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THE HOLOCENE NON-TROPICAL COASTAL AND SHELF CARBONATE PROVINCE OF SOUTHERN AUSTRALIA

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by

V.A. GOSTIN

A.P. BELPERIO
REGIONAL GEOLOGY

and

J.H. CANN

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V.A. Gostin 1, A.P. Belperio 2 and J.H. Cann 3

1 Department of Geology and Geophysics, University of Adelaide, G.P.O.Box 498, Adelaide, S.A.5001 [Australia]

2 Department of Mines and Energy, P.O.Box 151, Eastwood, S.A. 5063 [Australia]

3 School of Pure and Applied Science, SACAE, Salisbury East, S.A. 5109 [Australia]

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ABSTRACT

Carbonate-dominant sediments are currently forming and accumulating over the extensive marine shelf of the passive margin of southern Australia. A dearth of continental detritus results from both a very low relief and a predominantly arid climate. The wide continental shelf is bathed by cold upwelling ocean waters that support luxuriant growths of bryozoa and coralline algae, together with sponges, molluscs, asteroids, benthic and some planktonic foraminifera. The open ocean coast is battered by a persistent south-west swell, resulting in erosion of calcrete-encrusted Pleistocene eolianites. Much sediment is reworked and overall shelf sedimentation rates are low. High energy microtidal beach/dune systems occur between headlands and along the very long ocean beach in the Coorong region. The northern, more arid coastal areas also contain saline lakes that precipitate gypsum from infiltrated seawater, and display marginal facies of aragonite boxwork to fenestral carbonate crusts, with stromatolites and tepee structures. In contrast, the southern, seasonally humid Coorong region, has a predominantly continental groundwater regime where sulphate is rare, and the high summer evaporation precipitates dolomite, magnesite and aragonite muds. Fenestral crusts, breccias, tepees and some stromatolites are also present.

St. Vincent and Spencer gulfs both afford some protection from ocean swell, but tidal amplitude and currents increase, and a depth and inundation-related zonation of plants and animals is established. Muddy carbonate sand accumulates on the sea floor below 30m, where filter-feeding bryozoa, bivalves and sponges dominate. In shallower regions, seagrass meadows contain a rich fauna that results in rapid accumulation of an unsorted muddy bioclastic sand. Mangrove woodlands backed by saline marsh with cyanobacterial mats are common, and accumulate mud-rich and gastropod-bearing sediment. As tidal amplitude and desiccation increase northward into both gulfs, a supratidal zone bare of vegetation (sabkha) becomes the site for deposition of gypsum-rich and fenestral calcitic mud.

INTRODUCTION

Whilst the Great Barrier Reef of tropical, northeastern Australia is well known around the world for its spectacular carbonate sedimentation, it is not generally appreciated that on the southern edge of the same continent, a greater expanse of continental shelf is the site of non-tropical biogenic carbonate formation. This paper summarizes the variety of modern environments and sedimentary facies present in this region, and the major factors responsible for sediment accumulation and preservation.

The area discussed extends almost 2000 km from east to west, and spans eight degrees of latitude, from 40° south at Bass Strait to about 32° at the head of the Great Australian Bight, and at the northern tip of Spencer Gulf (Fig.1). A similar latitudinal position is occupied by the North Island, New Zealand, where closely comparable cool temperate carbonates are present [Nelson, 1978; Nelson et al., 1982].

TECTONIC SETTING

The southern edge of Australia has been a passive continental margin since rifting from Antarctica in the Cenomanian [95 Ma]. In gross morphological terms, this margin forms part of the Australian-Antarctic Depression whose meridional axis passes through Lake Torrens and Spencer Gulf [Veevers, 1982, 1984, Fig.150]. The two gulfs, Spencer and St Vincent are flanked by the South Australian Highlands [under 1000 m], and form active intra-cratonic graben complexes, as shown by moderate seismicity, and up to 600 m of Cainozoic sediment in St Vincent Basin [BMR, 1979; Daily et al., 1976]. On either side of this median zone lie two vast areas of low topographic relief, with the Mt. Gambier - Coorong region undergoing gentle upwarp during the Quaternary.

BATHYMETRY

The southern edge of the Australian continent has a wide continental shelf [up to 200 km] in the Great Australian Bight and at the mouth of the Murray River, with water depths mostly greater than 50 m. In contrast, the shelf is narrow and relatively steep off the southeast coast and in the vicinity of the central gulfs. In these regions the shelf-slope break is at 170-180 m, deeper than the 130-140 m recorded in the Bight and off Bass Strait. This indicates continued subsidence, as observed by Conolly and von der Borch [1967] and von der Borch et al. [1970]. These authors also described the structure and morphology of the carbonate-rich continental slope off southern Australia, including several spectacular submarine canyons.

Spencer Gulf extends 300 km into the continent and is 100 km wide near its mouth. Water depth is generally less than 25 m, and is only 45 m near its entrance. Similarly, Gulf St.Vincent, with an area of some 7,000 km^2, has a maximum water depth of only 41 m. Given the shallow character of the embayments and marine shelf, the ca 150 m sealevel fluctuations resulting from Pleistocene ice ages profoundly influenced the accumulation and preservation of marine sediment in this region [Hails et al.,1984].

CLIMATE AND THE MARINE ENVIRONMENT.

The prevailing climate is essentially cool temperate in the south and Mediterranean to semi-arid in the north, with a concentration of rainfall in winter that is greatly exceeded by evaporation during the rest of the year (Fig.1). Much of the southern coast faces the stormy Southern Ocean, and is generally windswept and battered by a persistent southwest swell [Short and Wright, 1984]. Even the gulf entrances do not escape this influence, although further north into the gulfs, the effect of swell decreases and waves generated locally within the gulfs become important.

The very low average elevation of the Australian continent, together with today's predominantly arid climate, results in limited erosion and sediment transport into the sea. The Murray-Darling river system debouches into the Southern Ocean along this coast, but the extremely low gradient of this system allows only the finest suspended sediment to be discharged. During the ice ages, increased runoff was channelled through this river system, transporting greater quantities of river sediment. However, this sediment bypassed the shelf completely, and was funnelled via a set of submarine canyons into the deep ocean.

The tidal amplitude in southern Australia is 1.5 to 2 m during Springs, reaching 3 m at the head of Gulf St Vincent and almost 4 m in Spencer Gulf. Storm coastal setup occasionally creates surges and increases this to 5 m. As a result, intertidal and supratidal environments are important areas of sedimentatiom in both gulfs.

Sea surface temperatures have a small seasonal range of about 10-17° around Tasmania, and 14-22° in the Bight [Bye, 1983; Womersley, 1981a]. Within the gulfs the temperature range increases and becomes 13-26° near Adelaide, reaching 10-29° at the head of Spencer Gulf [Bye, 1976; Johnson, 1981]. Salinities vary only slightly along the ocean coast due to a lack of significant stream discharge. Values are generally 35-37‰, but increase to maxima of 47‰ and 49‰ at the heads of gulfs St Vincent and Spencer, resulting in a reverse estuary effect [Bye, 1976, 1981; Womersley, 1981a]. Extensive intertidal flats in these northern areas have such high summertime salinities that ephemeral salt crusts may result, and supratidal muds usually contain gypsum.

Biogeographically, the southern Australian shallow-marine biota forms part of the Flindersian Province, a region characterised by a relatively distinct and homogeneous flora and fauna [Womersley, 1981b; J.A. Talent in Veevers, 1984, p. 82]. Indeed this province has an outstanding richness of marine plants, and along the coast their total biomass greatly exceeds that of the fauna [Womersley, 1981a]. Many of the larger algae and seagrasses provide shelter and a substrate for smaller plants and animals including diatoms and various carbonate-secreting biota like coralline algae, foraminifera, molluscs, and bryozoa. The general subtidal ecology is described by King [1981a], Womersley [1981a,b], and Shepherd and Sprigg [1976]. Within protected embayments and along low wave energy gulf coasts, a broad intertidal zonation of organisms is clearly evident. These include the single mangrove species Avicennia marina, and salt-marsh (halophytic) vegetation, cyanobacteria, and intertidal seagrasses [Belperio et al., 1988; King, 1981b; Womersley and Thomas, 1976].

Special attention has been focussed recently on the environmental variability of foraminiferal assemblages within recent sediments, an attribute that has proved successful in interpreting marine palaeo-environments and sea level histories, through the Quaternary [Cann and Gostin, 1985; Cann and Murray-Wallace, 1986; Cann et al., 1988].

MODERN ENVIRONMENTS OF CARBONATE SEDIMENTATION

Southern Australian carbonate sedimentation may best be described by referring to four main areas: the Central Gulfs, the Eyre Peninsula Coast, the Coorong Area, and the Continental Shelf.

