HOLOCENE and LATE PLEISTOCENE BENTHIC FORAMINIFERA and INFERRED PALAEO SEA LEVELS, SPENCER AND ST VINCENT GULFS and SOUTHEASTERN SOUTH AUSTRALIA

by

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SUMMARY

This study records assemblages of species of Late Quaternary benthic foraminifera recovered from vibrocored and surficial sediments of Spencer and St Vincent Gulfs, southern South Australia. The distributions of species within Late Pleistocene and Holocene sequences have been interpreted to infer southern Australian palaeo sea levels for these time intervals.

In modern gulf waters, bioclastic components predominate in a regime of cool-temperate carbonate sedimentation. Benthic foraminifera are abundant in all surficial sediments and the numerical distribution of many species is closely related to water depth. For example, *Massilina milletti* is most common in mid-gulf waters at depths of about 40 metres. In contrast, species such as *Nubecularia lucifuga* and *Discorbis dimidiatus* are characteristic of shallow subtidal seagrass environments. Two species of *Elphidium, E. crispum*, favouring shallow water, and *E. macelliforme*, more common in deeper water, provide a particularly useful numerical ratio. For the sediment size fraction 0.50 - 0.25mm, the logarithmic relative abundance of these two species strongly correlates with water depth. This was found to be particularly so for the cooler, deeper waters of Gulf St Vincent where a correlation factor of 0.89 was determined. These observations have been applied, in a uniformitarian sense, to interpret the significance of distributions of species of benthic foraminifera within vibrocored sediments taken from both gulfs.

An extensive suite of vibrocores were taken from northern Spencer Gulf by other workers, who determined a stratigraphic framework and palaeo sea level history for the sediments so obtained. Foraminiferal analysis of eight cores, identified by the original researchers to be particularly significant, generally supported the framework of sedimentation during oxygen isotope sub-stages 5e, 5c and 5a, with intervening regressions during the 5b and 5d sub-stages. However, on micropalaeontological evidence, there is a need for some revision of the original findings.

For example, vibrocore #SG179 contains neither fossils of foraminifera nor other evidence of marine sedimentation within the interval 200 to 80cm. The assignment of these sediments to the Lowly Point Formation, corresponding to the marine transgression of oxygen isotope sub-stage 5a, is therefore unlikely to have been correct.

Marginopora vertebralis was previously known as an indicator species of foraminifera for the 5e transgression sediments, locally known as the Glanville Formation. The present study shows that *Pseudomassilina australis* and *Quinqueloculina polygona* also appear to be confined to this unit. On the evidence of the combined presence of these three species, an interval within vibrocore #SG245, originally identified as Lowly Point Formation, should be reassigned to the older Glanville Formation.

Northern Spencer Gulf has a maximum depth of about 20 metres so was not inundated by the somewhat lower oxygen isotope stage 3 transgression. Vibrocored sediments of this age were, however, recovered from deeper waters of adjacent Gulf St Vincent. Radiocarbon and amino acid racemisation dates confirm that they were deposited during the interval 45 000 to 30 000yr B.P..

Using both the general assemblage of foraminiferal species, and the relative abundances of the two species of *Elphidium*, relative palaeo water depth curves were established for the Late Pleistocene and Holocene sediments and it was possible to recognise a pattern of sea level changes that could be reconciled with that determined for the uplifted coral reef terraces of the Huon Peninsula and elsewhere. Local palaeo sea level corresponding to Huon Peninsula transgression stage IIIb has been calculated to be -27 to -24 metres.

For Pleistocene intervals, where the euryhaline species *Elphidium articulatum* and *Ammonia beccarii* were present, the *E. crispum/E. macelliforme* failed to yield meaningful palaeo water depth signals. However, when numbers of *E. crispum* and *E. articulatum* were combined in the numerator, plausible inferences were derived from the data.

For Holocene intervals, palaeo water depths implied from both the general assemblage and the *Elphidium* ratio were consistently detailed and could be correlated between cores. In northern Spencer Gulf they are sufficiently detailed to have recorded isostatic events attributable to the Holocene transgression.

In southeastern South Australia, Late Pleistocene and Holocene sea levels are recorded in a sequence of coastal beach-dune-barrier complexes and interbarrier deposits of marine lagoonal shelly sediments. Molluscan faunas which inhabited Holocene lagoon and coastal marine environments were gathered as a food source by Aboriginal populations and are preserved as sequentially stratified midden deposits which have contributed useful data for palaeoenvironmental analysis.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university; nor, to the best of my knowledge and belief, does the thesis contain any material previously published or written by another person, except where due reference is made in the text of the thesis.

6 March 1992

NAME: John Herbert Cann **COURSE:** Doctor of Philosophy

I give consent to this copy of my thesis, when deposited in the University Library, being available for loan and photocopying.

SIGNED: **DATE:** 30 April 1992

ACKNOWLEDGEMENTS

The work reported in this thesis was completed on a part-time basis, spasmodically, over the past 15 years. During that time, predecessor institutions of the University of South Australia granted me two years of professional leave, and partly funded relevant conference travel.

The Department of Geology and Geophysics at the University of Adelaide provided facilities and technical support personnel. Dr Brian McGowran supervised the programme, and I thank him for his interest in my work, his critical reading of manuscripts as they were prepared for publication, but mostly for his patience and expressions of confidence that this thesis would eventually materialise. Mr Brenton Bowman prepared many sediment samples for microscopic examination, Mr Richard Barrett provided photographic assistance, Ms Sharon Proferes drafted figures 3.1 and 3.7 and Dr Karl Bartusek instructed me in the use of the scanning electron microscope.

During the course of the research reported here, my work has interfaced with that of other researchers, leading to cooperative ventures and often resulting in jointly authored papers. I acknowledge the significant and constructive influence that these people (listed alphabetically) have had on my own professional development:

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Prof. Paul Bronnimann, University of Geneva
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Finally, I am especially indebted to my wife Elizabeth Elliot for her personal encouragement and for technical assistance in word processing. She must receive a great deal of the credit for the professional standard of presentation of the text.

DEDICATION

One night in January, 1983, Louise Bell, then aged 10 years, disappeared from her parental home in a southern Adelaide suburb. Police believed that she had been abducted and murdered.

As part of the lengthy police investigation that followed, the little girl's pyjama top was located and found to be contaminated with various items, including foraminifera. I was asked to assist with forensic interpretation of the contaminants, which led to comprehensive sampling and examination of sediments from the estuary of the Onkaparinga River. During this survey, I learned a great deal about the seasonal distribution of species of foraminifera within the estuary and in adjacent smaller waterways. The contaminant foraminifera and other materials were eventually found to be consistent with summer time sediments and microbiota of the upper estuary.

Partly as a result of this evidence, a person was charged with an offence and I appeared as a witness for the prosecution in committal proceedings and the trial that followed.

My involvement in this case generated significant personal emotions. It remains for me a matter of lingering sadness that the details of Louise Bell's disappearance have not been resolved and that no traces of her remains have been found.

With due sensitivity and respect, this work is dedicated to her memory.

CHAPTER 1

Palaeo climates and palaeo sea levels; Late Quaternary sediments and stratigraphy of southern South Australia.

INTRODUCTION

The work reported in this thesis was primarily directed towards elucidating late Quaternary sea levels of southern South Australia. Chapter 1 briefly reviews some of the geological evidence for sea level change and the apparent synchroneity of these changes with episodic glacial and interglacial global climatic events. In this regard, the significance of the oxygen isotope signal and the Milankovitch orbital parameters are discussed. Global changes of sea level are not uniform and the variable geophysical and geographical characteristics of individual areas greatly influence local responses to eustatic change. The relative sea level curve developed for the Huon Peninsula (Chappell, 1983; Chappell and Shackleton, 1986) provides the best available framework for the present investigation. Local stratigraphic units, relevant to the study, are identified with appropriate comments.

GLACIATIONS AND CHANGING SEA LEVELS

The Quaternary Period has thus far been characterised by widely varying climatic conditions governed by episodic global warming and cooling. During cold episodes polar ice caps and alpine glaciers increased in mass and areal extent as much of the global water budget was stored as ice. Conversely, during times of climatic amelioration, glacial meltwater returned to the oceans. This episodic global cooling and warming led to concomitant glacio-eustatic changes in sea level.

Along coastlines that have remained essentially tectonically stable during the Quaternary, successive glacio-eustatic transgressions have left a record of on-lapping and off-lapping marine strata on the shallow continental shelves.

In recent years, many such sediments and their contained fossils have been investigated by coring programmes to elucidate their sea level histories; for example, in Eastern China (Wang et al., 1984g, 1984h; Lin et al., 1989), in the Gulf of Carpentaria (Torgersen et al., 1983, 1985, 1988; De Deckker et al., 1988; McCulloch, 1989), in Bass Strait (Blom, 1988), in Spencer Gulf (Hails and Gostin, 1984) and in Gulf St Vincent (Cann et al., 1988).

Quaternary sea levels are also recorded as discontinuous shoreline deposits and geomorphic features (Marshall and Thom, 1976; Veeh et al., 1979; Pickett et al., 1985; Semeniuk, 1985; Ward, 1985). Often preserved within such sediments are fossils of animals and plants having a known relationship to tidal zonation, and these have provided useful indicators of former sea levels; for example, subtidal sea grass in elevated Holocene sediments of northern Spencer Gulf (Burne, 1982; Belperio et al., 1984b). However, Belperio et al. (1983) have cautioned against possible misinterpretation of supratidal sediments that result from uncommonly high tides and energy regimes.

Erosional coastal landforms, such as elevated rock platforms, have long been recognised as debatable evidence for previous high stands of sea level. For example, Ward (1965) and Ward and Jessup (1965) believed that, in the Adelaide district, there had been as many as eight stands of the Quaternary sea higher than present sea level, several greater than +100m. These interpretations were seriously questioned by Twidale et al. (1967) on a number of grounds, especially the absence of any evidence for widespread inundations of southern Australia that would have resulted from such higher sea levels. Twidale (1976) accepted that there is some local evidence supporting a sea level stand at +8m, but related geomorphic features at +5m and +3m to modern coastal processes at present sea level. Interpretation of elevated platforms and other coastal geomorphic features, and their relationship to change in sea level has been reviewed by Gill (1972, 1973 and references therein).

Gill's studies were primarily based on the southern coast of Victoria where he was able to differentiate features forming today at present sea level from those formed at an earlier time and whose origins were attributable to a higher stand of sea level.

Substantial rise of sea level, such as the Holocene transgression, inundates the low lying continental shelf, flooding coastal river valleys and lake basins. Sydney Harbour, in coastal New South Wales, is an undisputed classic example of such a transformation of landscape from late Pleistocene to Holocene time. In South Australia, during the last glacial, when sea level was about 130-150m lower than at present, the River Murray apparently flowed out across the continental shelf somewhat south of present debouchment. The courses taken by these waters down the continental slope are today marked by several substantial submarine canyons over 1.5km deep (Sprigg, 1947; von der Borch, 1968, 1979).

Submerged coastal landforms and sediments that resulted from lower stands of sea level are also known. For example, submerged shorelines, up to 5km off shore, have been recognised in Gulf St Vincent (Shepherd and Sprigg, 1976) and multiple submerged shoreline features on the Bering Shelf have been related to regressive stillstands (Hopkins, 1973). Submerged erosional terraces occur at about -20m off the coast of southeastern South Australia (Sprigg, 1952) and at depths of up to -30m in the western Baltic Sea (Healy, 1981).

The most useful sets of data relating past sea levels to geomorphic features come from studies of flights of raised coral reef terraces along tectonically rising shorelines. Each reef terrace represents a stillstand peak of marine transgression, the rate of eustatic rise of sea level greatly exceeding that of tectonic uplift. Radiometric dating of the elevated reef materials provides a time framework for evaluating past successive sea levels.

Such studies include those at Vanuatu (formerly New Hebrides) (Neef and Veeh, 1977; Ash et al., 1978 and references therein; Bloom et al., 1978) (see also Fig. 1.1), Loyalty Islands (Marshall and Launay, 1978), San Clemente Island, California (Muhs, 1983), Bermuda (Bender et al., 1973; Harmon et al., 1978), the Bahamas (Neumann and Moore, 1975), Barbados (Mesolella et al., 1969; James et al., 1971; Matthews, 1972, 1973; Bender et al., 1973; Stearns, 1976; Shackleton and Matthews, 1977; Fairbanks and Matthews, 1978) and on the Huon Peninsula of Papua New Guinea (Veeh and Chappell, 1970; Chappell and Polach, 1972, 1976; Chappell, 1974a, 1974b, 1978, 1983; Bloom et al., 1974; Aharon, 1983; Aharon and Chappell, 1986; Chappell and Shackleton, 1986).

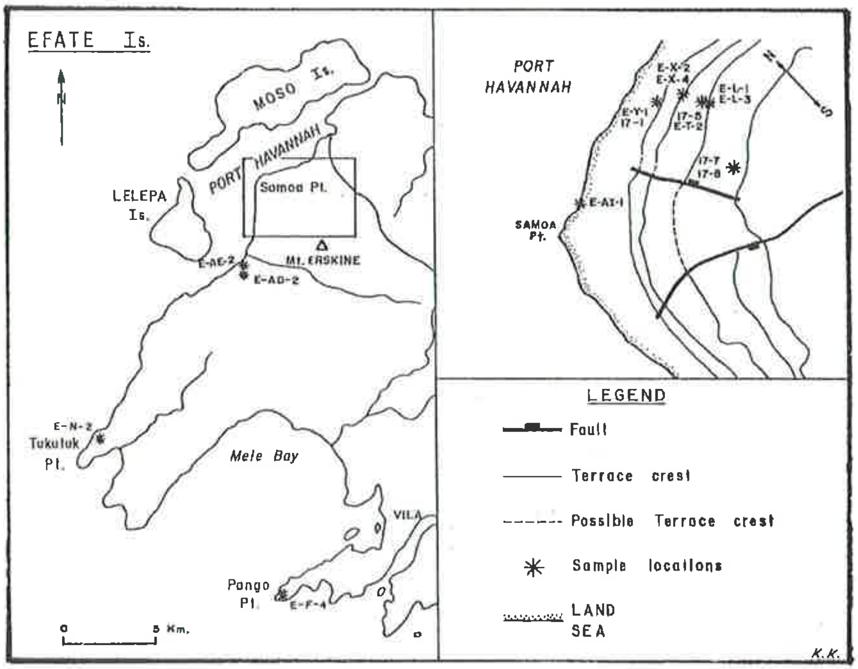
Southeastern South Australia is also an area of steady regional uplift*, but which is rising at a rate very much less than that of, say, the Huon Peninsula. The landscape is characterised by a series of low altitude ranges, subparallel to each other and to the present coastline, on an otherwise gently seawards sloping coastal plain. The ranges are constructive geomorphic features related to palaeo shorelines and their origins have long been attributed to processes associated with Quaternary sea level changes. In general terms, the age of any given range is proportional to its distance from the present shoreline, but most ranges show evidence of more than one constructional episode (Tindale, 1933; Sprigg, 1952; Cook et al., 1977; Schwebel, 1978, 1983, 1984; Belperio and Cann, 1990; Belperio, in press). This southeastern area is further discussed in Chapter 9.

OXYGEN ISOTOPE RECORD

A small but significant proportion of oxygen consists of the isotope ^{18}O. Water molecules with this isotope are about 10% heavier than the more common form of water. Evaporation favours the lighter molecules so that water vapour and all forms of precipitation are relatively enriched in ^{16}O by comparison with ocean waters.

* Refer Ch. 9

a


EFATE Is.
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Samoa Pt.
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Tukutuk Pt.
Mele Bay
VILA
Pango Pt.
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PORT HAVANNAH
E-X-2
E-X-4
E-Y-1
17-1
E-L-1
E-L-3
17-5
E-T-2
17-7
17-8
N
S
E-AI-1
SAMOA Pt.
LEGEND
Fault
Terrace crest
Possible Terrace crest
Sample locations
LAND
SEA
K.K.

b

c

Fig. 1.1

a. View of Lelepa Island from the western coast of Efate Island, Vanuatu. A stepped series of coral reef terraces predominate as surface features of Lelepa.

b. Location map of Bloom et al. (1978) showing positions of raised reef limestone terraces on the western coast of Efate Island, Vanuatu. Also shown are sites from which samples were collected for ^{230}Th/^{234}U isotopic dating. Sample 17-5, for example, yielded an age of 124,000 +/-7000yr B.P.. Thus, the terrace from which this specimen was collected is probably time equivalent to the local *Glanville Formation.

c. General view of the raised coral reef terraces above Samoa Point, Port Havannah, figured in the inset of the location map.

*Sth. Aust.

During cold climatic episodes, as precipitation feeds the growing ice fields, the proportion of ^{18}O to ^{16}O in the depleted oceans progressively increases. The oxygen isotope composition of carbonate secreting organisms, such as foraminifera, is influenced by that of the waters in which they live, though tests and sea water are not necessarily in isotopic equilibrium (Shackleton et al., 1973).

Oxygen isotope records derived from fossil foraminifera in cores of deep ocean sediments can be interpreted to signify relative amounts of global ice through the time of deposition. Higher ratios indicate larger ice masses and therefore lower sea levels, and vice versa. A time framework for the core samples is established by radiometric dating, by biostratigraphic correlation and by reversals of the palaeomagnetic timescale.

This line of investigation was pioneered by Emiliani (1955, 1958, 1961, 1966a, 1966b, 1970, 1971, 1972a, 1972b), who established the oxygen isotope stages, increasing numerically with age, and was soon followed by many other researchers, such as Shackleton and Opdyke (1973) and Shackleton (1982). The ice budget record, thus established, is generally supported by the climatic inferences of microfossils preserved in the deep sea cores (Ruddiman, 1971; Bandy, 1972; Berggren and van Couvering, 1974; Emiliani and Shackleton, 1974; Emiliani et al., 1975).

MILANKOVITCH HYPOTHESIS

It is possible to relate episodic changes of global climate to rhythmic variation of Earth's orbital parameters. This is commonly referred to as the Milankovitch hypothesis (Milankovitch, 1938). The known parameters and their periodicities are simply and concisely described by Calder (1976) and by Pittock et al. (1978).

a) Earth's orbit is elliptical with the Sun at one focus. The eccentricity of this orbit varies from almost circular to significantly elliptical with an average period of about 96,000 yr. When the orbit is in the extreme elliptical mode, the intensity of solar radiation reaching Earth's surface may vary by up to 30% from strongest to weakest. At present the orbit is nearly circular and radiation varies by only 3.5%.

b) Earth wobbles in its orbit like a spinning top. The axis of spin describes a cone in space, resulting in a phenomenon known as precession of the equinoxes. At present, southern hemisphere summers occur when Earth is closest to the Sun (perihelion). Precession has a periodicity of about 20,600 yr, so that in a little more than 10,000 years hence, northern hemisphere summers will occur at perihelion.

c) The tilt of Earth's axis from the normal to the plane of the orbit oscillates between 24^0 36' and 21^0 59' with a periodicity of about 40,000yr. The greater the tilt, the more pronounced is the difference between summers and winters. For the past 10,000 years the angle of tilt has been decreasing and is presently 23^0 27'.

The Milankovitch hypothesis seeks to account for global climatic change in terms of the periodicities outlined above.

While the hypothesis was invoked by Emiliani (1966a) to explain the observed periodicity of the ^{18}O record derived from Caribbean cores, the theory seems to have received bench mark credibility in a paper entitled "Variations in the Earth's orbit: pacemaker of the ice ages" by Hays et al. (1976). These researchers derived a climatic record for the past 450,000 years from studies of deep sea core sediments. They compared their observed intervals of climatic fluctuation with calculated variations in radiation due to the Milankovitch astronomical factors.

The sedimentary record clearly indicated periodicities of 23,000 yr, 42,000 yr and approximately 100,000yr. The first of these periods coincides with the periodicity of the precession of the equinoxes, the second to the oscillatory period of the inclination of Earth's axis, while the third approximates to the period of eccentricity of the planet's orbit about the Sun.

Thus emerged three powerful and independent means of investigating past Quaternary sea levels:

> flights of radiometrically dated sequences of tectonically elevated fringing reefs, for example Huon Peninsula;
>
> oxygen isotope records of sediments recovered by deep sea cores, within a radiometric, magnetic reversal and biostratigraphic time frame;
>
> calculated solar radiation budget incident on Earth within the periodicities of the Milankovitch parameters.

Chappell (1973, 1974b, 1978) was prominent among the early researchers to appreciate the potential congruence of data derived by such different means, and strongly supported the framework of the Milankovitch calculations. He derived a detailed palaeo sea level curve from the Huon Peninsula data (Chappell, 1983) and was later able to refine this, closely correlating with the oxygen isotope record, within an "orbitally-tuned" timescale (Chappell and Shackleton, 1986). At the time of writing, this refined palaeo sea level curve remains the most rigorously derived framework for further investigation of global climates and eustatic variation of sea levels for the past 250,000 years. For the first five oxygen isotope stages, up to 125,000 yr B.P., there is little change from the earlier data (Chappell, 1983).

EARTH RESPONSE TO DEGLACIATION

There is currently a much publicised "greenhouse" expectation that present and increasing levels of carbon dioxide atmospheric pollution, together with rapidly decreasing areas of equatorial rain forest, will lead to higher global temperatures, accelerated melting of glacial ice and higher stands of sea level. It is clear from media documentation of the "greenhouse" theory that the anticipated addition of glacial meltwater to the oceans is generally expected to uniformly raise sea level around the globe.

Such an expectation is based on everyday observations of small scale situations. For example, a cup of water added to a partly filled bucket raises the level uniformly. On a larger scale, addition of runoff to a reservoir appears to result in uniformly rising water levels, while consumption and evaporation leave a record of parallel, horizontal, recessive strandlines. Buckets and reservoirs are poor models for considering how a significant water mass will be globally redistributed and how the planet will respond to that change.

In a deglaciation event, redistribution of the water mass of very large ice sheets from polar latitudes to ocean basins significantly alters the gravitational configuration of the planet. The extent of that redistribution of meltwater within the oceans is constrained by the requirements of gravitational equilibration. For this reason alone, global rise in sea level can not be uniform. The change in sea level is then further complicated by the isostatic responses of the non-rigid Earth to the redistributed surface load. Beneath a decreasing ice mass, continental crust will rise, while increasing ocean water mass will cause isostatic subsidence (Walcott, 1972; Chappell, 1974c; Clark et al., 1978; Lambeck, 1988; Belperio, 1989). Long term tectonism, such as is experienced by the southeastern region of South Australia, further modifies relative sea level. Thus, if the "greenhouse" scenario eventuates, the response at different coastal sites will be a mixture of eustatic, isostatic and tectonic signatures and will not be uniform.

Isostatic response of the Earth to changing ice and water loads is partly elastic, in the lithosphere, and partly involves viscous mantle flow. Geophysical responses can be calculated from known empirical data (for example, Chappell, 1974c), but such data are geographically specific and it is difficult to confidently extrapolate over large areas. Present knowledge of Earth physics will not allow accurate area-specific predictions of response to increased sea water loading for all coastal regions.

Thus, Belperio (1989) has emphasised the need for compilation of data, specific to selected areas, that will isolate and discriminate between the factors influencing relative sea level. Empirical data, so obtained, can then be fed back into the various geophysical models, refining their predictive capacity.

For any given coastal area, the known geological effects of the Holocene transgression provide a potentially powerful predictive framework for considering the likely consequences of a "greenhouse" rise of sea level. Paraphrasing the Principle of Uniformitarianism, it maybe argued that our understanding of the immediate past will strongly govern our expectations of the near future. In this thesis, description of coastal sedimentary processes (Chapter 3), isolation of eustatic and isostatic signatures (Chapters 5 and 6) and documentation of Holocene environmental change on coastal Aboriginal populations (Chapter 9) contributes to such a predictive framework for South Australia.

LATE QUATERNARY STRATIGRAPHIC UNITS

Late Pleistocene and Holocene stratigraphic units of southern South Australia have mostly been established by Firman (1966, 1967a, 1967b) and summarised in Firman (1969) and Daily et al. (1976). Stratigraphic units that are referred to in this present work are detailed below.

Gulf St Vincent and adjacent areas

Holocene marine sediments are referred to the **St Kilda Formation**. This stratigraphic unit was redefined by Cann and Gostin (1985) and the name has since been applied to Holocene marine sediments elsewhere in the state (for example, Chambers et al., 1990).

Pleistocene sediments of oxygen isotope substage 5e, c.125,000 yr B.P., outcrop at present sea level or, in areas north of Adelaide, slightly elevated above sea level. These sediments contain fossils characteristic of water temperatures warmer than those prevailing in the modern gulfs. These include the cockle *Anadara trapezia* and the pearl oyster *Pinctada carchariarium* (Fig 1.2) and the large foraminifer *Marginopora vertebralis*. The strata were assigned to the **Glanville Formation** by Firman (1966) and a reference section (Figs 1.3 and 1.4) was established by Cann (1978). Largely because of its warm water fossil fauna, the Glanville Formation received early attention from geologists in South Australia, as documented by Ludbrook (1984).

Submarine sediments of oxygen isotope stage 3, c.45,000 to 30,000 yr B.P. were recovered from Gulf St Vincent by Cann et al. (1988), but these have not yet received formal stratigraphic designation. Presumably these strata are underlain by sediments of substages 5a and 5c, but vibrocores did not penetrate these deeper deposits.

The Adelaide region is bounded by Gulf St Vincent to the west and Mt Lofty Ranges to the east. Fluvial sediments derived by erosion of the ranges are deposited as proximal piedmont fans and distal coastal plains strata, which interleaf with the marginal marine sediments. Terrestrial deposits stratigraphically placed between St Kilda and Glanville Formations belong to the **Pooraka Formation**, while those underlying the Glanville Formation are assigned to the **Hindmarsh Clay**.

a

b

c

d

Fig. 1.2
a. *Anadara trapezia* from beach sediment, Port Vila, Vanuatu.

b. Coarse coralline beach sediment containing numerous specimens of *Anadara trapezia*, Port Vila, Vanuatu.

c. *Anadara trapezia* from coarse shelly sediments of the Glanville Formation, excavated at St Kilda, South Australia.

d. *Pinctada carchariarium,* also from the Glanville Formation at St Kilda, South Australia.

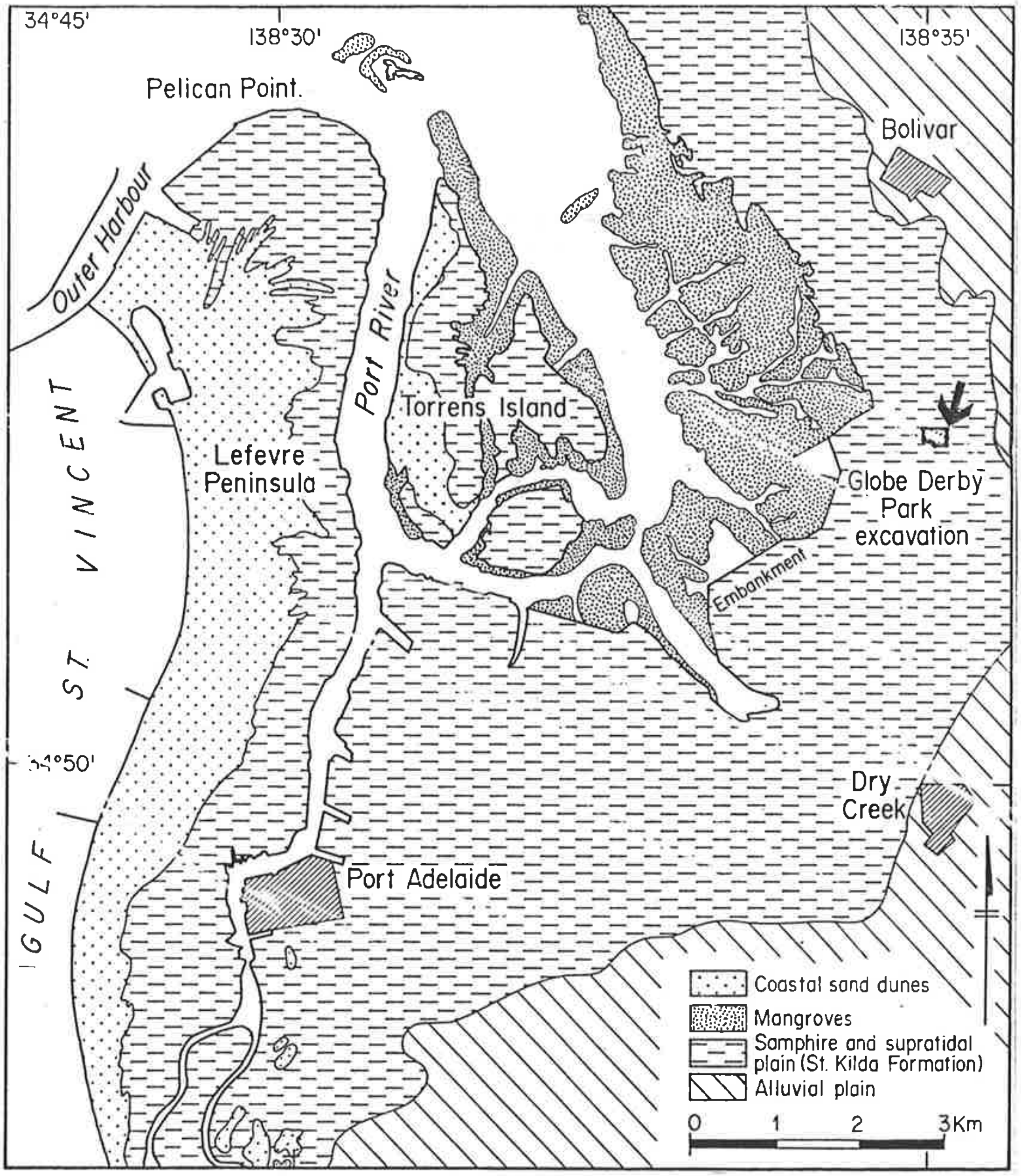


Fig. 1.3

Map of the coastal area north of Adelaide showing location of Globe Derby Park excavation (arrow) at the margin of the Penrice (formerly I C I) saltfields (after Belperio et al., 1988). A late Quaternary sedimentary sequence is exposed in this excavation.

A reference section for the Late Pleistocene Glanville Formation was established for this site by Cann (1978).

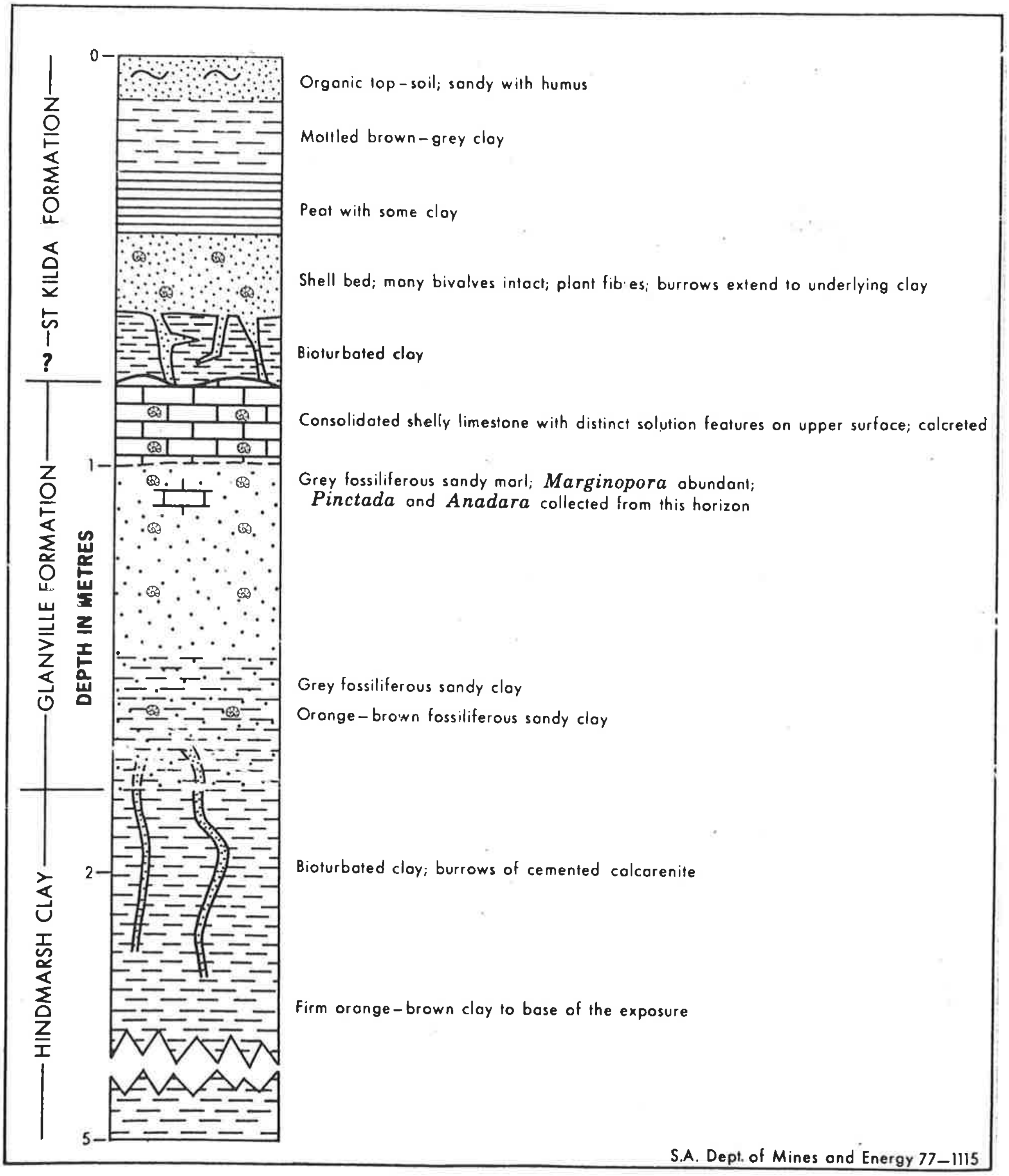


Fig. 1.4
Sedimentary section exposed in the northeastern corner of the Globe Derby excavation (from Cann, 1978). This exposure is a Reference Section for the Glanville Formation.

While this stratigraphic nomenclature can be usefully applied to marginal marine sequences, it is difficult to differentiate the two terrestrial units otherwise. Also, the stratigraphic constraints of the Pooraka Formation do not take account of terrestrial sedimentation that is time equivalent to the Holocene marine St Kilda Formation.

Spencer Gulf and adjacent areas

Holocene marine sediments within Spencer Gulf have been assigned to the **Germein Bay Formation** (Hails et al., 1984a). While this name has been observed in this present work, it has not been recognised by some other workers, for example, Chambers et al. (1990). The term "Germein Bay Formation" should probably be suppressed and the biologic, lithologic and chronostratigraphic equivalent "St Kilda Formation" be adopted for the Holocene marine sediments of Spencer Gulf.

Similarly, marine sediments of oxygen isotope substage 5e have been assigned to the **Mambray Formation** (Hails et al., 1984a). These sediments are in every sense equivalent to the Glanville Formation.

Submarine sections contain sediments of oxygen isotope substages 5c (c.105,000 yr B.P.) and 5a (c.82,000 yr B.P.). These strata have been respectively assigned to the **False Bay** and **Lowly Point Formations**. Spencer Gulf was too shallow to be influenced by the marine transgressions associated with isotope stage 3.

Marine sediments of isotope stage 7 have been recognised in Spencer Gulf, but these have not received formal stratigraphic designation.

Quaternary terrestrial sediments, surrounding Spencer Gulf and interbedded with submarine strata of the gulf, have been accommodated within the existing Pooraka and Hindmarsh Formations.

Southeastern Region

In southeastern South Australia, a complex of low altitude, sub-parallel ranges dominates the landscape of an otherwise gently seawards sloping coastal plain. These geomorphic features were mentioned earlier in this chapter, with reference to the tectonic setting of the region. The ranges are constructed of predominantly aeolian bioclastic calcarenites and had their origins as coastal beach-dune complexes. In general terms, the ranges increase in age away from the present coastline. This diachronous sequence of Pleistocene sediments belongs to the **Bridgewater Formation** (Boutakoff, 1963). Inter-range lagoonal sediments associated with the Holocene transgression, and that of oxygen isotope stage 5e, are respectively referred to the St Kilda and Glanville Formations.

CHAPTER 2

Quaternary benthic foraminifera as palaeoenvironmental indicators; techniques of sample preparation and analysis.

INTRODUCTION

It is now axiomatic that foraminifera are environmentally sensitive organisms and that the relative abundance of species in a sediment is closely related to the environmental conditions at the time of deposition (Phleger, 1960; Murray, 1973; Boltovskoy and Wright, 1976; Haynes, 1981). In the investigation of late Quaternary sea levels reported in this thesis, the author was persuaded that assemblages of fossil foraminifera recovered from vibrocored gulf sediments would permit diagnosis of changes in sedimentary environments, and thus, inferences of marine transgressions and regressions. This premise was based on an impressive body of literature in which previous researchers had identified associations of distinctive assemblages of species and sedimentary environments. Many of these earlier workers had also been able to identify those same assemblages in core sediment samples, and so infer successive changes in palaeoenvironmental conditions of deposition. The means by which foraminifera were recovered from surficial and core sediment samples, and the details of arithmetic comparison of the numerical distribution of species, differed slightly among researchers. In this chapter, the techniques of investigation used by the present author are described and their rationale discussed.

PREVIOUS INVESTIGATIONS

In addition to the four classic texts referred to above, an enormous body of literature records the investigations of sediments of every known environment likely to have hosted foraminifera. A comprehensive review of that literature was not attempted and was unlikely to have been achievable within the limitations of the present investigation.

However, it is apparent that a limited number of broad categories of sedimentary environments, hosting foraminifera, can be generalised from the literature. These are listed below, together with references to a selection of papers which were significant in contributing to the present author's understanding of the environmental constraints of foraminifera, and which were instrumental in the development of an investigatory strategy.

deep oceans

Atlantic Ocean - Streeter (1973), Lohmann (1978)
Indian Ocean - Be and Hutson (1977)

continental shelves

Africa - Lutze and Coulbourn (1983/1984)
Antarctica - Kennett (1968), Osterman and Kellog (1979), Milam and Anderson (1981)
Australia - Albani (1970)
China - Li and Wang (1984), Wang et al. (1984a, 1984b, 1984c, 1984d)
England - Murray (1970b, 1973, 1979), Rosset-Moulinier (1981), Murray et al. (1982)
New Zealand - Hedley et al. (1965), Hayward (1982)
North America (Atlantic) - Murray (1969), Culver and Buzas (1981), Rodrigues and Hooper (1982)
North America (Pacific) - Bandy (1961), Resig (1958)
Norway - Hald and Vorren (1984)

bays and harbours

Australia - Albani (1968), Collins (1974)
China - Wang and Bian (1984)
Korea - Chang (1984a)
New Zealand - Hulme (1964)

reefs

Australia - Collins (1958)

lagoons, marshlands and intertidal environments

Africa (Indian Ocean) - Chasens (1981)
Australia - Apthorpe (1980)
China - Wang et al. (1984f)
Greece - Scott et al. (1979)
North America (Atlantic) - Miller(1953), Murray (1968), Scott and Medioli (1978, 1980), Price (1980)
North America (Pacific) - Scott (1976), Scott et al. (1976), Scott and Medioli (1978)
Persian Gulf - Murray (1970a)

[There is also a useful comparative review of this environment by Murray (1971)].

estuaries

China - Wang et al. (1984e)
France - Pujos (1984)
North America (Atlantic) - Ellison and Nichols (1970), Scott et al (1980)
North America (Pacific) - Erskian and Lipps (1977)
Trinidad - Saunders (1958)

[There is also a useful comparative study of estuaries in Britain, China and Germany by Wang and Murray (1983)].

saline lakes

Australia - De Deckker and Geddes (1980), Cann and De Deckker (1981)

ENVIRONMENTAL DETERMINATION OF SPECIES DISTRIBUTIONS

In many reported studies of foraminifera there appears to be a relationship between the numerical distributions of species and water depths. For example, in the Santa Cruz Basin on the Californian continental shelf, Resig (1958) has compared species abundance with the water depth profile.

In the frequency distribution of the total population, three species of *Cassidulina*, *C. californica*, *C. limbata* and *C. tortuosa* show a preference for depths <600m, while three other species, *C. cushmani, C. delicata* and *C. translucens* are more common below that depth. Similarly, her data show that *Cibicides fletcheri* and *C. refulgens* together constitute about 20% of the assemblage at 200m water depth, but at 600m *Cibicides* is represented only by *C. tuberculata,* again approximately 20% of the assemblage.

From Resig's (1958) study, it is clear that the relative abundances of the species of *Cassidulina* and of the species of *Cibicides*, have potential for deriving a numerical relationship with water depth for the Santa Cruz Basin. Such a relationship, rigorously derived from empirical data, would have application in investigations of palaeo water depths for Quaternary sediments that might be taken by cores from within the basin.

There are many physical and chemical factors that could potentially influence changes in species distribution with depth, such as water temperature, turbulence, salinity, concentration of dissolved oxygen, etc. Many workers have attempted to evaluate the role of such factors and have sometimes been able to establish circumstantial correlations.

Reiss (1977), in reviewing foraminiferal research in the Gulf of Elat, claimed that the results of all studies in that area "indicated that the distribution of foraminifera shows a distinct depth-zonation in spite of the practically homogeneous - with regard to temperature, salinity, density and oxygen - water column" (p.14). Reiss shows, for example, that Soritid genera, such as *Peneroplis*, constitute about 25% of a shallow water assemblage, but are insignificant at depths of 50m or more. In contrast, the genera *Amphistegina* and *Operculina* (=*Nummulites*; Loeblich and Tappan, 1964, P. C645) constitute >50% of the assemblage at depths of 50 to 100m.

Depth zonation in the gulf is also apparent at a species level, and some species exhibit intraspecific, depth related variability of test features. Reiss (1977) points to the presence of photosynthetic symbionts in many genera, for example, *Peneroplis*, and presents a convincing case for depth zonation of species of foraminifera as a response to diminishing light intensity with increasing depth of water. It is, however, acknowledged by that author that some species which are distinctly depth distributed in the Gulf of Elat apparently do not possess symbionts.

From the distributions of genera given by Reiss (1977) for the Gulf of Elat, it is possible to predict the foraminiferal signal of marine transgression. If a core of Holocene sediment were taken from the shallow (<150m) shelf of the gulf, it would reveal the initial transgression by a faunal assemblage in which *Peneroplis*, *Spirolina* and *Sorites* were plentiful. These genera would give way up core to a deeper water fauna dominated by *Amphistegina* and *Operculina* (=*Nummulites*).

Even in estuaries, where the longitudinal salinity profile is likely to be a primary determinant of species distribution, water depth seems to be a very important factor. For example, Ellison and Nichols (1970) have shown how the distribution of forms of *Elphidium clavatum* and *Ammonia beccarii* increase markedly in abundance in the Rappahnock River, Virginia, with water depth ranging to about 20m. Similarly, in the intertidal zones of saline marshlands, the distribution of foraminifera is depth related, closely following intertidal plant zonation (Scott and Medioli, 1980, and references therein). These authors have indicated the palaeoenvironmental implications of their observations.

The literature therefore supports the premise that foraminifera, preserved as fossils in Quaternary sediments of South Australian Gulfs Spencer and St Vincent, have the potential to signify marine transgressive and regressive episodes, from which a palaeo sea level curve can be derived. As a precondition, the present distribution of species, with respect to water depth, must first be established for the surficial sediments of modern gulf environments.

Thus, for the studies reported in this thesis, foraminiferal biofacies were initially established for a broad, intertidal coastal area at Port Gawler, northern Gulf St Vincent, and for central gulf waters in the vicinity of Pt Pirie and Whyalla in Spencer Gulf. The results of these investigations are the subjects of Chapters 3 and 4. The data so obtained were then applied to samples of vibrocored sediments, particularly to some of those taken from Spencer Gulf in the comprehensive work of Hails and Gostin (1984). Detailed findings relating to fossil foraminiferal distributions within these vibrocores, and their palaeoecological implications, particularly with regard to late Pleistocene and Holocene sea levels of Spencer Gulf, are given in Chapters 5 and 6. More integrated investigations of the distributions of species of benthic foraminifera in the surficial sediments of Gulf St Vincent, and their fossil equivalents in late Pleistocene and Holocene submarine strata of this gulf, together with further and more refined implications for past sea levels, are reported in Chapters 7 and 8.

SAMPLE PREPARATION

Pretreatment volumes of sediment samples were about 200ml for those taken from surficial sediments in modern environments, and about 150ml for those taken from vibrocores. Surficial sediments often contained substantial quantities of plant debris - seagrasses, algae and cyanobacterial mat - which were impossible to quantitatively extricate from the clastic/bioclastic components. Thus, procedures involving standard volumes or weights of sediment were found to be not practicable.

Sediment samples which were partly consolidated, or in which there was substantial plant matter, were boiled in fresh water for about an hour to effect disaggregation and to break down the organic debris. Where necessary, a sonic probe was used to further facilitate mechanical separation of sediment components. Samples treated in this way, and samples of naturally unconsolidated sediment which were essentially free of plant debris, were wet sieved retaining the sand size fraction 2.00-0.063mm.

In the palaeontology laboratory in the Department of Geology and Geophysics at the University of Adelaide, it is standard procedure for foraminifera to be concentrated from prepared samples by dense liquid flotation on tetrabromoethane. This procedure is widely used by foraminiferal researchers, though other liquids also used include carbon tetrachloride (for example, Nagy, 1984), bromoform (for example, Hald and Vorren, 1984), dibromoethene (for example, Feyling-Hanssen, 1976) and ethylene bromide (for example, Knudsen, 1977). A high proportion of the foraminifera in a sample are recovered in the float and, generally, workers who have applied the technique have observed little difference in proportional counts of species in their floated versus unfloated samples (for example, Lees, 1975). Sediment samples were processed in this way for the present author to derive data presented in Chapters 3 to 6. Data in subsequent chapters were mostly obtained from samples that had not been concentrated by dense liquid flotation. All samples were divided into phi grain size fractions for microscopic examination.

MICROSCOPIC EXAMINATION OF SAMPLES

In the early stages of the investigation, much attention was given to species identifications and to developing "working species concepts". A conceptual picture of the ontogeny and variability of each of the common species was established by looking at progressive growth stages of juveniles in the finer fractions, and by noting the range of variation in adult specimens. It is not uncommon for different growth stages of a single species to be assigned to separate taxa.

For example, Resig (1962) was able to illustrate that forms commonly assigned to *Poroeponides cribrorepandus* and *Sestranophora arnoldi* are probably ontogenic stages of the more established species *Eponides repandus* In this present study, ontogenic reconstruction confirmed *Cribrobulimina polystoma* to be an adult microspheric form of *C. mixta* (Parr, 1932; Loeblich and Tappan, 1964). Similarly, it can be shown that very small tests of *Elphidium*, as illustrated by Albani (1979, Fig 106-6) and identified as *E. macellum aculeatum*, are almost certainly juveniles of *E. crispum*. Variability of adult tests was most noticeable in species of intertidal environments (Chapter 3). The variability of *Discorbis dimidiatus*, for example, as illustrated by Hedley et al. (1967) agrees with the interpretations of the present author.

For the purposes of determining percentage distributions of species in the samples, only the grain size fractions 1.00 - 0.50mm and 0.50 - 0.25mm were processed. Foraminifera in the smaller fractions were not considered for statistical purposes. The rationale for that decision is based on the following:

a) Individual tests of foraminifera <0.25mm are most susceptible to suspension load transport. Under conditions of high tidal and wave energy, smaller tests are winnowed from their environments of origin to be widely redistributed elsewhere (Loose, 1970; Broekman, 1974; Murray et al., 1982; Wang and Murray, 1983; Murray, 1984). Foraminiferal tests are hydrodynamically equivalent to other sediment particles of much smaller size. Thus, fine grained intertidal sediments may be enriched in small and thin-tested individuals as a result of hydrodynamic selection (Broekman, 1974).

Murray et al. (1982) found that tests of rounded benthic foraminifera <0.2mm in diameter, and of elongate benthic foraminifera, <0.3mmin length, were significant components of the sediment suspension load of waters of the western English Channel. Thus, for South Australian gulf sediments, those species whose adult size is <0.25mm are potentially less valuable as palaeoenvironmental indicators than those of larger size.

b) Juveniles constitute a high percentage of the foraminifera in finer size fractions. Below certain size limits, juveniles of some species can not be distinguished from those of others (Brolsma, 1978). One researcher, while examining different size fractions of a sediment sample for planktonic foraminifera, was unable to identify about 60% of the individuals in the fraction 0.088 - 0.062mm (Be and Hutson, 1977). Identification of some juvenile miliolid species can be particularly difficult. In ontogeny there is often a pronounced modification of test geometry. For example, juveniles of *Massilina* are quinqueloculine in form, and it is only in later development that the chambers are added in a single plane on alternate sides (Chapter 4, Fig 4.4). Also, within an assemblage of juveniles, there may be significant intraspecific variation, as observed by Schnitker (1967) for asexually produced juveniles of *Triloculina linneiana.*

c) Dissolution of calcareous tests may occur initially as an early post mortem event, and later, during sediment diagenesis. The tests of juveniles and small adults are the first to be dissolved, leading to selective loss of individuals and species from the fossil assemblage (Murray, 1984). Preservation thus favours larger individuals that are less prone to solution.

d) Larger individuals in coarser fractions require lower powers of microscopic magnification, enhancing accuracy of species identification and ease of separation and counting of individuals.

e) Use of fossil foraminifera to infer palaeo sedimentary environments is based on comparison of modern and fossil assemblages. When comparing assemblages, similarities and differences are most pronounced when the number of components (species) to be compared is small and differences in abundances of the components are large. By ignoring species whose adult sizes are consistently <0.25mm, the numbers of items are reduced, percentage differences are emphasised and comparisons simplified. An extension of this logic led to separate consideration of 1.00 - 0.50mm and 0.50 - 0.25mm sediment grain size fractions.

Species of *Elphidium*, for example, rarely exceed 0.50mm in diameter in local gulf waters. Their virtual absence from the coarser size fraction simplifies its foraminiferal signal. On the other hand, separate consideration of the finer fraction enhances the relative abundances of species of *Elphidium*.

Be and Hutson (1977) believed selection of sieve size to be the single, most critical factor in the methodology adopted by researchers investigating foraminiferal palaeoecology. It is clear from the literature that many workers would not agree with the methods used in the studies reported here. For example, Brolsma (1978) and Scott et al. (1984) both support examination and consideration of all material >0.063mm, in the belief that the smaller size fractions contain essential material for palaeoenvironmental interpretations. It is likely that different sediment grain size fractions can be used successfully to suit the specific needs and circumstances of various individual investigations. Meaningful results should follow, provided that the procedures are applied consistently within the investigation.

Percentage distributions of species data were determined by counting >200 randomly extracted individuals from each of the two size fractions, 1.00 - 0.50mm and 0.50 - 0.25mm. The larger size fraction often contained less than 200 individuals and occasionally was not statistically significant. Percentage distribution of species for the finer fractions were frequently calculated from numbers several times the mandatory 200 individuals. Only species constituting at least 5% of an assemblage were considered significant for the purposes of comparison (compare Lohmann, 1978).

? [illegible]

In addition to the author's own checks on reproducibility of results, a set of sub-samples, duplicates of those yielding the data given in Chapter 7, were processed by undergraduate palaeontology students at the Australian National University under the supervision of Dr. Patrick De Deckker. Percentage distributions of species were mostly found to be within a few percentage points of those determined by the author (De Deckker, personal communication).

CHAPTER 3

Coastal sedimentary facies and foraminiferal biofacies of the St Kilda Formation at Port Gawler, South Australia.

INTRODUCTION

The eastern coast of northern Gulf St Vincent is normally subject to a low energy wave regime. This fact, together with northward longshore drift, ensures that it is an area of active sedimentation. Low topographic relief of the coastal areas, and extensively developed sand and mud flats, result in broad intertidal areas. High tides associated with storm surges cause inundation of normally supratidal environments.

From seaward of the low tide shore line to the supratidal areas there is a pronounced zonation of plant communities. These range from subtidal and intertidal seagrass meadows, through mangrove woodlands and cyanobacterial mats, to supratidal samphires and saltbush. In various ways the plants baffle, trap and bind sediment causing aggradation and progradation of the sand flats. Molluscs and foraminifera are abundant and their shells and tests contribute significantly to the accumulating sediment. Also, species of these fauna are distinctively distributed through the zoned plant communities and there are several consistent plant/animal associations.

This chapter documents relationships between plant communities and sedimentary processes at Port Gawler, northern Gulf St Vincent. Foraminiferal biofacies are established for the various marginal marine sedimentary environments and these data are used in palaeoenvironmental analysis of two cores of Holocene sediment. Much of the research reported here is recorded in Cann and Gostin (1985), Belperio et al. (1986, 1988) and Cann et al. (1988).

For Port Gawler and surrounding coastal areas, all Holocene sediments deposited under marine influence belong to the St Kilda Formation, in the sense of Cann and Gostin (1985). This usage includes those sediments, subtidal, intertidal and supratidal, forming at present.

THE ST KILDA FORMATION AND LATE HOLOCENE SEA LEVELS

Firman (1966) defined the St Kilda Formation as "various lithologies delimited for mapping purposes by the low lying swampy tract which extends a mile or more inland near St Kilda and elsewhere along the modern coast." That is, he included the modern supratidal samphire sediments as a facies of the St Kilda Formation. This interpretation was followed by Thompson (1969) who referred "light-grey shelly stranded beach ridge deposits and shelly silts and sand overlain in places by modern intertidal and swamp deposits" to the Holocene St Kilda Formation, and showed these sediments to be distributed along the eastern coast of northern Gulf St Vincent, extending inland about 5km.

However, Firman's (1966) definition related sediments of the St Kilda Formation to the "raised sea-bed" of Tate (1879) and to the marine sands and clays of the Osborne high sea level (Aitchison et al., 1954). Daily et al. (1976) elaborated on this interpretation, clearly relating the formation to "a high stand of the Flandrian sea when shelly sand was deposited." Their evidence for a supposed higher Holocene sea level, about 1.5m above modern sea level, consisted largely of stranded beach ridges, and they cited dates of 3800 +/- 500 and 1120 +/- 75 radiocarbon yr B.P. respectively for the base and top of the St Kilda Formation.

Belperio et al. (1983) reviewed evidence relating to Holocene sea levels in South Australia and concluded that there was little to support the notion of higher Holocene sea levels in the Adelaide region. They emphasised the importance of processes of coastal progradation and intertidal and supratidal deposition, and considered shell ridges to rate poorly as evidence for higher sea levels.

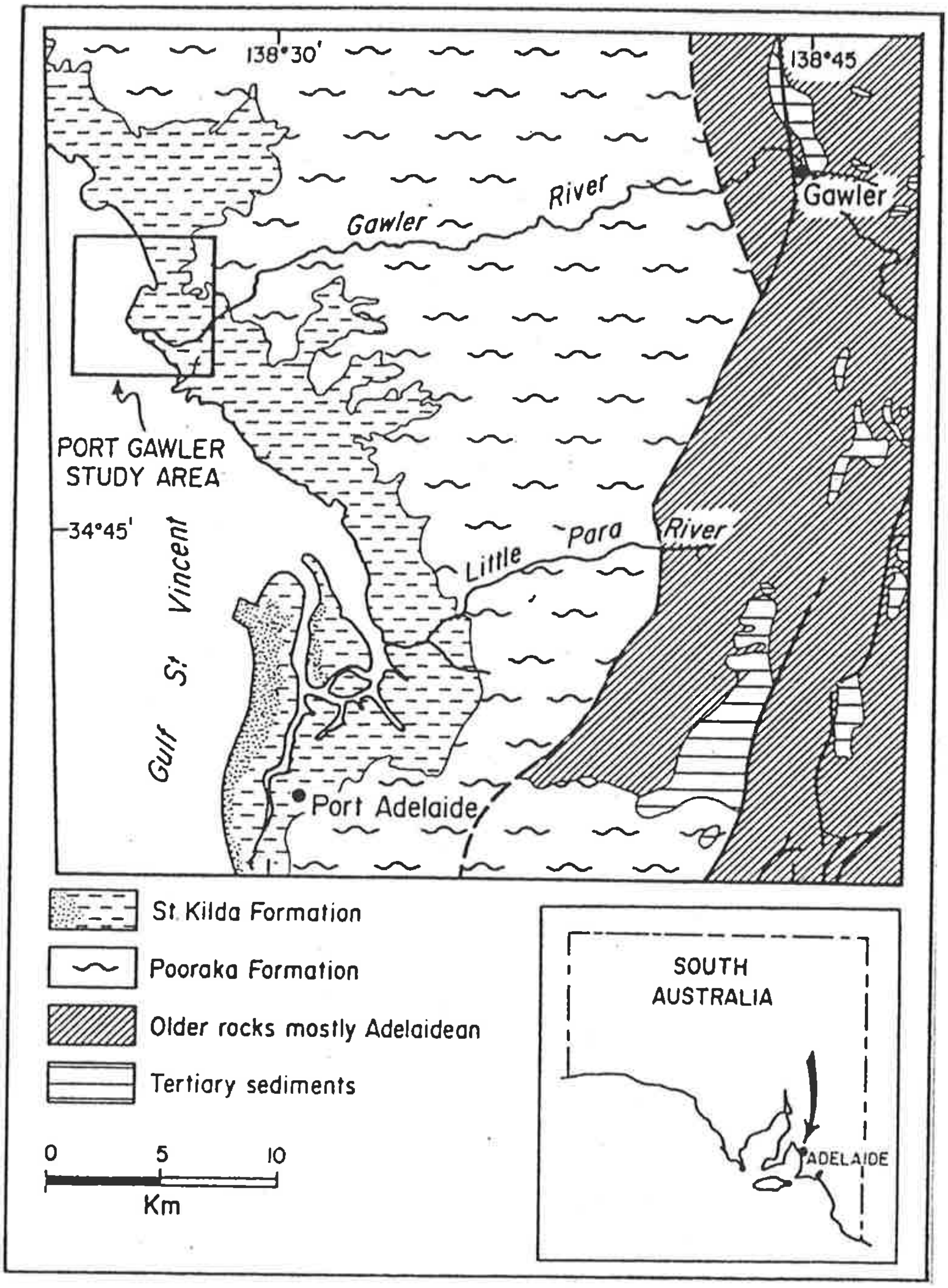


Fig 3.1
Location map showing surface distributions of the Holocene St Kilda and Pooraka Formations, as used in this chapter, and other simplified geology.

This view was supported by Cann and Gostin (1985) who saw no reason to invoke any recent lowering of sea level to account for their observations, and who were unable to stratigraphically differentiate the marginal marine Holocene sediments.

Within Gulf St Vincent and surrounding coastal lands they therefore recognised the St Kilda Formation to include all Holocene sediments deposited under the influence of marine processes, including estuarine deposits, coastal dunes and storm ridges. As such, the St Kilda Formation is a readily mappable unit consisting internally of various sedimentary facies, deposited under a variety of marine processes.

THE STUDY AREA

The study area is situated about 12km northwest of St Kilda, the type location for the St Kilda Formation (Fig 3.1). The area is almost topographically flat with samphire swampland to the east, passing through mangrove woodland and open sandflats to seagrass meadows westwards. Immediately eastwards are salt concentration evaporation ponds, the most northerly of a system leading to salt extraction at Dry Creek. The area includes the estuary of the Gawler River, site of the now disused Port Gawler (Lisbon Wharf, Figs 3.2, 3.5F).

Gawler River has its source in the Para Fault Block, about 40km east of Port Gawler. It is an intermittent stream, generally confined to a narrow, meandering channel as it traverses the northern Adelaide Plain. At times of heavy rainfall, fine grained clastic sediments are transported into the estuary, from where they are redistributed throughout the study area by coastal marine processes.

The region of South Australia which includes Port Gawler experiences a pronounced Mediterranean type of climate. Summers are mostly hot and dry with maximum temperatures greater than 40°C not uncommon. Winters are generally mild and night frosts are rare.

Fig. 3.2
Ruins of Lisbon Wharf, Port Gawler. This facility was historically important for the export of grain and wool in the years 1839 to 1914 (Toteff, 1983).

Average annual rainfall of 420mm at Port Gawler occurs mostly during the cooler months, though occasional summer thunder storms produce heavy falls of rain. Evaporation has been estimated at 1800mm annually (Toteff, 1983).

The areas influenced by normal tidal changes of sea level at Port Gawler are extensive. The gradient seawards from the samphire salt marsh is almost imperceptible and maximum astronomical tidal variations are about 2.5m. At maximum high tide, sea water covers the sand flats and floors of the mangrove woodland, and flows through tidal distributaries to the samphire marshland beyond. At minimum low tide, the sea retreats to the extreme seaward margin of the sand flat.

Superimposed on normal tidal fluctations are the longer term effects of surges with periods of 1 to 20 days, and thought to relate to the passage of weather systems (Provis and Radok, 1979). Kelly (1984) has reported storm surge sea level fluctations of 0.5m along the southern Australian coast. When a storm surge coincides with a spring high tide, unusually high water levels result. Abnormally large volumes of sea water move across the sand flats and through the mangrove tidal creeks, flooding the samphire marshland and adjacent (normally) supratidal areas. When these conditions are further accompanied by local winter storm activity, with strong south westerly winds, the sea is driven even more deeply into the coastal environments. The combined effects of tidal currents and storm waves in these circumstances can cause considerable erosion and redistribution of sediment.

The wave regime of Gulf St Vincent has been discussed by Bye (1976) and by Wynne et al. (1984). The configuration of the gulf is such that, along the eastern coast, prevailing south westerly winds generate waves of maximum fetch south of Adelaide. Adelaide beaches are subject to a lower wave energy regime which generates significant transport of sand alongshore northwards towards the study area. Except under storm conditions, wave energy from Port Gawler to the top of Gulf St Vincent is very low.

VEGETATION

The role of vegetation in determining the nature and distribution of sediments at Port Gawler is fundamental and is discussed in greater detail below. In general, the various cyanobacteria, algae, seagrasses, mangroves and other plants perform two significant functions. Firstly, they are autotrophs in food chains leading to organisms which secrete shells or tests of calcium carbonate. These shells and tests, either intact or comminuted, ultimately become part of the sediment. Secondly, in a variety of ways, they actually cause deposition of sediment, trapping and binding grains of calcium carbonate, quartz and other mineral matter.

Posidonia australis, the broad leaf species, is a seagrass commonly known as "tape-weed". It is common in Gulf St Vincent, living from low tide level to depths of about 10m. *Posidonia* has tough, roughly textured leaves that host a variety of epiphytes (Womersley, 1956). The flat ventral surface of the foraminifer *Nubecularia lucifuga*, abundant at Port Gawler, often shows striae like imprints of the venation of these leaves. Womersley and Thomas (1976) considered that few animals feed directly on the *Posidonia* leaves. The rhizome/root system and leaf sheaths of this plant are dense, fibrous and resistant to organic decomposition. *Posidonia australis* leaves can survive only brief periods of emergence at low tides. At Port Gawler it grows in the lower intertidal zone and seawards.

Zostera muelleri is another seagrass, of narrower leaf, and commonly referred to as "eel grass". Like *Posidonia*, this plant has a rhizome/root system and hosts epiphytic algae and animals (Womersley and Thomas, 1976). At Port Gawler, *Zostera*, together with species of *Heterozostera, Lepilaena* and *Ruppia* (as described by Robertson, 1984) form extensive, dense seagrass meadows seaward of the bare sandflat, and seaward of and adjacent to the mangrove woodland. These marine plants can survive longer periods of emergence at low tide.

Avicennia marina var. *resinifera* is the only species of mangrove found in South Australia and occurs at Port Gawler in both mature woodland and as younger colonising plants (Butler et al., 1977; Harbison, 1981; Burton 1982a, 1982b; Talbot, 1982; Toteff, 1983). Tidal distributaries form a dendritic pattern through the mature woodland. Sea water flushes accumulated salt from around the mangrove roots (Butler et al., 1977) and distributes algal, seagrass and other organic flotsam. Much of this organic debris probably provides nutrients for the mangroves and is a source of food for a variety of gastropods. Mangroves are confined in their distribution seawards by the need for their vertically protruding pneumatophores to be periodically exposed to the air, and landwards by their need for regular flushing of accumulated salt from the roots by sea water at high tide (Chapman, 1975). Juvenile mangroves are colonising the *Zostera* meadow seawards of the bare sand flat at Port Gawler. During the past 15 years the author has observed their establishment progressively over several hundred metres from the older trees.

Mats of cyanobacteria (=blue-green algae) colonise both the floor of the mangrove woodland and the mid-tide bare sand flat. They are dull green and slippery. Mats are constructed at the sediment/water interface by one or more species of cyanobacteria and may also contain a variety of true bacteria and other algae. Cyanobacterial mats are among the most productive of aquatic photosynthetic systems (Bauld, 1981). At Port Gawler the mats are apparently grazed by a variety of gastropods. Their distribution on the open sand flat appears to be delimited by grazing gastropods seawards, and by the infrequency and short duration of high tidal inundation of sediments closest to the beach.

Halosarcia halocnemoides and *Sarcocornia quinqueflora* are dominant plants of the samphire salt marsh community. These are low growing, fleshy plants which have considerable salt tolerance and occupy the zone immediately landwards of the mangroves.

SEDIMENTATION AT PORT GAWLER

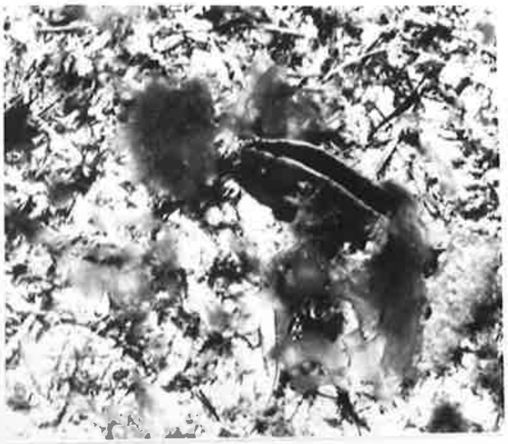
1. *Posidonia-Pinna* facies/zone

At low tide it is possible to observe the seaward margin of the sand flat. *Posidonia australis* grows in patches 20 to 30 square metres in area. *Pinna bicolor* (=*P. dolabrata* and *Subitopinna virgata*) (Butler and Brewster, 1979), known locally as "razor fish", is conspicuously abundant, living in among the seagrass. The sediment is coarse, poorly sorted, shelly sand. Carbonate content is >90%, much coming from lime secreting organisms hosted by the *Posidonia*. Foraminifera are particularly plentiful among the smaller grains. Among the larger shelly organisms, *P. bicolor* may grow to a length of 20cm in a single year (Butler and Brewster, 1979).

Patches of *Posidonia* on the outermost areas can be observed in various stages of burial by the mobile sand (Fig 3.3A). The baffling action of the seagrass apparently traps the sediment. Studies in the Bahamas by Scoffin (1970) and Neumann et al. (1970) show that seagrasses can reduce water velocity from 30 cm/sec, sufficient to transport loose sand grains along the bare sea floor, down to zero at the sediment/water interface. As the sediment accumulates, *Posidonia* grows upwards, but is constrained by its inability to survive low tide emergence and it ultimately dies. Large areas of the remains of recently dead seagrass, together with numerous empty *Pinna* shells, valves gaping and in life position, may be observed immediately landwards of the present day low water shore line (Fig 3.3B).

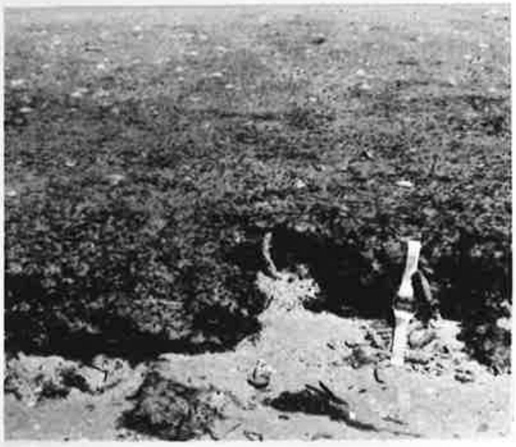
Carbonate sand is therefore accumulating up to low tide level, causing the outer margin of the sand flat to prograde seawards. In some areas, after death of *Posidonia*, the uppermost sediment remains bare of vegetation and consequently subject to tidal and storm wave transport. Such surfaces become scoured, channelled and rippled as the shelly sand is redistributed according to energy conditions.

A



B

C



D

E

F

Fig 3.3

A. Patch of partly buried, living *Posidonia*, adjacent to remains of recently dead *Posidonia*; outermost sandflat.

B. Dead *Posidonia* remains with dead *Pinna*, valves gaping, in life position; outermost sandflat.

C. Remains of agglutinated worm tubes, approximately 20mm diameter. These tubes are constructed of carbonate sand grains and oriented vertically in the uppermost 0.3 to 0.5m of sediment. Scouring by waves or tidal currents causes them to fragment. Outermost sandflat.

D. Dense, fibrous remains of dead seagrass (*Zostera*) after death and loss of foliage; section exposed in tidal channel; wrist watch for scale is 22cm long.

E. Recently dead *Katelysia*, valves attached and convex upwards; bare surface adjacent to *Zostera*.

F. *Zostera* in the seagrass meadow.

Mostly, however, the sediment mass remains essentially coherent, reinforced by seagrass fibre, by large vertically oriented *Pinna* shells, and by numerous worm tubes of agglutinated shell grit (Fig 3.3C). Algal growth on the substrate helps to minimise scouring by tidal currents and storm waves. The author has observed considerable progradation of the sand flat during the past 15 years.

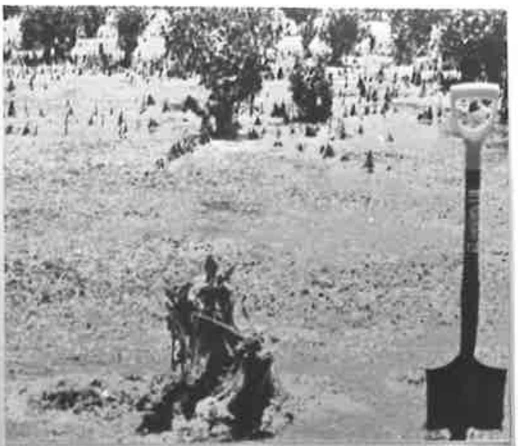
2. *Zostera-Katelysia* facies/zone

In the midtidal area, the sand flat is colonised by a seagrass meadow, consisting of several species, in which *Zostera muelleri* predominates (Fig 3.3F). The dominant bivalve mollusc is *Katelysia* sp. (Fig 3.3E). *K. scalarina* has been recorded from Port Gawler by Toteff (1983), but three species of *Katelysia* may be present (Ludbrook, 1984). Disarticulated valves of *Katelysia* have been widely redistributed throughout the study area.

Like *Posidonia, Zostera* baffles and traps sediment. The midtidal area is less influenced by wave action and tidal currents, so grain size is correspondingly smaller and there is a significant mud component. Sediment is rich in organic matter, supporting bacterial reduction of sulfate ions from sea water. Below the sediment/water interface it is black and has a strong sulfide odour (Fig 3.4A). Burrowing by small crabs tends to extend to the underlying, grain supported sand of the *Posidonia-Pinna* facies. Bioturbation tends to, in part, oxidise and homogenise the sediment.

Aggradation of sediment in the *Zostera* meadow continues to a level determined by the period of low tide emergence. Ultimately the plants on the landward side of the meadow are inadequately watered at high tides and they die (Fig 3.3D). On the seaward side, the meadow advances over the old *Posidonia-Pinna* substrate, and the finer sediment thus progrades.

A



B

C

D

E

F

Fig 3.4

A. Sediment of the *Zostera* meadow, shelly sand, rich in sulfide and mud.

B. Juvenile colonizing mangroves in the *Zostera* meadow; algal and other plant debris adheres to pneumatophores and smaller plants.

C. Mature mangrove trees adjacent to a tidal distributary.

D. Tidal distributary with mature mangrove woodland, left, and inner sand flat with cyanobacterial mat, right.

E. Gastropod shells, mostly *Batillaria*, are a major component of the sediment in the mangrove tidal distributary (C and D).

F. Sediment of tidal distributary which separates the *Zostera* meadow from the inner sandflat. Bivalves, mostly *Katelysia* and *Anapella* are disarticulated and convex upwards.

3. Mangrove facies/zone

At Port Gawler the author has observed the steady colonising advance of juvenile mangroves, *Avicennia marina* var. *resinifera*, across large areas of the *Zostera* meadow (Fig 3.4B). It is evident that the finer, muddier and organic rich sediment trapped by this seagrass is an ideal substrate for mangrove colonisation. The mangroves therefore represent a third major stage of plant/sediment succession.

Young mangrove trees quickly establish a lateral root system, each root bearing a series of vertically protruding pneumatophores. Each plant is surrounded by radiating rows of these spike like structures, 20-30cm high. For a time both mangroves and seagrass coexist, but as the density of pneumatophores increases, so too does the amount of organic flotsam that is trapped by, and adheres to, these subaerial roots. The *Zostera* thus dies under a blanket of accumulating marine compost.

Fine sediment continues to accumulate in this facies as the mangrove woodland grows to maturity. Algal and seagrass debris bring epiphytic carbonate organisms which remain as grains in the sediment. Thus aggradation proceeds to levels where the floor of the mature woodland (Fig 3.4C) is inundated for only brief periods during high tides. The sediment/water interface is then colonised and stabilised by a cyanobacterial mat which introduces new depositional processes, discussed below. The substrate is intensively burrowed by the small crab, *Helice haswellianus*, facilitating sea water permeability and aeration. The mangrove sediment thus becomes oxidised and homogenised.

Throughout this episode of deposition a dendritic pattern of tidal distributaries develops and is maintained.

4. Tidal distributary facies

Tidal water movement is concentrated along distributary channels (Fig 3.4D) which are best developed within the mangrove woodland. As a consequence of the dendritic pattern of channels, current speeds are variable and sediment type varies accordingly. Major shallow channels have coarse, shelly debris, rich in valves of *Katelysia* and *Anapella* (Fig 3.4F), disarticulated and convex upwards. Deeper backwater channels have a substantial component of sulfide mud.

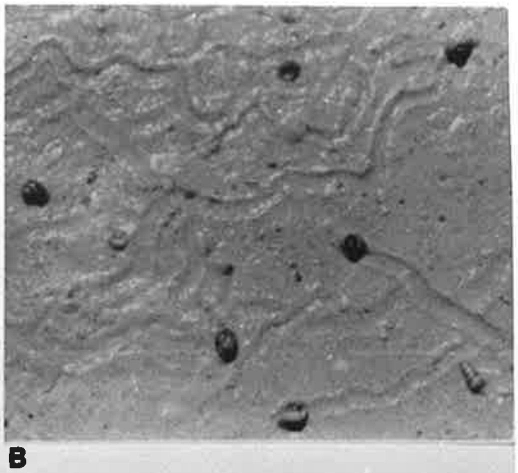
A major component of the shelly fauna within the mangrove tidal distributaries is the small turriform gastropod *Batillaria (Zeacumantus) diemenensis* (Ludbrook, 1984). Where channels meet the open sand flat, shells of this gastropod are numerous and current aligned (Fig 3.4E). They have been widely redistributed throughout the study area.

5. Cyanobacterial mat sand flat facies/zone

Bauld (1981) has illustrated the ability of cyanobacterial mats to fix sediment in Spencer Gulf. He described how entangled trichomes of *Microcoleus* sp., and their enveloping mucilaginous sheaths, trap and bind sediment in a thin coherent layer. In addition, photosynthesis at the mat surface removes carbon dioxide from sea water, increasing pH and favouring precipitation of calcium carbonate. Cyanobacterial mats cover a large part of the otherwise unvegetated sand flat, the floor of the mangrove woodland and some of the supratidal areas. These are therefore sites of sediment aggradation. Sediments bound by cyanobacterial mats are known to withstand current velocities up to five times higher than those required to erode mat-free sediment (Neumann et al., 1970).

Sections cut through the active mat (Fig 3.5C) reveal a thin layer of oxygenated sediment, below which is black, sulfide rich, laminated silty sand (Fig 3.5D). Anaerobic bacteria, nourished by the organic matter of previous layers of the mat, reduce sea water sulfate ions. Metals, particularly iron, are fixed in this way.


A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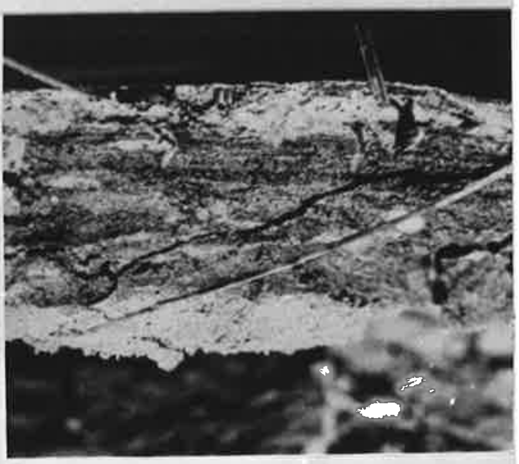
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Fig 3.5

A. Dead *Anapella* valves in life position, immediately beneath surface of inner sandflat; section exposed by mangrove tidal distributary.

B. Grazing gastropods limit growth of the cyanobacterial mat on the seaward areas of the inner sandflat.

C. Exposure of sediment beneath the cyanobacterial mat; dark horizon is sulfide rich.

D. Detail of sediment slab shown in C. Uppermost laminae are flushed with photosynthetic oxygen; dark lower laminae contain sulfide from bacterial reduction of seawater sulfate.

E. Inner sandflat and vegetated high tide beach.

F. Mature mangrove trees overhang the Gawler River estuary near the ruins of Lisbon Wharf.

Black sediment turns to a pale rust colour on prolonged exposure to the air. Calcium carbonate content may be as high as 70%.

The cyanobacterial mats support a dense population of grazing gastropods, notably *Salinator* sp.. On the seaward edge of the bare sand flat, persistent grazing appears to inhibit establishment of cyanobacteria (Fig 3.5B). In this area large numbers of the small bivalve *Anapella* sp., probably *A. cycladea* (Ludbrook, 1984), live clustered together immediately below the sand surface (Fig 3.5A). Disarticulated valves of *Anapella* are widely redistributed in sediments of the study area.

The bare sand flat is sharply separated from the *Zostera* meadow to the west, and the mangrove woodland to the south (Fig 3.4D) by intertidal distributaries. These tidal channels have remained essentially unchanged for the past 15 years.

6. Beach facies

High tide beach sediment at Port Gawler has a calcium carbonate content of about 80%. The texture is predominantly sandy, but shells originating in all of the other facies occur as constituents. Wide variation in grain size, from shell gravel to fine sand, may be related to variable wave energy, which is a function of water depth and wind strength. Sections cut through the beach reveal horizontal to gently tilted, well sorted laminae, and, rarely, higher angle cross beds.

Flotsam seagrass debris appears to significantly assist stabilization of beach sediment to seaward, while saltbush and other plants are established in, and fix, the upper beach sands (Fig 3.5E). The high tide beach is therefore a mass of accumulating sediment, prograding seawards across the inner sand flat.

7. Dune facies

Windblown carbonate sands occur some 50-100m inland of the beach. This area has been considerably modified by human activity, but the low dune forms, stabilised by saltbush and other vegetation, are clearly identifiable. The sediment is well sorted and consists of fine broken shell and entire small gastropods and foraminifera. Sections cut through the dunes reveal coarser underlying sediments.

8. Storm ridge facies

Storm ridges are formed at times of extremely high tides and local storm activity. Shelly material is driven shorewards under these conditions and may pile up in a ridge of coarse, poorly sorted shell debris, somewhat paralleling the shore line, but seawards of the beach. If the ridge is continuous, that part of the sand flat between the newly formed storm ridge and the pre-existing beach is isolated from further wave action. A new beach facies is established on the seaward side of the storm ridge, and a new dune facies to landwards.

At northern Port Gawler extensive storm ridges once existed in the area between the salt evaporation pans and the present high tide beach and dune facies. Shell grit mining has effectively removed most of this sediment, the location of the former ridges now being marked by a series of parallel, elongate, shallow depressions.

Immediately south of the Gawler River, a storm ridge some 1.5km long and up to 2m high lies within the mangrove woodland (Fig 3.6). It is situated several hundred metres landwards of, and parallel to, the seaward margin of the mangroves. The seaward side of the ridge is straight and steep, suggesting the form of a stranded beach (Toteff, 1983). On this surface P. Harbison (personal communication) has observed numerous large, square cut pieces of timber, similar to those used in the construction of early South Australian jetties. These items of driftwood were evidently emplaced at the time of, or shortly following, formation of the storm ridge.

Fig. 3.6
Composite aerial photograph of the Port Gawler study area showing the following:

a. *Posidonia* seagrass meadow, mostly subtidal. *Pinna* is the dominant bivalve in this environment.

b. Intertidal *Zostera* seagrass meadow. *Katelysia* is the dominant bivalve in this environment.

c. Juvenile mangroves colonising the *Zostera* seagrass meadow.

d. Inner sandflat with cyanobacterial mats. *Anapella* is the dominant bivalve in this environment.

e. Site of vibrocore #VC136, slightly seaward of the high tide beach.

f. Area of previous shell grit mining, once the site of numerous sub-parallel storm ridges. There are some low dune forms in this area.

g. Embankments enclose seawater evaporation ponds in the (otherwise) extreme supratidal areas.

h. Mature mangrove woodland.

i. Network of anastomosing tidal distributaries, landward of the mature mangrove woodland. Mangrove trees line these waterways.

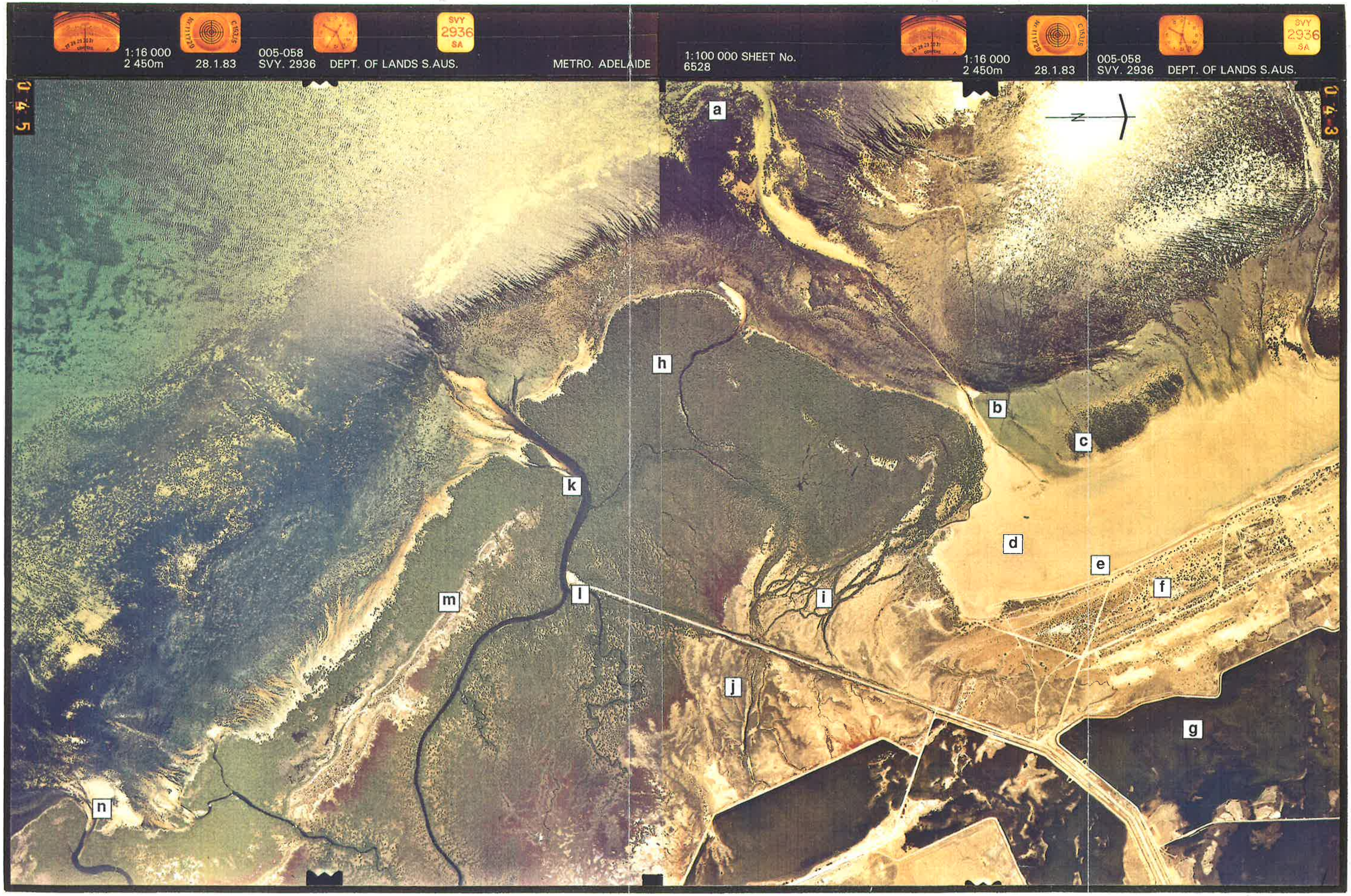
j. Supratidal samphire with minor tidal distributaries and small supratidal evaporative lagoons.

k. Gawler River estuary.

l. Site of vibrocore #VC138, in close proximity to the ruins of Lisbon Wharf.

m. Storm ridge within mangrove woodland.

n. Former site of debouchment of the Gawler River.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Along the coastal plain, north of Port Gawler, numerous more or less parallel storm ridges may be observed.

