INTERTIDAL SEDIMENTS AND BENTHIC ANIMALS OF ROEBUCK BAY, WESTERN AUSTRALIA
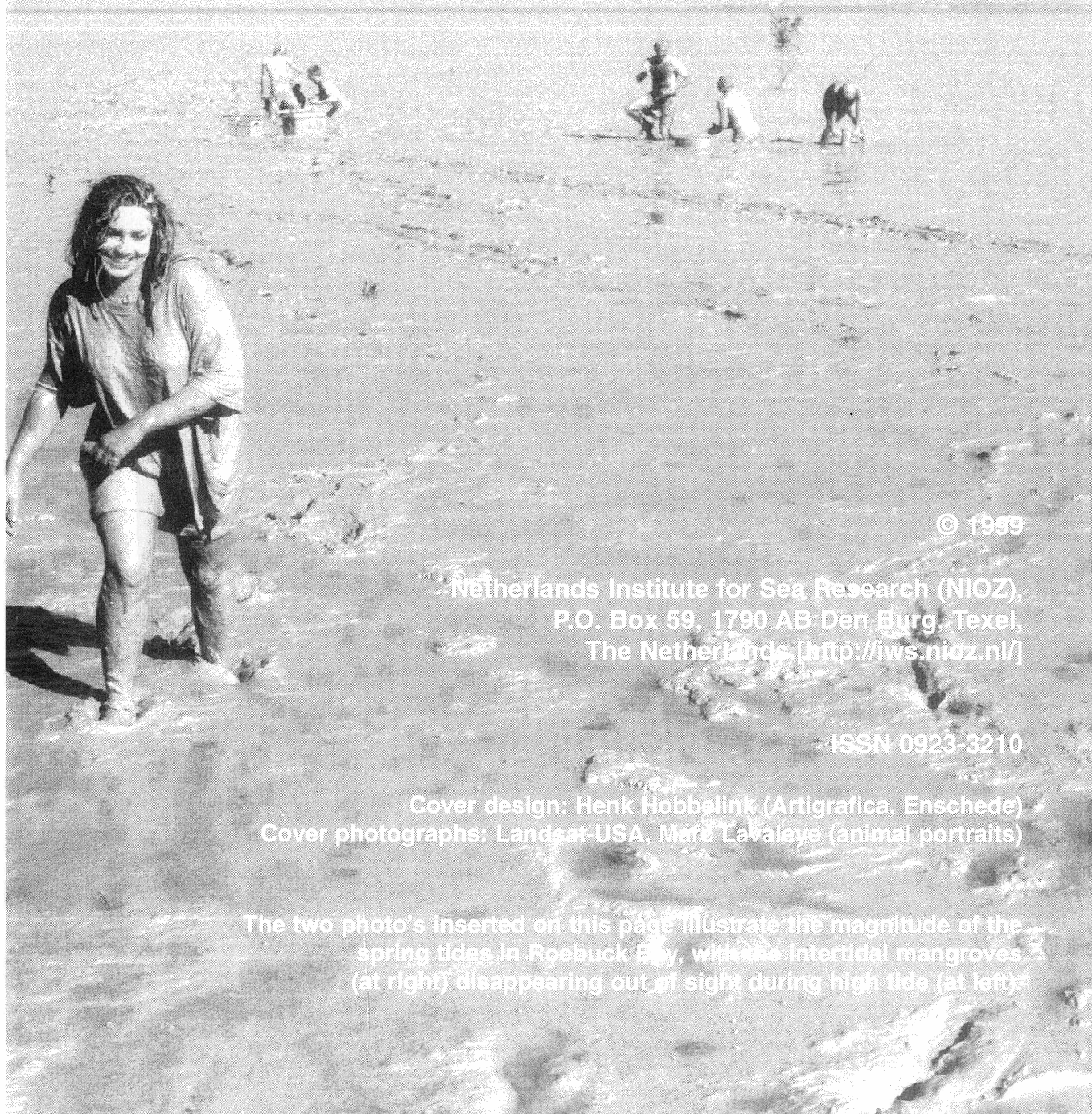
Edited by M. Pepping, T. Piersma, G. Pearson & M. Lavaleye

The two photo's inserted on this page illustrate the magnitude of the
spring tides in Roebuck Bay, with the intertidal mangroves
(at right) disappearing out of sight during high tide (at left).

Intertidal sediments and benthic animals of Roebuck Bay Western Australia

Report of the ROEbuck Bay Intertidal benthic Mapping programme, June 1997 (ROEBIM-97)

Edited by

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ABSTRACT

Roebuck Bay near Broome (NW Australia) is with its extensive tidal flats one of the foremost internationally important sites for shorebirds in the Asia-Pacific flyway system. It is home to 150,000 shorebirds (or 'waders') in the nonbreeding season, which suggests that the intertidal flats of the bay have abundant invertebrate food to offer. To answer the question why and how so many birds are able to make a living in the mud of Roebuck Bay, about a quarter of the intertidal area was quantitatively sampled for benthic animals in June 1997 by a team of about 30 volunteers and professionals. For a series of 12 successive days at almost every low tide 2-4 three-person teams walked parts of the study area. In addition there was a two-person Hovercraft team working the outlying sites. To the best of our knowledge, this is the first detailed mapping of benthic biodiversity on tropical intertidal mudflats. Covering the entire northern shore of Roebuck Bay, benthos and sediment cores were taken at more than 500 stations laid out in a gridlike fashion with intersections every 200 m. Each sampling station yielded a list of invertebrate species, along with their number and sizes, and a value for median grain size of the sediment. Most molluscs and many crustaceans were sorted to species (even though many of these species are presently unknown to science and need formal description). All worms (including the polychaetes, but also groups such as phoronids, nemertines and sipunculids) were sorted and counted to family level (polychaetes) or at least to the phylum level (e.g. phoronids and nemertines). A total of 161 taxa were identified from the quantitative samples; another 30 taxa were discovered opportunistically. The actual number of species within the different habitats of Roebuck Bay will be much higher, because first of all, most of the animals were identified to higher taxonomic levels, and secondly, no samples were taken from rocky habitats and within the mangals. The total density of macrobenthic animals retained on a 1-mm sieve was 1,287 ind./m^2. The polychaete families Chaetopteridae and Oweniidae dominated the fauna in terms of abundance and biomass. The 20 most abundant taxa made up more than 90% of the total numbers. Many rare taxa occurring at less than 2% of the stations were found. Polychaetes were most abun-dant with 70% of the individuals, followed by bivalves (12.5%), crustaceans (8%), brittle stars (4.2%), and gastropods (2.5%). All the remaining taxa amounted to only 2%. In terms of biomass polychaetes contributed a lower proportion (45.4%). The few large sipunculids made up 23%, followed by bivalves (16.3%), crustaceans (10.5%), and gastropods (3%). Brittle stars, though high in number, made up only 0.4 % of the biomass. Thus, the macrobenthic invertebrate fauna is very diverse, a feature quite typical for biota in the Indo-Pacific region. However, only 10% of the taxa could be confidently assigned a species name within the three months of volunteer specialist's work allotted to this aspect. This large proportion implies that we have only scratched the surface of describing true biodiversity in Roebuck Bay. Clear vertical zonation patterns of faunal assemblages were not obvious and were probably veiled by other factors. Gastropods and bivalves were characteristic of the upper intertidal areas independent of grain size. The mid- and lower intertidal areas were numerically dominated by polychaetes in the sandier regions, but bivalves prevailed in muddy substrates. At the earliest possible occasion, in October 1997, the shorebirds were mapped over the surveyed area. For shorebird species following the tideline, such as the two knot species (Red Knot *Calidris canutus* and Great Knot *C. tenuirostris*) and the two godwit species (Bar-tailed Godwit *Limosa lapponica* and Black-tailed Godwit *L. limosa*), it was rather difficult to find associations between their occurrence and the densities of preferred prey. Presumably these prey behave in ways that make them more easily detectable near the sea-edge than elsewhere. Studies on the burying behaviour of three bivalve species demonstrate that behavioural features linked to seawater movements may indeed be important in determining their availability as shorebird-food. The concentration of species specialized in feeding on large crabs and mudskippers (Eastern Curlew *Numenius madagascariensis*, Whimbrel *Numenius phaeopus*, and to a lesser extent Greenshank *Tringa nebularia*) on the soft and muddy sediments in the northeast corner of Roebuck Bay coincided nicely with the distribution of their presumed prey.

SAMENVATTING

Roebuck Bay, dat vlakbij Broome in noordwest Australië is gelegen, is met zijn uitgestrekte getijde gebieden een van de belangrijkste internationale steltlopergebieden in de Aziatisch-Pacifische trekroute. In deze baai overwinteren 150,000 steltlopers, hetgeen suggereert dat de wadplaten van Roebuck Bay rijk aan vogelvoedsel zijn. Om de vraag te kunnen beantwoorden waarom en hoe zoveel vogels hun kostje op het wad van Roebuck Bay bij elkaar kunnen scharrelen, heeft een internationale groep vrijwilligers in juni 1997 een kwart van de wadplaten kwantitatief bemonsterd op dieren die op en in de bodem leven. Op 12 achtereenvolgende dagen werden tijdens laagwater delen van het studiegebied bemonsterd door kleine teams van 2-4 personen. Daarnaast werd er gewerkt met een 2-persoons Hovercraft om de moeilijk begaanbare plekken te bemonsteren. Zover wij weten, is dit de eerste gedetailleerde gridbemonstering van een tropisch getijdegebied. Het grid bestond uit meer dan 500 stations die 200 m uit elkaar lagen en bedekte de gehele noordelijke deel van het wad van Roebuck Bay. Op ieder station werden benthos- en sedimentmonsters genomen. De monsters werden meteen uitgezocht en zo verkregen we van ieder station de aantallen en grootteverdeling van alle benthische organismen. In het laboratorium werd later de korrelgrootteverdeling van alle sedimentmonsters bepaald. De meeste weekdieren en veel kreeftachtigen werden uitgezocht tot op soortsniveau (alhoewel van het gros van de soorten de wetenschappelijke naam onbekend is gebleven; veel organismen zullen nog niet wetenschappelijk zijn beschreven). Alle wormen (inclusief de borstelwormen, maar ook groepen zoals phoroniden, nemertijnen en sipunculiden) werden in het beste geval tot op familie niveau (borstelwormen), maar verder tot op het niveau van hoofdgroepen (phyla) op naam gebracht (bijvoorbeeld de phoroniden en nemertijnen). In totaal zijn er in de monsters 161 verschillende taxa gevonden. Buiten deze kwantitatieve monstering om werden nog ca. 30 andere benthische taxa genoteerd. Het werkelijke aantal benthische soorten van Roebuck Bay zal zeker groter zijn dan 200, omdat de meeste groepen dieren door ons niet tot op soortsniveau zijn uitgezocht en we bovendien de rots- en mangrove- habitats in de getijdezone niet hebben bemonsterd. Op het wad bedroeg de gemiddelde totale dichtheid aan macrofauna 1,287 individuen/m². De borstelwormen-families Chaetopteridae en Oweniidae domineerden de bodemfauna in termen van aantallen en biomassa. De 20 meest voorkomende taxa waren verantwoordelijk voor meer dan 90% van de totale aantallen. Er kwamen dus ook veel zeldzame soorten voor. Bijna de helft van de taxa kwamen op minder dan 2% van de bemonsterde stations voor. Op het klasse-niveau waren de borstelwormen (70% van de individuen) het meest talrijk, gevolgd door de tweekleppige schelpdieren (12.5%), kreeftachtigen (8%), slangsterretjes (4.2%) en slakken (2.5%). Al de overige taxa zorgen voor de laatste 2%. Wat betreft biomassa was de dominantie van de borstelwormen niet zo sterk (45.5%). De grote sipunculiden zorgden voor 23% van de totale biomassa, gevolgd door de tweekleppige schelpdieren (16.3%), kreeftachtigen (10.5%) en weekdieren (3%). Alhoewel slangsterretjes in hoge aantallen voorkwamen, droegen ze slechts voor 0.4% bij aan de biomassa. De verspreiding van de belangrijkste taxa was erg ongelijk. De zoneringspatronen waren tamelijk vaag, maar niettemin lijken slakken en tweekleppigen karakteristiek te· zijn voor de hogere delen van het wad, onafhankelijk van korrelgrootte. Op het lage en middelhoge zandige wad domineerden de borstelwormen, maar op de modderige delen domineerden de tweekleppigen. Enkele maanden na de bemonstering, in oktober 1997, werden in hetzelfde gebied de steltlopers in kaart gebracht. Voor steltlopers die de waterlijn volgen en hoofdzakelijk langs de rand van de zee forageren (de twee kanoet-soorten *Calidris canutus* en *C. tenuirostris* en de twee grutto-soorten *Limosa lapponica* en *L. limosa*) was het moeilijk om verbanden te vinden tussen hun voorkomen en de dichtheden van hun voorkeursprooi-soorten. Waarschijnlijk gedragen hun prooien zich zodanig dat ze makkelijker vangbaar zijn als op het wad een laagje water staat. Inderdaad gaven observaties van het ingraafgedrag van drie soorten tweekleppigen aan dat de droogte van het substraat hun aktiviteiten in belangrijke mate beinvloed. Steltlopersoorten die vooral grote krabben en slijkspringers aten (oosterse wulp *Numenius madagascariensis*, regenwulp *Numenius phaeopus* en groenpootruiter *Tringa nebularia*) kwamen alleen voor waar hun prooien in grote dichtheden voorkwamen, namelijk op de zachte modderige wadplaten in de noordoost hoek van Roebuck Bay.

1 INTRODUCTION

Theunis Piersma & Grant Pearson

Rarely has there been a study area blessed by such beauty as this location in the Kimberley region on the north-west coast of Australia. Where the beautiful azure blue waters of the Indian ocean spill into the shallow expanses of Roebuck Bay, there are vast intertidal flats bordered with green mangroves, yellow beaches and deep- 'red'cliffs.

The intertidal mudflats, exposed twice daily at low tide, are home to a wonderful diversity of small crawling creatures. In turn, these are feasted upon by high numbers of migratory shorebirds that link the Siberian Arctic with this part of the Australian tropics. Indeed, Roebuck Bay near Broome is one of the foremost internationally important sites for shorebirds in the Asia-Pacific flyway system. It is home to 150,000 shorebirds (or 'waders') in the nonbreeding season. A series of wader banding expeditions over the last 10 years, and the establishment of a research- and visitor-centre on the shores of Roebuck Bay (the Broome Bird Observatory, BBO, an independent body within Birds-Australia), have lead to comprehensive assessments of the great ornithological importance of this area.

The thousands of shorebirds that occupy Roebuck Bay from August to April come from a huge breeding range in the north, spanning an arc of about 130 longitudinal degrees, from western Siberia to arctic Canada! Most of the species breed at high latitudes and altitudes, and lay their four-egg clutches in taiga and tundra at the only time of the year that these regions are free of snow and rich in arthropod food, in June and July. The young of the year travel the 10,000-15,000 km south to the intertidal lands of north-west Australia independently from their parents. They thus establish annual routines that may continue for 20-30 years in the ones that reach old age.

The very fact that so many shorebirds fly 30,000 km per year at a speed of about 70 km per hour (that makes 429 hours, or 18 days of continuous flight) to get to and away from Roebuck Bay, suggests that the bay has much to offer, particularly abundant food. Apparently, there is enough to make such demanding flights worthwhile. And sure enough, the climate is congenial and shorebirds don't need to spend much energy on keeping warm. But even though the muds have much to offer to the shorebirds, we should keep in mind that they may have few alternatives. All over the world intertidal lands are scarce, and intertidal lands that offer everything that a shorebird needs (sufficient food and safety) are even scarcer. To under-

stand whether the shorebirds at Roebuck Bay live in a land of plenty, or rather find it hard to make a living, one has to study their foraging, and to assess the quality of their food resources. Such knowledge is relevant in that it tells us the extent to which the frequent disturbance of beaches by tourists, the reclamation of parts of mudflats or the gradual pollution of the bay, are likely to affect shorebird populations immediately, or only in due course. By signing the Ramsar Convention and submitting Roebuck Bay as a Ramsar-site, Australia has pleaded responsible for the well-being of the bay, at a time when human encroachment is faster than ever.

To answer the question why and how so many birds are able to make a living in the mud of Roebuck Bay, to evaluate the food stocks for migratory shorebirds, and to provide the groundwork for future environmental impact assessments in the Roebuck Bay area, the intertidal area of Roebuck Bay was quantitatively sampled for benthic animals in June 1997, when a team of about 30 volunteers and professionals joined forces during *ROEBIM-97*, the '*ROE*buck *Bay Inter*tidal benthic *M*apping programme'. For a series of 12 successive days at almost every low tide 2-4 three-person teams walked parts of the study area. In addition there was a two-person Hovercraft team working the outlying sites. The mudders spent the remaining time on the sorting and processing of the samples. Little time was left for only the most urgent maintenance activities. To the best of our knowledge, this is the first detailed mapping of benthic biodiversity on tropical intertidal mudflats.

Representing 45 km², or about a quarter of the intertidal area of Roebuck Bay and covering the entire northern shore of Roebuck Bay, benthos cores were taken at 537 suitable stations laid out in a gridlike fashion with intersections every 200 m in the north and 500 m in the east (Fig. 1.1). Each sampling station yielded a list of invertebrate species, along with their number and sizes. Most molluscs and many crustaceans were sorted to species (even though some of these species are presently unknown to science and
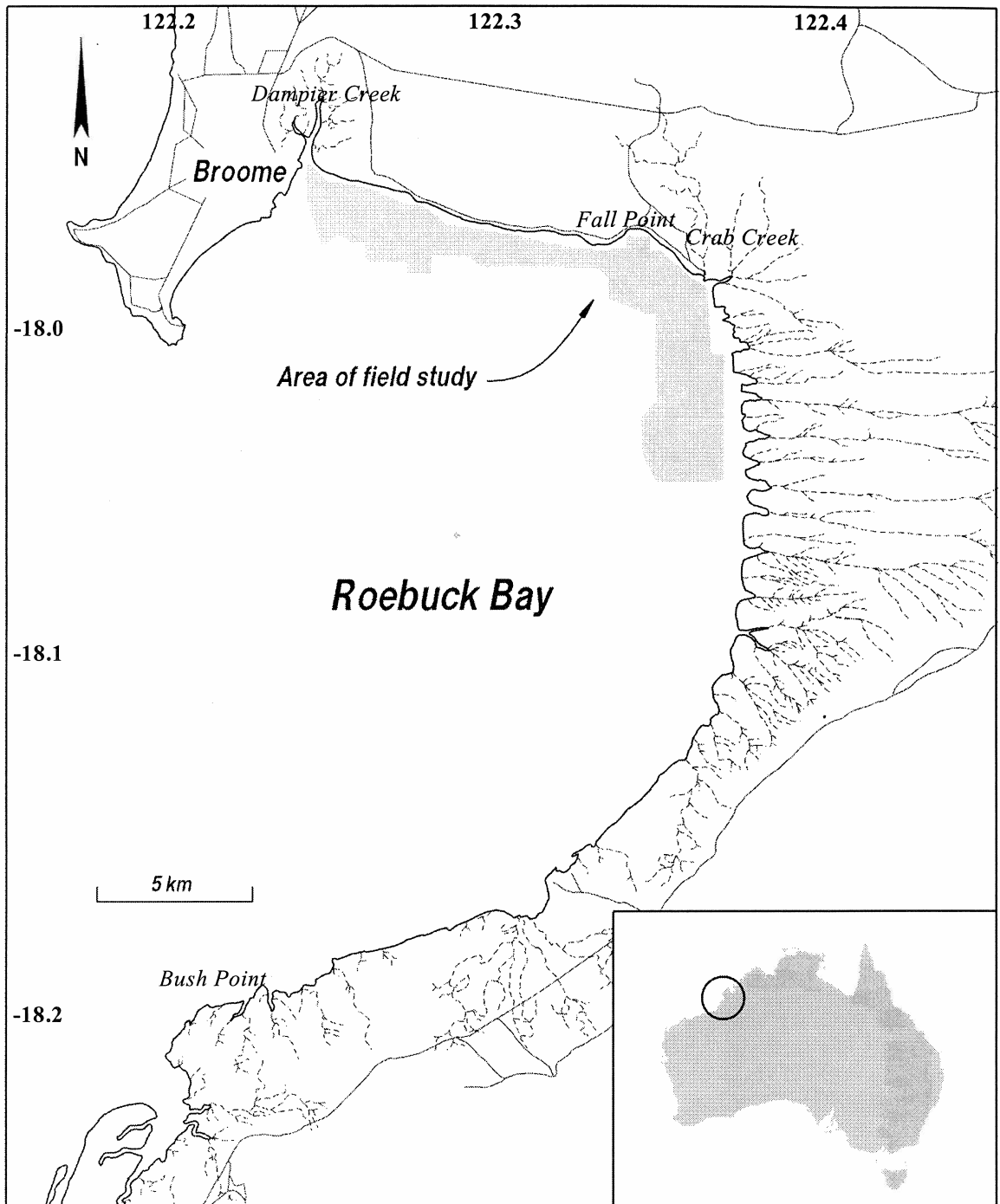
Fig. 1.1: Map of Roebuck Bay showing the location of the main study area. Additional cores were taken along two transects near Bush Point. The vast intertidal areas south of the main study area were only accessible by hovercraft, whereas most of the northern parts were sampled by teams on foot.

need formal description). All worms (including the polychaetes, but also groups such as phoronids, nemertines and sipunculids) were sorted and counted to family level at best (polychaetes) or phylum level at worst (phoronids and nemertines, for example).

We processed a total of 17,700 individual animals, about 10,000 of which were tubeworms. We found a total of more than 200 different taxa (either species, families, or larger taxonomic groupings). As we extended the surveyed area, the number of taxa grew steadily, suggesting a total diversity of at least 300, and possibly no fewer than 500, intertidal macrobenthic invertebrate species in Roebuck Bay. The distribution of most taxa was very patchy and densities often differed significantly between neighbouring stations. A few patterns were found, nevertheless, and depending on the substrate and the position within the tidal regime distinct assemblages of species were found.

In this report we aim to present and evaluate the data collected in June 1997 in Roebuck Bay. At the same time we also aim to convey the positive flair and flavour of this co-operative enterprise. In addition, we will report on closely related projects that followed in the footsteps of *ROEBIM-97*. Danny Rogers presents his data on wader distribution, collected as soon after the benthic mapping exercise as the birds had returned from the Arctic, in October 1997. In July 1998 several members of the *ROEBIM-97* team visited another large but hugely contrasting coastal wetland in the Kimberley region, King Sound near Derby, to examine intertidal benthic richness in relation to sediment characteristics using the methodologies developed in Roebuck Bay in 1997.
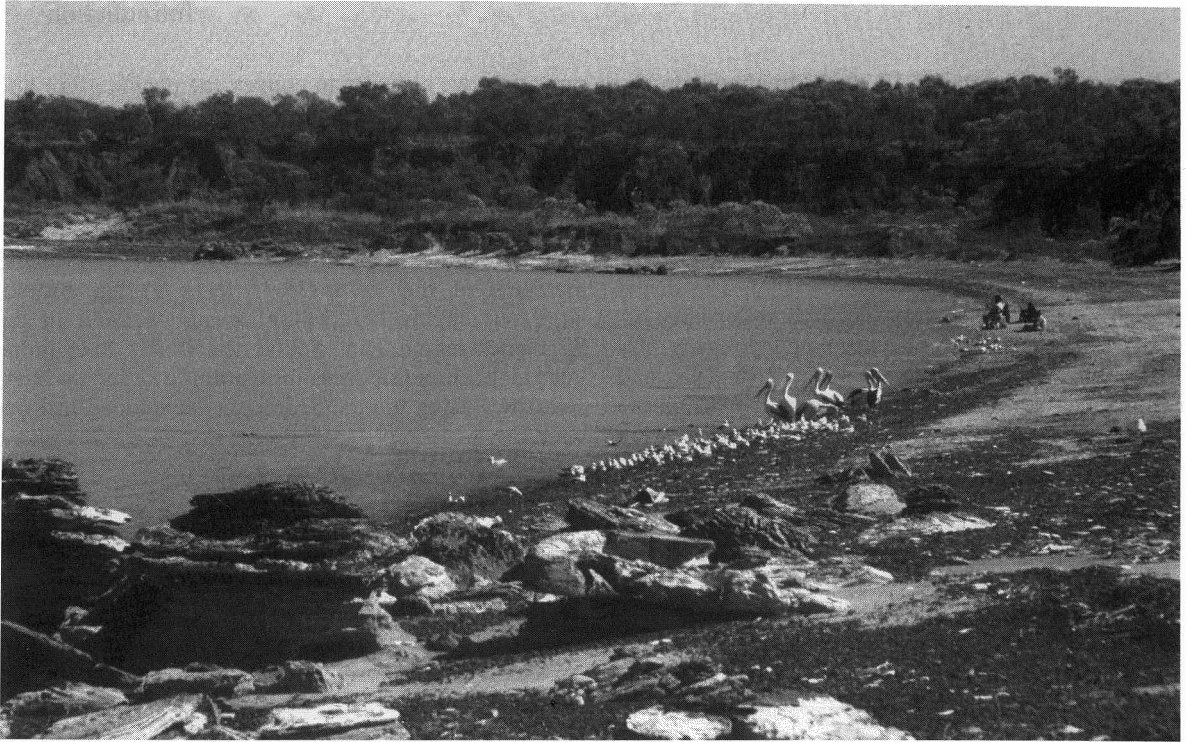
Top: High tide image of the northern coastline of Roebuck Bay between Fall Point and Nick's Beach. Cliff erosion is the dominant process shaping the morphology of the northern coastline. The sandy beaches between the cliffs and the high water mark are an important bird roost. Bottom: Low tide image at dusk in front of the Broome Bird Observatory. Photographs by Marc Lavaleye.

2 ORGANISATION AND LOGISTICS

Grant Pearson & Ted Costello

Fall Point in Roebuck Bay is located at latitude South 17:59:06, longitude East 122:20:18, about 2500 km north of Perth Western Australia. The Broome Bird Observatory, close to Fall Point, is located 5.5 nautical miles east of Broome along the northern shore of the Bay. In 1996 the Western Australian Lotteries Commission provided a grant of $37.410 for the construction of a new wet laboratory at the Observatory and the purchase of a small hovercraft. These two items were important contributors towards the success of the benthic monitoring projects.

The wet lab provided a base for workers away from the tropical sun and humidity of Broome. The sorting and microscopy could be carried out in well lit, cool conditions. The ever-present hordes of insects at night were unable to penetrate the insect screens (at least in theory) and the airconditioner pressurised the interior assisting with dust reduction.

Dominated by a hot, humid, tropical climate, Roebuck Bay presents field workers from cooler climes with problems they may only rarely encounter. The notorious deep muddy substrates of the intertidal regions in Roebuck Bay also demand an open-minded approach and the use of some specialised transport equipment. Scientific surveys in difficult and remote sites such as this demand special attention to logistical planning and detail. The objective to map the benthos of this vast area of mud and sand flats, totalling about 250 square kilometres, would always be limited by the number of field personnel available for sampling sorting and identification.

Organisation

Four research organisations were involved in the ROEBIM'97 project – NIOZ, CALM, Curtin University and Broome Bird Observatory. Each of these organisations is governed by its own protocol for operations. A sufficient lead-time for planning was necessary to ensure all aspects of collaboration were settled prior to the start of the fieldwork and expenditure of precious research funds. This in itself was a significant obstacle due to the geographical separation of the participants but one that was overcome to a large extent by the advent of the Internet and electronic mail.

Upon arrival in Perth, the Dutch contingent was able to spend the next four days during transit to Broome, preparing the field program. Calculations of

transect length, location and sampling procedures were also defined. Sample site locations were entered into database en-route using lap top computers, powered by a Honda 650, 240-volt AC power generator that was fixed to the roof rack of the travelling vehicle. A printout of the site locations and procedures was possible using a portable Canon Bubble-jet BJ10SX printer.

For daily activity programs, a table was drawn up and posted on the notice board at the end of each day. This provided details on the roster for each activity including laboratory teams, cooking teams, drivers of vehicles, sampling teams. The tidal information was essential given that the tidal movements determined how and when sampling took place.

Field training

On day one participants were introduced to the processes and techniques involved in the collection of samples from the mud. This involved an excursion to the Bay with much discussion and demonstration. Techniques were further refined during the survey. Instructions on the procedures for handling specimens in laboratory environments were drawn up and distributed. New sorters were able to refer to these at any time.

Team development

The ROEBIM'97 team was drawn from a wide variety of organisations and localities. It comprised many individuals with diverse backgrounds. On many occasions, visitors to the Observatory were so enchanted with the opportunity to spend endless hours sorting invertebrates, they stayed for several hours or returned on successive days. Teamwork was necessary to avoid overburden on any individual. The workload on the Biology and Geology teams was extremely high at times. A total of 17,000 specimens were sorted during the project and over 650 sites visited. Co-ordination of tasks was essential. The teamwork developed over the course of the project was instrumental in the eventual success of the project overall.

Team fitness

Carrying out exhaustive fieldwork in deep mud conditions is a memorable if not enervating exercise. Participants in this aspect of benthic monitoring require a

reasonable level of fitness. Adequate drinking water supplies are essential. Each person carried their own water bottles. Water additives such as electrolyte supplements were available and necessary at times. Those with a lower fitness level were able to participate equally, by attending to sorting, identification of samples and camp support.

Environmental conditions
Broome is located in a tropical monsoon climatic zone. The mean annual rainfall is 512 mm (Watkins 1993). Most of this rain falls between November and April and during this wet season cyclones may have a significant effect. Winds of over 160 km per hour have been recorded and the intense rainfall and tidal effect combined with wind driven swells can cause severe erosion to the cliffs around the Bay. The mean monthly maximum temperatures range between 20° C and 34° C, while minima range between 14° C and 29° C. The hottest months are March and April and the coolest months are June and July. During the 1997 Roebim survey, minimum overnight temperatures were recorded as low as 6° C. Maximum temperatures were about 30° C.

Medical advice
Areas around Roebuck Bay are notorious for the high level of mosquito biting incidence. Mosquito linked diseases such as Ross River Virus and Australian Encephalitis were major concerns for participants in the survey. Insect repellents and long sleeved loose fitting clothing were recommended apparel during dusk and dawn surveys- the peak mosquito nuisance times.

The good access roads to Broome town and the proximity to Broome District hospital assisted medical evacuation procedures. A first aid kit was available containing supplies of the commonly needed items for pain relief, eyewash and bandages. Several of the participants were trained in basic first aid procedures.

Communication
Good communications between field workers, the project leaders and the local community and community organisations were developed as an essential requirement.

For most of the sample collection, field communi-

Fig. 2.1: Sorting and identification of the benthos samples in the completed wet lab. The work in the laboratory often proceeded until late at night because under the tropical conditions the samples would have rotten within a few days. A conservation with formaldehyd or alcohol made identification even more difficult and was therefore tried to be avoided.
Photograph by Grant Pearson.

cations with base were unnecessary. However the boat was equipped with a 27 Mhz marine radio. A CALM VHF (High Frequency) radio was carried for contact, in the event of an emergency, with the Broome CALM office or Royal Flying Doctor Service (RFDS) Centres.

The location of sample sites was pre-determined the previous evening to coincide with tidal range and daylight. Samplers were able to navigate to these locations using a handheld GPS unit. Mobile telephones were of limited use but frequently of value when operating close to Broome. Small handheld CALM VHF (Very High Frequency) radios were carried on the hovercraft and on the boat. Communication was possible between both craft and with the Broome CALM office or mobile Rangers. The local AM radio broadcaster invited several members of the team to talk "on-air" about the project and its objectives. The regional television broadcaster interviewed three of the project leaders.

