SEDIMENTOLOGY OF THE MIOCENE NULLARBOR LIMESTONE; SOUTHERN AUSTRALIA

by

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Abstract

The Miocene Nullarbor Limestone is the most recent formation in the Cenozoic Eucla Group and was deposited in the Eucla Basin, southern Australia, at ~38°S paleolatitude during the early to middle Miocene. The rocks form the modern surface of the vast, karsted Nullarbor Plain. Older Eucla Group marine carbonates (Eocene-earliest Miocene) are cool-water in nature and dominated by bryozoans and echinoderms. The Nullarbor Limestone is subtropical in composition and rich in coralline algae (rhodoliths and articulated types), large and small benthic foraminifera and molluscs. Diverse zooxanthellate corals are also present but not numerous. Deposition is interpreted to have taken place in three main paleoenvironments: rhodolith gravels, seagrass banks, and open seafloors.

The Southern Ocean extended inboard ~450 km from the shelf edge during Nullarbor Limestone deposition. Interpreted paleodepths ranged from the top to the base of the photic zone, implying a small slope over a wide shelf. The Miocene Eucla platform is therefore interpreted to have been epeiric in nature. Paleoenvironment distribution is explained using epeiric platform sedimentation patterns and comparisons with modern environments. Open seafloor environments, the deepest settings, are thought to have been below fair-weather wave base. Rhodolith gravels accumulated at intermediate depths, where waves frequently swept the seafloor. Seagrass banks developed in the shallowest waters farthest inboard, where wave energy had been largely dissipated.

Diverse corals, large benthic foraminifera and micrite envelopes inboard and in the western part of the basin support the notion of paleotemperatures generally
above 20°C, the upper limit of subtropical carbonate accumulation. Although deposition occurred during the Miocene Climatic Optimum, a simple overall temperature increase cannot completely account for the subtropical nature of these sediments at mid-latitudes. Tropical components decrease from west to east, implying a temperature gradient, probably due to the warm proto-Leeuwin Current. Thus, these subtropical carbonates were deposited at mid-latitudes and their presence did not simply reflect a change in global climate.
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Although I owe my initial immersion in marine geology to my great friends at the University of Miami, I have never regretted my decision to attend Queen's for my M.Sc. The professors and fellow students here have taught me immeasurable amounts about geology and life, as they know it. Dr. Guy Narbonne first introduced me to Queen’s University one fateful day on the shores of Newfoundland and has continued to be an inspiring teacher throughout my time here. Dr. Bob Dalrymple and the “Alberta Trilogy” (Kain Michaud, Cody Miller, Bryce Jablonski) helped me venture into the fascinating worlds of siliciclastic sedimentology and sequence stratigraphy. This thesis benefitted from discussions with and editorial suggestions by Nikole Bingham-Koslowski, Kain Michaud, Cody Miller and Nick Riordan.

My fieldwork experience was enhanced by the guidance of Dr. Yvonne Bone, who shares my enthusiasm for fossils and wildlife, but surpasses me immensely in knowledge of them. Discussions with her by lamplight were integral to the ideas developed in this thesis. Cody Miller and I served as each other’s field assistants in the Nullarbor Plain and he deserves recognition for his easy-going nature (0 arguments in 1.5 months!). His willingness to stop in order to photograph birds was greatly appreciated. The Geological Survey of Western Australia also contributed to
the feasibility of fieldwork by outfitting us with field equipment, the most notable of which was Bruiser, the Land Cruiser. Bruiser kept us safe and comfortable on our off-road expeditions and kept us in daily contact with helpful personnel in Carlisle.

I would also like to thank my family, most notably my parents, siblings and in-laws for their support of everything that I do and faith in my abilities. I cannot fit enough words here to thank my husband, Johnny, who moved from Florida to the “Great White North” in order for me to pursue my dreams and always keeps a smile on his face.

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To Johnny,

who never underestimates me and never ceases to make me smile.
Chapter 1: General Introduction and Purpose of this Study

1.1 THE NULLARBOR LIMESTONE AND IMPORTANCE OF THIS STUDY

The late early and early middle Miocene Nullarbor Limestone outcrops atop the vast karst surface of the Nullarbor Plain and extends beneath the continental shelf of the Great Australian Bight. This limestone is highly fossiliferous, well cemented, and devoid of terrigenous sediment. As the youngest formation of the Eucla Platform, it is exposed across most of the surface of the Nullarbor Plain, an area of roughly 120,000 km². The underlying Eocene to earliest Miocene carbonates are made of cool-water components (Wilson Bluff and Abrakurrie limestones, Lowry, 1970; James and Bone, 1991; James and Bone, 1994; Li et al., 1996a). The Nullarbor Limestone has many fossils of Indo-Pacific affinity and is made of temperate and tropical skeletal components, despite its high paleolatitude during deposition (~38°S, McGowran et al., 1997a).

Limestones of the Eucla Group were not studied in detail until fairly recently in part due to the inaccessibility of the Nullarbor Plain and its outcrops (Lowry, 1970; James and Bone, 1991; James and Bone, 1994; Li et al., 1996a). The Nullarbor Limestone has only been examined in a reconnaissance fashion and is thus the poorest known unit of the Eucla Group (Lowry, 1970). Some fossils have been collected and described (Ludbrook, 1958a; Lindsay and Harris, 1975), but have not been put into a paleoenvironmental context. This study incorporates all aspects of
the Nullarbor Limestone, including detailed fossil analysis, paleoenvironmental interpretation, sequence-stratigraphic aspects and oceanographic implications.

Allochems of the Nullarbor Limestone include diverse temperate and tropical fossils. Large and small benthic foraminifera and coralline algae are most common, whereas molluscs and echinoids are widespread and locally abundant (Ludbrook, 1958a; Lowry, 1970). Scleractinian corals are also present locally (Lowry, 1970). Limestone texture ranges from mudstone to rudstone throughout (James and Bone, 1991). Large benthic foraminifera and zooxanthellate scleractinian corals are restricted to warm tropical to subtropical marine waters. Their presence in the Nullarbor Limestone is surprising since underlying limestones are dominated by bryozoans and are interpreted as strictly cool-water deposits.

In addition to the differences between the Nullarbor Limestone and underlying Cenozoic units, this limestone is also of interest because it records shallow-water deposition over an immense area. Thus, it may prove to be one of the largest examples of Miocene epeiric platform deposition.

1.2 PURPOSES OF THIS STUDY

This study has four interrelated purposes:

1. Present a detailed documentation of the Nullarbor Limestone, including a complete assessment of the calcareous biota.

2. Differentiate lithofacies and interpret paleoenvironments based on these facies.
3. Interpret the depositional system that produced the Nullarbor Limestone and account for spatial and temporal variations within the formation.

4. Develop a paleoceanographic model to explain the origin of the Nullarbor Limestone.
Chapter 2: Geological Setting and Methods

2.1 INTRODUCTION TO THE STUDY AREA

Australia is an ideal location for studying modern and Cenozoic carbonates. Modern carbonates cover most of the continental shelf and ancient limestones are found beneath these and along adjoining coastlines. In general, tropical deposits lie along northern shelves and temperate deposits lie along southern shelves (Davies, 1970; Collins, 1988; James and Bone, 1991; Boreen and James, 1995; Ferland and Roy, 1997; Collins et al., 1997; James et al., 2001; James et al., 2009). North to south gradients of modern tropical to temperate carbonate deposition exist along both the east and west coasts of the continent. Australia is currently the driest and flattest continent on Earth, so modern carbonate deposition along the coastlines of Australia is less diluted by terrigenous sedimentation than it is on other shelves worldwide.

The Eucla Basin, the field locality for this study, is one of the largest areas of Cenozoic temperate and sub-tropical limestones in Australia. It is located along the central portion of the Australian southern continental margin, the largest area of cool-water carbonate deposition in the modern world (James and Bone, 1991, James et al., 1994). The Eucla Platform caps sediments of the Eucla Basin onshore and extends beneath the continental shelf of the Great Australian Bight. The platform carbonates are most easily studied onshore, where they form the surface of the Nullarbor Plain. Eucla Platform limestones represent non-continuous deposition from the middle Eocene through the early middle Miocene (Fig. 2.1; Lowry, 1970;
Fig. 2.1. Eucla Basin stratigraphy (Lowry, 1970; Benbow et al., 1995).
James and Bone, 1991). The Nullarbor Limestone is late early to early middle Miocene in age and is exposed across most of the surface of the Nullarbor Plain (Lowry, 1970).

2.2 MODERN OCEANOGRAPHY ON THE AUSTRALIAN SOUTHERN MARGIN

The Great Australian Bight is a latitude-parallel shelf facing Antarctica along the cool Southern Ocean, as it also was during the Miocene (Fig. 2.2). The shelf is storm-dominated and subject to periods of downwelling (dominant) and upwelling (seasonal, summer) (James et al., 2001; James and Bone, 2011). The strength and magnitude of currents flowing onto the shelf are affected by seasonal wind patterns (Smith et al., 1991). The Leeuwin Current originates in the tropics off northwestern Australia and brings warm, low-salinity, oligotrophic surface waters south as a shelf-edge jet (Fig. 2.2). A pressure gradient forces this current towards the south along the western coast of Australia and east along the southern margin, into the Great Australian Bight (Smith et al., 1991). Surface water temperatures within the current decrease from ~26°C at the source to ~18°C in the Great Australian Bight. In the Great Australian Bight, the current currently flows along the edge of the shelf, and does not usually impinge onto the shallow shelf (James et al., 2001).

The South Australian Current is driven by winter winds from the west. These winds lead to Ekman transport of water towards shore, resulting in downwelling
Figure 2.2. Modern oceanography of Australian waters, from James and Bone (2011).
and the development of a ridge of water over the shelf break. This piled-up water flows east as the saline South Australian Current (Fig. 2.2; James and Bone, 2011).

2.3 GEOLOGICAL SETTING

The Nullarbor Plain is an extensive karst surface atop a succession of Cenozoic limestones that outcrop as high sea cliffs along the Great Australian Bight and straddle the border between South Australia and Western Australia (Fig. 2.3A, B; Fig. 2.4). Stratigraphy of the Nullarbor Plain includes Archean granite and gneiss basement rocks overlain by terrigenous Cretaceous sediments of the Eucla Basin and, finally, the Cenozoic limestones of the Eucla Platform (Fig. 2.1; Ludbrook, 1958a; James and Bone, 1991).

Breakup of Gondwana and the Formation of the Southern Australian Margin

The Australian landmass has gone through numerous changes during the Phanerozoic. It formed the eastern edge of the supercontinent Gondwana throughout most of the Paleozoic and Mesozoic (520-180 Ma) (Johnson, 2004). Australia did not have a southern coastline as part of Gondwana, since it was attached to Antarctica to the south and India to the southwest. The Indian, Australian and Antarctic landmasses did not begin to break apart until continental stretching and minor rifting began in the late Jurassic and early Cretaceous (160-132.5 Ma) (Veevers and Eittreim, 1988; Veevers et al., 1991). At that time, the Nullarbor Plain region was subsiding due to rifting and became a floodplain of
Figure 2.3. A) Cliffs along the Great Australian Bight ~70 m high show inaccessible, but exquisite outcroppings of Cenozoic Eucla Group limestones. Person is circled for scale. B) The Nullarbor Plain is an extensive, flat karst surface. Camel is circled for scale.
Figure 2.4. Map of the Nullarbor Plain showing field locations. Inboard extents of limestone units are estimated using Lowry (1970) and observations during this study. Field localities and corresponding numbers are shown to the left for reference. A, A’ and B, B’ correspond to cross-sections, Fig. 4.8 and Fig. 4.9.
braided river systems flowing from north to south (White, 1994). These rivers formed the sandstones and conglomerates that comprise the early Cretaceous Loongana Sandstone (Fig. 2.1; Lowry, 1970).

Rifting and continental extension continued throughout the early Cretaceous, and the proto-Indian Ocean started to open between the landmasses of India and Australia/Antarctica at ~118 Ma (Veevers et al., 1991). A seaway between Australia and Antarctica also began to form and opened from the southwest corner of Australia toward the east as rifting continued (proto-Southern Ocean or Australo-Antarctic Gulf) (White, 1994; Li et al., 2003). The Mesozoic equivalent of the central Great Australian Bight and Nullarbor Plain region (Eucla Basin) is collectively called the Bight Basin (Fig. 2.1; White, 1994).

Glacioeustatic sea-level rise peaked at 116 Ma and submerged much of the Australian landmass under the Eromanga Sea (Veevers et al., 1991; White, 1994). This sea temporarily connected the proto-Indian Ocean and Australo-Antarctic Gulf with the Pacific Ocean and flooded the Bight Basin for the first time (Veevers et al., 1991; White, 1994). Sandstones deposited in the Nullarbor region of the Bight Basin changed from fluvial to marine during the early to early middle Cretaceous (Lowry, 1970). These sandstones collectively make up the Madura Formation (Fig. 2.1; Lowry, 1970). Following the highstand, the Nullarbor Plain region (upper Bight Basin) became a floodplain of braided rivers again (White, 1994).

The middle Cretaceous (99-96 Ma) was a time of drastic change along the growing southwestern margin of Australia (Veevers et al., 1991; Veevers, 2000). The Indian Ocean began to expand rapidly, allowing for the onset of thermohaline
circulation and carbonate sedimentation along the west coast of Australia (Veevers, 2000). The middle Cretaceous also marked the onset of slow seafloor spreading along the rift separating Antarctica from Australia (Veevers and Eittreim, 1988; Veevers, 2000).

During the Late Cretaceous the southeastern corner of the Bight Basin (Ceduna Depocenter) (Fig. 2.5) subsided at a rate of 300m my⁻¹ (White, 1994; Veevers, 2000). The eastern side rose faster than rising sea level, such that the continent tipped towards the southwest creating highlands in the east (White, 1994; Veevers, 2000). Water from these highlands drained through the Nullarbor region, creating a continent-scale river system that was the larger predecessor to the modern Murray-Darling system (Fig. 2.5; Li et al., 2003). This river system dumped 15 km of siliciclastic sediments into the Ceduna Depocenter during the late Cretaceous (Fig. 2.5; Veevers, 2000; Li et al., 2003). Erosion was prevalent in the northern portion of the Bight Basin from middle Cretaceous to Eocene time, as these rivers cut through what is now the Nullarbor Plain (White, 1994).

The slow spreading between Australia and Antarctica continued until the middle Eocene (43 Ma), when spreading increased from 4 mm y⁻¹ to 8 mm y⁻¹ (Tikku and Cande, 1999; Veevers, 2000). Increased spreading caused the Austro-Antarctic Gulf to widen and deepen, flooding the Eucla Basin (Li et al., 2003). Deposition of the marine Hampton Sandstone occurred at this time throughout the Eucla Basin (Fig. 2.1; Lowry, 1970; Li et al., 2003). As the gulf deepened, siliciclastic sedimentation gave way to quartzose limestone with progressively less siliciclastic input until the late middle Eocene (Wilson Bluff Limestone; Li et al., 2003).
Figure 2.5. Localities in Australia mentioned throughout this thesis. Modern marine features are indicated by grey arrows.
Carbonate Sedimentation on the Southern Australian Margin

The late middle Eocene marks deposition of the first purely calcareous sediments along the southern Australian margin, particularly in the Eucla and St. Vincent Basins (Fig. 2.5; Lowry, 1970; Lindsay and Alley, 1995; McGowran et al., 1997a; Li et al., 2003). Several factors could have led to the onset of carbonate deposition in this region. Movement into lower latitudes could have increased ocean temperatures, allowing for carbonate deposition, but oceanography is thought to be a more important factor than latitude. The Indian Ocean became temperature stratified around this time, resulting in the formation of the proto-Leeuwin Current (McGowran et al., 1997a). This current brought tropical Indian Ocean waters from the northwest into the Australo-Antarctic Gulf along Australia’s southern margin and may have been responsible for carbonate initiation (McGowran et al., 1997b). The strength of this current is controlled by glacioeustacy and when it is turned on it brings warm water along the southern margin, as far east as the Otway Basin, and creates a sea-surface temperature gradient that decreases from west to east (Fig. 2.5; McGowran et al., 1997b).

The continents of Australia and Antarctica were still connected at this time across the South Tasman Rise (Li et al., 2003). Increased circulation in the Gulf allowed the shallow environments to the east to become lagoonal during the middle Eocene (Li et al., 2003). The Southern Ocean was born when this gateway completely opened at ~34-33 Ma (Li et al., 2003).
Limestones of the Eucla Basin

The Eucla Group includes the Wilson Bluff, Abrakurrie and Nullarbor limestones (Fig. 2.1; Table 2.1; Lowry, 1970). These units were deposited throughout the late Eocene to middle Miocene, forming the Eucla Platform during times of high sea level (McGowran et al., 1997a). They do not grade into each other, but are separated by unconformities. These packages correspond to global second-order sea-level cycles, as do the packages of other basins along the Australian southern margin (McGowran et al., 1997a). The Roe Calcarenite is a thin late Pliocene-early Pleistocene deposit atop a marine erosion surface that cuts into the limestones of the Eucla Group (Fig. 2.1; Lowry, 1970; James and Bone, 2007).

<table>
<thead>
<tr>
<th>Formation</th>
<th>Age</th>
<th>Main Lithologies</th>
<th>Marine Paleoenvironment</th>
<th>Key Reference(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roe Calcarenite</td>
<td>late Pliocene-early Pleistocene</td>
<td>unlithified, grainy fragments of benthic foraminifera, coralline algae and molluscs</td>
<td>warm-temperate shallow grass beds</td>
<td>Lowry, 1970; James and Bone, 2007</td>
</tr>
<tr>
<td>Nullarbor Limestone</td>
<td>late early-middle Miocene</td>
<td>benthic foraminifera, coralline algae, mollusc mdst.-rdst.</td>
<td>warm-temperate shallow shelf</td>
<td>Lowry, 1970</td>
</tr>
<tr>
<td>Abrakurrie Limestone</td>
<td>late Oligocene-early Miocene</td>
<td>med.-coarse grained bryozoan grnst.-pkst.</td>
<td>cool-water neritic</td>
<td>Lowry, 1970; James and Bone, 1991; Li et al., 1996a</td>
</tr>
<tr>
<td>Wilson Bluff Limestone</td>
<td>middle-upper Eocene</td>
<td>fine-grained bryozoan mdst.-grnst.</td>
<td>cool-temperate deep shelf</td>
<td>Lowry, 1970</td>
</tr>
</tbody>
</table>
Wilson Bluff Limestone

The middle to upper Eocene Wilson Bluff Limestone is the oldest formation of the Eucla Group (Fig. 2.1; Table 2.1; Lowry, 1970; Li et al., 2003). Bryozoans and planktonic foraminifera dominate the chalky mudstones, wackestones, packstones and grainstones of this unit (Lowry, 1970; James and Bone, 1991; Benbow et al., 1995). Most of the Wilson Bluff Limestone is fine-grained, but bryozoan and echinoderm grainstones and rudstones occur along the east and west platform margins (James and Bone, 1991). The depositional environment of the Wilson Bluff Limestone is interpreted as a cool-temperate deep-marine shelf (~ 300 m water depth) with temperatures similar to that of the modern Great Australian Bight (Lowry, 1970; Lindsay and Harris, 1975).

The Wilson Bluff Limestone was deposited during the maximum marine transgression on the Eucla Platform (Fig. 2.4; Hou et al., 2008). Along its outskirts to the north and east, it interfingers with fluvial, estuarine and deltaic sandstones (Benbow, 1990; Benbow et al., 1995; Hou et al., 2008). Reworking of these sediments during the Eocene formed large aeolian dune complexes of the Ooldea, Paling and Barton Ranges along the northeast Eucla Basin margin that mark the paleoshoreline at times of maximum sea level (Benbow, 1990; Hou et al., 2008).
**Abrakurrie Limestone**

The Abrakurrie Limestone (late Oligocene to early Miocene) unconformably overlies the Wilson Bluff Limestone (Fig. 1.1; Table 2.1; Lowry, 1970; James and Bone, 1991). It has a much smaller geographical extent than the Wilson Bluff Limestone and only occurs in the center of the Eucla Basin (Fig. 2.4; Lowry, 1970). The Abrakurrie Limestone is primarily medium to coarse-grained bryozoan grainstone and packstone with local fine-grained wackestone and coarse-grained floatstone and rudstone (Lowry, 1970; James and Bone, 1991). Abundant branching cheilostome and cyclostome bryozoans and simple poorly preserved benthic and planktonic foraminifera help distinguish the Abrakurrie Limestone from the overlying Nullarbor Limestone (James and Bone, 1994; Li et al., 1996a). The depositional environment of this limestone is interpreted as a cool-water shelf with water depths around 100 m (Li et al., 1996a). Meter-scale cycles within the Abrakurrie Limestone are bounded by hardgrounds and show vertical gradations in fossil content and grain size. These cycles have been interpreted as representing shifts in the base of wave abrasion due to fluctuations in sea level and climate (James and Bone, 1994).

**Nullarbor Limestone**

The Nullarbor Limestone is composed of late early Miocene to early middle Miocene fossiliferous mudstones to rudstones (Fig. 1.1; Table 2.1; Lowry, 1970; Lindsay and Harris, 1975). It covers a much greater area of the Eucla Platform than the Abrakurrie Limestone and thus overlaps the Abrakurrie Limestone in the central
portion of the platform and the Wilson Bluff Limestone along the inboard platform edges (Fig. 2.4; Lowry, 1970; James and Bone, 1991). The Nullarbor Limestone, however, is not as laterally extensive as the Wilson Bluff Limestone, implying that the local early Miocene transgression was not as extensive as the upper Eocene transgression (Lowry, 1970).

The Nullarbor Limestone grades laterally northward into the Colville Sandstone. This sandstone is the inboard facies equivalent of the Nullarbor Limestone, as it is lithologically similar, but has higher siliciclastic content (Lowry, 1970; Li et al., 2003). Beds of fine crystalline dolomite and presence of large benthic foraminifera suggest that the Colville Sandstone was deposited in supratidal and intertidal environments (Lowry, 1970). The Eocene aeolian Ooldea and Barton ranges along the northeast Eucla Basin margin rimmed the paleoshoreline during Nullarbor Limestone deposition. Nullarbor and Colville sediments may have contributed to the Ooldea dunes while the platform was inundated by the sea in the early-middle Miocene (Benbow, 1990; Benbow et al., 1995). The Ooldea range served as a barrier between marine and lacustrine environments during Nullarbor Limestone deposition. The lacustrine Garford Formation accumulated between the Ooldea and Barton barrier/dune complexes (Benbow et al., 1995; Hou et al., 2008). Lacustrine deposits also accumulated in paleovalleys of the Eucla platform, suggesting that stream gradients were extremely low (Hou et al., 2008).

Lowry (1970) differentiated three facies in the upper portion of the Nullarbor Limestone (Table 2.2). The overall interpreted depositional environment of the Nullarbor Limestone is a wide, open shelf with effective circulation and normal
marine salinity, approximately 30-45 m deep (Lowry, 1970). Large benthic foraminifera and scattered reef-building corals in the Nullarbor Limestone allude to deposition in warmer-water than the older limestones of the Eucla Platform (Lindsay and Harris, 1975).

Seismic data from the Western Australian portion of the Great Australian Bight show that prograding cool-water ramp deposits dominate Cenozoic sedimentation beneath the offshore Eucla Basin (Feary and James, 1995). Stacked buildups on the edge of the shelf, however, share seismic characteristics with Pleistocene coral reefs of the Great Barrier Reef (Feary and James, 1995). The well-cemented nature and high keep-up morphology of these buildups suggest that they may also be coral reefs. Since early-middle Miocene Nullarbor Limestone deposition marks the warmest period (and the only period of zooxanthellate coral growth) in the Eucla Basin, this “Little Barrier Reef” has been proposed as a coeval offshore extension of the Nullarbor Limestone (Feary and James, 1995).

