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SEA LEVEL HISTORY, 30000 TO 45000 YEARS B.P., INFERRED FROM BENTHIC FORAMINIFERA, GULF ST. VINCENT, SOUTH AUSTRALIA

GEOLOGICAL SURVEY

by

J.H. CANN
A.P. BELPERIO (REGIONAL GEOLOGY)
V.A. GOSTIN

and

C.V. MURRAY-WALLACE

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SEA LEVEL HISTORY, 30,000 to 45,000 YR B.P.,

INFERRED FROM BENTHIC FORAMINIFERA,

GULF ST VINCENT, SOUTH AUSTRALIA

BY

JOHN H. CANN[1], ANTONIO P. BELPERIO[2], VICTOR A. GOSTIN[3] and COLIN V. MURRAY-WALLACE[4]

1. School of Pure and Applied Sciences, Salisbury Campus of South Australian College of Advanced Education, Smith Road, Salisbury East, 5109, Australia.
2. Department of Mines and Energy, P.O. Box 151, Eastwood, 5063, Australia.
3. Department of Geology and Geophysics, University of Adelaide, G.P.O. Box 498, Adelaide, 5001, Australia.
4. N.W.G. Macintosh Centre for Quaternary Dating, University of Sydney, Sydney, 2006, Australia.

ABSTRACT

Surficial sediments of Gulf St Vincent, South Australia, are predominantly bioclastic, cool-temperate carbonates. Benthic foraminifera are abundant and distribution of species is closely related to water depth. For example, *Massilina milletti* is most common at depths ca. 40 m, while *Discorbis dimidiatus* is characteristic of shallow, subtidal environments. *Elphidium crispum*, a shallow water species, and *E. macelliforme*, favouring deeper water, provide a useful numerical ratio. Their logarithmic relative abundance, in the sediment size fraction 0.50-0.25 mm, correlates strongly with water depth.

Vibrocores SV 4 and SV 5 recovered undisturbed sections of Quaternary strata from the deepest part, ca. 40 m, of Gulf St Vincent. Amino acid racemisation and radiocarbon age determinations show that Late Pleistocene sections of the cores were deposited over the time ca. 45,000 to 30,000 yr B.P. Species of fossil foraminifera, recovered from these sections, are mostly extant in modern Gulf St Vincent, thus allowing palaeoecological inferences of Late Pleistocene sea levels.

These inferred sea level maxima can be correlated with those determined from study of Huon Peninsula coral reef terraces. Initial estimates of tectonically corrected sea levels for transgressions in Gulf St Vincent at 31,000 and 40,000 yr B.P. are -22 m and -22.5 m, respectively. The intervening regression lowered sea level to -28 m.

INTRODUCTION

QUATERNARY SEA LEVELS

Glacio-eustasy, geoidal eustasy, isostasy and local and regional tectonism are generally recognised as the main causes of sea level change in the Quaternary (e.g. Walcott, 1972; Mörner, 1976; Clark et al., 1978; Beard et al., 1982; Kidson, 1982). Apart from the indirect data provided by isotope studies of foraminifera from deep sea cores (Emiliani, 1961, 1972; Chappell, 1974b; Shackleton, 1982), absolute changes of sea level and geographic variability are still poorly known for much of the Quaternary. The best data for the past 140,000 years comes from the Huon Peninsula, where successive sea level still-stands are preserved in a sequence of tectonically elevated fringing reefs (Bloom et al., 1974; Chappell, 1974a, 1983; Chappell and Shackleton, 1986). Along more tectonically stable coastlines, such as those of Australia, Quaternary sea levels are recorded as discontinuous shoreline deposits (Marshall and Thom, 1976; Veeh et al., 1979; Pickett et al., 1985; Ward, 1985) and as on-lapping and off-lapping marine strata on the shallow continental shelf (Hails et al., 1984 a,b). In this study, we report on sea levels interpreted from shallow marine strata deposited between 30,000 and 45,000 years B.P. in Gulf St Vincent, Australia.

GULF ST VINCENT

Gulf St Vincent (Fig. 1) is a shallow elongate embayment on the continental shelf of southern Australia. It is approximately 7000 km^2 in area with a maximum depth of about 40 m.

The Gulf is complexly fault bounded with Fleurieu Peninsula to the east, Yorke Peninsula to the west and, in part, by Kangaroo Island to the south. These faults reflect Cambro-Ordovician structural trends that were reactivated in the early Tertiary by the separation of Australia and Antarctica. St Vincent Basin, thus formed, contains a significant record of Tertiary and Quaternary sedimentation (Daily et al., 1976, references therein). Present day Gulf St Vincent has resulted from the latest (Holocene) transgression into this Basin.

Details of the physical oceanography of Gulf St Vincent have been given by Bye (1976). He considered water circulation within the Gulf to be primarily related to prevailing wind direction. Water moves from the open ocean northwards adjacent to Yorke Peninsula and returns southwards along the eastern coast. Circulation is more restricted in most northern waters where, in summer, subtidal salinity may exceed 41^{o}/oo.

The wave regime of Gulf St Vincent has been discussed by Wynne et al. (1984). The configuration of the Gulf is such that prevailing south westerly winds generate waves of maximum fetch along the eastern coast south of Adelaide. Adelaide beaches are subject to a lower wave energy regime which generates northward littoral drift. Except under storm conditions, wave energy towards the head of the Gulf is very low.

Shepherd and Sprigg (1976) have described aspects of the substrate, sediments and subtidal ecology of Gulf St Vincent. South of Adelaide, Tertiary strata form submarine outcrops up to 5 km from the eastern shore, and submerged relict beach deposits, formed during Pleistocene times of lowered sea level, form prominent features of the near shore Gulf floor. Around much of the Gulf coast, and in shallow subtidal areas near Adelaide, strongly calcreted marine sediments of the last interglacial sea level high stand (ca. 125,000 yr B.P.; Belperio et al., 1984) are covered by only a thin veneer of Holocene sands and muds.

Seagrasses and algae are extensive throughout the Gulf. *Amphibolis antarctica* and *Posidonia australis* often form dense, monospecific, subtidal meadows while, especially in deeper water, other species occur as clumps or scattered plants. *P. australis* meadows cover vast areas of sandy sea floor. In the upper part of the Gulf these meadows extend from low tide level to a depth of about 10 metres, while to the south they may grow to depths of about 20 metres. Northern intertidal areas, such as at Port Gawler, display a well defined zonation of seagrasses, cyanobacterial mats, mangroves and samphire. Cann and Gostin (1985) have documented the significance of these communities in the production and fixing of Holocene sediments at Port Gawler.

There is little input of terrigenous sediment into Gulf St Vincent from fluvial systems. Streams on the eastern side flow only intermittently, mainly at times of winter rainfall, and no major streams flow into the Gulf from Yorke Peninsula. Siliciclastic components of Gulf sediments are most pronounced in near shore areas to the south of Adelaide where coastal erosion is reworking the outcropping Tertiary and Quaternary strata. Away from these areas, biogenic carbonate becomes increasingly significant. Sands and muds comprising greater than 90% biogenic calcium carbonate cover more than half the floor of Gulf St Vincent.

Little is known of the older strata beneath Gulf St Vincent. Results reported herein are part of a multidisciplinary research program aimed at elucidating the Quaternary geological history, palaeoclimates and former sea levels of the Gulf.

METHODS

VIBROCORES AND OTHER SEDIMENT SAMPLES

Vibrocores with a diameter of 85 mm and up to 4 m long were obtained using an electrically driven vibrocorer deployed from a barge. Positions were fixed using shipborne radar. A seafloor profiler, checked by leadline, was used to determine water depth, later adjusted to low water datum using local tidal records. Vibrocore sites were selected to lie along a defined transect (Fig. 1) into the central Gulf. Two shorter transects were undertaken in shallow water near Port Gawler. Seafloor grab samples were obtained at each vibrocore site and these were examined to determine general sediment characteristics and faunal content.

Vibrocores were carefully split in the laboratory, photographed, lithologically logged and subsampled. Sieves were used to separate major size fractions which were then examined microscopically. Bulk carbon/carbonate analyses were done on small samples by pyrolysis at 500°C and 1000°C for 2 hours each.

RADIOCARBON DATING

Large fossil bivalves extracted from the split cores were washed, dried and submitted for dating at the C.S.I.R.O. Division of Soils, Radiocarbon Laboratory, Adelaide. After removal of surficial contaminants, a dilute acid wash was used to remove about 10% of the outer layers of the valves. The oyster *Ostrea angasi* is sufficiently large that dating could be undertaken on single valves. This species is found free living, or sometimes fixed, in water depths of 2 to 20 m around low wave energy parts of the Gulf coast (Ludbrook, 1984). Its valves are composed entirely of calcite. For smaller mollusc species, *Katelysia rhytiphora* (intertidal cockle) and *Chlamys (Equichlamys) bifrons* (subtidal scallop), several valves were digested to provide the requisite sample size.

AMINO ACID RACEMISATION DATING

Fossil bivalves were extracted from the split cores. Encrustations and other surface features were initially removed from the shells using a variety of motor driven dental tools. Specimens were then sonically cleaned in dilute hydrochloric acid and distilled water and subsequently processed for AAR analysis.

Analytical procedures followed those described by Kimber and Milnes (1984), Cann and Murray-Wallace (1986) and Murray-Wallace and Kimber (1987), and after Kvenvolden et al. (1979) and Frank et al. (1978). Analyses were performed on the total acid hydrolysate, a complex mixture of polypeptides, smaller peptides and free amino acids.

FORAMINIFERA IN MODERN SEDIMENTS, GULF ST VINCENT

Grab samples of bottom sediment from vibrocore stations SV 1 to SV 18 (Fig. 1) were boiled in fresh water to break down organic debris and generally facilitate disaggregation. They were then wet sieved and sediment of sand size (2.00-0.063 mm) was retained. Foraminifera were concentrated from these sand fractions by flotation on tetrabromoethane. The dried foraminiferal concentrates were further sieved into phi grain size fractions for microscopic examination. For each sample, percentage abundances of foraminifera species were determined for the fractions 1.00-0.50 mm and 0.50-0.25 mm.

Use of these phi fractions, rather than the entire sample, has been discussed by Cann and Gostin (1985). They emphasise the following points:

- Larger individuals in coarser fractions require lower powers of microscope magnification, enhancing accuracy of identification, separation and counting of foraminifera.
- In finer fractions, juveniles constitute a high percentage of the foraminifera. Species identification is often difficult, particularly for miliolid genera. For example, juveniles of *Triloculina* often exhibit quinqueloculine coiling.

- Smaller tests are more easily winnowed from their environments of origin to be deposited elsewhere. They are therefore potentially less valuable as palaeoenvironmental indicators.
- During intraenvironmental transport, smaller, more fragile species are more prone to chemical and mechanical destruction than larger, more robust forms.
- Preservation favours larger individuals that are less prone to solution.

FORAMINIFERA IN VIBROCORES SV 4 AND SV 5

From the split cores, samples of about 100 cm^3 of sediment were taken at 20 cm intervals. They were processed as described above, except that foraminifera were not concentrated by dense liquid flotation.