Accommodation

The Broome Bird Observatory served as a base for the duration of the project. The excellent accommodation facilities included basic cabin type twin or single rooms, chalet style bunk- house or tent sites. Commu-

nal shower facilities were sumptuous. A large multi-burner gas stove, freezer and refrigerator serviced the communal kitchen. A special accommodation rate for project participants was charged by the Observatory to cover power, water and facility costs

Meals

All participants contributed a daily rate for food. A roster was drawn to ensure there would be a team of two every day to purchase and prepare the next days meals. Drinking water was provided from the BBO water supply. Personal water bottles were essential for samplers. Boat, vehicles and hovercraft were provided with bulk drinking water supplies.

Access to sites

Vehicle access to research sites was possible along the northern beaches of Roebuck Bay. Vehicles were able to drive along a well-made earthen road at the edge of the cliffs to a point opposite each transect. Sampler access from there was simple.

The Eastern Shore and the areas around Crab Creek were not so accessible. This was achieved by the use of a small two-person hovercraft, a 4.5 meter dinghy (Fig. 2.2), a homemade mud sled (Fig. 2.3) and foot transects. A set of cross-country snow skis was

Fig. 2.2: Hovercraft and dinghy provided access to the remote sites of the embayment. Without these vehicles the mapping of the muddy south-eastern parts would have been impossible. Photograph by Grant Pearson.

Fig. 2.3: Our self-constructed mud-sled that was supposed to make life easier on the mudflats. I turned out to be an utter disaster but was certainly worth a try. Photograph by Marc Lavaleye.

tried to 'hasten' travel over the deep mud. In the end it was found out that the simplest way, which means struggling through the mud on foot, was by far the most efficient way of sampling. At night samples were collected from near shore sites by foot parties and more remote sites from the boat. Concerns for the safety of foot parties included the risk of crocodile attack, disorientation and exposure to sea wasp stings.

Sampling
The number of sample sites visited was directly proportional to the number of sampling teams available. There was a core of 13 samplers from the participating organisations but these were never going to provide enough effort to complete the project. There would always be a need for a significant input from the local community. A further 13 regular participants were recruited from Perth and the local community. Visitors to the Broome Bird Observatory were often keen to participate in the sampling (Fig. 2.4) and sorting and did so opportunistically.

Funding
Each participating organisation contributed to the total costs of the project. Special contributions were received from:

- Wallis Drilling for the loan of the Wallis Hovercraft
- Broome Transport for the transport of the Wallis Hovercraft
- Son Autos (Wangara) for the provision of a replacement motor for the Wallis Hovercraft

Transport
Four wheel drive vehicles were the preferred option for access to most of the sites and along Crab Creek Road. CALM provided a 4x4 Rodeo utility and a two tonne trailer for the project that enabled the transport of the small hovercraft to Broome. Transport at Broome was augmented by the use of BBO and private vehicles.

Mechanical
The rough roads and terrain often caused minor mechanical problems. The inherent nature of hovercraft and boats is to demand frequent attention and maintenance. Mechanical problems were dealt with in-situ. Fibreglass repairs to the hovercraft were carried out using blanket fibreglass and resin. Rapid drying of the resin was achieved with a small heat gun. Mechanical repairs and servicing were carried out at the Observatory.

Fig. 2.4: The sampling on the mudflats. The material was sieved on the spot through a 1 mm mesh and bagged for subsequent sorting and identification in the lab. In addition to the biological cores sediment cores were taken to a depth of 10 cm. Field observations were recorded using a generalised roster. Photograph by Grant Pearson.

Sample site locations
There were three main sample areas:

1. Dampier Creek to Crab Creek.
Dampier Creek from Fall Point is 5.5 nautical miles. From Fall Point steer 235m degrees for 0.5 N.M., 275m degrees for 4.7 N.M., 345m degrees for 2N.M. (obstructions – see the marine chart -Aus 50, Australia - North West Coast, Western Australia, Approaches to Broome 1:50,000). Crab Creek from Fall Point steer approximately 150 degrees for 1N.M.

2. Bush Point
Fall Point to Bush Point. Bush Point is approximately 17 N.M. from Fall Point. The course required to be steered from Fall Point (BBO) is 235 Deg. True (chart AUS 50 shows a 2 degree easterly variation) giving a course to steer of 233 degrees magnetic. Allowances for the tidal variations have to be considered to maximise the tidal advantage. Special concern for the Pearl Culture beds, marked on the charts must be considered. These beds are not necessarily marked with special markers (yellow) and are not necessarily lit (at night)

but the Culture Farms have the option to do either. The positions are clearly marked on the chart AUS 50.

3. East of Crab Creek to Bush Point
The sediments in this region are deep fine silty mud. Foot progress in this type of sediment is difficult and slow. From Fall Point steer 120 Deg. True.

Field equipment
- Hovercraft - the Maurice Mulcahy- a two seater craft ideally suited to Roebuck bay conditions. Powered by a Rotax Bombadier 503 series two-stroke motor.
- Hovercraft - The Wallis Hovercraft – a four person craft powered by a Subaru 1.6 litre 4 stroke motor providing drive and a Bombadier Rotax 503 series two stroke motor for lift.
- Mud sled - a timber construction designed by Mr Ian Snadden to provide the capacity to carry a small number of sample bags while being propelled across deep mud. – An utter failure.
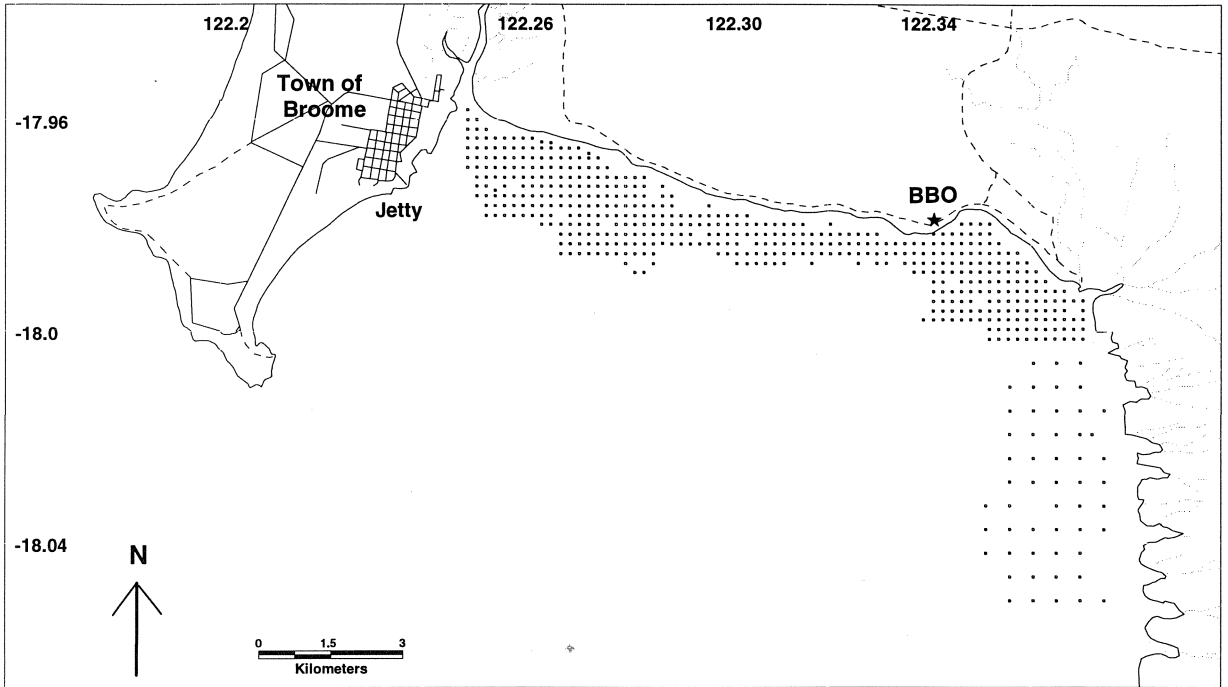
Fig. 2.5: Map showing the northern parts of Roebuck Bay and the stations that were sampled during the field trip. Also indicated are the locations of the Broome Bird Observatory and of the old jetty of Broome. Co-ordinates are Lat. / Long. decimal degrees.

- Sieves - circular plastic drum bases with one-mm gauze stretched across the base. Between 50 cm and 30 cm in diameter.
- Large Corers - lengths of PVC sewer pipe 10.2 cm diameter up to 60 cm long. Capped at one end with a 1 cm hole fitted with a rubber bung. Some were fitted with handles.
- Small Corers - a 200 mm length of 50 mm PVC pipe open at both ends. Cores were placed in small freezer bags for later analysis of grain size.

Checklist
- 2 cores geology + biology
- 1 sieve small for sandy areas
- 1 sieve big for muddy areas
- small pots
- biology plastic bags
- geology lunchbags + geology bags marker pen
- 1 clipboard
- protocol forms
- map
- poskey number
- pencils
- GPS
- reserve batteries
- compass
- bucket with handle

Boat survey requirements
Roebuck Bay is a large marine embayment subject to extreme tidal variations and moderate tidal flood speeds.

Take note of tidal diamonds in specific areas on appropriate charts. Boat and hovercraft activity in this area must be undertaken with full recognition of these influences and the need to carry adequate safety equipment.

There are regulations governing the use of boats and hovercraft on Roebuck Bay. The Western Australian Department of Transport has the following safety requirement boats less than 8 metres in length operating in Roebuck Bay:

- Operator must have a Certificate of Small Boat Proficiency
- Approved life-raft or internal buoyancy
- Coastal standard life jacket for each occupant
- Three parachute distress rockets
- Two hand flares
- One smoke signals
- Waterproof torch
- Portable fire extinguisher
- Appropriate charts
- Suitable bilge pump or baler
- Basic medical kit

- Navigation lights
- Efficient anchor and rope
- Hovercraft less than 50 metres operating in non-displacement mode requires all of the above safety items for a boat less than 8 metres, plus a yellow flashing light for night and day operation. (Small Ships manual, 1993, Queensland Department of transport, 10th edition, Rule 23B)
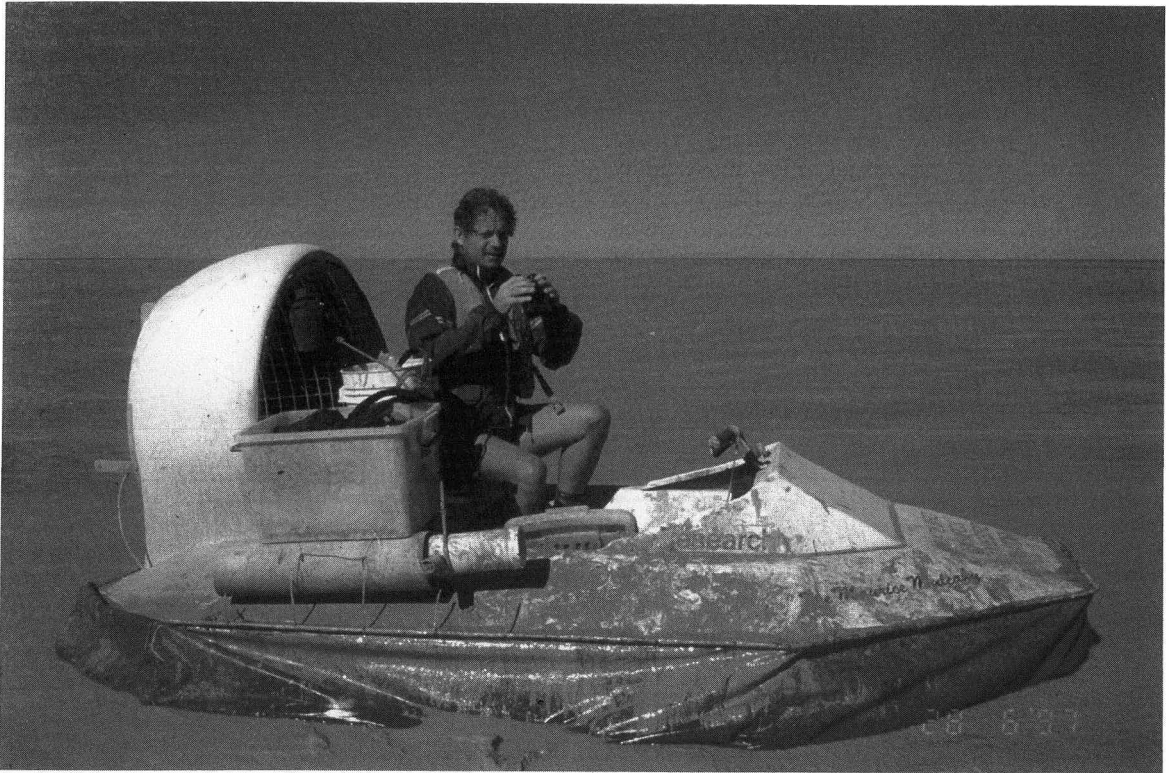
Top: Theunis Piersma on the hovercraft. The hovercraft was used to reach the more distant sample station where access on foot was impossible. Bird watching on the other hand was less successful, since the deafening noise of the engine chased away any flocks. Bottom: The construction of the wetlab, which served as our laboratory in 1997. Both wetlab and hovercraft were funded with a grant from the Western Australian Lotteries Commission. Photographs by Grant Pearson.

3 INTERMEZZOS

3.1 "A rhymery"

Grant Pearson

There was movement at the station for the word had passed around
that ROEBIM'97 would soon get underway.
Lots had joined the wild Broome mudders- it had cost a thousand pound
and all the cracks had gathered to the fray.

All the tried and noted benthics from the uni's near and far
had mustered at the shadehouse overnight,
for the mudders love hard slogging where the wild mud bivalves are,
and the hovercraft snuffs breakdowns with delight.

It began with things inventive, wild and crazy not invective
and it grew with cash from lotteries so they say.
The interest grew with relish and developed fresh perspective
on the faces of the bashers near the wetlab on the bay.

For the waders had been worked on with enthusiasm played on
by the man they all call Minton from a clinic in the east.
But now the problem focussed round some dutchpersons hocus pocus
and it lead to something grandly called – the beauty and the beasts.

There were Chris and Jane the wardens who left Blighty quite unburdened
and appeared as though t'was nothing left to do.
But would give a life of toil no reward but mortal coil
at a place near Roebuck Bay called paradiso BBO.

There was Ali bold and visioned with a purpose freshly risen
and a keenly fashioned ardour for a future in the mud,
and a husband pencil wielding while his wife he failed in shielding
from the dreadful fate below the splendid cliffs of pindan blood.

And one was there a stripling on a small and weedy beast.
It was something like a boat but undersized
with a touch of Broome of Spirit, and with two stroke power at least,
and such as are by mudders highly prized.

It was worn but freshly painted, just the sort that may say die,
there were dollars in the quick and shrouded tread
and it wore the badge of Lotteries, CALM, and Maurice of Mulcahy
and it beat the well constructed muddy sled.

There were Pieter, Marc and Petra wearing mud clogs in the Bay,
Danny, Sheila, Tanya, Ted were in the boat,
Lee and Eddy, Markus – were geologists (geographer) of fame
while Theunis, Ron and Grant would find the float.

There was Helen famed for cooking when the chips were really down,
and the crowd was milling hungrily about,
there was Ian who built the wetlab who would often call around
and was easily fleeced of dollars at the pub when called to shout.

There was Ollie French and gracious who assisted in the shop,
and would cook a flambe of excellence at the end.
There was Lee of longish fingernails and worried for the slop
from biologists with low statistic trends.

there were Mavis, Betty, Carmen who went boating in the wet,
Jim and Matt who came from somewhere but unclear,
Helen, Colma and a lady who was Grecian never met,
they all would venture mudwards without fear.

There was talk of mud ski sliding, skiing, boating, hover riding.
They all were one in seemly fettered mirth,
and the tension kept on building, for a strategy was melding
as the safety seemed to linger sorry last.

But if you pause a while and listen if you're ever passing by
even though your mind has turned to other things,
you can hear the plaintive calling of the Great Knots giving fly
you can hear the distant beating of their wings.

For when hovercraft and shouting had receded from the land,
and became an echo of an age, good times gone by,
it was merely apparitious and beyond your ken unspanned,
which has clearly left to quickly pass you by.

But the bold and galant bashers, fighting mud and prickly rashes,
forever live in memory in a benthic science heav'n,
and if future children ponder; why the bay's still rich in splendour
they will say in pride its due to "ROEBIM'97".

3.2 The Mud Journal

A concentrated study of the mud of Roebuck Bay

Mavis Russell

JUNE 13th: Several 'mudders' (Marc, Markus and Ed) already here and were joined by Jim Lane (CALM.) late this evening. Phone call from Grant Pearson (C.A.L.M.). Said that he and his party wouldn't be arriving until tomorrow. They're coming in the C.A.L.M. vehicle from Perth and towing the Hovercraft. He is bringing Tanya, Theunis, Petra and Pieter with him.

JUNE 14th: Everyone arrived today except for Betty Gilbert who arrives from the U.S.A. tomorrow. Day spent in sorting gear and discussion as to the best way to do things and checking gear brought up from Perth.

JUNE 15th: Ditto and group discussions, job allocations, sorting in the Mud Lab. etc. I fetched Betty from the Airport.

JUNE 16th: It all started today! I spent 4 hours plus out on the mud along the water's edge with Pieter and Ed taking samples at specific points determined beforehand and confirmed by G.P.S. - which meant one person had to stay clean to handle it and to make all the recordings. Ed and I did the sampling and got covered in mud but even the 'clean person' was muddy. The mud is indescribably glutinous and comes with deep pockets (over my knees) with scratchy, shelly bits in it with resulting nicks in skin from knees down and in fingers. As it was also quite chilly with an easterly wind blowing, we ended the day cold, muddy, scratched and extremely tired and stiff from dragging our legs in and out of the mud for 2-3 km. Ed also carried the samples - an extra 10 kg of weight - and between us we had sieves, buckets and corers. Four sample cores at each pre-determined spot - three for biology and one for geology. Then we had to walk another 2 km back to the B.B.O. along the beach. Ed and I only just made it despite him only being in his early 20's! Evening discussion (inquest?) on day's activities after dinner - beautifully prepared by Petra, Jim et moi! I left at 9 pm for sleep.

JUNE 17th: I was 'Hoovercraft' crew today. This is a one-person 'Hoovercraft' but two small people have to fit in it - with no seats on the petrol can with uncomfortable taps and a gauge on the top - water seeping through the bottom and over the top in a spray mixed with mud. It is noisy, smelly and highly unmanoeverable especially in yesterday's easterly on the unprotected mud flats, far out when the tide was out. I was the 'clean' person and I was covered in mud from head to toe. Lee (Coshell) was the one driving and getting out to sample. It was really dangerous getting me from the boat to the 'Hoovercraft' because of the choppiness of the water and because the H.-craft engine has to be kept on or it sinks - and there is no way of tying it alongside let alone an easy way of actually coming alongside. Having managed all this, we had trouble with the GPS - which eats batteries. Lee gave vent in a very unacademic language to his frustrations and eventually we made a start with me hanging on to him and to the GPS and record sheets. The next frustration was finding no recording pen/pencil and no marker pen for samples. We actually finally managed eight samples before the tide beat us. Lee dropped me off on the boat again before heading for shore - where I found they'd been sieving the geology samples instead of the biology ones! No wonder they weren't finding much in them! It was another hour and a half before we got ashore and I was shivering with cold by then - and these are the Tropics! Wet clothes and a caking of mud didn't help. Cup of tea, casseroled sausages and a beer restored me after a nice hot shower. The inquest last night was interesting! It ironed out a lot of the problems - and the 'Hoovercraft' should have an armchair or the equivalent in it today - room permitting. It was an interesting day but I enjoyed it and went where no B.B.O. person has ever been before. Lots of birds out there in patches but most flew off when the noisy 'Hoovercraft' approached.

JUNE 18th: I had a nice restful day off the mud - sorting, cleaning etc. and then went into Broome at 2.45 pm for my computer class and to drop Kathy off at the Physio. While I was away it all happened! The 'Hoovercraft' with Lee and Danny struck the boat while coming alongside and holed the H.C. - a dent 2 feet long in the fibreglass hull. No one was hurt fortunately. The boat's crew caught fish for Thursday's tea - shark fillets. Lots more sorting got done but yesterday's record sampling (23 samples) by Markus, Pieter and Ed, was not beaten. The tides are increasing in size again and and the timings for mud sampling are becoming more difficult as we have to go out later in the day. I returned from my class at 9.25 pm to find some 'dodgy' parking out front (2 vehicles at right an-

gles plus one with small dinghy on trailer) - and scraped the side of the Subaru getting through. There was a meeting going on over at the 'Shadehouse' (David, Ali, Chris. Janet, Theunis, Ron, Jim - about a grant) so I went straight to bed. Slept until 7 am but most slept even later -an indication that we're all tired.

JUNE 19th: A lot of work being done on the 'Hoovercraft' to get it repaired in time for this afternoon's work. Hair dryers borrowed and being used for drying fibreglass. I didn't think Grant was borrowing them to dry his hair! COLD, COLD morning - down to 7° C. Windy (easterly) later on. Sorting samples whenever there spare moments - especially with high morning tides. We, who are wallowing in the mud, couldn't get out to start collecting until 2 pm today. I went out with Jim and Ron, and Theunis assured us it was sandy underneath and therefore easier to walk in the mud. He lied! It was the usual hard slog and we were all dead tired when we reached "terra firma" again at dark. The mozzies greeted us in droves! Thank Goodness someone else was doing the cooking. Marc's talk in the late evening (about worms) was fascinating but I (and others) couldn't stay awake for all of it.

JUNE 20th: Another exciting (?) day with the usual foul-ups. Because of the tide we couldn't start until early afternoon so the boat was due to go into the water just after noon - only Grant didn't get back from Broome until nearly 1 pm and then insisted that the 'Hoovercraft' go down first so it was 1.20 pm before the boat got down there - and the water was nearly gone so they had to use the inflatable rollers to manhandle it out to the deeper water. Absolutely crazy! Then I was 'Hoovercrafted' out to it with all the necessary gear. The boat then made for a co-ordinate somewhere south of "One Tree" and we anchored and fished until the tide went out. Then we did seven samples at different points on what Theunis had said (for the second day running) was sand. It wasn't! It was still mud although fractionally less deep than the previous day's mud - except for pockets into which we went knee-deep again. Theunis' credibility is shot! It was almost dark by the time we got back to the boat so we sat and watched the moon come up and the tide return. When Ted thought it was deep enough he used the mobile phone to call up Grant to come to the beach to fetch us - and got a Telstra operator in Canberra! They had an interesting conversation and Ted said he'd phone again if he got bored. Eventually raised Grant and we set off for the B.B.O. The water was still too shallow for the boat when we reached Fall Point so Grant fetched us in the 'Hoovercraft' and as we reached the beach with a flourish, I overbalanced and melted my jacket on the exhaust! Good job I had it on or I'd have melted. Tea eventually at 8.15 - too late. I

couldn't get to sleep on that. Lots of the others sorted samples until midnight.

JUNE 21st: Another frustrating day. Betty and I were going into Broome early to laundrette and market. Eventually we left B.B.O. after 10 am with Tanya and Ron, 6 lots of laundry, shopping list and chores to do for Grant. We didn't get back until after 1.30 pm - me to find I was too late to go on the mud (sand?) with Theunis and Petra. Helen went instead and enjoyed herself and didn't get too muddy - so it must have been sand. I sorted and sorted and then went to see the moon come up -and two tawny frogmouths roosting in a tree by the beach path. Washing up was finished about 10.20 pm - too late. B.B.O. mistnetted in the morning but I didn't manage to join in much unfortunately. They caught (twice) the Grey Fantail that has been hanging around, off and on, for 3 weeks; also a White-throated Gerygone - and I missed it!

JUNE 22nd: Sorting, sorting and more sorting samples. Tide was wrong for much mudding but Grant took the 'Hoovercraft' out this morning - and tore its apron! He was out near Crab Creek trying to finish the sampling in that block when the apron split down a seam. It was a good job he was only in about a metre of water because the H.C. became almost unmanageable with its cushion of air escaping so he headed for shore and had more problems on the dunes with the H.C. tilting over. Now all they've got to do is mend it! The tides are wrong again tomorrow but we should be able to get some sampling done. In the meantime we've been sorting, sorting again in the Mud-Lab and have finished the initial sort of Friday's and Saturday's samples and started on the more specialised sorting with Markus, Petra, Danny and Theunis using the microscopes to identify animals other than worms of various species. (Pieter had a day off.) Some of them are beautiful under a microscope with all sorts of shapes and colours - like those T.V. pictures of plankton and krill. This mud is full of life although you wouldn't think so if you look at it in the bay. Most of the 'mudders' have gone to see 'Staircase to the Moon' tonight and then on to Sheila's house so 8 of us had a nice quiet meal and Bird Log. 4 of the 'mudders' are in my car!

JUNE 23rd: My car returned safely. Early start because of tides. Theunis, Markus and I went to Dampier Creek out on the flats after fighting our way through the mangroves. It was less muddy than the other places I've been in and therefore slightly less strenuous but we were fast because the tide was coming in its usual train-like fashion. The rest of the day was spent in sorting - a tedious job that makes you cross-eyed after an hour or two. Kathy and I managed to get in a swim at lunch time. Lovely - the first time she'd seen the bay full up with a high 8.5 m tide. Grant and co.

fetched the new 3-seater 'Hoovercraft' from Broome and, within 10 minutes of starting it, it had one of its engines blown up leaving Ted stranded about 1 km out on the mud. Grant's language was of the usual non-academic kind! He returned to get all hands down to the beach where they man-handled the craft back to the shore and onto the trailer and back to the B.B.O. He was not a happy man.

JUNE 24th: Another early start to the mud: Dampier Creek again with Ian and Markus this time. We got 12 samples done before being beaten by the tide. The journey to the flats was a bit 'hairy'. We had 2 GPS with us and virtually went round in circles in the mangroves before finally reaching the mud flats. Helen joined us at 6.15 am having taken a day off work and arriving with 4 cakes all suitable for Ed - egg free! She stayed all day and is still out on the boat now at 8.15 pm waiting for the tide to be high enough to come in. 9 people out altogether doing biology and geology cores etc. (in the dark) and I'm picking one lot up at 9 pm. Hope they had a successful evening. The rest of us sorted - what else? The 'mud boys' are burning the candle at both ends. They're up at 5.30 am after going to bed about 2am - and are still behind with lab work. I went to fetch Ron, Markus and Ed at 9 pm from "North Quarry". Their heavy geology gear and the sledge, I was told, would be brought back in the boat. It wasn't - and they didn't even get near the boat which was too far out. So I took Ed and Markus - leaving Ron to be picked up with the gear in the CALM vehicle - only we met Tanya driving it to fetch 6 others, so there was no room for Ron. So we turned and went back for Ron - minus sledge now on CALM vehicle. Their evening was a shambles, it appears, from it taking one and a quarter hours to get the geology sample to losing a corer and the geological hammer (weighing about 50 pounds) on the mud flats in the dark together with leaving recording gear on the boat. Needless to say, NO geological samples were taken by them! They did offer to clean my car! (Everyone who goes out on the mud drops dust and lumps of grey mud about for days after the event.) Mud boys meal tonight (Spag. Bol.) at 10 pm. I left them for bed.

JUNE 25th: Sorting, sorting again today. This has priority at present as some of the samples are beginning to smell. G.W.N. finally turned up and filmed Ron with the sledge and geology gear and Tanya falling over in the mud. 3 groups plus boat went out late 'arvo' again and the boat now has to wait out there until there is enough water to come in about 11 pm? They'll be starving and tired. One group went prepared for the mud with torch and spare batteries - and the bulb failed! Several 'chiefs' went into Broome for a 'conference'. I don't know what it was about but feel sure there must be money at the back of it. Another

grant perhaps? I went into town at 3.30 pm and played on Edith Cowan Uni.'s computer for an hour before going to see Paul Foulkes for tea and going to my penultimate computer class. King brown snake about 1 m in length seen at B.B.O. at lunchtime.

JUNE 26th: Janet's birthday! I was on the 'Hoovercraft' (1 person; 2 crew) with Grant. What more is there to say? To anyone who has had the same experience there is little more to add beyond the fact that we got 12 samples BUT to anyone who hasn't, explanations are in order. Grant loves driving the H.C. and drives it like a controlled maniac. He knows exactly what he is doing except when the wind catches it and it does 'wheelies' out on the mud - then he has a bit of trouble controlling it but most of the time he's singing while out there even when up to his knees in grey, glutinous stuff and water taking samples. We came back as the tide came in and spent the rest of the day sorting as usual. The geology 'boys' (Ron and Ed) took a huge core (2 m) and we then 'rescued' them and their gear (including the 50 lb. hammer) just ahead of the incoming tide. In the evening, 17 of us went to a Chinese Restaurant followed by a visit to the Sun Picture House -a very good evening.

JUNE 27th: I reverted to birding today and Janet, Chris, Kathy and I went to 80 Mile Beach through Anna Plains Station on the twice-yearly bird count and did a B.O.P. Watch on the way. Good views of a Square - tailed Kite. The beach count was disastrous as there were almost no birds for 11 km before we got a good flock of about 6,000 − 7,000 birds including an orange leg - flagged Red-necked Stint and 3 yellow leg - flagged Bar-tailed Godwits. Also saw 5 long fishing nets in the water. Had a nice curry round the camp fire and lots of laughs, went to bed at 7.30pm and slept snug in our sleeping bags until 5.15am. What a great place that is! Nothing but the sound of the sea and the occasional birds. I heard Greenshank and Whistling Ducks in the night.

JUNE 28th: Got up at 5.15 am and was it cold! Long pants, jackets, woolies, beanies and mittens the order of the day. We packed up rapidly, had a 'cuppa' and were up at the homestead by 6.35 am ready for a flight in the station 4-seater. We flew SE to Samphire where there is a surface lake after the 'wet' of 20 km by 1 and a half km and a variety of smaller lakes - and counted birds. There were thousands (29,000 plus) including rafts of moulting ducks unable to fly with one raft being hassled by a raptor as they are 'sitting targets' without the power of flight for 3 weeks. Many ibis (Straw-necked and White) and Black-winged Stilts breeding and lots of waders like Sharp-tailed Sandpipers (very fast flyers) and, possibly, Greenshank, and some of the smaller waders as well as terns by the score. Then we returned to Anna Plains via 80

Mile Beach. Good views from the air of the vastness of Anna Plains Station spreading east into the Great Sandy Desert. Lots of surface water everywhere even on the edge of the desert. We arrived back at the B.B.O. about 12.30 pm to be greeted by a hurrying Theunis who had just tipped onto the exhaust of the 'Hoovercraft', singed a hole in his shorts and burnt his bum! Grant wishes we would stop spreading rumours that he's a bad driver! It was a magic visit to Anna Plains - a lovely place with good company. Now its back to the grindstone. Practically all the mud sorting is finished and people are leaving. Just a few more geology cores to be taken and things to be cleaned and packed. The animals found in the mud are unbelievable - just like something out of Jules Verne - only real and not imaginary.

JUNE 29th: Up at 5.15 am and off to Helen's at Coconut Wells for mist-netting. 21 birds caught including a goshawk and several of those pesky little net mice - Double-barred Finches. Back to B.B.O. at lunch time. No more sorting; just clearing up. Things are winding down - or I wouldn't be writing this at 3.45 pm. Theunis, Grant and Ted have gone to take samples at Bush Point (in the boat) and Markus and Ed used the 'tinny' to sample at Dampier Creek and returned exhausted. (These geological cores are over 2 m in length and involve the use of the 50 pound hammer) Betty left today; Ron last night.