**Table 2.2. Facies of the upper portion of the Nullarbor Limestone as described by Lowry (1970)**

<table>
<thead>
<tr>
<th>Facies Name/Lithology</th>
<th>Components</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>fine to medium-grained, well-sorted calcarenite</td>
<td>fragmented large and small benthic foraminifera, coralline algae</td>
<td>north of the railway line</td>
</tr>
<tr>
<td>medium to coarse-grained foraminiferal calcarenite</td>
<td>foraminifera, interclasts</td>
<td>northern part of the Nullarbor Plain</td>
</tr>
<tr>
<td>medium to coarse-grained, poorly sorted calcarenite</td>
<td>large and small benthic foraminifera, coralline algae, minor bryozoans, echinoderms and molluscs</td>
<td>southern part of the Nullarbor Plain</td>
</tr>
</tbody>
</table>
The Mullamullang Limestone Member is the basal unit of the Nullarbor Limestone in the south central portion of the formation around Madura (Fig. 2.4; Lowry, 1970) and is simply referred to as the Mullamullang Member in this and other publications (James and Bone, 1991). This unit is made of “algal limestone” (Ludbrook, 1958b; Lowry, 1970), more recently described as rhodolith rudstone (James and Bone, 1991). Due to the uniformity of this member, Lowry (1970) suggested that it was deposited on a deep, calm shelf in approximately 15-30 m water depth.

A more geographically extensive and lithologically diverse package overlies the Mullamullang Member in south central regions and includes the rest of the Nullarbor Limestone in all other localities. The name ‘Rawlinna member’ is informally proposed for this upper package of the Nullarbor Limestone, due to exceptional outcrops available at Rawlinna Quarry (Fig. 2.6; this study).

The Nullarbor Plain

The Eucla Platform was exposed in the middle middle Miocene (~14 Ma) due to sea level fall at the end of the Miocene Climactic Optimum and uplift of the southern margin coincident with onset of tectonic inversion (McGowran et al., 1997a; Sandiford, 2003; James and Bone, 2007). Uplift and erosion of most of the platform has, therefore, been continuous since the middle Miocene (Sandiford, 2003). Limestones of the Eucla Platform are exposed on 100-m-high erosional sea cliffs that face the Great Australian Bight (Fig. 2.3; James and Bone, 1991).
The Roe Plain

Small sea level incursions in the Pliocene and Pleistocene cut into and eroded these cliffs and allowed for deposition of thin veneers of aeolian and marine carbonate sediments. During one such incursion in the center of the Nullarbor Plain, sea cliffs were eroded back, forming a shallow bay atop a marine erosion surface. The Roe Calcarenite was deposited in this bay. The Calcarenite contains abundant fossils that are characteristic of warm temperate waters including diverse molluscs and large benthic foraminifera (Table 2.1; Lowry, 1970). Small benthic foraminifera and articulated coralline algae are common. These sediments were most likely deposited in shallow grass beds, where water was warmed by partial restriction (James and Bone, 2007). When sea level fell in the earliest Pleistocene, the Roe Calcarenite was exposed and formed the Roe Plain, which currently lies just above sea level (Lowry, 1970; James and Bone, 2007). A paleo-sea cliff, the Hampton Range, backs the Roe Plain (James and Bone, 2007).

2.4 METHODS

Field Methods

Sea cliffs display Eucla Group limestones beautifully along the modern coastline with the Great Australian Bight, but are treacherous to climb and largely inaccessible (Fig. 2.3A). Outcrops are, therefore, restricted to caves, quarries and rare road cuts (Fig. 2.6). Study localities were chosen based on previous personal knowledge by N.P. James and Y. Bone, reports of exposed limestones by Lowry
Figure 2.6. Examples of Nullarbor Limestone outcrops. A) N12, Cook Quarry has talus suitable for walking on to measure stratigraphic sections; person circled for scale. Image courtesy of N.P. James. B) N7, Abrakurrie Cave displayed a thick section of Nullarbor Limestone; person circled for scale. Image courtesy of C.R. Miller.
(1970), and use of the Nullarbor Caving Atlas (Pilkington and Mott, 1986). Routes to these remote localities were plotted ahead of time using Google Earth satellite imagery and the 1:250,000 Geological Map Series (Geological Survey of Western Australia, Geological Drafting Section, Mines Department, 1969-1971), and these plans were executed with the help of a handheld GPS unit and a detailed map book (Devaraj et al., 2008). Some localities, such as new quarries, were discovered while in the field. Not all sites proved to be accessible. While visiting Haig Cave, the audacity of previous workers such as Lowry became evident. This cave was only accessible if one was willing to repel on eroding, friable, shear cave walls, but Lowry (1970) had collected fossils and documented details of the cave’s stratigraphy.

Fifteen stratigraphic sections were measured in caves (5), quarries (7), road cuts (2) and on the gently sloping sea cliff at Wilson Bluff (1), during this study (Fig. 2.4; Appendix). Measurements were carried out using standard field techniques and hand samples were collected for thin sections (Appendix). Field localities and their corresponding hand samples were numbered based on the order in which the sites were first visited. Cocklebiddy Cave, for example, was the first site and was numbered N1. Hand samples collected were numbered NL1.1, etc. Detailed notes on macrofossils included types, preservation, distributions, abundances, and sizes, and they were photographed for further identification. Wherever possible, attributes of contacts between the Nullarbor Limestone and Abrakurrie and Wilson Bluff Limestones were documented and the contacts were photographed and sampled.
Laboratory Methods

Thin-section microscopy was best suited for detailed study of these limestones due to their lithified nature. Seventy-two thin sections were made from hand samples and studied under a petrographic microscope using standard techniques. The relative percentages of calcrete and original limestone were estimated for each sample, since only the original depositional limestone was analyzed further during this study. Original percentages of skeletal grains, mud, cement and porosity were estimated using visual comparison charts in Flügel (2004). Of the skeletal grains, relative percentages of components (e.g., large benthic foraminifera, echinoderm fragments) were also estimated. Estimates of component percentages were used to qualitatively describe lithologies and to separate facies. Attributes related to components, such as grain size, taxa and preservation were documented. Limestones were named using Dunham’s classification scheme (Dunham, 1962).

Fossil identification was also facilitated by thin-section study. Taxa of large and small benthic foraminifera, coralline algae, serpulid worms, ostracods and bryozoans were identified using thin sections. Macrofossils such as echinoderms, corals, molluscs and bryozoans were identified on the outcrops and in the laboratory using field photos and hand samples.
Chapter 3: Components of the Nullarbor Limestone

3.1 INTRODUCTION

Skeletal carbonate components are diverse and dominate the Nullarbor Limestone. Terrigenous sediments are rare and non-skeletal carbonates are absent. Benthic foraminifera, coralline algae (encrusting and articulated branching), bivalves, gastropods and echinoids are common and widespread. Serpulid worm tubes, planktonic foraminifera, corals (zooxanthellate and azooxanthellate) and bryozoans also occur locally.

3.2 BENTHIC FORAMINIFERA

Benthic foraminifera are the most conspicuous components of the Nullarbor Limestone. Large benthic foraminifera (LBF) are often used as paleoenvironmental indicators and index fossils, and are indicative of warm, oligotrophic waters in the photic zone (Hallock and Glenn, 1985). Certain taxa can also help determine which substrates were available at the time of deposition. The diverse assemblage of LBF in the Nullarbor Limestone includes miliolines (*Marginopora vertebralis*, *Sorites* spp., *Austrotrillina howchini*, *Flosculinella* sp.) and rotaliines (*Miogypsina* spp., *Gypsina* spp., *Operculina* spp.). Small benthic foraminifera (SBF) are also widespread throughout the formation, but are often too small and fragmented to be identified to
the species level. *Quinqueloculina* and *Triloculina* are the most common genera of SBF.

**Large Benthic Foraminifera (LBF)**

The term “large benthic foraminifera” is used herein to refer to those species that are known to house algal symbionts and thus commonly attain large sizes (typically 1 mm-1cm). The mutualistic relationship between algae and foraminifera is similar to that of zooxanthellae dinoflagellates and scleractinian corals (Ross, 1972). Light availability, temperature, substrate type, and water energy are the most important environmental parameters controlling the distribution of LBF (Hottinger, 1983). Large benthic miliolines (porcelaneous tests) are most common in the shallowest depths due to test-wall properties that protect foraminifera from the harmful effects of UV light (Haynes, 1965). Generally, LBF are distributed around the equator in water temperatures that usually stay ≥ 25°C (Murray, 1991) and decrease in abundance and diversity with increased latitude and decreased summer water temperatures (Murray, 1991). Details on the ecology and symbiotic relationships of these protists are further discussed by Haynes (1965), Müller-Merz and Lee (1976), Kremer et al. (1980) and Hallock (2000).

**Large Benthic Miliolines**

Large benthic rota liines and miliolines are both present in the Nullarbor Limestone, but the assemblage is dominated by miliolines. Large benthic miliolines are rare in the Mullamullang Member. They generally increase upwards in the
Rawlinna member where they are copious in the western portion of the basin and all northern sections, including those in South Australia. *Marginopora vertebralis* and *Austrotrillina howchini* are the most abundant large miliolines (Fig. 3.1). *Sorites* spp., *Flosculinella* spp., nubecularids, and milioline sp. A are also present (Fig. 3.1, 3.2, 3.3). Flat, discoidal tests of the Family Soritidae (including *Marginopora* and *Sorites*) are the most widespread LBF (Fig. 3.1).

**Nubecularids**

Only a few nubecularids of the genus *Nubecularia* have been observed in the Rawlinna member (this study). Nubecularids are encrusting foraminifera that commonly grow attached to seagrasses and articulated coralline algae (James and Bone, 2007). They are thus associated with seagrasses and create profuse calcareous sediments in modern Australian seagrass banks (Shark Bay, Davies, 1970; Gulf St. Vincent, Cann et al., 1988; Fig. 2.5) and the Pliocene-Pleistocene Roe Calcarenite (James and Bone, 2007).

The largest benthic foraminifera in the Nullarbor Limestone are long, tube-shaped miliolines that are commonly longer than 3 cm and up to 5 mm wide (this study, Fig. 3.2, 3.3). They are only found at Rawlinna Quarry, but are profuse at this site. They have not been identified, since similar foraminifera have not been observed in the literature, but have been confirmed to be miliolines due to their porcelaneous tests. They have many layers of chambers and share characteristics with encrusting nubecularids (personal observation; P. Hallock, personal communication 2010). Tubes are hollow or partially filled with sediment, implying
Figure 3.1. Large benthic miliolines of the Nullarbor Limestone. A) Marginopora vertebralis (M), Old Homestead Cave (N19.14), B) Austrotrillina howchini (A), Cocklebiddy Cave (N1.8), C) Sorites sp. (S), Rawlinna Quarry (N22.5), D) Flosculinella sp. (F), Old Homestead Cave (N19.4).
Figure 3.2. Outcrop image showing tubes of milioline sp. A., Rawlinna Quarry (N22).
Figure 3.3. Photomicrographs of milioline sp. A, Rawlinna Quarry (N22). A) Transverse image showing multiple chamber layers and interior pore. B) and C) Longitudinal sections, showing long interior pores.
that they may have lived attached to ephemeral substrates, as nubecularids live attached to seagrasses (Fig. 3.2, 3.3). They will be referred to as 'milioline sp. A' in this thesis, since further classification is unknown.

*Marginopora vertebralis*

*M. vertebralis* has been described as the most “ubiquitous and abundant” (Ludbrook, 1958a) LBF of the Nullarbor Limestone (Fig. 3.1; Ludbrook, 1958a, b; Cockbain [in Lowry 1970]; Lindsay and Harris, 1975; Benbow and Lindsay, 1988; Li et al., 1996a; this study). *M. vertebralis* also attains the largest size of any foraminifera in the Nullarbor Limestone, with specimens ranging from 2 mm to 4 cm in diameter and up to 2 mm in thickness (this study).

Modern, living *M. vertebralis* are only found in warm, shallow, euphotic waters and require water temperatures between 20-33.5°C to reproduce (Ross, 1972; Langer and Hottinger, 2000). *M. vertebralis* has a wide salinity tolerance and is able to survive exposure to air, heavy rain, and direct sunlight for several hours a day during low tide (Severin, 1987; Smith, 1968). Abundant living *M. vertebralis* is found in a variety of environments from 0-30 m water depth (Table 1). Living *M. vertebralis* at 10 m have the maximum concentration of symbionts and the highest test growth rates (Ross, 1972; Cann and Clarke, 1993). The largest living specimens of *M. vertebralis* are consistently found at deepest water sites (Ross, 1972).

*M. vertebralis* live atop a variety of substrates, such as soft sediment (Ross, 1972), rocks (Cann and Clarke, 1993), calcareous algae (*Halimeda*; Jell et al., 1965), seagrass blades (Cann and Clarke, 1993; Severin, 1987; James and Bone, 2007), algal
turf-covered rocks (Hallock, 1984), shells, living ascidians, and wooden shipwrecks (Cann and Clarke, 1993). This species, however, is most common in seagrass beds, living attached to blades, on the sediment between blades, and on algal turf that covers hard substrates (Cann and Clarke, 1993; Hallock, 1984). *M. vertebralis*, often dominates *Posidonia* and *Cymodocea* seagrass communities (Shark Bay, Davies, 1970; Warnbro Sound, Rottnest Shelf, Western Australia, Carrigy, 1956; Fig. 2.5). These seagrasses are most abundant in areas of high water exchange at a minimum depth of mean low tide line (Davies, 1970).

Juveniles of *M. vertebralis* are usually attached to seagrass blades and brown alga thalli since adults typically grow too wide and heavy to fit on these substrates (Hohenegger, 1994; James and Bone, 2007). Also, the life cycle of *M. vertebralis* (up to 2 years) is much longer than that of seagrass blades, which are shed every few months (Ross, 1972; Nelsen and Ginsburg, 1986; James et al., 2009). Larger, older individuals of *M. vertebralis* often move to hard rock substrates after their temporary organic substrates have died (Hohenegger, 1994).

**Table 3.1. Examples of Modern Environments of Marginopora vertebralis**

<table>
<thead>
<tr>
<th>Location (Fig. 2.5)</th>
<th>Depth</th>
<th>Environment/Substrate</th>
<th>Reference(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dongara, Western Australia</td>
<td>0-1 m</td>
<td>seagrass flats</td>
<td>Davies, 1970</td>
</tr>
<tr>
<td>southern Rottnest Shelf, Western Australia</td>
<td>0-20 m</td>
<td>seagrass blades</td>
<td>Semeniuk, 2001</td>
</tr>
<tr>
<td>central Great Barrier Reef</td>
<td>5-22 m</td>
<td>coral reef</td>
<td>Carrigy, 1956</td>
</tr>
<tr>
<td>Papua New Guinea</td>
<td>0-1 m</td>
<td>seagrass flats</td>
<td>Ross, 1972</td>
</tr>
<tr>
<td>Fiji</td>
<td>0-1 m</td>
<td>muddy intertidal flats</td>
<td>Severin, 1987</td>
</tr>
<tr>
<td>Palau and Hawaii</td>
<td>0-30 m</td>
<td>coral reef</td>
<td>Smith, 1968</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Hallock, 1979, 1984</td>
</tr>
</tbody>
</table>
*Sorites* spp.

*Sorites* spp. are also flat discoid miliolines of the Family *Soritidae* (Loeblich and Tappan, 1988). They are present in the Nullarbor Limestone, but are only abundant locally (Fig. 3.1). Chamber forms and arrangements of *Sorites* specimens vary, suggesting that many species are present. Their discoid tests have diameters ranging from 0.75-2.6 mm and widths ranging from 0.06-0.15 mm. Identification using thin sections was limited to the genus level.

*Sorites* is a circumtropical, cosmopolitan genus, found on shallow shelves throughout the tropical Indopacific, Caribbean and Mediterranean (Langer and Hottinger, 2000). Living members of the genus *Sorites* are found as epiphytes in warm, low-energy settings of the upper photic zone and have been associated with these facies throughout the Neogene (Hottinger, 1983; Langer and Hottinger, 2000). Specimens are common in Miocene limestones from southern Queensland (Palmieri, 1984), and the Indian Ocean (Ludbrook, 1965).

LBF of the Subfamily Soritinae (*Sorites, Marginopora*) share many physical characteristics, as well as similar environmental ranges (Loeblich and Tappan, 1988) (Tables 2.1, 2.2). Their environmental parameters are similar in part because they have symbionts of the same algal class, *Dinophyceae* (Leutenegger, 1977). Some species of *Sorites* can withstand seasonal drops in water temperature better than *M. vertebralis* (Langer and Hottinger, 2000). For example, *Sorites orbiculus* can live in waters between 14 and 33.5 °C (Langer and Hottinger, 2000).

*Sorites* spp. live at variable depths in a wide range of environments due to the substrate preferences of each species (Hottinger, 1977). Some are adapted to a
wide variety of substrates and others are specifically adapted for life only as epiphytes on plants (Hottinger, 1977) (Table 2.2).

### Table 3.2 Examples of Modern Environments of *Sorites* spp.

<table>
<thead>
<tr>
<th>Location</th>
<th>Depth</th>
<th>Environment/Substrate</th>
<th>Reference(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dongara and Albany, W. A.</td>
<td>0-1 m</td>
<td>seagrass beds; seagrasses</td>
<td>Semeniuk, 2001</td>
</tr>
<tr>
<td>Palau and Hawaii</td>
<td>15-50 m</td>
<td>reef</td>
<td>Hallock, 1979; Lee and Hallock, 1987</td>
</tr>
<tr>
<td>off Okinawa, Japan</td>
<td>0-30 m</td>
<td>fore-reef slope, inter-reef channels; seagrasses, reef rubble</td>
<td>Hohenegger, 1994</td>
</tr>
<tr>
<td>Red Sea</td>
<td>0-60 m</td>
<td>seagrass beds; seagrasses, reef rubble, algal balls, pebbles</td>
<td>Hottinger, 1977</td>
</tr>
<tr>
<td>Mediterranean Sea</td>
<td>0-40 m</td>
<td>sandy-silty shelf; seagrasses and shells</td>
<td>Hyams et al., 2002; Leutenegger, 1977</td>
</tr>
<tr>
<td>Florida Bay and the Caribbean</td>
<td>1-4 m</td>
<td>seagrass beds; seagrasses, green calcareous and fleshy algae</td>
<td>Fujita and Hallock, 1999; Martin and Liddell, 1988; Müller-Merz and Lee, 1976</td>
</tr>
</tbody>
</table>

*Austrotrillina howchini*

*Austrotrillina howchini* is common in the Rawlinna member of the Nullarbor Limestone (Fig. 3.1; Ludbrook 1958a, b; Cockbain [in Lowry, 1970]; Lindsay and Harris, 1975; Li et al., 1996a; this study). It has also been identified rarely in the Mullamullang Member (Ludbrook, 1958b; this study). *A. howchini* range from 0.75-2.2 mm wide when cut tangentially. Wall thicknesses of these specimens range from 0.06-0.2 mm. Along the eastern edge of the Nullarbor Limestone, *A. howchini* usually occurs in association with other large miliolines (*Lepidocyclina, M. vertebralis* and...
*Flosculinella bontangensis*; Benbow and Lindsay 1988; Lindsay and Harris, 1975; Ludbrook, 1958a).

*Austrotrillina* helps define the middle Miocene (f₁-f₂) LBF assemblage of Australia (Crespin, 1950). *A. howchini* is most frequently found in eastern, southern and western Australian limestones (Palmieri, 1984). Foraminiferal associations throughout these and other limestones suggest that *Austrotrillina* required similar environmental conditions, as those of modern alveolinids (e.g. *Flosculinella*; Chaproniere, 1975; Hallock and Glenn, 1985).

*Flosculinella* sp.

Specimens of the genus *Flosculinella* are rare in the Rawlinna member (Fig. 3.1; Ludbrook, 1958a; Lindsay and Harris, 1975; this study) and have only been identified at two locations (Cocklebiddy Cave, Old Homestead Cave; this study). *Flosculinella* is a globular to ovate alveolinid and specimens identified in this study range from 1 to 1.25 mm in diameter.

*Flosculinella* has a range of Lower Miocene to Holocene and is restricted to the Indo-Pacific region (Loeblich and Tappan, 1964; Adams, 1976; Loeblich and Tappan, 1988). In Australia, it occurs in northwestern and Western Australia, in the Eucla Basin and on the Capricorn Shelf of southern Queensland (Fig. 2.5; Ludbrook, 1965; Palmieri, 1984).

*Flosculinella* has often been compared to modern alveolinids, which are restricted to warm, shallow, metahaline waters (Chaproniere, 1975). Alveolinid tests are adapted to withstand high wave energies while still allowing enough
surface area for symbionts to photosynthesize (Haynes, 1965; Chaproniere, 1975). Modern alveolinids, for example, are particularly numerous in high-energy shallow tropical reef environments.

*Flosculinella* itself is most common in limestones with shallow, metahaline, high-energy seafloors and reefs (Chaproniere, 1975; Carozzi et al., 1976). They are not found exclusively in high-energy deposits, however and also occur more rarely in back-reef facies (associated with *Australotrillina* and *Miogypsina*) and in muddy limestones (Carozzi et al., 1976; Betzler and Chaproniere, 1993).

Large Benthic Rotaliines

*Miogypsina/Gypsina* spp.

In this study, the term “(mio)gypsinid” includes both *Gypsina* and *Miogypsina*, because they cannot be differentiated easily in thin section. (Mio)gypsinids are most common as encrusting layers (0.15-2 mm thick) in rhodoliths. These layers comprise many overlapping tests since they tend to encircle coralline algae cores of rhodoliths. (Mio)gypsinids are also present but rare as free tests in the Nullarbor Limestone and have circular or ovate outlines in thin section (Fig. 3.4). Lengths range from 0.75-3 mm and widths range from 0.4-0.75 mm, depending on the shapes of the individuals. *Gypsina* was previously identified in the Nullarbor Limestone (Cockbain [in Lowry, 1970]).

Members of the genus *Miogypsina* are found in early-middle Miocene limestones from lagoon and shallow subtidal depositional environments (Flügel, 2004). Extant *Gypsina* spp. can survive in a wide range of seasonal water
Figure 3.4. Large benthic rotaliines of the Nullarbor Limestone. A) Gypsina sp., Cocklebiddy Cave (N1.8), B) Miogypsina sp., Eucla Pass (N9.8), C) Operculina sp., Cocklebiddy Cave (N1.8).
temperatures, but are most common in tropical, shallow waters (≤ 70 m depth) (Perrin, 1994; Ungaro, 1996). They are abundant on coralline algal ridges in water temperatures ranging between 18 and 27° C (Minnery, 1990). The tests of Gypsina and Miogypsina are reinforced with pillars between chambers as an adaptation to shallow, turbulent environments (Chaproniere, 1975).

Encrusting epiphytic species dominate fossil and modern assemblages, but free and loosely attached lifestyles also occur (Undaro, 1996). Hard-substrate-dwelling species of Gypsina encrust rocks, calcareous green algae or coralline red algae and tend to live in reef environments where these substrates are available (Scoffin and Tudhope, 1985; Debenay and Payri, 2010). Gypsina spp. are also ubiquitous as components in ancient and modern rhodoliths and on algal ridges alongside many species of coralline algae (Table 1.3).

Gypsina is commonly part of an encrusting community that includes serpulid worms, bryozoans, sponges, and coralline algae (Dravis, 1979). They can contribute to coral-reef frameworks by successfully competing with coralline algae for space on hard substrates (Barbados, Martindale, 1992). Gypsina spp. on rhodoliths can survive on the dorsal and ventral surfaces and are able to compete with coralline algae due to their adaptability to varying light levels (Prager and Ginsburg, 1989). In some areas, the abundance of Gypsina in rhodoliths decreases substantially with increasing depth between 20 and 70 m (Minnery, 1990).
Table 3.3. Examples of Modern Environments of *Gypsina* spp.

<table>
<thead>
<tr>
<th>Location</th>
<th>Depth</th>
<th>Environments/Substrates</th>
<th>Reference(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rottnest Shelf, Western Australia</td>
<td>27-60 m</td>
<td>shelf ridges</td>
<td>James et al., 1999</td>
</tr>
<tr>
<td>central Great Barrier Reef, Bahamas</td>
<td>60-100 m</td>
<td>detrital <em>Halimeda</em> sediments on outer shelf</td>
<td>Scoffin and Tudhope, 1985</td>
</tr>
<tr>
<td></td>
<td>1-11 m</td>
<td>hardground crusts and clasts on high energy platform surfaces of coral reefs and rhodoliths on platform</td>
<td>Dravis, 1979</td>
</tr>
<tr>
<td>Eastern Caribbean</td>
<td>8-60 m</td>
<td>rhodoliths on platform surfaces of coral reefs and rhodoliths on platform</td>
<td>Martindale, 1992; Reid and MacIntyre, 1988</td>
</tr>
<tr>
<td>Florida shelf</td>
<td>35-60 m</td>
<td>rhodoliths on shelf</td>
<td>Prager and Ginsburg, 1989</td>
</tr>
<tr>
<td>Flower Garden Banks, Gulf of Mexico</td>
<td>20-70 m</td>
<td>coralline algae on coral reefs, algal crust ridges and rhodoliths on shelf</td>
<td>Minnery, 1990</td>
</tr>
<tr>
<td>Miyako Islands, Japan</td>
<td>60-150 m</td>
<td>outer shelf and slope</td>
<td>Tsuji, 1993</td>
</tr>
</tbody>
</table>

*Operculina* spp.