Central Gulfs

Sediment accumulation within both gulfs is largely controlled by the action of tidal flows, and by waves along the more exposed coasts. This has resulted in a clear zonation of marine sediments, plants and animals (Figs 2,3,4 and 5), documented by Shepherd and Sprigg [1976], Burne and Colwell [1982], Gostin et al.[1984], Cann and Gostin [1985], Belperio et al.[1988], and Cann et al.[1988].

Deeper Subtidal Environments.

In the central parts of both gulfs, below about 15-20 m, the sea floor supports a filter-feeding benthos of sponges, bryozoa, bivalves, brachiopods, crinoids, ascidians, and seapens. Skeletal fragments derived from some of the above, together with those from benthic foraminifera, and predatory molluscs and echinoderms, are organically comminuted on the sea floor, and are bored by sponges, algae, and gastropods. Intense bioturbation by various fauna including prawns, crabs, and holothurians, has been observed by Shepherd and Sprigg [1976]. These processes have produced a poorly sorted, slightly muddy, fine sand which has accumulated at a fairly slow rate, forming a sheet-like deposit, 0.5-2 m thick, over the last 8000 years [Hails et al. 1984; Cann et al.,1988]. Most of the recognizable fragments are those of foraminifera, molluscs and bryozoa, with lesser amounts of echinoid, foram, coralline algal, and other grains. Within both St. Vincent and Spencer gulfs, benthic foraminifera are abundant in all surficial sediments. The relative abundance of various species correlates closely with water depth (Fig.3) and distinctive foraminiferal biofacies have been identified for intertidal, shallow subtidal and deeper subtidal environments. Down-core analyses of foraminifera in vibrocore samples has aided elucidation of Quaternary sedimentation and palaeoenvironments [Cann et al., 1988].

Near major headlands and in other regions of strong tidal currents, the sea floor may be swept clean of sediment or is covered by a veneer of coarse carbonate gravel. Such an area is generally flanked by, or passes downstream to a mobile sandy floor covered with megaripples. In northern Spencer Gulf at depths of 10-20 m, where tidal velocities may reach 1.5 m/sec, such an area of sea floor was mapped using side-scan sonar

[Gostin et al., 1984]. The megaripples here are usually 2-10 m from crest to crest, up to 1.3 m high, and commonly occur in 200-500 m wide belts. They consist of well sorted to moderately sorted, medium and coarse grained sand composed predominantly of bivalve fragments.

In the deep [30-70 m] entrances to Gulf St Vincent, strong tidal currents of 0.5-2.5 m/sec have been recorded [Shepherd and Sprigg, 1976]. The rocky surfaces generally consist of cemented Pleistocene carbonates colonised by sponges, algae, ascidians, bryozoans, crinoids, and gastropods. Debris from such areas is swept along until deposited in less vigorous areas where the sandy sea floor is colonised by sparse seagrass [Heterozostera tasmanica], brachiopods, seapens, and bryozoa especially Lunulites sp. (Fig.2). Isolated areas are sites of coralline algal [Lithothamnion] accumulation [Shepherd and Sprigg, 1976].

Shallow Subtidal Environments.

A most impressive and geologically important environment is seen in the extensive growth of seagrass meadows around the gently sloping gulf margins, and the formation of discrete seagrass banks (Figs 4,6). Three species of Posidonia [tapeweed] and Amphibolis antarctica form the predominant flora from low water down to about 10 m in the northern parts, increasing to 30 m at the gulf mouths. Seagrasses have well developed rhizome systems, strap-like leaves, and grow gregareously, thus enabling them to withstand water movement [King, 1981a]. They provide both a shelter and a substrate for a diverse biota, much of which is eventually trapped and bound together into a carpet-like matte. In the case of the shallow-water Posidonia australis, the decaying leaf sheaths also leave behind a pale fibre that gives the sediment matte additional strength.

Many species of red algae [including calcareous varieties], bryozoa, forams, sponges and diatoms form epiphytes on the long Posidonia leaves.

The fauna also includes various large bivalves [Pinna, Ostrea and Katelysia], smaller gastropods, hydroids, echinoderms, crustaceans, polychaetes and ascidians [Shepherd and Sprigg, 1976]. Detritus from such an organic factory accumulates largely in place, and its decomposition creates a strongly reducing environment. The dominance of forams, molluscs and algae is characteristic of a coolwater, high-salinity "foramol" province (Lees and Buller, 1972 ; Burne and Colwell, 1982). Near the coast, terrigenous and aeolian sands and muds become incorporated into the sediment which is best described as a structureless, uncompacted, and very poorly sorted skeletal sand [Gostin et al., 1984].

Accumulation rates vary from 0.2 to 2.7 mm/yr. In northern Spencer Gulf (Fig.6), during the last 6000 years, up to 6 m of sediment have accumulated in the shallow seagrass meadows, reducing the subtidal area by 60% [Belperio et al., 1984]. In low wave energy areas such as Port Gawler [Figs 1,2], seagrass growth and consequent bioclastic sedimentation, has led to a shallowing of the offshore profile, so decreasing the degree of storm wave attack. This has allowed mangroves to establish themselves in the intertidal zone, further reducing wave energy and consolidating the progradation of the coast [Cann and Gostin, 1985].

In contrast to the above, some coastal areas experience moderate to high wave energy. Here the resulting turbulence creates crescentic erosional gutters or 'blowouts' in the Posidonia meadows, and redistributes the sediment, some of which is swept away by longshore currents [Shepherd and Sprigg, 1976]. In the Adelaide area such complete sediment reworking occurs within a hundred years, and the revegetated matte is usually less than 1 m thick [Thomas and Clarke, 1988]. Coastal environments in such areas are typically sandy beaches backed by coastal dune systems, but locally these may form spits with associated swamplands such as those of the Port Adelaide area [Bowman and Harvey, 1986; Belperio et al., 1988].

Intertidal Environments.

Extensive intertidal flats and swamps are developed in very shallow and low wave energy northern areas of both gulfs [Figs 4,5]. These are distinctly zoned with each sub-environment having a characteristic plant and animal assemblage that is largely dependent on the degree of tidal inundation and hydrodynamic conditions [Womersley and Thomas, 1976; Belperio, 1985a,b; Cann and Gostin, 1985]. In the low intertidal zone the seagrasses Zostera and Heterozostera [eelgrass] usually dominate, and grade into sand flats bare of vegetation. Molluscs, crustaceans and polychaetes are the predominant infauna. Higher intertidal sand flats may be covered by cyanobacterial (algal) mat. Sediments on the sand flats and eelgrass areas are various mixtures of skeletal carbonate and terrigenous sands, the components generally being gastropods and forams, with some bivalves and calcareous algae.

Mangrove woodlands grow from about mean sea level to just below spring high tide level. These trees also line the upper reaches of tidal creeks where they penetrate into a saline marsh or samphire zone consisting of halophytes such as Halosarcia and Sarcocornia spp. Due to the very efficient baffling action of these plants, the sediments are usually silty or muddy and covered to varying degrees by cyanobacterial mats and diatoms. In depressions where the mats are thick, sulphate reducing bacteria are very active, and the surface sediment is black and anoxic. A short distance below however, mangrove pneumatophores, plant roots, and abundant crab burrows oxygenate the sediment. Depletion of carbonate may occur under the mangrove woodland by the leaching action of organic acids [Gostin et al., 1984]. A network of tidal channels usually crosses the woodland. Current speeds are variable and sediment type varies accordingly. Major channels have large disarticulated bivalves and a characteristic small turriform gastropod Batillaria diemenensis. Deeper backwater channels are enriched in black anoxic mud, and some have formed a peat from the accumulation of masses of washed-in organic debris.

Supratidal Environments.

Supratidal areas inundated only during storm tides or after heavy rains, are areas of extreme temperature and salinity variations. They increase in width northward with increasing desiccation and are best developed in northern Spencer Gulf. Here they are mainly bare carbonate and gypsiferous flats showing some evidence of deflation and formation of low gypsum sand dunes. Gypsum crystals and some dolomite precipitate within a fenestral, buff coloured, calcitic mud. Such areas resemble the coastal sabkhas of the Arabian Gulf, but lack the same variety and quantity of evaporite minerals [Gostin et al., 1984]. Cyanobacterial mats occur only after flooding and small depressions may become centres of temporary evaporite precipitation and charophyte growth. After further desiccation and burial the sediment may be characterised by a variable mixture of calcite, dolomite, charophyte oogonia, foraminifera, ostracods and wind-blown terrigenous sediment [Burne et al., 1980].

Lithification is absent from the gulf coasts except for a small area at Fisherman Bay [Fig.1], where springs of saline continental groundwater occur in the supratidal zone. These form aragonite cemented cavernous pavements with tepee structures, megapolygons, pisoliths and other spelean features, whose structure and chemistry have been described in detail by Ferguson et al. [1982].