JUNE 30th: Packing up day. Theunis packing up the Mud Lab while Danny and Petra do last minute identification; Grant and Ted packing up and returning the boat to CALM and 'Hoovercraft 2' (the broken down one) which has to be returned to the mining company in Perth from which it was borrowed. Grant et. al leave in the morning to drive down after talking with Rubibi (the local aborigines) at 11 am. Theunis and Petra then staying for a holiday and Markus and Danny to work. Ed goes tonight - also Ted. It will be so quiet without Ed who, despite his light and 'gung-ho' attitude, has worked extremely hard on the mud taking geological samples. It will be flat around here without all the activity. Maybe again next year?

JULY 1st: Murphy's Law dictates that there had to be a last minute 'hiccup' - and there was. Markus spent a long time out on the mud getting a last geology core only to find on his return that he'd used the wrong co-ordinates - so it had to be done all over again.

3.3 ROEBIM Journal, May 26th to June 21st, 1997

Excerpt from a diary

Marc Lavaleye

May 26th: Loaded with lots of luggage (photographic equipment, computer, taxonomic literature etc.) I manage to get from Texel (The Netherlands) to Perth. After a thorough control of my stuff by the customs, which became rather suspicious because of the few clothes that seemed to be only there to avoid the rattling of all the equipment, I finally meet Grant Pearson. In his enthusiasm he wanted to show me around, but the traffic, rain and the falling night were all against it. At the meeting with geologists of the Curtin University in a restaurant, where you had to bring your own alcoholic drinks, I first hear that geological samples will be taken too. That's good news. The grain size of the sediment will be an important parameter. Grant shows an impressive photograph of the hovercraft in action. In fact he blew away several reporters while moving around on a small lawn. After a few drinks Australian football comes to table, and I learn it is as popular as soccer in Europe. The 24 hour flight and the meal make me very sleepy, and that's what I do in Grants living room.

May 27th: After an early breakfast Grant brings me to the airport, and I am off to Broome. From the air I have a nice view over the country. Around Perth it is green, but soon it gets yellow to brown, and for almost 2,500 kilometres it stays a mere desert with few trees, some low eroded mountains and hardly any roads or houses. At the small cosy airport of Broome, Oliver, the assistant warden of the Broome Bird Observatory (BBO), picks me up in a four wheel drive. When we drive around in Broome to pick up stuff needed for the sampling, I learn that BBO is not a three star hotel, and consequently I buy food enough to survive a week. Broome is a very open city, which, however, is growing fast due to tourism. Some years ago there were hardly any hard roads. The trip to BBO takes about 30 minutes over a red and corrugated dirt road. Now and then I catch some glimpses of Roebuck Bay through the low trees of the Pindan. BBO consists of a few scattered buildings, a camping ground and some solar panels, and lies hidden in the Pindan forest a few minutes walk from the beach. I meet Chris Hassell, Janet Sparrow (both wardens), Mavis Russell and Tom Shaddon, all friendly people - a good start. The new built lab looks very nice, and I install my equipment for macro-photography here. In the Shade House, were you can cook your meal, I discover a nice library of natural history books. I get a small cabin as a room, with a bed, a chair and a fan; which is mosquito free if you keep your door closed. The public toilet seems to be the domain of the green and brown tree frogs, but after a while you don't feel embarrassed anymore. I head for the beach and hear the familiar sound of oystercatchers (common on Texel). On the red-orange sandy beach with black rocks and stones I collect my first shells on Australian soil. The few mangrove trees standing in the vast waters of Roebuck Bay give the whole scenery a tropical aspect. The night is coming in quickly, at 5.30 pm it is pitch dark. I sort my shells in the lab till late, everyone is asleep. With some luck I find my way back to the right cabin without a torch.

May 29th: My first day on the mudflats alone. After the sandy beach I sink about 20 cm into the mud. Dogwhelks (Nassarius) and small white Marginellidae are common, and creep actively over the wet surface, looking for prey. The tracks of three parallel lines are from the large and heavy bloody cockle (Anadara granosa). A bit further green Cephalaspidea, big Ingrid-eating snails (Nassarius dorsatus) and a few Trochidae crawl over the mud surface. During the cumbersome walk water is welled up in the many small and big holes. They intrigue me, but I have no clue who is responsible for these holes where you can put you whole arm in. The mud gets deeper, and it is more difficult to proceed without loss of a shoe. Then I hit a group of sponges. I am amazed to find sponges in such a muddy environment. How do they cope with the murky water? You would suspect that these filter feeders will clog up quickly, but here they are, a patch of a few hundred greenish cones, 5 cm high, and anchored firmly in the mud by a massive root system. I catch a large mud crab (Scylla serrata), which makes an impressive sound by clashing its massive fierce claws to each other. I try out sieving some samples of the sticky clay on the spot with some difficulties, and take the result with me back to the lab. On my return I had a quick look at the few spots of rocky shore and see a lot of exciting things but promise myself to stick to the sand- and mudflats, as these will absorb more than enough of the time. During the fetching of 20 liters of clean seawater to keep some of the animals alive for photography, I notice the many fiddler crabs and mudskippers and catch two soldier crabs in the sandy area. Sorting takes almost till the night falls. I

am expecting Markus Pepping, who did the trip Perth - Broome by Greyhound bus. As his pickup is scheduled wrongly he comes in with a cab. I am delighted to see him, especially because of the stereo-microscope which he is carrying. As every night at the BBO the bird sightings of the day are noted. My contribution of eight Brolgas is heavily questioned.

May 30th: In the morning Jane McCrae (CALM) pays a quick visit to have a look at the polychaetes and the mud. I show her the curious plastic worms (Chaetopteridae). The afternoon is quiet as everybody is gone to Broome for all sorts of things, and I am busy with identifying the bivalves. 4.30 pm the bunch is back with Ed Oldmeadow. A real Australian, vegetarian and enthusiastic geochemist. We have a quick look at the beach, but hasten back quickly because of the many mosquitoes. After a delicious meal cooked by Ed, I make my first photographs of the animals in the lab. Especially the fiddler crab gives me a hard time as it will not sit still. As the generator starts its noise at midnight, I call it the day.

May 31st: The three of us (Markus, Ed and myself) go to the mudflats. As they try out the geological sampling I try to sieve a large area (50x50 cm) as deep as possible. Among the bivalves the biggest surprise is a large mussel (*Modiolus micropterus*), which was living several centimeters deep into the sediment covered by a bunch of self made threads (byssus). Ed and Markus have difficulties taking a good sample. The muddy sediment is heavily compressed, and farther down a shell layers makes it difficult to get the core in deep. We decide to walk along the beach to Crab Creek where the mangrove forest starts. The mud here is much more fluid, and you have to keep moving otherwise you sink so deep that it is hard to come out again. There are many large mudskippers (two species) around here, that fight with each other over their territoria by raising the first dorsal fin. A silver gull tries to catch them in vain, and its funny to see that even the gull has trouble walking on the mud. A large fish is washed ashore and a whole stream of hundreds of dog-whelks are attracted by it. I discover many *Cerithidea* snails and another that looks like a tiny moonsnail. In fact it is a lungsnail of the genus *Salinator* that can survive submersion only for a limited time. During a small excursion through the mangrove forest to Little Crab Creek we notice that many stumps are heavily bored by the shipworm (Teredinidae), and we hear the snapping sound of claws of the hidden pistolshrimps. Little Crab Creek has eroded a two meter deep bed into the mudflat, and it is a delight to walk in it as its bottom is sandy. The beautiful orange fiddler crab (*Uca flammula*) is here abundant at eye level. We try to reach the junction with Crab Creek, but the water is coming up quick and we rush back to the beach and to

the BBO. Although we thought we had cleaned ourselves from the mud rather well, the term mudboys is quickly attached to us. I find the time to do the botanical trail, and as you have to keep walking because of the mosquitoes, I finish it in less than 15 minutes. But I spotted an Agile Wallaby and the nest of the bowerbird, which had a preference for bright green objects like green glass and fruits. In the evening I sort samples, Markus collates the air photographs to an overview of the whole Roebuck Bay, and Ed is preparing diner. We are all tired and before 11 pm we are sound asleep.

June 1st: Before breakfast I had a quick look at the waders on the flats. The Black-billed Stork was the largest of them all. Later with Markus, I sample a sandy spot near high tide level a couple of hundred meters west of BBO. On our way we pass a large dead stingray. These large fishes swim in with the tide onto the mudflats and sometimes make big pools during digging up prey. The pit we dug revealed many long armed bristle stars. I did not expect them so high in the tidal zone, but because they sit so deep into the sediment (at least 10 cm) they survive. With their very long arms they fish their food out of the water during high tide. Farther on the flats there are many starfishes (*Astropecten granulatus*), which suddenly appear out of the mud. Bright green polychaetes (Phyllodocidae) crawl without fear over the sediment (not tasty to birds?). Among a lot of small creatures we find 10 cm long fanshells (Pinnidae) that were almost completely hidden in the mud, and a razorshell (*Cultellus*), to which its predator the moonsnail was still attached. After lunch, sorting and identifying animals took most of the time. Markus filtered some water and had a look at the plankton. It is all benthic stuff and juvenile bivalves are the most abundant. We show some BBO tourist around during which the large mudcrab in a bucket had most of the attention, because of its leaps towards the enemy trying to grab it with its terrifying claws.

June 2nd: It is Labour Day. Because of the pile of animals still to be identified I am not going to the field. Markus is going to try out the GPS and assess how many points we can sample during the real grid sampling. We figure out that one man of each sampling team, has to be a "clean" man, to handle the GPS and keep notes. In the evening I explain to a group of birders what the purpose of our research here is. Next to scientific questions as which, where and how much animals live in and on the intertidal flats, and how potentially important (in the sense of food) the flats are for waders, there are two more reasons to study the flats. First this study can count as a baseline for future studies. Broome is growing fast due to tourism and this of course can have its effects on the environment.

And second: if you want to protect the bay in a more strict sense you need good data to defend that the bay indeed has special ecological qualities.

June 3rd: This morning I tried to identify the crabs we had sampled. Especially the fiddler crabs are troublesome. With the few specimens I have it stays a puzzle. So we decide to hunt some more. At our knees we wait quietly and patiently near the burrows of the crabs. Slowly they reappear and start eating and waving again. When one of them is gone too far from its burrow, we very quickly cover the opening of the burrow with one hand and catch the lost crab with the other. It looks if we are meditating there. It is real fun, and also Ed, who is completely recovered from his two day illness, is concentrated on the catch, though at first a bit frightened of the big, though harmless claws. Next to fiddler crabs we also catch Sentinel crabs (*Macrophthalmus*), which are related to the fiddler crabs and also have those long stalked eyes. The sentinel crabs have an oblique burrow and often their tracks going in and out the burrow are clearly visible. In the lab I put each one in a separate vial, and start to solve the puzzle of the fiddler crabs.

June 4th: The morning is very foggy. I make a walk along the Malurus trail, and my shoes soon get soaked by the wet grass. The trail goes north and than east along a cattle fence. The Pindan is thinning and changes into a grassland. Along the road a lot of large, bleached carapaces of crabs (*Neosarmatium* cf *meinerti*) are peculiar. What are they doing here so far from the sea? Acacia's are flowering and massive termite hills tower over the grassland. The trail nears the coast and now I see crabs running through the grass to hide in their deep burrows, which will only rarely be reached by the sea. Back at the lab I resolve the fiddler crab puzzle. It is now clear that at the small muddy patch (50 x 20 m) surrounded by coarse sand just below the beach in front of BBO not less than five species of *Uca* are living. Besides we caught a small blue one with yellow claws, which I cannot identify. May be a new species? During the night the three of us head for the mudflats armed with strong torches. Ghostcrabs are running over the beach. Most of the fiddlercrabs do not show up. Other crabs that are hidden during the day are common now especially the Grapsidae near rocks and the blue swimming crabs (*Thalamita spinimana*) in shallow water. The strange black "look alike nudibranchs" (*Onchidium*) as large as 5 cm crawl slowly over the mud. Before everything is sorted in the lab it is already the 5th of June.

June 5th: While almost everybody at BBO is going cannon netting waders on the beach, I try to identify the *Macrophthalmus* species from near BBO. Mainly because of the rounded telson I think they are *M. pacificus*. At 3.30 pm Ed and I explore a transect

about 1.5 km west of BBO. The first 100 m from the beach is mud again, but farther out the sediment gets more sandy. This is a relieve and walking is easy here. I sieve an area of 0.25 m² and catch a lot of shell gravel, a fair amount of brittle stars, but no living molluscs. We check the surrounding and discover sanddollars, starfishes (*Astropecten*), moonsnails with their collar like egg cases, and 3 cm large conspicuous orange flatworms. Dusk falls quick and we hurry back, but still manage to find a large snail *Vexillum* between the mud and the few tiny seagrass plants. Markus is also back. He went to Dampier Creek. There between the *Rhizophora* mangrove trees the bottom is covered with rocks. Big snails *Terebralia sulcata* sit at or near the trees. Small cerithid snails and hermit crabs abound on the sediment. Also large blue swimming crabs (*Thalamita spinimana*) are abundant in pools. Towards the creek the trees disappear and the sediment gets soft and muddy. Lots of mudskippers here. A pleasant break during the sorting of samples at night was the sight of a strange bird, the Tawny Frogmouth, which was sitting for quite a while on a branch in the dark.

June 6th: I phone Grant a list of all the things we still need. The main things are lights for the sorters and some microscopes. After designing a form to be filled in at each station with data on sediment and fauna, I go to Broome to buy among other things wood for the sledge and 4 kg salt to get out the mysterious inhabitants of big holes. In vain we try to buy a pump used for catching large mud worms, but it seems it is no longer in use here. Back home the supervisor of the Green Corps group that is willing to help me sampling the mudflats has arrived. I explain what we want to do and how they can help. Because of the tides we have to start early on Sunday, and ask him if he can be here at 6.30 in the morning. With this jolly good news he returns to the Green Corpers in the backpackers hotel in Broome.

June 7th: I make a list of species so far, inform the NIOZ-people in The Netherlands about the progress and tell them what sort of things we still need. Markus is busy to make a worm-pump himself, and assembles a coarse sieve from some wood and a nylon gauze. At 4 pm the tide is out far enough to try to solve the mystery of the deep large burrows on the mudflats. Armed with a shovel, the worm-pump and 2 kilo's of salt we head for one of these holes. I pour in a whole kilo of salt, but after waiting 15 minutes still nothing happens. Then it is Markus'turn, and putting in the pump he starts to pump with long jerks. The area turns quickly into a big mudpool, but nothing shows up. Than suddenly a lady turns up not from the hole but from the beach and without fear she walks with bare feet through the mud towards us. It is Ali Pentelow,

who is coordinating the monthly bottom-fauna sampling at Fall Point and One Tree. During our talk about her program and what we are doing here, at last something emerges from the mudpool. It is a large mantis shrimp (Squillidae). The mystery is solved and we are glad we did not put our hands in these holes, as the claws of these shrimps have the same effect as a dart thrown at full force. Satisfied we return to BBO. In the lab still a lot has to be done and it gets late again. Hit my bed at 0.30 am and am too tired to bother about the annoying mossies.

June 8th: At 6 o'clock we all three have breakfast. It is good we are early because the Green Corps tries to make a good impression by coming even earlier than agreed upon. Out of the big four-wheel drive 10 young people (age around 20) crawl out. We provide them with shoes for the mud and give everybody something to carry. Then we all walk over the mudflat. For all of them this is a new experience. The 300 meters towards the low water line are a tour de force, and the group breaks up to form a long line. But all make it (cursing or laughing), and the playing with the mud starts. Twenty cores of about 40 cm are taken, sieved on the spot over 2 mm mesh, and than sorted on a large sheet of plastic. No one stays clean in this process. For the first time we discover tiny crabs (Hymenosomatidae), which only start to move sometime after they are extracted from the sediment by the sieve. The coming water drives us back. Just before the beach we take another 20 cores. This time everything is going much quicker. And we have to, because soon the rising water has reached us again. Higher up the beach we dig a big hole, but no sign of any macroscopic organism is to be seen. It is only 10 o'clock when we are back at the lab sorting the samples. To all our surprise there is much more to be seen than we thought. Three species of sea cucumbers, sea squirts, bivalves (e.g. *Cultellus*), snails, crabs, hermits, brittle stars, lots of bristleworms, and even a sea anemone. After lunch we tackle the second sample. Here also lots is to be found. The most peculiar are the brachiopod *Lingula* and the quick swimming mussel shrimps (Ostracoda). 3.30 pm we are ready and we all need a long break. After preserving the samples and keeping up my diary I quickly fall asleep at 10 pm. I have put on the fan so I cannot hear the mossies anymore.

June 9th: The Green Corps is early again. Five of them stay at the BBO to paint the cabins and grit the road. With the others we drive back until half way Dampier Creek. We leave a small road block for the TV-crew that wants to film our work. We descend the cliff and make a station on a sandy spot not too far from the beach as the TV-team is expected soon. However, we do the twenty cores in a record time, and all is sieved and packed, when a young lady in neat clothes and with a microphone in company of a large heavy guy with a bulky TV-camera on his neck appear. After interviews with me and Rowan, the Green Corps supervisor, we hurry back to the others who already proceeded to the low water line and started sampling on their own initiative. To my surprise the TV-crew is following us, ruining their shoes, to make additional takes. The group today is very dedicated and we even can make another station on our way back to the beach. This is a station very rich in animal live. New things are a strange crab with a shell on his back for protection (Dorippidae), sipunculid worms, and crabs of the family Goneplacidae. When the work is done it is celebrated with a mud fight so I have to run. The sorting in the lab is also quick and in the evening I have finally time to make some macro-photographs of live animals.

June 10th: We are even earlier than the preceding days, and after a quick interview for the radio we drive to Dampier Creek with the other half of the Green Corps. Oliver on his motorbike and the radio girl join us. Just at the east side of the mangrove forest of Dampier Creek we enter the tidal flat and walk directly to the low water line. It is a fine sandy sediment with current ripples, so walking is easy and we expect no difficulties in sampling. However, this is an error. Its is difficult to get the cores deep into the sediment and even harder to get them out with the sediment still inside. If you put your hand underneath the core to avoid loosing the sample, it is very surprising to notice that you even have difficulties to get your own hand out of the sand. Large tubes of worms (Onuphidae), sea cucumbers (purple and orange) and sea squirts with roots are the most peculiar animals here. The other two stations closer to the beach are going quicker and 10 o'clock we are all back at BBO. The sorting is laborious and the measuring of the animals (to get an idea of the biomass) is left for me. Markus and Ian are busy with the mud sledge that is now near completion.

June 11th: Today the plan is to sample the One Tree transect near Crab Creek. I expect a hard time because of the fluid mud there. The Green Corpers are aware of that but five of them volunteer and are eager to make this experience. In a good mood we hit the mud, and it is really bad. We left all valuables on the beach, because nothing can stay clean here. I sink in till my knees. As I have no GPS I count 800 steps (about 400 m) to the low water line. If you stop for a while to rest you are in trouble while you sink even deeper, which costs you time and energy to get out again. At the station we sit on our knees to avoid this a bit. Coring is easy, but sieving is hard. The pool of water very soon turns into a pool of fluid mud, so you have to extract yourself from the mud again to look for another pool. Even before we are finished here the first clumps of

mud fly through the air. The battle begins. Even my authority fades in piles of mud and we have a great time making everybody unrecognisable. Still we do two other stations. Mudskippers and the bivalve *Siliqua winteriana* abound here. Notwithstanding the heat of the sun it gets cold in this cover of wet mud, so we walk to Little Crab Creek and clean ourselves as much as possible in the water here. After a much needed rest we sort all samples in the lab and finish the work half way the afternoon. As a surprise I announce that tomorrow we start at 8 pm instead of 6.30 pm, which is very much appreciated. Markus and Andrew are making a cabinet for the reference collection. I photograph until midnight. I have a hard time because the animals are too quick (crabs) or too lazy (snails) to get a nice photograph. Sandflies like my ankles.

June 12th: An easy morning. Ed has time for his Tai Chi. No sampling today. We have to get some order into all the stuff we collected, and to construct some picture identification panels for the group that will do the real grid sampling of Roebuck Bay. For shells this is relatively easy, as we paste the bivalves directly on the boards and add the latin names to it. The result looks great, and with the cabinet filled with vials containing animals on spirits it really starts to look like an educational museum. At 4.30 pm there is a barbecue as a farewell party for the Green Corps. Again a radio interview, now for the channel ABC with some fake noise of sieving on the beach as the high tide makes real sampling impossible. Chris invites us all to a bird tour with telescopes, and we see lots of curlews, bartailed godwits and many other waders in close-up. Than the time is come to say good bye to Rowan and his Green Corpers. It is amazing that in a few days you get so close. In the lab it is quiet now, and I finish the day by snapping some photographs.

June 13th: I continue arranging and labelling the hundreds of vials with animals. At 1.30 pm Chris and Janet call me to join them to Broome. We choose the bad road that crosses the Dampier Creek plain, and we manage to avoid getting stuck in the mud. They drop me off, and after a quick walk through town I head for the mangroves. There are at least five species of these trees here and also lots of fiddler crabs. As far as I can see it is only one species (*Uca mjobergi*) of which the males have a bright yellow claw. There is still time to take the bus to Cable Beach. This is an oceanic beach with white sand that stretches to the north as far as the eye can see. The sea is quiet and in an hour I pick up a whole collection of shells that is quite different from that found in Roebuck Bay so far. At the low tide level I see tracks in the wet sand of moonsnails and dog-whelks. I hurry back to catch the last bus (18.15) to town, where I meet Chris and Janet again. Back at BBO we see that the first people for the Roebuck Bay

Invertebrate Mapping have arrived. Ron Watkins (geologist), Danny Rogers (birder), Jim Lane (CALM) and captain Ted, the chauffeur of the boat. For the birders there is exciting news. In some lakes an hour drive from the BBO a Jacana has been spotted. Never seen before in this region. So they decide to go there tomorrow morning very early.

June 14th: At six o'clock five of us are ready to leave for the Jacana. First an hour over the road, then entering an open forest through a sand track. We stop near the first swamp, and, all armed with telescopes, wade quietly through the water. At the first larger lake we scan the far margin. Danny spots it first. And we all have a good look. The surrounding is beautiful, too. Fresh green and lots of flowers. We are already back for two hours when chaos is coming to the BBO. Grant Pearson with his four companions (Theunis, Petra, Pieter and Tanja) arrive by car loaded with expedition stuff. It took them three and a half days to travel from Perth to Broome. Bob Hickey, our computer man, turns up, too. Unpacking, storing, connecting computers, it all makes a big mess of the lab. Later we have a briefing and the field protocol-forms are discussed. After a diner barbecue the participants of the ROEBIM expedition are informed about the area and the expedition through several talks. Grant starts with an introduction to the expedition, I tell something about the fauna, Theunis gives the first results of the monthly monitoring of benthic animals at four stations (two transects), and Ron gives an introduction to the geology of the area. Afterwards there is a big discussion about the geological data and how to write that down in the protocols. Pieter, my roommate, tells me the story of their long car trip, and how he collected shells at 80-mile beach at night with a torch.

June 15th: At breakfast it is rather crowded, we are with a whole group now. Colma has arranged the food, what a luxury. On the beach I explain the sampling procedure and how to fill in the forms. Ron and Lee do the same for the geological part, and try to explain the difference between sandy mud and muddy sand. At 11.00 am we split into three groups each of about six people and start with the real work. There are about 800 stations scheduled to be sampled during this expedition, which together form a grid over the tidal flats of Roebuck Bay. Today we are going to take a bite out of that. Armed with GPS and sampling gear we trod through the mud to the low water line, each group on its own transect. Halfway we leave Tanja behind. She was lured by Grant with nice talks about tropical beaches, now she is really stuck. We manage to do five stations before the water is coming in. On our way back to the beach we pull out Tanja. At 3 pm we are all back and in total 15 stations were sampled. Not that bad for a first try with neap tide and inexperienced

people. Then sorting and identifying. Suddenly I am almost alone in the lab. Grant is trying out the hovercraft, which attracts a lot of attention. We finish the job at 11.30 pm, and by then all data also have been stored in the computer by Theunis. Petra has compassion with our tourist attraction, the big over-active mudcrab, and puts it back to sea.

June 16th: Colma and Petra have formed the groups for today. I am assigned to a group of males only (Bob, Oliver and Markus), so they gave us the worst transect, east of Little Crab Creek. We claim the sledge and Grant brings us by car to One Tree. All our stuff is unloaded and when Grant is gone we discover that two bags are not ours. The one full with food and drinks is very welcome. Through the mangroves we reach the creek. The sledge works reasonable well on the wet mud, but steering is difficult, and it likes to make big circles if you use it as a bike. But for pushing and walking on your knees behind it the sledge is ideal. The mud is so terrible here that each time we have sampled a station we return to the creek. There walking and sieving is easier. Bob is our clean man and sits like a prince on the bench of the sledge when we are sweating to get out another sample. At last we reach the junction with Crab Creek. It is about 30 m wide and looks deep. We send Markus to find out if we can cross it on foot. He managed to keep his head dry, but disturbs a couple of pelicans that thought he would never make it. We follow using the sledge as a boat for our samples and gear. The mud here is even worse. And we struggle slowly towards the mangroves again. The surface of the mud is covered with birdfeet prints, so it must be a rich feeding ground for them. The bivalve *Siliqua* cf *winteriana* is probably their target. Near the mangroves there is no film of water on the mud anymore and it is almost impossible to move the sledge here, so we leave it behind for the moment. On the way back to the creek we move on our knees, belly and arms. It sometimes looks if we swim. We cross Crab Creek again just in time, and narrowly escape losing our samples as water is coming in fast reaching to our necks, which makes balancing difficult. Far away to the west we see another group struggling. Grant has a great time on his hovercraft but cannot reach us because of the steep margins of the creeks. Exhausted we reach the beach and are glad Colma is there with a car. We first have to pull her out of the loose sand but than we are on our way. We are proud to say that we did 16 stations. The other two groups and the people on the boat did their work, too. The hovercraft furnished the boat with samples. These boat people had an easy time, as they sieved and sorted the small geological samples instead of the bulky biological ones. We laughed a lot about that, as the loss was repairable.

June 17th: I stay in the lab to finish the identifications and to give Danny his first lessons "How to identify marine invertebrates". After dark the teams are coming back. Exhausted and covered in mud. Lee, who handled the hovercraft today, has blisters on his hands. Had narrow escapes of drowning the craft as the engine stopped several times. The bloody thing does not float on its own. Therefore he had to keep on the deafening engine the whole time, and so communication with the team in the boat was impossible. A group of mudboys (Pieter, Markus, Ed and Bob) set a record of 23 stations today, a record that remained.

June 18th: Busy all day identifying and finishing the poster with pictures of crabs. The groups come in with more samples. The biggest news was the collision between the hovercraft and the boat. Part of the polyester hull is damaged, but the rubber cushion luckily still works.

June 19th: The hovercraft is repaired again. The procedure is changed now. The boat will ground itself so that it falls dry during low tide, which makes it easy for the hovercraft to stop by. This works well and besides has the advantage that the boat team can sample for themselves in the neighbourhood of the boat. Even for the hovercraft 20 stations a day is the maximum. In the lab I teach Danny, Pieter, Petra and Markus to identify polychaetes (bristle worms). A picture board of these animals is in the make. After dinner I have a talk about benthic marine invertebrates. The audience gives me a "worm" welcome. This night I need an extra blanket. It is cold in the tropics.

June 20th: Today I go sampling for the last time. With Theunis and Petra we form a Dutch group and Colma drops us near Dampier Creek. We are a bit too early as the water is still retreating. There are several natural flat rocky piers here. The rocks are densely covered with a small oyster. We zigzag along the falling tide and take samples as soon as the water level at the station is low enough . The area is sandy with current ripples. Peculiar are the anemones in the sand. There is a big one that has its short sand coloured greenish tentacles lying on the sediment. The others are the tube living Cerianthidae with long tentacles that are either white, brown or black. We reach a rocky island near the low water line, but there is no time to check out this species rich paradise. Sampling must go on. Our problem is that it is not the tide but darkness that makes us hurry. For the first time I see large bristle stars crawling over the sand. Sea-cucumbers are a regular feature here, too. There are many pools, half a meter across, and probably made by rays during high tide. On the way back I discover a group of gastropod egg cases. The eggcase sits on an elastic stalk that sticks into the sand. When I pull it out the anchor, a round disk plops out. I still don't know the maker. Sta-

tion 20 is the last one for today as the oxygenated layer in the sediment can hardly be detected by the dimming light. Soon it gets pitch dark. Disturbed ostracods leave tracks of a blue purple light on the sediment. The samples weigh heavily and we stumble to the cliffs. Fruit bats fly over us. The campfire of an aboriginal family helps us to find the way. We have not yet climbed the cliff half way when we hear a car coming. It is Colma. After dinner I thank everybody for the pleasant co-operation, as tomorrow I return to The Netherlands for another expedition to the Atlantic Ocean. Then we rush to the lab where lots of samples are waiting to be identified. At 1.30 in the night all samples are finished. Some were already a bit smelly, especially those with lots of plastic worms (Chaetopteridae). Petra, Pieter, Markus and Danny helped a lot. They have to do it all alone tomorrow.

June 21st: Pack my things. Clean up the last things in the lab. Clarify the last problems found by Theunis during entering the forms into the computer. And after a short meeting about future plans, and saying good bye to everybody, Ian brings me to the airport. In Perth I luckily slip through the hand luggage control, as to my horror only 5 kg are allowed. My fear of a flight delay turned out to have been unnecessary as I reach The Netherlands in time to embark on the "Pelagia", the research vessel of the Netherlands Institute of Sea Research. And in the morning of June 23rd I am already on the North Sea on my way to the Gulf of Biscay.

Grant Pearson (top) and Marc Lavaleye (left). Grant was in charge of the organisation and logistics of the field trip - a really daunting task in a location 2,000 km away from the next mayor city.

Marc was our taxonomist and is probably one of the few persons with a good general knowledge of the taxonomy of all mayor benthic invertebrate groups.

Photographs by Theunis Piersma.

4 TOWARDS A GIS-SYSTEM OF THE ROEBUCK BAY INTERTIDAL AREA

Robert J. Hickey & Ross Carew

Introduction

A study of the local tidal behavior plays a large part in understanding the Bay's ecosystems. Roebuck Bay has a large tidal range (>9 meters), which exposes around 190 km² of mudflat, approximately 45% of the Bay area, with tides traveling at speeds of up to 20 cm/sec mid cycle. These factors have an important impact on the intertidal ecology and lead to a characteristic species zonation throughout the tidal range. Consequently, the objective of this study is to produce a generalized model for the Roebuck Bay study area that can be used to characterize tidal inundation for ongoing biological studies, given the constraints of available data.

Tidal Processes

Ocean tides are primarily the result of centrifugal force and the gravitational attraction of the moon and sun acting on the earth's oceans. The daily manifestation of these forces is the high and low sea levels that occur along the coastline. As the earth rotates, locations on the earth's surface nearest to and furthest from the moon receive high tides, while those midway between receive low tides. This high-low cycle generally occurs twice a lunar day, the length of which is approximately 24 hours and 50 minutes (Pugh 1987).

Throughout the month the relationship between the gravitational forces of the moon and sun changes. At full or new moon phases, the direction of the sun's gravitational attraction is in line with that of the moon, thereby reinforcing its strength to produce the increased tidal range of a spring tide. Conversely, at the first and third quarter phases, the sun's gravitational attraction lies at 90° to the moon's, thereby counteracting its effect and producing a neap tide.