*Operculina* is rare in the Nullarbor Limestone (this study) and was first identified by Cockbain [in Lowry, 1970]. The planispiral tests are usually viewed tangentially in thin section (Fig. 3.4). Specimens examined in this study have lengths of 1.6-2.7 mm and widths of 0.4-0.75 mm.

*Operculina* is a cosmopolitan, tropical to subtropical genus and includes some of the most conspicuous LBF in the Indo-Pacific (Reiss and Hottinger, 1984; Loeblich and Tappan, 1988; Beavington-Penney and Racey, 2004). Members of the genus *Operculina* only live in warm waters of normal marine salinity (Chaproniere, 1975).

*Operculina* spp. are most abundant living on soft sediments (Hottinger, 1977; 1983; Reiss and Hottinger, 1984, p. 230). They are not considered epiphytic, but are locally associated with filamentous algae and seagrass (Reiss and Hottinger, 1984).
*Operculina* only uses pseudopods to attach loosely to substrates and, so, on reefs they are most commonly found nestled in cavities (Hohenegger, 2004). In seagrass beds, they usually seek shelter on the soft sediment between plants (Reiss and Hottinger, 1984).

Species of *Operculina* have symbionts (diatoms) that tolerate a wide range of light requirements (Leutenegger, 1984). Therefore, they have wide depth ranges (0-120 m) in clear waters (Hohenegger, 2004). They are active herbivores and, as a result do not rely on symbionts as much as most other LBF (Murray, 1991). In outer-reef shelf and inter-reef environments of the central and southern Great Barrier Reef, *Operculina* spp. are the most common benthic foraminifera between 60 and 70 m water depth, since many others are restricted to shallower areas (Jell et al., 1965; Scoffin and Tudhope, 1985). *Operculina* spp. are also dominant foraminifera on deep reef fronts and inter-reef channels in Indonesia (Remena, 2006).

*Operculina* specimens generally have increasingly flatter, thinner tests with increasing depth as a response to low light availability (Hohenegger, 1994; Reiss and Hottinger, 1984).

Miocene *Operculina* are interpreted to have inhabited similar settings as they do today: soft substrates, in low-energy environments in the lower photic zone (Hottinger, 1983). It was also common in main reef, back-reef, patch reef, intra-reef, and deeper off-reef facies similar to those of the modern Indo-Pacific (Carrozi et al., 1976; Epting, 1980; Bosellini, 2006).
Small Benthic Foraminifera (SBF)

These protists are common throughout the Nullarbor Limestone (Fig. 3.5A). They are, on the whole, more widespread than LBF, but not always as plentiful.

Miliolines

There are at least five common genera of whole milioline foraminifera in the Nullarbor Limestone, of which *Quinqueloculina* and *Triloculina* are the most common (Cockbain [in Lowry, 1970]; this study). Most small miliolines in the Nullarbor Limestone are ≤ 0.5 mm, but *Quinqueloculina* spp. locally attain slightly larger sizes.

Miliolines dominate modern foraminiferal assemblages of near-shore environments in water depths less than 50 m and can live in environments with extremes in temperatures and salinity (Murray, 1973; Flügel, 2004). They are abundant on modern reefs in normal oceanic salinities and also in metahaline environments such as Shark Bay, Western Australia (Davies, 1970; Hallock and Glenn, 1985; James et al., 1999). Miliolines often dominate the foraminiferal assemblage in metahaline environments because other groups are excluded (Grenier, 1969; Chaproniere, 1975).
Figure 3.5. Small benthic foraminifera of the Nullarbor Limestone. 
A) Small benthic miliolines (m) and rotaliines (r), Rawlinna Quarry (22.12), B) Textularia sp. (T) and LBF (M. vertebralis) fragment (M), Old Homestead Cave (19.9).
**Quinqueloculina**

*Quinqueloculina* spp. are the most common and widespread SBF in the Nullarbor Limestone. *Quinqueloculina* is a cosmopolitan genus and is usually dominant among SBF between 0 and 50 m water depth (Murray, 1991). Members of this genus are epifaunal herbivores and can live free on the sediment surface or attached to substrates such as plants (Murray, 1991). They can tolerate a wide variety of temperatures and salinities and are most numerous on shallow-marine shelves (Murray, 1991). They are commonly associated with seagrass beds and on sandy and muddy substrates in less than 12 m water depth (Davies, 1970; Murray, 1973; Murray, 1991; Betzler et al., 1997). *Quinqueloculina* spp. generally live on protected sediment subenvironments in seagrass meadows, rather than on the blades themselves (Davies, 1970). *Quinqueloculina* spp. also live on reefal sediments and are among the most abundant foraminifera on the modern Great Barrier Reef, Australia (Uthicke, 2010).

**Triloculina**

Whole specimens of *Triloculina* are common throughout the Rawlinna member of the Nullarbor Limestone, but are often less numerous than *Quinqueloculina* spp. Like *Quinqueloculina*, they are epifaunal and can live atop sediments or attached to substrates (Murray, 1991). *Triloculina* spp. are most abundant in temperate to tropical inner shelf and lagoonal environments and can tolerate salinities ranging from normal marine to hypersaline (up to 70‰ in Indian Ocean lagoons, Murray, 1991). *Triloculina* spp. are often found in association with,
and share the same life modes as, *Quinqueloculina* spp. in the Mediterranean Sea, Caribbean Sea and Western Australia (Davies, 1970; Murray, 1991).

**Small Benthic Rotaliines**

Small hyaline tests of rotaliine foraminifera are also abundant in the Nullarbor Limestone (Fig. 3.5A). Fragments are far more common than whole tests, making thin-section identification difficult. Small rotaliines are usually smaller than 0.5 mm, although rare *Planorbulina* can be 2.5 mm in diameter.

Small benthic rotaliine foraminifera occur in shallow and deep waters of modern oceans. They dominate outer shelves from 50-200 m water depth, partially due to the decrease of milioline foraminifera deeper than 50 m (Flügel, 2004). Rotaliines are restricted to waters with normal marine or slightly lower salinities (Flügel, 2004).

*Planorbulina*

*Planorbulina* is rare in the Nullarbor Limestone, but is the largest and most recognizable small rotaliine. Specimens are usually viewed tangentially in thin section and have diameters ranging from 1-2.5 mm. The attachment surfaces of these encrusting specimens have variable shapes in response to different substrates.

*Planorbulina* is cosmopolitan in temperate to warm waters of shallow shelves (Murray, 1991). *Planorbulina* spp. are common in modern Western Australian gulfs, including areas around Esperance and the Rottnest Shelf (Cann and Clarke, 1993; James et al., 1999). Despite its large size, *Planorbulina* is not a symbiont-bearing
species (Reiss and Hottinger, 1984). Instead, specimens are passive suspension-feeders that live attached to substrates such as algae, seagrass leaves and coral rubble (Choi, 1984; Murray, 1991; Wilson, 1998; Toefy et al., 2003). They are, therefore, typically restricted to high-energy shorelines where soft algal substrates and food particles are abundant (Toefy et al., 2003). *Planorbulina* spp. frequent shallow waters, due to their affinity for encrusting seagrass blades and fleshy algae (Reiss and Hottinger, 1984; Murray, 1991; Wilson, 1998). They can also serve as pioneers on hard substrates, encrusting reef cavities, rhodoliths and coral rubble in lagoons, reefs and fore-reefs (to 40 m depth) (Choi, 1984; Reiss and Hottinger, 1984).

**Agglutinated Foraminifera**

Agglutinated foraminifera are common in both members of the Nullarbor Limestone (Cockbain [in Lowry, 1970]; this study). The most abundant genus, the biserial form *Textularia*, is numerous throughout the Nullarbor Limestone, but is not found everywhere (Fig. 3.5B; Cockbain [in Lowry, 1970]; this study). Small (<1 mm in length) test are most typical, but large (1-1.75 mm in length) specimens are locally abundant. *Textularia* spp. are infaunal and thus are often preserved whole, as are most specimens of the Nullarbor Limestone (Murray, 1991; this study).

Triserial, milioline, trochospiral and encrusting agglutinated forms are locally present, but are less abundant than biserials. Encrusting specimens attain the largest sizes of any of the agglutinated foraminifera (up to 1.75 mm). They are restricted to one locality, but are abundant at this location. The most common
encrusting forms have flat attachment surfaces and are no longer attached to substrates when observed in these limestones. Rare attached forms are found encircling echinoderm spines. Agglutinated tests in the Nullarbor Limestone are composed chiefly of fragments of hyaline and porcelaneous foraminiferal tests.

Agglutinated foraminifera are infaunal and epifaunal detritovores as well as passive herbivores and can inhabit a variety of habitats with varying water temperature and salinities (Grenier, 1969; Reiss and Hottinger, 1984; Murray, 1991; Matteucci, 1996). Encrusting agglutinated foraminifera can live on a variety of substrates infaunally and epifaunally (shells, bryozoans, filamentous algae; Reiss and Hottinger, 1984) and are most gregarious in shallow, tidally influenced areas (Matteucci, 1996). They are particularly abundant near the roots of marine plants where they feed on concentrations of microalgae and detritus (Matteucci, 1996). They also frequent cryptic subenvironments on reefs, to avoid competition with photosynthesizing encrusters (Matteucci, 1996). Agglutinated foraminifera are uncommon in areas of elevated nutrients due to upwelling on southern Australian open shelves, but do require enough nutrients for feeding (Betzler et al., 1997).

3.3 PLANKTONIC FORAMINIFERA

Small planktonic foraminifera range from rare to common in samples of the Nullarbor Limestone but are difficult to differentiate in two-dimensional thin sections. Planktonic foraminifera are generally rare on shallow shelves because of their intolerance for non-marine salinities and terrigenous input, and thus are
indicative of deeper-water sedimentation (Flügel, 2004). Planktonic foraminifera contribute to sediments deeper than 60 m water depth (w.d.) on modern temperate southern Australian shelves (Li et al., 1996b; Betzler et al., 1997) and deeper than 100 m w.d. on the outer shelf of the tropical Carnarvon Ramp, Western Australia (James et al., 1999; Fig. 2.5).

3.4 CORALLINE ALGAE

Coralline algae are common constituents of both members of the Nullarbor Limestone. Articulated branching coralline algae occur as small, disarticulated segments of uniform size (Fig. 3.6). These rods generally range from 0.2-0.7 mm in length and 0.1 and 0.2 mm in width. They are commonly abraded and are less well preserved than encrusting coralline algae. Fragments of Corallina and Jania have both been identified in the Nullarbor Limestone (this study).

Encrusting coralline algae are plentiful in rhodoliths. Rhodoliths range in diameter from <1 mm to 7 cm, but are mostly 1-3 cm. Nodules are generally spheroidal in shape and have well-preserved concentric laminae. Branching and columnar rhodolith forms also occur, but are less common. Encrusting coralline algae also occur rarely as thin crusts on fossil fragments and clasts. Lithophyllum, Sporolithon and Lithoporella have all been identified as rhodolith constituents (Fig. 3.7; this study).

Coralline algae are widely distributed in tropical to polar normal marine waters, from intertidal depths to the base of the photic zone (Adey and MacIntyre,
Figure 3.6. Articulated coralline algae of the Nullarbor Limestone. A) *Corallina* sp., Mullamullang Cave, (13.10), B) *Jania* sp., Cocklebiddy Cave (1.15).
Figure 3.7. Rhodolith constituents of the Nullarbor Limestone. A) *Lithophyllum* sp. showing concepticles, Mullamullang Cave (13.14), B) *Sporolithon* sp. showing sporangia, Cocklebiddy Cave (1.8), C) (Mio)gypsiniid rotaliine foraminifera, light-colored layers, between dark coralline algae layers, Abrakurrie cave (7.9), D) *Celleporaria* sp., bryozoan (C) between dark coralline algae layers, Mullamullang Cave (13.7).
Geographical ranges of taxa are primarily controlled by water temperature and depth ranges of taxa are primarily controlled by light intensity (Adey and MacIntyre, 1973; Wray, 1977; Johansen, 1981).

**Articulated (geniculate) coralline algae**

Articulated coralline-algae branches consist of jointed thalli made of multiple calcareous segments connected by non-calcareous joints (Wray, 1977). When the alga dies, its joints disintegrate and its rod-shaped calcareous segments produce multitudinous well-sorted sand particles (Fig. 3.6; Wray, 1977). Articulated coralline algae have relatively high growth rates (3-5 cm y⁻¹) and low turnover times (0.5 yr), which increase their abundance in sediments further (Johnson, 1961; Smith, 1972). They grow most profusely in well-illuminated waters usually attached to hard substrates in high-energy environments, such as rocky coastlines (Johnson, 1961). Salinity tolerant species, such as some *Corallina* and *Jania* spp. form algal turfs in rocky intertidal zones (Kelaher et al., 2001). *Corallina* and *Jania* are the only genera that live in cool and temperate waters, as well as in warm waters (Johnson, 1961). Both genera are found in cool-water seagrass beds of southern Australia (Spencer Gulf and Gulf St. Vincent) and contribute large amounts of sediment to these areas (Fig. 2.5; Gostin et al., 1984; James et al., 2009).

**Corallina**

*Corallina* is the most conspicuous coralline alga in the Nullarbor Limestone (Fig. 3.6; this study) and was first identified by Lowry (1970). Disarticulated
segments are broken and abraded and range from 0.2 to 0.4 mm in length and from
0.05 to 0.2 mm in width.

*Corallina* is common in tropical, subtropical and temperate seas (Wray, 1977). These algae can live in waters with extremely high energy in a wide range of
salinities (Johnson, 1961; Shepherd and Womersley, 1981). *Corallina* is common on
rocky coasts in water depths between 0-20 m (Johnson, 1961; Shepherd and

*Corallina* also lives attached to flexible substrates and are prominent
epiphytes on seagrasses in southern Australia (Shepherd and Womersley, 1981;
James et al., 2009). Disarticulated rods of *Corallina* are numerous in sediments of
Spencer Gulf in depths from 10-40 m. These environments include seagrass banks,
subtidal channels and intertidal and supratidal flats (Burne and Colwell, 1982).
*Corallina* is also common on rocky substrates in kelp stands off of southern
California, U.S.A., at depths less than 10 m (Smith, 1972).

*Jania*

Disarticulated segments of *Jania* spp. are also present in the Nullarbor
Limestone, but are not nearly as abundant as those of *Corallina* spp. (Fig. 3.6). Rods
of *Jania* spp. range from 0.1 to 0.75 mm in length and from 0.1 to 0.2 mm in width.
*Jania* is also found in tropical, subtropical and temperate waters but prefer more
sheltered, lower energy environments than *Corallina* spp. (Johnson, 1961; Wray,
1977). They are often found alongside *Corallina* spp. on rocky coasts between 0-20
m water depth, but are again much less numerous than *Corallina* spp. (Canals and
Ballesteros, 1997). *Jania* is the most abundant taxa of branching coralline epiphytes on modern seagrasses in protected embayments in South Australia (James et al., 2009).

**Rhodoliths**

Encrusting coralline algae are particularly resistant to wave energy and abrasion, and are epiphytes that can form crusts and reefs on stable hard substrates and thin films on seagrasses. Tropical encrusting coralline algae often thrive in deeper or very high-energy waters, where many other calcifying organisms are excluded (Bosence, 1983).

In shifting sediments, coralline algae grow concentrically around nuclei of small hard clasts such as shell fragments and rocks. As these substrates move on the seafloor, the coralline algae continue to grow on the upper surfaces where light is available. Eventually these algae form subspherical rhodoliths. Rhodoliths live on unstable seafloors where there is (at least periodically) enough energy to roll them on the seafloor, thus exposing different surfaces of rhodoliths to light and coralline-algae growth (Johansen, 1981). Rhodoliths have slow growth rates compared to other coralline algae (<1 mm yr\(^{-1}\); Bosence, 1983; Reid and MacIntyre, 1988; Table 1, Foster, 2001). They can also be buried, exhumed and recolonized, further extending their formation times (Bosence, 1983).

Rhodolith morphologies are largely dependent on hydrodynamics (i.e., the frequency and mechanisms of overturning) (Bosellini and Ginsburg, 1971). Laminar internal structures form where there is high water energy and frequent overturning
and so rhodoliths in higher-energy environments have smooth or bumpy spheroidal shapes (Bosellini and Ginsburg, 1971; Bosence, 1983). Branching and columnar (fruticose) rhodoliths occur in lower-energy environments and they have less laminar internal structure. Fruticose rhodoliths frequent seagrass meadows with the lowest water energies (Bosellini and Ginsburg, 1971).

*Lithophyllum*

*Lithophyllum* is common in Nullarbor Limestone rhodoliths (Fig. 3.7). Modern *Lithophyllum* is found in all seas, but is concentrated around the tropics (Johnson, 1961; Bosence, 1983). Members of this genus are adapted for life in strong light conditions and so many species are restricted to shallow waters (Adey and MacIntyre, 1973; Johansen, 1981; Bosence, 1983). Despite their affinity for high light conditions, they are also common constituents of rhodolith gravels in depths between 35 and 75 m (Rottnest Shelf, Collins, 1988; Gulf of Mexico, Minnery, 1990).

*Sporolithon*

*Sporolithon* is also a common rhodolith constituent in the Nullarbor Limestone (Fig. 3.7). The genus *Sporolithon* (formerly *Archaeolithothamnium*) is constrained to tropical and subtropical environments, with many tropical species restricted to deeper waters (>60 m) (Johnson, 1961; Johansen, 1981; Bosence, 1983). In shallow tropical environments, *Sporolithon* spp. are restricted to shaded areas under plant and coral cover (Littler, 1973). *Sporolithon* spp. are particularly
common in rhodoliths in deeper tropical waters (60-90 m) (Adey and MacIntyre, 1973; Bosence, 1983).

*Lithoporella*

*Lithoporella* is a minor constituent of rhodoliths and a rare encruster of other shell fragments in the Nullarbor Limestone. It is easily identified in thin section because each thallus consists of a single layer of large cells. *Lithoporella* is found in all seas, but is most common in warm waters (Johnson, 1961). It is found associated with *Lithophyllum* in rhodolith pavements of the Rottnest Shelf (Collins, 1988).

3.5 BIVALVES

Bivalves are ubiquitous in much of the Nullarbor Limestone. Members of the Superfamily Ostreacea (*Ostrea*) and families Pectinidae (*Chlamys* and *Pecten*), Glycymerididae (*Glycymeris*), Cardiidae (*Fulvia* and others) and Veneridae (*Katelysia*, *Irus* and *Circomphalus*) are most numerous (Figs. 3.8, 3.9, this study).

**Epifaunal Bivalves**

**Oysters**

Whole articulated and disarticulated calcitic shells are well preserved and locally occur *in situ* encrusting each other in the Nullarbor Limestone (Fig. 3.8A). Shell sizes range from 2 to 4.5 cm in width and 3 to 6 cm in length. Lowry (1970)
Figure 3.8. Epifaunal bivalves of the Nullarbor Limestone. A) oysters, Old Homestead Cave (N19), B) pectens, Old Homestead Cave (N19), scale is in cm.
previously identified *Ostrea hyotidoidea* and *Ostrea* sp. among fossils that had presumably weathered out of Nullarbor Limestone outcrops. Oysters are filter feeders that live attached to hard substrates. Modern oysters along southern Australian coasts live in low to moderate energy settings, between 2 and 20 m water depth (Ludbrook, 1984). *Ostrea angasi* is the only large oyster native to modern southern and southwestern Australia (Morton et al., 2003). In Port Phillip Bay, Victoria, *O. angasi* is one of the most common benthic animals living between 10 and 20 m water depth (Fig. 2.5; Cohen et al., 2000). Small *O. angasi* build-ups provide habitat diversity, substrates and hiding places for other organisms (Cohen et al., 2000). Oysters are common in shallow estuarine settings and can tolerate brackish waters (Pufahl et al., 2004). For example, extensive, low-diversity oyster buildups indicate areas of brackish environments in Pliocene deposits of the Murray Basin (Fig. 2.5; Pufhal et al., 2004).

Scallops

*Scallops* (Family Pectinidae) are widespread in the Nullarbor Limestone (Ludbrook, 1958a; Ludbrook, 1958b; Lowry, 1970; this study) and are frequently occur in floatstone beds (Fig. 3.8B, this study). Lowry (1970) previously identified *Pecten murrayanus* in the Nullarbor Limestone. They are generally well preserved but shells exposed to weathering are friable and fragmented. They range in length from ~2-7 cm.

Southern Australian *Pecten* spp. live on a variety of soft sediment and hard substrates in temperate enclosed bays and open shelves, in water depths between 7
and 60 m (Ferland and Roy, 1997; Brand, 2006). They are most abundant in muddy sands near seagrass beds (Cohen et al., 2000). Scallop rudstones occur in shallow platform facies and also as storm beds at platform edges and slopes in Neogene Mediterranean temperate limestones (Spain, Braga et al., 2006).

Infaunal Bivalves

Dog Cockles

*Glycymeris* spp. (Family Glycymerididae) are widespread in the Nullarbor Limestone (Fig. 3.9A; Ludbrook, 1958b; Lowry, 1970; this study). Shells are mostly disarticulated and range in size from 0.3-2 cm in width. Internal molds are most common and allow for identification of *Glycymeris* based on detailed molds of valves and dentition (Fig. 3.9A).

Dog cockles are mobile, shallow-burrowing filter feeders (Ansell and Trueman, 1967; Thomas, 1975; Savina and Pouvreau, 2004). They live in normal marine waters on high-energy temperate and tropical continental shelves (10-100 m water depth) preferring to burrow in sand and coarser sediments. *Glycymeris* spp. are opportunistic and can withstand high wave and current energies that exclude other molluscs. Thus, they are most abundant in low diversity assemblages (Thomas, 1975).

*G. radians*, a common species in South Australia, prefers high-energy clean sands in seagrass (*Posidonia, Amphibolis*) environments (Ludbrook, 1984). *G. striatularis* also lives in areas with high current flow, but prefers finer sediments (Ludbrook, 1984). *Glycymeris* spp. are abundant on the Rottnest Shelf, southwestern
Figure 3.9. Infaunal bivalves of the Nullarbor Limestone. A) Glycymeris sp., Cook Quarry (N12), scale is in mm, B) Kateysia sp., Eucla Quarry, (N8), C) cockle, Old Homestead Cave (N19).
Australia, where they dominate the molluscan assemblage in wave-swept sands in water depths less than 50 m (Collins, 1988).

Cockles

Disarticulated cockle shells (Family Cardiidae) are locally abundant in the Nullarbor Limestone (Fig. 3.9C). Shells range in width from 1-3 cm. Typically, only portions of shell molds are visible, due to the lithified nature of the limestone. Identification to the genus level was not always possible, but at least one mold is of the genus *Fulvia* (Ludbrook, 1958a; Lowry, 1970; this study). Cockles are infaunal filter feeders that live buried under thin veneers of sandy and muddy sediment on shallow shelves, to about 30 m water depth (Ludbrook, 1984; Dame, 1996).

Venus Clams

Venus clams (Family Veneridae) are copious in the Nullarbor Limestone (this study). Not all molds could be identified to the genus level. Of complete exterior molds, *Katelysia* spp. (Fig. 3.9B) and *Irus* sp. are most common, whereas *Cicomphalus* spp. are rare (this study). Venerid shell widths range from 2-7 cm.

Venerid bivalves are infaunal suspension-feeders that are abundant in temperate and warm-temperate lagoons of New Zealand and Australia (including Shark Bay and Princess Royal Harbour, near Albany) (Peterson et al., 1994; Fig. 2.5).

*Katelysia* spp. have tropical Indo-Pacific affinities and are the most common molluscs of sandy beaches and littoral zones of modern southern Australia (Ludbrook, 1984). They also inhabit unvegetated sand flats near seagrass beds.
Some species are tolerant of salinity changes (Ludbrook, 1984).

