exact correlation with either the standard low-latitude zonal scheme of Bukry (1973, 1975) and Okada & Bukry (1980) or the similar constructs (Fig. 13) of Martini (1971) and Martini & Muller (1986). However, some broad correlations are possible, after making nomenclatural and taxonomic adjustments, using some of the other bioevents mentioned by these authors. Thus, undifferentiated correlation with Bukry's (1973, 1975) Early Miocene CN1, CN2, and lower CN3 Zones is indicated by the known stratigraphic position of the Bluecliffs section above the LAD *Reticulofenestra bisecta* (a top CP19b bioevent) and below the FAD *Calcidiscus macintyrei* s.l. (upper CN3). Similarly, correlation with Martini's (1971) Early Miocene upper NN1 and NN2 Zones is indicated by the known stratigraphic position of the Bluecliffs section above the LAD *Reticulofenestra bisecta* (a basal NN1 bioevent), above the FAD *Helicosphaera carteri* group (mid NN1), and below the FAD *Calcidiscus macintyrei* s.l. (top NN2).

Temperate–transitional zones

Berggren et al. (1995) integrated zonations developed for several mid-latitude regions in hemispheres into a unified scheme (Fig. 13). Zone Mt1, like low-latitude Zone M1, is based on the range of *Globorotalia kugleri* and is not recognisable with certainty at Bluecliffs. Zone Mt2 is defined by the partial ranges of *Globorotalia incognita* and *Globorotalia semivera* between the LAD of *Globorotalia kugleri* and the FAD of *G. praescitula*. The latter event marks the Otaian-Altonian boundary and was recorded from Southburn Sand at Bluecliffs (Scott 1972). However, because of their dependency on the LAD of *Globorotalia kugleri* Zones Mt1–Mt2 cannot be resolved satisfactorily at Bluecliffs. This situation applies throughout New Zealand.

Tasman Sea

DSDP Site 593 (Jenkins & Srinivasan 1986) records a lower bathyal oceanic sequence at the western edge of Challenger Plateau, c. 500 km northwest of Bluecliffs, and provides an informative perspective on the zones developed by Jenkins (1966) and Edwards (1982) from onshore sequences. *Globigerina woodi woodi* and *Globigerina woodi connecta* Zones were recorded by Jenkins & Srinivasan (1986), who identified *Globorotalia kugleri* from both zones. Possibly Zones Mt1–Mt2 can be identified at DSDP Site 593. This is not possible in sequences around the New Zealand landmass and indicates the value of the globigerinid zones proposed by Jenkins (1966) in neritic settings.

The calcareous nannofossil correlation between Bluecliffs and Site 593 is based on the interval between the top of consistently present *Reticulofenestra bisecta* (and coincident top of *Helicosphaera recta* and *Zygrhablithus bijugatus*) to the base of *Calcidiscus macintyrei*, an interval that Lohmann (1986) assigned to Martini's NN1, NN2, and lower NN3 Zones. This correlation is compatible with, but somewhat broader than, that indicated by the planktonic foraminifera. The most obvious difference between the two

