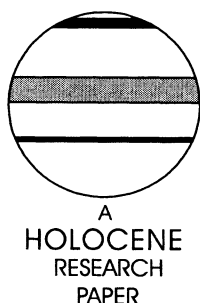


# Successive foraminiferal faunas and inferred palaeoenvironments associated with the postglacial (Holocene) marine transgression, Gulf St Vincent, South Australia

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**Abstract:** Gulf St Vincent is one of a pair of elongate, triangular, shallow water embayments into the southern coast of continental Australia. From the southern floor of this embayment, within a shallow basin-like depression where present-day water depth is about 40 m, vibracore SV23 recovered c. 4 m of late Quaternary sediments. The uppermost 1.5 m of this core comprises postglacial (Holocene) marine deposits; six radiocarbon ages for the interval 64–130 cm downcore are all around 10 000 cal. yr BP, while two for 18–24 cm are several thousand years younger. Radiocarbon analysis of an oyster shell at 154 cm yielded a minimum age of c. 37 000 cal. yr BP. Well-preserved benthic foraminifera are abundant in all the recovered sediments. The early phase of Holocene marine sedimentation in Gulf St Vincent was marked by the development of a marginal marine, perhaps lacustrine to estuarine environment, as signified by the presence of oogonia, gypsum crystals and the foraminifera *Miliolinella labiosa* and *Elphidium* cf. *articulatum*. Development of seagrass meadows followed; these were inhabited by *Nubecularia lucifuga* and *Discorbis dimidiatus*. As the marine transgression proceeded, the environment remained somewhat restricted, as indicated by *Ammonia beccarii*, but numbers of this species declined giving way to *Massilina milletti* as conditions began to resemble those of the modern Gulf St Vincent. Culmination of the transgression provided the conditions necessary for the dominance of *Ammobaculites reophaciformis* and *Flintina triquetra*. *A. reophaciformis* and *F. triquetra* therefore record the final episode of the transgression and transition to the modern, deeper water environment. At several lower horizons they also occur as conspicuous spikes, equivalent to their modern abundance. These spikes, which coincide with equivalent decreased numbers of *A. beccarii*, are interpreted to represent downward bioturbation of the overlying deeper water sediment.

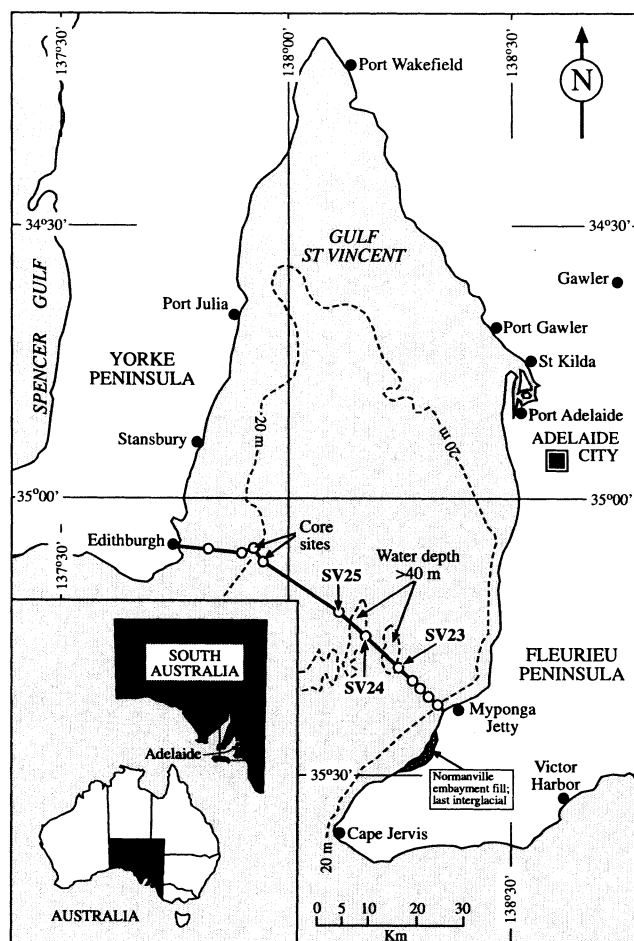
**Key words:** Foraminifera, bioturbation, oogonia, Holocene, marine transgression, postglacial, Gulf St Vincent, South Australia.

## Introduction

Gulf St Vincent and the adjoining Spencer Gulf are elongate, triangular marine embayments into the southern margin of the Australian continent (Figure 1). Gulf waters are relatively

shallow, mostly less than 40 m deep in Gulf St Vincent. Regional annual rainfall is low so there is minimal input of siliciclastic sediment from fluvial sources. In shallow, subtidal coastal areas, luxuriant seagrass meadows and algae support marine invertebrate faunas that have generated widely distributed carbonate bioclasts. Entire and comminuted mollusc shells and foraminifera are abundant in the surficial sediments

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**Figure 1** Map of Gulf St Vincent showing the positions of vibracores SV#23, SV#24 and SV#25 and the locations of core sites from which grab samples were also taken to determine the assemblages of species of benthic foraminifera within the surficial sediment (after Cann *et al.*, 1993). These data are shown in Figure 2. Also shown is the location of a last interglacial embayment fill near Normanville; see text for details

that are part of the cool-temperate carbonate province of southern Australia (Gostin *et al.*, 1988).

Although some details of global geophysical models (eg, Peltier, 2002) remain to be fully reconciled with data derived from geochronologically constrained sedimentological and palaeontological observations, it is generally supposed that during the last glacial maximum, sea level was between  $-130$  m and  $-120$  m (Chappell and Shackleton, 1986; Bard *et al.*, 1990; Chappell *et al.*, 1996; Yokoyama *et al.*, 2000, 2001; Murray-Wallace *et al.*, 2005). Consequently, during that episode of lower sea level, the southern Australian coastline was well south of the present mouth of Gulf St Vincent. The postglacial marine transgression into the gulfs culminated some 7000 years ago (Belperio *et al.*, 2002). Subsequent changes in relative sea level have been minor and have generally been attributed to glacio-hydroisostatic adjustment processes (Lambeck and Nakada, 1990; Belperio, 1995). In the area of the core sites, a relative sea-level fall associated with the glacio-hydroisostatic adjustment processes is likely to be  $<0.5$  m, by analogy with the southern Eyre Peninsula record (Lambeck and Nakada, 1990; Belperio, 1995).