The total thickness of upper intertidal and supratidal sediments is usually less than 1 m, yet these sediments form a distinctive cap to a prograding carbonate sequence that can be recognised in older formations.

Eyre Peninsula Coast.

The sweep of coastline from the head of the Great Australian Bight to the gulf entrances is over 500 km long, with many islands, rocky headlands, small embayments, and surf-pounded beaches. Coastal geography has largely been controlled by the irregular to undulating surface of calcreted Pleistocene eolianites and the underlying Precambrian basement that was submerged by the postglacial high sea level. Dominant coastal processes are those of wind, and a persistent strong southwesterly swell. Only in protected embayments and in coastal saline lakes has there been any accumulation of recent aqueous sediments. In addition, strong winds have transported the coastal sediments inland covering large areas with carbonate-rich sand dunes. The largest active sand sheet, measuring 300 km^2, is in southern Eyre Peninsula, but many large areas have become active after disturbance of the protective vegetative cover. These dune sands consist mainly of fragmented bivalves and gastropods with lesser amounts of coralline algae, foraminifera, echinoid spines, and bryozoan debris, an assemblage reflecting the thriving biota in the present nearshore zone [Warren, 1983]. The mineralogy of both the beach and dune sands is dominantly low-Mg calcite, with variable proportions of aragonite and high-Mg calcite. Pleistocene equivalents of these sands cover extensive areas of Eyre Peninsula (Fig.1). These ancient dunes are generally weakly cemented and erode with relative ease, so that reworked grains form a significant proportion of the Holocene sands.

Protected Embayments.

A study of several bays shows progradation of intertidal sand flats, mangroves and cyanobacterial- halophyte marsh across seagrass banks dominated by Posidonia australis. In the case of Tourville Bay [Fig.1], with an area of 100 km^2, modern and reworked bioclastic sediment virtually infilled the area with up to 7 m of sediment in only 2,000 years after the

Holocene stillstand [Belperio et al., 1988]. The plant/sediment zonation is thus similar to that in the central gulfs, benthic foraminifera are a major component of the sediment [Lablack, 1985], and the vertical sequence of lithofacies generated is similar to that of the gulfs. Port Douglas embayment within Coffin Bay [Fig.1], lacks any mangroves, but has abundant seagrass and extensive subtidal sand shoals developed as a flood tidal delta cutting through a barrier beach [Freeman, 1985]. Most of the sediment is medium to fine bioclastic sand, with a high content of reworked carbonate grains resulting in a subequal proportion of calcite to aragonite.

Cut-off Embayments and Coastal Saline Lakes.

Where an embayment became completely cut off by transgressive dunes, (eg. Fowlers Bay, Marion Lake, Figs. 1 and 7), or where seawater was able to seep into coastal depressions (eg. Lake MacDonnell), well-developed gypsum precipitates formed as a result of the extreme aridity that was relieved only by some winter rains. The variety of carbonate and gypsum structures and facies that filled these depressions are well illustrated by von der Borch et al.[1977], and Warren [1982a,b]. Lake Macdonnell, a large depression with an area of 160 km^2, contains crystalline gypsum up to 10 m thick creating gypsum reserves in excess of 500 million tonnes [Warren, 1982b; Flint, 1987]. Sections typical of protected and cut-off embayments are illustrated in Fig. 8.

According to Warren, it is the hydrological setting that controls the depositional fabric and grain size of gypsum. Young deep lakes have stable high salinities of the near-bottom brines causing continuous deposition of gypsum and aragonite surrounded by an algal/bacterial mush. The gypsum crystals grow freely, pushing aside the aragonite pelletoids and interlocking to eventually form gypsum domes. With progressive shallowing and reduction in lake volume, seasonal freshening and water level variation induces a pronounced layering of aragonite and gypsum. Some dissolution of gypsum then occurs, creating a flat surface of vertically orientated twinned gypsum crystals [Fig.9A]. With a shrinking brine pond, the seasonal salinity changes increase, and a laminated to ripple-marked gypsarenite forms (Fig.8). In ephemeral lakes, the upper surface is much reworked, and a finer grained gypsite unit is normally present. The lake margins meanwhile precipitate various aragonitic structures including a widespread basal, highly porous boxwork boundstone. This passes upward into a fenestral veneer boundstone crust that may grade lakeward into an algal [tufa] or a stromatolitic boundstone (Fig.9B, von der Borch et al., 1977). Furthermore, the marked seasonal changes in groundwater level within the surrounding dunes increase the pore pressures within the boxwork boundstone, deforming the overlying less permeable crust into tepee structures (Fig.9C), and thrusts formed along major polygonal sutures. The wide variety of tepee structures and their associated fabrics has been reviewed by Kendall and Warren [1987].

Most of these coastal salt lakes precipitate gypsum and aragonite rather than dolomite, because the salinity and the Mg/Ca ratio are kept low by continual brine renewal and/or dilution by meteoric waters [Warren, 1982b]. On the other hand, De Deckker et al.[1982] using ostracods, found that some dolomite had formed under permanent water cover.

Coorong region

Extending 300 km southeast from the central gulfs, the coastal zone consists of a low plain, gently tilted to the west by uplift around the Mt Gambier volcanic area during the Quaternary (Fig. 10). Given the predominant westerly wind and southwesterly ocean swell, a parallel set of stranded barrier beach/dune systems has resulted from this uplift and the glacio-eustatic sealevel oscillations [Sprigg, 1979; Cook et al., 1977; Schwebel, 1984]. The beach/dune systems form ridges of calcarenite, up to 40 m above the broad interdune flats or corridors. In the northwest the presently active beach/dune system is 180 km long, backed by a shallow lagoon (Coorong), 130 km long and up to 4 km wide [Figs 10 and 11A]. Only a single shallow channel connects the Coorong to the sea. This forms the mouth of the Murray River, which, during times of low flow and severe storms, allows sea water to enter and create impressive flood tidal deltas [Bourman and Harvey, 1983]. Sediments in the vicinity of the river mouth are mixed siliceous/ carbonate, but the river's contribution is predominantly terrigenous clay. Consequently away from the river, the carbonate content of both the beach/dune sands and the Coorong sediment steadily increase.

The beach/dune sand is made up mainly of molluscan and calcareous algal debris with varying proportions of older carbonate grains and quartz. Carbonate minerals in Holocene sands are biogenically derived calcite, high-Mg calcite [60-80%], and aragonite [20-40%]. In successively older beach/dune sediments, the content of aragonite and high-Mg calcite is reduced, and occasional dolomite crystals may be found [Schwebel, 1984].

Coorong Lagoon and Ephemeral Lakes.

The Coorong and former lagoonal areas consist of bioclastic sands derived from molluscs, ostracods, and foraminifera, with various amounts of carbonate mud [Brown, 1965; von der Borch, 1976]. Sediment cores indicate that the initial protected marine environment became progressively restricted and subjected to severe salinity fluctuations. These sediments are black pelletoid aragonite and Mg-calcite muds containing tests of the gastropod Coxiella confusa, the foram Ammonia beccarii, various ostracods, and oogonia. It is important to note that no dolomite or gypsum occurs in this environment.

Dolomite mud in the Coorong region was first discovered in ephemeral lakes by Mawson [1929], later confirmed and studied by Alderman and Skinner [1957] and amplified by von der Borch [1965, and subsequent papers]. In his 1976 paper, von der Borch describes how parts of the Coorong lagoon became cut off from direct contact with marine waters, and developed into coastal ephemeral lakes with the same biota as in the restricted lagoon facies, but with protodolomite and high-Mg calcite in the surface muds. Some lakes in this setting precipitate hydromagnesite and aragonite, the cause of which is presently unknown. Ephemeral lakes that are further removed from the sea, or are more than 1 m higher than the lagoon surface, precipitate protodolomite (and partly ordered dolomite) as a structureless, aphanitic, 'yoghurt' mud. This sediment consists of very fine grained amorphous spherular aggregates together with several percent of amorphous silica [Peterson and von der Borch, 1965].

Dolomite is also presently forming in interdune corridors and ephemeral lakes far from the coast (Fig.10). Its formation is therefore independent of marine waters, but rather is a result of evaporation of Ca and Mg-bicarbonate rich groundwaters [von der Borch et al., 1975; von der Borch and Lock, 1979]. The Mg is thought to derive from high Mg-calcite in the eolianites, the volcanics of the Mt Gambier region, and possibly from marine aerosols. Most of the dolomite-bearing lakes are situated where annual rainfall is between 500 and 700 mm, and mean temperature is 13.5°C. In higher rainfall areas of the Mt. Gambier region, only fresh water lakes and swamps are found.