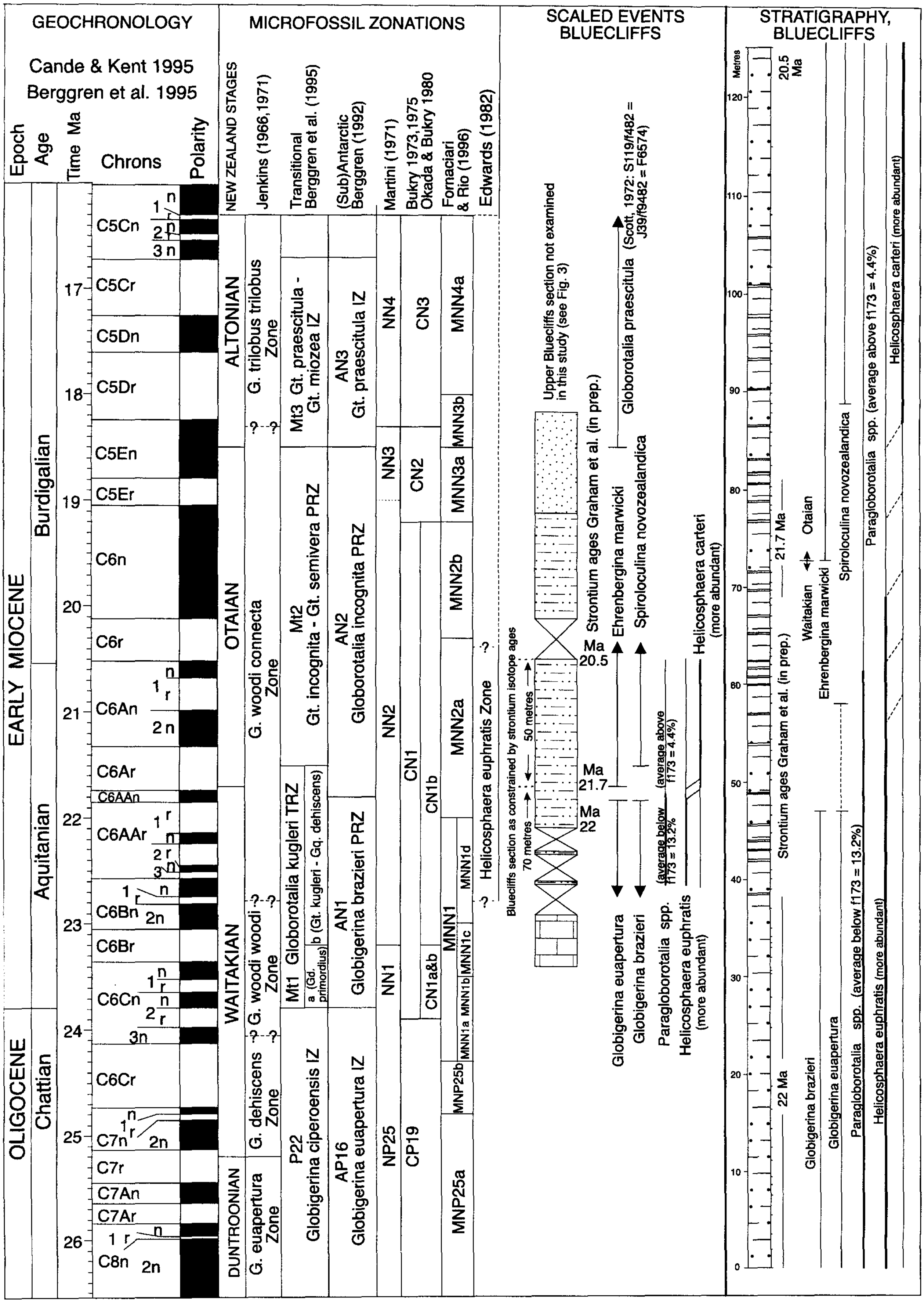

Fig. 13 Oligocene–Early Miocene geochronology, New Zealand stages, planktonic foraminiferal and calcareous nannofossil zonations. Geochronological data (*left*) and bioevent proxies from Bluecliffs (*centre*) are plotted on the international time-scale; (*right*) location of these data in the boundary section.

nannofloras is that *Coronocyclus nitescens*, *Discoaster druggi*, *Sphenolithus belemnos*, *S. dissimilis*, and *Triquetrorhabdulus carinatus* occur rarely at Site 593 but have not been found at Bluecliffs, and that *Helicosphaera* has not been recorded from this part of the Early Miocene at Site 593. It is likely that these dissimilarities reflect paleoenvironmental rather than biostratigraphic differences.

