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The Pliocene climatic and environmental evolution of southeastern Australia: evidence from the marine and terrestrial realm

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Abstract

During the Pliocene the global climate fluctuated markedly with the expansion and contraction of the Northern and Southern Hemisphere ice sheets. The signals of this change are well preserved in the thick (up to 1 km) Seaspray Group cool-water carbonate sediments in the Gippsland region and associated thin terrestrial deposits in southeastern Australia. This study uses seismic, facies, foraminiferal proxy data and palaeobotanical data to chart the Pliocene climate and environmental change in the marine and terrestrial realms of southeastern Australia. Complex submarine canyoning occurred at the shelf/upper bathyal transition during the Pliocene in Gippsland. Low-energy pelagic marl (wackestone/packstone) characterise canyon and inter-canyon environments in the earliest Pliocene, depositing plankton oozes with interbedded calciturbidites. From upper Early Pliocene to Late Pliocene time high-energy limestone (grainstone) facies infilled these submarine canyons associated with progradation of the succession from outer to middle shelf palaeoenvironments. Plankton proxy data suggest cool conditions in the basal part of Early Pliocene. Relatively stable warmer marine conditions prevailed throughout most of the Early Pliocene, corresponding to a period of globally low $\delta^{18}\text{O}$ values in the oceans associated with minor Antarctic ice sheet expansion. From middle to Late Pliocene time marked fluctuations in the abundance of cool and warmer water plankton taxa occurred, corresponding to a time of global marine $\delta^{18}\text{O}$ fluctuations and generally heavier $\delta^{18}\text{O}$ values associated with the expansion of the Antarctic ice and Northern Hemisphere ice sheets. Upwelling is interpreted to have occurred throughout much of the warmer Early Pliocene, caused by a more northerly (compared to today) positioned and weaker Subtropical Front. Upwelling was prevalent in the outer shelf to upper slope facies at the 'palaeo' Bass Canyon and the Subtropical Front migrated northwards to Gippsland during Late Pliocene glacial periods. Terrestrial palaeobotanical records indicate a shift from widespread Araucarian forests and rainforest, including 'tropical' taxa now extinct in the region, to a landscape by the end of the Late Pliocene similar to that of the present day with a mosaic of *Eucalyptus*–*Acacia*–*Casuarinaceae* sclerophyllous forests and open vegetation, with local areas of *Nothofagus*-dominated cool temperate rainforests. Palaeobotanical proxy data indicate that regional climate oscillated between warm–wet and cool–dry phases, with an overall cooling–drying trend through the Pliocene. Earliest Pliocene climates in southeast Australia were warm–wet with a summer rainfall peak (mean annual temperature, MAT, 2–4°C

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higher than present, mean annual precipitation, MAP, 50–70% higher than present), whereas terminal Late Pliocene climates were drier–cooler with a winter rainfall peak (MAT 0–2°C higher than present, MAP 0–30% higher than present).

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1. Introduction

The Pliocene was a time of change, the global climate fluctuated with the expansion and contraction of the Northern and Southern Hemisphere ice sheets. The evidence of this change is well preserved in the thick (up to 1 km) Seaspray Group cool-water carbonate sediments that were deposited in the Gippsland region and the thin terrestrial deposits that occur in southeastern Australia. Throughout most of the Tertiary, sequences of shelfal sediments were deposited in the onshore part (up to 700 m thick) of the Gippsland Basin (Holdgate and Gallagher, 1997) and up to 2.5 km of shelf to bathyal sediments were deposited in the offshore Gippsland Basin (Holdgate et al., 2000). This marine record preserves a near-continuous record of Cenozoic climate and environmental change (Gallagher et al., 2001).

By Late Miocene times the Gippsland region lay palaeogeographically close to where it is at present (Veevers et al., 1991). The end of this epoch was characterised by a period of Antarctic glacial expansion and intensification of wind-driven and atmospheric circulation (see summary in Gallagher et al., 2001). These events coincided with the establishment of a cool, strongly stratified (latitudinally and vertically) Southern Ocean, evidence which is preserved in the Gippsland Basin and in other areas in southeastern Australia (Gallagher et al., 2001). Major variations in Antarctic glacial extent occurred during the Pliocene (Warnke et al., 1992) and evidence for several periods of warming (especially during the Early Pliocene) has been reported by Burckle et al. (1996) and Bohaty and Harwood (1998). The palaeobotanical record of terrestrial vegetation documents fluctuations in the relative dominance by rainforest and wet sclerophyll forests in southeastern Australia through the Pliocene (Macphail,

1997). Evidence for Pliocene climate change is likely to be best preserved in marine sequences deposited close to continental margin regions like southeast Australia. Over a hundred wells drilled for hydrocarbon exploration containing late Cenozoic marine sediments exist for the offshore Gippsland Basin: these data make this basin one of the best sampled shelf to bathyal transition sequences along the southern margin of Australia. The offshore Gippsland Basin is therefore an ideal setting for studying the climatic record of changes in the Southern Ocean during the late Cenozoic.

In this paper, we aim to chart the Pliocene palaeoenvironmental and palaeoclimatic evolution of a well sampled and preserved carbonate succession in Gippsland. We chart the foraminiferal biofacies and palaeoenvironmental evolution of the Gippsland shelf edge throughout the Pliocene, building on previous work completed by Gallagher et al. (2001) on the Miocene Seaspray Group. To enhance the palaeoceanographic and palaeoclimatic interpretations of the foraminiferal faunas we interpret Pliocene spore/pollen palynological data from selected wells and outcrops in the region. By using this integrated approach we arrive at a palaeoenvironmental and palaeoclimate summary for the Pliocene of southeastern Australia.

2. Methods

Samples for this study were obtained from the Flounder-5 and Mackerel-1 petroleum wells from a middle shelf area 80 km southeast of the Gippsland coast middle shelf section (Fig. 1). Seismic interpretation in this work is based on the Esso G92A 2D high-resolution multichannel 75-fold seismic data (see Holdgate et al., 2000). The

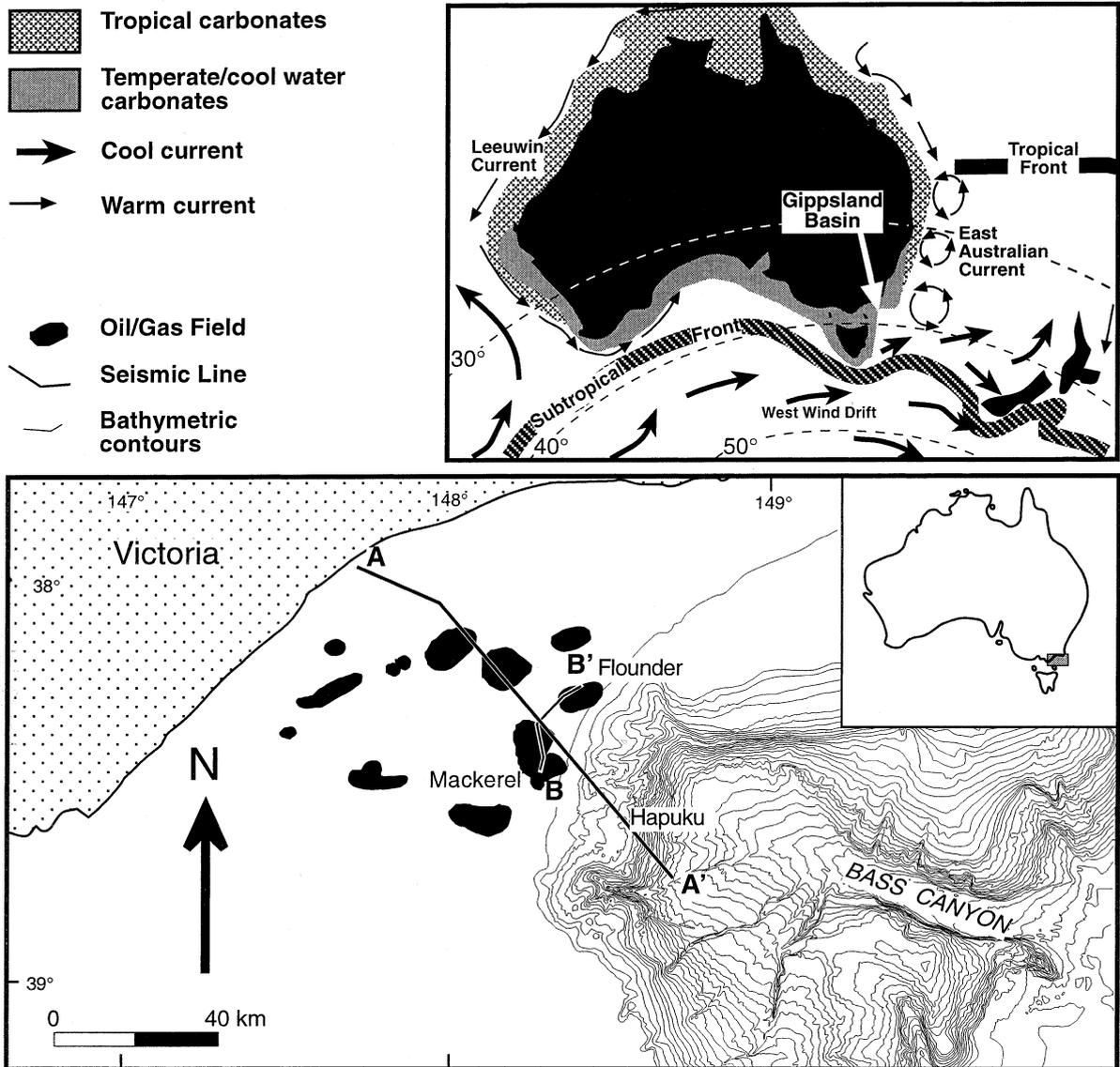


Fig. 1. The location of transect A–A' (Fig. 2) and B–B' (Fig. 3). Note the location of the Flounder, Mackerel and Hapuku wells are indicated.

time–depth conversion of seismic sections in Figs. 5 and 6 was carried out using Seismic Plugin (Jay Lieske Jr.) version 3.0 for Adobe Photoshop[®]. The location of the selected seismic line is shown in Fig. 1. The gamma and velocity log data were supplied by Wiltshire Geological Services and Esso. The ditch cutting (DC) samples and sidewall cores were obtained from the sample libraries of

the National Museum of Victoria and the Department of Natural Resources and Environment. The carbonate content of the DC samples was determined by standard acid digestion techniques. The facies analyses used to construct the logs in Figs. 5–12 were carried out by microfacies analyses of thin sections of sidewall cores and cuttings, point counting some of these slides, describing DC sam-

ples by texture, and analysing the unprocessed microfossil samples, using a binocular microscope in the laboratory.

Twelve DC samples were processed for foraminifera in the Mackerel-1 well. In addition, foraminifera were collected from five DC samples from Flounder-5. Nearly 300 foraminifera were picked, sorted and identified from each sample for the quantitative analyses. One hundred and eight benthic and 35 species of planktonic foraminifera were identified (in over 3700 foraminifera studied) from Mackerel-1. Of the 1128 foraminifera collected from Flounder-5, 57 species of benthic and 19 species of planktonic foraminifera were identified. The data collected are illustrated as percentages of the total, benthic or planktonic faunas in Figs. 8 and 9. The DC data for Flounder-5 are compared with foraminiferal analyses of 35 sidewall cores completed by D. Taylor (Fig. 9). Analyses by D. Taylor of the Hapuku-1 well yielded the semiquantitative foraminiferal data in Fig. 11.

The ditch cuttings in Mackerel-1 and Flounder-5 were sampled by the drillers at 10 m intervals and each sample represents averaged facies and microfauna from a 10 m section. Foraminiferal diversity increases significantly between the sidewall core (SWC) and DC samples analysed. This is caused by 'mixing' of the faunas and facies and makes interpretations of the palaeoenvironment of the sampled units more difficult and less precise. The high association between the coarse to fine ditch cuttings and variable gamma values together with the association of uniformly fine DC assemblages with uniform gamma values in the Pliocene sections studied, suggest that overall the ditch cuttings are a good representation of the facies and foraminiferal assemblages in the selected interval assuming caving during drilling (if it happened) was minor. Thus, below we have interpreted the biofacies as relatively uncontaminated and in situ on the 10 m DC interval scale and clear faunal and facies trends can be discerned in the intervals sampled. In the Miocene to Pliocene units studied in Flounder-5, the faunal patterns can be compared to data for the sidewall cores in the selected interval. Unfortunately, none of the original sidewall core remains. Facies

trends can also be described using not only the DC descriptions, but the wireline and seismic attributes of these sections. Good wireline logs exist and thin sections were made of this interval for Mackerel-1. No wireline logs exist for the Hapuku Subgroup in Flounder-5 and the lithofacies description relies on observations of unprocessed DC samples.

Macphail (1997) has provided the most recent review of the microfossil record of Pliocene vegetation for Australia, with the most detail in his account being for southeastern Australia. His account included data on terrestrial plant spore–pollen assemblages from the Hapuku-1 sediment core (Fig. 12), as well as records from southern New South Wales (e.g. Martin, 1991), Tasmania and different areas in Victoria. Additional data on Pliocene environments were reviewed in Kershaw et al. (1994), including a discontinuous record from the Latrobe Valley. In this paper palaeobotanical proxies of climate were derived from the Hapuku-1 palynological data (Macphail, 1997) using bioclimatic analysis of geographical distributions of modern plant genera (Kershaw and Nix, 1988; Kershaw, 1996). For this analysis 'climatic profiles' (the 5, 25, 75 and 95 percentiles of climatic parameters such as mean annual temperature (MAT) and precipitation (MAP); Fig. 13) were generated based on summaries of climatic variables for the known modern geographical records of each taxon. These values constitute the climatic profiles for each taxon in a fossil flora, based on the identification of each nearest living relative (Kershaw and Nix, 1988). Typically, profiles are calculated for individual genera, but in some cases were generated for species-groups within a genus where a similar degree of taxonomic resolution was possible for fossil material. These profiles were based on the Australia-wide modern distribution of genera, using the electronic database of the Australian National Herbarium, and climatic summaries generated for each record using BIOCLIM (Busby, 1991; Kershaw, 1996). These were supplemented in some cases using published climate profiles for taxa that are extinct in Australian today (i.e. regional late Cenozoic extinctions), but still extant on neighbouring land masses (e.g. *Nothofagus* subge-

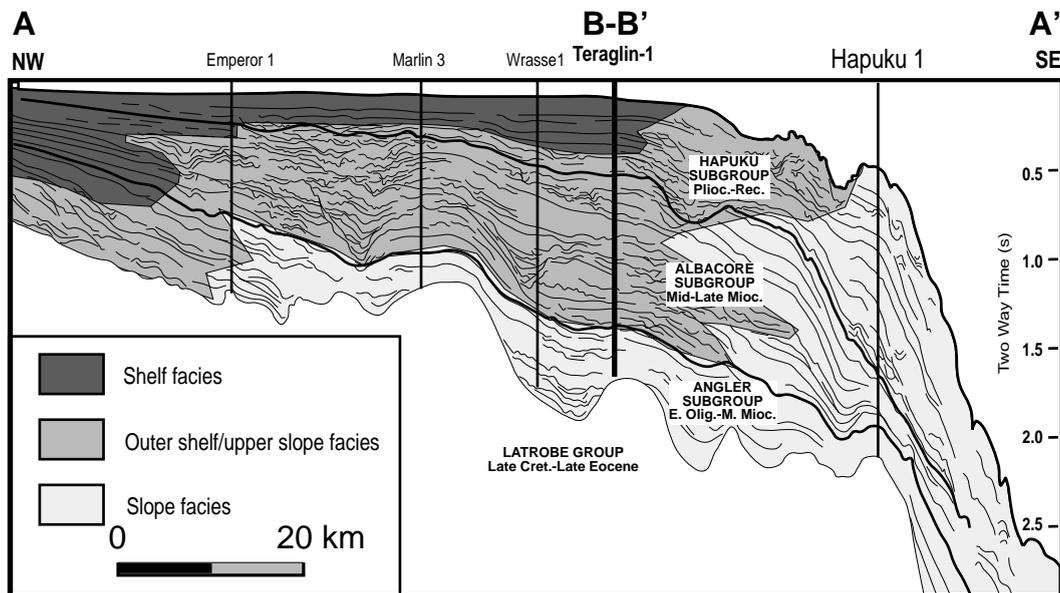


Fig. 2. An interpreted seismic line A–A' (see Fig. 1 for location) showing the three subgroups in the Seaspray Group.

nus *Brassopora*, based on published data from Papua New Guinea and New Caledonia: Read and Hope, 1996; Macphail, 1997). The zone of overlap of profiles between the majority of taxa in an individual assemblage, for a given set of climatic variables, defines the most likely climate envelope the taxa occupied during each phase of the Pliocene (Kershaw and Nix, 1988). The Gippsland Plain today experiences MAT 12–14.5°C and MAP 60–110 cm/yr, with highland areas such as the Errinundra Plateau cooler (MAT ~8°C) and wetter (MAP ~170 cm/yr) than the lowlands. Climate reconstructions using the bioclimatic profiles of plant taxa are expressed relative to these values.