Previous work (J.H. Cann, unpublished data) has shown that relative abundances of foraminiferal species in concentrated and unconcentrated sediment samples are essentially the same. An exception to this observation has been *Nubecularia lucifuga*. Some forms of this species have open planispiral chambers that do not enclose air. Such forms therefore cannot be concentrated by flotation. Thus *N. lucifuga* is over-represented in the unfloated vibrocore samples by comparison with the floated grab samples.

For each grab and core sample, percentage abundances of species were determined, from a count of at least 200 randomly selected individuals, in the phi grain size fractions 1.00 to 0.50 and 0.50 to 0.25 mm.

RESULTS

VIBROCORE AND OTHER SEDIMENT SAMPLES

Vibrocores recovered from the eastern side of Gulf St Vincent penetrated a thin veneer of Holocene marine shell sand resting disconformably on calcreted marine strata. These pedogenically altered sediments were deposited during the last interglacial sea level maximum. They are locally known as the Glanville Formation and have been dated at $110,000 {}^{+19\,000}_{-17\,000}$ yr B.P. (Cann, 1978; Belperio et al., 1984). Vibrocores from the deepest waters of central Gulf St Vincent, in particular cores SV 4 and SV 5, penetrated a relatively unaltered Pleistocene sequence apparently younger than the last interglacial deposits. Sediments recovered in vibrocores SV 4 and SV 5 were selected for detailed analysis.

SV 4 and SV 5 sites lie at the northern end of a central, elongate and essentially flat sea floor (Fig. 1). Core SV 5 recovered almost 4 m of sediment from a depth 3.5 m shallower than SV 4. Figure 2 illustrates the general lithology of these cores. Colour boundaries at 65 cm in core SV 4, and 53 cm in core SV 5, mark the disconformity between Holocene and Pleistocene marine sediments. In core SV 4 the lower 25 cm of the Holocene interval contains indistinct intraclasts, similar to the underlying sediment, and probably reworked from it. Both cores penetrated more than 2 m of the underlying, unlithified, fossiliferous carbonate mud, deposited during an interstadial high sea level.

The interstadial sediment is a rather homogeneous, calcitic mud with variable proportions of shallow marine bivalves, gastropods, foraminifera and other miscellaneous bioclastic debris. The lack of lithification, and the presence of well preserved aragonitic fossils such as *Katelysia*, *Chlamys* and *Batillaria*, indicate that, apart from a little iron oxide staining, no significant diagenesis has occurred. Intense pedogenic alteration, such as previously observed in older Pleistocene marine sediments of northern Spencer Gulf (Billing, 1984) is noticeably absent.

RADIOCARBON DATING

Vibrocores from sites SV 4 and SV 5 yielded seven radiocarbon dates which are presented in Table 1. Below surficial Holocene sands and muds, the marine sediments are of Late Pleistocene age. Individual shell dates indicate that Late Pleistocene marine sedimentation occurred between 45,000 and 37,000 yr B.P. at SV 5, and at site SV 4, from about 36,000 to 30,500 yr B.P.

TABLE 1: Radiocarbon Ages for Cores SV 5 (Water Depth 36.4 m) and SV 4 (water depth 39.9 m)

Laboratory Code	Core	Core Depth (cm)	Elevation* (m)	$\delta^{13}C$ PDB	Conventional ^{14}C age yr B.P.	Material Dated
CS-545	SV 5	25	- 36.7	1.4	1940 ± 90	Chlamys (Equichlamys) bifrons
CS-546	SV 5	140	- 37.8	1.4	37,600 + 1700 - 1400	Katelysia rhytiphora
CS-547	SV 5	161	- 38.0	0.9	> 40,000	Ostrea angasi
CS-662	SV 5	196	- 38.4	2.72	37,700 + 3000 - 2200	Ostrea angasi
CS-548	SV 5	370	- 40.1	1.0	45,100 + 5100 - 3100	Ostrea angasi
CS-549	SV 4	59	- 40.5	0.8	30,500 + 650 - 600	Ostrea angasi
CS-558	SV 4	279	- 42.7	1.4	36,300 + 1450 - 1250	Ostrea angasi

* Sample elevation relative to present mean sea level.

AMINO ACID RACEMISATION DATING

Derivatives of bivalve shells from vibrocores SV 4 and SV 5 were analysed for leucine, valine and isoleucine ("total acid hydrolysate"). Results of D/L ratios for these amino acids are presented in Table 2. For calibration, representative amino acid D/L ratios for *Katelysia rhytiphora* from core SV 5 are compared with values for established older and younger individuals of the same species from elsewhere around South Australia (Fig. 3). The older specimen was taken from last interglacial (ca. 120,000 yr B.P.) sediments while the younger was a Holocene shell of known ^{14}C age. The specimens from vibrocore SV 5 are clearly older than Holocene and younger than the last interglaciation. A confident age estimate of 30-45 Ka B.P. (latest Pleistocene) was obtained for core SV 5 using this calibration (Murray-Wallace, 1987).

Amino acid D/L ratios for *K. rhytiphora* and for *Fulvia tenuicostata* from vibrocore SV 5 (Table 2), and from other Gulf St Vincent data (Murray-Wallace, 1987), show little intergeneric differences in relative rates of racemisation for these species. In contrast, *Ostrea angasi* racemises at a faster rate. D/L ratios for *F. tenuicostata* in core SV 4 may thus be compared with those for both this species and *K. rhytiphora* in core SV 5. With one exception, analyses of *F. tenuicostata* and *K. rhytiphora* from core SV 4 are similar to those of the designated latest Pleistocene section of core SV 5. The specimens from 58 to 64 cm in core SV 4 are clearly of latest Pleistocene age, though they occur as reworked fossils in the basal, overlying Holocene sequence.

TABLE 2: Extent of amino acid racemisation in molluscan fossils from vibrocores SV 4 and SV 5, Gulf St Vincent

Core Site	Species	Depth in Core (cm)	amino acid D/L ratio "total acid hydrolysate" LEU	VAL	ALLO/ISO	ASP†	Age
SV 4	*Katelysia rhytiphora*	58-60	0.29 ± 0.006	0.19 ± 0.003	0.19 ± 0.002	0.45 ± 0.02	
	Fulvia tenuicostata	64	0.22 ± 0.002	0.12 ± 0.004	0.15 ± 0.005	0.32 ± 0.002	
	*Ostrea angasi**	58-60	0.49 ± 0.003	0.33 ± 0.002	0.49 ± 0.009	0.45 ± 0.02	All Late Pleistocene ca. 30,000 to 45,000 yr B.P.
	Fulvia tenuicostata	247	0.28 ± 0.003	0.19 ± 0.003	0.22 ± 0.005	0.41 ± 0.02	
	Fulvia tenuicostata	277	0.33 ± 0.01	0.24 ± 0.005	0.30 ± 0.004	0.40 ± 0.001	
SV 5	*Circomphalus disjecta*	25-27	0.11	0.05	0.05	0.26	Holocene
	Katelysia rhytiphora	54	0.28	0.23	0.23	0.46	
	K. rhytiphora	138-140	0.29	0.25	0.25	0.42	
	Fulvia tenuicostata	200	0.28	0.23	0.26	0.45	Late Pleistocene ca. 30,000 to 45,000 yr B.P.
	F. tenuicostata	219	0.28	0.18	0.24	0.43	
	K. rhytiphora	350	0.28	0.26	0.26	0.45	
	K. rhytiphora	369	0.29	0.20	0.18	0.45	

LEU-leucine VAL-valine ALLO/ISO- D-alloisoleucine/L-isoleucine ASP-aspartic acid

* ^{14}C age of this specimen 30,500 $^{+650}_{-600}$ yr B.P.

† Aspartic acid D/L ratios are artificially high for the Late Pleistocene specimens due to co-elution of γ-amino-n-butyric acid with L-aspartic acid. The Holocene specimen was analysed before this problem occurred.

FORAMINIFERA IN MODERN SEDIMENTS AND IN VIBROCORES SV 4 AND SV 5, GULF ST VINCENT

For each grab sample along a transect, the percentage distribution of all species of foraminifera comprising ≥ 5% of counted individuals, for at least one site, was determined, and compared with water depth profiles (Figs. 4, 5). Figure 4 shows percentage distributions within size fractions 1.00-0.50 mm and 0.50-0.25 mm, across Gulf St Vincent from St Kilda on the east coast to Edithburgh on the west. Water depths of stations on this transect range from about 15 m at SV 1 to 40 m at SV 4. Figure 5 shows percentage distributions in more shallow waters near Port Gawler, while Figure 6, modified from Cann and Gostin (1985), shows the occurrence of major species across the broad, intertidal Port Gawler sand flats.

For vibrocore SV 4, downcore distributions of foraminifera species are shown as Figure 7a for size fraction 1.00-0.50 mm and Figure 7b for the smaller fraction 0.50-0.25 mm. These figures show distributions for only those species constituting ≥ 5% of randomly counted individuals (> 200), for at least one size fraction subsample down the core. Similarly, data are presented for vibrocore SV 5 as Figure 8a and b.

All statistically significant species recovered from grab samples and/or vibrocores are illustrated in Figure 9 and 10.

D I S C U S S I O N

VALIDITY OF RADIOCARBON DATA

Considerable debate has occurred over past decades as to the reliability of ^{14}C age determinations in the range 30,000 yr B.P. to 45,000 yr B.P. (e.g., Olsson et al, 1968; Mörner, 1971) and consequent interstadial sea level interpretations (Thom, 1973). Age determinations > 30,000 yr B.P. are less reliable than younger ages because results can be strongly affected by minor contamination, and large standard deviations can result from limited sample size. Collectors and dating laboratories are now more aware of these problems, and sample pretreatment to remove superficial contaminants is a fundamental part of radiocarbon analysis. In this study, the risk of sample contamination has been reduced, where possible, by use of large single specimens of the calcitic oyster *Ostrea angasi*, and by careful sample handling and pretreatment. In other cases, where molluscs such as *Katelysia rhytiphora* and *Chlamys (Equichlamys) bifrons* were used for radiocarbon dating (or amino acid racemisation analysis), the mineralogy was in all cases aragonite. Our confidence in the reliability of the dates obtained is highlighted by both the excellent coherence of dates down the cores, and the independent confirmation of a 30,000 to 45,000 yr B.P. age range by AAR analyses of adjacent samples. The failure to obtain a finite age for sample CS-547 resulted from insufficient sample rather than the presence of dead carbon and the result does not contradict the other dates. We are thus confident that the strata in cores SV 4 and SV 5 were deposited in the time interval 45,000 to 30,000 radiocarbon years B.P.