Southern oceans

As with other interregional Early Miocene schemes, the planktonic foraminiferal zonation (Fig. 13) proposed by Berggren (1992) for subantarctic sequences fits poorly with Bluecliffs data. The LAD of *Globigerina euapertura* is located at the base of Zone AN1 (= base of Miocene), whereas at Bluecliffs it occurs at the level of the LAD of *G. brazieri*, which defines the top of Subantarctic Zone AN1. However, Zone AN2 (for the interval between the LAD of *Globigerina brazieri* and the FAD of *Globorotalia praescitula*) is recognisable at Bluecliffs. The Waitakian-Otaian boundary lies near the base of this zone.

The Bluecliffs nannofloras correlate with an unnamed Early Miocene biostratigraphic interval recognised by Wei & Wise (1992) at ODP Sites 747, 748, and 751. Their unnamed interval, which they tentatively correlated with Bukry's Zones CN1–CN3, extends up from the top of *Reticulofenestra bisecta* to the base of "*Calcidiscus leptoporus–C. macintyrei*". In New Zealand, the LAD of *Reticulofenestra bisecta* is in middle Waitakian, whereas the FAD of "*Calcidiscus leptoporus–C. macintyrei*" is in upper Otaian (Edwards 1982).

Mediterranean

The Waitakian-Otaian boundary at Bluecliffs (Fig. 13) can be correlated directly with the calcareous nannofossil Zone MNN1–MNN2 boundary of Fornaciari & Rio (1996). Both are marked by a reversal in the abundance of *Helicosphaera carteri* and *H. euphratis*, specifically the top of the acme of *H. euphratis*. Fornaciari & Rio (1996) also indicated that this event provides an easy means of distinguishing between the Aquitanian and Burdigalian Stages in the Mediterranean region. The LAD of *Chiropteridium* spp. (Dinophyceae), which is present up to J39/f182 (Fig. 2), occurs in the Lemme-Carrisio Section, Italy, 1 m below the proposed position of the Oligocene-Miocene boundary (Steininger et al. 1997), although other evidence suggests the genus ranges into the Middle Miocene (Williams et al. 1993).

DATING

Paleomagnetism

Previous studies have shown New Zealand Neogene mudstones to have complex and variable paleomagnetic properties and behaviour. They generally have low-intensity primary magnetisation (generally $<10^{-3}$ A/m) commonly overprinted by secondary magnetisations (e.g., Wright & Vella 1988; Roberts et al. 1994; Wilson & McGuire 1995). Rock magnetic and petrographic investigations have demonstrated that common remanence carriers for these sediments are titanium-rich ferrimagnetic iron-oxides (titano-magnetite and hemo-ilmenite) and iron sulfide (greigite and pyrrhotite) minerals (Roberts & Turner 1993; Wilson & Roberts 1999). For these reasons, and also because the sediments from South Canterbury have not previously been studied for paleomagnetism, we conducted a pilot study of the Bluecliffs section to assess paleomagnetic behaviour and stability of remanence and to assess appropriate demagnetisation techniques.

All specimens measured from Bluecliffs were overprinted by a low-coercivity normal overprint from the present geomagnetic field. This was generally cleaned by 150°C of heating or peak alternating fields of 15 mT. Vector component plots were noisy, and stable endpoints were not reached before thermal alteration of the clay component of the specimens. Thermal demagnetisation allowed identification of trends in demagnetisation. Where primary remanence was of reversed polarity, a further normal geomagnetic field overprint overlapping in blocking temperature spectra prevented elucidation of a stable primary component (e.g., Fig. 14A, B). AF demagnetisation was not effective in cleaning this component and, in general, vector component plots for specimens cleaned by AF methods were noisy and showed random behaviour at peak fields above 20 mT (e.g., Fig. 14F, H). The minerals holding the magnetic remanence in the Bluecliffs section are of low coercivity and low unblocking temperature and do not always respond to AF demagnetisation methods. The signal is perhaps due to a combination of titanomagnetite and ilmeno-hematite grains, but the presence of partially reduced sulfides cannot be ruled out. Petrographic analysis revealed ubiquitous pyrite in several thin sections prepared from unheated paleomagnetic samples and minor titano-magnetite in one thin section (D. Smale pers. comm. 1993). The ubiquitous pyrite suggests full reduction of the iron-sulfide component of the Bluecliffs sediments.