Seasonal flushing of the ephemeral lakes by groundwaters ensures that no gypsum or halite remain in the lake sediments. Such lakes do however contain a varied and distinctive biota of charophyte oogonia, ostracods, and foraminifera [Burne et al., 1980; Cann and de Deckker, 1981]. Some lakes contain discoidal oncolites, and stromatolites, while others have the small gastropod Coxiella confusa, that has completely pelletised the carbonate mud [Mawson, 1929; Walter et al., 1973]. Desiccation of the ephemeral lake margins has produced fenestral and laminar crusts with polygonal cracks, tepee structures, and mud-chip breccias that have direct analogues in ancient carbonate rocks [Muir et al., 1980].

Continental Shelf

Most of the shelf, including the floor of Bass Strait, lies between 50 and 100 m below present sealevel. Immediately outside the Coorong however, the sea floor slopes more gently away from the long surf beach. In this region the shallow floor is seagrass covered with coarse bioclastic sands that become clay rich near the Murray River mouth.

Much of the shelf is covered either by rippled sands, or by bryozoal, sponge, and coralline algal meadows. The sediment is coarse grained, grading seaward into finer grained sands composed of fragments of bryozoa, coralline algae, molluscs, and forams, with lesser amounts of echinoids, serpulids, pteropods, corals, crustaceans, asteroids, ostracods and reworked calcareous skeletal detritus [Conolly and von der Borch, 1967; Lowry, 1970; Wass et al., 1970]. On the outer continental shelf a second band of coarse grained sands probably results from both the former location of low sealevel stands and stronger present-day currents. This region has a predominant filter-feeding biota, with thriving bryozoal 'forests' between 90 and 220m [Wass et al., 1970]. On and beyond the shelf edge the seafloor is again finer grained with bryozoal debris and planktonic foraminifera forming significant components.

DISCUSSION AND SUMMARY

The arid to cool temperate southern coast of Australia, with its generally low relief, provides only minor terrigenous sediment to the large central gulfs and wide continental shelf. This permits the growth of carbonate secreting organisms, and leads to the accumulation of bioclastic debris. Bioclastic sedimentation is thus dominant over a vast area of the continental border, forming an important modern carbonate province. These carbonate sediments occur in diverse open-marine and coastal sub-environments, from continental slope to gulfs, bays and peritidal areas, transgressive eolianite sheets, and interdune ephemeral saline lakes.

In the open sea, bryozoa are widespread, from thick forests near the nutrient-rich shelf edge, to mixed bryozoal-sponge-bivalve filter-feeding biota on the mid-shelf and the deeper parts of the tidal gulfs. Most sediments are a variable mixture of fragmented bryozoa, coralline algae, benthic foraminifera, echinoidea, and mollusca, whose composition varies with local oceanographic and substrate conditions. Sedimentation rates are generally low, and incorporation of reworked bioclasts is significant.

The interaction of climate and oceanographic setting results in three principal styles of nearshore and coastal sedimentation. These are schematically illustrated in Fig. 12. The thickest accumulation of recent carbonates occurs within bays and in the northern shallow parts of the large central gulfs [Fig. 12A]. Here the environment is protected from strong and persistent wave activity, and subject to increased tidal fluctuations. Seagrass meadows thrive in the shallow waters of generally high salinity and summer heat. They support a diverse biota that is eventually trapped and bound into a very poorly sorted organic rich skeletal sand. The skeletal fragments are typically those of foraminifera, mollusca, coralline algae, and bryozoa. An extensive intertidal area is developed displaying a clear organic and sediment zonation involving mangroves and a saline marsh, backed by a bare supratidal flat ('sabkha'), with fenestral and gypsiferous calcitic mud. Evidence of seasonal fresh-water flooding may occur in the form of ostracods and charophyte oogonia.

The second typical style of sedimentation [Fig. 12B] is that along the coastal zone of semi-arid Eyre Peninsula, an area rich in marine plants, but where a wind and wave dominant environment erodes and reworks contemporary bioclasts and older eolianites. These form thick coastal sand dunes, barrier/lagoon complexes, and transgressive eolian sand sheets. Inter-dune saline lakes typically show crystalline and seed gypsum, with marginal aragonite precipitates in the form of crusts, boxworks, stomatolites, intraclasts, and tepee structures.

The third sedimentary style is that along the coast of the Coorong lagoon [Fig. 12C], where a similar coastal beach-barrier/lagoon environment is tempered by a seasonally wet climate. The strong wind and wave activity has formed a very long sand barrier/lagoon system backed by ephemeral lakes situated in the older inter-dune depressions. Large seasonal fluctuations of evaporation and rainfall create an aragonite and Mg-calcite pelletoid mud in the lagoon, with a restricted fauna including distinctive small gastropods, foraminifera, ostracods and oogonia. The interdune depressions contain lakes during high groundwater periods, and precipitate aragonite, dolomite, and hydromagnesite muds, with a small amount of amorphous silica. Sulphates are notably absent. Structures include crusts, polygonal cracks, tepees, stromatolites, and mud-chip breccias.

It is significant that marine deposits of this carbonate province lack any major coral reef structures, large foraminifera, giant clams and gastropods, and the dominant green alga Halimeda, so typical of the tropical Australian shelf. Also absent are ooid shoals and indurated pellets or aggregates. Submarine lithification does not occur, though this is replaced by equally important processes of subaerial calcretization. Given the almost uniform salinity of the open seas, it must be presumed that lower temperatures have been a major factor controlling the types of carbonate grains. This situation has been recognised by several authors, among which Lees and Buller [1972], Schlanger and Konishi [1975], Nelson [1978], and Marshall and Davies [1978] argue the case for a distinct temperate marine millieu.

Most of the Holocene sedimentary environments described in the preceding pages have their direct analogues in the Pleistocene. Their occurrence has been controlled by glacio-eustatic sealevel changes, and their preservation depends on their degree of lithification and ultimately on tectonic subsidence. Such Pleistocene equivalents of the gulf-style sediments have been described from cores and outcrops in the same region [Hails et al., 1984; Belperio 1985a,b; Cann et al., 1988].

Schwebel [1984], following Sprigg [1979], describes the Pleistocene beach/dune, lagoonal, and lacustrine analogues of the Coorong system. Calcretization is an important process, and Warren [1982a,b,1983] describes how the Pleistocene eolianites have been preserved due to their protective calcrete carapace.

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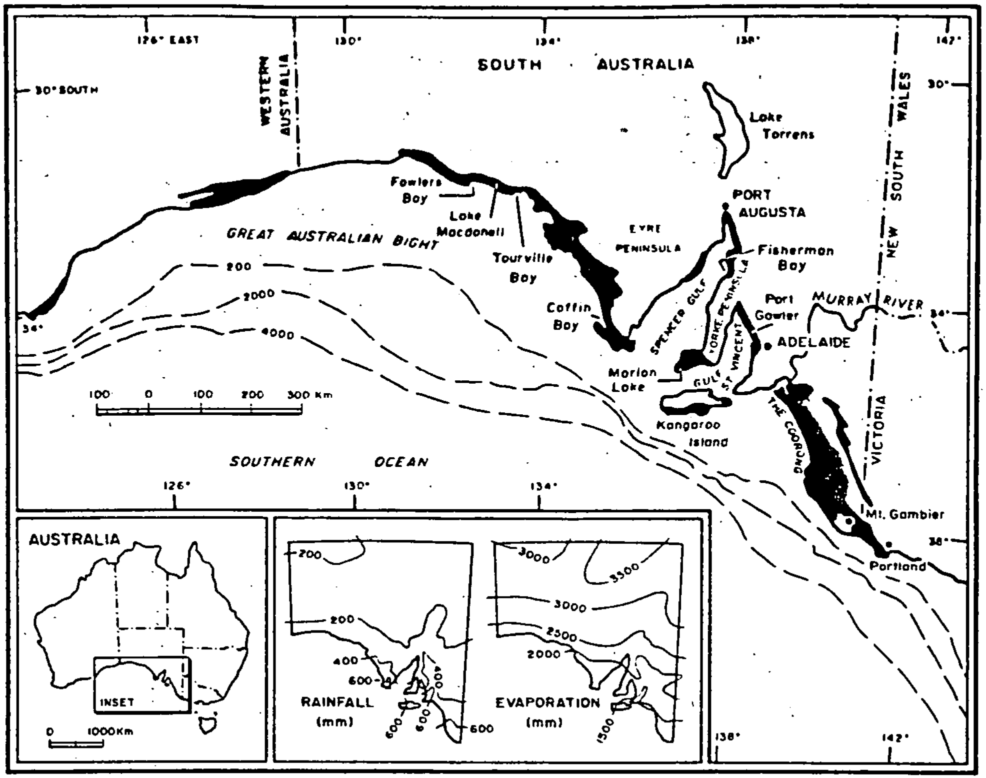


Fig.1 Location map showing distribution of Quaternary coastal carbonate sediments of southern Australia, and sites mentioned in the text. Isobaths in metres.