The distribution of benthic foraminiferal species within the surficial gulf sediments has been the subject of several studies, which together have shown patterns that are related to modern water depths (Cann and Gostin, 1985; Cann and Murray-Wallace, 1986; Cann *et al.* 1988, 1993, 2000a, 2002). For

example, *Elphidium articulatum* occurs in high intertidal and marginal marine lagoonal settings; coastal seagrass faunas are dominated by *Nubecularia lucifuga*, *Peneroplis planatus* and other miliolids; in Northern Spencer Gulf, *Massilina milletti* (miliolid) increases numerically with increasing water depth; and in Gulf St Vincent two agglutinated species *Ammobaculites reophaciformis* (textulariid) and *Flintina triquetra* (miliolid) are most abundant in the deeper waters (Figure 2). In addition, rotaliid species *Elphidium crispum*, a shallow water species, and *Elphidium macelliforme*, which favours deeper water, provide a useful numerical ratio. Their logarithmic relative abundance in the sediment grain size fraction 0.50–0.25 mm correlates closely with water depth (Figure 3).

Much of the work cited above, particularly Cann *et al.* (1988, 1993) was concerned primarily with elucidation of Late Pleistocene palaeo sea levels. Vibracored sediments recovered from the floor of Gulf St Vincent were analysed for their fossil foraminifera, and palaeo sea levels were inferred from both the general assemblages of species and from the *Elphidium* ratio. The data thus obtained were placed within a geochronological framework that was derived from radiocarbon ( $^{14}\text{C}$ ) and amino acid racemization (AAR) analyses of fossil mollusc shells (Murray-Wallace *et al.*, 1993).

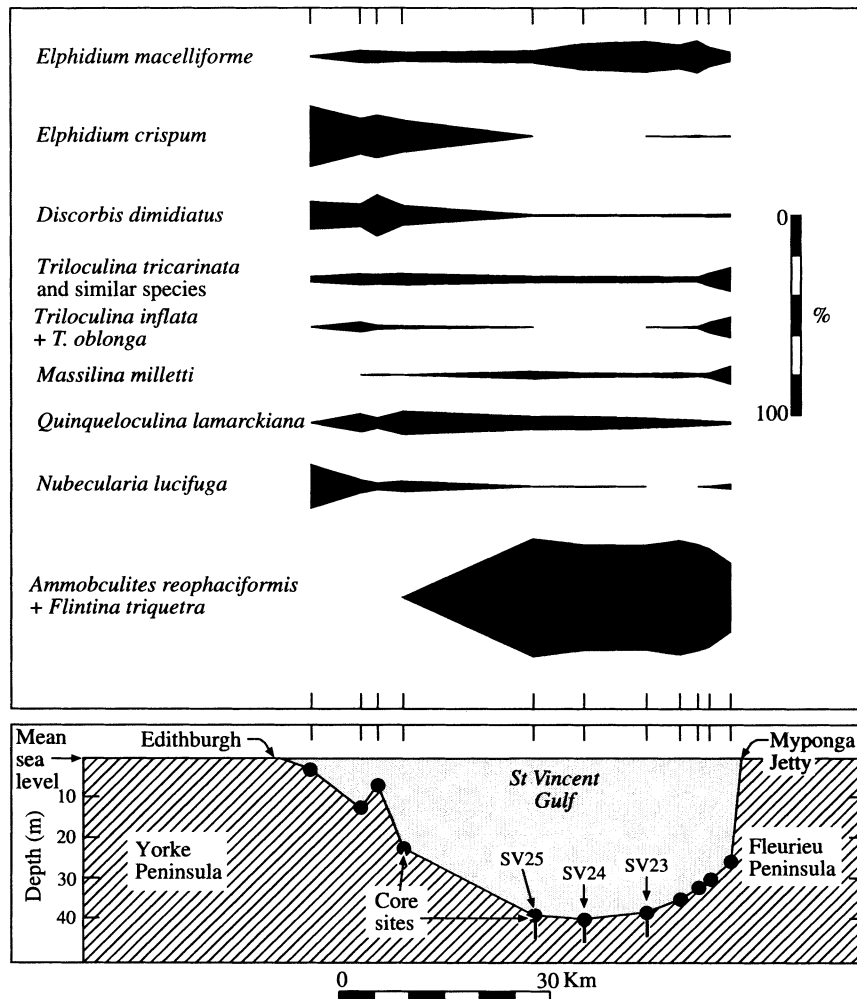
However, the Holocene intervals of the cores did not represent the primary focus of these investigations. Disconformities that separate Holocene sediments from underlying Pleistocene successions were inferred mainly on lithological criteria and on the distributions of the  $^{14}\text{C}$  and AAR derived ages. In our previous studies, the core sample interval was 20 cm, which was assumed appropriate for the research questions being investigated and that interpolation between data points was acceptable. It was further assumed that the postglacial marine transgression had proceeded monotonically without short-term relative sea-level changes that might have perturbed the sedimentary and palaeontological record. Subsequent additional sampling at closer intervals (results unpublished) revealed that while many of the new foraminiferal data points lay close to where interpolation might otherwise have predicted, there were some that were substantially removed from the formerly derived curves. Furthermore, elsewhere, recent high-resolution analyses of cores of Holocene sediments by other workers (eg, Cronin *et al.*, 1999, 2000; Chesapeake Bay, USA) have revealed the potential application of microfossil analyses in the recognition of short-term events associated with climatic variability.

Thus, by comparison with our earlier study (Cann *et al.*, 1993), within a more detailed timeframe of  $^{14}\text{C}$  and AAR ages, the work reported here seeks finer resolution of the postglacial marine transgression into Gulf St Vincent, as recorded by successive upcore fossil assemblages of benthic foraminifera in vibracore SV#23. In particular, the study aimed to identify an ecological succession of species that would provide proxies for successive palaeoenvironments from lacustrine and marginal marine (eg, *Elphidium articulatum*), at the onset of the transgressive flooding at the core site, ranging through shallow-water seagrass meadows (eg, *Nubecularia lucifuga*) to deeper-water environments (eg, *Massilina milletti*) and culminating in the deepest waters that are characteristic of the modern gulf (eg, *Ammobaculites reophaciformis*).

## Methods

### Sediment core and foraminifera

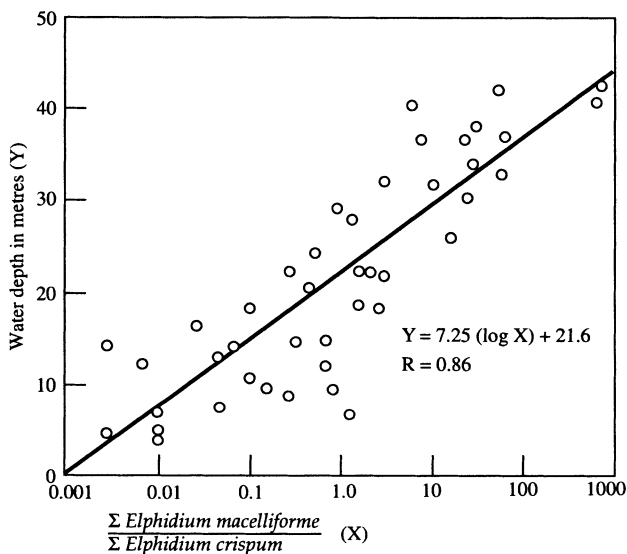
An electrically driven vibracorer deployed from a barge recovered almost 4 m of sediment from the deepest part of Gulf St Vincent, SV23 (Figure 1). The core was split lengthwise and one half was sampled for the study reported in Cann *et al.*