9. Supratidal lagoon facies

Areas of sand flats that have been isolated from open marine influence may still receive sea water via tidal distributaries. Alternatively, water may be supplied by seasonal heavy rain or rising ground water. On the floors of these supratidal lagoons, cyanobacterial mats often flourish. They maintain low diversity populations of carbonate fixing organisms such as the gastropod *Salinator* sp. and the foraminifer *Elphidium* sp., similar to those illustrated by Cann and De Deckker (1981). Photosynthesis favours chemical precipitation of calcium carbonate and fine wind blown sand is trapped by the mats. Gypsum crystals may form during summer evaporation. Samphire plants grow around the margins of these lagoons, where they trap supratidal seagrass flotsam and sediment. In this way they gradually encroach on these areas and contribute to their shallow infilling. Supratidal lagoons are therefore sites of active sediment accumulation.

To the north of Port Gawler, extensive supratidal lagoon systems occur landwards of the storm ridges. However, within the study area, this facies has effectively been replaced by salt evaporation ponds.

10. Estuarine facies

Large quantities of seagrass, algal and other plant flotsam may be observed on the surface waters of the Gawler River estuary, transported back and forth by the tides. Some of this material becomes entangled in the pneumatophores of the mangroves that overhang the water way (Fig 3.5F). Other plant debris accumulates on the muddy bed of the estuary, particularly in backwaters. The resulting sediments are therefore peats and organic rich muds. Sediments of this facies were encountered in vibrocore VC138 and are discussed further below.

FORAMINIFERAL BIOFACIES AT PORT GAWLER

mark as Fig 3.6

Sediment samples were collected, on two approximately straight line transects, from the environments described above. The first transect extended from high tide beach to the edge of the *Posidonia* meadow, the second from a small supratidal lagoon within the samphire zone to a mangrove tidal distributary. Samples of approximately 200ml were taken from the surface to a depth of about 5cm and processed for foraminiferal examination as described in Chapter 2.

In the studied size fractions, 1.00 - 0.50mm and 0.50 - 0.25mm, 28 species of foraminifera were recorded. The percentage numerical distributions of the more common species, with reference to the sedimentary environments of Port Gawler, are shown in Fig 3.7. These species are illustrated by scanning electron photomicrographs in Figs 3.8 and 3.9.

SYSTEMATIC NOTES ON SELECTED SPECIES OF FORAMINIFERA

Nubecularia lucifuga is extremely variable in morphology, its shape often influenced by the object to which it adheres. Some forms are plano-convex, the flat surface usually incomplete and revealing a planispiral arrangement of chambers. Many individuals have globular, twisted, tube like tests, with multiple apertures, and were presumably unattached. Both attached and unattached forms are recognised here as the same species.

Peneroplis planatus forms thin, translucent, planispiral tests in deeper water, but in warm intertidal areas, where salinity rises with high rates of evaporation, tests are thick and often aberrant. The range of morphology that may be observed in such populations of *Peneroplis* has been well illustrated by Sellier de Civrieux (1970) for the Mediterranean and by Hughes-Clarke and Keij (1973) for the Persian Gulf. Similar forms occur in Port Gawler sediment and are considered here as a single species.

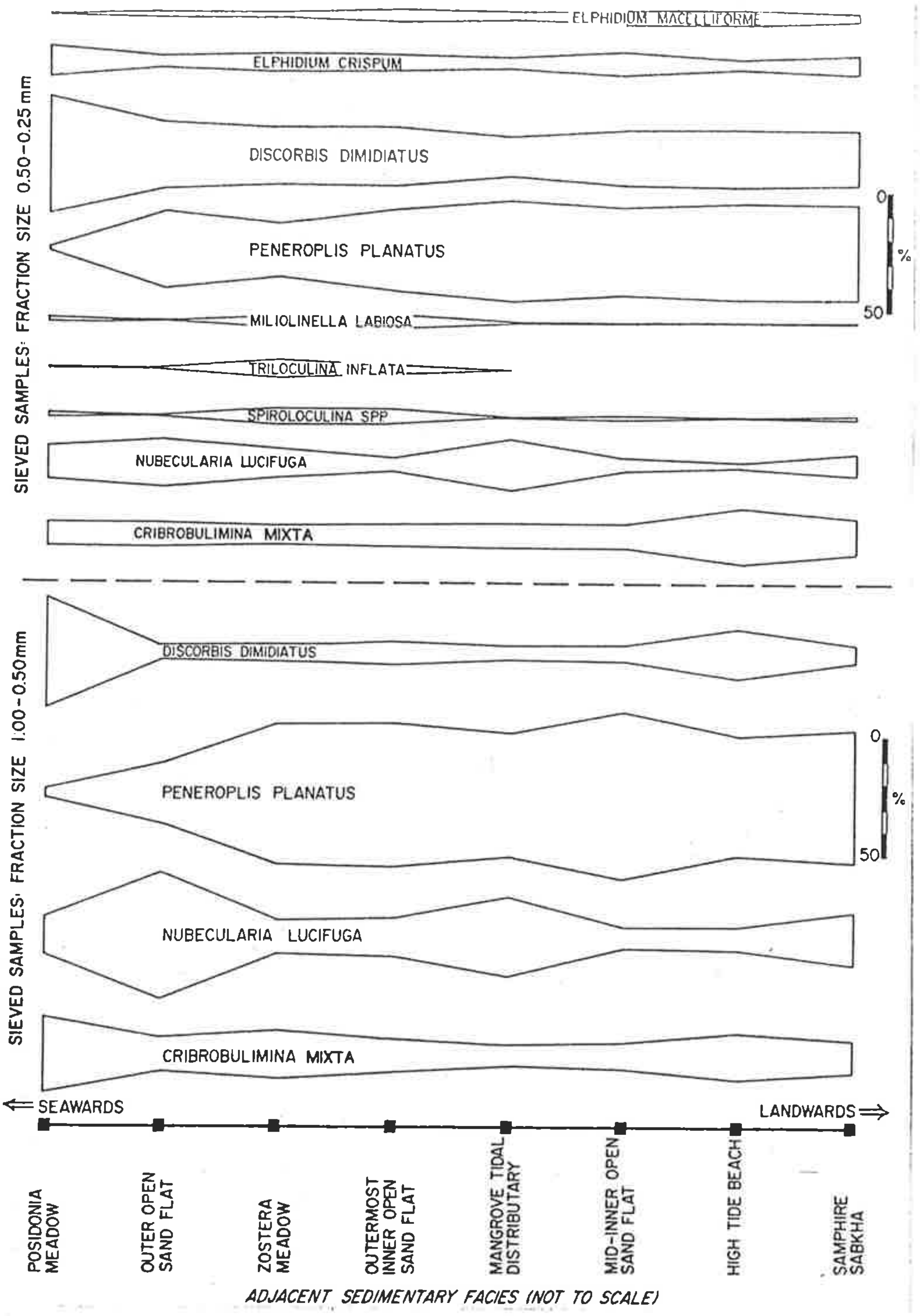

Fig 3.7
Foraminiferal biofacies; relative abundance of selected species through modern, adjacent sedimentary environments at Port Gawler.

Spiroloculina spp. here includes *S. antillarum* and also forms having chambers of more quadrate section, lacking the numerous costae of *S. antillarum,* but bearing distinct longitudinal ridges at the edges of the chambers, and often a third, parallel, and in the centre of the flat peripheral surface. Such forms are referable to *S. tricosta* Cushman and Todd, 1944. Some individuals have features intermediate between those definitive of these two species.

Discorbis dimidiatus is here used essentially in the sense of Hedley et al. (1967). They recognised that forms having greatly varying morphology, such as keeled or lobate periphery, high or low spire, large or small ventral flaps, correctly belong to a single species. All of their illustrated forms have been recognised in the Port Gawler material, and when many specimens are examined at one time, it is apparent that variation is continuous.

Elphidium macelliforme is medium to large for the genus, distinguished by its thick, lens like form, with numerous involute, non-inflated chambers. Sutures are raised, curved and limbate, joined by many slender retral processes. There is a prominent imperforate umbilical boss which is neither raised nor depressed. The interiomarginal aperture is obscured by pustular carbonate low on the apertural face. The periphery bears a low narrow keel. The surface is uniformly white and glossy.

This species, which is common in South Australian gulf waters, was established by McCulloch (1981). The present author is the first to refer individuals of the local fauna to *E. macelliforme.* It is likely that in previous records of Australian Holocene foraminifera, the species has been identified as *Elphidium advenum* Cushman 1922. Cushman (1922) originally described *E. advena* as having a depressed umbilical region, and lacking any significant boss or similar material. However, in subsequent work (1939), he referred forms having a rhomboid section and flush umbilical plug (for example, Brady, Plate CX, Figs a, b) to that species. Australian workers, such as Chapman (1941), Parr (1945) and Collins (1974), have followed this later interpretation.

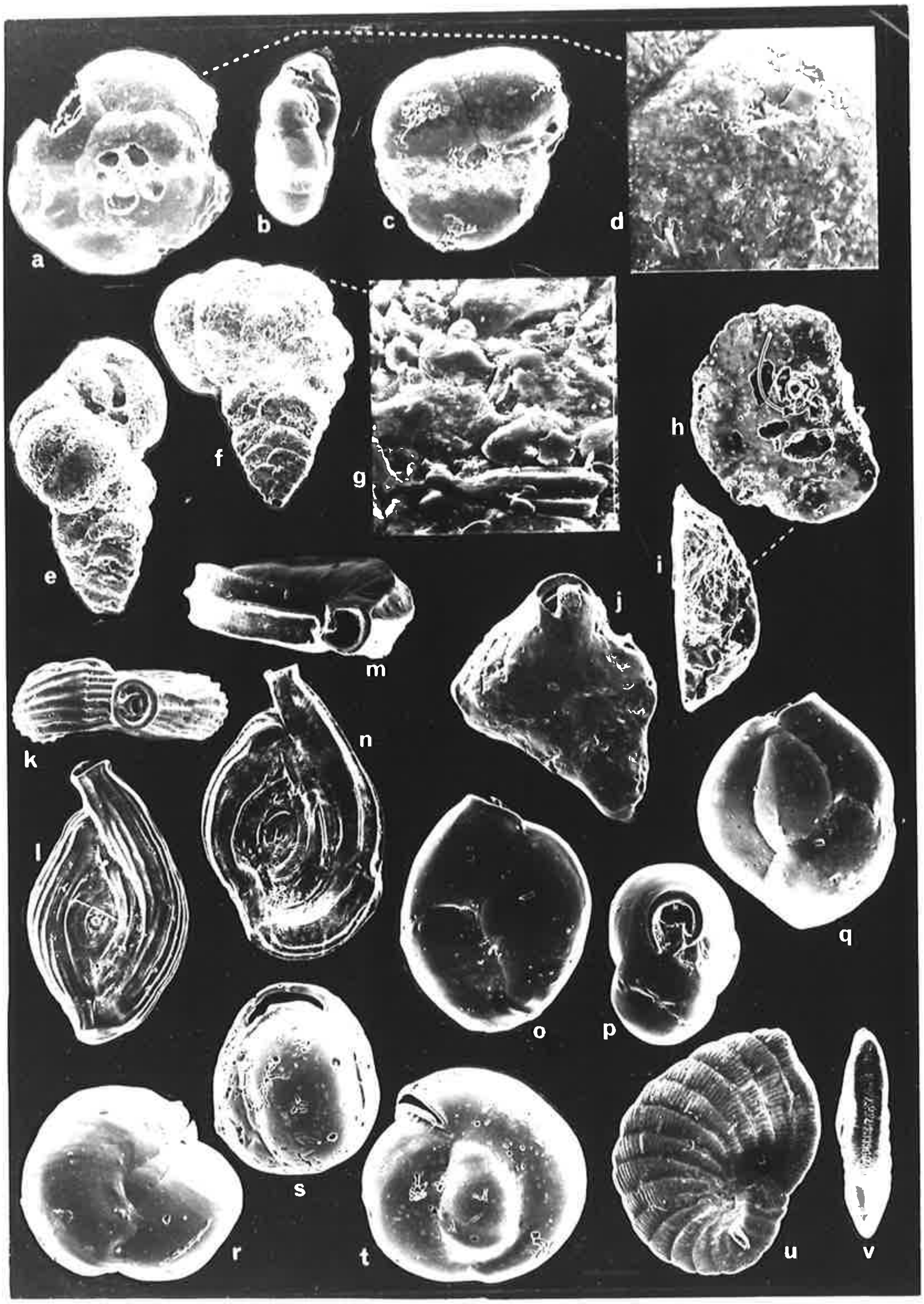
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Fig 3.8
Trochammina inflata (Montagu) 1808; **a, b, c** X120; **d** X660.
Cribrobulimina mixta Cushman 1927; **e, f** X40; **g** X660.
Nubecularia lucifuga Defrance 1825; **h, i, j** X40.
Spiroloculina antillarum d'Orbigny 1839 **k, l** X50.
Spiroloculina tricosta Cushman and Todd 1944; **m, n** X60.
Triloculina inflata d'Orbigny 1826; **o, p, q** X60.
Miliolinella labiosa (d'Orbigny) 1839; **r, s, t** X80.
Peneroplis planatus (Fichtel and Moll) 1798; **u, v** X30

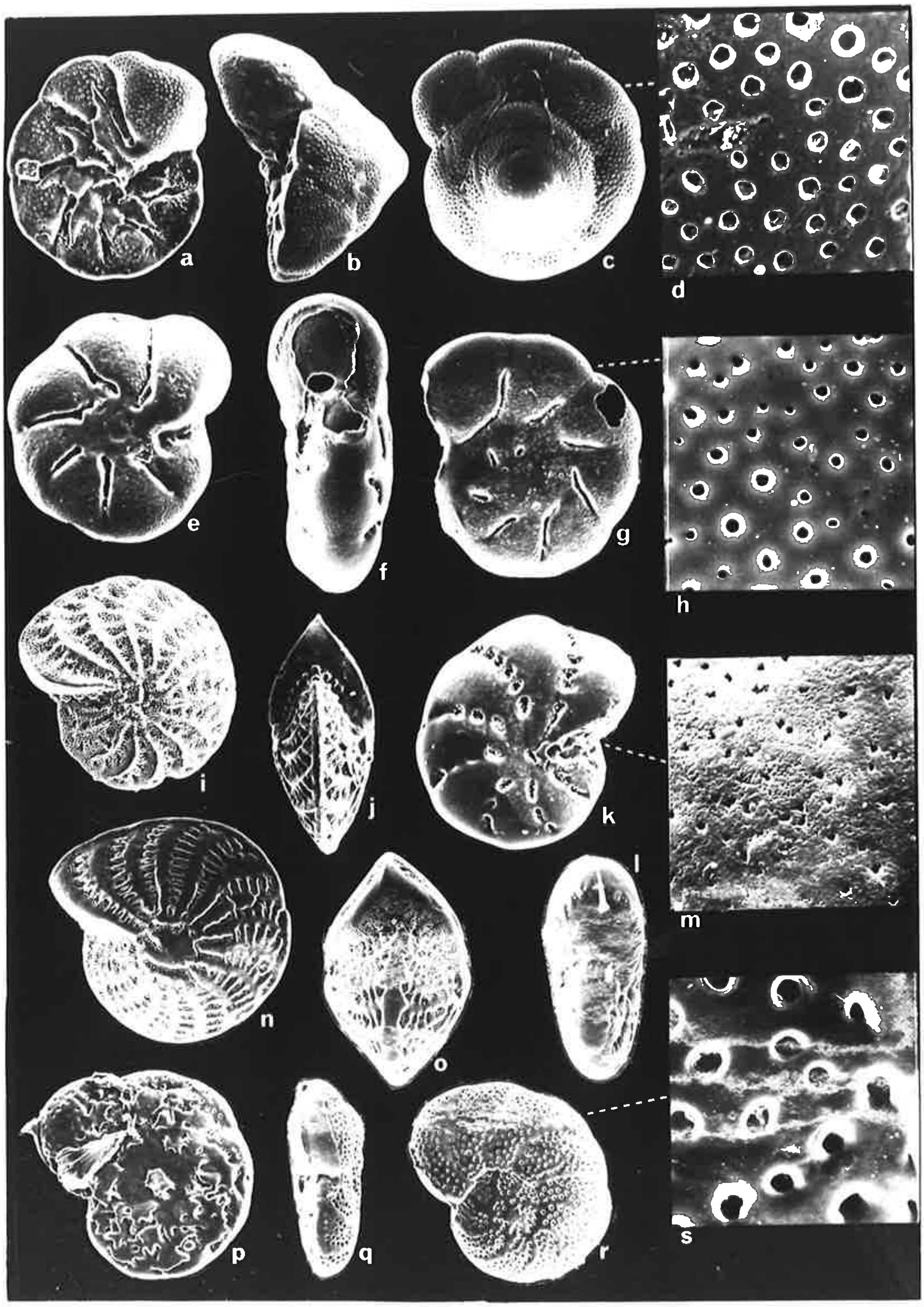
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Fig 3.9

Discorbis dimidiatus (Parker and Jones) 1862; **a, b, c** X35;
d X350.
Ammonia beccarii (Linne) 1758; **e, f, g** X120; **h** X1300.
Elphidium articulatum (d'Orbigny) 1839; **k, l** X140; **m** X3300.
Elphidium crispum (Linne) 1758; **i, j** X70.
Elphidium macelliforme McCulloch 1981; **n, o** X60.
Trichohyalus tropicus (Collins) 1958; **p, q, r** X65; **s** X650.
[Although *T. tropicus* abundance is less than 5% throughout both vibrocores, #VC136 and #VC138, it is present in significant numbers in the surface sediment of the estuarine mangrove woodland. Cann and De Deckker (1981) reported this species from a saline lake].

Vella (1957) maintained a distinction between forms having a depressed umbilicus with a small central boss of clear shell material, and those forms having the umbilicus covered by flattened, glossy plugs not protruding beyond the outline of the shell. For the latter forms Vella (1957) erected *Elphidiononion charlottensis,* which appears closely similar to the species figured by Brady, cited above.

McCulloch (1981) also believed that Cushman's later interpretation of *Elphidium advenum* included more than one species and accordingly established *E. macelliforme,* described above. Her descriptions and figures agree with a species of *Elphidium* occurring in the Holocene sediments of Port Gawler, and elsewhere in both Gulf St Vincent and Spencer Gulf.

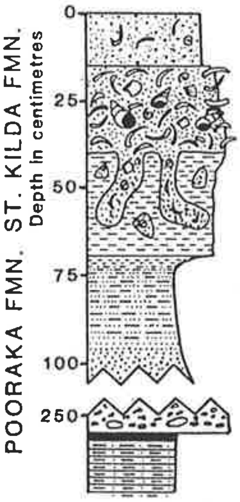
Apthorpe's *Elphidium macellum* (1980, Plate 26, Fig 11) also appears to belong to *E. macelliforme* and her *E. advena* (1980, Plate 26, Fig 10) may be a juvenile of the species.

PORT GAWLER VIBROCORES VC136 AND VC138

Vibrocores were taken at the sites indicated on the aerial photograph, Fig 3.6, VC136 on the open inner sandflat and VC138 in the mangrove woodland, adjacent to the Gawler River estaury. Both cores penetrated almost 3m of sediment.

In the laboratory, the cores were split lengthwise and lithological logs were prepared by Dr. V. A. Gostin and the present author (Figs 3.10 and 3.11). From one half, samples were taken at 25cm intervals and processed as described earlier in Chapter 2. For each sample, percentage abundances of foraminifera were determined for the size fractions 1.00 - 0.50mm and 0.50 - 0.25mm. The percentage distributions of the more common species down core are shown as Fig 3.12 and Fig 3.13, respectively, for the productive intervals of VC136 and VC138.

VIBROCORE VC 136



Description	Environment
Yellowish grey, mixed quartz-carbonate, well sorted, fine sand.	Cyanobacterial sandflat
Greyish yellow, poorly sorted, coarse shell debris with some fine quartz sand.	Storm debris shoreface
Dark greenish grey bioturbated mud with poorly sorted, muddy, shell debris and fine quartz sand.	Samphire
Dark yellowish brown, indistinctly mottled, micaceous, sandy silt. Silty, very fine, quartz sand.	Alluvial flood plain
Mean grain size increases down core to very coarse , angular, quartz sand with quartz pebbles.	River channel
Dark yellowish brown clay.	
Reddish brown, stiff, sandy mud.	Alluvial flood plain

Penetrated 294 cm
Recovered 272 cm

Fig 3.10
Descriptive and interpretive log of vibrocore #VC136.

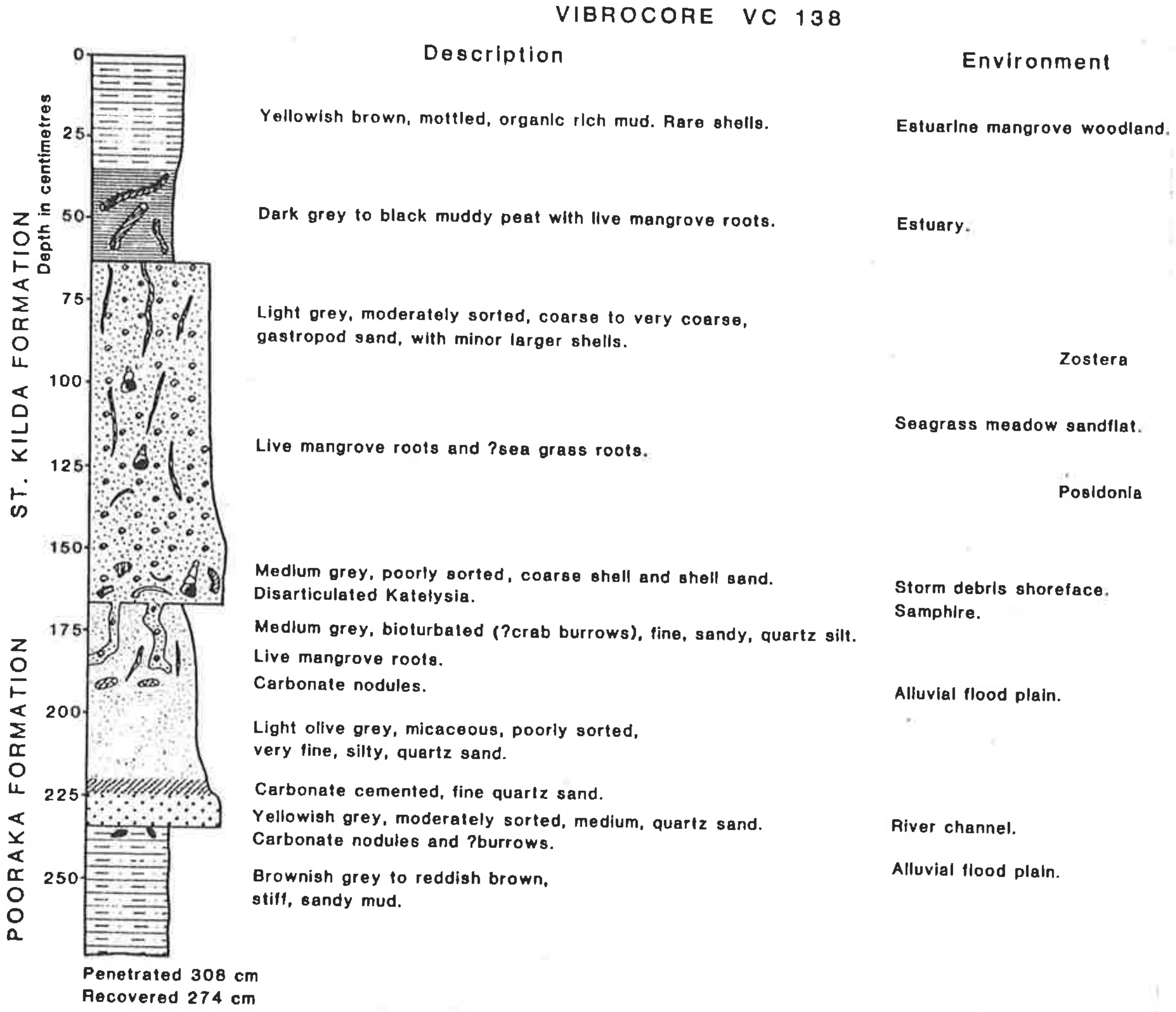


Fig 3.11
Descriptive and interpretive log of vibrocore #VC138.

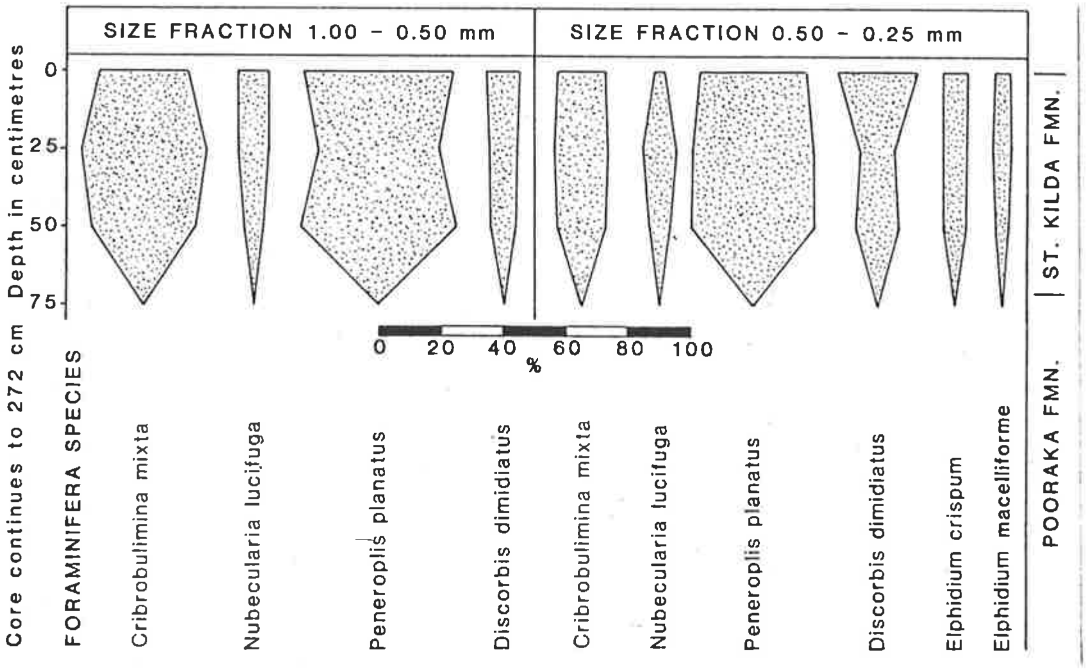


Fig 3.12

Percentage distributions of selected species of foraminifera within vibrocore #VC136, open inner sandflat, Port Gawler.

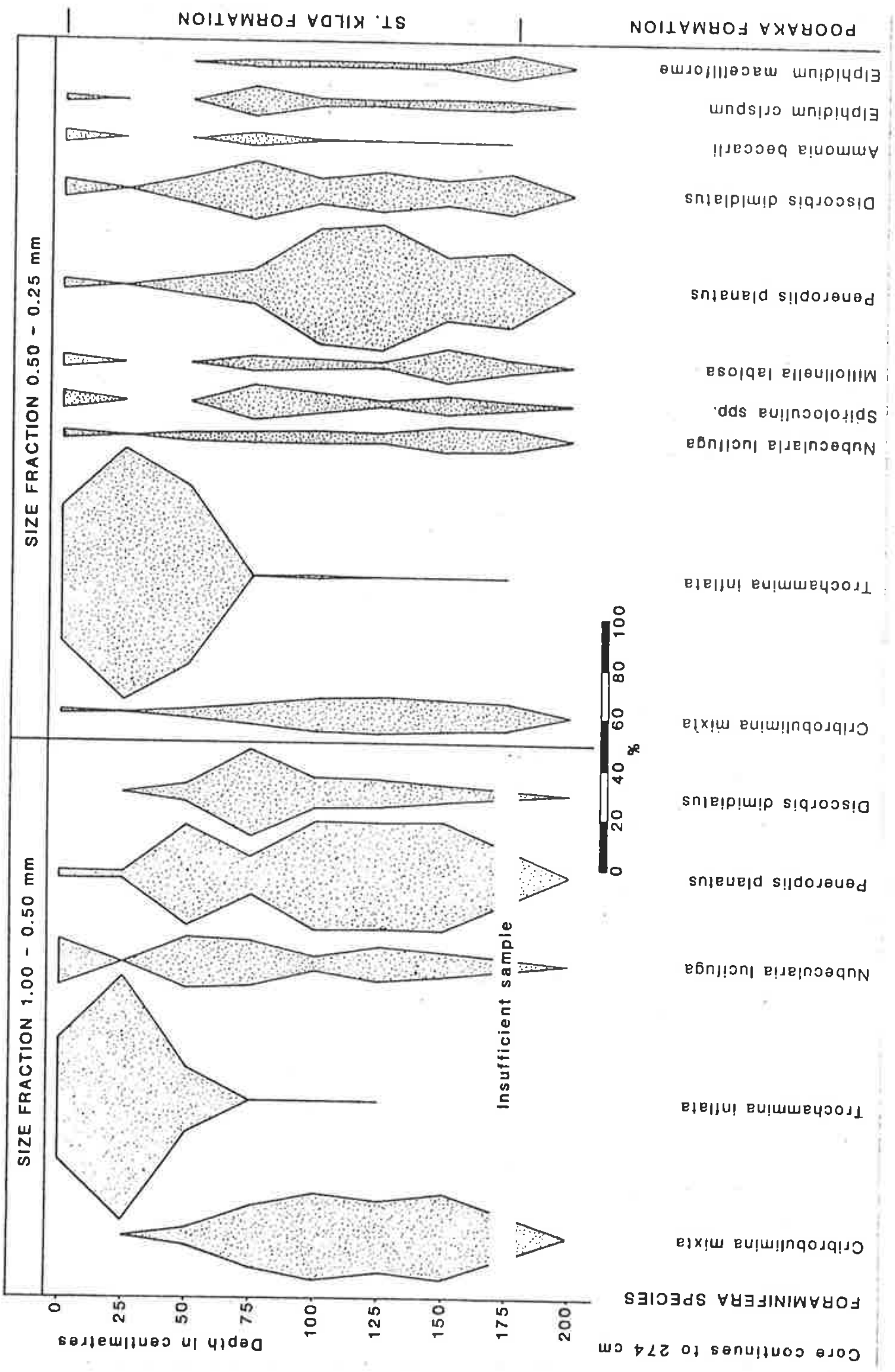


Fig 3.13

Percentage distributions of selected species of foraminifera within vibrocore #VC138, estuarine mangrove woodland, Port Gawler.

Each core represents a sequence of near shore marine environments, recording both the initial Holocene transgression and some of the later episodes of sedimentation that followed sea level stability. The down core foraminiferal assemblages are, at least in part, indicative of those environments, and may be compared with the foraminiferal data obtained for the various facies described earlier.

The reliability of the data was initially tested by comparing two samples from the cyanobacterial mat facies of the inner sand flat, the first from the surface transect, the second from the top of vibrocore VC136 (Fig 3.14). The data for the size fractions 0.50 - 0.25mm are remarkably similar. Less similarity is shown by the coarser fractions, perhaps reflecting the smaller number of specimens counted for that size range. The numbers of individuals recovered from the 1.00 - 0.50mm fractions were 80 and 123 for the transect sample and top of VC136 respectively. Equivalent numbers for the finer fractions were 211 and 717.

For the sediment size fraction 0.50 - 0.25mm, where the number of individual foraminifera comprising the fraction is approximately 200 or greater, the percentage abundance of species can therefore be regarded as a reliable environmental indicator.

RESULTS AND INTERPRETATION OF CORES

Vibrocore VC136

The earliest sediments of the St Kilda Formation recorded in vibrocore VC136 represent the supratidal facies of the samphire zone. This is signified by the closely similar distributions of species in the core sample at 50cm, and the transect sample from the modern samphire zone (Fig 3.15). The overlying coarse shelly sand, sampled at 25cm, is interpreted as remnant storm driven shell debris. Although no foraminiferal data were determined for an actual storm ridge, the percentage abundance of species obtained for the high tide beach, developed on the seaward side of a low storm ridge, is essentially similar to that at 25cm in VC136. The top sample of VC136 has been discussed above.

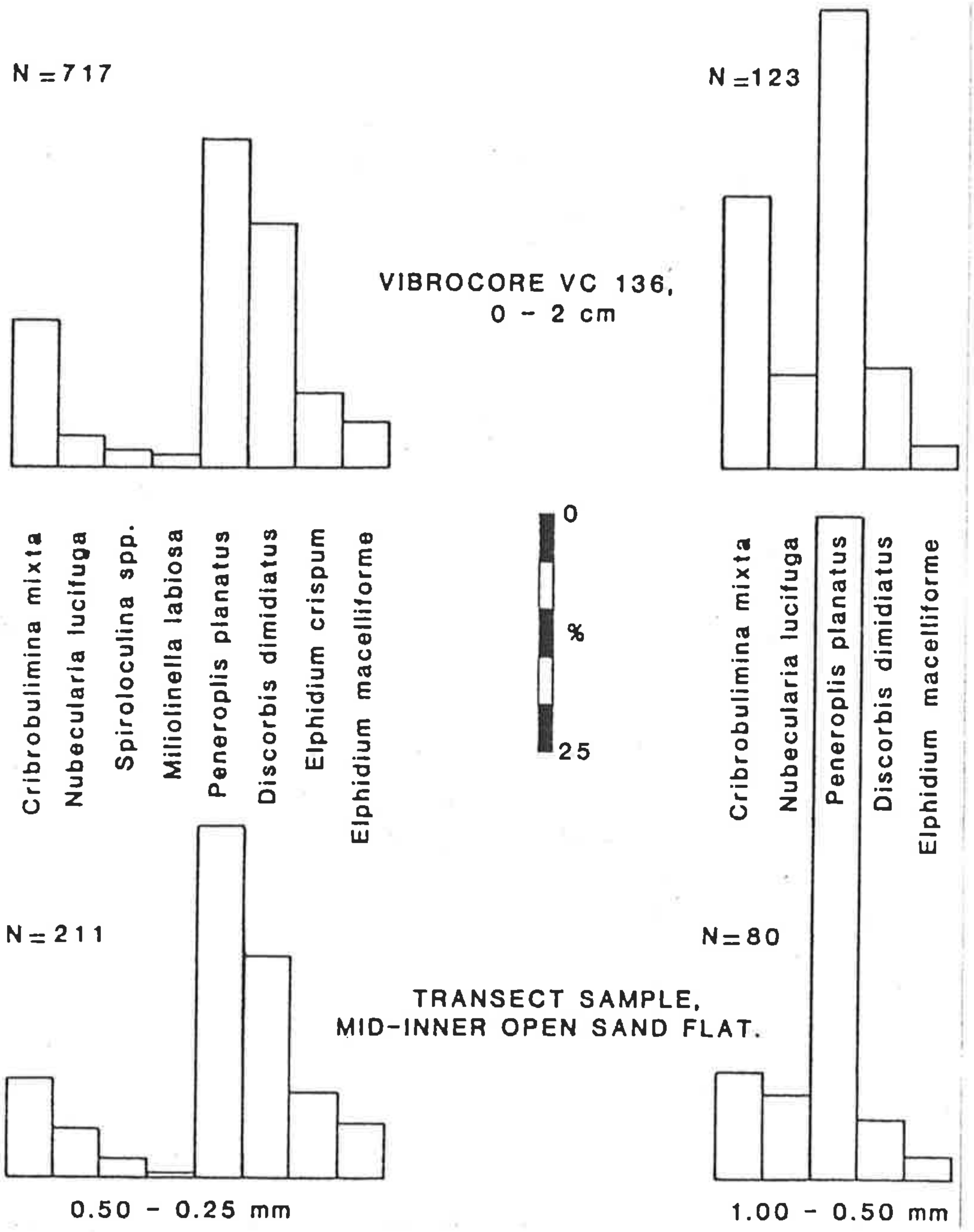


Fig 3.14
Comparative percentage distributions of species of foraminifera for two samples from the inner open sandflat. **N** refers to the number of individuals constituting the size fraction.

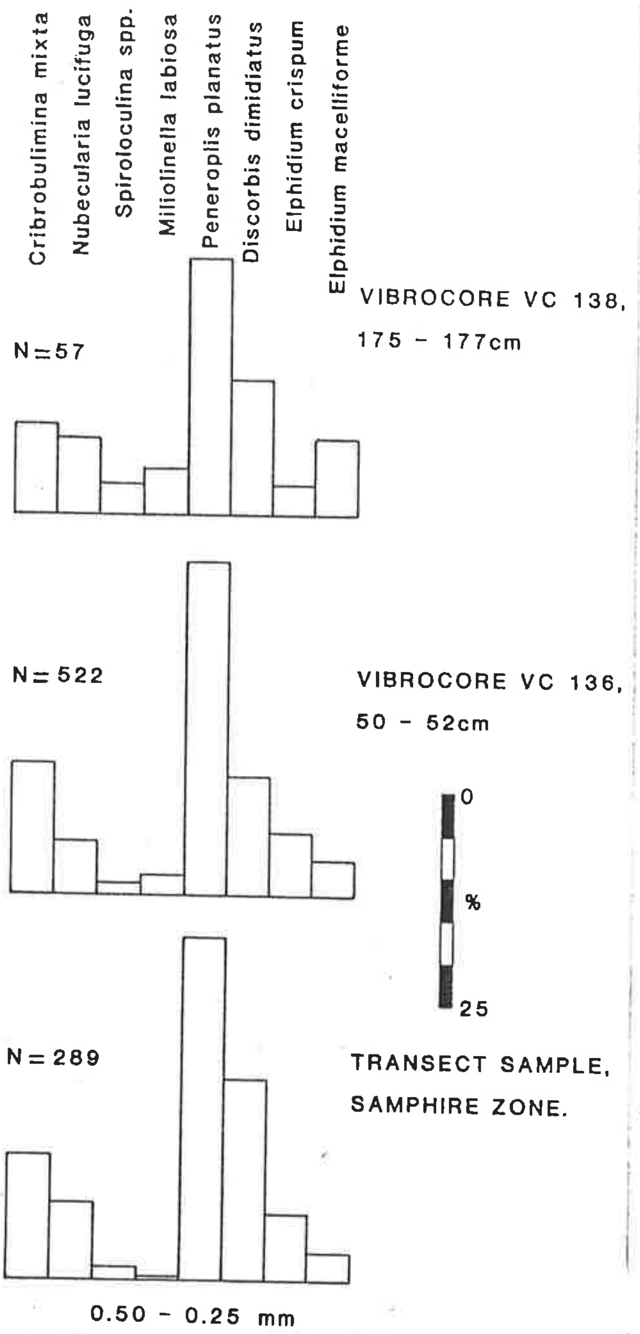


Fig 3.15
Percentage distributions of species of foraminifera for samples from vibrocores #VC136 and #VC138, compared with a surface sample from the samphire zone. Only the size fraction 0.50 - 0.25mm is considered. **N** refers to the number of individuals constituting the size fraction. The similarity of the histogram for the samphire zone and the mid-inner open sandflat (Fig 3.12) reflects the landward sites of deposition and similarity of sedimentary processes.

Vibrocore VC136 thus records the Holocene transgression as initially marginal marine supratidal sediments, overlain by storm debris, remnant of the episodes of storm ridge formation. The uppermost sediments are the result of aggradation on cyanobacterial mats.

Vibrocore VC138

The proximity of the site of vibrocore VC138 to the Gawler River estuary suggests that sediments penetrated by this core would have been deposited under conditions of fluctuating salinity. However, tidal channels 2km and 2.5km south east of Port Gawler probably indicate former sites of debouchment of the Gawler River. The present course of the estuary has apparently developed only in later Holocene.

Although only 57 individuals are recorded at 175cm in VC138, for the size fraction 0.50 - 0.25mm, the percentage distribution of species of foraminifera agrees well with data established for supratidal samphire sediments (Fig 3.15). The distribution of species at 125cm is very similar to that observed for the high tide beach and apparently indicates storm sediment. Thus, the transgressive sequences of VC138 and VC136 are essentially the same.

From 100cm to 75cm the increase in numbers of *Spiroloculina* spp., *Miliolinella labiosa, Discorbis dimidiatus* and *Elphidium crispum,* with decreasing numbers of *Peneroplis planatus*, is consistent with the development of seagrasses (Fig 3.16). Over this same interval, the increase in abundance of *Ammonia beccarii*, a noted polyhaline species (for example, Murray, 1971), suggests increased influence of fresh water from the Gawler River.

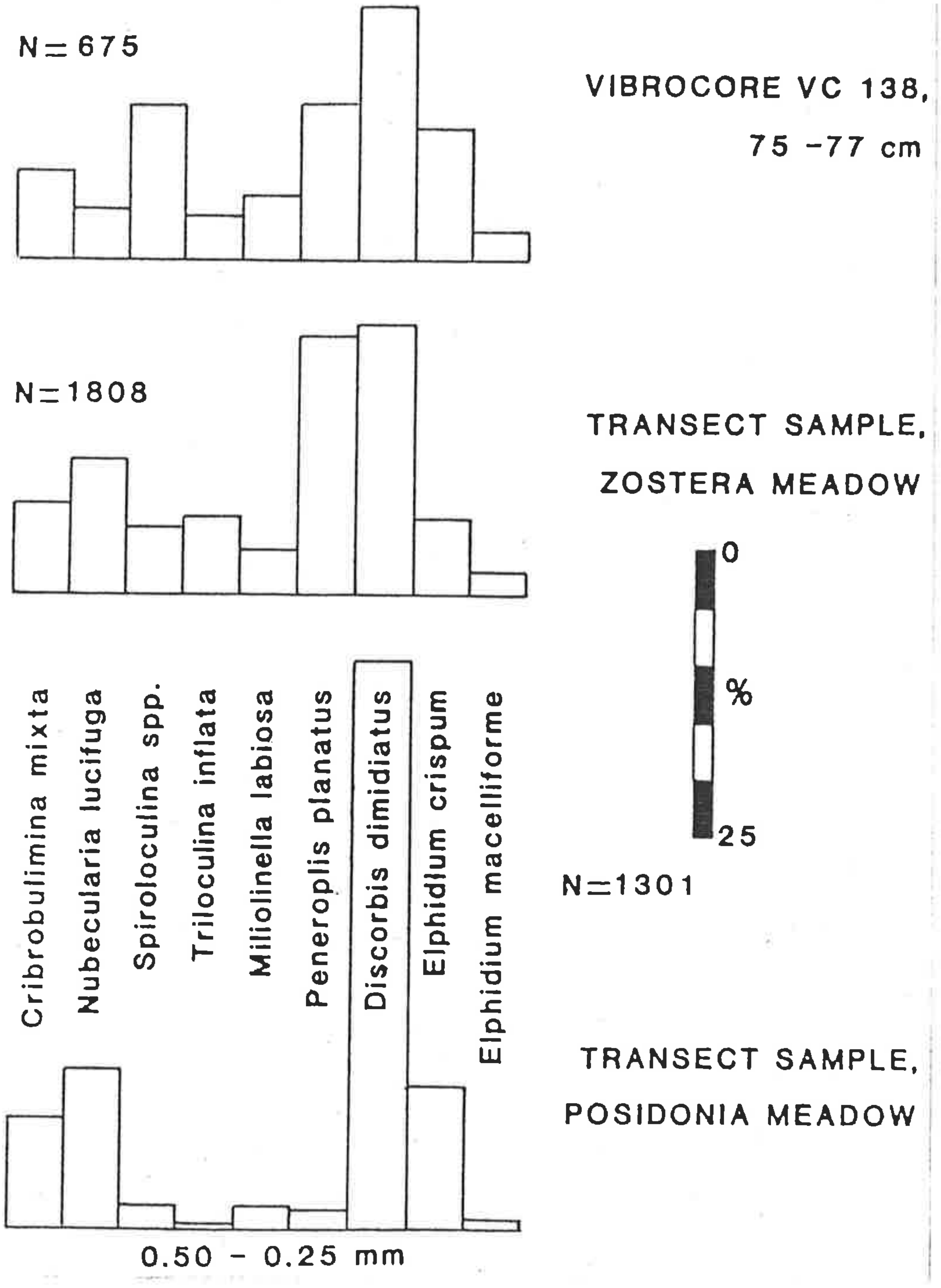


Fig. 3.16
Percentage distribution of species of foraminifera for surface samples from seagrass meadows compared with a sample from vibrocore #VC138. Only the size fraction 0.50 - 0.25mm is considered. **N** refers to the number of individuals constituting the size fraction.

A dramatic change in the foraminiferal assemblage occurs at 50cm in VC138, as *Trochammina inflata* numbers increase from almost zero to >70% and most other species disappear. *T. inflata* is well established in the literature as an estuarine dweller (for example, Collins, 1974). Apthorpe (1980) reported this species from low salinity waters of the Gippsland Lakes, Victoria. Cann (1984) found the species to be a significant component of the foraminiferal fauna of the upper Onkaparinga River estuary, south of Adelaide. The peak abundance of *T. inflata*, 100% of the 0.50 - 0.25mm size fraction at 25cm, marks the development of the Gawler River estuary at its present site.

Finally, reappearance of most species in the uppermost sediments of the mangrove woodland suggests a return to conditions of tolerable salinity. If this interpretation is correct, there may have been a real decrease in fresh water debouchment due to increasing climatic aridity, or due to human modification of fresh water drainage since European settlement of the area. Alternatively, the reappearance of these species may simply be due to the trapping of seagrass debris, with associated foraminiferal tests, by the pneumatophores of the recently grown mangroves.

CONCLUSIONS

The sediments at Port Gawler record depositional events at northern Gulf St Vincent since stabilisation of Holocene sea level. In the final stages of the post glacial Holocene transgression, an originally alluvial landscape was rapidly modified as storm shell ridges were thrown up along the north eastern coast of the gulf, transgressing supratidal samphire marshlands. With stability of sea level came an ordered ecological zonation of marine plants and animals which greatly influenced shallow subtidal, intertidal and supratidal processes of sedimentation. The relationship between plant commmunities and aggradation of sediment led to a succession of plant community/sediment associations. Shallow subtidal *Posidonia* seagrass meadows, with coarse shelly sands, gave way through aggradation to intertidal *Zostera* seagrass meadows which trapped and bound more muddy sediments.

These conditions were then favourable for colonisation by mangroves and cyanobacterial mats which, in their own ways, further contributed to sedimentation. Even in the supratidal environments, a combination of fluvio-marine and aeolian processes has ensured that the area is one of sediment accumulation. Through progadation, the various sediment/organism facies/zones gradually migrated seawards as a significant Holocene sedimentary event.

Within the various facies/zones the distributions of species of foraminifera are distinctive and can be differentiated from those of adjacent environments. These same distributions of species can be recognised in sediments recovered by vibrocores, thus permitting palaeoenvironmental interpretations of successive stratigraphic horizons. Any geological history derived from such data can be related to change of sea level.

CHAPTER 4

Distribution of species of benthic foraminifera compared with water depth, surficial sediments of northern Spencer Gulf, South Australia.

INTRODUCTION

The study of sedimentation and foraminiferal biofacies at Port Gawler, Gulf St Vincent (Chapter 3) identified a number of potentially useful species, characteristic of marginal marine intertidal and supratidal environments. The aim of the investigation reported in this chapter was to identify those species of foraminifera that might be characteristic of deeper subtidal gulf waters. At the time of the investigation, no suitable sediment samples had been collected from Gulf St Vincent, but material from adjacent Spencer Gulf was available to the author. This chapter describes the distribution of benthic foraminifera along a transect in subtidal waters, up to 20m deep, in northern Spencer Gulf. The relationship of species distribution to water depth is evaluated.

Some results of this investigation are reported in Cann and Murray-Wallace (1986), Cann et al. (1988) and Gostin et al. (1988).

THE STUDY AREA

Surficial sediment samples were obtained as tops of vibrocores taken along a transect from about 5km south of Whyalla to about 25km west of Port Pirie, northern Spencer Gulf (Fig 4.1). Water depths along this transect ranged from slightly shallower than 10m to a little deeper than 20m.

Relevant climatic and oceanographic data for the study area are given by Burne and Colwell (1982) and Gostin et al. (1984a) and in references cited by these authors. Waters along the transect have salinity values in excess of those of the open ocean, such as $41^{0}/_{00}$ across Eastern Shoal (Fig 4.1).

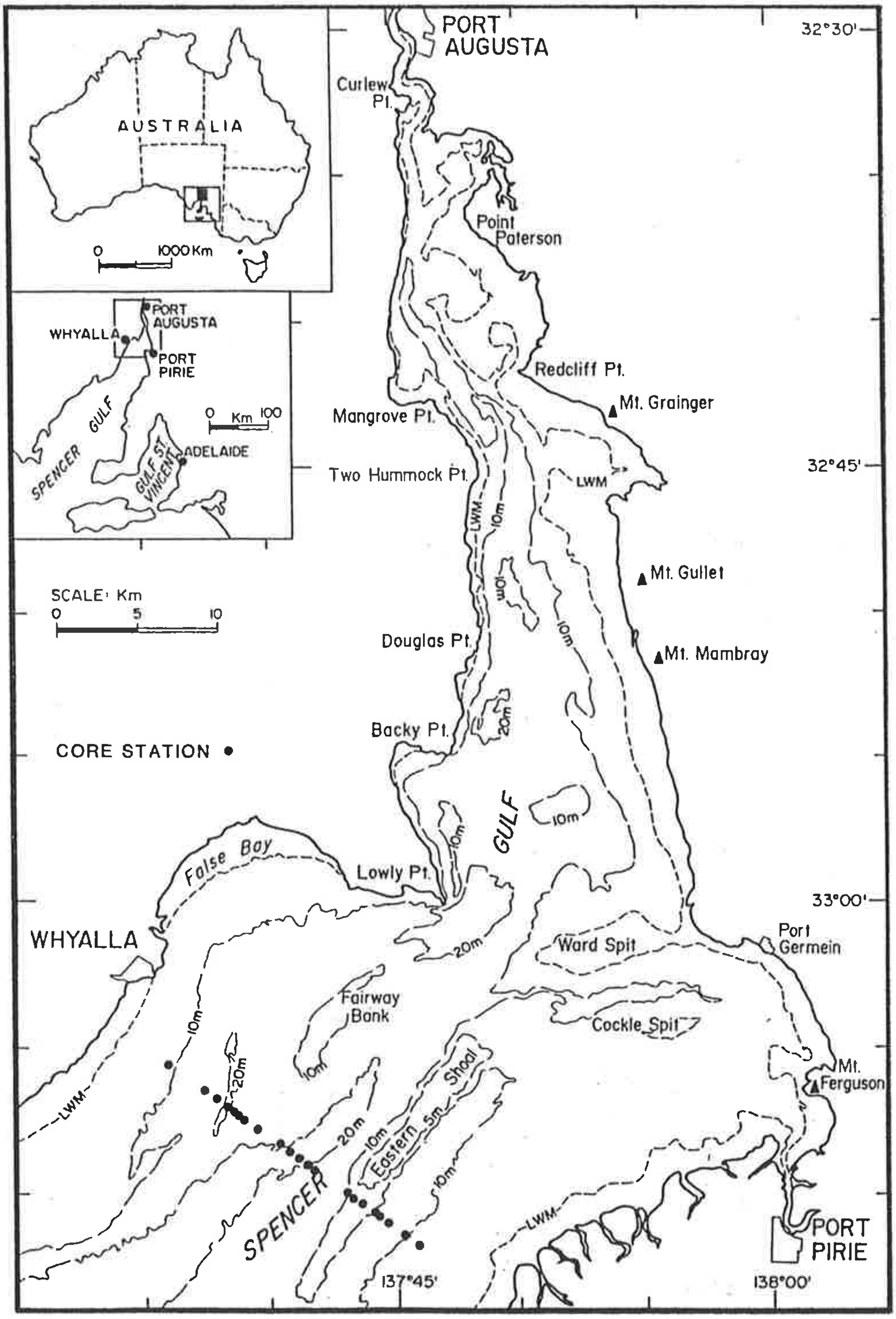


Fig 4.1
Map of northern Spencer Gulf showing locations of core stations along a transect in the vicinity of Whyalla and Port Pirie. Modern sediments from these sites yielded foraminifera which were the subject of the investigation reported in this chapter.

Such high values in northern Spencer Gulf result from hot dry summers with evaporation rates of about 2400mm/yr. Winter rainfall of about 300mm/yr is rarely sufficient to cause runoff directly into the northern gulf. Water temperatures ranging from 13.5^{0}C minimum to 23^{0}C maximum are reported for Eastern Shoal (Shepherd, 1973).

Posidonia seagrasses are prolific in subtidal waters shallower than 10m. As at Port Gawler, these seagrass meadows host an abundance of carbonate fixing organisms and they are largely instrumental in trapping and binding the resulting bioclastic sediment. Terrigenous sediment is introduced by ephemeral creeks only in times of flood, so sediments along the transect are predominantly bioclastic carbonate sands and muds. Burne and Colwell (1982) have identified northern Spencer Gulf as a high salinity "foramol" province, in the sense of Lees and Buller (1972), terminology endorsed by Gostin et al. (1988).

METHODS

The transect vibrocores, recovered by other researchers (see Chapter 5) had been split lengthwise and lithological logs prepared (Hails et al., unpublished). Sediment samples taken from the uppermost 2cm of one half of each core were processed for foraminiferal analysis as described in Chapter 2. For each sample, percentage abundances of species of foraminifera were determined for the size fractions 1.00 - 0.50mm and 0.50 - 0.25mm. The coarser fractions yielded an average total count of almost 300 individuals. An average of slightly more than 500 individuals were counted for the finer fractions.

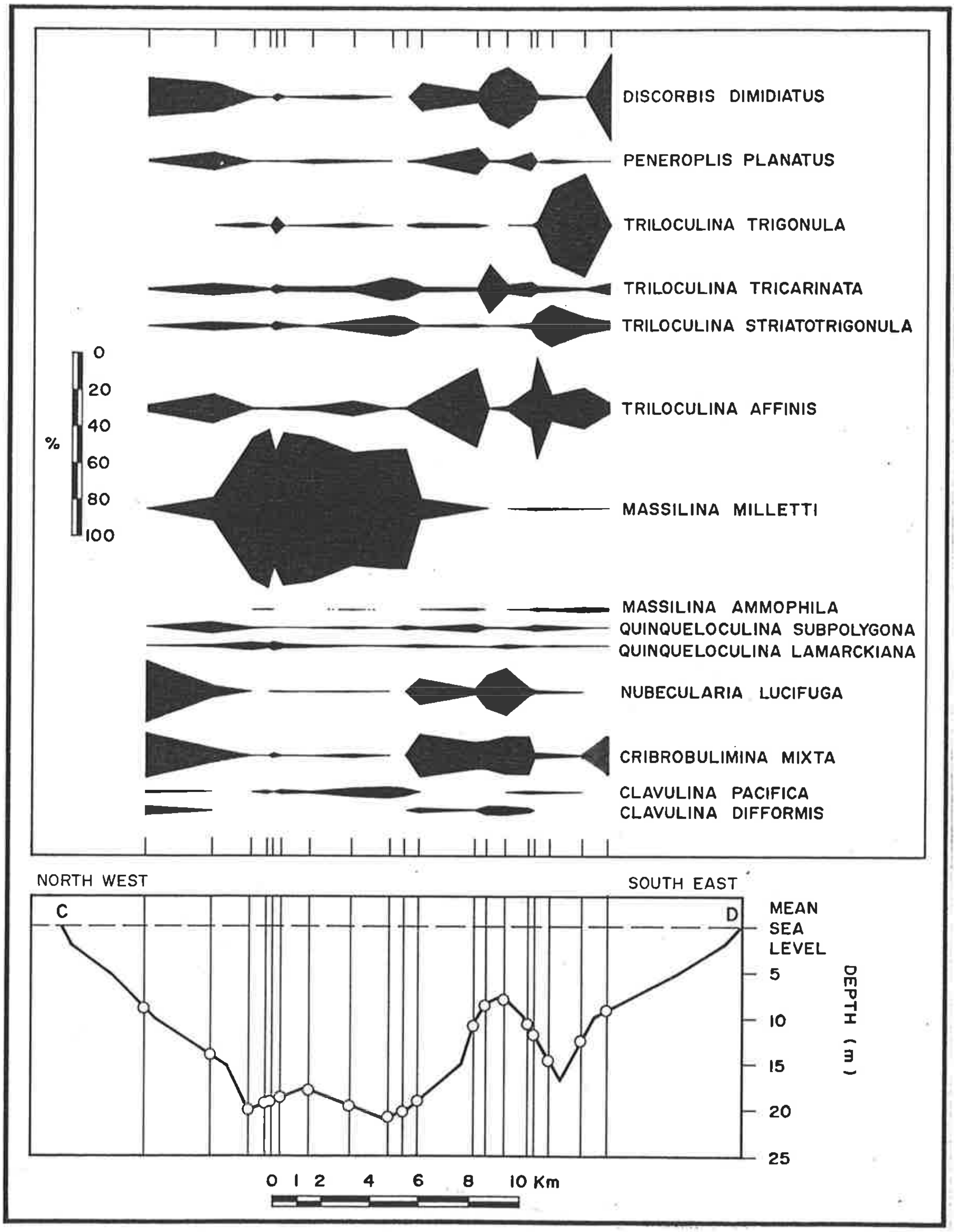


Fig 4.2

Percentage distributions of selected species of benthic foraminifera compared with water depth profile along the transect indicated on the location map (Fig 4.1).
Size fraction 1.00 - 0.50mm.

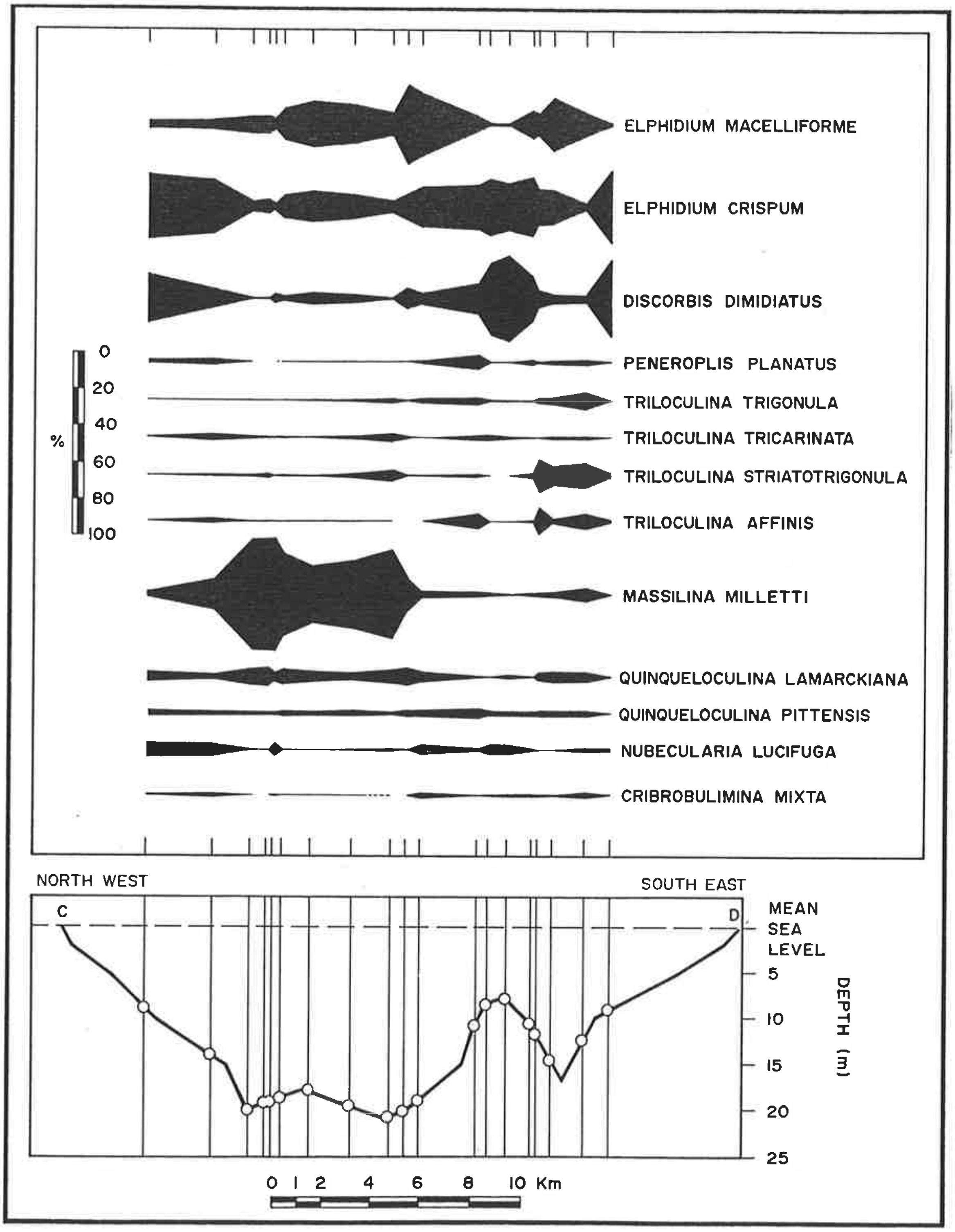


Fig. 4.3
Percentage distributions of selected species of benthic foraminifera compared with water depth profile along the transect indicated on the location map (Fig 4.1).
Size fraction 0.50 - 0.25mm

RESULTS

Species of foraminifera comprising at least 5% of counted individuals, for at least one sample along the transect, are considered to be statistically significant for the transect. Percentage distributions of all such species are compared with the water depth profile in Fig 4.2 for the size fraction 1.00 - 0.50mm and Fig 4.3 for the finer size fraction 0.50 - 0.25mm.

DISCUSSION

In the coarser fraction it is most obvious that *Massilina milletti* is the predominant species in the deeper water assemblages. The large numbers of this species, and its clear relationship to water depth, indicate its potential use as a fossil in palaeoenvironmental investigations.

A more subtle relationship to water depth is shown by the two species of *Clavulina*. *C. difformis* has maximum abundance in shallow waters to the north west and over Eastern Shoal. *C. pacifica*, on the other hand, is only sporadically present in the shallows, favouring the deeper central gulf waters. These species, if present together as fossils in significant numbers, could also be useful indicators of palaeo water depths.

Of the four species of *Triloculina*, the relationships between numerical distributions and water depths are not as clear. *T. affinis* appears to have a preference for depths of 10-15m, the species conspicuously avoiding the more shallow waters of Eastern Shoal. Similarly, *T. striatotrigonula* exhibits maxima either side of Eastern Shoal, but in slightly deeper water. The large population of *T. trigonula* south east of Eastern Shoal, and the low numbers at comparable depths elsewhere on the transect, suggest that a factor or factors other than water depth may be primarily responsible for its polarised distribution. There is no immediately discernible relationship between the distribution of *T. tricarinata* and water depth.

Discorbis dimidiatus, Nubecularia lucifuga and *Cribrobulimina mixta*, previously noted from intertidal Port Gawler (Chapter 3), are now shown to significantly range to depths of around 10m. The distribution of *Peneroplis planatus*, however, appears to be bimodal, favouring the inner sand flat at Port Gawler, and depths of 10-15m on this northern Spencer Gulf transect. Also, these deeper water individuals have relatively thin, translucent tests of more uniform shape, by comparison with those reported from Port Gawler.

Given that the water depth range of *Posidonia* seagrasses in northern Spencer Gulf is 0-10m, it seems likely that distribution of the seagrass meadows is a major factor influencing the depth zonation of foraminifera species shown in Figs 4.2 and 4.3. Burne and Colwell (1982) include *Discorbis* spp., *Peneroplis* spp. and *Nubecularia* sp. as forms of foraminifera "most common in sea-grass areas" of upper Spencer Gulf. Their *Spiroloculina* spp. probably includes *Massilina milletti*, as adult forms of *Spiroloculina* and *Massilina* are very similar in appearance. *Massilina* is distinguished by its quinqueloculine arrangement of chambers in early ontogeny (Fig 4.4).

Many species of the coarser fraction (Fig 4.2) are similarly represented in the finer fraction (Fig 4.3), the two most obvious being *Massilina milletti* and *Discorbis dimidiatus*. *M. milletti* clearly favours the deeper water beyond the seagrass meadows, while *D. dimidiatus* consistently predominates in depths of 10m or less. A few species, however, are generally smaller than 0.5mm at maturity and so are unrepresented in the coarser fraction. In this context, the two species of *Elphidium* are particularly conspicuous.

There is clearly some form of inverse numerical relationship between the distribution of *Elphidium macelliforme* and *E. crispum*. For example, across the relatively shallow Eastern Shoal, *E. crispum* constitutes approximately 30% of the assemblage, within the 0.50 - 0.25mm size fraction, while *E. macelliforme* are at a minimum for the transect. A similar relationship prevails at both the south eastern and north western ends of the transect where water depths are <10m.

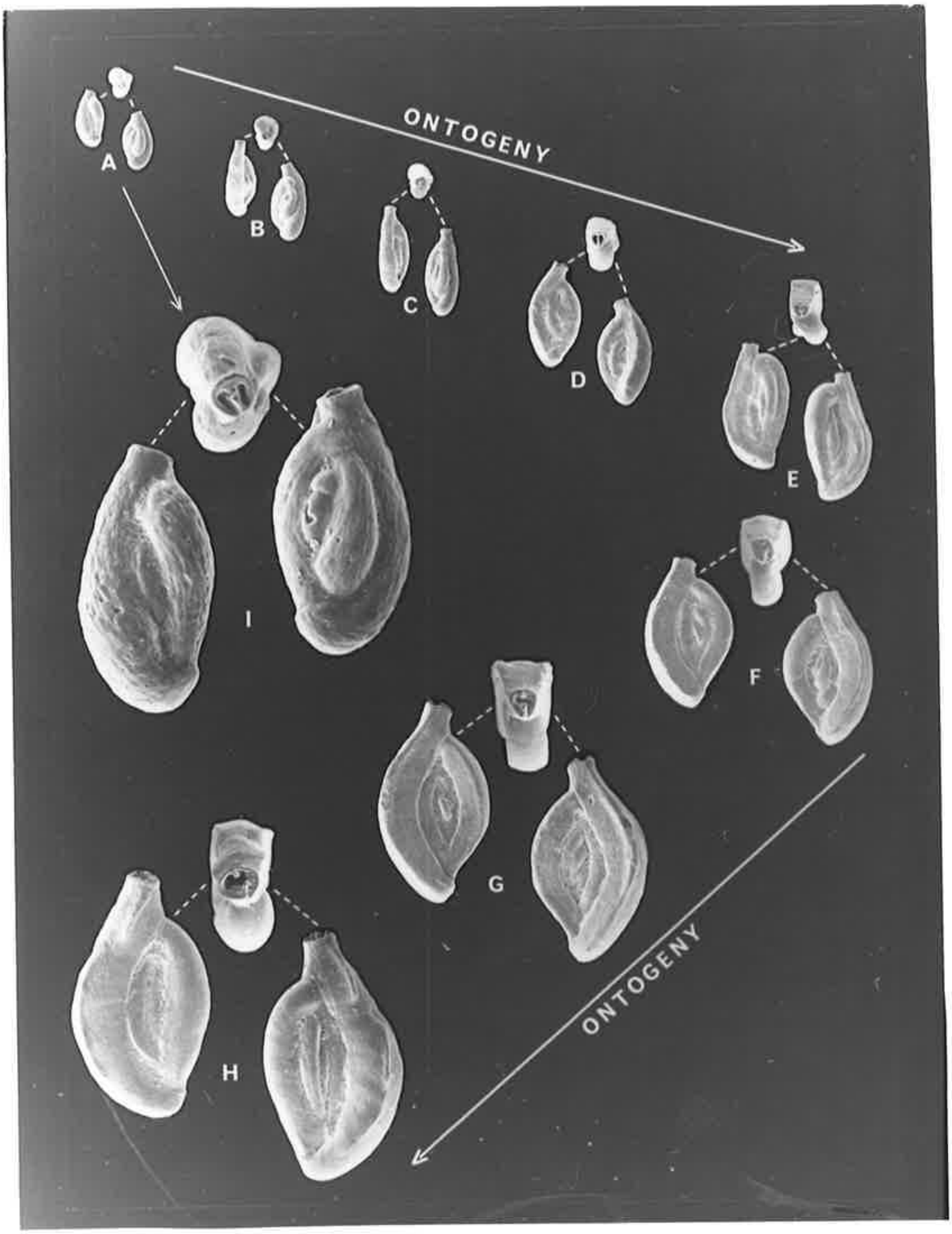

ONTOGENY
A
B
C
D
E
F
G
H
I
ONTOGENY

Fig 4.4
Reconstructed ontogeny of *Massilina milletti.*
A to H (x40) show increasing size of individuals. Juveniles show a quinqueloculine arrangement of chambers. In adults, the later biloculine chambers embrace and obscure the juvenile form. The smallest individual, A, is shown also at higher magnification (x200) as I.

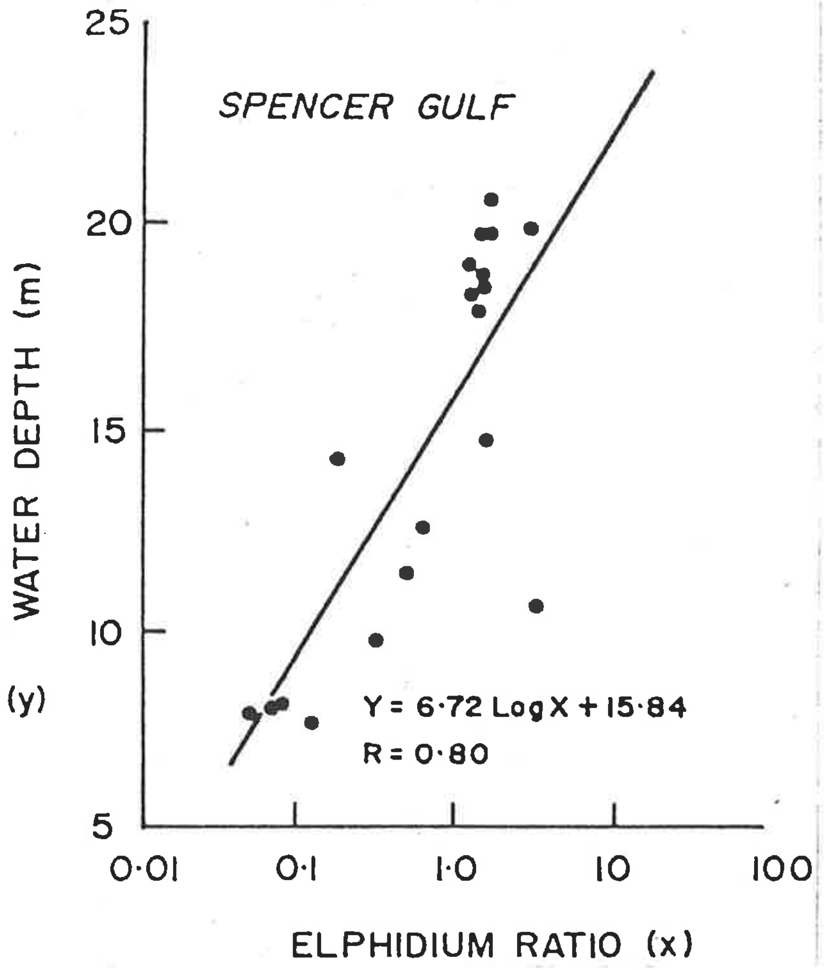


Fig 4.5
Log-linear plot of water depth versus ratio of numbers of individuals of *Elphidium macelliforme* to numbers of individuals of *Elphidium crispum* for surficial samples from northern Spencer Gulf. Also shown is the line of best least-squares fit, the calculated regression equation and Pearson's correlation coefficient for the data set.

However, in deeper waters, while it is apparent that numbers of *E. crispum* are less than those of *E. macelliforme*, the details of the relationship are less obvious.

The ratio of *E. macelliforme* to *E. crispum* is generally <0.1 in water shallower than 10m, but at depths of about 20m the ratio is about 1.0, a magnitude higher. Regression analysis of water depth versus logarithm of the *Elphidium* ratios, for all surficial samples along the transect, indicates a simple linear relationship with a correlation coefficient of 0.80 (Fig 4.5). This relationship has potential use as both a qualitative and quantitative palaeo water depth indicator. The regression equation shows that:

$$\text{water depth} = 6.72 \log \left(\frac{\text{sum of individuals of } \textit{E. macelliforme}}{\text{sum of individuals of } \textit{E. crispum}} \right) + 15.84$$

CONCLUSIONS

At the salinity and water temperature values of northern Spencer Gulf:

a) *Massilina milletti* is a very significant indicator of water depths 10-20m.

b) *Cribrobulimina mixta, Nubecularia lucifuga and Discorbis dimidiatus* are members of the *Posidonia* seagrass community and signify depths of around 0-10m.

c) *Peneroplis planatus* has a bimodal depth distribution, above and below the seagrass meadows. Individuals from depths >10m can be distinguished from those of intertidal environments in that the former, by comparison, have thin translucent tests of more consistent planispiral form.

d) *Elphidium crispum,* a shallow water species, and *E. macelliforme,* favouring deeper water, together provide a useful numerical ratio. Their logarithmic relative abundance, in the sediment size fraction 0.50 - 0.25mm, correlates closely with water depth.

Addendum to Chapter 4

The major findings of this thesis rest upon identified relationships between water depths and the numerical distributions of some species of modern foraminifera in the surficial sediments of South Australian Spencer and St Vincent Gulfs. These data have then been applied to assemblages of those same species, occurring as fossils in the submarine strata of the gulfs, to derive palaeo sea levels and other palaeoecological interpretations. The studies rely heavily on premises of uniformitarianism.

In the early stages of the work it became apparent that some species of local benthic foraminifera were numerically abundant in the shallow coastal waters, while a few others showed a marked preference for the deeper, more central parts of the gulfs. It was thus clear that these same species, as fossils, had potential to qualitatively signify palaeo water depths for their host sediments, recovered from the gulfs by vibrocoring. Thus evolved diagrams such as figures 4.2 and 4.3, which show percentage distributions of species of contemporary foraminifera, compared with water depth, across northern Spencer Gulf, and diagrams showing down core distributions of [mostly] these same species, such as figures 6.3 and 6.4 which show these data for vibrocore #SG198 from Spencer Gulf.

Interpretation of the numerical distributions of fossil species within the cores is [mostly] a relatively simple matter, given knowledge of their present day distributions, particularly with regard to water depth. For example, the early stages of marine transgressions can be identified by the relatively large numbers of shallow water species. As the seas further invaded the gulfs, inundating the shallow water habitats, these species gave way to others that favoured deeper water. The diagrams which are presented in the thesis, sometimes known as "kite diagrams", are particularly effective in their communication of these data and their implications for past sea level changes.

As numerical data accumulated through the study, the author was persuaded to explore other ways of processing the information, through application of some of the present day computer programmes in statistics. Multivariate analysis of the data did little more than confirm the obvious. Statistical packages of numerical distributions of species in surficial sediments could be related to water depths, and palaeo water depths could be derived for similar data obtained from core sediments. Two species of the genus *Elphidium*, *E. crispum* and *E. macelliforme* appeared to be particularly significant in this sense.

Elphidium crispum and *E. macelliforme* have special significance in that they are represented as species, usually together, at all water depths in the surficial sediments of the gulfs. This is in marked contrast to the majority of species, whose distribution is more tightly confined to a range of water depth. Also, both species occur throughout the stratigraphic range of the sediments recovered in the vibrocoring programme, both Holocene and Late Pleistocene. Thus, their distribution, both spatially and temporally, guarantees their potential for application in these studies.

The numerical distributions of these two species of *Elphidium* in surficial sediments, compared with water depths, is not as immediately apparent as for some other species, say *Discorbis dimidiatus*, though clearly *E. crispum* prefers more shallow waters than those favoured by *E. macelliforme* [figure 4.3]. Their relative abundance was found to have a log-linear relationship with water depth in Spencer Gulf [figure 4.5] and in Gulf St Vincent [figures 8.11, 8.12 and 8.13] and this relationship, so established, was applied to distributions of the species within vibrocores.

The following two diagrams illustrate comparisons of selected data from the thesis, compared with equivalent data derived by multivariate analysis of numerical distributions of species of foraminifera.

Table 5.1
Stratigraphic units established for late Quaternary sediments of northern Spencer Gulf (after Hails and Gostin, eds., 1984). These units are underlain by Hindmarsh Clay and unnamed "older Pleistocene marine beds" which have undergone intense pedogenic alteration (Billing, 1984).

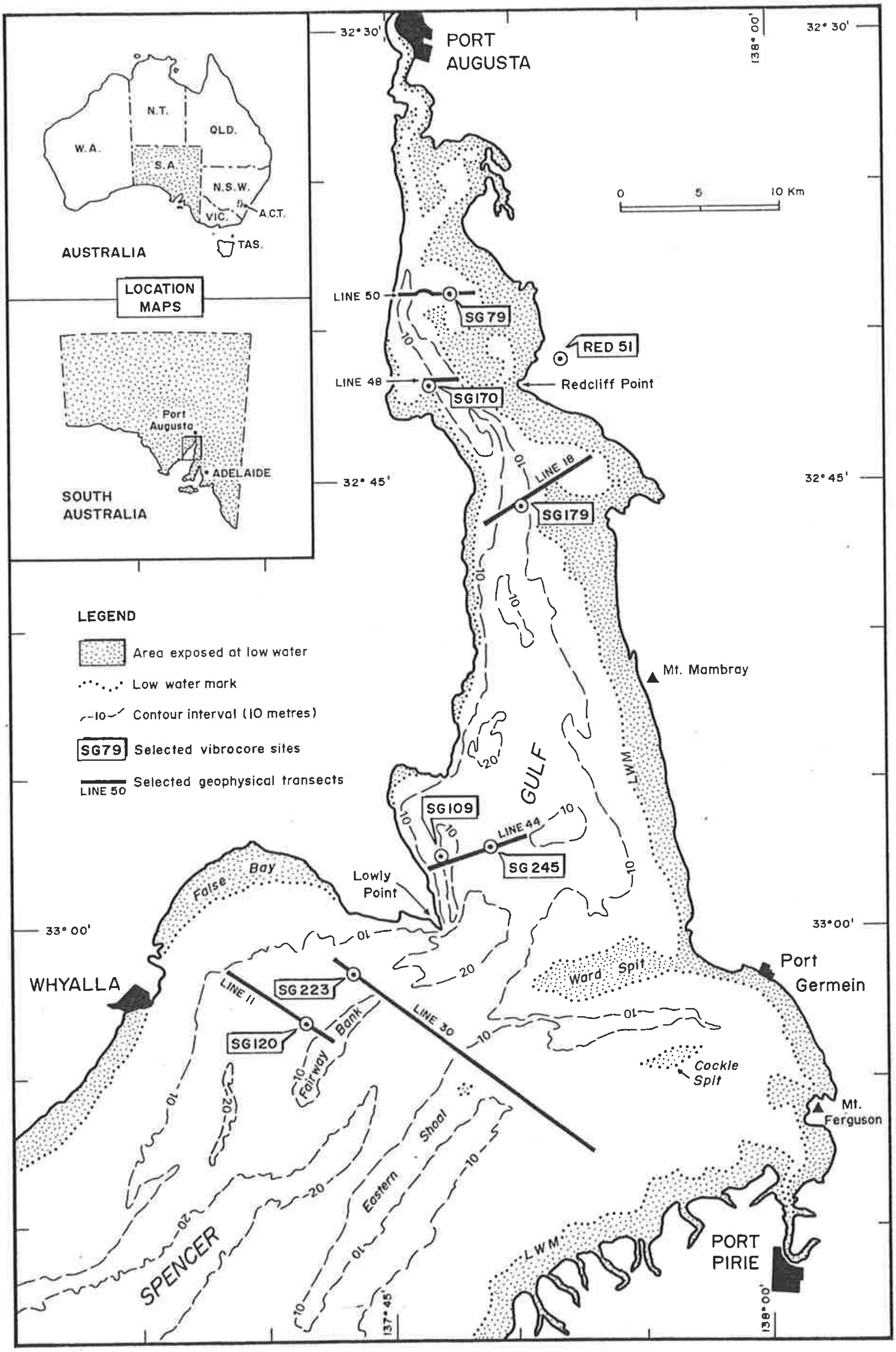
CHAPTER 5

Distributions of species of benthic foraminifera in cores of Late Quaternary sediments, northern Spencer Gulf, South Australia; inferred palaeo sedimentary environments and sea levels.

INTRODUCTION

In 1976 an extensive examination of sedimentation and stratigraphy of Northern Spencer Gulf was initiated, culminating in a series of papers describing many aspects of the late Quaternary geology of the area (Hails and Gostin, editors, 1984). A major part of the programme involved collection of sediments by vibrocores. A total of 330 cores, up to 4.5m in length, were recovered from an area north of and including the transect described in Chapter 4. Vibrocoring was generally confined to lines that were also subjected to high resolution continuous seismic reflection analysis (Gostin et al., 1984b). Lithological, pedological and limited palaeontological data from the vibrocores were matched with the seismic reflectors to construct the sub-bottom stratigraphy (Billing, 1984; Hails et al., 1984a). The stratigraphy so derived was assessed within the constraints of late Pleistocene and Holocene sea levels (Hails et al., 1984b). Thus, for northern Spencer Gulf, the stratigraphic details shown in Table 5.1 were established.

STRATIGRAPHIC UNIT	AGE yr B.P.	OXYGEN ISOTOPE STAGE	RELATIVE SEA LEVEL (m)
Germein Bay Fmn (=St Kilda Fmn)	0 - 7000	1	+1
Pooraka Fmn (non-marine)		2, 3, 4	
Lowly Point Fmn	c.82,000	5a	- 14
False Bay Fmn	c.105,000	5c	- 8
Mambray Fmn (=Glanville Fmn)	c.125,000	5e	+ 4



AUSTRALIA
W.A.
N.T.
QLD.
S.A.
N.S.W.
VIC.
A.C.T.
TAS.
LOCATION MAPS
SOUTH AUSTRALIA
Port Augusta
ADELAIDE
LEGEND
Area exposed at low water
Low water mark
-10- Contour interval (10 metres)
SG79 Selected vibrocore sites
LINE 50 Selected geophysical transects
32° 30'
32° 45'
33° 00'
138° 00'
137° 45'
PORT AUGUSTA
0 5 10 Km
LINE 50
SG79
RED 51
LINE 48
SG170
Redcliff Point
LINE 18
SG179
Mt. Mambray
LWM
GULF
SG109
LINE 44
SG245
Lowly Point
False Bay
WHYALLA
LINE 11
SG223
SG120
LINE 30
Fairway Bank
Ward Spit
Cockle Spit
Port Germein
Mt. Ferguson
Eastern Shoal
SPENCER
PORT PIRIE
LWM
10
20

Fig 5.1

Map of northern Spencer Gulf showing selected vibrocore sites and associated selected geophysical transects.
Sediment samples from the numbered vibrocores yielded foraminifera and provided materials for the investigations reported in this chapter.

Following regression of the sea from northern Spencer Gulf after deposition of the Lowly Point Formation, there was a long period of emergence, during which time the alluvial Pooraka Formation was formed. Presumably, similar deposits may have accumulated during other emergent episodes at oxygen isotope substages 5b and 5d. Palaeosols developed on Mambray, False Bay and Lowly Point Formations during regressive episodes (Billing, 1984).

While a great many vibrocores were examined to derive the above details, a small number were judged to be of such significance that, in publication, they were illustrated in colour to show lithological horizons, disconformities and palaeosols (Billing, 1984; Hails et al., 1984a). These cores and their original lithological logs were made available to the present author for foraminiferal analysis and they provided material for the work reported here. The vibrocore sites and the locations of the their associated seismic transects are shown in the location map (Fig 5.1).

AIMS

The investigations reported in this chapter set out to address a number of key questions:

a) The cores provided a potentially tight frame of reference for evaluating the significance, as fossils, of those species of foraminifera previously identified (Chapters 3 and 4) as likely indicators of past sedimentary environments, particularly with reference to water depth. For example, would the Holocene sequences show initial transgressive assemblages of shallow water species, such as *Discorbis dimidiatus* and *Nubecularia lucifuga,* giving way to deeper water assemblages dominated by *Massilina milletti*?

b) Would changes in assemblages of species document the marine transgressions and regressions of the three late Pleistocene formations?

c) Would changes in the ratio of numbers of *Elphidium macelliforme* to numbers of *E. crispum* throughout the cores provide meaningful signals for past changes in relative sea level?

d) *Marginopora vertebralis* is known to have become locally extinct after deposition of the Glanville (=Mambray) Formation (Cann, 1978 and references therein). In local late Pleistocene stratigraphic studies, the presence of this fossil species is *prima facie* evidence of deposition during oxygen isotope substage 5e. Are there other species that might serve as biostratigraphic indicators for the late Pleistocene formations represented by the cores?

e) Can meaningful biostratigraphic correlations be established between cores that recovered sediments of the same formations?

METHODS

From one half of each of the split cores, sediment samples through 2cm were taken at 25cm intervals, for example, core depths 0 to 2cm, 25 to 27cm, etc. Occasionally circumstances such as previous sampling or palaeosol lithification enforced minor modification of the sampling interval. Generally, the cores had, to some extent, discoloured and hardened since split by the original researchers, and sampling palaeosol horizons was particularly difficult. Foraminifera were extracted from the samples following procedures outlined in Chapter 2.

For all floated concentrates, percentage abundances of species were determined for the size fractions 1.00 - 0.50mm and 0.50 - 0.25mm. These data were in most instances based on counts of >200 individuals per fraction, though some samples yielded insufficient foraminifera for percentage values to be statistically meaningful. This was particularly so for some pedogenic horizons.

Because of the special significance of the ratio of numbers of *Elphidium macelliforme* to those of *E. crispum*, the calculated relative abundance of these species was often refined by additional supplementary counting. Where possible, a combined total of >100 individuals of these species was used to determine this ratio for a sample.