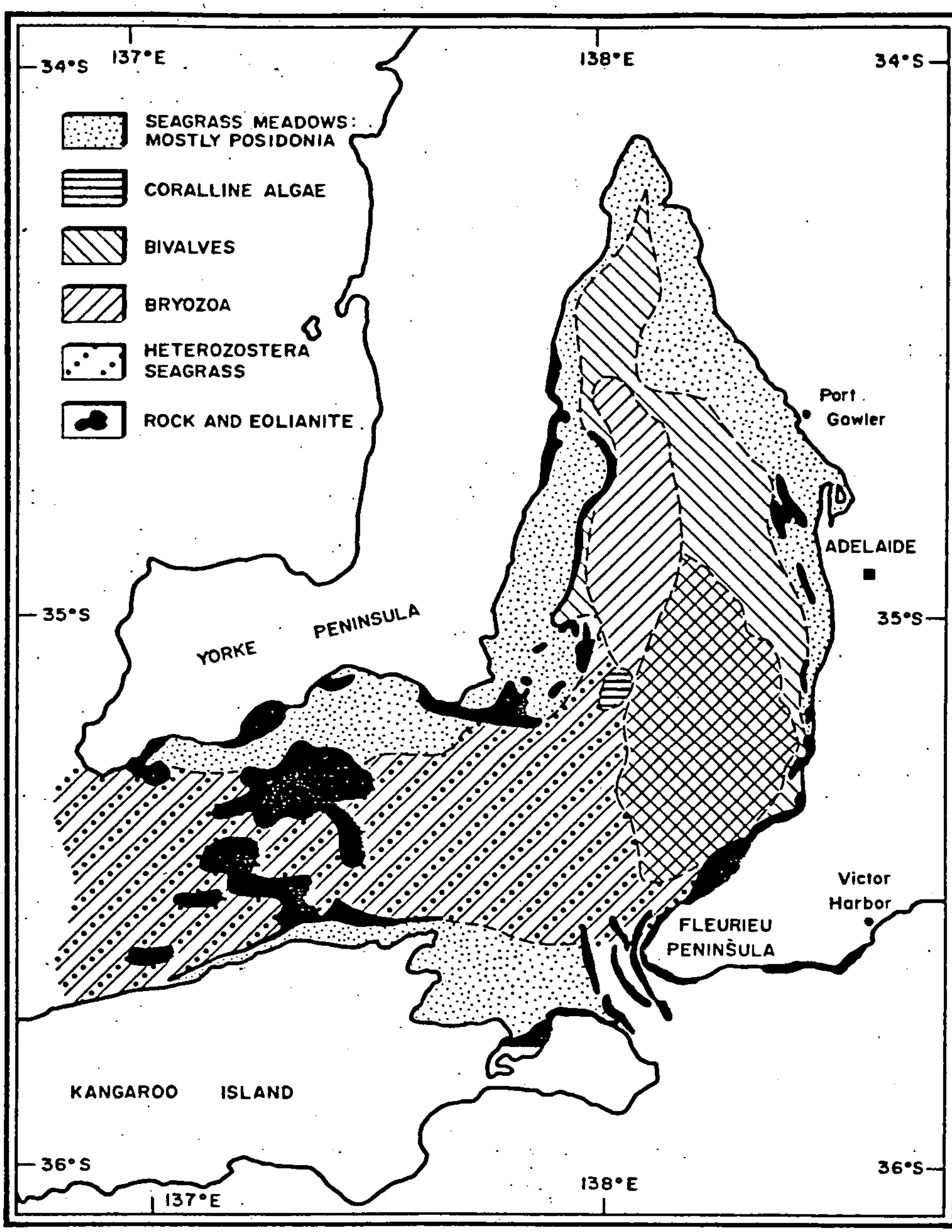


Fig.2 Distribution of communities of marine macro-organisms in Gulf St Vincent (after Shepherd and Sprigg, 1976).

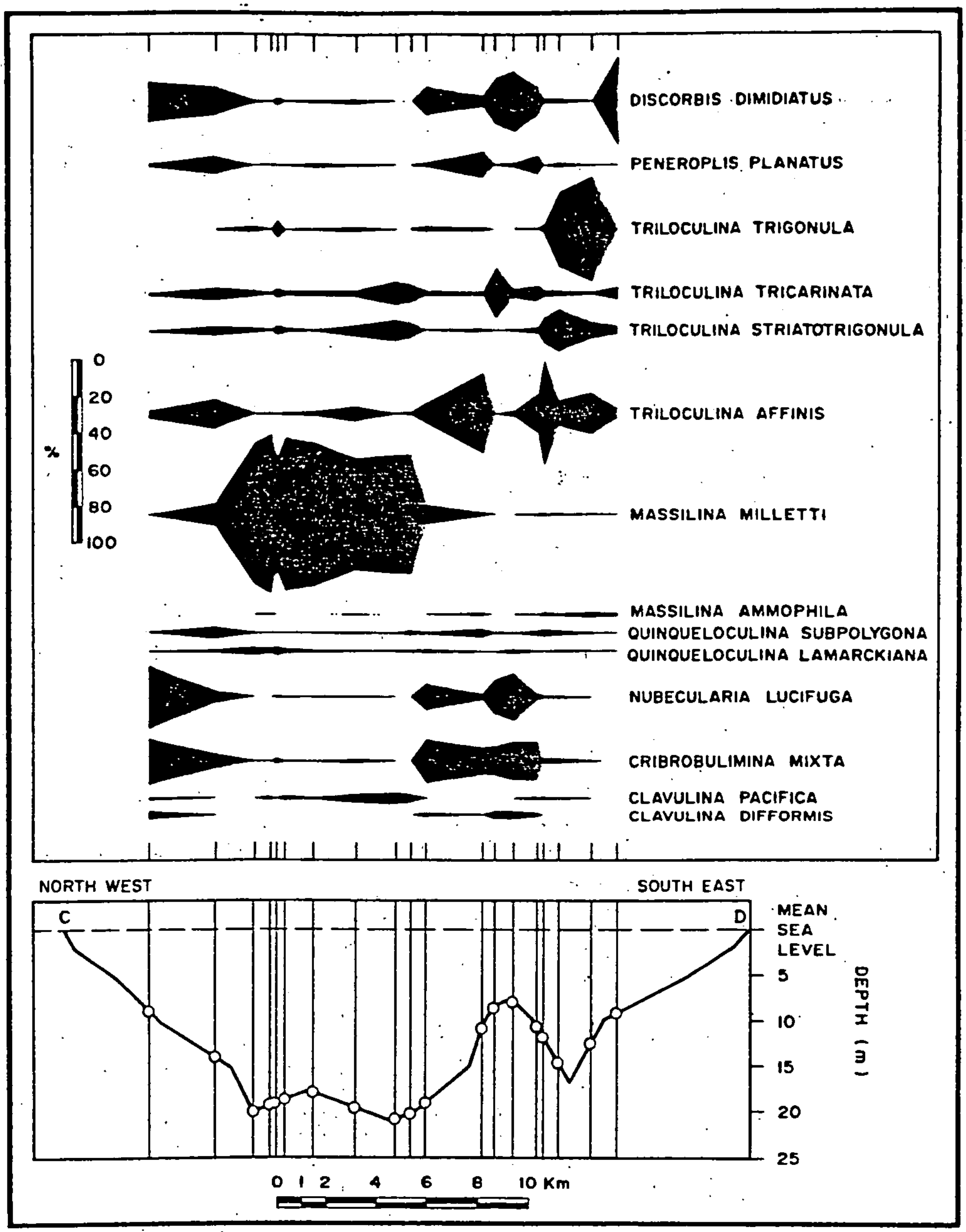


Fig.3 Percentage distribution of selected species of foraminifera compared with water depth, vicinity of Whyalla - Port Pirie, northern Spencer Gulf. Location of transect indicated on Fig 4.