Remagnetisation great circle analysis (for methodology see McFadden & McElhinny 1988) on several samples from within a small stratigraphic range (Fig. 15) demonstrates that, although stable endpoints were not identified, demagnetisation trends from a number of specimens can be used to identify a reliable endpoint for sites that are clearly trending towards a primary remanence of reversed polarity. More detailed and comprehensive paleomagnetic sampling and analysis will identify a magnetostratigraphy for the Bluecliffs section. However, several specimens must be collected from each site and they must be subject to a rigorous and closely spaced thermal demagnetisation procedure for site polarity means to be identified by great circle remagnetisation analysis.

Strontium isotopes

Whole rock, benthic, and planktonic foraminiferal shells were analysed for ^{87}Sr/^{86}Sr data. Sample locations are shown in Fig. 2. Analytical methods are discussed by Graham et al. (in press). Ages were obtained using the "look-up" tables of Howarth & McArthur (1997), relative to the time-scale of Cande & Kent (1995). For most of the section, benthic and planktonic foraminiferal shells give consistent but slightly offset ratios. Overall, they increase gradually up the section, although there are several excursions to lower ratios caused by interaction with pore fluids. Samples from the lower siltstone lithofacies between R16440 and R16693 (Fig. 13) have similar ratios corresponding to a mean age of c. 22 Ma. From 66 m (R16453), upward through the Waitakian-Otaian boundary at 73 m, to the highest sample