Many *Irus* spp. are present in very shallow modern southern Australian marine environments (Ludbrook, 1984). *Irus crenatus*, for example, is stenohaline, but lives in mud and sand on the outskirts of tidal inlets and estuaries (Ludbrook, 1984; Semenuik and Wurm, 2000).

*Circomphalus* spp. are found on sublittoral shelves and embayments of southern Australia and prefer sandy substrates associated with *Posidonia* seagrass beds (e.g. Gulf St. Vincent; Ludbrook, 1984; Fig. 2.5).

### 3.6 GASTROPODS

Gastropods in the Nullarbor Limestone were aragonitic and are so are only preserved as interior and exterior molds. Identification of gastropods beyond the family level was difficult in such circumstances (Table 3.4). Identification to the genus level was, however, locally possible due to exceptional mold quality (Fig. 3.10, Table 3.4).
Table 3.4. *Gastropod taxa identified in the Nullarbor Limestone.*

<table>
<thead>
<tr>
<th>Superfamilies</th>
<th>Families</th>
<th>Genera</th>
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<td><em>Xenophora</em></td>
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<td>Fasciolariidae</td>
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<td>Buccinidae</td>
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<td>Volutidae</td>
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<td>Cerithiacea</td>
<td>Turritelidae</td>
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<td>Cerithiidae</td>
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<td>Trochacea</td>
<td>Phasianellida</td>
<td><em>Phasianella</em></td>
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**Predatory Gastropods**

This group includes the Superfamily Muricacea, Family Conidae and some cowries (Cypraeacea).

**Tulip Snails and Spindle Snails**

Tulip snails and spindle snails (Family Fasciolariidae, *Fusinus*) were identified in the Nullarbor Limestone during this study. Most shells are around 2 cm in length, but one specimen discovered is 6.5 cm long. These carnivores occur in temperate and tropical seas (Ludbrook, 1984; Wells and Bryce, 1988; Synder, 2003). *Fusinus australis* is the most abundant fasciolariid of southern Australia and is found on low to moderate energy shallow shelves (1-30 m water depth), commonly associated with seagrasses (Ludbrook, 1984; Wells and Bryce, 1988).
Figure 3.10. Common gastropods of the Nullarbor Limestone. A) Mitre, Old Homestead Cave (N19), B) *Xenophora* sp., Old Homestead Cave (N19), C) *Batillaria* sp., Watson Quarry (N11), D) Pheasant snail (P) and turritellid (T), Old Homestead Cave (N19).
Mitres

Mitres (Family Mitridae) range in length from 2-4 cm in the Nullarbor Limestone (Fig. 3.10A, this study). They are diverse carnivores of the tropical Indo-Pacific and live in shallow-water environments, under rocks or buried in sand (Wells and Bryce, 1988). They feed at night and live buried under the sand, in their prey’s habitat, during the day (Ludbrook, 1984). Some species are abundant in seagrass beds due to abundance of prey such as worms (Ludbrook, 1984).

Whelks

True whelks (Family Buccinidae, *Penion*) in the Nullarbor Limestone range in length from 4-5 cm (this study). Whelks are carnivores and scavengers. Smaller whelk species (such as these) are mainly restricted to shallow tropical waters, and often live beneath rocks and rubble and in seagrass beds (Wells and Bryce, 1988). *Penion mandarinus* is common on the modern continental shelves of the Great Australian Bight, Tasmania and New South Wales (Fig. 2.5; Ludbrook, 1984).

Volutes

Volutes (Family Volutidae, including *Lyria* sp.) in the Nullarbor Limestone range in length from 2-5 cm (this study). Members of this family are most common in Australia (compared to the rest of the world) and were most diverse in southern Australia during the Tertiary (Ludbrook, 1984). They are predatory and live in lower intertidal and subtidal sands (Wells and Bryce, 1988).
The genus *Lyria* is considered to be of tropical Indo-Pacific affinity (Darragh, 1985). *Lyria mitraeformis* are found in southern Australia on high-energy shelves from 1-50 m water depth on sand flats and pockets of sand between reefs (Ludbrook, 1984).

Cowries

*Cowries (Family Cypraeidae)* occur in the Nullarbor Limestone and range in length from 1-1.5 cm. Ludbrook (1958a) and Lowry (1970) previously identified cowries of the genus *Cypraea*.

Cowries are mainly found in the tropical Indo-Pacific but many species are also endemic to southern Australia (Hyman, 1967). They were most abundant and diverse in that area during the Miocene (Ludbrook, 1984). In modern Western Australia, the diversity of cowries increases northward into tropical areas (Wells and Bryce, 1988).

Cowries feed in a variety of ways and species are usually specialists, adapted for particular food sources (Wells and Bryce, 1988). Many are grazing herbivores and some are carnivores that feed on sponges and ascidians (Ludbrook, 1984). Modern southern Australian cowries feed on sponges (Ludbrook, 1984). Cowries are most abundant in shallow waters, <30 m water depth (Ludbrook, 1984). They are often found hiding beneath coral and rock rubble (Kay and Weaver, 1963).
Cone Shells

Cone shells (Family Conidae, Conus) are numerous in the Nullarbor Limestone (Ludbrook, 1958a; Lowry, 1970; this study) and range in size from 1-3 cm (interior mold widths).

Most cone shells are restricted to shallow tropical environments, but southern Australia also has some endemic temperate species (Wells and Bryce, 1988). Members of this group live in sand or beneath protective substrates such as rocks and coral boulders (Wells and Bryce, 1988). *Conus* spp. are common in rocky and sandy intertidal zones and under beach-rock benches (Kohn, 1959; Kohn and Leviten, 1976; Ludbrook, 1984).

**Herbivorous Gastropods**

This group includes Potamididae, Cerithiidae and some cowries (Cypraeacea).

Mud whelks

Mud whelks (Potamididae, including *Batillaria* spp.) in the Nullarbor Limestone have shells ranging in length from 3-5 cm (Fig. 3.10C). Modern species are conspicuous on muddy and sandy intertidal flats, mangrove swamps, and estuaries of southern Australia (Ludbrook, 1984). Mud whelks feed on detritus and benthic algae and can tolerate normal and decreased salinities of estuaries. Due to their flexibility, they can dominate intertidal mollusc assemblages (Wells and Bryce, 1988).
Ceriths

*Hypotrochus* spp. (Family Cerithiidae) are rare in the Nullarbor Limestone and are only 1 cm in length (this study). Modern *Hypotrochus* spp. generally live in shallow normal-marine waters (Wells and Bryce, 1988). *Hypotrochus monachus* for example, lives on muddy substrates and algae in southern Australia (5-20 m water depth) and can also be associated with the seagrass *Posidonia* (Ludbrook, 1984).

**Detritus-feeding Gastropods**

This group includes Xenophoridae, Diastomatidae and some members of Potamididae.

**Carrier Shells**

Carrier shells (Family Xenophoridae; *Xenophora*) are locally abundant to dominant among gastropod assemblages of the Nullarbor Limestone (Fig. 3.10B; Lowry, 1970; this study). Most shells are interior molds and range in width from 1-3.5 cm. Shell lengths are slightly less than shell widths. Molds with widths between 2 and 3 cm dominate.

*Xenophora* is a tropical taxa and is primarily an Indo-Pacific group (Hyman, 1967; Darragh, 1985; Nielsen and DeVries, 2002). Xenophoridae are unique among gastropods because they can cement sedimentary particles, such as shells, pebbles, living sponges, brachiopods, solitary corals and foraminifera to their shells (Morton, 1958; Hyman, 1967). This unique characteristic has earned them the name 'carrier
shells’ and the adaptation is thought to be an extreme method of camouflage (Morton, 1958; Hyman, 1967). *Xenophora* spp. feed by scavenging along the seafloor and are typically found in deeper waters of continental shelves (e.g., ~80 m off North Island, NZ; Morton, 1958; Hyman, 1967). They are, therefore, often associated with fine-grained sediments in the rock record (Darragh, 1985).

**Diastomatidae**

The Family *Diastomatidae, (Diastoma)* includes high-spired gastropods that range in length from 2-4 cm in the Nullarbor Limestone (Ludbrook, 1958a; Lowry, 1970; this study). *Diastoma* spp. are detritovores that often dominate molluscan assemblages in tropical and temperate seagrass beds and their associated limestones (Marsh, 1976; Valentine and Heck, 1993). They are, for example, copious in the Pliocene Roe Calcarenite (Ludbrook, 1984; James and Bone, 2007).

**Filter-feeding Gastropods**

**Turritellids**

*Turritellids* (Family Turritelidae) are the most common high-spired gastropods of the Nullarbor Limestone (Fig. 3.10D; Ludbrook, 1958a; this study) and their shells range from 1-3.2 cm in length.

Members of this family live just below the surface of sand and mud and filter feed using siphons that stick up out of the sediment (Ludbrook, 1984). They occur in a wide variety of marine environments, but are most common in shallow to middle shelves (10-100 m water depth) (Allmon, 1988). Most species prefer water
temperatures ranging from 15-20°C, but some taxa are tropical and prefer warmer waters (Allmon, 1988). Modern turritellids live on a variety of substrates, from soft muds to firmer scoured surfaces (Allmon, 1988). *Gazameda iredale* thrive along southern coasts from Western Australia to Tasmania in sediment between seagrass (*Posidonia*) (Ludbrook, 1984). Turritellids seem to prefer siliciclastic sediments to carbonate sediments, but this may be due to nutrient and food availability rather than strictly sediment preference.

Turritellids can be concentrated in areas of seasonal upwelling, particularly in New Zealand and Australia. This may be in response to increased food (phytoplankton) production (Allmon, 1988). In South Australia, the abundance of *Gazameda gunni* increases during times of winter upwelling (Allmon, 1988).

**Specialist Herbivores**

Pheasant Snails

Pheasant snails (Family Phasianellidae, including *Phasianella* sp.) are found in the Nullarbor Limestone and range in length from 1-3 cm (Fig. 3.10D, this study). *Phasianella* spp. are specialist herbivores that feed on certain types of algae, including red algae (Hyman, 1967). Modern *Phasianella* spp. live in shallow coastal waters and are some of the most abundant gastropods in southwestern Australian seagrass (*Posidonia, Amphibolis*) beds (2-9 m water depth) (Tuya et al., 2010). *Phasianella* spp. are most abundant in the centers of patchy seagrass meadows where vegetation biomass is highest and predator density is lowest (Tuya et al.,
3.7 SCAPHOPODS

Scaphopods (genus *Dentalium*) occur in the Nullarbor Limestone (Ludbrook, 1958a; b; Lowry, 1970; this study). Each shell is long (≥ 2 cm) and thin (0.5-1 cm) and has a shell that tapers gradually to a pointed apex. Scaphopods are benthic molluscs that live in both the neritic and bathyal parts of the world’s oceans (Knight et al., 1960). They live at the sediment-water interface and feed on small organisms, such as foraminifera (Knight et al., 1960).

3.8 CORALS

Corals are, overall, sparse in the Nullarbor Limestone but can be locally numerous. They are usually preserved as external molds but are locally replaced by chert, preserving internal structure (Fig. 3.11E). For the most part, corals were not preserved in growth position and are fragmented. The crystalline nature of the limestones allowed for detailed mold preservation and, thus, identification of taxa to family and sometimes genus levels (Fig. 3.11, 3.12).
Zooxanthellate Corals

Zooxanthellate corals of the families Faviidae (cf. *Montastraea*, *Cyphastrea*), Pocilloporidae (*Stylophora*, *Seriatopora*) and Poritidae (*Porites*, *Goniopora*) occur in the Nullarbor Limestone (Fig. 3.11, 3.12, this study). Other zooxanthellate corals of the families Faviidae (*Cladocora*), Fungiidae (solitary, zooxanthellate), Mussidae (zooxanthellate) and Oculinidae (zooxanthellate, azooxanthellate) are also present (this study), but require further study for confirmation. Zooxanthellate corals are restricted to warm oligotrophic areas of the photic zone.

Faviids

Faviids (family Faviidae) are the largest corals identified in the Nullarbor Limestone, but are rare (Fig. 3.11C, D, E). Most faviids are rounded, do not fragment easily and are thus preserved whole. They may or may not be in original growth position. The skeletons have lobate to hemispherical shapes and some specimens seem to be abraded fragments. Whole faviids range in diameter from 5-18 cm and in height from 9-30 cm. Some of the Nullarbor specimens have characteristics similar to those of the modern genera *Montastrea* and *Cyphastrea* (B. Rosen, pers. comm. 2010). Rare faviid branches may be *Cladocora* sp. as well, which are ~0.5 cm in diameter and 1-2.5 cm in length.

Faviids (other than the branching *Cladocora* spp.) are reef/frame-building corals that often reach large sizes. They are primarily tropical, but some modern faviids (including one species of *Cyphastrea*) live in temperate environments, such as
Figure 3.11. Corals of the Nullarbor Limestone. A and B) pocillogorids (P), Watson Quarry (N11), C) faviid, Old Homestead Cave (N19), D) faviid, Watson Quarry (N11), E) partially silicified faviid, Watson Quarry (N11), image courtesy of N.P. James, F) flabellid, Eucla Pass (N9).
Figure 3.12. Poritid corals of the Nullarbor Limestone. A) *Goniopora* sp., Rawlinna Quarry (N22), B) *Porites* sp., Rawlinna Quarry (N22).
the Arabian Gulf, and can withstand large seasonal temperature fluctuations (Coles and Fadlallah, 1991).

*Cyphastrea* spp. inhabit a wide variety of reef environments, from lagoons to reef slopes and shallow rocky substrates. At least some *Cyphastrea* spp. are common in subtropical environments (Veron and Stafford-Smith, 2000). Nullarbor Limestone faviids that resemble modern *Montastraea* spp. have corallites with diameters ranging from 3-5 mm. Similar modern *Montastraea* spp. with small corallites (<7 mm) inhabit many reef environments, particularly shallow reef flats (Veron and Stafford-Smith, 2000).

*Cladocora* are not massive corals, but instead form clumps of delicate branches. They grow in shallow turbid environments, such as seagrass beds, and also in deeper waters, where some *Cladocora* spp. do not contain symbiotic zooxanthellae (Veron, 1995; Veron and Stafford-Smith, 2000).

Pocilloporids

Branching corals of the Family Pocilloporidae are rare overall, but are common in localized horizons of the Nullarbor Limestone (Fig. 3.11A, B). All pocilloporids in the Nullarbor Limestone are molds of branch fragments. Some are silicified but others have been recrystallized, preserving internal structure. Many fragments are of ramose branches and show branch divergence points. *Seriatopora* and *Stylophora* may both be present in the Nullarbor Limestone. *Seriatopora* branches range from 0.3-1 cm wide and up to 10 cm long. *Stylophora* branches range from 0.4-0.7 cm wide and up to 4 cm long.
*Seriatopora* has previously been recorded in the Miocene from the Marshall Islands and Indonesia (Veron and Kelley, 1988; Veron and Stafford-Smith, 2000). Most *Seriatopora* colonies are composed of thin branches and are common in shallow, protected reef environments. Some species have the ability to create thicker, shorter branches to withstand higher wave action (Veron and Stafford-Smith, 2000).

Two species of *Stylophora* (*S. pistillata* and *S. subseriata*) dominate among modern species and live in a wide range of reef environments, from high-energy reef flats to low-energy reef slopes and lagoons. They have variable growth forms adapted to wide ranges of wave energies and light levels. Robust branches of *S. pistillata* commonly dominate the coral assemblages on high-energy reef flats of modern tropical Australia. More delicate branches of *S. pistillata* are also found on sheltered reef slopes (Veron and Stafford-Smith, 2000).

Poritids

Poritids (Family Poritidae, *Goniopora, Porites*) are only found in the Nullarbor Limestone at one locality (Rawlinna Quarry, Fig.3.11), but are numerous at that location. Nullarbor Limestone poritids are not molds, but have been calcitized, preserving their porous mesh-like internal structures (Fig. 3.11). They occur only as fragments and are not preserved in growth position. Some are clearly fragments of massive corals and others are rounded fragments of robust branching, massive or columnar forms. Fragments range in diameter from 1.5 to 7 cm.
Living *Goniopora* have distinctively long polyps that are extended during the day and night. They live in a wide variety of shallow reef environments, most often in calm, but turbid waters (Veron and Stafford-Smith, 2000). They typically construct large monospecific structures in areas where other corals are restricted due to high terrigenous sediment input (Veron, 1995). *Porites* spp. often dominate modern reefs and have been dominant reef-builders since the Miocene (Veron, 1995). They are common in a wide variety of shallow reef environments (Veron and Stafford-Smith, 2000).

**Azooxanthellate Corals**

Azooxanthellate Flabellidae and Dendrophyllidae (*Dendrophyllia* or *Balanophyllia*) have been confirmed in the Nullarbor Limestone (this study). Azooxanthellate corals of the family Caryophyllidae may also occur.

**Flabellids**

Corals of the Family Flabellidae are solitary azooxanthellate corals (Fig. 3.11F). They occur in the Nullarbor Limestone and range in diameter from 0.5 to 5 cm with most individuals between 1 and 2.5 cm in diameter. They have a large modern geographic range since they can live in temperatures ranging from tropical waters to -1°C and depths ranging from 0 to 3,200 m. Flabellids can live attached to substrate via rootlets or free-living, atop the sediment (Cairns, 2002).
Blocky echinoderm fragments are ubiquitous and occur throughout the Nullarbor Limestone. Whole echinoid megafossils are rare and, when present, are all irregular types. Due to the crystalline nature of the Nullarbor Limestone, lateral cross-sections are usually all that is visible of whole irregular echinoids. Based on these profiles, at least one taxa each of sand dollars, heart urchins, and hat urchins are present (this study). Rare tests of *Lovenia* sp. (heart urchin) have been partially weathered out of the limestone and were able to be identified to the genus level. Philip (1970) has identified three irregular echinoid genera in the Nullarbor Limestone: *Lovenia* (*L. forbesii*, heart urchin), *Monostychia* (sand dollar) and *Peronella* (thick-tested hat urchin).

Spines of regular echinoids also occur sparsely, but no whole tests were observed. Regular echinoids have poor preservation potential compared to that of irregular echinoids and their tests are often reduced to fragments upon death. Their epifaunal lifestyle makes them more susceptible to predation and test fragmentation by waves and currents (Smith, 1984).

All echinoderms are useful as paleoenvironmental indicators since they are only found in normal-marine waters (Melville and Durham, 1966). Modern echinoids are common in littoral and sublittoral zones, but many live in deeper waters (Melville and Durham, 1966). Irregular echinoids are passive detritovores that are adapted for burrowing in soft sediment (Baker, 1982; Flügel, 2004).
Heart urchins are adapted for living in burrows in consolidated and unconsolidated sediments (Fischer, 1966). *Lovenia* spp. are common in open sands and *Posidonia* seagrass beds of southwestern Australia (35-45 m water depth) (James et al., 1999).

The Order Clypeasteroida includes sand dollars and hat urchins. Clypeasterids live on or just beneath the sediment surface, most often in sublittoral and littoral zones (Durham, 1966b). In southern Australia, *Peronella peronii* lives in sediments between 10 and 360 m water depth (Baker, 1982). Sand dollars (*Clypeaster* spp.) occur with *Lovenia* spp. shallowly buried in sand flats and *Posidonia* seagrass bed sediments of the inner Rottnest Shelf (35-45 m water depth) (James et al., 1999).

### 3.10 SERPULID WORMS

Serpulid worm tubes are widespread, but rarely abundant in the Nullarbor Limestone. Most are whole, but fractured and fragmented tubes also occur.

Serpulids are filter feeders that generally live attached to hard substrates (Shepherd and Thomas, 1982). They are most common in shallow, coastal waters (<30 m deep), but are also found in deeper waters (Wood, 1999; Scholle and Ulmer-Scholle, 2006). The worms usually occur in normal-marine environments, but can also tolerate hypersaline conditions (Scholle and Ulmer-Scholle, 2006). They are abundant in tropical seagrass beds (Frankovich and Ziemann, 1994) but are only
minor sediment producers in temperate and subtropical seagrass beds (Perry and Beavington-Penney, 2005; Giovannetti et al., 2008; James et al., 2009).

3.11 BRYOZOANS

Bryozoans are rare in the Nullarbor Limestone (Lowry, 1970; this study). Large encrusting celleporiform bryozoans (*Celleporaria*) occur locally, but are sparse. *Celleporaria* create hollow branches 1-2 cm in width and up to 15 cm in length that are commonly interlayered with coralline algae in rhodoliths (Fig. 3.7D). Other types of bryozoans have more limited distributions and are uncommon (delicate branching cyclostomes and delicate branching, robust branching and foliaceous cheilostomes).

Bryozoans can tolerate a wide range of water temperatures (10-30°C) and most are stenohaline (32-37‰) (Nelson et al., 1988b; Bone and Wass, 1990). They are most abundant on shelves from 0-200 m water depth, but can also live below the photic zone (Nelson et al., 1988b).

Bryozoans are major contributors to epiphyte sedimentation in modern temperate seagrass beds (*Amphibolis* spp. and *Posidonia* spp.) of southern Australia. Sheet-like, delicate branching, articulated fenestrate and encrusting (*Celleporaria* sp.) bryozoans are abundant on these seagrasses (James et al., 2009).

Foliose erect rigid bryozoans live attached to hard substrates in shallow waters (Bone and James, 1993). Robust branching bryozoans are best suited for wave-swept settings, whereas delicate branching types live in quieter waters of
middle and outer shelves, deeper than 130 m (Nelson et al., 1988b; Bone and James, 1993).

High-energy shelves with shifting sediments dominate areas of temperate carbonate deposition, such as the modern southern Australian shelf. Therefore, encrusting bryozoans, such as Celleporaria, typically live attached to other sessile invertebrates (sponges, hydroids, tunicates, worm tubes, octocorals) and seagrasses (Hageman et al., 2000; James et al., 2009). Celleporaria spp. can create hollow branches in the rock record due to their encrustation of these ephemeral organic substrates. Celleporaria of southwestern Australia, for example, grow on single digits of the sponge, Oceanapia (Hageman et al., 2003).

3.12 OSTRACODS

Ostracods are rare and only occur locally in the Nullarbor Limestone. These crustaceans are extremely versatile scavengers that are tolerant of virtually all salinities and temperatures. Ostracods are found in a variety of muddy environments, but are only dominant in stressed environments, where other organisms are excluded. Therefore, they are not particularly useful as paleoenvironmental indicators unless they are dominant.
Chapter 4: Sedimentology

4.1. FACIES ASSOCIATIONS

There are five facies associations in the Nullarbor Limestone and each is named for its major constituents (Table 4.1).

Rhodolith Facies Association (Mullamullang Member)

Facies — Rhodolith Rudstone-Floatstone (Fig. 4.1)

Description

This facies association encompasses the entire Mullamullang Member and consists of only one lithofacies: rhodolith rudstones and floatstones with an articulated branching coralline algae, SBF and echinoderm-fragment grainstone and packstone matrix (Fig. 4.1).

Rhodoliths are primarily constructed of Sporolithon and Lithophyllum with occasional layers of Lithoporella. Encrusting bryozoans (Celleporaria) and rotaliine foraminifera (Gypsina or Miogypsina) are locally interlayered with coralline algae (Fig. 4.1, 3.6). Other encrusting rotaliine foraminifera are rare. Pores between laminations are filled with calcite spar and, rarely, geopetal sediment.

Rhodoliths are generally spheroidal in shape with well-preserved concentric laminar internal structures (Fig. 4.1). Some have more irregular fruticose morphologies. Internal layering is generally loose with high proportions of internal sediment and nuclei are rarely visible (cf. type B rhodoliths, Nalin et al., 2008).
Table 4.1. Nullarbor Limestone lithofacies. Percentages of components were estimated petrographically. Percentages are displayed as numbers or are rare (R). Abbreviated rare accessory components include: ostracods (O), encrusting bryozoans (en. bry.), branching bryozoans (bran. bry.) and quartz grains (Q). Continued on the next page.