3. Regional geology

The Seaspray Group reaches a maximum thickness in the offshore Gippsland Basin of 2.5 km and consists of shelf to bathyal cool-water carbonates. This succession was deposited on the Cretaceous to Palaeogene Latrobe Group from Oligocene to Recent times. Three principal subgroups have been described in the Seaspray

Group on the basis of lithologies and wireline log characteristics: the Angler, Albacore and Hapuku subgroups, respectively (Holdgate et al., 2000). The Seaspray Group has prograded from bathyal to shelf facies through time and the present shelf break is located near the well Hapuku-1 (Figs. 2 and 3).

The Seaspray Group carbonates are characterised by an abundance of submarine canyons and these features have caused considerable problems for seismic structural interpretations. Severe structural distortion occurs under these canyons because of the high velocity nature of the canyon fills and this produces 'pull up' structures on seismic profiles (Wallace et al., 2002). Some submarine canyons are present in the Oligocene and Early Miocene Angler subgroup slope facies, but only become abundant in the Albacore subgroup, beginning in the Middle Miocene. The initiation of intense canyoning in the Middle Miocene has a dramatic effect on the Seaspray Group stratigraphy, with a sudden influx of carbonate-rich sediments occurring in the slope facies (the base of the Albacore subgroup coincides with this influx).

The sudden onset of intense canyoning within the Seaspray Group is enigmatic, with several ex-

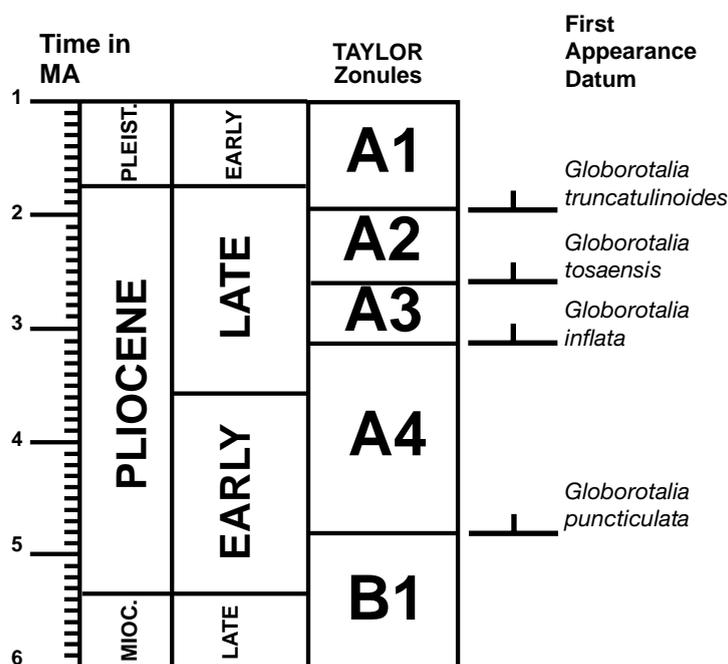


Fig. 3. The biostratigraphic zonation scheme (Taylor's zonules) used in this study adapted from Bernecker et al. (1997) and McGowran et al. (1997). The chronology of this chart is from Berggren et al. (1995).

planations being possible. Feary and Loutit (1998) have applied a sequence stratigraphic approach to the Seaspray Group carbonates, and have linked canyoning events with low stands. However, the onshore record for carbonates of equivalent age displays no evidence for a significant low stand event. Brown (1986) suggested that tectonism may have played a role in the onset of canyoning and proposed a major middle Miocene tectonic event for the Gippsland Basin. However, this event was largely proposed on the basis of intense canyoning and has not been found in surrounding basins (Dickinson et al., 2001). Canyoning continued to play an important role in the Seaspray Group from the middle Miocene to the present day, with the outer shelf and slope environments being dominated by submarine canyons of various types during this period. We believe that the submarine canyons are largely (if not entirely) controlled by deepwater processes and that their initiation and development are probably not tied to regressions or other processes affecting shallow water environments.

Neogene tectonism has recently been recognised

as having an important effect on the Tertiary stratigraphy of the SE Australian basins (Dickinson et al., 2002). The most significant Neogene tectonic event in the region occurred during the Late Miocene to Early Pliocene period (Dickinson et al., 2001, 2002). However, in the offshore Gippsland Basin, the effects of this event are not pronounced (excluding the northern part of the basin). In the offshore Gippsland Basin, there are no regional upper Miocene–Pliocene unconformities of the type found in more near-shore positions. Furthermore, there are no major episodes of upper Miocene–Pliocene canyoning which can be related to tectonism. A slight increase in clastic input at the base of the Hapuku subgroup may be the only effect of upper Miocene tectonism in the offshore Gippsland Basin (Holdgate et al., 2000).

4. Biostratigraphy

Over 35 species of planktonic foraminifera were documented in the wells analysed. The distribu-

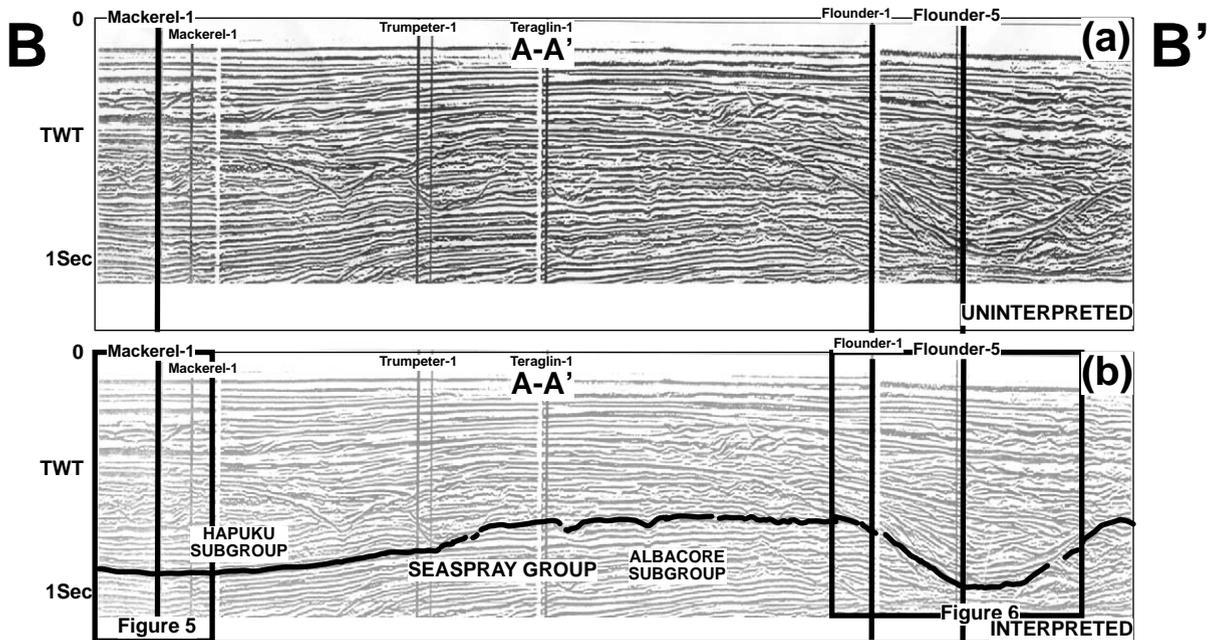


Fig. 4. The seismic stratigraphy of transect B–B' showing the location of the Mackerel-1 and Flounder-5 wells (Figs. 5 and 6). Note the canyon fill reflectors of the Albacore and Hapuku subgroups. (a) Uninterpreted seismic line, (b) interpreted seismic line.

tion of key planktonic species and groups in the Mackerel-1 (12 DC) and Flounder-5 (six DC) samples is illustrated in Figs. 8 and 9. These data are supplemented with biostratigraphic data from Flounder-5 and Hapuku-1 sidewall cores (Figs. 9 and 11). The plankton data used follow the biostratigraphic schemes outlined in Bernecker et al. (1997), Holdgate and Gallagher (1997), McGowran et al. (1997) and Gallagher and Holdgate (2000) and are included in Fig. 4.

4.1. Albacore subgroup (nine SWC and one DC data)

The age of this unit has been described in detail in Gallagher et al. (2001). It ranges in age from the Late Miocene B2 to B1 zonule.

4.2. Hapuku subgroup (18 DC+SWC data)

Planktonic foraminifera are relatively common in the DC samples of the Hapuku subgroup, comprising between 46 and 53% of the total forami-

niferal fauna. At 452 m in Mackerel-1 and 427 m in Flounder-5, planktonic percentages reduce markedly to around 25% compared to the underlying samples. In Mackerel-1, the first-appearance dates (FADs) of *Globorotalia mons* and *Truncorotalia crassaformis* at 1219 m were followed closely up section by the FADs of *Globoconella puncticulata* and *G. pliozea* at 1131 m defining the base of the Early Pliocene A4 zonule. In Flounder-5, DC samples from 966 to 344 m were analysed for foraminifera. These are just above the base of the Early Pliocene A4 zonule at 995 m as identified from SWC data based on the first appearance of *G. puncticulata*. In Hapuku-1, the FADs of *T. crassaformis* and *G. puncticulata* occur at 1905 m, defining the base of the A4 zonule. The base of the Pliocene A3 zonule is defined on the first appearance of *Globorotalia inflata* at 763 m in Mackerel-1, 567 m in Flounder-5 and 1280 m in Hapuku-1. The FAD *Truncorotalia tosaensis* at 681 m in Mackerel-1 defines the base of the Late Pliocene A2 zonule. No samples were studied above 305 m in Mackerel-1 or above

344 m in Flounder-5 in this work. The base of the A2 zonule can be assigned at 270 m in Flounder-5 SWC and 643 m in Hapuku-1 based on the FAD of *Neogloboquadrina humerosa* and *T. tosaensis*.

5. Results

It was necessary to integrate foraminiferal analyses, wireline, microfacies, carbonate content and seismic attributes to interpret the palaeoenvironment of the Pliocene succession. The palaeoenvironmental interpretations are based on comparisons with Recent forms (Vella, 1962; Hayward, 1990; Murray, 1991; Jones and Yassini, 1995; Li et al., 1996; Gallagher et al., 1999; 2001; Smith et al., 2001). Interpretation of the Hapuku-1 spore/pollen record was based on assigning the principal taxa to climatic groups, based on the bioclimatic analysis of these taxa. These groupings were used to infer shifts in temperature and rainfall regimes in terrestrial environments, in response to changing oceanographic regimes interpreted from the marine sequences.

5.1. The Hapuku subgroup

Similar to the underlying Albacore subgroup (as described in Gallagher et al., 2001), the Hapuku subgroup is characterised by intervals of canyoning and parallel reflectors. This unit and its geophysical, lithological and foraminiferal characteristics will be described in two sections: the (uppermost Miocene) lower Pliocene and the upper Pliocene.

5.2. The (uppermost Miocene Albacore subgroup) lower Pliocene Hapuku subgroup

5.2.1. Seismic facies and wireline log character

In Mackerel-1, the uppermost Miocene to lower Pliocene section (Fig. 5) is typified by strong parallel reflectors with two distinct units:

A lower interval (1308–1073 m) of fluctuating high gamma values (30–40 API) and low carbonate values from 53 to 63%. Facies range from spicule-rich marl (wackestone) to cemented bryo-

zoan limestone (packstone). Bioclasts include abundant sponge spicules, common bryozoans and rare articulated ostracods.

An upper interval (955–863 m) of constant low gamma values (25–30 API) and high carbonate values (78%). The DC samples in this interval are unconsolidated and it is not immediately clear what the facies are. Based on gamma and carbonate values, it is suggested that the facies are uncemented bryozoan marl. In addition to abundant fine-grained foraminifera, other coarse bioclasts are abundant in this unit, with abundant stick bryozoans, common bivalves, sponge spicules and echinoderm spines and rare articulated ostracods.

The lower Pliocene sediments of Flounder-5 infill a canyon over 500 m thick in seismic section (Fig. 6). Within this canyon the apparent dip of complex cross-cutting reflectors is to the northeast. Two intervals can be distinguished in this canyon:

The lower interval (995–764 m) is characterised by alternations of cemented and uncemented bioclast-poor marl (wackestone to packstone) with high carbonate values from 68 to 78%. Bioclasts include rare sponge spicules, bivalves and echinoderm spines. One bioclast-rich horizon occurs at 878 m.

Cemented limestone (packstone to grainstone) occur in the upper interval (765–582 m). Carbonate values are variable, ranging from 60 to 78%. Limonite staining of bioclasts is pervasive at this level. Bioclasts include common stick and sheet bryozoans, bivalves, rare echinoderm spines and plates and rare ostracods.

The lower Pliocene sediments of Hapuku-1 infill a complex of canyons (Fig. 7) with two distinct units:

A lower interval of v-shaped canyons characterised by marl (wackestone/packstone) with high gamma values, > 30 API. Carbonate values range from 65 to 75%.

An upper interval of strong dipping parallel reflectors consisting of limestone (grainstone) with low gamma values, < 30 API. The limestone is laminated and well sorted with interbeds of marl. This interval is carbonate-rich (75–90%).