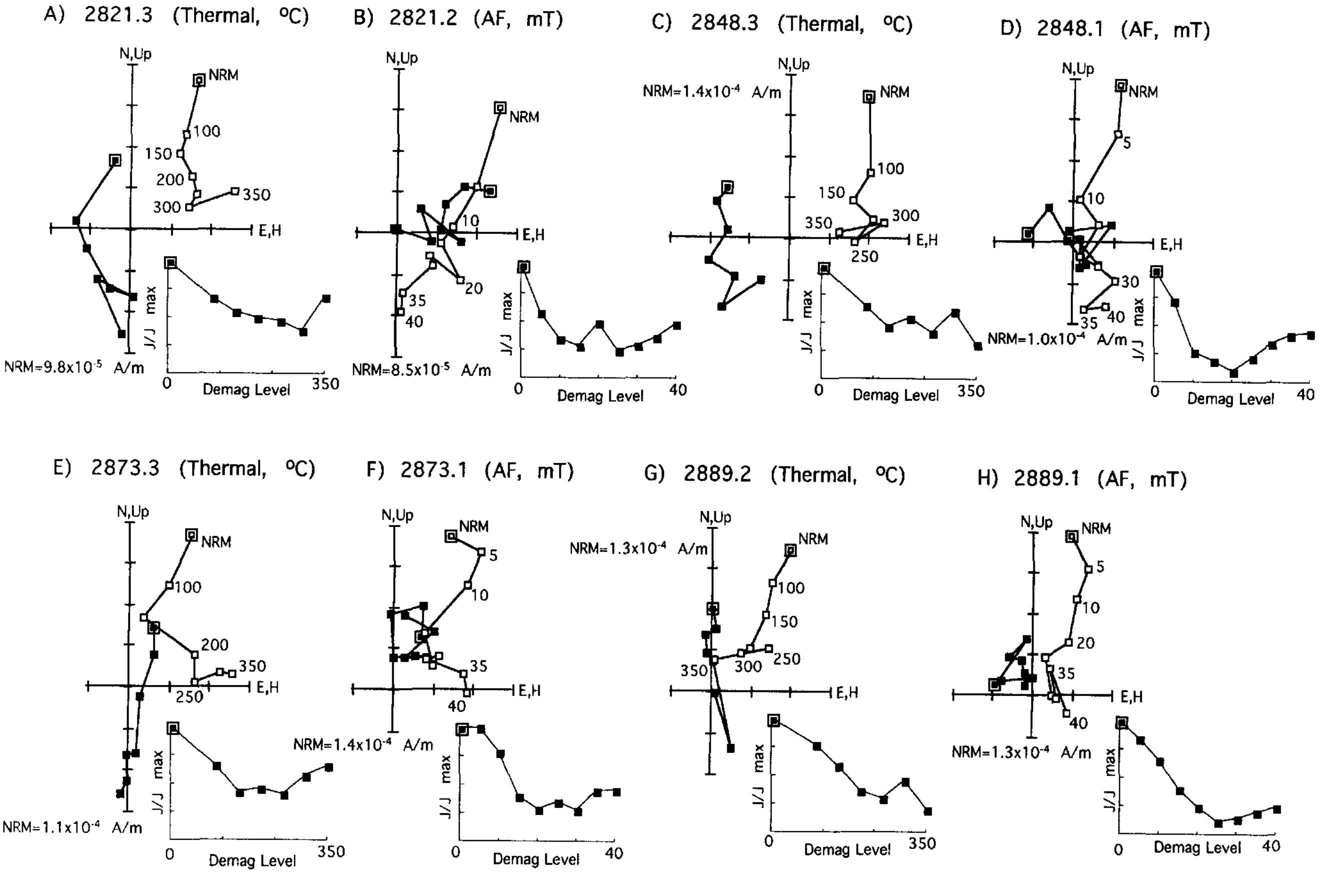

Fig. 14 Vector component diagrams of demagnetisation behaviour of representative samples (Fig. 2) from the pilot study of the Bluecliff section. **A**, **B**, Comparison of thermal and AF demagnetisation of reversed polarity trending samples 2821.3 and 2821.2, respectively. **C**, **D**, Comparison of thermal and AF demagnetisation of reversed polarity trending samples 2848.3 and 2848.1, respectively. **E**, **F**, Comparison of thermal and AF demagnetisation of reversed polarity trending samples 2873.3 and 2873.1, respectively. **G**, **H**, Comparison of thermal and AF demagnetisation of normal polarity samples 2889.2 and 2889.1, respectively.

(R16462) at 125 m, ratios increase smoothly. In the immediate vicinity of the Waitakian-Otaian boundary, they correspond to an age of 21.7 Ma. At 125 m the age is c 20.5 Ma, equivalent to the Aquitanian-Burdigalian boundary. Confidence limits for the ratios at the 95% level correspond with age ranges of ±0.25 Ma.

Stable isotopes

Wright & Miller (1992) located the base of oxygen isotope Zone Mi1a at a prominent enrichment event in Early Miocene benthic foraminiferal isotope data at 282.8 m bsf in north Atlantic DSDP Site 563. It occurs in Chron C6Ar (21.32–21.77 Ma, Cande & Kent 1995). To determine the presence of this event at Bluecliffs, carbonate from the benthic foraminifera *Cibicides novozelandicus* and *Euuvigerina* spp. was analysed from 46 samples at c. 2 m intervals through the section (Fig. 2, 5). Major features of the data are the generally heavier values and larger excursions for *Euuvigerina* spp. than for *Cibicides novozelandicus*, variable covariance of the signatures, and the presence of several enrichment/depletion cycles between 25 and 63 m. The largest excursion is the enrichment of 2.08‰ in *Euuvigerina* spp. between 34 and 43 m (Fig. 5). However, this is not mirrored by *Cibicides novozelandicus*, and we are uncertain of its climatic significance. The signatures covary more closely near the enrichment maximum in *Euuvigerina* spp. (1.73‰) at 63 m, although the amplitude of the excursion is much greater than in *Cibicides novozelandicus*.

Widely spaced samples, variable and sometimes weak covariance between the benthic signatures, use of benthic taxa not previously analysed in stable isotope studies, lack of data from planktonic carbonate, and the possibility of contamination or exchange with sedimentary carbonate in some samples inhibit robust interpretations of the data. Therefore, we rely on the gross pattern of the signatures, both of which record larger amplitude enrichment/depletion cycles between 25 and 63 m than elsewhere in the sequence, and identify this interval as a possible record of Mi1a.

