Fossil foraminiferal assemblages from Pleistocene seagrass-bank deposits of the southern Perth Basin, Western Australia, and their palaeotemperature implications

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Abstract

Fossil foraminifera were collected from three Pleistocene seagrass-bank deposits in the laterally contiguous Tims Thicket Limestone, Myalup Sand, and Kooallup Limestone in the southern Perth Basin, Western Australia. In total, 112 species of foraminifera were recorded. Tims Thicket Limestone and Kooallup Limestone had diverse assemblages (> 90 species) characterised by a *Marginopora-Amphisorus-Cibicides* assemblage. The limestone lens in the quartz-rich Myalup Sand had a moderately diverse assemblage (35 species) and was characterised by a *Lamellodiscorbis-Rotorboides* assemblage. Comparisons of the fossil assemblages with modern ecological assemblages from seagrass communities from a range of warm to cool climate settings along the Western Australian coast indicate that the limestone and siliciclastic formations formed in warm and cool water settings, respectively. Hence, these formations preserve a warm-cool-warm cycle of carbonate deposition in the late Quaternary, most likely linked to latitudinal shift in climate zones compounded by changing strength of the Leeuwin Current.

Keywords: Pleistocene foramininfera, seagrass facies, Perth Basin, Pleistocene limestone, sea temperatures

Introduction

In Western Australia, seagrass banks contributed to the formation of abundant carbonate deposits along the coast from the Neogene to Quaternary, as a result of prolonged sedimentation in a passive-margin tectonic setting (Davies 1970; Searle & Semeniuk 1985; Semeniuk & Searle 1985; Semeniuk *et al.* 1988). In the Perth Basin, both local modern and Pleistocene seagrass-bank material is available for study. This material is ideal for palaeoecological reconstruction based on foraminiferal assemblages due to its species richness and the continuity of Pleistocene species up to the present. Modern ecological analogues based on living foraminiferal assemblages for different climate settings are described for the Western Australian coast in T A Semeniuk (2000, 2001). These assemblages provide a baseline for the palaeoecological interpretation of Pleistocene material in this study. Semeniuk (1996) provides a detailed stratigraphic framework for the three Pleistocene formations.

Neontology incorporates both living assemblages (biocoenoses) and death assemblages (thanatocoenoses). Traditionally, fossil assemblages in palaeoecology are compared with death assemblages within modern (neontological) assemblages, since death assemblages are viewed as a long-term 'average' accumulations of the living assemblages. It is these death assemblages also that are most likely to be preserved in the stratigraphic column. However, in this study, Pleistocene assemblages are compared with living epiphytic assemblages of foraminifera, *i.e.*, those foraminiferal assemblages that are living on seagrass leaves in the modern environment. There are several reasons for this. Firstly, living epiphytic populations do not show the heterogeneity related to spatial variation in microhabitat that is typical for benthic populations of foraminifera, and thus, they can be easily used to characterise a specific habitat at the local scale (T A Semeniuk 2000). Secondly, epiphytic populations of foraminifera appear to closely reflect local ambient environmental conditions such as water chemistry, temperature and related epiflora at the time of sample collection, and thus are more reliable environmental and temperature indicators than benthic species (T A Semeniuk 2001). Thirdly, death assemblages represent a mix of epiphytic and benthic species of foraminifera accumulated over an unknown time interval. In addition, death assemblages typically contain reworked material, especially in the nearshore environments of southwestern Australia, where reworking of local onshore deposits is typical. As such, the death assemblages can reflect integrated population dynamics of different species, integrated assemblages from different local environmental conditions over time, effects of sedimentary processes on sediment composition, including preferential preservation and sorting of foraminiferal tests, as well as a minor contribution from reworked Holocene or older material derived from onshore deposits. Thus, in the nearshore environment, living foraminiferal assemblages can be used to clarify which components of a neontological assemblage are related to a given set of environmental conditions, which components result from long-term accumulation or reworked material.
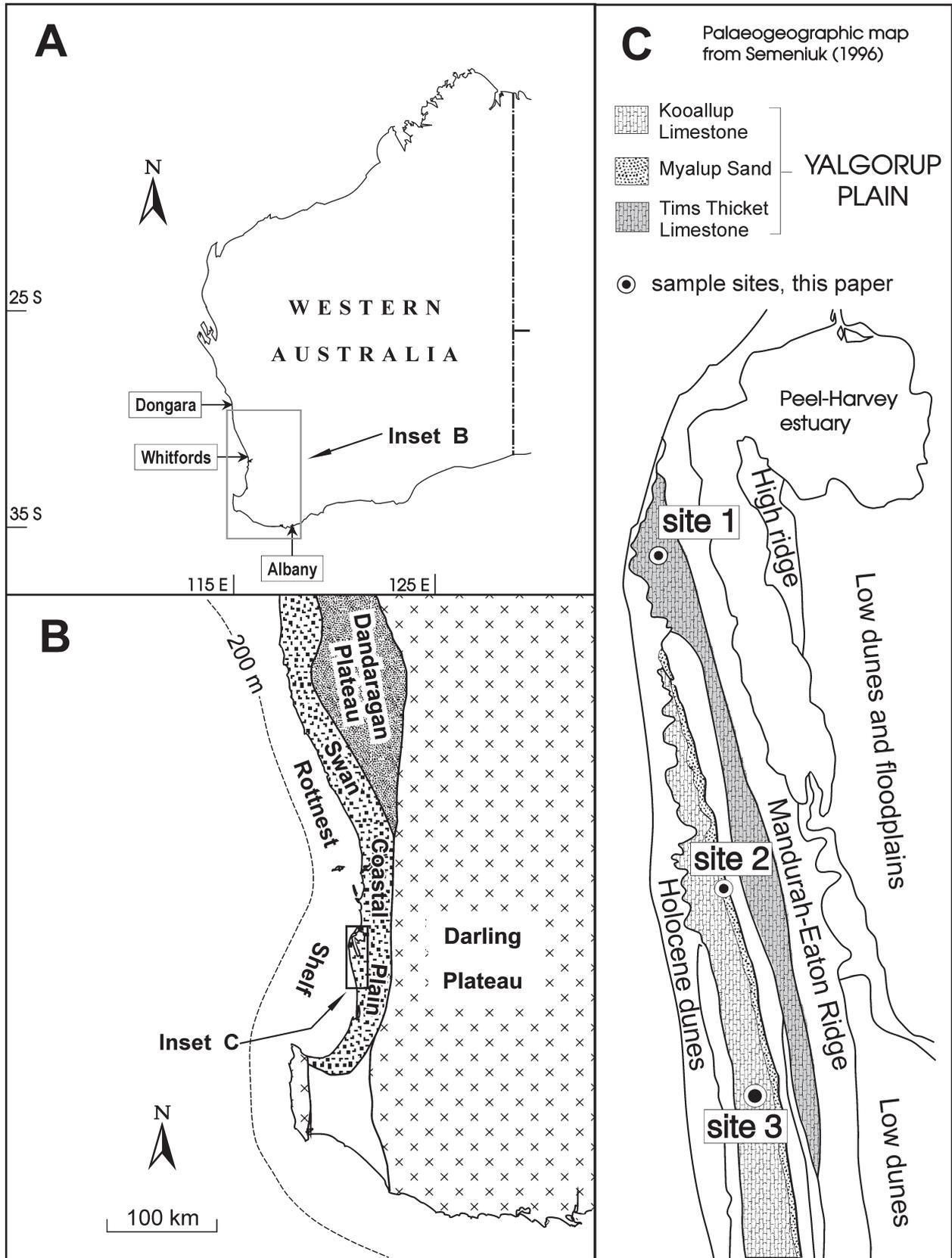
Figure 1. A. Location map, and location of sampling sites (Dongara, Whitfords, Albany) of T A Semeniuk (2000) for living assemblages of foraminifera. B. The Swan Coastal Plain (McArthur & Bettenay 1960), and location of detailed study area of the Yalgorup Plain (inset C). C. Outcrop of the Tims Thicket Limestone, Myalup Sand and Kooallup Limestone formations on the Yalgorup Plain, and location of the sampling sites, this paper, at quarry sites in the Tims Thicket Limestone (site 1) and the Kooallup Limestone (site 3), and the location of the transect through Myalup Sand (site 2) as shown in Figure 2.