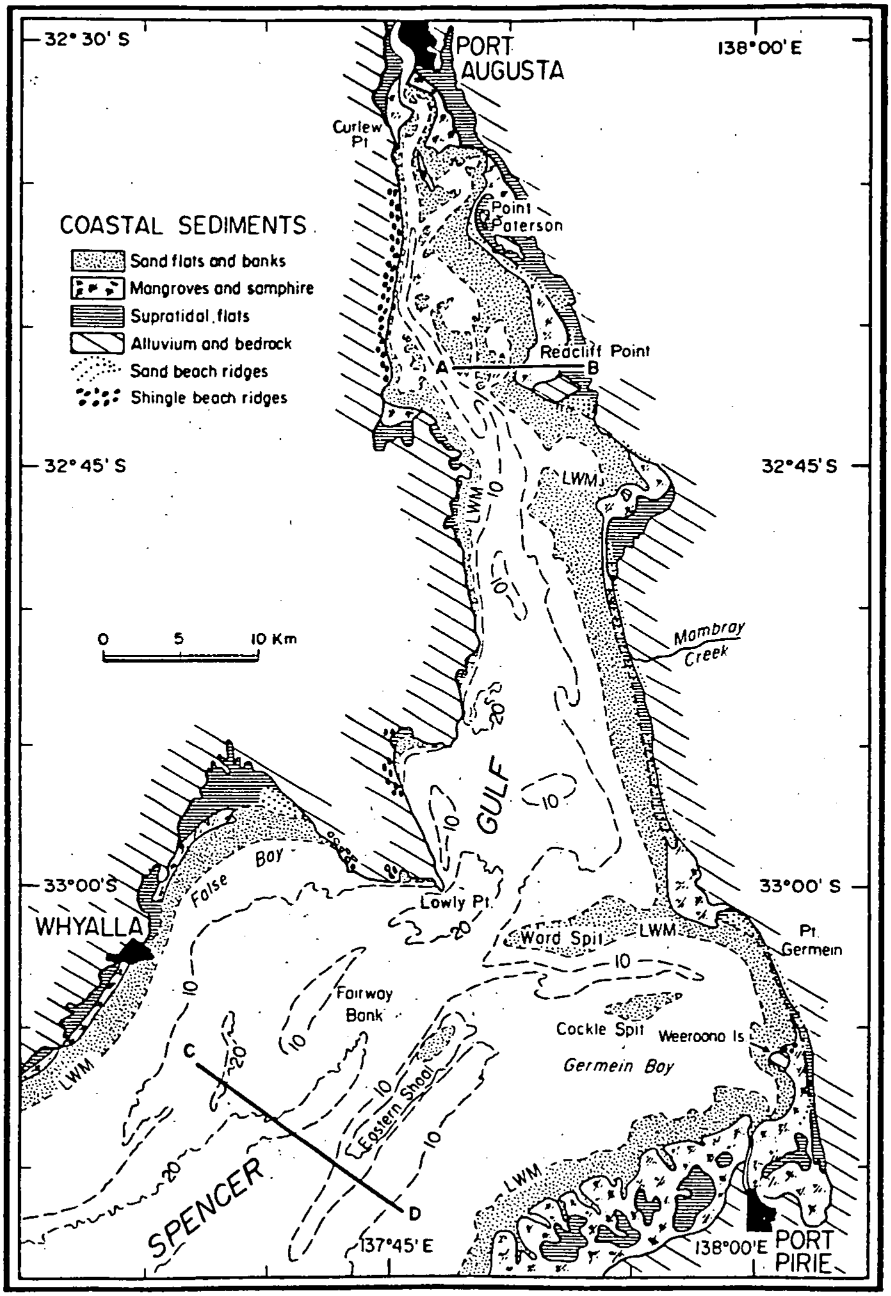


Fig.4 Coastal environments of northern Spencer Gulf (after Hails et al. 1984). For cross-sections A-B see Fig. 6, and C-D see Fig.3.

Fig.5 Vertical air photograph of the eastern Spencer Gulf shoreline near Port Pirie (near point D on Fig.4), showing shore-parallel, peritidal zonation of sub-environments: 1. shallow subtidal seagrass meadow, 2. low intertidal sand flat, 3. mangrove woodland, 4. saline marsh (samphire), and 5. supratidal flat.

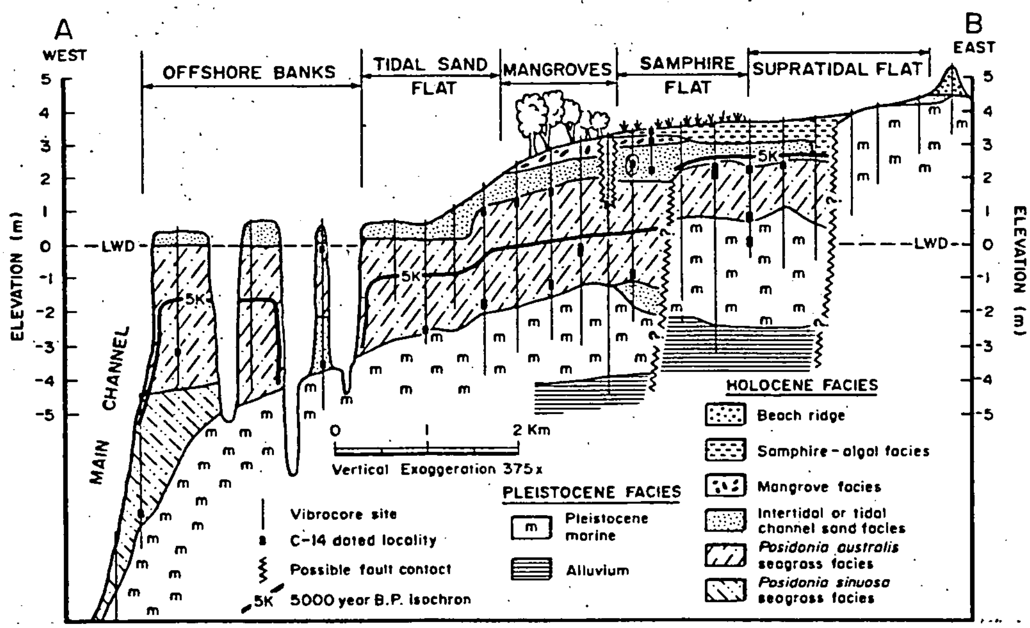


Fig.6 East-West cross-section of peritidal sediments, northern Spencer Gulf (based on core data of Belperio et al., 1984).

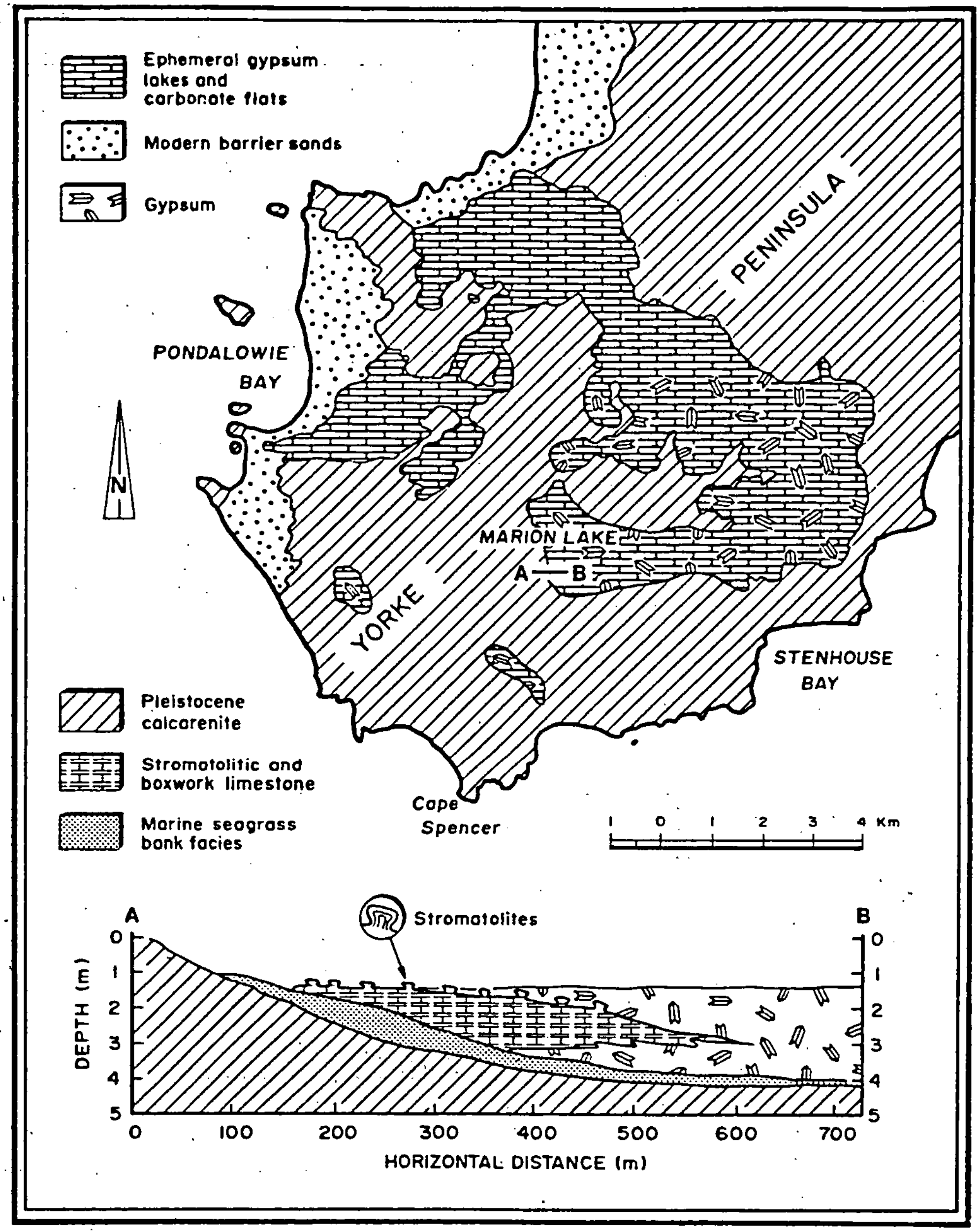


Fig.7 Saline lakes of southern Yorke Peninsula, and schematic cross-section of the margin of Marion Lake (after von der Borch et al. 1977).