RESULTS

Downcore analysis of foraminifera for each of the eight selected reference cores are presented in this chapter as separate diagrams for the 1.00 - 0.50mm and 0.50 - 0.25mm size fractions. In each case the diagrams are accompanied by details of the original unpublished lithological log and, where applicable, that published by Billing (1984). Also presented are details of the stratigraphic setting of the core, taken from Hails et al. (1984a) and, again where applicable, from Billing (1984) (Table 5.2). Thus, the foraminiferal assemblages at each sampled horizon of a core can be assessed within the frame of reference previously established by the original researchers.

Again, for each core, the ratio of the numbers of individuals of *Elphidium macelliforme* to those of *E. crispum* has been logarithmically plotted against sample depth in core. Larger values of the *Elphidium* ratio signify relatively deeper waters and *vice versa*, so these diagrams can be regarded as *de facto* palaeo water depth curves.

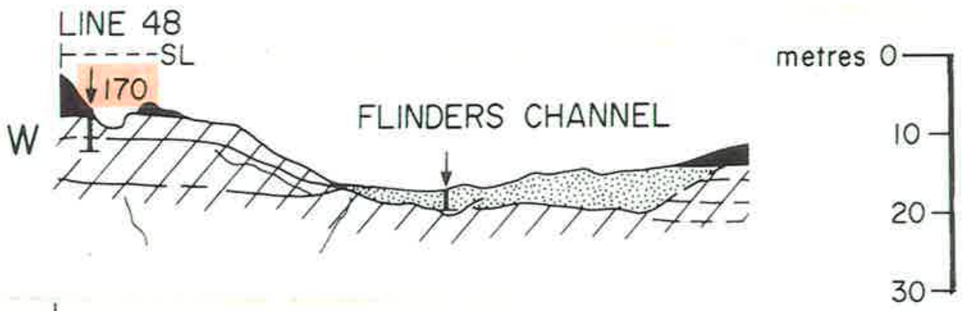
The *'s in Table 5.2 indicate the formations represented in the eight cores, as interpreted by the original researchers. The order from left to right is also the sequence in which the data sets are presented in this chapter, each with relevant observations and comments. Later in the chapter these details, as appropriate, are brought together in a synthesis which addresses the stated aims.

STRATIGRAPHIC FORMATION	SG 170	SG 79	RED 51	SG 120	SG 109	SG 223	SG 179	SG 245
Germein Bay Fmn (=St Kilda Fmn)	*	*	*	*	*	*	*	*
Lowly Point Fmn				?		*	*	*
False Bay Fmn				*	*	*	*	
Mambray Fmn (=Glanville Fmn)	*	*	*					
Older Pleistocene marine beds	*							

Table 5.2
Occurrence of late Quaternary stratigraphic formations within northern Spencer Gulf vibrocores, signified by *.

A

SG 170



B

↓ VIBROCORE SITE WITH DEPTH INDICATED

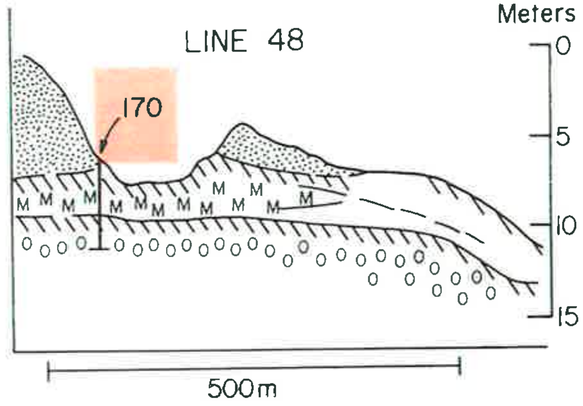
■ GERMEIN BAY FORMATION

☐ POORAKA FORMATION EQUIVALENT

▧ LOWLY POINT FORMATION

▒ FALSE BAY FORMATION

▨ MAMBRAY FORMATION AND OLDER UNITS



Germein Bay Formation ▒
(Holocene marine)

Lowly Point Formation (L)

False Bay Formation (F)

Mambray Formation (M)

Older Pleistocene marine beds (O)

C

Fig 5.2

A. Vibrocore #SG170, split core (after Billing, 1984, fig 3; Hails et al., 1984a, fig 3).

B, C. Sections showing location of SG170 in relation to Quaternary stratigraphy (B after Hails et al., 1984a, fig 4; C after Billing, 1984, fig 4).

VIBROCORE SG 170 (Fig 5.2)

GERMEIN BAY FORMATION

Much of the loose shelly sand constituting the upper part of this core was lost through spillage prior to sampling for foraminifera, and that sediment which remained had been considerably mixed. Thus the uppermost sample represents an interval 0 to 27cm and this is so indicated in Figs 5.4, 5.5 and 5.6 as identical values for sample depths zero and 25cm.

The placement of the Holocene/Pleistocene boundary between 75 and 100cm by Billing (1984) (Fig 5.3) is generally supported by the distribution of species. Minimum numbers of *Massilina milletti* occur at 100cm and the Holocene transgression is signified by increasing numbers of this deeper water indicator species up core. In contrast, numbers of shallow water species, *Discorbis dimidiatus, Nubecularia lucifuga* and *Cribrobulimina mixta* decrease markedly up core from 75 to 50cm (Figs 5.4 and 5.5). The *Elphidium* ratio also signals water deepening between 75 and 50cm, but this trend is reversed above 50cm (Fig 5.6).

?FALSE BAY FORMATION

In addition to the established shallow water indicator species *Discorbis dimidiatus*, the coarser size fraction is dominated by *Peneroplis planatus* and *Vertebralina striata* (Fig 5.4). The specimens of *P. planatus* have heavily calcified tests of highly variable form showing that they are probably of intertidal origin. *V. striata* was only sporadically present at Port Gawler (Chapter 3) and on the northern Spencer Gulf transect (Chapter 4), but Collins (1974) has reported that its habitat is "shallow water in sheltered localities."

The interpretation of shallow water sedimentation is largely supported by the finer fraction data (Fig 5.5), but not by the *Elphidium* ratio, which is more indicative of deposition at water depths of about 20m.

However, numbers of individuals of *E. macelliforme* and *E. crispum* at 100cm are relatively low, by comparison with their percentage distributions elsewhere in vibrocore SG170, and Billing's (1984) observation of reworking is confirmed by the presence of *Marginopora vertebralis* at this horizon. Thus the *Elphidium* ratio may be indicative of a depositional water depth for a later eroded and reworked horizon of the underlying Mambray Formation.

The balance of evidence favours a shallow water environment of deposition, perhaps in part intertidal, for the interval identified by Billing (1984) as "?False Bay Formation." Sediment within this interval was contaminated by reworked material from the underlying Mambray Formation.

MAMBRAY FORMATION

Reinterpretation of Billing (1984) shows that the Mambray Formation is represented in vibrocore SG170 by the interval 238 - 120cm. Significant numbers of *Marginopora vertebralis* at 175cm, in the coarser size fraction, strongly support this assertion (Fig 5.4).

Small numbers of oogonia are present at most horizons within the core. Oogonia are the calcified female reproductive organs of a unique group of salt tolerant aquatic plants called charophytes (Womersley, 1984). The sizes of oogonia are such that they occur in both grain size fractions used in this study. Maximum numbers of oogonia occur at 125cm.

Burne et al. (1980) detail a number of lacustrine and marginal marine environments of South Australia in which charophytes feature in plant communities. Within these environments, salinity values ranged from only slightly brackish to twice that of sea water. The plants were found to grow either within lake basins or in surrounding swamps and marshes. Wang et al. (1984e) record oogonia in estuarine sediments also containing foraminifera and both marine and nonmarine ostracods.

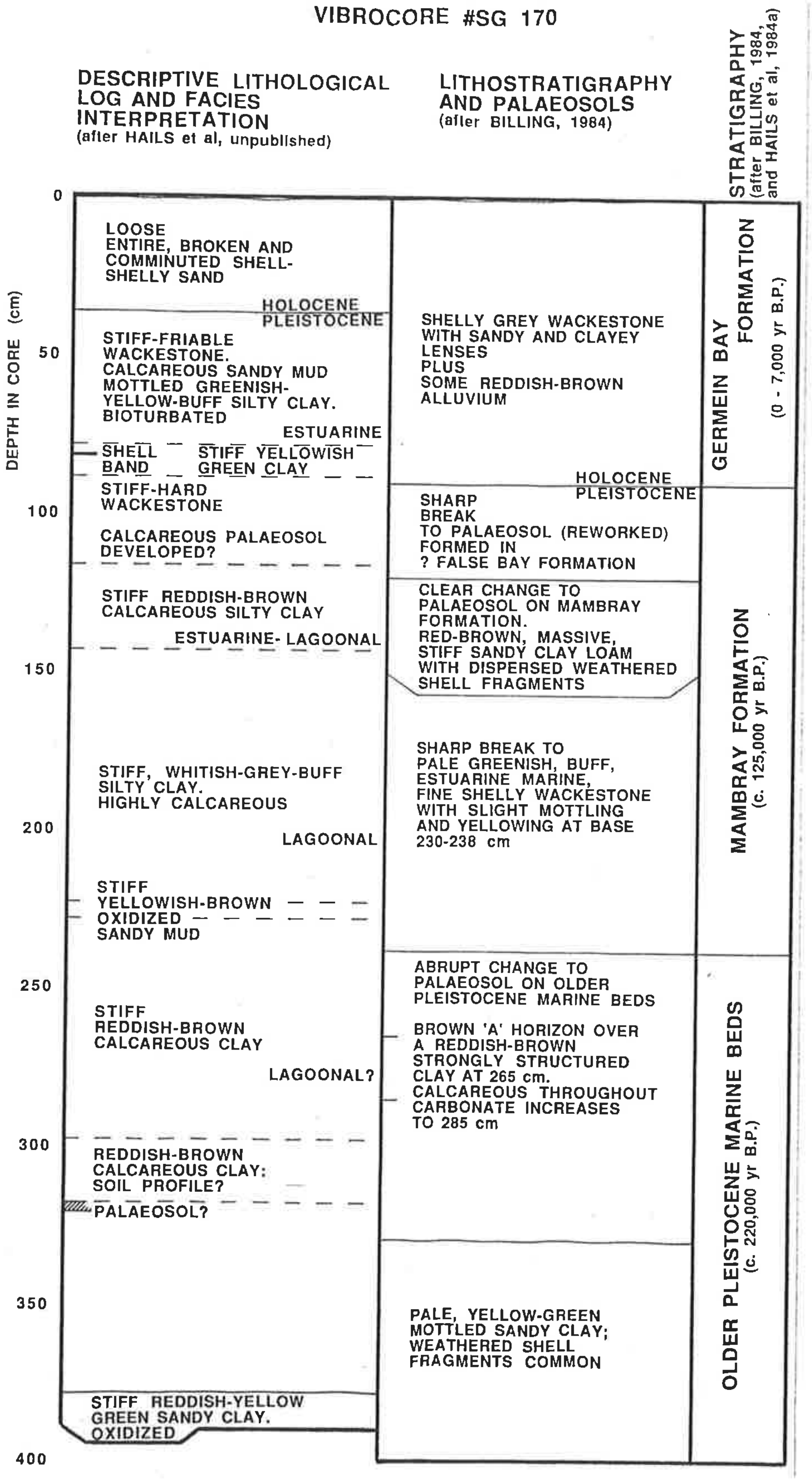

VIBROCORE #SG 170
DESCRIPTIVE LITHOLOGICAL LOG AND FACIES INTERPRETATION
(after HAILS et al, unpublished)
LITHOSTRATIGRAPHY AND PALAEOSOLS
(after BILLING, 1984)
STRATIGRAPHY
(after BILLING, 1984, and HAILS et al, 1984a)
DEPTH IN CORE (cm)
0
50
100
150
200
250
300
350
400
LOOSE ENTIRE, BROKEN AND COMMINUTED SHELL-SHELLY SAND
HOLOCENE
PLEISTOCENE
STIFF-FRIABLE WACKESTONE. CALCAREOUS SANDY MUD MOTTLED GREENISH-YELLOW-BUFF SILTY CLAY. BIOTURBATED
ESTUARINE
SHELL BAND
STIFF YELLOWISH GREEN CLAY
STIFF-HARD WACKESTONE
CALCAREOUS PALAEOSOL DEVELOPED?
STIFF REDDISH-BROWN CALCAREOUS SILTY CLAY
ESTUARINE- LAGOONAL
STIFF, WHITISH-GREY-BUFF SILTY CLAY. HIGHLY CALCAREOUS
LAGOONAL
STIFF YELLOWISH-BROWN OXIDIZED SANDY MUD
STIFF REDDISH-BROWN CALCAREOUS CLAY
LAGOONAL?
REDDISH-BROWN CALCAREOUS CLAY: SOIL PROFILE?
PALAEOSOL?
STIFF REDDISH-YELLOW GREEN SANDY CLAY. OXIDIZED
SHELLY GREY WACKESTONE WITH SANDY AND CLAYEY LENSES PLUS SOME REDDISH-BROWN ALLUVIUM
HOLOCENE
PLEISTOCENE
SHARP BREAK TO PALAEOSOL (REWORKED) FORMED IN ? FALSE BAY FORMATION
CLEAR CHANGE TO PALAEOSOL ON MAMBRAY FORMATION. RED-BROWN, MASSIVE, STIFF SANDY CLAY LOAM WITH DISPERSED WEATHERED SHELL FRAGMENTS
SHARP BREAK TO PALE GREENISH, BUFF, ESTUARINE MARINE, FINE SHELLY WACKESTONE WITH SLIGHT MOTTLING AND YELLOWING AT BASE 230-238 cm
ABRUPT CHANGE TO PALAEOSOL ON OLDER PLEISTOCENE MARINE BEDS
BROWN 'A' HORIZON OVER A REDDISH-BROWN STRONGLY STRUCTURED CLAY AT 265 cm. CALCAREOUS THROUGHOUT CARBONATE INCREASES TO 285 cm
PALE, YELLOW-GREEN MOTTLED SANDY CLAY; WEATHERED SHELL FRAGMENTS COMMON
GERMEIN BAY FORMATION
(0 - 7,000 yr B.P.)
MAMBRAY FORMATION
(c. 125,000 yr B.P.)
OLDER PLEISTOCENE MARINE BEDS
(c. 220,000 yr B.P.)

Fig 5.3

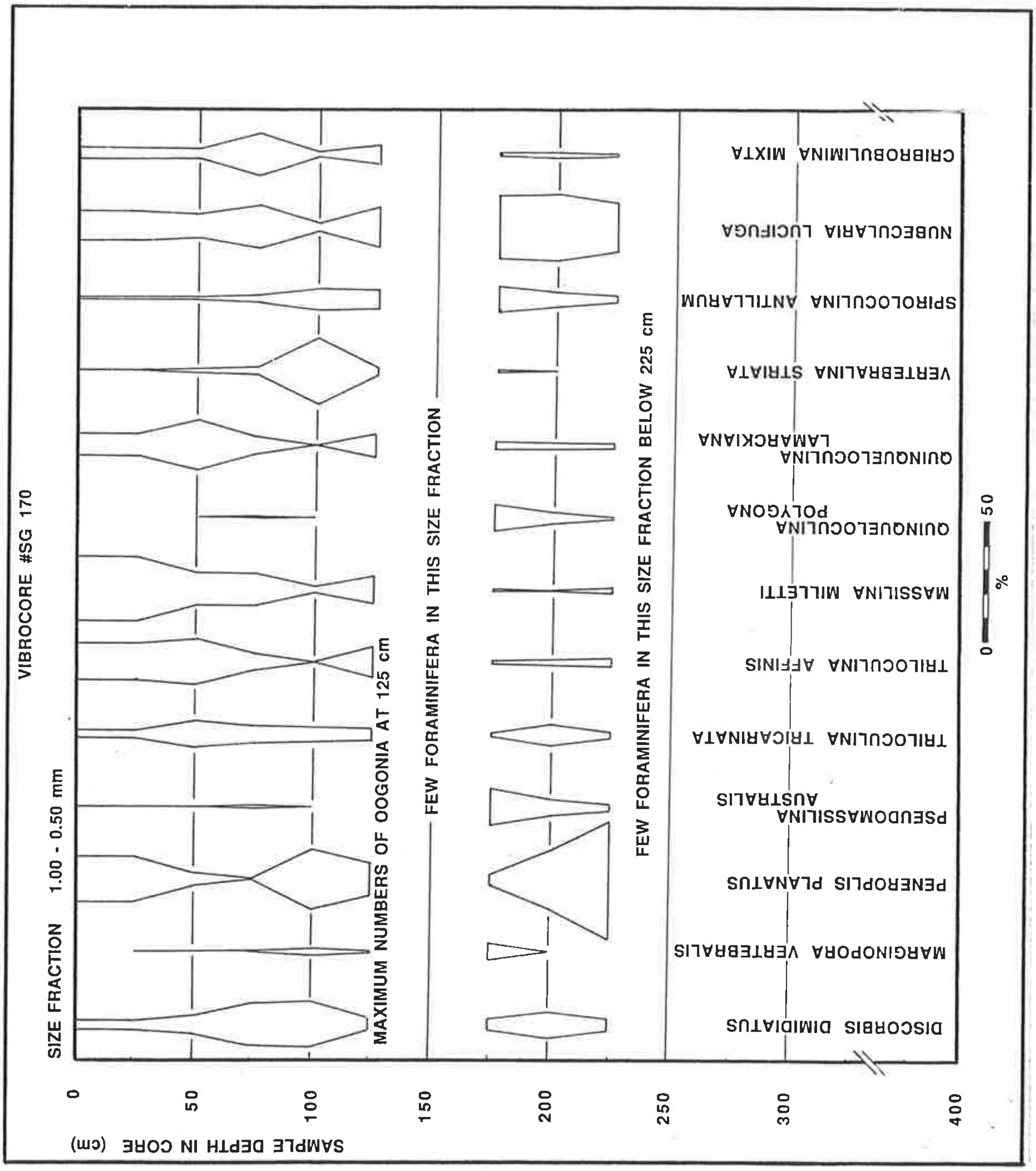


Fig 5.4

Percentage distributions of selected species of benthic foraminifera within vibrocore #SG170.
Size fraction 1.00 - 0.50mm.

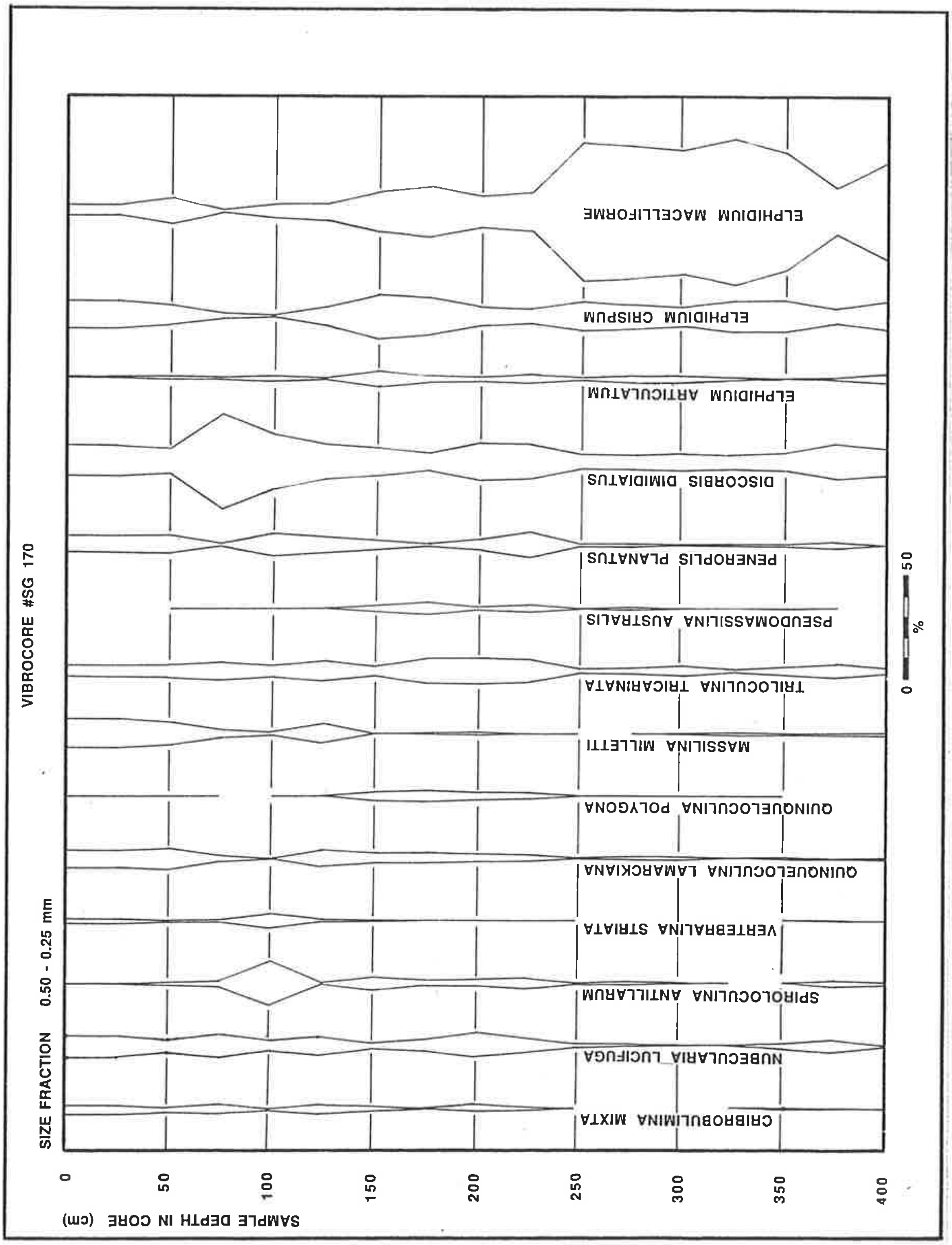


Fig 5.5
Percentage distributions of selected species of benthic foraminifera within vibrocore #SG170.
Size fraction 0.50 - 0.25mm.

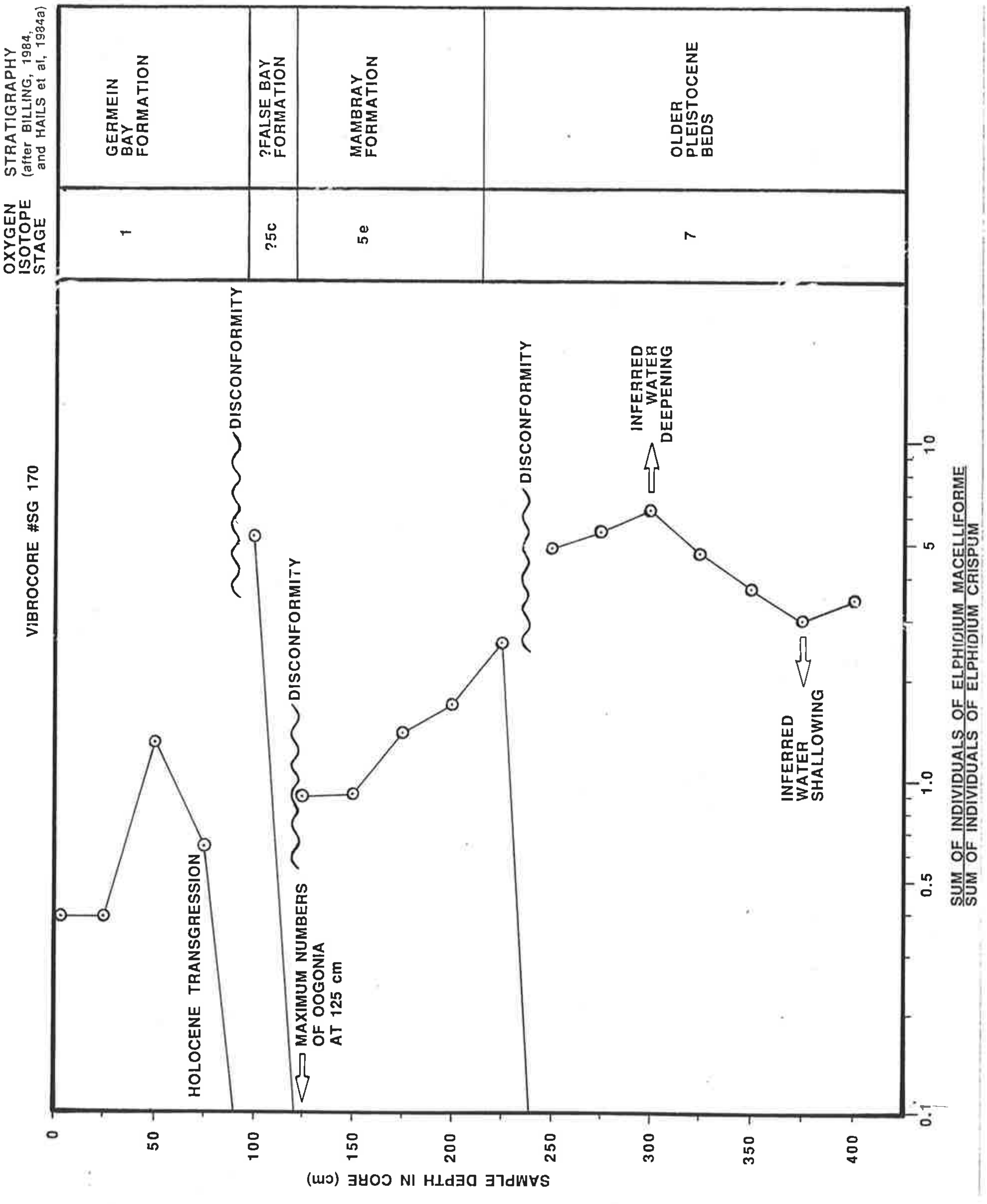


Fig 5.6

Log-linear plot of sample depth in vibrocore #SG170 versus ratio of numbers of individuals of *Elphidium macelliforme* to numbers of individuals of *Elphidium crispum* for core samples. Inferred changes of palaeo sea levels derived from this ratio are signified. The stratigraphic framework is that of Hails et al, 1984a and unpublished, and Billing, 1984 (Fig 5.3).

The presence of oogonia in horizons of vibrocore SG170 is unequivocal evidence of saline non-marine or marginal marine environments. Maximum numbers of oogonia at 125cm may be confidently interpreted to signify emergence, to be most likely associated with the lithological boundary documented at 120cm by Billing (1984). However, the limited presence of oogonia at horizons above and below 125cm again supports the assertion of reworking of sediment and associated fossils (Billing, 1984).

Deposition of Mambray Formation sediments, recovered by SG170, occurred in relatively shallow water, as signified by the percentage abundances of *Nubecularia lucifuga* and intertidal forms of *Peneroplis planatus* in the coarser fraction. This interpretation is supported by the species distribution in the finer fraction, for example, *Discorbis dimidiatus*. The *Elphidium* ratio signals a steady fall in relative sea level throughout the Mambray Formation interval. This may be due in part to upwards shoaling, to eustatic fall of sea level or to tectonic (perhaps isostatic) uplift of the study area.

Quinqueloculina polygona and *Pseudomassilina australis* are species which were not observed in any surficial sediment. They appear here to be essentially confined to the Mambray Formation and may have potential use in that context.

OLDER PLEISTOCENE MARINE BEDS

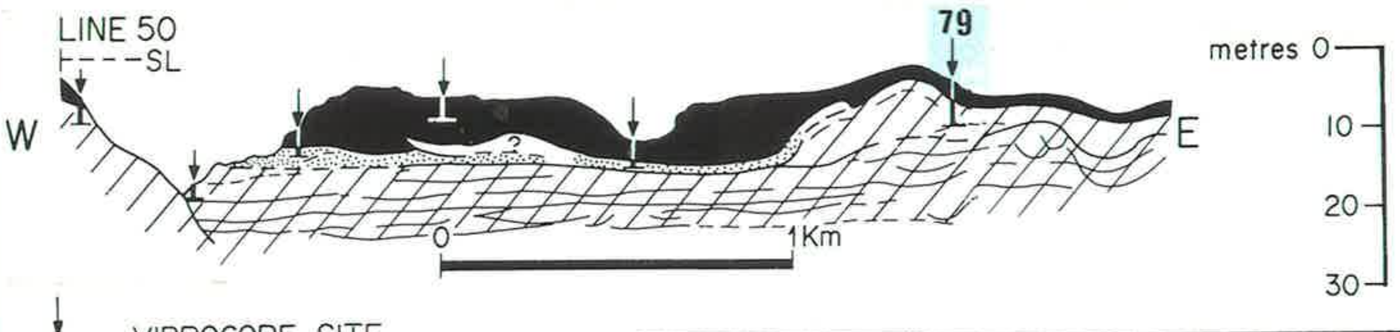
Shells from this unnamed stratigraphic unit, taken from other vibrocores in the study area, were subjected to amino acid racemisation analysis. They yielded a mean age of 200,000 +/- 50,000 yr B.P., confirming that deposition occurred during the penultimate interglacial, oxygen isotope stage 7 (Murray-Wallace et al., 1988b).

The core logs (Fig 5.3) record extreme pedogenesis of these older marine sediments and few foraminifera were recovered in the 1.00 - 0.50mm fraction.

However, the finer fraction yielded an average of almost 300 individuals per sample and the abundances of *Elphidium macelliforme* and *E. crispum* throughout (Fig 5.5) lends confidence to the relative sea level signal derived from these species (Fig 5.6). Minimum sea level for the oxygen isotope stage 7 transgression is indicated by the *Elphidium* ratio at core depth 375cm and this observation is supported by the coincident peak of *Nubecularia lucifuga*. Maximum water depth is recorded by the 300cm core sample, while the two samples immediately above show a relative fall in sea level. The internal consistency of these palaeo sea level interpretations for the "older Pleistocene marine beds" is particularly encouraging.

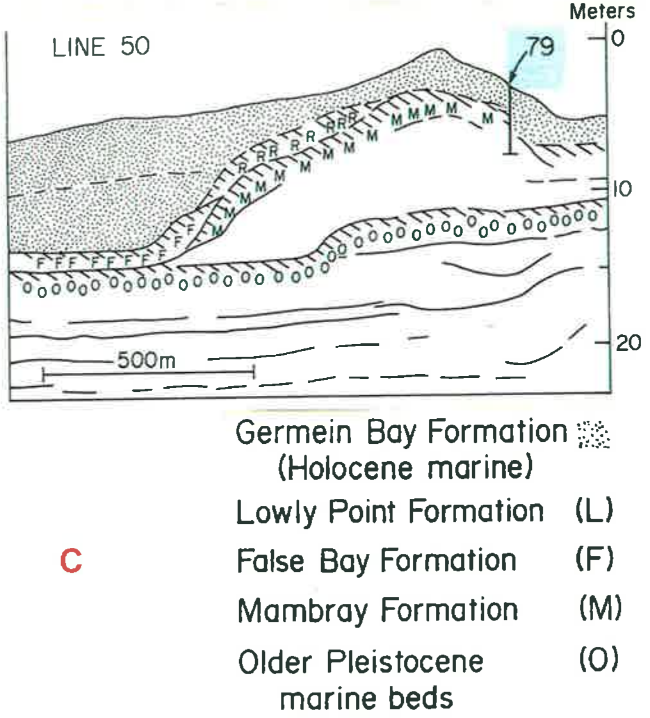

No. 79
1
2
3
4

A


LINE 50
SL
W
E
79
?
0
1Km
metres 0
10
20
30
VIBROCORE SITE WITH DEPTH INDICATED
GERMEIN BAY FORMATION
POORAKA FORMATION EQUIVALENT
LOWLY POINT FORMATION
FALSE BAY FORMATION
MAMBRAY FORMATION AND OLDER UNITS

B

SG 79


LINE 50
79
Meters
0
10
20
500m
R
M
F
Germein Bay Formation
(Holocene marine)
Lowly Point Formation (L)
False Bay Formation (F)
Mambray Formation (M)
Older Pleistocene marine beds (O)

C

Fig 5.7
A. Vibrocore #SG79, split core (after Billing, 1984, fig3).
B, C. Sections showing location of SG79 in relation to Quaternary stratigraphy (B after Hails et al, 1984a, fig 4; C after Billing, 1984, fig 6).

VIBROCORE SG79 (Fig 5.7)

GERMEIN BAY FORMATION

The core descriptions (Fig 5.8) show that about 1.5m of the Germein Bay Formation is represented in this core, the basal Holocene sediments being mixed with reworked palaeosol of the underlying Mambray Formation. This observation is supported by the presence of charophyte oogonia in the core interval 200 to 150cm, the oogonia signifying effective emergence and nonmarine, probably lacustrine environments of varying salinity.

In the size fraction 1.00 - 0.50mm few foraminifera were recovered from horizons below 125cm, but for the Holocene interval, samples yielded an average of nearly 300 individuals. The distribution of species in this size fraction (Fig 5.9) records the original shallow water conditions at the onset of the transgression, followed by maximum water depth and subsequent fall of sea level. This is best illustrated by the shallow water indicator species *Nubecularia lucifuga* which is relatively abundant at core depths 125 to 100cm. Minimum numbers of this species at 75cm signify the peak of the transgression, while increasing numbers up core show marine regression. This interpretation is corroborated by maximum abundance of the deeper water indicator *Massilina milletti* at 75cm, with numbers of this species decreasing up core.

In the finer size fraction (Fig 5.10) this sea level record is elegantly illustrated by the distribution of *Massilina milletti*, the 75cm sample recording maximum numbers and thus signifying the peak of the transgression.

The *de facto* sea level curve derived from the ratio of numbers of *Elphidium macelliforme* and *E. crispum* also reveals the peak of the Holocene transgression at 75cm, while the samples higher in the core record a steady fall in relative sea level (Fig 5.11).

The remarkable internal consistency of these data lends great credibility to the techniques of investigation here applied.

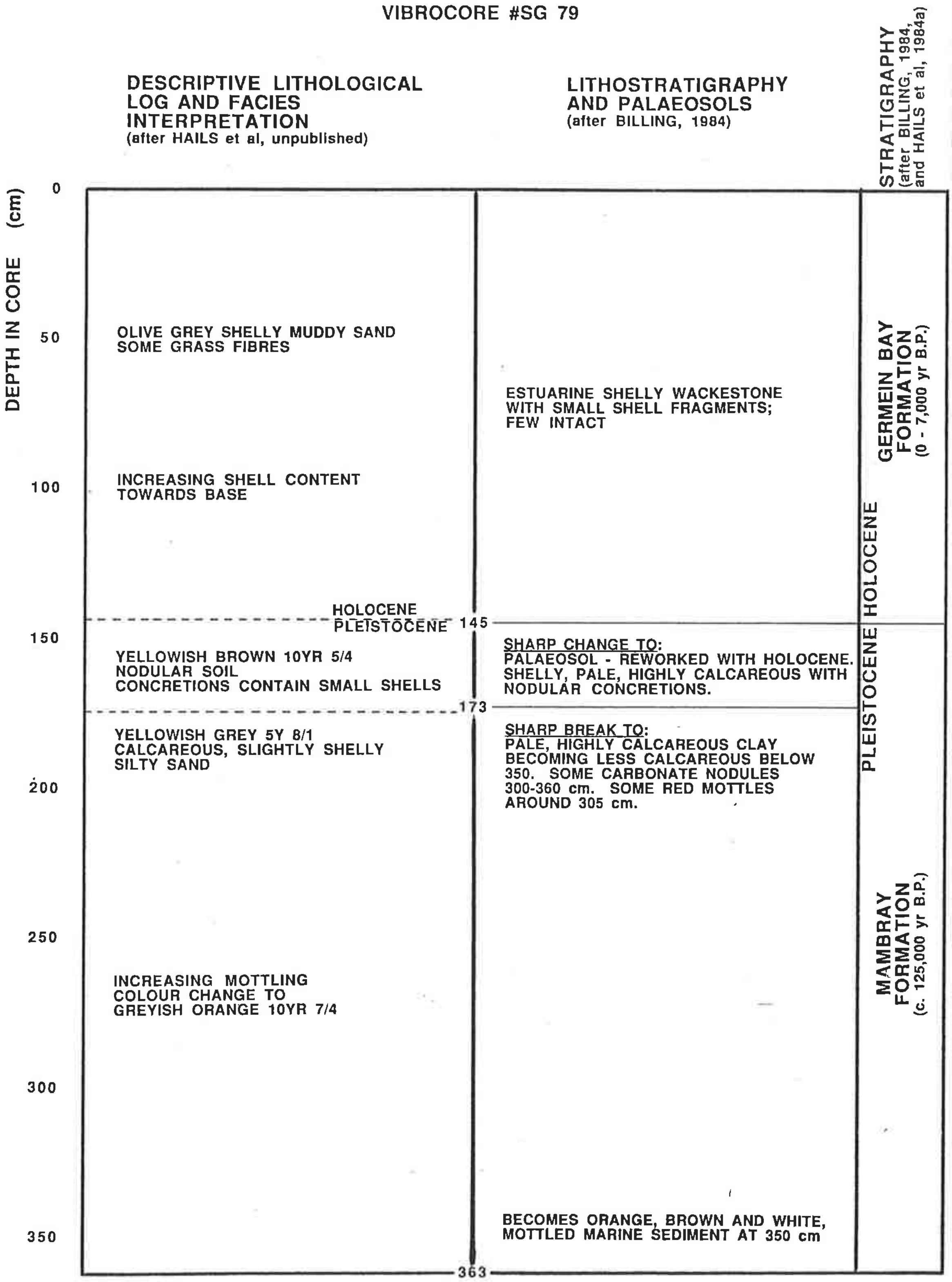

VIBROCORE #SG 79
DESCRIPTIVE LITHOLOGICAL LOG AND FACIES INTERPRETATION
(after HAILS et al, unpublished)
LITHOSTRATIGRAPHY AND PALAEOSOLS
(after BILLING, 1984)
STRATIGRAPHY
(after BILLING, 1984, and HAILS et al, 1984a)
DEPTH IN CORE (cm)
0
50
100
150
200
250
300
350
OLIVE GREY SHELLY MUDDY SAND SOME GRASS FIBRES
INCREASING SHELL CONTENT TOWARDS BASE
HOLOCENE
PLEISTOCENE
145
YELLOWISH BROWN 10YR 5/4 NODULAR SOIL CONCRETIONS CONTAIN SMALL SHELLS
173
YELLOWISH GREY 5Y 8/1 CALCAREOUS, SLIGHTLY SHELLY SILTY SAND
INCREASING MOTTLING COLOUR CHANGE TO GREYISH ORANGE 10YR 7/4
363
ESTUARINE SHELLY WACKESTONE WITH SMALL SHELL FRAGMENTS; FEW INTACT
SHARP CHANGE TO:
PALAEOSOL - REWORKED WITH HOLOCENE. SHELLY, PALE, HIGHLY CALCAREOUS WITH NODULAR CONCRETIONS.
SHARP BREAK TO:
PALE, HIGHLY CALCAREOUS CLAY BECOMING LESS CALCAREOUS BELOW 350. SOME CARBONATE NODULES 300-360 cm. SOME RED MOTTLES AROUND 305 cm.
BECOMES ORANGE, BROWN AND WHITE, MOTTLED MARINE SEDIMENT AT 350 cm
HOLOCENE
PLEISTOCENE
GERMEIN BAY FORMATION
(0 - 7,000 yr B.P.)
MAMBRAY FORMATION
(c. 125,000 yr B.P.)

Fig 5.8

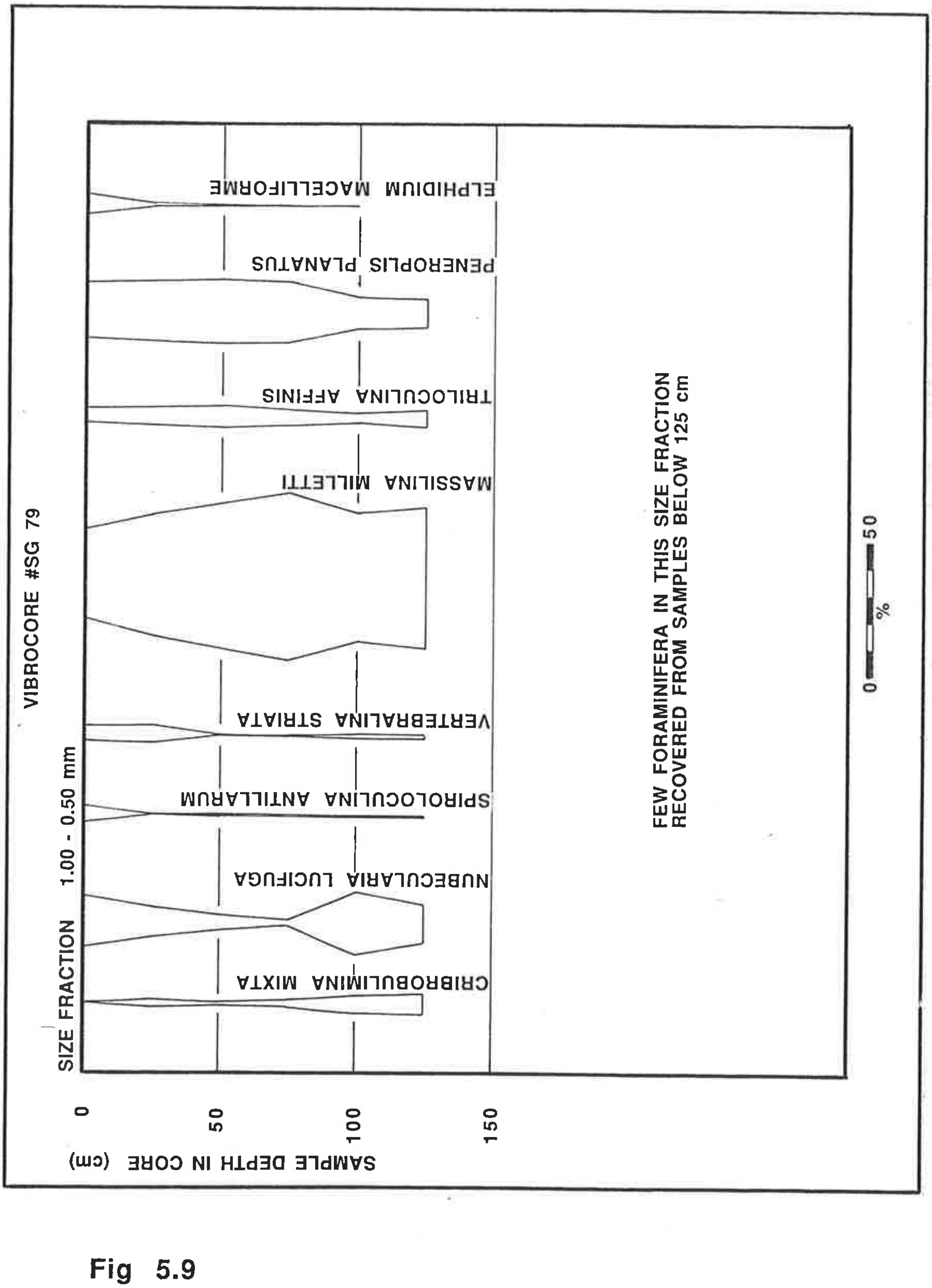


Fig 5.9

Percentage distributions of selected species of benthic foraminifera within vibrocore #SG79.
Size fraction 1.00 - 0.50mm.

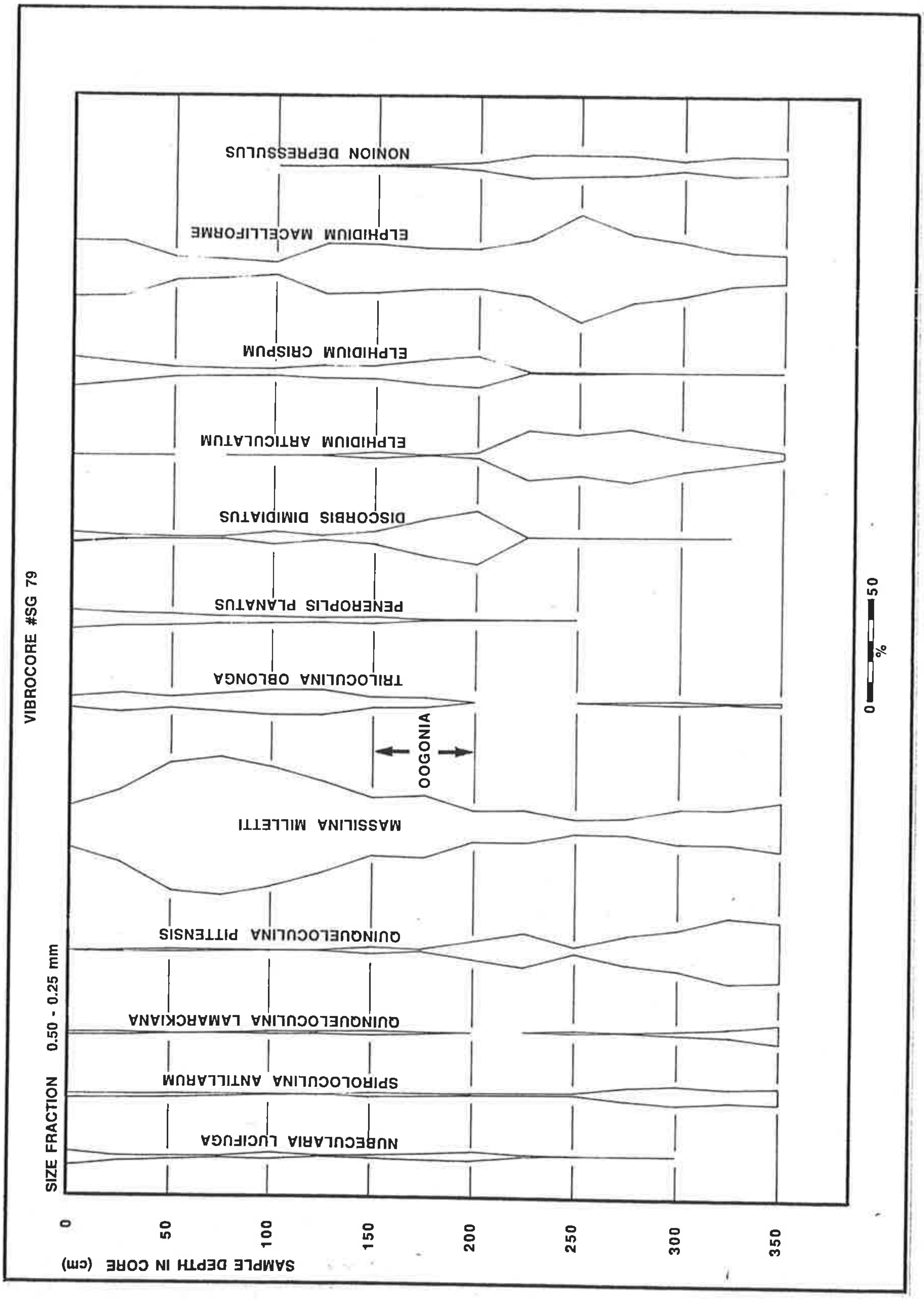


Fig 5.10
Percentage distributions of selected species of benthic foraminifera within vibrocore #SG79.
Size fraction 0.50 - 0.25mm.

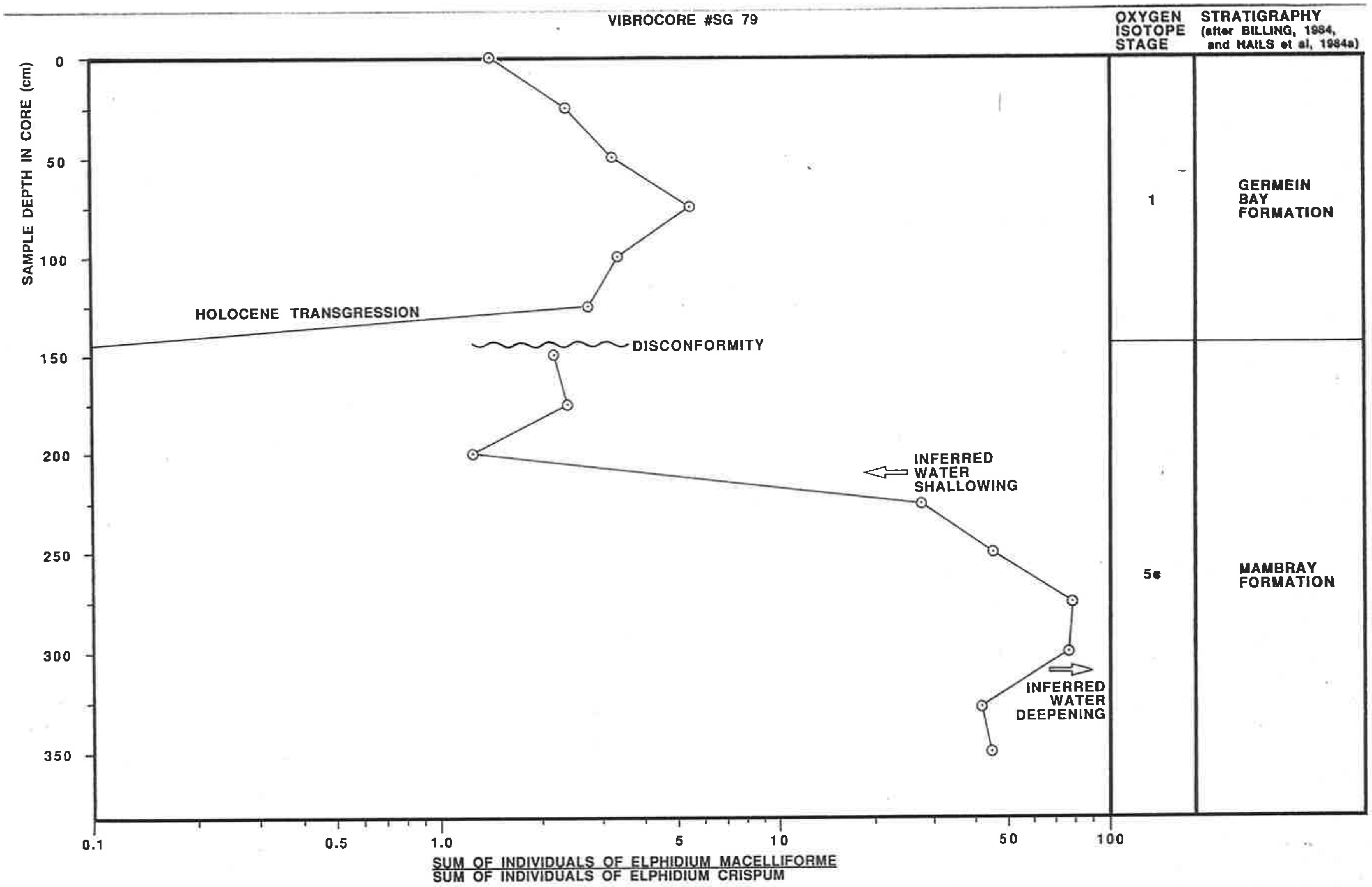

VIBROCORE #SG 79
OXYGEN ISOTOPE STAGE
STRATIGRAPHY (after BILLING, 1984, and HAILS et al, 1984a)
SAMPLE DEPTH IN CORE (cm)
0
50
100
150
200
250
300
350
HOLOCENE TRANSGRESSION
DISCONFORMITY
INFERRED WATER SHALLOWING
INFERRED WATER DEEPENING
1
GERMEIN BAY FORMATION
5e
MAMBRAY FORMATION
0.1
0.5
1.0
5
10
50
100
SUM OF INDIVIDUALS OF ELPHIDIUM MACELLIFORME
SUM OF INDIVIDUALS OF ELPHIDIUM CRISPUM

Fig 5.11
Log-linear plot of sample depth in vibrocore #SG79 versus ratio of numbers of individuals of *Elphidium macelliforme* to numbers of individuals of *Elphidium crispum* for core samples. Inferred changes of palaeo sea levels derived from this ratio are signified. The stratigraphic framework is that of Hails et al., 1984a and unpublished, and Billing, 1984 (Fig 5.8).

MAMBRAY FORMATION

In the finer size fraction, Mambray Formation samples yielded an average of >300 specimens, *Elphidium macelliforme* dominating the assemblages (Fig 5.10). The *Elphidium* ratio (Fig 5.11) indicates that deposition of the lowermost sediments of the Mambray Formation occurred in relatively deep water. The Last Interglacial transgressive maximum is indicated by high ratios derived from samples at 300 and 275cm. Significant marine regression is then suggested by the data from 250 to 200cm. Given the evidence of reworking of sediment at the Pleistocene/Holocene disconformity, *Elphidium* ratios at 175 and 150cm should be assessed with caution.

The general distribution of species in the core (Fig 5.10) lends some support to the inferences of the *Elphidium* ratio. *Nubecularia lucifuga* and *Discorbis dimidiatus*, for example, show maximum abundances at 200cm, indicating relatively shallow water and supporting the notion of marine regression. The significance of distributions of other species is less clear, partly because of the statistical "swamping" effect of the large numbers of *E. macelliforme* (>50% at 250cm) and partly because the habitat details of several of the more abundant species are poorly established for the modern gulf environments.

Quinqueloculina pittensis is represented in the northern Spencer Gulf sediments (Fig 4.3), but there is no apparent relationship between its relative abundance and water depth. Albani (1974) reports the species from eastern Australian coastal embayments of stable "hydrological conditions", always at depths <10m, but not in shore samples. His specimens were recovered from sandy to muddy-sandy substrates. Thus decreasing numbers of *Q. pittensis* up core from 325 to 250cm could be interpreted as water shallowing.

The water shallowing inferred by *Q. pittensis* is supported by a similar distribution of *Massilina milletti* through the lower part of the core. Numbers decrease from 24% at 350cm to 7% 100cm higher in the core.

As this species positively correlates with water depth (Fig 4.3), its distribution over this interval indicates marine regression.

Elphidium articulatum is reported from intertidal sand flats and hyposaline lagoons and estuaries (for example, Bandy, 1963; Murray, 1971). Collins (1974) described a subspecies of *E. articulatum* from Altona Bay, a restricted coastal embayment, and from the Barwon estuary, in Victoria. In the estuarine Gippsland Lake System, also in Victoria, *E. articulatum* is common in shallow waters of variable salinity, ranging from about half that of sea water to 40 parts per thousand (Apthorpe, 1980). Cann and De Deckker (1981) described a highly variable species of *Elphidium*, that may be referred to *E. articulatum*, from saline lakes of south eastern South Australia. South of Adelaide, in the estuary of the Onkaparinga River, *E. articulatum* is a dominant species in summer (observation of the present author).

The remaining numerically significant species in the Mambray Formation interval of SG79 is *Nonion depressulus*. Apthorpe (1980) reports this species also from the Gippsland Lakes where it constituted more than one third of the foraminifera in some low energy muddy areas. Collins (1974) reports that the species "favours shallow, muddy stillwater conditions, and is tolerant of lowered salinity."

Thus, the balance of evidence contradicts the *Elphidium* ratio implications of deeper water sedimentation for the 300 to 275cm interval. Instead, the general distribution of species within the Mambray Formation of SG79 reveals that, at the apex of Spencer Gulf (Fig 5.1), Last Interglacial sedimentation occurred under estuarine conditions of relatively shallow water and variable salinity. Increasing numbers of *E. articulatum* and correspondingly decreasing numbers of *Q. pittensis* and *M. milletti* are consistent with a steady, relative fall in sea level.

What does this mean about the *Elphidium* ratio and palaeo water depth? Does it have significance for the Pleistocene interval of SG79? Throughout this core there is clearly a simple inverse relationship between the abundances of *E. articulatum* and *E. crispum*. It is likely, since both species favour shallow waters, that this relationship concerns not so much water depth, but water salinity. That is, in relatively shallow marine environments, modification of the salinity regime from normal marine to fluctuating hyposalinity/hypersalinity, results in displacement of *E. crispum* by *E. articulatum*. If this hypothesis is correct, in such changing conditions there may be a relationship between water depth and the expression:

$$\frac{\text{number of individuals of } E.\ \textit{macelliforme}}{\text{number of individuals of } (E.\ \textit{crispum} + E.\ \textit{articulatum})}.$$

Further exploring this notion, values derived for the above expression for core samples 325 to 200cm generally lie between 1.6 and 1.1 (contrast values >50 for the *E. macelliforme* : *E. crispum* ratio, Fig 5.11) decreasing up core and consistent with shallowing upwards, although the 250cm value remains anomalously high.

This new numerical ratio is temptingly in accord with the conclusions derived from the general assemblage. However, it must be recognised that the association, while logical, is circumstantial and has no basis in observations of modern assemblages and environments. This matter deserves further investigation and has potential for derivation of Pleistocene sea level curves.

VIBROCORE RED51

GERMEIN BAY FORMATION

Unlike the other cores, prefix **SG**, that are the subject of this chapter, all of which recovered submarine sections, RED51 was vibrocored in a tidal creek slightly north of Redcliff Point (Fig 5.1). The core description (Fig 5.12) shows that 1.2m of Holocene Germein Bay Formation were recovered, including the uppermost 25cm of present day tidal creek facies. The surrounding plain is topographically 1.5m above the vibrocore site in the creek. This 1.5m, for which no data are available, most likely consists, at least in part, of intertidal and supratidal sediments similar to those described for Port Gawler (Chapter 3).

In the size fraction 1.00 - 0.50mm (Fig 5.13), dominated by *Nubecularia lucifuga*, the five significant species comprising the assemblage are all diagnostic of shallow water environments. Only a few individuals of *Peneroplis planatus* show aberrant morphology and heavier calcification of the test, so a subtidal sequence is indicated for the interval 120 to 25cm. Thus, the "possible truncated surface" indicated in the descriptive log (Fig 5.12) is confirmed.

The general assemblage of species in the finer fraction (Fig 5.14) also supports a shallow subtidal environment of deposition. The *Elphidium* ratio, derived from this size fraction, indicates a general upwards shallowing for the Holocene subtidal interval.

MAMBRAY FORMATION

Placement of the Pleistocene/Holocene boundary at 120cm on the evidence of pedogenesis (Fig 5.12) is confirmed by the distribution of *Marginopora vertebralis* through the core. The abundance of this species, particularly in association with the bivalve *Anadara trapezia*, is *prima facie* evidence that the marine sediments below 120cm can be assigned to the Mambray (=Glanville) Formation.

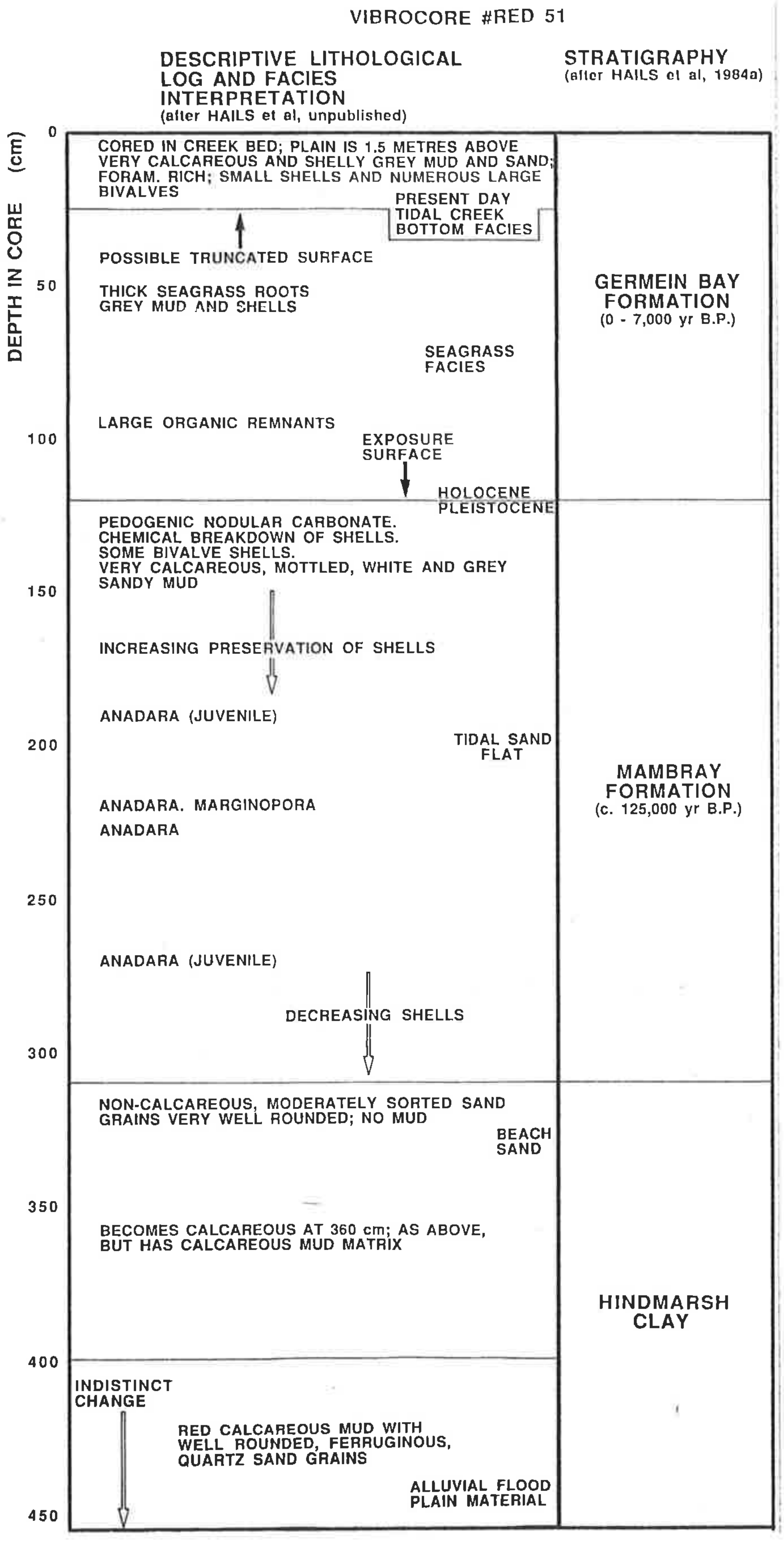

VIBROCORE #RED 51
DESCRIPTIVE LITHOLOGICAL LOG AND FACIES INTERPRETATION
(after HAILS et al, unpublished)
STRATIGRAPHY
(after HAILS et al, 1984a)
DEPTH IN CORE (cm)
0
50
100
150
200
250
300
350
400
450
CORED IN CREEK BED; PLAIN IS 1.5 METRES ABOVE
VERY CALCAREOUS AND SHELLY GREY MUD AND SAND;
FORAM. RICH; SMALL SHELLS AND NUMEROUS LARGE BIVALVES
PRESENT DAY TIDAL CREEK BOTTOM FACIES
POSSIBLE TRUNCATED SURFACE
THICK SEAGRASS ROOTS
GREY MUD AND SHELLS
SEAGRASS FACIES
LARGE ORGANIC REMNANTS
EXPOSURE SURFACE
HOLOCENE
PLEISTOCENE
PEDOGENIC NODULAR CARBONATE.
CHEMICAL BREAKDOWN OF SHELLS.
SOME BIVALVE SHELLS.
VERY CALCAREOUS, MOTTLED, WHITE AND GREY SANDY MUD
INCREASING PRESERVATION OF SHELLS
ANADARA (JUVENILE)
TIDAL SAND FLAT
ANADARA. MARGINOPORA
ANADARA
ANADARA (JUVENILE)
DECREASING SHELLS
NON-CALCAREOUS, MODERATELY SORTED SAND
GRAINS VERY WELL ROUNDED; NO MUD
BEACH SAND
BECOMES CALCAREOUS AT 360 cm; AS ABOVE, BUT HAS CALCAREOUS MUD MATRIX
INDISTINCT CHANGE
RED CALCAREOUS MUD WITH WELL ROUNDED, FERRUGINOUS, QUARTZ SAND GRAINS
ALLUVIAL FLOOD PLAIN MATERIAL
GERMEIN BAY FORMATION
(0 - 7,000 yr B.P.)
MAMBRAY FORMATION
(c. 125,000 yr B.P.)
HINDMARSH CLAY

Fig 5.12

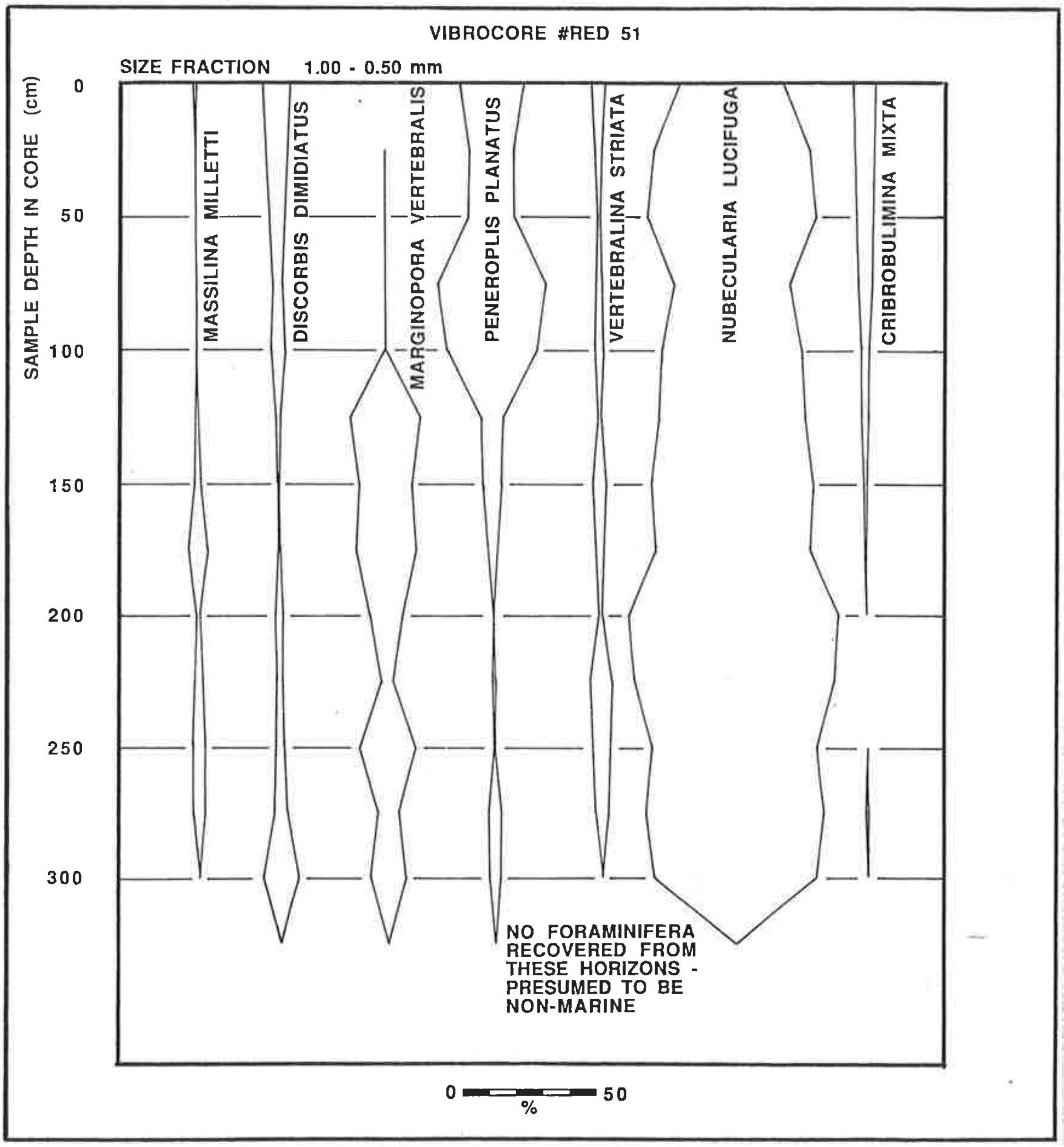


Fig 5.13

Percentage distributions of selected species of benthic foraminifera within vibrocore #RED51.
Size fraction 1.00 - 0.50mm.

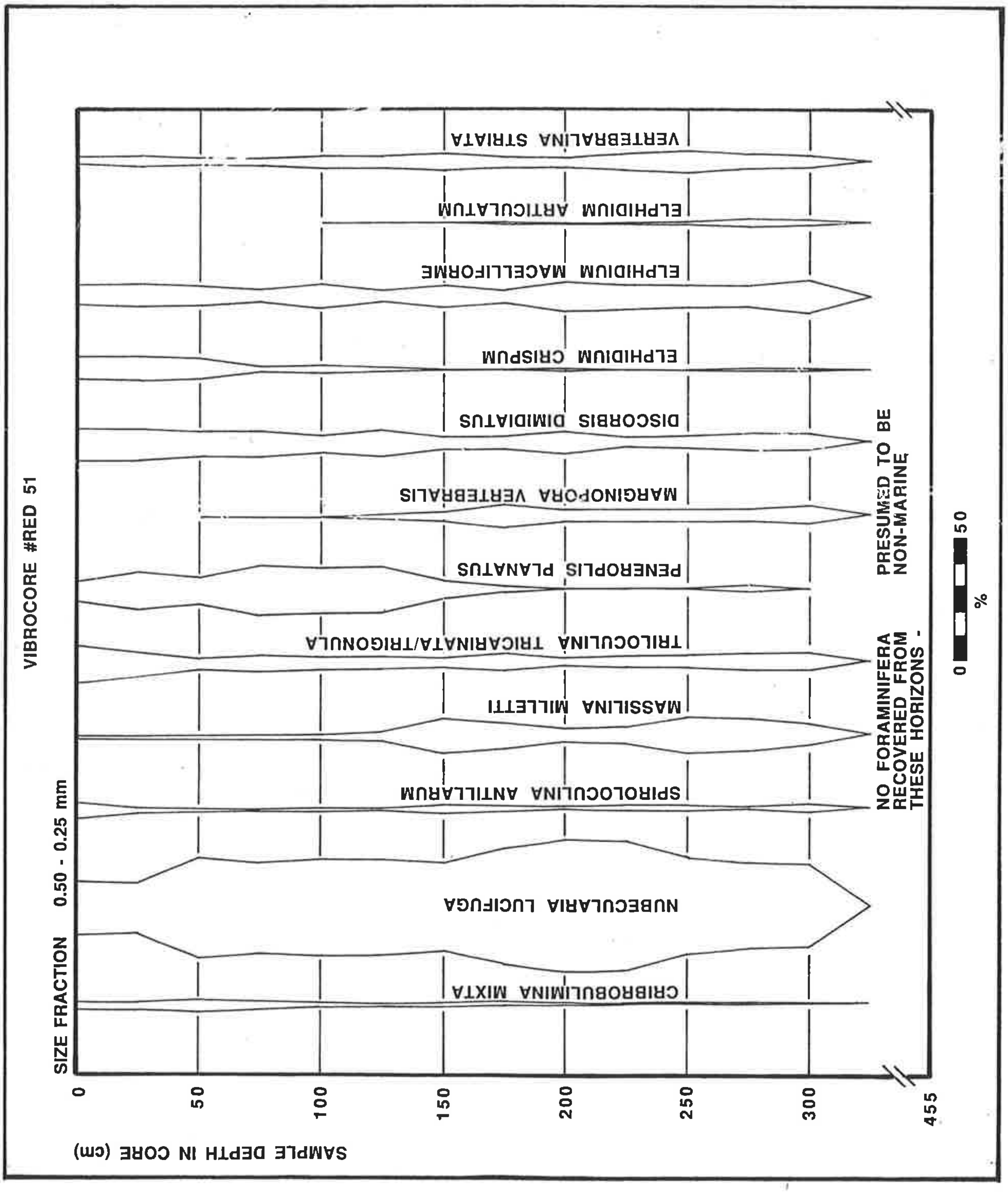


Fig 5.14
Percentage distributions of selected species of benthic foraminifera within vibrocore #RED51.
Size fraction 0.50 - 0.25mm.

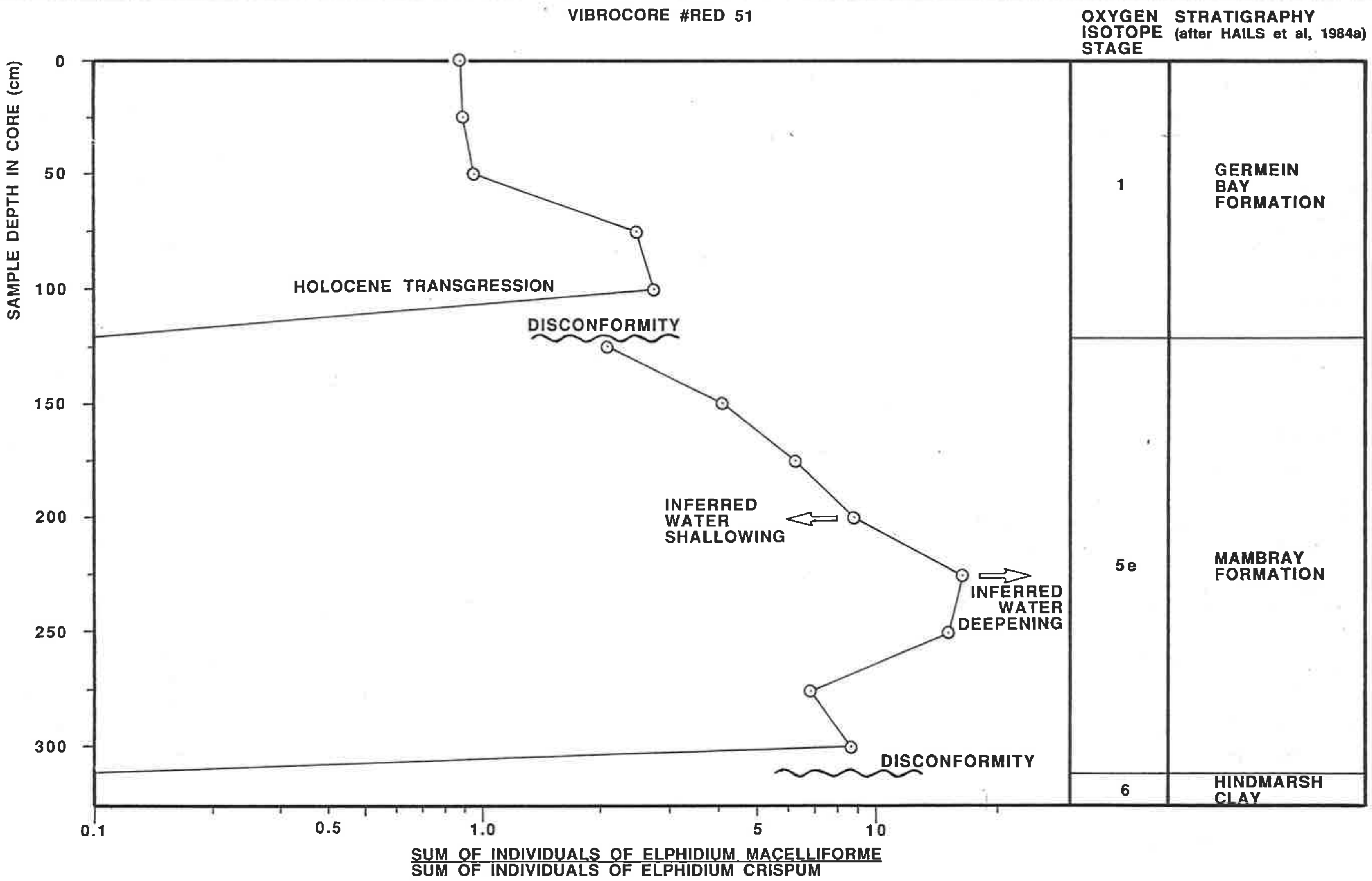

VIBROCORE #RED 51
OXYGEN ISOTOPE STAGE
STRATIGRAPHY (after HAILS et al, 1984a)
SAMPLE DEPTH IN CORE (cm)
0
50
100
150
200
250
300
HOLOCENE TRANSGRESSION
DISCONFORMITY
INFERRED WATER SHALLOWING
INFERRED WATER DEEPENING
DISCONFORMITY
1
5e
6
GERMEIN BAY FORMATION
MAMBRAY FORMATION
HINDMARSH CLAY
0.1
0.5
1.0
5
10
SUM OF INDIVIDUALS OF ELPHIDIUM MACELLIFORME
SUM OF INDIVIDUALS OF ELPHIDIUM CRISPUM

Fig 5.15
Log-linear plot of sample depth in vibrocore #RED51 versus ratio of numbers of individuals of *Elphidium macelliforme* to numbers of individuals of *Elphidium crispum* for core samples. Inferred changes of palaeo sea levels derived from this ratio are signified. The stratigraphic framework is that of Hails et al, 1984a and unpublished.

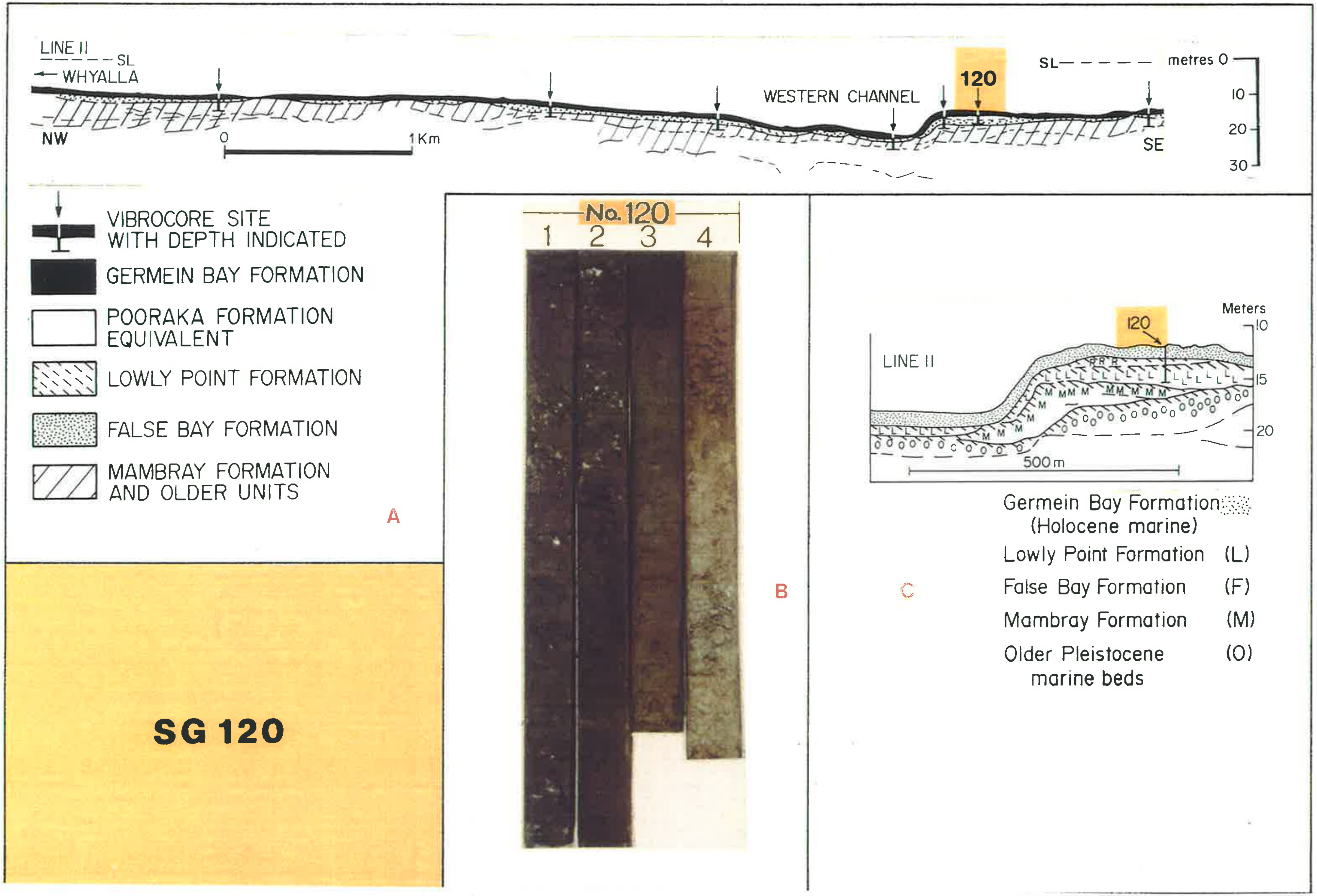
For the 1.00 - 0.50mm size fraction (Fig 5.13), samples between 125 and 300cm yielded an average of only 140 specimens. Samples at 125, 250 and 275cm were all relatively deficient and only 23 individuals were extracted from the coarser fraction at 300cm. However, the finer fraction (Fig 5.14) yielded an average of >400 specimens per sample. The distribution of species in both size fractions shows that relatively shallow, mostly subtidal environments prevailed throughout the time of deposition of the Mambray sediments. In particular, changes in relative abundances of reliable water depth indicator species is similar for both size fractions.

As for the Holocene interval of the core, the abundance of *Nubecularia lucifuga* confirms shallow environments of deposition, the peak of this species around 200cm signifying minimum water depth. Smaller numbers of *N. lucifuga*, both above and below 200cm, are associated with increased numbers of *Massilina milletti* and subtidal forms of *Peneroplis planatus*, together indicating slightly deeper waters.

This internally consistent and simple pattern of change in relative sea level within a shallow subtidal depositional environment does not support the inferences of the *Elphidium* ratio (Fig 5.15). These data imply maximum water depth at 225cm, followed by continued upwards shallowing to the disconformity. Even when the numbers of *E. articulatum* are taken in conjunction with those of *E. crispum* in calculating the ratio, as discussed above for vibrocore SG79, the values so obtained lend no support to the sea level changes so neatly implied by the general assemblage.

Marginopora vertebralis is well established as an extant form favouring warm shallow tropical environments (for example, Barker, 1960; Smith, 1968). Also,the present author has observed the species in shallow marine environments on several islands of both Kiribati and Vanuatu in the Pacific.

Thus, given the abundance of *M. vertebralis* in the Mambray Formation of RED51, it may safely be assumed that, at the time of deposition of these sediments, waters at the head of Spencer Gulf were much warmer and perhaps more saline than those of today. It is apparent that the logarithmic relationship of the relative abundances of *Elphidium macelliforme* and *E. crispum* to water depth, as determined for modern northern Spencer Gulf waters, cannot be used to infer palaeo water depths for sediments deposited under such different environmental conditions. Application of the ratio to the late Pleistocene sediments of vibrocore RED51 has, in this case, exceeded the constraints of the Principle of Uniformitarianism.


LINE II
SL
WHYALLA
NW
0
1 Km
WESTERN CHANNEL
120
SL
metres 0
10
20
30
SE
VIBROCORE SITE WITH DEPTH INDICATED
GERMEIN BAY FORMATION
POORAKA FORMATION EQUIVALENT
LOWLY POINT FORMATION
FALSE BAY FORMATION
MAMBRAY FORMATION AND OLDER UNITS
A
No. 120
1 2 3 4
B
C
LINE II
120
Meters
10
15
20
500 m
Germein Bay Formation (Holocene marine)
Lowly Point Formation (L)
False Bay Formation (F)
Mambray Formation (M)
Older Pleistocene marine beds (O)

SG 120

Fig 5.16

A, C. Sections showing location of vibrocore #SG120 in relation to Quaternary stratigraphy (A after Hails et al, 1984a, fig 6; C after Billing, 1984, fig 9). **B.** Vibrocore #SG120, split core (after Billing, 1984, fig 3).

VIBROCORE SG120 (Fig 5.16)

GERMEIN BAY FORMATION

At least 1.5m of Germein Bay Formation is represented in this core, though initial examination suggested that the Pleistocene/Holocene boundary could be a further metre below at 2.5m. Although a clear lithological boundary was recognised at about 1.5m by both Hails et al. (unpublished) and Billing (1984), the boundary was not accompanied by any discernible palaeosol development (Fig 5.17). The lithological unit identified in Fig 5.17 as simply "2A" was initially thought by Hails et al. to be an early transgressive phase of the Holocene, though this opinion gave way to a later interpretation in which the unit was assigned to "Pooraka Formation equivalent" (Fig 5.16A). Billing (1984) acknowledged the stratigraphic uncertainty of the 2A interval, but nevertheless placed it within the Pleistocene. In this present account, it is initially assumed that the base of the Germein Bay Formation is correctly placed at 150cm, but the possibility that it should be at 250cm is also explored.

Distribution of species of foraminifera through the core are shown for the size fractions 1.00 - 0.50mm and 0.50 - 0.25mm as figures 5.18 and 5.19 respectively. In the coarser fraction, >200 individuals were counted for the samples at 150 and 125cm, but many fewer specimens were extracted from this fraction higher in the core. For the finer fraction, an average of >600 individuals per sample were used to calculate the percentage distributions of species. The data shown in Fig 5.19 are therefore the more reliable, though there is no significant disagreement between the two data sets.

At 150cm in the core, a shallow water assemblage consisting of *Discorbis dimidiatus, Peneroplis planatus* (showing variable form), *Nubecularia lucifuga* and *Cribrobulimina mixta* accounts for >80% of the coarser fraction and almost 70% of the finer fraction. In contrast, *Massilina milletti*, which favours deeper waters (Figs 4.2, 4.3), accounts for only 4% and 8% respectively.