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<tbody>
<tr>
<td>Rhodolith Facies Association</td>
<td>1.4, 3.8C-4, 3.11, 13.7, 13.13, 7.9</td>
<td>rhodoliths</td>
<td>R/10-25</td>
<td>R</td>
<td>R-10/0</td>
<td>5-20</td>
<td>5-25</td>
<td>~50</td>
<td>en. bry, bran. bry (0-20)</td>
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<td>Echinoderm Facies Association</td>
<td>E1- Echinoid/SBF grnst/fitst</td>
<td>Cellepora, infaunal echinoids</td>
<td>gastropods, oysters, scallops</td>
<td>0/20</td>
<td>R</td>
<td>10/R</td>
<td>40</td>
<td>R</td>
<td>0</td>
<td>0</td>
<td>en. bry. (5), bran. bry (10)</td>
<td>15</td>
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<td>E2-Echinoid grnst</td>
<td>5.2</td>
<td>LBF</td>
<td>5/25</td>
<td>R</td>
<td>35</td>
<td>15</td>
<td>10</td>
<td>0</td>
<td>bran. bry., Q, Intra. (10)</td>
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<td>Articulated Coralline Algae Facies Association</td>
<td>A1-Articulated coralline algae grnst</td>
<td>1.5, 1.10, 13.10, 13.17</td>
<td>rhodoliths, infaunal echinoids (locally common)</td>
<td>infaunal echinoids, Cellepora, gastropods, bivalves</td>
<td>R-10/10-30</td>
<td>R-5</td>
<td>R/R</td>
<td>5-20</td>
<td>20-40</td>
<td>R-10</td>
<td>O, bran. bry., Q, clasts (15)</td>
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<tr>
<td>A2-Articulated coralline algae/SBF grnst (fine-grained)</td>
<td>7.13, 7.14, 10.4, 10.8</td>
<td>rhodoliths, infaunal echinoids, gastropods, bivalves</td>
<td>0-R/10-25</td>
<td>0-5</td>
<td>0-10/0-10</td>
<td>10-25</td>
<td>R-15</td>
<td>20-50</td>
<td>0-5</td>
<td>en. bry, bran. bry.</td>
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<td>1.12, 1.15, 13.14</td>
<td>small rhodoliths</td>
<td>infaunal echinoids, gastropods, bivalves</td>
<td>10/15</td>
<td>R-5</td>
<td>R/0</td>
<td>5-10</td>
<td>5</td>
<td>25-40</td>
<td>10-20</td>
<td>coral, en. bry., bran. bry.</td>
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<td>A4-Mollusc/LBF fitst</td>
<td>1.8</td>
<td>bivalves, gastropods</td>
<td>zoanthellate and azooxanthellate corals</td>
<td>15/25</td>
<td>R</td>
<td>10/10</td>
<td>10</td>
<td>5</td>
<td>20</td>
<td>5</td>
<td>en. bry., bran. bry.</td>
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<td><strong>SBF/LBF Facies Association</strong></td>
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<td>F1-SBF/LBF grnst</td>
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<td>large benthic foraminifera</td>
<td>gastropods, bivalves, corals, <strong>Celleporaria</strong></td>
<td>10-35/15-40</td>
<td>R</td>
<td>0-20/0-15</td>
<td>0-15</td>
<td>R</td>
<td>0-20</td>
<td>R</td>
<td>O (0-10), coral, en. br., bran. bry., Q (0-10), clasts (0-15)</td>
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<td>F3-Skeletal fitst</td>
<td>19.8, 11.3, 21.5, 22.12</td>
<td>large benthic foraminifera, bivalves, gastropods</td>
<td>corals, <strong>Celleporaria</strong>, scaphopods</td>
<td>10-30/20-30</td>
<td>R</td>
<td>5-25/5-20</td>
<td>0-15</td>
<td>0</td>
<td>5-15</td>
<td>R</td>
<td>en. bry., Q, clasts, coral in field</td>
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<td>F4-Coral fitst</td>
<td>12.15</td>
<td><strong>Celleporaria</strong>, large benthic foraminifera</td>
<td></td>
<td>15/35</td>
<td>R</td>
<td>10/0</td>
<td>5</td>
<td>0</td>
<td>10</td>
<td>coral (15 in thin section)</td>
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<td>20, micritized</td>
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<td><strong>SBF and Planktonic Foraminifera Facies Association</strong></td>
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<tr>
<td>P1-SBF and planktonic foraminifera grnst (fine to very fine-grained)</td>
<td>8.4, 9.6, 9.8, 9.10, 9.13, 5.4, 11.10</td>
<td>infaunal echinoids, gastropods, bivalves, <strong>Celleporaria</strong></td>
<td></td>
<td>0-R/10-30 0 (10-80)</td>
<td>R-R/10-10</td>
<td>0-15</td>
<td>0-15</td>
<td>0-15</td>
<td>R frags.</td>
<td>O (0-10), en. bry., bran. bry, Q, clasts</td>
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<td>P2-SBF and planktonic foraminifera pkst (fine-grained)</td>
<td>8.1, 8.2, 22.15, 22.16</td>
<td></td>
<td></td>
<td>0-R/20-35</td>
<td>50-60</td>
<td>5-10/R</td>
<td>5-20</td>
<td>0-10</td>
<td>0-10</td>
<td>O (0-10), bran. bry., Q, clasts</td>
<td></td>
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</table>
Surfaces of some rhodoliths are smooth and others are covered with bumpy protrusions that are anastomosing as they have been cemented together by younger crust layers. Borings on the surfaces of rhodoliths are common. Most rhodoliths are 1-4 cm in diameter, but some are as large as 7 cm.

Major matrix constituents include articulated branching coralline algae (*Corallina*), SBF, and echinoderm fragments. Among benthic foraminifera, rotaliines are more common than miliolines. Megafossils other than rhodoliths include azooxanthellate corals (Family Flabellidae) and infaunal bivalves (families Cardiidae and Veneridae (especially *Katelysia*)).

**Interpretation**

Coralline algae and large benthic rotaliines are the only light-dependent biota in this facies and these biota are indicative of the oligophotic zone, where light is too dim to support other photosynthesizers (Pomar, 2001; Pomar et al., 2004). *Lithophyllum* is common as a rhodolith builder to 75 m water depth on the modern Rottnest Shelf (Collins, 1988). *Sporolithon* is restricted to low light conditions and has been found as deep as 90 m (Adey and McIntyre, 1973; Bosence, 1983). *Gypsina* is common in rhodoliths on shelves between 35 and 70 m water depth (Table 1.3; Reid and McIntyre, 1988; Prager and Ginsburg, 1989; Martindale, 1992). These constituents, along with abundant rotaliine foraminifera indicate water depths in the lower photic zone (subphotic zone, James and Bourque, 1992; oligophotic zone, Pomar, 2001). Fossils that are restricted to the upper photic zone are lacking. Although *Gypsina* is tolerant of a wide range of temperatures, *Sporolithon* and
Figure 4.1. A and B) outcrop images of rhodolith rudstones, Mullamullang Cave (N13), images courtesy of N.P. James, C) Photomicrograph of rhodolith rudstone, Mullamullang Cave (N13), rhodoliths dominated by coralline algae (A) with layers of Celleporaria sp. (C), bryozoan.
*Lithophyllum* imply subtropical to tropical conditions. Abundant echinoderm fragments indicate normal-marine waters.

Interlayering of coralline algae and *Gypsina* and overall morphologies of these rhodoliths are similar to those described by Minnery (1990) from the Gulf of Mexico (20-70 m water depth). Since these rhodoliths have laminated internal structures and rounded shapes, they must have been regularly overturned (Bosellini and Ginsburg, 1971). Mud in some of these limestones indicates periods of quiet water deposition, suggesting periodicity of high energy for rhodolith overturning. Therefore, periodic currents or storm waves may have entrained rhodoliths. Infaunal bivalves imply that there was some open sandy or muddy areas suitable for burrowing and some water movement for filter feeding. Solitary azooxanthellate coals could also have lived atop these sandy patches or attached to rhodolith substrates.

This facies is interpreted to have been deposited in subtropical to tropical normal-marine waters of the lower photic zone (oligophotic zone), where there would have been sufficient light for coralline algae and large encrusting rotaliine foraminifera, but not enough light for other photic taxa.

**Echinoderm Facies Association**

This minor facies association is composed of two different lithofacies that both contain abundant echinoderm fragments and benthic foraminifera.
Facies E1—Echinoid-SBF Grainstone-Floatstone (Fig. 4.2A)

Description

Echinoderm fragments are the most abundant component (Fig. 4.2A). Small benthic foraminifera (rotaliine, milioline and agglutinated) and delicate branching bryozoan fragments (both cyclostomes and cheilostomes) are less numerous. Planktonic foraminifera are rare. Prevalent megafossils include whole infaunal echinoids and encrusting bryozoans (*Celleporaria*; hollow branches ≤ 1 cm diameter). This facies is dominated by grainstones, but discontinuous floatstone lenses occur where megafossils are most abundant. About 20% of the grains are iron-stained. Half of the stained grains are rounded, extensively bored, and have darkest staining around micrite envelopes (Fig. 4.2A).

Interpretation

None of the fossils require light or particularly warm waters, so water temperatures could have been temperate or tropical and depths were most likely below the photic zone. The abundance of echinoids and diverse SBF imply normal-marine salinities. Rotaline foraminifera are just as common as milioline foraminifera, suggesting that water depth likely exceeded 50 m (Flügel, 2004)

Infaunal echinoids are preserved whole, indicating that they were living in this environment and the sands were unconsolidated and suitable for burrowing. Shifting sands may, however, have hindered bryozoan recruitment (Hayton et al., 1995). Clean sands also imply moderate wave energy or no source of lime mud.
Figure 4.2. Echinoderm Facies Association, A) Facies E1, boring in echinoid test (B), Mullahangang Cave (13.3), B) Facies E2, echinoderm fragment (E), A. howchini (A), serpulid worm tube (S), Wilson Bluff (5.2).
Hollow tubes of *Celleporaria* form due to encrusting ephemeral organic substrates such as sessile invertebrates and seagrasses (Hageman et al., 2003). This environment was not likely home to seagrasses, since there are no light-dependent fossils. Alternatively, *Celleporaria* most likely encrusted benthic invertebrates such as sponges (c.f. Hageman et al., 2003). The abundance of infaunal echinoids and *Celleporaria* implies that this facies was deposited under mesotrophic conditions (Hageman et al., 2003).

Stained grains meet the description of relict grains found on modern southern Australian seafloors (Rivers et al., 2007). Relict grains are interpreted to have been deposited in shallow waters during previous sea level lowstands and altered during subsequent sea-level fluctuations (James et al., 1999; Rivers et al., 2007). Relative abundance of stained relict grains represents low sedimentation rates (Rivers et al., 2007).

These sediments were most likely deposited in moderate-energy, cool waters under mesotrophic normal-marine conditions.

*Facies E2 — Echinoid Grainstone (Fig. 4.2B)*

Description

Echinoderm fragments are the most common component of this grainstone (Fig. 4.2B). SBF (rotaliine, milioline and agglutinated), serpulid worm tubes, articulated coralline algae (*Corallina*) and LBF also occur. Planktonic foraminifera are rare. Benthic foraminifera (large and small) are typically fragmented. Whole SBF include *Quinqueloculina, Triloculina* and various forms of textulariids.
*Austrotrillina* is the only common LBF (Fig. 4.2B). Whole benthic rotaliines include *Operculina* and rare *Planorbulina*. *Celleporaria* and whole infaunal echinoids are common megafossils. Iron-stained, rounded limestone clasts are rare. Many of these clasts have been extensively bored. Whole and fragmented benthic foraminifera are the most common clast constituents.

Interpretation

This facies is quite similar to Facies E1. The addition of photosynthesizing organisms such as coralline algae and LBF indicates that these sediments were deposited in the photic zone. Dominance by non-light-dependent fossils (echinoids, SBF, serpulids), nonetheless, restricts this deposit to the lower photic zone. *Corallina* lives in tropical, temperate and cool waters (Johnson, 1961), whereas modern LBF are restricted to warm subtropical to tropical waters.

Rotaliine foraminifera are more common than milioline and agglutinated foraminifera, implying that the seafloor was deeper than 50 m water depth (Flügel, 2004). *Operculina* (rarely whole in this facies) is common in modern tropical Australia to depths of 70 m (Jell et al., 1965; Scoffin and Tudhope, 1985) but modern alveolinids (relatives of extinct *Austrotrillina*) are only abundant in shallow, high-energy environments of the upper photic zone (Haynes, 1965; Chaproniere, 1975). The presence of *Austrotrillina* (alveolinid) tests might imply that this facies was deposited in a shallow, high-energy environment, but no other components suggest that this is the case. The presence of LBF, however, does imply that low nutrient levels and subtropical to tropical water temperatures were present.
Most of the light-dependent biota of this facies (coralline algae, rotaliine LBF) are common in the oligophotic zone, as defined by Pomar (2001). The oligophotic zone is the lower photic zone (50-100 m in clear waters) and is inhabited by organisms that require lower light levels and light-independent biota (Pomar, 2001). Large benthic miliolines (eg., Austrotrillina) are not generally adapted for low light conditions, so its presence in this association is puzzling. It is possible that meroplanktonic juvenile miliolines were brought to this environment via ocean currents and survived despite low light levels. Abundance of alveolinids (A. howchini) and clean sands may also imply moderate energy levels (Haynes, 1965; Chaproniere, 1975).

Most fossils here require low to no light, so deposition of this facies most likely occurred near the base of the oligophotic zone, under normal marine salinities and low nutrient levels. Iron-stained clasts are most likely relict grains that have similar origins to those of Facies E1.

_Echinoderm Facies Association Synopsis_

Echinoderm facies accumulated in normal-marine waters, just above (E2) or below (E1) the base of the photic zone.

_Articulated Coralline Algae Facies Association_

This facies association is distinguished by articulated coralline algae grainstones (Facies A1, A2) that are interbedded with lenses of other minor facies.
A3, A4, A5. Articulated coralline algae and benthic foraminifera are the dominant components.

**Facies A1 — Articulated Coralline Algae Grainstone (Fig. 4.3A)**

**Description**

Articulated coralline algae are the most abundant constituents of these medium to fine grainstones (Fig. 4.3A). *Corallina* is the most conspicuous algae and *Jania* is rare. Large and small benthic foraminifera and echinoderm fragments are common. Small rhodoliths (*Sporolithon, Lithophyllum*) are locally common and rarely include encrusting foraminifera such as *Miogypsina* or *Gypsina*. LBF are dominated by miliolines (*M. vertebralis, A. howchini* and *Sorites* spp.). Nubecularids and large benthic rotaliines such as *Gypsina, Miogypsina, Operculina* and *Pararotalia* are present but rare. SBF include miliolines, rotaliines and agglutinated taxa, but miliolines are generally most frequent. Megafossils include infaunal echinoids, encrusting bryozoans (*Celleporaria*), gastropods (families *Potamididae, Cerithidae, Fascioliariidae, Turritelidae, Conidae, Mitridae*) and bivalves (families *Pectinidae, Ostreacea, Cardiidae*).

**Interpretation**

The presence of LBF, tropical rhodolith-building coralline algae (*Sporolithon, Lithophyllum*) and diverse molluscs implies tropical to subtropical temperatures. Large benthic miliolines (such as *M. vertebralis*) suggest temperatures commonly
Figure 4.3. Articulated Coralline Algae Facies Association. A) Facies A1, Mullamullang Cave (13.10), M. vertebralis (M), Corallina (C), B) Facies A2, rhodolith (R), Abrakirrie Cave (7.13), C) Facies A3, rhodolith (R), Corallina sp. (C), Mullamullang Cave (13.14), D) Facies A3 outcrop image of small rhodolith, Mullamullang Cave, E) Facies A4, Cocklebiddy Cave (1.8), large benthic miliolines (M), F) Facies A5, gastropod molds (G), Weebubbie Cave (10.7).
above 20°C (Langer and Hottinger, 2000). The presence of mitres also suggests some tropical influence (Wells and Bryce, 1988). Green calcareous algae are absent and LBF are not dominant, indicating that temperatures were sub-tropical, rather than tropical.

Coralline algae and LBF are light dependent and imply that this facies formed in the photic zone. Large benthic miliolines require higher light levels than coralline algae and thrive in well-lit, oligophotic waters. The large benthic miliolines (particularly *M. vertebralis*) found in this facies are most common living in waters shallower than 30 m (Leutenegger, 1984). Nubecularids and large benthic rotaliines are rare, but further indicate an illuminated seafloor. The overall dominance of miliolines over rotaliines and agglutinated SBF also suggests that these sediments were deposited at water depths shallower than 50 m (Flügel, 2004). *Corallina* produces sediment in southern Australian waters shallower than 40 m (Burne and Colwell, 1982). Oysters are also most abundant in shallow Australian waters, to depths of 20 m (Ludbrook, 1984; Cohen et al., 2000). Many gastropods are also restricted to shallow intertidal zones (Mitridae, Potamididae, Cerithiidae, Conidae) (Ludbrook, 1984; Wells and Bryce, 1988). The presence of echinoderm fragments and *Operculina* implies that normal marine salinities prevailed, despite shallow depths (Chaproniere, 1975).

Many fossil components of this facies require attachment to hard or flexible substrates and are found as seagrass epiphytes in modern subtropical and temperate seas (articulated coralline algae, some benthic foraminifera, serpulid worms, *Celleporaria*) (Betzler et al., 1997; James et al., 1999; Perry and Beavington-
Penney, 2005; James et al., 2009). Nubecularids in particular are indicative of seagrasses. In southern Australia, *Corallina* spp. are prominent sediment producers in seagrass beds, subtidal channels and tidal flats (Shepherd and Womersley, 1981; Burne and Colwell, 1982; James et al., 2009). Modern Australian members of the gastropod families Fasciolaridae, Turritelidae, Cerithidae and Mitridae are also common in or near seagrass beds on low to moderate energy shelves between 1 and 30 m water depth (Ludbrook, 1984; Wells and Bryce, 1988). Although pectens are widespread to depths of ~60 m, some southern Australia species are locally restricted to seagrass beds and live among the blades to hide from predators (Morton, 2000; Brand, 2006).

The production of clean sands from seagrass-bed deposits requires moderate energy, as is the case in northern Spencer Gulf (Fig. 2.5; Burne and Colwell, 1982). This water energy could also have overturned rhodoliths and allowed sessile filter-feeding bivalves (Ostreacea, Cardiidae) and gastropods (Turritellidae) to obtain adequate food from bottom waters. Open patches of sediment without dense seagrass root mats must have been present to allow for shallow burrowing by infaunal bivalves (Cardiidae) and echinoids (Ludbrook, 1984). *A. howchini* is closely related to modern alveolinids that are most abundant in shallow, high-energy environments. They could have also lived atop open sands, with local higher energy conditions. These sediments were produced in seagrass meadows and open sand patches of the upper photic zone, on a shallow sub-tropical seafloor.
Facies A2 — Articulated Coralline Algae-SBF Grainstone (Fig. 4.3B)

Description

Articulated coralline algae and SBF dominate these fine-grained to very fine-grained grainstones (Fig. 4.3B). *Corallina* dominates the articulated coralline algae assemblage, but *Jania* also occurs locally. Echinoderm fragments are common throughout. Serpulid tubes, planktonic foraminifera, and bivalve and gastropod fragments occur locally. LBF (*A. howchini*) and rhodoliths (with *Gypsina* or *Miogypsina*) are rare. SBF, in order of abundance, include rotaлиnes, miliolines and agglutinated forms.

Interpretation

This facies is similar to Facies A1, except warm-water indicators are sparse. Based on the abundance of seagrass epiphytes (articulated coralline algae, benthic foraminifera, serpulid worms) its formation is interpreted as cooler-temperate seagrass-bed sedimentation on a shallow shelf. The lack of biota that require high light levels and planktonic foraminifera could imply that a deeper environment is represented here, but seagrass sedimentation is limited by the light requirements of the seagrasses themselves (upper photic zone). Coralline algae and LBF also require an illuminated seafloor. Thus, these sediments were likely deposited on a cooler-temperate shallow shelf, in dense seagrass meadows of the upper photic zone.
Facies A3 — *Rhodolith Floatstone* (Fig. 4.3C, D)

**Description**

The matrix of this facies is composed of Facies A1 (articulated coralline algae grainstone). This facies only differs from Facies A1 because of the higher rhodolith content. Rhodoliths are smaller (most ≤ 1 cm) and less abundant than in Rhodolith Facies association R, but have the same coralline algal constituents (*Lithophyllum, Sporolithon, Lithoporella*) (Fig. 4.3C, D). *Lithophyllum* is dominant and *Lithoporella* is rare. Rhodoliths are generally knobby and branching with branch fragments occurring sparsely as matrix components (Fig. 4.3C, D). Rare megafossils include infaunal echinoids, gastropods (families Potamiidae, Cerithidae, Fascioliariidae) and bivalves (Family Cardiidae). LBF are the same as in Facies A1 (*A. howchini*, *Gypsina*), with the addition of rare *Flosculinella* fragments and the absence of *Operculina*.

**Interpretation**

Based on component similarities, this facies must have a comparable environment to Facies A1. Coralline algae (especially tropical *Lithophyllum*), LBF and intertidal gastropods imply deposition in shallow tropical to subtropical waters. Abundance of epiphytic fossils and seagrass-associated gastropods (Cerithidae, Fascioliariidae) provide evidence for deposition in or near seagrass beds (Ludbrook, 1984; Wells and Bryce, 1988; Betzler et al., 1997). Rhodolith-building *Lithophyllum* is adapted for life in shallow waters with high light levels and its abundance may support interpretation of a shallow environment suitable for seagrass growth (Adey and MacIntyre, 1973; Johansen, 1981; Bosence, 1983). Branching and knobby
rhodolith morphologies support the interpretation of a seafloor partially protected by seagrasses (Bosellini and Ginsburg, 1971).

The addition of more rhodoliths and alveolinids (*Flosculinella*) may imply a higher-energy environment than that of seagrass meadows of Facies A1. Such higher energy was perhaps attained in shallower environments or in bare sand patches between seagrass meadows. The presence of infaunal bivalves (Cardiidae) implies that this facies may represent moderate-energy sand patches between seagrass meadows. In conclusion, this facies is interpreted to represent deposition in tropical to subtropical normal-marine, moderate-energy seagrass beds and sand patches on a shallow, illuminated seafloor.

**Facies A4 — Mollusc-LBF Floatstone (Fig. 4.3E)**

Description

The matrix of this floatstone is the same as Facies A1 (articulated coralline algae grainstone) and only differs from Facies A1 based on additional megafossils. Megafossils in this floatstone include LBF (*M. vertebralis, A. howchini*, rare *Sorites* spp., *Flosculinella* and *Operculina*), gastropods (families Fasciolariidae (*Fusinus*), Volutidae, Mitridae, Conidae, Potamididae and Turritelidae), bivalves (families Pectinidae, Ostreacea, Cardiidae, Veneridae (*Katelysia*)) and rare azooxanthellate (Family Flabellidae) and zooxanthellate corals (Faviidae (cf. *Cyphastrea*), Pocilloporidae). Sparse rhodoliths are composed of *Sporolithon*. 
Interpretation

The constituents of Facies A1 provide the matrix of this floatstone and are indicative of subtropical deposition in the photic zone, specifically in and around seagrass beds. The addition of zooxanthellate corals and tropical gastropods (Mitridae, Conidae) and bivalves (*Katelysia*) confirms tropical to subtropical deposition on a shallow well-lit seafloor.

Many molluscs of this facies are most abundant in modern intertidal and subtidal zones (Volutidae, Mitridae, Conidae, Potmidae, *Katelysia*) (Ludbrook, 1984; Darragh, 1985; Wells and Bryce, 1988). It is no surprise that carnivorous gastropods (Fasciolariid (including *Fusinus*), Volutes, cone shells, Mitres) occur in this assemblage, since they often feed on other molluscs (Ludbrook, 1984; Wells and Bryce, 1988; Snyder, 2003).

*Sporolithon* can tolerate dimmer light than *Lithophyllum*, so rhodoliths of this facies might imply a deeper environment than that of the previous seagrass bed facies. *Sporolithon* is also common environments with abundant light, however, and large benthic miliolines, zooxanthellate corals and molluscs imply that this environment was well illuminated.

*Fusinus* is often associated with seagrass beds in southern Australia (Ludbrook, 1984). Mitres often frequent seagrass meadows (Ludbrook, 1984). Members of some of the gastropod families Cerithiidae, Fasciolaridae, Turritelidae, Mitridae and infaunal bivalves (*Katelysia*) are also common in or near seagrass beds in low- to moderate-energy environments of southern Australia (1-30 m water depth) (Ludbrook, 1984; Wells and Bryce, 1988). *Katelysia*, specifically, frequents
shallow sand flats adjacent to seagrass meadows (Peterson et al., 1994). Turritelids are infaunal filter feeders and require phytoplankton in suspension as their food source (Allmon, 1988).