**Figure 2** Distribution of species of foraminifera within the surficial sediment of Gulf St Vincent along a transect from Myponga Jetty, Fleurieu Peninsula, to Edithburgh, Yorke Peninsula, amended from Cann *et al.* (1993). The locations of the sample sites are shown in Figure 1

(1993). The remaining half, which provided material for the present study, was wrapped in plastic and curated at the Core Library of Primary Industries and Resources SA. In this study,

the remaining half core was continually sampled in 2 cm slices; the sediment samples were bagged separately and removed to a laboratory for processing. Sediments were disaggregated by soaking in fresh water for a day or more, depending on the degree of sediment induration. Sediment samples were wet sieved over 0.125 mm mesh and the retained residues were dried at ambient temperature. These samples were further dry sieved and the grain size fractions of 0.50–0.25 mm were set aside for microscopic examination; this grain size fraction has repeatedly proved satisfactory for the type of palaeoenvironmental investigation reported here (eg, Cann *et al.*, 2002 and references therein). Most of the subsamples contained abundant tests of foraminifera and easily yielded > 200 individuals that were microscopically extracted, fixed to a microfossil slide, identified and counted. The presence of oogonia, the calcified fruiting bodies of non-marine aquatic charophyte plants, was also noted and their numbers recorded.



**Figure 3** The logarithmic ratio of numbers of *E. macelliforme* and *E. crispum* compared with water depth in Gulf St Vincent. Foraminifera were extracted from samples of surficial sediment taken at various sites, including those shown in Figures 1 and 2 (from Cann *et al.*, 1993)

Two additional cores, SV24 and SV25 (Figure 1) were similarly recovered and processed. The uppermost 45 cm of SV24, and 50 cm of SV25, comprise the postglacial sediments. The distribution of species of fossil benthic foraminifera in the Holocene sediments of SV25 was determined as described above for SV23 (ie, derived for the grain size fractions 0.50–0.25 mm). However, in the microscopic examination of subsamples of SV24, sediment in the grain size range 1.00–0.063 mm was analysed at the University of Wollongong as a single fraction (Riggs, 2002). Data derived from these cores are supplementary to the central study of SV23.

### Mollusc shells and radiocarbon dating

Radiocarbon analyses on marine fossil molluscs were undertaken by accelerator mass spectrometry at the Australian Nuclear Science and Technology Organization (ANSTO) facility at Lucas Heights (laboratory codes OZF and OZG in Table 1) using standard techniques (Lawson *et al.*, 2000). The shells were pretreated by removing the outer surfaces with a dilute HCl etch. For those ages within the range of calibration, the conventional radiocarbon ages were calibrated to sidereal years and corrected for the marine reservoir effect using the CALIB program (version 5.0.1) of Stuiver and Reimer (1993), with revised data of Hughen *et al.* (2004) and McCormac *et al.* (2004). Correction for the marine reservoir effect used a  $\Delta r$  value of  $137 \pm 86$  in the calibration program, equivalent to that determined by Gillespie and Polach (1979) for southern Australian ocean surface waters. Calibrated radiocarbon ages are reported as ranges ( $2\sigma$  confidence level), and as ages and their associated uncertainties also at the same confidence level (Tables 1 and 2). The latter were rounded to the nearest 10 years in accordance with standard practice (Gupta and Polach, 1985).

### Mollusc shells and amino acid racemization (AAR) analyses

Samples of the fossil molluscs *Glycymeris* sp., *Bassina* sp., *Fulvia tenuicostata*, *Brachiodontes* sp., *Chlamys* sp., *Ostrea* sp. and

*Katelysia rhytiphora* were selected for AAR analyses (total acid hydrolysate) from two of the gulf vibracores (Table 2). These species were common in the cored sediment. Sediment and carbonate encrustations adhering to the surfaces of the shell samples, and diagenetically modified aragonite, particularly slightly chalky surfaces, were removed with a dental drill, followed by successive washes in distilled water using an ultrasonic bath. A dilute acid etch (2 mol HCl) was subsequently undertaken to remove the remaining outer surfaces (10–15% by mass) of the shells that had been in contact with the host sediment. Samples were then hydrolysed for 22 hours at 110°C in 8 mol HCl. Following cation exchange isolation of the amino acids, sample eluents were freeze dried and derivatized. Chromatography of the N-pentafluoropropionyl D, L-amino acid 2-propyl esters was performed using a Hewlett-Packard 5890A Series II gas chromatograph with a flame ionization detector and 25 m coiled, fused silica capillary column coated with the stationary phase Chirasil-L-Val. Full details of the analytical protocol are reported elsewhere (Murray-Wallace, 1993). Enantiomeric ratios were determined for the fast racemizing amino acid aspartic acid (ASP) in order to resolve time over a Holocene timescale.

### The Holocene/Pleistocene disconformity in SV23

Cann *et al.* (1993) determined that the Holocene/Pleistocene disconformity in SV#23 occurred at a core depth of about

**Table 1** Radiocarbon ages derived for fossil bivalves from vibracores SV#23, SV#24 and SV#25, Gulf St Vincent, South Australia