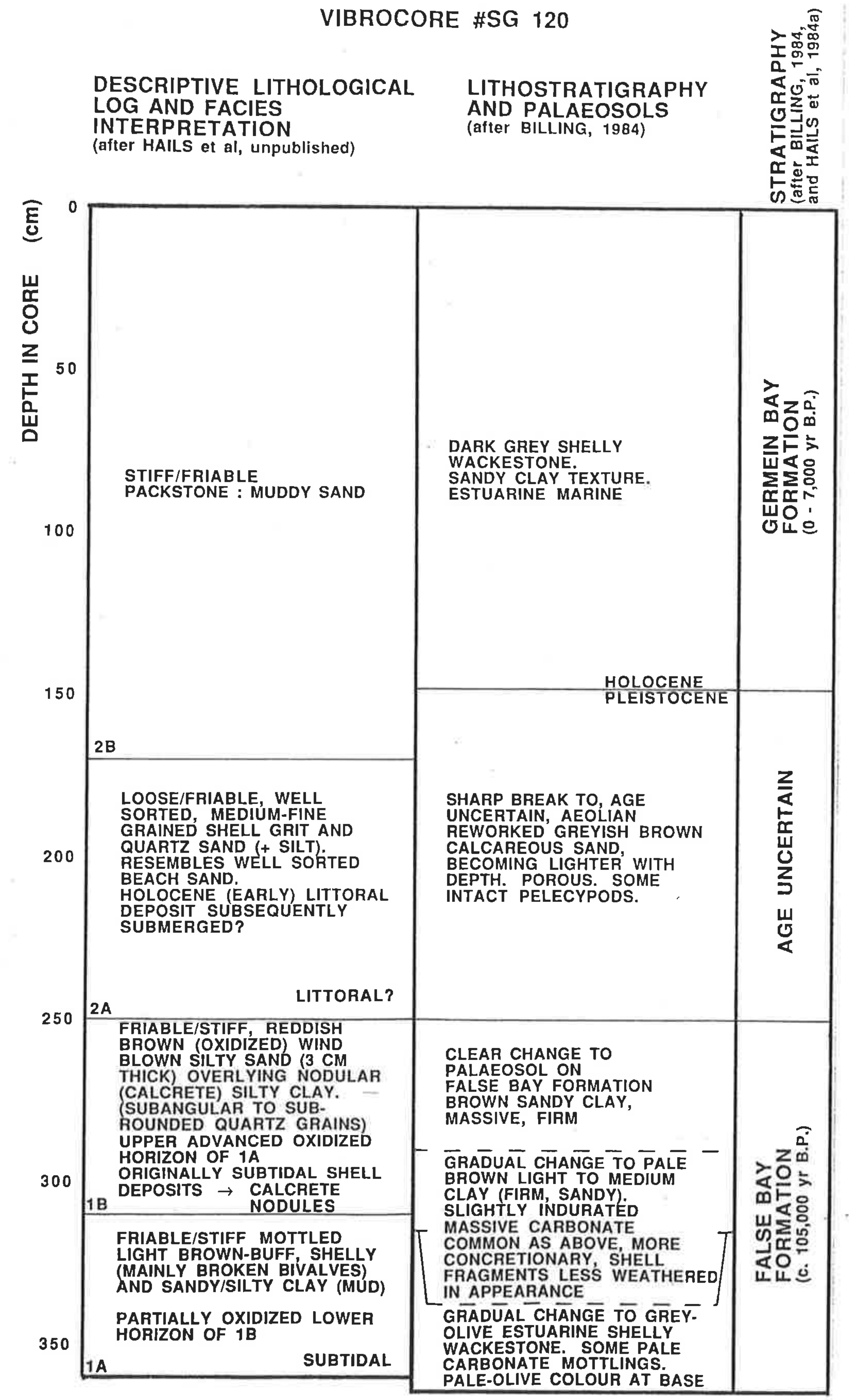

VIBROCORE #SG 120
DESCRIPTIVE LITHOLOGICAL LOG AND FACIES INTERPRETATION
(after HAILS et al, unpublished)
LITHOSTRATIGRAPHY AND PALAEOSOLS
(after BILLING, 1984)
STRATIGRAPHY
(after BILLING, 1984, and HAILS et al, 1984a)
DEPTH IN CORE (cm)
0
50
100
150
200
250
300
350
STIFF/FRIABLE PACKSTONE : MUDDY SAND
2B
LOOSE/FRIABLE, WELL SORTED, MEDIUM-FINE GRAINED SHELL GRIT AND QUARTZ SAND (+ SILT). RESEMBLES WELL SORTED BEACH SAND. HOLOCENE (EARLY) LITTORAL DEPOSIT SUBSEQUENTLY SUBMERGED?
LITTORAL?
2A
FRIABLE/STIFF, REDDISH BROWN (OXIDIZED) WIND BLOWN SILTY SAND (3 CM THICK) OVERLYING NODULAR (CALCRETE) SILTY CLAY. (SUBANGULAR TO SUB-ROUNDED QUARTZ GRAINS) UPPER ADVANCED OXIDIZED HORIZON OF 1A ORIGINALLY SUBTIDAL SHELL DEPOSITS → CALCRETE NODULES
1B
FRIABLE/STIFF MOTTLED LIGHT BROWN-BUFF, SHELLY (MAINLY BROKEN BIVALVES) AND SANDY/SILTY CLAY (MUD)
PARTIALLY OXIDIZED LOWER HORIZON OF 1B
SUBTIDAL
1A
DARK GREY SHELLY WACKESTONE. SANDY CLAY TEXTURE. ESTUARINE MARINE
HOLOCENE
PLEISTOCENE
SHARP BREAK TO, AGE UNCERTAIN, AEOLIAN REWORKED GREYISH BROWN CALCAREOUS SAND, BECOMING LIGHTER WITH DEPTH. POROUS. SOME INTACT PELECYPODS.
CLEAR CHANGE TO PALAEOSOL ON FALSE BAY FORMATION BROWN SANDY CLAY, MASSIVE, FIRM
GRADUAL CHANGE TO PALE BROWN LIGHT TO MEDIUM CLAY (FIRM, SANDY). SLIGHTLY INDURATED MASSIVE CARBONATE
COMMON AS ABOVE, MORE CONCRETIONARY, SHELL FRAGMENTS LESS WEATHERED IN APPEARANCE
GRADUAL CHANGE TO GREY-OLIVE ESTUARINE SHELLY WACKESTONE. SOME PALE CARBONATE MOTTLINGS. PALE-OLIVE COLOUR AT BASE
GERMEIN BAY FORMATION
(0 - 7,000 yr B.P.)
AGE UNCERTAIN
FALSE BAY FORMATION
(c. 105,000 yr B.P.)

Fig 5.17

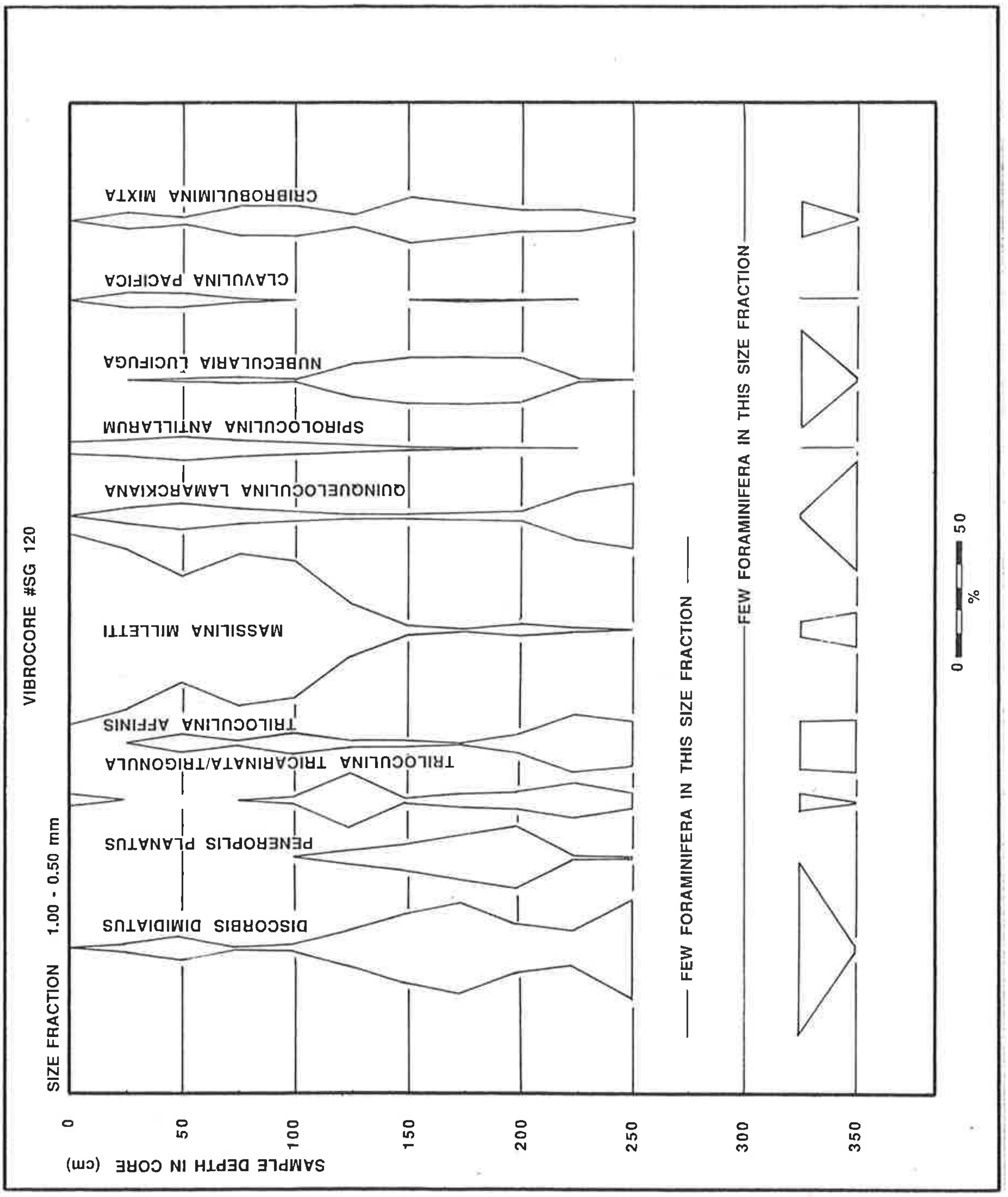


Fig 5.18
Percentage distributions of selected species of benthic foraminifera within vibrocore #SG120.
Size fraction 1.00 - 0.50mm.

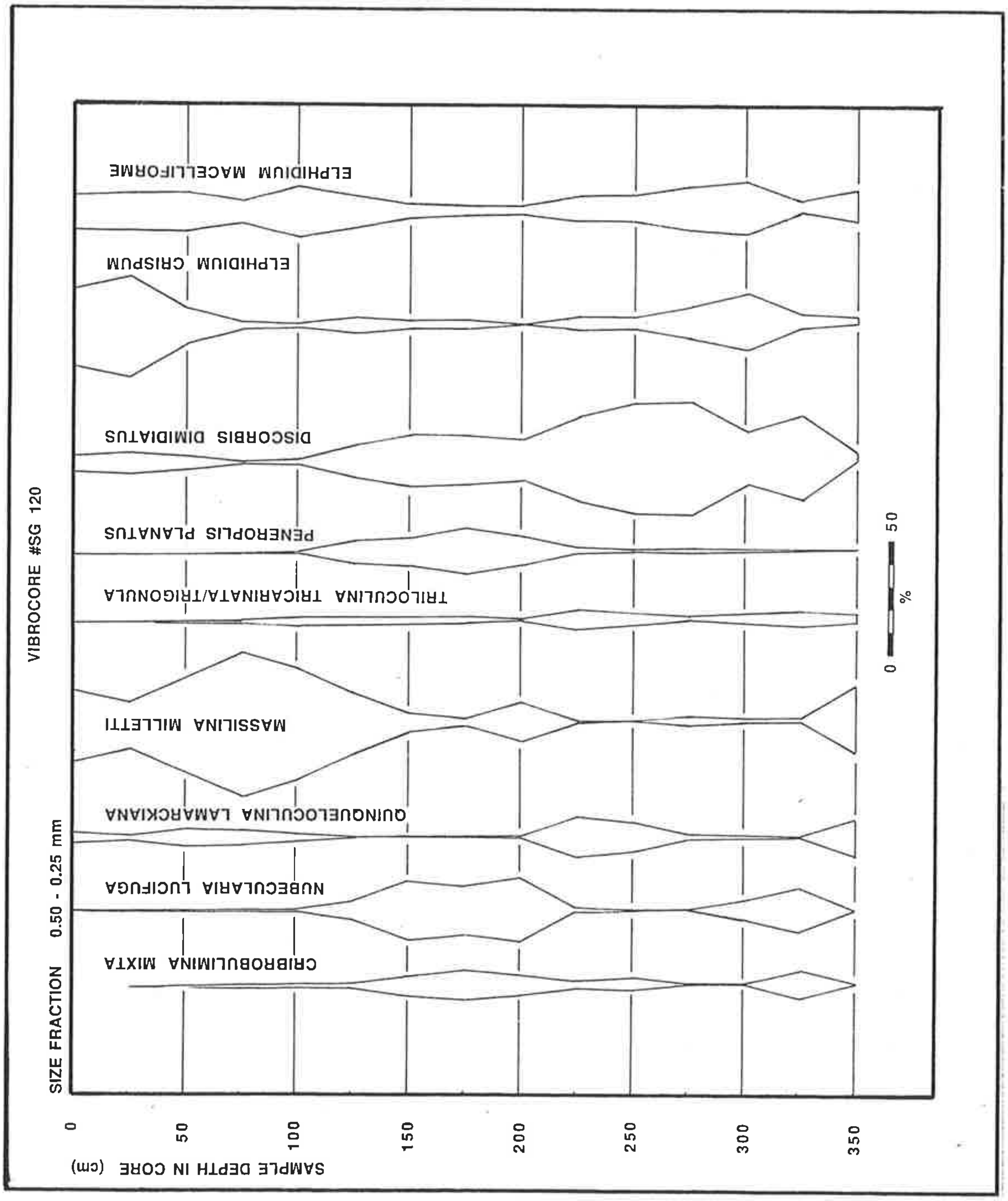


Fig 5.19
Percentage distributions of selected species of benthic foraminifera within vibrocore #SG120.
Size fraction 0.50 - 0.25mm.

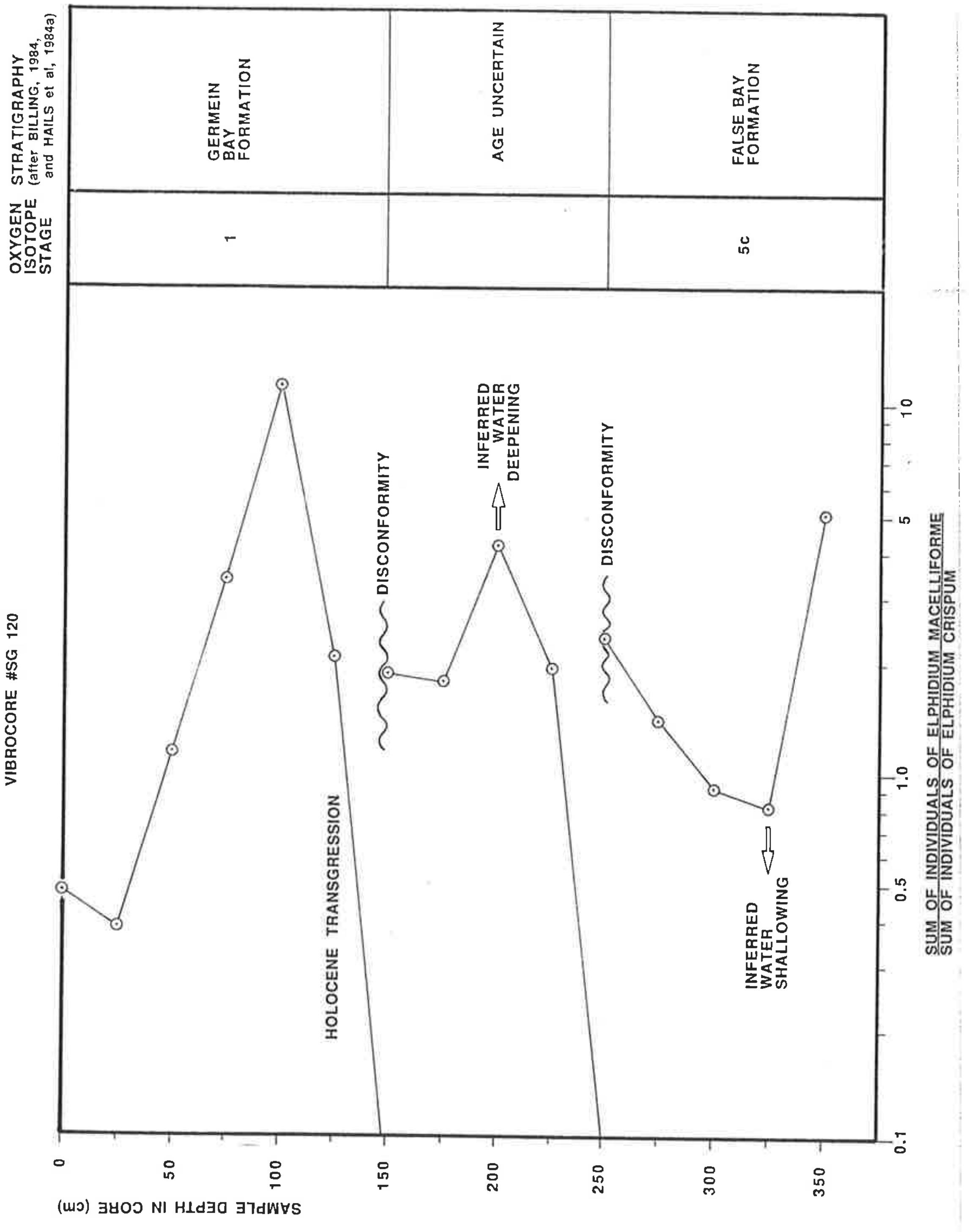


Fig 5.20

Log-linear plot of sample depth in vibrocore #SG120 versus ratio of numbers of individuals of *Elphidium macelliforme* to numbers of individuals of *Elphidium crispum* for core samples. Inferred changes of palaeo sea levels derived from this ratio are signified. The stratigraphic framework is that of Hails et al, 1984a and unpublished, and Billing, 1984 (Fig 5.17).

The Holocene transgression and subsequent changes in sea level are elegantly illustrated by the changes in abundances of these five species up core. *M. milletti* markedly increases in numbers up core showing a peak, indicating maximum sea level, at 75cm. Above this horizon, in the fraction 0.50 - 0.25mm (Fig 5.19) (coarser fraction samples above 75cm average <50 individuals and are therefore less reliable for this interpretation), marine regression is signified by decreasing *M. milletti* and increasing *D. dimidiatus* to 25cm. A final surge in *M. milletti* at the top of the core suggests further water deepening late in Holocene time.

For the same core interval, the *Elphidium* ratio (Fig 5.20) reveals the same sea level history, though signifying the peak of the Holocene transgression at 100cm, one sample interval lower than the horizon deduced from the *M. milletti* distribution. This slight discrepancy does not significantly perturb the remarkable internal consistency of the data and the close agreement of the sequence of relative palaeo water depths derived from the data sets.

AGE UNCERTAIN (LITHOSTRATIGRAPHIC UNIT 2A)

The "intact pelecypods" recorded by Billing (1984) (Fig 5.17), in his description of this unit, are inconsistent with any notion of reworking, particularly by aeolian processes. Identification of the bivalve species probably would have been sufficient to infer a sedimentary environment similar to one of those described for Port Gawler (Chapter 3). Initially, Hails et al. considered these sediments to have formed in a littoral environment (Fig 5.17). This is consistent with the preferred interpretation presented here, that the unit represents an episode of normal gulf sedimentation.

The four species of foraminifera typifying the shallow water assemblages of the Germein Bay Formation, discussed above, are also well represented in the 2A interval 250 to 150cm. However, within this interval, in the finer size fraction, there is a distinctive peak of the deeper water species *Massilina milletti*, 17% at 200cm. This peak signifies maximum sea level for this episode of deposition. Thus, a simple record of transgression and regression, in a shallow subtidal to intertidal sequence, is indicated by the general assemblage for the unit 2A.

The detail of this simple record of relative sea level change is reinforced by the *Elphidium* ratio for the 2A interval (Fig 5.20). Changes in palaeo water depth, inferred by this ratio, coincide exactly with those deduced from the general assemblage. A sea level maximum is indicated at 200cm, with subsequent marine regression.

Holocene marine inundation of the site of SG120 was effected late in the transgression, sea level having risen more than 100m before flooding northern Spencer Gulf. The established record of this transgression (Chapter 1) is one of rapid, steady rise in sea level. For the 2A sediments to have been deposited at this time would have required a hesitant fluctuation of sea level, as shown by both the general assemblage of species and by the *Elphidium* ratio. As there is no known record of such a fluctuation in the Holocene transgression, it must be concluded that unit 2A has been correctly assigned to the Pleistocene. Stratigraphic constraints require that it be recognised as Lowly Point Formation.

? [illegible]

If the above assessment is correct, the transgressive episode of oxygen isotope stage 5a, which resulted in deposition of the Lowly Point sediments, may have been slightly more extensive than envisaged by Hails et al. (1984a, b). Some modifications are then required for the c.82,000yr B.P. palaeo shore line of Billing (1984) and the isopach map of the Lowly Point Formation prepared by Hails et al. (1984a).

FALSE BAY FORMATION

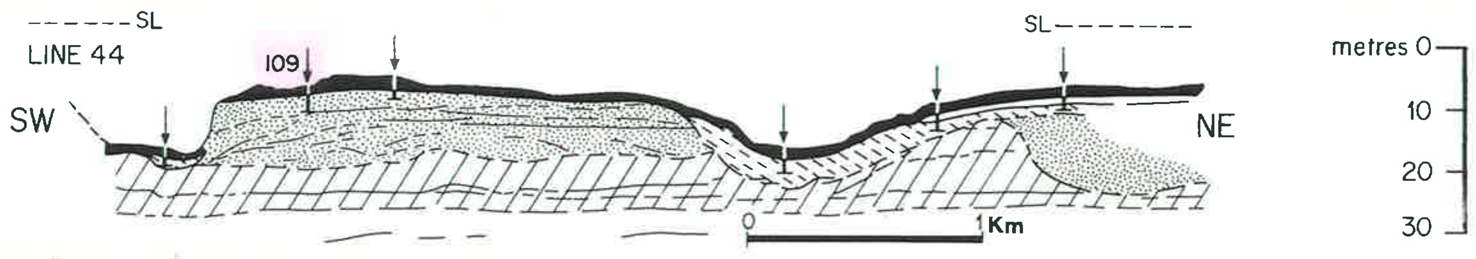
This unit is inadvertently indicated to be Lowly Point Formation in Fig 5.16C, taken from Billing (1984). In this diagram the symbol "L" actually refers to the False Bay Formation.

Core descriptions (Fig 5.17) show that the uppermost horizons of this formation in SG120 have been significantly affected by pedogenesis. Few foraminifera were recovered in the coarser fraction from samples taken at 275 and 300cm (Fig 5.18) In the finer fraction (Fig 5.19), foraminifera from the 300cm sample were heavily encrusted with calcium carbonate, making species identification difficult. Data presented for this horizon should therefore be assessed with caution.

From 350 to 325cm marine regression is signified by the general assemblage of species in both size fractions. *Discorbis dimidiatus, Nubecularia lucifuga* and *Cribrobulimina mixta* all increase markedly in numbers while there is a corresponding reduction in the abundance of *Massilina milletti.* This regression is confirmed by the *Elphidium* ratio (Fig 5.20).

Above 325cm, due to pedogenic alteration of the sediment, interpretation of assemblages is accompanied by a degree of uncertainty. In the fine fraction (Fig 5.19), specimens of *Elphidium macelliforme* and *E. crispum* were well represented and their ratios may be the best guide to inferred changes of sea level (Fig 5.20). This ratio up core suggests water deepening and this is supported by falling numbers of *Nubecularia lucifuga.* However, no clear sea level signal can be deduced from the general assemblage between 325cm and the disconformity at 250cm.

A



VIBROCORE SITE WITH DEPTH INDICATED

■ GERMEIN BAY FORMATION

□ POORAKA FORMATION EQUIVALENT

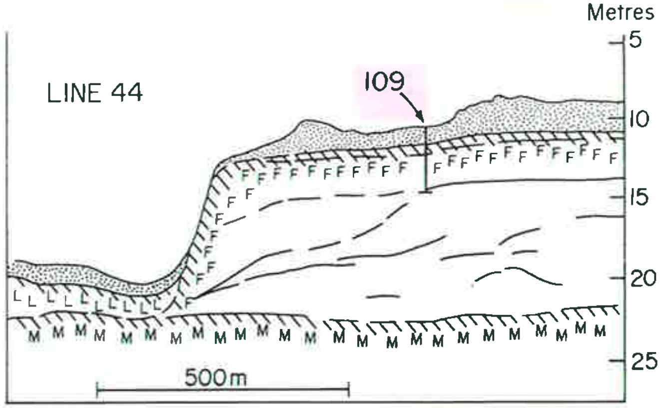
▧ LOWLY POINT FORMATION

▒ FALSE BAY FORMATION

▨ MAMBRAY FORMATION AND OLDER UNITS

B

SG 109



Germein Bay Formation ▒
(Holocene marine)

Lowly Point Formation (L)

False Bay Formation (F)

Mambray Formation (M)

Older Pleistocene marine beds (O)

C

Fig 5.21
A. Vibrocore #SG109, split core (after Billing, 1984, fig 3).
B, C. Sections showing location of SG109 in relation to Quaternary stratigraphy (B after Hails et al, 1984a, fig 5; C after Billing, 1984, fig 8).

VIBROCORE SG109 (Fig 5.21)

GERMEIN BAY FORMATION

In this core, Billing (1984) recognised the Pleistocene/ Holocene boundary at 130cm, on the basis of palaeosol development on the underlying False Bay Formation (Fig 5.22). Core samples above this horizon yielded an average of only 100 individual foraminifera for the size fraction 1.00 - 0.50mm, but nearly 450 for the finer fraction. In both size fractions, Holocene marine inundation of northern Spencer Gulf is unambiguously signalled by increasing numbers up core of *Massilina milletti* (Figs 5.23, 5.24), the species most obviously favouring the deeper waters of the modern gulf (Figs 4.2, 4.3). Associated decreasing numbers of shallow water species, such as *Nubecularia lucifuga* and intertidal forms of *Peneroplis planatus* confirm water deepening. The peak of *Discorbis dimidiatus* at 107cm, particularly in the finer fraction (Fig 5.24), signifies the occupation of a shallow subtidal *Posidonia* seagrass environment by this species. The up core distribution of *D. dimidiatus* is also significant in that after the minimum abundance at 75cm, the species reappears higher in the core, thus ~~inferring~~ implying a slight fall in sea level. The palaeo water depth implications of *M. milletti* are confused in the core record above 50cm, though both fractions indicate maximum water depth at that horizon of the core. Accepting the greater numerical reliability of the finer fraction (Fig 5.24), water shallowing is signified by samples above 50cm.

The *Elphidium* ratio (Fig 5.25) indicates that maximum Holocene water depth is ~~inferred~~ located at 100cm, but these *Elphidium* ratio values near the base of the Germein Bay interval may reflect some reworking from the False Bay Formation below. Note the very high ratio of *E. macelliforme* to *E. crispum* in the immediately underlying sediments. Both the original core description of Hails et al. (unpublished) and that of Billing (1984) (Fig 5.22) indicate that the Pleistocene/Holocene boundary is not sharp and thus some reworking of Pleistocene foraminifera should be anticipated. Many individuals of *E. macelliforme* recovered from the lower horizon of the Germein Bay interval are dull, chipped or carbonate encrusted.

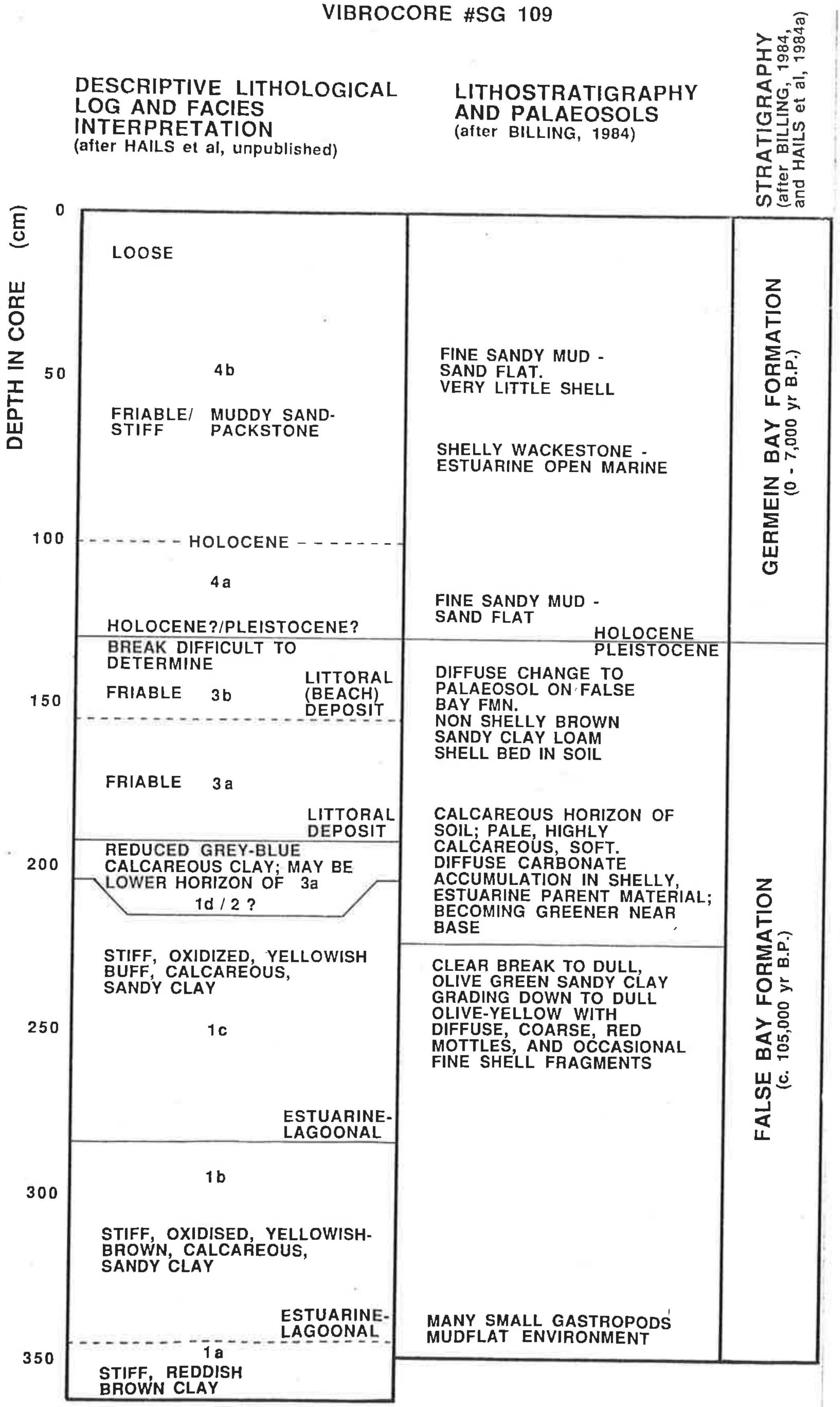

VIBROCORE #SG 109
DESCRIPTIVE LITHOLOGICAL LOG AND FACIES INTERPRETATION
(after HAILS et al, unpublished)
LITHOSTRATIGRAPHY AND PALAEOSOLS
(after BILLING, 1984)
STRATIGRAPHY
(after BILLING, 1984, and HAILS et al, 1984a)
DEPTH IN CORE (cm)
0
50
100
150
200
250
300
350
LOOSE
4b
FRIABLE/ STIFF
MUDDY SAND-PACKSTONE
HOLOCENE
4a
HOLOCENE?/PLEISTOCENE? BREAK DIFFICULT TO DETERMINE
FRIABLE 3b
LITTORAL (BEACH) DEPOSIT
FRIABLE 3a
LITTORAL DEPOSIT
REDUCED GREY-BLUE CALCAREOUS CLAY; MAY BE LOWER HORIZON OF 3a
1d / 2 ?
STIFF, OXIDIZED, YELLOWISH BUFF, CALCAREOUS, SANDY CLAY
1c
ESTUARINE-LAGOONAL
1b
STIFF, OXIDISED, YELLOWISH-BROWN, CALCAREOUS, SANDY CLAY
ESTUARINE-LAGOONAL
1a
STIFF, REDDISH BROWN CLAY
FINE SANDY MUD - SAND FLAT. VERY LITTLE SHELL
SHELLY WACKESTONE - ESTUARINE OPEN MARINE
FINE SANDY MUD - SAND FLAT
HOLOCENE
PLEISTOCENE
DIFFUSE CHANGE TO PALAEOSOL ON FALSE BAY FMN.
NON SHELLY BROWN SANDY CLAY LOAM
SHELL BED IN SOIL
CALCAREOUS HORIZON OF SOIL; PALE, HIGHLY CALCAREOUS, SOFT. DIFFUSE CARBONATE ACCUMULATION IN SHELLY, ESTUARINE PARENT MATERIAL; BECOMING GREENER NEAR BASE
CLEAR BREAK TO DULL, OLIVE GREEN SANDY CLAY GRADING DOWN TO DULL OLIVE-YELLOW WITH DIFFUSE, COARSE, RED MOTTLES, AND OCCASIONAL FINE SHELL FRAGMENTS
MANY SMALL GASTROPODS MUDFLAT ENVIRONMENT
GERMEIN BAY FORMATION
(0 - 7,000 yr B.P.)
FALSE BAY FORMATION
(c. 105,000 yr B.P.)

Fig 5.22

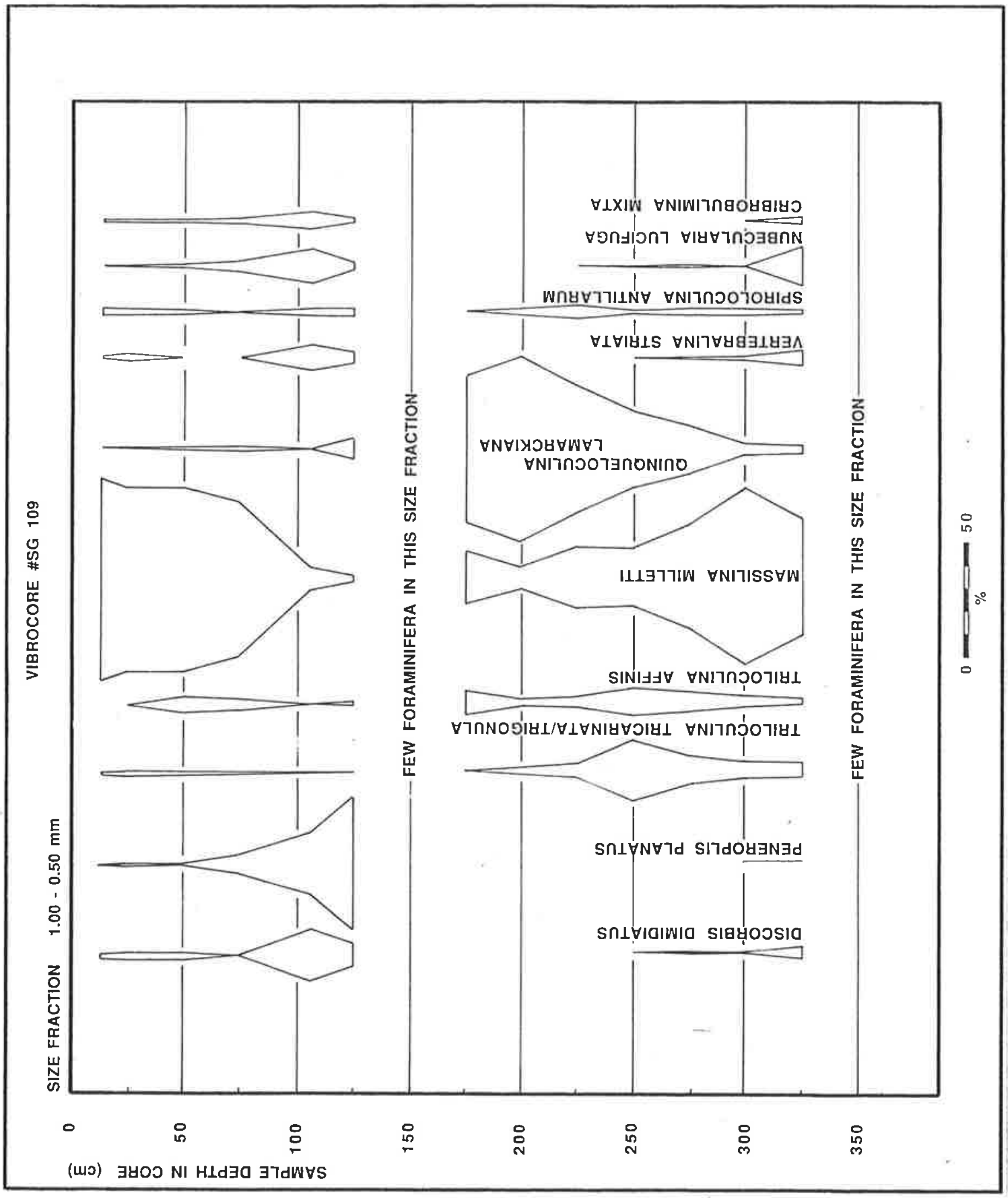


Fig 5.23
Percentage distributions of selected species of benthic foraminifera within vibrocore #SG109.
Size fraction 1.00 - 0.50mm.

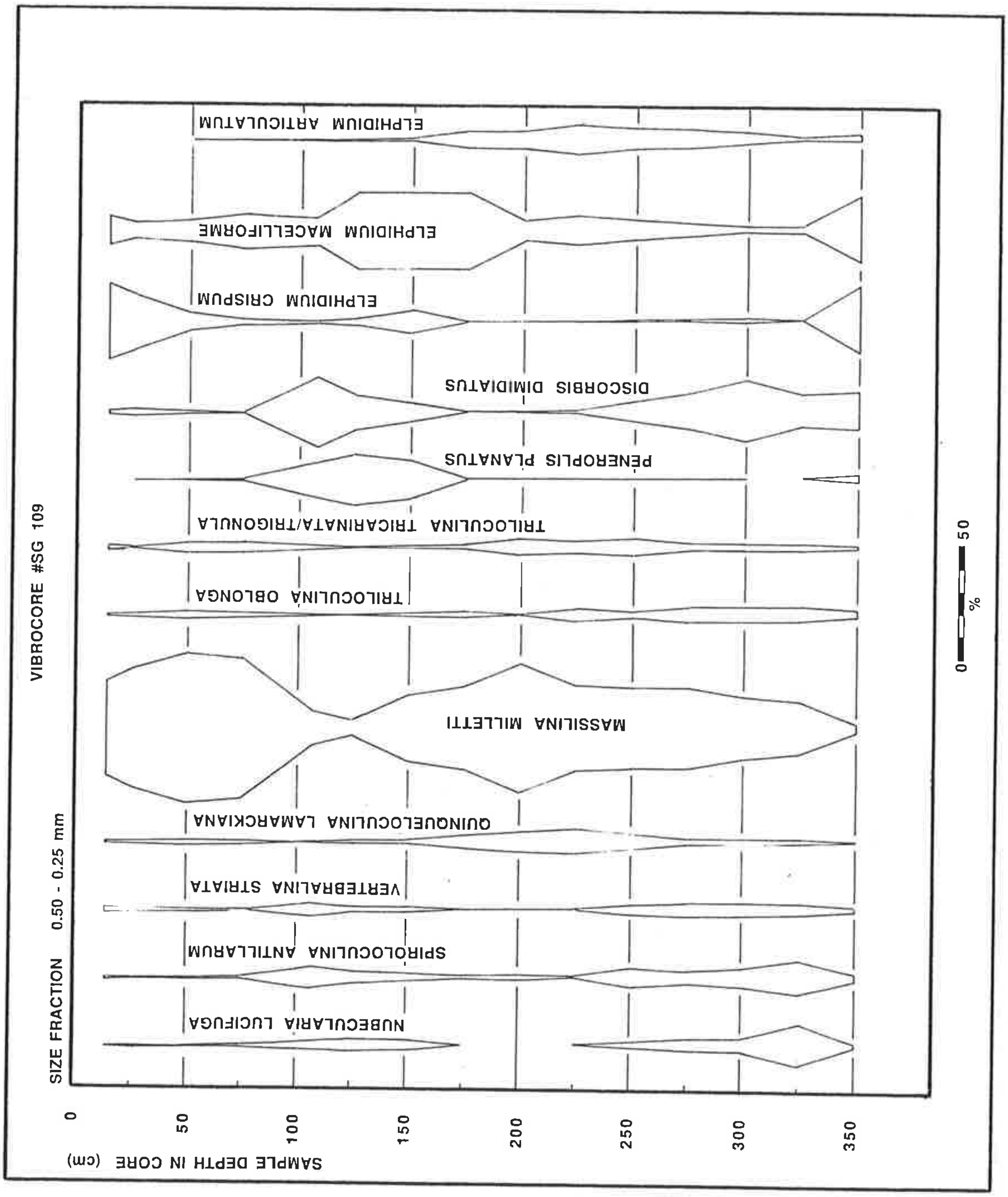


Fig 5.24
Percentage distributions of selected species of benthic foraminifera within Vibrocore #SG109.
Size fraction 0.50 - 0.25mm.

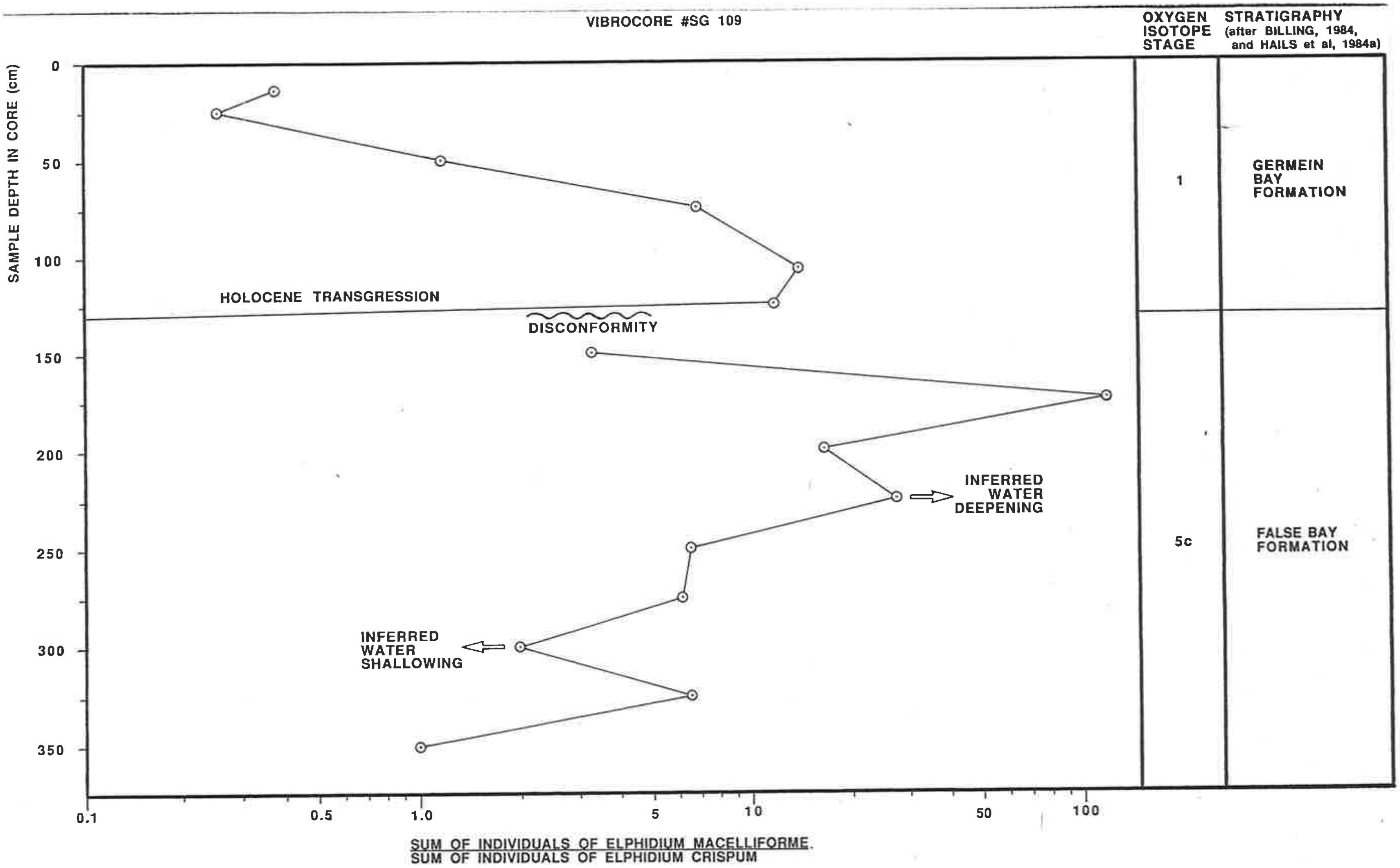

VIBROCORE #SG 109
OXYGEN ISOTOPE STAGE
STRATIGRAPHY (after BILLING, 1984, and HAILS et al, 1984a)
SAMPLE DEPTH IN CORE (cm)
0
50
100
150
200
250
300
350
HOLOCENE TRANSGRESSION
DISCONFORMITY
INFERRED WATER DEEPENING
INFERRED WATER SHALLOWING
1
GERMEIN BAY FORMATION
5c
FALSE BAY FORMATION
0.1
0.5
1.0
5
10
50
100
SUM OF INDIVIDUALS OF ELPHIDIUM MACELLIFORME
SUM OF INDIVIDUALS OF ELPHIDIUM CRISPUM

Fig 5.25
Log-linear plot of sample depth in vibrocore #SG109 versus ratio of numbers of individuals of *Elphidium macelliforme* to numbers of individuals of *Elphidium crispum* for core samples. Inferred changes of palaeo sea levels derived from this ratio are signified. The stratigraphic framework is that of Hails et al, 1984a and unpublished, and Billing, 1984 (Fig 5.22).

They contrast visually with the translucent glossy specimens more characteristic of the species in samples taken from higher in the core. Hence, little credence is given to palaeo water depth implications of the *Elphidium* ratios for samples at core depths 125cm, 107cm and possibly even 75cm.

The balance of evidence suggests that sediments around 75 to 50cm were deposited in the deepest Holocene waters of northern Spencer Gulf, at site SG109. After that time waters shallowed, but there appears to have been a final late Holocene sea level rise. This is signified by an increase in *Massilina milletti* in the coarser fraction (Fig 5.23) and by a slight increase in the *Elphidium* ratio (Fig 5.25).

FALSE BAY FORMATION

The Pleistocene interval of SG109 yielded widely varying numbers of foraminifera in the size fraction 1.00 - 0.50mm. For example, 377 individuals were recovered from the 325cm sample, but only 10 and 11 from samples at 350cm and 150cm respectively. Other samples averaged slightly less than 100 specimens. However, all samples in the finer fraction contained statistically significant numbers of foraminifera, the average being nearly 500. The relative palaeo sea level record derived from this fraction is thus potentially credible.

The distribution of *Massilina milletti* in the finer fraction (Fig 5.24) implies a simple transgressive-regressive sequence, maximum palaeo sea level signified by the sample at 200cm. This interpretation is supported by the presence of shallow water species, such as *Nubecularia lucifuga*, at both the top and the bottom of the False Bay interval, but not in the middle. *Discorbis dimidiatus* shows a similar distribution, though the peak abundance of this species at 300cm could represent a slight regressive event.

In the coarser fraction, the up core distribution of *M. milletti* apparently does not match that derived for the numerically more reliable 0.50 - 0.25mm size fraction.

This is largely a statistical artefact generated by the increasing numbers of *Quinqueloculina lamarckiana* up core. The significance of this species is not immediately apparent from its distribution in the modern sediments of northern Spencer Gulf (Fig 4.2).

The *Elphidium* ratio derived for the False Bay interval of vibrocore SG109 (Fig 5.25) is patently difficult to reconcile with the palaeo sea level implications of the general assemblage. For example, the palaeo water depth inferred for the 175cm sample, based on the data of Fig 4.5, is about 30m. Given that Hails et al. (1984b) calculated a maximum sea level of -8m for the oxygen isotope substage 5c transgression, and that the basal sediments penetrated by SG109 are <15m below present sea level, the inferred water depth of 30m is, at best, implausible.

perhaps Hails et al were wrong

As previously observed for the Mambray Formation in vibrocore SG79, this False Bay interval in SG109 shows an inverse numerical relationship between the distributions of *Elphidium articulatum* and *E. crispum*. The possible palaeoecological implications of this observation were earlier discussed for core SG79. A consequent modified relationship of the *Elphidium* ratio was shown to provide plausible values, inferring palaeo water depths that could be reconciled with those derived from the general assemblage of species in that core.

For this core, SG109, similarly calculated values for the expression:

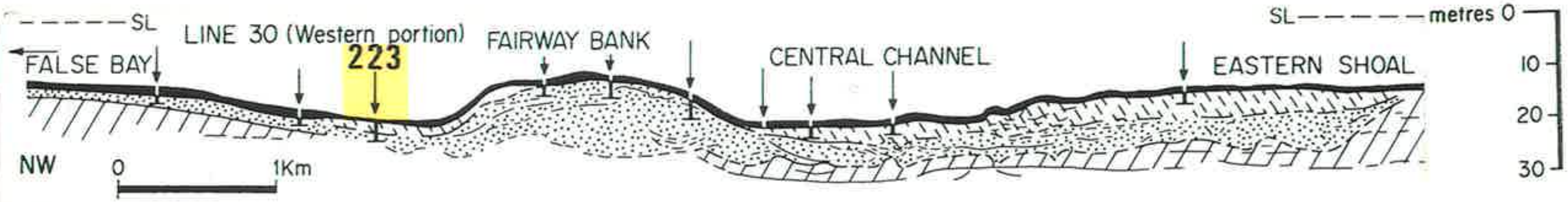
$$\frac{\text{sum of individuals of } \textit{Elphidium macelliforme}}{\text{sum of individuals of } (\textit{E. articulatum} + \textit{E. crispum})}$$

generated numbers still inferring transgressive peaks at 325 and 175cm, but at much lower values of 1.9 and 4.3 respectively. At 300cm, where marine regression is implied by both the original *Elphidium* ratio (Fig 5.25) and by the *Discorbis dimidiatus* maximum (Fig 5.24), the modified expression generates a minimum value of 0.4. Above this horizon, values increase gradually to 1.0 at 200cm before the transgressive peak, 4.3 at 175cm.

If these values are seen within the frame of reference of the originally determined relationship of the *Elphidium* ratio to water depth in the modern Spencer Gulf environment (Fig 4.5), they ~~infer~~ imply plausible palaeo water depths. Furthermore, the changes in relative sea level implied up core can be credibly accommodated within the framework of the general species distribution. However, as cautioned earlier for SG109, a basis for such a relationship between the three species of *Elphidium* and water depth has yet to be established for modern environments.

For the False Bay Formation recovered from vibrocore SG109, the strongest indicator of changes in palaeo water depth is generated by the up core distribution of *M. milletti* in the size fraction 0.50 - 0.25mm. The balance of evidence suggests a simple pattern of transgression and regression, with maximum water depth signified by the 200cm sample.

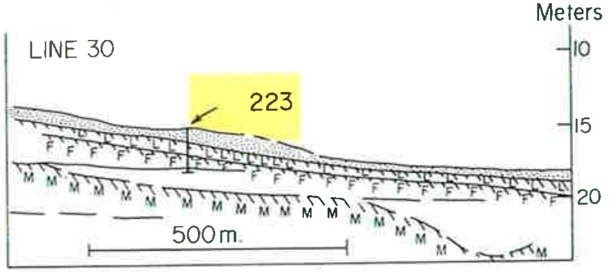
A



- ↓ VIBROCORE SITE WITH DEPTH INDICATED
- ▇ GERMEIN BAY FORMATION
- ☐ POORAKA FORMATION EQUIVALENT
- ▨ LOWLY POINT FORMATION
- ░ FALSE BAY FORMATION
- ▧ MAMBRAY FORMATION AND OLDER UNITS

B

SG 223



Germein Bay Formation ░
(Holocene marine)

Lowly Point Formation (L)

False Bay Formation (F)

Mambray Formation (M)

Older Pleistocene (O)
marine beds

C

Fig 5.26

A. Vibrocore #SG223, split core (after Billing, 1984, fig 3).
B, C. Sections showing location of SG223 in relation to Quaternary stratigraphy (B after Hails et al, 1984a, fig 6; C after Billing, 1984, fig 11).

VIBROCORE SG223 (Fig 5.26)

Three formations are represented in this core, Holocene Germein Bay Formation, underlain by Pleistocene Lowly Point and False Bay Formations (Fig 5.26). Stratigraphic boundaries were recognised by Billing (1984) on the basis of palaeosols in the upper horizons of the two Pleistocene units (Fig 5.27).

GERMEIN BAY FORMATION

The 1.00 - 0.50mm size fraction of the Holocene interval yielded nearly 200 individuals per sample, thus providing statistically useful distributions of species. As for the other cores discussed earlier in this chapter, *Massilina milletti* increases in abundance up core (Fig 5.28) signifying a response to the deepening waters of the Holocene transgression. *Nubecularia lucifuga* and *Peneroplis planatus*, on the other hand, illustrate the transgression by their decreasing numbers up core.

The various species of *Triloculina* together provide a less obvious signal (Fig 5.28). In the modern environment of northern Spencer Gulf, *T. affinis* and *T. striatotrigonula* were found to favour waters of intermediate depth, the latter species showing a preference for slightly deeper water (Fig 4.2). In SG223 these preferences seem to be reflected in the peak abundance of *T. affinis* at 75cm, while that of *T. striatotrigonula* is higher in the core at 50cm (Fig 5.28).

In the finer size fraction (Fig 5.29), samples yielded an average of >400 individuals for the Germein Bay interval. *Massilina milletti* dominates the assemblage, its peak abundance at 50cm signifying palaeo water depth for the Holocene at the site of SG223. The *Elphidium* ratio (Fig 5.30) infers maximum water depth somewhat lower in the core, around 100 to 75cm.

The internal consistency of the foraminiferal data for the uppermost metre of the core encourages the belief that there has been minimal reworking of sediment in this interval.

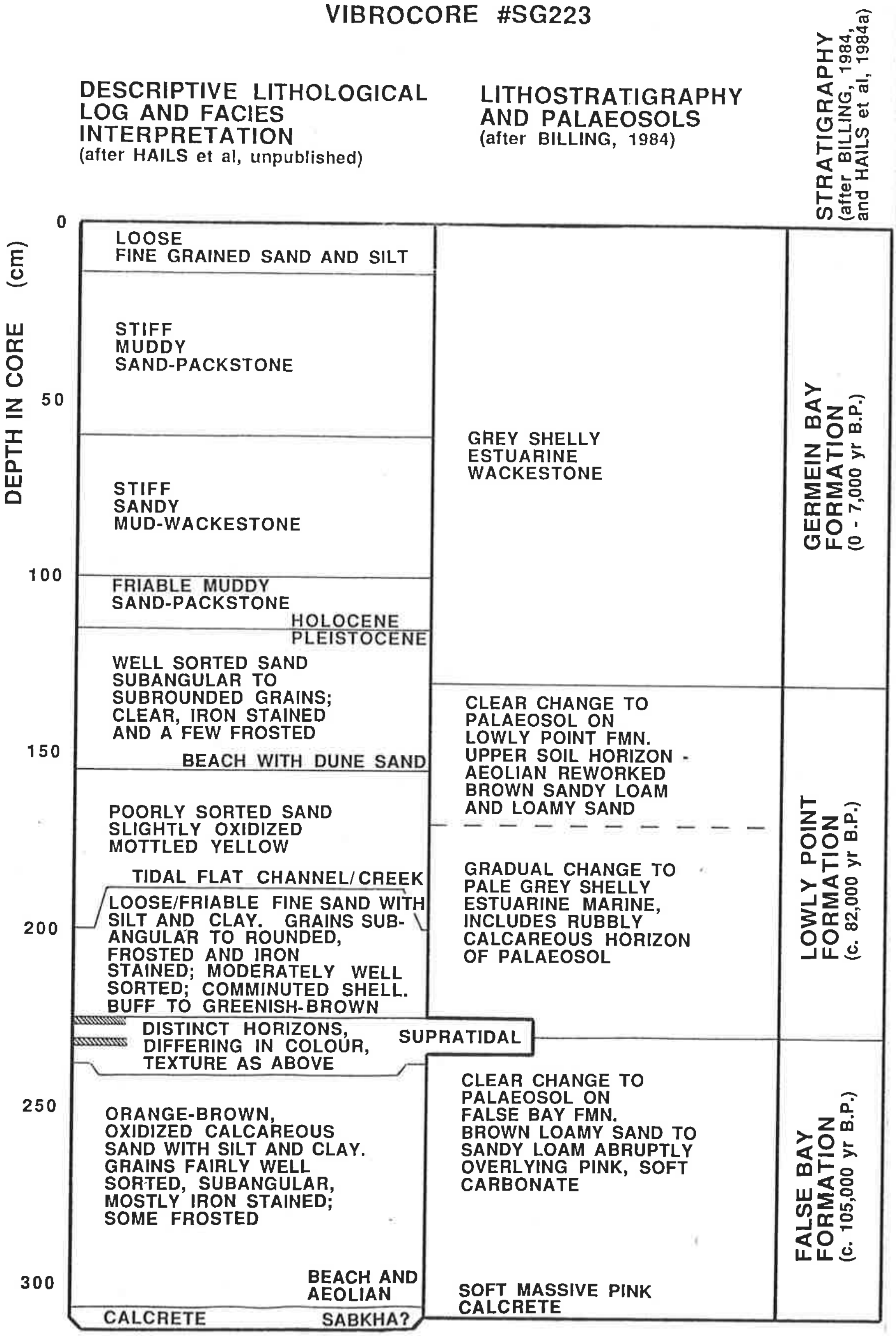

VIBROCORE #SG223
DESCRIPTIVE LITHOLOGICAL LOG AND FACIES INTERPRETATION
(after HAILS et al, unpublished)
LITHOSTRATIGRAPHY AND PALAEOSOLS
(after BILLING, 1984)
STRATIGRAPHY
(after BILLING, 1984, and HAILS et al, 1984a)
DEPTH IN CORE (cm)
0
50
100
150
200
250
300
LOOSE FINE GRAINED SAND AND SILT
STIFF MUDDY SAND-PACKSTONE
STIFF SANDY MUD-WACKESTONE
FRIABLE MUDDY SAND-PACKSTONE
HOLOCENE
PLEISTOCENE
WELL SORTED SAND SUBANGULAR TO SUBROUNDED GRAINS; CLEAR, IRON STAINED AND A FEW FROSTED
BEACH WITH DUNE SAND
POORLY SORTED SAND SLIGHTLY OXIDIZED MOTTLED YELLOW
TIDAL FLAT CHANNEL/CREEK
LOOSE/FRIABLE FINE SAND WITH SILT AND CLAY. GRAINS SUB-ANGULAR TO ROUNDED, FROSTED AND IRON STAINED; MODERATELY WELL SORTED; COMMINUTED SHELL. BUFF TO GREENISH-BROWN
DISTINCT HORIZONS, DIFFERING IN COLOUR, TEXTURE AS ABOVE
SUPRATIDAL
ORANGE-BROWN, OXIDIZED CALCAREOUS SAND WITH SILT AND CLAY. GRAINS FAIRLY WELL SORTED, SUBANGULAR, MOSTLY IRON STAINED; SOME FROSTED
BEACH AND AEOLIAN
CALCRETE
SABKHA?
GREY SHELLY ESTUARINE WACKESTONE
CLEAR CHANGE TO PALAEOSOL ON LOWLY POINT FMN. UPPER SOIL HORIZON - AEOLIAN REWORKED BROWN SANDY LOAM AND LOAMY SAND
GRADUAL CHANGE TO PALE GREY SHELLY ESTUARINE MARINE, INCLUDES RUBBLY CALCAREOUS HORIZON OF PALAEOSOL
CLEAR CHANGE TO PALAEOSOL ON FALSE BAY FMN. BROWN LOAMY SAND TO SANDY LOAM ABRUPTLY OVERLYING PINK, SOFT CARBONATE
SOFT MASSIVE PINK CALCRETE
GERMEIN BAY FORMATION (0 - 7,000 yr B.P.)
LOWLY POINT FORMATION (c. 82,000 yr B.P.)
FALSE BAY FORMATION (c. 105,000 yr B.P.)

Fig 5.27

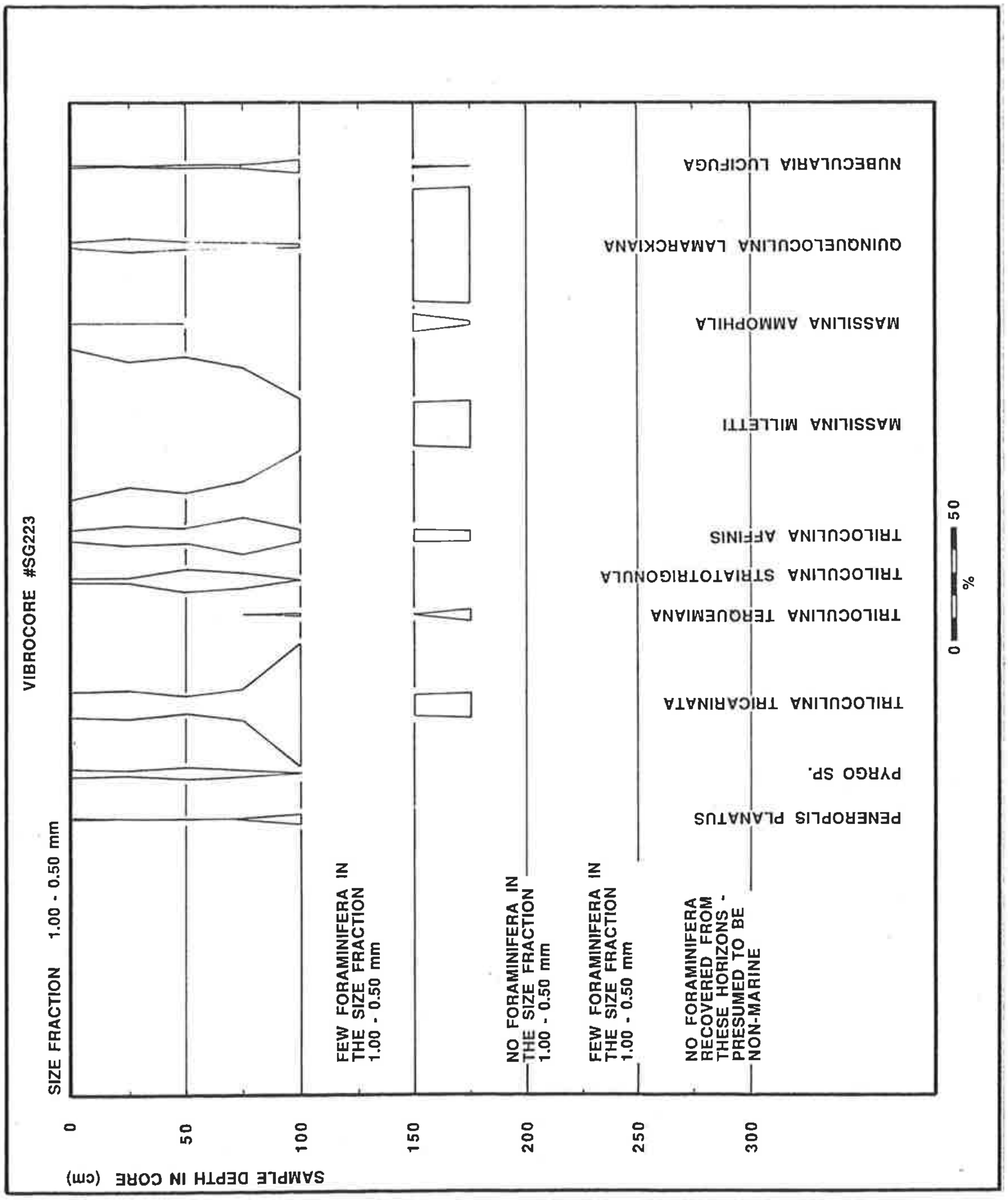


Fig 5.28
Percentage distributions of selected species of benthic foraminifera within vibrocore #SG223.
Size fraction 1.00 - 0.50mm.

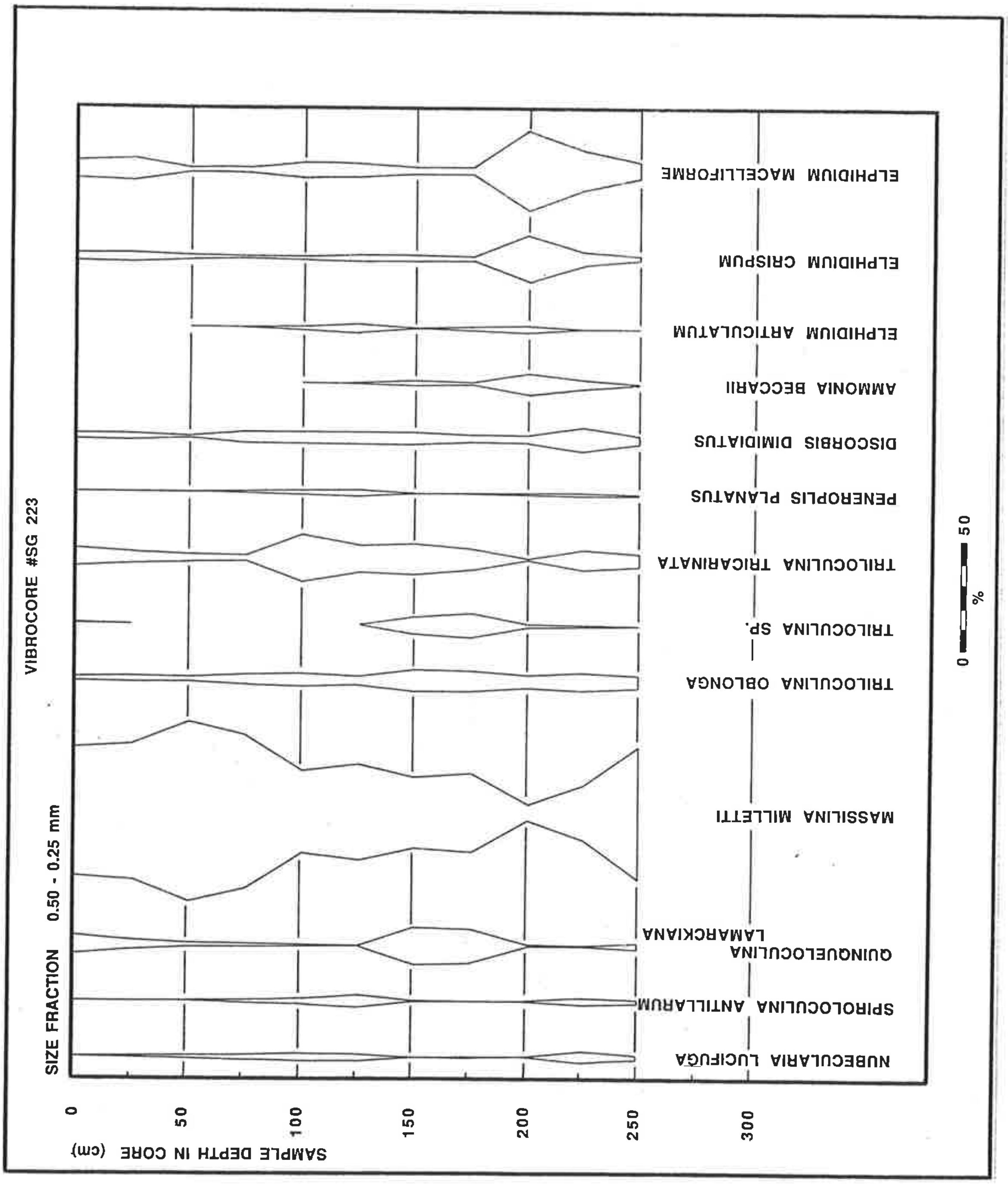


Fig 5.29
Percentage distributions of selected species of benthic foraminifera within vibrocore #SG223.
Size fraction 0.50 - 0.25mm.

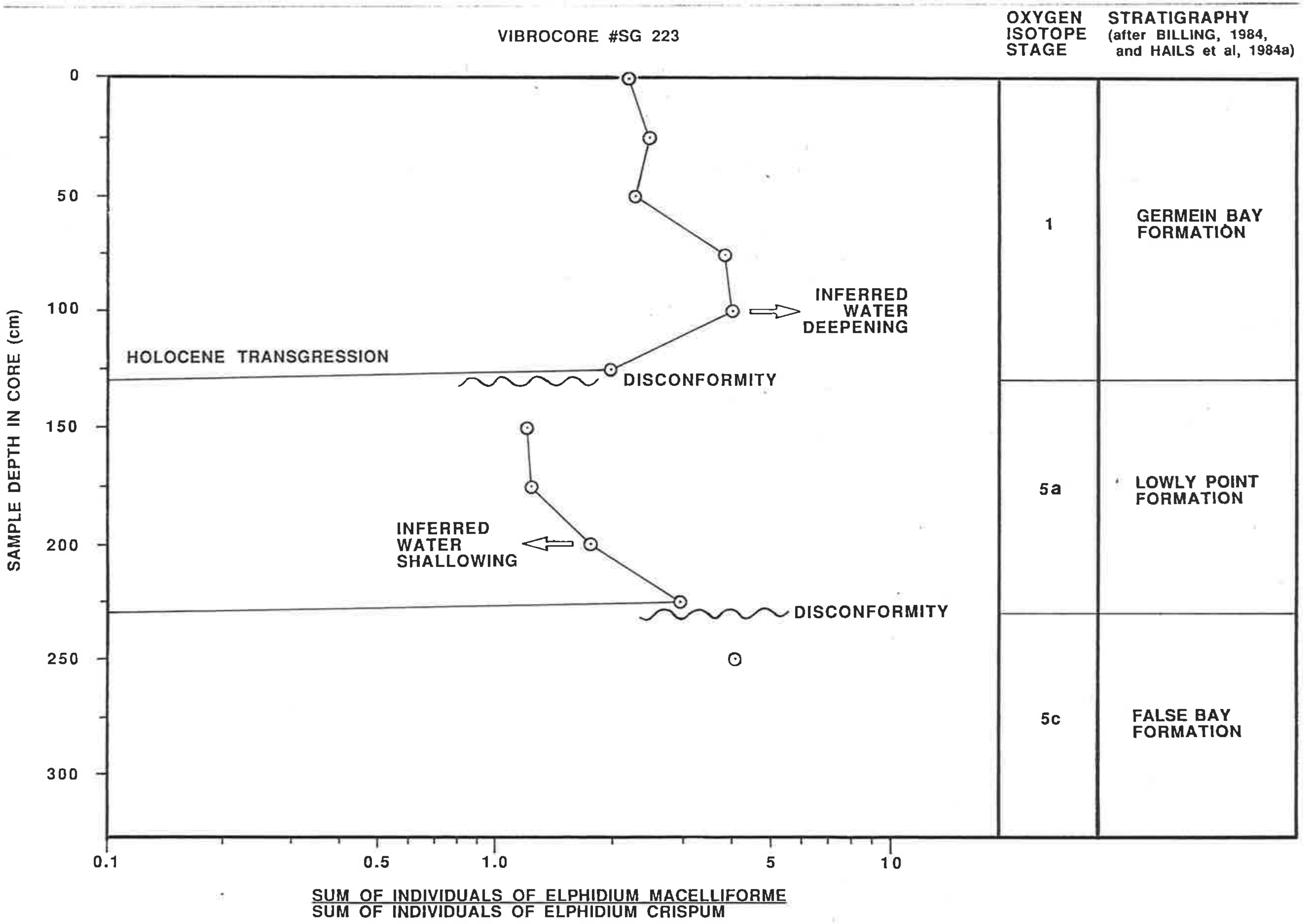

VIBROCORE #SG 223
OXYGEN ISOTOPE STAGE
STRATIGRAPHY (after BILLING, 1984, and HAILS et al, 1984a)
SAMPLE DEPTH IN CORE (cm)
0
50
100
150
200
250
300
HOLOCENE TRANSGRESSION
DISCONFORMITY
INFERRED WATER DEEPENING
INFERRED WATER SHALLOWING
DISCONFORMITY
1
5a
5c
GERMEIN BAY FORMATION
LOWLY POINT FORMATION
FALSE BAY FORMATION
0.1
0.5
1.0
5
10
SUM OF INDIVIDUALS OF ELPHIDIUM MACELLIFORME
SUM OF INDIVIDUALS OF ELPHIDIUM CRISPUM

Fig 5.30

Log-linear plot of sample depth in vibrocore #SG223 versus ratio of numbers of individuals of *Elphidium macelliforme* to numbers of individuals of *Elphidium crispum* for core samples. Inferred changes of palaeo sea levels derived from this ratio are signified. The stratigraphic framework is that of Hails et al, 1984a and unpublished, and Billing, 1984.

However, the persistent abundance of *Massilina milletti* across the Pleistocene/Holocene disconformity indicates that there was significant mixing of Pleistocene and Holocene foraminifera at this horizon.

LOWLY POINT FORMATION

Within the Pleistocene section of the core, meaningful data were obtained for the coarser size fraction from only the samples taken at 175cm and 150cm (Fig 5.28). *Massilina milletti* and *Quinqueloculina lamarckiana* dominate this interval. The absence of any of the established shallow water species, together with the large numbers of *M. milletti*, imply deeper water sedimentation. By association, *Q. lamarckiana* can now be regarded as a species characteristic of deeper water.

The finer size fraction yielded an average of >450 individuals per sample for the Pleistocene section of the core, thus permitting credible analysis of the assemblages. At 200cm, *Ammonia beccarii* accounts for 10% of the assemblage (Fig 5.29). Individual specimens are small, glassy and fragile, strongly resembling those that may be observed in the modern Onkaparinga estuary south of Adelaide. Thus, the interpretations of the depositional environment for the 200cm horizon by Billing (1984), "estuarine marine", and by Hails et al. (unpublished), "tidal flat channel/creek" (Fig 5.27) are supported by the presence of this species. The onset of the oxygen isotope substage 5a marine transgression is signified between 225 and 200cm.

From 200cm up core to the Pleistocene/Holocene disconformity, *Massilina milletti* dominates the assemblage, but never at the same levels of abundance that the species shows in the Holocene interval. This is in accord with the -14m sea level for the c.82,000yr B.P. transgression calculated by Hails et al. (1984b). The large numbers of *M. milletti* at 125cm give no hint of marine regression. Rather, it appears as if the uppermost sediments of the Lowly Point Formation have been removed by erosion and that at least some of the Pleistocene foraminifera were reworked into the basal Holocene.

FALSE BAY FORMATION

Billing (1984) shows the disconformity between the False Bay and overlying Lowly Point Formations to be at 230cm. Fig 5.27 however, shows some minor discrepancies in the lithological and pedogenic boundaries established originally by Hails et al. (unpublished), and later by Billing (1984). After initial opening of the cores, the recovered sediments dry and harden in just a few weeks, and shrinkage fractures develop at irregular intervals. These results of dehydration naturally induce a potential source of error of measurement when recording sample depths in such a core. The sample taken by the present author from 225 - 227cm for foraminiferal analysis, supposedly Lowly Point Formation, given the disconformity at 230cm, may well be the top of the False Bay Formation in SG223.

Although the above interpretation is not followed in Fig 5.30, if the *Elphidium* ratio at 225cm is considered to be below, rather than above the disconformity, the decline from 4.1 at 250cm to 3.0 at 225cm would be more in accord with the record of the general assemblage. For example, *Massilina milletti* decreases from >60% to <25% of the assemblage over that core interval (Fig 5.29). Both sets of data would signify marine regression.

If the 225cm sample is considered to lie within the Lowly Point Formation, the *Elphidium* ratio (Fig 5.30) shows a poor relationship with the general assemblage of that formation, and the False Bay Formation is represented by only the 250cm sample. Even so, both the single *Elphidium* ratio value and the percentage abundance of *M. milletti* indicate a deeper water depositional environment for the False Bay Formation, by comparison with that similarly indicated for the Lowly Point Formation. This is in agreement with a higher -8m palaeo sea level for the c.105,000yr B.P. transgression, compared with -14m for that of c.82,000yr B.P. (Hails et al., 1984b).

Athough >0.5m of sediment was recovered below 250cm, and both Billing (1984) and Hails et al. (1984a) include this interval within the False Bay Formation (Fig 5.27), no foraminifera or other marine fossils were observed. It must therefore be concluded that the sediments at 275 and 300cm are of non-marine origin and therefore do not belong to the False Bay Formation. There is some implication in Fig 5.26c that Billing (1984) was aware of this, in that his diagram shows the base of core SG223 within a unit lacking any symbolic stratigraphic identification.

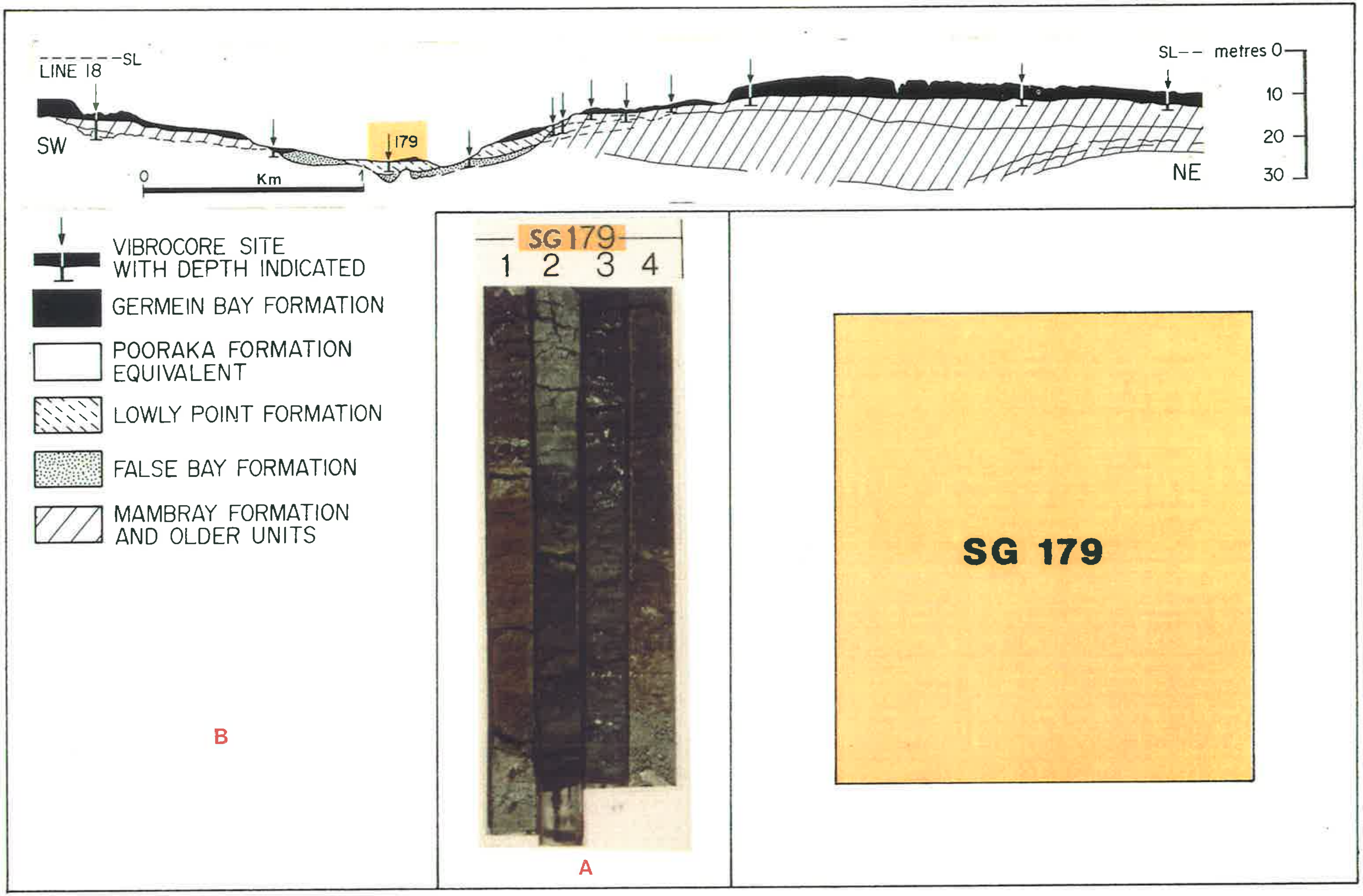

SL
LINE 18
SW
179
0
Km
1
SL
metres 0
10
20
30
NE
VIBROCORE SITE
WITH DEPTH INDICATED
GERMEIN BAY FORMATION
POORAKA FORMATION
EQUIVALENT
LOWLY POINT FORMATION
FALSE BAY FORMATION
MAMBRAY FORMATION
AND OLDER UNITS
B
SG 179
1
2
3
4
A
SG 179

Fig 5.31

A. Vibrocore #SG179, split core (after Hails et al, 1984a, fig 3). **B.** Section showing location of SG179 (after Hails et al, 1984a, fig 5).

VIBROCORE SG179 (Fig 5.31)

The first stated aim of the investigations reported in this chapter was evaluation of the palaeoenvironmental significance of the fossil foraminifera of the northern Spencer Gulf cores, within the stratigraphic frame of reference established by the original researchers. The stratigraphic setting of the sediments recovered in vibrocore SG179 (Hails et al., 1984a) is somewhat ambiguous.

Firstly, this core is illustrated by colour photograph by Hails et al. (1984a, Fig 3, p. 350). The illustration shows that below a thin surficial layer of Holocene Germein Bay Formation, about 3.5m of Pleistocene Lowly Point Formation is in turn underlain by 0.2m of False Bay Formation. However, in the same paper, a seismic-stratigrahic section, here reproduced as Fig 5.31B, shows vibrocore SG179 to not penetrate False Bay sediments, but to be essentially confined to the Lowly Point Formation.

Secondly, the present investigation has determined that neither foraminifera nor other evidence of marine sedimentation occur within the interval 200 to 80cm. These nonmarine sediments, by definition, cannot be included in the Lowly Point Formation. The stratigraphy represented by this core must therefore be re-evaluated. Lithological boundaries recognised by Hails et al. (unpublished) (Fig 5.32) take on a new significance.

The top 5cm of the core yielded typical shallow water foraminifera, such as *Nubecularia lucifuga*, which were mostly broken, polished and stained with iron oxide. This state of preservation is certainly not typical of foraminifera in the surficial sediment of the Germein Bay Formation. Such material implies subaerial exposure of marine sediments in which there was originally some fixation of iron as sulfide. Today this occurs in shallow marginal marine environments, such as those described for Port Gawler (Chapter 3). An episode of emergence is also indicated by the presence of oogonia at 20cm and 40cm.

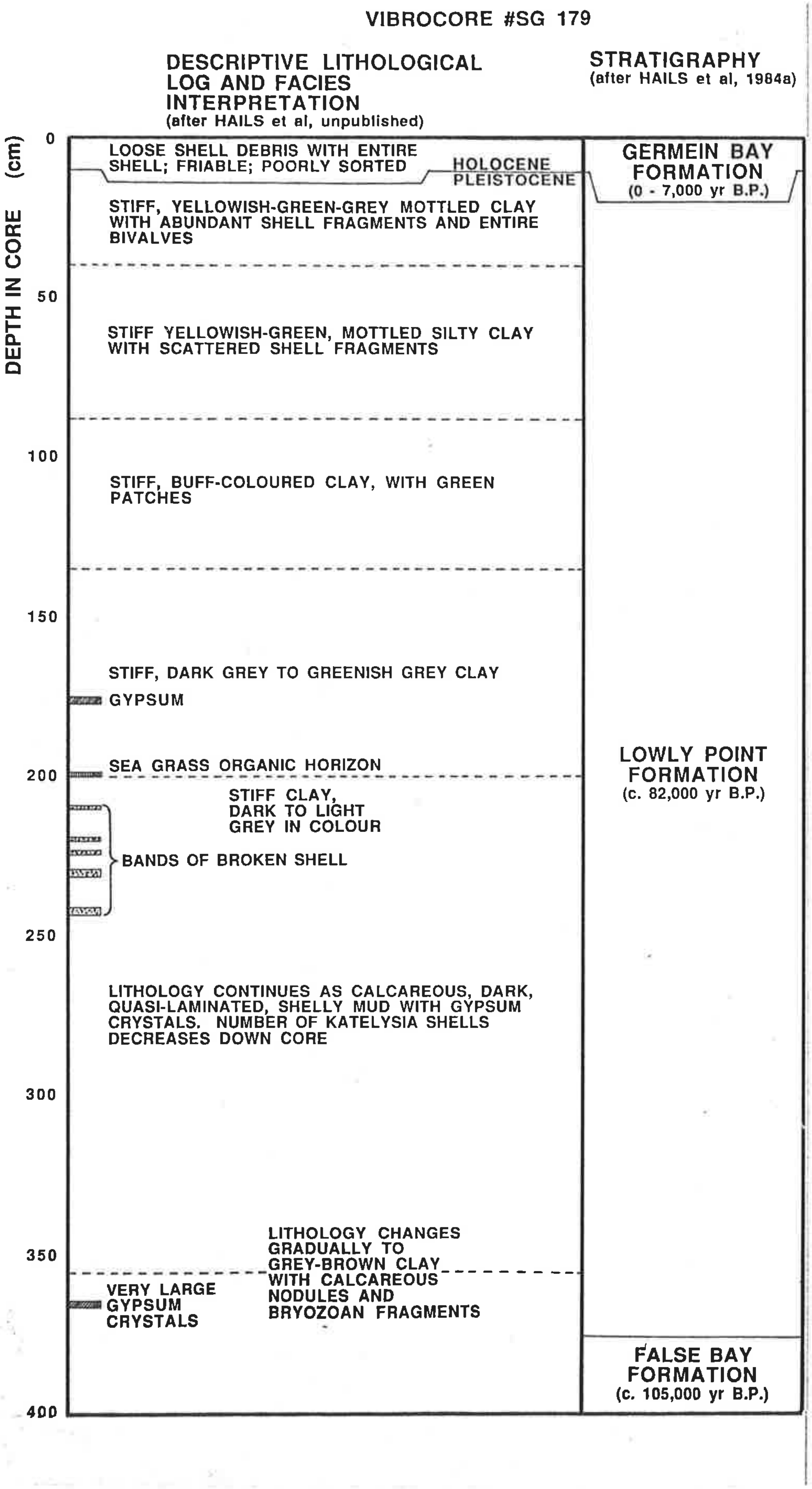

VIBROCORE #SG 179
DESCRIPTIVE LITHOLOGICAL LOG AND FACIES INTERPRETATION
(after HAILS et al, unpublished)
STRATIGRAPHY
(after HAILS et al, 1984a)
DEPTH IN CORE (cm)
0
50
100
150
200
250
300
350
400
LOOSE SHELL DEBRIS WITH ENTIRE SHELL; FRIABLE; POORLY SORTED
HOLOCENE
PLEISTOCENE
STIFF, YELLOWISH-GREEN-GREY MOTTLED CLAY WITH ABUNDANT SHELL FRAGMENTS AND ENTIRE BIVALVES
STIFF YELLOWISH-GREEN, MOTTLED SILTY CLAY WITH SCATTERED SHELL FRAGMENTS
STIFF, BUFF-COLOURED CLAY, WITH GREEN PATCHES
STIFF, DARK GREY TO GREENISH GREY CLAY
GYPSUM
SEA GRASS ORGANIC HORIZON
STIFF CLAY, DARK TO LIGHT GREY IN COLOUR
BANDS OF BROKEN SHELL
LITHOLOGY CONTINUES AS CALCAREOUS, DARK, QUASI-LAMINATED, SHELLY MUD WITH GYPSUM CRYSTALS. NUMBER OF KATELYSIA SHELLS DECREASES DOWN CORE
LITHOLOGY CHANGES GRADUALLY TO GREY-BROWN CLAY WITH CALCAREOUS NODULES AND BRYOZOAN FRAGMENTS
VERY LARGE GYPSUM CRYSTALS
GERMEIN BAY FORMATION
(0 - 7,000 yr B.P.)
LOWLY POINT FORMATION
(c. 82,000 yr B.P.)
FALSE BAY FORMATION
(c. 105,000 yr B.P.)