These coarser-grained floatstone lenses may represent bare, sandy patches between seagrass beds that could have been formed by storm blowouts, as described by Patriquin (1975) and Wanless (1981). Concentrations of large fossils occur as lags at the bases of these blowouts and are formed by storms, waves and continuous high energy (Patriquin, 1975; Wanless, 1981). Without the protection of seagrasses, fair-weather waves after the storm could continue to winnow fine particles, fragment foraminiferal tests and concentrate large mollusc shells. Corals could be concentrated in these areas due to the availability of hard shell substrates and higher light levels (without the shade of grass blades).

Facies A5 — *Gastropod Floatstone (Fig. 4.3F)*

Description

The matrix of this floatstone is composed of Facies A2 (articulated coralline algae-SBF grainstone). Common megafossils include gastropods and infaunal echinoids. Turritelids are the most abundant gastropods and other families (Phasianellidae, Potamididae, Volutidae (*Lyria*) and Diastomatidae) also occur. Infaunal echinoids include clypeasterids and spatangoids (*Lovenia* sp.). Infaunal bivalves (Glycymerididae (*Glycymeris*), Ostreacea) and rhodoliths (*Sporolithon*) are rare. Azooxanthellate (Flabeliidae) and zooxanthellate corals are extremely rare in this facies. Zooxanthellate corals may be of the family Faviidae (*Cladocora*) or
Oculinidae or Caryophyllidae (some azooxanthellate). LBF are also scarce, but large
*M. vertebralis* were observed in the field at one location.

**Interpretation**

Based on the matrix composition, this facies must have formed in a similar
environment to that of Facies A2. Coralline algae and rare *M. vertebralis* restrict the
facies to the photic zone. Lack of other photosynthesizers and abundance of small
benthic rotaliines imply that this facies was deposited in the lower photic zone.
*Sporolithon*, in particular, is adaptable to lower light levels than many other coralline
algae (Johnson, 1961). Presence of the tropical coralline algae (*Sporolithon*),
gastropods (*Lyria*) and rare LBF and zooxanthellate corals implies that there must
have been some warm-water influence (Johnson, 1961; Ludbrook, 1984).

Articulated coralline algae and some gastropods (Turritellidae,
Phasianellidae, Diastomatiidae, Potmididae) imply shallow deposition that may be
associated with seagrass beds. Infaunal echinoids (Clypeasterids (*Lovenia*),
Spatangoids) are most common in intertidal and subtidal zones of modern southern
Australia and are often associated with seagrasses (Durham, 1966b; James et al.,
1999). The presence of *Cladocora* would further strengthen the argument for
seagrasses since shallow-dwelling *Cladocora* spp. are most abundant in turbid
environments such as seagrass beds (Veron, 1995; Veron and Stafford-Smith, 2000).

The abundance of turritelid gastropods and infaunal echinoids could be
attributed to increased food availability due to elevated nutrient levels (Allmon,
1988). Thus, this facies may represent deposition during a period of elevated
trophic resources. Infaunal *Glycymeris* are most abundant in high-energy sands (Thomas, 1975). *Lyria* is also abundant on shallow, high-energy seafloors (Ludbrook, 1984).

The occurrence of rare, large *M. vertebrais* (tropical, upper photic zone) seems out of place in an environment that has thus far been interpreted as temperate-subtropical lower photic zone. Ross (1972) noted that *M. vertebrais* individuals living below ideal temperature and depth ranges are unable to reproduce. Since *M. vertebrais* die during reproduction, rare individuals living below reproduction limits often are able to live longer lives and grow to abnormally large sizes (Ross, 1972). This environment could have recruited vagrant *M. vertebrais* from the meroplankton of oceanic currents.

In conclusion, these sediments are thought to have been produced on a temperate to subtropical seafloor influenced by seagrass-associated carbonate production, similar to that of articulated coralline algae grainstone facies A2. The environment was most likely middle photic zone, with increased nutrients and moderate wave energy.

*Articulated Coralline Algae Facies Association Synopsis*

The facies in this association represent deposition in the upper and middle part of the photic zone in subtropical to temperate waters. The plethora of components produced by epiphytic and seagrass-associated biota advocates the interpretation of seagrass-meadow sedimentation.
Benthic Foraminifera Facies Association

A diverse assemblage of benthic foraminifera (large and small) dominates this facies association. Facies F1 (grainstone) is the most widespread and volumetrically significant facies. Floatstones (facies F3 and F4) occur locally as lenses within Facies F1, where megafossils are most numerous. Facies F2 is only found at one locality (Cook Quarry, N11, Fig. 1.2)

Facies F1 — Small and Large Benthic Foraminifera Grainstone (Fig. 4.4A)

Description

Large and small benthic foraminifera are equally abundant in this facies. The benthic foraminiferal assemblage is dominated by miliolines. M. vertebalis is the most abundant and widespread LBF. A. howchini, Sorites spp. and milioline sp. A. are locally common (Fig. 3.2, 3.3) whereas Miogypsina sp. and Gypsina sp. are rare. SBF include diverse miliolines (Quinqueloculina, Triloculina, Massilina, Miolinella and others), diverse textulariids and less diverse rotaliines, including rare Planorbulina. Mollusc, echinoid and articulated coralline algae fragments occur locally. LBF are the most common megafossils, but rare gastropods (Turritellidae, Fasciolariidae, Conus, Xenophora), bivalves (Pectenidae, Cardiidae, Ostreacea), scaphopods (Dentalium) and Celleporaria also occur. Mollusc fragments are often visible petrographically due to micrite envelopes. Poritid corals (Goniopora, Porites) are present in this facies at one locality.
Figure 4.4. Small and Large Foraminifera Facies Association, A) Facies F1, *M. vertebrales* (M), Old Homestead Cave (N19.14), B) Facies F2, SBF (S), LBF fragments (L), Cook Quarry (N12.6), C) Facies F3, *Flocculina* sp. (F), mollusc molds, (m), Old Homestead Cave (N19.8), D) Facies F4, plocilporid (P), Cook Quarry (N12.15).
Interpretation

Abundance of LBF, coralline algae and rare poritid corals suggests that the seafloor was well within the photic zone and waters were warm. In modern tropical seas, corals and large benthic miolines are most plentiful in the upper photic zone, shallower than 30 m (Leutenegger, 1984). A milioline-dominated foraminiferal assemblage further implies shallow deposition. *Dentalium* most likely occurs due to the abundance of their food source, benthic foraminifera (Knight et al., 1960).

Modern LBF are most common in waters that usually stay ≥ 25°C (Murray, 1991). *M. vertebrales*, the most abundant large foraminifera, requires water temperatures between 20-33.5°C in order to reproduce (Langer and Hottinger, 2000). As stated previously, abundance of LBF and variability in test size may imply that reproduction was occurring locally. *Xenophora*, zooxanthellate corals and micrite envelopes found in this facies also indicate tropical temperatures (Hyman, 1967; Betzler et al., 1997). Organisms relying on zooxanthellae endosymbionts (large benthic foraminifera, corals) imply oligotrophic conditions.

Epiphytic organisms of this facies (*M. vertebrales*, *Sorites* spp., articulated coralline algae, *Celleporaria*) are common constituents of tropical and sub-tropical seagrass deposits (Davies, 1970; Severin, 1987; Cann and Clarke, 1993; Hohenegger, 1994; Betzler et al., 1997; James and Bone, 2007). The large milioline sp. A also appears to have been epiphytic on ephemeral substrates, since tests are shaped like hollow tubes. Some turritellid and fasciolariid gastropods are also common on shallow seafloors and can be associated with seagrass beds in modern Australia (Ludbrook, 1984; Wells and Bryce, 1988). Sediments sourced from seagrass
meadows are copious in this facies and imply that seagrasses populated the seafloor in this environment.

Mud is absent from this facies, implying at least moderate energy or no source of mud. Tests of alveolinids (A. howchini) and soritids (M. vertebralis and Sorites spp.) are adapted to withstand high wave energies while still allowing adequate surface area for photosynthetic symbionts (Haynes, 1965; Chaproniere, 1975). Alveolinids are particularly indicative of high-energy environments and may have been swept into the seagrass environment from adjacent high-energy sand flats or bare pockets between seagrass beds. The presence of large infaunal bivalves (Cardiidae) also implies that open sands occurred in this environment (James and Bone, 2007). Therefore, this facies was deposited on a moderate-energy tropical to sub-tropical shelf in the upper photic zone, with abundant seagrass beds and intermittent patches of open sand.

Facies F2 — Cross-Bedded Grainstone (Fig. 4.4B, 4.5A, B)

Description

Trough cross-bedded grainstones only occur at one locality (Cook Quarry, N12). Trough crossbeds are oriented NE-SW (Fig. 4.5A, B). Crossbeds are decimeters in height and capped by ripple cross-laminated layers (< 5 cm thick), showing herringbone structures. Sands are well sorted, and fine upwards, from coarse- to fine-grained sands. Foraminifera are highly fragmented, making identification difficult (Fig. 4.4B). SBF are most abundant, but large benthic
Figure 4.5. Facies Association F outcrop photos, A and B) Facies F2 trough cross-beds, Cook Quarry (N12), images courtesy of N.P. James, C) Facies F3 mollusc floatstone, gastropods (G), bivalves (B) and pocilloporid corals (P), Watson Quarry (N11), image courtesy of N.P. James, D) silicified pocilloporid coral, Facies F4, Cook Quarry (N12).
miliolines are also present. Miliolines are slightly more abundant than rotaliines. The assemblage seems to be more diverse at the base of the section due to less fragmentation, and includes identifiable *M. vertebralis*. Bivalve, echinoderm and articulated coralline algae fragments make up most of the remaining particles. Fine-grained and micritized grains are numerous. Rare megafossils include molds of abraded bivalves and pecten shells. *Skolithos* and *Monocraterion* occur sporadically and some of these burrows have been replaced by chert.

**Interpretation**

The abundance of coralline algae and LBF and dominance of miliolines imply that this facies was deposited in the upper photic zone (Flügel, 2004). Echinoid fragments imply normal-marine salinity. Ephemeral substrates such as sessile invertebrates, seagrasses or algae must have been present to allow for growth of articulated coralline algae. A similar fossil association to that of Facies F1 implies seagrass bed influence.

Trough cross bedding indicates that these sands were frequently moved by currents or waves. Therefore, sediment production may have occurred elsewhere. Trough cross beds and ripples are produced by bidirectional current flow (Prothero and Schwab, 2004). This cross-bedded unit and lithofacies is similar to those in Oligo-Miocene deposits of New Zealand (Anastas et al., 1997; Anastas et al., 2006). Bottom currents or tidal currents most likely produced these trough cross-beds (Anastas et al., 2006). The current direction (NW-SE) is perpendicular to the paleoshoreline, suggesting that tidal or rip currents may have been responsible for
their formation. Modern tidal channels cut between banks covered in seagrass meadows and seagrasses inhabit the floors of some channels (Shark Bay, W.A., Davies, 1970; Spencer Gulf, Burne and Colwell, 1982). Since these sediments are dominated by seagrass-associated biota and are comparable to seagrass bank and tidal channel deposits of Shark Bay, this facies is interpreted to represent tidal channel deposition. In conclusion, deposition of this facies was likely associated with tidal channels, on the shallow illuminated seafloor of a seagrass bank.

_Facies F3—Skeletal Floatstone (Fig. 4.4D, 4.5C)_

_Description_

The matrix of this floatstone is composed of Facies F1 (SBF and LBF grainstone) and only differs from Facies F1 because of more abundant and diverse megafossils (Fig. 4.5C). The LBF assemblage is the same as in Facies F1, but LBFs outnumber SBFs in this facies and are often large enough to be considered megafossils. _Milioline sp. A_ is the dominant floatstone megafossil at one locality (Fig. 3.2, Rawlinna Quarry, N22).

Diverse gastropods (Fasciolariidae, Turritelidae, Potamididae, _Austroharpa_, Mitridae, _Phasianella, Conus, Volutidae, Hypotrochus, Diastomatidae, Cypraeidae, Xenophora_) and bivalves (Ostreacea, Pectinidae, Cardiidae, Veneridae (including _Katelysia_)) are locally abundant and scaphopods (_Dentalium_) occur rarely. Scarce azooxanthellate corals include flabellids and dendrophyllids (_Dendrophyllia_ or _Balanophyllia_) and caryophyllids might also be present. Rare zooxanthellate corals include poritids (_Goniopora, Porites_), faviids (cf. _Montastraea_ and _Cyphastrea_) and
pocilloporids (*Stylophora* and/or *Seriatopora*). *Cladocora* (Faviidae), Oculinidae, Fungiidae and Mussidae may also occur. Micrite envelopes are common around coral and mollusc fragments, allowing these molds to be identified in thin sections.

**Interpretation**

The major components of this facies are similar to those of Facies F1 (except more megafossils) and thus their interpreted environments are similar. Additional bivalves (*Katelysia*) and gastropods (*Mitridae, Conus, Xenophora*), more diverse zooxanthellate corals, and micrite envelopes support a warm-water interpretation for this facies, but many other taxa live in both tropical and temperate seas. In addition, the diversity of LBF and zooxanthellate corals implies oligotrophic conditions.


Evidence for seagrass influence in these sediments is even more convincing than for Facies F1 due to the presence of two gastropod groups that often dominate modern seagrass beds (*Diastomatidae* and *Phasianella*) (Marsh, 1976; Tuya et al., 2010). *Phasianella* and *Hypotrochus* (Cerithiidae) are restricted to the photic zone as they graze on algae (Hyman, 1967; Wells and Bryce, 1988). Fasciolariids and Volutes feed on other molluscs and may have been attracted by their abundance in
this environment (Snyder, 2003). *Dentalium* feeds on SBF and may also be present due to food availability (Knight et al., 1960). *Katelysia* spp. are common on unvegetated sand flats near seagrass beds and therefore imply open areas among grass beds (Peterson et al., 1991; Harvey et al., 1999).

The presence of turritellid gastropods is usually an indicator of elevated nutrient levels (Allmon, 1988), but the abundance of LBF and zooxanthellate corals imply that waters must have been predominantly oligotrophic.

The concentration of larger fossils could be due to successive seagrass bed storm blowouts and associated winnowed, coarse-grained deposits, as in Facies A4 (Wanless, 1981). This floatstone facies, however, is much more extensive and is not only observed as lenses among grainstones. The seafloor of this facies could instead be inhabited by sparse seagrasses with large patches of exposed sand for inhabitation by molluscs and corals. The coarse, sandy lower unit of the Roe Calcarenite has a similar interpretation (James and Bone, 2007).

This facies is interpreted as a shallow, oligotrophic illuminated subtropical seafloor, inhabited by seagrasses and influenced by periodic high-energy events.

**Facies F4 — Coral Floatstone (Fig. 4.4D, 4.5D)**

Description

Thin branching coral fragments of the Family Pocilloporidae (*Stylophora* or *Seriatopora*) typify this facies and many are silicified (Fig. 4.5D). Bivalves (*Glycymeris*) and gastropods (Family Potamididae, rare *Austroharpa*) also occur. Micrite envelopes preserve mollusc fragments and internal structure of corals in
thin sections. The matrix of this floatstone is a fine- to medium-grained small and large benthic foraminifera grainstone. It has the same fossil components as Facies F2, but is not crossbedded.

Interpretation

Corals, coralline algae and large benthic miliolines require an illuminated seafloor and their abundance implies that this facies was deposited in the photic zone. Zooxanthellate corals and LBF also require oligotrophic conditions to flourish. The presence of Potamididae and dominance of milioline foraminifera also imply shallow-water deposition (< 50 m water depth) (Flügel, 2004; Ludbrook, 1984).

Pocilloporid corals can live in a wide range of light and energy conditions (Veron and Stafford-Smith, 2000). The fine-grained nature of the grainstones and thin branches of pocilloporid corals (Stylophora, Seriatopora) could imply a quiet environment, but the abundance of Glycymeris suggests deposition on a shallow, wave-swept seafloor (Veron and Stafford-Smith, 2000; Ludbrook, 1984; Collins, 1988). Moderate-energy shifting sands could also account for the large percentage of fractured foraminiferal tests. Pocilloporids develop thin branches, such as those in this facies, in settings with lower energies than the reef crest: shallow protected areas and deeper reef slopes (Veron and Stafford-Smith, 2000). Therefore, this seafloor was most likely exposed to moderate but not high wave energy. The matrix sands of this facies are similar to those of Facies F2, implying that deposition of this facies also occurred in or near seagrass meadows. The diversity of fossils and presence of echinoid fragments in this facies implies normal marine salinity. In
conclusion, this facies was deposited near seagrass meadows, on a well-illuminated moderate-energy seafloor with warm, oligotrophic normal marine waters.

Small and large benthic foraminifera facies association synopsis

These sandy lithofacies are interpreted to have been deposited on shallow illuminated (upper photic zone) tropical- subtropical seafloors dominated by moderate energy. Most of the sediment was covered by seagrass meadows, as seagrass-associated biota are the most abundant particles. Floatstones formed in unprotected areas between seagrass meadows that were subjected to higher energies. Tidal channels cutting through grass banks led to the formation of local crossbedded sands.

Benthic-Planktonic Foraminifera Facies Association

Small benthic and planktonic foraminifera dominate this facies association, with echinoderm and articulated coralline algae fragments present at most localities. This association is composed of two lithofacies: P1 (grainstone) and P2 (packstone).

Facies P1 — Small Benthic-Planktonic Foraminifera Grainstone (Fig. 4.6A)

Description

These sediments are generally fine to very fine-grained with planktonic foraminifera comprising at least 30% of the foraminiferal assemblage, the rest being small benthics and rare fragments of large rotaliines. Overall, among SBF, rotaliines > miliolines>agglutinated foraminifera, but all three are common. Foraminifera are
Figure 4.6. Benthic-Planktonic Foraminifera Facies Association. A) Facies P1, planktonic foraminifera (P), Eucla Pass (9.13), B) Facies F2, planktonic foraminifera (P), small benthic foraminifera (B) and echinoderm fragments (E), Eucla Quarry (8.1).
mainly fragmented, with whole planktonics more frequent than whole benthics. Echinoderm fragments are common throughout and are often the largest grains in these limestones. Articulated coralline algae are more rare. Sparse megafossils include infaunal echinoids (Clypeasteroids), *Celleporaria*, gastropods (Diastomatidae, Potamididae, Cerithiidae (*Hypotrochus*), Cassidae, Cypraeacea (*Cypraea*)), bivalves (Veneridae (*Katelysia*), Pectinidae and Ostreacea) and rhodolith fragments.

Interpretation

Scarcity of light-dependent biota (large benthic rotaliines, coralline algae) and abundance of small benthic rotaliines imply that this facies was deposited in a deeper-water environment, near the base of the photic zone. The fine-grained nature of the sands and abundance of planktonic foraminifera in this facies further suggest a deeper environment, far from the paleoshoreline. Coralline algae and large rotaliine foraminifera are adapted for life at the base of the photic zone, so these sediments may have been produced in the dim light of this environment. The presence of *Hypotrochus* and mud whelks (Potamididae) also implies light availability, as these gastropods feed on benthic algae (Wells and Bryce, 1988). Scarce large benthic rotaliines and *Katelysia* suggest that there was some warm-water influence (Darragh, 1985).

Infaunal echinoids and bivalves (*Katelysia*) confirm that the sediment was soft and suitable for burrowing. The presence of *Celleporaria*, filter-feeding bivalves and infaunal echinoids also suggests that there were somewhat elevated nutrient
levels that may have increased food supplies (Allmon, 1988). Diastomatidae are deposit feeders, so may have also benefitted from higher nutrient levels (Marsh, 1976). *Celleporaria* also required ephemeral organic substrates, so marine invertebrates that do not leave a good fossil record (e.g., sponges) may have been present (Hageman et al., 2003). Modern southern Australian cowries feed on sponges and the presence of *Cypraea* may also imply sponge growth (Ludbrook, 1984). In conclusion, this lithofacies was deposited in quiet normal-marine temperate-subtropical waters, at the base of the photic zone.

_Facies P2 — Small Benthic-Planktonic Foraminifera Packstone (Fig. 4.6B)_

**Description**

Planktonic foraminifera make up at least 50% of the foraminiferal assemblage, with the rest being small benthics. LBF are extremely rare. The rest of the fossil assemblage is similar to that of Facies P1, with the addition of lime mud. This lithofacies has a higher percentage of whole foraminifera due to its higher percentage of planktonics.

**Interpretation**

This lithofacies was deposited in an environment similar to that of Facies P1. The addition of lime mud and more whole planktonic foraminifera implies that this facies may have been deposited in an even quieter, deeper setting. Coralline algae are present, so deposition likely occurred near the base of the photic zone.
Benthic-Planktonic Foraminifera Facies Association Synopsis

These lithofacies were deposited in normal-marine temperate waters with minor warm-water influence, near the base of the photic zone.

Summary of Nullarbor Facies Interpretations

Facies of the Nullarbor Limestone represent deposition on a temperate to subtropical platform. Differences between facies associations can be attributed to water depth, seawater temperature and hydrodynamics. Interpreted paleobathymetry is summarized in Figure 4.7.
Fig. 4.7. Paleobathymetry of Nullarbor Limestone Facies. This diagram is meant to show relative depths of facies deposition on a hypothetical slope. Nullarbor Limestone fossil assemblages were largely dependent on light availability, and, thus, are shown here in relation to the upper photic zone, lower photic zone and disphotic zone. Facies associations are labeled by letters and facies within these associations are labeled by numbers. Facies associations (F.A.) include: Small and Large Benthic Foraminifera F.A. (F), Articulated Coralline Algae F.A. (A), Rhodolith F.A. (R), Echinoderm F.A. (E), and Small Benthic and Planktonic Foraminifera F.A. (P).
4.2 SPATIAL DISTRIBUTIONS OF FACIES

Facies distribution trends in the northern and southern regions of the Nullarbor Limestone differ greatly. Facies Association F dominates the northern region, whereas limestones of the southern region are more heterogeneous (Fig. 4.8, 4.9). In the southern region, Facies Association F is found in the west and grades into Facies associations A and R to the east, as benthic foraminifera become less dominant and coralline algae become more profuse (Fig. 4.8, 4.10). Further east, planktonic foraminifera increase in abundance and coralline algae and benthic foraminifera are less volumetrically important (Facies Association P; Fig. 4.8, 4.10). Fossils with tropical affinities (such as LBF and some molluscs) generally decrease from west to east (Fig. 4.10).

Facies associations grade into each other laterally, as do the facies within them (Fig. 4.8, 4.9). Floatstones (facies A3, A4, A5, F3 and F4) occur as lenses within facies associations that are dominated by grainstones (Fig. 4.8, 4.9). The Mullamullang Member is interbedded with adjacent, time equivalent facies of the Rawlinna member (Fig. 4.8).
Figure 4.8. Southern distribution of facies and facies associations of the Nullarbor Limestone. The M ullamullang Member is thickest in the center of the study area and interfingers with the Articulated Coralline Algae Facies Association. The Rawlinna Member is composed of the Small and Large Benthic Foraminifera, Articulated Coralline Algae and Small and Planktonic Foraminifera facies associations, from west to east, respectively. These associations and their facies grade into each other. The Abrakurrie Limestone serves as the datum for this cross-section. A and A' can be viewed on Fig. 2.4.
Fig. 4.9. Northern distribution of facies and facies associations of the Nullarbor Limestone. The northern Nullarbor Limestone is dominated by the Small and Large Benthic Foraminifera Facies Association (F). The Small Benthic and Planktonic Foraminifera Facies Association (P) is found in the far west and far east localities and may be absent from other areas due to erosion. The Wilson Bluff Limestone is used as a datum, but is only accessible at one locality. B and B’ can be viewed on Fig. 2.4.
Fig. 4.10. Qualitative abundance of fossil components, based on petrographic estimates. This figure is meant to display general trends from west to east in the southern portion of the study area, corresponding to the southern cross-section, Fig. 4.8. Stratigraphic section locations are shown in grey.
Chapter 5: Paleoenvironments

The interpreted paleoenvironments of facies associations in the Nullarbor Limestone (Chapter 4) fall into three major categories: rhodolith paleoenvironment, seagrass-bank paleoenvironment and open-seafloor paleoenvironment. These paleoenvironments can be reconstructed based on modern and ancient analogues.