Species of bivalve	Core number	Core depth (cm)	Radiocarbon laboratory code	$\delta^{13}\text{C}$ (‰)	Conventional $^{14}\text{C}$ age (yr BP)	Calibrated* $^{14}\text{C}$ age range and age $\pm$ uncertainty ( $2\sigma$ ) (cal. yr BP)	Reference
<i>Katelysia scalarina</i>	SV23	18–20	SUA-2710	1 $\pm$ 1	4730 $\pm$ 70	(4492–5135) 4820 $\pm$ 320	Cann <i>et al.</i> (1993)
<i>Bassina</i> sp.	SV23	22–24	OZF-049	0.67	6360 $\pm$ 50	(6429–6911) 6670 $\pm$ 240	This study <sup>†</sup>
<i>Brachiodontes rostratus</i>	SV23	64–66	OZF-050	0.49	9130 $\pm$ 60	(9464–10 038) 9750 $\pm$ 290	This study
<i>Brachiodontes rostratus</i>	SV23	73–75	SUA-2711	1 $\pm$ 1	9390 $\pm$ 100	(9645–10 391) 10 020 $\pm$ 370	Cann <i>et al.</i> (1993)
<i>Fulvia tenuicostata</i>	SV23	100–110	SUA-2712	1 $\pm$ 1	9460 $\pm$ 90	(9772–10 473) 9880 $\pm$ 350	Cann <i>et al.</i> (1993)
<i>Brachiodontes rostratus</i>	SV23	116–122	SUA-2713	1 $\pm$ 1	9290 $\pm$ 100	(9545–10 212) 9880 $\pm$ 330	Cann <i>et al.</i> (1993)
<i>Katelysia rhytiphora</i>	SV23	126–130	OZF-051	1.78	9680 $\pm$ 60	(10 185–10 583) 10 380 $\pm$ 220	This study
<i>Katelysia rhytiphora</i>	SV23	128–130	OZF-052	1.61	9600 $\pm$ 60	(10 121–10 457) 10 330 $\pm$ 210	This study
<i>Ostrea</i> sp.	SV23	154–156	OZF-053	2.68	36 600 $\pm$ 550	BCR	This study
<i>Chlamys</i> sp.	SV24	18–20	OZF-118	1.26	4860 $\pm$ 40	(4782–5273) 5030 $\pm$ 250	This study <sup>†</sup>
<i>Fusinus undulatus</i>	SV24	34–36	OZF-119	1.33	6120 $\pm$ 50	(6206–6631) 6420 $\pm$ 210	This study
<i>Brachiodontes rostratus</i>	SV24	40–42	OZF-120	1.02	9130 $\pm$ 60	(9464–10 038) 9750 $\pm$ 290	This study <sup>†</sup>
<i>Katelysia rhytiphora</i>	SV24	160–162	OZF-121	1.76	49 600 $\pm$ 1900	BCR	This study <sup>†</sup>
<i>Placamen flindersi</i>	SV25	14–16	OZG-599	2.8	2130 $\pm$ 40	(1339–1786) 1560 $\pm$ 220	This study
<i>Fulvia tenuicostata</i>	SV25	24–26	OZG-600	0.5	8430 $\pm$ 50	(8554–9106) 8830 $\pm$ 280	This study
<i>Fulvia tenuicostata</i>	SV25	34–36	OZG-601	0.9	5450 $\pm$ 40	(5483–5889) 5690 $\pm$ 200	This study
<i>Katelysia rhytiphora</i>	SV25	44–46	OZG-602	1.5	9530 $\pm$ 60	(9949–10 497) 10 220 $\pm$ 270	This study

\*Ages calibrated to sidereal years using the calibration program of Stuiver and Reimer (1993; Calib 5.0.1) with revised data of Hughen *et al.* (2004) and McCormac *et al.* (2004); uncertainty terms of calibrated ages are reported at the  $2\sigma$  level. BCR, beyond calibration range.

\*\*Estimated  $\delta^{13}\text{C}$  values are  $1 \pm 1\%$ .

<sup>†</sup>Same shell specimen used for both radiocarbon and amino acid racemization analyses.

**Table 2** Extent of aspartic acid racemization in fossil molluscs from vibrocores SV#23 and SV#24, Gulf St Vincent, South Australia

Species of bivalve	Core number	Core depth (cm)	Shell material analysed	AAR laboratory code	Aspartic acid D/L ratio	AAR age <sup>†</sup>	Radiocarbon age
<i>Glycymeris</i> sp.	SV#23	8–10	fragment (articulated)	UWGA-866	0.124 ± 0.018		
<i>Glycymeris</i> sp.	SV#23	10–12	entire valve (articulated)	UWGA-867	0.175 ± 0.022		
<i>Bassina</i> sp.	SV#23	12–14	entire valve (articulated)	UWGA-670	0.466 ± 0.046	11 150 ± 1100	
<i>Bassina</i> sp.	SV#23	12–14	entire valve (disarticulated)	UWGA-868	0.226 ± 0.030	1860 ± 240	
<i>Glycymeris</i> sp.	SV#23	14–16	two valves (articulated)	UWGA-869	0.195 ± 0.006		
<i>Bassina</i> sp.	SV#23	14–16	entire valve (disarticulated)	UWGA-671	0.443 ± 0.037	9900 ± 1000	
<i>Bassina</i> sp.*	SV#23	22–24	articulated valve	UWGA-672	0.374 ± 0.018	calibration*	6670 ± 240 (OZF-049)
<i>Fulvia tenuicostata</i>	SV#23	24–26	entire valve (disarticulated)	UWGA-606	0.312 ± 0.008		
<i>Brachiodontes</i> sp.	SV#23	34–36	entire valve (disarticulated)	UWGA-673	0.345 ± 0.027	5480 ± 600	
<i>Fulvia tenuicostata</i>	SV#23	46	entire valve (disarticulated)	UWGA-607	0.305 ± 0.002		
<i>Brachiodontes</i> sp.*	SV#23	64–66	umbo region (disarticulated)	UWGA-675	0.440 ± 0.009	calibration*	9750 ± 290 (OZF-050)
<i>Fulvia tenuicostata</i>	SV#23	76	umbo region (fragment)	UWGA-674	0.328 ± 0.001		
<i>Brachiodontes</i> sp.	SV#23	86–88	umbo region (disarticulated)	UWGA-676	0.314 ± 0.008	4360 ± 500	
<i>Ostrea</i> sp.*	SV#23	154–156	half valve (disarticulated)	UWGA-679	0.558 ± 0.001	79 000 ± 12 000	36 600 ± 550 (OZF-053)
<i>Chlamys</i> sp.	SV#24	18–20	hinge (articulated)	UWGA-815	0.325 ± 0.002	calibration*	5030 ± 250 (OZF-118)
<i>Brachiodontes rostratus</i>	SV#24	40–42	hinge (articulated)	UWGA-816	0.400 ± 0.001	calibration*	9750 ± 290 (OZF-120)
<i>Katelysia rhytiphora</i>	SV#24	160–162	hinge of disarticulated valve	UWGA-817	0.539 ± 0.039	calibration*	49 600 ± 1900 (OZF-121)

\*Samples also directly dated using AMS radiocarbon; radiocarbon laboratory codes are indicated.

<sup>†</sup>Amino acid racemization numeric ages calculated using a model based on apparent parabolic kinetics.

Radiocarbon sample OZF-050 was used as a calibration for calculation of AAR ages for *Brachiodontes* sp. and OZF-049 for *Bassina* sp.

150 cm downcore. They noted that the sediment, when first exposed, was a light olive grey colour and lithologically similar across this horizon. Below 150 cm fossil bivalves were larger and more numerous; upcore the larger bivalves were fewer, giving way to smaller bivalves, gastropods and ostracods. Without the support of the <sup>14</sup>C ages, those observations alone would not have been sufficient to confidently infer the disconformity. In the present study, the disconformity between the Holocene interval of the core and the underlying Pleistocene sediments was determined on the following criteria: <sup>14</sup>C and AAR ages; changes in the relative numbers of oogonia (non-marine) and foraminifera (marine); changes in the *Elphidium* ratio that correlates with water depth; and changes in the general foraminiferal assemblages.