FORAMINIFERA IN MODERN SEDIMENTS

The relative abundance of many species of foraminifera in Gulf St Vincent is clearly related to water depth (Figs. 4-6). For example, *Discorbis dimidiatus* (Fig. 10 i,j,k), present in moderate numbers on intertidal sand flats (Fig. 6) is extremely abundant in shallow subtidal areas (Fig. 5) and essentially absent from deeper Gulf waters (Fig. 4). Several species of *Triloculina* (Fig. 9 v,w; Fig. 10 a-h) conspicuously increase in number with increasing water depth (Fig. 4) while *Ammobaculites reophaciformis* (Fig. 9 a,b) is abundantly distributed through intermediate depths of about 20-30 m (Fig. 4). *Quinqueloculina lamarckiana* (Fig. 9 h,i), in the smaller size fraction, shows a particularly good relationship between abundance and water depth (Fig. 4b), as does *Massilina milletti* (Fig. 4; Fig. 9 s,t,u), a correlation already noted for Spencer Gulf, to the west of Yorke Peninsula (Cann and Murray-Wallace, 1986).

Some species occur in statistically significant numbers, discontinuously, in more than one environment. For example, *Peneroplis planatus* (Fig. 10 n,o) is a major component of the foraminifera on the intertidal sand flat (Fig. 6), its numbers decreasing seawards to just a few percent. In shallow subtidal environments (Fig. 5) the species is no longer present in significant numbers, but in deeper subtidal waters, 15-20 m, it again constitutes a large component of the foraminiferal fauna (Fig. 4).

As mentioned in methods above, *Nubecularia lucifuga* (Fig. 9g) is not adequately represented in Figs. 4-6 because these data are based on samples in which foraminifera tests were concentrated by floating on tetrabromoethane. Some forms of *N. lucifuga* have open chambers and therefore cannot be concentrated by flotation.

To better understand the distribution of this species, additional grab samples from various water depths in Gulf St Vincent were examined. They were processed as for previous samples, except that tests were not concentrated by dense liquid flotation. *Nubecularia lucifuga* proved to be extraordinarily abundant in shallow, subtidal, nearshore environments. For example, in 2.6 m of water, in the vicinity of Largs Bay near Adelaide (Fig. 1), the species constitutes more than 70% of the total foraminifera fauna in the 1.00-0.50 mm size fraction, and nearly 50% in the smaller size fraction. In deeper Gulf waters the species is rare to absent. These observations significantly qualify the percentage distribution diagrams (Figs. 4-6) and constitute essential additional data for interpretation of the cores.

Of particular interest is an inverse relationship that exists in the numerical distribution of the two common Gulf species of *Elphidium*. *E. crispum* (Fig. 10 r,s) is abundant in shallow subtidal environments (Figs. 4b, 5) while *E. macelliforme* (Fig. 10 t,u) is more common in deeper parts of the Gulf (Fig. 4b). Thus the ratio of *E. macelliforme* to *E. crispum* is consistently < 0.1 in water shallower than 10 m, but increases to values in excess of 30 in deeper parts of the Gulf. Regression analysis of water depth versus logarithm of the *Elphidium* ratios for all Gulf St Vincent surficial samples indicates a simple linear relationship with a correlation coefficient of 0.95 (Fig. 11a). This relationship is of interest because of its potential use as a qualitative and quantitive palaeo water depth and palaeo sea level indicator.

However, it is apparent that other physical factors, besides water depth, can influence the *Elphidium* ratio. Similar data have been prepared for Northern Spencer Gulf (Fig. 11b). While a consistent relationship between the ratio and water depth can again be demonstrated, a given ratio corresponds to shallower water than in Gulf St Vincent. For example, a ratio of 1.5 corresponds to a water depth of 28 m in Gulf St Vincent, but only 17 m in Spencer Gulf. By comparison with the present study area, northern Spencer Gulf waters are shallower, less influenced by the open southern ocean, and are consequently warmer and more saline. The ratio of *E. macelliforme* to *E. crispum* as an indicator of water depth is thus sensitive to the present geographic variability of environment within the South Australian Gulfs. This has a major bearing on the application of the technique to interpreting palaeo water depths for the Pleistocene sediments.

FORAMINIFERA IN VIBROCORES

Down core percentage distributions of foraminifera species in vibrocores SV 4 (Fig. 7 a,b) and SV 5 (Fig. 8 a,b) have palaeoenvironmental significance, particularly with reference to Late Pleistocene sea levels. Successive changes in water depth for sites SV 4 and SV 5 can be inferred by comparing foraminiferal distributions through the core with those of present day Gulf St Vincent sediments. The degree of resolution of such inferences is limited by the downcore sampling interval which, in this study, was 20 cm.

VIBROCORE SV 4

Vibrocore SV 4 recovered Late Pleistocene sediments deposited within the ^{14}C time constraints of $36{,}000 \begin{smallmatrix} +1450 \\ -1250 \end{smallmatrix}$ yr B.P. and $30{,}500 \begin{smallmatrix} +650 \\ -600 \end{smallmatrix}$ yr B.P. The Holocene/Pleistocene disconformity is indicated by a distinct colour boundary at 65 cm.

As indicated above, numbers of *Massilina milletti* reliably correlate positively with water depth. The relative abundance of this species in the Pleistocene interval of the core, size fraction 1.00-0.50 mm (Fig. 7a) infers the following changes in water depth during sedimentation:

base of recovered core to 260 cm - water shallowed
240 cm to 180 cm - water deepened
180 cm to 160 cm - water shallowed
100 cm to 60 cm - final Pleistocene regression

Within the same size fraction, these inferences are supported by corresponding inverse distributions of *Peneroplis planatus*, their larger numbers indicating deposition in shallower waters. Maximum numbers of *Discorbis dimidiatus* at 80 cm show that during the final Pleistocene regression, the environment at site SV 4 was one of shallow subtidal sedimentation.

In the smaller size fraction 0.50-0.25 mm (Fig. 7b) the distribution of *Quinqueloculina lamarckiana* (Fig. 9 h,i), which in the modern sediment has a positive correlation with water depth (Fig. 4b), shows that for the interval 160-100 cm, water deepened at site SV 4, prior to the final Pleistocene regression.

Onset of the Holocene transgression is signalled at about 60 cm (actually 65 cm, as indicated above) for both size fractions (Fig. 7 a,b) by appearance and subsequent optimum development of *Ammobaculites reophaciformis, Flintina triquetra* and the two species of *Triloculina*. Intertidal and shallow subtidal indicator species, *Cribrobulimina mixta, Nubecularia lucifuga, Peneroplis planatus* and *Discorbis dimidiatus* are all present in significant numbers near the Holocene/Pleistocene boundary. As Holocene sea level rose in Gulf St Vincent, numbers of these species rapidly decreased at site SV 4 and they are essentially absent from the uppermost parts of the core. Conversely, *Massilina milletti*, together with other deeper water species, increased in number. These inferred changes in Late Pleistocene and Holocene sea levels, derived from interpretation of the general assemblage of foraminifera species, are summarised in Figure 12a.

The logarithmic plot of ratios of numbers of *Elphidium macelliforme* to *E. crispum* against sample depths in core SV 4 (Fig. 12a) supports the above interpretations. Using the relationship with water depth derived from Figure 11a, the *Elphidium* ratios, without exception, confirm the changes in water depth detailed above. Figure 12a can thus be regarded as a *de facto* relative sea level curve for site SV 4.

VIBROCORE SV 5

Late Pleistocene sedimentation, as recorded in vibrocore SV 5, commenced about 45,000 yr B.P. and continued for some 10,000 yr. Lithological evidence indicates that the Pleistocene/Holocene boundary occurs at a core depth of 53 cm.

For the Pleistocene interval of core SV 5, *Massilina milletti* can again be used as a water depth indicator species. Although its numbers are relatively small, increases and decreases in abundance (Fig. 8 a,b) are interpreted to indicate rises and falls of Late Pleistocene sea level. On this evidence, peaks of sea level are signified at core depths of 387 cm (bottom of recovered core), 340 cm and 240 cm, while lower sea levels are indicated at 360 cm and 300 cm.

Other foraminiferal data are somewhat less informative, though the dominance of *Nubecularia lucifuga* at 100 cm is unequivocal evidence of a shallow subtidal environment. This conclusion is based on the Largs Bay sample, referred to above, where water depth was only 2.6 m and where *N. lucifuga* constituted >70% of the coarser sediment size fraction. *Peneroplis planatus* numbers, both immediately above and below 100 cm, are interpreted as deeper subtidal populations (water depth ca. 10-20 m; Fig. 4) rather than intertidal (Fig. 6). At 100 cm the species is absent. Thus the combined record of *P. planatus* and *N. lucifuga* in the interval, for example, 140 cm to 60 cm, is evidence for water shallowing followed by water deepening. As the core sample at 60 cm is closest to the Pleistocene/Holocene boundary at 53 cm, there is no direct foraminiferal data indicating final Pleistocene shallowing and emergence at SV 5. From the evidence of both the foraminifera and the radiocarbon dates, erosion has removed the topmost facies at site SV 5.

Foraminifera in the interval 0-53 cm clearly record increasing water depth of the Holocene transgression (Fig. 8 a,b). Deeper water species, such as *Ammobaculites reophaciformis*, *Massilina milletti* and *Triloculina striatotrigonula* steadily increased in numbers as sea level rose in Gulf St Vincent. Conversely, species characteristic of shallow subtidal and intertidal environments, *Nubecularia lucifuga, Peneroplis planatus* and *Discorbis dimidiatus* decreased in numbers and are effectively absent from the top of the core. The internal consistency of these data indicates that there has been little significant bioturbation of the uppermost sediment.

These inferred changes in Late Pleistocene and Holocene sea levels at site SV 5 are summarised in Figure 12b. Although there is some minor displacement of maxima and minima, the pattern of sea level fluctuations derived from the *Elphidium macelliforme/Elphidium crispum* ratio for this core agrees very closely. Figure 12b can thus be regarded as a *de facto* relative sea level curve for site SV 5.

ABSOLUTE SEA LEVEL HISTORY

The southern Australian coastline has frequently been considered an area of relative crustal stability. With few exceptions (e.g. Schwebel, 1984), vertical tectonic movements, as deduced from elevations of Quaternary shorelines have generally been of the order of a few metres (e.g. Hails et al., 1984b; Veeh et al., 1979).

Around Gulf St Vincent, sediments of the last interglacial maximum outcrop at a level comparable with that of present sea level. Long-term subsidence has therefore been minimal and has been estimated at < 0.04 mm/yr (Belperio, 1985).

Vibrocores SV 4 and SV 5 were taken at depths of 39.9 m and 36.4 m, respectively, below present mean sea level. They indicate continuous marine inundation (i.e., sea level above -36 m) for the time interval 45,000 to 30,000 yr B.P. Sea level fell below -40 m at 30,000 yr B.P. and did not rise above this level until the Holocene transgression at c. 9800 yr B.P. (Belperio et al., 1983, 1987).

On the tectonically uplifted Huon Peninsula, coral terraces II and IIIb, dated by $^{230}Th/^{234}U$ at 31,000 ± 2500 and 40,000 ± 3000 yr B.P. respectively (Bloom et al., 1974; Chappell and Veeh, 1978) are shoreline correlatives of the strata in cores SV 4 and SV 5. Tectonically corrected sea levels at these times have been estimated at -41 ± 1 m and -39 ± 6 m, assuming a level of +6 m for the last interglacial maximum (Bloom et al., 1974). Our data for the South Australian Gulfs clearly indicate sea levels higher than these for this period.