Fig 5.32

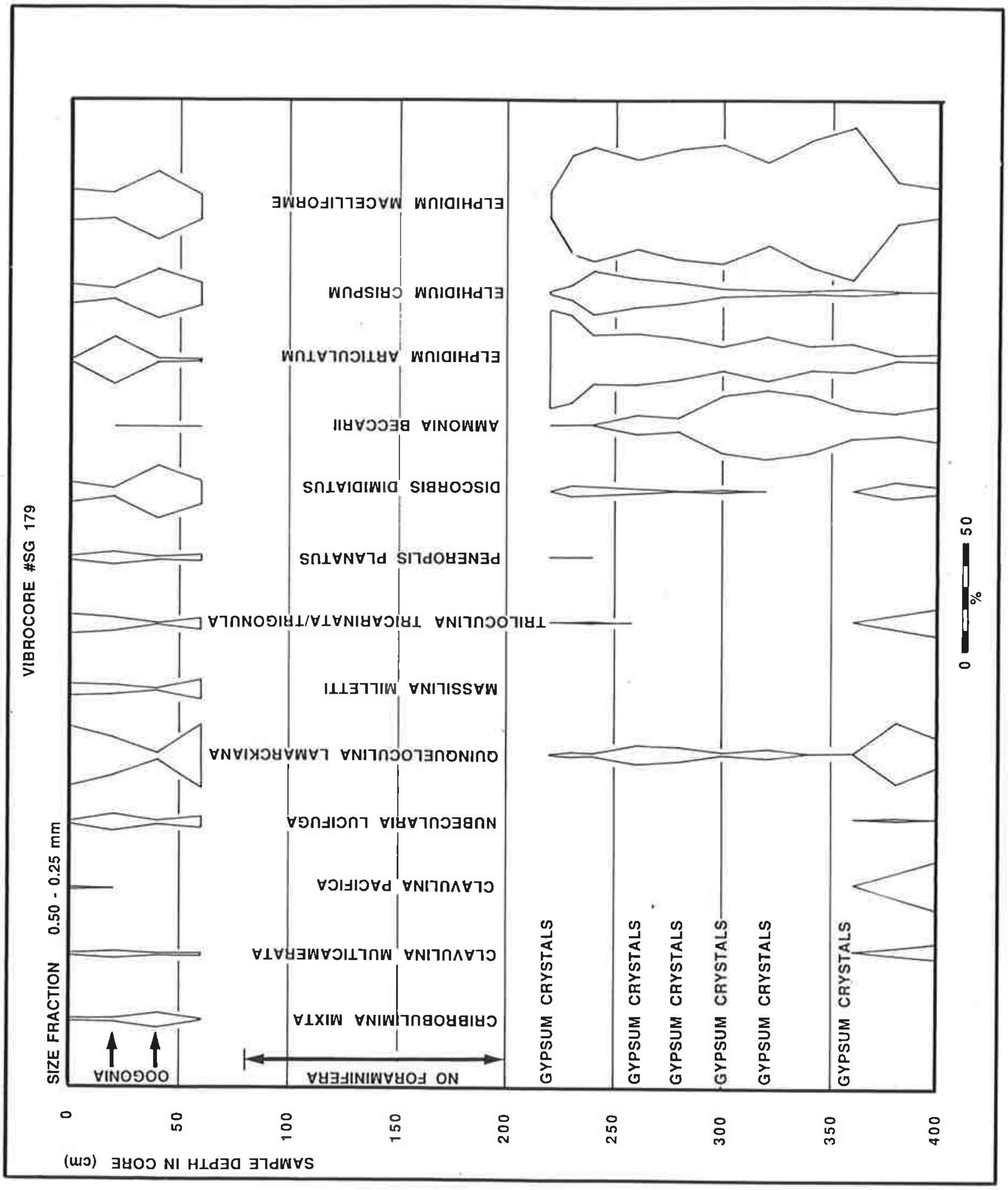


Fig 5.33
Percentage distributions of selected species of benthic foraminifera within vibrocore #SG179.
Size fraction 0.50 - 0.25mm. Few individuals in the size fraction 1.00 - 0.50mm were recovered from this core.

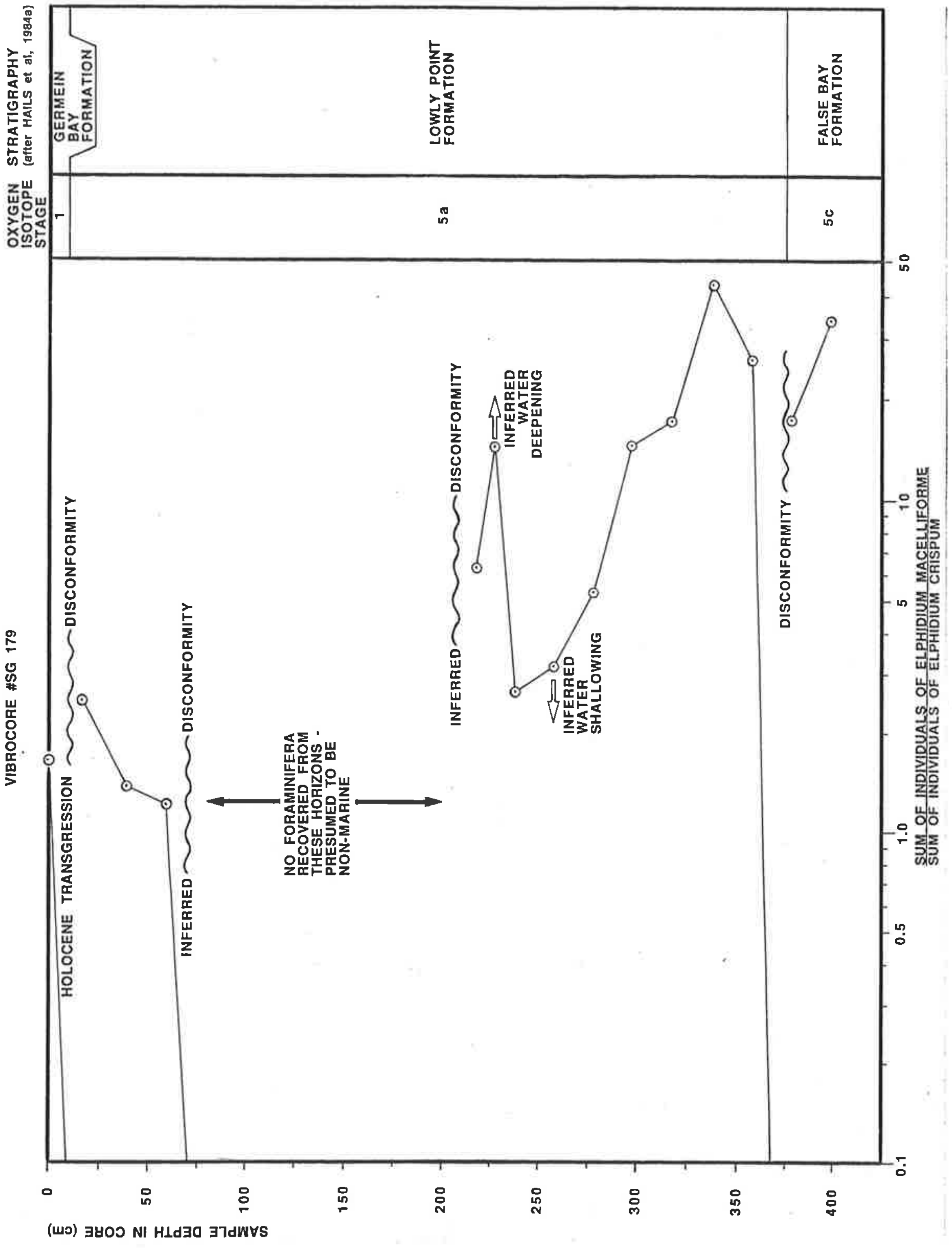


Fig 5.34

Log-linear plot of sample depth in vibrocore #SG179 versus ratio of numbers of individuals of *Elphidium macelliforme* to numbers of individuals of *Elphidium crispum* for core samples. Inferred changes of palaeo sea levels derived from this ratio are signified. The stratigraphic framework is that of Hails et al, 1984a and unpublished.

As noted earlier in this chapter, oogonia are the calcified fruiting bodies of charophytes, a group of aquatic plants which grow in saline lakes and marshes, but not in holomarine environments.

The interval 60 to 0cm therefore apparently consists of Lowly Point Formation, with little effective input of Holocene material. The present day site of SG179 is seemingly one of erosion rather than deposition. The non-marine interval 200 to 80cm represents terrestrial sediments probably deposited during the marine regression associated with oxygen isotope substage 5b. It then follows that the marine sediments in the core interval 360 to 220cm must represent those of the isotope substage 5c transgression of c.105,000yr B.P., False Bay Formation. Sediments below the disconformity, 360 to 375cm, can be assigned to the Mambray Formation, substage 5e.

Within this revised stratigraphic framework, here established, the distribution of species in SG179 is now considered. Data are provided for only the 0.50 - 0.25mm size fraction (Fig 5.33), there being few specimens in the larger size fraction.

GERMEIN BAY FORMATION

As described above, the surficial sediment, 5 to 0cm, contained many foraminiferal tests showing clear signs of having been reworked from an earlier emergent deposit. That is, the thin veneer of friable, poorly sorted shell debris (Fig 5.32) has, to a significant extent, been derived from the underlying Lowly Point Formation. Because of this reworking, little significance can be attached to the assemblage of species at the top of the core. The site of SG179 is, at present, not one of active sediment accumulation and thus the Germein Bay Formation is effectively absent.

LOWLY POINT FORMATION

This formation is represented by three samples at 60, 40 and 20cm, respectively yielding 145, 436 and 129 individuals. It would normally be difficult to recognise significant changes in distributions of species over such a short interval, but in this case it is especially so. Given the relatively low numbers of foraminifera at 20cm and 60cm, evidence of reworking of sediment and a lithological boundary a little above 50cm (Fig 5.32), there is no possibility of interpreting the data with confidence. Nevertheless, nearly one quarter of the specimens recovered at 40cm were *Discorbis dimidiatus* (Fig 5.33), signifying a probable *Posidonia* seagrass palaeoenvironment. This observation is consistent with the presence of other shallow water species, such as *Cribrobulimina mixta*. The *Elphidium* ratio (Fig 5.34) infers a simple marine transgression, but again the data should be assessed with caution. Ratio values at 60cm and 20cm were calculated from only 31 and 21 specimens respectively, compared with 228 at 40cm.

FALSE BAY FORMATION

This formation is represented by samples within the interval 360 to 220cm. It is overlain by approximately 1.5m of non-marine sediment and its base is signified by a diffuse disconformity around 360cm. The descriptive log (Fig 5.32) implies a regressive sequence. This is indicated by the presence of intertidal *Katelysia* shells, bands of broken shell and seagrass fibre towards the top of the interval.

Samples generally yielded relatively low numbers of foraminifera. This was particularly so from 320 to 260cm, where <50 individuals were recovered from samples at 320, 280 and 260cm. Abnormal salinities, signified by the presence of gypsum crystals and the foraminifera *Ammonia beccarii* and *Elphidium articulatum* (Fig 5.33) probably account for both low numbers and reduced diversity of species.

The general distribution of species up core provides no immediately obvious interpretation of palaeo sea levels, though the small peak of *Discorbis dimidiatus* towards the top of the interval is in keeping with other evidence of marine regression. The *Elphidium* ratios (Fig 5.34) generally infer water shallowing for most of the interval, but the actual water depths so implied (Fig 4.5) are far in excess of those that could have prevailed at the time of deposition (Hails et al., 1984b).

This problem has been discussed, earlier in this chapter, for data derived for SG79 and SG109. It has been shown that where *Elphidium articulatum* is numerically significant, the expression:

$$\frac{\text{sum of individuals of } \textit{Elphidium macelliforme}}{\text{sum of individuals of } (\textit{E. articulatum} + \textit{E. crispum})}$$

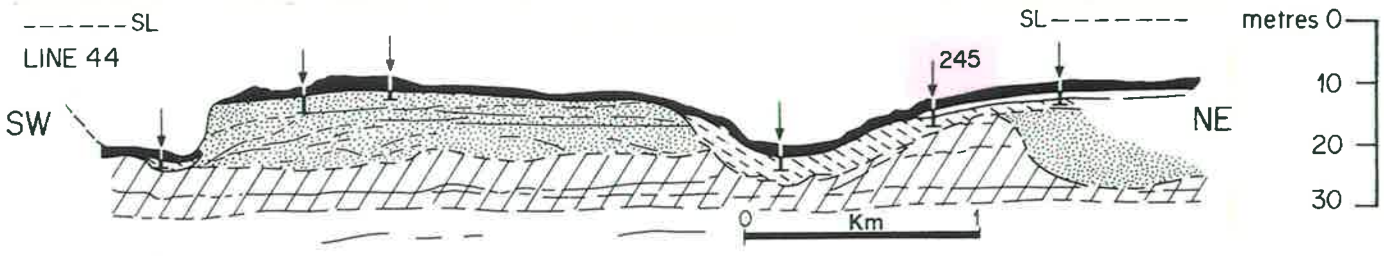
generates values which can be plausibly related to palaeo water depths inferred by the general assemblage of species up core. Ratios so derived for the False Bay interval of vibrocore SG179 show a general decline from 4.5 at 360cm to 1.0 at 230cm. These numbers are certainly more in accord with those that might be expected from the palaeo sea level interpretations of Hails et al. (1984b), and they more credibly support the notion of a marine regressive sequence. Thus, once again, the potential value of this modified *Elphidium* ratio, including the numbers of *E. articulatum*, is shown to be worthy of further investigation.

MAMBRAY FORMATION

The interval here interpreted to be Mambray Formation, not False Bay Formation (Hails et al., 1984a), is represented by only two samples. The 8% peak of *Discorbis dimidiatus* at 380cm infers a subtidal seagrass facies, but the associated 10% of *Ammonia beccarii* (Fig 5.33) shows that salinity probably varied significantly in the depositional environment.

The two *Elphidium* ratio values (Fig 5.34) infer marine regression during the time of deposition, but at improbably high palaeo sea levels. However, when the relative abundance of *E. articulatum* is also taken into consideration, as discussed above, ratios of 3.8 and 5.1 are obtained for 400cm and 380cm respectively, inferring marine transgression and palaeo water depths of about 20m.

A



- ↓ VIBROCORE SITE WITH DEPTH INDICATED
- ■ GERMEIN BAY FORMATION
- ☐ POORAKA FORMATION EQUIVALENT
- ▨ LOWLY POINT FORMATION
- ░ FALSE BAY FORMATION
- ▨ MAMBRAY FORMATION AND OLDER UNITS

B

SG 245

Fig 5.35

A. Vibrocore #SG245, split core (after Hails et al, 1984a, fig 3). **B.** Section showing location of SG245 in relation to Quaternary stratigraphy (after Hails et al, 1984a, fig 5).

VIBROCORE SG245 (Fig 5.35)

The stratigraphic setting established by the original researchers (Hails et al., (1984a) for this core is internally inconsistent. Their colour illustration (Fig 3, p.350) shows that SG245 consists of two units only, 1.3m of Germein Bay Formation overlying 2.7m of Lowly Point Formation. However, the seismic-stratigraphic section (Fig 5, p.355), here reproduced as Fig 5.35B, indicates that the middle third of the core is Pooraka Formation equivalent and therefore of non-marine origin.

The original unpublished core description (Fig 5.36) placed the Pleistocene/Holocene boundary at 130cm and another lithological boundary was recognised at 200cm. The sediments of this mid-core interval, originally interpreted as lagoonal and estuarine sediments, probably correspond to those later shown as Pooraka Formation equivalent (Hails et al., 1984a).

Significant numbers of foraminifera were recovered from all samples throughout the core (Figs 5.37, 5.38), particularly in the size fraction 0.50 - 0.25mm. The notion that SG245 recovered an interval of non-marine Pooraka Formation is therefore here rejected.

Another factor which further clouds the stratigraphy established for SG245 by Hails et al. (1984a) is the observation that three species of foraminifera, characteristic of the Mambray Formation, occur below the Pleistocene/Holocene disconformity. *Marginopora vertebralis* occurs at 150cm, *Pseudomassilina australis* is present throughout the core below 150cm and *Quinqueloculina polygona* was recovered from samples between 225 and 175cm (Fig 5.38). It was earlier observed for SG170 that these species appeared to be confined to the Mambray Formation. Thus, the sequence of sediments below 150cm has either been extensively contaminated by foraminifera derived from older deposits, or the interval represents Mambray Formation, not Lowly Point Formation.

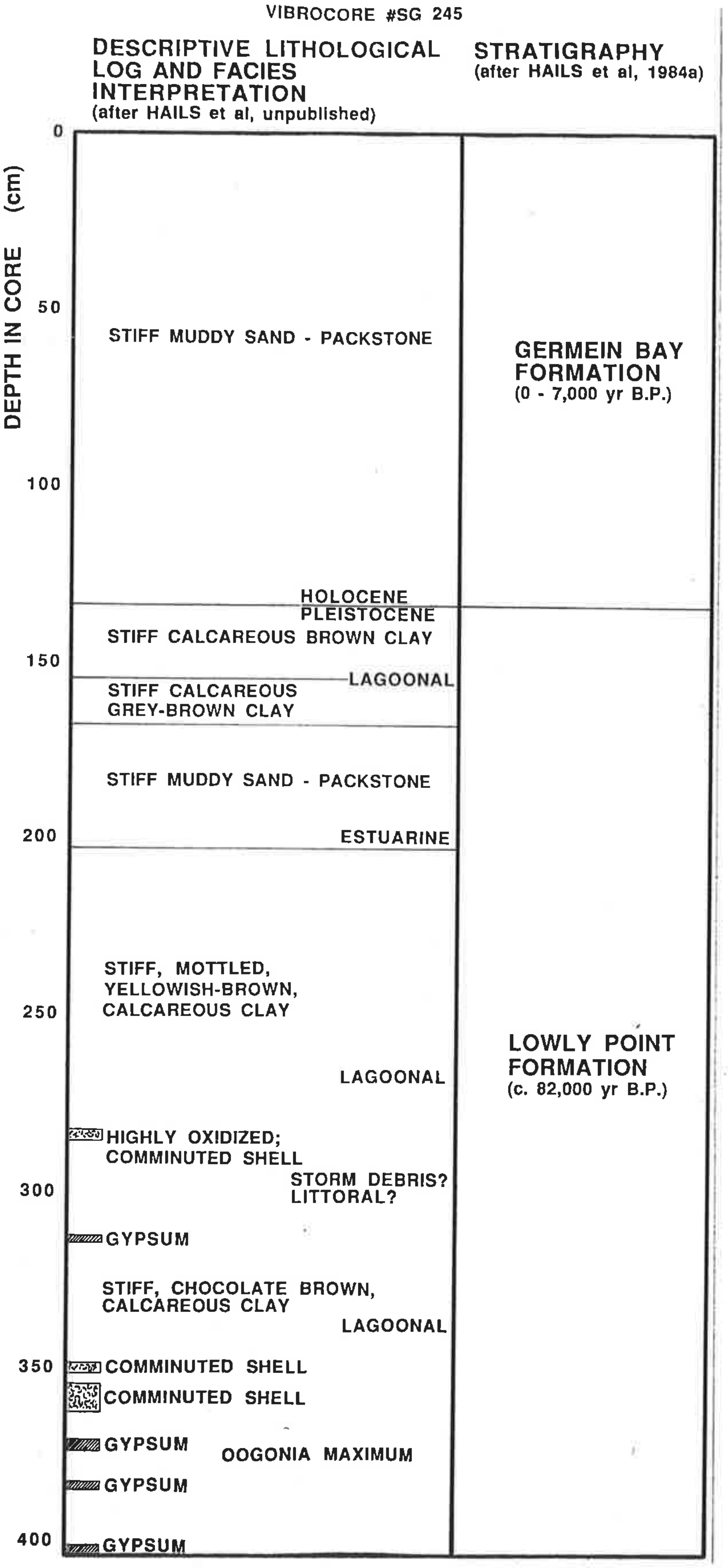

VIBROCORE #SG 245
DESCRIPTIVE LITHOLOGICAL LOG AND FACIES INTERPRETATION
(after HAILS et al, unpublished)
STRATIGRAPHY
(after HAILS et al, 1984a)
DEPTH IN CORE (cm)
0
50
100
150
200
250
300
350
400
STIFF MUDDY SAND - PACKSTONE
GERMEIN BAY FORMATION
(0 - 7,000 yr B.P.)
HOLOCENE
PLEISTOCENE
STIFF CALCAREOUS BROWN CLAY
LAGOONAL
STIFF CALCAREOUS GREY-BROWN CLAY
STIFF MUDDY SAND - PACKSTONE
ESTUARINE
STIFF, MOTTLED, YELLOWISH-BROWN, CALCAREOUS CLAY
LAGOONAL
LOWLY POINT FORMATION
(c. 82,000 yr B.P.)
HIGHLY OXIDIZED; COMMINUTED SHELL
STORM DEBRIS? LITTORAL?
GYPSUM
STIFF, CHOCOLATE BROWN, CALCAREOUS CLAY
LAGOONAL
COMMINUTED SHELL
COMMINUTED SHELL
GYPSUM
OOGONIA MAXIMUM
GYPSUM
GYPSUM

Fig 5.36

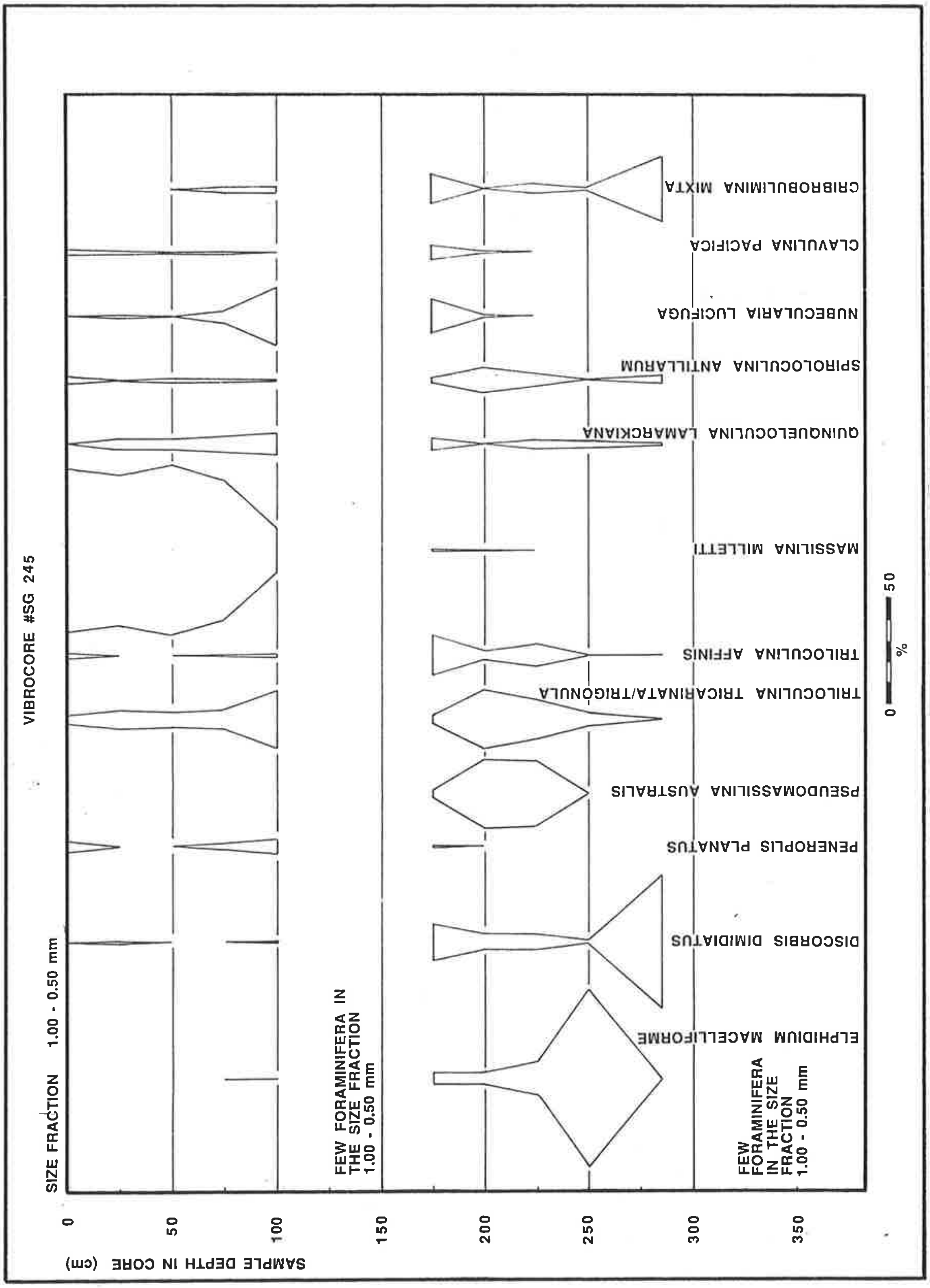


Fig 5.37

Percentage distributions of selected species of benthic foraminifera within vibrocore #SG245.
Size fraction 1.00 - 0.50mm.

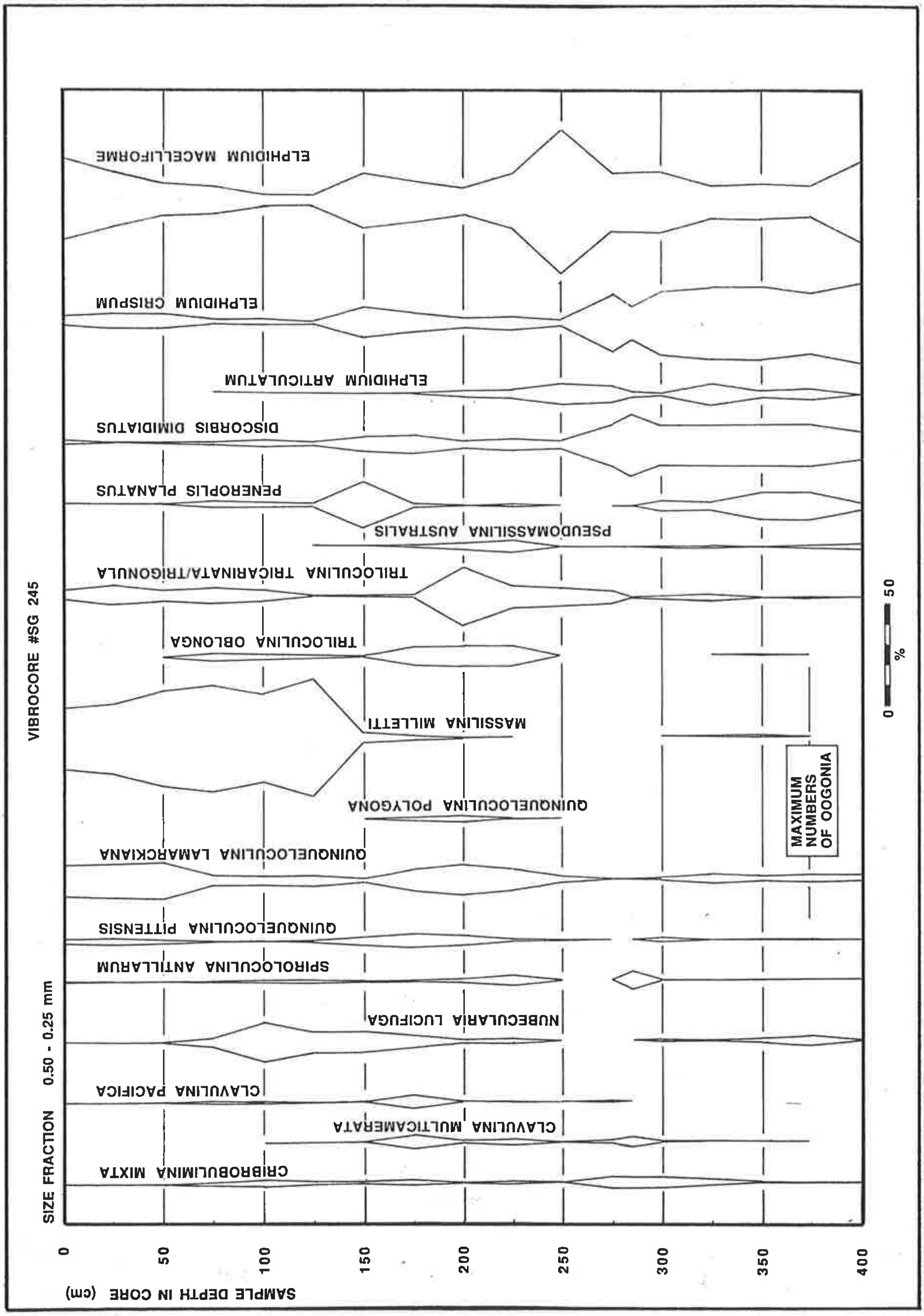


Fig 5.38

Percentage distributions of selected species of benthic foraminifera within vibrocore #SG245.
Size fraction 0.50 - 0.25mm.

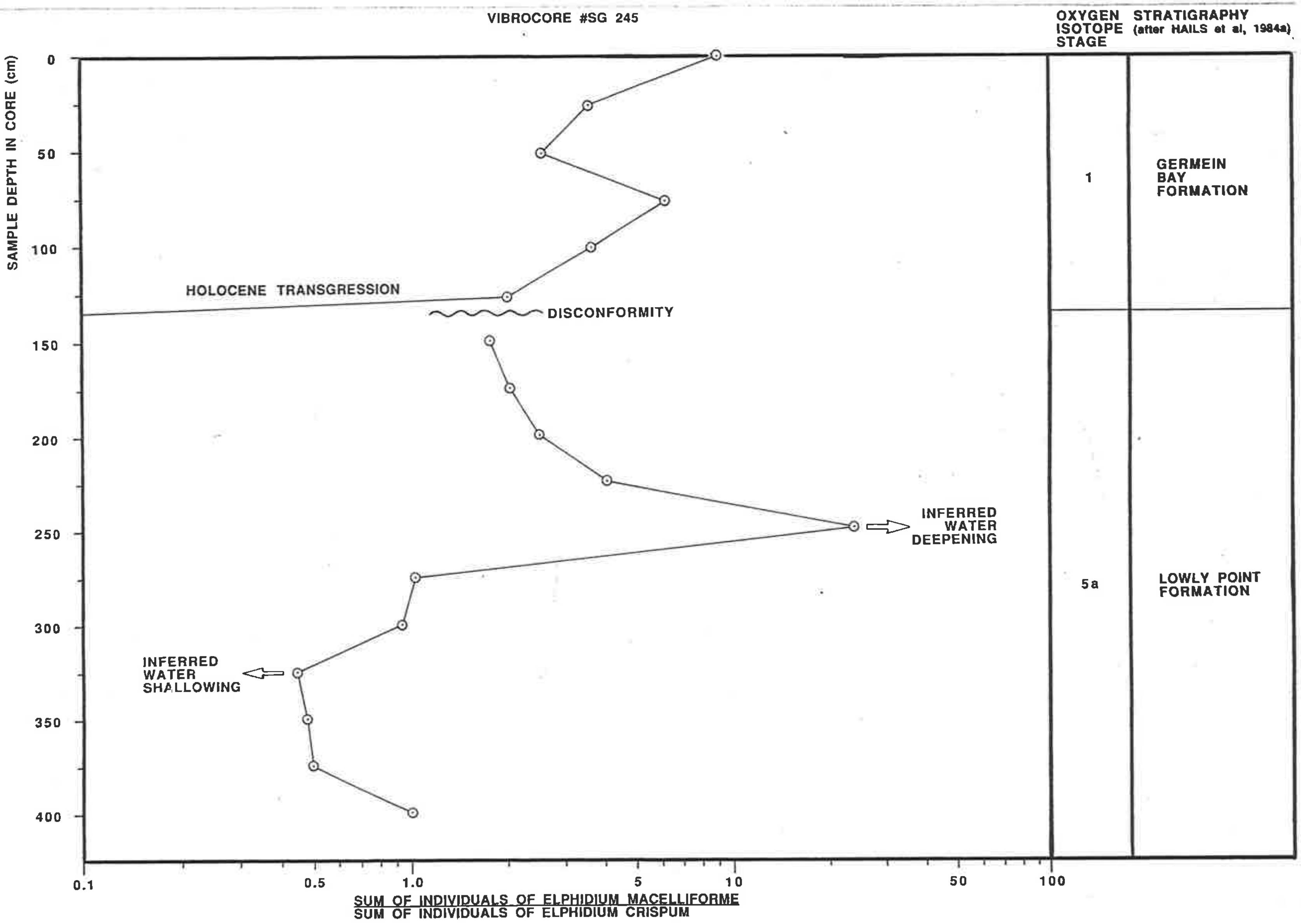

VIBROCORE #SG 245
OXYGEN ISOTOPE STAGE
STRATIGRAPHY (after HAILS et al, 1984a)
SAMPLE DEPTH IN CORE (cm)
0
50
100
150
200
250
300
350
400
HOLOCENE TRANSGRESSION
DISCONFORMITY
INFERRED WATER DEEPENING
INFERRED WATER SHALLOWING
1
GERMEIN BAY FORMATION
5a
LOWLY POINT FORMATION
0.1
0.5
1.0
5
10
50
100
SUM OF INDIVIDUALS OF ELPHIDIUM MACELLIFORME
SUM OF INDIVIDUALS OF ELPHIDIUM CRISPUM

Fig 5.39
Log-linear plot of sample depth in vibrocore #SG245 versus ratio of numbers of individuals of *Elphidium macelliforme* to numbers of individuals of *Elphidium crispum* for core samples. Inferred changes of palaeo sea levels derived from this ratio are signified. The stratigraphic framework is that of Hails et al, 1984a and unpublished.

GERMEIN BAY FORMATION

The Holocene transgression in northern Spencer Gulf is most obviously indicated, again in this core, by the up core distribution of *Massilina milletti.* In the size fraction 1.00 - 0.50mm, increasing numbers of this species, which favours deeper gulf waters, are associated with decreasing numbers of the shallow water *Nubecularia lucifuga* (Fig 5.37). In the finer fraction (Fig 5.38), the distribution of *M. milletti* seems to indicate water shallowing from 75cm upwards, but this is mainly a statistical artefact of the larger numbers of several other species through that interval, notably *Elphidium macelliforme.*

The *Elphidium* ratios derived for the Holocene interval of this core (Fig 5.39) are based on average counts of >100 individuals of *E. macelliforme* plus *E. crispum* and are therefore statistically very reliable. The palaeo sea level signal inferred by the numerical ratio of these two species indicates a sea level maximum at 75cm, marine regression to 50cm, followed by continued water deepening to the top of the core.

MAMBRAY FORMATION

As indicated above, the lower part of the core, below the Pleistocene/Holocene boundary, contains species of foraminifera that provide *prima facie* evidence that the sediments belong to the Mambray Formation, not the Lowly Point Formation, as designated by Hails et al. (1984a). For example, in the coarser size fraction (Fig 5.37), *Pseudomassilina australis* is particularly significant at 250 and 200cm. Its relative abundance indicates that it is unlikely to have been reworked from older sediments.

Sediments comprising the lower part of the Mambray Formation in core SG245, from 400 to 275cm, were deposited in shallow, hypersaline, subtidal seagrass environments. The relatively shallow water depth is signified by horizons of comminuted shell (Fig 5.36), by consistently large numbers of *Discorbis dimidiatus* (Fig 5.38) and by *Elphidium* ratio values of 1.0 or less (Fig 5.39).

The *Elphidium* values are even lower if numbers of *E. articulatum* are taken into consideration, as discussed earlier. Sediments close to the bottom of the core also have preserved charophyte oogonia in significant numbers, indicating effective emergence and the influence of saline marshlands and similar marginal marine marine environments. High salinities are signified by horizons of gypsum (Fig 5.36) and the distribution up core of *Elphidium articulatum* (Fig 5.38).

Above 275cm, slightly deeper depositional environments prevailed. This is best indicated by reduced numbers of *D. dimidiatus* (Fig 5.38) and higher *Elphidium* ratio values (Fig 5.39). Again, if numbers of *E. articulatum* are considered in the *Elphidium* expression, lower values are obtained. For example, at 250cm the value is reduced from 24.1 to 5.5. However the pattern of relative sea level change, implied by the ratio up core, remains one of marine regression. In the general assemblage (Fig 5.38), this observation is nicely supported by increasing numbers of *Nubecularia lucifuga*, and at 150cm there is a peak of highly variable and heavily calcified *Peneroplis planatus*.

The original core description (Fig 5.36) shows no significant lithological boundaries in the lower half of SG245. However, both the general distribution of species (Fig 5.38) and the *Elphidium* ratio relative sea level signal (Fig 5.39) could be interpreted to infer a disconformity between 275 and 250cm. In this context, the band of "highly oxidised comminuted shell" at 285cm (Fig 5.36) may have significance. Marine regression and subaerial exposure, even for a relatively short time, could certainly account for this observation.

Thus, the Mambray interval of vibrocore SG245 may record the double peak of sea level associated with the oxygen isotope substage 5e marine transgression of c.120,000yr B.P. (Chappell and Shackleton, 1986, and references therein). Although such an interpretation must, on present evidence, remain conjectural, it is nevertheless worth observing that the earlier of the 5e sea level maxima of Chappell and Shackleton (1986) was the higher of the two.

In contrast, the evidence of SG245 shows that sea levels of the second transgression were higher than those of the first.

SYNTHESIS AND CONCLUSIONS

The distributions of fossil foraminifera in eight vibrocores taken from Quaternary sediments of northern Spencer Gulf have been documented in this chapter. Species which were significantly present within the cores are illustrated as scanning electron photomicrographs in figure 5.40, unless similarly featured elsewhere in the thesis. Discussion of the significance of the species distributions has been effectively constrained by the stratigraphic framework established for the vibrocored sediments by the original researchers (Billing, 1984; Hails et al., 1984a, 1984b). In some instances, however, micropalaeontological observations have forced the present author to re-evaluate some of the original findings.

The following comments and observations primarily refer to the aims expressed earlier in this chapter.

a) Most species of foraminifera occurring as fossils in the vibrocores are also known from the present day surficial sediments of Port Gawler (Chapter 3) and northern Spencer Gulf (Chapter 4). Thus assemblages of fossil species within the cores were used to infer palaeoenvironments analagous to those known today.

This was particularly so with reference to water depth. *Massilina milletti* consistently indicated deeper water, while intertidal and shallow subtidal environments were signified by an assemblage of species, notably *Nubecularia lucifuga*, *Peneroplis planatus* (heavily calcified and morphologically variable), *Discorbis dimidiatus* and *Cribrobulimina mixta.* Relative abundances of these characteristic species in core samples were used to infer palaeo water depths. Successive assemblages of species up core in the Germein Bay intervals consistently and unambiguously signified the Holocene transgression in northern Spencer Gulf.

Effective emergence and the influence of saline marshlands, lakes and other similar marginal marine environments were inferred by from the presence of fossil oogonia, the calcified reproductive bodies of charophytes. This unique group of aquatic plants is unknown in modern holomarine environments.

Palaeoenvironments of variable salinity were recognised by the significant presence, as fossils, of *Ammonia beccarii* and *Elphidium articulatum*. These inferences were based on the present author's observations of modern assemblages of estuarine and lacustrine fauna, and on the work of other researchers, for example, Apthorpe (1980).

b) For northern Spencer Gulf, palaeo sea levels of oxygen isotope substages 5c and 5a were calculated by Hails et al. (1984b) to be respectively -8m and -14m, with reference to present sea level. Thus, the marine environments created in the northern gulf by the transgressions of c.82,000yr B.P. and c.105,000yr B.P. were considerably shallower than those existing today. Sediments of the False Bay and Lowly Point Formations rarely yielded fossil assemblages in which *Massilina milletti* documented the 5c and 5a transgressions as effectively as that species signifies the Holocene transgression in the Germein Bay Formation.

However, at sites where late Pleistocene waters were deeper, and sufficient sediment accumulated, the foraminiferal assemblages elegantly document the changes in palaeo sea level. A good example is given by core SG109 in which more than two metres of False Bay sediments were recovered. The distribution of fossil species through this interval records the c.105,000yr B.P. transgression, the peak of sea level, and the subsequent regression.

Thus, where late Pleistocene sedimentary environments were similar to those of the present, past transgressive and regressive events can be interpreted from up core distributions of foraminifera, within the constraints of Uniformitarianism.

c) The relationship between inferred palaeo water depths and the ratio of numbers of *Elphidium macelliforme* to *E. crispum* throughout the cores provided much interesting data. These are best summarised separately for the Holocene and Pleistocene.

Holocene

The Germein Bay Formation was effectively absent from the top of SG179, but all other cores yielded useful intervals of up to 1.5m of these Holocene sediments. Without exception, the *Elphidium* ratios infer maximum water depths in the lower horizons of the Holocene intervals, after which water shallowing is signified by successive samples higher in the cores. This is most clearly illustrated for SG79 (Fig 5.11). Such water shallowing may be due to upwards shoaling of sediment, to eustatic fall in sea level or to crustal uplift.

imply

Upwards shoaling of sediment resulted in maximum reduction of water depth by only 1.5m. This is insufficient to alone account for the changes in palaeo water depths implied by the *Elphidium* ratio curves for the various cores. At best, upwards shoaling was a minor contributing factor.

Eustatic fall of sea level would have resulted in a consistent body of evidence for a higher stand of the Holocene sea. Such evidence would take the form of raised coastal geomorphic features, sediments and fossil biota. Belperio et al. (1983) have reviewed such supposed evidence for South Australia and concluded that there has been no significant change in sea level since the Holocene transgression reached its present level c.6500yr B.P..

Tectonic uplift of northern Spencer Gulf was invoked by Crawford (1963) to account for elevated sediments and geomorphic features near Lowly Point. Later, Burne (1982) described elevated subtidal and intertidal sedimentary facies in the northern gulf within a framework of radiocarbon dates.

He calculated that relative sea levels had been 3 to 5m higher than those of the present and tentatively supported tectonic uplift of the region to account for the apparent fall in sea level. Similarly, Belperio et al. (1984) constructed a relative sea level curve for northern Spencer Gulf from elevated subtidal seagrass sediments and the radiocarbon dates derived from the organic debris. They concluded that a higher relative sea level of at least +2.5m prevailed from c.6000yr B.P. to c.1700yr B.P. and that relative fall to present sea level occurred immediately following that time. Tectonic uplift was again invoked to account for the change in relative sea level.

While earlier workers consistently favoured a tectonic explanation for their observed evidence of falling relative sea level, alternative mechanisms were considered. For example, Belperio et al. (1983) pointed to the fact that upper Spencer Gulf is that part of coastal South Australia most distant from the continental shelf edge and that, as a consequence of this geographic situation, hydro-isostatic upwarp could be a responsible factor. It is this hypothesis, strongly supported by Lambeck (1988), which is here favoured by the present author. Holocene flooding of the southern continental shelf, and increased water mass over the adjacent continental slope, caused isostatic subsidence of the most heavily loaded areas. This in turn generated a compensatory upwarp of coastal areas, including northern Spencer Gulf.

Thus, the *Elphidium* ratio curves for the Holocene intervals of the vibrocores have recorded the relative uplift of northern Spencer Gulf, which occurred as an isostatic response to water loading of the southern continental shelf and slope. It is clear that the method of investigation employed to derive these data has potential for further resolving this response to the Holocene transgression.

One further observation may have significance in the context of Holocene sea levels. Cores SG109, SG120 and SG245 all show a final water deepening signal at the tops of the Germein Bay Formation.

Despite a range of uncertainties relating to derivation of the data, the balance of evidence seems to indicate that global sea level has been rising at a rate of about 1.5mm/yr for the past century (Lambeck, 1988). Is this signified in the uppermost *Elphidium* ratios of these three cores?

It is unlikely that a recent rise in sea level, of the magnitude envisaged by Lambeck (1988), could result in such a powerful signal. Instead, this late Holocene water deepening, which appears to be confined to the southern part of the study area, can more probably be attributed to minor isostatic subsidence, in response to the load of transgressive flooding of the inland gulf. Thus, a lesser isostatic subsidence appears to have subtly overprinted the earlier, more pronounced isostatic uplift of the gulf area.

Pleistocene

Use of the *Elphidium* ratio to derive inferred palaeo sea levels for the Pleistocene interval of the cores was generally unsuccessful. In some instances, impossibly deep waters were implied by the ratio values, and the palaeo sea level signal signified by the general assemblage was at marked variance with that of the *Elphidium* ratio. Such a situation is well illustrated for the False Bay Formation in vibrocore SG109.

For several cores it was observed that where numbers of *Elphidium crispum* were greatly reduced, *E. articulatum* was a significant species in the assemblage. Given the present day distribution of *E. articulatum* in estuarine and lacustrine settings of variable salinity, it was rationalised that this species apparently occupies the niche of *E. crispum* when salinity varies from that of normal sea water. Thus, it has been argued that where all three species of *Elphidium* are present in significant numbers, water depth will be related to the expression:

$$\frac{\text{sum of individuals of } \textit{Elphidium macelliforme}}{\text{sum of individuals of } (\textit{E. articulatum} + \textit{E. crispum})}$$

Numerical data generated by the above expression were of credible magnitude and could be plausibly related to palaeo water depths implied by the general distributions of species in the cores. Evidence supporting a relationship between this new expression and water depth is circumstantial and interpretations derived from its application are thus conjectural. However, its potential for deriving palaeo sea level signals for the Pleistocene is apparent and future work should seek to evaluate the relationship in analagous modern environments.

d) No species of foraminifera were found to be diagnostic of Pleistocene sediments assigned to either the False Bay or Lowly Point Formations. Species of limited Pleistocene range were encountered only in the Mambray Formation (=Glanville Formation). *Marginopora vertebralis* was previously known as a distinctive fossil for this formation, and in the northern Spencer Gulf cores it is associated with *Quinqueloculina polygona* and *Pseudomassilina australis* (Fig 5.40).

e) Attempts to correlate the Pleistocene sediments in the cores were hampered by a lack of distinctive faunal assemblages for the False Bay and Lowly Point Formations. Correlations were also made more difficult by diminished confidence in the stratigraphic framework of the original researchers. For example, in SG179, absence of foraminifera or other evidence of marine sedimentation from strata in the middle of an interval assigned to the Lowly Point Formation necessarily requires reinterpretation of the stratigraphy. Conversely, in SG120, a unit designated as Pooraka Formation equivalent, and therefore of non-marine sedimentation, contains abundant foraminifera.

As indicated above, Mambray Formation can be correlated on the common presence of *Marginopora vertebralis*, *Quinqueloculina polygona* and *Pseudomassilina australis* (Fig 5.40). On this basis, the sediments in vibrocore SG245 that were attributed to the Lowly Point Formation by the original researchers, can now be reassigned to the Mambray Formation.

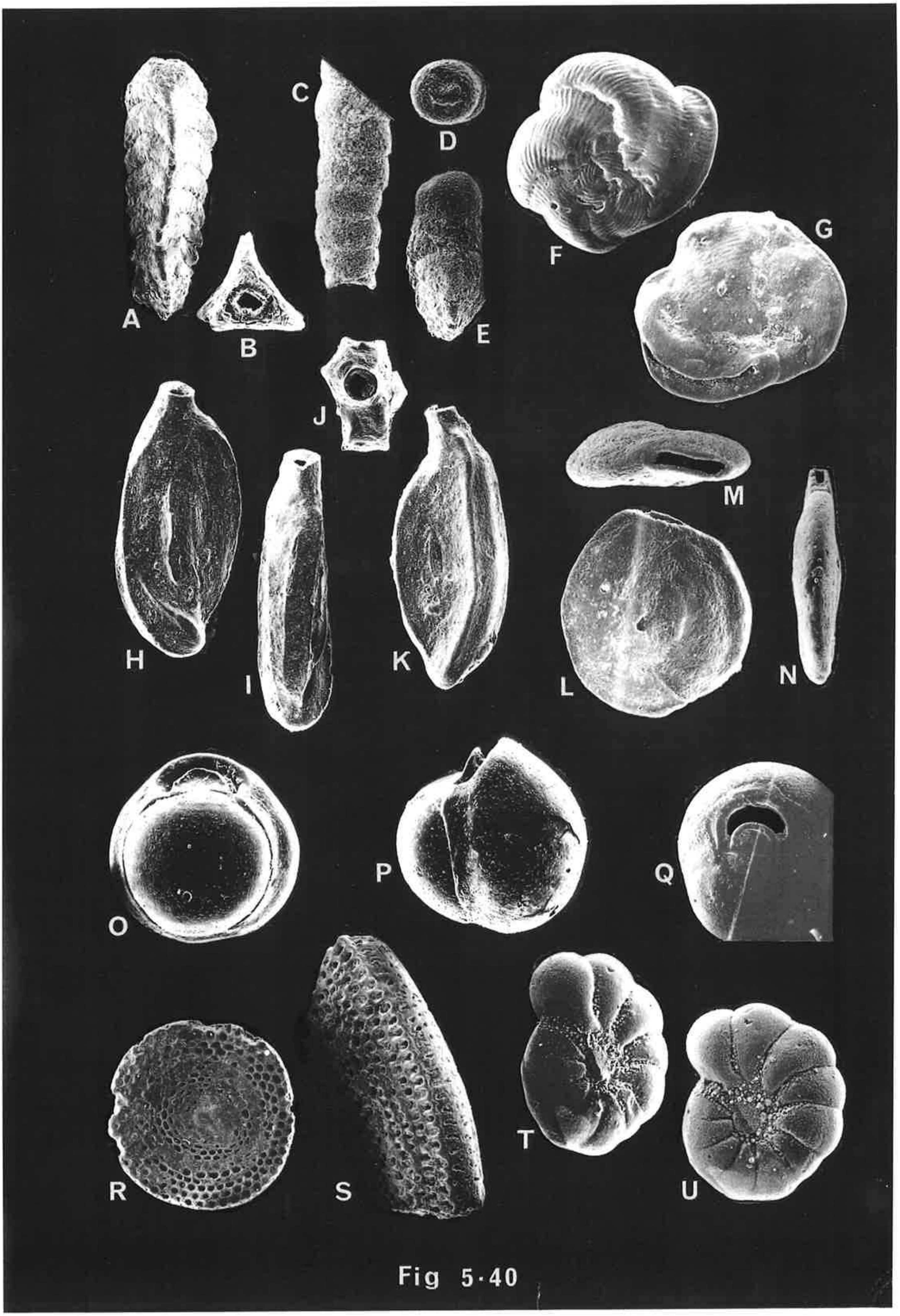


Fig 5·40

Fig 5.40
Illustration of species of foraminifera referred to in the figures and text of this chapter and not otherwise illustrated in the plates in chapters 3 and 7:

Clavulina pacifica Cushman; **A, B** X55; Core SG212, 0cm
Clavulina multicamerata Chapman; **C, D, E** X75; Core SG109,
400cm
Vertebralina striata d'Orbigny; **F, G** X105; Core RED51, 150cm
Quinqueloculina polygona d'Orbigny; **H, I, J, K** X70; Core SG245,
200cm
Pseudomassilina australis (Cushman); **L, M, N** X110;
Core SG245; 225cm
Pyrgo sp; **O, P, Q** X90; Core SG223, 50cm
Marginopora vertebralis Blainville; **R, S** X55; Core RED51,
175cm
Nonion depressulus (Walker and Jacob); **T, U** X150; Core RED51,
275cm

Addendum to Chapter 5

Correlation of Spencer Gulf palaeo sea levels

A correlation diagram, summarising sea-level results from all Spencer Gulf cores, analogous to Fig. 8.15 for St Vincent Gulf] would have been a highly desirable outcome of the investigations reported in Chapter 5. The stated aims of that work were certainly directed towards such a goal.

The original researchers [Hails *et al.*] recognised a chronology and pattern of sea level changes which had been established by earlier work of Bloom *et al.* (1974), Chappell (1976) and Chappell and Thom (1977).

> Chappell, J. (1976) Aspects of late Quaternary palaeogeography of the Australian - east Indonesian region. *In* R.L. Kirk and A.G Thorne (Editors) The origin of the Australians. Australian Institute of Aboriginal Studies, Canberra, A.C.T., pp.11-22.
>
> Chappell, J. and Thom, B.G. (1977) Sea levels and coasts. *In* J. Allen, J. Golson, and R. Jones (Editors), Sunda and Sahul: Prehistoric Studies in Southeast Asia, Melanesia and Australia. Academic Press, London, pp.275-291.

They reasoned that northern Spencer Gulf [which at present has a maximum water depth of little more than 20 metres] had been inundated only at times of high sea level. At these times, and only at these times, marine sediments were deposited, and the elevations of these sediments within the topography of Spencer Gulf are functions of those palaeo sea levels. Hails *et al.* identified three Late Pleistocene marine sedimentary formations [figure 10.2B].

Regrettably, for reasons set out in this chapter, such a correlation of palaeo sea levels for these Late Pleistocene sedimentary formations cannot be effected. These reasons in summary are:

(a) Not all cores contain a complete record of Late Pleistocene sedimentation within Northern Spencer Gulf [table 5.2]. During times of low sea level, when Spencer Gulf contained no sea water, previously formed sediments were exposed to, and may have been partially or totally removed by, erosional processes. Also, cores taken from higher elevations, cannot preserve a record of sedimentation that occurred during the lower stands of sea level within the Gulf. Thus a degree of uncertainty potentially prevails in the identification of these three Late Pleistocene formations.

(b) Sediments of the Glanville [= Mambray] Formation may be correlated on the occurrence of several fossil species, but "no species of foraminifera were found to be diagnostic of Pleistocene sediments assigned to either the False Bay or Lowly Point Formations" [page 5.81]. Thus, only the Glanville Formation has potential for palaeo sea level correlation.

(c) Figure 8.15 uses palaeo sea level curves derived from the relative numerical distributions of two species of fossil foraminifera of the genus *Elphidium*. While this diagram clearly indicates the value of the procedure in its application to the sediments of Gulf St Vincent, "use of the *Elphidium* ratio to derive inferred palaeo sea levels for the Pleistocene interval of the [Spencer Gulf] cores was generally unsuccessful. In some instances, impossibly deep waters were implied by the ratio values, and the palaeo sea level signal signified by the general assemblage was at marked variance with that of the *Elphidium* ratio" [page 5.80].

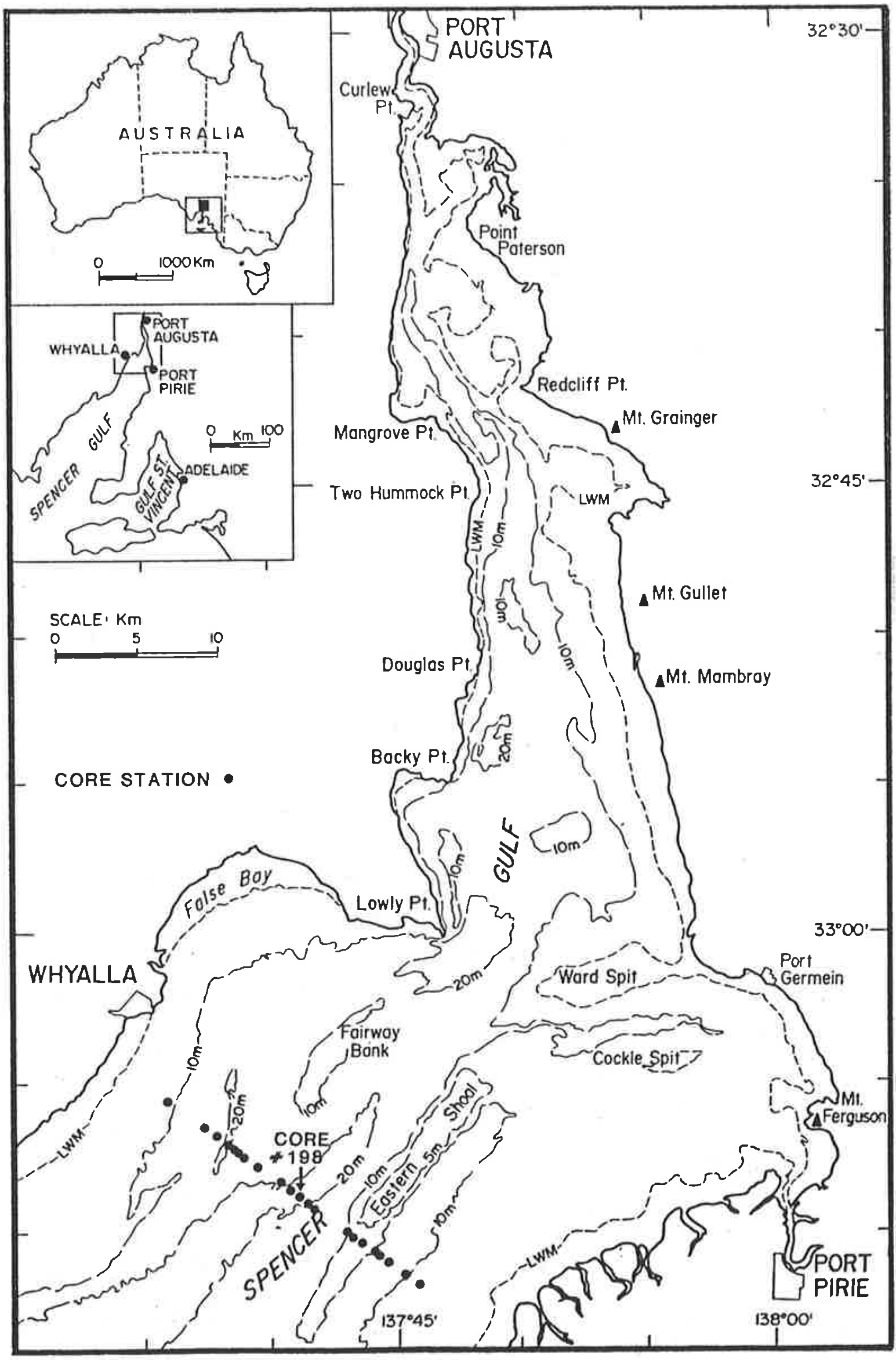


Fig. 6.1
Map of northern Spencer Gulf showing location of vibrocore #SG198 (arrow), one of several cores taken along a transect in the vicinity of Whyalla and Port Pirie (Chapter 4).

For this purpose, core SG198 (Fig 6.1) was selected because:

*the core recovered almost the maximum possible thickness of sediment within the limitations of the equipment used;

*the vibrocore site is one of the deepest in northern Spencer Gulf; it was therefore thought likely that the vibrocore would contain sediments representing each of the oxygen isotope stage 5 marine transgressions;

*the original descriptive log of Hails et al. (unpublished) indicated many identified lithological boundaries (Fig 6.2) which signified either facies changes or disconformities.

Some results of this investigation are reported in Cann and Murray-Wallace (1986).

METHODS

Sediment samples were taken from SG198 and processed for foraminifera analysis following procedures previously described in Chapters 3, 4 and 5.

RESULTS

Downcore analysis of foraminifera in core SG198 is presented for both size fractions, 1.00 - 0.50mm (Fig 6.3) and 0.50 - 0.25mm (Fig 6.4). Also, the ratio of numbers of individuals of *Elphidium macelliforme* to *E. crispum* has been logarithmically plotted against sample depth in core, signifying relative changes in palaeo water depth (Fig 6.5).

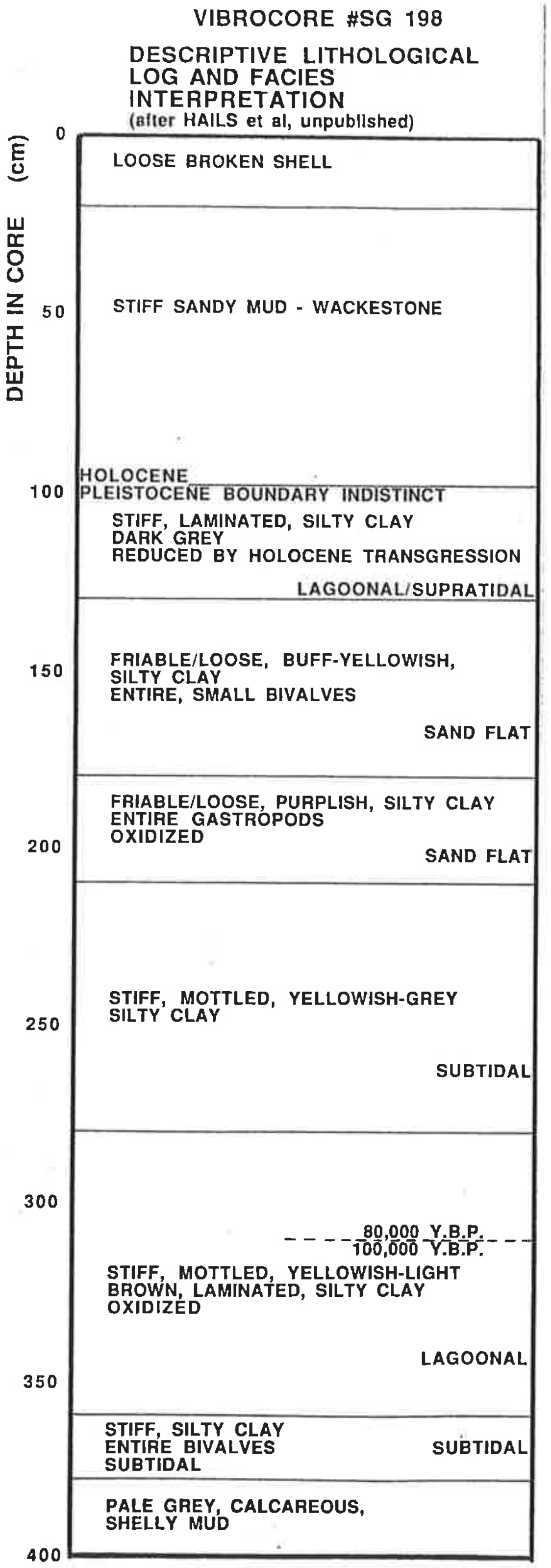


Fig. 6.2
Descriptive lithological log and facies interpretation of vibrocore #SG198, after Hails et al., unpublished.

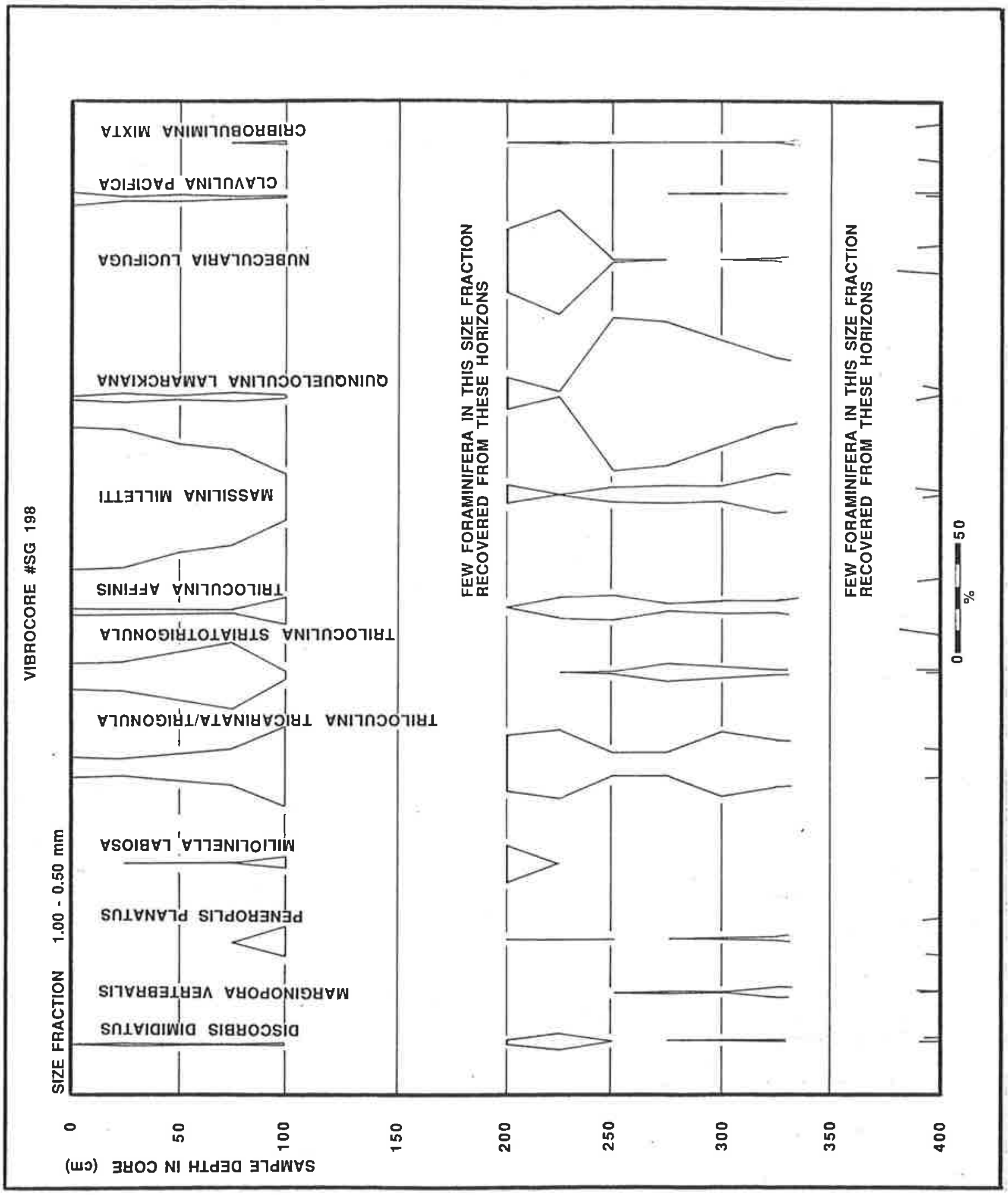


Fig. 6.3

Distribution of selected species of foraminifera within vibrocore #SG198. Size fraction 1.00 - 0.50mm.

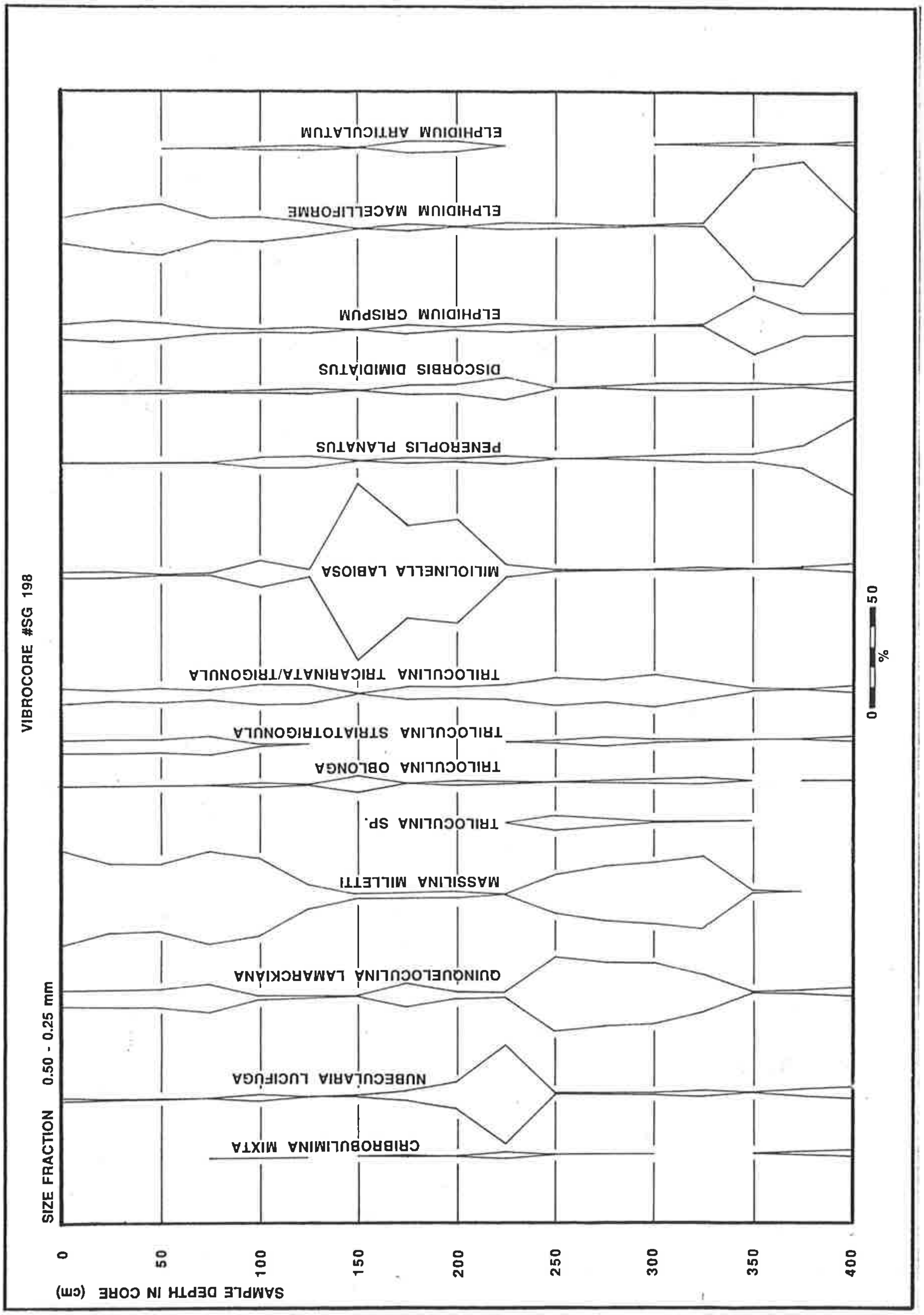


Fig 6.4
Distribution of selected species of foraminifera within vibrocore #SG198. Size fraction 0.50 - 0.25mm.

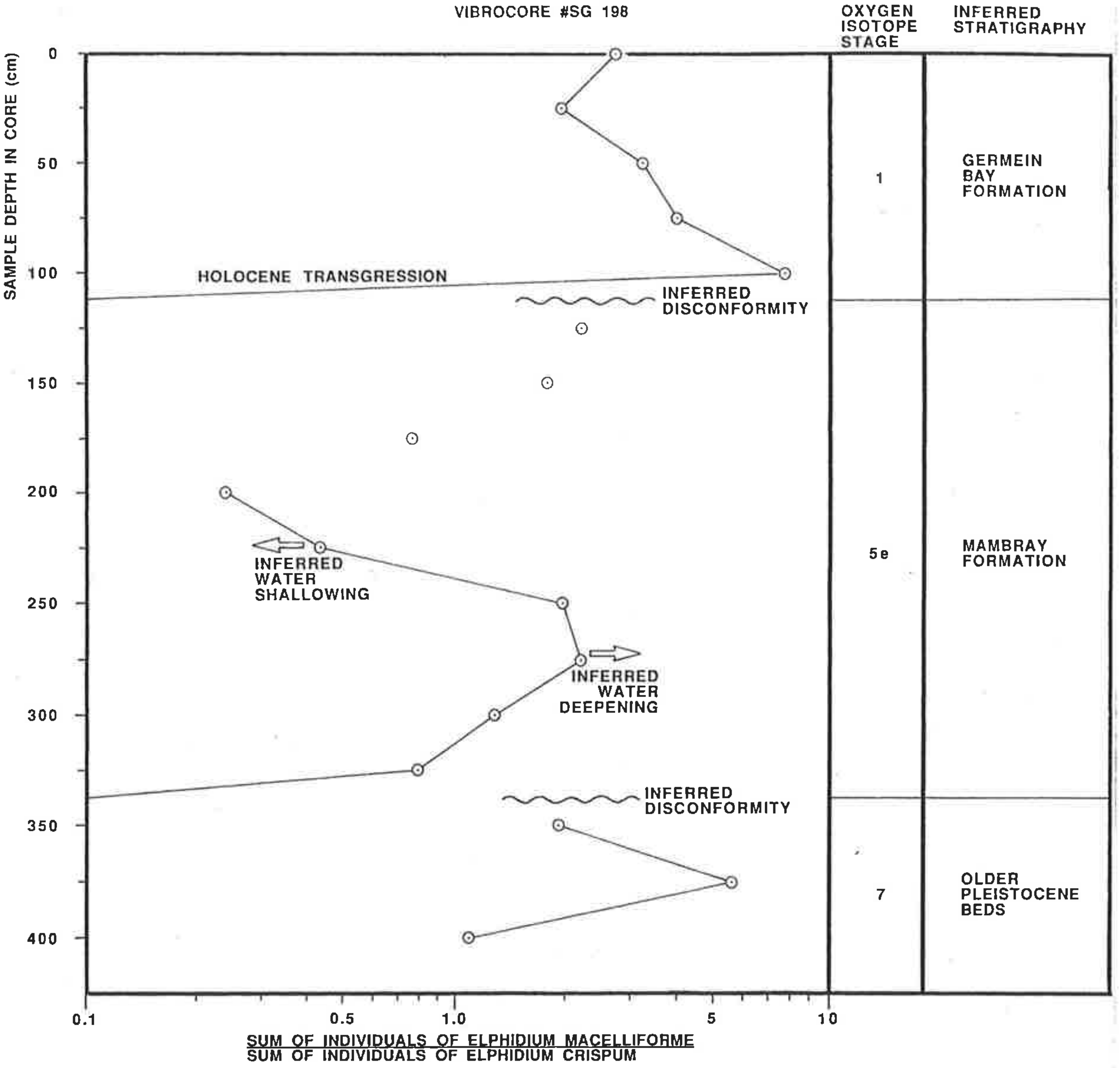


Fig. 6.5
Log-linear plot of sample depth in vibrocore #SG198 versus ratio of numbers of individuals of *Elphidium macelliforme* to numbers of individuals of *Elphidium crispum*. Also shown are inferred changes in palaeo sea level, derived from the *Elphidium* ratio, and the stratigraphy here inferred from lithological and palaeontological observations.

DISCUSSION AND CONCLUSIONS

Amino acid racemisation values obtained from tests of *Massilina milletti* in SG198 by Murray-Wallace (Cann and Murray-Wallace, 1986) confirm that specimens at 127cm were of Holocene age. Cann and Murray-Wallace therefore placed the Pleistocene/Holocene boundary between 150 and 125cm. However, the relatively small numbers of foraminifera recovered from the 125cm horizon are consistent with the original observations of Hails et al. (Fig 6.2) and the implication of mixing of basal Holocene and uppermost Pleistocene sediments. Accordingly, the base of the Germein Bay Formation in SG198 is here placed between 125 and 100cm (Fig 6.5).

The Holocene transgression is signified by increasing numbers of *Massilina milletti* up core, in association with decreasing small numbers of *Discorbis dimidiatus*, *Peneroplis planatus, Nubecularia lucifuga* and *Cribrobulimina mixta* (Figs 6.3 and 6.4).

The *Elphidium* ratio provides a palaeo water depth signal that perfectly matches the pattern previously established for Holocene Spencer Gulf. That is, following marine transgression, there was a relative fall in sea level which has been attributed to isostatic compensatory uplift of the study area. This uplift was in response to water mass loading of the nearby continental shelf and slope (Chapter 5). A small late Holocene relative rise in sea level (Lambeck, 1988) may be signified by the *Elphidium* ratio at the top of the core. Compare similar data for SG109, SG120 and SG245 (Chapter 5).

The general distribution of species up core from about 350cm to the base of the Germein Bay Formation can be interpreted as a single regressive sequence. Maximum water depth is signified at 325cm by the peak of *Massilina milletti* (Figs 6.3 and 6.4) and at 300cm by the *Elphidium* ratio (Fig 6.5). Decreasing numbers of *M. milletti* give way to peaks of *Nubecularia lucifuga* and *Discorbis dimidiatus* at 225cm, signifying a change to a shallow subtidal environment (Figs 4.2 and 4.3).

The dominance of *Miliolinella labiosa* through the interval 200 to 150cm confirms 0.5m of intertidal sedimentation (Chapter 3).

This regressive event is documented by the *Elphidium* ratio up core to 200cm (Fig 6.5). The next three ratio values up core of 200cm are based on very low numbers of specimens (for example, a total of 13 at 125cm) and it is certain that at least some superbly preserved individuals, included in the counts, are actually of Holocene age, preserved in a zone of mixed sediments. The increasing numerical value of the *Elphidium* ratio at these three horizons may well correspond to the early stages of the Holocene transgression.

Marginopora vertebralis occurs through the interval 325 to 275cm. The distribution of this species must be accepted as *prima facie* evidence that the sediments belong to the Mambray Formation. There is no unequivocal evidence to suggest that sediments of either the False Bay or Lowly Point Formations have been preserved in the SG198 sedimentary sequence. However, that possibility undoubtedly exists within the interval 225 to 150cm.

The balance of evidence is here accepted to signify that the sediments from 350cm up core to the Pleistocene/Holocene boundary are most logically assigned to the Mambray Formation. Lithological boundaries within this interval (Fig 6.2) are thus to be seen as facies changes associated with successive changes in water depth. It is not possible to accommodate the inferred disconformity at about 310cm (Fig 6.2), unless this boundary actually corresponds to the very marked change in species distribution between 350 and 325cm (Fig 6.4).

Sediments below the inferred disconformity between 350 and 325cm are constrained to the "older Pleistocene marine beds". The foraminifera within this unit are dominated by *Elphidium macelliforme* and *E. crispum* (Fig 6.4) which together signify simple transgression and regression (Fig 6.5) at water depths similar to those that have prevailed during the Holocene.

CHAPTER 7

Sea level history 45 000 to 30 000yr B.P. inferred from benthic foraminifera, Gulf St Vincent, South Australia.

INTRODUCTION

The distribution of species of foraminifera in surficial sediments of intertidal and supratidal environments at Port Gawler, on the northeastern coast of Gulf St Vincent, was described in Chapter 3. In this chapter, the distribution of species is documented for shallow subtidal areas adjacent to Port Gawler, and for deeper waters of central Gulf St Vincent. These data, and those established in earlier chapters, are used to interpret the significance of the distributions of species in two vibrocores which recovered undisturbed sections of Quaternary sediments from the deepest part of the gulf. Palaeoecological inferences of water depths are assessed within a time frame established by amino acid and radiocarbon age determinations. Estimates of palaeo sea levels for transgressions in Gulf St Vincent at 40,000 and 31,000yr B.P. are -22.5 and -22m respectively, while the intervening regression lowered sea level to -28m. These inferred changes of sea level can be accommodated within the late Pleistocene sea level curve established for the Huon Peninsula (Chappell, 1983; Chappell and Shackleton, 1986).

The findings reported in this chapter were the subject of a paper by Cann et al. (1988). Co-researchers, Dr Antonio Belperio and Dr Victor Gostin obtained the vibrocores and other sediment samples, prepared descriptive lithological logs of the cores, and selected appropriate materials for radiocarbon age determinations. Co-researcher, Dr Colin Murray-Wallace, as part of his Ph.D. programme, determined amino acid racemisation ages for some of the fossil molluscs taken from the cores. The work of these three colleagues established a time-stratigraphic framework for evaluation of the foraminiferal data by the present author.

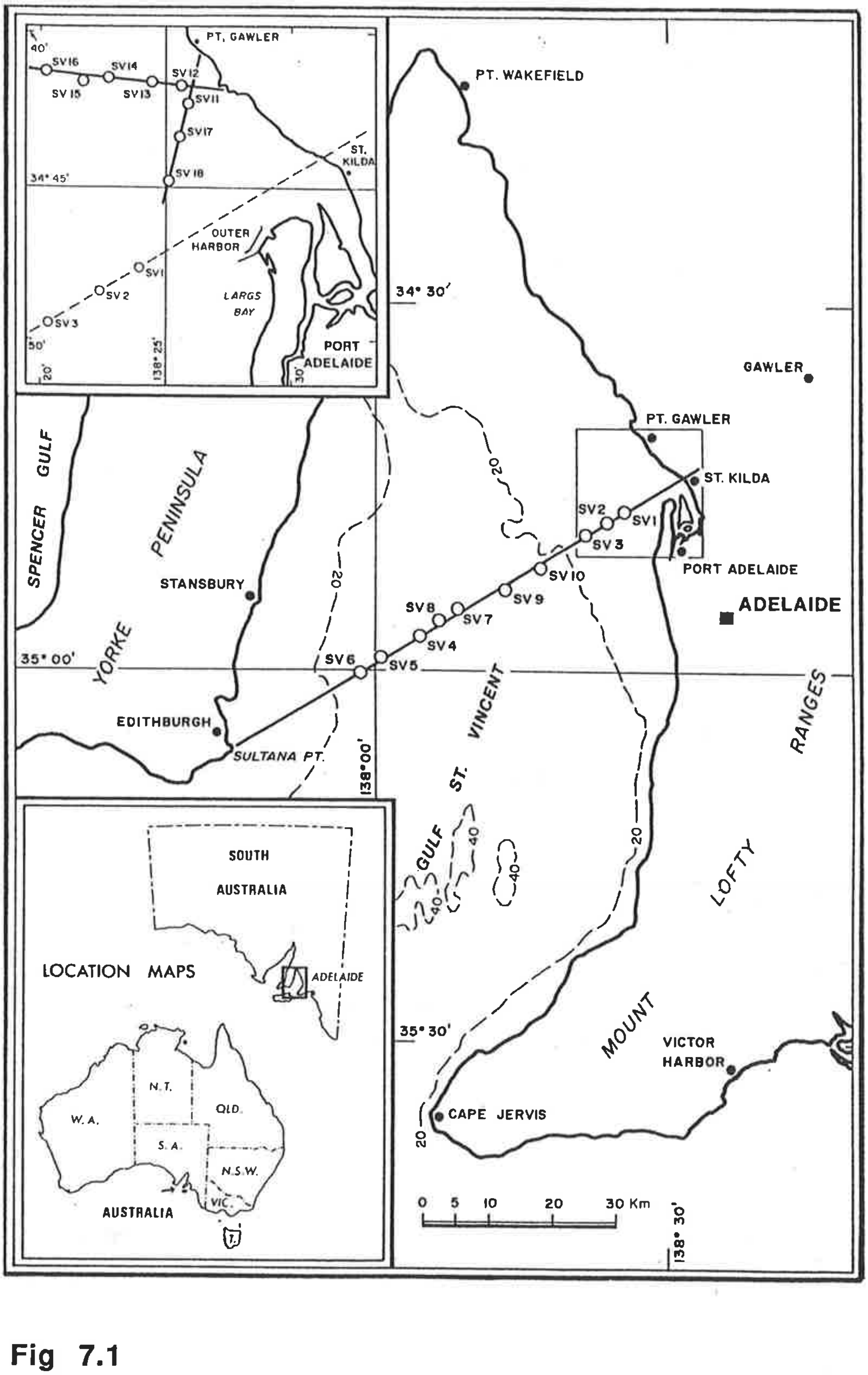


Fig 7.1
Location map showing sites of grab samples and vibrocores in Gulf St Vincent, South Australia. Water depth contours in metres.

THE STUDY AREA

Gulf St Vincent (Fig 7.1) is a shallow elongate embayment on the continental shelf of southern Australia, c.7000 sq km in area, with a maximum depth of about 40m. It is complexly fault bounded, with Fleurieu Peninsula to the east, Yorke Peninsula to the west and, in part, Kangaroo Island to the south.