## Results

### Radiocarbon dating

An array of <sup>14</sup>C ages derived for fossil molluscs (Table 1; some data from Cann *et al.* (1993) and others determined in the present study) reveals a Late Pleistocene age below 150 cm in core SV#23, while all other analyses upcore of 150 cm conform to a Holocene age.

The calibrated <sup>14</sup>C ages on marine shells from the postglacial sediments in core SV#23 span much of Holocene time. With

the exception of the specimen of *Ostrea* sp. of presumed Late Pleistocene age (OZF-053, Table 1), where the  $\delta^{13}\text{C}$  values have been directly determined, they are characteristic of fully marine conditions ( $\delta^{13}\text{C}$  of  $1 \pm 1\%$ ; Gupta and Polach, 1985) and point to the integrity of the radiocarbon analyses on these shell samples. Six shell samples from the depth interval 64–130 cm within core SV#23 span a period of only about 630 years, within the range of  $10\,380 \pm 220$  cal. yr BP (OZF-051) to  $9750 \pm 290$  cal. yr BP (OZF-050; Table 1). Of the six calibrated <sup>14</sup>C ages, samples OZF-050 and OZF-051 are only just significantly different at the 2 $\sigma$  level. Following the method of Gupta and Polach (1985), a pooled-mean radiocarbon age for these six shell samples is  $10\,130 \pm 110$  cal. yr BP.

### Amino acid racemization dating

With the exception of two Pleistocene shells (*Ostrea* sp. at 154–156 cm in core SV#23 and *Katelysia rhytiphora* at 160–162 cm in core SV#24; Table 2), the extent of aspartic acid racemization in the fossil molluscs from cores SV#23 and SV#24 conform with values previously determined in radiocarbon-dated Holocene specimens from southern Australia (Murray-Wallace, 2000). As the rate of the racemization reaction in molluscs is genus-dependent, numeric ages have been derived only for genera where shells have also been dated using radiocarbon in order to quantify reaction rates (eg, *Bassina* sp., *Brachiodontes* sp.; Table 2). However, inferences concerning

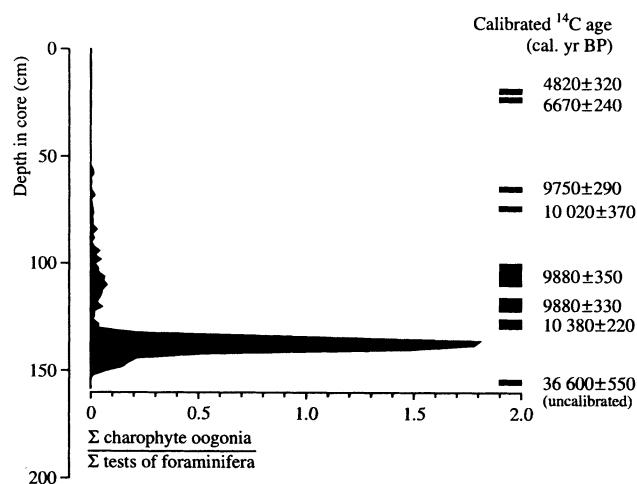
relative age differences between shells of different genera can still be derived, based on the extent of racemization alone, as the genus effect is less pronounced in Holocene shells; it becomes more apparent in Pleistocene fossils because of the parabolic nature of racemization kinetics (Sloss *et al.*, 2004).

The extent of aspartic acid racemization does not increase uniformly with depth downcore in SV#23, consistent with a systematic increase in age of the fossil shells, and apparent reversals in the extent of racemization are noted. These differences in amino acid D/L ratios exceed any likely differences resulting from a genus effect on the racemization rate, and far exceed uncertainties relating to differences in the extent of racemization in replicate shells of a common age (Murray-Wallace, 2000). The most likely explanation is that some components of the shelly fauna represent reworked shells (eg, *Bassina* sp. at 12–14 cm in core SV#23). The amino acid data suggest that the shells in the interval from 46 cm to the top of core SV#23 are younger than  $6670 \pm 240$  cal. yr BP (OZF-049), based on the extent of racemization in these shells and the  $^{14}\text{C}$  age on an articulated specimen of *Bassina* sp. together with the extent of racemization in this same specimen. Exceptions are the two disarticulated *Bassina* sp. valves at 14–16 cm and 12–14 cm with higher aspartic acid D/L ratios and corresponding numeric ages of 9900 yr and 11150 yr, respectively.

The extent of aspartic acid racemization in the two Pleistocene shells (*Ostrea* sp. at 154–156 cm in core SV#23 and *Katelysia rhytiphora* at 160–162 cm in core SV#24) is similar, yet the  $^{14}\text{C}$  ages are significantly different. Although the genus effect on racemization might in part explain these differences, it is most likely that the shells are of common age and that the radiocarbon results represent apparent, 'finite' ages, reflecting differential contamination by  $^{14}\text{C}$  with a modern activity. Accordingly, the age of  $36600 \pm 550$  yr BP (OZF-053) would reflect 1% contamination by modern  $^{14}\text{C}$ , which could not be isolated during sample pretreatment. The extent of aspartic acid racemization (ASP D/L = 0.539 to 0.558) in both these shells is similar to that measured in *Mactra australis* (ASP D/L = 0.58 to 0.60) from a last interglacial (125 ka) embayment fill succession at Normanville, southern Fleurieu Peninsula (Bourman *et al.*, 1999; Figure 1). Thus it is implied that the true age of the shells is beyond the range of radiocarbon dating (> 50 ka), but possibly younger than the last interglacial maximum. These findings are at odds with the conclusions of Cann *et al.* (1988, 1993) and will be subject to more detailed discussion elsewhere.

### Oogonia

Oogonia are the calcified fruiting bodies of charophytes, multicellular green algae that are also known as stoneworts (Womersley, 1984). Although these aquatic plants tolerate a wide range of salinities, they have not been observed in any holomarine (normal marine salinity) settings (Burne *et al.*, 1980; García *et al.*, 2002). In vibrocore SV#23, oogonia were particularly abundant over the interval 134–142 cm; these samples yielded 169, 385, 534 and 497 oogonia, respectively, outnumbering foraminiferal tests by almost 2:1 (Figure 4). This interval is thus interpreted to represent a non-marine (eg, saline lake) to marginal marine environment (eg, an estuarine coastal lagoon) and signifies the initial phase of Holocene sedimentation. The acme of oogonia thus provides unequivocal evidence of the Pleistocene/Holocene disconformity. The presence of euhedral to subhedral gypsum crystals within this same interval supports the notion of restricted circulation.