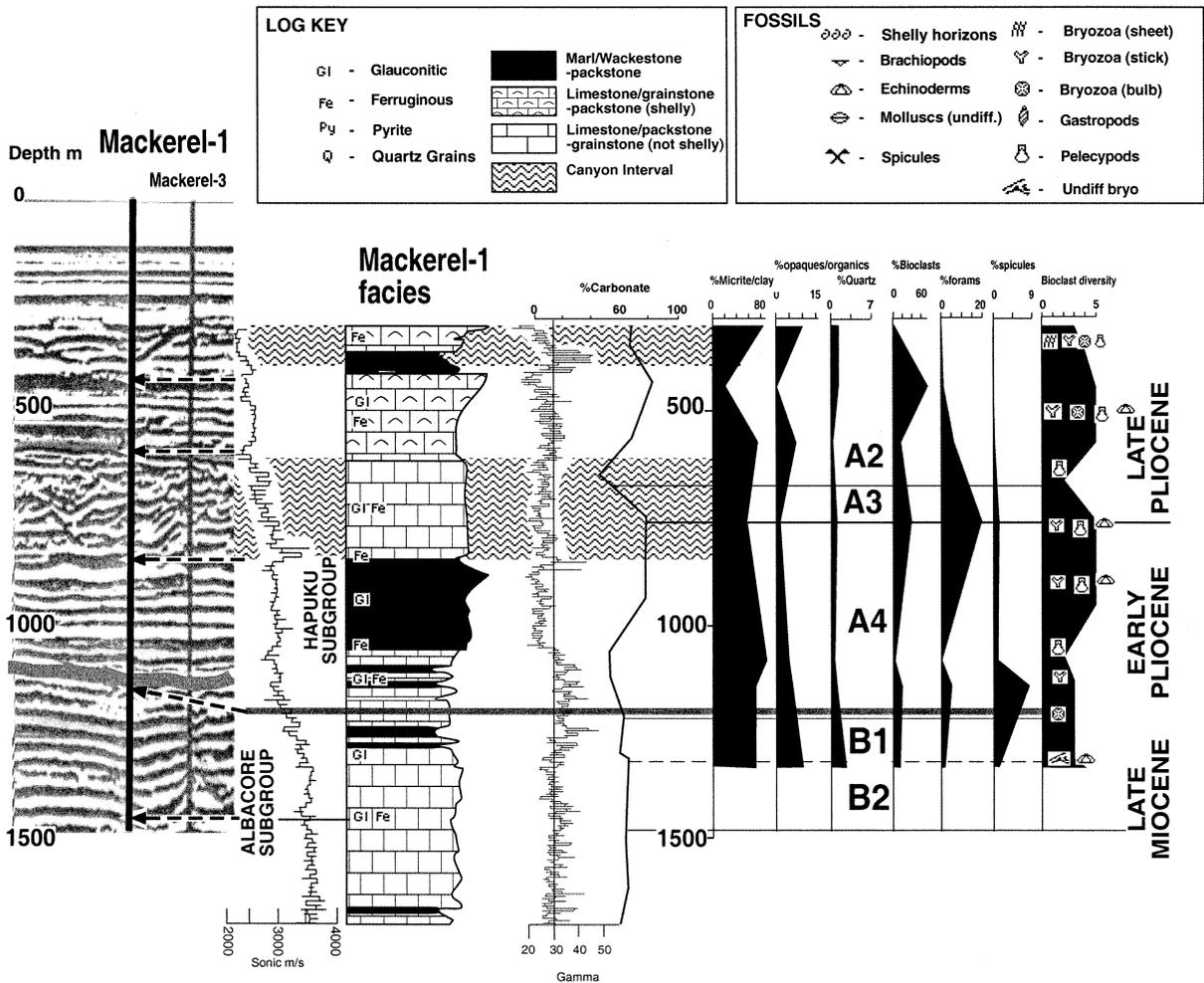


Fig. 5. The facies, gamma and sonic logs of Mackerel-1 correlated to seismic data (both depths in metres). The time–depth conversion of seismic section in this figure was carried out using Seismic Plugin (Jay Lieske Jr.) version 3.0 for Adobe Photoshop[®]. The biostratigraphy of this well is shown in Fig. 8. The percentage of bioclasts, micrite, quartz and organics/opaque in this figure was obtained by point counting thin sections. Note the shaded intervals are canyoning intervals; all other non-shaded units are here interpreted as inter-canyon seismic facies.

5.2.2. Planktonic foraminiferal distribution

The plankton percentages in the Pliocene ditch cuttings are relatively low compared to samples from sidewall cores in the same intervals or in the upper Miocene. For example in Flounder-5, where previous studies on SWC samples by D. Taylor yielded plankton percentages from 75 to 100%, the equivalent DC samples yielded values from 28 to 70%. Therefore, it is clear that either caving has masked the plankton values or averaging of the foraminiferal assemblage has occurred

due to the fact that the ditch cuttings sample lithologies over a 10 m interval. Thus one cannot use the absolute plankton percentage values in the ditch cuttings for palaeoenvironmental studies. Notwithstanding this constraint, useful trends are apparent in the plankton values. Plankton values are relatively high (63–73%) in the lower interval of the lower Pliocene of Mackerel-1 compared to the upper interval (56%). This corresponds to a change from relatively common *Globigerinoides*, *Orbulina universa* and keeled *Glo-*

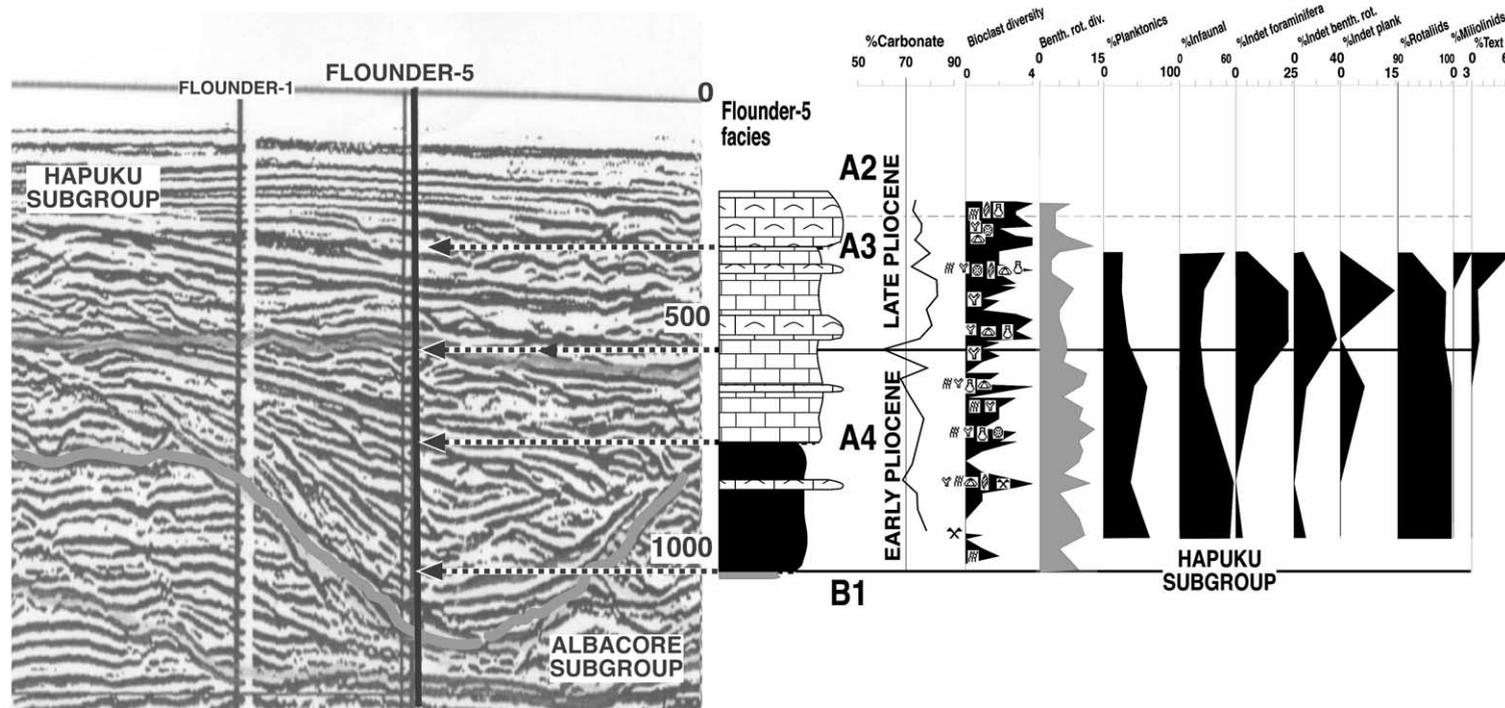


Fig. 6. The facies, gamma and sonic logs of Flounder-5 correlated to seismic data (both depths in metres). The reflector on this section is the base of the submarine canyon and the base of the Hapuku subgroup. The time–depth conversion of seismic section in this figure was carried out using Seismic Plugin (Jay Lieske Jr.) version 3.0 for Adobe Photoshop®. The key to the facies in this well is given in Fig. 5.

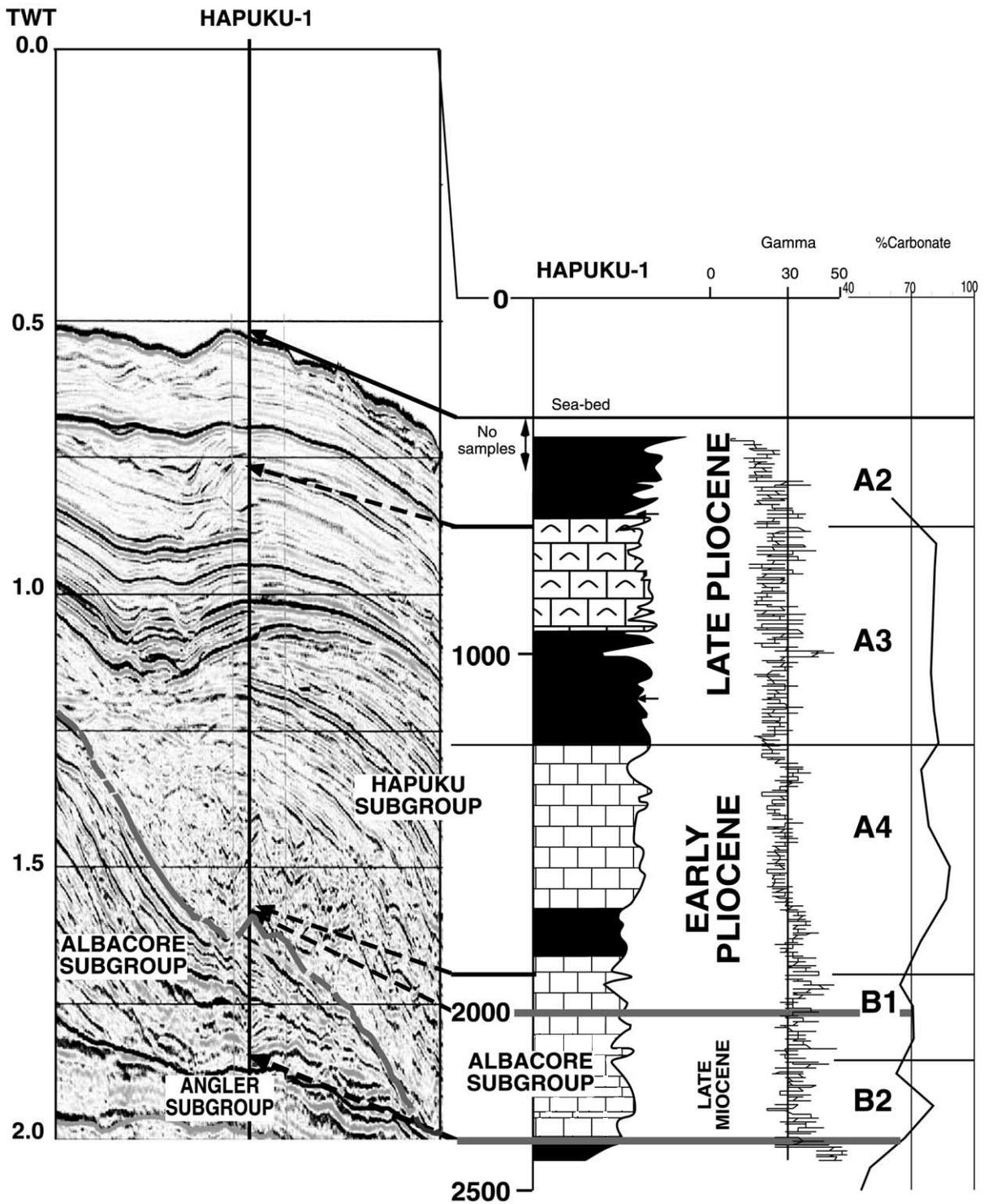


Fig. 7. The facies, gamma and sonic logs of Hapuku-1 correlated to seismic data. Note: the depth of the well is in metres and the seismic data are in two-way travel time (TWT). The biostratigraphy of this well is shown in Fig. 11.

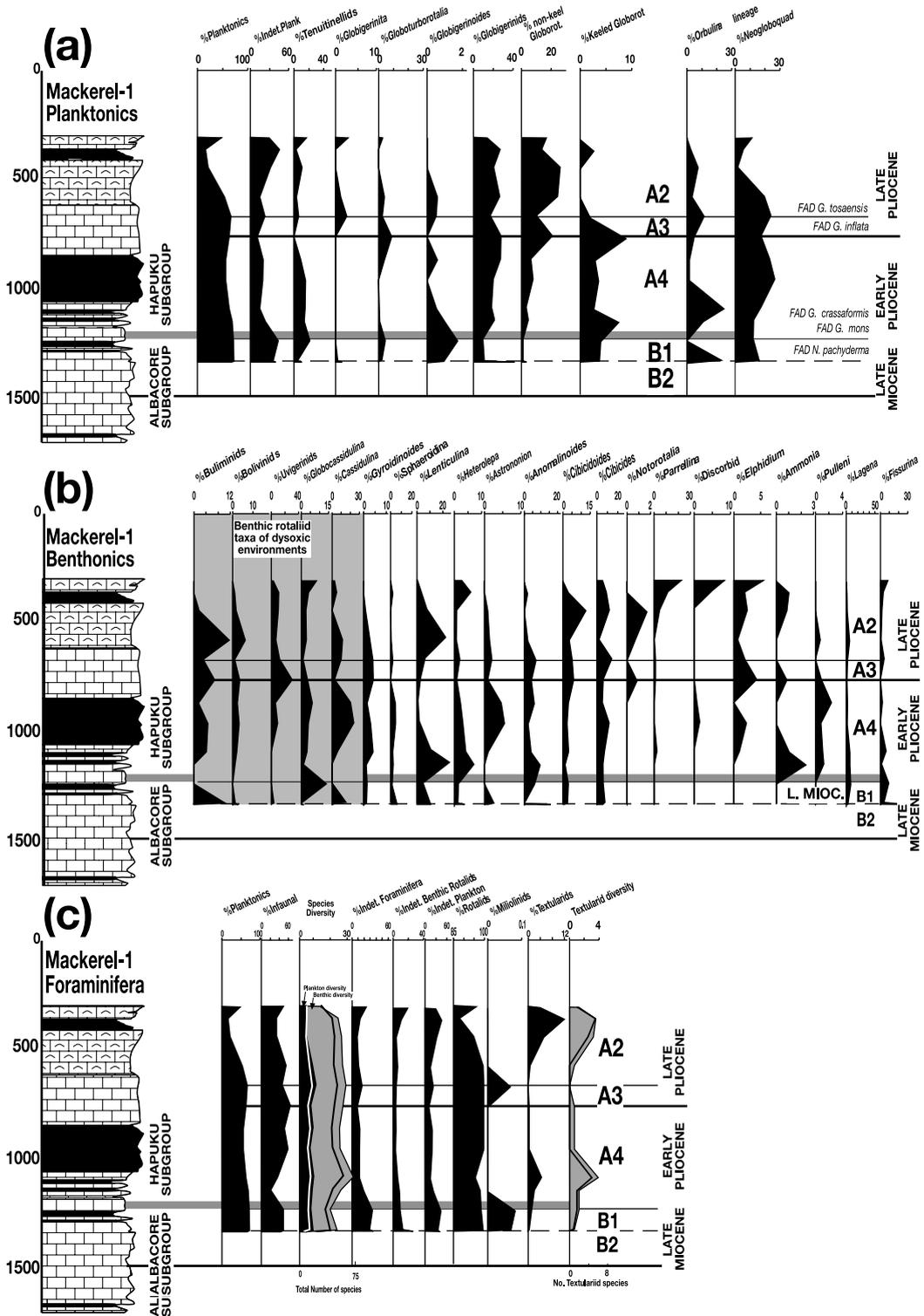


Table 1

A list of the planktonic foraminiferal taxa identified in the Mackerel-1, Flounder-5 and Hapuku-1 wells