Bioevent proxies

Globigerina brazieri

Li et al. (1992) recorded the LAD of *Globigerina brazieri* at 124 m bsf at ODP Site 747A, Kerguelen Plateau, in Chron C6Bn (Heider et al. 1992, 22.59–23.07 Ma). Berggren (1992) recorded the LAD in Chron C5En (18.28–18.78 Ma) at ODP Sites 747A and 748B, and in C5Dn (17.28–17.61 Ma) at ODP Site 751A (all Kerguelen Plateau). However, the specimens figured by Berggren (1992, pl. 1,

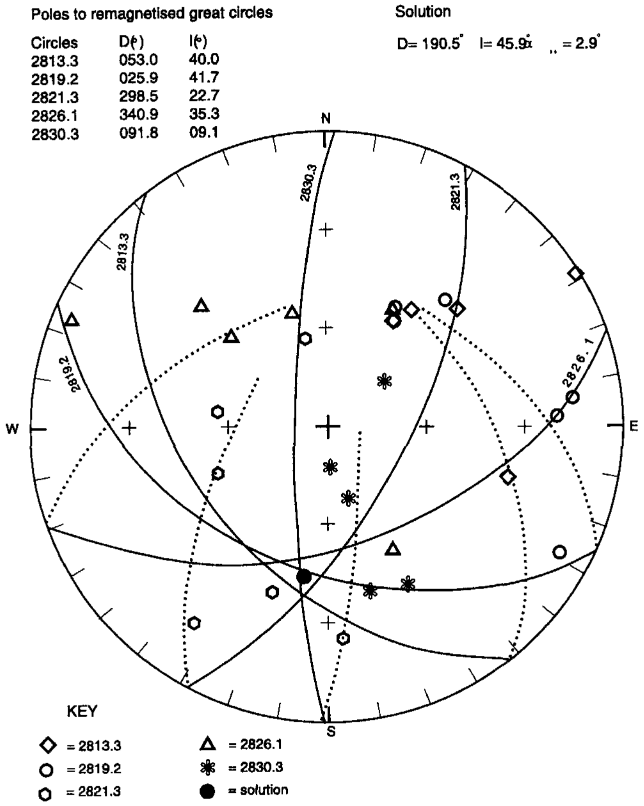

Fig. 15 Example of remagnetisation great circle analysis for obtaining the characteristic remanence direction for several specimens from a short stratigraphic interval.

fig. 4, 5) do not match our interpretation of *Globigerina brazieri*, and his data may not be relevant.

Globigerina euapertura

From records in ODP Sites 747A and 747B, Berggren et al. (1995) placed the LAD of *Globigerina euapertura* in Chron C6Cn.2n (23.68–23.80 Ma), at the Oligocene-Miocene boundary and before the FAD of *Globoquadrina dehiscens* (Chron C6Br, 23.07–23.35 Ma). This order conflicts with our record of the LAD of *Globigerina euapertura* well above the FAD of *Globoquadrina dehiscens*. The discrepancy may be due to the earlier extinction of *Globigerina euapertura* in southern high latitudes than at Bluecliffs, or conversely an earlier appearance of *Globoquadrina dehiscens* in New Zealand, or to differences in taxonomic concept.

Abundance of ***Helicosphaera***

The abundance reversal of the nannofossil taxa *H. euphratis* and *Helicosphaera carteri* occurs close to the Waitakian-Otaian Stage boundary. Correlation of this event with the Mediterranean Neogene zonal scheme of Fornaciari & Rio (1996), and with data in Steininger et al. (1997), indicates an age of less than 21.3 Ma, or c. 21 Ma. Although Fornaciari & Rio (1996) used the latter date for the Aquitanian-Burdigalian boundary, Berggren et al. (1995) placed it at 20.5 Ma. The age of the reversal event, less than 21.3 Ma, is too young compared to the strontium isotope date of 21.7 Ma. This inconsistency may be a combination of error on the strontium isotope date (±0.25 Ma) and a slightly earlier abundance reversal in New Zealand.