Qualitative sea level changes, interpreted from the *de facto* sea level curves provided by the *Elphidium macelliforme* to *Elphidium crispum* ratios within cores SV 4 and SV 5, agree with the pattern and ages of sea level peaks established by Chappell (1983) for the Huon Peninsula (Fig. 13 a,b).

The use of these curves to establish absolute sea levels, however, is clouded by the uncertainty of palaeoenvironmental conditions of Late Pleistocene Gulf St Vincent. For example, using the regression equation for present day Gulf St Vincent (Fig. 11a) results in palaeo water depth calculations of between 18 m and 29 m for the time of recorded sedimentation at sites SV 4 and SV 5. However, applying the regression equation for modern Spencer Gulf to the core data (Fig. 11b) results in shallower palaeo water depth calculations of 10 to 18 m. Other foraminiferal evidence, in particular, the large numbers of *Nubecularia lucifuga* throughout the Late Pleistocene sections of cores SV 4 and SV 5, confirm that palaeo water depths, for the times of deposition, were always shallow. Thus the calculations derived from Spencer Gulf data are preferred. Water depths of 10 to 18 m at the sample sites correspond to palaeo sea levels of between -23 and -29 m (Fig. 13c). More specifically, the 30,000 and 40,000 yr B.P. sea level peaks are estimated at -23 and -24 m respectively, with the intervening regression falling to -29 m. These sea level estimates require a correction of 1.2-1.6 m for subsidence since sedimentation.

Although there is some uncertainty in the above application of the *Elphidium* species ratio in determining absolute values for palaeo sea levels, the estimates are clearly much higher than those derived from the coral reef terraces of Huon Peninsula. We are continuing research into the geographic variability, within Gulf St Vincent, of the *E. macelliforme*/*E. crispum* ratio as a measure of water depth so that the palaeo sea level estimates presented here may be further refined.

CONCLUSIONS

Foraminifera are sensitive indicators of environment and depth in the cool temperate carbonate facies of present day Gulf St Vincent. With due regard for possible palaeoenvironmental differences, foraminiferal species may also be used for qualitative and quantitative palaeo water depth and palaeo sea level estimation. This technique has been applied to Late Pleistocene strata recovered in submarine cores from Gulf St Vincent.

The Late Pleistocene sea of 30,000 - 45,000 yr B.P. inundated Gulf St Vincent to a maximum water depth of approximately 18 m. The sea regressed from the Gulf about 30,000 yr B.P. and did not return again until the Holocene. Initial estimates of tectonically corrected levels (assuming a level of +6 m for the last interglacial maxima) for the 31,000 and 40,000 yr B.P. transgressions in Gulf St Vincent are -22 m and -22.5 m respectively. The intervening regression at about 36,000 yr B.P. lowered sea level to -28 m.

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Dr. Paul Aharon and Dr. John Chappell reviewed the paper and we have incorporated some of their suggested modifications to the diagrams.

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CAPTIONS FOR FIGURES

Fig. 1 Location map showing sites of grab samples and vibrocores in Gulf St Vincent, South Australia.

Fig. 2 Descriptive lithological logs of two vibrocores recovered from Gulf St Vincent, (a) SV 4 and (b) SV 5.

Fig. 3 Scatter diagram summarising the extent of aspartic acid racemisation against isoleucine epimerisation in molluscan fossils of Late Quaternary age. The widely scattered data for the Glanville Formation (aminozone) is due to the wide geographic range of sample localities that have experienced different "Effective Quaternary Temperature" histories (Murray-Wallace, 1987). An interstadial age for the marine strata from Gulf St Vincent is clearly indicated in this plot.

Fig. 4 Percentage distribution of species of foraminifera in surficial sediment, compared with water depth, Gulf St Vincent, South Australia. Sample sites are indicated in figure 1.

(a) phi grain size fraction 1.00-0.50 mm.

(b) phi grain size fraction 0.50-0.25 mm.

Fig. 5 Percentage distribution of species of foraminifera in surficial sediment, compared with water depth, in the vicinity of Port Gawler, Gulf St Vincent, South Australia. Sample sites are indicated in figure 1. Separate data are shown for the phi grain size fractions 1.00-0.50 mm and 0.50-0.25 mm.

(a) Transect SV 12 to SV 16 is approximately east-west.

(b) Transect SV 11 to SV 18 is approximately north-south.

Fig. 6 Percentage distribution of selected species of foraminifera in adjacent intertidal sedimentary environments at Port Gawler (modified from Cann and Gostin, 1985).

Fig. 7 Down core percentage distributions of selected species of foraminifera in vibrocore SV 4, (a) size fraction 1.00-0.50 mm and (b) size fraction 0.50-0.25 mm. The Holocene/Pleistocene boundary is lithologically indicated at a core depth of 65 cm (Fig. 2a).

Fig. 8 Down core percentage distributions of selected species of foraminifera in vibrocore SV 5, (a) size fraction 1.00-0.50 mm and (b) size fraction 0.50-0.25 mm. The Holocene/Pleistocene boundary is lithologically indicated at a core depth of 53 cm (Fig. 2b)

Fig. 9 Species of foraminifera referred to in figures and text:

a,b *Ammobaculites reophaciformis* Cushman; x 25; SV 9.

c,d *Textularia pseudogramen* Chapman & Parr; x 40; SV 3.

e,f *Cribrobulimina mixta* Cushman; x 35; SV 12.

g *Nubecularia lucifuga* Defrance; x 25; SV 12.

h,i *Quinqueloculina lamarckiana* d'Orbigny; x 75; SV 8.

j,k *Quinqueloculina pittensis* Albani; x 75; SV 6.

l,m,n *Quinqueloculina subpolygona* Parr; x 40; SV 3.

o,p *Flintina triquetra* (Brady); x 50; SV 5.

q,r *Massilina ammophila* (Parr); x 30; SV 5.

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All illustrated specimens are from grab samples.

Fig. 10 Species of foraminifera referred to in figures and text:

a,b *Triloculina oblonga* (Montagu); x 40; SV 6.

c,d *Triloculina striatotrigonula* Parker & Jones; x 45; SV 9.

e,f *Triloculina tricarinata* (d'Orbigny); x 40, SV 7.

g,h *Triloculina trigonula* (Lamarck); x 45; SV 9.

i,j,k *Discorbis dimidiatus* (Parker & Jones); x 35; SV 12.

l,m *Scutuloris parri* Collins; x 75; SV 17.

n,o *Peneroplis planatus* (Fichtel & Moll); x 35; SV 4.

p,q *Elphidium articulatum* (d'Orbigny); x 75; SV 5.

r,s *Elphidium crispum* (Linné); x 55; SV 12.

t,u *Elphidium macelliforme* McCulloch; x 60; SV 6.

v *Planorbulina mediterranensis* d'Orbigny; x 25.

All illustrated specimens are from grab samples except *Peneroplis planatus* and *Elphidium articulatum*, which are taken from vibrocore subsamples.

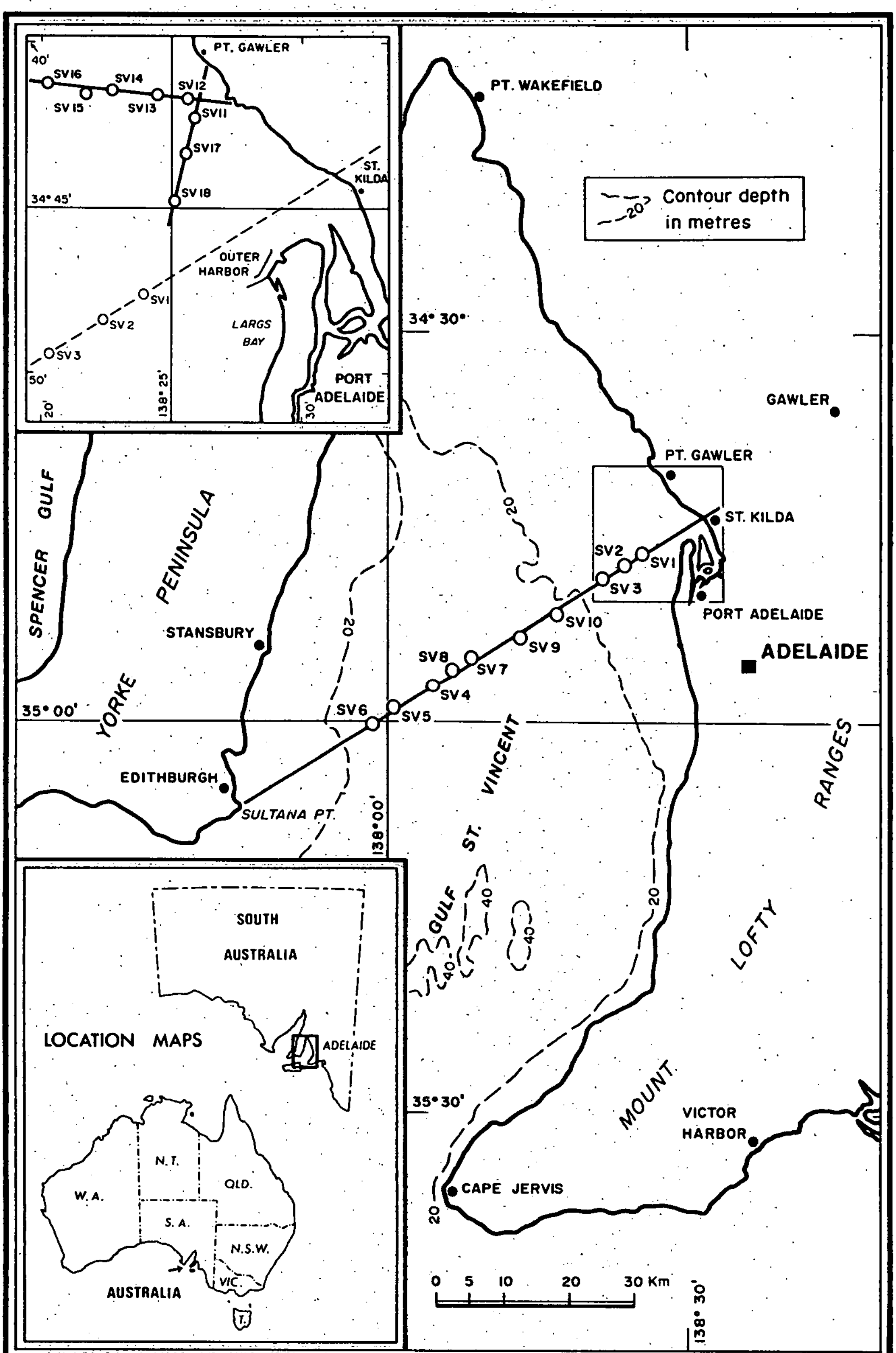
Fig. 11 Log-linear plot of water depth versus ratio of numbers of individuals of *Elphidium macelliforme* to numbers of individuals of *Elphidium crispum* for surficial samples from (a) Gulf St Vincent and (b) Spencer Gulf. Also shown are the lines of best least squares fit, the calculated regression equations and Pearson's correlation coefficient for the data sets.