Plankton climate indices		Plankton depth distribution	
G	CT <i>Globigerina bulloides</i>	G	D <i>Globigerina bulloides</i>
nk	CT <i>Globoconella inflata</i>	nk	D <i>Globoconella inflata</i>
K	C <i>Globoconella miotumida</i> s.l.	K	D <i>Globoconella menardii</i>
GT	CT <i>Globoturborotalia woodi woodi</i>	K	D <i>Globoconella miotumida</i> s.l.
N	C <i>Neogloboquadrina pachyderma</i>	GT	D <i>Globoturborotalia woodi woodi</i>
K	CT <i>Truncorotalia tosaensis</i>	G	D <i>Hastigerina aequilateralis</i>
O	W <i>Borbulina bilobata</i>	N	D <i>Neogloboquadrina acostaensis acostaensis</i>
may	W <i>Fohsella peripheroronda</i> (rw)	N	D <i>Neogloboquadrina dutertrei</i>
G	W <i>Globigerina falconensis</i>	N	D <i>Neogloboquadrina pachyderma</i>
GD	W <i>Globigerinoides sacculifer</i>	O	S <i>Borbulina bilobata</i>
GD	W <i>Globigerinoides trilobus</i>	may	S <i>Fohsella peripheroronda</i> (rw)
GD	W <i>Globigerinoides trilobus elongate</i>	G	S <i>Globigerina falconensis</i>
nk	W <i>Globoconella subconomiozea</i>	GD	S <i>Globigerinoides sacculifer</i>
nk	W <i>Globoconella conomiozea</i>	GD	S <i>Globigerinoides trilobus</i>
nk	W <i>Globoconella crassaconica</i>	GD	S <i>Globigerinoides trilobus elongate</i>
nk	W <i>Globoconella juanai</i>	nk	S <i>Globoconella subconomiozea</i>
K	W <i>Globoconella menardii</i>	may	S <i>Globorotalia mayeri</i> (rw)
K	W <i>Globoconella mons</i>	may	S <i>Globorotalia praescitula</i>
K	W <i>Globoconella panda</i>	nk	S <i>Orbulina scitula scitula</i>
K	W <i>Globoconella pliozea</i>	O	S <i>Orbulina suturalis</i>
wk	W <i>Globoconella praemenardii</i>	O	S <i>Orbulina universa</i>
nk	W <i>Globoconella punctulata punctuloides</i>	nk	S <i>Truncorotalia crassaformis</i>
may	W <i>Globorotalia mayeri</i> (rw)		
nk	W <i>Globorotalia praescitula</i>		
GT	W <i>Globoturborotalia nepenthes</i>		
G	W <i>Hastigerina aequilateralis</i>		
N	W <i>Neogloboquadrina acostaensis acostaensis</i>		
N	W <i>Neogloboquadrina dutertrei</i>		
nk	W <i>Obandyella scitula scitula</i>		
O	W <i>Orbulina suturalis</i>		
O	W <i>Orbulina universa</i>		
	W <i>Sphaeroidinellopsis disjuncta</i>		
nk	W <i>Truncorotalia crassaformis</i>		
G	W <i>Zeaglobigerina decoraperta</i>		

Misc. Planktonics	
G	<i>Globigerina obesa</i>
nk	<i>Globoconella conica</i>
nk	<i>Globorotalia amuria</i>
nk	<i>Globorotalia punctulata sphericomiozea</i>
K	<i>Globorotalia tumida</i>

SYMBOL KEY	
D	Deep dwellers (>50m)
S	Surface dwellers (0-50m)
C	Cool water indices (0-15°C)
CT	Cool-temperate indices (15-18°C)
W	Warm indices (19-22°C)
rw	interpreted reworked forms
G	Globigerinid
GD	<i>Globigerinoides</i>
nk	Globorotaliid (no keel)
K	Globorotaliid (with keel)
wk	Globorotaliid (with weak keel)
may	Globorotaliid of mayeri group
GT	Globoturborotaliid
N	<i>Neogloboquadrina</i>
O	Orbulina lineage
T	Tenuitellid

The plankton climate indices are compiled from modern distributions based on data in Bé and Tolderlund (1971), Bé and Hutson (1977) and Andrijanic (1988). Sources for the palaeoclimate distribution of these taxa are included in Kennett and von den Borch (1986), Wright and Thunell (1988) and Spezzaferri (1995). The interpreted depth distribution of the plankton was adapted from Bé and Tolderlund (1971) for modern forms and Keller (1985), Norris et al. (1993) and Spezzaferri (1995) for Cenozoic forms.

borotalia in the lower interval to abundant *Neogloboquadrina pachyderma*, *N. acostaensis* and *Globigerina bulloides* in the upper interval.

In Flounder-5, plankton comprises between 60 and 90% of the lower Pliocene fauna. *Globigerina bulloides* is the dominant plankton in the Early Pliocene. In the ditch cuttings *Globorotalia*

mayeri, *Globigerinoides*, non-keeled *Globorotalia* and *Orbulina universa* are most common at the base of the Flounder canyon. These taxa decrease in abundance upward, to be replaced by *Globigerina* sp. above 765 m. In the sidewall cores, *Globigerinoides trilobus*, *Globigerina falconensis* and *O. universa* are more common in the upper inter-

Fig. 8. The distribution of foraminifera in the ditch cutting of the Mackerel-1 well. The %planktonics is expressed as a percentage of the total fauna. All other data are a percentage of the total plankton fauna (a) or a percentage of the benthic rotaliid fauna (b). See Tables 1 and 2 for a full list of the planktonic and benthic species in these wells.

val compared to the lower interval (where *G. bulloides* is most common). Abundant sinistral *Neogloboquadrina pachyderma* occurs in the upper 50 m of the lower Pliocene ditch cuttings.

Plankton is abundant in the sidewall core of Hapuku-1 (Fig. 11), with values averaging between 85 and 100%. The plankton diversity is relatively low in the Early Pliocene, with the lower interval characterised by common *Globorotalia miotumida*. *Orbulina universa*, *Globoturbotalia decoraperta* and *Globigerina bulloides* are common in the transitional unit between the upper and lower intervals (Fig. 11). The upper interval has a low diversity fauna of *O. universa*, *Hastigerinella aequilateralis* and *G. bulloides*.

5.2.3. Benthic foraminiferal distribution

The uppermost Miocene to lower Pliocene ditch cuttings of Mackerel-1 yield a diverse benthic assemblage (26–53 species). The fauna in the lowest interval consists of both coarse (> 1 mm) and fine (< 0.25 mm) grained foraminifera, whereas fine-grained foraminifera prevail in the upper interval. The coarse component of the lower interval is mainly large *Lenticulina* species such as *L. mamilligera*. Other important elements in this interval include *Fissurina*, *Lagena*, *Anomalinoidea*, *Heterolepa*, *Globocassidulina subglobosa* and Polymorphinids. Foraminiferal abundance peaks at 1073 m (53 species), where *Cassidulina laevigata*, *Bulimina marginata*, *Bolivina* and *Globocassidulina subglobosa* dominate the assemblage, plus minor elements such as *Ammonia beccarii*, *Elphidium* and *Parrellina imperatrix*. The fauna of the upper lower Pliocene interval is similar to that of the lower interval except large *Lenticulina* and *Parrellina* are rare or absent, and *Sphaeroidina bulloides*, *Astrononion* and *Uvigerina bassensis* are common. A minor but diverse assemblage of *Elphidium* species occurs in the uppermost lower Pliocene.

In Flounder-5, the sidewall cores in the lower part of the lower Pliocene Flounder canyon are typified by common *Gyroidinoides*, with *Bolivina*, *Uvigerina*, *Cassidulina* and *Cibicides pseudoungerianus*. The two DC samples in this interval contain 22–28 species of fine-grained foraminifera with abundant *Uvigerina bassensis*, *U. canariensis*, *Bolivina*, *Gyroidinoides*, *Cassidulina laevigata*, *Cibicides* and *Astrononion*. Minor *Elphidium*, *Cribo-nonion* and *Discorbis* occur. The sidewall cores in the upper interval of the Flounder canyon yield abundant *Cassidulina* and *Bolivina*. *Uvigerina* are abundant in the lower part of this interval. *Trifarina bradyi* and *Globobulimina pacifica* are most common above 644 m. The single DC sample in the upper part of the Early Pliocene contains a fine-grained assemblage of 12 species of foraminifera characterised by common *Cibicides mediocris*, *Globocassidulina subglobosa* and *Uvigerina bassensis*, with minor *Heterolepa*, *Astrononion* and *Notorotalia*.

Benthic foraminifera comprise a relatively minor component of the Early Pliocene assemblages in Hapuku-1; this low-diversity fauna is dominated by relatively small benthic forms. *Cassidulina* is the most abundant genus in the lower and uppermost Early Pliocene. In addition, bolivinids, *Lagena* and uvigerinids (*U. bassensis* and *U. proboscidae*) are relatively common with lesser amounts of *Anomalinoidea* and *Cibicidoides*. Other taxa include rare *Epistominella exigua*, *Melonis pompiliodes* and *Globobulimina pacifica*.

5.2.4. Palaeoenvironment and biofacies

The most common microfaunal elements in the Early Pliocene of Mackerel-1 and Flounder-5 are typical of outer shelf to upper bathyal palaeoenvironments (see Table 2). The lack of obvious canyoning in the seismic section through Mackerel-1 in this interval suggests that the lower Plio-

Legend Table 2.

The palaeoenvironmental interpretations are based on comparisons with extant forms with reference to Vella (1962), Hayward (1990), Murray (1991), Jones and Yassini (1995), Li et al. (1996), Gallagher et al. (1999) and Smith et al. (2001). The interpretation of dysoxic taxa was based on a review by Sen Gupta and Machain-Castillo (1993) of modern OMZ foraminiferal distributions, incorporating data from Jorissen et al. (1994) and Van der Zwaan et al. (1999). Note: the codes on the left column are as follows: I=inner shelf, M=middle shelf, O=outer shelf, ub=upper slope, mb=middle slope; 1=rare, 2=common, 3=abundant. The symbol O on the right column=a taxon of dysoxic environment.

cene section preserves sedimentary processes operating outside or adjacent to the canyons. Conversely, the lower Pliocene sediments of Flounder-5 and Hapuku-1 infill canyons. The sediments of Hapuku-1 during lower Pliocene time are interpreted from seismic stratigraphic studies to represent slope facies (Fig. 2). The abundant plankton and a low-diversity benthic assemblage in this slope facies in Hapuku-1 suggests a deeper water palaeoenvironment than the lower Pliocene of intervals of Mackerel-1 or Flounder-5. These considerations, combined with the presence of the bathyal indicators (*Epistominella exigua*, *Melonis pompilioides* and *Globobulimina pacifica* that occur at >1000 m depths today, Kurihara and Kennett, 1986) suggests this facies preserves middle to lower bathyal deposition.

The DC microfauna in the lowest interval of the Hapuku subgroup in Mackerel-1 has a distinctive bimodal size distribution. This compares with the wireline log and facies variation, which fluctuates from marl to limestone (packstone) facies. In the upper interval, fine-grained faunas occur in bryozoan marl. It is suggested that the basal lower Pliocene strata were deposited in low-energy pelagic conditions (the spicule-rich marl) with periodic deposition of higher-energy distal calciturbidites (the bryozoan packstone) that transported minor inner shelf taxa such as *Ammonia beccarii* and *Elphidium* and middle shelf forms such as *Parrellina* into this interval. Toward the top of the lower Pliocene, a more stable, predominantly lower-energy environment was established, with minor inner shelf forms (*Elphidium*) transported by current activity into the area. Plankton taxa indicative of warm ocean surface conditions (*Orbulina* and *Globigerinoides*) are relatively common at the base of the Early Pliocene. The warm oceanic taxa are replaced up section by deep dwelling plankton taxa such as *Neogloboquadrina* and cool oceanic taxa such as *Globigerina bulloides* associated with an increase in infaunal foraminifera typical of dysoxic environments. Thus, a change from warm oligotrophic deposition to cold eutrophic (upwelling) conditions occurred during the deposition of the lower Pliocene strata of Mackerel-1.

The two distinct seismic and facies intervals in

the Flounder-5 canyon represent two infill stages: (1) the lower section was deposited in a relatively lower-energy passive canyon infill with occasional transported bioclastic debris such as bryozoans, and (2) high-energy canyon facies fills the upper part of the canyon, with abundant transported bioclastic material such as bryozoans and bivalves. The DC and SWC fauna of the lower Pliocene Flounder-5 canyon is comprised principally of a fine-grained infaunal assemblage typical of the upper bathyal oxygen minimum zone (Sen Gupta and Machain-Castillo, 1993). The abundance of the cool-water *Globigerina bulloides* throughout this interval suggests considerable upwelling occurred during deposition. Similar to the lower Pliocene of Mackerel-1, the minor inner shelf forms that occur in this canyon are interpreted to have been transported by current activity in the canyon environment. Warmer oceanic plankton taxa occur with the cooler forms at the base of the Flounder-5 canyon; warm oceanic indicators are absent in the rest of the lower interval. Warm-water forms such as *Globigerina falconensis*, *Orbulina universa* and *Hastigerinella aequilateralis* are common in the upper part of the lower Pliocene strata of Flounder-5. These are replaced by the cool-water sinistral *Neogloboquadrina pachyderma* just below the end of the lower Pliocene.