Around much of the gulf coast, and in subtidal areas near Adelaide, Holocene sands and muds occur as a thin veneer overlying strongly calcreted marine sediments of the Glanville Formation (Firman, 1966; Cann, 1978; Ludbrook, 1984, and references therein). These sediments were deposited during the last interglacial sea level high stand c.125,000yr B.P., oxygen isotope substage 5e. There is little input of terrigenous sediment into the modern gulf so present day sediments consist predominantly of biogenic carbonates. Gostin et al. (1988) have recognised Gulf St Vincent, together with Spencer Gulf, as one of the major environmental divisions of the "Holocene non-tropical coastal and shelf carbonate province of southern Australia". Extensive meadows of seagrasses and algae support active populations of carbonate producing organisms (Shepherd and Sprigg, 1976) whose remains accumulate under the baffling, trapping and binding actions of the plants. A well defined plant/sediment facies zonation is typical of northern intertidal areas, such as at Port Gawler (Chapter 3).

METHODS

Vibrocores and other sediment samples

Under the supervision of Dr Victor Gostin and Dr Antonio Belperio, cores of up to 4m of recovered sediments 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 tide records.

Vibrocore sites were selected to lie along a defined transect into the central gulf (Fig 7.1). Two shorter transects were undertaken in shallow waters near Port Gawler. Seafloor grab samples were obtained at each vibrocore site for foraminiferal analysis. In the laboratory, cores were carefully split and descriptive lithological logs were prepared.

Radiocarbon dating

Large fossil bivalves, extracted from the split cores by Dr Antonio Belperio, were washed, dried and submitted for dating at the CSIRO Division of Soils Radiocarbon Laboratory in 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 living free, or sometimes attached, in water depths of 2 to 20m around parts of the gulf coast where low wave energy prevails (Ludbrook, 1984). The oyster valves are composed entirely of calcite. For smaller bivalve species, *Katelysia rhytiphora*, an intertidal cockle, and *Chlamys* (*Equichlamys*) *bifrons*, a subtidal scallop, several valves were digested to provide the requisite sample size.

Amino acid racemisation dating

Fossil bivalves were extracted from the split cores by Dr Colin Murray-Wallace. 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. The procedures used by Dr Colin Murray-Wallace to derive the AAR age determinations for these samples followed those outlined by Frank et al. (1978), Kvenvolden et al. (1979), Kimber and Milnes (1984), Cann and Murray-Wallace (1986) and Murray-Wallace and Kimber (1987).

Foraminifera in modern sediments, Gulf St Vincent

Grab samples of bottom sediment from vibrocore stations SV1 to SV18 (Fig 7.1) were processed using the techniques described in earlier chapters. The samples were boiled in fresh water to break down organic debris and generally facilitate disaggregation, and sediment of sand size was retained by wet sieving. Foraminifera were concentrated from these sand fractions by flotation on tetrabromoethane. The dried foraminiferal concentrates were further sieved into phi grain size fractions. For each grab sample, percentage abundances of foraminifera species were determined from a count of at least 200 randomly selected individuals in the grain size fractions 1.00 - 0.50mm and 0.50 - 0.25mm.

Foraminifera in vibrocores SV4 and SV5

Samples of about 100ml of sediment were taken at 20cm intervals from the split cores, and processed as described above, except that foraminifera were not concentrated by dense liquid flotation. As noted previously (Chapter 2), relative abundances of foraminiferal species in concentrated and unconcentrated sediment samples are essentially the same. However, in this case, *Nubecularia lucifuga* is a significant exception to that observation. Some forms of this species have open planispiral chambers that do not enclose air and therefore cannot be concentrated by flotation. Thus, *N. lucifuga* is over represented in the unfloated vibrocore samples when compared with the floated grab samples. For each core sample, percentage abundances of species were determined from a count of at least 200 randomly selected individuals in the grain size fractions 1.00 - 0.50mm and 0.50 - 0.25mm.

RESULTS

Vibrocore and other sediment samples

Vibrocores recovered from eastern Gulf St Vincent penetrated a thin veneer of Holocene marine shelly sand resting disconformably on calcreted marine strata of the Glanville Formation.

These pedogenically altered sediments were deposited during the last interglacial sea level maximum, oxygen isotope stage 5e, c.125,000yr B.P. Vibrocores from the deeper waters of the central gulfs, particularly cores SV4 and SV5, penetrated a relatively unaltered Pleistocene sequence of strata, apparently younger than last interglacial. Sediments recovered in vibrocores SV4 and SV5 were selected for detailed analysis.

Sites of vibrocores SV4 and SV5 lie at the northern end of a central, elongate and essentially flat sea floor (Fig 7.1). The cores recovered 2.77 and 3.90m of sediment respectively, SV4 from waters 3.5m deeper than those of SV5. Descriptive lithological logs prepared by co-researcher Dr Victor Gostin (Cann et al., 1988) are here reproduced as figures 7.2 and 7.3. Colour boundaries at 65cm in core SV4, and 53cm in core SV5, mark the disconformity between Holocene and Pleistocene marine sediments. In core SV4 the lower 25cm of the Holocene interval contains indistinct intraclasts, similar to the underlying sediment, and probably reworked from it. The Pleistocene sediments in both cores consisted of unlithified fossiliferous carbonate muds, deposited during an interstadial high sea level.

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

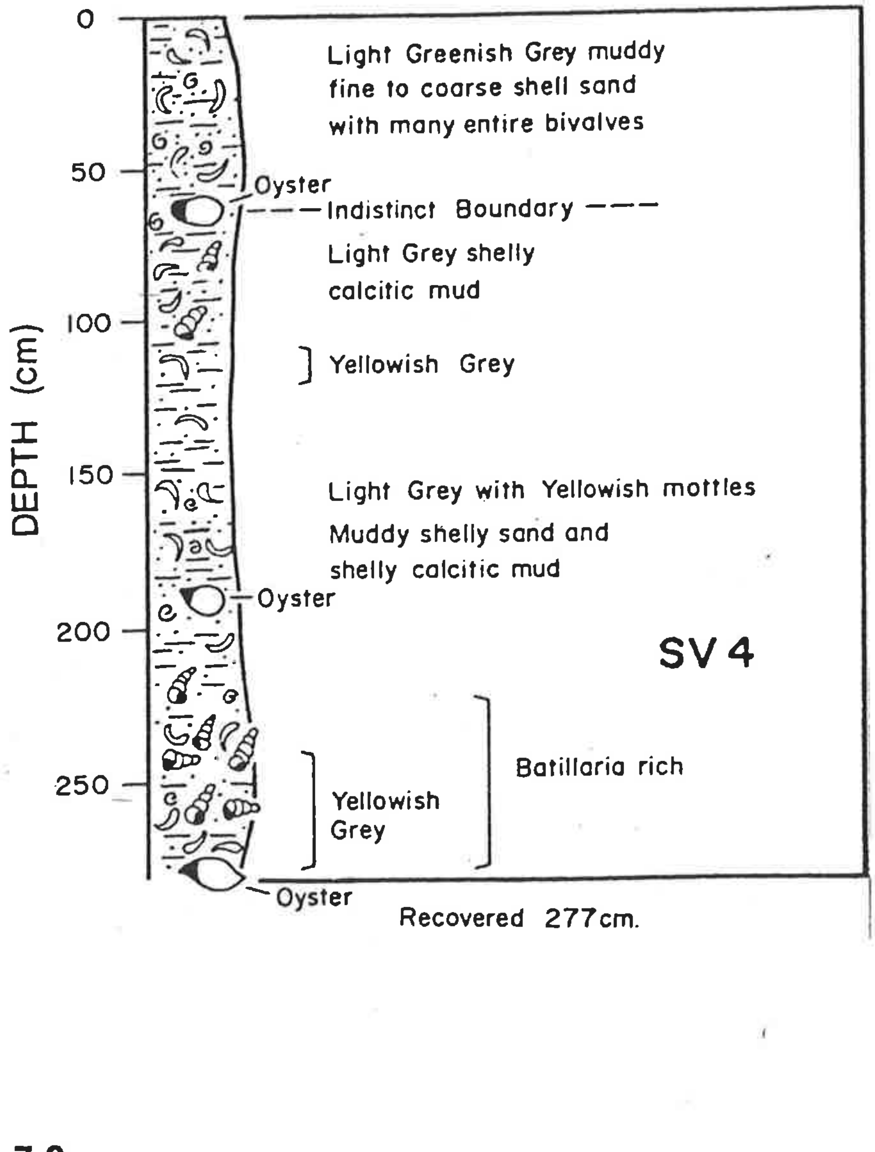


Fig 7.2
Descriptive lithological log of vibrocore #SV4 recovered from Gulf St Vincent.

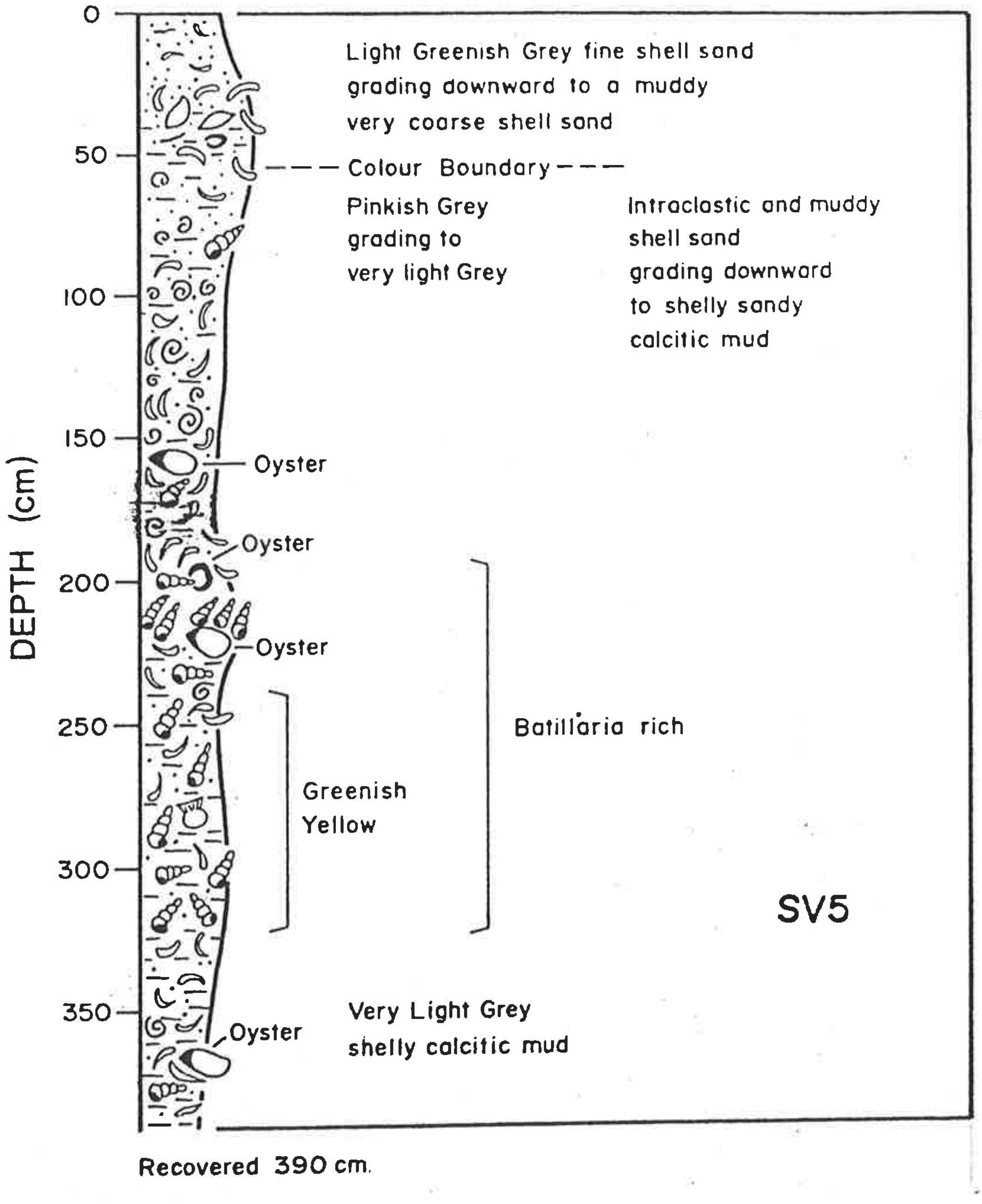


Fig 7.3
Descriptive lithological log of vibrocore #SV5 recovered from Gulf St Vincent.

Radiocarbon dates

Vibrocores SV4 and SV5 yielded seven radiocarbon dates (Cann et al., 1988, table 1) which indicated that below the Holocene sands and muds, the marine sediments were of late Pleistocene age. Individual shell dates indicated that late Pleistocene sedimentation occurred between 45,000 and 37,000yr B.P. at site SV5 and between 36,000 and 30,500yr B.P. at site SV4.

Amino acid racemisation dates

Derivatives of bivalve shells from vibrocores SV4 and SV5 were subjected to amino acid racemisation analysis by co-researcher Dr Colin Murray-Wallace (Cann et al., 1988, table 2). Specimens from core SV5 were clearly shown to be pre-Holocene in age and younger than last interglacial, and were confidently estimated to be 45,000 to 30,000yr B.P.. Similar age determinations were obtained for specimens taken from the Pleistocene interval of core SV4. Specimens immediately above the Pleistocene/Holocene disconformity were shown to be of latest Pleistocene age, and had therefore been reworked into the younger sediments following the Holocene transgression (Cann et al., 1988).

Foraminifera in grab samples

Species of foraminifera comprising at least 5% of counted individuals, for at least one grab sample along a transect, are considered to be statistically significant for that transect. Percentage distributions of all such species, in the grain size fractions 0.50 - 0.25mm and 0.50 - 0.25mm, are compared with the water depth profile for the transect across Gulf St Vincent, from St Kilda on the east coast, to Edithburgh on the west (Figs 7.4 and 7.5). Water depths of stations on this transect ranged from about 15m at SV1 to 40m at SV4. Similarly, for the shallower waters near Port Gawler, percentage distributions of significant species have been determined for two short transects (Fig 7.6 and 7.7).

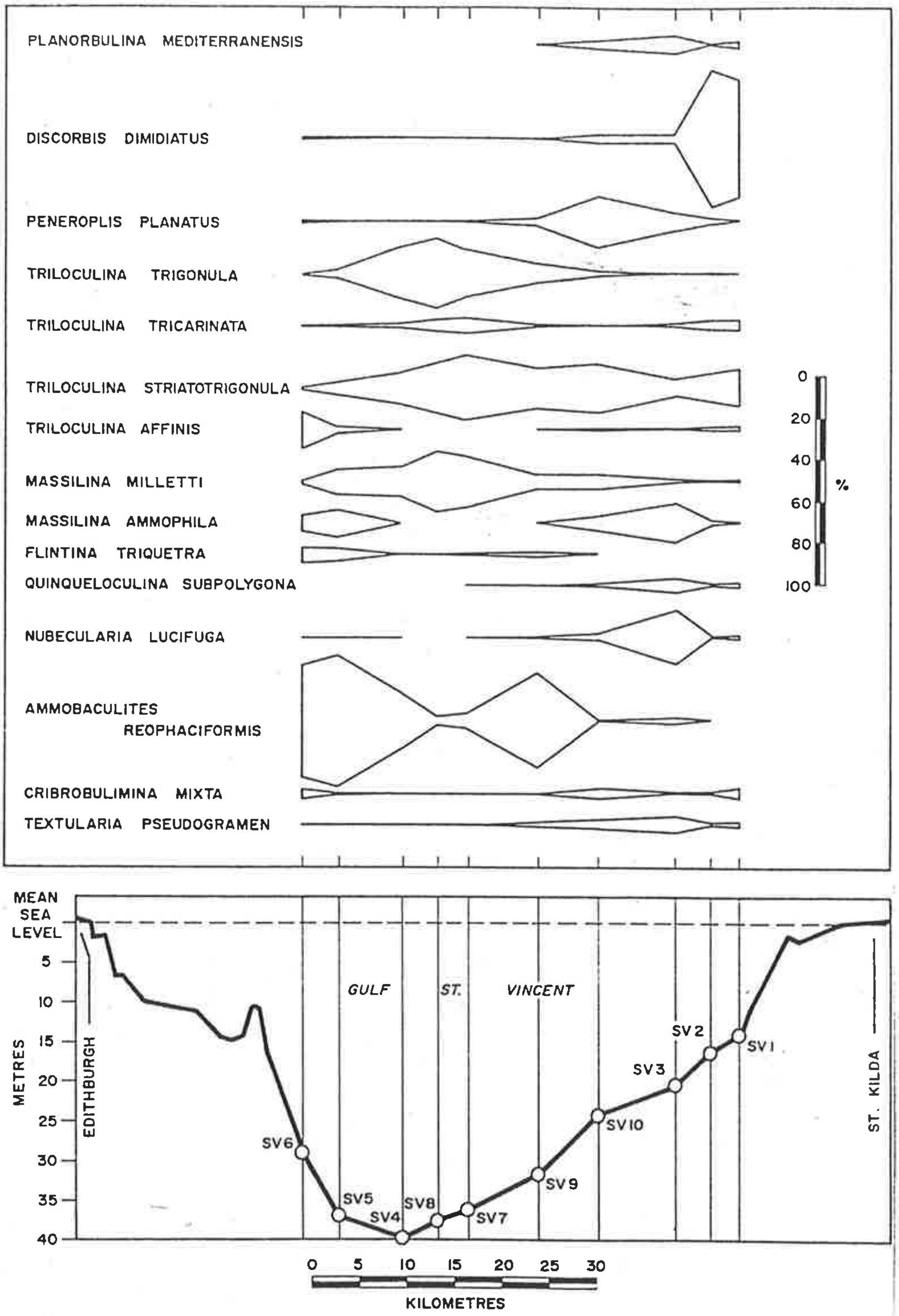


Fig 7.4

Percentage distributions of selected species of foraminifera in surficial sediment, compared with water depth, along a transect from St Kilda towards Edithburgh, Gulf St Vincent. Grain size fraction 1.00 - 0.50mm.
Sample sites are shown in fig 7.1.

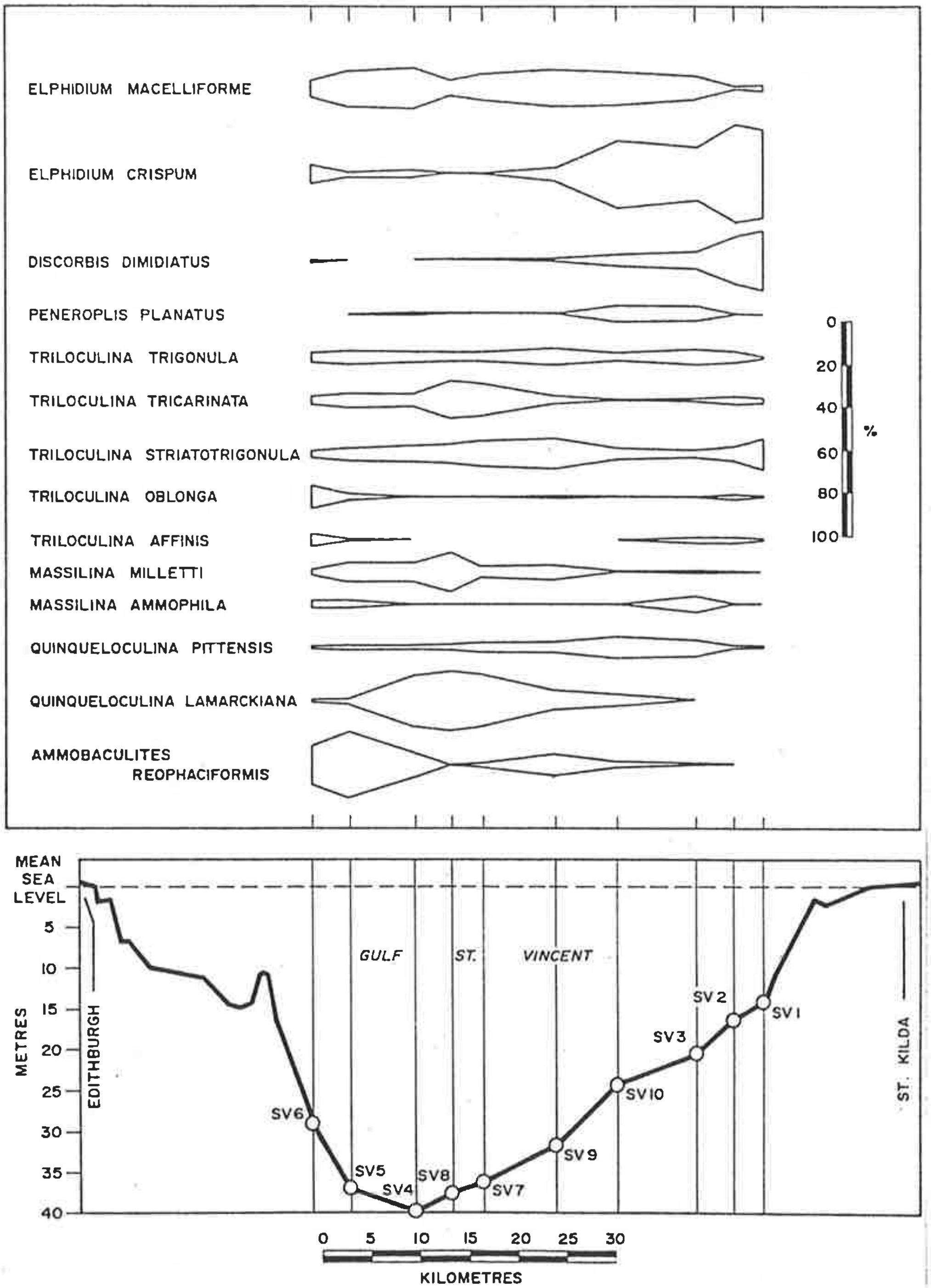


Fig 7.5
Percentage distributions of selected species of foraminifera in surficial sediment, compared with water depth, along a transect from St Kilda towards Edithburgh, Gulf St Vincent. Grain size fraction 0.50 - 0.25mm.
Sample sites are shown in fig 7.1.

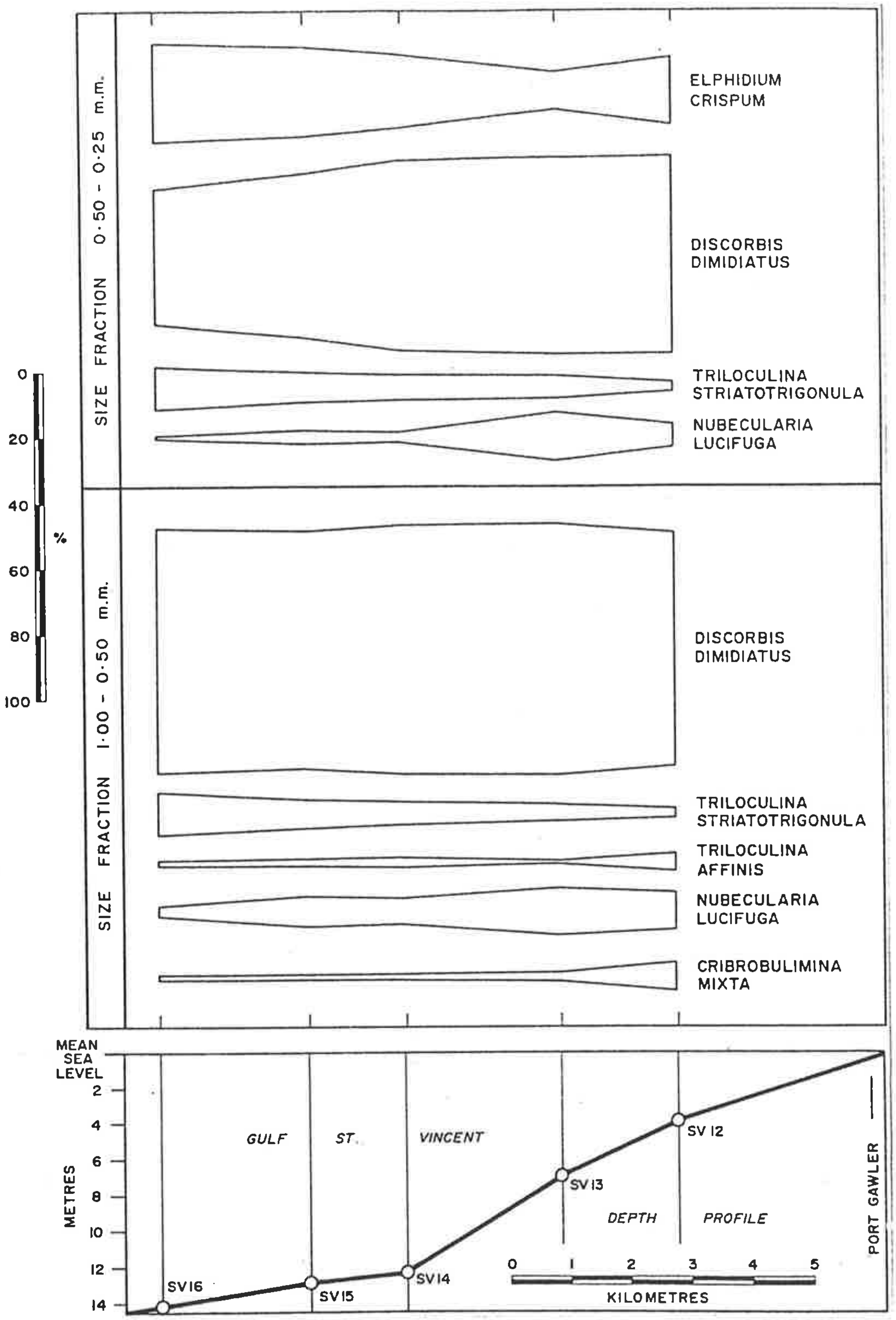


Fig 7.6
Percentage distributions of selected species of foraminifera in surficial sediment, compared with water depth, along an approximately east-west transect in the vicinity of Port Gawler, northern Gulf St Vincent. Separate data are shown for the grain size fractions 1.00 - 0.50mm and 0.50 - 0.25mm. Sample sites are shown in fig 7.1.

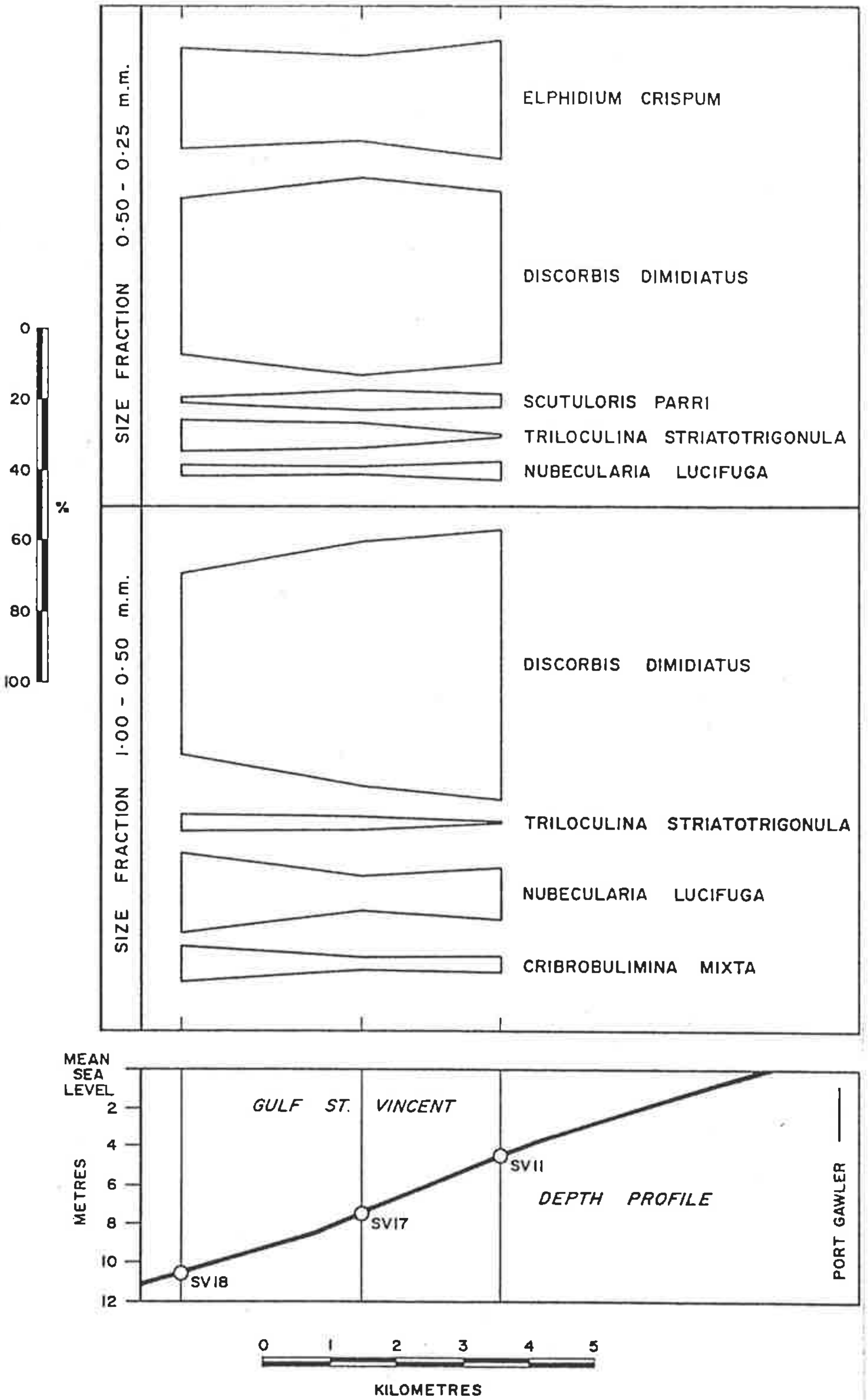


Fig 7.7
Percentage distributions of selected species of foraminifera in surficial sediment, compared with water depth, along an approximately north-south transect in the vicinity of Port Gawler, northern Gulf St Vincent. Separate data are shown for the grain size fractions 1.00 - 0.50mm and 0.50 - 0.25mm. Sample sites are shown in fig 7.1.

Foraminifera in vibrocore samples

As for grab samples on a transect, species of foraminifera comprising at least 5% of counted individuals, for at least one core sample, are considered to be statistically significant for that core. Percentage distributions of all such species, in the grain size fractions 1.00 - 0.50mm and 0.50 - 0.25mm, have been determined for vibrocores SV4 (Figs 7.8 and 7.9) and SV5 (Figs 7.10 and 7.11).

All statistically significant species recovered from grab samples and/or vibrocores are illustrated in figures 7.12 and 7.13.

DISCUSSION

Validity of radiocarbon data

Considerable debate has occurred over past decades as to the reliability of radiocarbon age determinations in the range 30,000 to 45,000yr B.P. (for example, Olsson et al., 1968; Morner, 1971) and consequent interstadial sea level interpretations (Thom, 1973). Age determinations >30,000yr B.P. can be 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 the study reported here, co- researcher Dr Antonio Belperio reduced the risk of sample contamination by selecting, where possible, large single specimens of the calcitic oyster *Ostrea angasi* for radiocarbon analysis, and by careful sample handling and pretreatment. Where other molluscs, such as *Katelysia rhytiphora*, were selected for age determinations, the aragonite shell mineral had not been altered by diagenesis. Reliability of the dates obtained is indicated by both the excellent coherence of dates down the cores, and the independent confirmation of a 30,000 to 45,000yr B.P. age range by the amino acid racemisation analyses of Dr Colin Murray-Wallace.

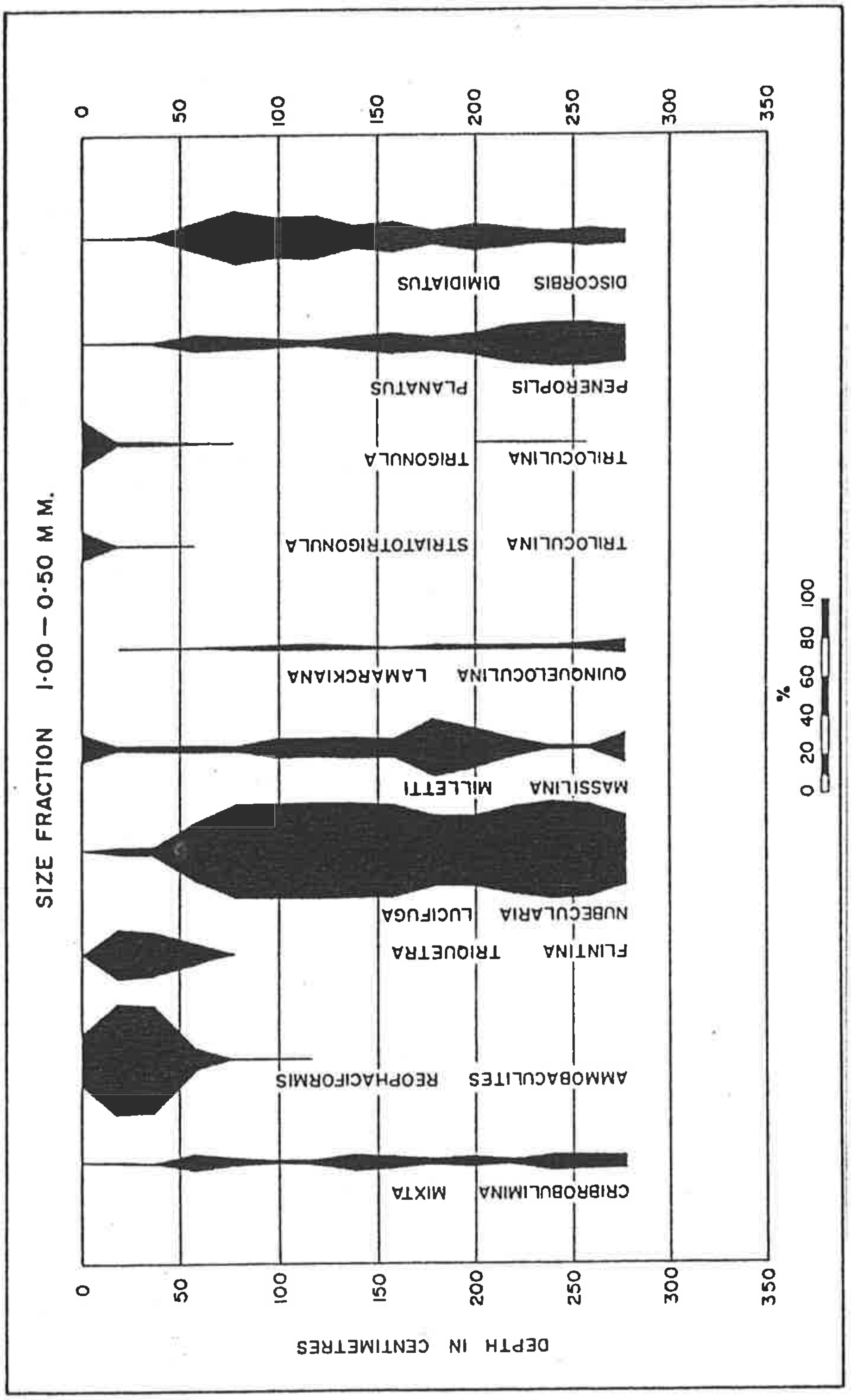


Fig 7.8
Percentage distributions of selected species of foraminifera within vibrocore #SV4. The Pleistocene/Holocene boundary is lithologically indicated at a core depth of 65cm (fig 7.2). Grain size fraction 1.00 - 0.50mm.

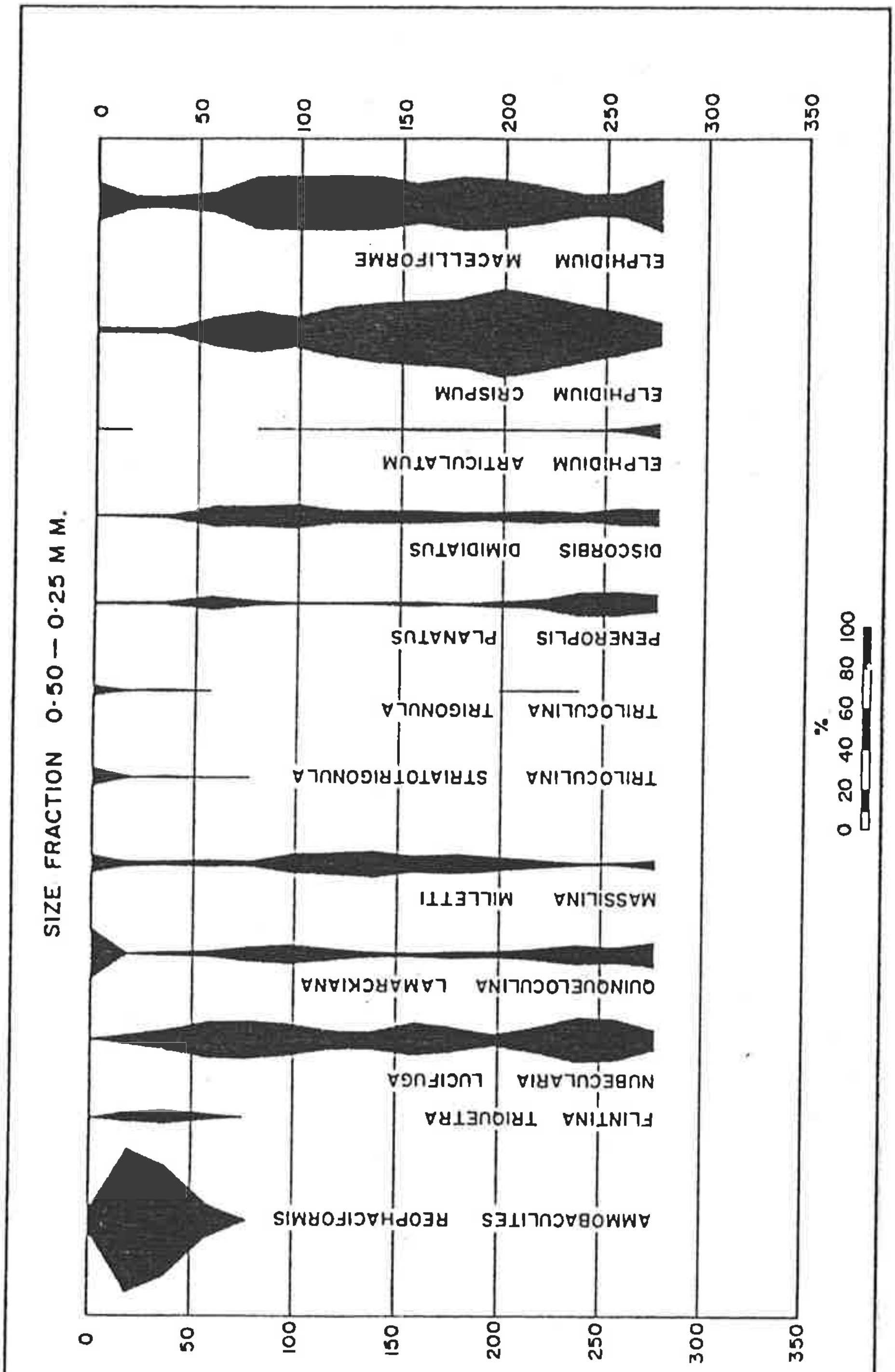


Fig 7.9
Percentage distributions of selected species of foraminifera within vibrocore #SV4. The Pleistocene/Holocene boundary is lithologically indicated at a core depth of 65cm (fig 7.2). Grain size fraction 0.50 - 0.25mm.

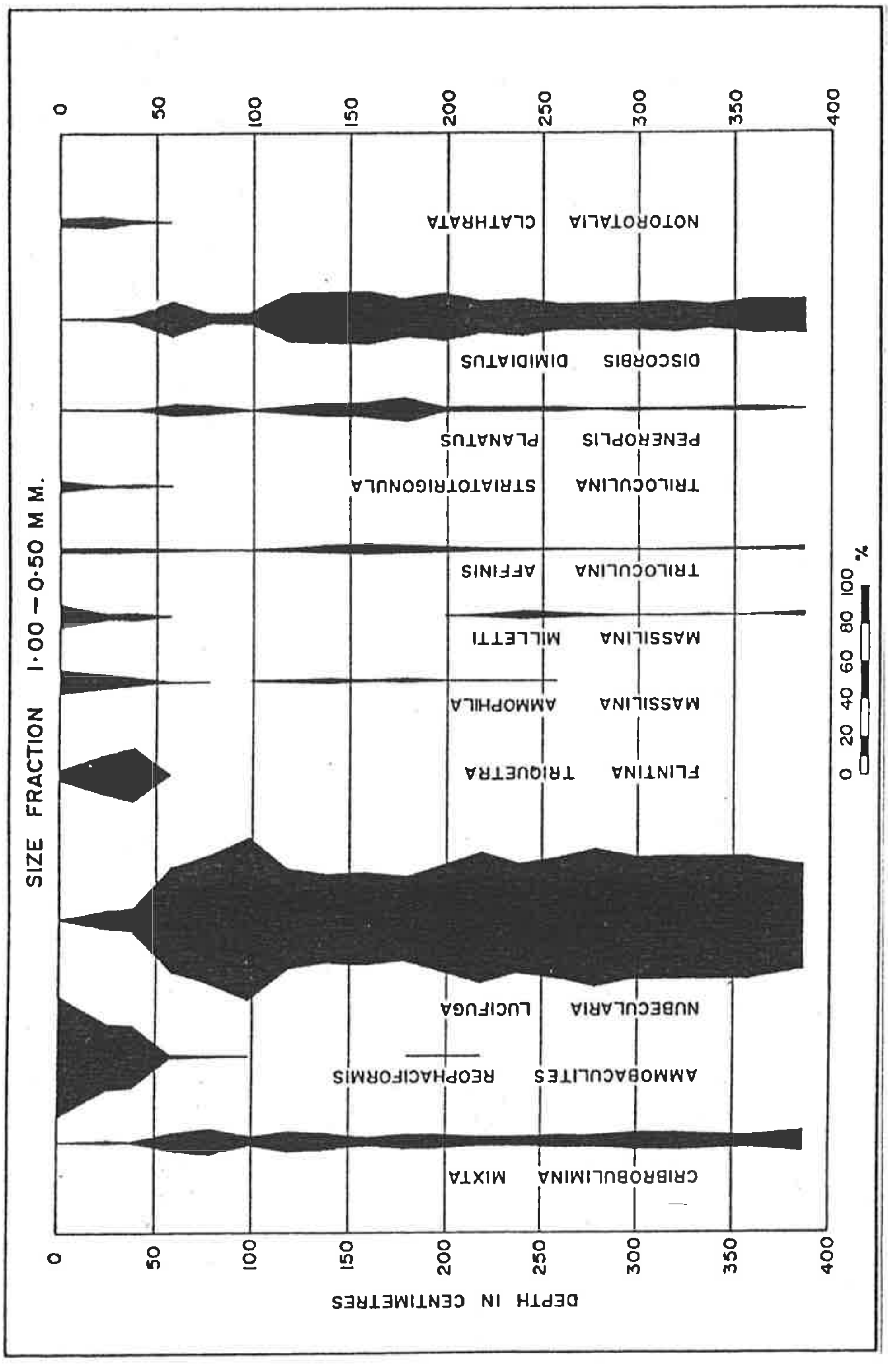


Fig 7.10
Percentage distributions of selected species of foraminifera within vibrocore #SV5. The Pleistocene/Holocene boundary is lithologically indicated at a core depth of 53cm (fig 7.3). Grain size fraction 1.00 - 0.50mm.

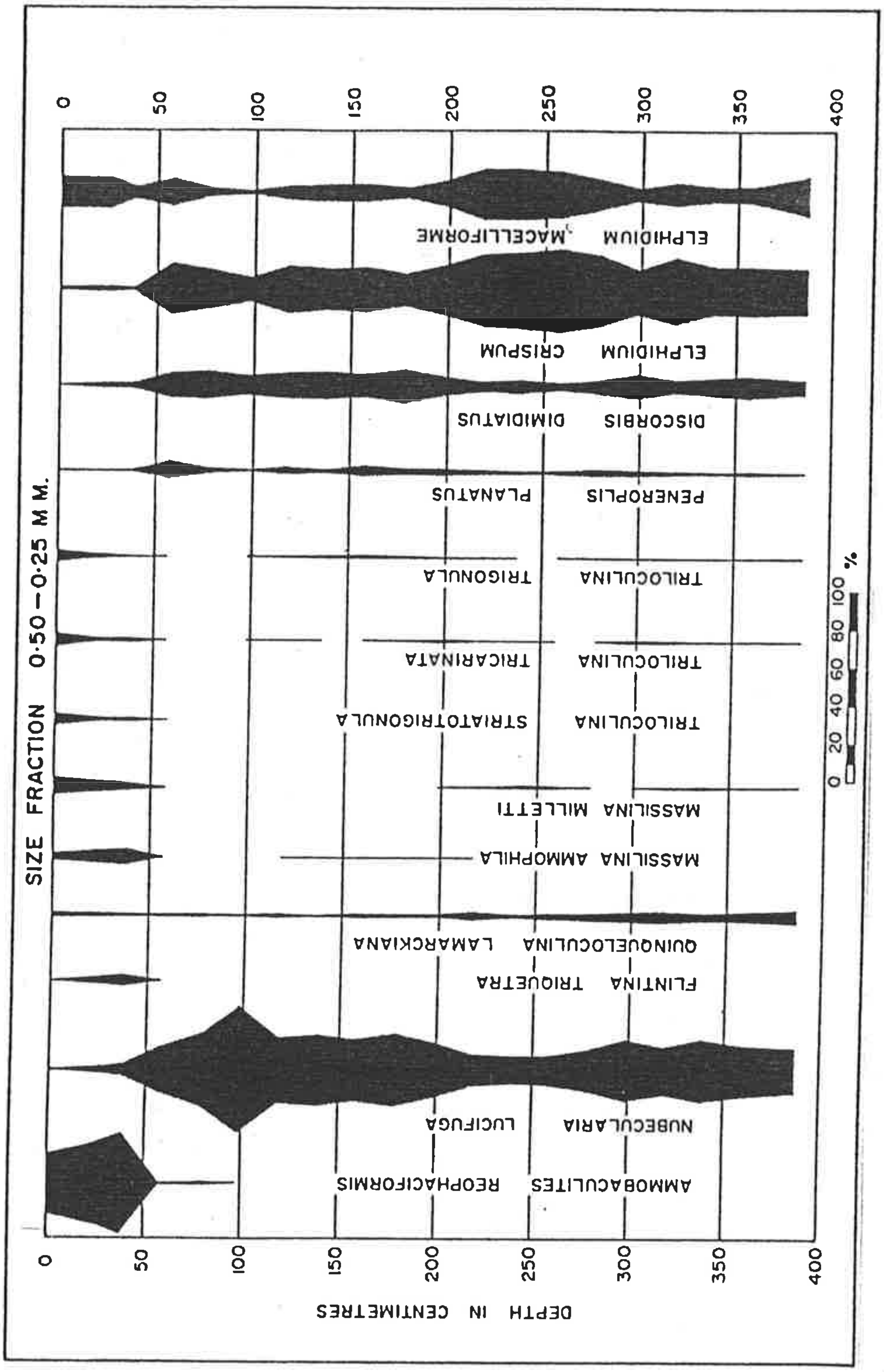


Fig 7.11
Percentage distributions of selected species of foraminifera within vibrocore #SV5. The Pleistocene/Holocene boundary is lithologically indicated at a core depth of 53cm (fig 7.3). Grain size fraction 0.50 - 0.25mm.

Cann et al. (1988) were thus confident that the strata in cores SV4 and SV5 were deposited in the time interval 45,000 to 30,000yr 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 7.4, 7.5, 7.6 and 7.7). For example, *Discorbis dimidiatus*, present in moderate numbers on the intertidal sand flats of Port Gawler (Chapter 3, Fig 3.7), is extremely abundant in shallow subtidal areas, but essentially absent from deeper gulf waters. Several species of *Triloculina* conspicuously increase in number with increasing water depth, while *Ammobaculites reophaciformis* is abundantly distributed through intermediate depths of 20 to 30m. *Quinqueloculina lamarckiana*, in the smaller grain size fraction 0.50 - 0.25mm, shows a particularly good relationship between abundance and water depth, as does *Massilina milletti*, a correlation already noted for Spencer Gulf (Chapter 4).

Some species occur in statistically significant numbers, discontinuously, in more than one environment. For example, *Peneroplis planatus* is a major component of the foraminifera on the intertidal sand flats of Port Gawler (Chapter 3, Fig 3.7), its numbers decreasing seawards to just a few percent. In shallow subtidal environments (Figs 7.6 and 7.7) the species is no longer present in significant numbers, but in deeper subtidal waters, 15 to 20m, it again constitutes a large component of the foraminiferal fauna (Figs 7.4 and 7.5).

As mentioned earlier, *Nubecularia lucifuga* is not adequately represented in Figs 7.4 to 7.7 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.

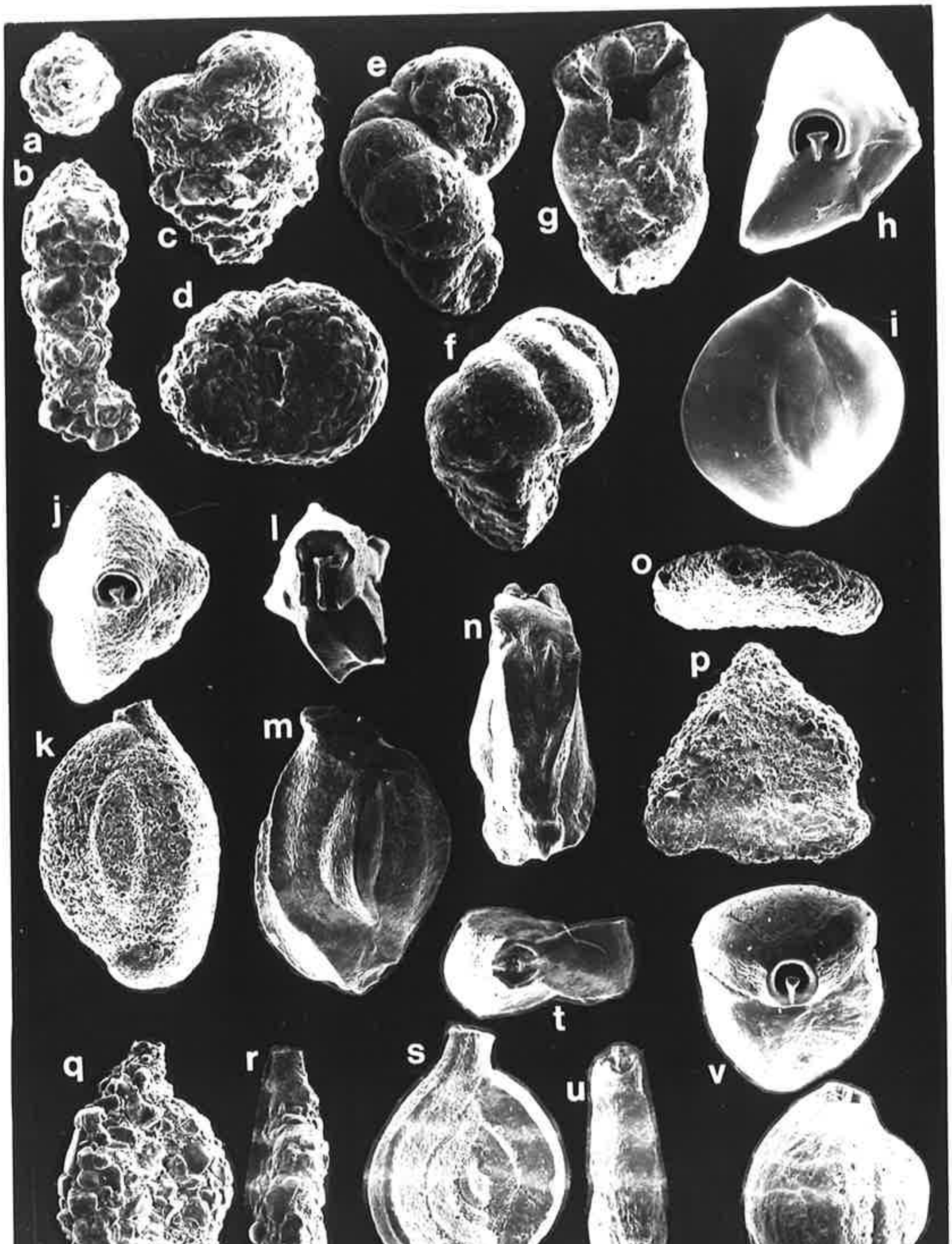

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Fig 7.12

Species of foraminifera referred to in the figures and text of this chapter:

Ammobaculites reophaciformis Cushman; **a, b** X25; SV9.
Textularia pseudogramen Chapman and Parr; **c, d** X40; SV3.
Cribrobulimina mixta Cushman; **e, f** X35; SV12.
Nubecularia lucifuga Defrance; **g** X 25; SV12.
Quinqueloculina lamarckiana d'Orbigny; **h, i** X75; SV8.
Quinqueloculina pittensis Albani; **j, k** X75; SV6.
Quinqueloculina subpolygona Parr; **l, m, n** X40; SV3.
Flintina triquetra (Brady); **o, p** X50; SV5.
Massilina ammophila (Parr); **q, r** X30; SV5.
Massilina milletti (Wiesner); **s, t, u** X40; SV9.
Triloculina affinis (d'Orbigny); **v, w** X35; SV12.
All illustrated specimens are from grab samples.

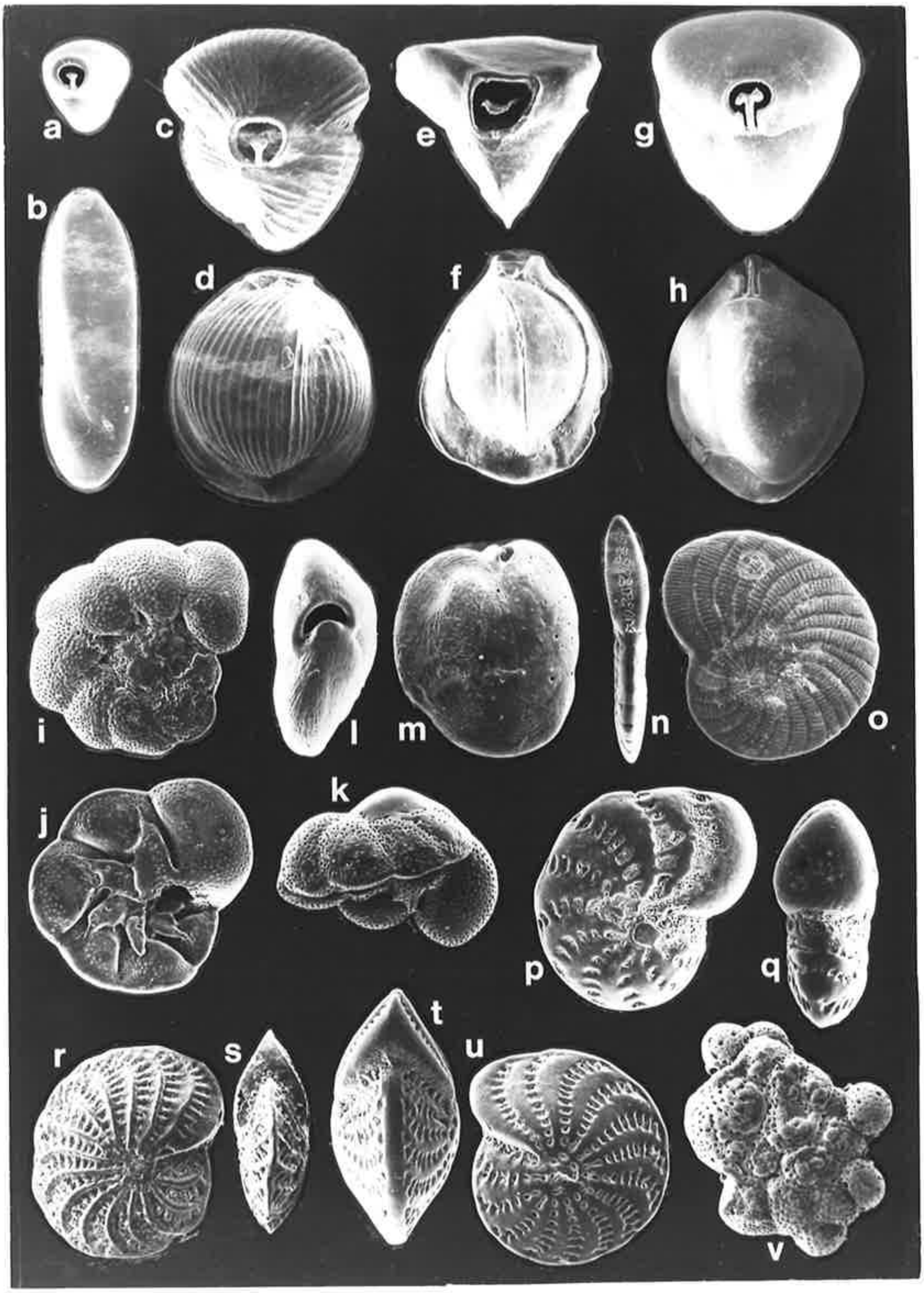
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Fig 7.13

Species of foraminifera referred to in the figures and text of this chapter:

Triloculina oblonga (Montagu); **a, b** X40; SV6.
Triloculina striatotrigonula Parker and Jones; **c, d** X45; SV9.
Triloculina tricarinata (d'Orbigny); **e, f** X40, SV7.
Triloculina trigonula (Lamarck); **g, h** X45; SV9.
Discorbis dimidiatus (Parker and Jones); **i, j, k** X35; SV12.
Scutuloris parri Collins; **l, m** X75; SV17.
Peneroplis planatus (Fichtel and Moll); **n, o** X35; vibrocore SV4
Elphidium articulatum (d'Orbigny); **p, q** X75; vibrocore SV5.
Elphidium crispum (Linne); **r, s** X55; SV12.
Elphidium macelliforme McCulloch; **t, u** X60; SV6.
Planorbulina mediterranensis d'Orbigny; **v** X25; SV3.

All illustrated specimens are from grab samples, except where otherwise indicated.

To better understand the distribution of this species, additional grab samples were collected from various water depths in Gulf St Vincent and examined for their foraminiferal contents. Samples were processed as described earlier, except that tests were not concentrated by dense liquid flotation.

N. Lucifuga proved to be extraordinarily abundant in shallow, subtidal nearshore environments. For example, in 2.6m of water, in the vicinity of Largs Bay near Adelaide (Fig 7.1), the species constitutes >70% of the foraminifera in the 1.00 - 0.50mm size fraction, and nearly 50% in the finer fraction. In deeper gulf waters the species is rare to absent. These observations significantly qualify the percentage distribution diagrams (Figs 7.4 to 7.7) and constitute essential additional data for interpretation of the cores.

Of particular interest is the inverse relationship that exists in the numerical distribution of two common gulf species of *Elphidium*. As previously observed for Spencer Gulf (Chapters 4 and 5), *E. crispum* is abundant in shallow subtidal environments of Gulf St Vincent (Figs 7.5, 7.6 and 7.7) while *E. macelliforme* is more common in deeper parts of the gulf (Fig 7.5). In Gulf St Vincent, the ratio of *E. macelliforme* to *E. crispum* is consistently <0.1 in water shallower than 10m, but increases to >30 in deeper waters. Regression analysis of water depth versus logarithm of the *Elphidium* ratios, for all Gulf St. Vincent surficial samples collected for this investigation, reveals a simple linear relationship with a correlation coefficient of 0.95 (Fig 7.14). As noted earlier for both the surficial and underlying sediments of Spencer Gulf (Chapters 4 and 5), this relationship has demonstrable potential for deriving palaeo water depths.

However, it is apparent that other physical factors, besides water depth, can influence the *Elphidium* ratio. Similar data prepared for Spencer Gulf (Fig 4.5) also demonstrate a consistent relationship between the ratio and water depth, but 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 28m in Gulf St Vincent, but only 17m in Spencer Gulf.

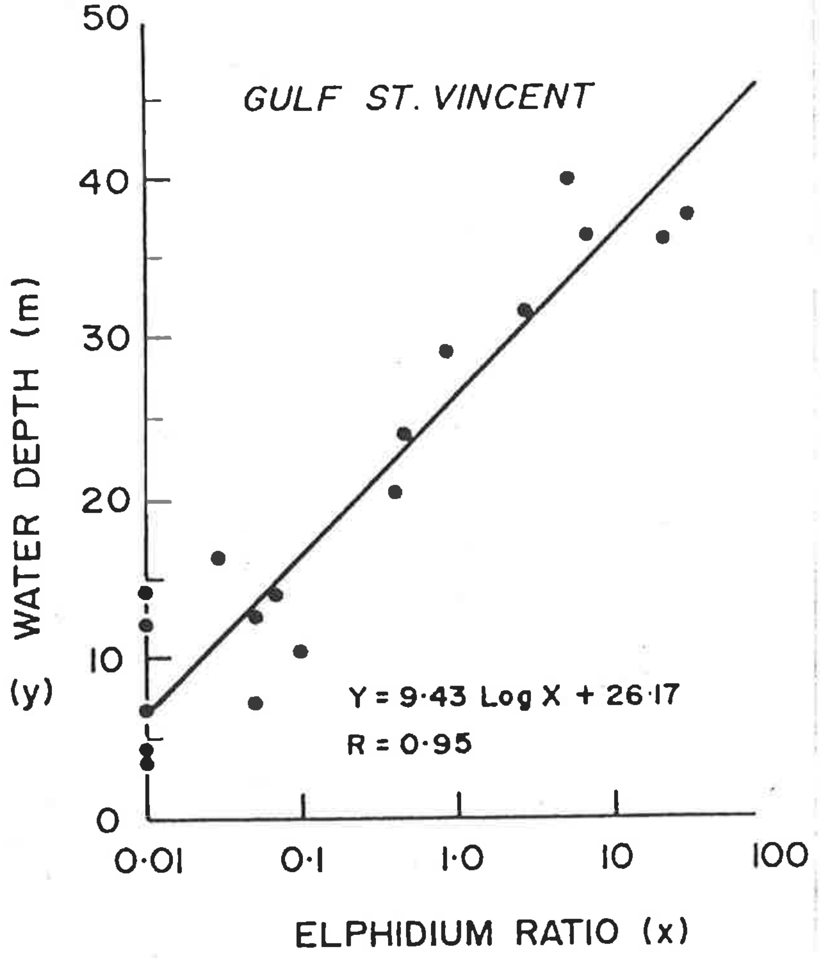


Fig 7.14
Log-linear plot of water depth versus ratio of numbers of individuals of *Elphidium macelliforme* to numbers of individuals of *Elphidium crispum* for surficial samples from Gulf St Vincent. Also shown is the line of best least-squares fit, the calculated regression equation, and Pearson's correlation coefficient for the data set.

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. As previously illustrated for the Pleistocene sediments of Spencer Gulf (Chapter 5), this has a major bearing on the application of the technique in the derivation of palaeo sea level signals.

Foraminifera in vibrocores

Percentage distributions of foraminifera species in cores SV4 (Figs 7.8 and 7.9) and SV5 (Figs 7.10 and 7.11) have palaeoenvironmental significance, particularly with reference to late Pleistocene sea levels. Successive changes in water depth for sites SV4 and SV5 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 down core sampling interval which, for these cores, was 20cm.

Vibrocore SV4

Core SV4 recovered late Pleistocene sediments deposited between 36,000 (+1450/-1250) and 30,500 (+650/-600)yr B.P.. The Pleistocene/Holocene disconformity is indicated by a distinct colour boundary at 65cm.

It has now been established for both gulfs that 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 - 0.50mm (Fig. 7.8), implies the following changes in water depth during sedimentation:

base of recovered core to 260cm, water shallowed
240cm to 180cm, water deepened
180cm to 160cm, water shallowed
160cm to 100cm, sea level unchanged
100cm to 60cm, 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 80cm show that during the final Pleistocene regression, the environment at SV4 was one of shallow subtidal sedimentation.

In the finer size fraction, 0.50 - 0.25mm (Fig 7.9), the distribution of *Quinqueloculina lamarckiana*, which in modern sediments has a positive correlation with water depth (Fig 7.5), shows that for the interval 160 to 100cm, water deepened at site SV4 prior to the final Pleistocene regression.

Onset of the Holocene transgression is signaled at about 60cm (actually 65cm, as indicated above) for both size fractions (Figs 7.8 and 7.9) by the appearance and subsequent optimum development of *Ammobaculites reophaciformis*, *Flintina triquetra* and the two species of *Triloculina*. Intertidal and shallow subtidal species, *Cribrobulimina mixta, N. lucifuga, P. planatus* and *D. dimidiatus* are all present in significant numbers near the Pleistocene/Holocene boundary. As Holocene sea level rose in Gulf St Vincent, numbers of these species rapidly decreased at site SV4 and they are essentially absent from the uppermost parts of the core. Conversely, *M. milletti*, together with other deeper water species, increased in numbers. These inferred changes in late Pleistocene and Holocene sea levels, derived from interpretation of the general assemblage of foraminifera species, are summarised in figure 7.15.

The logarithmic plot of ratios of numbers of *E. macelliforme* to *E. crispum* against sample depths in core SV4 (Fig 7.15) supports the above interpretations. Using the relationship with water depth derived from figure 7.14, the *Elphidium* ratios, without exception, confirm the changes in water depth detailed above. Figure 7.15 can thus be regarded as a *de facto* relative sea level curve for the site of vibrocore SV4.

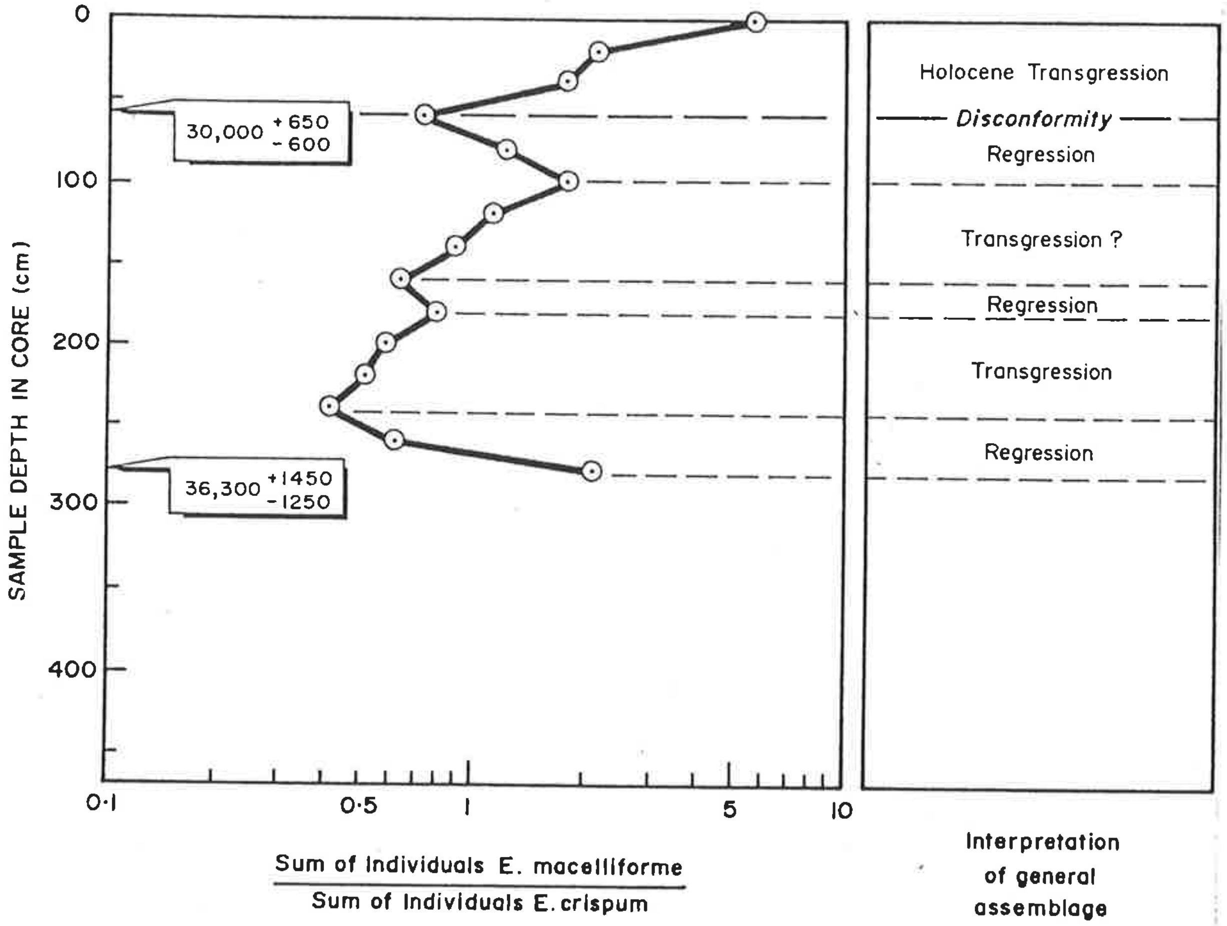


Fig 7.15
Log-linear plot of sample depth in core versus ratio of numbers of individuals of *Elphidium macelliforme* to numbers of individuals of *Elphidium crispum* for samples from vibrocore #SV4. The curve is compared with inferred changes in late Pleistocene and Holocene sea levels in Gulf St Vincent, derived from the general assemblages of foraminifera within the core. Also shown are ^{14}C dates of samples taken from the horizons indicated.

Vibrocore SV5

Late Pleistocene sedimentation, as recorded in core SV5, commenced about 45,000yr B.P. and continued for some 10,000yr. Lithologic evidence indicates that the Pleistocene/Holocene boundary occurs at a core depth of 53cm.

For the Pleistocene interval of core SV5, *M. milletti* can again be used as a water depth indicator species. Although its numbers are relatively small, increases and decreases in abundance (Figs 7.10 and 7.11) 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 (bottom of recovered core), 340 and 240cm, while lower sea levels are indicated at 360 and 300cm.

Other foraminiferal data are somewhat less informative, although the dominance of *N. lucifuga* at 100cm is unequivocal evidence of a shallow subtidal environment. This conclusion is based on the sample from Largs Bay, where water depth was only 2.6m and where *N. lucifuga* constituted >70% of the coarser sediment size fraction. *P. planatus* numbers, both immediately above and below 100cm, are interpreted as deeper subtidal populations, water depth 10 to 20m (Fig 7.4), rather than intertidal (Fig 3.7). At 100cm the species is absent. Thus, the combined record of *P. planatus* and *N. lucifuga* in the interval 140 to 60cm is evidence for water shallowing followed by water deepening. As the core sample at 60cm is closest to the Pleistonene/Holocene boundary at 53cm, there are no direct foraminiferal data indicating final Pleistocene shallowing and emergence at SV5. From the evidence of both the foraminifera and the radiocarbon dates, erosion has removed the topmost Pleistocene facies at site SV5.

Foraminifera in the interval 53cm to the top of core clearly record increasing water depth of the Holocene transgression (Figs 7.10 and 7.11). Deeper water species, such as *A. reophaciformis*, *M. milletti* and *Triloculina striatotrigonula*, steadily increased in numbers as sea level rose in Gulf St Vincent.

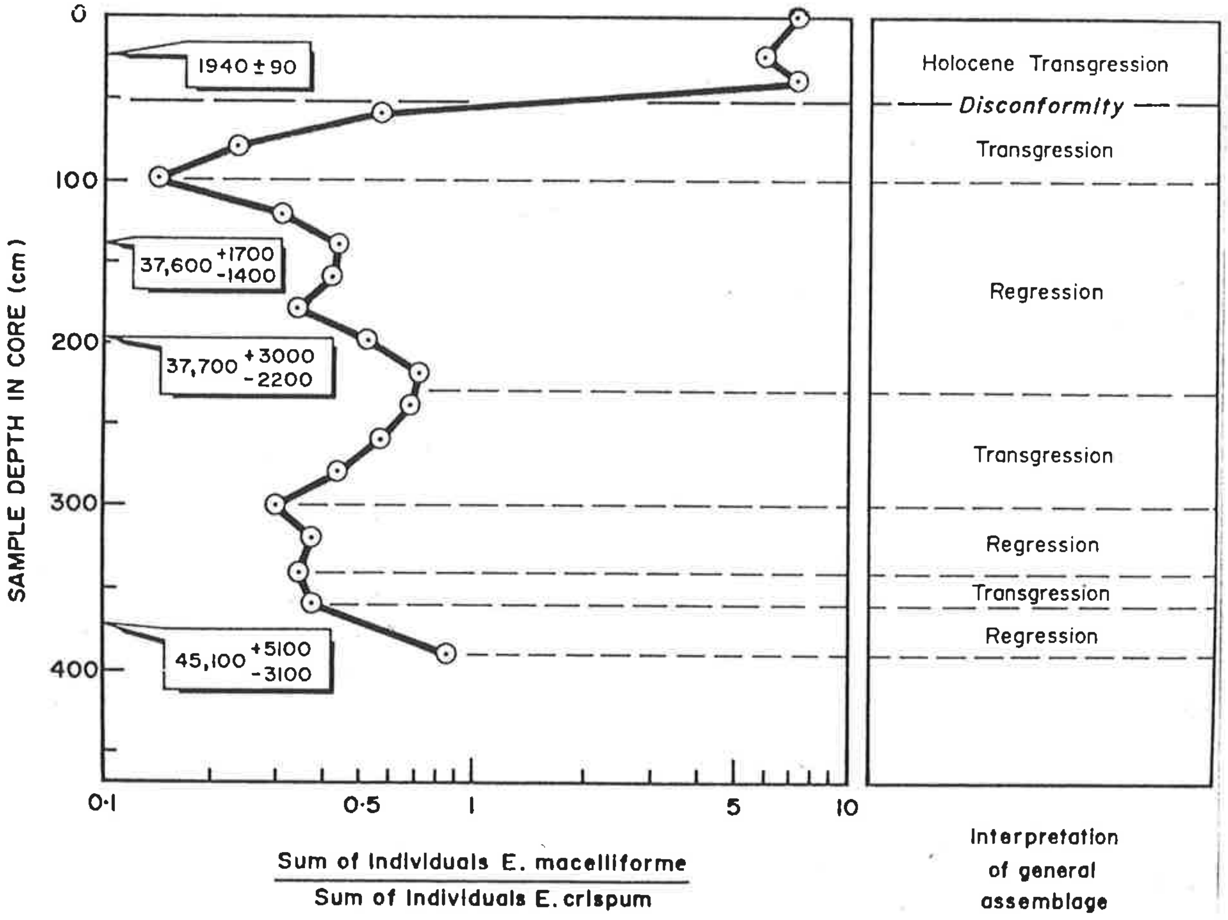


Fig 7.16
Log-linear plot of sample depth in core versus ratio of numbers of individuals of *Elphidium macelliforme* to numbers of individuals of *Elphidium crispum* for samples from vibrocore #SV5. The curve is compared with inferred changes in late Pleistocene and Holocene sea levels in Gulf St Vincent, derived from the general assemblages of foraminifera within the core. Also shown are ^{14}C dates of samples taken from the horizons indicated.

Conversely, species which are characteristic of shallow subtidal and intertidal environments, *N. lucifuga*, *P. planatus* and *D. 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 SV5 are summarised in figure 7.16. Although there is some minor displacement of maxima and minima, the pattern of sea level fluctuations derived from the *Elphidium* ratio for this core agrees very closely. Figure 7.16 can thus be regarded as a *de facto* relative sea level curve for the site of vibrocore SV5.

Absolute sea level history

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

Around Gulf St Vincent, sediments of the last interglacial maximum, oxygen isotope substage 5e, crop out near present sea level. Long term subsidence has therefore been minimal and is estimated at <0.04mm/yr (Belperio, 1985).

Vibrocores SV4 and SV5 were taken at depths of 39.9m and 36.4m respectively, below present mean sea level. They indicate continuous marine inundation (that is, sea level above -36m) for the time interval 45,000 to 30,000yr B.P. Sea level fell below -40m at 30,000yr B.P. and did not rise above this level until during the Holocene transgression about 9800yr B.P. (Belperio et al., 1983, 1988).

On the tectonically uplifted Huon Peninsula, coral terraces II and IIIb, dated by $^{230}Th/^{234}U$ at 31,000 +/- 2500 and 40,000 +/- 3000yr B.P. respectively (Bloom et al., 1974; Chappell and Veeh, 1978), are shoreline correlatives of the strata in cores SV4 and SV5. Tectonically corrected sea levels at these times have been estimated at -41 +/- 1m and -39 +/- 6m, assuming a level of +6m for the last interglacial maximum (Bloom et al., 1974). The data here derived 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 *E. macelliforme/E. crispum* ratios within cores SV4 and SV5 agree with the pattern and ages of sea level peaks established by Chappell (1983) for the Huon Peninsula (Figs 7.17a and b). The use of these curves to establish absolute sea level, 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 7.14) results in palaeo water depth calculations of between 18 and 29m for the time of recorded sedimentation at sites SV4 and SV5. However, applying the regression equation for modern Spencer Gulf (Fig 4.5) to the core data results in shallower palaeo water depth calculations of 10 to 18m. Other foraminiferal evidence, in particular the large numbers of *N. lucifuga* throughout the late Pleistocene sections of cores SV4 and SV5, 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 18m at the sample sites correspond to palaeo sea levels between -23 and -29m (Fig 7.17c). More specifically, the 31,000 and 40,000yr B.P. sea level peaks are estimated at -23 and -24m respectively, with the intervening regression falling to -29m. These sea level estimates require a correction of 1.2 to 1.6m 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.

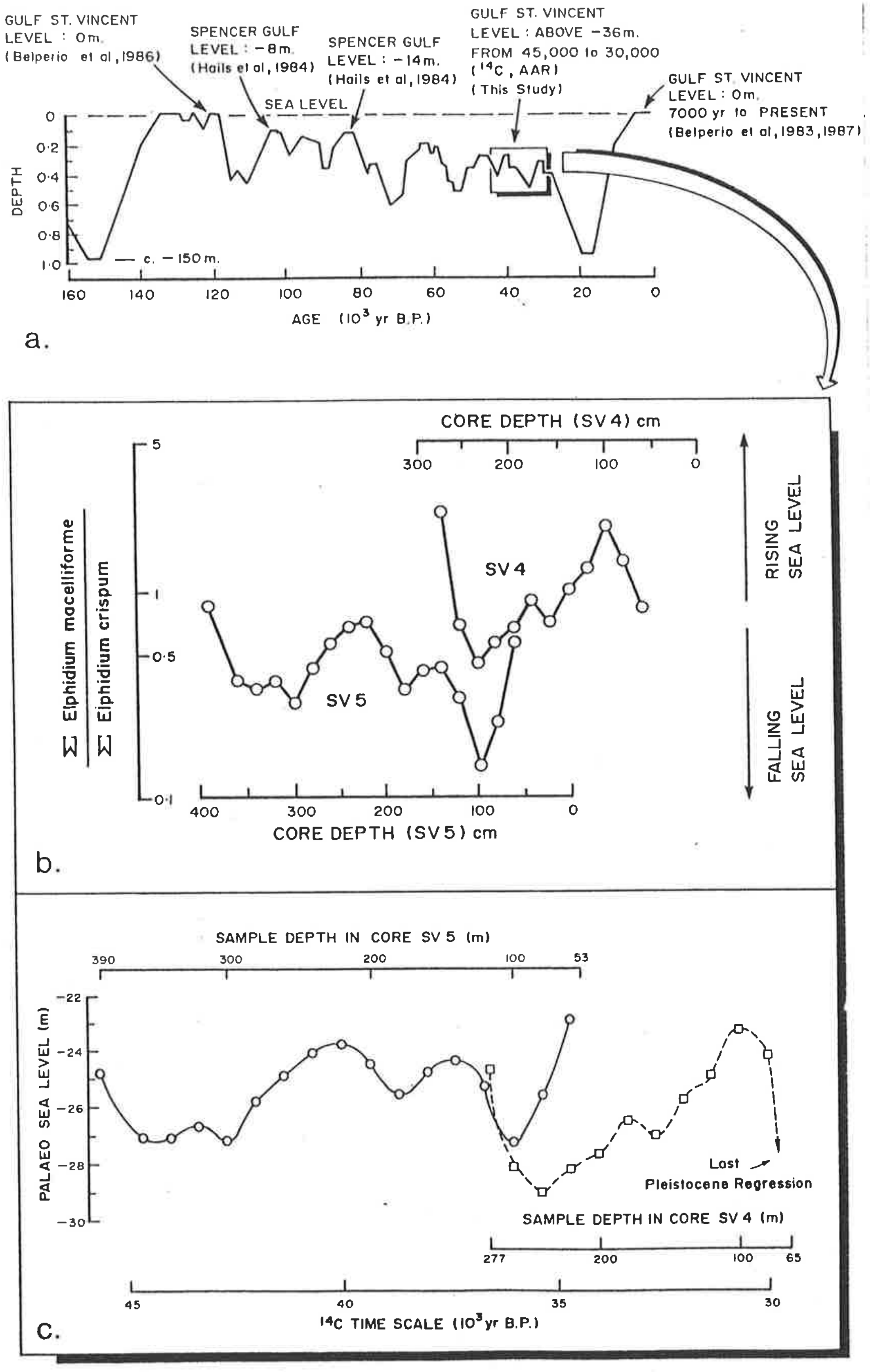

GULF ST. VINCENT LEVEL : 0m. (Belperio et al, 1986)
SPENCER GULF LEVEL : −8m. (Hails et al, 1984)
SPENCER GULF LEVEL : −14m. (Hails et al, 1984)
GULF ST. VINCENT LEVEL : ABOVE −36m. FROM 45,000 to 30,000 (14C , AAR) (This Study)
GULF ST. VINCENT LEVEL : 0m. 7000 yr to PRESENT (Belperio et al, 1983, 1987)
SEA LEVEL
DEPTH
0
0·2
0·4
0·6
0·8
1·0
— c. −150 m.
160
140
120
100
80
60
40
20
0
AGE (10³ yr B.P.)
a.
CORE DEPTH (SV4) cm
300
200
100
0
5
1
0·5
0·1
Σ Elphidium macelliforme / Σ Elphidium crispum
SV4
SV5
RISING SEA LEVEL
FALLING SEA LEVEL
400
300
200
100
0
CORE DEPTH (SV5) cm
b.
SAMPLE DEPTH IN CORE SV 5 (m)
390
300
200
100
53
PALAEO SEA LEVEL (m)
−22
−24
−26
−28
−30
Last Pleistocene Regression
SAMPLE DEPTH IN CORE SV 4 (m)
277
200
100
65
45
40
35
30
14C TIME SCALE (10³ yr B.P.)
c.

Fig 7.17

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

b. Relative sea level fluctuations for the time interval 45,000 to 30,000 ^{14}C yr B.P. interpreted from the *Elphidium* species ratio and ^{14}C data (Figs 7.15 and 7.16) from vibrocores #SV4 and #SV5, Gulf St Vincent.

c. Late Pleistocene palaeo sea levels interpreted from the *Elphidium* species ratios and ^{14}C data (Figs 7.15 and 7.16) from vibrocores #SV4 and #SV5, using the regression equation derived from northern Spencer Gulf data (Fig 4.5).

CONCLUSIONS

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

CHAPTER 8

Contemporary benthic foraminifera in Gulf St Vincent, South Australia, and refined Late Pleistocene sea levels.

INTRODUCTION

It has now been established that benthic foraminifera are abundant in surficial sediments of Gulf St Vincent, and that the distribution of many species is related to water depth. For example, *Nubecularia lucifuga* has been shown to be most abundant in shallow northern waters, while *Ammobaculites reophaciformis* is more common in deeper southern parts of the gulf. As in Spencer Gulf, *Elphidium crispum*, a shallow water species, and *E. macelliforme*, favouring deeper waters, provide a useful numerical ratio. Their logarithmic relative abundance in the sediment size fraction 0.50 - 0.25mm correlates closely with water depth, though uncertainties remain in the quantitative interpretation of such data derived from late Pleistocene sediments of Gulfs Spencer and St Vincent.

Vibrocore SV23 recovered an undisturbed section of Quaternary strata from one of the deepest parts of Gulf St Vincent, water depth about 40m, and some 40km south of the sites of SV4 and SV5 (Chapter 7). Late Pleistocene sediments recovered by SV23 belong to oxygen isotope stage 3, and can be correlated with those of SV4 and SV5. These stage 3 marine sediments in core SV23 are overlain by rapidly deposited lacustrine and restricted marginal marine deposits, in turn followed by those of more open Holocene gulf marine conditions.

Using the *Elphidium* ratios, and other supporting foraminiferal data derived from analyses of modern surficial gulf sediments, assessed on a framework of radiocarbon dates, a palaeo sea level curve is established from the fossils extracted from SV23.

Changes in sea level so derived for the period 45,000 to 30,000yr B.P. agree closely with those calculated for Gulf St Vincent sediments in vibrocores SV4 and SV5 (Chapter 7) and can be correlated with those determined from studies of the Huon Peninsula coral reef terraces. Palaeo sea level maxima of -30 to -27m are indicated from the work reported in this chapter.

AIMS

The research reported in this chapter was initiated with several clearly defined aims. These were as follows:

a) To further investigate the numerical relationship between the abundances of *Elphidium macelliforme* and *E. crispum* with respect to water depth. For surficial sediments of Gulf St Vincent, Cann et al. (1988) (Chapter 7) found a 95% correlation of the *Elphidium* species abundance ratio, expressed logarithmically, with depth of water in Gulf St Vincent. In Spencer Gulf, where the northern waters are warmer and more saline than those of Gulf St Vincent, a similar, but not identical, numerical relationship was derived with 80% correlation. The sampling programme for the investigation reported in this chapter was designed to supplement work reported in earlier chapters and so provide a systematic geographic coverage of Gulf St Vincent that might reveal some of the factors influencing the *Elphidium* ratio.

b) To further investigate, within defined limits of grain size and abundance, the numerical distribution of benthic foraminifera in the gulf. In particular, there was a need to quantify the distribution of *Nubecularia lucifuga*. In previous work reported in Chapter 3 (Cann and Gostin, 1985) and in Chapter 7 (Cann et al., 1988), foraminifera had been concentrated from surface sediment samples using the common micropalaeontological technique of dense liquid flotation. As indicated in Chapter 7, some forms of *N. lucifuga* have open, planispiral or irregularly arranged chambers that do not enclose air, and as such, cannot be concentrated by flotation.