Fig. 12 Log-linear plot of sample depth in core versus ratio of numbers of individuals of *Elphidium macelliforme* to numbers of individuals of *Elphidium crispum* for samples from (a) SV 4 and (b) SV 5. Curves are compared with inferred changes in Late Pleistocene and Holocene sea levels in Gulf St Vincent, derived from interpretation of general assemblages of foraminifera species. Also shown are ^{14}C dates of samples taken from the horizons indicated.

Fig. 13 (a) Palaeo sea level data from southern Australia using the Huon Peninsula sea level curve of Chappell (1983) as a framework.

(b) Relative sea level fluctuations for the time interval 30,000 to 45,000 ^{14}C yr B.P. interpreted from the *Elphidium* species ratios and ^{14}C data (Fig. 12) from vibrocores SV 4 and SV 5, Gulf St Vincent.

(c) Late Pleistocene palaeo sea levels interpreted from the *Elphidium* species ratios and ^{14}C data (Fig. 12) from vibrocores SV 4 and SV 5, using the regression equation derived from northern Spencer Gulf data (Fig. 11b).



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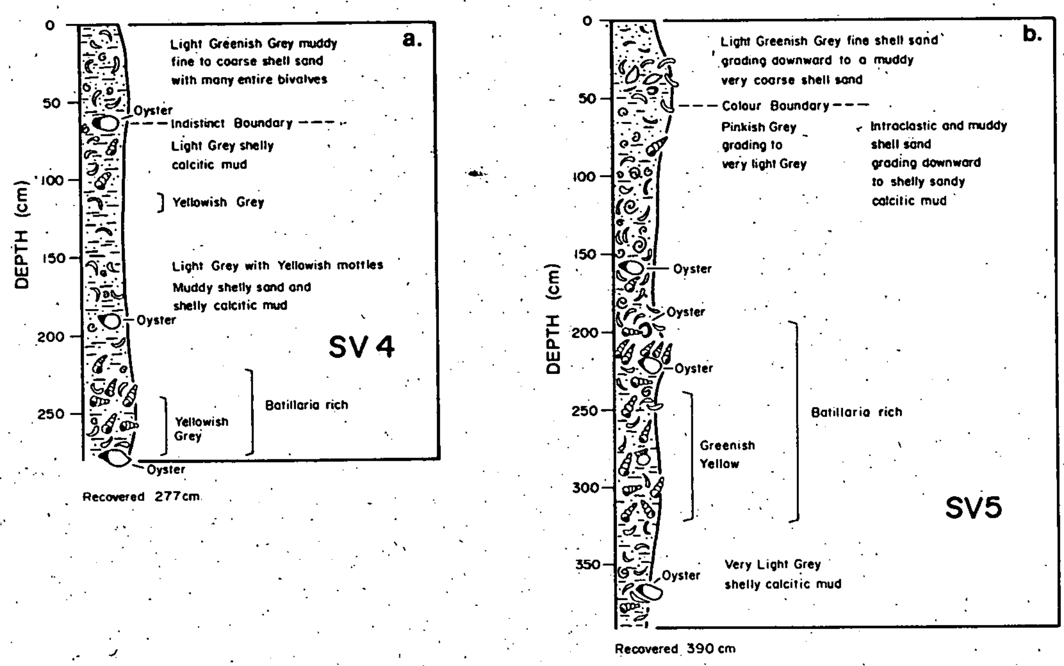

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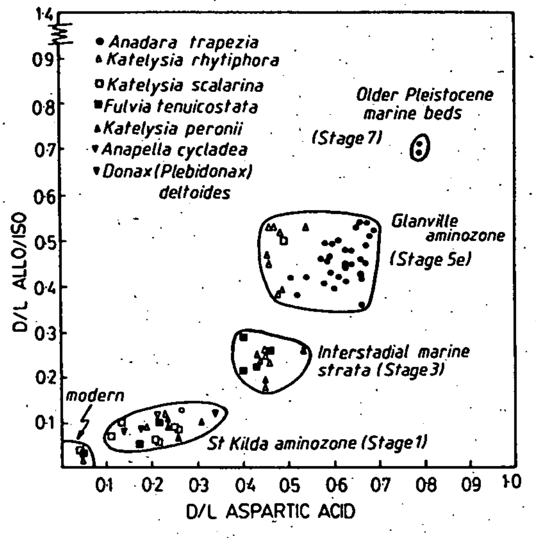

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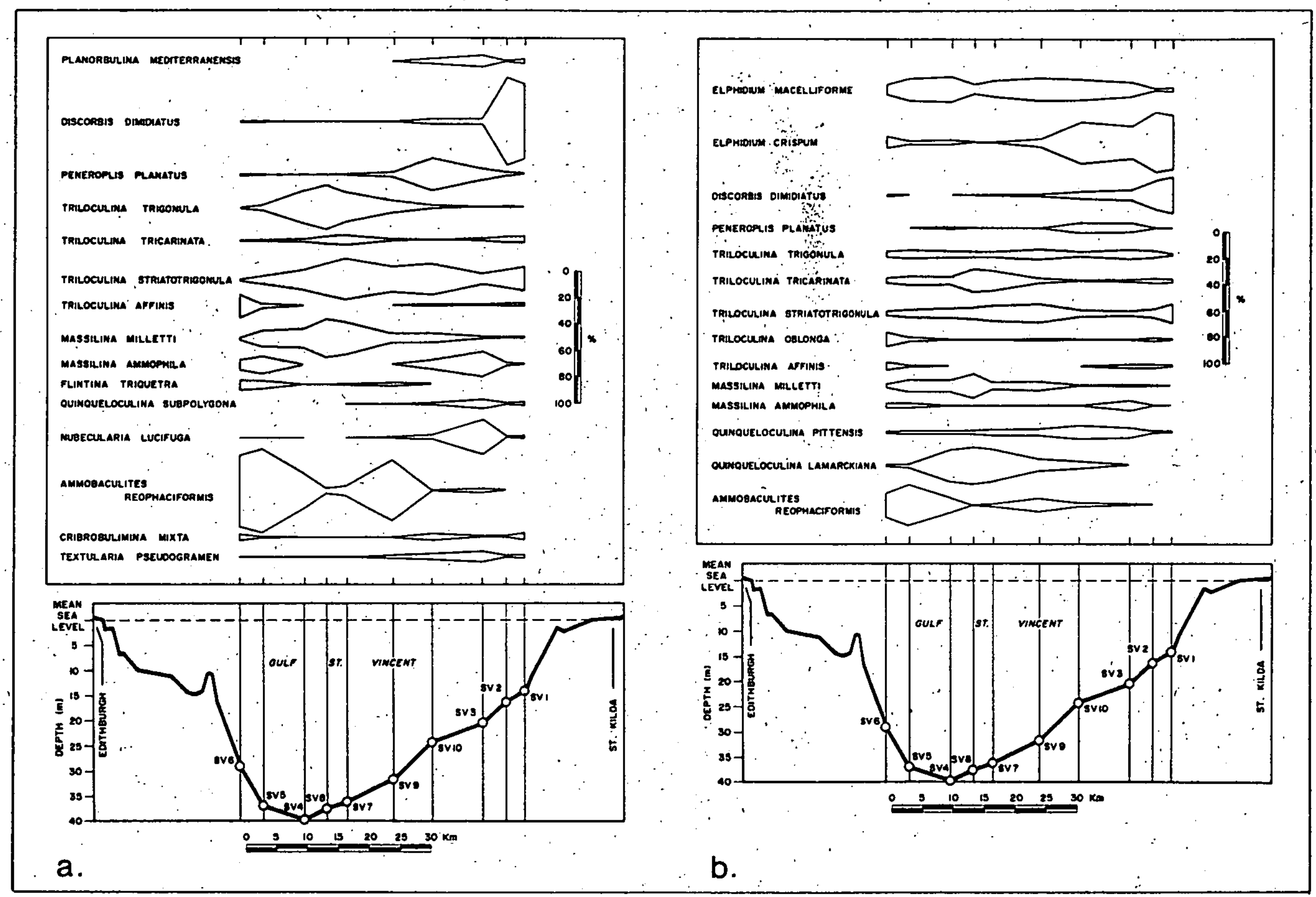

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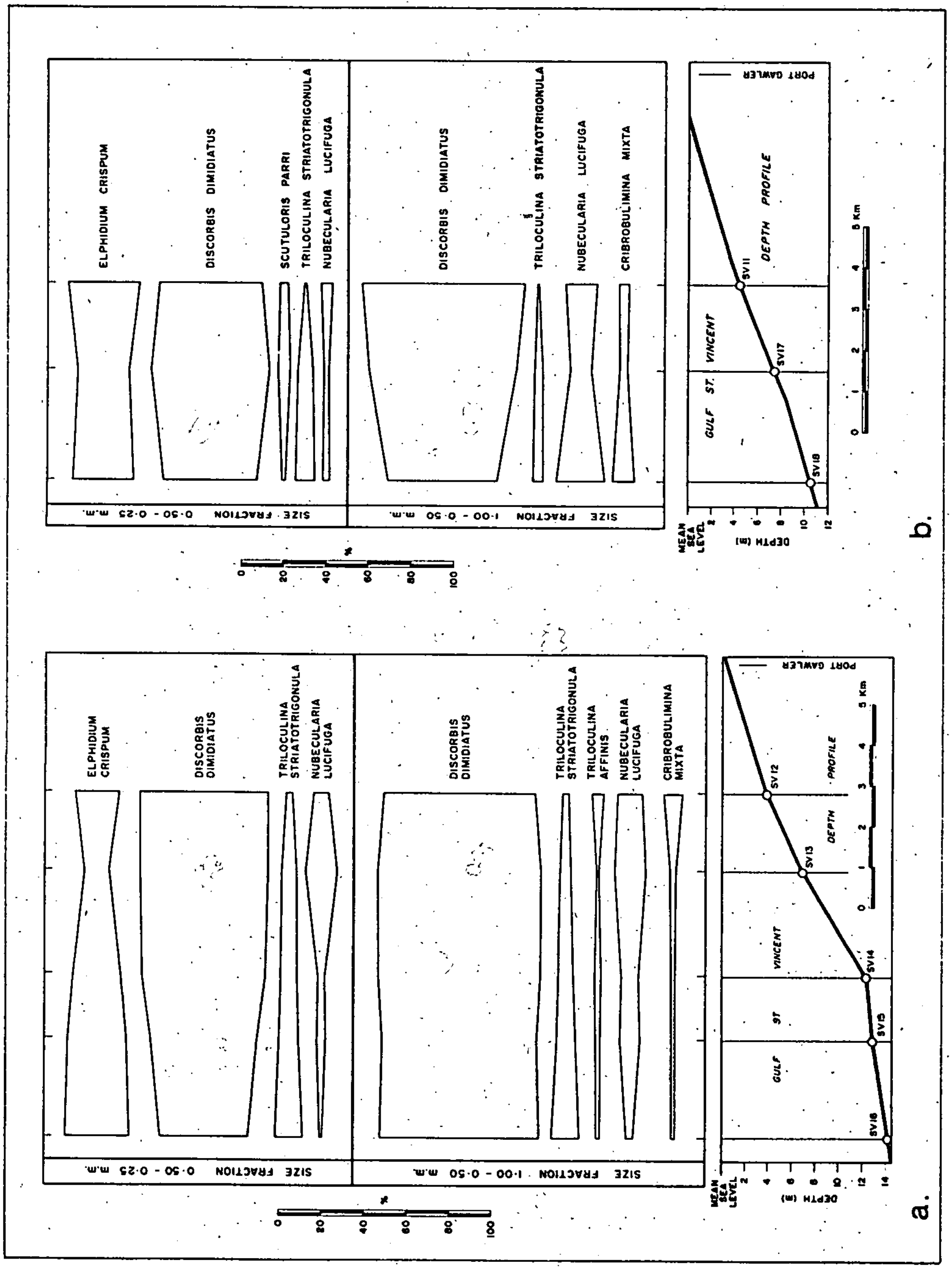