Benthic foraminiferal taxa typical of dysoxic conditions are also common in the basal v-shaped canyon interval in Hapuku-1 associated with the cool-water planktonic form *Globorotalia miotumida* sensu lato. Although *Globigerina bulloides* is rare in this interval, the co-occurrence of typically cool-water plankton taxa and dysoxic benthic taxa is interpreted here to suggest upwelling during this time. Although not abundant, the occurrence of a relatively diverse warmer-water plankton assemblage including *Neogloboquadrina acostaensis*, *Hastigerinella aequilateralis*, *Globoturbotalia decoraperta* and *Orbulina universa* in the absence of abundant cooler-water taxa suggests warmer oceanic conditions by the end of the Early Pliocene in Hapuku-1. Benthic rotaliid taxa typical of dysoxic environments are common in the upper Early Pliocene of Hapuku-1. The assemblage in this interval is not strongly associ-

ated with cooler plankton indicators and thus it is not likely that upwelling was occurring during this time. The benthic fauna and seismic facies of this interval suggest dysoxic mid to outer bathyal deposition and that the Oxygen Minimum Zone existed close to this site during this time.

5.3. The upper Pliocene Hapuku subgroup

5.3.1. Seismic facies and wireline log character

Three units can be distinguished in the upper Pliocene Hapuku subgroup in Mackerel-1 (Fig. 5).

The basal 250 m thick unit is an intensely canyoned interval with irregular and v-shaped reflectors (canyons < 100 m high). Gamma values are low, varying from 25 to 30 API. Carbonate percentages are variable, with the highest values recorded at the base (79%) and the lowest of 46% at the top of the interval. The facies in this canyoning interval are poorly cemented to cemented molluscan packstone. Bioclasts include stick bryozoans, sponge spicules and abundant bivalves. Rare articulated ostracods and echinoderm spines occur.

A 100 m interval of parallel reflectors. Gamma values fluctuate in this interval from a maximum of 35 API at the base to a minimum of 20 API at the top. Carbonate values are high, ranging from 69 to 84%. Cemented coarse-grained bryozoan grainstone with minor poorly cemented wackestone characterise this interval. Stick, sheet and bulbous bryozoans and bivalves are abundant with minor sponge spicules, ostracods and echinoderm spines.

The uppermost unit sampled in Mackerel-1 is a small (< 100 m) canyon that cuts a thin flat reflector (arrowed in Fig. 5). Gamma values reach 40 API in the basal part of this interval, decreasing upward to 20 API. Two samples were studied in this unit, both with 68% CaCO₃: the lowest sample is a spicule-rich packstone and wackestone facies. The upper sample is a limonite-stained bioturbated molluscan and bryozoan packstone. Bioclasts are common in this canyon and include abundant bivalves and diverse bryozoans (stick, sheet and bulbous).

The upper Pliocene of Flounder-5 is character-

ised as a complex interval of small v-shaped canyons with prograding and parallel reflectors (Fig. 6). Limonite-stained bryozoan limestone (packstone to grainstone) are the main facies of this interval. Carbonate values are high, ranging from 72 to 83%. Bivalves, gastropods and regular echinoderm spines are common in addition to stick, sheet, encrusting and bulbous bryozoans.

In Hapuku-1, strong reflectors parallel to the edge of the present Bass Canyon are typical of the upper Pliocene comprising two units (Fig. 7). With the exception of the upper carbonaceous marly facies (CaCO₃ = 60%), the upper Pliocene facies are carbonate-rich (80%). Gamma values vary greatly in this interval, probably reflecting metre-scale alternations of limestone and marl facies (Fig. 7). The upper Pliocene facies is predominantly marl (wackestone/packstone). Bioclastic limestone (grainstone) with marl (wackestone/packstone) interbeds is most common near the top of zonule A3 strata.

5.3.2. Planktonic foraminiferal distribution

Globigerina bulloides and *Globorotalia inflata* are the most common plankton taxa in the upper Pliocene strata of Mackerel-1, Flounder-5 and Hapuku-1. *Orbulina universa* is common in the upper Pliocene of Hapuku-1.

Plankton percentages and diversity are highest in the canyon facies at the base of the upper Pliocene of Mackerel-1 (Fig. 8). Plankton percentages and diversity decrease significantly above this canyon, until the uppermost sample where 48% plankton occurs. *Neoglobobiquadrina pachyderma* and *N. acostaensis* are common in Mackerel-1. Keeled *Globorotalia* are common at the base of the upper Pliocene and decrease in abundance above this level. Significant peaks of larger (> 150 µm) *Orbulina* occur at 671 and 452 m.

In Flounder-5, SWC plankton percentages are lowest (50–80%) at the base and top of the upper Pliocene and reach a maximum of 80–100% between 459 and 373 m (Fig. 9). The ditch cuttings yield significantly lower plankton values (28–40%) in this interval compared to the sidewall cores. *Hastigerinella aequilateralis*, *Globigerinoides trilobus* and *Globigerina falconensis* dominate the lower part of the A3 zonule in the absence of com-

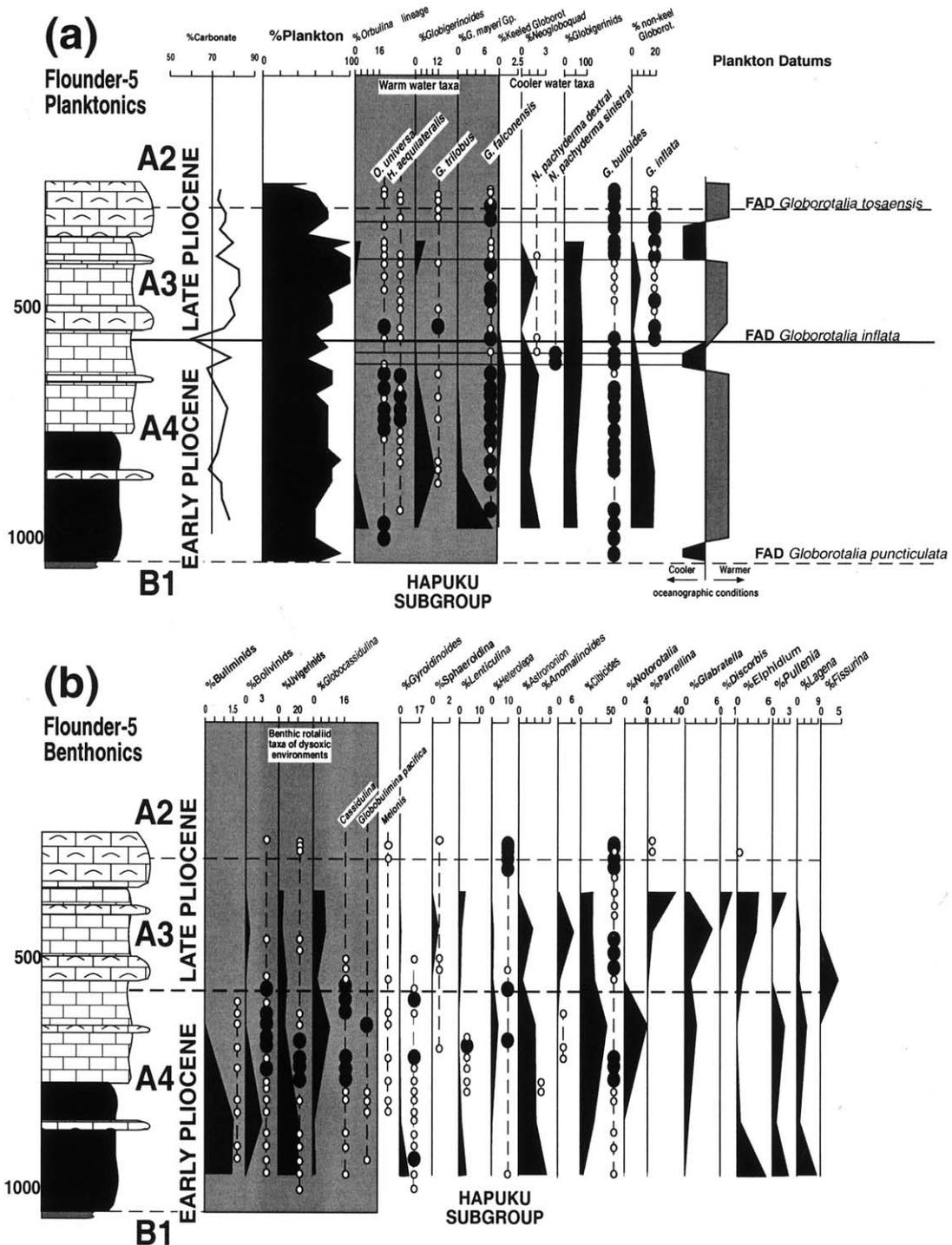


Fig. 9. The distribution of foraminifera in the Flounder-5 well. The %planktonics is expressed as a percentage of the total fauna. All other data are a percentage of the total plankton fauna (a) or a percentage of the benthic rotaliid fauna (b). The semiquantitative data are represented by circular symbols, where each small white circle represents a 1–20 specimen yield per sample and the black circles denote a yield of over 20 specimens per sample. The derivation of the interpreted oceanographic relative palaeo-temperature curve is shown in panel a.

mon *Globigerina bulloides* (Fig. 10). *G. inflata* and *G. bulloides* predominate towards the top of the A3 zonule. A similar fauna to the lower part of the A3 zonule occurs in the upper interval of the upper Pliocene, but with abundant *Globoconella bulloides*.

Plankton dominates the upper Pliocene foraminiferal assemblages in Hapuku-1 (Fig. 11). The nature of the plankton assemblages changes markedly up section. There are several intervals with common *Hastigerinella aequilateralis*, *Globigerinoides trilobus*, *Globoturborotalia decoraperta* and *Globigerina falconensis* that alternate with intervals without these taxa (Fig. 11).

5.3.3. Benthic foraminiferal distribution

A high-diversity, fine-grained benthic foraminiferal assemblage occurs in the ditch cuttings of the lower canyon interval in the upper Pliocene of Mackerel-1 (Fig. 8). *Uvigerina bassensis*, *Bulimina marginata*, *Cibicidoides perforatus* and *Cassidulina laevigata* typify the fauna in this canyon. Other forms include *Sphaeroidina bulloides*, *Anomalinoidea macroglabra* and *Globocassidulina subglobosa*. *Ammonia beccarii*, *Parrellina* and *Elphidium* species are minor elements of the assemblage within this canyon. A diverse mixed coarse (*Lenticulina mamillegera* and *Parrellina imperatrix*) and fine-grained foraminiferal fauna (similar to the underlying lower Pliocene canyon interval) occurs in the bioclastic packstone to grainstone of the overlying interval. Minor *Notorotalia*, *Glabratella*, *A. beccarii* and *Elphidium* occur in this bioclastic facies. The uppermost Pliocene canyon interval yields coarse to fine-grained foraminifera. The basal sample of this canyon contains abundant *U. bassensis*, *P. imperatrix* and *Discorbinella bertheloti* with common *Heterolepa opacus*, *C. laevigata*, *G. subglobosa* and *Discorbis*. *Elphidium*, *Rosalina*, *P. imperatrix*, *D. bertheloti*, *G. subglobosa* and *U. bassensis* are common in the upper sample of this canyon.

In Flounder-5, the upper Pliocene sequence is characterised by relatively low-diversity benthic assemblages in the sidewall cores (Fig. 10). Common *Cibicides*, *Cassidulina* and *Bolivina* occur in the lowest section (483–566 m). A sparse cibicidid assemblage occurs between 460 and 386 m. Above

386 m, *Cibicides* species are abundant and diverse. *Uvigerina*, *Parrellina imperatrix*, *Sphaeroidina bulloides*, *Elphidium* and *Guttulina problema* occur in the upper sidewall cores of Flounder-5. Fine-grained foraminifera characterise the two lower DC samples of Flounder-5 at 536 and 427 m. In these samples, *Cibicides mediocris*, *Uvigerina bassensis*, *Globocassidulina subglobosa*, *Discorbinella* and *Anomalinoidea* dominate the fauna. Minor *Elphidium* and *Glabratella* occur at 536 m, these taxa become more common above this level. *Parrellina* and *Cibicides* species are abundant in the coarse to fine-grained benthic assemblage of the upper DC study at 344 m with minor *Lenticulina* and *G. subglobosa*.

In Hapuku-1, the upper Pliocene benthic assemblage resembles that of the underlying lower Pliocene although the fauna is more diverse. In particular, *Virgulina*, *Globobulimina pacifica* and *Epistominella exigua* become common to abundant compared to the underlying lower Pliocene. Rare *Notorotalia* occur at the A3/A2 zonule boundary.

5.3.4. Palaeoenvironment and biofacies

The upper Pliocene strata of Mackerel-1 and Flounder-5 preserve canyon and intra-canyon facies that were deposited initially in an outer shelf to upper bathyal environment, shallowing to the present middle shelf environment (Fig. 10). Middle bathyal to upper bathyal canyon facies dominate Hapuku-1, shallowing to the present upper bathyal Bass Canyon environment (Fig. 11). The upper Pliocene plankton fauna is typified by cool to temperate oceanic forms (*Globigerina bulloides* and *G. inflata*), with several incursions of warmer-water plankton taxa (*Hastigerinella aequilateralis*, *Globigerina falconensis*, *Globigerinoides trilobus* and *Globoturborotalia decoraperta*). These taxa are rare or absent in the modern Gippsland offshore region.

In Mackerel-1, the lowest canyon interval is infilled with relatively high-energy molluscan facies, probably deposited in a canyon head dysoxic palaeoenvironment with transported inner shelf foraminifera. This canyon is in turn overlain by high-energy middle to outer shelf bryozoan facies with *Lenticulina* and *Parrellina*. The minor can-

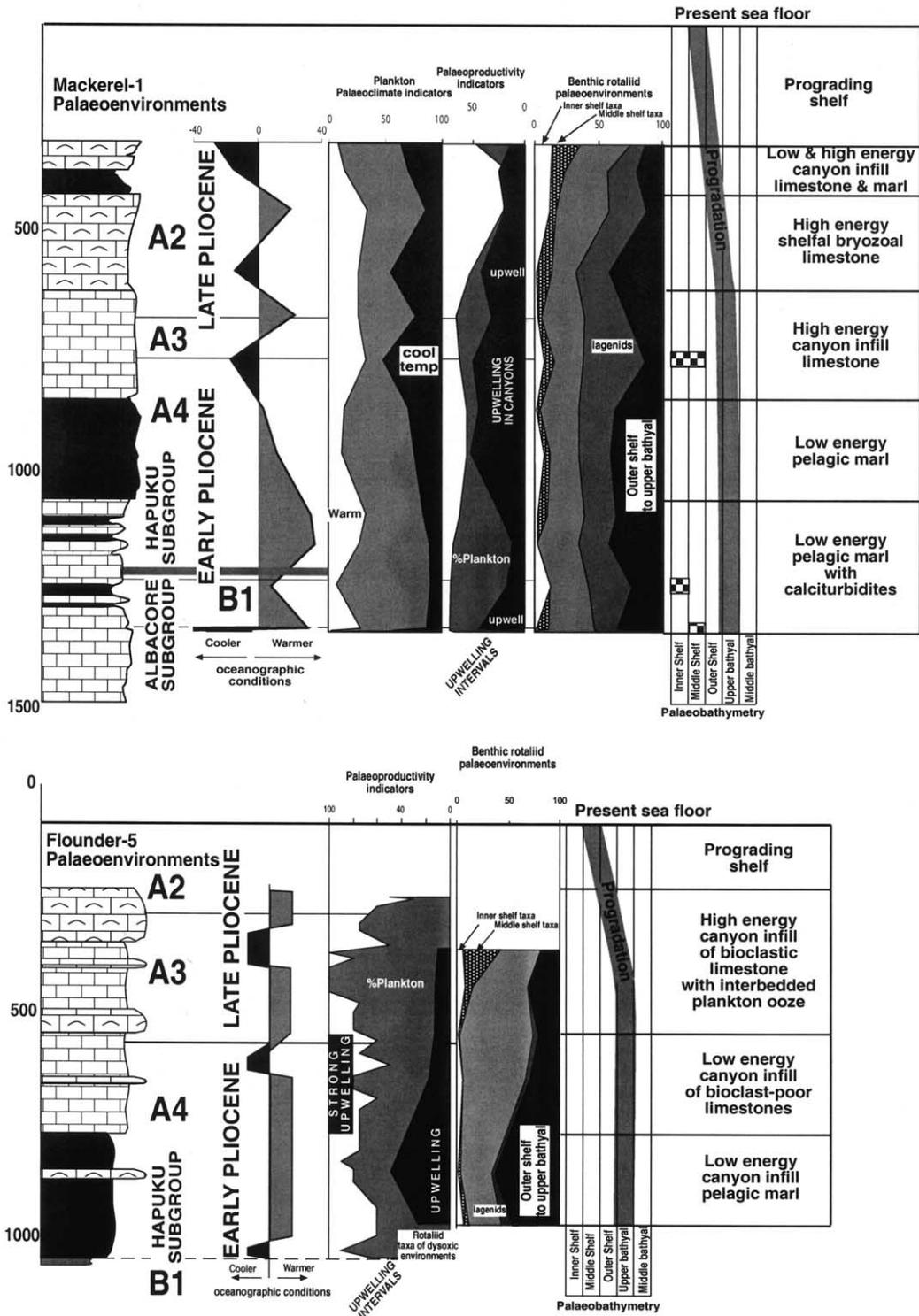


Fig. 10. A summary of the palaeoenvironments and facies of Mackerel-1 and Flounder-5. A list of the inner, middle and outer shelf to upper bathyal benthic rotaliid taxa used to compile the palaeoenvironment curve can be found in Table 2. The check pattern denotes intervals with transported inner to middle shelf taxa.