While there are many other astronomical cycles influencing the frequency and intensity of tides, it is these semi-diurnal and spring/neap tidal variations that dominate the inundation of intertidal mudflats and are of consequence to ecological studies.

Tidal calculation is a complex problem, and aside from the variations in magnitude and frequency of the earth's tides caused by astronomical changes there are numerous terrestrial factors affecting tides. The hydraulic properties of fluids affect the earth's oceans, causing wave action and friction between ocean and undersea topography. Along the coastline, the interaction between tidal waters and landmasses can affect the direction, magnitude and time of arriving tides at any location. Meteorological effects on tides can include changes in barometric pressure, wind strength and direction, and storm surges. Large-scale oceanographic effects also contribute to local tides, including the Southern Ocean Oscillation event (El Niño) which may affect mean sea level by up to 0.6 m (RAN 1995).

While these factors may preclude the exact determination of the time and height of tides for a specific location where no tidal records exist, a degree of predictability is possible due to the relationship between astronomical forces and observed tides. Prediction methods generally use a semi-empirical approach to combine an understanding of the astronomical relation-

Table 4.1: Average tidal levels for the port of Broome, Western Australia (RAN 1995)

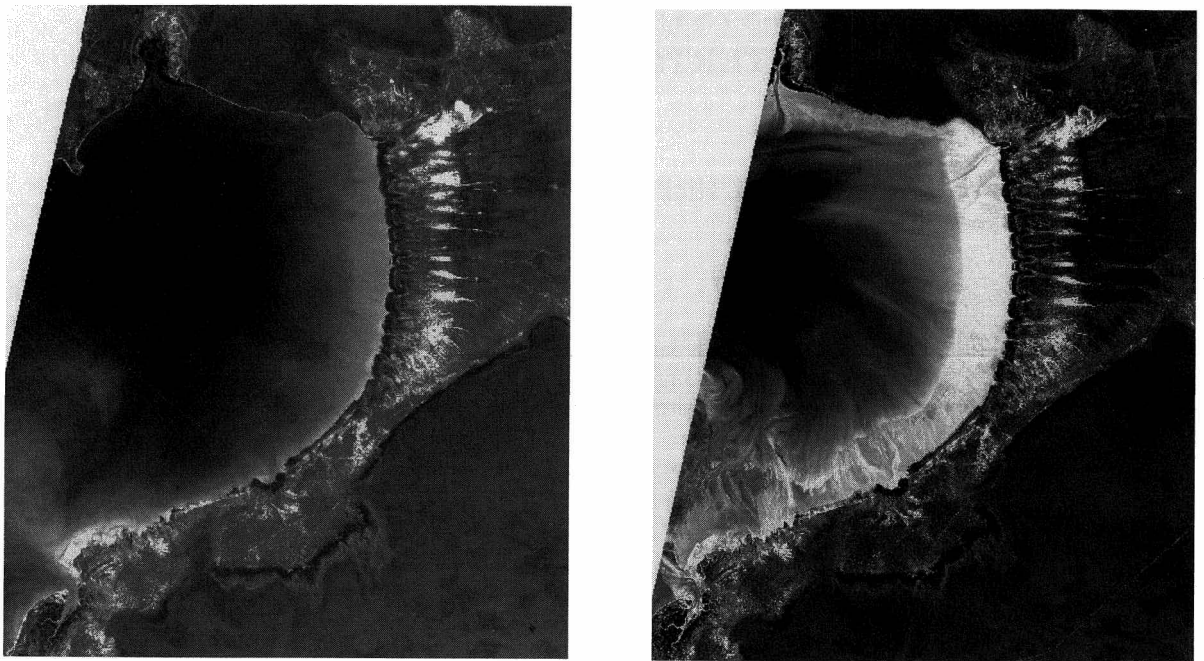| Tidal level	Height in meter above Broome Tidal Datum
Highest Astronomical Tide (HAT)	9.6
Mean High Water Spring (MHWS)	8.5
Mean High Water Neap (MHWN)	5.6
Mean Sea Level (MSL)	4.5
Mean Low Water Neap (MLWN)	3.5
Mean Low Water Spring (MLWS)	0.3
Lowest Astronomical Tide (LAT)	-0.9

Fig. 4.1: Landsat Thematic Mapper imagery used for the study. Left: 1994 high tide image (7.11 m). Right: 1995 low tide image (1.58 m)

ships of the earth, moon and sun with actual observations of tides over an extended period of time. Maximum accuracy in prediction is achieved after observation for an entire tidal cycle of 18.6 years. After this period of observation, all relevant astronomic variations will have occurred and average tidal levels can be computed (Pugh 1987).

For the purposes of determining a general tidal inundation model for the Roebuck Bay mudflats, data from the tidal observation station at the port of Broome was used. Daily predictions combined with interpolation equations provide the tidal height at any specific time, and the mean recorded tidal levels shown in Table 4.1 allow for generalising inundation characteristics over the intertidal surface. In the absence of a more rigorous method of determining local tidal characteristics, these tidal data provide a convenient basis for generating inundation times for the mudflats once they have been spatially defined.

Modelling the intertidal surface

Spatial definition of the intertidal zone
One factor that hampered the initial data collection strategies adopted by biologists and geologists was a lack of base maps at a scale suitable for integration with the 200 m grid used for sampling. While there is

1:100,000 series mapping coverage, as well as a 1:50,000 nautical chart of the approaches to the port, both of these were compiled in 1970 and fail to provide the required coastline and bathymetric details. As a solution to this, two Landsat 5 Thematic Mapper (TM) images of the Bay at approximately high and low tides were acquired (Fig. 4.1). Using tide tables in conjunction with the capture times for the two scenes, the predicted sea level for each image was determined using tidal interpolation equations.

Using the ER Mapper image processing package (Earth Resource Mapping 1995), rectification of the Landsat images took place in two stages. The low tide image (1995) was rectified to control digitised from the 1:100,000 series sheet – an interesting task, given the lack of well-defined features and the age of the base map. The high tide image (1994) was then registered to the low tide image; ensuring the best possible pixel to pixel match for change detection purposes. Both rectifications used an affine transformation with cubic-convolution resampling.

Waterline extraction - low tide (1995)
The use of Landsat TM near infra-red band 4 (0.76 - 0.90 μm) for delineating the land/water interface is a simple but effective technique for extracting coastlines and has been well documented elsewhere (Jensen, 1996; Lillesand & Kiefer 1994). The 1995 TM band 4
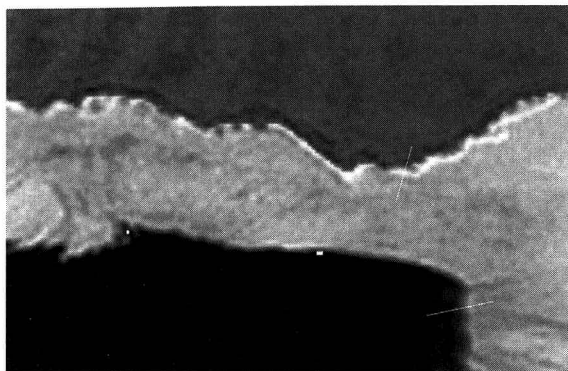
Fig. 4.2: Landsat TM Band 4 spectral response across land water interface for 1994 (high tide) and 1995 (low tide) images.
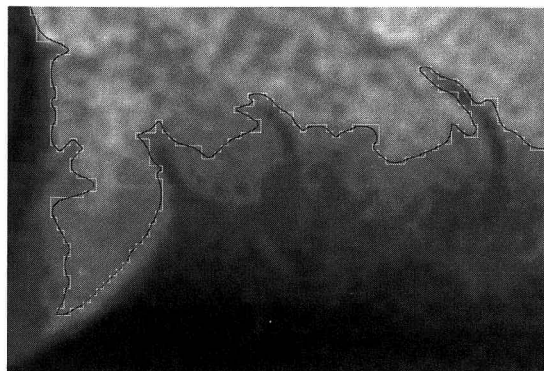

Fig. 4.3: Waterline extracted from the low tide image. Rectilinear vectors produced by the vectorising routine were smoothed by converting to isolinesand adjusting the curves order.

image was interrogated using traverse extraction at a location where the gradient of change in spectral response between the mudflats and water was at a minimum (Fig. 4.2). The mid-point between the mean spectral response values for the mudflat and open water was determined, and a binary land/water image was created by thresholding.

The vectorising routine in ER Mapper was utilised to extract the waterline from the binary image by raster tracing. The resulting rectilinear vectors were then smoothed using a threaded splining technique within MicroStation (Bentley Systems 1995) to improve representation of the original boundary. A section of the smoothed waterline is shown in figure 4.3.

Waterline extraction – high tide (1994)
While automatic extraction of the waterline at low tide was straightforward, the high tide image introduced some new issues. Approximately a third of the high waterline in the 1994 image is obstructed from view by mangroves, therefore, it is not possible to use the spectral response of band 4 in the same manner as above.

A study of a mangrove zonation in north-western Australian tidal flats has been documented by Semeniuk (1983). His research indicates that a transition between mangal and salt flats typically occurs at approximately Mean High Water Spring (MHWS) tide, with the salt flat extending up to areas inundated under very high spring tides. In the Dampier Creek estuary to the west of the sampling area, this zonation is clearly apparent (Fig. 4.4 left). TM band 5 mid infra-red (1.55 - 1.75 μm), with its sensitivity to soil and vegetation moisture; delineates the mangals from the salt flat quite clearly as shown in figure 4.4 (right). Band 5 was used to determine the boundary between the mangals and salt flat areas, producing a binary image by interrogat-

ing the image histogram and again applying thresholding. The edge was vectorised and smoothed as for the 1995 image. In areas where mangroves exist, the boundary follows the landward side of the mangal zone, whereas in other areas the waterline at time of imaging is recorded.

The predicted height of the tide at the time of image capture in the 1994 image was 1.4 m below the MHWS level for Broome, however the spatial error in non-mangal areas of the shoreline is expected to be low due to the increase in slope that typically occurs at the beach and hinterland margin. For the purposes of defining the intertidal zone, and given the restrictions of a 30 m resolution and absence of any better data, it was decided to adopt this waterline as the MHWS level for the inundation model.

Modelling the intertidal surface - assumptions and issues
Having acquired the waterlines from the Landsat imagery, it now becomes possible to derive a continuous raster surface between the two contours from which to derive inundation values. However, a number of assumptions have to be made at this point. The capture dates of the two images differ by 10 months, which infers that the mudflats are expected to remain static over this period. In reality, this is not the case as the intertidal region is highly dynamic in nature and seasonal storm activity can dramatically change the shape of both the mudflats and beaches. It is to be expected that the spring high water line will remain relatively static, however, the low waterline captured from the 1995 image will be more affected by mass sediment transport due to longer exposure to hydrodynamic processes. So effectively, the temporal characteristics of a surface derived from these data will be predominantly determined by the 1995 low water line.
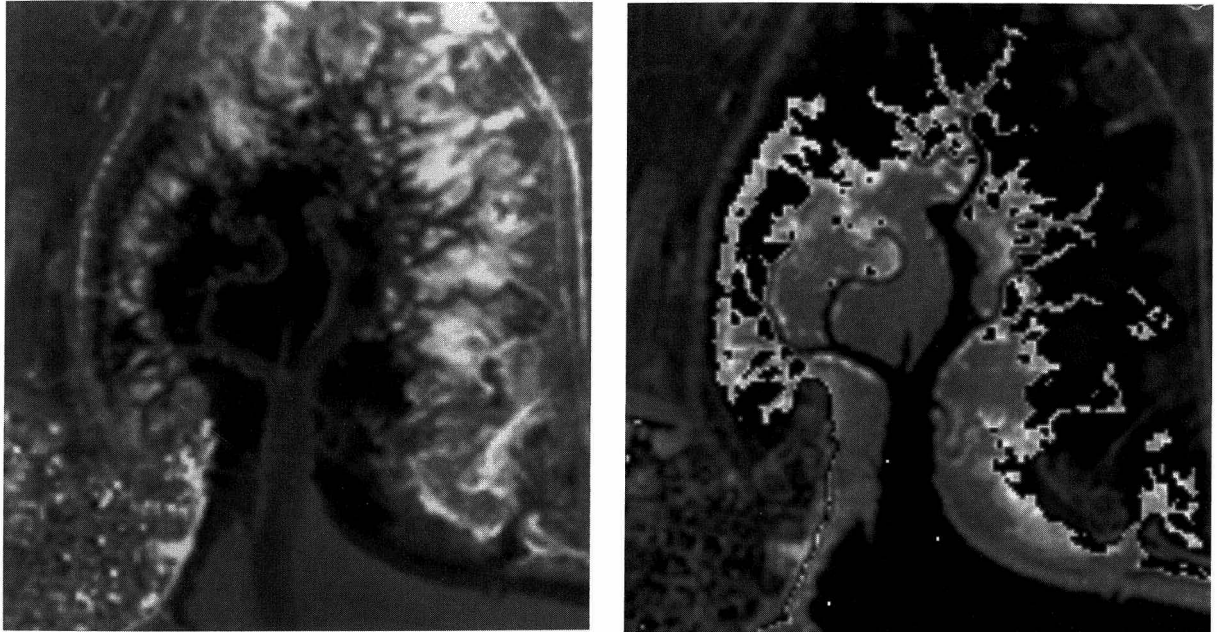
Fig. 4.4: Dampier Creek estuary. Left: TM Bands 3,2,1 RGB composite. Right: Delineation of water/mangal areas from hinterland using TM Band 5.

The total reliance for elevation data on these two waterlines alone forces the assumption that the gradient of the inter-tidal surface is linear. Although this may be reasonable in this case due to the sheer expanse of the mudflats, it rules out modelling any local micro-topographic variability of the surface that may occur due to drainage patterns or changes in substrate. A more rigorous approach entails capture of waterlines at different heights over the whole surface from multiple images as has been demonstrated using ERS-1 SAR imagery by Mason et al. (1995).

A more serious consequence of the given data is that the complete mean spring tidal range from the Broome tidal data is not represented in the extracted waterlines. While the MHWS waterline was derived from a transition in the 1994 image between mangroves and salt flat, the 1995 low waterline is still approximately 1.3 m above the desired Mean Low Water Spring (MLWS) tidal height of 0.3 m. The solution adopted was to utilise the assumed linearity of the surface mentioned above to extrapolate the 1995 low waterline to the correct distance/depth. The relationships between the mean tidal data and predicted heights extracted from the TM imagery are illustrated in figure 4.5, showing the portion of the tidal surface requiring extrapolation.

Generation of an intertidal digital elevation model
To determine the location of the required 0.3 m spring low waterline requires extrapolation based on parameters derived from a surface interpolated between the known data. To this end the waterlines were imported into Arc/Info from MicroStation and z_value attributes created for arcs, using the values discussed above (ESRI 1995). The TOPOGRID command, based on the ANUDEM program developed by Hutchinson (1988), was utilised to generate a Digital Elevation Model (DEM) between the two waterlines. Aimed at the correct modelling of surface morphology resulting from fluvial processes, the program combines a drainage enforcement algorithm to remove pits from the DEM, with automatic ridge and stream line definition from areas of maximum curvature on the input contours (Hutchinson 1988).

While micro-fluvial processes take place on the mudflats during their exposure, they are not a dominant factor in the overall morphology of the tidal surface, which is governed by sediment transport due to hydro-dynamic processes taking place during immersion. For this reason, the interpolation was performed without the drainage enforcement feature, resulting in a smoothing minimum curvature interpolation which approaches the objective of having linear interpolation taking place across directions of maximum slope. In this instance, memory and processing limitations re-
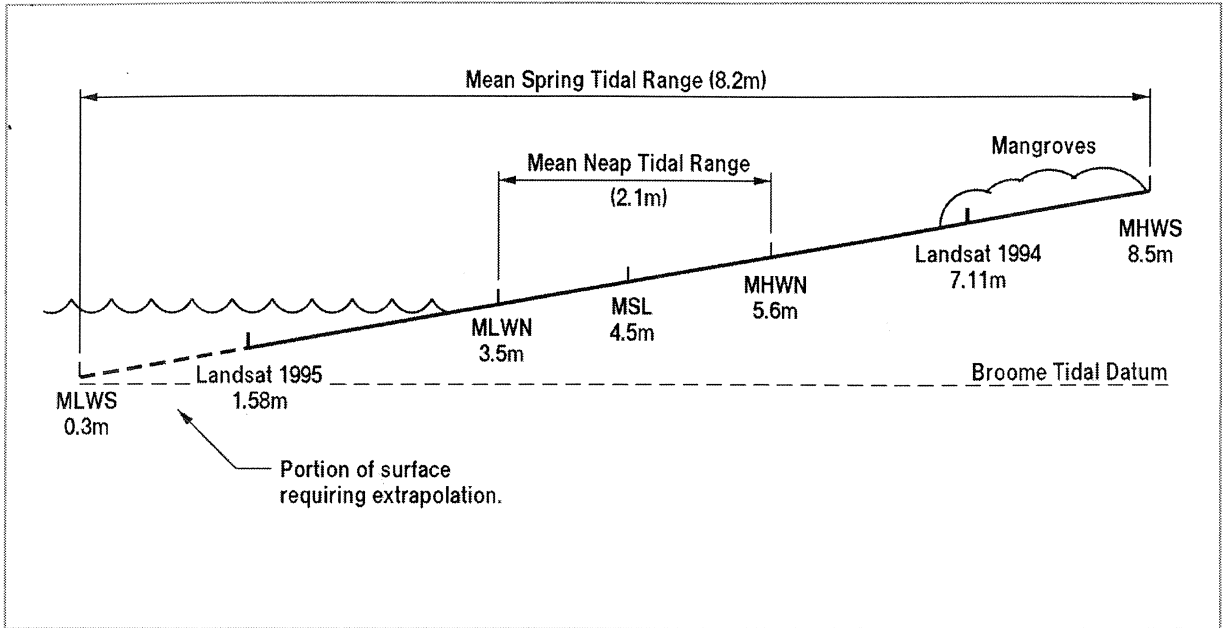
Fig. 4.5: Hypothetical profile of a linear intertidal surface showing the location waterlines extracted from imagery in relation to observed tidal data for Broome.

stricted the cell size to 10 m, which was felt to provide adequate resolution for subsequent analysis.

To achieve an optimum surface, it was necessary to fine-tune the input tolerances and re-examine the resulting interpolation. Modification of the low waterline was also necessary to remove the Crab Creek outlet at the east of the Bay, as the program was falsely inferring drainage characteristics for the surface in that area. This initial intertidal DEM is shown in figure 4.6.

Linear Extrapolation of the DEM Surface

To extrapolate this surface to the desired MLWS elevation of 0.3 m it is necessary to continue the trend in slope and aspect of the lower edge of the DEM to a distance that is expressed by:

Dist. = (cell Z_value - 0.3m) / TAN (Slope angle of cell)

The distance is combined with the aspect value and coordinates of each cell to compute the location of the equivalent cell in the extrapolated boundary, using coordinate geometry:
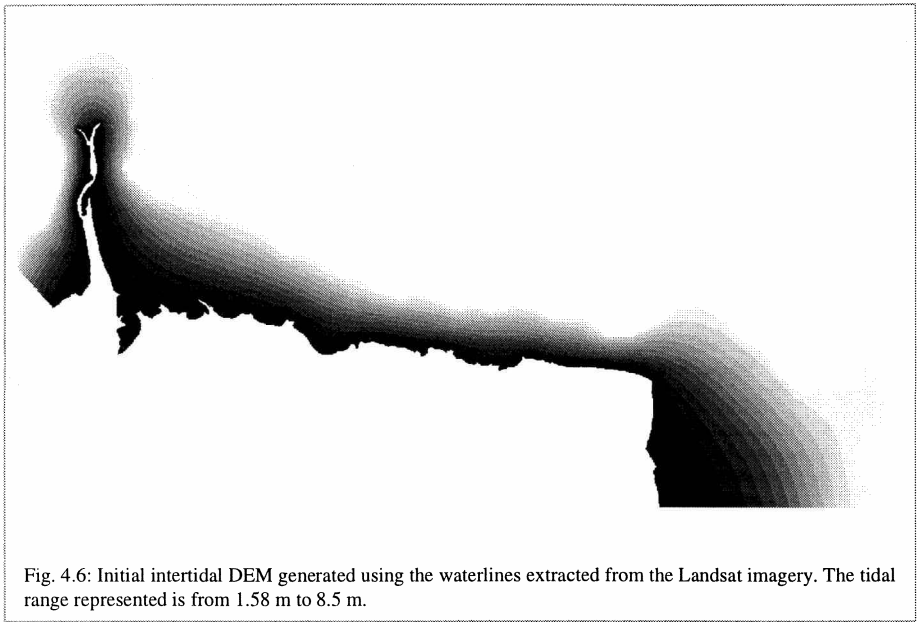
*extrap_X = cell_X + Distance * SIN (Aspect of cell)*
*extrap_Y = cell_Y + Distance * COS (Aspect of cell)*

While the morphological characteristics of the existing low waterline may be desirable as a source of proper-

ties for extrapolation, there is a trade-off to be made in terms of spurious values and general edge effects. The complexity of the low waterline itself gives rise to radical values locally in slope and aspect that are not representative of the surface as a whole, and have the potential to produce artefacts. In some cases, there are pits along this edge resulting from the interpolation routine, and although they may be filled using standard methods, the slope and aspect derivatives from the surrounding cells will remain anomalous. To avoid these possible problems in the output, the surface derivatives were extracted from the two metre elevation line. This was felt to be an adequate compromise between the artefacts that would result from edge effects and the smoothing due to the minimum curvature interpolation, which is dominant midway between the waterlines.

Using the analysis tools in Arc/Info GRID (ESRI 1995), a band along the two metre elevation of the DEM was thinned to a continuous line one cell wide and extrapolation distances calculated for each cell as above. This line of distance values provides the input to an ARC Macro Language (AML) routine, developed to iteratively process each cell along the line. The AML calculates the coordinates of the extrapolated cell using the equations above, adding the new location to an output grid on each iteration. To ensure spatially continuous output and to avoid errors resulting from quantisation, the output of each iteration is a group of

Fig. 4.6: Initial intertidal DEM generated using the waterlines extracted from the Landsat imagery. The tidal range represented is from 1.58 m to 8.5 m.

cells selected within a radius of 25 m of the output coordinates. This gives rise to a linear cluster of cells following the extrapolated waterline that is suitable for subsequent thinning and vectorisations. Figure 4.7 shows the two metre contour on the source surface and the extrapolated points. The AML took approximately 1.40 minutes per iteration on a HP Apollo 715/50 workstation, resulting in a total processing time of around 70 hours for approximately 23 km of coastline in the study area.

The AML routine generally performed as expected, with particularly good results to be seen in the middle of the study area. However, there are a few interesting consequences of the extrapolation. The Dampier Creek estuary at the eastern end of the mudflats has been 'closed off' at the depth of 0.3 m by the extrapolation. Conspicuously, the outlying portion of the flat at its mouth has failed to be included within the new (and lower) waterline. Another area that the extrapolated values appear to be unrealistic is in the eastern half of the Bay, where diminishing gradient in the source surface has resulted in seemingly excessive distances in

Fig. 4.7: Intertidal DEM contoured at 0.5 m, two meter contour used as the source for the extrapolation, and the raster clusters output from the extrapolation routine.
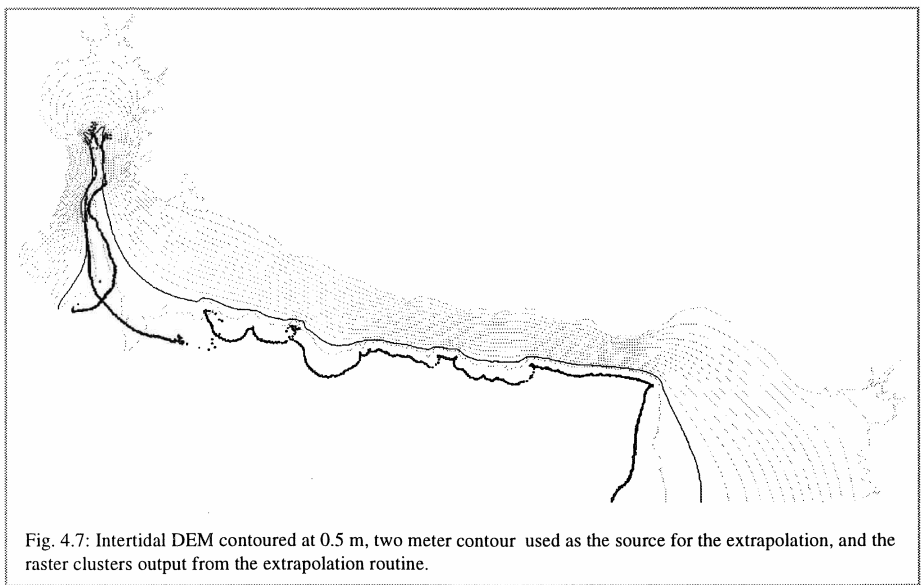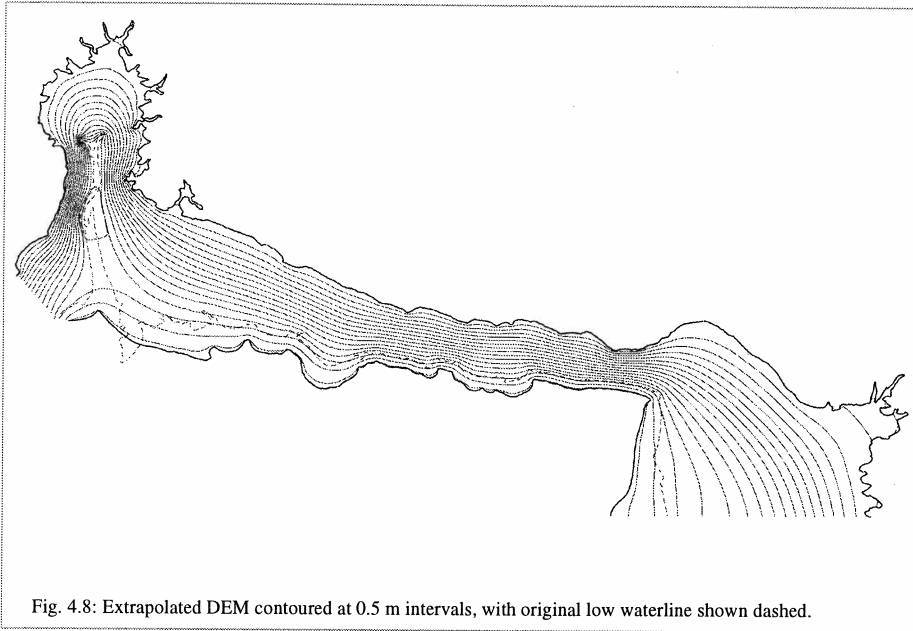
Fig. 4.8: Extrapolated DEM contoured at 0.5 m intervals, with original low waterline shown dashed.

the extrapolation. These artefacts are a direct conse-
quence of the original surface characteristics and the
choice of the two meter contour as the source for ex-
trapolation values. Clearly, an improvement in the in-
terpolation of the source DEM is necessary to achieve
results that are more consistent.

A model of the entire tidal surface

Bearing these inconsistencies in mind, the extrapolated
data were used to derive a second DEM of the exten-
sion to the surface. To ensure logical consistency, the
new low waterline was inspected visually and edited to
remove dangling arcs and loops, most notably the large
loop occurring at Dampier Creek. The data were com-
bined with the 2 m line to generate the extrapolated
surface, which was subsequently merged with the main
DEM to complete the elevation model of the entire
spring tidal range, shown in figure 4.8.

As a measure of the accuracy of the extrapolation
routine, the overlapping areas of the original source
DEM were subtracted from the new surface, generating
a coverage of the residual height differences between
the two models. The summary statistics of elevation
differences between the source and extrapolated DEM
are as follows:

Minimum	-0.176m
Maximum	2.041m
Mean	0.143m
Standard Deviation	1.114m

The high discrepancies appear around Dampier Creek
and are to be expected due to the occlusion of the estu-
ary mouth in the extrapolation. Other nominal eleva-
tion differences across the surface were within 0.15 m
and felt to be of minor consequence to the outcome of
the inundation model.

Determination of Tidal Inundation

As mentioned above, a theoretical equilibrium tidal
cycle for semidiurnal tides is dominated by the princi-
pal lunar component that has a period of 12.42 hours.
To determine the time during this cycle that the tide
reaches a particular height on the surface, equations
developed to interpolate between predicted tides may
be used as follows:

Rising time over cell = 6.21 (A/π - 1)
where
$A = 2\pi - cos^{-1} [2 (HC - MLW) / (MHW - MLW) - 1]$ *rad*
and
$HC = height\ of\ cell$

(Adapted from RAN 1995)

Where MHW and MLW are the maximum and mini-
mum values of the intertidal surface respectively. To
calculate the Falling time over cell, the MHW and
MLW values are interchanged. From the above, the
total predicted inundation time for each cell on the sur-
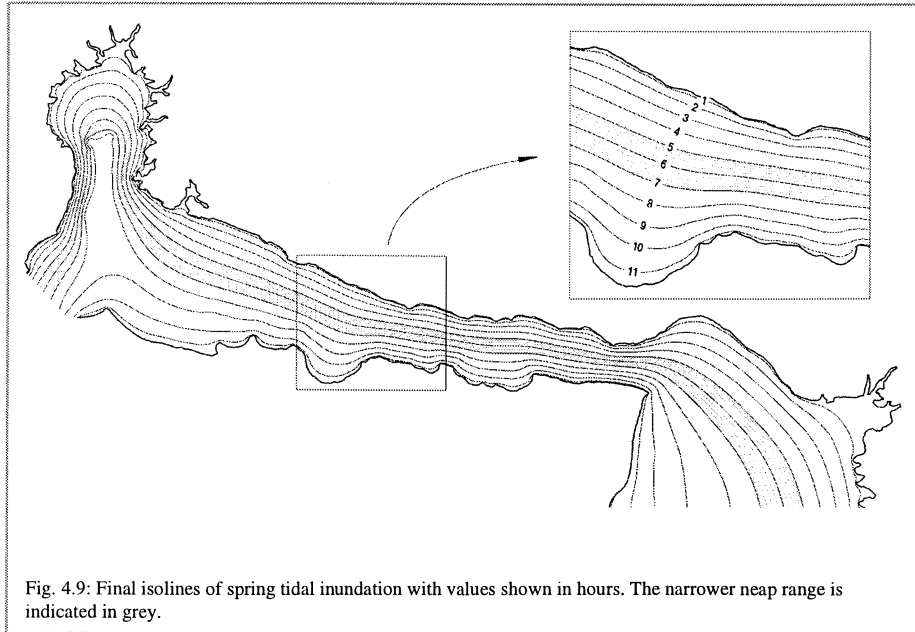face is calculated by:

Fig. 4.9: Final isolines of spring tidal inundation with values shown in hours. The narrower neap range is indicated in grey.

$CIT = abs (TR - 6.21) + TF$
where
CIT = *cell inundation time*
TR = *time rising*
TF = *time fallling*

After extracting the neap tidal surface from the spring intertidal DEM, both surfaces were processed using the above equations and contoured to produce hourly isolines of predicted inundation time as shown in figure 4.9. Discrete values were also extracted from the inundation surfaces for each of the sample points used in the pilot study.

Summary

This paper has presented a methodology that integrates image processing, CAD, and grid-based modelling within a GIS environment to produce a generalised model of tidal inundation. The approach is particularly pertinent to large remote study areas suchas Roebuck Bay where there is a lack of suitable data and direct observation is not feasible.