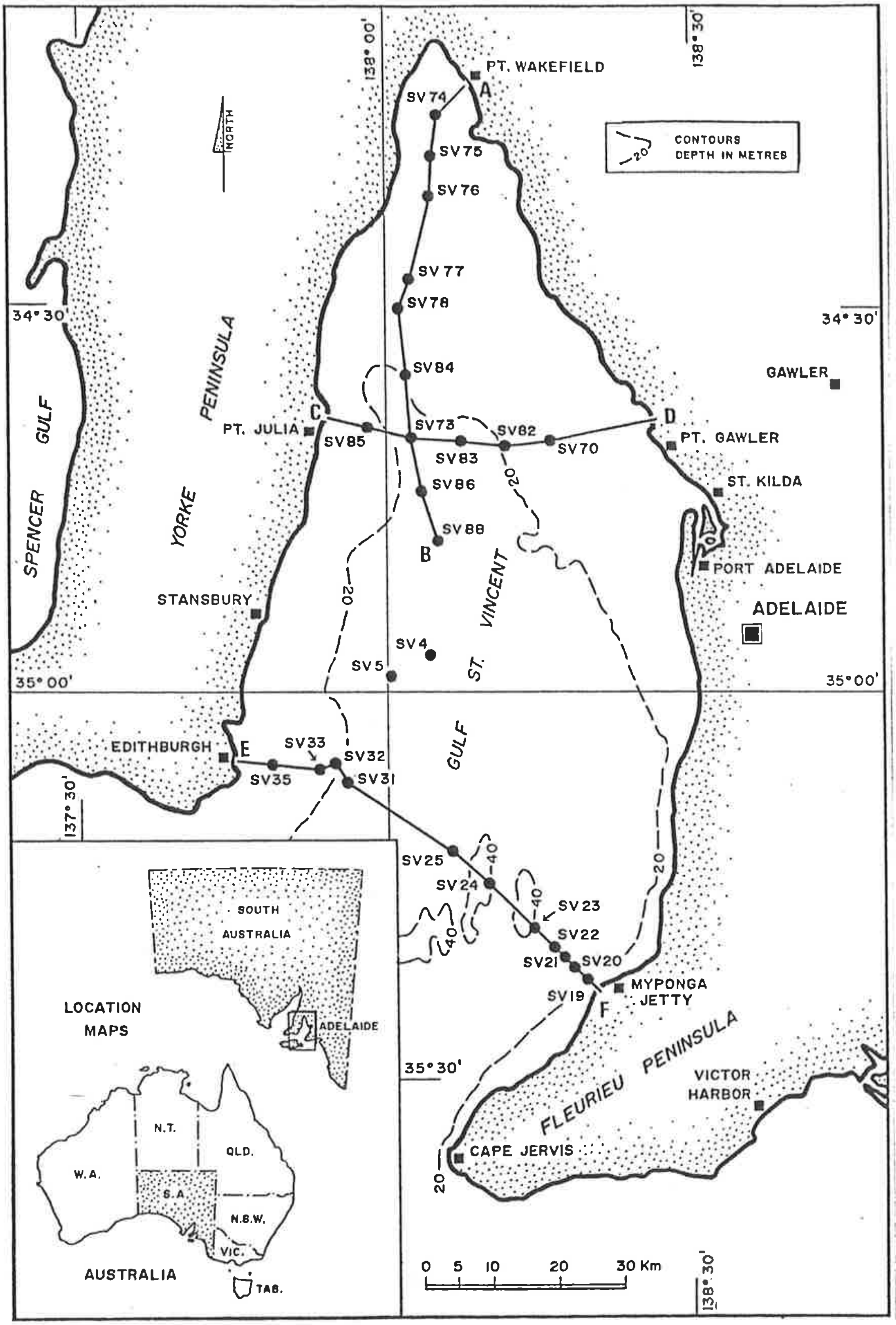


Fig 8.1
Location map showing sites of grab samples and vibrocores in Gulf St Vincent, South Australia. Depth contours in metres.

While this difficulty was acknowledged in the previous chapter, and appropriate allowance was made in the interpretation of distribution of species in unfloated samples from vibrocores SV4 and SV5, no data was available for the distribution and quantitative relative abundance of *N. lucifuga* in the surficial sediments of Gulf St Vincent. The transects selected for the investigation reported in this chapter allowed adequate opportunity to explore a possible relationship between abundance and water depth for this species.

c) To confirm the sea level curve, calculated in Chapter 7, from the *Elphidium* ratios of cores SV4 and SV5 (Cann et al., 1988), by seeking a correlation with similarly derived data from a core taken elsewhere in the gulf. Site SV23, more than 40km to the south east of SV4 and SV5 (Fig 8.1) was selected for this purpose.

d) Finally, the site selected for vibrocore SV23 is the deepest known part of Gulf St Vincent, situated in a shallow basin like depression, topographically lower than the surrounding gulf floor. It may be reasoned that this depression could have held water as either a saline or fresh water lake during times of regression, such as during the last glacial. Saline lake sediments have distinctive foraminiferal and other microfossil assemblages (Cann and De Deckker, 1981) and it was hoped to identify any episode of lacustrine sedimentation on such criteria.

METHODS

Vibrocores and other sediment samples

Materials for the study reported here were recovered from the surficial sediments and submarine Quaternary strata of Gulf St Vincent by co-researchers Dr Victor Gostin and Ms Roberta Rice. Methods were essentially as described in the previous chapter.

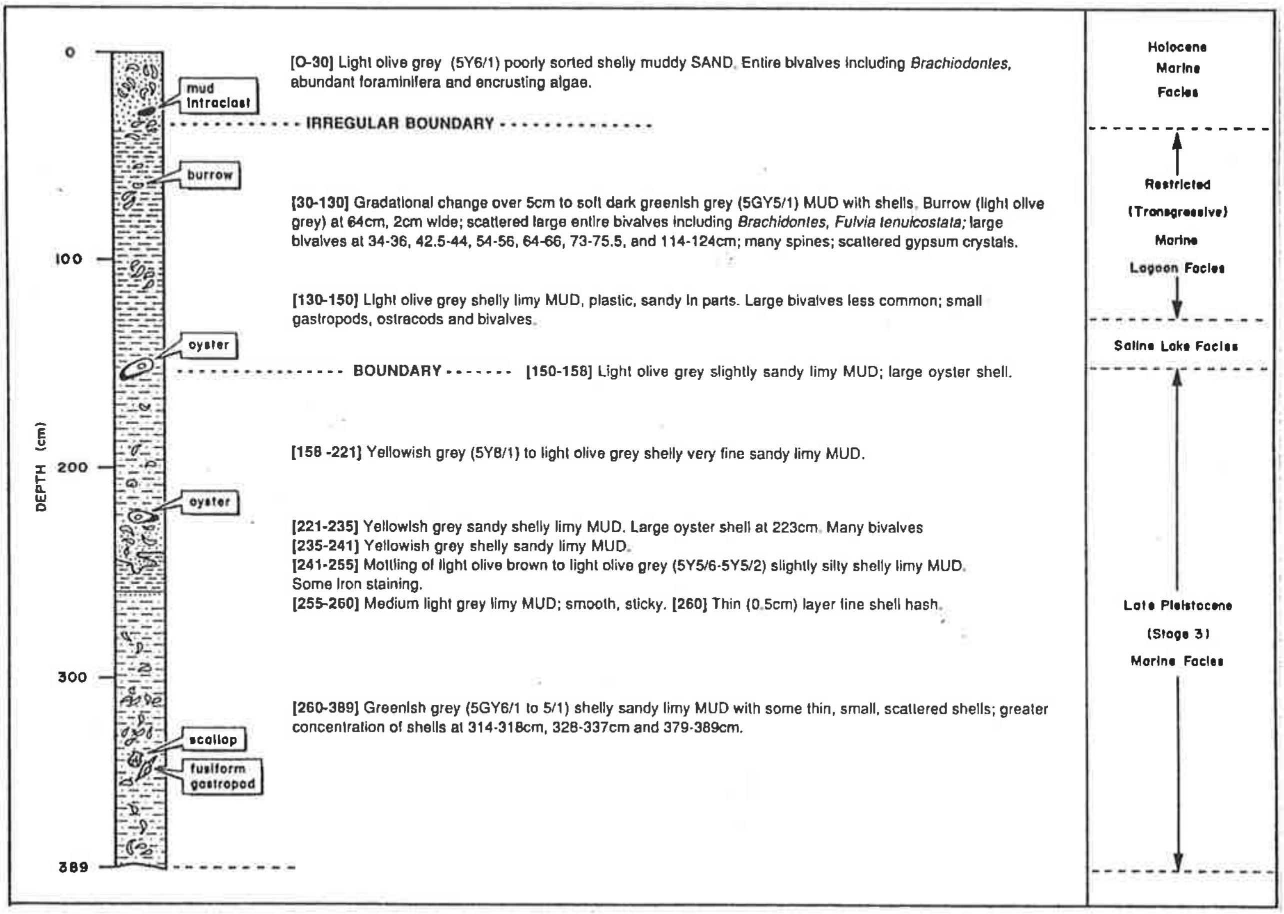
Radiocarbon dating

Molluscs extracted from eight levels down core SV23 were washed, dried and submitted for dating at the NWG Macintosh Centre for Quaternary Dating, University of Sydney. After removal of surficial contaminants, a dilute acid wash was used to remove 10% of the outer layers of the fossils. In most cases, several valves of the same species in close proximity were used to provide a requisite sample size (14-74gms) for standard radiocarbon dating procedures.

Foraminifera in modern sediments and in vibrocore SV23, Gulf St Vincent

Grab samples of bottom sediment from 24 stations on 3 transects (Fig 8.1) were prepared for foraminiferal analysis. The sediment samples generally disaggregated easily during wet sieving, which eliminated grains <0.063mm. The retained material was dried and further sieved into phi grain size fractions for microscopic examination. Benthic foraminifera were plentiful in most samples and procedures of concentration of tests by dense liquid flotation were not used for any material. No planktonic foraminifera were observed.

Similarly, sediment samples taken at 20cm intervals from one half of the split vibrocore SV23 were prepared for micropalaeontological examination, following the procedures outlined above and earlier. For each sample, except that from 140cm, more than 200 randomly selected individuals from the grain size fraction 0.50 - 0.25mm were identified and counted to determine percentage abundances of foraminiferal species. For the size fraction 1.00 - 0.50mm, <200 individuals were available in the intervals 60 to 160cm and 258 to 340cm. All other core samples yielded >200 tests.



[0-30] Light olive grey (5Y6/1) poorly sorted shelly muddy SAND. Entire bivalves including *Brachiodontes*, abundant foraminifera and encrusting algae.

[30-130] Gradational change over 5cm to soft dark greenish grey (5GY5/1) MUD with shells. Burrow (light olive grey) at 64cm, 2cm wide; scattered large entire bivalves including *Brachidontes, Fulvia tenuicostata;* large bivalves at 34-36, 42.5-44, 54-56, 64-66, 73-75.5, and 114-124cm; many spines; scattered gypsum crystals.

[130-150] Light olive grey shelly limy MUD, plastic, sandy in parts. Large bivalves less common; small gastropods, ostracods and bivalves.

[150-158] Light olive grey slightly sandy limy MUD; large oyster shell.

[158 -221] Yellowish grey (5Y8/1) to light olive grey shelly very fine sandy limy MUD.

[221-235] Yellowish grey sandy shelly limy MUD. Large oyster shell at 223cm. Many bivalves
[235-241] Yellowish grey shelly sandy limy MUD.
[241-255] Mottling of light olive brown to light olive grey (5Y5/6-5Y5/2) slightly silty shelly limy MUD.
Some iron staining.
[255-260] Medium light grey limy MUD; smooth, sticky. **[260]** Thin (0.5cm) layer fine shell hash.

[260-389] Greenish grey (5GY6/1 to 5/1) shelly sandy limy MUD with some thin, small, scattered shells; greater concentration of shells at 314-318cm, 328-337cm and 379-389cm.

Fig 8.2
Descriptive lithological log and lithofacies interpretation of vibrocore #SV23, recovered from Gulf St Vincent (Fig 8.1).

LABORATORY CODE	SAMPLE DEPTH IN CORE (cm)	MATERIAL DATED	CONVENTIONAL ^{14}C AGE (yr B.P.)
SUA-2710	18-20	*Katelysia scalarina*	4730+/-70
SUA-2711	73-75	*Brachiodontes (A.) rostratus*	9390+/-100
SUA-2712	100-110	*Fulvia tenuicostata*	9460+/-90
SUA-2713	116-122	*Brachiodontes (A.) rostratus*	9290+/-100
SUA-2714	157-159	*Ostrea angasi*	32,200+700 -600
SUA-2715	222-224	*Brachiodontes erosus*	36,500+1100 -1000
SUA-2716	334-338	*Fusinus australis*	42,400+2400 -1800
SUA-2717	390	*Ostrea angasi*	43,900+1300 -1100

Table 8.1
Radiocarbon dates derived from various bivalve shells obtained from selected horizons within vibrocore #SV23.

RESULTS

Vibrocore and other sediment samples

The sea floor over most of the gulf consists of a greenish to light olive grey, variable mixture of bioturbated shelly sand and calcareous mud, containing only a small siliceous component. Such sediment forms a veneer, usually <1m thick, overlying a~~n~~ oxidised, and variably calcreted, uppermost surface of the c.125,000yr B.P. Glanville Formation.

In the deeper central parts of the gulf, however, no lithification was observed and core recovery was much improved. The detailed lithology of core SV23 was described by co-researcher Dr Victor Gostin and is here presented as Fig 8.2. From this figure, it can be seen that the shelly mud sediment below 150cm is similar in appearance to the pre-Holocene muds of SV4 and SV5 (Chapter 7, and Cann et al., 1988). This suggests that they were deposited during the same interstadial high sea level, confirmed by radiocarbon dates presented herein. However, the 30 to 150cm interval in core SV23 is clearly not present in either core SV4 or SV5. This is essentially a dark to light grey mud with a distinctive marine bivalve assemblage, and significantly including ostracods, oogonia and scattered gypsum crystals at certain levels. Such a lithology suggests an early Holocene lagoon to saline lake environment.

Radiocarbon dating

Fossil molluscs selected from the recovered sediments of vibrocore SV23 by co-researcher Dr Antonio Belperio yielded dates shown in Table 8.1 opposite. This bipartite series of dates indicates distinct phases of Holocene (0 to 9500yr B.P.) and late Pleistocene (32,000 to 44,000yr B.P.) sedimentation. The sequence of dates is similar to that recorded by Cann et al. (1988) from cores SV4 and SV5 (Chapter 7). Late Pleistocene sediments recovered from Gulf St Vincent by these cores were deposited during the time interval 45,000 to 30,000yr B.P..

Foraminifera in modern sediments and in vibrocore SV23, Gulf St Vincent

Species of foraminifera comprising at least 5% of counted individuals, for at least one grab sample along a transect, are considered to be statistically significant for that transect. Percentage distributions of all such species are compared with water depth profiles in figures 8.3 to 8.8. Figs 8.3 and 8.4 show species distributions along a southerly transect, of about 70km, from Port Wakefield near the head of the gulf. Water depths along this transect increase gradually to a maximum of about 30m. Figs 8.5 and 8.6 show percentage distributions across the gulf from Port Julia in the west to the Port Gawler area in the east. Maximum water depth along this transect is about 25m at site SV83. Additional data from eight other stations between SV70 and the general subtidal area adjacent to Port Gawler are given in Cann et al. (1988) (Chapter 7). Figs 8.7 and 8.8 show percentage distributions of species from Edithburgh on southwestern Yorke Peninsula to Myponga Jetty on Fleurieu Peninsula. This transect includes some of the deepest parts of Gulf St Vincent, including the site of SV23, which is 40m below mean sea level. Within the central to southern gulf area, species distribution data were determined for ten other stations, including SV4 and SV5, along a transect from St Kilda to Edithburgh by Cann et al. (1988) (Chapter 7). All stations related to the investigation reported in this chapter, and the lines of transect for figures 8.3 to 8.8 are shown, together with geographic names mentioned in the text, on the location map (Fig 8.1).

For vibrocore SV23, down core distributions of foraminifera species are shown in Fig 8.9 for size fraction 1.00 - 0.50mm and Fig 8.10 for the finer fraction 0.50 - 0.25mm. These figures show distributions of only those species comprising at least 5% of randomly counted individuals (>200), for at least one size fraction subsample down the core.

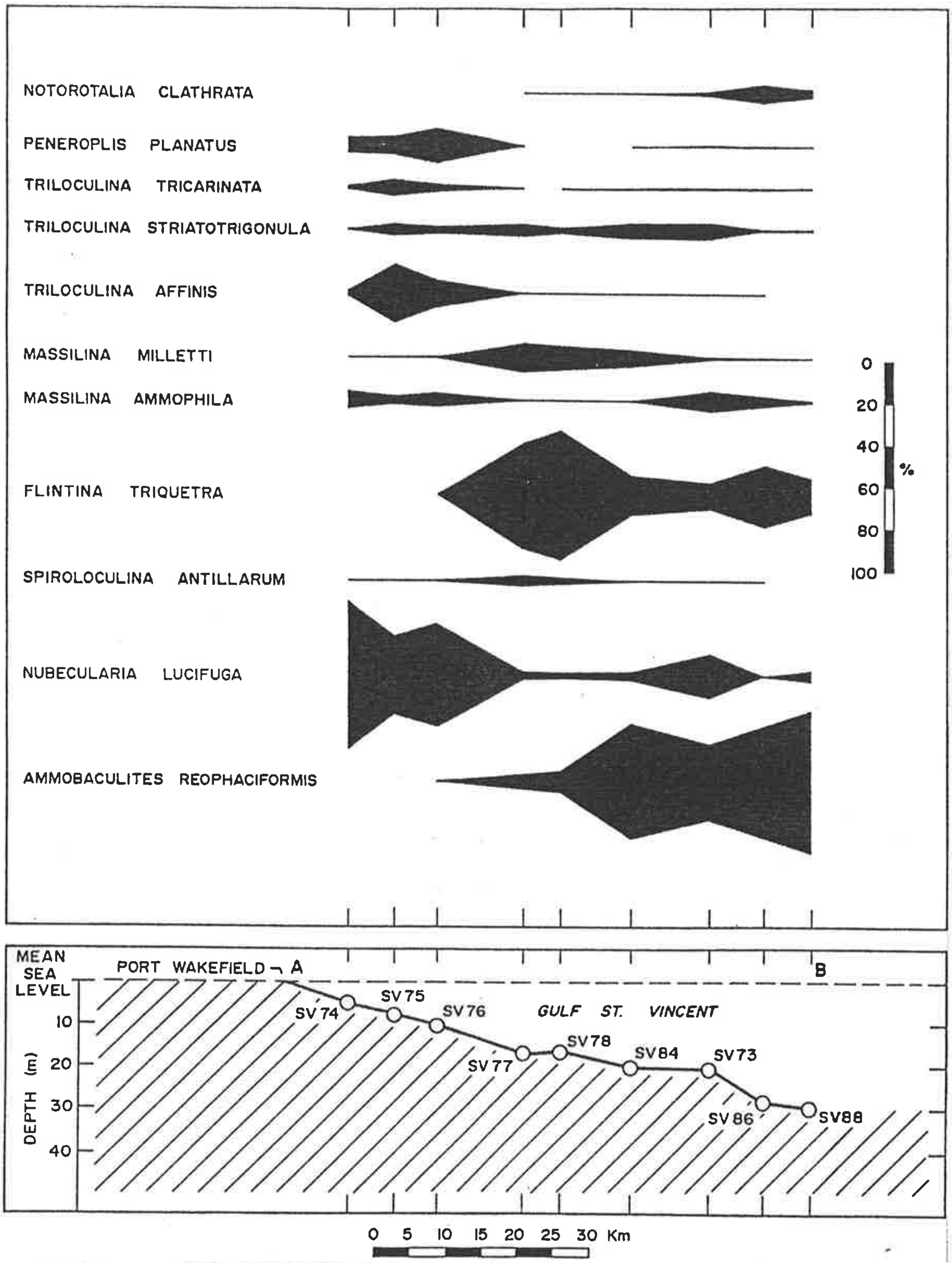


Fig 8.3
Percentage distribution of selected species of foraminifera in surficial sediment compared with water depth along a transect south from Port Wakefield, Gulf St Vincent. Sample sites are indicated in Fig 8.1. Grain size fraction 1.00 - 0.50mm.

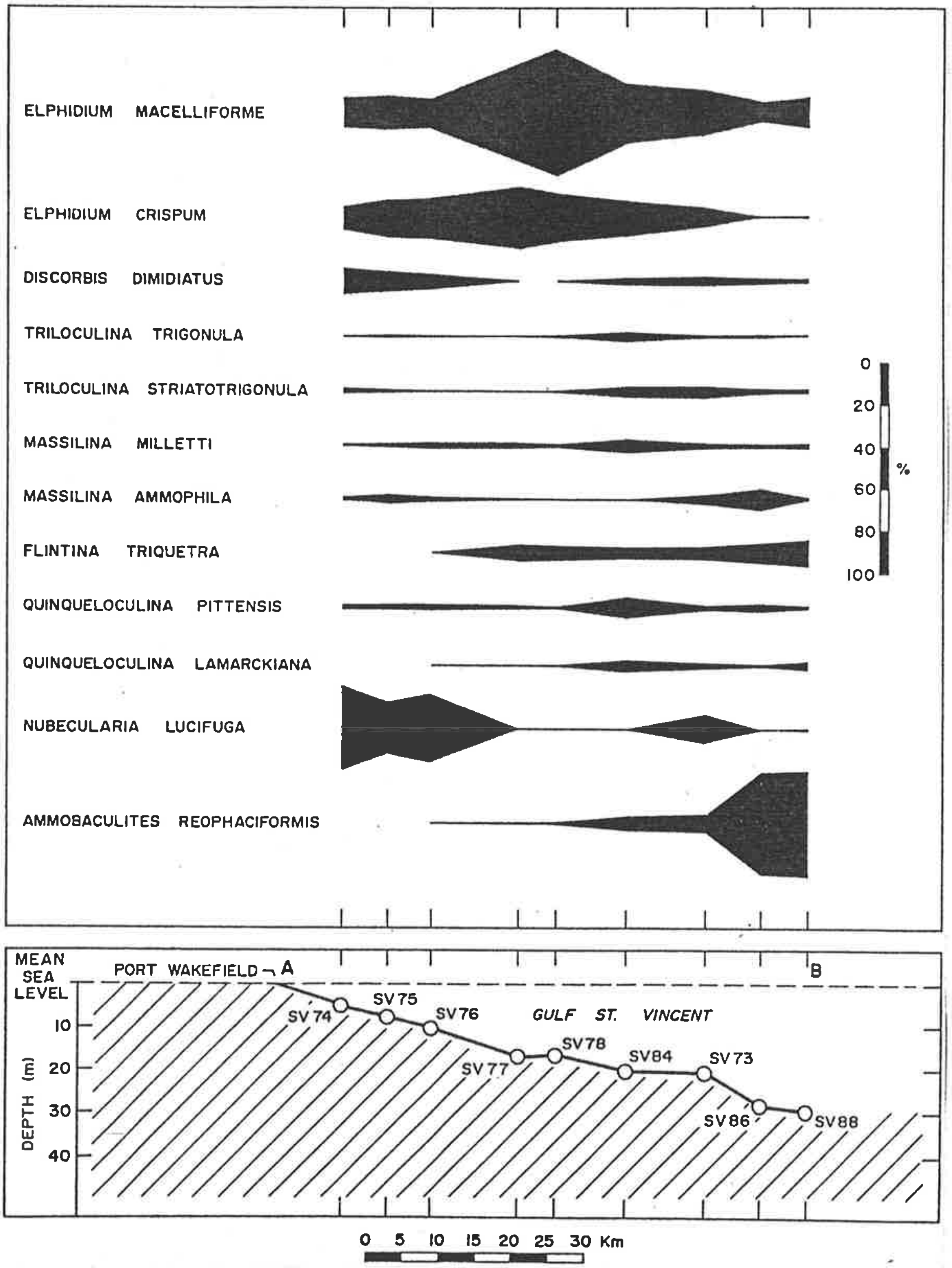


Fig 8.4

Percentage distribution of selected species of foraminifera in surficial sediment compared with water depth along a transect south from Port Wakefield, Gulf St Vincent. Sample sites are indicated in Fig 8.1. Grain size fraction 0.50 - 0.25mm.

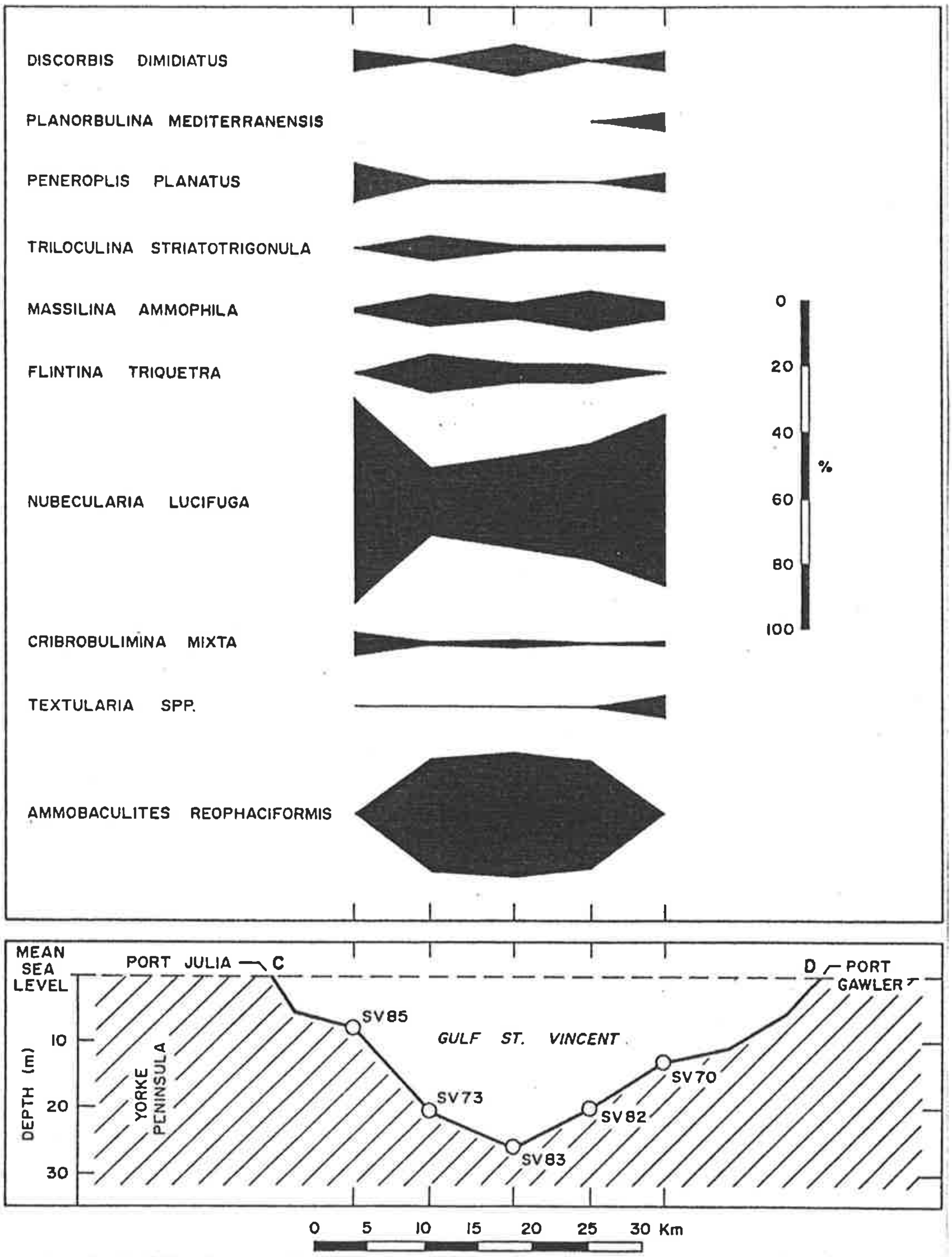


Fig 8.5
Percentage distribution of selected species of foraminifera in surficial sediment compared with water depth along a west-east transect in line with Port Julia and Port Gawler, Gulf St Vincent. Sample sites are indicated in Fig 8.1. Grain size fraction 1.00 - 0.50mm.

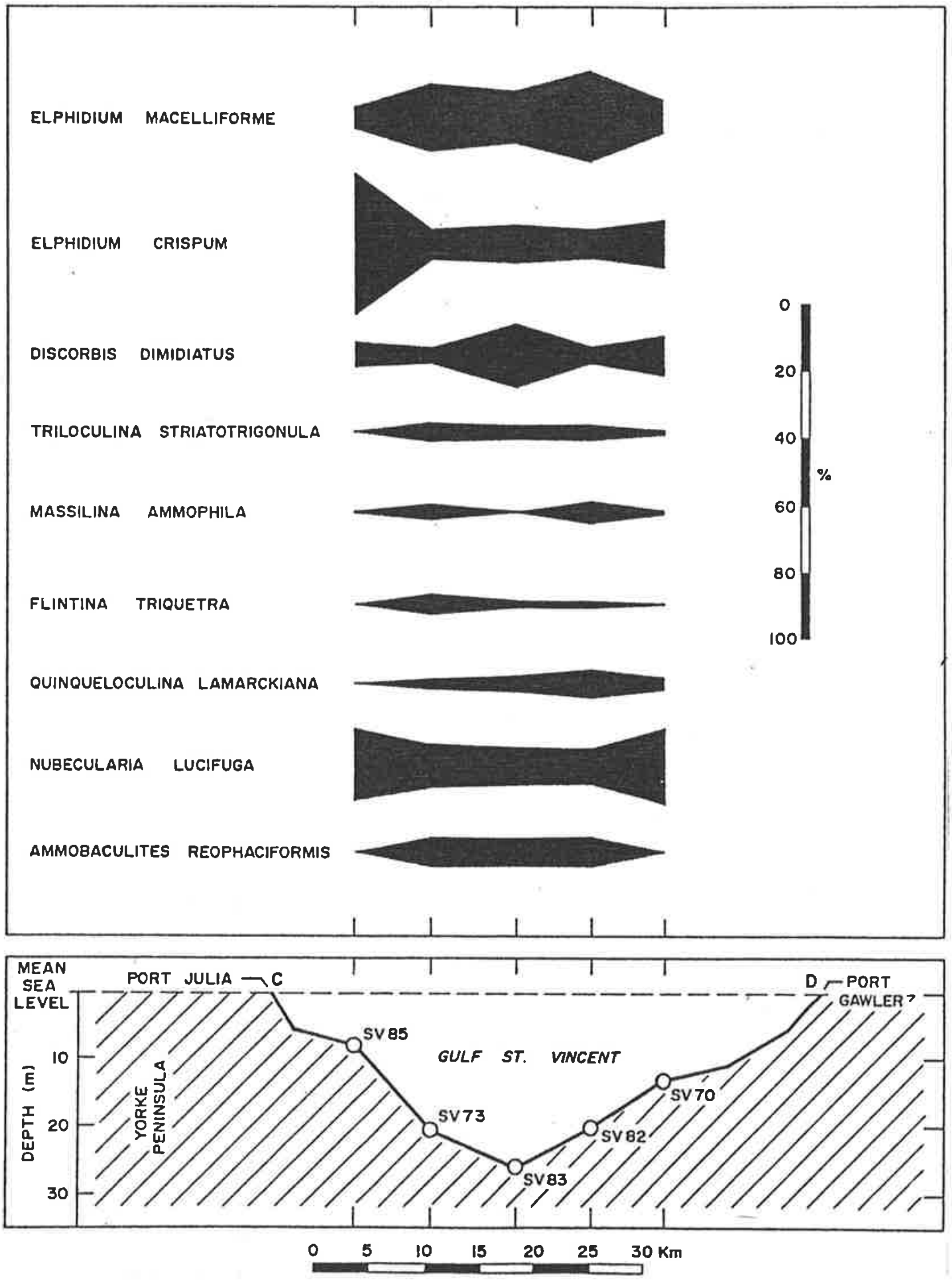


Fig 8.6
Percentage distribution of selected species of foraminifera in surficial sediment compared with water depth along a west-east transect in line with Port Julia and Port Gawler, Gulf St Vincent. Sample sites are indicated in Fig 8.1. Grain size fraction 0.50 - 0.25mm.

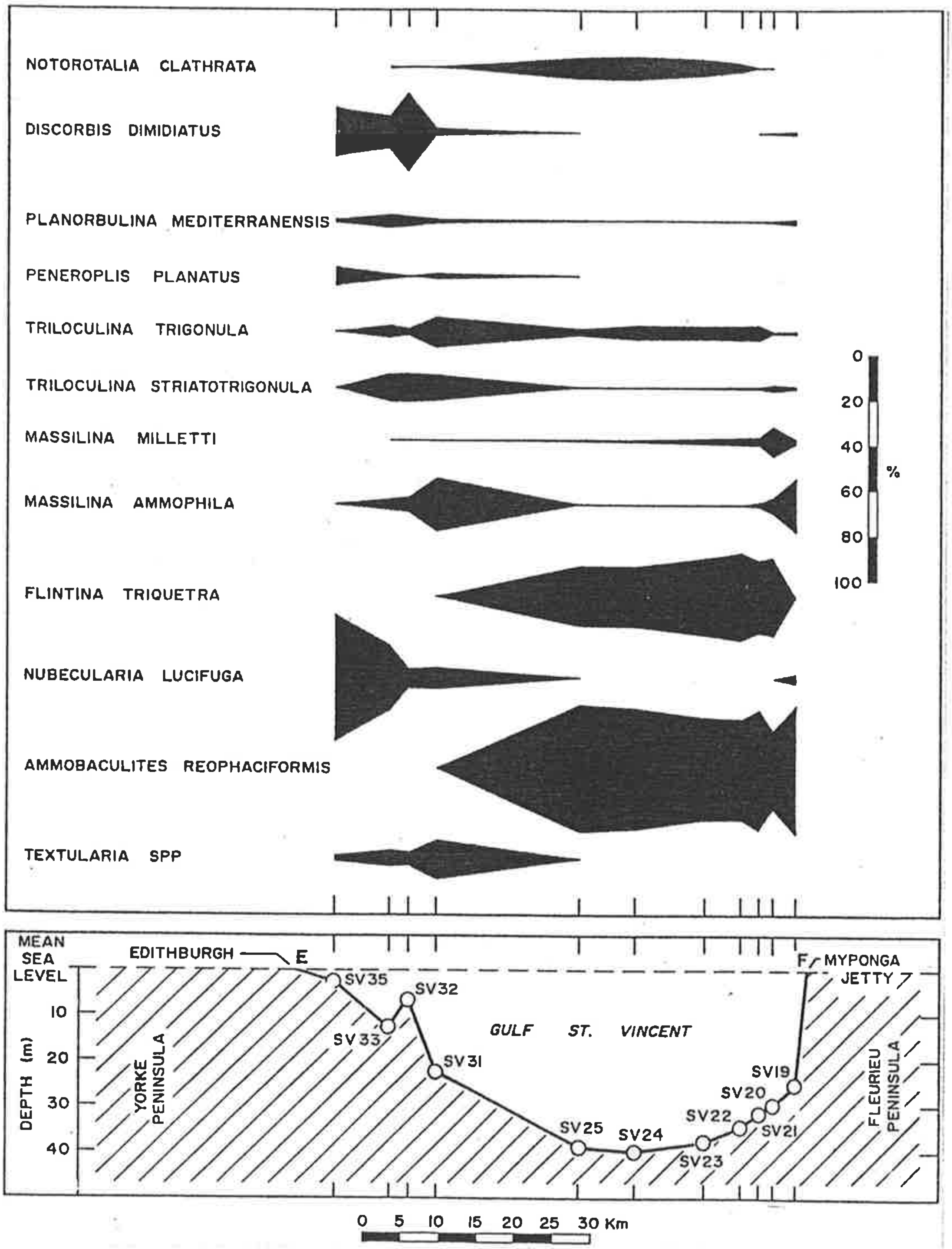


Fig 8.7
Percentage distribution of selected species of foraminifera in surficial sediment compared with water depth along a northwest-southeast transect from Edithburgh to Myponga Jetty, Gulf St Vincent. Sample sites are indicated in Fig 8.1. Grain size fraction 1.00 - 0.50mm.

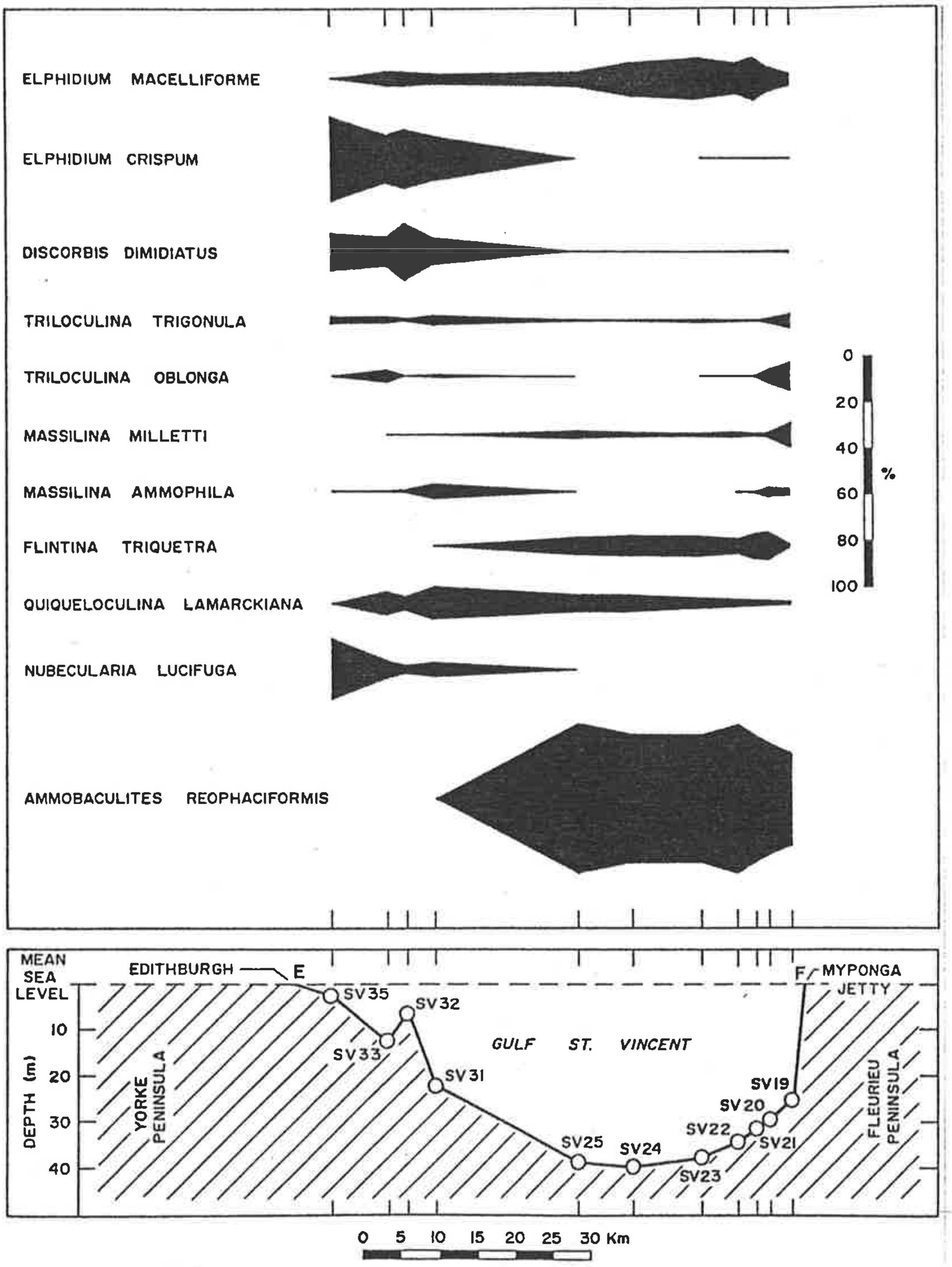


Fig 8.8
Percentage distribution of selected species of foraminifera in surficial sediment compared with water depth along a northwest-southeast transect from Edithburgh to Myponga Jetty, Gulf St Vincent. Sample sites are indicated in Fig 8.1. Grain size fraction 0.50 - 0.25mm.

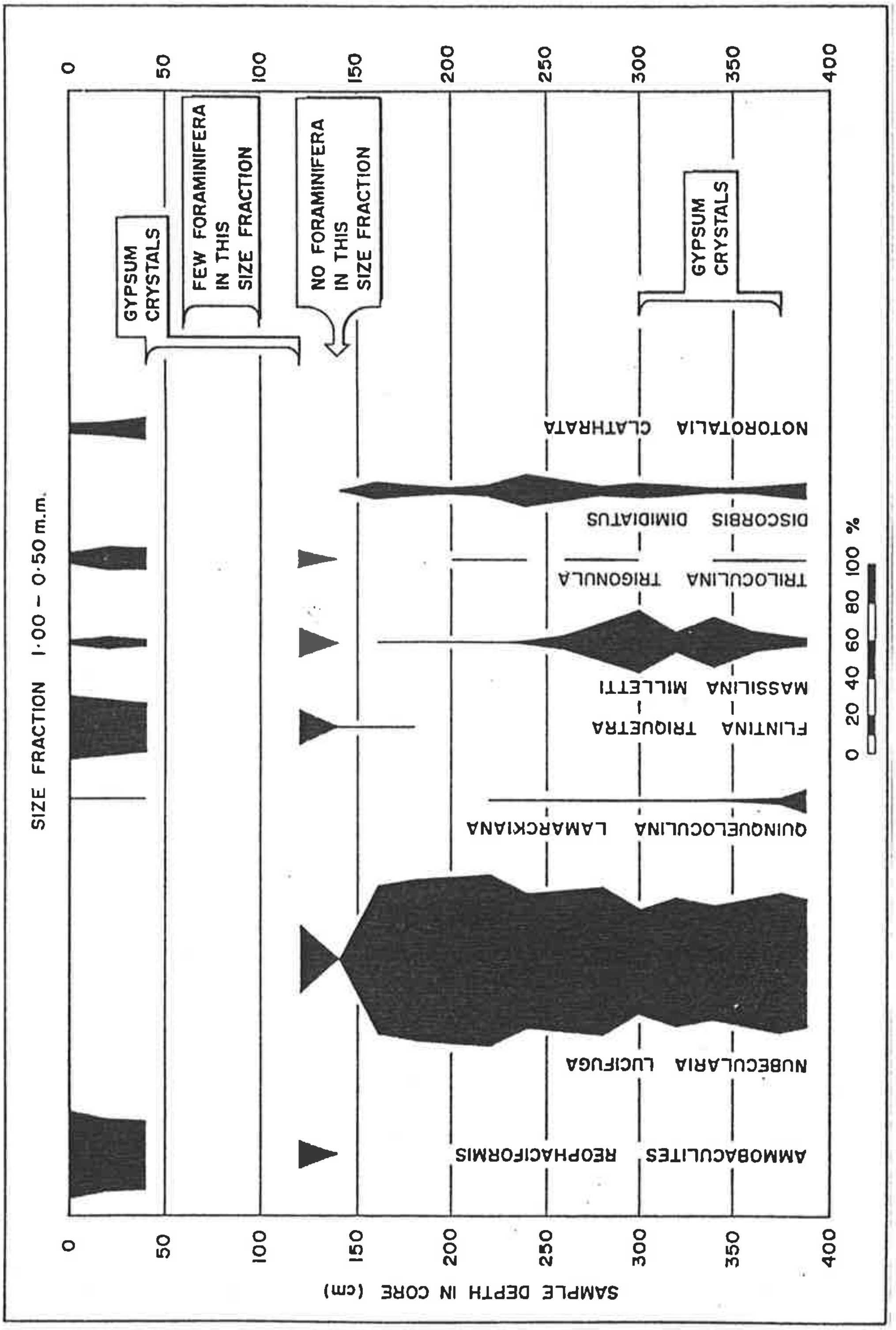


Fig 8.9
Percentage distributions of selected species of foraminifera within vibrocore #SV23 from Gulf St Vincent (Fig 8.1). The Pleistocene/Holocene boundary is lithologically indicated at a core depth of 150 cm. Grain size fraction 1.00 - 0.50mm.

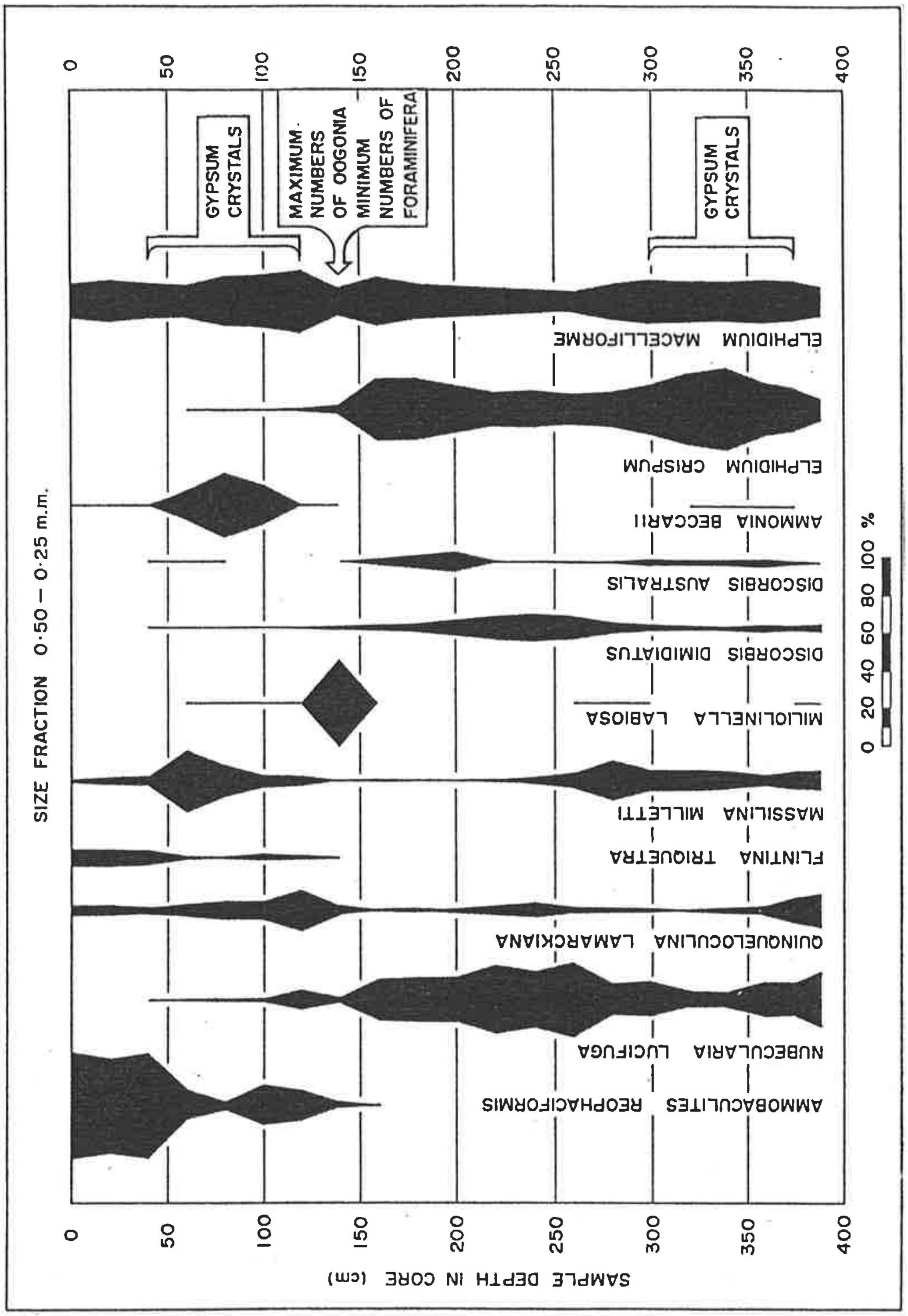


Fig 8.10
Percentage distributions of selected species of foraminifera within vibrocore #SV23 from Gulf St Vincent (Fig 8.1). The Pleistocene/Holocene boundary is lithologically indicated at a core depth of 150 cm. Grain size fraction 0.50 - 0.25mm.

DISCUSSION

Validity of radiocarbon data

The 45,000 to 30,000yr B.P. age range for the late Pleistocene sediments of vibrocores SV4 and SV5 (Cann et al., 1988; Chapter 7) was determined by both radiocarbon and amino acid racemisation dating procedures. The corroborative nature of the data so obtained generated great confidence in the reality of the ages. The similar distribution of radiocarbon dates in SV23, together with their down core coherence within the late Pleistocene interval, attest to the credibility of the interpreted ages.

The cluster of radiocarbon dates for the lagoon sequence 130 to 30cm in core SV23 indicates that early Holocene coastal palaeoenvironments changed quickly in response to rising sea levels. This interval of the core corresponds to initial maritime flooding of the study site by a rapidly transgressing Holocene sea 9500 to 9300yr B.P.

Foraminifera in modern sediments

Figures 8.3 to 8.8 show a clear relationship between percentage abundance of foraminifera species in surficial sediment and water depth at the sites of collection. The more obvious correlations have been previously highlighted in earlier chapters, and in Cann and Murray-Wallace (1986), Cann et al. (1988) and Gostin et al. (1988). For example, *Discorbis dimidiatus* reaches maximum numbers in the seagrass banks around a water depth of 10 to 15m. *Ammobaculites reophaciformis* is more characteristic of deeper waters, favouring depths of 30 to 35m. *Nubecularia lucifuga* is shown by these data to be a species having a strong preference for shallow subtidal environments, its numbers decreasing markedly with increasing water depth.

Elphidium crispum is most abundant in shallow subtidal environments while *E. macelliforme* is more common in deeper waters. These distributions are most obviously apparent in Fig 8.8. Numerical relationships between the relative abundance of these two species of *Elphidium* and water depth for South Australian gulfs has been the subject of considerable discussion in earlier chapters. In Chapter 7 it was shown that, for Gulf St Vincent, the ratio was consistently <0.1 in water shallower than 10m, but increased to values >30 for deeper parts of the gulf (Cann et al., 1988). Regression analysis of water depth versus logarithm of the *Elphidium* ratio indicated a simple linear relationship with a correlation coefficient of 0.95. For Spencer Gulf, similarly prepared data derived a comparable relationship, but with a reduced correlation coefficient of 0.80 (Chapter 4).

The work reported in this chapter provided much additional data on the relationship between water depth and the *Elphidium* ratio. Fig 8.11 shows the log-linear plot of water depth versus the ratio of numbers of individuals of *E. macelliforme* to those of *E. crispum* for Gulf St Vincent, based on all the findings reported in this and earlier chapters. The correlation coefficient of 0.86 confirms that the *Elphidium* ratio remains a powerful tool for investigation of immediately past sea levels. However, separate examination of data from the northern gulf (= north of and including the C-D transect of Fig 8.1) and those of the southern gulf (= south of the C-D transect of Fig 8.1) shows that correlation values are greatest in deeper gulf waters (Fig 8.12; R = 0.89) and less for shallow water environments (Fig 8.13; R = 0.64). Thus, for shallow water environments, the Spencer Gulf regression equation (Cann et al., 1988; Chapter 4), with its higher correlation coefficient (R = 0.80) remains the preferred basis on which to calculate shallow palaeo water depths for core sediment samples. The presence of large numbers of the species *Nubecularia lucifuga* in a sample would be adequate evidence of shallow water sedimentation.

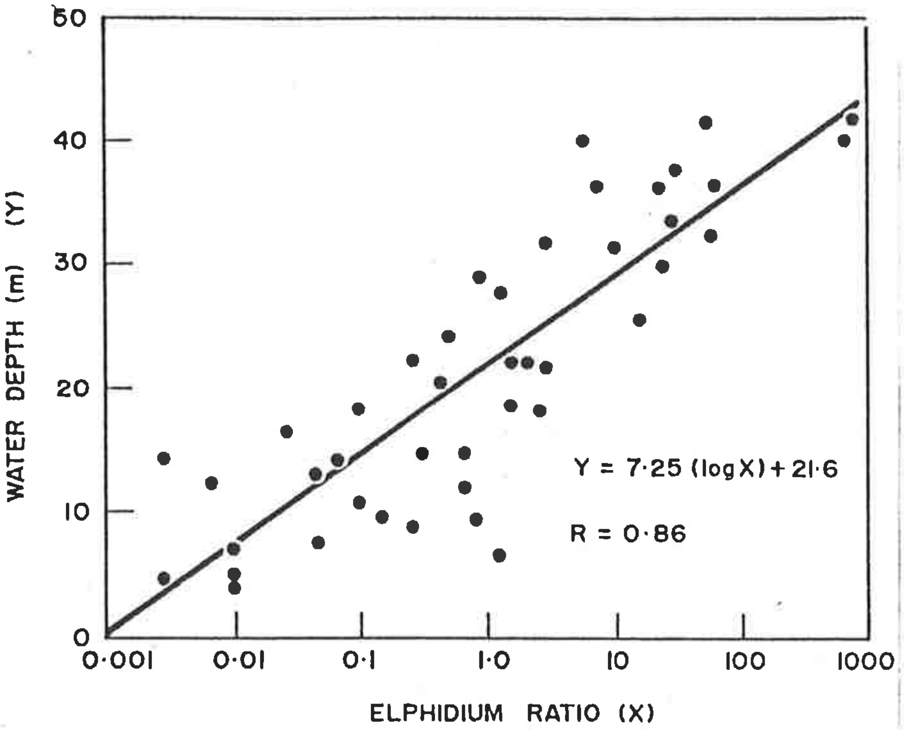


Fig 8.11
Log-linear plot of water depth versus ratio of numbers of individuals of *Elphidium macelliforme* to numbers of *Elphidium crispum* for all surficial samples from Gulf St Vincent. Data includes that of Cann et al. (1988) reported in Chapter 7. Also shown is the line of best least-squares fit, the calculated regression equation, and Pearson's correlation coefficient for the data set.

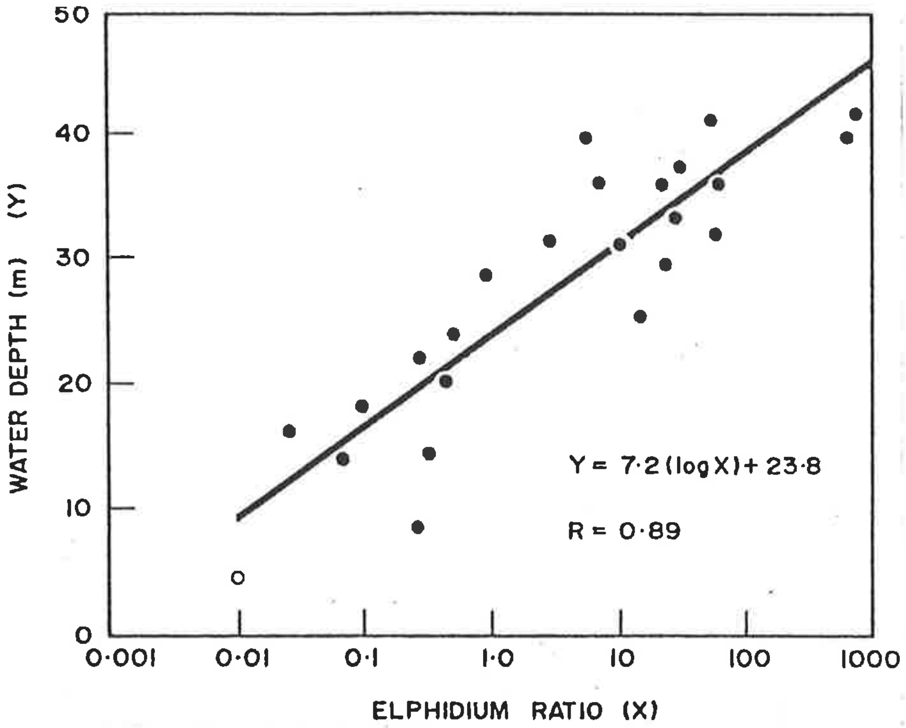


Fig 8.12
Log-linear plot of water depth versus ratio of numbers of individuals of *Elphidium macelliforme* to numbers of *Elphidium crispum* for surficial samples from all sites south of the transect C-D (Fig 8.1), Gulf St Vincent. Data includes that of Cann et al. (1988) reported in Chapter 7. Also shown is the line of best least-squares fit, the calculated regression equation, and Pearson's correlation coefficient for the data set.

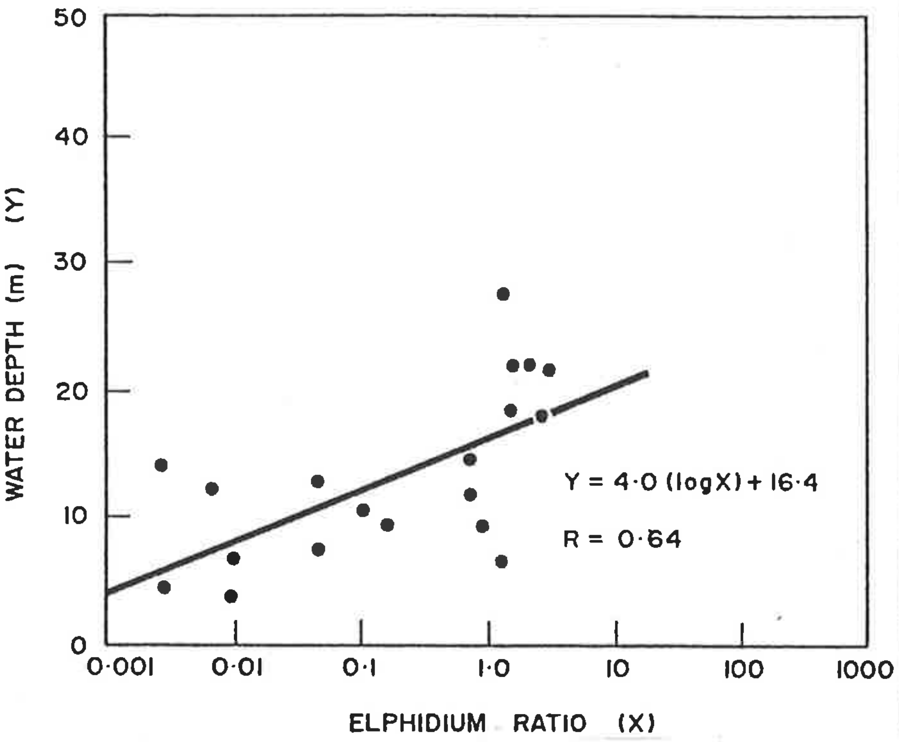


Fig 8.13
Log-linear plot of water depth versus ratio of numbers of individuals of *Elphidium macelliforme* to numbers of *Elphidium crispum* for surficial samples from all sites along and north of the transect C-D (Fig 8.1), Gulf St Vincent. Data includes that of Cann et al. (1988) reported in Chapter 7. Also shown is the line of best least-squares fit, the calculated regression equation, and Pearson's correlation coefficient for the data set.

The more variable distribution of the two *Elphidium* species in shallower waters may reflect, in part, a physical mixing of sediment under high wave energy conditions. However, it is the northern shallow waters of the gulf that are most prone to seasonal variation of temperature and salinity and it is likely that these are more significant factors.

Foraminifera in vibrocore SV23

Down core percentage distributions of foraminifera species in vibrocore SV23 (Figs 8.9 and 8.10) have palaeoenvironmental significance. For the Pleistocene section of the core, below 150cm, successive changes in water depth for site SV23 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 down core sampling interval which, for SV23, was 20cm.

The most obvious feature of Fig 8.9 is the dominance of *Nubecularia lucifuga* (size fraction 1.00 - 0.50mm) in the Pleistocene interval, generally suggesting that sedimentation occurred in water perhaps as shallow as 10m. However, over the interval 340 to 280cm, core samples yielded an average of only 72 individuals for this size fraction, so data for this section must be assessed with caution. The remainder of the Pleistocene interval is statistically significant for the coarser size fraction. Thus, for example, the slight peak of *Discorbis dimidiatus* at 240cm, with accompanying reduced numbers of *Massilina milletti*, may be inferred as a water shallowing event.

Information presented in Fig 8.10 is based on counts of >200 individuals for all samples except at 140cm where a total of only 39 tests were recovered. The Pleistocene data may therefore be interpreted with reasonable confidence. Thus, sea level maxima are indicated at the base of core and at 280cm by peaks of *Massilina milletti*, and sea level minima at 340cm and towards the top of the Pleistocene interval by large numbers of *Elphidium crispum.*

Lower sea level can be inferred by peaks of *Nubecularia lucifuga* and *Discorbis dimidiatus* at 260 to 240cm.

These interpretations are largely supported by the palaeo water depths implied by the numerical ratios of numbers of individuals of *Elphidium macelliforme* to those of *E. crispum* in the Pleistocene section of SV23 (Fig 8.14). As shown in Fig 8.14, larger ratios correspond to deeper water (Figs 8.11 to 8.13) while smaller ratios indicate lesser depths. Thus Fig 8.14 can be regarded as a *de facto* sea level curve for site SV23.

At 140cm there are very few foraminifera; only 39 individuals were recovered from this interval. However, nearly half of these were *Miliolinella labiosa*, a species which successfully inhabits broad intertidal sand flats (Cann and Gostin, 1985; Chapter 3). Thus a marginal marine environment is implied. Other evidence, discussed below, suggests that a strong lacustrine influence was prevalent at the time of deposition of these sediments.

Between 100 and 60cm *Ammonia beccarii* occurs in large numbers, constituting approximately 35% of the 0.50 - 0.25mm size fraction at 80cm. This species has an extreme tolerance to salinity variability. Locally, in summer months, *A. beccarii* thrives in the upper reaches of the Onkaparinga Estuary, south of Adelaide. Apthorpe (1980) records the species from estuarine lakes in Victoria, while Cann and De Deckker (1981) showed it to be a significant species, both living and fossil, in some saline lake faunas. Clearly, its abundance through the Holocene interval 100 to 60cm implies an environment in which salinity was at variance from that of normal marine conditions. The presence of small euhedral gypsum crystals in this section of the core suggests that hypersaline conditions may have prevailed in a restricted, marginal marine setting.

Following the onset of the Holocene transgression at site SV23, the hypersaline conditions indicated by *A. beccarii* and gypsum crystals gave way to deeper, less restricted waters, as shown by the peak of *M. milletti* at 60cm.

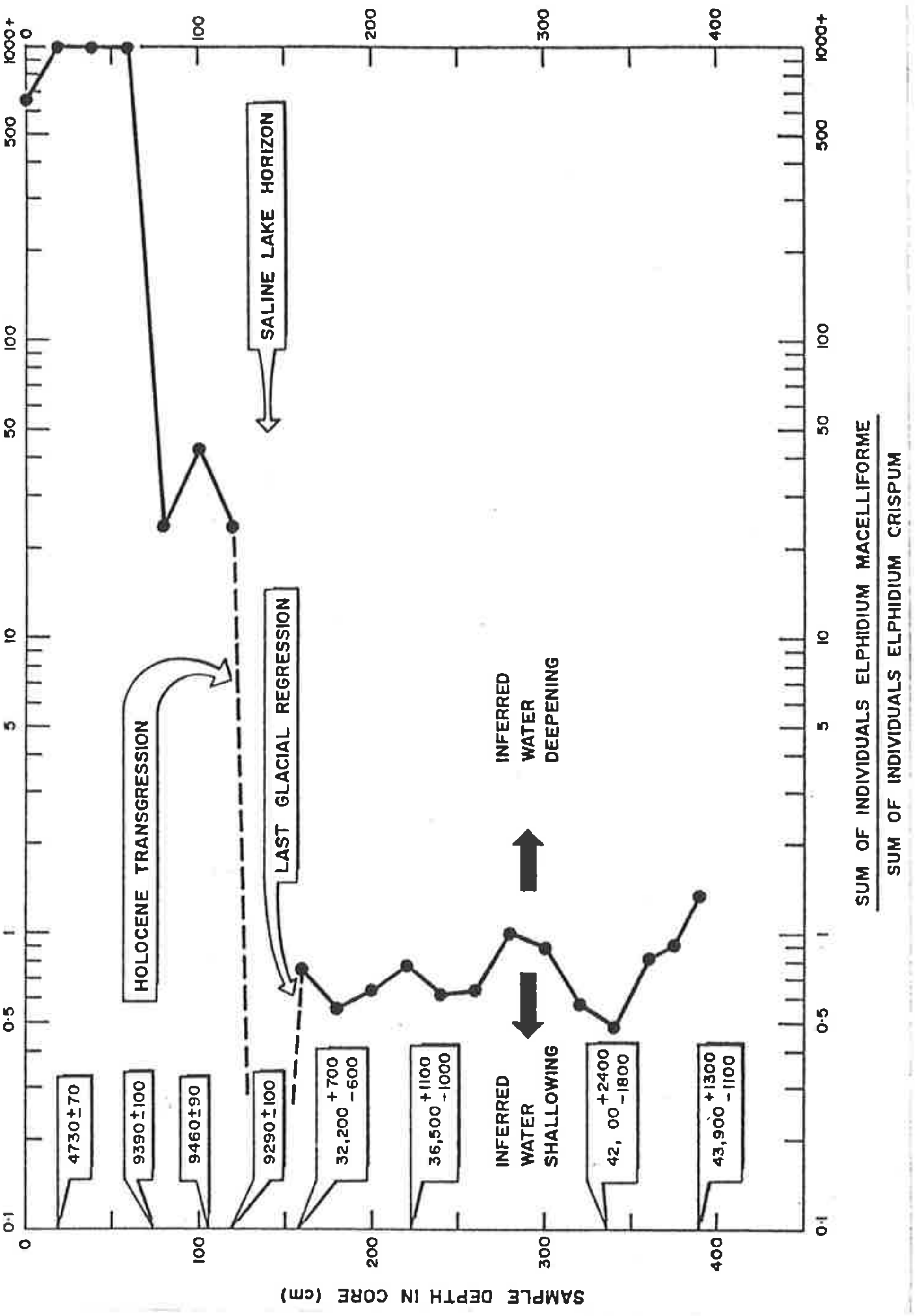


Fig 8.14
Log-linear plot of sample depth in core versus ratio of numbers of individuals of *Elphidium macelliforme* to numbers of individuals of *Elphidium crispum* for samples from vibrocore #SV23. Larger values infer deeper water and, conversely, smaller values infer shallower water at the time of deposition. Palaeontological and lithological evidence together indicate the Pleistocene/Holocene boundary at 150cm. Also shown are ^{14}C dates of samples taken from the horizons indicated.

As Holocene waters deepened in Gulf St Vincent, large populations of *Ammobaculites reophaciformis*, *Flintina triquetra* and *Elphidium macelliforme* were established. Conversely, species that were dominant in the shallow waters of the late Pleistocene, *Nubecularia lucifuga*, *Discorbis dimidiatus* and *Elphidium crispum*, were unable to survive in the deeper gulf waters at site SV23 as Holocene waters reached their peak, and they are thus absent from the uppermost 50cm of the core.

The lacustrine horizon in vibrocore SV23

As detailed above, the foraminiferal record in vibrocore SV23 (Figs 8.9, 8.10 and 8.14) clearly differentiates late Pleistocene sediments below 160cm from those of Holocene age above 120cm. Lithological evidence places this boundary at 150cm.

Microscopic examination of the 140cm sample revealed low numbers of foraminifera, but abundant smooth, fragile ostracod valves and significant numbers of well preserved oogonia. *Cyprideis australienensis*, *Leptocythere lacustris* and *Diacypris* sp. were all significant members of this faunal assemblage, and together they constitute unequivocal evidence of a lacustrine environment in which salinity was probably less than that of normal sea water (De Deckker, personal communication). The oogonia confirm that the depositional environment was certainly not holomarine (Burne et al., 1980). As indicated earlier, oogonia are the calcified female reproductive organs of a unique group of salt tolerant aquatic plants called charophytes (Womersley, 1984). The sizes of oogonia are such that they occur in both grain size fractions used in this study. This saline lake facies occupies the interval 150 to 130cm in core SV23 (Figs 8.2, 8.12 and 8.14).

An association of oogonia and gypsum crystals from two localities marginal to northern, semi-arid Spencer Gulf, reported by Burne et al. (1980) are significant for the lower Holocene interval of vibrocore SV23. These authors concluded that such an association indicates that deposition occurred in a saline lake.

Such lakes typically contain brines derived from groundwaters of either wholly or partly non-marine origin, and are seasonally brackish or fresh.

The results of the microscopic studies reported here suggest that sediment at 140cm in vibrocore SV23 was deposited in a saline lake. The absence of gypsum crystals at this horizon shows that discharge of saline groundwaters was not a significant factor at that time, but equally, the abundance of the mineral up core indicates a converse situation. The gypsum bearing lithologies above the saline lake facies, and their age sequence, indicates an increasingly marine influence. Clearly, the section of vibrocore SV23 between 160 and 120cm warrants much closer examination if the changes in palaeoenvironments suggested here are to be more comprehensively understood. A further, more detailed investigation of the foraminifera, ostracods and geochemistry of this interval has been initiated with co-researcher Dr Patrick De Deckker.

Absolute sea level history

The late Quaternary shoreline of South Australia has been subjected to only minor changes due to elevation or subsidence (Veeh et al., 1979; Hails et al., 1984a; Belperio, 1985). Vibrocores SV4 and SV5 (Cann et al., 1988; Chapter 7) were taken at depths of 39.9 and 36.4m respectively, below present mean sea level. These cores recorded continuous marine inundation (that is, sea level higher than -36m) for the time interval 45,000 to 30,000yr B.P. and did not rise above this level until during the Holocene transgression about 9800yr B.P. (Belperio et al., 1983, 1987). Vibrocore SV23, taken from 40.0m below present mean sea level, provides a record of continuous marine sedimentation over a similar late Pleistocene time interval for that established for SV5 (Cann et al., 1988; Chapter 7).

As discussed in Chapter 1, coral reef terraces on the tectonically uplifted Huon Peninsula have yielded a series of radiometric dates which correspond to successive peaks of sea level (Bloom et al., 1974; Chappell and Veeh, 1978).

Most recently derived data by Chappell and Shackleton (1986) provide slightly refined estimates of dates and magnitudes of late Pleistocene palaeo sea levels for these terraces. Those shown in Table 8.2 have significance for Gulf St Vincent.

HUON REEF TERRACE	AGE (yr B.P.)	ESTIMATED PALAEO SEA LEVEL (m)
IIIA	45.000	-46
IIIB	40,000	-41+/-4
II	28,000	-44+/-2

Table 8.2
Estimated palaeo sea levels and ages of selected Huon Peninsula coral reef terraces (after Chappell and Shackleton, 1986).

Terraces IIIA, IIIB and II are shoreline correlatives of the strata recovered in vibrocores SV4, SV5 and SV23. Data yielded by these cores clearly indicate sea levels higher than those derived for the equivalent Huon Peninsula reefs.

Qualitative changes of sea level, interpreted as *de facto* sea level curves from *E. macelliforme*/*E. crispum* ratios within vibrocores SV4 and SV5, were calculated by Cann et al. (1988) (Chapter 7). These data for the late Pleistocene sections of the cores positively correlate with the record obtained for vibrocore SV23 (Figs 8.14 and 8.15). The *Elphidium* ratios and radiocarbon dates strongly suggest that vibrocores SV5 and SV23 record the same signal of sea level changes. The combined signals of SV4 and SV5 agree with the pattern and ages of sea level peaks established by Chappell (1983) and Chappell and Shackleton (1986) for the Huon Peninsula (Cann et al., 1988; Chapter 7). Similarly, the signal of vibrocore SV23 may be matched with the appropriate interval of the Huon Peninsula curve (Figs 8.16a and b).

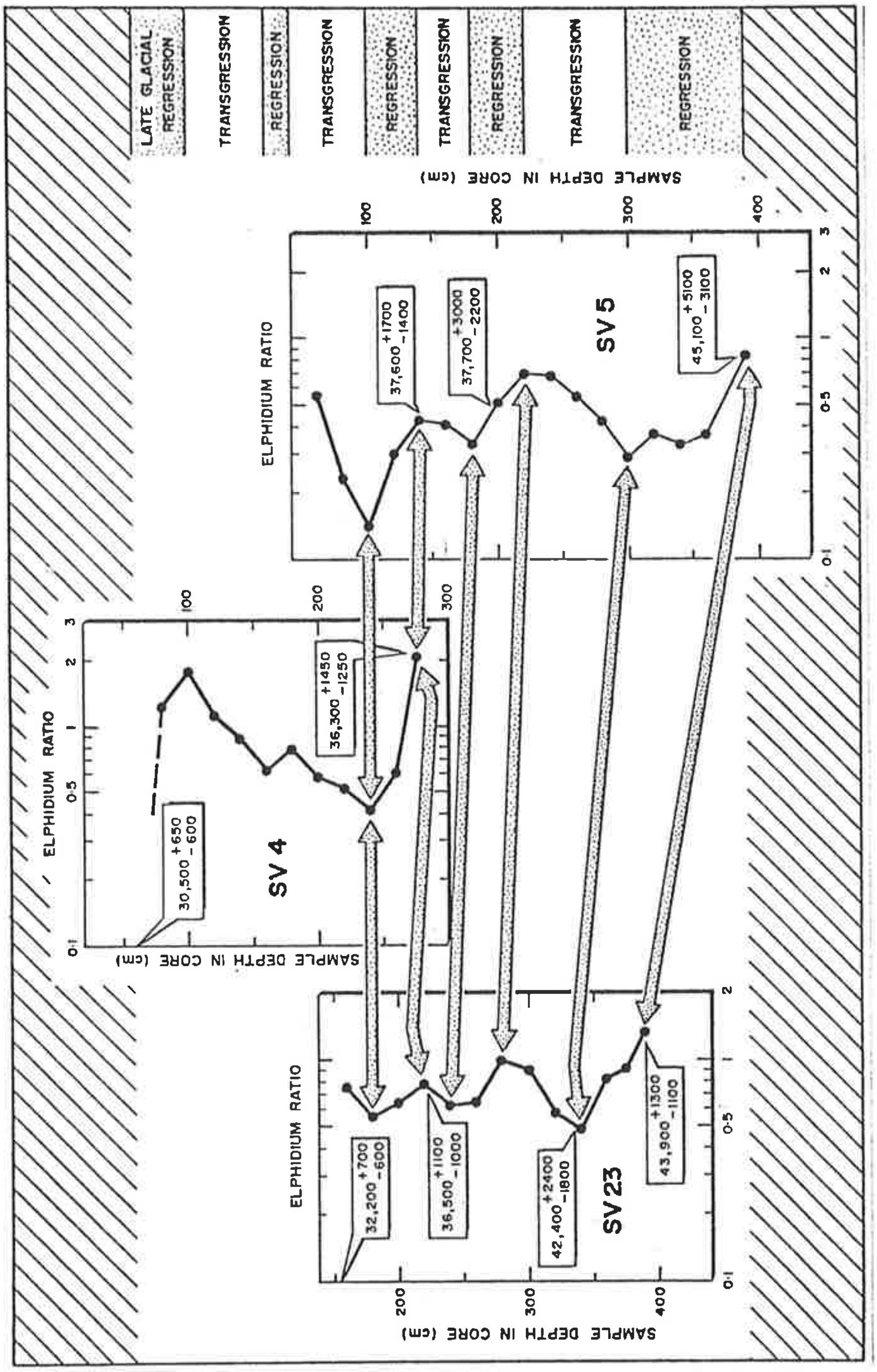


Fig 8.15

Elphidium species ratio curve derived from the late Pleistocene interval of vibrocore #SV23, left, correlated with similar intervals of vibrocores #SV4, centre, and #SV5, right. Correlation has been effected on the shapes of the curves within the constraints of the ^{14}C dates which are also shown. Inferred relative sea level fluctuations are indicated as regressions and transgressions.

The use of these *Elphidium* curves to derive quantitative changes in sea level remains subject to palaeoenvironmental considerations of the gulfs. The large numbers of *Nubecularia lucifuga* throughout the Pleistocene section of vibrocore SV23 show that palaeo water depths for that site were relatively shallow throughout the time of deposition.

Thus, the regression equation for shallow water environments of northern Gulf St Vincent (Fig 8.13) or that for Spencer Gulf (Cann et al., 1988; Chapter 4) are clearly more appropriate than the equations based on data from the deeper and cooler waters of southern Gulf St Vincent (Figs 8.11 and 8.12; Cann et al., 1988; Chapter 7). As indicated earlier, the Spencer Gulf regression equation, with its higher correlation coefficient ($R = 0.80$) therefore remains the preferred basis on which to calculate palaeo water depths for SV23. That is,

$$Y = 6.72 \log (X) + 15.84$$

where Y is water depth in metres and X is the ratio of the numbers of individuals of *Elphidium macelliforme* to the numbers of individuals of *Elphidium crispum*.

Palaeo sea levels relative to those of the present may be determined for a core sample by subtracting the calculated water depth (using the regression equation) from the sum of the present depth at site SV23 (40m) and the sample depth in core (Table 8.3 and Fig 8.16c).

Under the constraints of the radiocarbon dates at 336cm and 223 cm in vibrocore SV23, the calculated relative palaeo sea level of -27m for sediment at 280cm may be inferred to correlate with terrace IIIb of Huon Peninsula. Similarly, the lowest relative sea level of 29.6m determined for SV23 (at 340cm) corresponds to the regression between the formation of terraces IIIa and IIIb. This palaeo sea level rise of about 3m is essentially the same as that proposed by Cann et al. (1988) (Chapter 7) for the equivalent part of the curve derived from vibrocore SV5. In absolute terms, the SV5 palaeo sea levels were calculated to be about 3m higher than those calculated from SV23.

Sample depth (d) in core SV23 (m)	*Elphidium* ratio (x)	Palaeo water depth (y)	Palaeo sea level relative to present
	[y = 6.72 log (x) + 15.84]		[= 40 + d - y]
1.6	0.78	15.1+/-1.2	-26.5+/-1.2
1.8	0.57	14.2+/-1.2	-27.6+/-1.2
2.0	0.66	14.6+/-1.2	-27.4+/-1.2
2.2	0.79	15.2+/-1.2	-27.1+/-1.2
2.4	0.64	14.5+/-1.2	-27.9+/-1.2
2.6	0.65	14.6+/-1.2	-28.0+/-1.2
2.8	1.0	15.8+/-1.3	-27.0+/-1.3
3.0	0.89	15.5+/-1.3	-27.5+/-1.3
3.2	0.58	14.3+/-1.2	-29.0+/-1.2
3.4	0.49	13.8+/-1.2	-29.6+/-1.2
3.6	0.83	15.3+/-1.3	-28.3+/-1.3
3.75	0.93	15.6+/-1.3	-28.1+/-1.3
3.89	1.34	16.7+/-1.4	-27.2+/-1.4

Table 8.3

Calculated palaeo water depths and palaeo sea levels determined for core samples from vibrocore #SV23 using the *Elphidium* ratio values and the regression equation calculated from northern Spencer Gulf data (Chapter 4). Error values have been determined within the 95% confidence envelope.

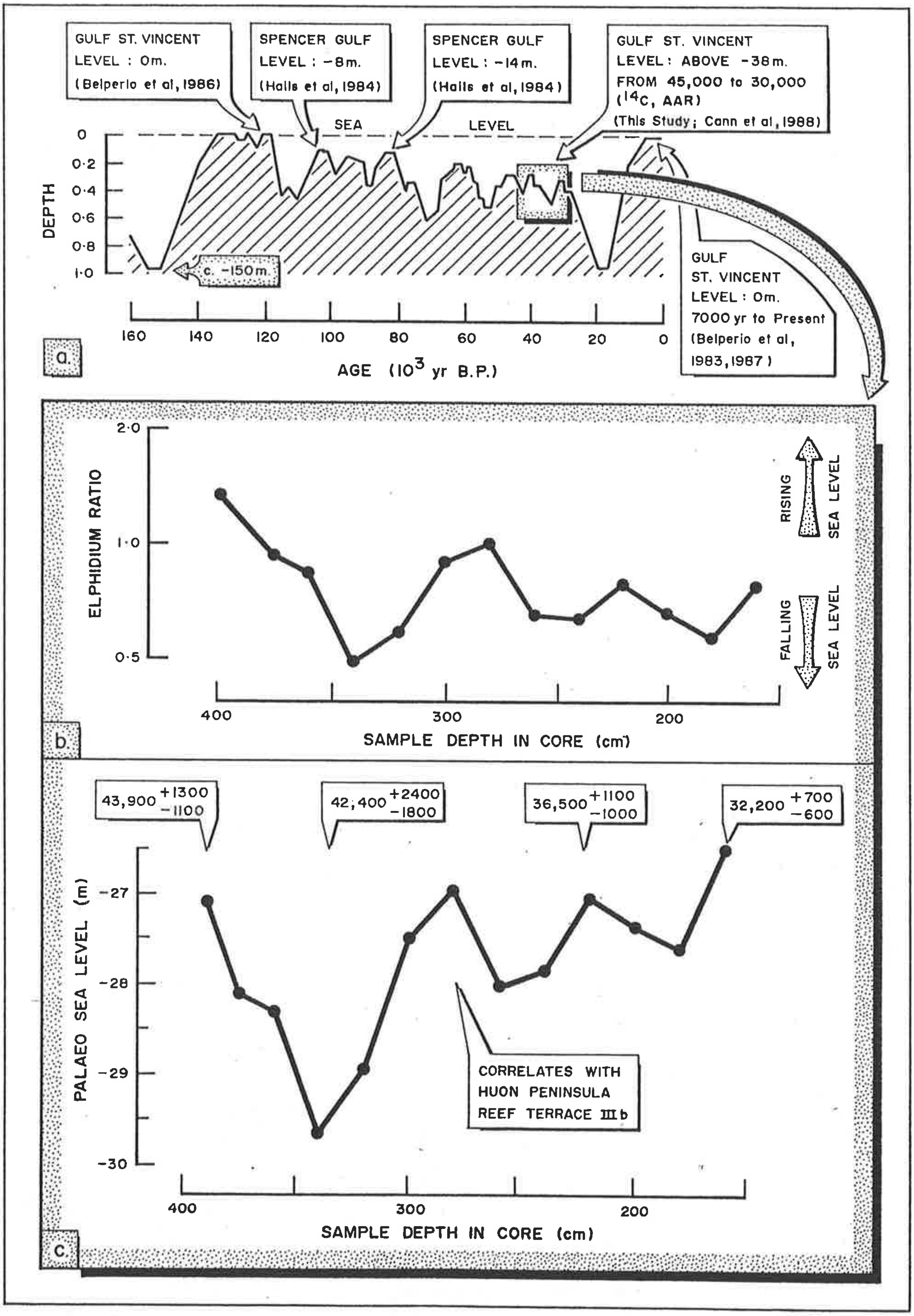

GULF ST. VINCENT
LEVEL : 0m.
(Belperio et al, 1986)
SPENCER GULF
LEVEL : −8m.
(Hails et al, 1984)
SPENCER GULF
LEVEL : −14m.
(Hails et al, 1984)
GULF ST. VINCENT
LEVEL: ABOVE −38m.
FROM 45,000 to 30,000
(14C, AAR)
(This Study; Cann et al, 1988)
SEA LEVEL
DEPTH
0
0·2
0·4
0·6
0·8
1·0
c. −150m.
160 140 120 100 80 60 40 20 0
AGE (10³ yr B.P.)
a.
GULF
ST. VINCENT
LEVEL : 0m.
7000 yr to Present
(Belperio et al,
1983, 1987)
ELPHIDIUM RATIO
2·0
1·0
0·5
RISING SEA LEVEL
FALLING SEA LEVEL
400 300 200
SAMPLE DEPTH IN CORE (cm)
b.
43,900 +1300 −1100
42,400 +2400 −1800
36,500 +1100 −1000
32,200 +700 −600
PALAEO SEA LEVEL (m)
−27
−28
−29
−30
CORRELATES WITH
HUON PENINSULA
REEF TERRACE IIIb
400 300 200
SAMPLE DEPTH IN CORE (cm)
c.

Fig 8.16

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 c.44,000-32,000yr B.P. interpreted from the *Elphidium* species ratio and ^{14}C data from vibrocore #SV23.

c. Late Pleistocene palaeo sea levels interpreted from the *Elphidium* species ratio and ^{14}C data from vibrocore #SV23, using the regression equation derived from northern Spencer Gulf data (Fig 4.5). Calculations are shown in Table 8.3. For the sake of clarity, error bars have not been included. Correlation with Huon Peninsula reef terrace IIIb is indicated.

CONCLUSIONS

Within Gulf St Vincent many species of foraminifera have consistently proved to be sensitive indicators of environments and water depths. Numerical distributions of species up core can be used to infer successive palaeoenvironments. The relative distribution of two species of *Elphidium*, *E. macelliforme* and *E. crispum* has provided a consistent record of late Quaternary sea levels. In vibrocores taken more than 40km from each other, late Pleistocene transgressions and regressions can be correlated within Gulf St Vincent. The pattern of these changes in palaeo sea levels matches that determined for the Huon Peninsula, but differs in absolute values.

Local palaeo sea level corresponding to Huon Peninsula transgression stage IIIb has been calculated from vibrocore SV23 to be -27m. This compares favourably with a previously calculated value of -24m for Gulf St Vincent from vibrocore SV5 (Cann et al., 1988; Chapter 7). Both values are clearly much higher than refined estimates of about -40m based on the Huon Peninsula terrace (Chappell and Shackleton, 1986).