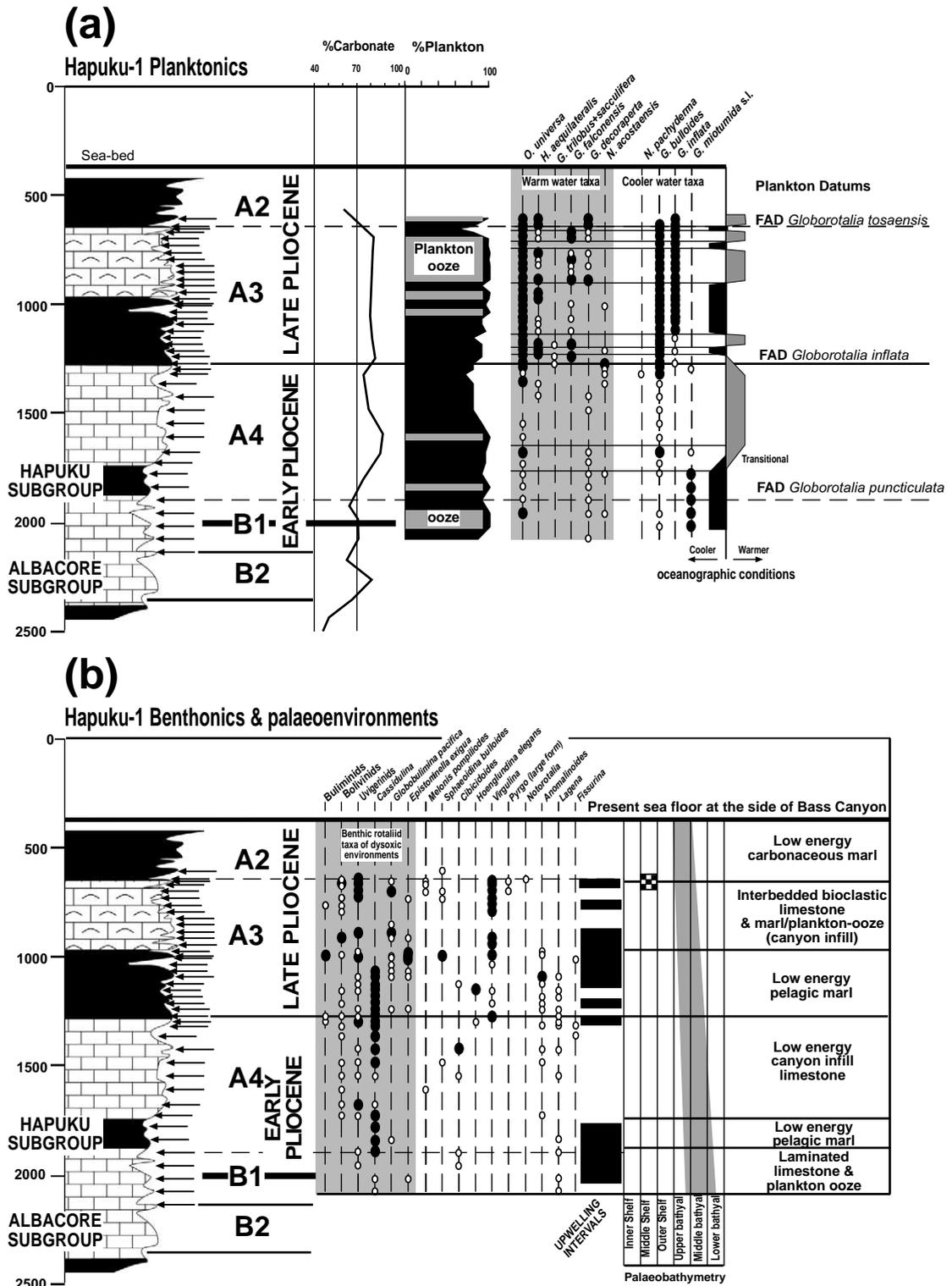


Fig. 11. The distribution of foraminifera in the Hapuku-1 well with a palaeoenvironmental interpretation. The semiquantitative data key is explained in the caption of Fig. 9.

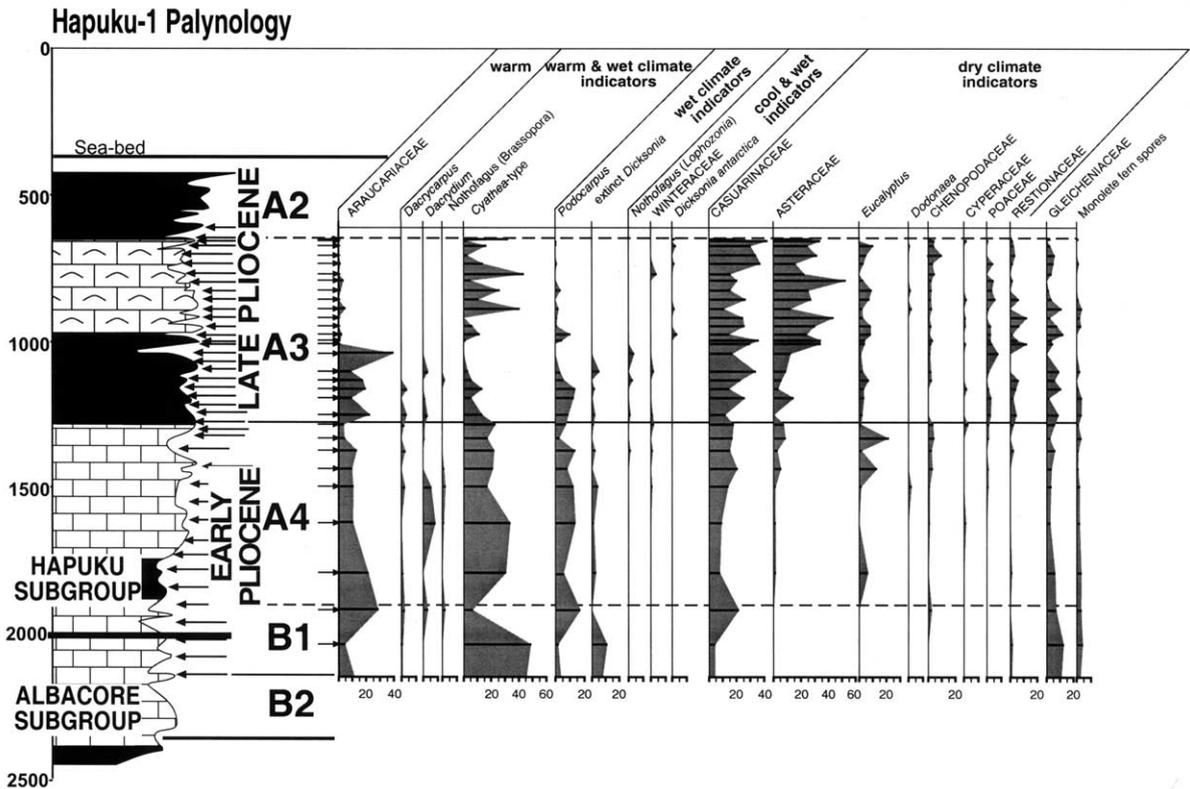


Fig. 12. The distribution of key palynomorph types in the Hapuku-1 well. The data are derived from Macphail (1997), the values are expressed as percentages of the total count. The palaeoclimate interpretation of the different groups is included in the text.

yon at the top of Mackerel-1 is interpreted to represent the upper reaches of a canyon head that initiated in a low to high-energy middle shelf palaeoenvironment toward the top of the lower Pliocene. The upper Pliocene complex canyon interval of Flounder-5 preserves canyon head facies deposited in a relatively high-energy palaeoenvironment near the outer shelf edge that shallowed upward. The presence of abundant *Globigerina bulloides* and dysoxic foraminiferal indicators in Hapuku-1 suggests upwelling was prevalent in the upper to middle bathyal environment at the head of the 'palaeo' Bass Canyon during most of the Late Pliocene.

5.4. Bioclimatic analysis of the Hapuku-1 spore/pollen taxa

Reconstruction of palaeovegetation and palaeo-

climate using spore–pollen assemblages is based on a number of assumptions (Macphail et al., 1994): (1) whereas dominance of floras by taxa may reflect physical or numerical dominance of the source plant(s), this cannot be assumed as some taxa (e.g. *Nothofagus*, *Cyathea*) are over-represented and others are under-represented; (2) in Australia, many spores and pollen types are primarily transported to sedimentary sites by water, and so the nature of the sedimentary environment and source region will introduce biases reflecting the stature, pollen production and location in the landscape of the source plants; and (3) that modern-day climatic tolerances and ecological constraints on distribution were the same in the past as they are today. The Hapuku-1 record is primarily a bathyal marine sequence, and can be expected to contain a record of terrestrial vegetation biased towards well represented sources in

the Gippsland coastal plain vegetation, such as coastal plants and riparian vegetation, but also major canopy trees with good pollen dispersal characteristics (Macphail et al., 1994).

The spore–pollen taxa from Hapuku-1 today all occupy mesothermal to marginal megathermal climates (MAT 14–24°C), but one group (e.g. *Dicksonia*, *Nothofagus* subgenus *Lophozonia* and *Tasmannia*) extend into microthermal regimes (MAT < 12°C; Fig. 13). The most significant differences between the taxa are the preference of a small number (e.g. *Dacrycarpus*, *Nothofagus* subgenus *Brassospora* and *Podocarpus*) for high rainfall (i.e. MAP > 180 cm/yr), and groups that prefer a warm-quarter rainfall maximum (e.g. *Cyathea*, *Agathis*, and *Araucaria*) or a cold-quarter rainfall maximum (e.g. *Nothofagus* subgenus *Lophozonia* and *Tasmannia*). Intervals during the Pliocene dominated by these climate groupings may therefore reflect regional climate at these times.

6. Pliocene palaeoenvironmental evolution of the bathyal to shelf transition in the Gippsland Basin

Throughout the Pliocene the Hapuku subgroup prograded southeastward toward the present Bass Canyon (Figs. 1 and 2). Figs. 10 and 11 summarise the palaeoenvironmental evolution of the Hapuku subgroup Pliocene succession in Mackerel-1, Flounder-5 and Hapuku-1. Complex canyoning occurred in Mackerel-1 and Flounder-1 at the shelf/upper bathyal transition throughout the Pliocene: these canyons ultimately infilled due to the progradation of shelf sediments. Lower to upper bathyal canyon sedimentation prevailed at Hapuku-1 on the side of the ‘palaeo’ Bass Canyon during the Pliocene.

Predominantly low-energy pelagic marl (wackestone/packstone) characterises canyon and inter-canyon environments in the earliest Pliocene, depositing plankton oozes with interbedded calciturbidites. From upper Early Pliocene to Late Pliocene times, high-energy limestone (grainstone) facies infilled the canyons in Mackerel-1 and Flounder-5, associated with the shallowing of the succession from outer to middle shelf palaeoenvironments. The interbeds of plankton-rich

pelagic marl (wackestone/packstone) within the canyons represent occasional quiescent phases during this deposition.

7. Pliocene palaeoceanographic evolution of the Gippsland Basin

Due to the nature of the plankton data collected from the wells studied (DC versus SWC samples and quantitative versus semiquantitative data) the Pliocene palaeoceanographic evolution of the wells was constructed in two principal ways:

The percentage abundance of warm (19–22°C) and cool to cool-temperate (0–18°C) planktonic taxa was plotted for Mackerel-1 ditch cuttings (see Fig. 10, where the taxa used in the analyses are listed in Table 1). By subtracting the total percentage of cool to cool-temperate taxa from the total percentage of warm taxa a curve is derived that relates to marine palaeotemperatures (oceanic conditions).

Where semiquantitative data were collected from sidewall cores in Flounder-5 and Hapuku-1, an interpretative curve was constructed (Figs. 9a and 11a) based on alternate influxes of common to abundant warm and cool-temperate planktonic taxa (Table 1). Where both warm and cool plankton abundance are similar, transitional oceanic conditions were interpreted.

The stratigraphy of the three wells studied with their interpreted oceanographic curves and upwelling intervals is shown in Fig. 14. Fig. 15 illustrates the relationship between the palaeoclimate curves and interpretations of this work based on foraminifers and spore/pollen data (see Sections 6 and 8) correlated to the Greenlee and Moore eustatic curve and the oxygen isotope curve for ODP Site 846 (Shackleton et al., 1995). The positions of major Southern Hemisphere oceanographic fronts are also illustrated for two time slices, 3–4 Ma and 2–3 Ma. The palaeoceanographic conditions for southern and western Australia are adapted from Wright and Thunell (1988), representing Early Pliocene (4.0 Ma) and Late Pliocene (2.4 Ma) marine conditions. The average sea surface temperatures for the eastern

sector are derived from Smolka (2000), where the position of the Subtropical Front (STF) is interpreted to coincide with the average sea surface isotherm of 10°C and the Polar Front coinciding with the 4°C isotherm (cf. Wells and Okada, 1996).