The method chosen to interpolate/extrapolate the intertidal DEM is fundamental to the overall success of the inundation modelling, and further work is planned to improve the quality of the DEM by utilising an increased number of images as the source for waterline (elevation) data. Alternative methods of interpolationill also be examined, particularly with regard to the surface characteristics near the Dampier and Crab Creek estuaries, in an effort to provide an improved result in the surface extrapolation. It is anticipated that an accuracy assessment of the model will be carried out in the field utilising differentially corrected GPS data. Statistical regression would then be applied to determine the validity of the model. The intertidal zone is a complex dynamic system, and the approach presented here only accounts for a few of a large number of variables that determine tidal inundation patterns. However, it is felt that given an understanding of the accuracy issues involved, the techniques discussed may be judiciously applied to characterise the inundation of intertidal mudflats when there is a shortage of field tidal data.

GIS and remote sensing analysis combined with cartographic visualisation provide a number of benefits to the research program. They include database management, database visualisation, and the calculation of parameters which would otherwise be impractical (if not impossible) to derive for the entire mudflats (i.e. inundation times).

5 GENERAL DESCRIPTION OF THE STUDY AREA

Markus Pepping

Climate

Meteorological conditions

Two major weather types can be recognised over the Kimberley, each characterising one of the two major seasons. These are separated by short transitional periods.

Between May and October the normal situation is an anticyclonic belt over the southern half of Western Australia. These extensive anticyclones typically have an east-west diameter of 3,000 to 4,000 km and travel with speeds of 600 to 700 km/d across southern and central Australia. They follow each other in periods of a few days, but may also lie quasi stationary over the centre for days. The Kimberley at this time of the year lies at the northern edge of these anticyclones. Here the airflow near the surface is deflected by surface friction into a south-easterly tradewind, which brings dry air from the interior to the northern and north-western coast.

Towards the end of the dry season a low-pressure system develops over the Kimberley and extends southward, while a ridge of high pressure extends from the semi-permanent anticyclone in the Indian Ocean parallel to the north-west coast. Under these conditions surface winds are westerly in the coastal districts. As the low pressure system extends in inland areas during November, this situation occurs more frequently.

Westerly winds bring increased humidity, and scattered thunderstorms develop as the wet season approaches. These westerlies are not permanent, being displaced from time to time by easterlies as anticyclones over the southern divisions intensify and extend northward.

During the wet season from November to March, a low-pressure area is generally situated over northern Australia, and a trough extends from the Northern Territory towards the Onslow-Carnarvon area. The pre-
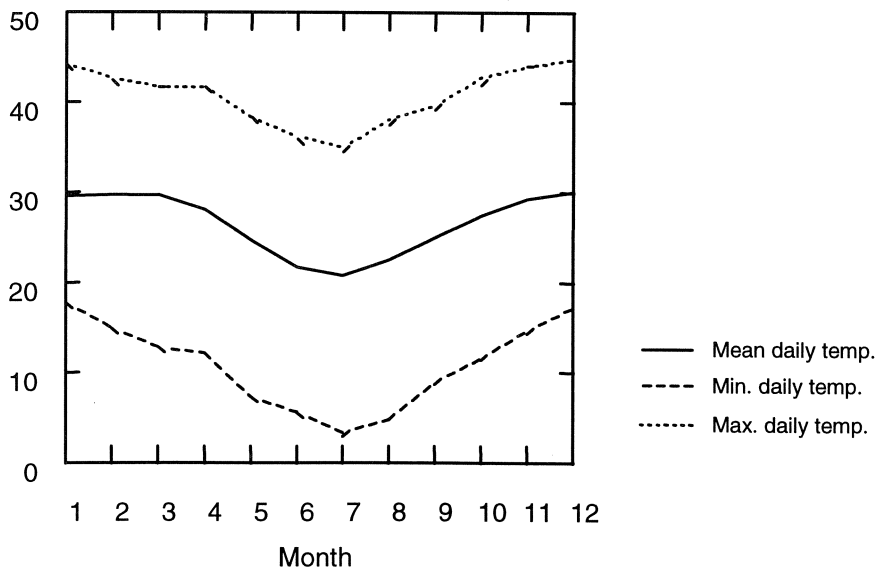
Mean and extreme daily temperatures

Fig. 5.1: Mean daily temperatures and daily temperature extremes at Broome station. Minimum and maximum temperatures were recorded from 1919 to 1971, the mean temperatures from 1941 to 1971, respectively.

vailing winds are westerlies in the coastal areas, bringing moist air from the Indian Ocean. Compared with the preceding four months there is a marked increase in humidity, cloud cover and rainfall. Much of the rain comes from thunderstorm, but the most widespread heavy falls occur as the result of cyclonic disturbances. These cyclones frequently originate in the Timor Sea, but occasionally come from the Arafura Sea or even further eastward. Cyclones of this latter kind generally bring extremely heavy rains and very strong winds. As the cyclonic centres move inland or pass southward, wind speed abates, but heavy rains may continue for several days. Such disturbances are likely throughout the wet season but are distinctly most frequent in January. Only rarely do they occur before December or after April (Gentilli 1971).

Temperatures
Lowest temperatures occur in July and the highest just prior to the onset of the wet season. The somewhat lower temperatures during the height of the wet season between January and March as compared to December are related to the greater cloud cover at that time. This effect is most evident in the mean daily temperature range, which is much less during the rainy season (Fig. 5.1). Mean temperatures are high throughout the year, remaining above 18°C. Normal daily maximum and minimum temperatures are about 35° and 25°C in January, and 28° and 13°C in July. Just prior to the wet season daily maxima may reach over 38°C at Broome station.

Rainfall
The area lies within a region which, according to Köppen´s (1931) classification, may be described as having semi-arid and arid monsoonal climates. Almost all of the rainfall occurs between November and April. During the remainder of the year falls are light and sporadic, and several consecutive rainless months at this time are not uncommon.

The average annual rainfall at Broome station is between 500 and 600 mm/a, the tank evaporation ranges from approximately 2,000 to 2,500 mm/a (Fig. 5.2). At the most, precipitation exceeds the evaporation during the four months of the wet season, which is at the same time the growing season for the plant life.
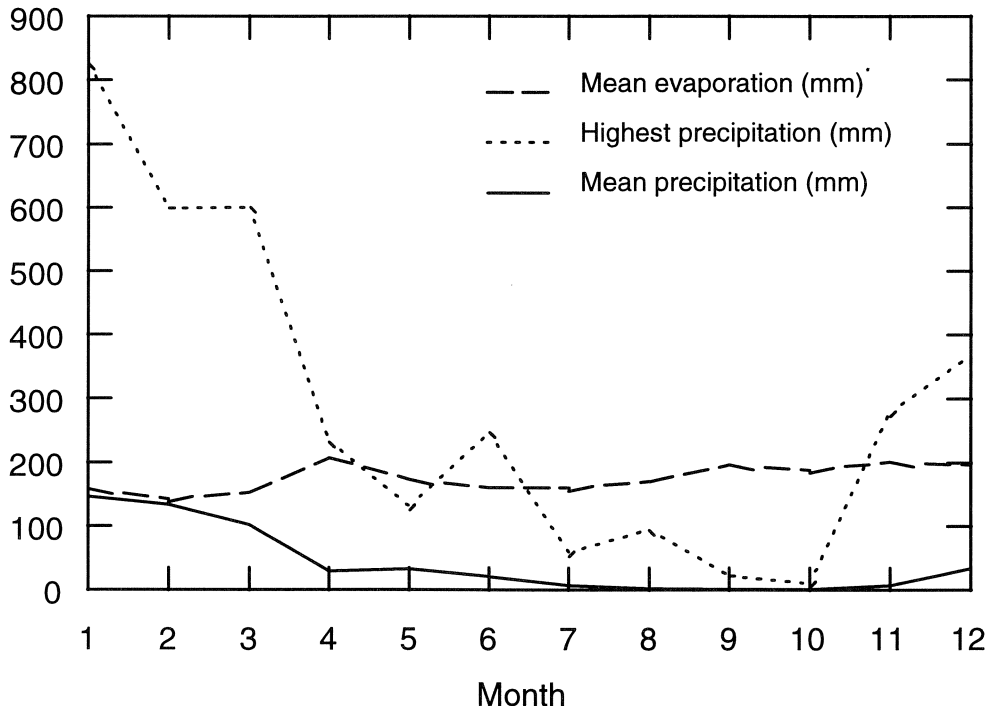

Fig. 5.2: Mean evaporation and maximum and mean precipitation at Broome Station. Evaporation was estimated using the Fitzpatrick Method. The figures for the maximum and mean precipitation are based on recording for the years 1941 to 1971 for the mean and 1919 to 1971 for the maximum precipitation.

Table 5.1: Climatic data on temperatures, precipitation and evaporation for Broome Station, Western Australia. Note the high variability of the precipitation over the years of observation. Temperatures are in degrees Celsius, precipitation and evaporation in millimetres.

Month	Mean T.	Max. T.	Min. T.	Mean T. range	Mean prec.	Max. prec.	Days with prec. > 0.25 mm (> 2.5 mm)	Mean evap.
Jan.	29.6	44.2	17.8	6.7	146	825	11 (6)	158
Feb.	29.7	42.7	15.0	7.1	134	599	9 (5)	142
March	29.7	41.7	12.8	8.6	102	600	7 (6)	152
April	28.1	41.7	12.2	12.1	29	232	3 (1)	206
May	24.7	38.3	7.3	12.9	33	131	2 (1)	173
June	21.7	36.2	5.6	12.8	21	246	2 (1)	160
July	20.8	35.0	3.3	13.8	7	59	2 (<1)	160
Aug.	22.5	38.1	4.8	13.9	2	95	0 (0)	170
Sept.	25.0	39.7	8.9	13.2	1	22	1 (<1)	196
Okt.	27.4	42.8	11.6	10.2	1	10	0 (0)	188
Nov.	29.3	44.0	14.7	8.9	7	279	1 (<1)	201
Dec.	30.1	44.8	17.2	7.7	34	368	5 (2)	196
Annual	25.6	44.8	3.3	10.6	517	1084	43 (22)	2094
Years obs.	30	74	74	30	30	52	30 (10)	estimated

Year to year variations in precipitation are very high. Averaged over the last 30 years, monthly evaporation exceeds precipitation for any one month. Even during the rainy season, rainfall is highly sporadic. Averaged over the last ten years a maximum of only six days with rainfall in excess of 2.5 mm/d was measured for the month of January, which is during the height of the rainy season. Plants need to be adapted to make as much use as possible out of these brief periods of rainfall. Only cyclonic events, which hit the coast irregularly, may lead to torrential rainfalls in sufficient quantities to exceed the monthly evaporation by far.

Hydrography

Roebuck Bay is a good example for a tide dominated, low energy coastline. Wave size is controlled by three variables – fetch (distance over which the wind blows), wind velocity and wind duration. During the dry season from May until October the prevailing wind direction is SE from the interior and the wind velocity is generally low, so high wind-driven waves cannot build up. During the wet season westerly winds with slightly higher wind velocities dominate. This and the higher fetch over the Indian Ocean result in higher wave trains hitting the coastline.

Tides in Western Australia are semidiurnal with a period of 12h 25min. The average tidal amplitude over 25 spring and neap tide cycles for the year 1997

amounts to 5.7 m (Fig. 5.3). The maximum tidal amplitude calculated for this period is 10.4 m during the equinoctial spring tide of the 19th of October. The lowest amplitude measured was 1.1 m and took place during the equinoctial neap tide of the 17th of April. The highest tides occur with 3 days lag time after the full and new moon, the lowest tides 3 days after half moon, respectively. With a tidal range in excess of 10 m this macrotidal environment has one of the greatest tidal amplitudes in the world, being surpassed only by the Bay of Fundy in Canada and King Sound in NW Australia. Although the tidal range is enormous, tidal current velocities are generally low due to the shape of the embayment and the unrestricted exchange of water masses with the open ocean. Only where convergence occurs, like in the Inner Anchorage or in the mayor tidal creek systems, current velocities are higher.

The dominant ocean current off Western Australia is the Leeuwin Current, flowing within a relatively stable hydrological environment with little or no upwelling. The current differs from the other Southern Hemisphere eastern boundary currents of the Pacific and Atlantic Oceans. The Benguela Current and the Humboldt Current carry cool southern waters northward. These current systems are also associated with large-scale, seasonal, wind-driven upwelling in which nutrient-rich subsurface waters are drawn onto the continental shelf. In contrast, the southward-flowing Leeuwin Current, which transports warm water, is associated with downwelling of surface waters along the
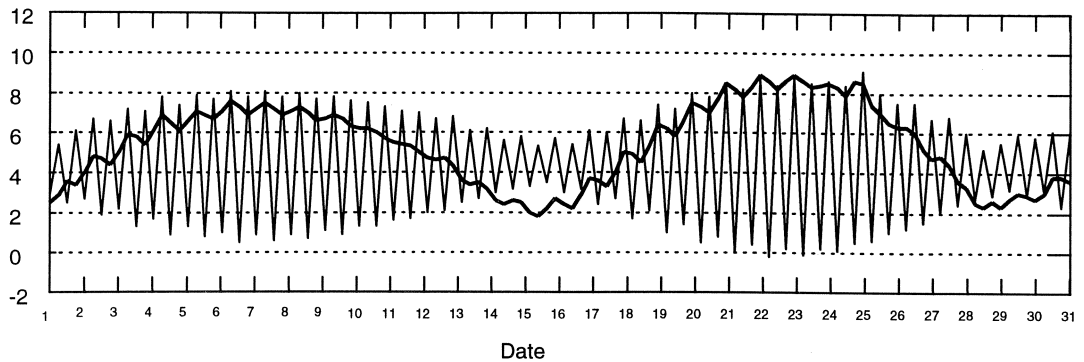
Tidal range July 1997

Fig. 5.3: Tidal range and tidal amplitude (thick line) at Broome Harbour in July 1997. Heights of high and low water are given relative to chart datum, which is approximately the level of Indian Spring Low Water.

Western Australian coast (Cresswell & Golding 1980). The current flows most strongly during the autumn and winter months from April to September as a result of seasonal changes in the wind stress off south-western Australia. Inter-annual changes in current velocities are highly correlated with the Southern Oscillation Index, the current being weaker during ENSO events. The maximum recorded current velocity is over 1.7 m/s, though average speeds are generally of the order of 0.5 m/s. On the continental shelf the currents are weaker than those within the Leeuwin Current and seasonal reversals of the net alongshore drift are observed (Cresswell et al. 1989). Current velocities are generally of the order of 0.1 to 0.2 m/s, well below the threshold velocity of water required to entrain particles, but high enough to keep particles < 0.1mm in suspension.

For Roebuck Bay and its macrobenthic communities the Leeuwin Current is of manifold importance. First it supplies oceanic water poor in nutrients. This, and the factor that river runoff is limited and terrestrial soils are poor in nutrients, limits the primary production of the area and therefore effects the ecology of the embayment. Second it has a mayor influence on the community structure, since it affects the larval stages of many benthic organisms and their settlement and survival. Last but not least the current velocities of the Leeuwin Current on the shelf are theoretically high enough to keep finer sediments in suspension till they are finally deposited in more protected environments. In this way the current is affecting the sediment budget of Roebuck Bay.

Compared to Cable Beach to the north, wave energy in the embayment is diminished by dissipation and reflection of wave energy at offshore shoals and the protruding landmass in the north-western part of

the bay. Wave dissipation, due to shallow gradients in the bay, is generally so great that most of the energy is lost before shore-breaking. In the NW of the bay this process is further enhanced because the substrate is finer. Waves crossing soft muddy flats are easily damped, with a high proportion of the stress being dissipated within both the sediment-rich water column and the bed. Energy dissipation over muddy bottoms can be an order of magnitude higher than over sandy bottoms. So the combined effects of shallow gradients, offshore sandbanks and shoals, and muddy substrates in places make Roebuck Bay a very low energy environment, indeed. Exceptions are rare cyclonic events, causing storm-floods and extremely high waves, which may drastically alter coastal morphology and the topography of the bay with its offshore structures like shoals and sand-banks.

Like in many tidal bays in the tropics, the upper inter-tidal areas are characterised by mobile mud substrates, in places with a landward mangrove fringe. The sediment grades seaward into silts and sands. This shore-normal size-grading may be explained by Postma's (1961) settling-lag model, whereby totally suspended sediment accumulates onshore. Tidal asymmetry, with higher flood than ebb velocities, may reinforce this pattern. A complementary process may be the preferential offshore movement of the more easily entrained sand-fraction (especially fine sands), leaving the muds as an intertidal lag deposit.

In Roebuck Bay there is a second gradient of grain-size from W to E, reflecting the change in velocity of the tidal currents. Incoming currents converge in the north-western part of the bay, resulting in high current velocities of up to 2.5 m/s in the Inner Anchorage, a narrow channel up to 18 m deep that runs parallel to

the northern shoreline of the bay. Farther east the channel widens and shallows out and this divergence leads to lower current velocities. Cliff erosion, incised channels and coarser sediments in the NW of the bay are indicative of a net erosion in this part of the bay. The finer material is suspended and finally deposited along the western coast of the embayment. Here the gradients are especially shallow (1:1,500) and wide areas are exposed during neap tide. Most of the 150 km² of tidal flats are found here. Farther offshore and especially in the southern part of the embayment the conditions become gradually more marine and wave energy increases. Sediments are accordingly coarser and shifting sandbanks and shoals are common morphological features.

Geology

The study area is part of the Canning Basin, which is the largest sedimentary basin in Western Australia and second largest, after the Great Artesian Basin, in Australia. It covers some 415,000 km² onshore and 115,000 km² offshore. The underlying basement is built up of Precambrian sedimentary rocks, which were intruded by igneous rocks. Intensive metamorphism took place. These rocks were eroded till the Early Ordovician, when a shallow sea transgressed part of the area. The basin experienced cycles of sedimentation and erosion since the Ordovician age. Sediments are of continental, marine and paralic origin, depending on the relative sea level during the different geological ages, though marine facies make up most of the sequence. The onshore Canning Basin consists predominantly of Palaeozoic sedimentary rocks with a thin Mesozoic and Tertiary cover, while the offshore part contains a thick Mesozoic and Tertiary sequence

The following description of the local geology is based on the La Grange and Broome sheets of the Australia 1:250,000 Geological series and personal observations.

The oldest outcrop in the study area is the Broome Sandstone, which is considered to have been deposited as the Late Jurassic – Early Cretaceous sea shallowed owing to regression. The lithology is fine to very coarse sandstone, some mudstone and minor conglomerate. Ripple marks, cross-bedding and intensive bioturbation are indicative of its shallow marine origin. The Broome Sandstone is widely distributed, though poorly exposed. The best outcrops are at Gantheaume Point in the Northwest of the bay, which is famous for the dinosaur footprints found there. The maximum exposed thickness is 12 m, but an additional 274 m of section is present in the subsurface of the Broome area. All the other facies exposed in the area are Quaternary

deposits. Five different physiographic units with different lithologies can be distinguished:

- Tidal flat and mangrove swamps
- Supratidal mudflats
- The Bossut Formation, which consists of coastal deposits
- Coastal aeolian dune sand with reworked material of the Bossut Formation
- Aeolian seif dunes and sand sheets.

These units are discussed in detail because of their impact on the sedimentology of the embayment.

The tidal flats have sediments of biogenic and terrigenic origin, ranging in grainsize from silty clay to coarse sand depending on the sorting due to different current velocities in the bay and the origin of the sediments. Generally there is a trend from coarser material in the northern parts of the bay to finer sediments in the south where the currents diverge. The near surface sediments of the mangals show similar ranges in grainsize depending on the location of the mangals and the origin of the sediments. Anoxic black muds rich in organic material are typical for the extensive mangals around Dampier Creek and especially Crab Creek.

Supratidal mudflats border the mangrove systems around Dampier Creek and Crab Creek further inland and consist of clay, silt and sand with minor salt. This physiographic unit is best represented in Roebuck Plains, an extensive alluvial and estuarine plain that extends some 30 km inland. It was structurally laid out by the Fitzroy River before it changed its course after uplift in the Miocene and Pliocene. During periods of higher sea levels in the Quaternary and moister conditions estuarine conditions were present.

The Bossut Formation (Fig. 5.4) consists of fine to coarse calcareous and quartzose sandstone, calcilutite and oolite. It is considered to be of Quaternary age because of its occurrence at or close to the present-day shoreline, and because it is in part poorly cemented. This formation forms cliffs and beach ridges between Dampier Creek and Fall Point in the northern part of the bay and is well exposed due to cliff erosion. Cross-bedding and fossilised gastropods, bivalves and forams are proof of the coastal origin of the sediments. The maximum thickness is approximately 20 m.

Coastal aeolian sand deposits with calcareous, partly oolithic sand including reworked material of the Bossut Formation form high dunes along most of the coastline. Most of these dunes are now inactive and vegetated. A good example is Cable Beach, which is an extensive white sand beach and one of the major tourist attractions of the area. In Roebuck Bay these deposits are only found between Fall Point and One Tree in the north-western part of the bay.

Fig. 5.4: Eroded sandstone in the northern parts of Roebuck Bay between Fall Point and Quarry Beach. The rocks in the foreground are thought to belong to the Bossut Formation, which was deposited in the early Quaternary under shallow marine conditions. Cross-bedding and fossilised burrows of marine benthos are common. Cliff erosion is an ongoing process, as can be seen by the steep Pindan cliffs in the background. During times of heavy rainfall, the water cuts steep gullies into the poorly cemented soils. Photograph by Marc Lavaleye.

Aeolian deposits occur over most of the area as sand sheets and seif dunes. They consist of fine to medium red sand and minor silt. The maximum thickness is around 15 m. These deposits give the Pindan soil its characteristic brightly red colour. They are poorly cemented and subject to cliff erosion, as can best be seen along the northern coast of the embayment.

Coastal Morphology

The recent coastal morphology formed during the Quaternary through influence of ancestral landforms and fluvial and shoreline accretion, coastal erosion, and cementation under an arid setting. The basic sequence from the ocean in inland direction is a tidal flat, followed by a fringe of mangroves, a narrow sand beach, salt flats with occasional sand ridges, supratidal flats and Pindan woodland depending on the height above MSL. Quite often only parts of the sequence are found.

The vast intertidal flats in the embayment cover some 150 km^2, which are exposed during Mean Low Water Level (MLW). In the northern part of the bay erosion seems to be the dominant process, the intertidal zone is with less than one km in front of Fall Point and up to three kilometres at Dampier Creek comparatively narrow. This is due to the hydrography of the bay. The south flowing Leeuwin Current is deflected into the bay and current velocities of up to 2.5 m/s are encountered where it converges. This current created a shore parallel channel which cuts off the intertidal zone. Sediments of these flats are generally grading from fine to very fine sands in the Northwest to silty muds in the Northeast of the bay. In front of Dampier Creek tidal channels with finer sediments along their embankments are dissecting the tidal flats. In the north-western part of Roebuck Bay the currents diverge and the energy dissipates on the mudflats. The sediments there deposited are accordingly finer grained and consist of silty muds. This is most prominent in front of Crab Creek, where the waterlogged and thixotropic muds are more than knee-deep. The carbonate rich muds have a light

grey colour and are predominantly of biogenic marine origin. The terrestrial input is probably derived from sheet erosion and river runoff from the silty Roebuck Plains. In front of the western shoreline the intertidal flats widen out and extend up to 13 km offshore at the south-western end of the bay. Sediments are fine sands and the bigger grain size might be explained by higher wave energy. Sandbanks are common and an important roost for shorebird.

Mangals range in size from a narrow fringe just a few trees wide to extensive areas around the main tidal creek systems. In the northern part of the bay there is an extensive area of mangals around Dampier Creek (Fig. 5.10) in the north-west and Crab Creek in the north-east. In between these tidal creek systems the mangals narrow out rapidly and are completely absent on most of the shoreline except for a few solitary trees or small groups. In this part of the bay erosion is the dominant process and prevents the establishment of mangrove communities. Along the eastern side of the bay there is a continuous band of mangroves averaging 500 m in width and fringing the indented coastline. Along the various tidal creek systems these communities extend further inland depending on the size of the creek systems. At the southern end of the bay around Bush Point mangals are absent except for a lagoon protected by sand ridges at the seaward side. Conditions are more openly marine and too energetic for mangrove establishment.

Narrow sand beaches are most common in the northern parts of Roebuck Bay where mangroves are absent. They consist of quartzose sands and shell fragments with boulders of beach rock, sandstone and conglomerates in places. They are widest in little pockets, cut into the Pindan cliffs by rare cyclonic events and storm surges. Where rocks of the Bossut Formation protrude right into the tidal flats, sand beaches are absent.

Salt flats are nearly planar, salt-encrusted high tidal hypersaline surfaces, devoid of vegetation and generally devoid of burrowing benthos. They typically occur along arid coasts where there is insufficient rainfall or seawater recharge to break down the extreme hypersalinity that forms in response to high evaporation (Semienuk 1996). Salt flats are underlain by a variety of materials, since the critical factor in their formation is not substrate type, but salinity of groundwater. Most of the salt flats in the study area have developed on muddy tidal flats now above tidal range. At levels of MHWS and HAT they are underlain by groundwater whose salinity is superhaline to brine (100 – 200 psu). Consequently the salt flat surface is encrusted with fine halite crystals, and locally crystals of gypsum in the subsurface. If not covered by sand dunes and sand sheets they normally fringe the mangals where groundwater salinity increases to values that exceed the tolerance of the mangroves, which is 80-90 psu at maximum. These conditions are present around Dampier Creek and Roebuck Plains.

Supratidal flats normally follow salt flats further inland when salinity decreases to values that enable the growth of samphire vegetation and other salt tolerant plants. Roebuck Plains is the best example for this unit. This vast area is covered with greyish silt of fluvial and estuarine origin as opposed to the red aeolian sands that cover most of the region. Genetically Roebuck Bay seems to be an arid delta complex with watercourses that are now dry for most of the year. In pluvial times during the Quaternary runoff must have been at least intermittent with a sediment input into Roebuck Bay that was a lot higher than today's.

The Pindan woodland creates the last part of the morphological sequence and follows the supratidal flats inwards. The often well defined boundary between supratidal flats and dense Pindan woodland is explained by a steep rise in terrain, so that saline groundwater doesn't reach the roots of the shrubs and trees. The underlying material is red Pindan soil of aeolian origin.

Two major exceptions to the above described sequence occur in the area. In the northern part of the bay the overall sequence is reduced to tidal flat, a narrow sand beach with breccia of beach rock and sandstone and finally red Pindan cliffs towering up to 15 m above the beach. The dominant morphological process is cliff erosion. Mangroves, salt flats and supratidal flats are missing. At the southern end of the bay there are large sand dunes and high sand bars that constitute the main wader roost of the area. These dunes are largely inactive and vegetated by Spinifex grasses. Farther inland supratidal flats follow with grassland and spare vegetation of *Melaleuca* and *Acacia* shrubs grading into open Pindan woodland. Mangroves and saltflats are missing from the typical sequence.

Surface sediment distribution

Methodology
During a two week period in June and July 1997, 537 sediment samples were collected for biological and sedimentological analysis from a 45 km^2 area in the northern and north-eastern sections of Roebuck Bay (Fig. 5.5). Sampling was done on a 200 m grid in the area north of Crab Creek, and on a 500 m grid in the area south of Crab Creek. Samples for sediment analysis were collected using 5 cm diameter PVC pipes inserted into the sediment to a depth of 10 cm. Along four short transects perpendicular to the coast sediment cores were taken to a depth of 20 cm. These were used
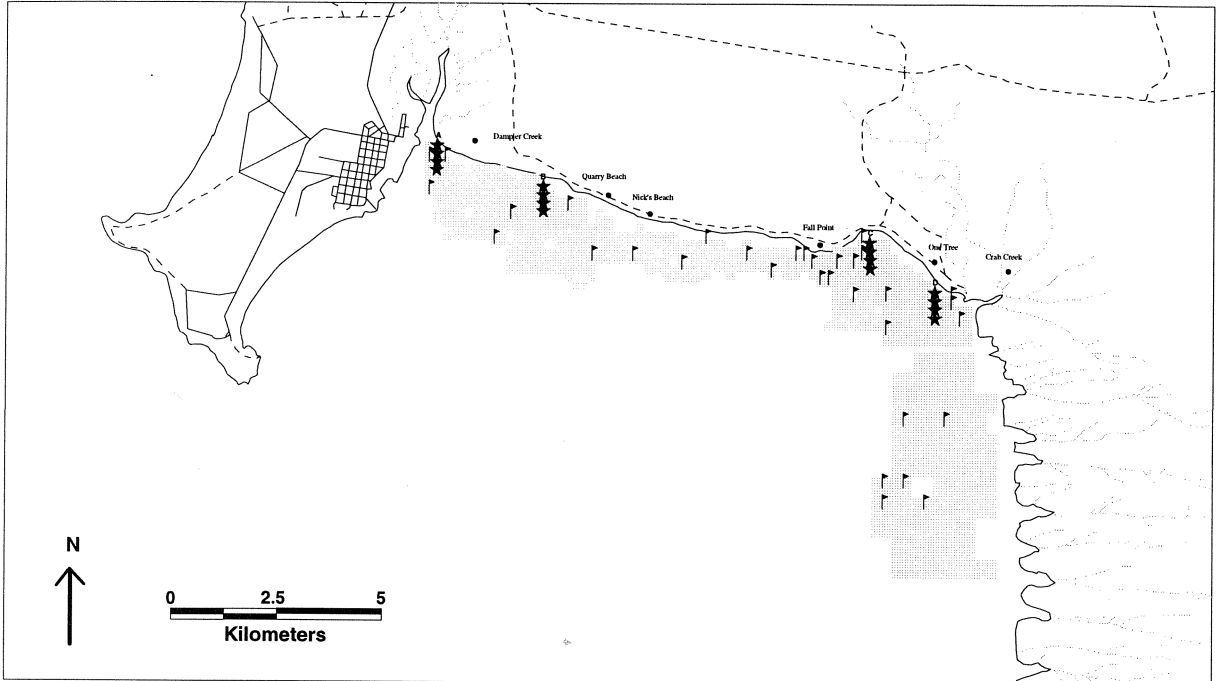
Fig. 5.5: Map showing the study area in Roebuck Bay. Samples in the northern parts were sampled on a predefined 200 m grid, stations in the south-east on a 500 m grid, respectively. Also shown are the four shore-normal transects A-D (marked with star symbols) and the locations of the 36 stations whose sediments were analysed for total carbon (marked with flags).

to investigate the stratification of the upper sediment layers.

Granulometric analysis was done in the laboratories at Curtin University. The sediment samples were first wet-sieved over a 63 μm mesh. A chemical treatment of the sediment to break down aggregates was not necessary. The residue bigger than 63 μm was then dry-sieved using a stack of sieves with mesh sizes of 125, 250, 355, 500 and 1000 μm. The following parameters were computed to describe the sedimentology of the area: Silt content (<63 μm), Median Grain Size, the sorting coefficient S_0 (only for the sand fraction between 63 and 1000 μm), and the mass percentage of the coarse fraction (>1000 μm). The Median Grain Size and the sorting coefficient were determined graphically by plotting cumulative weight percentages against size classes and reading the grain size for the different quartiles (Q_1 = 25 %, Q_2 = 50 %, Q_3 = 75 %) off the x-axis. The sorting coefficient S_0 is here defined as $S_0 = (Q_1/Q_2)^{0.5}$.

Sediments of 36 selected stations encompassing the whole range of silt contents from 0 to 96 % were analysed for total carbon. Prior to analysis the material was ground for approximately 20 minutes with a ball-mill. From every fifth sample a double was taken to estimate repeatability.