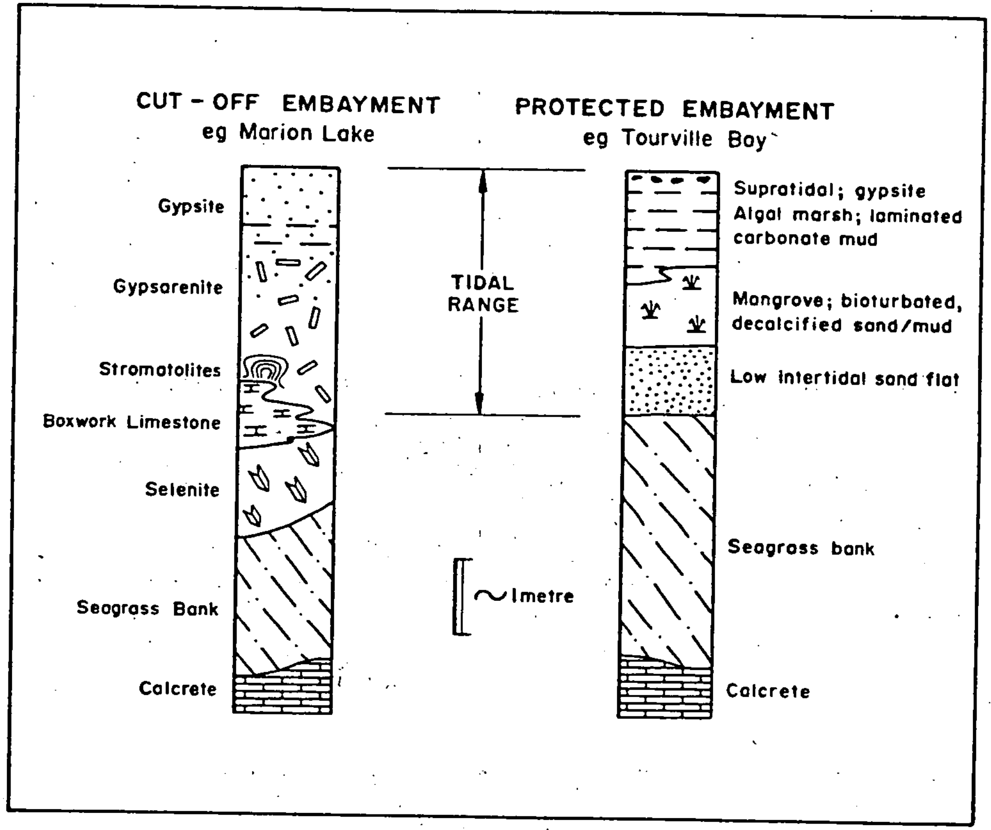


Fig.8 Generalized vertical sequences in protected and cut-off embayments on the Eyre and Yorke peninsula coasts (after Belperio et al., 1988). Example locations are shown in Fig. 1.

Fig.9 A. Cross-section through vertically orientated twinned gypsum crystals [selenite], showing horizontal dissolution and growth surfaces, Lake Macdonell, Eyre Peninsula (scale 7cm).

9 B. Stromatolitic boundstone near margin of Marion Lake.

9 C. Large tepee structure in marginal carbonates of a coastal saline lake, Eyre Peninsula.

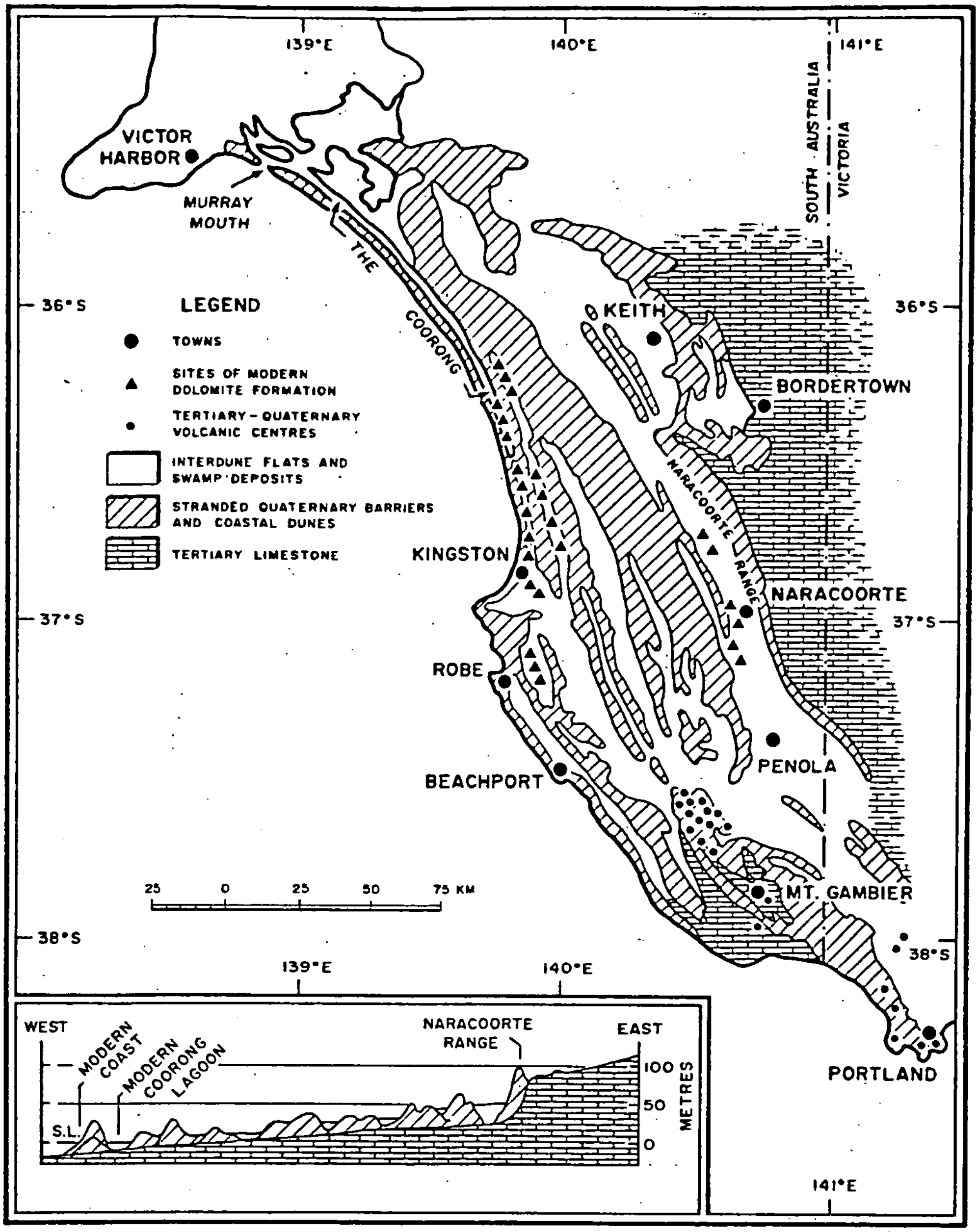
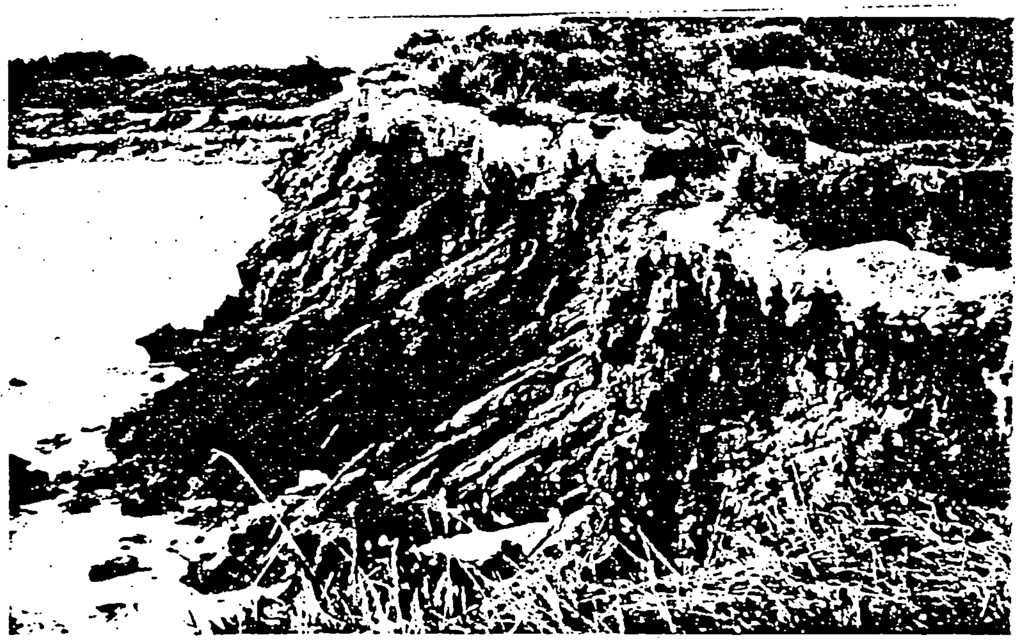