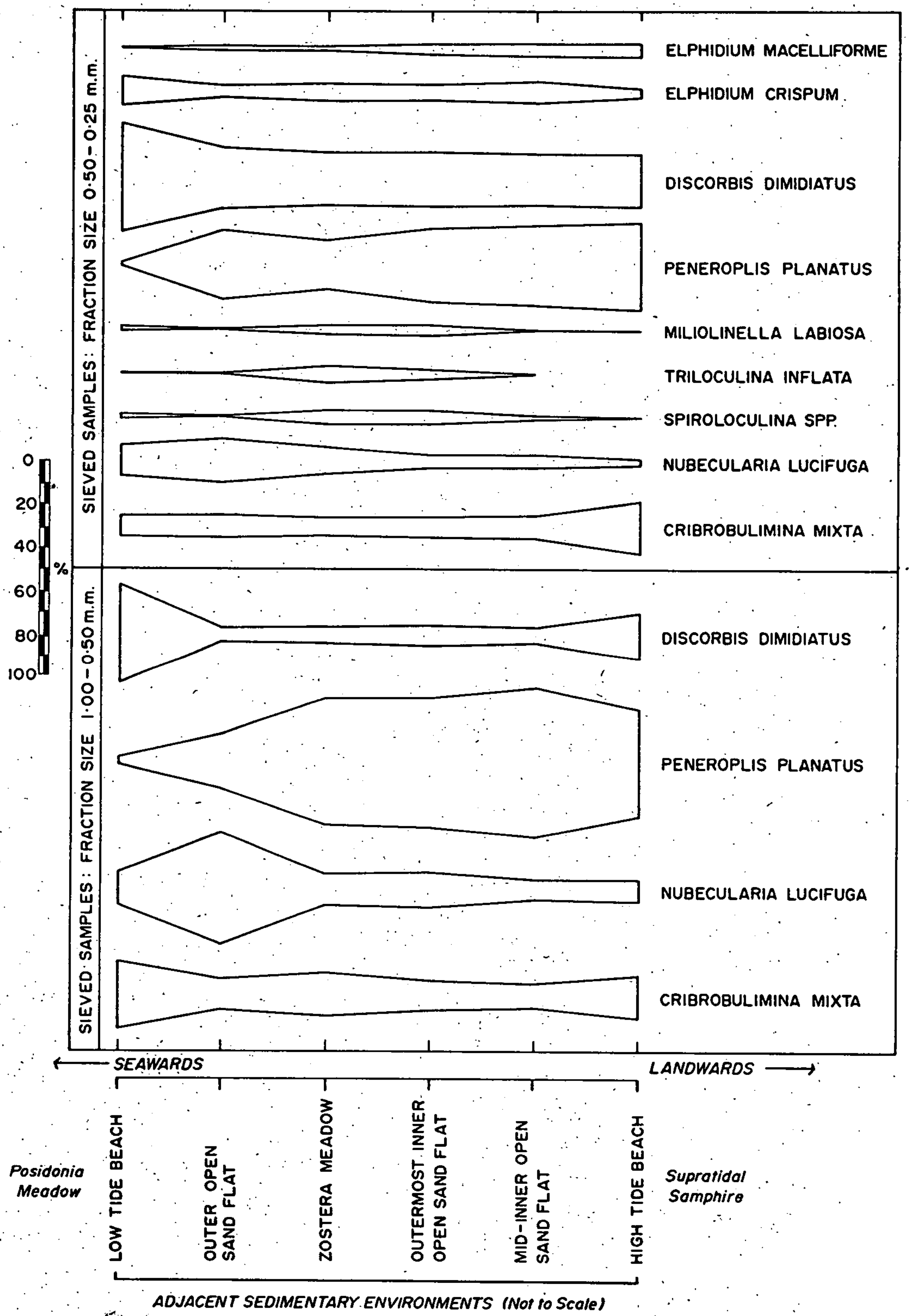

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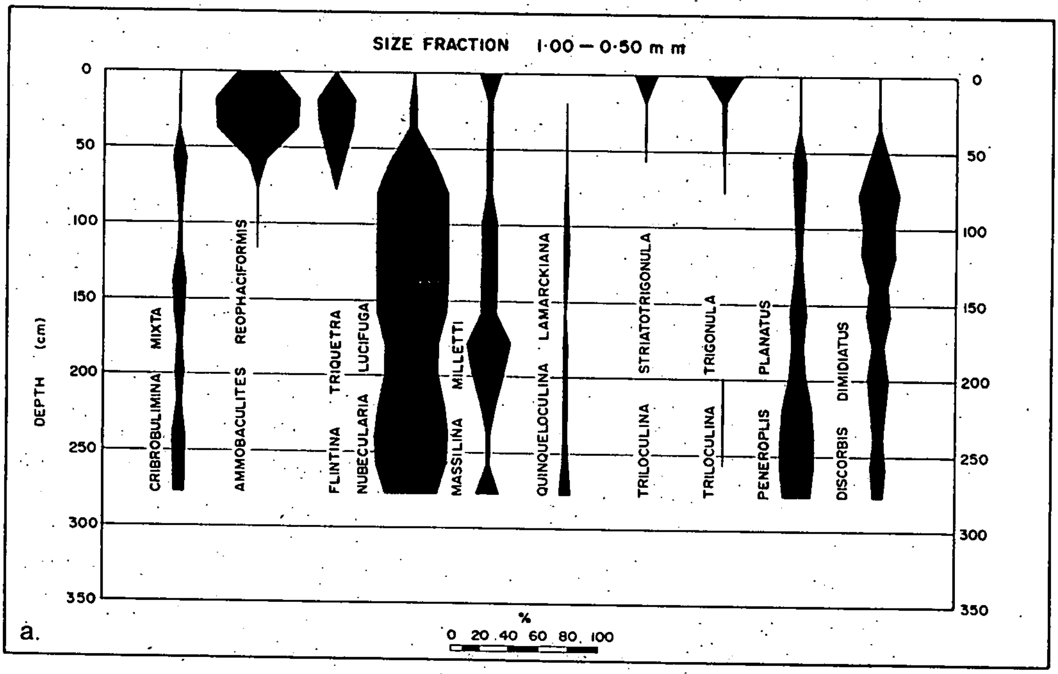