Spatial distribution of grain size parameters
Silt content, median grain size, and the sorting coefficient S_0 are a function of the hydrodynamic conditions present and the biological interactive forces at work. The silt content, i.e. the mass percentage of the particles smaller than 63 μm of the total dry weight, is lowest in the lower intertidal region of the north-central part of Roebuck Bay and increases towards the upper intertidal and both towards the east and the west (Fig. 5.6). The MGS follows a trend in the opposite direction and is highest in the lower intertidal between Quarry Beach and Fall Point (Fig. 5.8). This is supported by correlation statistics. Using the Pearson correlation coefficient as a measure shows that MGS and silt content are highly negatively correlated (-0.738, N = 536). The tidal currents and the morphology of the bay seem to be primarily responsible for these patterns.

The correlation between the sorting coefficient S_0 and the silt content is much weaker (-0.353, N = 536). The highest degree of sorting, i. e. the lowest sorting coefficients, are found in the muddy eastern parts of the bay (Fig. 5.7). This trend reverses in the northern parts of Roebuck Bay, as silt content and sorting coefficients seem to be positively correlated. Sediments are poorly sorted in the siltier regions of the upper intertidal zone. Farther offshore, the energy input by waves and tidal currents is higher and the sediment is re-

worked and sorted to a greater extent, resulting in sandier substrates and lower sorting coefficients.

The area at the mouth of the Dampier Creek System is protected against wind driven waves by the Broome Peninsula. The energy input is accordingly low to intermediate and, disregarding rare cyclonic events, entirely due to tidal currents. Erosional and depositional processes change on a small scale and the morphology of this particular area has a very heterogeneous aspect. The degree of sorting in this region changes on small scales as well, but on average the substrate seemed to be poorly sorted compared to the provinces farther east (Fig. 5.7). The sediments consisted of fine to very fine sands with an average median grain size of 120 μm.

In the north-central part of the embayment, the energy input through tide and wind generated currents is highest and current velocities in excess of 1.5 m/s are encountered where tidal currents converge. Erosion seemed to be the dominant process, manifesting itself

in cliff erosion and the presence of rocks close beneath the surface. The lower intertidal experiences the highest energy input and the sediments are constantly reworked and shifted by the currents and small waves. This explains the low silt content (an average of 7.3 %) and the rather high degree of sorting. Even these figures on the silt content might be an overestimation. Faecal pellets are aggregates of finer particles. Hydrodynamically they may behave like grains of the sand fraction and should, therefore, be classified according to the size of the pellets, rather than the size of the constituting particles. Though quite stable in situ they might have become physically destroyed during handling and sieving of the sediments, so that they were subsequently classed as silt.

The eastern and south-eastern parts of Roebuck Bay consist of fine muds with an average silt content around 75 %. The sediments are extremely well sorted and the average sorting coefficient is 1.19. The carbonate muds consist predominantly of calcareous shell

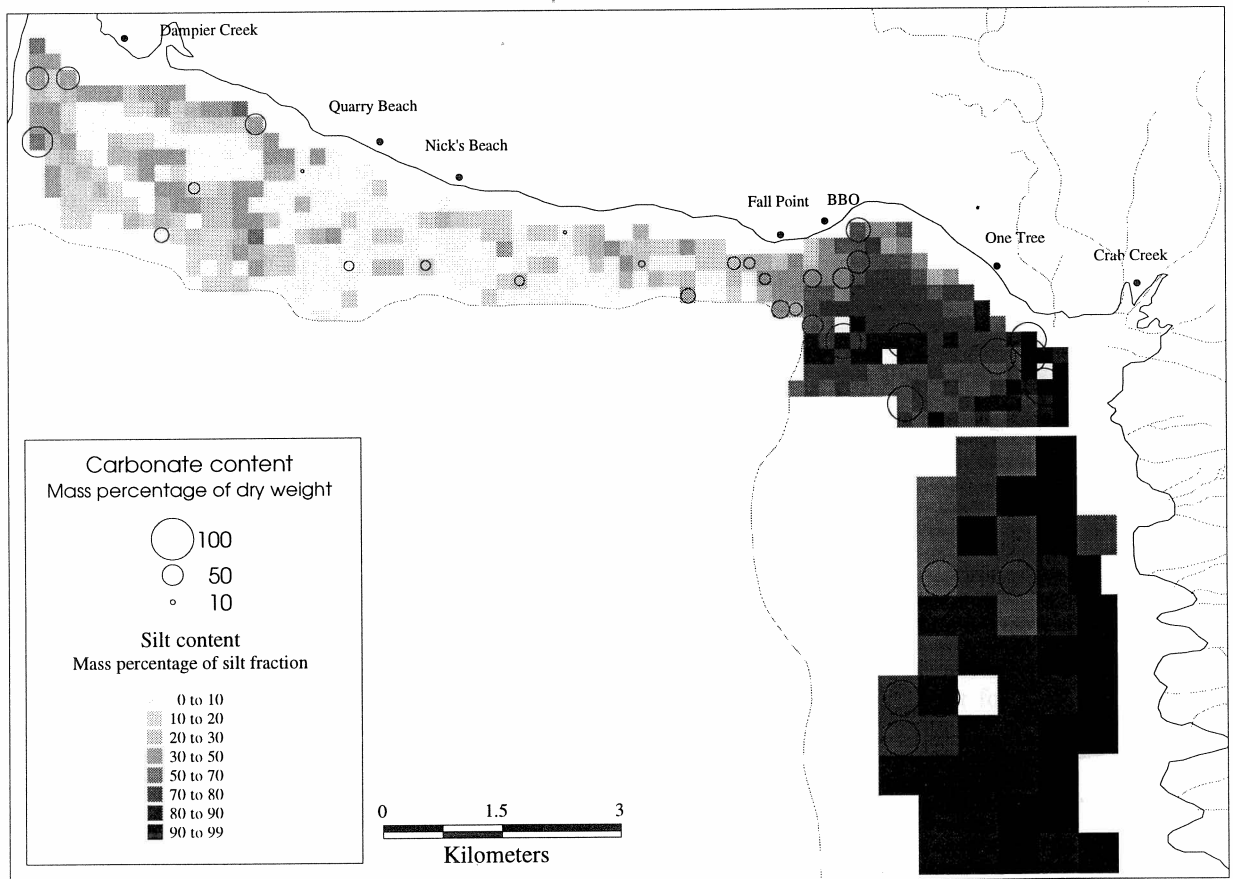

Fig. 5.6: Map showing the silt content of the 537 sample stations and the mass percentage of CaCO₃ of 36 selected stations. Carbon content follows the trends of silt content in that it is highest in the eastern parts of the embayment. The spatial distribution of both parameters reflects the hydrodynamic conditions present in the bay.

fragments of the silt and clay fraction, probably deposited out of suspension. Figure 5.8 shows the median grainsize (MGS) of the sample stations. Some stations in the muddy eastern province show outlying figures that probably resulted from errors during the sieving and weighing process. With these few exceptions, the median grain size of the sand fraction is in the range from 63 to 250 micrometres. These fine to very fine sands dominate the sediments of even the most exposed sites of the study area and show that at least the northern parts of Roebuck Bay are a low-energy environment, indeed.

Provenance of the sediments
In the northern parts of the embayment the sediments are mostly made up of fine to very fine sands. They consist mainly of quartz and shell fragments and only little mica or dark minerals. The grains are angular to subangular in shape, which indicates that transport was

only short and that the sediments underwent only few cycles of erosion.

Some of the quartz grains, especially within the fraction larger than 0.5 mm, are coated with iron oxide and were probably eroded from the outcropping quaternary sandstone and holocene pindan cliffs.

The rest of the sediments is very likely to be of mixed terrigeneous (fluvial and aeolian) and marine origin. Some questions, e.g. which processes are primarily effecting the sediment budget of the bay and what the primary source of the sediments is, cannot be answered at the moment.

The provenance of the silt / clay dominated sediments is equally unknown. The very high carbonate content of the sediments and the presence of foraminifera indicate a marine origin. Another possible source is 'Roebuck Plains', the extensive flood plain deposits adjacent to the north-east of Roebuck Bay. The plains are believed to have developed during the early Creta-
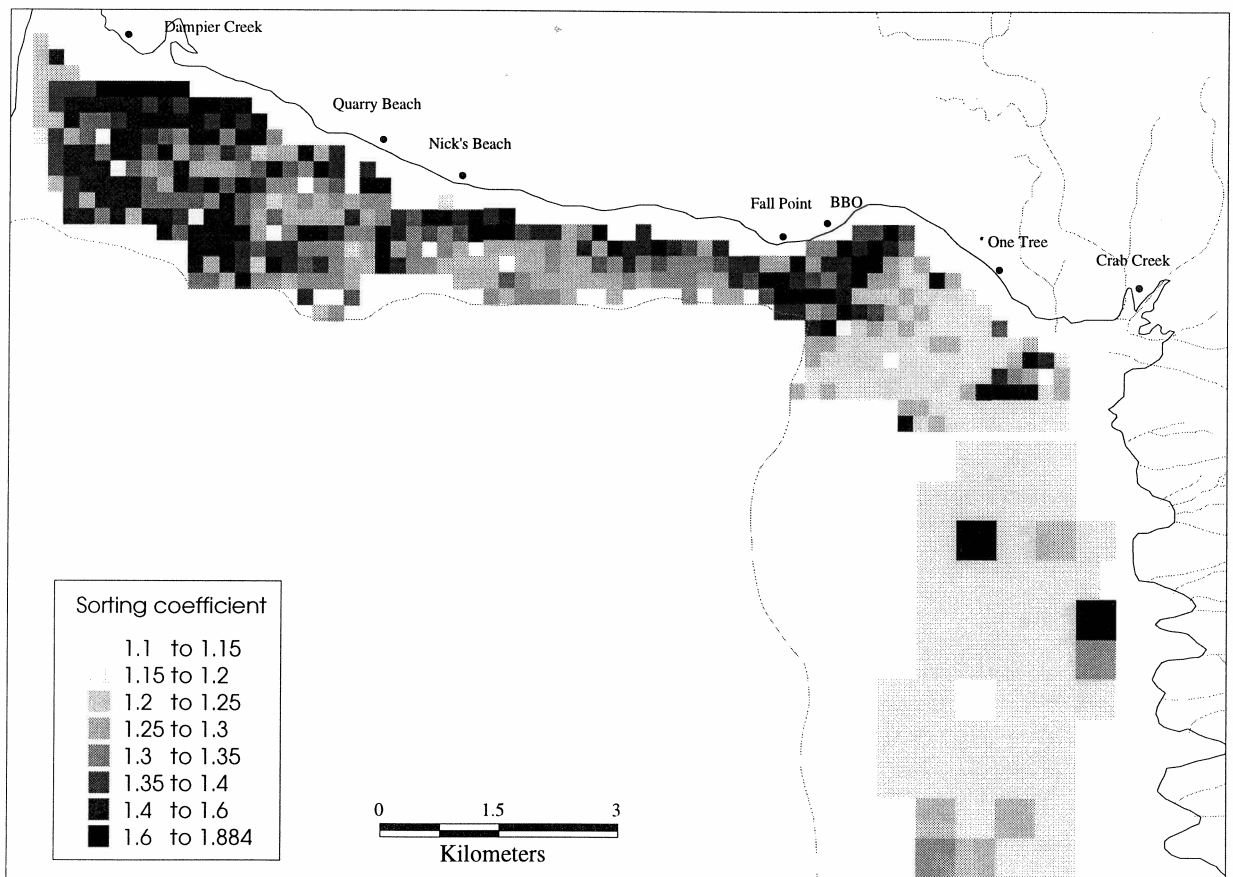
Fig. 5.7: Map showing the sorting coefficient S_0 for each sample station. The sediments in the muddy eastern and south-eastern parts are well sorted with average coefficients of 1.19. The few very high coefficients in this area can only be explained by mistakes during the sieving and weighing process and should therefore be disregarded. Note the very sharp gradient between the muddy parts to the east and the adjoining north-central area around Fall Point.

ceous, when the Fitzroy River entered the ocean at the position of the present day Roebuck Bay. So geologically, the Roebuck Plains represent an ancient delta system and the sediments are of mixed terrigeneous and marine origin.

During the dry season (March to October), these floodplains are highly consolidated. However, during the wet season (October to March), cyclonic weather results in extensive flooding of Roebuck Plains and sheet erosion. The erosion is greatly enhanced by physico-chemical and biological processes. Water can enter the consolidated surface easily through shrinkage cracks and animal burrows. During the dry season, the flats become hypersaline and salt crystals form. During spring tides or during the wet season when the plains are inundated, these crystals dissolve readily and the mud collapses. A thick suspension is formed that is set in motion at very low current velocities. Biological reworking is dominated by the habits of crabs, which hibernate in the plains during the dry season and come out of hibernation during the wet season when they travel to Roebuck Bay and lay their eggs. During hibernation, the crabs dig 30 to 50 cm deep holes, which can be spotted by the loose mound of sediment around them. This sediment, plus sediment disturbed via physical processes, flushes into the Bay on high tides.

The importance of this tidal flushing is highlighted around the mouths of the tidal creeks, where the water column contains large amounts of suspended matter.

An alternative source of the sediments in the silt/clay province may be the sand- and siltstone of the Bossut Formation, seen in outcrops around the northern perimeter of the bay. However, these outcrops are locally restricted and mostly made up of sand sized particles. It is therefore unlikely that the minimal amount of eroded sediment would be enough to sustain the large volumes of fine muds in the silt/clay province.

The genesis of the silt/clay province is most probably geologic in nature. It is highly likely, however, that the interaction of stabilising and destabilising biological forces in the silt/clay province help to keep the sediment system in a state of a dynamic equilibrium.

Siliclastic and carbonate systems

Carbon analysis showed that the concentration of total carbon differed strikingly between samples and that carbon content was significantly correlated with the silt content (Pearson correlation coefficient 0.956). Figures for total carbon ranged from 0.4 % in the very sandy regions to 10.6 % in the muddy regions to the east. The content of organic carbon in tropical mudflats is generally very low and rarely exceeding one percent of the dry mass (Alongi 1990), so most of the total carbon must be bound in the form of carbonates.

Recent carbonate deposits in the tropics are made up of aragonite and high Mg-calcite. Under normal conditions, only aragonite can precipitate directly from seawater. In the calcite lattice, magnesium tends to replace calcium and inhibits crystallisation. This may be due to the fact that Mg^{2+} ions are more firmly hydrated by polar water molecules than are Ca^{2+} ions. More thermodynamic work must be done to dehydrate these Mg^{2+} ions than to dehydrate Ca^{2+} for the growth of aragonite lattices (Leeder 1982). Direct precipitation of carbonates is rare and restricted to a few subtropical and tropical locations. The majority of the shelf carbonates is of biological origin and derived from the calcareous hard parts of invertebrates and algae. Assuming that most of the total carbon is bound in the form of inorganic $CaCO_3$, the carbonate concentration can be computed from total carbon by multiplying the concentration of total carbon by a factor of 8.33. This results in carbonate concentrations of up to 88 % of the total dry weight in the muddy settings to the east and south-east of Roebuck Bay. The strong correlation between silt content and carbonate content simply indicates that most of the carbonate rich material belongs to the clay and silt fraction (Fig. 5.6). In the sandy parts, where energy input is high, only the coarse shell fragments are deposited. These contribute very little to the overall carbonate content of the otherwise mostly siliclastic sediments. The smaller shell fragments behave hydrodynamically different and are deposited in energetically calmer environments, mainly in the south-eastern parts of the embayment.

Biogenic stratification

A common feature to most of the stations sampled was the presence of a shell layer, composed predominantly of fragmented bivalve and gastropod shells. This layer was typically between 2 and 5 cm thick, and occurred at depths between 5 and 30 cm. The cores used for the biological sampling program were taken to a maximum depth of 50 cm, but more often than not a shell layer prevented coring to full depth. The sampling depth was recorded at each sample station and is, therefore, a good measure of the depth of the shell layer, except for those locations where sand- and mudstone was outcropping or close beneath the surface.

The depth of the shell layer followed the trends of other sedimentological parameters, especially of the silt content. It was very shallow in the upper intertidal region of the north-western parts of the embayment and increased towards the siltier eastern and south-eastern regions. The origin and the different depths of the shell layer have to be explained by a combination of physical and biological processes that differ between provinces. The shell layer was most prominent in high energy environments where erosional processes domi-

nated. The currents remove the finer particles and the coarser shell grit is left behind and relatively enriched. Especially in the areas between Dampier Creek and Fall Point, cliff erosion, mainly during cyclonic events, is an ongoing process. Geologically, the cliffs belong to the Quaternary Bossut formation and were deposited under shallow marine conditions. There is abundant shell material in the parent rock and this might add to the in situ material of the northern parts. In the areas to the east and south-east, accretion of finer particles is the dominant process and this prevents the building up of a prominent shell grit layer.

The concentration of the dead shells in characteristic bands must be explained by an interaction of biological and physical processes. The density of the carbonate shells (2.7 g/m^2) is of the same order as that of quartz grains (2.6 g/m^2). Thus, it is very unlikely that the slight difference in density is responsible for the layering and, even if it was, there is no reason why shells should accumulate in characteristic bands.

Therefore, there must be other agents at work that transfer the shell material to greater depths. Bioturbation and biogenic stratification seem to be this structuring agent. Both deposit and suspension feeding animals abound in Roebuck Bay and, taken together, must exert a big influence on the sedimentology of the area. In-faunal species feeding below the surface, so-called 'conveyer belt species' like maldanid and capitellid polychaetes and holothurians, process subsurface sediments and its organic material in their guts and excrete it as faecal pellets on the surface. Because they can only ingest particles up to a certain size limit, coarser fragments are left behind and are relatively enriched at depth.

Suspension feeders remove suspended particulate food from the water column, aggregate the ingested materials in the gut, and void these faeces as discrete pellets or faecal strings. These pellets have a higher settling velocity and require higher current velocities for entrainment than their constituent particles and

1 Fine grained sand province
2 Very fine grained sand province
3 Silt / clay province

Median grain size
MGS in micrometers

63 to 100
100 to 125
125 to 200
200 to 250
250 to 355
355 to 500

0   1.5   3
Kilometers

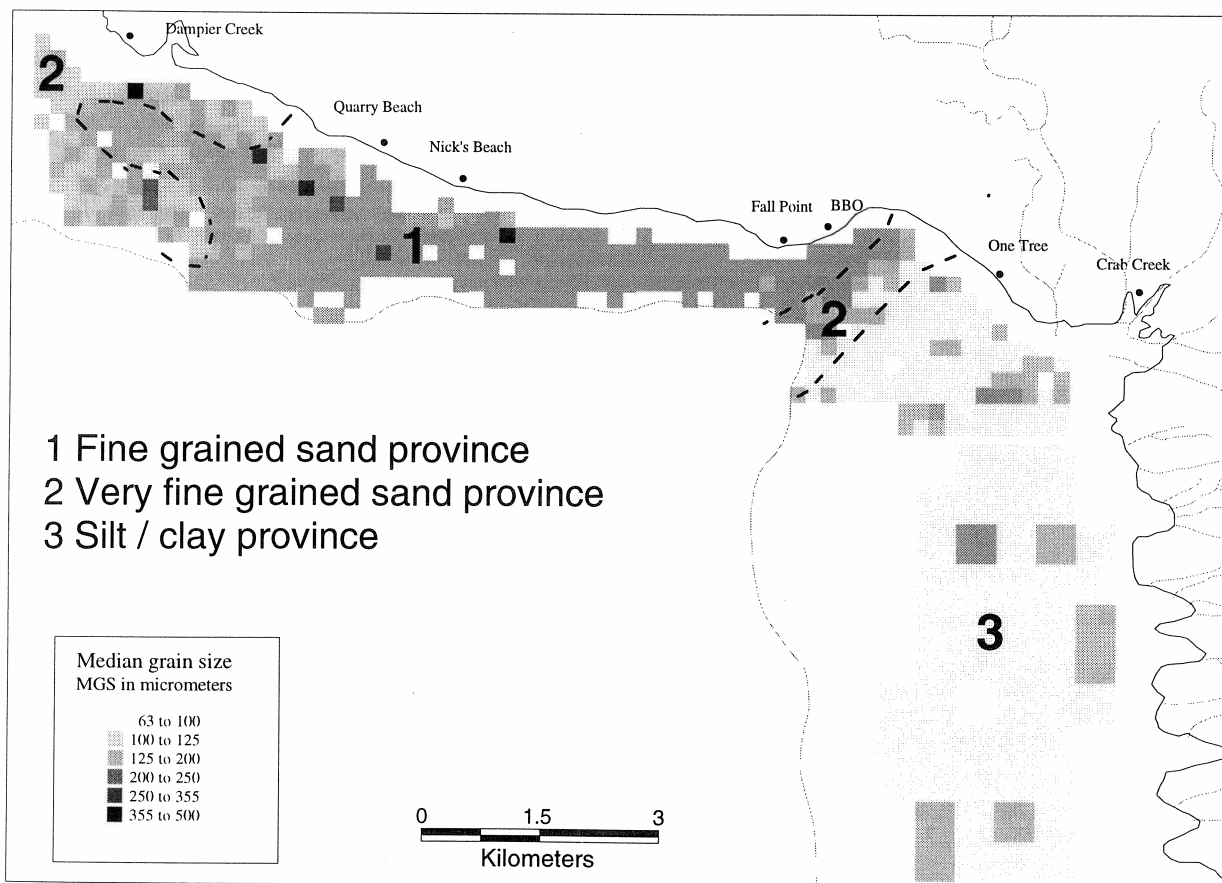Fig.5.8: Map showing the median grain size (MGS) for each sample station. Except for a few stations the MGS lies in the range from 63 to 250 micrometers. These fine to very fine sands are indicative of the low energy environment present in the northern parts of Roebuck Bay. The few rather high values in the south-eastern parts are likely to be errors that occured during the analysis of the grain size parameters.

may, therefore, settle out near the site of production (Rhoads 1974). This, together with the deposition during slack tides, may help to explain the layer of finer sediments near the surface, which showed very low concentrations of coarse shell fragments. The two most abundant taxa in Roebuck Bay, the colonial tube building polychaetes Chaetopteridae and Oweniidae, and most of the bivalves of the area are primarily filter feeders. Together they remove huge amounts of particulate matter out of the water column and must, therefore, have an important influence on the sediment budget of the area. The faecal pellets are quickly colonised by bacteria and may then offer food for other benthic taxa.

At higher sedimentation rates, the influence of the benthos on the sedimentary particles decreases. This might be the reason why shell layers are not as prominent in the south-eastern regions, where accretion dominates. First, the relative percentage of coarser materials will be lower due to the higher sediment input of finer particles. A second reason of importance is that the absolute amount of shell material is lower. The terrigeneous input is low in the south-eastern area and probably restricted to sheet erosion of the salt flats of Roebuck Plains during the wet season. Sheet erosion is a low energy process and it will only be able to transport particles of the clay and silt fraction into the bay. Thus, the shell grit found in the eastern parts will al-

most certainly be in-situ products or remnants of rare cyclonic events. Characteristic of the muddy eastern parts was the high number of burrows made by mantis shrimps and crabs of the genus Macrophthalmus. These holes reach down to a depth often exceeding one meter and the excavation and maintenance of the burrows must rework large amounts of sediments. Unlike the conveyer belt species mentioned above, the bioturbation by crustaceans reaches deeper layer of the sediments and they might prevent the establishment of a well-defined shell layer.

The deposition of faecal pellets and the vertical transport of finer particles to the surface result in a vertical gradient of particle sizes. For the above mentioned reasons this layering is most conspicuous in the northern parts of Roebuck Bay. The silt content is generally highest close to the surface and decreases with depth. The opposite is true for the percentage of shell grit, which increases with depth (Fig. 5.9). These patterns were most noticeable at the station highest up in the intertidal along transect B; on the other hand, it is hardly visible in the very muddy parts of transect D.

Two stations, B1 and D1, were selected to exemplify these trends. Station B1 is typical for the sandy regions in that there was a marked increase in shell grit material around a depth of 10 to 15 cm. The very high silt content of the top layer was only observable in the upper intertidal but not in the lower regions where en-
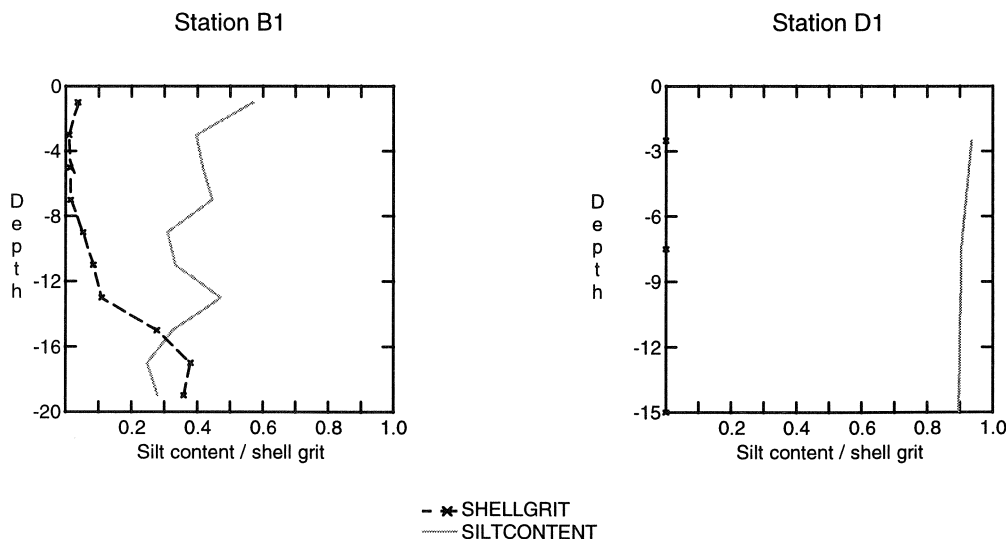
Fig. 5.9: Graphs showing the vertical distribution of silt content and shell fragments (> 2 mm) for two selected stations B1 and D1. The position of the transects B and D is shown in Fig. 5.5, stations are numbered from top to bottom. Stations of transect B were analysed with a higher resolution of 2 cm, whereas at the other stations only three depth layers (0-5, 5-10 and 10 to 20 cm) were taken. Note the sharp increase of coarse material at station B1 around a depth of approximately 13 cm and the high silt contents of the upper 2 cm. These trends are not observable at station D1. Here, the concentration of particles > 2mm is close to zero and the silt content decreases only weakly with depth.

ergy input was higher and the deposition of finer parti-
cles during slack tides negligible. In the muddy eastern
parts, here exemplified by station D1, the silt content
decreases only moderately with depth and a shell layer
was conspicuously absent.

Selected important faunal - sedimentological relationships

The aim of this section is not to discuss the complex
relationships that exist between sediment and inverte-
brate fauna, but to highlight the effects some biological
organisms have on the sedimentology of Roebuck Bay
and vice versa. What is feasible is to classify key fau-
nal and floral elements into groups that either stabilise
or destabilise the sediment surface. A list of these ani-
mals is shown below:

Stabilising agents

- Tube-building polychaetes: In Roebuck Bay the
  tube building polychaete families Chaetopteridae
  and Oweniidae are the most abundant macrofaunal
  taxa and reached local densities of up to 16,000 in-
  dividuals per square meter. Apart from physically
  binding sediment in the tubes, they also reduce the
  current velocity near the bottom and, therefore, de-
  crease erosion. These two families were mainly
  found in the fine and very fine sand province but
  virtually missing in the silt / clay province. Stability
  of the bottom and the suspension load of the water
  column seem to be the important environmental pa-
  rameters affecting these distribution patterns.
- Root systems of mangroves: Extensive mangals are
  present in the Dampier Creek area to the north-west
  and along the eastern shoreline of Roebuck Bay.
- Sea grass meadows: Although the coverage of the
  ground was very poor and the plants tiny, they still
  act as stabilising agents. The two species of sea-
  grass that were encountered in the study area oc-
  curred mainly in the fine to very fine sands of the
  northern parts. The reasons for that are probably
  similar as for tubeworms. Unstable bottoms and
  high suspension loads might physically bury the
  plants and greatly reduce the light transmission
  within the water column and, thus, the rate of pho-
  tosynthesis.
- Algae: Some lower algae, e. g. diatoms, excrete a
  mucus of carbohydrates that binds the sediment.
  This applies especially to carbonate muds and can
  be observed by the presence of a glutinous upper
  layer that shows characteristic cracks when drying
  out.

Destabilising elements

- Suspension and deposit feeding taxa: Suspension
  feeders remove suspended particulate food from the
  water column, aggregate the ingested materials in

the gut, and void these faeces as discrete pellets or
faecal strings. Especially mobile deposit-feeders
produce pelletal surfaces and sediments with an
open fabric. The near-surface porosity is high,
while compaction and cohesion are low and the
mud surface is easily suspended (Rhoads 1974).
Suspension- and deposit-feeding are the dominant
feeding modes among the macrofauna in the bay,
especially within the most abundant classes Poly-
chaeta and Bivalvia.

- 'Bulldozers': Larger gastropods like Nassarius dor-
  satus and members of the family Naticidae displace
  substrate of the upper layers and disrupt the sedi-
  mentary structure. This is especially true for the
  latter family, which hunts close beneath the surface.
- Burrowers: Burrowing species, mainly crabs and
  possibly mudskippers, dig deeply into the substrate
  and are probably the most effective bioturbators in
  the study area. Especially in the muddy substrates
  to the east, large burrows were a common feature.
  During the excavation and maintenance of the bur-
  rows the sediment is severely disturbed and can
  easily be suspended by wave action and tidal cur-
  rents.

Bioturbated sediments have, in most cases, water con-
tents greater than 50 % and may approach 80 - 90 %. It
is not surprising to find, therefore, that intensively
bioturbated bottoms are frequently resuspended by
wind-driven waves and tidal streams. So, although the
net sedimentation rate may be low, frequent resuspen-
sion of the bottom surface produces an environment
that is effectively a high sedimentation rate area to
which macrobenthic species have to adapt. The inter-
action of deposit-feeders, sediments and currents just
described, characteristically produces a very flat sea
floor that also tends to be homogeneous in sediment
composition over large areas. This is exactly the im-
pression the observer gets when looking at the vast
muddy areas of the eastern parts of Roebuck Bay,
where bioturbation and recycling of the sediments
seem to be the dominant process.

Vegetation

The following description of the vegetation of the
study area is based on the Vegetation Survey of West-
ern Australia (1979). The mangrove community is later
described in greater detail, because it influences the
sedimentology and sediment chemistry of the neigh-
bouring mudflats and thus their benthic communities.

The coastal plains of Dampierland are typified by
the Roebuck Plains of Broome, but there are numerous
smaller areas both to north and south which are similar

in their structure and vegetation. Along the edge of the sea, within the rise and fall of normal tides, there are mangrove communities, which are tallest along the seaward margin, declining inland. They vary in width from just a few trees wide in the north of the bay to mangrove fringes more than a kilometre wide along the eastern shoreline and extensive areas of up to 6 km² around the major tidal creek systems of Dampier Creek (Fig. 5.10) and Crab Creek. A detailed description follows further down.

Inland of the mangroves is the usual belt of bare mud, subject to inundation at high spring tides, and unvegetated because it is hypersaline. This belt is usually narrow but may reach up to 2 km in width depending on topography, groundwater levels and substrate.

Behind it comes a broader band of samphire flats up to 4 km, vegetated densely with succulent shrubs from 75 to 120 cm tall of *Arthrocnemum halocnemoides, A. leiostachyum* and *Sesuvium portulacastrum.* Associated plants normally are rare or absent, but ephemeral grasses and forbs are present in the wet season.