Fossils of the Nullarbor Limestone are not interpreted to be in life position since they were deposited as loose sediment grains. The fossil assemblages, thus, fall into the category of “indigenous”, which are “derived, but in same environment as original living community” (Craig and Hallam, 1963). Evidence against transport includes: poorly sorted sediments, low fragmentation, and common whole and articulated molluscs and echinoids. Fossil sediments may have been transported meters from original locations, but were deposited in their living environments.

5.1 RHODOLITH PALEOENVIRONMENT

Introduction

The Mullamullang Member (Facies Association R) is found at the base of the Nullarbor Limestone in the southwest region of the Eucla Platform. This rhodolith floatstone/rudstone unit is thickest around Madura (Fig. 2.4) and thins to the west and east (Fig. 5.1). Skeletal components imply that these sediments were deposited in the oligophotic zone in subtropical to tropical waters (Chapter 4) and that the seafloor was covered with rhodoliths and carbonate sand.
Figure 5.1. Simplified map view of the Rawlinna member, as it is exposed on the surface of the Nullarbor Plain. The study area is represented by colored areas. Area within bold is extent of the Nullarbor Limestone. Letters represent facies and facies associations.
Modern Rhodolith Gravels

Rhodolith gravels consist of rhodoliths and other sediments that cover the seafloor and create rhodolith rudstones and floatstones in the rock record. These environments produce diverse (but coralline algae-dominated) calcareous sediments, most often on open shelves and platforms. Tropical rhodolith gravels are found on seafloors where faster-growing chlorozoans do not occur and cannot outcompete coralline algae (e.g., light is too dim, energy or nutrients are too high, Pomar et al., 2004; Nalin et al., 2008). Temperate rhodolith gravels can accumulate in shallower waters, where cool temperatures limit chlorozoan growth (2-12 m w.d., Gulf of California, Marrack, 1999; 1 m w.d., New Zealand, Nalin et al., 2008).

Rhodoliths gravels are most abundant in mesotrophic ocean waters (Pomar et al., 2004; Halfar and Mutti, 2005; Nalin et al., 2008).

Water energy must be between two thresholds in order for rhodoliths to accumulate. If energy is too high and rhodoliths are overturned too often, the erosion rate will surpass the slow growth rate of rhodoliths. If the energy is too low or events are too infrequent, deposited sediments can easily bury rhodoliths (Marrack, 1999; Ryan et al., 2007). Storm waves and currents are thought to be responsible for the movement of rhodoliths but overturning by grazing fish, and burrowing crustaceans, eels and echinoderms has also been observed on the seafloor at small scales (Marrack, 1999; Foster, 2001).

Modern rhodolith gravels are usually found in the lower photic zones (oligophotic zones) of tropical and temperate platforms and shelves, between 25 and 150 m water depth (Rottnest Shelf, Fig. 2.5; Collins et al., 1988; James et al.,
1999; Eastern Caribbean, Reid and MacIntyre, 1988; Florida Shelf, Prager and Ginsburg, 1989; Japan, Tsuji, 1993; eastern Australia, Harris et al., 1996; Spain, Fornos and Ahr, 1997; Italy, Basso, 1998; Great Australian Bight, James et al., 2001; Ryan et al., 2007). See Foster (2001, Fig. 4) for a summary of modern worldwide rhodolith-bed distribution.

Rhodolith-gravel environments are common on modern Australian temperate and subtropical shelves (Rottnest Shelf, Collins, 1988; James et al., 1999; along Fraser Island, Harris et al., 1996; Great Australian Bight, James et al., 2001; Ryan et al., 2007; Fig. 2.5, locations). Subtropical carbonate sediments of the Rottnest Shelf (Fig. 2.5) form thin veneers (~1m) atop disconformities. Rhodolith-gravel pavements dominate high-energy areas of the inner Rottnest Shelf out to the shelf margin, between ~30 and 60 m w.d. (Collins, 1988; James et al., 1999). Rhodolith gravels on the seaward side of Fraser Island (Fig. 2.5) also extend to the shelf margin, but are common below storm wave base (between 24 and 100 m w.d., Harris et al., 1996). These rhodoliths are overturned by shelfal intrusions of the East Australian Current (Harris et al., 1996). Rhodolith pavements also occur on the western inner shelf of the high-energy Great Australian Bight, on the exposed shelf and in Esperance Bay, which is somewhat protected from wave energy (James et al., 2001; Ryan et al., 2007; Fig. 2.5). Rhodolith gravels have developed on the western shelf because of warm waters of the tropical Leeuwin Current (James et al., 2001).
Cenozoic Rhodolith Gravels

Coralline-algae facies (including rhodolith gravels) were most common and widespread during the Cenozoic, especially during the middle Miocene (worldwide distribution, Halfar and Mutti, 2005; Mediterranean distribution, Esteban, 1996; Brandano and Corda, 2002; Pomar et al., 2004). Rhodalg deposits, including coralline-algae-dominated mounds, gravels and biostromes, are the most extensive Miocene limestones in the Mediterranean region (Esteban, 1996). Temperate foramol (cf. Lees and Buller, 1972), rhodalg (cf. Hayton et al., 1995), and briymol (cf. Nelson et al., 1988) assemblages dominated shallow platforms of this region despite inferred tropical water temperatures (Pomar et al., 2004). Mediterranean rhodolith gravels formed on inner ramps and upper ramp slopes that were winnowed by bottom currents and wave-influenced off-reef settings (mesophotic and oligophotic zones, ~40-100 m inferred water depth, Pomar et al., 2004). Rhodolith production may have been most profuse during times of sea-level lowstand, when much of the shallow basin floor was illuminated (Pomar et al., 2004). The dominant sediment producers controlled architecture of the platforms. For example, low-angle ramps developed due to high sedimentation rates of outer ramp sediments, including rhodoliths (Pomar et al., 2004). Increased nutrients during the middle Miocene can explain the abundance of temperate-style deposits in the tropical Mediterranean and the switch from early Miocene chlorozoon assemblages (Brandano and Corda, 2002; Pomar et al., 2004). Nutrient influx diminishes growth of chlorozoans and thus allows for dominance by organisms such
as coralline algae and filter feeders, which are usually associated with temperate platforms.

Coralline-algae facies are also abundant in tropical and subtropical Pacific Miocene deposits (Bourrouilh-Le Jan and Hottinger, 1988). Early Miocene rhodolith facies underlie much of the Great Barrier Reef and were deposited under subtropical conditions, as Australia migrated north during the Cenozoic (Davies et al., 1989). Many tropical Pacific island platforms were dominated by calcareous green algae and coral reefs during the early Miocene (Bourrouilh-Le Jan and Hottinger, 1988). During the middle Miocene, temperatures on these platforms remained high, but coralline algae became the dominant carbonate producers (including extensive rhodolith gravels, Bourrouilh-Le Jan and Hottinger, 1988). Multiple workers believe that elevated nutrient levels may have occurred worldwide, not only in the Mediterranean, driving the switch from chlorozoan to rhodalgal sedimentation (Bourrouilh-Le Jan and Hottinger, 1988; Brandano and Corda, 2002; Pomar et al., 2004; Halfar and Mutti, 2005).

**Interpretation of Nullarbor Limestone Rhodoliths (Facies Association R)**

Rhodolith rudstones and floatstones of the Mullamullang Member must have accumulated as rhodolith gravels with carbonate sand matrices on the seafloor. Large sizes (commonly ≥ 4 cm), dense encrustations and spheroidal shapes imply formation in high-energy settings, subject to frequent overturning (Bosellini and Ginsburg, 1971). Like modern tropical and subtropical rhodolith gravels, this environment probably occurred in warm waters, but was restricted to the
oligophotic zone (Eastern Caribbean, Reid and Maclntyre, 1988; Florida Shelf, Prager and Ginsburg, 1989; eastern Australia, Harris et al., 1996). Presence of these gravels implies that this area of the Eucla Platform was exposed to wave action, to allow for frequent rhodolith overturning, like modern rhodolith pavements of the Rottnest Shelf (Collins, 1988; James et al., 1999). Bioturbation by fish and crustaceans may have locally overturned rhodoliths (cf. Marrack, 1999), but the massive size of the deposit suggests that periodic waves or currents must have also been involved. Mullamullang rhodoliths may have occurred on the western side of the Eucla Platform (Fig. 5.2A), due to incursions of the warm, Leeuwin Current from the west, as they do on the Great Australian Bight today (James et al., 2001; Ryan et al., 2007).

5.2 SEAGRASS-BANK PALEOEENVIRONMENT

Introduction

Facies associations F and A are interpreted as representing seagrass-associated paleoenvironments (Chapter 4). These facies are located in the northern and western parts of the study area, in areas that would have been the most inboard on the early to middle Miocene Eucla Platform (Fig. 5.1). Facies within associations F and A differ based on fossil assemblages, grain sizes and sedimentary structures. Thus, the seagrass subenvironments must have also differed. Differences between the two facies assemblages can be attributed to temperature, whereas differences between facies can be attributed to water energy and nutrient levels.
Figure 5.2. Interpreted paleoenvironments on the Eucla Platform during Nullarbor Limestone deposition. Information on inboard facies from Lowry (1970) and Hou et al. (2008). Question marks represent unknown areas of the platform due to lack of samples. A) Interpreted paleoenvironments during time-slice A (Fig. 4.8, p. 119), including rhodolith gravels of the Mullamullang Member. B) Interpreted paleoenvironments during time-slice B (Fig. 4.8, p. 119), when seagrass banks dominated the platform.
Requirements for Seagrass Growth

Seagrass distribution is limited worldwide by light (depth) and substrate availability. Seagrasses are most common in the subtidal zone of the upper photic zone, where light is plentiful, but not powerful enough to damage plant tissues (Hemminga and Duarte, 2000). The shallow, upslope range of most taxa is just below sea level, but some species can withstand desiccation and grow right at sea level, in the intertidal zone (Hemminga and Duarte, 2000). Substrate suitability and availability is often more of a limiting factor than light (Hemminga and Duarte, 2000). Most seagrasses require soft sand or mud substrates for root growth. Seagrasses cannot colonize an area if sediments are constantly shifting due to high water energy. Some species, including *Posidonia oceanica* and *Thalassodendron pachyrhizum*, can grow atop rocks and are thus adapted for life in extremely high-energy environments (Collins, 1988; Hemminga and Duarte, 2000). Shallow-marine sandy and muddy seafloors are often uninhabitable by plants due to anoxia of the surface sediment. Thus, seagrasses usually cannot colonize substrates high in organic matter because of phototoxic compounds produced by bacteria (e.g. sulphide, Hemminga and Duarte, 2000).

Modern seagrasses are widely distributed on tropical and temperate shallow shelves (Hemminga and Duarte, 2005, Fig. 1.4). Temperate seagrass banks are most abundant on moderate- to high-energy open platforms in the Mediterranean Sea (Fornos and Ahr, 1997; Pomar, 2001), and along the western and southern Australian coasts (Shark Bay, Davies, 1970, Walker and Woelkerling, 1988; Spencer
Seagrass Sedimentation

Seagrass environments, as carbonate factories, can create large sediment accumulations in tropical and temperate environments (Ginsburg and Lowenstam, 1958; Brasier, 1975; Walker and Woelkerling, 1988; Betzler et al., 1997; Pomar et al., 2001). Seagrasses have the ability to stabilize deposited sediments with their rhizomes (root systems) and baffle suspended sediments by creating microenvironments of calmer conditions between blades (Ginsburg and Lowenstam, 1958). Seagrass cover can protect organisms and seafloors from waves and storms (Ball et al., 1967; Burne and Colwell, 1982; Betzler et al., 1997). These plants also provide habitats for diverse calcareous benthic organisms, in addition to sediment baffling and fixation (Ginsburg and Lowenstam, 1958; Collins, 1988; James at al., 2009). Blades and stalks provide substrates for epiphytic organisms, which differ based on oceanic conditions and seagrass types (Ginsburg and Lowenstam, 1958; Perry and Beavington-Penney, 2005; James et al., 2009). Tropical seagrass epiphyte associations are dominated by LBF, SBF, serpulid worm tubes and crustose and articulated coralline algae (Patriquin, 1975; Nelsen and Ginsburg, 1986). Crustose and articulated coralline algae, bryozoans and SBF dominate temperate epiphyte associations (James et al., 2009). Subtropical seagrass assemblages often have combinations of tropical and temperate epiphytes (Shark Bay, Davies, 1970; Rottnest Shelf, Burne and Colwell, 1982).
Seagrasses themselves have diverse morphologies, from long, strap-like blades of *Posidonia* and *Thalassia* to short stalks with small leaves (*Amphibolis*) (Ginsburg and Lowenstam, 1958; Womersley, 1984). Seagrass genera and densities control epiphyte distribution and sediment-baffling potentials (Davies, 1970; Scoffin, 1970; James et al., 2009). Crustose corallines, for example, are common epiphytes of wide *Posidonia* and *Thalassia* blades, but articulated coralline algae occur on *Amphibolis*, which has longer stems and small leaves (Nelsen and Ginsburg, 1986; James et al., 2009). Thin veneers of crustose coralline algae are a source of mud in temperate seagrass sediments (along with delicate bryozoans) and articulated coralline algae break into sand-sized fragments. Thus, the texture of the sediments can be controlled by seagrass type (James et al., 2009).

Infaunal and epifaunal biota, such as foraminifera, echinoderms, grazing gastropods and burrowing bivalves frequent sediments between grasses and beneath rhizomes, where detritus provides ample food (Ginsburg and Lowenstam, 1958; Brasier, 1975; Burne and Colwell, 1982; Betzler et al., 1997). Distribution of these organisms is controlled by seagrass density, water energy and temperature with molluscs being more common in warmer waters (Davies, 1970; Collins, 1980; Burne and Colwell, 1982). Tropical seagrass meadows often have abundant calcareous green algae (such as *Halimeda*) and scattered zooxanthellate corals living amongst grasses and on open sand patches (Patriquin, 1975).

The trapping and binding actions of seagrasses, as well as *in situ* accumulation of skeletal sediments, can form thick accumulations of poorly sorted sediment up to sea level (Ginsburg and Lowenstam, 1958; Scoffin, 1970; Burne and
Seagrass meadows on higher-energy platforms produce sandier sediments than their typical warm-water protected counterparts, and are often devoid of lime mud (Burne and Colwell, 1982; Collins, 1988). Seagrass facies often lead to basinward coarsening trends, since finer sediments are trapped and produced in shallow seagrass beds and offshore sediments are not protected by grasses (Betzler et al., 1997; Pomar, 2001; Ryan et al., 2007). Seagrass banks accumulate sediments most rapidly among subtropical carbonate environments and are capable of prograding as accommodation space is filled (Betzler et al., 1997). Seagrasses are very rarely preserved in the rock record. Therefore, identification of ancient deposits is based on biological associations and sedimentology (Brasier, 1975).

**Seagrass-Bank Architecture**

Seagrass banks are build-ups of carbonate sediments that been deposited *in situ* due to seagrass cover. The seafloor on a seagrass bank is not a continuous underwater field of seagrass. It is a mosaic of patchy seagrass meadows and open sand due to varying bottom energy levels, storm events that disrupt seagrass growth and seagrass recruitment and colonization processes (Davies, 1970; Kendrick et al., 1999).

Higher energy generally leads to less dense seagrasses and less dense seagrasses in turn lead to higher energy since blades are no longer packed tightly enough to reduce wave energy. Thus, unvegetated or sparsely vegetated sand flats
develop on areas of a bank exposed to the highest wave energies, which are often the shallowest areas (e.g., Mediterranean, Fornos and Ahr, 1997). In addition, periodic, intense events such as storms can cause large areas (m²-scale) of seagrasses to be eroded, forming pockets of the seafloor that are no longer protected by vegetation ('seagrass blowouts'; Wanless, 1981). These blowouts can continue to grow and migrate seaward on the bank (~1-2 m yr⁻¹, Partiquin, 1975), if the bank is consistently exposed to wave energy near the upper threshold for seagrass bed stability (Wanless, 1981). These sparsely- to un-vegetated sands have concentrations of megafossils because of winnowing of fine sediments and colonization of open sands by molluscs (particularly infaunal bivalves, Davies, 1970). Therefore, they are often preserved as floatstone lenses in the rock record.

Seagrass banks are also discontinuous due to channels that concentrate tidal currents (Davies, 1970; Belperio et al., 1984). Tidal channels on Wooramel Bank, commonly reach lengths of many kilometers and widths of 200 m (Davies, 1970). Rip and longshore currents can also form channels on seagrass banks, but these channels tend to be smaller and more localized (e.g., 100 m long, 10-20 m wide, Mediterranean, Fornos and Ahr, 1997).

**Seagrasses During the Miocene**

Evidence of seagrass sedimentation throughout the Pacific and Indo-Pacific is scarce before the early Miocene (Brasier, 1975), but their potential influence on sedimentation should be considered when analyzing shallow-water limestones that are Miocene and younger (Brasier, 1975; Pomar, 2001). Miocene seagrass meadows
were concentrated around the Mediterranean and the Indo-Pacific, including areas of southern Australia (Mediterranean, Canals and Ballesteros, 1997; Pomar et al., 2004; Murray Basin, southern Australia, Lukasik et al., 2000). The Miocene Murray Basin was floored by temperate seagrass meadows, and bryozoans, gastropods, bivalves, SBF and LBF dominate these sediments (Fig. 2.5; Lukasik et al., 2000).

Facies Association F (Subtropical Seagrass Bank)

The sediments of Facies Association F closely resemble those of modern tropical-subtropical seagrass banks (Davies, 1970; Collins, 1988; Betzler et al., 1997; James et al., 1999). Zooxanthellate corals are sparse and calcareous green algae are absent, indicating that temperatures were subtropical, rather than tropical (Patriquin, 1975). Facies Association F has the most abundant tropical (molluscs) and tropical, light-dependent (LBF, coralline algae, zooxanthellate corals) fossil components of any association of the Nullarbor Limestone. LBF cannot reproduce in waters cooler than 20-22 °C and cannot survive if water temperatures drop below 14 °C for extended periods (Murray, 1991; Hohenegger, 2004). The abundance and diversity of LBF and the presence of zooxanthellate corals and micrite envelopes suggest that water temperatures on this seagrass bank were usually above 20°C (the lower limit of *M. vertebrales* reproduction, Ross, 1972; Betzler et al., 1997; Langer and Hottinger, 2000).

Seagrass-bank facies differ based on energy levels on the seafloor. Dense seagrass meadows are dominated by epiphyte sedimentation, resulting in formation of grainstones (F1). Well-sorted, cross-bedded sands (F2) form in shallow tidal
channels (cf. Spencer Gulf, Burne and Colwell, 1982). Floatstone facies (F3, F4) can represent open sand patches on the seafloor that experience higher wave energy and may have been formed as seagrass blowouts during storms (Davies, 1970; Patriquin, 1975; Wanless, 1981).

**Facies Association A (Subtropical-Temperate Seagrass Bank)**

Organisms that indicate temperate seagrass-bank sedimentation (articulated coralline algae, SBF, molluscs; cf. Spencer Gulf, Belperio et al., 1984; James et al., 2009) dominate Facies Association A although LBF, corals and molluscs with tropical affinities also locally occur. Thus, the paleoenvironment of Facies Association A is interpreted as a subtropical-temperate seagrass bank, with cooler temperatures (hovering around the lower limit for LBF reproduction, 20°C, Betzler et al., 1997; Langer and Hottinger, 2000) than the seagrass bank of Facies Association F.

Although all seagrass-associated facies imply deposition in the upper photic zone, depositional environments within association A can be divided further based on the extent of tropical, shallow-dwelling LBF, molluscs and zooxanthellate corals. Grainstone A1 and floatstones A3 and A4 contain tropical and subtropical components, whereas grainstone A2 and floatstone A5 show evidence of deposition under temperate conditions (Chapter 4). Epiphyte-dominated grainstones (facies A1 and A2) are produced in dense seagrass meadows, as previously discussed for facies F1, whereas floatstones could be created due to higher energies on open sand flats (facies A3, A4, A5) (Davies, 1970; Patriquin, 1975; Wanless, 1981). Increased
nutrient levels, along with moderate energy, can account for the high concentration of turritellid gastropods and infaunal bivalves in facies A5 (Allmon, 1988).

Wooramel Bank as an Analog for Nullarbor Limestone Seagrass-Bank Deposition

Wooramel Bank is an elongated seagrass bank in northern Shark Bay, Western Australia. Modern sedimentary environments of Wooramel Bank may serve as appropriate modern analogues for interrelated seagrass-associated facies of the early-middle Miocene Nullarbor Limestone (Facies Associations F and A). Like Nullarbor Limestone deposits, seagrass-bed sediments of Wooramel Bank are dominated by epiphytes, including large and small benthic miliolines and articulated coralline algae (Davies, 1970). Some taxa are the same as those common to facies associations F and A (e.g., Quinqueloculina spp., M. vertebralis, Corallina) and others have similar epiphytic growth forms (Davies, 1970). A diverse assemblage of molluscs also occurs in sheltered grass beds and on open sand flats.

Subenvironments include: 1. dense seagrass meadows of Posidonia and Cymodocea, 2. sparsely vegetated sand flats, and 3. tidal channels that generally cut into the bank perpendicular to the shoreline (Logan and Cebulski, 1970). These seagrass-bank subenvironments are excellent analogues for seagrass facies of the Nullarbor Limestone (1. F1, A1, A2; 2. F3, F4, A3, A4, A5; 3. F2).

There are major differences, however, between seagrass-bank deposits of the Nullarbor Limestone and Wooramel Bank. The Nullarbor Seagrass Bank must have extended at least 100 km from the paleoshoreline (Fig. 5.1, 5.2), whereas Wooramel Bank only extends out 9-19 km from shore. As part of Shark Bay, which is famous
for its restricted ooid shoals and extensive tidal flats, it is not surprising that Wooramel Bank also experiences elevated salinities (38-49 ‰, Davies, 1970). Wooramel Bank is restricted from the open Indian Ocean by peninsulas, ancient eolianite ridges and submerged banks (sills) (Logan and Cebulski, 1970). Echinoid fragments throughout Nullarbor Limestone deposits imply that the Nullarbor Seagrass Bank was predominantly normal marine, whereas echinoids are absent from Wooramel Bank. Wooramel Bank is also situated at a lower latitude (25°S) than that of Nullarbor Limestone deposition (~38°S, McGowran et al., 1997a), although interpreted temperatures of Nullarbor seagrass banks may have been similar to those of Wooramel Bank (16-26°C, Davies, 1970). Tropical chlorozoans (green calcareous algae, such as *Halimeda*) contribute to the sediments of Wooramel Bank but are completely lacking from the Nullarbor Limestone, presumably due to lower temperatures and aragonite saturation (Betzler et al., 1997). Seagrass-bed sediments of Wooramel Bank generally have ~30% silt- and clay-size particles made of fragmented benthic foraminifera and crustose coralline algae (Davies, 1970). Lime muds are largely absent from Nullarbor Limestone seagrass deposits. This may be due to higher energy levels on the bank, lower density of seagrass blades that are thus unable to baffle fine particles or lack of crustose coralline algae due to seagrass genera (Seagrass Sedimentation, this thesis; James et al., 2009).
5.3 OPEN-SEAFLOOR PALEOENVIRONMENT

**Introduction**

Facies associations E and F represent deposition on an open seafloor with soft sediments. Facies of the association E are only found at one location each, directly above the contact with the Abrakurrie Limestone (Fig. 4.8). Facies Association P is found at the easternmost study localities along the southern coast (Fig. 4.8, 5.1). This area would have been the most basinward area of deposition when the Nullarbor Platform was inundated by the Southern Ocean (Fig. 5.2). Facies Association P is also found at and near the top of stratigraphic sections from two northern study localities (Fig. 4.9).

**Modern Open Seafloors**

Open seafloors are those that have soft sandy or muddy sediments and lack carbonate buildups and are not covered with plant or algae growth. Carbonate buildups and banks most often occur in shallow, tropical waters due to rapid growth rates of photo-dependent chlorozoans and substrates for calcareous biota (e.g., seagrasses, algae, etc.). Therefore, open seafloors are most common below the photic zone or in temperate waters. Bryozoans, planktonic and benthic foraminifera and infaunal echinoids often characterize open-seafloor sediments (Bone and James, 1993).
Facies Association E

Limestones of this facies association are interpreted to represent intermediate environments between the Abrakurrie Limestone and the Nullarbor Limestone. Their stratigraphic locations just above the contact with the Abrakurrie Limestone support this idea. Milioline foraminifera are larger and more diverse and bryozoans are less abundant and diverse in these facies than in the Abrakurrie Limestone (James and Bone, 1991; Li et al., 1996a). Warm-water influence led to inhabitation by LBF in Facies E2. Shifting sands favor infaunal echinoids and alveolinid foraminifera (A. howchini, E2), rather than bryozoans and may explain the dominance of echinoids and foraminifera in these facies (Haynes, 1965; Chaproniere, 1975). Suitable substrates and nutrient concentrations may also have been lacking from these environments, inhibiting diverse bryozoan growth (Hayton et al., 1995).