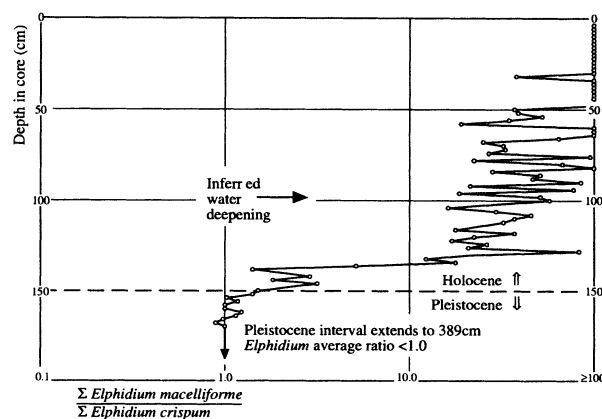
**Figure 4** The distribution of relative numbers of charophyte oogonia and foraminifera within the Holocene interval of vibrocore SV#23. The dominance of oogonia at 134–142 cm signifies that the environment of sedimentation for that interval was non-marine. Also shown are the calibrated radiocarbon ages (cal. yr BP), derived from analyses of fossil bivalves at the horizons indicated (Table 1). The Holocene/Pleistocene disconformity is inferred at c. 150 cm

### The *Elphidium* ratio

For the surficial sediments of Gulf St Vincent, Cann *et al.* (1993) showed that the logarithmic ratio of numbers of tests of *Elphidium macelliforme* to those of *Elphidium crispum* correlates closely ( $r = 0.86$ ) with water depth:

$$\text{water depth} = 7.25 \log \left( \frac{\Sigma \text{ tests of } E. \text{ macelliforme}}{\Sigma \text{ tests of } E. \text{ crispum}} \right) + 21.6 \text{ (Figure 3)}$$

Below 150 cm and extending to the bottom of the core the average numbers of *E. crispum* and *E. macelliforme* are approximately equal, signifying Late Pleistocene water depths of about 20 m. These data will be reported elsewhere. Upcore from 142 cm, numbers of *E. macelliforme* exceed those of *E. crispum*, in accordance with increasing water depth, the ratio for the uppermost 50 cm >100:1 (Figure 5). Thus the *Elphidium* ratio records the postglacial marine transgression, with the onset of the transition from marginal marine to holomarine conditions signified upcore from 142 cm. While the overall trend of this transgressive signal is unambiguous, it is



**Figure 5** The logarithmic ratio of numbers of *E. macelliforme* and *E. crispum* compared with sample depth in the Holocene interval of Vibrocore SV#23. Larger ratios signify greater water depth. The initial postglacial marine transgression into Gulf St Vincent is unambiguously signified by these data upcore from 142 cm

clear that factors other than water depth at the site of sedimentation have influenced the *Elphidium* ratio. This observation is discussed below.

### The general assemblage of foraminifera

At 138–142 cm, within the horizon that has been recognized above to be of marginal marine sedimentation, *Miliolinella labiosa* constitutes *c.* 40% of the foraminiferal assemblage (Figure 6E). *M. labiosa* is widely distributed in southern Australian coastal embayments (Parr, 1932, 1945; Collins, 1974), but was not reported from studies of mid-shelf faunas (Li *et al.*, 1996, 1998). However, in a regressive Holocene succession in southeastern South Australia, the abundance of this species increased upcore to a maximum of 50% in sediments that were transitional from holomarine to a saline-carbonate lacustrine environment (Cann *et al.*, 1999). Coincidentally, within the same horizon of SV#23 (138–142 cm), *Elphidium cf. articulatum* also has its acme of *c.* 14% (Figure 6K). This species is known for its tolerance to a wide range of salinities and in particular for its ability to survive in the ephemeral saline lakes of southeastern South Australia (Cann and De Deckker, 1981). These occurrences of *M. labiosa* and *E. cf. articulatum* within SV#23 are thus taken as further support for the proposed marginal marine environment that marked the initial stage of the postglacial marine transgression into Gulf St Vincent.

The earliest holomarine environment is marked by the appearance upcore of *Nubecularia lucifuga*, a species that dominates the modern local *Posidonia australis* seagrass meadows (Cann *et al.*, 1993, 2000a). *N. lucifuga* comprises *c.* 65% of the assemblage at 130 cm (Figure 6B) and is accompanied by the acme of another seagrass species, *Discorbis dimidiatus*, *c.* 8% (Figure 6F). (*D. dimidiatus* is used here in the sense of Hedley *et al.* (1967) who included forms of greatly varying morphology, such as keeled or lobate periphery, high or low spire, large or small ventral flaps, etc.) Above 130 cm, decreased numbers of these species signify their response to the rising sea surface, giving way to miliolid species such as *Triloculina striatotriginula*, *T. tricarinata* and *T. trigonula* (Figure 6D), and to the rotaliid *Elphidium macelliforme* (Figure 6J). In contrast, numbers of *Elphidium crispum* (Figure 6H) decrease upcore; in the uppermost 50 cm this species is absent from many horizons.

By 110 cm *Ammonia beccarii* is a substantial component of the core assemblage, expanding upcore to 46% at 96 cm, and maintaining a significant but declining presence upcore to *c.* 45 cm (Figure 6G). (*A. beccarii* is used here in the sense of Schnitker (1974) who demonstrated experimentally that, by varying environmental parameters, multiple forms of the species could be generated by asexual reproduction from common parental stock. Thus Schnitker (1974) proposed that *Ammonia* should be regarded as a monospecific genus. In marked contrast, Hayward *et al.* (2004) have analysed DNA from living *Ammonia* and have associated those results with test morphology. They identified several species and predicted that their methods might lead to recognition of 25–30 living species. This matter awaits resolution.) *A. beccarii* thrives in euryhaline waters and is ubiquitous in the Coorong coastal lagoon of southeastern South Australia (Cann *et al.*, 2000b). Thus the presence of this species throughout the interval 110–45 cm is interpreted as evidence of euryhaline waters, which occupied a basin-like depression of restricted circulation, with somewhat limited access to the waters of the Southern Ocean.

Increasing holomarine influence and deeper water are indicated by incoming *Massilina milletti*, which reaches its acme of *c.* 62% at 52 cm (Figure 6C). In modern sediments of

Northern Spencer Gulf, the relative abundance of *M. milletti* correlates closely with water depth (Cann and Murray-Wallace, 1986), so the steadily increasing numbers of this species upcore provide strong evidence of the deepening water.

Above 50 cm, the fossil assemblage is progressively dominated by two agglutinated species, the textulariid *Ammobaculites reophaciformis* and the miliolid *Flintina triquetra* (Figure 6A), reflecting their relative occurrence as deeper water forms in the modern surficial sediment (Figure 2). These species therefore record the final episode of the transgression.

## Supplementary results, SV24

Core SV#24 was recovered from a site about 10 km northwest of that of SV#23, in water of similar depth, about 40 m (Figure 1). The uppermost 45 cm of SV#24 comprises the Holocene interval of this core. Three <sup>14</sup>C and two AAR ages obtained from analyses of fossil molluscs signify sedimentation during the period *c.* 5000–10 000 yr BP (Tables 1 and 2; Riggs, 2002). No oogonia were reported for this core.