In lower Gulf St Vincent, during the last glacial regression, a saline lake occupied a broad shallow depression in the gulf floor. With the onset of the Holocene transgression, the lake was significantly influenced by saline ground waters and gypsum was precipitated. The encroaching sea initially established a hypersaline environment of restricted circulation. This rapidly gave way to deeper waters and gulf conditions more like those of today.

Addendum to Chapter 8

Some of the results in Chapter 8 are significantly different from well-known results in the literature, for sea-levels during the interval between about 30,000 and 45,000 years ago. The differences are significant because they may be interpreted to imply that there are substantial differentials in global sea levels changes between interstadial and interglacial periods.

The data reported in Chapter 8, and also in Chapter 7, refer to sediments recovered in vibrocores #SV4, #SV5 and #SV23 from the deepest parts of Gulf St Vincent, about 40 metres below Mean Sea Level. Fossil molluscs from the pre-Holocene intervals of these cores yielded radiocarbon dates in the range 45,000 to 30,000 years before present. These dates, which approach the normally accepted limits of radiocarbon age determination methods, were checked by Murray-Wallace using amino acid racemisation [AAR] dating procedures. His findings were totally corroborative, thus generating a high degree of confidence in the original radiocarbon dates. Fossils from vibrocore #SV23 [Chapter 8] yielded a similar set of radiocarbon dates to those obtained for SV4 and SV5, so reinforcing acceptance of the 45,000 to 30,000yr B.P. age determination.

Since preparation of the thesis, this matter has been the subject of rigorous review by Murray-Wallace *et al.* That work confirms the ages initially determined for these Gulf St Vincent sediments

Murray-Wallace, C.V., Belperio, A.P., Gostin, V.A. and Cann, J.H. (1993) Amino acid racemization and radiocarbon dating of interstadial marine strata (oxygen isotope stage 3), Gulf St Vincent, South Australia. *Marine Geology*, 110, 83-92.

Study of raised coral reef terraces on the Huon Peninsula by Chappell and others has led to a series of inferred palaeo sea levels, including estimates for the time interval under discussion here. These data are given in table 8.2. They show that sea level in the vicinity of Papua New Guinea, for the period 30,000-45,000yr B.P., was always more than 40 metres below present sea level. On the other hand, radiocarbon and AAR dating reveals that we have subtidal marine sediments, of that same age, within a gulf in which the sea floor is generally less than 40 metres below present sea level. Further, the author's calculations of water depths for the episode of deposition, based on fossil foraminifera within the vibrocores, yield plausible values for palaeo water depths of about 15 metres. There is, therefore, a disparity of conclusions, and herein lies the difference referred to above.

In the simplest analysis, it would appear that there are only three possible solutions to the apparent dilemma:

(a) When water is added to the global ocean budget from melting ice sheets, for a variety of reasons it is not uniformly distributed throughout the ocean basins. [Refer to "Earth response to deglaciation", pages 1.9 and 1.10]. However, it seems unlikely that either differential gravitational distribution of meltwaters, or localised isostatic responses to water loading, could account for the differences in palaeo sea level estimates.

(b) If the floor of Gulf St Vincent had been topographically about 15 metres lower than at present, during the time of sedimentation [45,000-30,000yr B.P.], and subsequently elevated to its present altitude, this could rationalize the apparent discrepancy. However, locally the last interglacial shoreline [125,000yr B.P.] coincides with that of the modern sea. Currently, best estimates place last interglacial sea level at +2 metres for southern Australia. Thus, for the time interval under discussion, the elevation of Gulf St Vincent was within a metre of its present position.

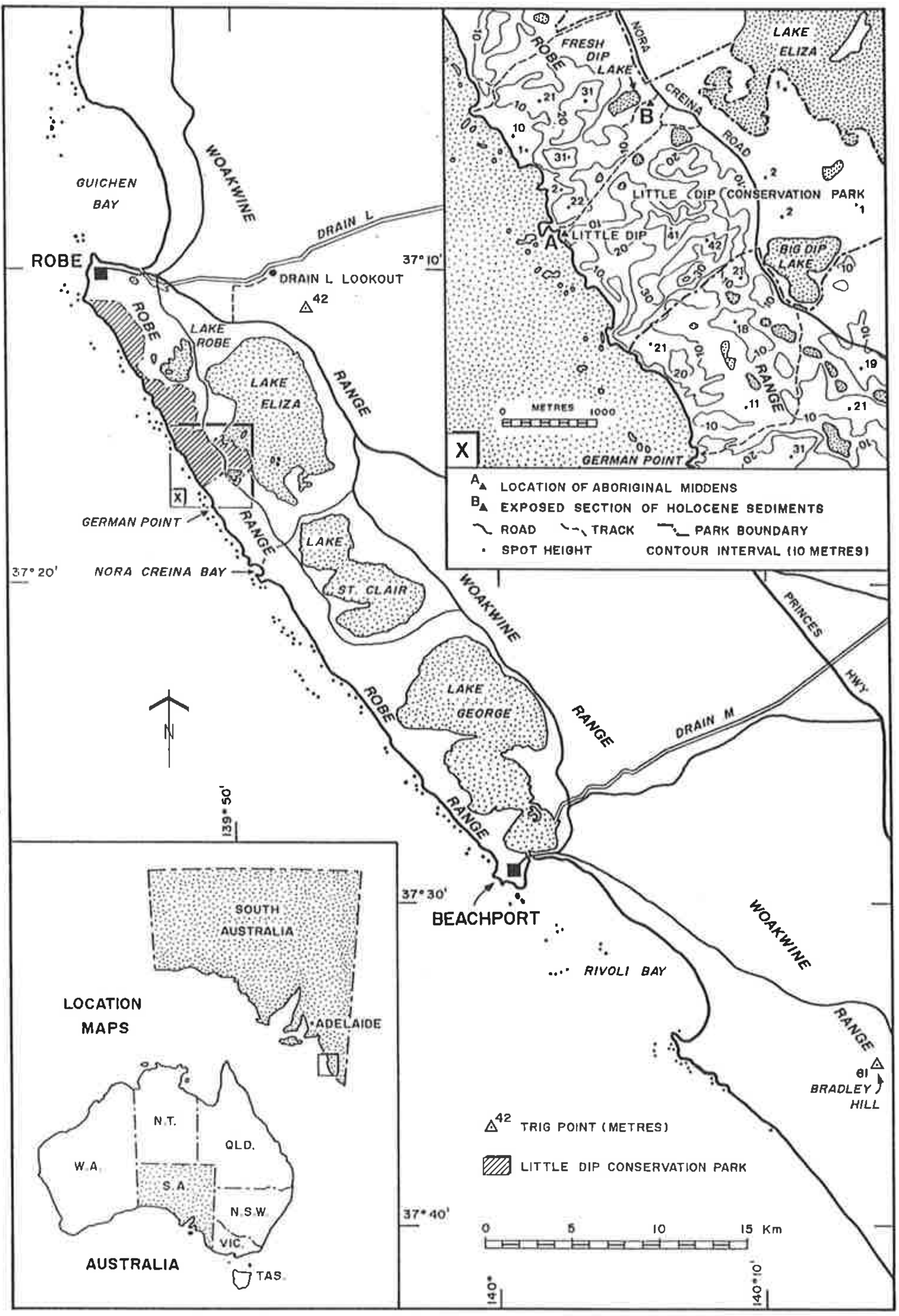


Fig 9.1

Map of study area and surrounding region indicating locations of sites and features referred to in the text.

Thus, the oldest sites of Aboriginal occupation along the coast are contemporary with the peak of Holocene sea level, and contain the remains of a molluscan fauna harvested from the inter-range lagoon. Younger sites contain shells of molluscs which favour a rocky open ocean shoreface.

The palaeoenvironmental significance of these midden materials has been evaluated within a timeframe of radiocarbon and amino acid racemisation dates, obtained by co-researchers Dr Patrick De Deckker and Dr Colin Murray-Wallace, from shells and charcoal collected by the present author (Cann et al., 1991) Some of this work has also been presented in Belperio and Cann (1990).

PREVIOUS INVESTIGATIONS

Aboriginal coastal occupation in southeastern South Australia

A mounting body of archaeological evidence suggests that Aboriginal populations were established in southern Australia between 40,000 and 30,000yr B.P. (for example, Allen, 1989; Cosgrove, 1989). From approximately 45,000 to 30,000yr B.P., in southern Australia, sea levels fluctuated between -30 and -22m (Cann et al., 1988; Chapters 7 and 8). During the last glaciation sea levels were some 130 to 150m below present mean sea level (Chappell, 1983; Chappell and Shackleton, 1986), while the ensuing transgression reached present sea level about 7000yr B.P. It has been calculated that Holocene sea levels rose as rapidly as 1.5 and 2.4cm/yr (Woodroffe et al., 1988; Belperio, in press). This rise in sea level and the associated environmental changes are likely to have significantly affected those Aboriginal populations, with hunter/gatherer economies, reliant on coastal resources. It has been argued by some that this most recent and extreme rise in sea level would have forced all populations on the now submerged continental shelf to retreat inland (Ross, 1985). It is clear that the earliest dates that can be expected for emergent sites of Aboriginal occupation in southeastern South Australia will approximate to the peak of the Holocene transgression.

The most comprehensive work detailing early Aboriginal sites in the south east is that of Luebbers (1978). The significance of this largely unpublished study can be gauged by the extent to which it has been cited by other researchers (for example, Pretty, et al., 1983; Ross, 1985; Head, 1986; Godfrey, 1988, 1989; Egloff et al., 1989). Luebbers (1978) established a chronology for Aboriginal occupation in the south east, identifying two discrete episodes of occupation which he termed "Early Horizon" and "Late Horizon". The term "horizon", in this context, is used in a time-cultural sense rather than in reference to the physical materials of the sites.

Aboriginal middens of the Early Horizon occur in terra rosa soils developed on exposed surfaces of late Pleistocene beach/dune barriers, such as the Robe Range. Luebbers (1978) described materials from two such middens, one at Cape Martin and another at Bevilaqua Cliffs, about 5km south east of Cape Buffon (Fig 9.1). The Cape Martin site contained shells of *Katelysia* and *Mytilus*, flint tools, and charcoal which yielded a "questionable" radiocarbon date. The other site contained "a small number of nondescript tools" together with shells of *Plebidonax* and charcoal. For this second site, dates of 8250+/-60 and 6350+/-100yr B.P. were reported for charcoal and shell respectively.

For these sites and another inland, Luebbers (1978) remained unsatisfied with the stratigraphic control, and believed it was possible that younger overlying materials, perhaps from a more recent occupation, had been incorporated into the lower terra rosa soil. Thus no specific site was designated by Luebbers as an archaeological type locality for his Early Horizon.

Late Horizon sites occur in unconsolidated sand and in places, such as Bevilaqua Cliffs, may stratigraphically overlie an Early Horizon site. Luebbers (1978) subdivided his Late Horizon into an "Early Phase" and a "Late Phase". Middens of the Early Phase range in age from 5800 to 1300yr B.P., and contain small numbers of tools and "monospecific deposits of *Plebidonax* or *Brachiodontes*".

Middens of the "Late Phase" are younger than 1300yr B.P., and contain numerous flint implements and shells of *Turbo* (=*Subninella*) and other gastropods extant on southern Australian rocky foreshores.

Recent work by Egloff et al. (1989) in southeastern South Australia has revealed abundant Turbo shells in middens, dated by radiocarbon on charcoal, as old as 2560+/-120 and 3060+/-230yr B.P. These dates seriously call into question the Luebbers (1978) subdivision of the Late Horizon time-culture unit on the basis of the types of shells preserved in coastal middens.

Geologic and geomorphic framework

As indicated earlier, the landscape of southeastern South Australia is characterised by a series of low altitude ranges, sub-parallel to each other and to the present coastline. Between Naracoorte and Robe thirteen geomorphically distinct ranges can be identified on the otherwise gently sloping coastal plain (Sprigg, 1952; Schwebel, 1983). The region has undergone steady regional uplift of about 0.07mm/yr throughout the late Pleistocene (Schwebel, 1983; Belperio, in press). In general terms, the ranges are geomorphic features associated with palaeo shorelines and they increase in age away from Robe towards Naracoorte. The geological origin of these features has long been associated with sea level changes (for example, Tindale, 1933; Sprigg, 1952; Cook et al., 1977; Schwebel, 1978, 1983; Belperio and Cann, 1990; Belperio, in press). The ranges were termed "stranded coastal dunes" by Sprigg (1952), though he recognised that at least some ranges had been constructed during several episodes of marine transgression and that they incorporated sediments of beach, dune and lagoonal palaeoenvironments.

Sediments composing the ranges are predominantly aeolian bioclastic calcarenites with some seaward horizons of shelly limestones in which the fossil molluscs can be associated with rocky foreshore sedimentation. This complex of Pleistocene sediments has been termed the Bridgewater Formation (Boutakoff, 1963).

Between the ranges closest to the present coastline, sediments are lagoonal and lacustrine bioclastic to muddy limestones. Fossil molluscs in the lagoonal sediments clearly indicate a variety of shallow subtidal and intertidal palaeoenvironments.

In the work reported here, the coastal Robe Range, the adjacent Woakwine Range, and the lagoonal sediments confined by these two features, provide an important geomorphic and palaeoenvironmental framework (Fig 9.1).

Woakwine Range

The internal structure of the Woakwine Range has been exposed in the DRAIN L and WOAKWINE cuttings, two excavations through the range to effect drainage of wet lands to the north east. These cuttings reveal a complex Quaternary stratigraphy which resulted from perhaps as many as five separate stands of high sea level. The deposits of each of these sea level maxima are separated by conglomerates, soils, calcretes and strong carbonate cementation (Schwebel, 1983). Basal transgressive sediments in the WOAKWINE cutting consist of shelly and pebbly horizons that include flint cobbles, up to 10cm diameter, derived from the underlying Tertiary Gambier Limestone. These are overlain in turn by seawards dipping subtidal sands, beach sediments and landwards dipping sands of the transgressive dune sands (Belperio and Cann, 1990; Belperio, in press).

In the DRAIN L cutting, Sprigg (1952) observed that several planes of marine erosion were immediately overlain by sediments containing "a typical reef fauna" fossil assemblage (Fig 9.2). Blocks of shelly limestone corresponding to this facies can be observed today on the roadside overlooking this cutting. Significant faunal components are fossils of abalone and *Turbo* (Figs 9.2 and 9.3), gastropods which are characteristic of modern rocky foreshores. Sprigg (1952) deduced that the dune sediments had to have been substantially lithified during subaerial exposure. Thus they remained as a coherent geomorphic feature and provided a rocky substrate following marine inundation.

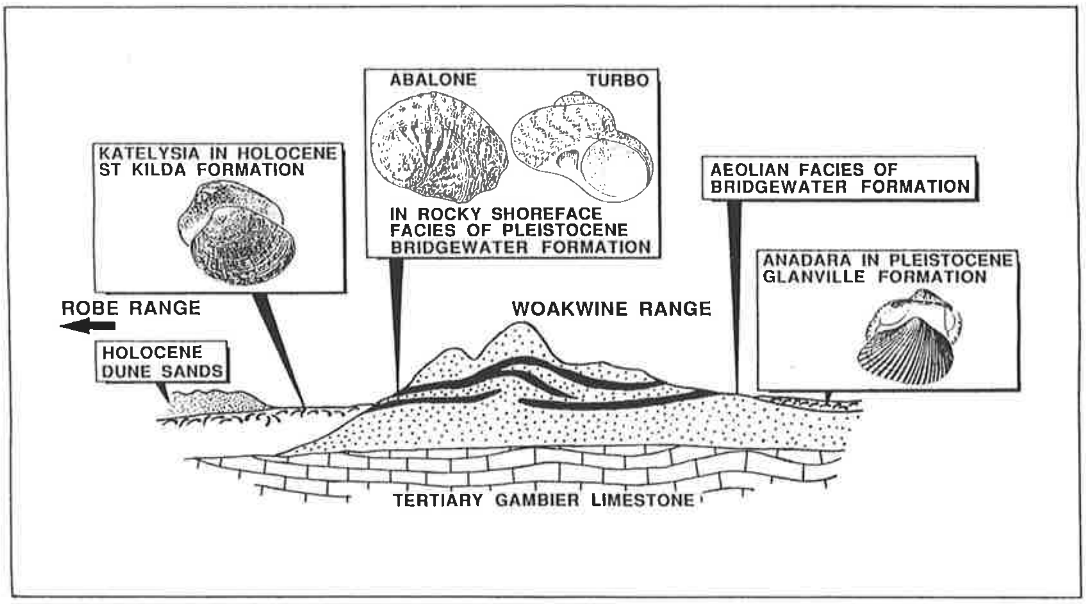
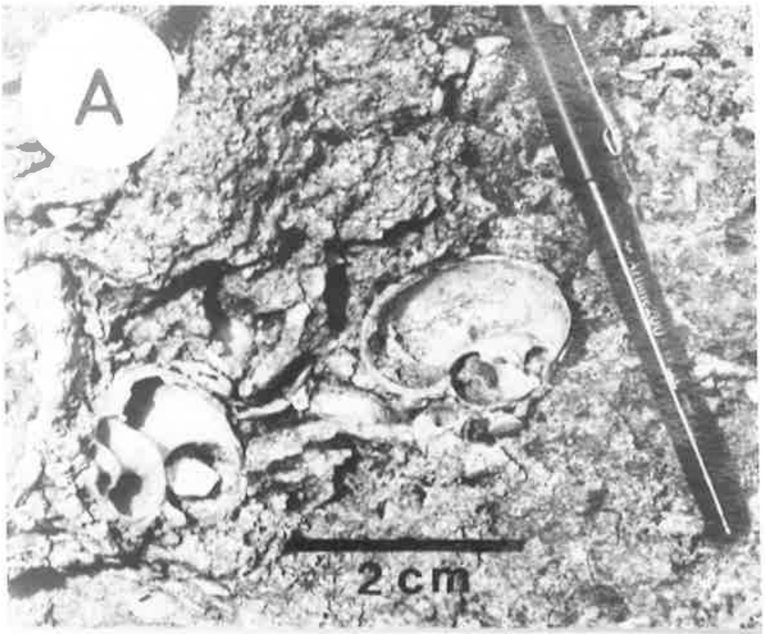


Fig 9.2
Diagrammatic section through Woakwine Range (after Sprigg, 1952) illustrating stratigraphic distribution of distinctive fossil molluscs.


A
2 cm

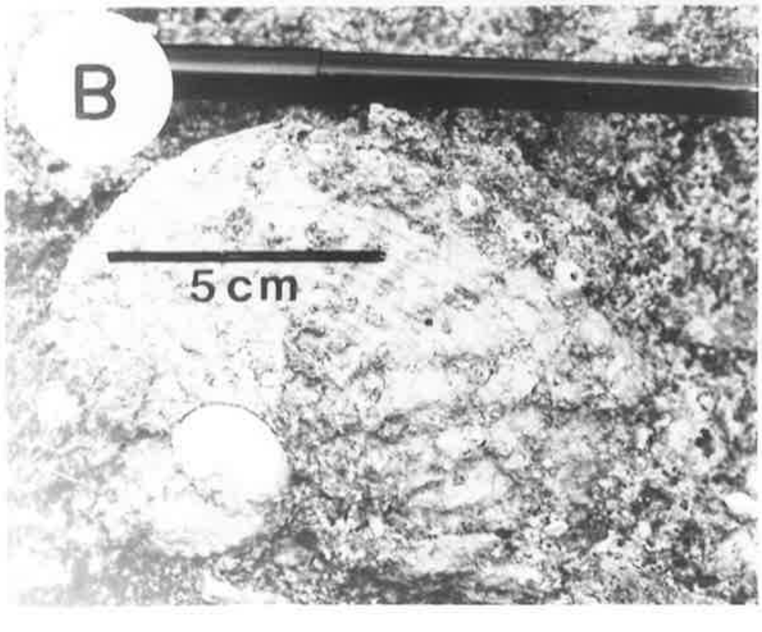

B
5 cm

Fig 9.3

Fossil gastropods within the rocky shoreface facies of the Bridgewater Formation, Drain L cutting, Woakwine Range:

A. *Turbo* shell

B. Abalone shell

On this basis he was able to recognise three episodes of marine regression followed by transgression in the construction of the Woakwine Range.

Fossils of the bivalve *Anadara trapezia* occur in lagoonal sediments onlapping the landward side of Woakwine Range (Fig 9.2). This species is characteristic of the late Pleistocene Glanville Formation (Cann 1978; Murray-Wallace et al., 1988a) and similar marine sediments of earlier Pleistocene age (Murray-Wallace et al., 1988b).

Robe Range

Robe Range is the youngest of the emergent stranded coastal dunes. Within the study area (Fig 9.1) it outcrops as an erosional rocky shoreline with numerous irregular stacks and islands in which aeolian bedding structures are clearly evident (Fig 9.4). Basal sediments of this range rest unconformably on Tertiary Gambier Limestone 10 to 15m below present sea level, and there are no horizons of fossiliferous rocky foreshore facies such as were recognised in the Woakwine complex (Sprigg, 1952).

Schwebel (1983) identified three stages of development for the Robe Range. The late Pleistocene constructional stages were equated with oxygen isotope substages 5c and 5a. Equivalent marine sediments were deposited in Spencer Gulf at sea level maxima of -8 and -14m respectively (Hails et al., 1984b). The most recent deposition has resulted from the Holocene transgression, during which there was extensive build up of dune sands over the older components of the Robe Range. These Holocene sands remain essentially unlithified.

Inter-range sedimentation

Despite the steady regional uplift, maximum sea level of the Holocene transgression was sufficient to flood the low lying corridor between the Robe and Woakwine Ranges.

Fig 9.4
Erosional rocky shoreface of Robe Range at Little Dip (Location A, Fig. 9.1)

Numerous road cuttings and other shallow excavations reveal a wealth of Holocene fossil molluscs characteristic of relatively protected (lagoonal) shallow subtidal and intertidal environments (Fig 9.5A-D). The floor of Lake Robe (Fig 9.1), for example, is littered with the shells of oysters, scallops and cockles, particularly the intertidal *Katelysia*. These richly fossiliferous sediments belong to the St Kilda Formation, in the sense of Cann and Gostin (1985).

PRESENT INVESTIGATION

The work reported in this chapter had three specific **AIMS**:

a) to evaluate critically the cultural-chronostratigraphic concept adopted by Luebbers (1978), within a framework of chronologic, palaeontologic and geomorphic investigation;

b) to nominate a suitable type section for the Early Horizon and Late Horizon cultural sites;

c) To document the palaeoenvironmental significance of the nominated type area, for the period c.125,000yr B.P. to present, with particular reference to palaeo sea levels during that time.

The investigation was centred on the Little Dip Conservation Park, south east of Robe (Fig 9.1). The **study area** includes coastal exposures of the late Pleistocene Robe Range (Fig 9.4) and Holocene shell beds deposited in the low lying areas between the Robe and Woakwine Ranges. These features are to a large extent covered by transgressive Holocene sand dunes, some of which are fixed by modern vegetation, while others are little vegetated and subject to present day erosion. The gastropod *Turbo* is extant on the rocky foreshore and its shells are easily collected at the waters edge (Fig 9.6). Several shells were taken for amino acid racemisation analysis.

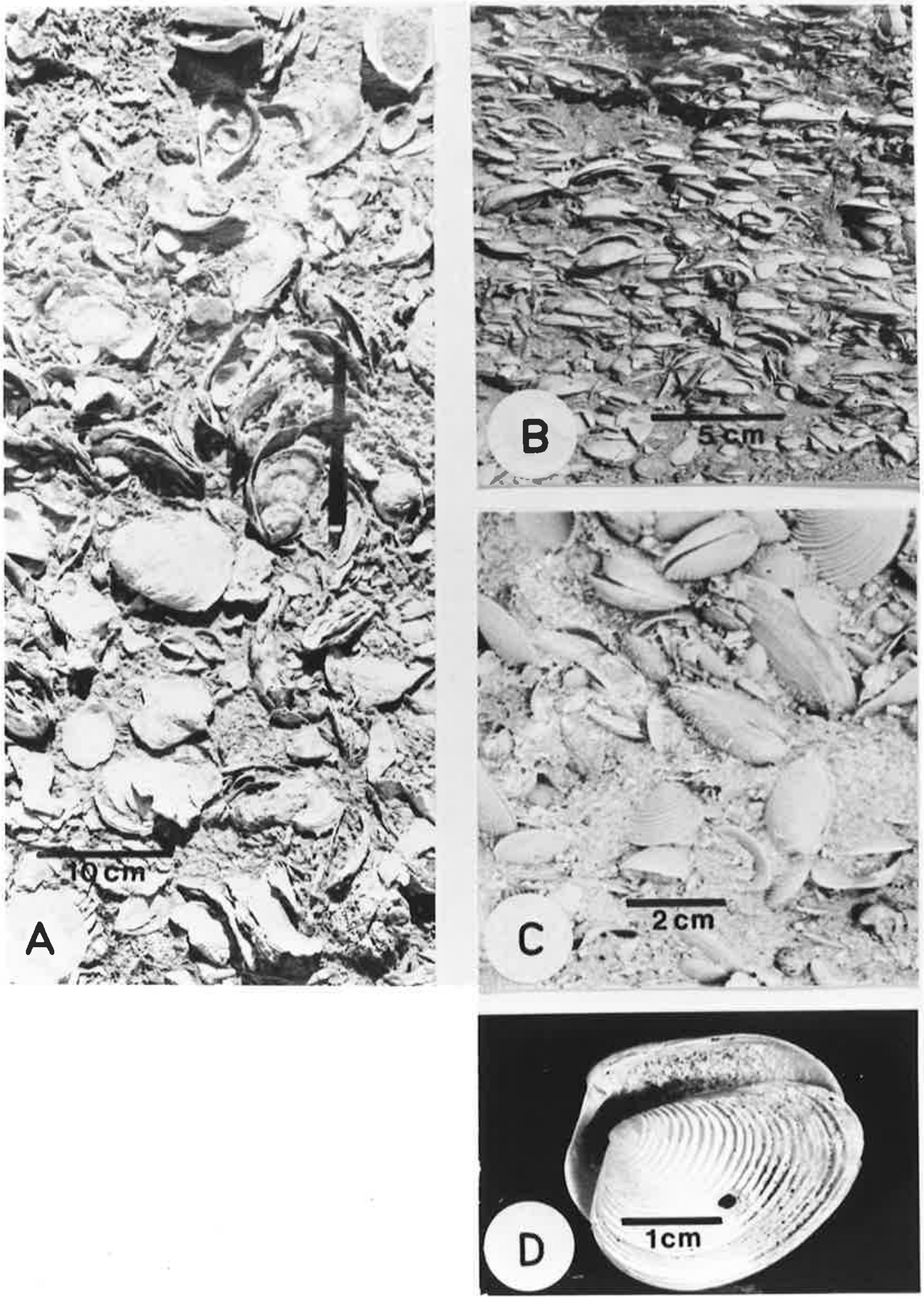

10 cm
A
B
5 cm
2 cm
C
1cm
D

Fig 9.5
Fossil molluscs of Holocene St Kilda Formation between Robe and Woakwine Ranges.

A. Oyster shells on the floor of Lake Robe.

B. Predominantly shells of *Katelysia*, disarticulated and convex upwards, signifying moderate energy transportation; small roadside excavation, Princes Highway.

C. Predominantly shells of *Katelysia*, mostly articulated, signifying little or no transportation. An intertidal environment of deposition is inferred (Location B, Fig. 9.1).

D. *Katelysia* showing the characteristic "drill" hole inflicted by predatory gastropods (Location B, Fig. 9.1).

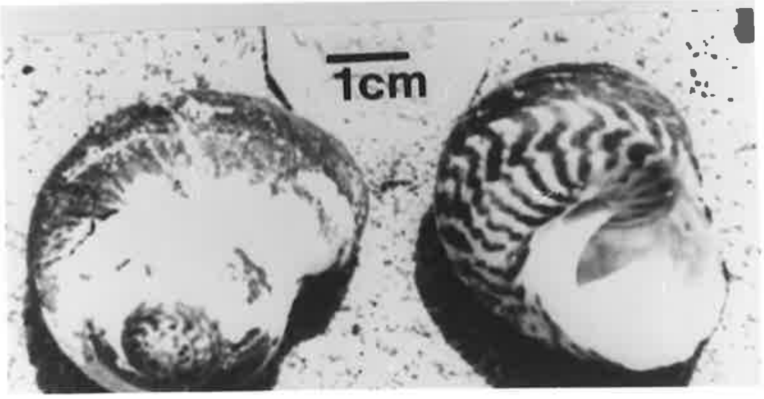

1cm

Fig 9.6
Shells of *Turbo*, extant on the rocky foreshore of Robe Range at Little Dip (Location A, Fig. 9.1).

OBSERVATIONS and METHODS

Aboriginal middens

At the study site (Fig 9.1, location A) a poorly vegetated coastal dune overlooks the foreshore. The seaward side of this dune has been subjected to wind deflation and a lag deposit of abundant shells and opercula of *Turbo*, together with numerous fragments of flint, litters the surface (Figs 9.7A and 9.7B). Some opercula are chipped or fractured and are more numerous in some areas than others, as if selectively sorted. Above the lag deposit there are numerous conspicuous *Turbo* shells in a greyish, poorly consolidated horizon of the dune (Figs 9.7A and 9.7C). The shells and flint fragments appear to have been derived from this layer which, on field evidence, is interpreted as an Aboriginal midden belonging to the Late Phase of the Late Horizon as defined by Luebbers (1978). Shells from this midden were taken for radiocarbon and amino acid racemisation dating.

On the landward side of the dune the Holocene sand sharply overlies a well consolidated red-brown terra rosa soil developed on the Bridgewater Formation of the Robe Range (Fig 9.8A). Embedded within this palaeosol are numerous shells of the bivalve *Katelysia* and substantial fragments of charcoal (Figs 9.8B and 9.8C, 9.9A and 9.9B). Although no flint fragments were observed, a human origin is also proposed for this material. This assertion is based on the following observations:

a) The shells are disarticulated, lack any preferred orientation and many are severely broken. It is difficult to imagine a natural sedimentary environment that would cause such fracturing of shells, but had they been naturally transported under conditions of high wave or current energy, the shells would show signs of attrition and would have been deposited predominantly convex upwards and tightly imbricated.

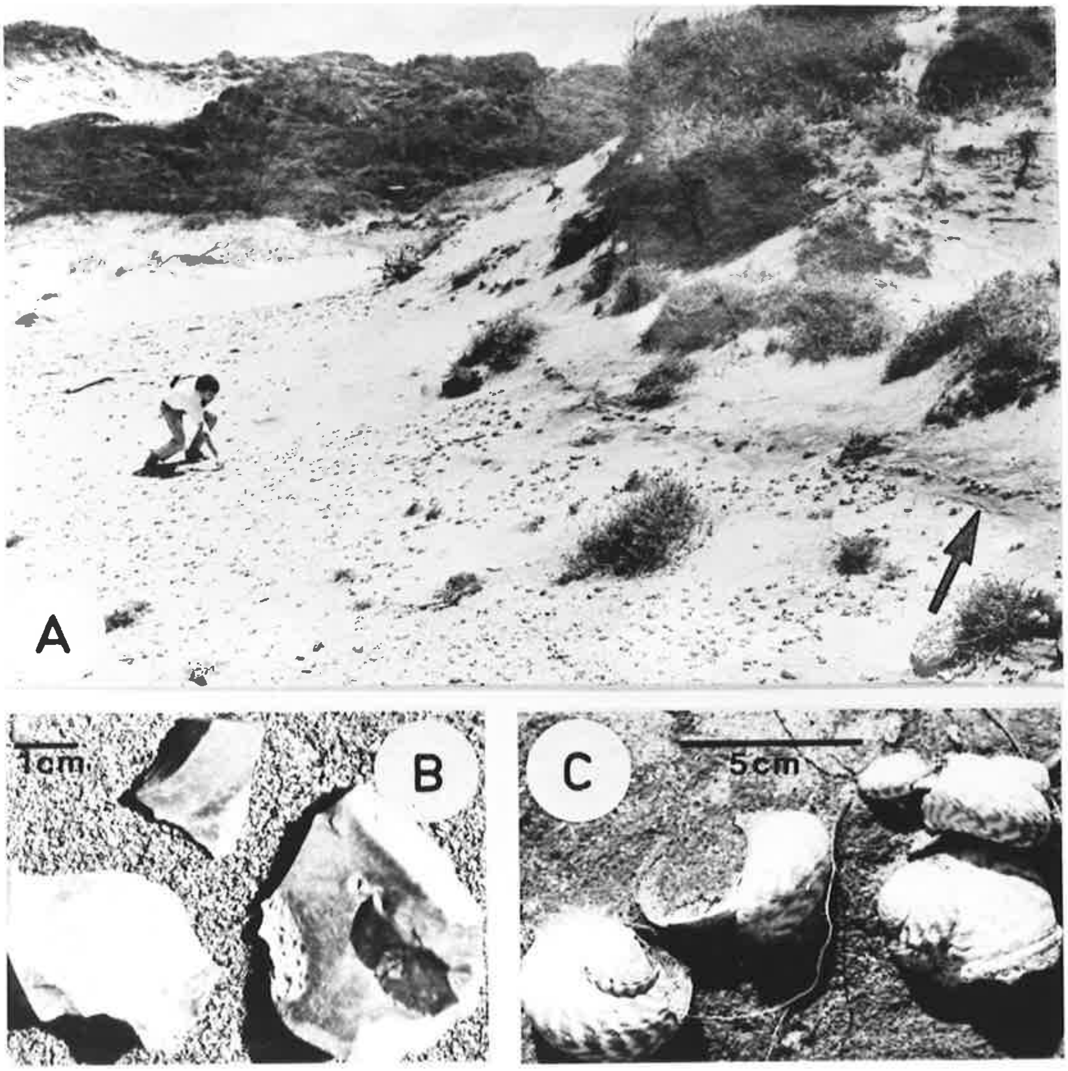

A
1cm
B
C
5cm

Fig 9.7

A. Lag deposit of *Turbo* shells and flint fragments apparently derived from stratum indicated by arrow. This deposit is interpreted as a Late Horizon Aboriginal midden (Location A, Fig. 9.1).

B. Flint fragments from the lag deposit.

C. *Turbo* shells within the stratum indicated by the arrow in A.

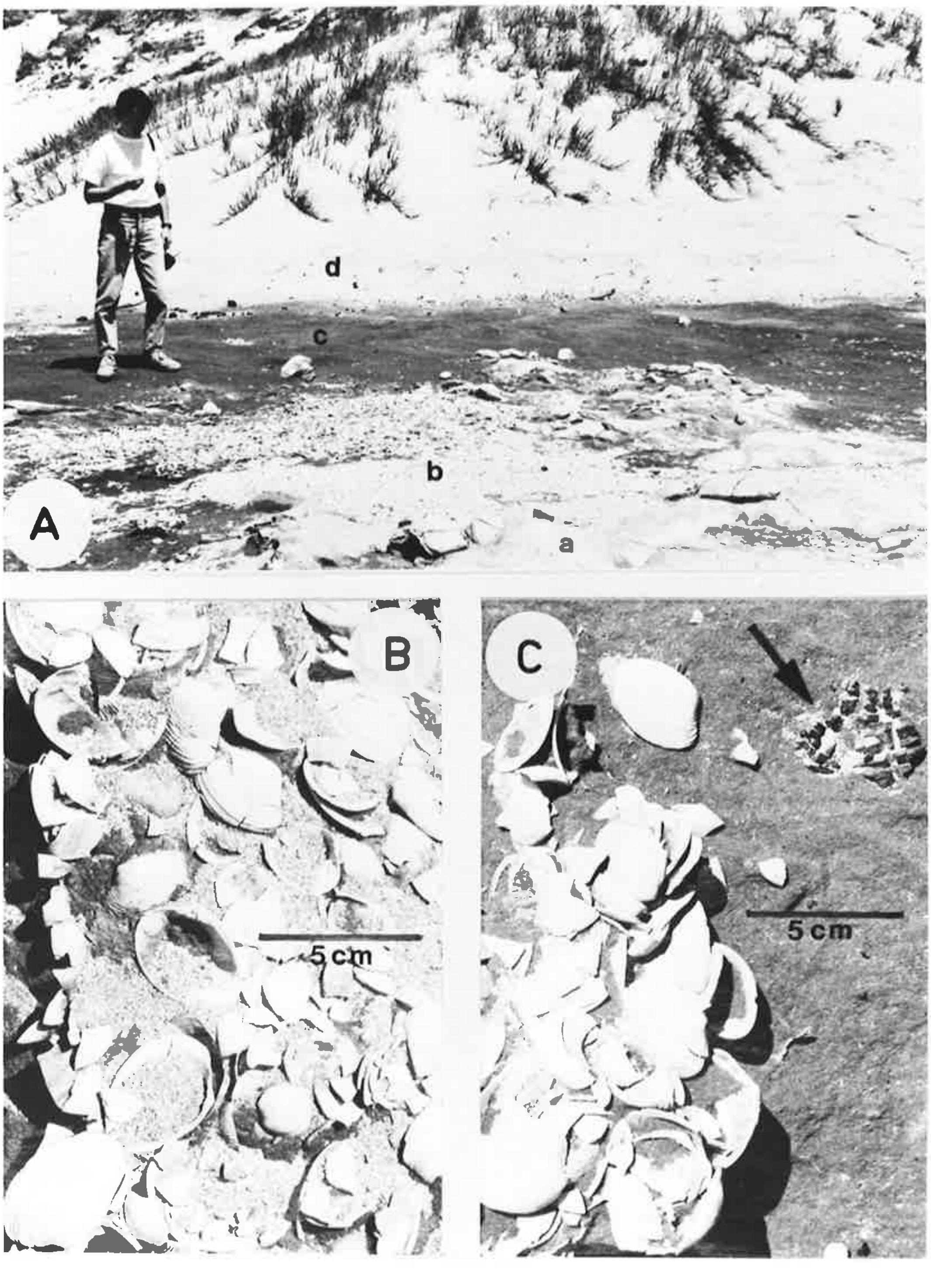

A
d
c
b
a
B
5 cm
C
5 cm

Fig. 9.8

A. Early Horizon Aboriginal midden within terra rosa palaeosol on Bridgewater Formation,
Robe Range (Location A, Fig. 9.1).

- **a.** Karstified rocky outcrop of Bridgewater Formation.
- **b.** *Katelysia* shells of the Early Horizon midden.
- **c.** Terra rosa palaeosol.
- **d.** Holocene sand dune which includes the Late Horizon *Turbo* midden (Fig. 9.6). Note the sharp contact between this and the underlying terra rosa palaeosol.

B. Detail of *Katelysia* shells within the midden. Note that shells are disarticulated, lack preferred orientation and none shows signs of gastropod predation.

C. Detail of part of the midden in which charcoal, indicated by arrow, is embedded in the terra rosa palaeosol.

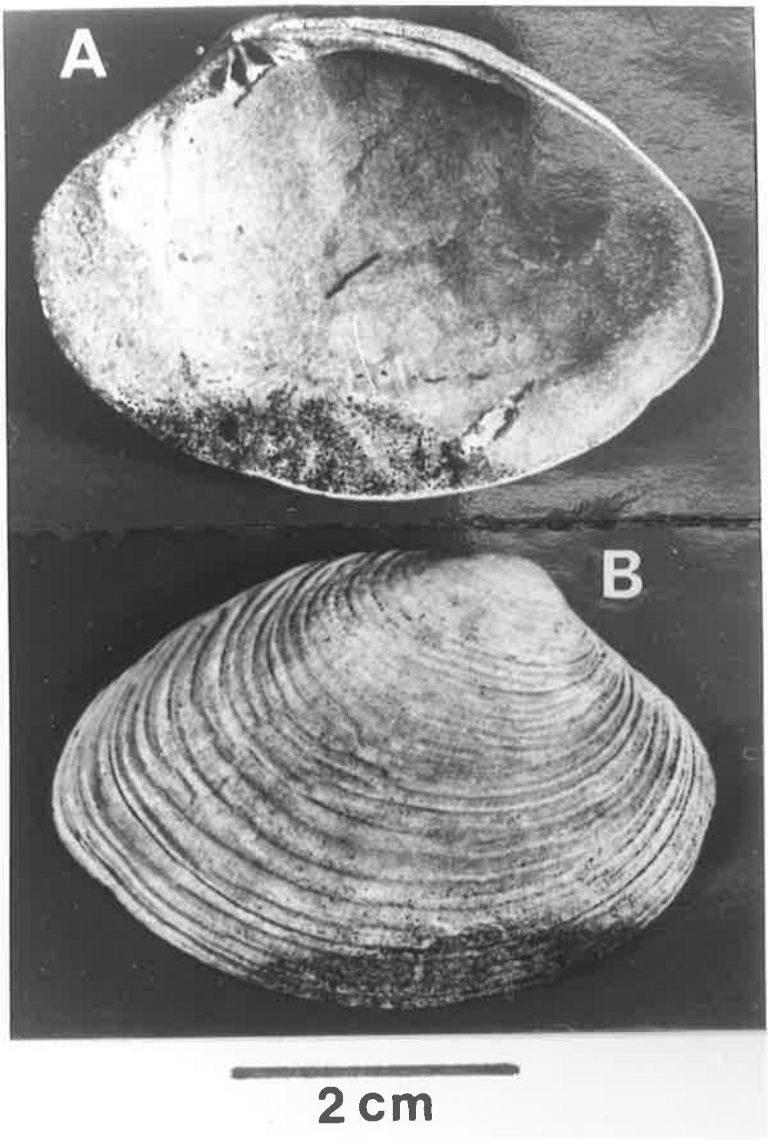

A
B
2 cm

Fig. 9.9
Selected valve from the Early Horizon midden showing features of *Katelysia*.

A. Internal view

B. External view.

Such a fabric can be seen in some of the Holocene shell beds between Robe and Woakwine Ranges (Fig 9.5B) and in some older Pleistocene lagoonal sediments, such as those exposed in a small quarry on the landward side of Woakwine Range, adjacent to Princes Highway. Where shells have not been actively transported their valves usually remain more or less paired (Fig 9.5C).

b) Characteristic "drill" holes, inflicted by predatory gastropods, were not observed in the exposed *Katelysia* valves, yet within the nearby Holocene shelly sediments such valves with "drill" holes are numerous (Fig 9.5D). Clearly some form of selective process has operated to eliminate bivalves affected by this type of predation. Selection also seems to have favoured larger individuals.

c) Sand enclosed by paired *Katelysia* valves from the Holocene lagoonal sediment was microscopically examined and found to contain species of foraminifera also known from the intertidal sandflats of northern Gulf St Vincent (Cann and Gostin, 1985; Chapter 3). Species included *Elphidium crispum*, *E. macelliforme* and *Miliolinella labiosa*. The present author has used the abundance of estuarine foraminifera in a shell deposit at Warrnambool, Victoria, to show that it formed by natural sedimentary processes, and is not of human origin (Gill et al., 1991). Microscopic examination of the terra rosa matrix enclosing the *Katelysia* shells revealed no foraminifera within the deposit under present discussion.

d) Stratigraphic elevation of the *Katelysia* deposit at the crest of the Robe Range makes natural sedimentation implausible if these shells are to be correlated with those undisputedly deposited in the Holocene lagoon between Robe and Woakwine Ranges.

Thus the deposit is interpreted as an Aboriginal midden belonging to the Early Horizon, as defined by Luebbers (1978). Shell and charcoal were taken from this midden for radiocarbon assessment via co-researcher Dr Patrick De Deckker. Shell was also taken for amino acid racemisation dating by co-researcher Dr Colin Murray-Wallace. Paired *Katelysia* valves from the nearest accessible deposit of Holocene lagoonal sediments (Fig 9.1, location B) were taken for comparative AAR dating .

Dating methods: radiocarbon dating

Charcoal and *Katelysia* shell were carefully removed from the terra rosa matrix of the Late Horizon midden and packed in clean plastic bags. Similarly, *Turbo* shells were taken from the Early Horizon midden (Fig 9.1, location A). These materials were forwarded to the Radiocarbon Laboratory of the Australian National University, Canberra, for radiocarbon dating. Conventional methods followed the guidelines of Gupta and Polach (1985).

Dating methods: amino acid racemisation analyses

The following materials were collected for AAR analysis for the purpose of age determination:

a) disarticulated shells of *Katelysia rhytiphora* and *K. scalarina* from the Early Horizon midden (Fig 9.1, location A);
b) articulated shells of *K. scalarina* from Holocene lagoon sediments (=St Kilda Formation) within the Robe-Woakwine corridor (Fig 9.1, location B);
c) articulated shells of *K. scalarina* from late Pleistocene lagoon sediments (=Glanville Formation) on the landward side of the Woakwine Range, exposed in a small quarry adjacent to Princes Highway;
d) shells of *Turbo* sp. from the Late Horizon midden, and from the immediately adjacent modern shoreface sediments (Fig. 9.1, Location A).

Amino acid racemisation analyses were undertaken by co-researcher Dr Colin Murray-Wallace on all the collected shell materials. Data obtained from the *Katelysia* shells of the Early Horizon midden were compared and contrasted with the extent of racemisation in specimens obtained from the Holocene and late Pleistocene lagoon sediments. Details of the methods used in these age determinations are given in Cann et al. (1991).

RESULTS AND DISCUSSION

Age determinations

Charcoal from the Early Horizon midden yielded a radiocarbon age of 8270+/-80yr B.P.. *Katelysia* shell, also from the older midden, was determined to have a marine reservoir corrected age of 7910+/-140yr B.P.. *Turbo* shell from the overlying Late Horizon midden had a radiocarbon age, again corrected for the marine reservoir effect, of 470+/-160yr B.P..

Amino acid racemisation analyses by co-researcher Dr Colin Murray-Wallace are presented and discussed in full in Cann et al. (1991). His data confirm that:

a) *Turbo* shells of the Late Horizon midden are only slightly older than present;

b) *Katelysia* shells of the Early Horizon midden, and those of the Holocene lagoon facies between Robe and Woakwine Ranges, are of closely similar age;

c) *Katelysia* shells of the landward side of the Woakwine Range are of late Pleistocene age, oxygen isotope substage 5e, c.125,000yr B.P.

The amino acid racemisation data for the shells of the Early Horizon midden were interpreted by Murray-Wallace to indicate that the midden materials had been buried for much of the time since their concentration by humans. This observation is consistent with the geomorphologic evidence of recent dune deflation and consequent exposure of the midden.

The archaeological site: a nominated type locality

The stratigraphic boundary between the *Katelysia* bearing terra rosa palaeosol of the Bridgewater Formation and the overlying *Turbo* bearing Holocene dune sand is both sharp and easily observable (Fig 9.8A). The palaeosol is well consolidated and has not been contaminated by younger overlying sediment, shells or artifacts.

The two sets of midden materials, as described here and by Cann et al. (1991), undoubtedly conform to those specified by Luebbers (1978) for his Early Horizon and Late Horizon of Aboriginal occupation of southeastern South Australia. Equally, the age determinations of both shells and charcoal, particularly the close agreement of radiocarbon and AAR dates, meet the constraints of time applied to this time-cultural classification.

Given that the site meets these tight stratigraphic, archaeological and time constraints, and given that it is located within the boundaries of a Conservation Park, Cann et al. (1991) have proposed the site as a type locality and type section for the time-cultural Early Horizon and Late Horizon of Luebbers (1978).

Other archaeological sites: reference localities

It is likely that future investigations will reveal other sites that will equally illustrate, or further clarify, the Luebbers (1978) chronology. If appropriate, such sites should be designated as reference localities and reference sections. In this context, middens within Discovery Bay Coastal Park near Cape Bridgewater in southwestern Victoria seem worthy of further study.

Godfrey (1989) differentiated middens in this area into two episodes of occupation, though did not use the Luebbers (1978) terminology. The older middens, 8490 to 3860yr B.P., are in terra rosa soils of the Bridgewater Formation and contain shells of a species of mussel no longer extant along the present shore. The younger middens are in unconsolidated sand and contain shells of species, such as *Turbo*, which inhabit the present shoreline, together with numerous flint fragments. Dates of 1050 to 360yr B.P. were recorded by Godfrey (1989) for these younger sites.

AN ENVIRONMENTAL SCENARIO FOR THE STUDY AREA

The following is an account of the interaction of physical and biological processes, from c.105,000yr B.P. to late Holocene, leading to the evolution and early human exploitation of the study environment.

At 105,000yr B.P., oxygen isotope substage 5c, marine transgression brought palaeo sea level to -8m (Hails et al., 1984b; Belperio, in press). Robe Range stage III sediments accumulated as unconsolidated beach and dune sands (Schwebel, 1983).

During isotope substage 5b, the sea receded allowing subaerial diagenesis and at least partial lithification of the carbonate rich sands of the stage III sediments. Protective calcretes developed on exposed surfaces.

At 80,000yr B.P., isotope substage 5a, marine transgression brought sea level to -14m (Hails et al., 1984b; Belperio, in press). Robe Range stage II sediments were deposited at this time. Sea level was not sufficiently high to erode the earlier formed stage III sediments, which were mantled by the dune facies of the stage II transgression.

Following this peak of sea level, the ocean again regressed across the continental shelf and for the remainder of Pleistocene time the shoreline remained seawards of Robe Range. The carbonate sands thus underwent further extensive diagenesis and consolidation under the influence of subaerial processes.

Between 45,000 and 30,000yr B.P., isotope stage 3, there were fluctuations of sea level between -30m and -22m (Cann et al., 1988; Chapters 7 and 8), but these were insufficient to influence Robe Range. Also, by 30,000yr B.P. the base of the range had undergone about 5m of tectonic uplift, further compounding the impact of the regression. Early humans may have first appeared in southeastern Australia at this time.

From 30,000 to 18,000yr B.P., during isotope stage 2, the last glacial regression lowered sea level to -130m (Chappell and Shackleton, 1986). Aboriginal populations occupied the emergent continental shelf and in coastal areas probably exploited a variety of sea food resources.

At 18,000yr B.P. sea level began to rise, sometimes as rapidly as 2.4cm/yr, totally submerging the continental shelf by 7000yr B.P. (Belperio and Cann, 1990; Belperio, in press). Unconsolidated sands were driven shorewards by the rising seas, mantling seaward outcrops of Robe Range stage II and, where exposed, stage III. Sea water flooded the low lying corridor between Robe and Woakwine Ranges, providing sheltered shallow subtidal and intertidal environments in which mollusc populations thrived. Aboriginal people occupied Robe Range, open ocean to one side and sheltered lagoon to the other. At the study site they exploited the intertidal cockle *Katelysia*. Elsewhere, for example, at Bevilaqua Cliffs to the south east, ocean beach cockles, *Plebidonax*, were the prime food source.

Bioclastic sedimentation within the shallow Robe-Woakwine lagoon was rapid. Sedimentary sections reveal upward shoaling sequences of subtidal oysters overlain by intertidal *Katelysia* and *Anapella*. Shoaling was further facilitated by tectonic uplift of about 0.5m from the time of stabilisation of Holocene sea level to present.

Meanwhile, on the seaward side of Robe Range, sands continued to accumulate. In the absence of any preferred direction of longshore transport (Sprigg, 1952), the strong persistent swell (Gostin et al., 1988) moved sands onshore from where they were distributed to form a blanket of dunes. Some sands were also redistributed, both up and down the coast, to the protected areas of Guitchen Bay to the north west and Rivoli Bay to the south east. Sedimentation in these areas effectively isolated the Robe-Woakwine lagoon from further marine influence.

At the study site, continued marine erosion of the Holocene sands once again exposed the earlier stage sediments of Robe Range. Their long subaerial emergence through the late Pleistocene resulted in a high degree of carbonate cementation, and in Holocene time, they have outcropped as a rugged, irregular, erosional coastline. A coastal marine mollusc fauna, dominated by the large gastropod *Turbo*, became established along this rocky, high wave energy environment. Thus was repeated, on the Holocene shoreface of Robe Range, ecological events that are recorded by the late Pleistocene horizons of "typical reef fauna" (Sprigg, 1952) in the Woakwine Range.

For a second time, Aboriginal people occupied the study site and exploited this newly established food resource.

The two middens at the study site therefore reflect profound changes in landscape. The elapsed time between the two periods of recorded human occupation is a valuable clue to the rate of environmental change.

CHAPTER 10

CONCLUDING COMMENTS

The work reported in this thesis has been directed towards two broad aims, namely,

a) to determine the occurrence of species of benthic foraminifera in local waters with specific reference to relationships that exist between their distribution patterns and sedimentary environments, and in particular, the parameter of water depth.

b) to derive palaeoenvironmental interpretations of assemblages of fossil benthic foraminifera that are abundantly preserved in the late Pleistocene and Holocene sediments of St. Vincent and Spencer Gulfs, and in particular, to recognise those associations of fossil species that could be used to infer palaeo sea levels.

In addressing the **first** of these aims, study materials were obtained from surficial sediment samples of Investigator Strait (on the South Australian continental shelf), St. Vincent Gulf and Spencer Gulfs, Onkaparinga Estuary, (south of Adelaide) and various saline lakes (especially in the Coorong district of South Australia). Distinctive assemblages of species were recognised for each of these environmental settings.

Sediments of the continental shelf are rich in planktonic fauna of the common genera, such as *Globigerina, Globigerinoides* and *Orbulina* and bethnic forms dominated by *Cibicides* spp. and the agglutinated genera *Textularia* and *Ammobaculites.*

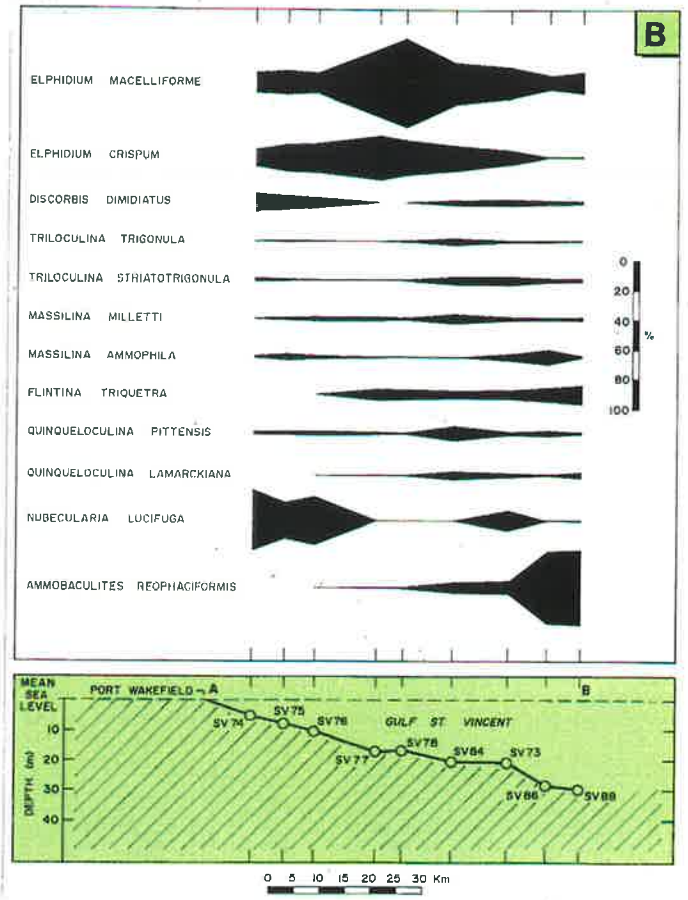
Saline lake and estuarine fauna are dominated by *Ammonia beccarii* and *Elphidium articulatum*. Tests of these species are variable in their size and degree of calcification.

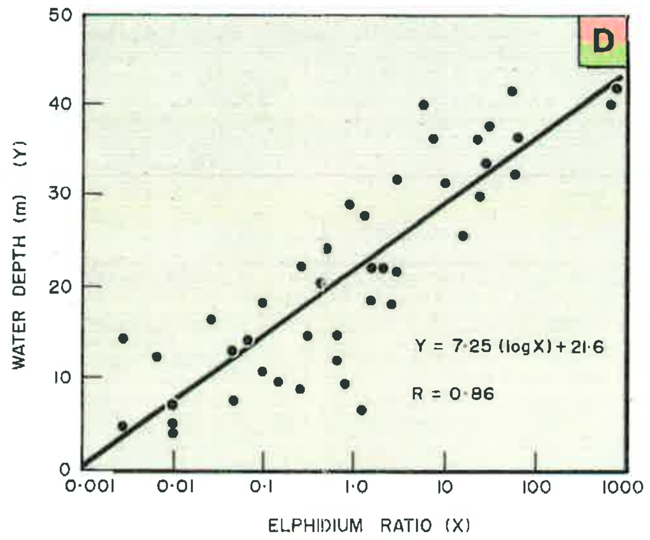
Planktonic foraminifera are absent from the sediments of both Spencer and St Vincent Gulfs. However, it is the gulf waters that show greatest species variety, diversity and interesting patterns of distribution, closely corresponding to parameters of the sedimentary environments. Marginal marine environments in which there are large intertidal areas, such as at Port Gawler, are characterised by species such as *Cribrobulimina mixta, Discorbis dimidiatus, Nubecularia lucifuga* and *Peneroplis planatus.*

Fig 10.1
Composite summary diagram illustrating the numerical abundance of significant species of benthic foraminifera, with respect to water depth, in surficial sediments of South Australian Gulfs Spencer and St Vincent.
Size fraction 0.50 - 0.25mm.

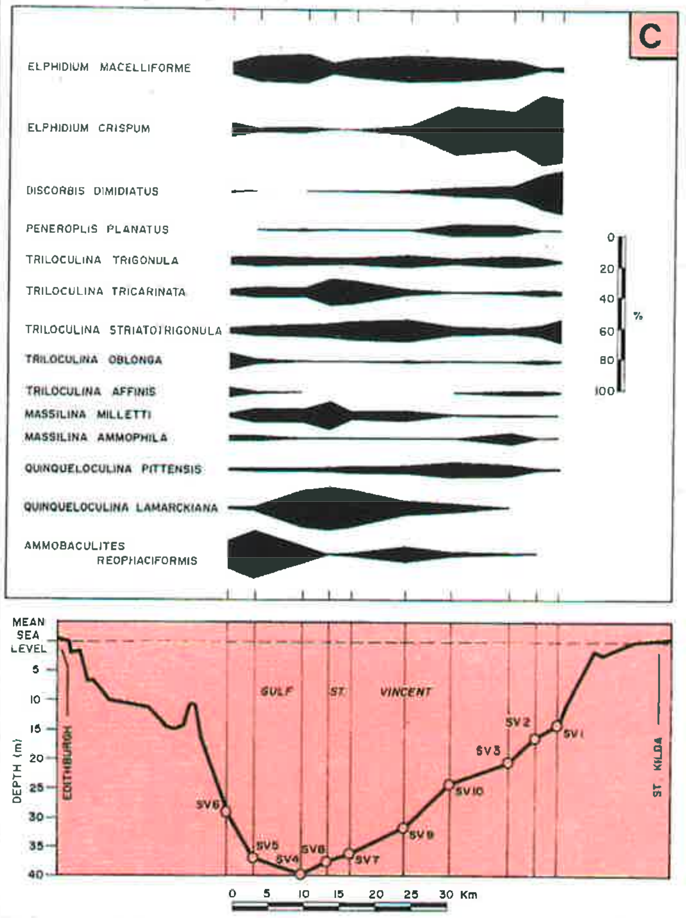
Fig 10.1.1 (left) Gulf St Vincent
A. Location map showing sites of most vibrocores and grab samples. Some sites in the vicinity of Port Gawler have been omitted for the sake of clarity (see Fig 7.1). The transects Port Wakefield to central Gulf St Vincent (green colour) and St Kilda to Edithburgh (pink colour) provided the data for B and C respectively.
B. Percentage distribution of species compared with the water depth profile, Port Wakefield to central gulf (green colour).
C. Percentage distribution of species compared with the water depth profile, St Kilda to Edithburgh (pink colour).
D. Log-linear plot of water depth versus ratio of numbers of individuals of *Elphidium macelliforme* to numbers of *Elphidium crispum* for all surficial sediment samples taken from sites shown in A, plus those from the vicinity of Port Gawler (see Fig 7.1). Also shown is the line of best least-squares fit, the calculated regression equation and Pearson's correlation coefficient for the data set.

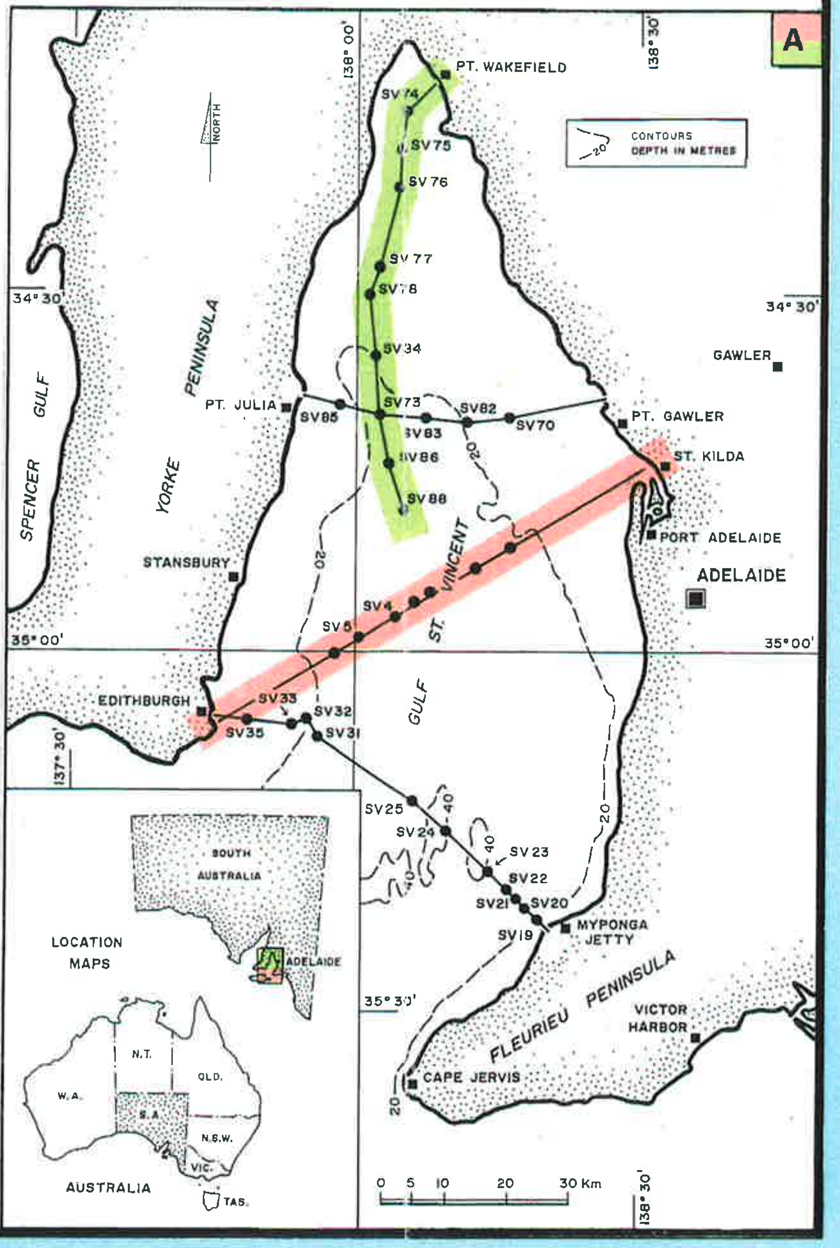
Fig 10.1.2 (right) Spencer Gulf
A. Location map showing sites of vibrocores on a transect in the vicinity of Whyalla to Port Pirie (yellow colour). The surficial sediments on this transect provided the data for B.
B. Percentage distribution of species compared with the water depth profile, vicinity of Whyalla to Port Pirie (yellow colour).
C. Log-linear plot of water depth versus ratio of numbers of individuals of *Elphidium macelliforme* to numbers of *Elphidium crispum* for all surficial sediment samples taken from the transect shown in A. Also shown is the line of best least-squares fit, the calculated regression equation and Pearson's correlation coefficient for the data set.

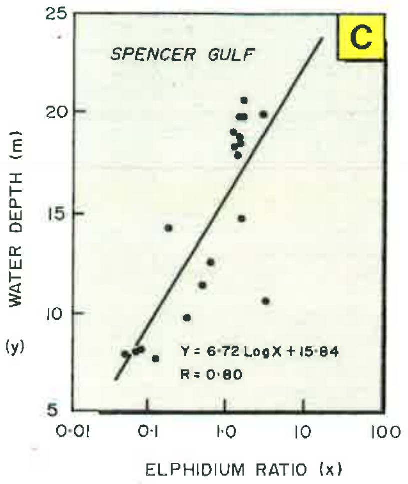


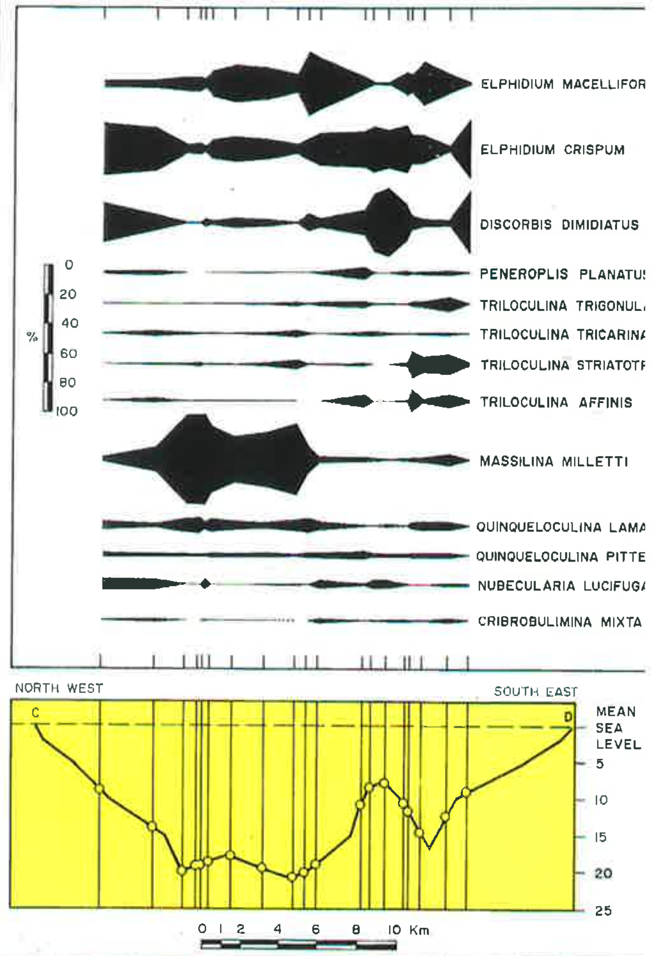


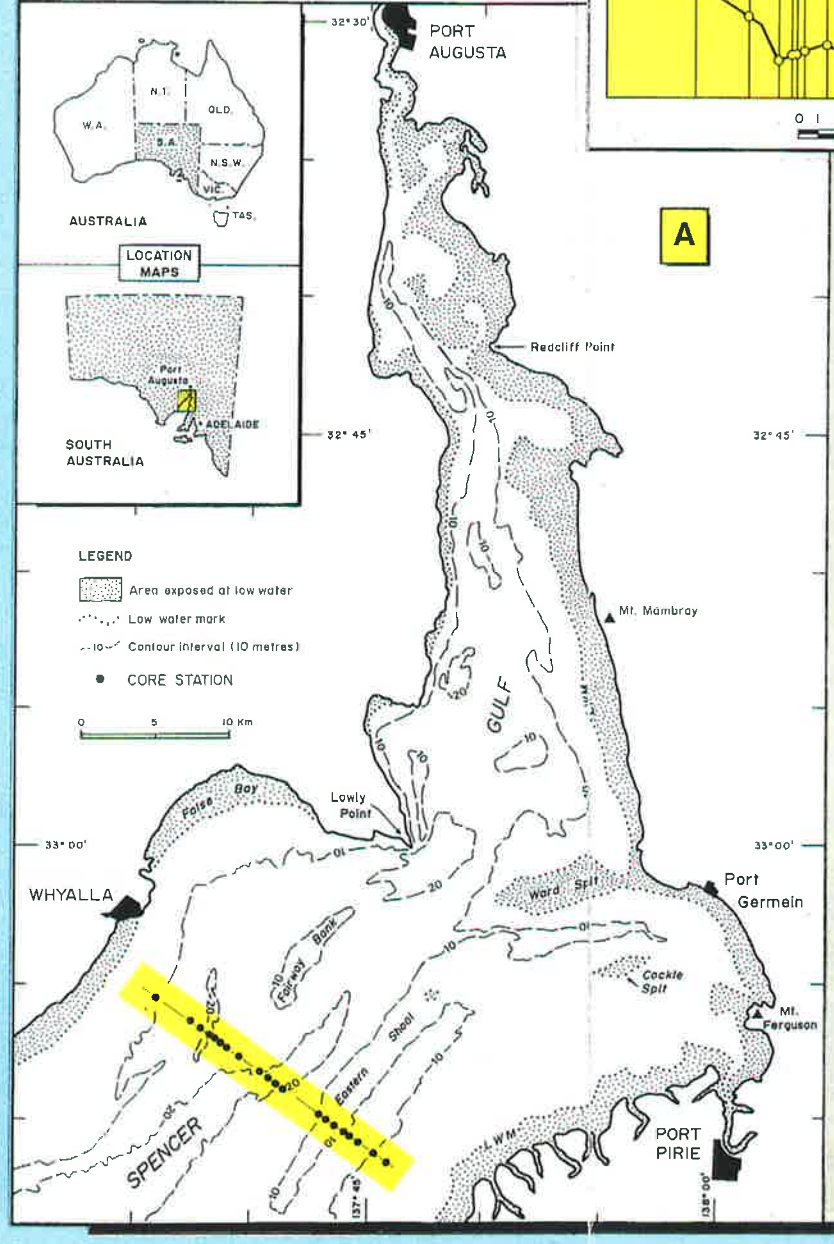
Gulf St. Vincent











Spencer Gulf

Away from these coastal environments, some species show a clear relationship with water depth. In northern Spencer Gulf, for example, numbers of individuals of *Massilina milletti* are greatest in the deepest waters, while those characteristic of the shallower coastal areas are essentially absent (Fig 10.1.2 A, B) The same and similar relationships with species distributions (for example, *Quinqueloculina lamarckiana*) and depth of water can be observed in adjacent St. Vincent Gulf (Fig 10.1.1 A, B, C).

Within gulf environments, particular attention has been given to the numerical distribution of two species of *Elphidium, E. crispum* and *E. macelliforme.* Their relative abundance is quantitatively related to water depth (Fig 10.1.1 D, 10.1.2 C).

Thus, the various southern Australian sedimentary environments, hosting foraminifera, have species assemblages which are distinctive for those environments and, in gulf waters, are closely associated with water depth.

In addressing the **second** aim, study materials were obtained by vibrocorer from Late Pleistocene and Holocene sediments of Spencer and St. Vincent Gulfs.

Late Pleistocene

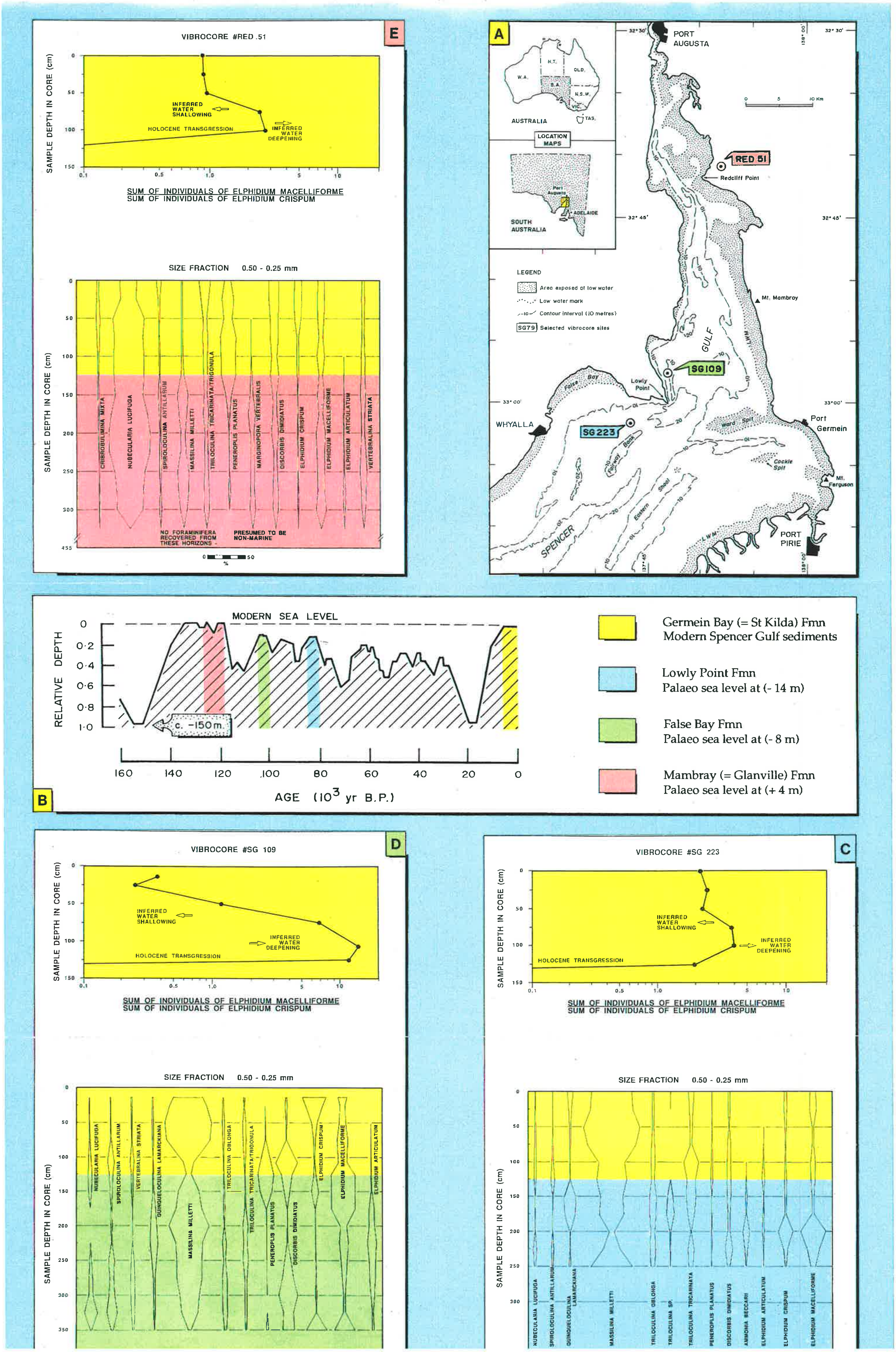
Spencer Gulf cores yielded disconformable sets of strata that had been previously assigned formal stratigraphic names by earlier researchers (Hails et al., 1984a). Deposition of these sediments can be related both spatially and temporally with Late Pleistocene peaks of sea level as follows:

Mambray Formation (equivalent of Glanville Formation,
known elsewhere in South Australia)
sea level at +4 metres, c.125,000 yr B.P.
False Bay Formation
sea level at -8 metres, c.105,000 yr B.P.
Lowly Point Formation
sea level at -14 metres, c.82,000 yr B.P.

Late Pleistocene fossil foraminifera of Spencer Gulf are mostly species that are also extant in present day gulf sediments. However, in the Mambray Formation, *Marginopora vertebralis, Pseudomassilina australis* and *Quinqueloculina polygona* are distinctive members of the fossil assemblage and are unknown locally in sediments of younger ages.

Fig 10.2
Composite summary diagram illustrating the numerical distributions of significant species of benthic foraminifera within late Pleistocene sediments of Spencer Gulf.
Size fraction 0.50 - 0.25mm.

A. Location map showing sites of three selected vibrocores, SG223 (blue colour), SG109 (green colour) and RED51 (pink colour).
B. Palaeo sea level curve, after Chappell (1983). Colour bands corresponding to marine transgressions at c.125,000, c.105,000 and c.82,000yr B.P. indicate time intervals for deposition of late Pleistocene (pink, green, blue) and Holocene (yellow) sedimentary formations within Spencer Gulf.
C. Distribution of selected species of benthic foraminifera within vibrocore #SG223, Lowly Point Formation (lower) and Germein Bay (=St Kilda) Formation (upper). Also shown for the Holocene section is the implied palaeo sea level curve derived from the *Elphidium* ratio.
D. Distribution of selected species of benthic foraminifera within vibrocore #SG109, False Bay Formation (lower) and Germein Bay (=St Kilda) Formation (upper). Also shown for the Holocene section is the implied palaeo sea level curve derived from the *Elphidium* ratio.
E. Distribution of selected species of benthic foraminifera within vibrocore #RED51, Mambray (=Glanville) Formation (lower) and Germein Bay (=St Kilda) Formation (upper). Also shown for the Holocene section is the implied palaeo sea level curve derived from the *Elphidium* ratio.


E
VIBROCORE #RED .51
SAMPLE DEPTH IN CORE (cm)
0
50
100
150
INFERRED WATER SHALLOWING
HOLOCENE TRANSGRESSION
INFERRED WATER DEEPENING
0.1
0.5
1.0
5
10
SUM OF INDIVIDUALS OF ELPHIDIUM MACELLIFORME
SUM OF INDIVIDUALS OF ELPHIDIUM CRISPUM
SIZE FRACTION 0.50 - 0.25 mm
200
250
300
455
CRIBROBULIMINA MIXTA
NUBECULARIA LUCIFUGA
SPIROLOCULINA ANTILLARUM
MASSILINA MILLETTI
TRILOCULINA TRICARINATA/TRIGONULA
PENEROPLIS PLANATUS
MARGINOPORA VERTEBRALIS
DISCORBIS DIMIDIATUS
ELPHIDIUM CRISPUM
ELPHIDIUM MACELLIFORME
ELPHIDIUM ARTICULATUM
VERTEBRALINA STRIATA
NO FORAMINIFERA RECOVERED FROM THESE HORIZONS -
PRESUMED TO BE NON-MARINE
0
50
%
A
AUSTRALIA
N.T.
QLD.
W.A.
S.A.
N.S.W.
VIC.
TAS.
LOCATION MAPS
Port Augusta
ADELAIDE
SOUTH AUSTRALIA
LEGEND
Area exposed at low water
Low water mark
Contour interval (10 metres)
SG79 Selected vibrocore sites
32° 30'
32° 45'
33° 00'
138° 00'
137° 45'
PORT AUGUSTA
0
5
10 Km
RED 51
Redcliff Point
Mt. Mambray
GULF
LWM
SG109
False Bay
Lowly Point
WHYALLA
SG223
Port Germein
Ward Spit
Fairway Bank
Cockle Spit
Mt. Ferguson
Eastern Shoal
SPENCER
PORT PIRIE
10
20
B
MODERN SEA LEVEL
RELATIVE DEPTH
0
0·2
0·4
0·6
0·8
1·0
c. -150 m.
160
140
120
100
80
60
40
20
0
AGE (10³ yr B.P.)
Germein Bay (= St Kilda) Fmn
Modern Spencer Gulf sediments
Lowly Point Fmn
Palaeo sea level at (- 14 m)
False Bay Fmn
Palaeo sea level at (- 8 m)
Mambray (= Glanville) Fmn
Palaeo sea level at (+ 4 m)
D
VIBROCORE #SG 109
SAMPLE DEPTH IN CORE (cm)
INFERRED WATER SHALLOWING
INFERRED WATER DEEPENING
HOLOCENE TRANSGRESSION
SUM OF INDIVIDUALS OF ELPHIDIUM MACELLIFORME
SUM OF INDIVIDUALS OF ELPHIDIUM CRISPUM
SIZE FRACTION 0.50 - 0.25 mm
350
NUBECULARIA LUCIFUGA
SPIROLOCULINA ANTILLARUM
VERTEBRALINA STRIATA
QUINQUELOCULINA LAMARCKIANA
MASSILINA MILLETTI
TRILOCULINA OBLONGA
TRILOCULINA TRICARINATA/TRIGONULA
PENEROPLIS PLANATUS
DISCORBIS DIMIDIATUS
ELPHIDIUM CRISPUM
ELPHIDIUM MACELLIFORME
ELPHIDIUM ARTICULATUM
C
VIBROCORE #SG 223
SAMPLE DEPTH IN CORE (cm)
INFERRED WATER SHALLOWING
INFERRED WATER DEEPENING
HOLOCENE TRANSGRESSION
SUM OF INDIVIDUALS OF ELPHIDIUM MACELLIFORME
SUM OF INDIVIDUALS OF ELPHIDIUM CRISPUM
SIZE FRACTION 0.50 - 0.25 mm
NUBECULARIA LUCIFUGA
SPIROLOCULINA ANTILLARUM
QUINQUELOCULINA LAMARCKIANA
MASSILINA MILLETTI
TRILOCULINA OBLONGA
TRILOCULINA SP.
TRILOCULINA TRICARINATA
PENEROPLIS PLANATUS
DISCORBIS DIMIDIATUS
AMMONIA BECCARII
ELPHIDIUM ARTICULATUM
ELPHIDIUM CRISPUM
ELPHIDIUM MACELLIFORME

Distributions of assemblages of species of fossil foraminifera within the late Pleistocene sections of Spencer Gulf cores can generally be interpreted on the basis of the presence of the same species in the modern surficial sediments of the gulfs. In particular, palaeo sea level changes can be inferred from changes, within cores, in percentage abundances of selected species, such as *Massilina milletti*, which have known relationships to sea level in the modern setting.

Thus, for example, the distribution of *M. milletti* in the Mambray Formation of vibrocore #RED 51 (Fig 10.2E) signifies a bipartite peak of sea level c.125,000 yr B.P., an observation that is further substantiated by lithological and palaeontological evidence in the equivalent interval of vibrocore #SG245 (see page 5.75 for text discussion).

M. milletti similarly signals the peak of sea level at c.105,000yr B.P. in the False Bay Formation of vibrocore #SG109 with maximum abundance at a core depth of 200cm (Fig 10.2D). Both above and below this horizon its numbers are less, and more shallow waters are also signified by larger numbers of species such as *Discorbis dimidiatus* and *Nubecularia lucifuga.*

Only one of the Spencer Gulf cores examined in the course of these studies provided any meaningful palaeontological record of the c.82,000 yr B.P. transgression. The Lowly Point Formation in vibrocore SG223 is about one metre thick (Fig. 10.2C). *M. milletti* and *Quinqueloculina lamarckiana* are the dominant species within this interval, together signifying deeper water sedimentation for the unit, which appears to have been truncated by erosion.

Subsequent late Pleistocene high stands of sea level were too low for further innundation of Spencer Gulf. However, in adjacent and deeper Gulf St. Vincent, the vibrocore programme recovered stratigraphically unnamed sediments deposited during 45,000 to 30,000 yr B.P.. These presumably overlie older late Pleistocene strata, including the Glanville Formation and stratigraphic equivalents of False Bay and Lowly Point Formations.

The numerical *Elphidium crispum/E. macelliforme* relationship with water depth, derived from modern populations of these foraminifera in northern Spencer Gulf, has been applied to equivalent fossil assemblages preserved in the 45,000 to 30,000yr B.P. strata of Gulf St Vincent, so generating sets of calculated palaeo water depths. Successive values so obtained for sediments recovered by vibrocores #SV4 and #SV5 show that sea levels in Gulf St Vincent for this time fluctuated between -22 and -28 metres (Chapter 7). Similar values of -27 to -30 metres were obtained for vibrocore #SV23, further to the south (Chapter 8).

In southeastern South Australia, the late Pleistocene sea level fluctuations greatly influenced coastal and marginal marine sedimentation, and consequent phases in the construction of Robe and Woakwine Ranges. Emergence of the southern Australian continental shelf, during oxygen isotope stage 2, exposed large areas of predominantly bioclastic carbonate sands, which were subsequently redistributed by wind, forming blankets of dunes. The Holocene marine transgression geomorphically restructured much of this material as the modern coastal beach/dune complex.

Holocene

Present day Spencer and St Vincent Gulfs lie within "the Holocene non-tropical coastal and shelf carbonate province of southern Australia" (Gostin et al., 1988). They receive little deposition from terrigenous sources, but, nevertheless, biogenic input has ensured a steady supply of sediment throughout Holocene time.

Most Spencer Gulf vibrocores recovered meaningful sections of the Holocene Germein Bay (=St Kilda) Formation (Fig10.2C, D, E). The onset of the Holocene transgression is generally signified by the presence of established shallow water species, such as *Peneroplis planatus* and *Discorbis dimidiatus* and relatively small numbers of *M. milletti.* Increasing depths of water resulted in rapidly expanded populations of *M. milletti* and loss of the shallow water species. Later and significant Holocene water shallowing is indicated by these species towards the tops of these cores. These features are well illustrated for the Germein Bay Formation in vibrocore SG109 (Fig.10.2D).

Late Holocene shallowing in northern Spencer Gulf can be attributed to isostatic uplift of this region in response to increased water mass loading of the Holocene ocean (see pages 5.78 to 5.80 for text discussion). In more southern, central Gulf St Vincent, where it could be predicted that such an isostatic signal should be absent, or at least less apparent, the *Elphidium* ratios in vibrocores #SV4, #SV5 and #SV23 provide no convincing evidence for Late Holocene shallowing (Figs 7.15, 7.16 and 8.24).

At the time of writing, much conjecture prevails concerning the future of global sea level. Demonstrably increased levels of pollutant carbon dioxide and other gases in Earth's atmosphere have led to credible predictions of "greenhouse" global warming, increased melting of polar ice masses and consequent rise of sea level. However, the findings reported in this thesis, and those of many other contemporary researchers, clearly document a record of dramatic sea level fluctuations for the Late Quaternary. Earth's natural systems may yet prevail and counteract the "greenhouse" influence.

In any scenario, it is clear that modern seaboard human populations, like our earlier Aboriginal counterparts of coastal southeastern South Australia (Chapter 9), will need to accommodate the future variability of sea level.

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