The living assemblages described in earlier papers by T A Semeniuk (2000, 2001) are used in this study to decipher environmental or climate signals in the fossil thanatocoenoses on the basis of indicator species or taxonomic groups determined from modern analogues in different climate settings. Comparison of modern and Pleistocene material provides estimates of palaeo sea temperatures for each Pleistocene formation, as well as insights into carbonate productivity and climate change during the late Quaternary.

Stratigraphic and palaeogeographic setting

The nearshore-marine carbonate deposits which formed along the coast of Western Australia during the interglacial periods of the late Pleistocene to Holocene include units derived from seagrass and marginal seagrass environments (Semeniuk & Johnson, 1982; Semeniuk 1996). One of the best-developed and laterally extensive deposits, comprising seagrass-bank, beach and dune sequences underlies the Yalgorup Plain of the southern Swan Coastal Plain in the Perth Basin (McArthur & Bettenay 1960; Semeniuk 1996). Here, seagrass-bank units occur in three contiguous Pleistocene formations (Fig. 1).

The Pleistocene coastal limestones in this region were originally referred to by previous workers as Coastal Limestone, then as Tamala Limestone (Playford *et al.* 1976). However, on the basis of lithology, stratigraphy and geological history, Semeniuk (1995) assigned the sedimentary carbonate and quartz sand deposits in this area to the Tims Thicket Limestone, Myalup Sand and Kooallup Limestone. The three formations are shore-parallel and are separated by unconformities, suggesting that there were at least three separate marine transgressions during the late Pleistocene (Fig. 1). Semeniuk (1996) identified units within the marine portion of the sequences as seagrass-bank deposits based on their position within the shoaling stratigraphic sequence, their microstratigraphic and sedimentological features, and their fossil molluscan fauna.

Based on their stratigraphy, Semeniuk (1996) reconstructed the palaeogeography and palaeoenvironments of the three Pleistocene formations and showed that they formed as cuspate forelands, barrier or ribbon shoreline deposits at different sealevel stands (Table 1). The formations have very different carbonate content, suggesting differences in carbonate productivity linked to changes in palaeogeographic or climate setting.

Methods

Field techniques

Data on epiphytic foraminifera from modern seagrass meadows form the basis of the information on the living foraminiferal assemblages used in this paper. In the modern environments, T A Semeniuk (2000) sampled epiphytic foraminifera in seagrass meadows in 1.0–1.5 m depth of water in three climatically distinct areas (Fig. 1), *i.e.*, at Dongara, a warm water environment, at Whitfords, an intermediate climate setting, and at Albany, a relatively cool water environment. Within each geographic/climate setting, nine 9-cm diameter cores (three cores within 1m^2 separated by at least 25 m from the next set of three cores) were used to harvest seagrass leaves and their foraminiferal epiphytes. The results of the study into living foraminiferal assemblages are presented in T A Semeniuk (2000, 2001), and will not be re-iterated here other than for comparative purposes.

Samples of weakly cemented Pleistocene limestone containing foraminifera were collected from the Tims Thicket Limestone and Kooallup Limestone from vertical exposures in quarry sites within the Yalgorup Plain (Fig. 1). The Tims Thicket Limestone sampling site (site 1, this paper) is a quarry at 32° 39' 09.52" 115° 37' 18.85" located at site 5 transect 1 of Semeniuk (1995). The limestone lens in the Myalup Sand (site 2, this paper) was intersected in a core at 32° 54' 51.19" 115° 42' 11.08" located at site 6 transect 2 of Semeniuk (1995). The Kooallup Limestone sampling site (site 3, this paper) is a quarry at 32° 01' 23.71" 115° 42' 27.55" located at site 2 transect 4 of Semeniuk (1995).

In the quarries cut into the Tims Thicket Limestone and the Kooallup Limestone, material was sampled from a horizon about 10–20 cm thick within the seagrass facies, located 1 m below trough-bedded low-tidal to shallow-water beach facies of Semeniuk (1996), and 0.5 m below the upper seagrass-unit boundary (Fig. 2). In modern environments, this stratigraphic interval is equivalent to sediments from 1.0–1.5 m of water, *i.e.*, the depth at which collections of modern living foraminiferal material took place (T A Semeniuk, 2000), as described above, *i.e.*, the sampling interval in the Pleistocene limestone was the facies-equivalent of the sampling sites in the modern environments. The thickness of the beach facies in the Pleistocene deposits is similar to that in Holocene sequences (Semeniuk 1996; Semeniuk & Johnson 1982), suggesting that the tidal range was microtidal during the deposition of the Pleistocene units.

Table 1

Summary of palaeogeographic setting, stratigraphy, Pleistocene sealevel position, and lithologic signature of the three contiguous Pleistocene formations of the Yalgorup Plain (after Semeniuk 1996)