Chiropteridium **spp.**

The highest occurrence of this taxon is in sample J39/f182. In the proposed Paleogene-Neogene boundary stratotype in the Lemme-Carrosio section, Italy, its LAD is 1 m above the boundary (23.80 Ma, Steininger et al. 1997). However, other records suggest that the genus *Chiropteridium* extends into the Middle Miocene (Williams et al. 1993).

EVALUATION

We focus on features of the Bluecliffs section relevant to its utility as a reference for the Waitakian-Otaian boundary.

Sedimentary record

Although the stage boundary is conceptually a surface, we have examined a 125 m sequence about the boundary to place it in environmental context and to locate events in its vicinity that might serve as "near boundary" markers. The section meets primary reference requirements of good exposure and accessibility. The fine clastic lithofacies is relatively uniform throughout, apart from the cemented horizons in the banded lithofacies. Fossils are well preserved. The sequence has no structural complications and there are no indications of breaks in deposition.

In closer focus, the depositional record at Bluecliffs is much less uniform than field examination indicates. As judged by patterns of foraminiferal specimen abundance and supported by the coarse fraction signature, sediment influx was cyclic with a succession of well-defined minima that identify condensed intervals. The cyclic pattern centres on prominent events at 64 and 27 m below the boundary and wanes upward to be a minor feature at, and above, the boundary. The pattern suggests that the stratigraphic scale is unlikely to be a linear measure of time, particularly below the boundary. The pattern might affect the separation of closely spaced events occurring within any of the condensed intervals. To the extent that the sedimentary pattern is a eustatic response, it should be recorded below the boundary throughout the region.

Paleogeographically, the section represents a depositional site at upper bathyal depths, intermediate between shoreline and open ocean. No significant changes in this setting occur in the vicinity of the boundary, although the basin shallowed. New Zealand Cenozoic stages are local units used by stratigraphers studying landward marine and terrestrial basins. Only at the outer limits of the offshore economic zone are fully oceanic sequences encountered. In this perspective, the intermediate location of the Bluecliffs site is valuable as it records both terrestrial and oceanic events, although neither record is optimal. More limiting for correlation of local biostratigraphic units with regional and international equivalents is the southern setting of the site in the vicinity of a major water-mass boundary, the Subtropical Convergence (Edwards 1975). The absence of typical *Globorotalia kugleri* from the Early Miocene Canterbury Basin is an example of this paleogeographic restriction.

Bioevents

For biostratigraphy, the diverse biota preserved in Bluecliffs Silt is valuable as it associates bioevents with distinct biogeographies and potentially allows more rigorous testing of their stratigraphic order. While large molluscs and other macro-invertebrates are poorly represented near the boundary, probably because of the paleodepth, small molluscs occur in foraminiferal residues, as do ostracods. Among the protists, the foraminiferal record is excellent, although several significant siliceous groups (radiolarians, diatoms) have not been found in our material. Algae are well represented by coccoliths and dinoflagellate cysts. Importantly, for terrestrial correlations, there is a fair record of pollens and spores. In overview, with several exceptions, there is a good fossil record near the boundary at Bluecliffs. To a degree, the small number of bioevents currently suitable for biostratigraphy reflects the small amount of research on the preserved biota.