Fig.10 Map of the Coorong region showing sites of modern dolomite formation, stranded Quaternary barriers, coastal dunes and interdune areas. The composite section is drawn from the Naracoorte Range in the east through to the Coorong Lagoon and Southern Ocean coast in the west (after von der Borch and Lock, 1979; Cook et al., 1977).

Fig.11 A. Coastal dune/lagoon system near the southern ephemeral lagoon part of the Coorong, southeastern South Australia.



11 B. Erosional cross-section through coastal eolianite at Robe, showing steep, large scale cross-bedding (cliff height 5m), capped by a calcrete carapace.

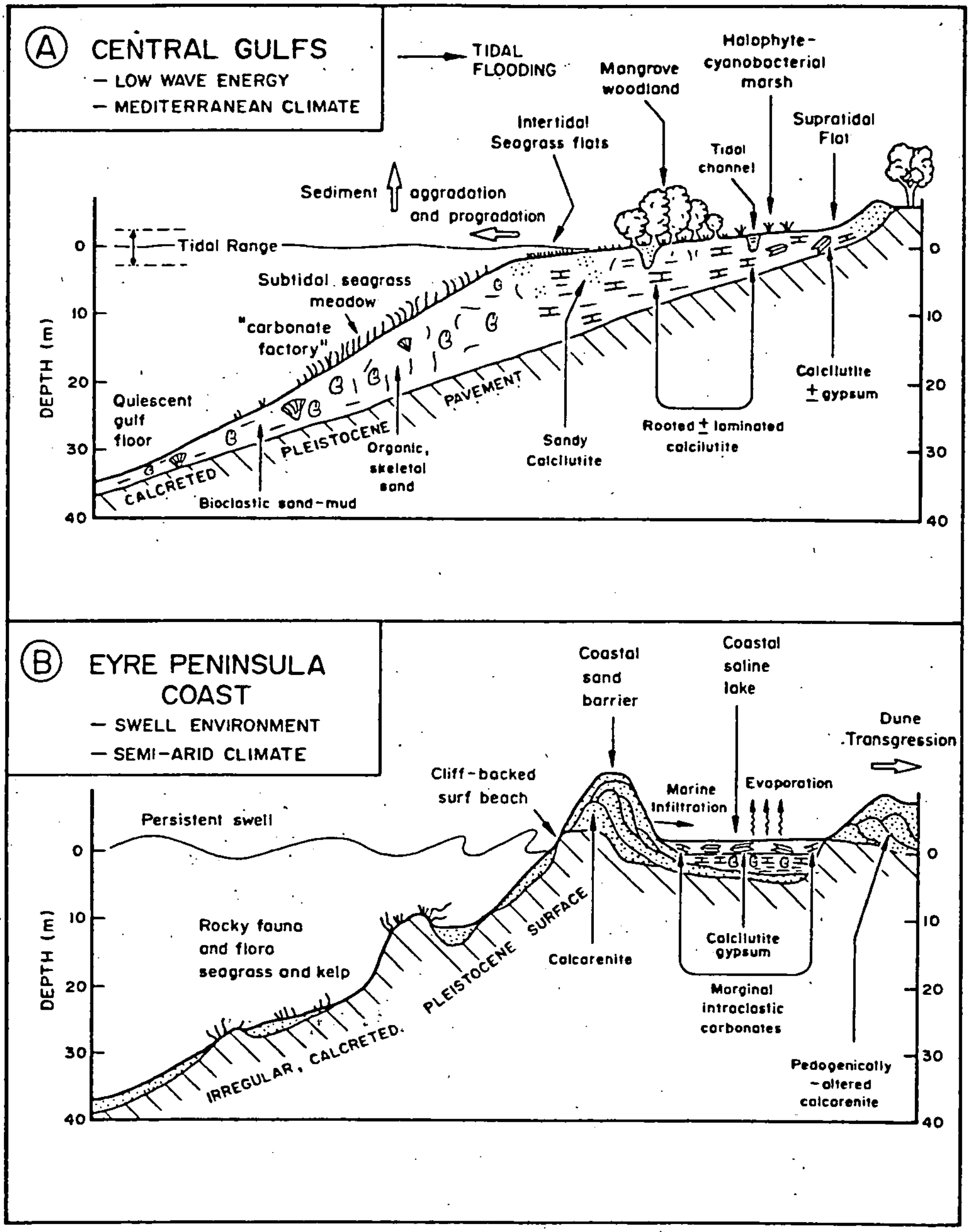


Fig.12. Schematic representation of the principal environments and styles of Holocene coastal and nearshore shelf sedimentation of southern Australia.

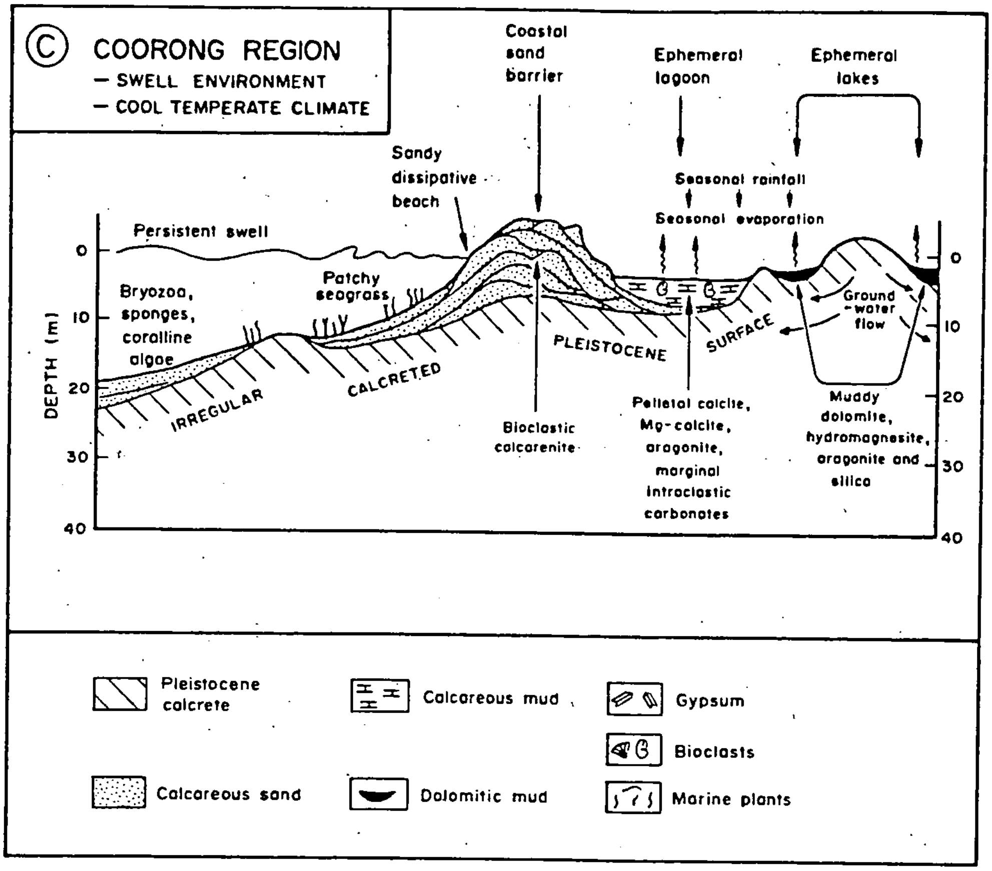


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Fig.12. Schematic representation of the principal environments and styles of Holocene coastal and nearshore shelf sedimentation of southern Australia.