| Formation	Palaeogeographic setting	Simplified stratigraphic setting	Pleistocene sealevel position	Carbonate content
Tims Thicket Limestone	cuspate foreland	shoaling sequence of seagrass bank to dune facies	+ 3 m above present MSL	high
Myalup Sand	shoreline ribbon	limestone lenses with a coastal quartz sand formation	- 2–3 m below present MSL	low
Kooallup Limestone	cuspate foreland	shoaling sequence of seagrass bank to dune facies	+ 3–4 m above present MSL	high
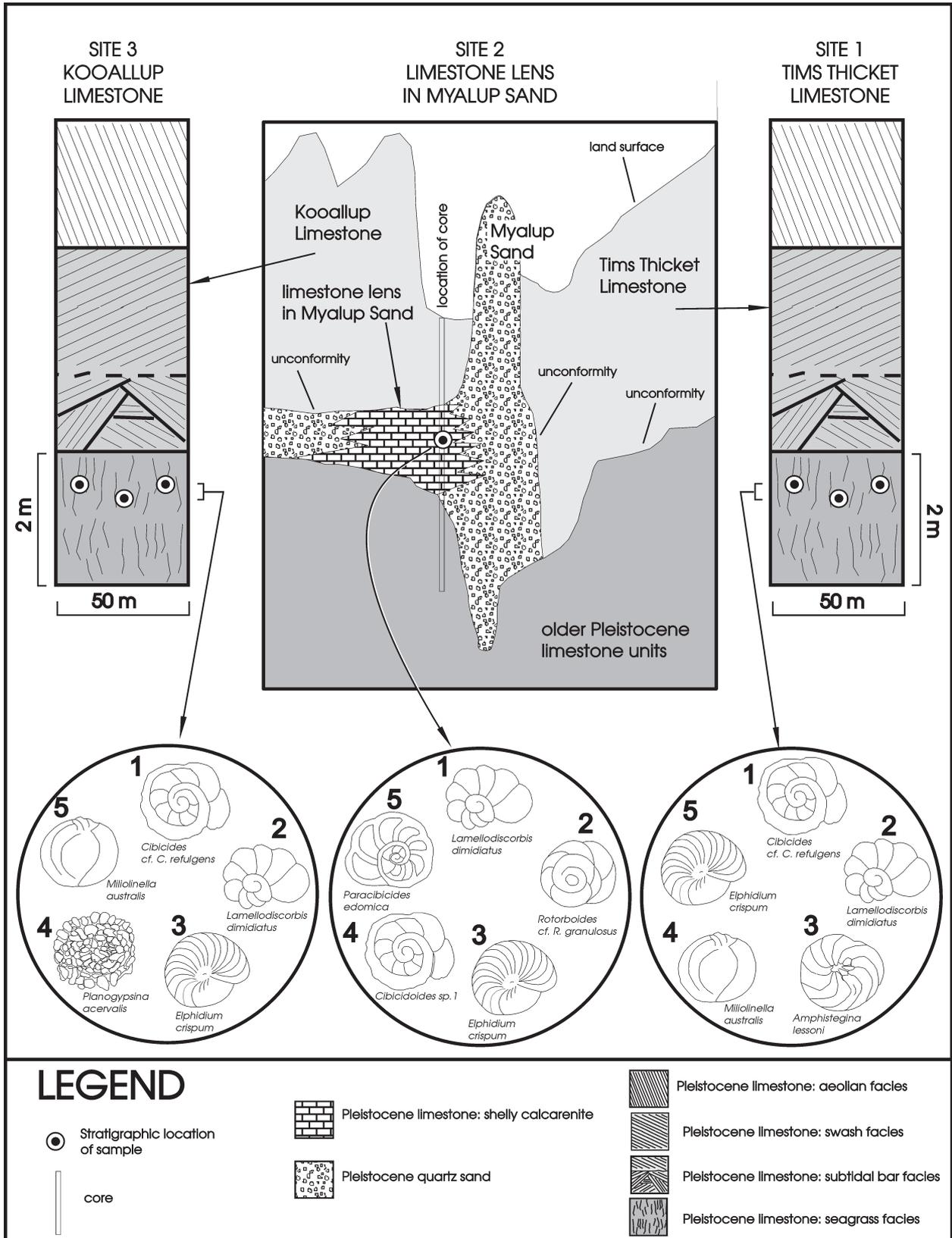
Figure 2. Stratigraphic setting of samples for the three Pleistocene formations: detailed stratigraphy from quarry sections, showing location of samples for the Tims Thicket Limestone at site 1 and Kooallup Limestone at site 3, and location of drill core and sample for the localised limestone lens in the Myalup Sand at site 2. The five most abundant foraminifera from each Pleistocene formation are diagrammatically shown in order of abundance; Tims Thicket Limestone – 1. *C.* cf. *refulgens*, 2. *L. dimidiatus*, 3. *A. lessoni*, 4. *M. australis*, and 5. *E. crispum*; Myalup Sand – 1. *L. dimidiatus*, 2. *R.* cf. *granulosus*, 3. *E. crispum*, 4. *Cibicidoides* sp. 1, and 5. *P. edomica*; Kooallup Limestone: 1 – *C.* cf. *refulgens*, 2. *L. dimidiatus*, 3. *E. crispum*, 4. *P. acervalis*, 5. *M. australis*.

For the Tims Thicket Limestone and Kooallup Limestone, three replicate samples of Pleistocene limestone were collected in close mutual proximity (within 50 m of each other; Fig. 2). The samples were collected in replicate to assess lateral variation in composition within a formation and to determine the statistical significance of composition differences between formations. Samples consisted of about 250 ml of friable material collected 5 cm below the weathered vertical surface in the quarry section.

The limestone lenses in the Myalup Sand do not crop out, but one carbonate-rich sample (100 ml in volume) was obtained from a drill-core. The location of the drill hole in the Myalup Sand relative to the local stratigraphy is shown in Figure 2.

Laboratory techniques

Standard palaeontological methods, outlined in Haynes (1981), were followed in this study. Pleistocene samples were soaked in water to disaggregate sediment as much as possible. Material was wet sieved through a 63-µm mesh and oven dried. The vast majority of material was very weakly cemented or uncemented, and so it disaggregated readily and fully. At least 300 specimens were picked from sediment scattered on a picking tray. The volume of sediment picked was recorded to calculate the approximate number of foraminifera occurring in one cubic centimeter of sediment. Specimens were sorted on taxonomic slides and identified using standard reference material (Ellis & Messina 1940 *et seq.*) and taxonomic literature relevant for the Western Australian region including Jones (1994), Loeblich & Tappan (1988, 1994), and Parr (1932a, 1932b, 1945). Assemblage data on the number of individual specimens of each species were compiled for each sample (Appendix 1).

Quantitative data analyses

Density and diversity of foraminiferal assemblages were calculated using standard ecological measures. The total foraminiferal density was calculated from three replicates for each formation, whereas diversity was calculated for each sample and a mean diversity was calculated for each formation. The Fisher index (Fisher *et al.* 1943; Fisher & Yates 1953) was used to categorise species heterogeneity while the Shannon index (Pielou 1975) was used to determine evenness of the assemblages from each formation.

Analysis of variance was carried out on the species abundance for the Tims Thicket Limestone and Kooallup Limestone (statistical analysis was only possible for formations with replicate samples) to identify important differences between formations. A significant F-ratio is obtained for species that showed greater variation between formations than within replicates from a given formation. Non-significant F-ratios imply that the lateral variation within a formation is of sufficient magnitude to obscure differences between formations, in which case the hypothesis that all samples characterise an identical assemblage cannot be rejected at the 95% confidence level. The criterion used to choose species for statistical analysis was a mean sample count of greater than three specimens. Seventeen of the total 112 species met this criterion.

Palaeoecological reconstructions

Modern assemblages of foraminifera, described and illustrated in detail in T A Semeniuk (2000, 2001) form the basis of comparison and palaeo-environmental interpretation of Pleistocene foraminiferal assemblages of this paper. Assemblages are from semi-arid to sub-humid subtropical climate settings, wherein annual sea temperatures range from 20–25 °C at the warmest site and 16–20°C at the coolest site (Pearce *et al.* 1999; T A Semeniuk 2000), Characteristics of the live epiphytic assemblages from these modern sites are:

1. they are all hyaline dominant assemblages

2. moderately diverse assemblages with high evenness characterise the warmest site; the dominant species are *Quinqueloculina* cf. *Q. incisa, Vertebralina striata, Peneroplis planatus, Amphisorus hemiprichii* and *Marginopora vertebralis.*

3. the coolest site has low diversity and moderate evenness and is characterised by the species *Lamellodiscorbis dimidiatus, Annulopatellina annularis* and *Rosalina* spp.

Using information on the distribution of living foraminiferal species in modern environments in relation to sea temperatures, criteria to interpret former sea temperatures for Pleistocene environments were developed. The criteria were based on modern taxa, whose abundance and distribution patterns most likely reflect sea temperature (T A Semeniuk 2001). In principle, these criteria would provide a basis for interpreting sea-temperature differences between Pleistocene formations, although in the fossil record this effect cannot be completely decoupled from other abiotic and biotic factors.