7.1. Marine temperatures

With the exception of the evidence for cool conditions at the base of the Early Pliocene (at the B1/A4 zonule boundary), the majority of the Early Pliocene strata in the three wells is characterised by a predominance of warmer-water taxa. Evidence for a predominantly warmer Early Pliocene (chronological equivalent to the A4 zonule, Fig. 15) is documented elsewhere in the Indian Ocean by Wright and Thunell (1988) and Wei (1998) in the Tasman Sea. These warmer oceanic conditions also correlate to a period of low marine $\delta^{18}\text{O}$ values (Fig. 15; Shackleton et al., 1995) and to a time when predominantly low ice sheet volumes are interpreted in Antarctica (Bart, 2001). Toward the A3/A4 boundary transitional and cool-water assemblages occur. By Late Pliocene (A3 zonule) times marked fluctuations in warm and cool-water assemblages occur. This is best shown in Hapuku-1, where evidence for at least four of these events is preserved (Fig. 14). Only part of the Late Pliocene A2 zonule strata was sampled in the wells studied. Notwithstanding this constraint, it is clear that the faunal overturn preserved in A3 zonule strata is also evident during this time. The change from a relatively stable warm Early Pliocene to a climatically variable cooler Late Pliocene preserved in the outer shelf to bathyal strata of Gippsland correlates with a time of heavier marine $\delta^{18}\text{O}$ values reported by Shackleton et al. (1995) and with the expansion of the Antarctic and Northern Hemisphere ice sheets during the Middle to Late Pliocene (as summarised in Abreu and Anderson, 1998).

7.2. Upwelling and the position of the STF

Many of the benthic rotaliid taxa in Mackerel-1, Flounder-5 and Hapuku-1 are typical of dys-

oxic environments (sensu Sen Gupta and Machain-Castillo, 1993, see Table 2). Upwelling (eutrophic) intervals were interpreted, where abundant dysoxic taxa co-occur with common cool temperate faunas (the cool intervals described above). While this pattern is true for the majority of the interpreted upwelling intervals (Fig. 14), there is evidence that upwelling was occurring in the Flounder-5 canyon during the warmer Early Pliocene. Here *Globigerina bulloides* co-occurs with abundant benthic taxa typical of dysoxic environments and warmer planktonic taxa, so it seems even during warmer phases upwelling was occurring in canyon head environments at the shelf/bathyal transition of Gippsland. This might be explained by upwelling associated with a more northerly positioned STF during this time compared to today where it lies South of Tasmania (Figs. 1 and 15). Similar upwelling signals in the Late Miocene strata of the Lakes Entrance Oil Shaft in Gippsland have been interpreted by Li and McGowran (1994) to reflect a northerly fluctuation of the STF to the region. Fig. 15 illustrates the average position of the STF in the Early and Late Pliocene. The data suggest that the STF occurred in the Gippsland region during the Pliocene (Fig. 15). The STF south of Tasmania was interpreted from proxy foraminiferal and nannofossil data by Nees (1997), Wells and Okada (1996) and Wells and Connell (1997) to have migrated northward up to 6° latitude during the Late Quaternary (in the last 500 ka). While these authors interpret the largest northerly STF movements to have occurred during glacial periods, Nees (1997) suggests some northward shift in the STF during interglacials. It is probable that the warm-water eddies associated with the present East Australian Current (that help to maintain the present southerly position of the STF) would not have been present or were weaker during the warmer Early Pliocene, hence the STF could migrate northwards over Gippsland during this time with its associated upwelling conditions. The warmer Pliocene oceanic conditions would be expected to have led to an ocean that was less stratified latitudinally and vertically (cf. the Early Miocene, Gallagher et al., 2001), hence the overall effect of the STF in the region would have been

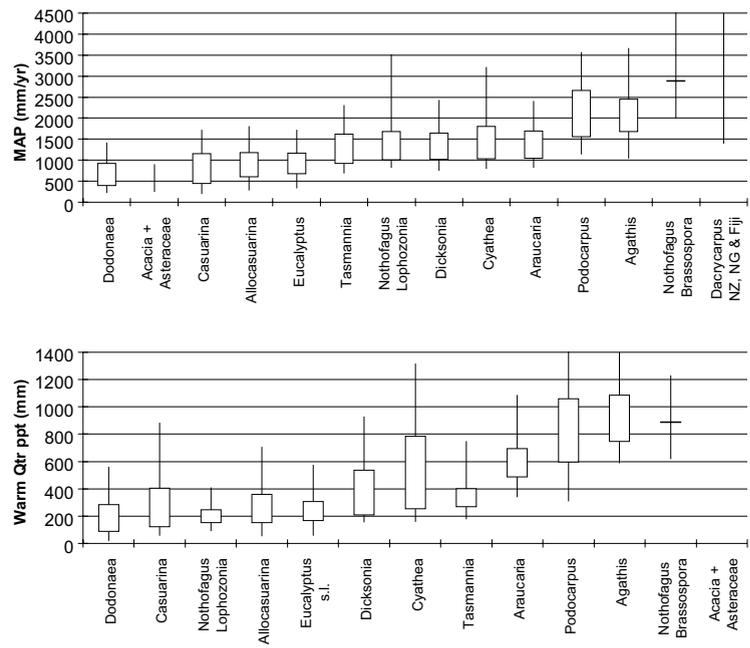
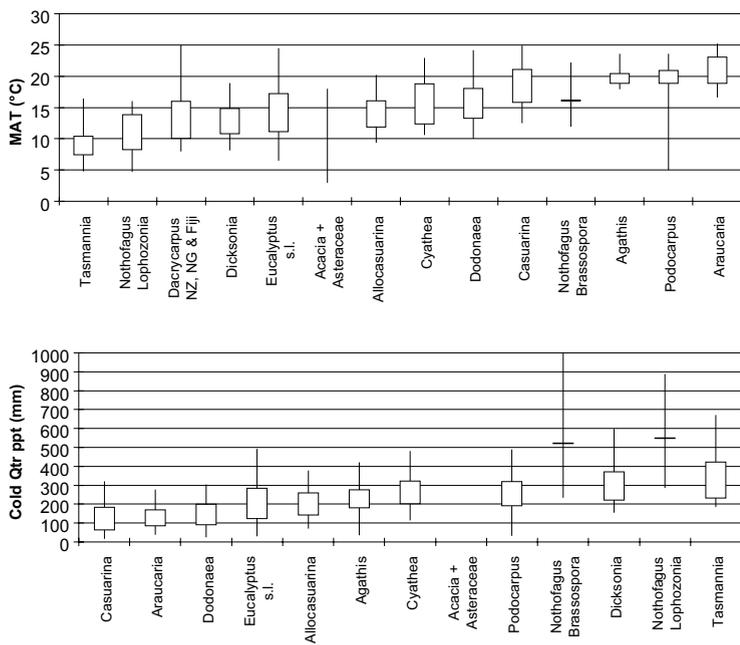


Fig. 13. Box plots of 5–95% (line) and 25–75% values (box), or range with mean (line and cross bar) for MAT, MAP, winter rainfall, and summer rainfall, for selected plant genera from the Hapuku-1 record. Climate values derived (this study) using BIOCLIM for herbarium records (ANH) of extant distribution, Australia-wide unless specified otherwise. The values for ‘euc veg’ are for East Gippsland only (lowland to subalpine). Non-Australian occurrences (range and mean of values only) from [Read and Hope \(1996\)](#) and [Macphail \(1997\)](#). Taxa are grouped according to main climatic intervals during the Pliocene. NB: ‘*Podocarpus*’ was based solely on the species naturally occurring in southeastern Australia (*P. alpinus*, *P. elatus* and *P. spinulosus*).

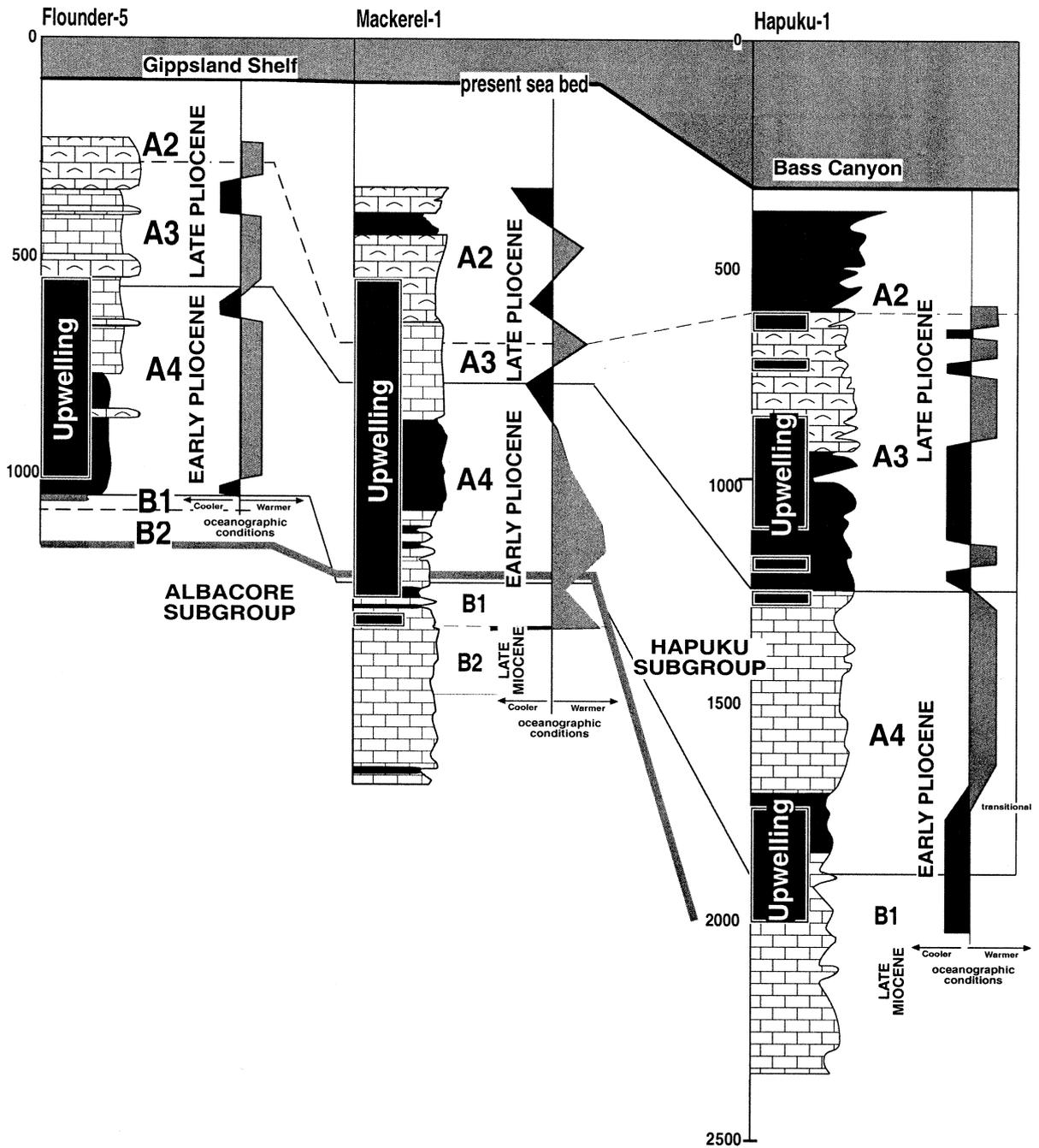


Fig. 14. A correlation of the Pliocene stratigraphy, marine upwelling and palaeoceanographic curves between Mackerel-1, Flounder-5 and Hapuku-1 wells.

Table 3

Pattern of Pliocene vegetation development and inferred climates for the Gippsland Plain from the Hapuku-1 core and Latrobe Valley palynosequences (data from Kershaw et al., 1994; Macphail, 1997; Greenwood et al., 2000)

Interval	Vegetation	climate	SST
Basal Early Pliocene A4 in part	Araucarian-dominated rainforests widespread; treeferns in riparian settings (Cyatheaceae), and more complex rainforests or sclerophyllous vegetation (with <i>Eucalyptus</i> and Casuarinaceae) in local microclimates	mesothermal moist ● MAT 2–4°C higher than present ● MAP 50–70% higher than present	warm phase
Mid to late Early Pliocene A4 in part	Araucarian rainforests interspersed with open sclerophyllous forests (and woodlands?) containing <i>Acacia</i> , <i>Eucalyptus</i> and Casuarinaceae (presumably <i>Casuarina</i> and <i>Allocasuarina</i>); graminoids and forbs may be components of the understory, treeferns (Cyatheaceae) declining in importance. Coastal Chenopodiaceae saltmarshes.	mesothermal moist to humid ● MAT 0–4°C higher than present ● MAP 30% higher than present	cooler till mid Early Pliocene, warmer from mid Early Pliocene till late Early Pliocene; cooler in latest Early Pliocene
Basal to mid Late Pliocene A3	regional mosaic of open <i>Eucalyptus</i> (sclerophyllous) forests and drier open woodlands with <i>Acacia</i> and Casuarinaceae, with either heathy understories (Asteraceae and Epacridaceae) or grassy understories (Asteraceae, Cyperaceae, Poaceae and Restionaceae). Coastal Chenopodiaceae saltmarshes.	microtherm– mesotherm interzone moist to humid ● MAT 0–2°C lower than present ● MAP = present day	basal Late Pliocene warm interval, but cool phase through most of the Late Pliocene
Latest Late Pliocene A2	regional mosaic of open <i>Eucalyptus</i> (sclerophyllous) forests and drier open woodlands with <i>Acacia</i> and Casuarinaceae, with either heathy understories (Asteraceae and Epacridaceae) or grassy understories (Asteraceae, Cyperaceae, Poaceae and Restionaceae); localised development of cool temperate rainforests (cool wet highlands?) with <i>Nothofagus cunninghamii</i> and treefern understories (<i>Dicksonia antarctica</i>). Coastal Chenopodiaceae saltmarshes.	mesotherm moist ● MAT 0–2°C higher than present ● MAP 30% higher than present	warm phase

MAT, mean annual temperature; MAP, mean annual precipitation; SST, sea surface temperature.

weakened, leading to a mixed warm/cool upwelling biofacies signature.

Evidence for upwelling occurs in the transitional oceanic palaeoenvironment at the A3/A4 zonule boundary. This correlates to two oxygen isotope peaks that occur near the top of A4 and at the A3/A4 boundary (Shackleton et al., 1995). This is probably associated with the Middle Pliocene Chill IV phase of McGowran et al. (1997). By Late Pliocene time, upwelling was prevalent in the outer shelf to upper slope facies at Hapuku-1, whereas evidence for upwelling is not strong in the shelfal facies of Flounder-5 and Mackerel-1. It is suggested, based on this interpretation, that

the shelf break (with associated upwelling) had prograded southeast of Mackerel-1 and Flounder-5 by the Late Pliocene. It is likely that regular movements of the STF northwards to Gippsland during Late Pliocene glacial periods caused considerable upwelling along the shelf edge. This is significant, since only local upwelling is occurring at the present shelf break at the head of the Bass Canyon (Smith et al., 2001). In addition, the present position of the Gippsland shelf and Bass Canyon is far from significant organic flux zones (the Tasman Front and the Subtropical Front, Fig. 15) and their associated upwelling conditions.