This community grades into the adjoining saline short-grass plains, which occupy over half the total area of the coastal plains on flats lying slightly higher than the zone of periodic inundation. The dominant species is *Sporobolus virginicus* forming a dense grassland 15-30 cm tall. Associated plants are largely absent except for occasional clumps of samphire, also *Bassia* spp., *Eragrostis falcata*, and in shallow drainage lines *Dichanthium fecundum* and *Salsola kali.*

A change of slope, often abrupt, forms the inland boundary of these grasslands and is commonly marked by a dense but narrow band of *Melaleuca* low forest or thicket, which may attain 4-10 m in height. The dominant species is *M. acacioides.* There is a grass layer that may contain *Chrysopogon* spp., *Dichanthium fecundum* and *Sehima nervosum* or *Xerochloa barbata*, *X. imberbe, Aristida hygrometrica* and *Sporobolus virginicus.*

A limited number of beach dunes is found on the seaward margin of some plains, though not on the Roebuck Plains themselves. *Spinifex longifolius* is the principal coloniser and normally covers the foredunes.

The higher sandplain made up of red earthy sands is entirely covered with Pindan formation, except locally, where it is attenuated to shrub steppe on shallow rocky outcrops. Essentially the Pindan is a grassland wooded by a sparse upper layer of trees and a dense, thicket-forming middle layer of unarmed, phyllodal *Acacia*. It has, however, many aspects, being subject to fire which destroys the ground layer and the middle *Acacia* layer, leaving the trees intact. Depending on the different stages of re-establishment of the grass- and *Acacia* layer, the Pindan shows an aspect, according to local rainfall, of a tree steppe, tree savannah or savannah woodland. Gradually the *Acacia* shrubs regenerate, grow taller and become dominant, suppressing the grasses, forbs and small woody plants. After a certain number of years the aspect is three-layered, with scattered trees, a shrub thicket and a sparse ground layer. Later still the *Acacia* individuals reach the height of the trees, which disappear from view, giving the aspect of a tall thicket or low forest of *Acacia* (Beard 1967). The commonest trees are *Eucalyptus polycarpa* and *E. papuana forma* with some *E. setosa, Erythrophleum chlorostachys, Gyrocarpus americanus* and *Lysiphyllum cunninghamii.* The Pindan layer consist of *Acacia eriopoda* (Pindan wattle) with some *A. holosericea, Dolichandrone heterophylla, Gardenia keartlandii, Grevillea refracta, G. heliosperma, Hakea arborescens, H. macrocarpa, Petalostigma pubenscens, Terminalia circumalata.* The grass layer is mainly of *Plectrachne pungens* with some *Chrysopogon.*

The above described formations are only of minor importance for the benthic community structure this thesis is about, only in as far as sediment input into the bay is controlled by surface runoff and erosion of the neighbouring landforms. The major source of terrigeneous sediments for the bay are thus very likely the coastal plains, which are in parts devoid of vegetation and in parts only sparsely covered. Of greater importance are the mangrove systems, which influence the sedimentation and sediment chemistry of the adjoining tidal flats. These are now discussed in detail.

Mangroves are trees or bushes that usually grow between high spring tide and mean sea level. The term mangrove here refers to individual trees or species, while the mangrove plant community is called a mangal. Mangroves belong to many different families that may not be closely related in a phylogenetic sense but may have in common a number of special characteristics such as pneumatophores and a viviparous seeding habit. Throughout the world there are some 60-70 species of mangrove belonging to 30 genera in over 20 families. In Western Australia there are only 17 species; they belong to 15 genera distributed in 13 families. Mangals are typically zoned, with the zonation depending on a variety of interacting factors such as frequency of flooding, soil type, soil salinity, drainage and plant and animal interactions. Most commonly mangroves are found on soft muddy substrates. This is partly because they grow in that part of the tidal range where mud is deposited naturally, and partly because mangroves retard tidal currents and so tend to cause the deposition of the suspended soil particles. For this latter reason clean sand substrates, when colonised by mangroves, frequently become muddy in time. Well-developed mangrove soils vary from permanently wa-

Fig.: 5.10: Prop roots (pneumatophores) of *Avicennia marina*, the most abundant mangrove species of the region. Although mangrove roots are thought to trap silt particles in the upper intertidal regions, scouring of the sediments along the cable roots is obvious. So it is still debatable, whether mangroves grow in a region where deposition of finer particles normally occurs or whether they actively trap sediments. In the backround the beginning of the extensive mangals of the Dampier Creek area can be seen. Along the seaward edge Avcennia was dominating the mangrove flora, in the interiour pure stands of *Rhizophora stylosa* were found. Photograph by Markus Pepping.

ter logged to merely moist. The soils commonly contain abundant networks of ramifying cable roots, meshworks of finer nutritive roots, pneumatophores, buried fallen branches and trunks, and other organic matter in varying stages of decomposition. There are numerous open burrows, filled burrows and tunnels made by crabs, other crustaceans, worms, molluscs and fishes. Upper levels of the soil contain more oxygen than the lower and it is at the upper levels that nutritive roots of mangroves are found. At deeper levels, which are permanently moist, the soil becomes odorous with hydrogen sulphide and may be saturated with iron sulphide which is fixed by bacteria under reducing conditions. Many mangroves species are found on specific soil types and they depend on these either for their survival or for their luxuriance. In contrast some mangroves (e.g. *Avicennia marina*) are tolerant of a wide range of soil types and conditions (Semeniuk, Kenneally & Wilson 1978).

The study area falls into a biogeographic region of tropical semi-arid conditions. 13 species are recognised for this region. These are: *Avicennia marina, Aegialitis annulata, Aegiceras corniculatum, Rhizophora stylosa, Ceriops tagal, Osbornia octodonta, Bruguiera exaristata, Camptostemon schultzii, Excoecaria agallocha, Sonneratia alba, Xylocarpus australasicus, Pemphis acidula* and *Lumnitzera racemosa*. In the field one often finds typical species associations of either pure stands, paired associations or mixed stands.

The dominant species in the Roebuck Bay area is *Avicennia marina*, which forms pure stands especially where mangals are developed as a narrow fringe or only solitary trees are found. Pure *Rhizophora stylosa* stands are found in interior parts of mangals, where their dense canopy subdues other species. In pure stands both species reach tree dimensions. Paired associations typically occur in a distinct habitat related to tide level. The most common association of the study area is *Avicennia marina /Aegialitis annulata*, typical

of high spring tidal flats. *Avicennia* is stunted and the association forms a low shrubland with the bushes less then one meter high.

Mixed associations are the most complex of mangrove associations. They may contain up to six species. The species most common in these associations in the area according to locality records are *Avicennia marina*, *Aegialitis annulata*, *Aegiceras corniculatum*, *Rhizophora stylosa*, *Ceriops tagal* and *Camptostemon schultzii* with *Avicennia marina* being the dominant species in the area.

Within the more extensive mangrove communities, as for example along the western part of the bay and around Crab Creek and Dampier Creek, one may find zonations. The full sequence, as described by Macnae (1968) with a landward fringe of *Avicennia*, a zone of *Ceriops*, then *Bruguiera*, *Rhizophora*, the seaward *Avicennia* fringe and finally a zone of *Sonneratia*, is only developed in the more humid regions of Western Australia.

In the study area this zonation is reduced as follows:
- stunted *Avicennia* as a landward fringe (as a pure stand, or as an *Avicennia/Aegialitis* paired association)
- zone of *Ceriops*
- zone of *Rhizophora*
- zone of seaward *Avicennia*.

From personal observations most mangals of the study area show a dominance of *Avicennia marina*, being the most opportunistic of the represented species with physiological adaptations that enable it to thrive in a wide range of habitats.
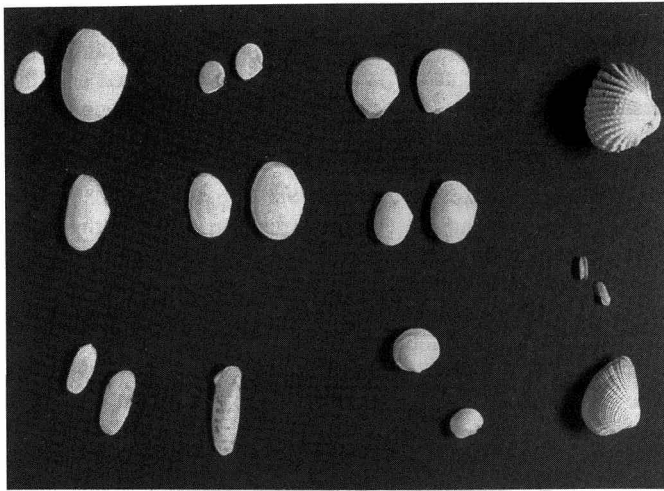
Class Bivalvia
1: *Tellina capsoides*
2: *Macoma roebuck*
3: *Tellina piratica*
4: *Tellina amboyensis*
5: *Tellina oval*
6: *Mud-Tellina*
7: *Anadara granosa*
8: *Solemya*
9: *Siliqua* cf. *winteriana*
10: *Cultellus cultellus*
11: *Divaricella irpex (D. ornata)*
12: *Anodontia* cf. *omissa*
13: *Anomalocardia squamosa*
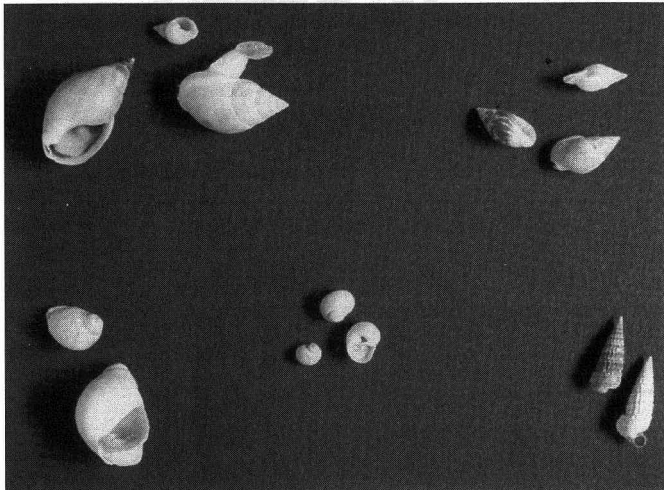
Class Gastropoda
14: *Nassarius dorsatus*
15: *Nassarius* spec. (small Ingid)
16: *Polynices conicus*
17: *Salinator* cf. *burmana*
18: *Cerithidea cingulata*
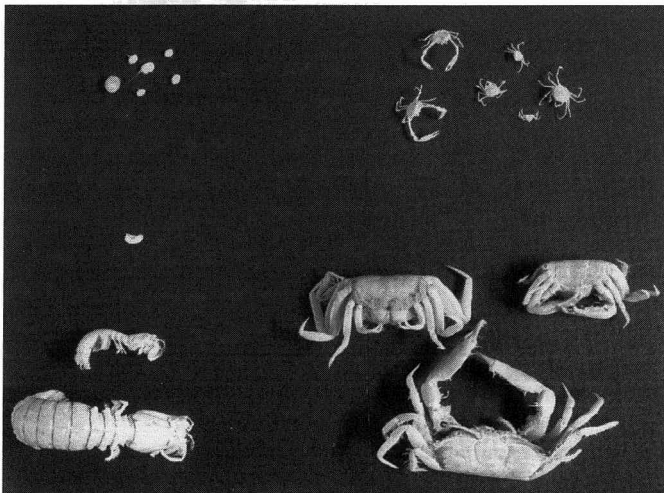
Class Crustacea
19: Ostracoda
20: *Gammarus*
21: Hymenosomatidae
22: *Squilla*
23: *Macrophthalmus*

Some of the most abundant taxa
of Roebuck Bay within the classes
Bivalvia, Gastropoda and Crustacea.
Photographs by Julia Wrede

6 MACROZOOBENTHOS

Marc Lavaleye, Betty Gilbert, Petra de Goeij, Pieter Honkoop, Grant Pearson,
Theunis Piersma & Markus Pepping

6.1 Annotated species list

Introduction

The mapping of the benthic fauna of the intertidal flat of Roebuck Bay was organised in such a way that most animals collected during the sampling were identified within one day of collection.

The advantages of this system were that most animals were seen alive and intact. This highly facilitated sorting and field identification. As data were stored in the computer every day, it was possible to publish some of the results (Piersma et al. 1998) and to draw distribution maps of species quickly after the expedition. Another reason for choosing this procedure was that is was foreseen that none of the participants (most of them voluntary) could spend much time on the samples after the expedition. The disadvantages – keeping in mind the enormous amount of animals (more than 17.000), the many sampling stations (537) and the limited time (14 days) - the identifications could not be as thorough as in a well equipped lab or natural history museum with taxonomic specialists, reference collections and literature at hand. In all we recognised about 200 different taxa (163 in the quantitative samples), but this figure will grow substantially if groups as e.g. the Polychaeta are split up into species instead of families.

For logistic reasons it was not possible to keep all material collected during the expedition, nor was it possible to keep material from each station separately. However, of all recognised species a reference collection was made. Most species were preserved in formalin (4%), and later stored in alcohol. After the expedition a reference collection of the common species was left behind at BBO, while the rest was stored at NIOZ for the time necessary to complete the report. At this moment part of the collection (Echinodermata and some other interesting species) have been donated to the WAM (Western Australian Museum). It is our purpose that the complete reference collection will be donated to the WAM (Perth) in time.

Annotated species list

In this list the species encountered during the quantitative grid sampling as well as the species seen in the field during the sampling will be mentioned and discussed shortly. If not indicated otherwise the identifications were made on my responsibility.

Most of the material was also actually seen by me in the period until 20 June. The following persons helped me after a short training to identify the material: Pieter Honkoop, Petra de Goeij, Markus Pepping and Danny Rogers. They also had the difficult task to identify the animals on their own in the period after the 20th of June, as I had obligations otherwise. However, all material from this last period that raised questions or could not be identified was preserved to be checked by me later at NIOZ. All identifications have to be taken with some reserve and any critique or additional information will be appreciated. We hope that in the near future material send to specialists will give a more detailed view of the fauna of Roebuck Bay. Sometimes a made-up English name for animals was coined during the expedition, and these names are preserved in this list.

Body length range, number of stations where the species were encountered and the highest density is indicated for every taxon. At each station three random samples, each with a surface of about 83 cm^2 and maximum depth of 40 cm were taken for the macrobenthos survey. So the densities in this report are based on a total sampled surface of 250 cm^2 per station. Furthermore the range and mean of the silt content (< 63μm) and medium grain size (MGS) of the sediment in which the animals were found is indicated for every species. Sediment samples were taken at each station down to a depth of approximately 10 cm. (For the exact methodology of grain size analysis see Ch. 5). The silt content in percentage of the total weight varied from 3 to 99 %. The range of the medium grain size over all stations was 94 to 371μm.

Porifera

Of this group material was seen in rocky areas under stones, but at the mud and sand flats this group was not expected. Therefore it was the biggest surprise for me during the whole expedition to find a species adapted to a very muddy substrate. The species forms a cone about 5 cm high with a rounded top. The cone sits on the surface of the sediment and is anchored in the sediment by a root system that is at least as big as the cone itself. The cone can have a reddish to greenish colour (because of algae?), which is mostly masked by a thin layer of mud. Shallow gutters run from the top radial to the sides, probably with the function to ease the removal of mud from the surface.

The mudsponges had a very restricted distribution. A group of a hundred specimens was found near the BBO, somewhat higher on the mudflat than the low water neap tide line. This means that during every tide they fall dry for several hours, although the danger of drying out looks small because the sediment consist of soft mud from which the water is not easily drained. The population seemed to me very vulnerable to disturbance, but to my surprise I did not find evidence for that in 1998 after the cyclone of December 1997. That this cyclone must have had a large impact on the area was clear by the fact that it completely eradicated the nearby Little Crab Creek, which during the 1997 field trip had a depth of about 2 to 3 metres. During the quantitative grid sampling these sponges were found at only one station, with a density of 200/m^2, and a length of 8-23 mm. Sediment characteristics: 32% silt and a medium grain size of 150 μm. As I could not find this species in any of the handbooks we used, material was handed to the curator of sponges of WAM, Dr. J. Fremont, for identification.

Cnidaria

At least six species of sea anemones were found. Two of those were restricted to hard substrates. One of this is not really a species of the open tidal flats, as it was only found on the roots of the mangrove trees (between One Tree and Little Crab Creek), which is the reason why we called it the mangrove anemone. The other, the shell sea anemone, was always attached to a bivalve shell, and had a flattened appearance. Uncommon.

In the quantitative samples only two species were encountered, both probably belonging to the family Edwardsiidae. These are relatively small and slender sea anemones that have a burrowing habit. The relatively few tentacles normally stick out of the sediment to catch prey, but can be retracted quickly on distur-bance. One species had a length of 4-20 mm and was found at 14 stations with a highest density of 200 ind./m^2. Sediment characteristics: Silt %: 9-79 (mean 45), MGS: 96-179 (mean 127 μm).

Two larger anemones were encountered, both in the more sandy part east of the Dampier Creek at half tide level. One of these is *Stoichactis* spec. This species easily reaches a length of 20 cm and a diameter of 10 cm. The sea anemone is buried in the sand, the oral disc with the short but normal slender tentacles has the same level as the surface of the sediment. Because of its marbled colors, which mimic the colors of the sandy surrounding, the anemone is not very conspicuous. Several individuals were found, but never closely together.

The other large sea anemone does not belong to the order Actiniaria as all the other sea anemones here mentioned, but to the order Ceriantharia. This animal lives in a flexible felt-like tube that protrudes for a part above the sediment. The animal itself is worm-like and has many long slender tentacles. It can retract itself quickly into the tube. We have seen animals with uniform white, brown and nearly black tentacles. The maximum observed length of the tube was about 40 cm. The animals were seen in the same area as the *Stoichactis* species.

From all species one or more specimens were collected and these were presented to J.C. den Hartog of Naturalis (Leiden, NL) for identification.

Of the Scleractinaria some colonies were seen at rocky outcrops near the low water line. In some samples dead eroded specimens of a solitary coral that live in symbiosis with a sipunculid worm were found (Ch. 6.3).

Platyhelminthes (flat worms)

Orange flatworm, belongs to the Turbellaria. Length 2 cm. Unpalatable worms which openly crawl around on the sandy flats. Carnivorous. In the quantitative samples no specimens were found, but in the field is was seen rather frequently.

Nemertini

These slimy worms easily break up during collecting or conservation. Identification to the species level is hard. Length 5-80 mm. It was found at 23 stations. Highest density was 160 ind./m^2. Sediment characteristics: Silt %: 3-96 (mean 47), MGS: 95-185 (mean 131 μm).

Phoronida

These worm-like animals live in a sandy tube that has a resemblance to the tubes of the polychaete family Oweniidae. The animal itself is easily distinguished from polychaetes, because it lacks chaeta. Their tentacle crown, often lost upon collection, is also quite different from the more fleshy crown of the Oweniidae. Shell length 15-42 mm. It was found at 11 stations. Highest density was 240 ind./m^2. Sediment characteristics: silt %: 5-38 (mean 19), MGS: 119-213 (mean 167 μm).

Brachiopoda (Lampshells)

Lingula spec. (Burrowing lampshell) – Family Lingulidae (Plate 6.3). Shell length 2-16 mm. This peculiar animal looks like a bivalve, but is not related at all to molluscs. With the peduncle, which cannot be retracted into the shell, it can burrow a bit. Filterfeeder. Species very similar to our species existed more than 400 million years ago. The *Lingula* species of today are therefore called "living fossils". Another peculiarity is that it is the only member of the phylum Brachiopoda that is eaten·in Australia by man (Parker, 1982). Found at 19 stations with a maximum density of 320 ind./m^2. Sediment characteristics: silt %: 8-65 (mean 28), MGS: 101-186 (mean 148 μm).

Mollusca

On the intertidal flats more than 50 species of bivalves, 2 species of tusk shells (Scaphopoda) and 33 species of gastropods were found. We will shortly discuss these species one by one. On the beach and in the gravel several other species of empty shells were found, but we never found these alive on the mudflats. We will not deal with these species, since they probably do not live on the tidal flat but probably in the rocky areas, in the mangroves, or in deeper waters.

Class Bivalvia (bivalve shells)

During a short visit to the Western Australian Museum in 1998 a small collection of bivalves was donated to the curator of the Mollusca, Shirley Slack-Smith.

Nucula cf *astricta* (Iredale,1931). - Family Nuculidae. This species looks a bit like *N. astricta*, but has a clear escutcheon that is bordered by a ridge. Also the general form of the shell is different. It is also not *N. obliqua,* as it has a light colored periostracum and a spoon like pocket for the resilium. Range in length 2-10 mm. The living shell has a green skin (periostracum). The inside of the shell is nacreous, and the hinge has many teeth (like the bloody cockle). The animal has no siphons. The rim of the foot is fringed. This species was found at 24 stations, and always as a single specimen. This species was also reported in Roebuck Bay by Tulp & de Goey (1994) as *Nucula* spec. Sediment characteristics: silt %: 6-80 (mean 35), MGS: 96-186 (mean 137 μm).

Ledella spec. - Family Nuculanidae. The shell is elongated with coarse concentric ridges. Range in length 5-11mm. This species was found at 7 stations, mostly as a single specimen, but once up to three. Sediment characteristics: silt % 36-51 (mean 44), MGS: 104-186 (mean 133 μm).

Solemya cf *terraereginae* (Iredale,1931)– Family Solemyidae. Range in length 3-14 mm. This species was found at 67 stations. The highest density at a station was 9 (360 ind./m^2). Sediment characteristics: silt %: 3-65 (mean 23), MGS: 97-241 (mean 141 μm).

Modiolus micropterus (Deshayes,1836) – Family Mytilidae. This species was identified with Dharma (1992: pl. 18). Range in shell length 4-30 mm. It was found at 13 stations, with a highest density of 4 (160 ind./m^2). Normally mussels sit firmly attached on rocks by their byssus threads, which they make with their foot. This one strangely lives buried in the fine mud, and can survive there because it constructs a kind of tube with the byssus threads towards the surface. Within this tube it could not pump water through the shell for filtering, as the animal does not have long siphons. During our expedition only a few specimens were found. We however think that at times a large spat fall can be present. Evidence for this was found in 1991, when very often fragments of these shells were found in bird droppings (Tulp & de Goey, 1994), constituting more than 39% of the prey intake. Sediment characteristics: silt %: 11-73 (mean 31), MGS: 100-181 (mean 145 μm).

Anadara granosa (Linnaeus,1758) - Family Arcidae. This species has a heavy and strong shell. Range in shell length 2-44 mm. It was found at 33 stations on the mudflat, mostly within 100 m from the sandy beach. Encountered densities were up to 9 juveniles (360 ind./m^2) and 3 adults (120 ind./m^2). The shell never burrowed itself deep into the sediment, and often part of the shell was exposed above the sediment. Evidence that the posterior part was exposed on a regular or continuous basis was formed by the barnacles and other sessile animals that were attached to the shell. During low tide the animals also often crawled over the soft muddy sediment for a distance up to half a meter or more, leaving a characteristic trail of three parallel lines. The mid-line of the track is formed by the foot while the two other lines are left behind by the gaping valves. The species was identified with Wells & Bryce (1985: fig. 550), Lamprell & Healy (1998:

# Plate 6.1: Selected bivalves found in Roebuck Bay
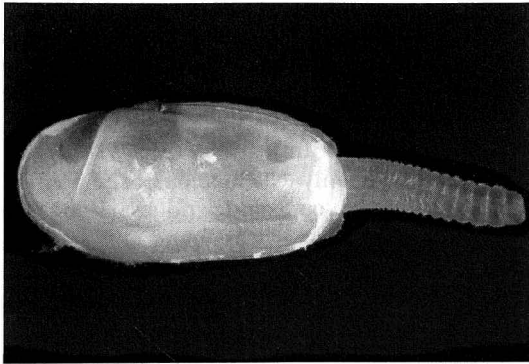
Siliqua cf. *winteriana*: One of the most abundant bivalves in Roebuck Bay. Two species of the bivalve family Cultellidae were found in the study area: The 'razor shell' *Cultellus* spec. and the here presented *Siliqua* cf. *winteriana*. Both bivalves are relatively thin-shelled and rapid burrowers, but *Siliqua* prefers finer substrates. The shell does not offer much protection, but a depth refuge does. The fine muds, which become semifluid when water-logged and stirred by wave action, put restrictions on the morphology of the shells. Thicker shelled bivalves with a higher density would sink in these muds. Typical for the family are the highly segmented syphons that break off easily when grabbed by a predator.
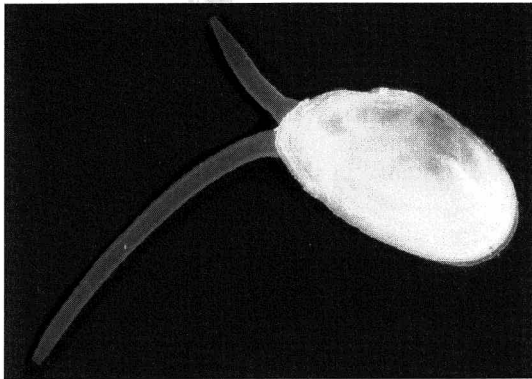
Tellina amboyensis: One species of the very diverse family Tellinidae. Tellins seem to be especially adapted to a wide range of habitats and were found in all soft bottom environments of the bay.
T. amboyensis occurred mostly in the muddy substrates of the eastern parts of the study area. Typical for the family are the long syphons and the laterally com-pressed and thin shell. With the longer inhalent syphon it picks up par-ticles from the surface, with the shorter exhalent syphon it expels water and faeces. Most of the species within the family are considered facultative deposit feeders but may also be capable of filter-feeding.
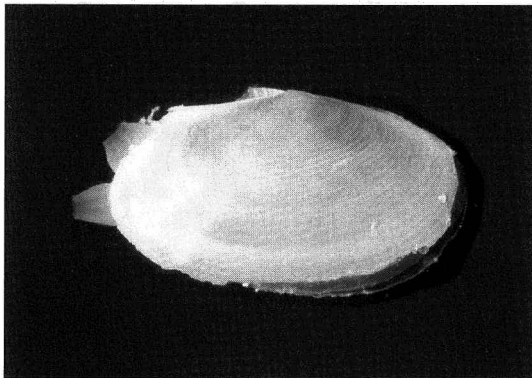
Gari lessonii: A member of the family Psammobiidae. The shells are very similar to those of the Tellinidae, but they lack a posterior flexure and never have lateral teeth. The genus *Gari* is mostly found in sandy substrates but may inhabit mangrove swamps as well. Some species show special adaptations against predation. Some can leap out of reach by an extension of their foot, others can autotomise the tips of their siphons when grabbed by predators.
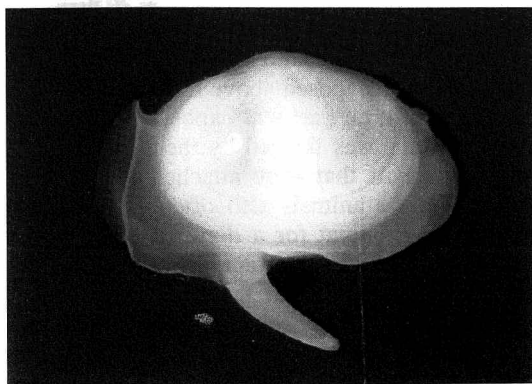
Galeomatidae: Galeomatid shells are morphologically very divers but normally small (less than 20 mm), thin, and often fragile. Some, like this genera, have the shell gaping widely when the animal is at rest, but can close the shell when disturbed. In some species it gapes permanently. In some taxa the shell is enclosed in the mantle and can be reduced, some-times to a rudiment. The foot and the mantle are well developed and often modified for crawling. Galeomatids are a beautiful example for the many adaptations bivalves have evolved through time. They live in association with many types of invertebrates. Often they live on the bodies of some annelids, other bivalves, sea anemones, sea urchins, shrimps or holothurians.

All photographs by Marc Lavaleye.

fig. 78) and Dharma (1992: pl. 18). This species is common along the coast of the northern half of Australia, but has been found as far south as Freemantle (WA). In Roebuck Bay it was also reported by Tulp & de Goey (1994). Sediment characteristics: Silt %: 7-91 (mean 50), MGS: 95-198 (mean 112 µm).

Family Pinnidae - A few specimens were found at the flats, almost completely burrowed in the sediment. These Fan or Pen shells are sometimes called Razorfish or Razor-back (Cotton, 1961). This probably refers to the danger of cutting your feet on these shells when walking bare-footed on the mud flats. The largest specimen measured about 10 cm.

Anodontia omissa (Iredale,1930) - Family Lucinidae. Identified with Lamprell & Whitehead (1992: fig. 140). Shell length 1-15 mm. It was found at 112 stations. Highest density was 1,840 ind./m^2, but these were all juveniles. This species was also reported from Roebuck Bay by Tulp & de Goey (1994). Sediment characteristics: Silt %: 3-89 (mean 56), MGS: 95-199 (mean 120 µm).

Divaricella irpex (E.A. Smith, 1885), synonym *D. ornata* (Reeve,1850) – Family Lucinidae. Identified with Dekker & Goud (1994), Lamprell & Whitehead (1992: fig. 143). Shell length 4-20 mm. It was found at 43 stations. Highest density was 200 ind./m^2. This species was also reported from Roebuck Bay by Tulp & de Goey (1994). Sediment characteristics: Silt %: 3-83 (mean 40), MS: 95-255 (mean 137 µm).

Divaricella bardwelli (Iredale, 1936) (Bushpoint Divaricella) – Family Lucinidae. Identified with Dekker & Goud (1994). Similar to the previous species, but the sculpture on the middle of the shell is faint. It also lives in another habitat in the southern part of the bay. Shell length 4-21 mm. The type locality of this species is Roebuck Bay. We, however, found it at only 1 station with a density of 120 ind./m^2. Sediment characteristics: Silt %:: 10.

Ctena spec. - Family Lucinidae. A small species with a solid and inflated shell, with strong radiating and concentric ridges. Shell length 2-3 mm. It was found at 7 stations. Highest density was 40 ind./m^2. Sediment characteristics: Silt %:5-70 (mean 21), MGS: 125-185 (mean 153 µm).

Montacuta spec. - Family Galeommatidae Shell length 4 mm. Only one specimen was found at one station. Sediment characteristics: Silt % 6, MGS: 185 µm.

Scintilla spec. - Family Galeommatidae (Plate 6.1). This species was only found once and not during the quantitative sampling.

Heterocardia gibbosula Stoliczka,1871 - Family Mactridae. A brittle shell, of which the surface is not shining. Identified with Lamprell & Whitehead (1992: fig. 275). Tulp & de Goeij (1994) reported this species

from Roebuck Bay under the name *Standella* cf *pellucida*.. Shell length 8-22 mm. It was found at 6 stations. Highest density was 40 ind./m^2. Sediment characteristics: Silt %: 9-74 (mean 49), MGS 95-179 (mean 138 µm).

Mactra grandis (Gmelin,1979) (Brown bean shell). - Family Mactridae. A large brown *Mactra* species. Identified with Lamprell & Whitehead (1992: fig. 258). Shell length 2-42 mm. It was found at 6 stations. Highest density was 40 ind./m^2. Sediment characteristics: Silt %: 8-28 (mean 16), MGS: 151-184 (mean 170 µm).

Mactra pura (Reeve,1854) - Family Mactridae. A heavy shell with fine concentric riblets.Identified with Lamprell & Whitehead (1992: fig. 242). Not found during the quantitative sampling.

Mactra spec.1 - Family Mactridae. Only one specimen was found at one station. Sediment characteristics: Silt %: 8, MGS: 177 µm.

Mactra spec.2 - Family Mactridae. Only one specimen was found at one station. Sediment characteristics: Silt %: 5.

Mactra spec.3 - Family Mactridae. Only two specimens were found at one station. Sediment characteristics: Silt %: 10, MGS: 163 µm.

Mactra spec.4 - Family Mactridae. Not found during the quantitative sampling.