Initially, a number of criteria deriving from the modern assemblages were considered for use in reconstructing palaeo sea temperature settings of Pleistocene seagrass-bank environments. These included compositional attributes of the living assemblages at Order, Family, Genus and species level that had strong positive correlation with climate setting, including the number of rotallid, buliminid and miliolid taxa, the number of larger foraminifera, the number of *Quinqueloculina* species, abundance of select species such as *V. striata, Q.* cf. *Q. incisa, Sorites variabilis* and *Bolivina subreticulata*. In this study, however, the number of larger foraminifera, the numbers of rotallid and miliolid taxa, as well as the abundance of select species such as *S. variabilis*, are used as indicators to interpret former sea temperatures.

Using the information from modern environments as a tool, the composition of fossil foraminiferal assemblages from each of the three formations were compared with modern living epiphytic foraminiferal assemblages, and their former sea temperature settings were interpreted.

Results

General composition of fossil assemblages

A total of 112 species was recorded in fossil foraminiferal assemblages from the seagrass-bank units of the Pleistocene formations (Table 2). Species counts for

Table 2

Complete list of species of Pleistocene foraminifera collected from the Tims Thicket Limestone, Myalup Sand and the Kooallup Limestone.

Order	Taxa	Order	Taxa
Textularia		Rotaliina	
	Gaudryina sp 1	(spirillinids	*Patellina corrugata*
	Textularia pseudogramen		*Planispirillina spinigera*
	Textularia cf. T. sagittula		*Spirillina limbata*
	Textularia sp 1		*Spirillina sp. 1*
Miliolina		(lagenids)	*Fissurina bradyformata*
	Amphisorus hemiprichii		*Sigmoidella elegantissma*
	Biloculinella sp. 1	(buliminids)	*Bolivina sp. 1*
	Cornuspira involvens		*Bolivina sp. 2*
	Cornuspira sp. 1		*Bolivina quadrilatera*
	Cornuspira acicularis		*Buliminoides williamsonianus*
	Marginopora vertebralis		*Fijiella simplex*
	Miliolinella australis		*Loxostoma cf. L. digitale*
	Miliolinella labiosa		*Loxostomina costulatum*
	Miliolinella sp. 1		*Loxostomina limbata*
	Nubecularia luciuga		*Pavonina flabelliformis*
	Parrina bradyi		*Reussella armata*
	Peneroplis pertusus		*Reussella simplex*
	Peneroplis planatus		*Saidovina sp. 1*
	Pseudomassilina australis		*Sigmavirgulina tortuosa*
	Pseudomassilina subgranulata		*Trifarina sp. 1*
	Pyrgo sarsi	(rotallids)	*Acervulina mahabeti*
	Quinqueloculina baragwanathi		*Amphistegina lessoni*
	Quinqueloculina carinata		*Angulodiscorbis quadrangularis*
	Quinqueloculina cf. Q. bicarinata		*Annulopatelinella annularis*
	Quinqueloculina sulcata		*Anomalinoides globosus*
	Quinqueloculina cf. Q. incisa		*Anomalinoides sp. 1*
	Quinqueloculina cf. Q. laevigata		*Anomalinoide sp. 2*
	Quinqueloculina cf. Q. patagonica		*Cibicidina (?) sp. 1*
	Quinqueloculina cf. Q. neostriatula		*Cibicides cf. C refulegens*
	Quinqueloculina crassicarinata		*Cibicides pseudolobatus*
	Quinqueloculina cuvieriana		*Cibicidiodes mabahethi*
	Quinqueloculina distorqueata		*Cibicidiodes sp. 1*
	Quinqueloculina patagonica		*Conorbella pulvinata*
	Quinqueloculina poeyana		*Cribononion kerguelense*
	Quinqueloculina quinquecarinata		*Cymbaloporetta squammosa*
	Quinqueloculina sp. 1		*Discorbinella chincaensis*
	Quinqueloculina sp. 2		*Dyocibicides sp. 1*
	Quinqueloculina subpolygona		*Dyocibicides sp. 2*
	Spiroloculina communis		*Elphidium aculeatum*
	Spiroloculina corrugata		*Elphidium adventum*
	Spiroloculina parvula		*Elphidium craticulatum*
	Spiroloculina venusta		*Elphidium crispum*
	Triloculina cf. T. quadrata		*Elphidium depressulum*
	Triloculina striatotrigonula		*Elphidium jenseni*
	Triloculina trigonula 4		*Elphidium macellum*
	Triloculina triquetrella		*Elphidium repandus*
	Triloculina cf. T. parisa		*Glabratella patelliformis*
			Glabratella sp. 1
			Heronallenia lingulata
			Lamellodiscorbis dimidiatus
			Neoconorbina terquemi
			Paracibicides edomica
			Pararotalia stellata
			Planoglabratella opercularis
			Planogypsina acervalis
			Planulina sp. 1
			Rosalina sp. 1
			Rotorbinella cf. R. rosea
			Rotorbis mirus
			Rotorboides cf. R. granulosus
			Rugobolivinella pendens
			Siphonina reticulata
			Siphoninoides echinatus
			Siphoninoides laevigatus
			Svratkina sanmiguelensis
			Trichohyalus tropicus

Table 3

Dominant fossil foraminifera of the three Pleistocene formations of the Yalgorup Plain. NB: *** = abundant (>10%), ** = common (>5%), * = uncommon (<5%), - = not recorded. Only species with total sample mean >3 are listed herein; these species are illustrated in Plate 1.

Taxa	Tims Thicket Limestone	Limestone lens (MyalupSand)	Kooallup Limestone
Amphisorus hemiprichii	*	–	*
Marginopora vertebralis	*	–	*
Miliolinella australis	**	*	**
Miliolinella labiosa	*	–	*
Peneroplis planatus	*	–	*
Quinqueloculina baragwanathi	*	–	*
Quinqueloculina poeyana	*	*	*
Quinqueloculina subpolygona	*	*	*
Amphistegina lessoni	**	*	*
Cibicides cf. *C. refulgens*	***	–	***
Elphidium crispum	**	**	***
Lamellodiscorbis dimidiatus	***	***	***
Pararotalia stellata	*	*	*
Planogypsina acervalis	*	–	**
Rotorbinella cf. *R. rosea*	**	*	**
Rotorbis mirus	**	*	**
Rotorboides cf. *R. granulosus*	*	**	*

each sample are presented in Appendix 1. Remanié foraminifera, reworked from older Pleistocene formations, were present in all samples. Remanié foraminifera had a more iron-stained weathered appearance and so were readily distinguishable; hence they were excluded from analyses.

The dominant species recorded from each formation are listed and compared in Table 3 and illustrated in Plate 1. The Tims Thicket Limestone and Kooallup Limestone have hyaline-rich assemblages (65%) with subdominant porcellaneous components. The limestone lens in the Myalup Sand has a hyaline-dominant assemblage (85%) with a minor porcellaneous component. The presence of *A. hemiprichii*, *M. vertebralis*, and *Planogypsina acervalis* in the fossil material confirm that the material is seagrass-derived (Reiss & Hottinger 1984; T A Semeniuk 2000).

The Tims Thicket Limestone and Kooallup Limestone both have very high total foraminiferal densities with greater than 40 000 foraminifera per ml of sediment. The limestone lens in the Myalup Sand has a relatively low foraminiferal density with ca. 250 foraminifera per ml.

Diversity of fossil assemblages

Both Tims Thicket Limestone and Kooallup Limestone assemblages are species diverse, and have even composition. Tims Thicket Limestone and Kooallup Limestone assemblages had at least 90 species present. Fisher indices for the Tims Thicket Limestone and Kooallup Limestone are 22 and 19, respectively. In contrast, the limestone lens in the Myalup Sand had moderate diversity with 35 species recorded for the limited amount of material analyzed. This gives a Fisher index of 11.