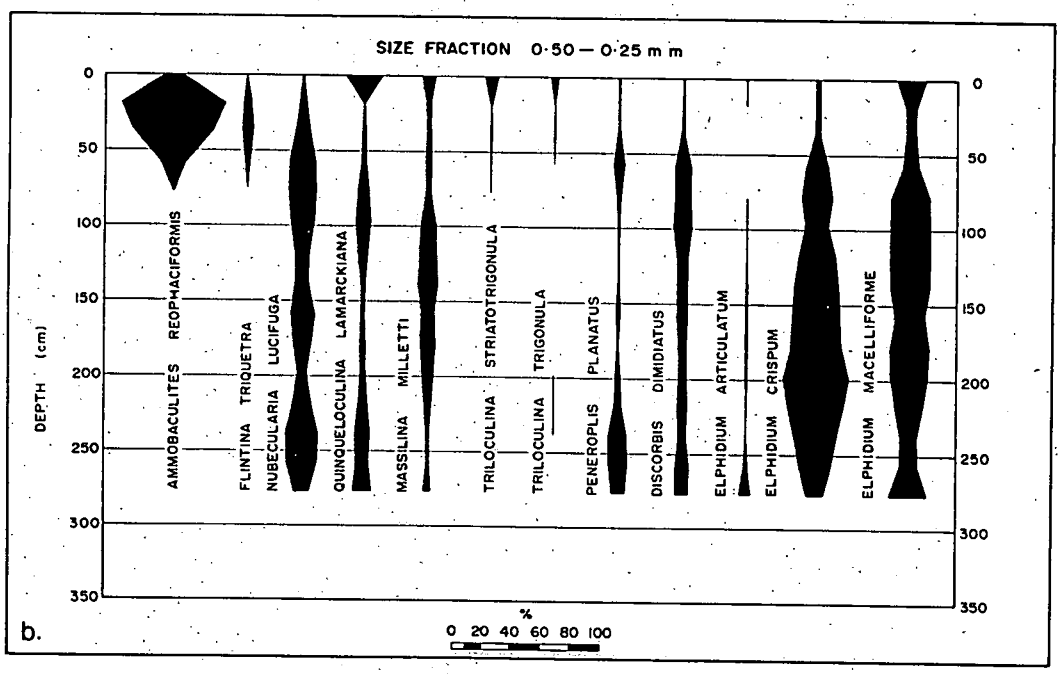

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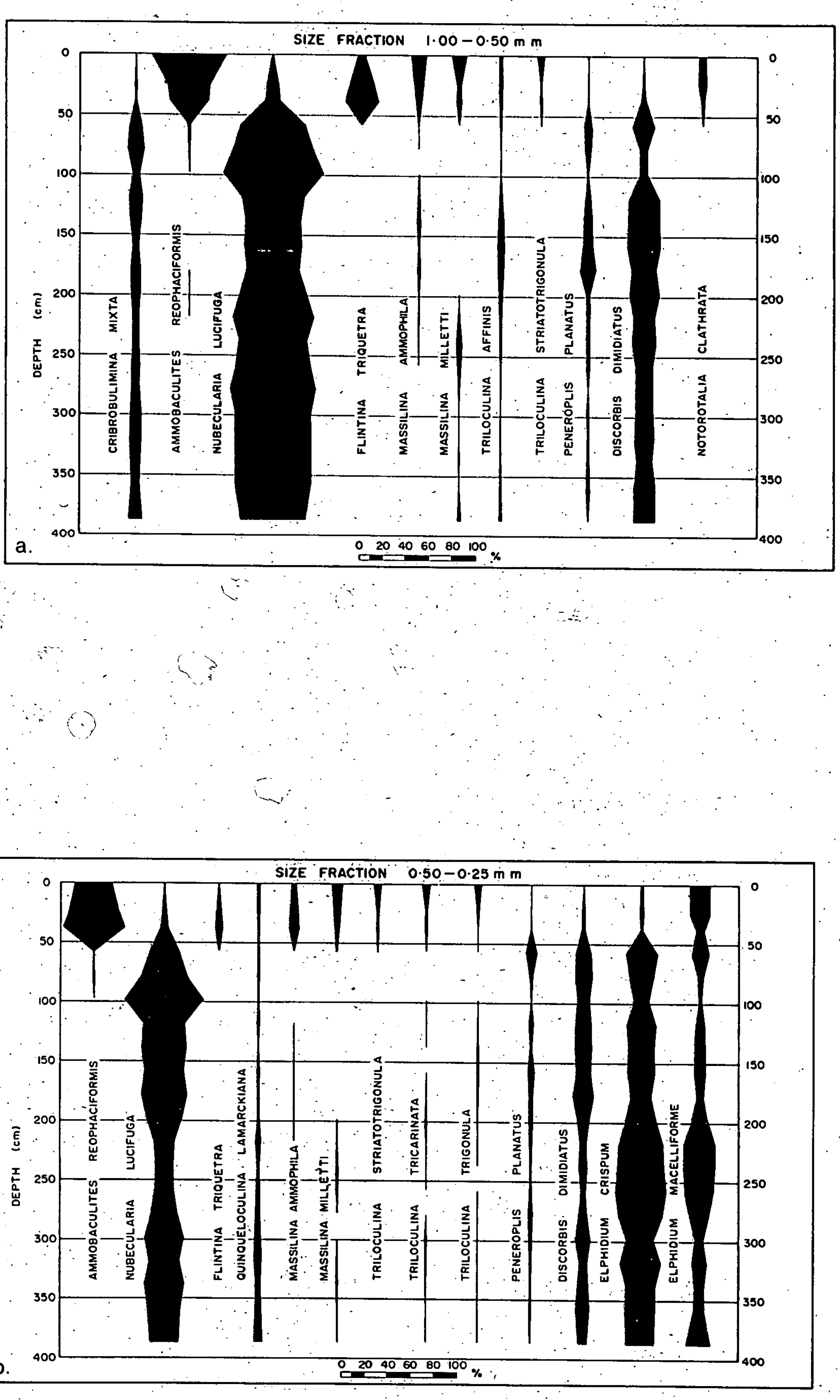

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Fig. 10 Species of foraminifera referred to in figures and text:

a,b *Triloculina oblonga* (Montagu); x 40; SV 6.

c,d *Triloculina striatotrigonula* Parker & Jones; x 45; SV 9.

e,f *Triloculina tricarinata* (d'Orbigny); x 40, SV 7.

g,h *Triloculina trigonula* (Lamarck); x 45; SV 9.

i,j,k *Discorbis dimidiatus* (Parker & Jones); x 35; SV 12.

l,m *Scutuloris parri* Collins; x 75; SV 17.

n,o *Peneroplis planatus* (Fichtel & Moll); x 35; SV 4.

p,q *Elphidium articulatum* (d'Orbigny); x 75; SV 5.

r,s *Elphidium crispum* (Linné); x 55; SV 12.

t,u *Elphidium macelliforme* McCulloch; x 60; SV 6.

v *Planorbulina mediterranensis* d'Orbigny; x 25.

All illustrated specimens are from grab samples except *Peneroplis planatus* and *Elphidium articulatum*, which are taken from vibrocore subsamples.

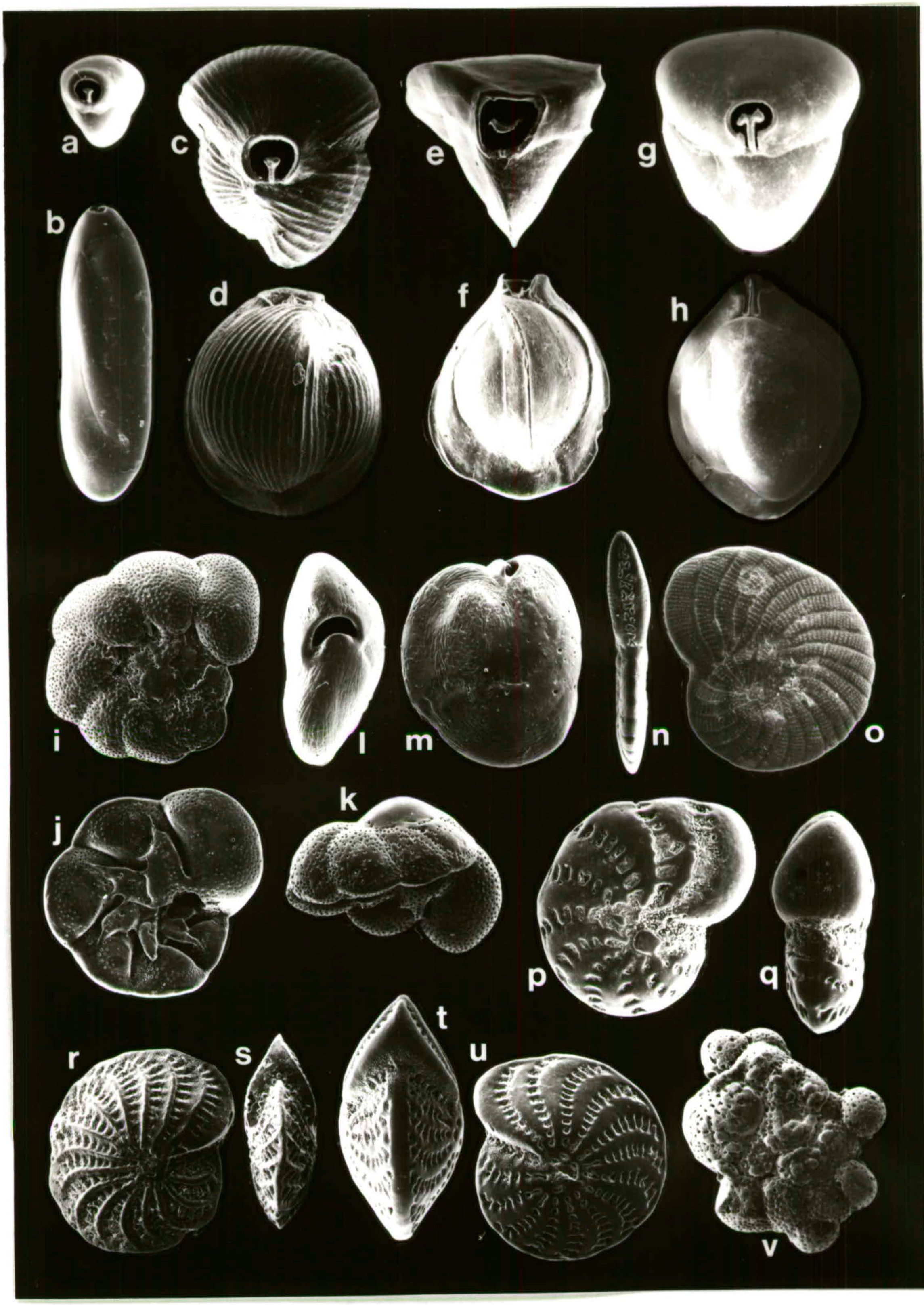


Fig .10

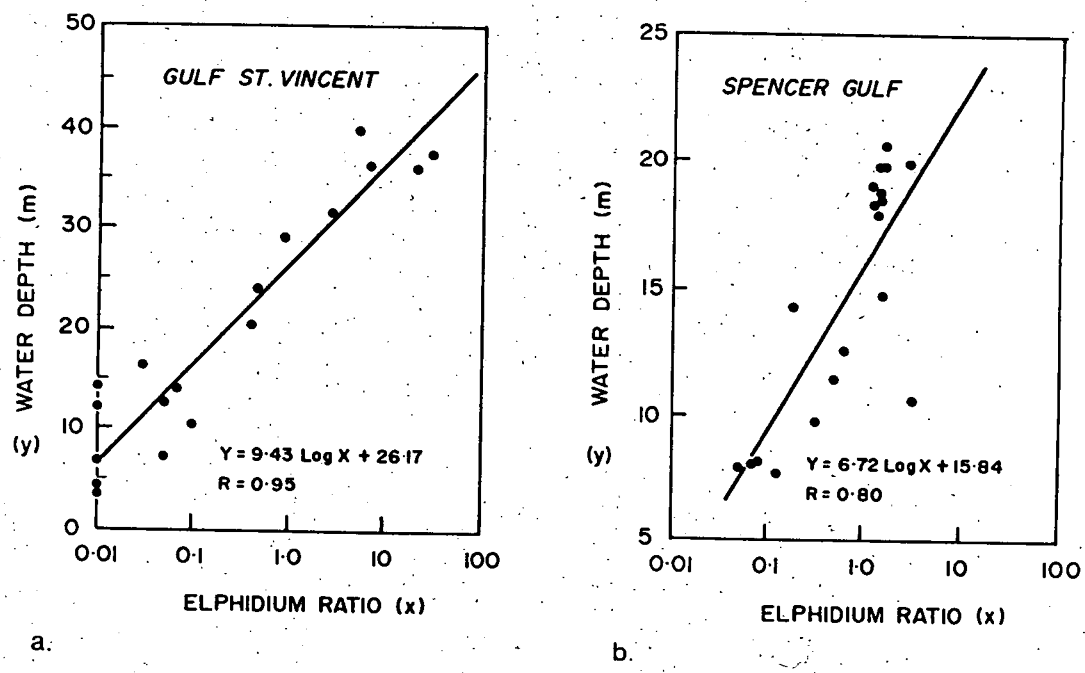
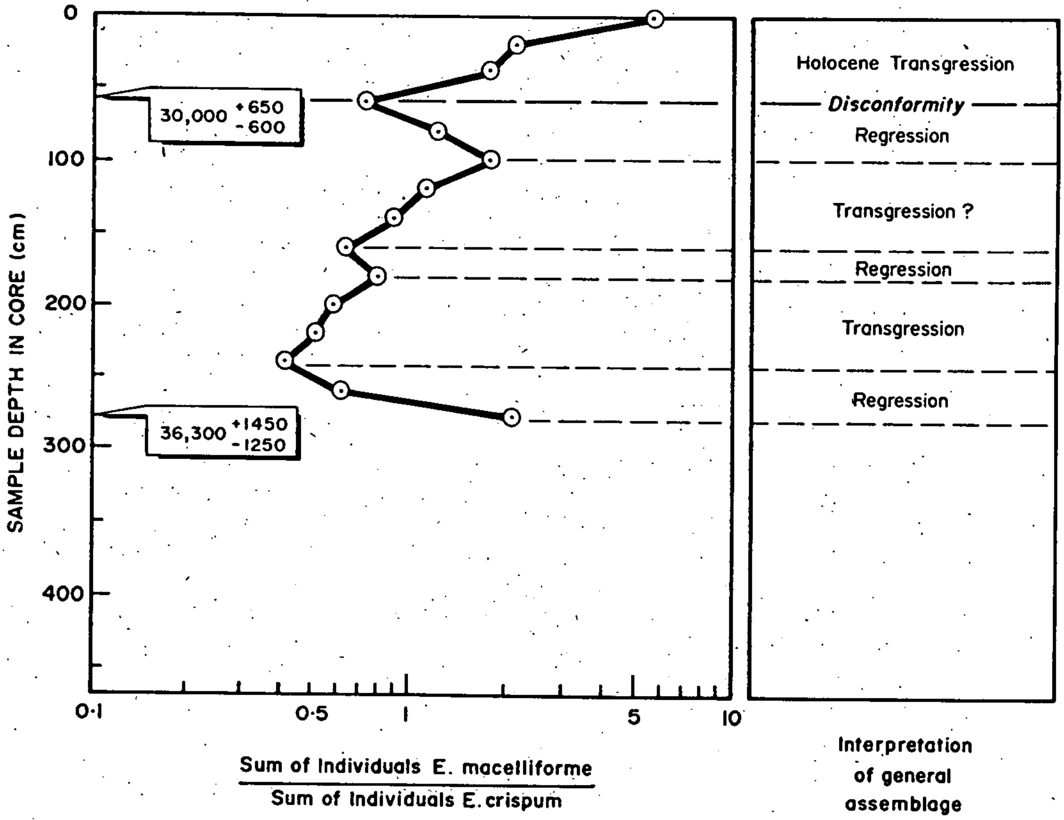
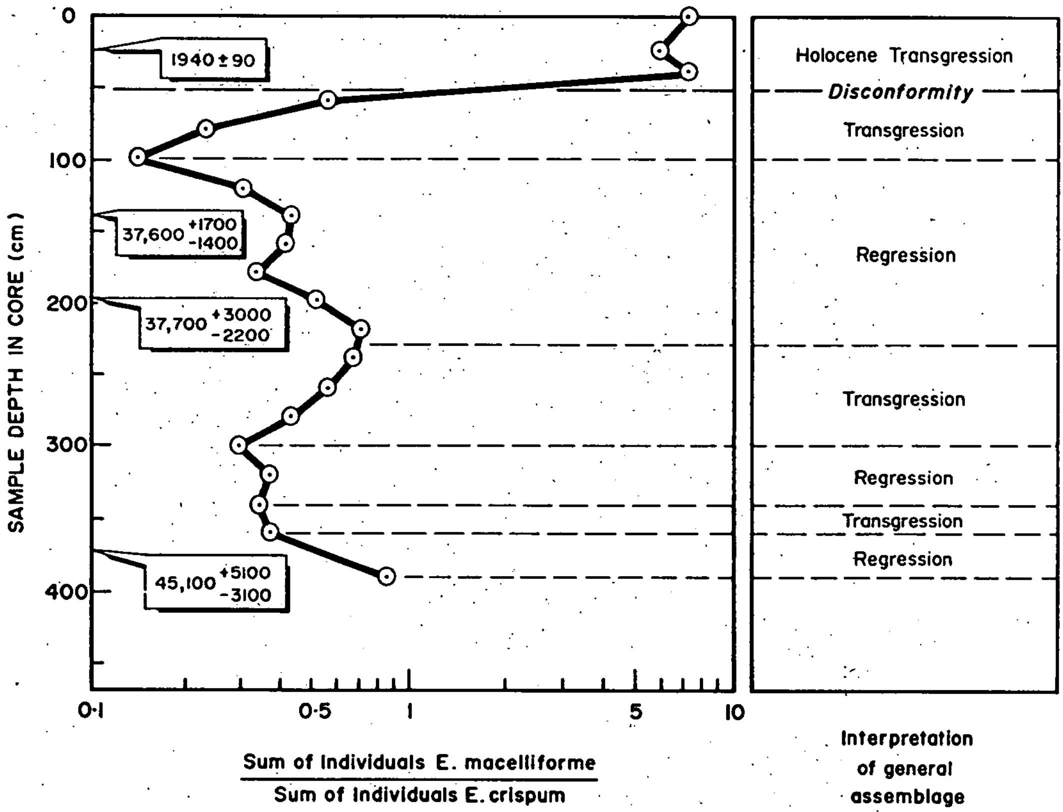