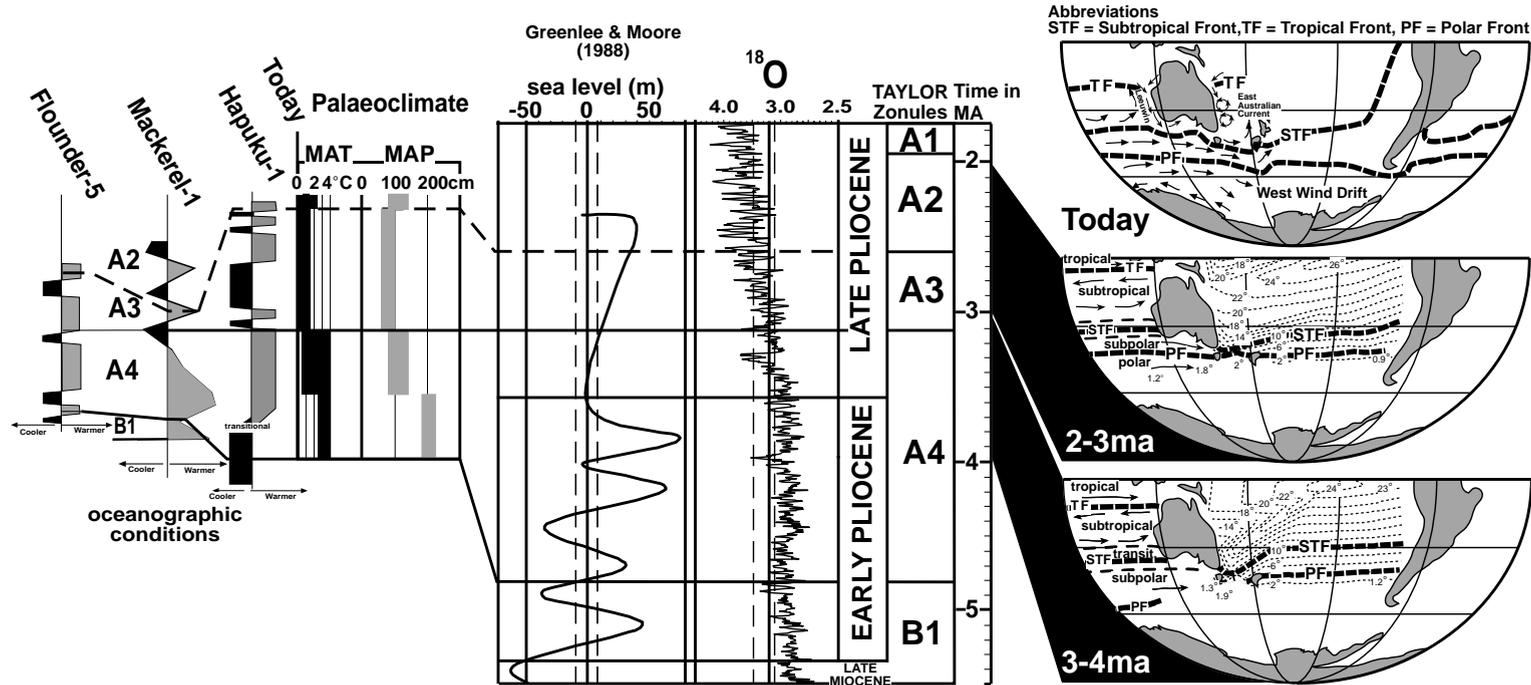


Fig. 15. The correlation of Gippsland marine events (of Fig. 13) with interpreted MAT and MAP for Hapuku-1. These curves are correlated to the Greenlee and Moore (1988) eustatic curve and the Pliocene oxygen isotope curve of Site 846 by Shackleton et al. (1995). The evolution of the Southern Ocean and Tasman Sea from Pliocene times is adapted from Wright and Thunell (1988) and Smolka (2000).

8. Palaeobotanical record of southeastern Australian terrestrial Pliocene climate

The terrestrial palaeobotanical record provides additional evidence of climate change in southeastern Australia through the Pliocene. Microfloral, macrofloral and faunal evidence supports the idea of a dramatic retreat of rainforest from sites in the continental interior and areas inland from the Great Dividing Range through the latter parts of the Miocene and into the Pliocene (Archer et al., 1994; Martin, 1994, 1997; Macphail, 1997; Greenwood and Christophel, in press). A short recovery phase for rainforest was noted for the earliest part of the Early Pliocene in some areas of southeastern Australia (Martin, 1991; Kershaw et al., 1994). Abundant sedimentological and fossil evidence testifies to a significant shift towards much drier (but not yet arid) climates by the Late Miocene and Pliocene, than in the Palaeogene. This pattern is also evident in southeastern Australia. However, rainforests appear to have remained significant components of the landscape across southeastern Australia, but a significant tropical floristic element now endemic to northeastern Queensland (e.g. Lauraceae, various taxa in the Proteaceae), and characteristic of late Early Miocene and Palaeogene floras in the region appears to be in significant decline by the Pliocene and was regionally extinct in southeastern Australia by the Pleistocene (Kershaw et al., 1994; Kershaw, 1998; Greenwood et al., 2000; Greenwood and Christophel, in press; Vadala and Greenwood, 2001). Some taxa were extinct across Australia by the Late Pleistocene, but are extant in nearby landmasses (e.g. *Dacrycarpus* and *Nothofagus* subgenus *Brassospora*). The principal microfloral evidence for these patterns is reviewed here.

Little is known of the upper Miocene and Pliocene macrofloral record of Australia (Greenwood et al., 2000); however, the Hapuku-1 core (Fig. 12) provides a record of terrestrial vegetation of the Gippsland coastal plain from the latest Oligocene to Late Pliocene–Pleistocene (Macphail, 1997). As such, the Hapuku-1 record provides a similar chronological sequence to that provided from composite spore–pollen records from the upper Lachlan River Valley in southern New

South Wales and the Latrobe Valley (Kershaw et al., 1994; Martin, 1994). The three records tell substantially similar stories, implying that these palynosequences record regional vegetational responses, and thus regional climatic events. In each of the sequences, rainforest declined in regional importance from the Early Miocene, with a substantive influence from open-canopied sclerophyllous forests established by the Late Miocene–Early Pliocene. *Acacia*, *Eucalyptus* and *Casuarinaceae* (likely representing *Allocasuarina* and/or *Casuarina*), key taxa in present-day sclerophyllous forests and woodlands in eastern Australia, are mostly absent or present in only trace amounts prior to the Early Pliocene. According to Kershaw (1998), counts for *Casuarinaceae* > 5% in the modern pollen rain of southeastern Australia are mainly restricted to sites receiving rainfall < 100 cm/yr and MAT > 13°C. From our bioclimatic analysis, across Australia *Allocasuarina* and *Casuarina* (*Casuarinaceae*) are restricted to climates where MAP < 180 cm/yr (and generally to MAP < 120 cm/yr) and seasonal rainfall regimes (Fig. 13). The sclerophyll taxa show marked increases through the Early Pliocene, concomitantly with rises in herbaceous or low shrubby taxa (*Asteraceae*, *Chenopodiaceae*, *Poaceae*, and *Restionaceae*) in the Hapuku-1 record, taxa that are well represented in (while not exclusive to) present-day open-canopied sclerophyllous vegetation in eastern Australia. These changes in regional importance of rainforest versus open-canopied sclerophyllous vegetation have been previously interpreted as indicating a drying trend across southeastern Australia over the Middle Miocene to Pleistocene (from > 180 cm/yr to < 80 cm/yr), particularly so a shift from non-seasonal rainfall or perhaps summer rainfall pattern to a winter (summer drought) rainfall pattern (Martin, 1991; Kershaw et al., 1994; Macphail, 1997). Within the Hapuku-1 record there are some interesting details that are brought out by the bioclimatic analysis of the taxa (Fig. 13).

In the Hapuku-1 record (Fig. 12) *Araucariaceae* (likely including both *Araucaria* and *Agathis*) maintain high values throughout the Early Pliocene, but decline sharply at the Early–Late Pliocene boundary. These taxa today in Australia oc-

cur in warm climates with a seasonal peak of rainfall in the warmest quarter (Fig. 13). Over the Pliocene Casuarinaceae and *Eucalyptus* fluctuate, but generally increase over the interval, with Casuarinaceae increasing to >40% for much of the latest Early Pliocene to Late Pliocene. The decline in Araucariaceae and increase in Casuarinaceae coincide with a relatively rapid cycling between inferred cooler oceanographic conditions in the latest Early Pliocene and warmer conditions in the basal Late Pliocene, and the maintenance of cooler conditions through most of the Late Pliocene. It is unlikely that temperature changes per se caused the Pliocene vegetational shifts (e.g. commentary in Martin, 1994 and Kershaw et al., 1994). Warmer oceanographic conditions likely correspond to higher regional rainfall, and cooler conditions to lower rainfall, and likely also shifts from non-seasonal to seasonal rainfall. Other conifers (e.g. *Podocarpus*) display similar patterns to Araucariaceae in the Hapuku-1 record, with *Dacrydium*, *Dacrycarpus* and *Lagarostrobos* absent from the Late Pliocene (Fig. 12). Of these taxa, only *Lagarostrobos* (Huon pine) and *Podocarpus* maintain a presence in southeastern Australia today. *Lagarostrobos* is restricted to high-rainfall sites in western Tasmania; however, *P. alpinus* is widespread in Tasmania and occurs in scattered patches in the highlands of southern New South Wales and Victoria, including the Erinundra Plateau in East Gippsland (Adam, 1994a). The principal taxa of present-day temperate rainforests in southeastern Australia, *Nothofagus cunninghamii* (subgenus *Lophozonia*), *Dicksonia antarctica* (a treefern), and Winteraceae (e.g. *Tasmania* spp.), today in Australia occur in cool wet climates with a winter rainfall maximum (Fig. 13). These taxa are largely absent from the older parts of the Hapuku-1 record, but are present in the Late Pliocene, particularly the youngest part of the record where oceanographic conditions are inferred to be warmer again (i.e. higher regional rainfall). Counts of *N. cunninghamii* >2% in the modern pollen rain are restricted to sites with MAP >120 cm/yr (Kershaw, 1998). Different taxa appear to fill the niche of the modern taxa in the older part of the Hapuku-1 record, with *Nothofagus* subgenus *Brassospora* and extinct spe-

cies of *Dicksonia* absent in the Late Pliocene. These patterns suggest two processes (as per Martin, 1994) in the source areas for the Hapuku-1 record: (1) the climatically mediated gradual replacement of the last vestiges of the species-rich mesothermal moist mixed rainforests ± araucarians by mesothermal moist–humid sclerophyllous forests and other open vegetation through the Early Pliocene, and; (2) that cool temperate rainforests like those currently restricted to cool wet valleys in upland areas in Victoria and in Tasmania first appeared in the latest Pliocene, implying the establishment at this time of suitable climates for this community type within the local region (mesotherm–microtherm interzone moist, i.e. MAT 7–12°C, MAP >140 cm/yr, driest quarter precipitation >15 cm).

In the modern pollen rain in southeastern Australia high percentages of Chenopodiaceae are typical of saline coastal sites (Kershaw, 1998), and chenopod shrublands are typical of the semi-arid (i.e. MAP <27 cm/yr, driest quarter precipitation <3 cm; Macphail, 1997) interior of southern Australia. The increasing Chenopodiaceae in the Hapuku-1 record may therefore reflect critical shifts in climate on the Gippsland coastal plain; however, coastal vegetation is more likely to be represented in the marine record than low stature inland vegetation, and Chenopodiaceae may be over-represented in palynofloras (Macphail et al., 1994). Coastal saltmarshes are dominated by Chenopodiaceae, and typically broadscale saltmarshes develop where mangroves cannot (through, for example, low temperatures, i.e. MAT <16°C, or hypersalinity), but may also form a landward ecotone fringing mangroves (Adam, 1994b). Along the Victorian coast today mangroves (*Avicennia marina*) occur in small stunted stands at Corner Inlet and nearby areas, at their southern limit. Elsewhere along the Victorian coast, and along the Tasmanian coast, are found saltmarshes dominated by Chenopodiaceae. Chenopods dominate coastal saltmarshes under Mediterranean climates (i.e. wet mild winters and warm to hot dry summers), whereas a substantive rush and sedge element (Cyperaceae and Restionaceae) is present in temperate saltmarshes experiencing non-seasonal rainfall (Adam, 1994b).

The overall pattern suggests that by the Late Pliocene climates and environments for the Gippsland coastal plain were similar to present-day settings. The sequence of regional vegetation patterns is summarised in Fig. 12 and Table 3 (largely based on Macphail, 1997).

9. Conclusions

This study integrates biofacies, foraminiferal analyses and palaeobotanical data from the Pliocene marine succession in Gippsland and other thin Pliocene terrestrial deposits in southeastern Australia to conclude the following:

1. Complex canyoning occurred at the shelf/upper bathyal transition throughout the Pliocene.
2. Lower to upper bathyal canyon sedimentation prevailed on the side of the ‘palaeo’ Bass Canyon during the Pliocene.
3. Low-energy pelagic marl (wackestone/packstone) characterises canyon and inter-canyon environments in the earliest Pliocene, depositing plankton oozes with interbedded calciturbidites.
4. From upper Early Pliocene to Late Pliocene times high-energy limestone (grainstone) facies infilled the canyons associated with progradation of the succession from outer to middle shelf palaeoenvironments.
5. Plankton proxy data suggest cool conditions in the basal part of the Early Pliocene.
6. Relatively stable warmer marine conditions prevailed throughout most of the Early Pliocene corresponding to a period of low marine $\delta^{18}\text{O}$ values (Fig. 15; Shackleton et al., 1995) and to a time when predominantly low ice sheet volumes prevailed in the Antarctic (Bart, 2001).
7. From Middle to Late Pliocene time, marked fluctuations in the abundance of cool and warmer-water plankton taxa correspond to a time of $\delta^{18}\text{O}$ fluctuations and general heavier or higher marine $\delta^{18}\text{O}$ values (Shackleton et al., 1995). This was associated with the expansion of the Antarctic and Northern Hemisphere ice sheets.
8. Marine upwelling is interpreted to have occurred throughout much of the warmer Early Pliocene. This may reflect a more northerly (com-

pared to today, where it is South of Tasmania) positioned and weaker STF.

9. By Late Pliocene time, upwelling was prevalent in the outer shelf to upper slope facies at the ‘palaeo’ Bass Canyon. This evidence together with the alternations of warmer and cooler marine conditions was probably caused by regular movements of the STF northwards to Gippsland during Late Pliocene glacial periods.

10. Terrestrial palaeobotanical records indicate a shift from widespread rainforests \pm araucarians, including ‘tropical’ taxa now extinct in the Gippsland coastal plain and region, to a landscape by the end of the Late Pliocene similar to that of the present day with a mosaic of *Eucalyptus*–*Acacia*–*Casuarinaceae* sclerophyllous forests and open vegetation, with local areas of *Nothofagus*-dominated cool temperate rainforests.

11. Regional terrestrial climate oscillated between warm–wet and cool–dry phases, with an overall cooling–drying trend through the Pliocene. Basal Early Pliocene climates were warm–wet with a summer rainfall peak (MAT 2–4°C higher than present, MAP 50–70% higher than present), whereas by the end of the Late Pliocene climates were drier–cooler with a winter rainfall peak (MAT 0–2°C higher than present, MAP 0–30% higher than present).

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