Variation in fossil assemblages

Two-way ANOVA on dominant species was used to assess variance in composition between replicate samples of Tims Thicket Limestone and Kooallup Limestones. All species show such lateral variation between replicate

samples that compositional differences between these two Pleistocene limestone formations are not statistically significant. The results of ANOVA are presented in Appendix 2.

Provisional names for fossil assemblages

Each formation has a different assemblage composition, although the two limestone formations have similar dominant species. Definition and nomenclature of foraminiferal assemblages in this study are based primarily on the most abundant species in each formation, but also include species that characterise a particular formation, or species that are volumetrically dominant. For example, the larger foraminifer *M. vertebralis* is volumetrically abundant and conspicuous in the Tims Thicket Limestone and Kooallup Limestone, but is numerically uncommon. Two types of fossil foraminiferal assemblages are documented:

1. a *Marginopora-Amphisorus-Cibicides* assemblage, which characterises the Tims Thicket Limestone and Kooallup Limestone; and

2. a *Lamellodiscorbis-Rotorboides* assemblage, which characterises the limestone lens in the Myalup Sand.

Palaeoecological interpretation

General compositional features of all fossil foraminiferal assemblages are similar to modern assemblages from shallow-water seagrass habitats (T A Semeniuk 2000). They are all hyaline dominant. In fact, the high overlap in species composition between Pleistocene assemblages and live epiphytic assemblages suggests that the major component of the Pleistocene assemblages *was derived from epiphytic foraminiferal species*. The main noteworthy difference between Pleistocene and modern living assemblages is that *Cibicides* cf. *C. refulgens* was not recorded in any of the living assemblages.

In detail, both the Tims Thicket Limestone and Kooallup Limestone have closest similarity to living assemblages at the warmest site of Dongara of T A
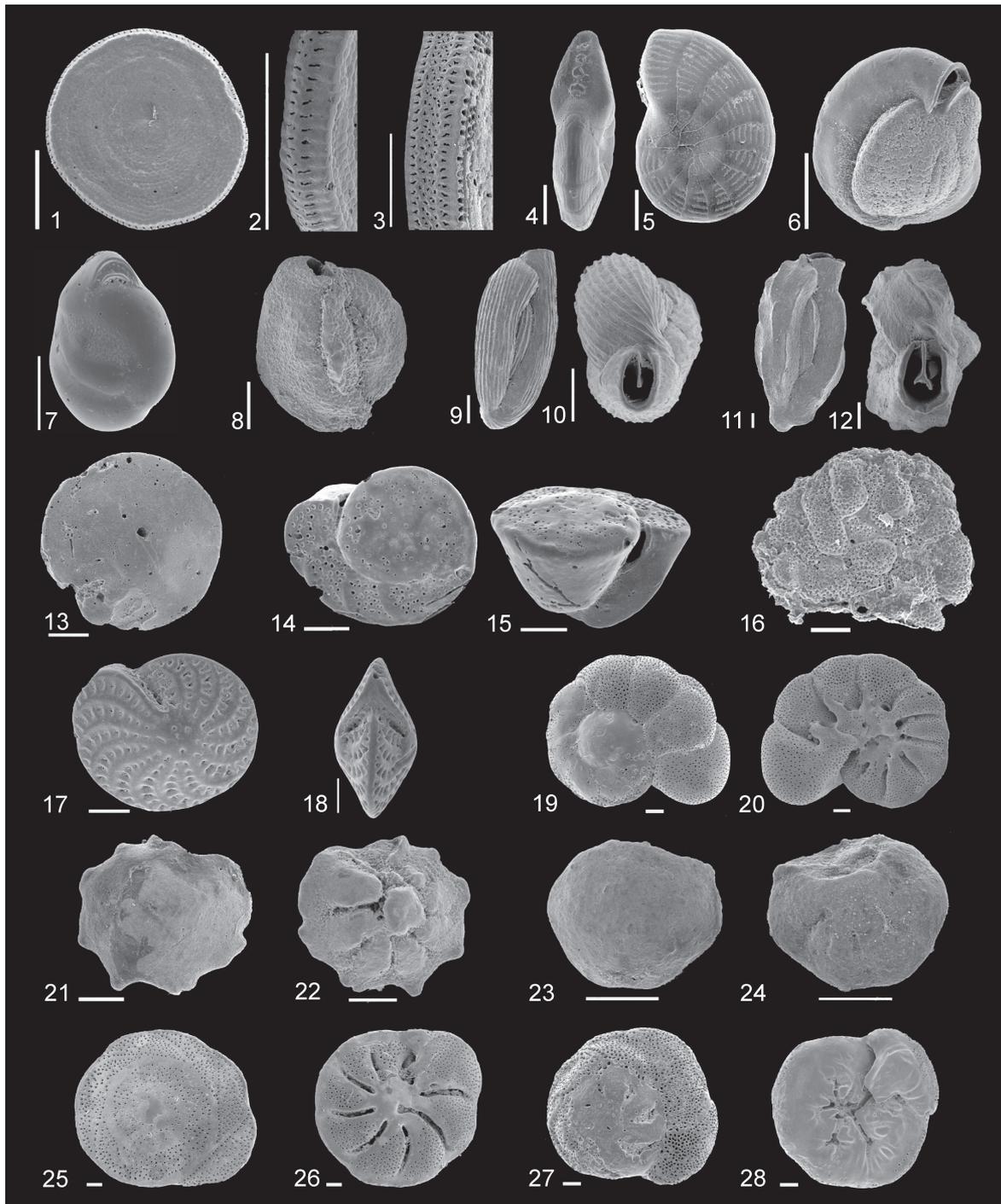
Plate 1. Scanning electron microscope photomicrographs of the foraminifera listed in Table 3. Both Holocene and Pleistocene specimens are used to illustrate the taxonomy. Numbers in brackets indicate the size of the scale bar associated with each foraminifer. **1** *Amphisorus hemiprichii* Ehrenberg, 1839; Dongara, Holocene; Habitus (1.0mm); **2** Aperture (1.0mm); **3** *Marginopora vertebralis* Quoy and Gaimard, 1830; Dongara, Holocene; Aperture (1.0mm); **4** *Peneroplis planatus* (von Fichtel and von Moll, 1798). Dongara, Holocene; Habitus (1.0 mm); **5** Aperture (1.0 mm); **6** *Miliolinella australis* (Parr, 1932); Whitfords, Holocene; Habitus (0. 1 mm); **7** *Miliolinella labiosa* (d'Orbigny, 1839); Albany, Holocene; Habitus (0. 1 mm); **8** *Quinqueloculina baragwanathi* Parr, 1945; Kooallup Limestone, Pleistocene; Habitus (0. 1mm); **9** *Quinqueloculina poeyana* d'Orbigny, 1839; Tims Thicket Limestone, Pleistocene; Habitus (0. 1mm); **10** Aperture (0. 1mm); **11** *Quinqueloculina subpolygona* Parr, 1945; Tims Thicket Limestone, Pleistocene; Habitus (0. 1mm); **12** Aperture (0. 1mm); **13** *Amphistegina lessoni* d'Orbigny, 1826; Tims Thicket Limestone, Pleistocene; Spiral side (0. 1mm); **14** *Cibicides* cf. *C. refulgens* Monfort, 1808; Tims Thicket Limestone, Pleistocene; Spiral side (0. 1mm); **15** Aperture (0. 1mm); **16** *Planogypsina acervalis* (Brady, 1884); Whitfords , Holocene; Spiral side (0. 1 mm); **17** *Elphidium crispum* (Linné, 1785); Tims Thicket Limestone, Pleistocene; Spiral side (0. 1mm); **18** Aperture (0. 1mm); **19** *Lamellodiscorbis dimidiatus* (Jones and Parker, 1862). Albany, Holocene; Spiral side (0. 1 mm) **20** Umbilical side (0. 1 mm); **21** *Pararotalia stellata* (de Férussac, 1827); Kooallup Limestone, Pleistocene; Spiral side (0. 1 mm) **22** Umbilical side (0. 1 mm); **23** *Rotorbinella* cf**.** *R. rosea* (d'Orbigny, 1826); Myalup Sand, Pleistocene; Spiral side (0. 1 mm) **24** Umbilical side (0. 1 mm); **25** *Rotorbis mirus* (Cushman, 1922); Albany, Holocene; Spiral side (0. 1 mm) **26** Umbilical side (0. 1 mm); **27** *Rotorboides* cf. *R. granulosa* (Heron-Allen and Earland, 1915); Albany, Holocene; Spiral side (0. 1 mm) **28** Umbilical side (0. 1 mm).