Climate is a powerful engine of biogeographic and evolutionary change. Although the existence of an episode of cool climate in the immediate vicinity of the boundary is not confirmed by the land flora, and the isotope data are inconclusive, patterns of marine bioevents in this vicinity indicate environmental change and faunal turnover. There are extinctions (*Globigerina brazieri* and *G. euapertura*) below the boundary. The waning and then intermittent representation of the latter (Fig. 11) before extinction suggest niche contraction and eventual loss (Maynard Smith 1989). Other taxa (e.g., *Paragloborotalia* spp.) survived through the boundary in small numbers, or responded with changes in dominance (*Helicosphaera euphratis*, *H. carteri*). In contrast, the appearance of the benthic foraminifers *Ehrenbergina marwicki* and *Spiroloculina novozealandica* might be viewed as migrants taking advantage of newly available territory. While these scenarios are speculative, they suggest that the present stratigraphic position of the Waitakian-Otaian boundary possibly is tuned to a significant environmental event and usefully located for biostratigraphy. Further events similar to those above might be found near the boundary and in the preceding c. 60 m.

CONCLUSIONS

The base of the Early Miocene Otaian Stage in its stratotype section at Bluecliffs is recognised as the boundary stratotype for the Waitakian and Otaian Stages. The FAD of the benthic foraminifer *Ehrenbergina marwicki* defines the boundary and occurs at 73 ± 1 m above the base of the section. The boundary is well exposed.

The fine clastic sequence adjacent to the boundary was deposited on a passive margin at upper bathyal depths in a basin defined by a submarine high and archipelago. The site was distant from shorelines. The cool-temperate water mass was in an intermediate position between neritic and oceanic water and possibly adjacent to the Subtropical Convergence. There was good southward fetch. Landmasses had a warm-temperate climate, were forest covered, and wet.

Abundance signatures of foraminiferal specimens below the boundary are cyclic. The spikes covary with declines in relative weights of coarse sediment (>75 µm fraction) and likely identify condensed intervals produced by highstands. On this interpretation there is a minor condensed interval at the boundary but neither here, nor through the preceding section which contains larger amplitude cycles, is there field evidence that the sequence is significantly incomplete. We consider that the sedimentary record of the section does not compromise its utility as a reference at the current level of biostratigraphic resolution.

Climatic instability through the c. 40 m section immediately underlying the boundary is indicated by cycles in the relative abundance of spinose globigerinids (a cool-water proxy) and by the oxygen isotope data for benthic taxa, although the two signals do not closely covary. Several planktonic foraminifera become extinct in this interval and there are major changes in the relative abundances of nannofossil and planktonic foraminiferal taxa. These events, and the cyclic sedimentary record in the same interval, may be connected with global oxygen isotope Zone Mi1a. Dating is insufficiently precise to confirm the linkage but it is possible that the Waitakian-Otaian Stage boundary is located close to a significant global climatic event and might be a useful local proxy.

The diverse biota in the vicinity of the boundary includes plankton and bottom dwellers, as well as a record of terrestrial vegetation. This diversity assists biostratigraphic studies by allowing events in several groups to be interrelated. However, the paleogeographic position of the section in a cool-temperate water mass at a southern site limits its utility as a reference, particularly in interregional correlation.

The FAD of *Ehrenbergina marwicki*, the primary event marking the Waitakian-Otaian boundary, is well defined in the section and widely distributed in outer shelf to upper bathyal marine biofacies around New Zealand. It should be retained. Molluscan events cited for the boundary by Finlay & Marwick (1947) occur in Waitakian strata significantly below the boundary and need to be reassessed. Supplementary, widely dispersed bioevents that identify the boundary are required.

We did not find high-resolution planktonic foraminiferal or calcareous nannofossil events in the immediate vicinity of the boundary that assist its recognition in offshore sequences. Below the boundary there are events (abundance changes in *Paragloborotalia* spp. and *Helicosphaera* spp., LAD of *Globigerina euapertura*) in these groups that appear to be useful "proximity" indicators.

Strontium isotopes date the boundary at 21.7 Ma. Although our work slightly modifies the date conjectured by Edwards et al. (1988), the need for improved precision remains. The conflict with the nannofossil date of c. 21 Ma also needs to be resolved. Paleomagnetic studies indicate that it should be possible to resolve a magnetostratigraphy for the section. A priority for future chronostratigraphic research should be the selection of a boundary parastratotype with quality polarity and diverse bioevent signatures.

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