Fig. 11 Log-linear plot of water depth versus ratio of numbers of individuals of *Elphidium macelliforme* to numbers of individuals of *Elphidium crispum* for surficial samples from (a) Gulf St Vincent and (b) Spencer Gulf. Also shown are the lines of best least squares fit, the calculated regression equations and Pearson's correlation coefficient for the data sets.

Fig. 12 Log-linear plot of sample depth in core versus ratio of numbers of individuals of *Elphidium macelliforme* to numbers of individuals of *Elphidium crispum* for samples from (a) SV 4 and (b) SV 5. Curves are compared with inferred changes in Late Pleistocene and Holocene sea levels in Gulf St Vincent, derived from interpretation of general assemblages of foraminifera species. Also shown are ^{14}C dates of samples taken from the horizons indicated.


0
100
200
300
400
SAMPLE DEPTH IN CORE (cm)
30,000 +650 -600
36,300 +1450 -1250
0·1
0·5
1
5
10
Sum of Individuals E. macelliforme
Sum of Individuals E. crispum
Holocene Transgression
Disconformity
Regression
Transgression ?
Regression
Transgression
Regression
Interpretation of general assemblage

a.


0
100
200
300
400
SAMPLE DEPTH IN CORE (cm)
1940 ± 90
37,600 +1700 -1400
37,700 +3000 -2200
45,100 +5100 -3100
0·1
0·5
1
5
10
Sum of Individuals E. macelliforme
Sum of Individuals E. crispum
Holocene Transgression
Disconformity
Transgression
Regression
Transgression
Regression
Transgression
Regression
Interpretation of general assemblage

b.

Fig. 12

Fig. 13 (a) Palaeo sea level data from southern Australia using the Huon Peninsula sea level curve of Chappell (1983) as a framework.

(b) Relative sea level fluctuations for the time interval 30,000 to 45,000 ^{14}C yr B.P. interpreted from the *Elphidium* species ratios and ^{14}C data (Fig. 12) from vibrocores SV 4 and SV 5, Gulf St Vincent.

(c) Late Pleistocene palaeo sea levels interpreted from the *Elphidium* species ratios and ^{14}C data (Fig. 12) from vibrocores SV 4 and SV 5, using the regression equation derived from northern Spencer Gulf data (Fig. 11b).

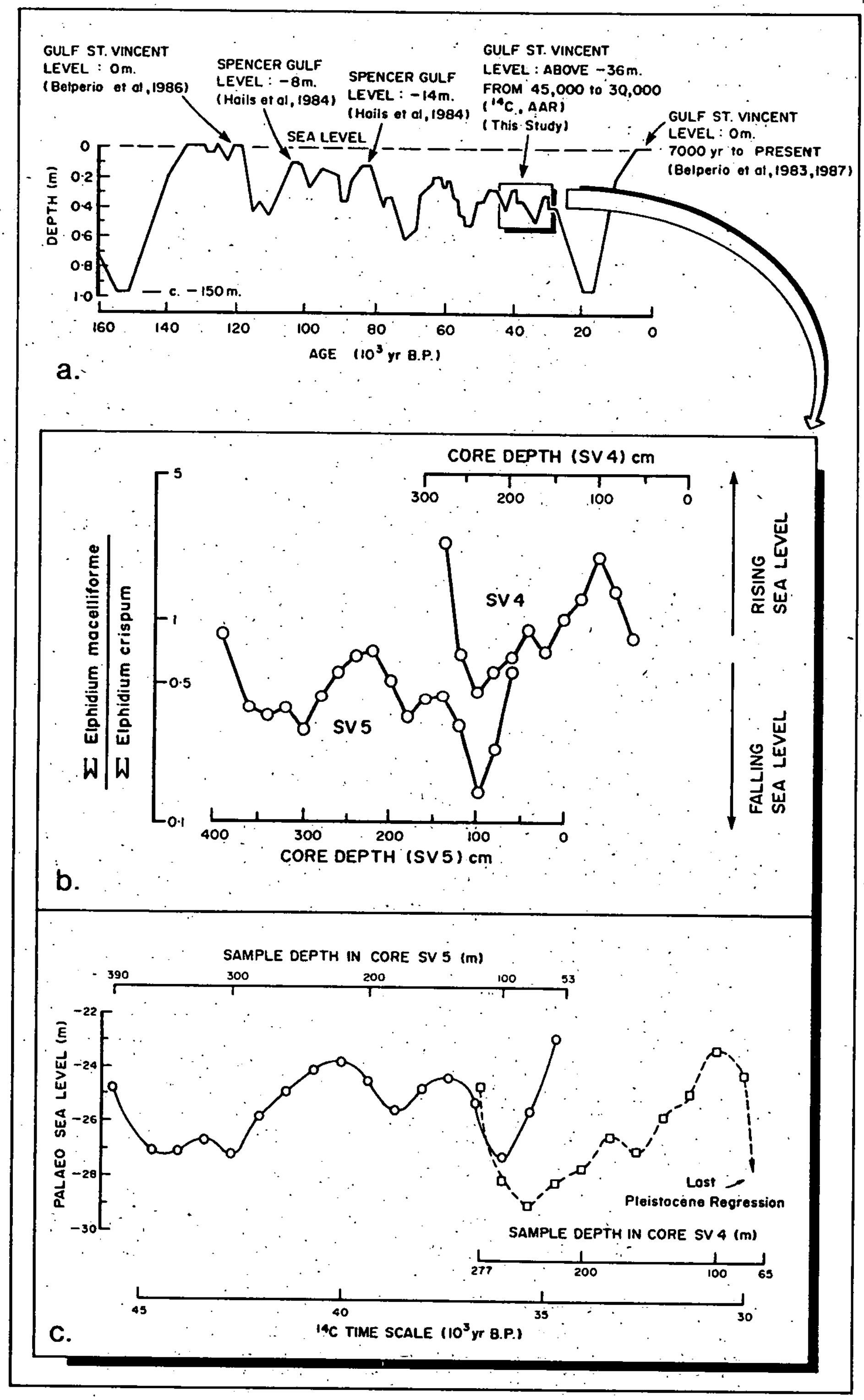

GULF ST. VINCENT LEVEL : 0m. (Belperio et al, 1986)
SPENCER GULF LEVEL : -8m. (Hails et al, 1984)
SPENCER GULF LEVEL : -14m. (Hails et al, 1984)
GULF ST. VINCENT LEVEL : ABOVE -36m. FROM 45,000 to 30,000 (14C, AAR) (This Study)
GULF ST. VINCENT LEVEL : 0m. 7000 yr to PRESENT (Belperio et al, 1983, 1987)
SEA LEVEL
DEPTH (m)
c. -150 m.
AGE (10³ yr B.P.)
a.
CORE DEPTH (SV4) cm
Σ Elphidium macelliforme / Σ Elphidium crispum
SV4
SV5
RISING SEA LEVEL
FALLING SEA LEVEL
CORE DEPTH (SV5) cm
b.
SAMPLE DEPTH IN CORE SV 5 (m)
PALAEO SEA LEVEL (m)
Last Pleistocene Regression
SAMPLE DEPTH IN CORE SV 4 (m)
14C TIME SCALE (10³yr B.P.)
c.

Fig. 13