Semeniuk (2000, 2001), *i.e.*, 39 and 44 species in common with species at Dongara, respectively. The assemblage from the limestone lens in the Myalup Sand has greatest similarity with living assemblages from an intermediate site of Whitfords of T A Semeniuk (2000, 2001), *i.e.*, 17 species in common.

Tims Thicket Limestone and Kooallup Limestone have at least 7 buliminid taxa and 34 miliolid taxa, compared with 3 buliminid taxa and 10 miliolid taxa recorded for the limestone lens in the Myalup Sand. The number of miliolid taxa recorded in the Tims Thicket Limestone and Kooallup Limestone is similar to the living assemblages at the warmest site at Dongara (around 30 species), whereas the limestone lens in the Myalup Sand is similar to the living assemblages at the coolest site at Albany (both have around 10 taxa). The number of taxa of buliminids in the Pleistocene formations is much reduced; around 3–7 compared with 16–23 recorded in the modern living assemblages, hence, they could not easily be compared.

Larger foraminifera found in the Tims Thicket Limestone and Kooallup Limestone include *A. lessoni*, *A. hemiprichii*, *M. vertebralis*, *P. planatus, Peneroplis pertusus*, and *S. variabilis*, whereas Myalup Sand has only *A. lessoni* present. Again, the Tims Thicket Limestone and Kooallup Limestone had greatest similarity with the living assemblages at the warmest site at Dongara since they all contain the larger benthic species *M. vertebralis*, *A. hemiprichii*, *P. planatus* and *S. variabilis*. Additionally, *P. pertusus* and *A. lessoni* were recorded in the fossil assemblages from the Tims Thicket Limestone and Kooallup Limestone. Only one larger foraminifer occurs in the limestone lens in the Myalup Sand.

Compositional comparison of modern assemblages with fossil assemblages using the criteria above suggest that both the Tims Thicket Limestone and Kooallup Limestone were deposited in warm sea water, whereas Myalup Sand accumulated in cooler water.

Discussion and conclusions

The fossil foraminiferal assemblages from the three Pleistocene formations have strong similarity to live epiphytic assemblages from modern seagrass environments and contain the same indicator species for seagrass habitat. This supports the general palaeo-environmental interpretations based on stratigraphic and sedimentary features, and molluscan fauna (Semeniuk 1996), that the shallow-marine units of Tims Thicket Limestone and Kooallup Limestone are seagrass-bank deposits. Palaeoecological reconstructions based on modern foraminiferal assemblages indicate that there are significant sea-temperature differences in the depositional settings of the three Pleistocene formations. Criteria useful for interpreting the sea-temperature setting of the seagrass material include the miliolid fraction, the number of species of larger benthic foraminifera, and the presence or abundance of specific indicator species such as *S. variables*; which all show an increase in abundance with more tropical conditions (T A Semeniuk 2001). The significant reduction in buliminid content of fossil assemblages and common

occurrence of broken tests in fossil material suggest that post-mortem processes have affected the preservation of these more fragile taxa and that this criterion is not useful for reconstructing palaeoclimate settings.

Sea-temperature estimates

A number of studies previously have used modern larger benthic foraminiferal assemblages to infer climate setting in Holocene to Tertiary successions (*e.g.*, Reiss & Hottinger 1984; Murray 1987, 1991; Adams *et al.* 1990). Tropical climates are inferred using both specific shallow-water benthic tropical species or symbiont-bearing larger foraminifera (Reiss & Hottinger 1984; Adams *et al.* 1990). Symbiont-bearing larger foraminifera are an informal group of unrelated taxa. Adams *et al.* (1990) include the genera *Amphistegina*, *Amphisorus*, *Marginopora*, *Peneroplis* and *Sorites* as part of this group, and these species also are considered in this study. The modern distributions of these taxa are confined to an equator-centered area bounded to the south and north by the 18–20°C isotherm for the warmest month of the year, restricting these taxa to sub-tropical and tropical regions (except where warm currents influence their distributions).

The number of species of larger foraminifera decreases away from equatorial regions, forming a gradational distribution pattern about the equator, symmetrical in both northern and southern hemispheres (Adams *et al.* 1990). The number of species of larger foraminifera can be used as an index of tropical conditions, and specific taxa can be used to infer minimum winter temperatures. For example, *A. hemiprichii* has a present-day biogeographic limit corresponding to a minimum winter isotherm of 17°C (Reiss & Hottinger 1984) and *A. lessoni* has a biogeographic limit corresponding to a minimum winter isotherm of 14°C (Larsen 1976). It is pertinent to compare these findings with those of the present study. Using the presence/absence of *A. hemiprichii* as an index of tropical conditions, the results of this study suggest that the Tims Thicket Limestone and Kooallup Limestone were deposited in seas with temperatures greater than 17°C, whereas the Myalup Sand accumulated in seas with temperatures lower than 17°C, but greater than 14°C.

Sea temperatures and carbonate productivity

In the palaeogeographic reconstruction of Pleistocene conditions on the Yalgorup Plain by Semeniuk (1996), changes in sedimentation style from carbonate-rich prograded beach-ridge plains to quartz-rich barrier dune systems were attributed to changes in carbonate productivity linked to sea-temperature changes, or to the variable influx of quartz sand, which diluted *in situ* carbonate production. Foraminiferal diversity indices and other compositional assemblage criteria that are sensitive to climate setting have corroborated that these differences are at least in part due to sea-temperature changes. Specifically, the diversity of fossil assemblages correlates well with carbonate abundance in these Pleistocene limestone formations. There were high species counts (high diversity) in limestones with high abundance of carbonate grains, representing periods of high carbonate production, whereas there are low species counts (moderate diversity) for the localised carbonate

layers in quartz sand-rich formations, representing times of minimal carbonate production. Although carbonate content alone could be a reflection of palaeogeographic setting, the high diversity of selected foraminifera taxa is correlated with warm sea-temperatures.

Pleistocene sea-temperature record

The differences in fossil foraminiferal assemblages from the Pleistocene formations appear to record changes in palaeo sea-temperature differences through time. In particular, the succession of limestones and quartz-rich sands under the Yalgorup Plain records a warm-cool-warm cycle of carbonate deposition during the late Pleistocene. Cycles of warm-water and cool-water sedimentation also were proposed by Kendrick *et al.* (1991) in order to explain the general alternation of quartz-rich and carbonate-rich sedimentation in the Pliocene to Pleistocene along the Western Australian coast, and by Semeniuk (1996) to explain the changes in sedimentation style in the development of the Yalgorup Plain.