The components of these facies are similar to those of the ‘echinofor’ assemblage described by Hayton and others (1995). In reference to non-tropical deposits in New Zealand and elsewhere, the echinofor assemblage has been interpreted as occurring on sandy substrates of outer slopes between 50 and 300 m water depth (Hayton et al., 1995). This facies has a similar assemblage to that of Miocene limestones in Greece (Pamoni-Papaioannou et al., 2002). According to their paleoenvironmental interpretation, these echinofor limestones were deposited on a gentle shallow ramp downslope from the main chlorozoan carbonate factory (Pamoni-Papaioannou et al., 2002). Similarly, these open-seafloor sediments of the
Nullarbor Limestone most likely accumulated on seafloors that were uninhabitable for chlorozoans; either too cold or too deep.

**Facies Association P**

Facies association P is dominated by small benthic and planktonic foraminifera and is interpreted to represent deposition at the base of the photic zone. The seafloor here was presumably too deep for light penetration to support seagrasses, based on the lack of seagrass-associated biota. Without the seagrass carbonate factory, sedimentation rates were drastically reduced compared to other facies of the Rawlinna member. Reduced sedimentation rates and increased distances from the paleoshoreline allowed for planktonic foraminifera to make a significant contribution to these deposits. Delicate tests of planktonic foraminifera can only be deposited and preserved in areas of low turbulence, so are most common in deeper areas or off of the shelves of carbonate platforms (Hayton et al., 1995). Components and lithologies of Facies Association P are similar to those of modern southern and western Australian middle and outer shelves (Lacepede Shelf, Li et al., 1996b; Carnarvon Ramp, James et al., 1999; Fig. 2.5, locations). Photo-dependant fossils (coralline algae, rare LBF) do occur in these facies of the Nullarbor Limestone, however, implying that deposition occurred just above the base of the photic zone (photocline). The presence of lime mud in F2 packstones indicates a quieter, deeper setting than F1. Elevated nutrients may have allowed infaunal gastropods and echinoids to colonize the fine sands of facies F1.
Environments of the Nullarbor Limestone are distributed based on their locations on the paleoplatform (depth, light, temperature) (Fig. 5.2). Other factors (energy, nutrient availability) control the distribution of facies within these associations. Seagrass banks were the most inboard environments of the early-middle Miocene Eucla Platform (Fig. 5.2). On the outer seagrass banks, abundance of tropical fossil components decreased to the east. This is thought to record a gradual cooling, but not deepening, trend. Rhodolith gravels and open seafloor environments dominated in deeper, basinward areas (Fig. 5.2).

The Mullamullang Member represents widespread rhodolith gravel deposition. The Rawlinna member, however, has diverse components and lithologies (Fig. 4.8, 4.9, 5.1). Within the Rawlinna member, differences between paleoenvironments due to temperature and depth gradients can explain the distribution of tropical, shallow biota from west to east and from north to south (Fig. 4.10, 5.1, 5.2). Tropical and photosynthesizing organisms decreased to the east and to the south as depth increased and temperature decreased.
Chapter 6: Temporal Variation

6.1 AGE OF THE NULLARBOR LIMESTONE

The Nullarbor Limestone was deposited between the late early to early middle Miocene (Ludbrook, 1958a; Ludbrook, 1958b; Lowry, 1970; Benbow and Lindsay, 1988). Large benthic foraminifera identified in this and previous studies confirm this age (A. howchini, M. vertebralis, F. bontangensis, Sorites, Operculina). Previous authors estimate that Nullarbor Limestone deposition began ~16.5-16 Ma and continued until ~14.5-15 Ma (McGowran et al., 1997a; Li et al., 1996a; Li et al., 2004).

6.2 SEA LEVEL DURING THE EARLY-MIDDLE MIocene

Eustatic sea-level reconstructions show two periods of rapid sea-level rise during the time of Nullarbor Limestone deposition, corresponding to third-order sea level cycles (Fig. 6.1; Haq et al., 1987; McGowran et al., 1997a). Li et al. (2004) discussed limestone depositional hiatuses along the southern Australian coast and concluded that all periods of nondeposition corresponded to third-order sea-level lowstands, but tectonic forces altered duration and extent of relative sea level rises and falls. Uplift of the southern Australian margin occurred between 15 and 16 Ma due to a jump in the rate of Southern Ocean seafloor spreading (Li et al., 2004).
6.3 GRADUAL RISE IN RELATIVE SEA LEVEL: INITIATION OF NULLARBOR LIMESTONE DEPOSITION

The Mullamullang Member (Facies Association R) is interpreted as a transgressive deposit (Fig. 6.1). Rhodolith rudstone/floatstone facies are commonly associated with rises in relative sea level since rhodoliths can withstand high-energy conditions along transgressive surfaces of marine erosion and can handle limited light levels during deepening (Nalin et al., 2008). Numerous Cenozoic and modern transgressive rhodolith gravels overlie lithified unconformity surfaces, similar to that between the Nullarbor and Abrakurrie limestones (Great Australian Bight, James et al., 1994; New Zealand, Nalin et al., 2008). Rhodolith beds are generally thin (~1 m) because encrusting coralline algae grows relatively slowly and rhodolith sedimentation cannot usually keep up with rapidly rising sea level (~0.4mm yr\(^{-1}\); Bosence, 1983; Reid and MacIntyre, 1988; Nalin et al., 2008). Thus, rhodolith facies are easily drowned and capped with fine-grained, deep shelf sediments. Relative sea-level rise would have to occur at a slow enough rate to allow rhodolith production to keep pace in order to produce a thick (up to 9 m), homogenous rhodolith gravel deposit such as the Mullamullang Member (Fig. 6.1). Rhodoliths would need to stay in the depth window where light is sufficient for coralline-algae growth but not strong enough for competition of faster-growing chlorozoans (oligophotic zone, Pomar, 2001; see modern examples, section 5.1). A slow, gradual sea-level rise contrasts with that of the rapid global sea-level rise at ~16.5 Ma (Fig. 6.1), and may have been gradual due to tectonic, in addition to eustatic, forcing.
Figure 6.1. Composite stratigraphic section of the Nullarbor Limestone, showing interpreted palaeoenvironments and interpreted relative sea-level curve, compared to global sea-level curve of Haq et al. (1987); letters represent facies associations. Sections were compiled from Rawlinna Quarry (N22) and Cocklebiddy Cave (N1).
While rhodoliths accumulated offshore and were subjected to active hydrodynamics, large seagrass banks may have been initiated inboard near the end of the transgressive systems tract (Facies Association F) (Fig. 5.2A).

6.4 DECREASE IN RELATIVE SEA LEVEL RISE

A decrease in the rate of relative sea level rise must have occurred to allow deposition of upper photic zone seagrass-associated sediments (facies associations F, A) atop the oligophotic rhodolith sediments (Fig. 6.1). The rate of base-level rise may have decreased as it approached highstand, allowing rhodoliths to fill accommodation space faster than the rate of sea-level rise. During highstand, seagrass sediments may have prograded seaward as accommodation space was filled inboard (Fig. 5.2; cf. Betzler et al., 1997). Seagrasses could have colonized sandy sediments between rhodoliths, thus preventing wave energy from overturning them. The fate of most living rhodoliths at this time would have been burial beneath rapidly accumulating seagrass-bed sediments. Seagrass meadows have the highest rates of sediment accretion in the subtropical and temperate realm (<1.5 m 100 yr⁻¹, southern Australia, Boreen and James, 1993; 1 m kyr⁻¹, Mediterranean Sea, Betzler et al., 1997). Energy may have been sufficient in some areas to overturn small rhodoliths and these may have continued growing in seagrass beds. This may be the source of rhodoliths in Facies A3, capping the Mullamullang Member at one locality (Mullamullang Cave, N13). During highstand,
seagrass-associated sediments may have been deposited concurrently in the north (Facies Association F) and south (facies associations F and A) (Fig. 5.2B).

Deeper-water facies, benthic and planktonic foraminifera grainstone (P1) and packstone (P2), occur east of the center of Mullamullang Member rhodolith deposition, near Eucla (Fig. 5.2). This area would have been farthest from the paleoshoreline on the Eucla Platform (among localities of this study) (Fig. 5.2) and may have been below fair-weather wave base with light levels too dim for most photic biota. The interval of the deepest facies (packstones, P2) within the dominating grainstones (P1) may represent the maximum-flooding interval.

6.5 SECOND, RAPID TRANSGRESSION AND HIGHESTAND

Deeper open-seafloor facies P1 and P2 also occur near the top of the stratigraphic sections at northwestern Rawlinna Quarry (N22) and northeastern Watson Quarry (N11), atop shallow seagrass deposits of Facies Association F (Fig. 4.9). The sudden change from upper photic zone sediments to sediments from the base of the photic zone up section implies a rapid sea-level rise (Fig. 6.1). The seafloor of most of the study area was most likely at or below the base of the photic zone at this time, since relatively deep-water sediments are present at northern locations that were thought to be near the paleoshoreline during the previous highstand. If present, these deposits have been eroded away since exposure of the platform in the middle Miocene. There may have been a sea-level fall separating the inundations, but there is no evidence of subaerial exposure. The second sea-level
rise interpreted from these deeper sediments may correspond with the second, global sea-level rise during Nullarbor Limestone deposition (Fig. 6.1).

6.6 SEA LEVEL FALL

Seagrass-associated sedimentation was once again initiated in the north, as indicated by upper photic zone Facies F1 atop lowest photic zone Facies P2 at Rawlinna Quarry (N22) (Fig. 4.8, 6.1). This may have occurred due to relative sea-level fall, after the second interval of rapid relative sea-level rise. Seagrasses were able to start growth atop soft fine-grained sediments once sea level fell. Seagrasses were probably widespread across the northern Eucla Platform at this time, but post-deposition subaerial erosion has erased any evidence. This regression may mark the last interval of limestone deposition across the Eucla Platform and may have culminated in subaerial exposure of the platform. This sea-level fall corresponds to global sea-level fall, but is also likely due to uplift of the southern Australian margin (Fig. 6.1; Li et al., 2004).
Chapter 7: Discussion

7.1 SUBTROPICAL CARBONATES IN A TEMPERATE REALM

The Nullarbor Limestone has many constituents that imply tropical conditions (Chapter 3). Subtropical seagrass deposits (Facies Association F), in particular, have copious LBF, molluscs, micrite envelopes, and rare zooxanthellate corals that together imply water temperatures around 20°C (Chapter 4). According to Betzler et al. (1997), 20°C is the lower limit of true tropical deposition and the upper limit of warm temperate (subtropical) deposition. As outlined above, some components restricted to tropical platforms in the modern realm were not observed in the Nullarbor Limestone: zooxanthellate coral reef buildups, chemically precipitated muds and ooids, and green calcareous algae. The lack of these features favors interpretation of subtropical limestones, with lower (and perhaps seasonally fluctuating) water temperatures, and less aragonite saturation than on true tropical platforms (Betzler et al., 1997).

7.2 TROPICAL CURRENT INFLUENCE AND THE MIocene CLIMATIC OPTIMUM

Increased water temperatures can partly account for lithological differences between the subtropical Nullarbor Limestone and older temperate Eucla Basin limestones (Lowry, 1970). Nullarbor Limestone deposition coincides with the Miocene Climatic Optimum, a time of elevated temperatures and high sea levels.
worldwide, that caused expansion of tropical waters and biota into higher latitudes (Miocene oscillation, from the latest early Miocene through the late Miocene, McGowran et al., 1997b).

Biogeographic distributions of tropical biota (mainly LBFs) during this time along the southern margin of Australia, however, cannot be explained by a general warming alone (McGowran et al., 1997b). This is because a west-to-east temperature gradient occurs, suggesting the early-middle Miocene Leeuwin Current extended down the western coast and along the southern Australian margin (McGowran et al., 1997b; Chapter 2, this thesis). Coeval early-middle Miocene limestones of the Pirie, Murray and Otway basins (east of the Eucla Basin, respectively, Fig. 2.5) are dominated by temperate skeletal components (small benthic foraminifera, echinoderms, brachiopods, and bryozoans; Alley and Lindsay, 1995; Smith et al., 1995; Lukasik et al., 2000). Late Eocene to middle Miocene Otway Basin deposits are strictly cool-water in nature (abundant chert, sponge spicules and bryozoans; Smith et al., 1995). Large benthic foraminifera occur in Pirie and Murray basin sediments, in addition to cool-water constituents, suggesting that these waters were warmer than those of the Otway Basin (Alley and Lindsay, 1995; Smith et al., 1995; Lukasik et al., 2000). This implied temperature gradient from the subtropical Eucla Basin in the west to the cool Otway basin in the east implies evidence of Leeuwin Current influence (McGowran et al., 1997b).

This large-scale cooling from west to east confirms that the Leeuwin Current was influencing sedimentation along the southern Australian margin. Trends within the Nullarbor Limestone suggest that warm waters of the Current also affected
facies distributions within the Miocene southern Eucla Basin. Seagrass sedimentation of the Nullarbor Limestone (facies associations F and A) changes gradually from west to east, as LBF become less abundant and articulated coralline algae increase in abundance. These differences could be attributed to a general eastward deepening, but seagrass-bank sediments are restricted by seagrasses themselves, which generally inhabit the upper photic zone. Thus, facies associations F and A are interpreted to represent sedimentation at similar depths, but different temperatures, presumably due to incursions of the Leeuwin Current.

Incursions of the Leeuwin Current could also be responsible for the distribution of rhodoliths and branching coralline algae in southern Australian basins (James et al., 1992; Fuller et al., 1994; James et al., 2001). Modern coralline-algae gravels are deposited in western portions of southern Australian basins, where offshoots of inflowing currents create regions of elevated temperatures (Spencer Gulf, Fuller et al., 1994; Great Australian Bight, James et al., 2001). Rhodolith gravels of the Nullarbor Limestone may also have developed in the western portion of the Eucla Basin due to warm-water incursions of the Leeuwin Current. This theory is further supported by the abundance of tropical coralline algae and large benthic rotaliines in the Mullamullang Member (Chapter 4, this thesis).

7.3 EPEIRIC-PLATFORM DEPOSITION

The submerged Eucla Platform must have extended at least 450 km landward from the shelf edge during deposition of the Nullarbor Limestone. The most distal
facies interpreted from this study must have been at least 200 km from the paleoshoreline and yet depths were interpreted to have only extended to the base of the photic zone. The extremely low slope angle and large platform width imply epeiric-platform (Irwin, 1965; Pomar, 2001) or epeiric-ramp (Lukasik et al., 2000) deposition (Pratt and Holmden, 2008).

Idealized epeiric-platform sedimentation patterns could help explain facies distribution within the Nullarbor Limestone. Distal facies of epeiric platforms are deposited below fair-weather wave base and could be represented by Facies Association P (Fig. 7.1; Shaw, 1964; Zone X, Irwin, 1965).

Rhodolith-gravel deposits (Facies Association R) of the Mullamullang Member required the highest energy of all deposits of the Nullarbor Limestone. The most turbulent seafloor on an epeiric platform is in the center of the platform, at intermediate depths, where waves impinge upon the seafloor (Shaw, 1964; Zone Y, Irwin, 1965). The epeiric-ramp model postulates this zone as resulting in the formation of hardgrounds or coarse, grainy deposits affected by winnowing (Irwin, 1965; Lukasik et al., 2000). Rhodolith gravels may have been deposited in this high-energy setting at intermediate depths on the Eucla Platform (Fig. 7.1).

Interpreted paleodepths and facies distribution on the platform imply that seagrass deposits occurred inboard of rhodolith deposits and then prograded outboard on top of them. Epeiric-platform models postulate that wave energy is dissipated by friction with the seafloor over hundreds of kilometers before reaching the shallowest environments (Shaw, 1964; Zone Z, Irwin, 1965). Seagrass
Fig. 7.1. Models of epeiric-platform deposition. A) Idealized model of an epeiric platform (Irwin, 1965), B) Model of Nullarbor Limestone deposition on an open epeiric platform/ramp, C) Model of Nullarbor Limestone deposition on an epeiric platform with a protective barrier reef. Concepts for B and C from Lukasik et al. (2000).
sedimentation may have been initiated in this protected landward zone (Zone Z, Fig. 7.1), as also interpreted for extensive seagrass deposition on the epeiric ramp of the Miocene Murray Basin (Lukasik et al., 2000).

7.4 CORALS AND RIMMED PLATFORM?

Source of Nullarbor Limestone Corals

Diverse assemblages of reef-building zooxanthellate corals are usually concentrated around the tropics, in waters that maintain temperatures above 18 °C (Veron, 1995). The diversity of corals in the Nullarbor Limestone is surprising considering high paleolatitude during deposition, but interpreted temperatures around 20 °C could have allowed corals to inhabit shallow seagrass environments. Oceanic surface currents control the latitudinal distribution of coral taxa, as they transport propagules (meroplanktonic larvae) from the tropics. These propagules either survive or do not, depending on environmental conditions downstream (Veron, 1995). Since the Leeuwin Current is most likely responsible for bringing warm, oligotrophic waters to the southern margin, Indonesia or the western coast of Australia could be the source region for tropical Indo-Pacific zooxanthellate corals of the Nullarbor Limestone.

The Indo-West Pacific region (including the North West Shelf of Western Australia, Fig. 2.5) has the highest modern zooxanthellate coral diversity worldwide (Wilson and Rosen, 1998). This was far from true earlier in the Cenozoic, however,
since suitable habitats were not always widely available and source areas for coral taxa were geographically isolated (Wilson and Rosen, 1998).

The early-middle Miocene was a time of widespread carbonate deposition, coral diversification, and reef development in the region due in part to the Miocene Climatic Optimum (Wilson and Rosen, 1988). During this time, a large barrier reef system developed off of the North West Shelf, Western Australia, which stretched over 1,600 km, from the North West Cape, Western Australia, to the Timor Sea, Northern Territory (Fig. 2.5; Ryan et al., 2009). These reefs had diverse morphologies and, presumably, diverse coral taxa, and may have been the initial source of Nullarbor Limestone zooxanthellate corals.

**Rimmed Platform?**

Early-middle Miocene Eucla Platform deposition shares many features with epeiric platforms and epeiric ramps. Epeiric platforms are most common in tropical settings and are usually protected by barrier reefs, whereas epeiric ramps generally have higher energy levels and more sloped morphologies because they occur on unrimmed temperate shelves (Lukasik et al., 2000). The distinction between these two depositional models for the Nullarbor Limestone may be the existence of an offshore barrier reef (Little Barrier Reef, as proposed by Feary and James, 1995) (Chapter 2, this thesis).

Zooxanthellate corals in this study confirm that a diverse suite of reef-building corals can exist in less than tropical conditions, at mid-latitudes. Many Nullarbor Limestone coral taxa are common frame-builders on modern reefs
(Chapter 3), and presumably would have been capable of forming a reef on the Eucla Platform if conditions had been more favorable (Veron, 1995; Veron and Stafford-Smith, 2000). Corals in the Nullarbor Limestone studied herein are scattered and do not show evidence of reef building.

A coeval Little Barrier Reef, hundreds of kilometers offshore, would imply that water conditions were more conducive to reef growth and marine cementation offshore than they were inboard. This could have been due to stronger warm Leeuwin Current flow offshore than on the shelf (Fig. 2.2). The modern Leeuwin Current flows along the shelf edge along the Rottnest Shelf and the Great Australian Bight (James et al., 1999; James et al., 2001). Thus, temperatures along the edge of the modern Rottnest Shelf (> 50 km offshore) are warm enough for development of coral buildups and rare reefs (above 18°C year round; James et al., 1999). Zooxanthellate corals are virtually absent on the inner shelf, where winter water temperatures commonly fall to 15°C, too cold for reef growth (James et al., 1999). The Little Barrier Reef could have developed under similar conditions, experiencing higher water temperatures and attaining tropical meroplanktonic juvenile benthic organisms from the Leeuwin Current (Fig. 7.2).
Figure 7.2. Interpreted paleoenvironments on the Eucla Platform during Nullarbor Limestone deposition with the addition of the shelf-edge Little Barrier Reef, as proposed by Feary and James (1995). Information on inboard facies from Lowry (1970) and Hou et al. (2008). Question marks represent unknown areas of the platform and uncertainties.
Chapter 8: Conclusions

Prior to this study, the Nullarbor Limestone was interpreted as a warmer deposit than older Cenozoic limestones of the Eucla Group due to the occurrence of tropical benthic taxa. The main conclusions of this study include:

1) fossil-component analysis. The early-middle Miocene Nullarbor Limestone is a well-cemented, skeletal limestone with virtually no terrigenous particles. Coralline algae (rhodoliths and articulated), large and small benthic foraminifera, gastropods, bivalves and echinoids dominate skeletal components. Serpulid worm tubes, planktonic foraminifera and zooxanthellate and azooxanthellate corals also occur locally.


3) paleoenvironmental interpretations of lithofacies. The above facies are interpreted to represent deposition in three main paleoenvironments: Rhodolith Gravels, Seagrass Banks, and Open Seafloor. The abundance and diversity of large benthic foraminifera, micrite envelopes and diverse zooxanthellate corals (rare)
imply inboard water temperatures generally above 20°C during deposition. These sediments share characteristics with other Miocene limestones and modern environments worldwide, especially along the western and southern margins of Australia.

4) *interpretation of relative sea level.* Sea level during deposition was most likely driven by eustatic as well as tectonic controls. Interpretation of Nullarbor Limestone deposition: rhodolith gravels of the Mullamullang Member deposited during a gradual sea-level rise, progradation of shallow seagrass banks during highstand, fine grained benthic and planktonic foraminifera open-seafloor sediments deposited during a second rapid sea-level rise and shallow seagrass bank sediments deposited during a final sea-level fall.

5) *interpretation of subtropical temperatures and oceanography.* The Nullarbor Limestone was deposited during the Miocene Climatic Optimum, but the subtropical nature of these sediments cannot be explained by a general increase in temperature alone. Tropical fossils decrease in abundance and diversity from west to east on the interpreted seagrass banks, confirming that the proto-Leeuwin Current was probably responsible for providing warm waters to the Miocene Eucla Platform.

6) *interpretation as an epeiric platform.* Paleodepths of Nullarbor Limestone sediments range from upper photic zone to the base of the photic zone over hundreds of kilometers, implying low slopes, in line with models of epeiric
platforms. Epeiric-platform sedimentation patterns (based on energy levels and depths) can explain the distribution of paleoenvironments on the platform. The tropical Leeuwin Current may have been focused along the shelf edge, promoting formation of the Miocene Little Barrier Reef, which would have rimmed this platform.

The Nullarbor Limestone represents a superb example of subtropical carbonates deposited at mid-latitudes (~38°S). Results of this study should serve as a warning that subtropical-tropical deposition can occur at temperate latitudes and that a rapid transition between temperate and tropical lithologies does not necessarily imply large-scale climatic change. Warming of this platform was a function of local influence of a tropical ocean current as well as global climate change.
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Appendix - Section Logs

N21 Quarry near Balladonia

Key

- Large benthic foraminifera
- Marginopora vertebralis
- Austrotrillina howchini
- Milloline sp. A

Molluscs

- Epifaunal bivalve
- Infaunal bivalve
- Gastropod
- Scaphopod

Corals

- Solitary coral
- Colonial coral

- Rhodolith
- Infaunal echinoid
- Serpulid worm tube
- Celleporaria

Cross bedded sands

- Calcrete
- Fe stained surface

Sample collected for thin section (sample numbers indicated)
N7 Abrakurrie Cave

Fine-grained articulated coralline algae/SBF grainstone

N7.14

N7.13

Rhodolith rudstone with fine-grained SBF/echinoid grainstone/packstone matrix

N7.9

Abrakurrie Limestone

N10 Weebubble Cave

Fine-grained articulated coralline algae/SBF grainstone

N10.8

Gastropod floatstone with fine-grained SBF/articulated coralline algae grainstone matrix

N10.7

Fine-grained articulated coralline algae/SBF grainstone

N10.4

N10.2

Abrakurrie Limestone

N10.1

Pk Gr Flt Rd