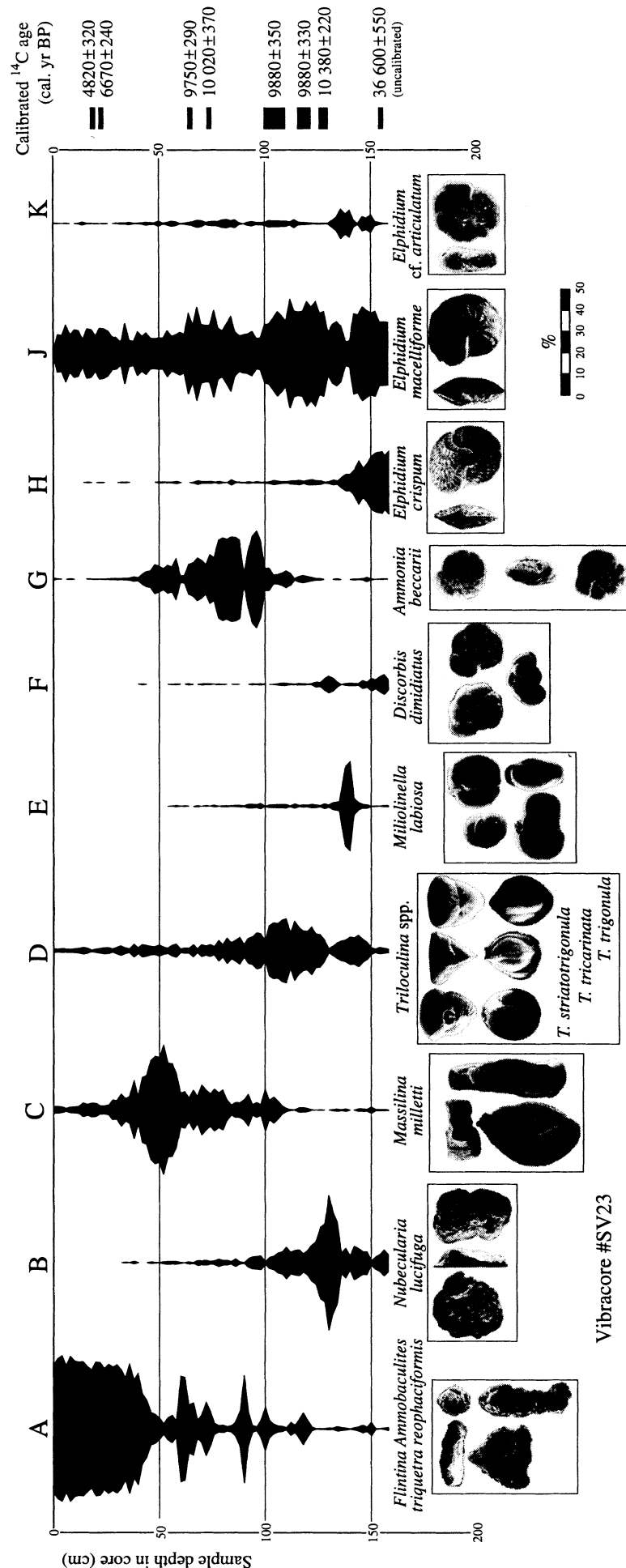
The eco-succession of species, related to increasing water depth, which has been demonstrated for SV#23, is not at all apparent in the distribution of foraminifera in this core. Instead, Riggs (2002) records the presence of *A. reophaciformis* plus *F. triquetra*, which together signify water depths of  $\geq 30$  m (Figure 2), throughout the entire Holocene interval, though gradually increasing in numbers upcore in accord with expectations of the species response to deepening water. *A. beccarii* is similarly present throughout the interval, with an equivalent decrease in numbers. Two contrasting environments are signified by these species. It might reasonably have been anticipated that, as in SV#23, *A. beccarii*, signifying a euryhaline environment, would have occurred lower in the succession than the holomarine species *A. reophaciformis* plus *F. triquetra*. On the evidence of the combined presence of these three species, and despite the stratigraphic coherence of the <sup>14</sup>C and AAR ages, it must be concluded that the entire Holocene interval of SV#24 has been subjected to sediment mixing of at least the sand fraction.

## Supplementary results, SV25

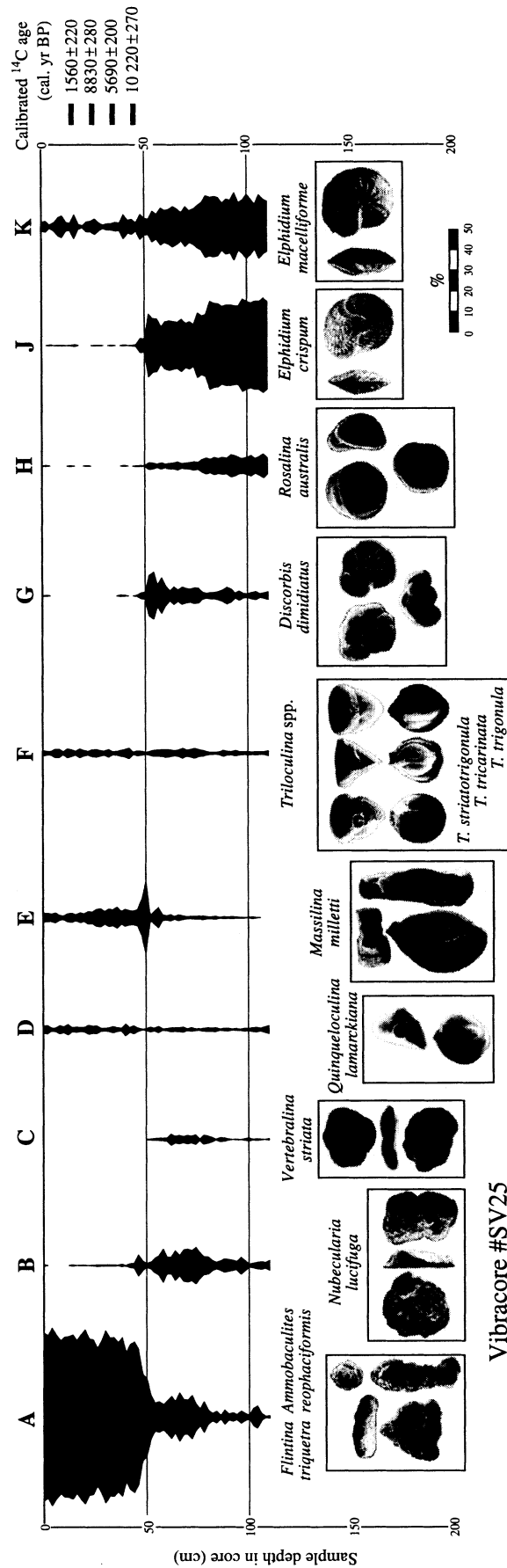
Core SV#25 was recovered from a site about 20 km northwest of that of SV#23, in water of similar depth, about 40 m (Figure 1). Core SV#25 recovered 362 cm of marine sediment, of which the uppermost 0.5 m was judged, on lithological evidence, to represent the postglacial marine transgression. At 51 cm there was a change downcore from light olive grey (5Y6/1) bioclastic sand (shell hash) to a yellowish grey (5Y8/1) very fine sandy carbonate mud. Four <sup>14</sup>C ages derived from fossil molluscs confirm a Holocene age for this interval (Table 1). No oogonia were observed in any of the core samples.