In theory, three mechanisms could have triggered warmer and cooler sea-temperature phases along the Western Australian coast during Pleistocene interglacials. Firstly, climate change related to Milankovich cycles may have generated more southern tropical zones along the coast. Secondly, changing strength of a palaeo-Leeuwin Current (as proposed by Cann & Clarke 1993; Wells & Wells 1994) may have elevated winter water temperatures in a narrow zone close to the coast (the Leeuwin Current in the modern setting is a warm low salinity oceanic current, dominant during autumn and winter, that flows southwards along the inner shelf from the warm water tropical regions of Western Australia to the cooler water temperate regions; Cresswell 1991). Lastly, changes in sea level may have generated a Rottnest-type setting (in which warmer-water isotherms linked to the Leeuwin Current were intersected at greater distance from the coast). There is no supporting palaeogeographic or foraminiferal facies evidence for this last hypothesis. The evidence for different mechanisms to sea-temperature change along the Western Australian coast, acting independently and in combination, is discussed below.

Milankovich cycles can occur within less than 100,000 yrs (Berger 1988; 1992). Hence, it is possible that the changing climate conditions documented for the Pleistocene formations from the Yalgorup Plain represent such cyclicity. This hypothesis cannot be evaluated until the Pleistocene formations from the region are accurately dated to determine whether this cyclicity is correlated with known astronomical forcing intervals. In addition, there is strong palaeoclimate evidence from South Australia and off-shore drill core material from Northern Western Australia that the strength of the Leeuwin Current changes with climate (McGowran *et al.* 1997; Okada & Wells 1997), and hence their mutual effect on foraminiferal distributions cannot be completely decoupled.

A change in strength of the Leeuwin Current could be triggered by sea-level change associated with tectonic activity or by climate change. If the Leeuwin Current had a greater nearshore influence during interglacial times this would account for a warmer sea-temperature fauna at more southern latitudes than at present, since elevated winter temperatures would allow tropical species to move further south. The interpretation and reconstruction of the palaeo sea temperature from shallow water deposits, based on the fossil foraminifera in this case, may not point to marked regional climate change, but rather to the changing influence of the Leeuwin Current. In order to establish the cause for such a change in current strength, the palaeohistory of the Leeuwin Current would need to be corroborated with other evidence for sea-level and climate change.

The Pleistocene history of the Leeuwin Current has been investigated by a number of authors. Cann & Clarke (1993) attributed the abundance of *M. vertebralis* (which normally has tropical affinity) in last interglacial sediments from Spencer Gulf Region, South Australia, to the presence of a palaeo Leeuwin Current. They postulated that this Current had greater ecological influence across the continental coast in South Australia at times of global warming and at higher sealevels. Other neritic benthos, nektonic nautiloids, and planktonic foraminifera within the Gulf show exhibit similar changes in their biogeographic ranges, consistent with transport of warmer waters by the Leeuwin Current in the last interglacial (McGowran *et al.* 1997). Faunal successions in planktonic foraminifera suggest the current intensifies during interglacials and weakens or ceases during glacial periods on time scales of *ca* 10^5 yr. This idea is supported by the work of Wells & Wells (1994) on planktonic foraminifera in deep-sea cores from offshore Western Australia. They determined sea-surface temperatures and gradients during the last 130 ka, concluding that during the last interglacial maximum, sea-surface temperatures were similar to those of today in summer and up to 3° C warmer in winter. Wells & Wells (1994) postulated that the Leeuwin Current flowed as an intensified current in a narrow zone close to the coast during the last interglacial maximum. Nanofossil records from these deep-sea cores suggest a weakening or cessation of the Leeuwin Current for glacial periods (Okada & Wells 1997).

Studies in both these regions suggest that the Leeuwin Current was more intense during the last interglacial and that the intensity of the current reflects climate. Thus, it is most likely that interplay of these mechanisms occurred to generate the Pleistocene warm-cool-warm cycle of carbonate deposition in shallow water settings in southwestern Australia, *i.e.*, increased activity of a palaeo-Leeuwin Current accompanied changes in sea-level and climate.

This study compared foraminiferal assemblages from local Pleistocene seagrass-bank deposits of southwestern Australia to Holocene equivalents. It utilised the variation in composition of modern living foraminiferal assemblages with respect to climate setting to interpret the fossil assemblages. There are many Quaternary coastal marine sequences documented around the globe that show similarity of sedimentary style, facies, and climate setting between local Holocene and Pleistocene deposits that would be suitable for palaeoecological reconstruction using the approach outlined in this study. In order to apply this approach globally, it is first necessary to document compositional changes in modern foraminiferal assemblages for a single habitat in

relationship to a regional or sub-regional climate gradient. The work reported in this paper suggests that there is scope to refine the palaeoecological reconstructions of Pleistocene sequences to a greater level than has hitherto been recorded in the literature.

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Appendix 1

Results of species counts from Pleistocene samples.

Order	Taxa	Sampling sites (see key below)						
		TT1	TT2	TT3	MS1	KL1	KL2	KL3
Textularia								
	Gaudryina sp. 1	0	0	1	0	1	0	0
	Textularia pseudogramen	1	0	0	0	0	0	0
	Textularia cf. T. sagittula	1	0	0	0	0	0	0
	Textularia sp 1	1	0	0	0	0	0	0
Miliolina								
	Amphisorus hemiprichii	12	1	3	0	12	4	0
	Biloculinella sp. 1	3	3	1	0	1	1	1
	Cornuspira involvens	0	0	0	0	1	0	1
	Cornuspira sp. 1	0	3	0	0	0	0	2
	Cornuspira acicularis	0	0	0	0	3	3	2
	Marginopora vertebralis	11	0	6	0	8	8	0
	Miliolinella australis	4	29	16	10	16	16	15
	Miliolinella labiosa	2	12	4	0	0	0	6
	Miliolinella sp. 1	0	3	6	0	3	0	3
	Nubecularia luciuga	0	0	0	0	0	1	1
	Parrina bradyi	0	0	0	0	1	0	2
	Peneroplis pertusus	2	0	0	0	1	0	0
	Peneroplis planatus	10	6	7	0	6	0	0
	Pseudomassilina australis	1	0	0	0	0	0	0
	Pseudotriloculina subgranulata	0	0	1	2	2	0	0
	Pyrgo sarsi	0	0	4	0	0	1	0
	Quinqueloculina baragwanathi	1	6	5	0	0	0	18
	Quinqueloculina carinata	0	2	0	0	0	0	2
	Quinqueloculina cf. Q. bicarinata	1	1	0	0	0	0	0
	Quinqueloculina sulcata	0	1	1	0	0	0	0
	Quinqueloculina cf. Q. incisa	3	3	8	0	2	2	2
	Quinqueloculina cf. Q. laevigata	1	3	3	0	6	1	4
	Quinqueloculina cf. Q. patagonica	1	1	0	0	0	0	0
	Quinqueloculina cf. Q. neostriatula	5	3	3	0	1	1	0
	Quinqueloculina crassicarinata	0	0	0	0	1	3	1
	Quinqueloculina cuvieriana	0	0	0	4	1	0	0
	Quinqueloculina distorqueata	0	0	1	0	1	1	1
	Quinqueloculina patagonica	0	0	0	0	1	0	3
	Quinqueloculina poeyana	6	0	8	1	2	5	2
	Quinqueloculina quinquecarinata	7	3	0	1	0	0	4
	Quinqueloculina sp. 1	3	3	1	1	2	0	0
	Quinqueloculina sp. 2	0	1	2	1	2	0	2
	Quinqueloculina subpolygona	7	4	10	1	3	1	4
	Spiroloculina communis	1	0	0	0	0	0	0
	Spiroloculina corrugata	2	2	1	0	1	0	4
	Spiroloculina parvula	0	1	0	0	0	0	0
	Spiroloculina venusta	0	0	0	0	0	0	3
	Triloculina striatotrigonula	4	2	5	1	2	3	0
	Triloculina trigonula	4	0	2	4	1	8	0
	Triloculina triquetrella	5	3	2	0	1	0	0
	Triloculinella cf. T. parisa	1	8	1	0	1	1	0
Rotaliina								
(spirillinids)	*Patellina corrugata*	0	1	4	0	0	0	2
	Planispirillina spinigera	1	2	0	0	1	0	2
	Spirillina limbata	0	3	0	0	0	0	0
	Spirillina sp. 1	0	0	0	0	0	0	1
(lagenids)	*Fissurina bradyformata*	0	1	0	0	0	0	0
	Sigmoidella elegantissma	1	0	0	0	0	0	0
(buliminids)	*Bolivina sp. 1*	0	0	0	0	0	0	2
	Bolivina sp. 2	0	0	0	0	1	0	2
	Bolivina quadrilatera	0	0	0	0	0	0	1
	Buliminoides williamsonianus	0	0	0	0	0	0	1
	Elongobula andromache	0	0	0	0	1	0	0
	Fijiella simplex	0	0	1	1	0	0	2
	Loxostoma cf. L. digitale	0	4	0	1	3	0	0
	Loxostomina costulatum	1	0	5	0	0	1	0
	Loxostomina limbata	0	1	2	0	0	1	1
	Pavonina flabelliformis	0	0	0	0	1	0	0

Order	Taxa	Sampling sites (see key below)						
		TT1	TT2	TT3	MS1	KL1	KL2	KL3
	Reussella armata	0	1	2	1	2	1	0
	Reussella simplex	0	1	0	0	0	2	0
	Saidovina sp. 1	0	0	1	0	0	0	0
	Sigmavirgulina tortuosa	0	0	0	0	0	0	2
	Trifarina sp. 1	0	0	0	0	1	0	0
(rotallids)	*Acervulina mahabeti*	1	0	2	0	0	0	0
	Amphistegina lessoni	16	10	11	1	30	9	3
	Angulodiscorbis quadrangularis	1	2	0	0	0	0	2
	Annulopatelinella annularis	0	0	0	0	0	0	2
	Anomalinoides globosus	10	2	0	3	3	11	1
	Anomalinoides sp. 1	1	0	1	0	0	0	0
	Anomalinoide sp. 2	0	0	0	0	0	0	1
	Cibicidina (?) sp. 1	0	0	0	0	1	0	0
	Cibicides cf. C refulegens	37	43	60	0	41	81	24
	Cibicides pseudolobatus	0	1	2	8	1	0	1
	Cibicidiodes mabahethi	0	0	0	0	1	3	2
	Cibicidiodes sp. 1	0	0	0	15	0	0	0
	Conorbella pulvinata	0	1	1	2	0	0	2
	Cribononion kerguelense	1	0	0	0	0	0	0
	Cymbaloporetta squammosa	0	0	1	0	0	0	0
	Discorbinella chincaensis	0	0	0	0	0	0	1
	Dyocibicides sp. 1	0	1	6	0	2	0	3
	Dyocibicides sp. 2	8	1	1	3	0	0	0
	Elphidium aculeatum	0	0	1	1	1	0	0
	Elphidium adventum	1	0	1	1	3	2	1
	Elphidium craticulatum	2	0	0	9	2	4	0
	Elphidium crispum	30	16	29	19	30	53	15
	Elphidium depressulum	0	1	2	0	0	0	0
	Elphidium jenseni	3	4	3	5	1	2	1
	Elphidium macellum	3	2	5	0	2	0	3
	Elphidium repandus	0	0	2	0	0	0	1
	Glabratella patelliformis	0	2	4	0	3	4	4
	Glabratella sp. 1	0	1	0	1	0	0	0
	Heronallenia lingulata	0	0	0	0	0	0	2
	Lamellodiscorbis dimidiatus	51	17	34	67	41	55	24
	Neoconorbina terquemi	0	1	0	0	1	2	2
	Paracibicides edomica	0	0	0	15	0	0	0
	Pararotalia stellata	1	1	0	1	6	11	3
	Planoglabratella opercularis	0	1	1	0	0	0	0
	Planogypsina acervalis	1	4	0	0	13	0	49
	Planulina sp. 1	0	2	2	1	4	5	1
	Rosalina sp. 1	0	0	0	2	0	0	0
	Rotorbinella cf. R. rosea	4	21	10	4	6	4	17
	Rotorbis mirus	14	7	8	1	2	12	9
	Rotorboides cf. R. granulosus	5	3	4	27	8	2	1
	Rugobolivinella pendens	0	1	0	0	0	0	0
	Siphonina reticulata	1	0	0	0	0	0	1
	Siphoninoides echinatus	0	0	0	0	1	0	1
	Siphoninoides laevigatus	0	0	1	0	0	1	0
	Svratkina sanmiguelensis	1	0	0	0	1	0	0
	Trichohyalus tropicus	0	0	0	0	0	0	1

TT1 = Site 1 (Tims Thicket Limestone) replicate sample 1
TT2 = Site 1 (Tims Thicket Limestone) replicate sample 2
TT3 = Site 1 (Tims Thicket Limestone) replicate sample 3
MS1 = Site 2 Myalup Sand sample
KL1 = Site 3 (Kooallup Limestone) replicate sample 1
KL2 = Site 3 (Kooallup Limestone) replicate sample 2
KL3 = Site 3 (Kooallup Limestone) replicate sample 3

Appendix 2

Two-way ANOVA results for lateral variation in species from the Tims Thicket Limestone and the Kooallup Limestone for species with sample mean > 3.

Taxa	F value	P value	F-critical
Amphisorus hemiprichii	0	1	7.7086
Marginopora vertebralis	0.0064	0.9398	7.7086
Miliolinella australis	0.0085	0.9309	7.7086
Miliolinella labiosa	1.2	0.3348	7.7086
Peneroplis planatus	4.05	0. 1145	7.7086
Quinqueloculina baragwanathi	0. 1043	0.7628	7.7086
Quinqueloculina poeyana	0.4098	0.5569	7.7086
Quinqueloculina subpolygona	4.9706	0.0897	7.7086
Amphistegina lessoni	0.0394	0.8522	7.7086
Cibicides cf. C. refulgens	0.0120	0.9180	7.7086
Elphidium crispum	0.4126	0.5556	7.7086
Lamellodiscorbis dimidiatus	0.2038	0.6751	7.7086
Pararotalia stellata	6.48	0.0636	7.7086
Planogypsina acervalis	1.6695	0.2659	7.7086
Rotorbinella cf. R. rosea	0. 1730	0.6988	7.7086
Rotorbis mirus	0.2951	0.6158	7.7086
Rotorboides cf. R. granulosus	0.2174	0.8899	7.7086

* indicates F value is greater than F-critical