Again, the entire postglacial interval is dominated by *A. reophaciformis* plus *F. triquetra*, and these species are accompanied by subordinate numbers of *M. milletti* (acme of 35% at 50 cm) and *E. macelliforme* that similarly favour deeper water (Figure 7). Comparison of this figure with that showing the distribution of species for SV23 (Figure 6) reveals that the faunal distributions in the uppermost 50 cm of both cores are closely similar. It would seem that the early Holocene succession that occupies the interval 50–150 cm in SV23 has not been preserved in SV25.

The Pleistocene/Holocene disconformity at 50 cm in SV25 is signified clearly by the record of *Elphidium crispum*, a



**Figure 6** The distribution of selected species (or groups of species) of foraminifera, for the sediment grain size fraction 0.50–0.25 mm, within the Holocene interval of vibracore SV#23. The location of the core is indicated in Figure 1. The arrangement A to K is in approximate accord with the broadly accepted classification of foraminifera: A, *Ammobaculites reophaciformis* (in part), textulariid; B, *Nubecularia lucifuga*, to E, *Miliolinella labiosa*, miliolids; F, *Discorbis dimidiatus*, to K, *Elphidium cf. articulatum*, rotaliids. The scanning electron microscope images illustrate specimens taken from various gulf sediment samples. Also shown are the calibrated <sup>14</sup>C ages, the Holocene/Pleistocene disconformity is inferred at c. 150 cm



**Figure 7** The distribution of selected species (or groups of species) of foraminifera, for the sediment grain size fraction 0.50–0.25 mm, within the Holocene interval of vibracore SV#25. The location of the core is indicated in Figure 1. The arrangement A to K is in approximate accord with the broadly accepted classification of foraminifera: A, *Ammobaculites reophaciformis* (in part), textulariid; B, *Nubecularia lucifuga*, to F, *Triloculina* spp., miliolids; G, *Discorbis dimidiatus*, to K, *Elphidium macelliforme*, rotalids. The scanning electron microscopic images illustrate specimens taken from various gulf sediment samples. Also shown are the calibrated <sup>14</sup>C ages. The Pleistocene/Holocene boundary is inferred at a core depth of 50 cm lithologically, by the record of *Elphidium crispum* and by numerical dating

shallow-water species that dominates the Pleistocene sediments below 50 cm, but is effectively absent from those above. Similar observations apply to the less abundant *Vertebralina striata*, *Discorbis dimidiatus* and *Rosalina australis*. The occurrence of the two agglutinated species, *A. reophaciformis* and *F. triquetra* downcore from the disconformity to below 100 cm testifies to the extent to which the Holocene and Pleistocene sediments were mixed at the core site.

## Discussion

In core SV#23, the sediment between 64 cm and the disconformity at 150 cm, representing the boundary between Holocene and Late Pleistocene sediments, appears to have been deposited relatively quickly compared with typical rates of sediment accumulation in the temperate carbonate province of the South Australian gulfs (cf. Belperio *et al.*, 1984). This interval of sediment was deposited immediately following Melt Water Pulse-1B, as defined by Bard *et al.* (1990) based on a relative deglacial sea-level curve derived from Barbados corals. Notwithstanding analytical uncertainties in radiocarbon determinations, during the time interval 10 380 to 9750 cal. yr BP, relative sea level in Barbados rose from approximately –37 m to –33 m. Although for the majority of Holocene time (the past 7–8 ka) the relative rate of sea-level rise at Barbados appears to have lagged behind that independently derived for southern Australia (Belperio *et al.*, 2002), the earlier deglacial rise in sea level in the Barbados record provides a reliable indicator of glacio-eustatic sea-level changes, and implies shallow water deposition at the core site of SV#23 some 10 ka ago.

High-resolution microfossil analysis of vibrocore SV23 has revealed a foraminiferal eco-succession that has permitted detailed palaeoenvironmental inferences. In contrast, analyses of the foraminiferal assemblages within vibrocore SV24 and SV25 have revealed that the sand fractions that comprise the Holocene intervals have been substantially mixed. In these cores, no detail remains of the fine-scale ecological changes that were associated with the postglacial marine transgression into Gulf St Vincent.

In core SV#23 the early record (below 50 cm) of the incoming *A. reophaciformis* and *F. triquetra*, which favour the deepest water, is marked by brief intervals (eg. at a core depth of 90 cm) in which the tests are atypically abundant, with a corresponding 'pinch effect' in the record of *A. beccarii*. It is likely that, at these horizons, the core intersected a burrow down which sandy sediment had infiltrated from above. Cann *et al.* (1993) illustrate the presence of a burrow at 64 cm, which coincides with one of the 'peak/pinch' horizons. Alternatively, the peaks could represent storm-driven transport, from deeper water, of sediment that contained *A. reophaciformis* and *F. triquetra*, into the restricted environment that was inhabited by *A. beccarii*.

Storm-driven transport of deeper water sediment could possibly also account for the erratic record of *Elphidium macelliforme*, and hence the variability of the *E. macelliforme*/*E. crispum* ratios. However, it is also possible that the *E. macelliforme* population has responded to some other environmental factor. For example, the species is known to have preference for the cooler, deeper waters of the gulfs, so the 'spikes' of increased abundance could have been in response to incoming colder water from the Southern Ocean, and thus have palaeoclimatological significance. This is clearly a matter of conjecture at this time and will require further investigation for clarification.

## Conclusions

The early phase of Holocene marine sedimentation in Gulf St Vincent commenced about 10 000 years ago when sea level was c. –40 m. It was marked by the development of a marginal marine, perhaps lacustrine to estuarine environment, as signified by the presence of oogonia, gypsum crystals, and the foraminifera *Miliolinella labiosa* and *Elphidium* cf. *articulatum*. Development of seagrass meadows followed; these were inhabited by *Nubecularia lucifuga* and *Discorbis dimidiatus*. As the marine transgression proceeded, the environment remained somewhat restricted, as indicated by the euryhaline *Ammonia beccarii*, but numbers of this species declined giving way to *Massilina milletti* as conditions began to resemble those of the modern holomarine Gulf St Vincent. Culmination of the transgression provided the conditions necessary for the dominance of *Ammobaculites reophaciformis* and *Flintina triquetra* in the modern environment.

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