Solen spec. - Family Solenidae. Shell length 9-29 mm. It was found at 3 stations. Highest density was 120 ind./m^2. Sediment characteristics: Silt %: 5-40 (mean 18), MGS: 150-156 (mean 153 µm).

Cultellus cultellus (Linnaeus, 1758) - Family Cultellidae. Shell length 3-50 mm. It was found at 10 stations. Highest density was 120 ind./m^2. Sediment characteristics: Silt %: 4-49 (mean 19), MGS 102-183 (mean 147 µm).

Siliqua cf. *winteriana* (Dunker,1852) – Family Cultellidae (Plate 6.1). This bivalve is abundant in the fluid mud. Peculiar is that it is adapted to predation by waders. The siphons are united and segmented and break off easily, which can safe the animal. Besides it reacts on the slightest touch by starting frantically to burrow deeper (to get away from the bill of the predator). Filter-feeder. The name *Siliqua* cf *winteriana* was already used for Roebuck Bay specimens by Tulp & De Goeij (1994). Although the differences with the true *S. winteriana* seem to be clear (our shell stays much smaller, there is no periostracum, the internal ridge is perpendicular to the upper site and the shell is not tapering posteriorly. Compare our figures (Plate 6.1 and Ch. 8) with Dharma (1992: pl. 24) and Abbott & Dance (1982: p. 340). Also *Siliqua tenerior* (Hedley,1915) figured by Lamprell & Healy (1998: fig.526) is quite different. As we do not have a better solution yet, we stick for the moment for reasons of continuity

to this name. Shell length 4-26 mm. It was found at 113 stations. Highest density was 520 ind./m². Sediment characteristics: Silt %: 17-99 (mean 74), MGS 94-188 (mean 103 µm).

Tellina capsoides (Lamarck,1818) - Family Tellinidae. Identified with Lamprell & Whitehead (1992: fig. 338). Tulp & de Goeij (1994) reported this species from Roebuck Bay under the name *Quadrans pristis.* Shell length 6-44 mm. It was found at 19 stations. Highest density was 200 ind./m². Sediment characteristics: Silt %: 18-86 (mean 58), MGS 95-167 (mean 117 µm).

Tellina piratica (Hedley,1918) - Family Tellinidae. Lamprell & Whitehead (1992: fig. 324). Tulp & de Goeij (1994) reported this species from Roebuck Bay under the name *Tellina ostracea.* Shell length 2-41 mm. It was found at 70 stations. Highest density was 600 ind./m². Sediment characteristics: Silt %: 3-89 (mean 14), MGS 100-371 (mean 166 µm).

Tellina amboynensis (Deshayes,1854) - Family Tellinidae (Plate 6.1). Identified with Lamprell & Whitehead (1992: fig. 373). This species is very similar to *T. exotica.* See for differences under *T. exotica.* Tulp & de Goeij (1994) reported this species from Roebuck Bay under the name *Tellina* cf *ancilla..* It has long siphons, one of which acts as a vacuum cleaner to get food from the bottom surface. Shell length 4-40 mm. It was found at 76 stations. Highest density was 280 ind./m². Sediment characteristics: Silt %: 16-96 (mean 71), MGS 95-186 (mean 108 µm).

Tellina cf *remies* (Linnaeus,1758) (syn. *Tellina sulcata* Lamarck,1818) - Family Tellinidae. Identified with Lamprell & Whitehead (1992: fig. 342). Shell length 7 mm. Only one specimen was found at one station. Sediment characteristics: Silt %: 38, MGS 122 µm.

Tellina spec. 1 - Family Tellinidae. Shell length 5-26 mm. Only found at two stations. Highest density was 80 ind./m². Sediment characteristics: Silt %: 8-27 (mean 18), MGS 107-134 (mean 120 µm).

Tellina spec. 2 (Bushpoint Tellina) - Family Tellinidae. Looks similar to *T. exotica*, but is larger and much flatter. Shell length 32 mm. Only one specimen was found at one station. Sediment characteristics: Silt %: 10.

Tellina spec.3 (Pointed Tellina) - Family Tellinidae. Shell length 10-16 mm. It was found at 4 stations. Highest density was 160 ind./m². Sediment characteristics: Silt %: 9-73 (mean 35), MGS 97-178 (mean 133 µm).

Tellina spec. 4 (Oval Tellina) - Family Tellinidae. Shell length 2-31mm. It was found at 7 stations. Highest density was 80 ind./m². Sediment characteristics: Silt %: 51-98 (mean 84), MGS 95-110 (mean 103 µm).

Tellina spec. 5 (Mud Tellina) - Family Tellinidae. Shell length 2-16 mm. It was found at 23 stations. Highest density was 680 ind./m², but then only juvenile specimens (spatfall). Sediment characteristics: Silt %: 24-94 (mean 57), MGS 94-370 (mean 124 µm).

Tellina spec. 6 (Mysia Tellina) - Family Tellinidae. Shell length 13-15 mm. It was found at 2 stations. Highest density was 40 ind./m². Sediment characteristics: Silt %: 38-51 (mean 45), MGS 110-118 (mean 114 µm).

Tellina spec. 7 (Orange Tellina) – Family Tellinidae. A small shell that has some orange colour, the dorso-posterior area is coarsely ribbed. At least 5 specimens were found during the quantitative sampling.

Tellina cf *exotica* - Family Tellinidae. This species is very similar to *T. amboynensis*, and therefore was frequently mixed up with this species. The dorso-posterior corner of the shell is hooked instead of rounded. Furthermore, the dorso-posterior area is not smooth but ribbed (microscope). Tulp & de Goeij (1994) reported this species from Roebuck Bay under the name *Macoma* spec. To some of their samples the name *Macoma exotica* was attached, and therefore that name got stuck and is still used here. To my information, however, the name "exotica" only exist as the name of a subgenus and not as a species name within the genus *Macoma*. Shell length 3-20 mm. It was found at 55 stations. Highest density was 320 ind./m². Sediment characteristics: Silt %: 5-99 (mean 59), MGS 94-199 (mean 119 µm).

Macoma spec.1 (Roebuck Macoma) - Family Tellinidae. Shell length 7-13 mm. It was found at 4 stations. Highest density was 40 ind./m². Sediment characteristics: Silt %: 73-86 (mean 78), MGS 96-105 (mean 99 µm).

Semele spec.1 - Family Semelidae. Not found during the quantitative sampling.

Gari lessoni (Blainville,1826) – Family Psammobiidae (Plate 6.3). Identified with Lamprell & Whitehead (1992: fig. 391). One of the larger bivalves. Filter feeder. Note the purple colour and the oblique ridges on the shell. Shell length 8-25 mm, but also larger specimens up to 50 mm were found in the area. It was found at 9 stations. Highest density was 40 ind./m². Sediment characteristics: Silt %: 18-78 (mean 55), MGS 98-179 (mean 130 µm).

Donax spec. 1 - Family Donacidae. Shell length 2-4 mm. Only three specimens were found at 1 station. Sediment characteristics: Silt %: 3, MGS 180 µm.

Anomalocardia squamosa (Linnaeus,1758) - Family Veneridae. Identified with Lamprell & Whitehead (1992: fig. 465) and Abbott & Dance (1982: p. 366). Tulp & de Goeij (1994) also reported this species from Roebuck Bay. Shell length 2-39 mm. It was found at

47 stations. Highest density was 520 ind./m². Sediment characteristics: Silt %: 4-75 (mean 26), MGS 99-371 (mean 147 µm).

Placamen gilva (Philippi,1849) - Family Veneridae. Identified with Lamprell & Whitehead (1992: fig. 474). Shell length 9-32 mm. It was found at 4 stations. Highest density was 40 ind./m². Sediment characteristics: Silt %: 8-91(mean 40), MGS 95-188 (mean 158 µm).

Placamen gravescens (Menke,1843) - Family Veneridae. Identified with Lamprell & Whitehead (1992: fig. 473). Shell length 5-24 mm. It was found at 2 stations. Highest density was 80 ind./m². Sediment characteristics: Silt %: 11-17 (mean 14), MGS 108-138 (mean 123 µm).

Tapes spec. 1 (Dampier Tapes) - Family Veneridae. Not found in the quantitative samples.

Tapes spec. 2 - Family Veneridae. Shell length 7-25 mm. It was found at 7 stations. Highest density was 120 ind./m². Sediment characteristics: Silt %: 7-85 (mean 44), MGS 96-170 (mean 120 µm).

Gafrarium dispar (Holten,1802) - Family Veneridae. Identified with Lamprell & Whitehead (1992: fig.503). Shell length 5-26 mm. It was found at 7 stations. Highest density was 80 ind./m². Sediment characteristics: Silt %: 9-67 (mean 29), MGS 96-178 (mean 132 µm).

Venus spec. 1 (Bushpoint Venus) - Family Veneridae. Not found in the quantitative samples.

Dosinia spec. 1 - Family Veneridae. Shell length 21 mm. It was found at 2 stations. Highest density was 40 ind./m². Sediment characteristics: Silt %: 3-8 (mean 5), MGS 176-186 (mean 181 µm).

Dosinia spec. 2 (Inflated Dosinia) – Family Veneridae. Not found in the quantitative samples.

Veneridae spec. 1 - Family Veneridae. Shell length 4-6 mm. Only three specimens were found at 1 station. Sediment characteristics: Silt %: 10.

Corbula spec. 1 - Family Corbulidae. Shell length 5-7 mm. It was found at 11 stations. Highest density was 360 ind./m². Sediment characteristics: Silt %: 3-31 (mean 14), MGS 143-181 (mean 171 µm).

Corbula spec. 2 (Heavy ribbed Corbula) - Family Corbulidae. Shell length 8 mm. Only one specimen was found. Sediment characteristics: Silt %: 4, MGS 188 µm.

Laternula creccina (Reeve,1860) - Family Laternulidae. Identified with Wells & Bryce (1985: Fig. 663) and Lamprell & Healy (1998: Fig. 622) Length 3cm. Lives in the mud. Filter feeder. The two siphons are united to a fleshy chimney, the small tentacles on top of the siphons can prevent larger particles to enter. Shell length 7-25 mm. It was found at 3 stations. Highest density was 40 ind./m². Sediment characteristics: Silt %: 35-43 (mean 40), MGS 104-162 (mean 124 µm).

Class Scaphopoda (tusk shells)

Dentalium cf *bartonae* (Lamprell & Healy,1998) (Ribbed Dentalium) - Family Dentaliidae. *D. bartonae* looks similar to our species and was also found in Roebuck Bay, though not intertidally but at 32 m depth (Lamprell & Healy, 1998). Shell length 9-15 mm. It was found at 18 stations. Highest density was 200 ind./m². Sediment characteristics: Silt %: 4-92 (mean 43), MGS 95-186 (mean 140 µm).

Laevidentalium cf *lubricatum* (G.B. Sowerby,1860) (Smooth Dentalium) - Family Dentaliidae. *L. lubricatum* was also found in Roebuck Bay and looks similar, but is much larger (6 cm) (Lamprell & Healy, 1998). Our intertidal specimens had a length of 7-36 mm. It was found at 38 stations. Highest density was 120 ind./m². Sediment characteristics: Silt %: 4-50 (mean 16), MGS 99-298 (mean 193 µm).

Class Gastropoda (snails)

Clanculus spec. - Family Trochidae. Shell length 2-5 mm. It was found at 4 stations. Highest density was 40 ind./m². Sediment characteristics: Silt %: 4-11 (mean 7), MGS 117-186 (mean 153 µm).

Calliostoma spec. - Family Trochidae. Not found in the quantitative samples. This species was seen crawling on the mudflats near BBO.

Nerita spec. - Family Neritidae. Shell length 12 mm. Only one specimen was found at one station. Sediment characteristics: Silt %: 96, MGS 96 µm.

Cerithidea cingulata (Mud Cerithium) – Family Potamididae. At first we confused this snail with the very similar *Cerithium* species. Also Tulp & de Goeij (1994) reported this species from Roebuck Bay under the name *Cerithium* spec. Because of its circular multiwhorled operculum it, however, clearly belongs in this family. The distribution of the species of this family is almost always restricted to the mangroves and the direct surroundings. In accordance with this, *C. cingulata* was only found in Roebuck Bay on the soft mud near mangroves. It crawls over the surface of the mud and is a deposit feeders (eats small algae). Shell length 3-29 mm. It was found at 15 stations. Highest density was 200 ind./m². Sediment characteristics: Silt %: 20-98 (mean 59), MGS 96-186 (mean 122 µm).

Terebralia sulcata – Family Potamidae. This large snail is common in the mangrove forest near Dampier Creek.

Family Littorinidae - Shell length 4-5 mm. It was found at 2 stations. Highest density was 80 ind./m². Sediment characteristics: Silt %: 16-24 (mean 40), MGS 124-147 (mean 136 µm).

Stenothyra spec. - Family Stenothyridae. Shell length 2-3 mm. It was found at 3 stations. Highest density was 240 ind./m^2. Sediment characteristics: Silt %: 67-96 (mean 86), MGS 109-110 (mean 109 µm).

Polinices conicus (Lamarck, 1822) (Conical sand snail) - Family Naticidae. The shell is white with a brown corneous operculum. Often traces of the burrowing activity of this snail just underneath the sandy surface could be seen, and therefore the hidden animal was easily found. Once an animal was unearthed still attached to his bivalve prey, in this case a *Cultellus*. A few times a large (diameter 7 cm), crystal clear jelly sausage-like mass bent into a circle was found on the sand flats. Though is does not look much like the typical sand incrusted girdle like egg masses of Naticidae, it was proven by Murray (1962), that it was the egg mass of *P. conicus*. Shell length 9-17 mm. It was found at 5 stations in the quantitative samples, but was seen frequently in the field. Highest density was 40 ind./m^2. Sediment characteristics: Silt %: 6-49 (mean 27), MGS 99-165 (mean 133 µm).

Natica spec. 1 - Family Naticidae. Colour of the shell uniform and dull. By the calcareous operculum it is easily distinguished from the former species. Shell length 6 mm. Only one specimen was found at one station. Sediment characteristics: Silt %:12, MGS 165 µm.

Natica spec. 2 (White operculum Natica) - Family Naticidae. Shell with brown streaks. Like the former species it has a white calcareous operculum. Shell length 3-6 mm. It was found at 3 stations. Highest density was 40 ind./m^2. Sediment characteristics: Silt %: 9-17 (mean 13), MGS 146-174 (mean 162 µm).

Epitonium spec. - Family Epitoniidae. Shell length 5-13 mm. It was found at 3 stations. Highest density was 40 ind./m^2. Sediment characteristics: Silt %: 29-71 (mean 44), MGS 96-150 (mean 125 µm).

Eulima spec. - Family Eulimidae. Shell length 3-5 mm. It was found at 3 stations. Highest density was 820 ind./m^2. Sediment characteristics: Silt %: 5-28 (mean 19), MGS 124-185 (mean 155 µm).

Niso spec. – Family Eulimidae. Not found in the quantitative samples.

Family Muricidae - Shell length 17 mm. Only one specimen was found. Sediment characteristics: Silt %: 42, MGS 162 µm.

Small brown Columbella - Family Columbellidae. Shell length 3-11 mm. It was found at 4 stations. Highest density was 40 ind./m^2. Sediment characteristics: Silt %: 6-34 (mean 24), MGS 110-186 (mean 138 µm).

Family Columbellidae - Shell length 2-10 mm. It was found at 15 stations. Highest density was 160 ind./m^2. Sediment characteristics: Silt %: 8-51(mean 33), MGS 101-169 (mean 124 µm).

Nassarius dorsatus (Röding,1798) (Large Ingrid eating snail) - Family Nassariidae. Identified with Abbott & Dance (1982: p. 180), Wells & Bryce (1985: Fig. 347) and Wilson (1994: pl. 14). Very commonly seen everywhere on the flats crawling around looking for prey or carrion. The foot is very powerful, and when holding the shell in your hand it will wriggle forcibly with that foot to free itself. The name "Ingrid eating snail" was coined because these animals were particularly attracted by the legs of Ingrid Tulp, who did pioneering work on the benthos of Roebuck Bay in 1991 (Tulp & De Goey, 1994). Shell length 2-28 mm. It was found at 81 stations. Highest density was 400 ind./m^2. Sediment characteristics: Silt %: 4-96 (mean 54), MGS 95-199 (mean 119 µm).

Nassarius spec. 1 (Small Ingrid eating snail) - Family Nassariidae. Shell length 4-14 mm. It was found at 15 stations. Highest density was 160 ind./m^2. Sediment characteristics: Silt %: 4-98 (mean 52), MGS 95-199 (mean 120 µm).

Nassarius spec. 2 - Family Nassariidae. Shell length 6 mm. Only one specimen was found. Sediment characteristics: Silt %: 34, MGS 141 µm).

Family Marginellidae - Carnivorous and scavenging white snails, common on the mud flats, crawling over the mud flat during low tide looking for prey. With a siphon it can still breath when it is buried in the mud. This flexible organ is also the "nose" of the animal. It can dye your fingers purple if you squeeze them. Shell length 3-7 mm. It was found at 18 stations. Highest density was 120 ind./m^2. Sediment characteristics: Silt %: 6-58 (mean 30), MGS 100-371 (mean 141 µm).

Family Mitridae - Shell length 8-10 mm. It was found at 2 stations. Highest density was 40 ind./m^2. Sediment characteristics: Silt %: 41-58 (mean 49), MGS 135-141 (mean 138 µm).

Vexillium radix (Sowerby,1874) - Family Costellariidae. Identified with Wells & Bryce (1985: Fig. 430). Shell length 3-13 mm. It was found at 15 stations. Highest density was 80 ind./m^2. Sediment characteristics: Silt %: 4-57 (mean 31), MGS 121-181 (mean 160 µm).

Melo amphora (Solander, 1786) – Family Volutidae. This species, which is common at 80 mile beach, was only seen once at the mudflat near Dampier creek at the low water line. That the species is not common here is strengthened by the fact that the one specimen found was a juvenile.

Family Turridae - Shell length 15-18 mm. It was found at 2 stations. Highest density was 40 ind./m^2. Sediment characteristics: Silt %: 36-55 (mean 45), MGS 121-178 (mean 149 µm).

Family Terebridae - Shell length 9-21 mm. It was found at 3 stations. Highest density was 80 ind./m^2.

Sediment characteristics: Silt %: 33-71 (mean 47), MGS 119-175 (mean 150 μm).

Family Pyramidellidae - Shell length 2-5 mm. It was found at 2 stations. Highest density was 40 ind./m². Sediment characteristics: Silt %: 58-79 (mean 68), MGS 97-151 (mean 124 μm).

Chrysallida spec. - Family Pyramidellidae. Shell length 3 mm. Not found in the quantitative samples.

Turbonilla spec. - Family Pyramidellidae. Shell length 3 mm. Only one specimen was found. Sediment characteristics: Silt %: 57.

Leucotina spec. - Family Amathinidae. Following Beesley *et al*. (1998) this genus was removed from the Pyramidellidae to this family. Shell length 5-9 mm. It was found at 4 stations. Highest density was 40 ind./m². In shell grit samples from the four long term monitoring stations (near BBO) this shell is rather abundant. Sediment characteristics: Silt %: 42-84 (mean 67), MGS 95-162 (mean 112 μm).

Acteon spec. – Family Acteonidae. Shell length 10 mm. Only one specimen was found. Sediment characteristics: Silt %: 38, MGS 118 μm.

Retusa spec. – Family Retusidae. Shell length 3-5 mm. It was found at 9 stations. Highest density was 80/m². Sediment characteristics: Silt %: 49-97 (mean 85), MGS 94-137 (mean 102 μm).

Haminoea spec. (Green Haminoea) – Family Haminoeidae. belongs to the opisthobranch snails. During low tide it crawls over the mudflats. Carnivorous. Animals are dark green, colour fades away quickly in captivity. They have two tiny eyes and a thin shell. Shell length 4-7 mm. It was only found at 3 stations during the quantitative sampling, but was commonly seen at the mud flat near BBO about 100 m off the sandy beach. .Highest density was 80 ind./m². Sediment characteristics: Silt %: 17-45 (mean 36), MGS 99-116 (mean 106 μm).

Onchidium spec. – Family Onchidiidae. This peculair shell-less snail was not found in the quantitative samples. However, the large animals (up to 6 cm) were often seen crawling over the mudflats close to the beach and near rocks. Their presence was also marked by their long thread like fecal trail that they leave behind.

Salinator cf *burmana* (Blanford,1867) – Family Amphibolidae. This species differs from the two species (*S. solida* and *S. fragilis*) from southern Australia by having a corrugated umbilicus (Beesley *et al*., 1998: Fig. 17:29). Because of its form and its partly calcified operculum it looks quite similar to a small moon snail (Naticidae). As it also was only found in the neighbourhood of the mangroves we called it the Mangrove moon snail. Shell length 2-8 mm. It was found at 15 stations. Highest density was 280 ind./m².

Sediment characteristics: Silt %: 9-98 (mean 84), MGS 95-178 (mean 111 μm).

Cassidula spec. – Family Ellobiidae. Shell length 7 mm. It was found at 2 stations. Highest density was 80 ind./m². Sediment characteristics: Silt %: 37-45 (mean 41), MGS 104-179 (mean 142 μm).

Sipuncula

Cf *Phascolion* spec. – Family Golfingiidae. Length 10-40 mm. It was found at 7 stations. Highest density was 40 ind./m². Sediment characteristics: Silt %: 11-78 (mean 53), MGS 97-150 (mean 114 μm).

Sipunculida spec. 1 (Ringed sipunculid) - Length 9-130 mm. It was found at 34 stations. Highest density was 120 ind./m². Sediment characteristics: Silt %: 3-89 (mean 46), MGS 95-186 (mean 151 μm).

Sipunculida spec. 2 - Length 5-130 mm. It was found at 46 stations. Highest density was 240 ind./m². Sediment characteristics: Silt %: 4-82 (mean 24), MGS 98-210 (mean 146 μm).

Echiura

Echiurus spec. Length 22-50 mm. It was found at 3 stations. Highest density was 40/m². Sediment characteristics: Silt %: 9-64 (mean 32), MGS 96-174 (mean 147 μm).

Annelida

Class Hirudinea

One species of marine leech. This active animal has a slender body covered with wards, and with suckers at both ends. Not all leeches are blood suckers, this one eats probably small food particles. Length 12-22 mm. It was found at 2 stations. Highest density was 40/m². Sediment characteristics: Silt %: 30-46 (mean 38), MGS 150-170 (mean 160 μm).

Class Polychaeta

During the macrobenthic survey it is was impossible to identify the polychaetes further than the family level. For this we used the following literature: Day, 1967; Fauchald, 1977. We here give some general descriptions of the animals with characteristics that are easily recognised. It has to be noted, however, that the microscopical features of the setae (bristles) often form an important key for the identification of Polychaeta.

Family Orbiniidae - Length 4-92 mm. These worms have a pointed head without appendages. They are mostly easily recognized by the pair of flattened

Plate 6.2: Selected polychaete families occurring in Roebuck Bay
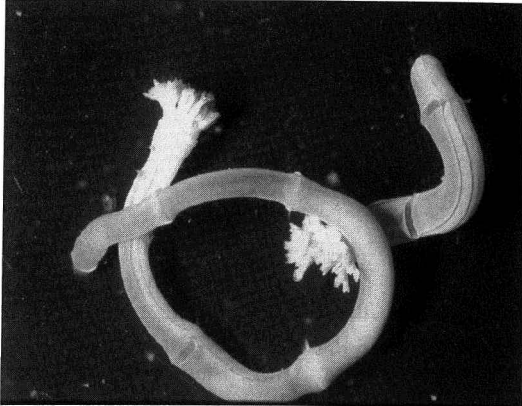
Oweniidae: Oweniids, together with chaetopterid tube-worms, dominated the fauna in Roebuck Bay in terms of sheer numbers. Densities of over 10,000 individuals per square meter were reached in some locations. Oweniids live in straight tubes of sand particles and shell fragments, glued together by mucus. The stiff bristles are arranged very tightly in bands between the segments and made it very difficult to extract the worms from their tubes. The encrusted tubes offer protection against predators, and at the same time create an aerated environment in se-diments that are frequently anoxic at depth. With the tentacular crown they are capable of both filter-feeding and surface depo-sit-feeding. While doing the latter, the lips pick up particles directly.
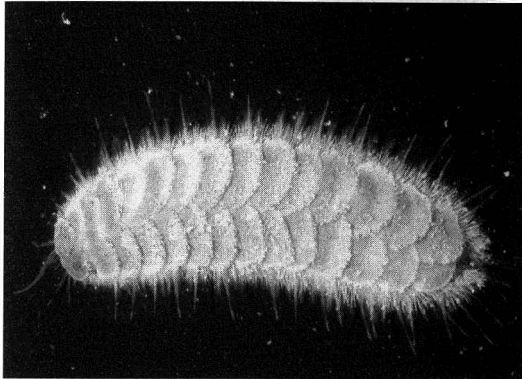
Polynoidae: These scale worms are common intertidal and shallow-water worms on all surfaces. They are free living and considered to be carnivorous, feeding on small crustaceans, echinoderms, polychaetes, gastropods and hydroids. All poly-noids have a muscular eversible pharynx armed with jaws. Life habits vary widely within the family. Most of the specimens sampled in Roebuck Bay were similar in morphology to the polynoid shown on the picture. The animal shown had a length of approximately 5 mm.
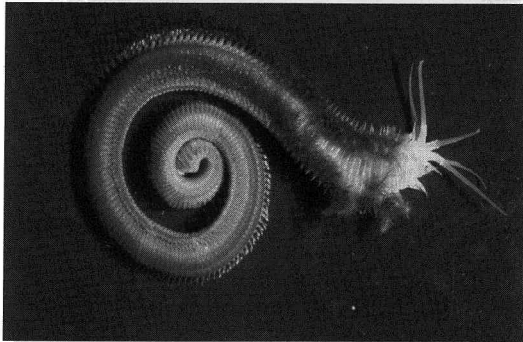
Onuphidae: The largest of the tube-building worms found in the study area. The tubes are very conspicuous and built of very coarse sand and shell fragments. At the top end the tube bends around, giving it the impres-sion of a walking stick. The feeding habits differ bet-ween closely related species. It is un-clear whether these animals should be considered herbivores or generalised scavengers. In the study area onuphids were mostly en-countered near the muddy banks of tidal creeks, pre-dominantly in the otherwise sandy areas of the Dampier Creek region.
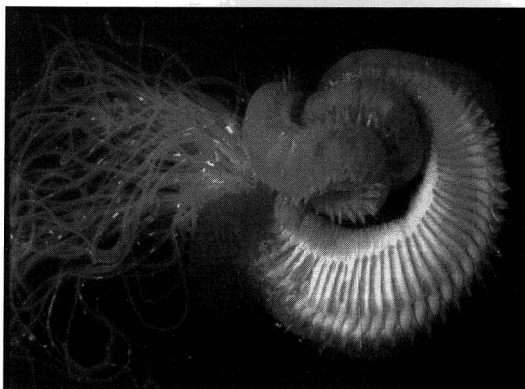
Terebellidae: Terebellids are rather large, mostly tubi-culous polychaetes. The anterior end is equipped with a series of very extensible tentacles, which are used to filter diatoms, other unicellular algae, and various small invertebrates out of the water column. The here shown specimen of the genus *Amphritite* was found in rocky areas in the northern parts of Roebuck Bay.

Photographs by Marc Lavaleye.

papillae sitting on the back of most of the segments. It was found at 7 stations. Highest density was 40 ind./m². Sediment characteristics: Silt %: 3-89 (mean 17), MGS 94-298 (mean 159 µm).

Family Polynoidae (Plate 6.2) - Scale worms. Polychaetes with a restricted amount of elytra (scales), mostly 12 or 15. The body is flattened, and length/width ratio is mostly less than 10. Predator with large proboscis (evertable mouth with jaws). During collection some animals break spontaneously. Some live commensally in tubes of other polychaetes. Length 2-52 mm. It was found at 93 stations. Highest density was 400 ind./m². Sediment characteristics: Silt %: 3-92 (mean 33), MGS 95-255 (mean 144 µm).

Family Sigalionidae - Polychaetes that have elytra (scales) like the family Polynoidae, but number of elytra is much larger. The body is also long, slender and worm-like. Length 2-82 mm. It was found at 43 stations. Highest density was 200 ind./m². Sediment characteristics: Silt %: 4-88 (mean 48), MGS 95-188 (mean 127 µm).

Family Amphinomidae - The most peculiar characteristic is the possession of bundles of brittle, glass-like setae, which mostly look whitish. However, some Spionidae have similar setae. The notopodia (the dorsal part of the parapodia) have branched or multiple cirri, which Spionidae lack. Especially in large specimens, these glassy hollow setae can pierce the skin of humans and inject a poison, which gives a painful burning feeling. Length 5-30 mm. It was found at 18 stations. Highest density was 120 ind./m². Sediment characteristics: Silt %: 6-80 (mean 32), MGS 96-181 (mean 142 µm).

Family Onuphidae (Onuphid bristle worms) (Plate 6.2) - This family is sometimes incorporated in the family Eunicidae. The worms have a distinct head with five long antennae. The basis of these antennae is annulated (with rings). Most species in Roebuck Bay had comb-like gills on their backs. The worms have powerful jaws and live in a sand- and shell encrusted tube that often sticks out of the sediment like a periscope. The animal does not leave the burrow but stretches itself to catch prey and algae. Length 4-72 mm. It was found at 89 stations. Highest density was 560 ind./m². Sediment characteristics: Silt %: 4-94 (mean 40), MGS 95-186 (mean 137 µm).

Family Lumbrineridae (Lumbrinerid bristle worm) - The head is conical or rounded and has no appendages or eyes. The body is cylindrical and the surface often iridescent. The parapodia are small and not divided into two parts. The black jaws are often visible through the body wall. The animal is a predator that moves around freely through the sediment. Length 6-130 mm. It was found at 88 stations. Highest density

was 120 ind./m². Sediment characteristics: Silt %: 3-95 (mean 29), MGS 95-284 (mean 145 µm).

Family Arabellidae - Very similar to the family Lumbrineridae, but can be separated because they can have eyes, and the jaws have posteriorly a pair of long slender supporting hard parts. Only found once during the quantitative sampling.

Family Pilargidae - These worms are most easily recognised by the large curved spine in the dorsal part of the parapodium. The spines look much like a fish hook (without a barb), and they are often curved over the dorsal side of the animal as a kind of protection. Length 8-20 mm. It was found at 9 stations. Highest density was 80 ind./m². Sediment characteristics: Silt %: 9-82 (mean 63), MGS 95-168 (mean 112 µm).

Family Nereidae - The head has 4 eyes, 8 tentacles, and thick palps at the front of the head. Furthermore it has two powerful jaws, and the parapodia clearly have two bundles of setae. Length 3-60 mm. It was found at 18 stations. Highest density was 40 ind./m². Sediment characteristics: Silt %: 3-88 (mean 32), MGS 96-189 (mean 144 µm).

Family Syllidae - These small worms have strange, ringed, long barrel shaped stomachs, which can easily be seen through the body wall. The parapodia only have one bundle of setae, and the cirri and tentacles often have the appearance to be segmented. Length 8-33 mm. It was found at 11 stations. Highest density was 40 ind./m². Sediment characteristics: Silt %: 4-85 (mean 33), MGS 96-186 (mean 143 µm).

Family Phyllodocidae (Train worm) - The name is coined because they have the habit of crawling over the bottom during the day. At least two different species were encountered, one of which is bright green. Especially this green species was abundantly seen in the field, crawling openly over the sediment. The uncoloured species had a length of 4-52 mm, was found at 46 stations with a highest density of 120 ind./m². Sediment characteristics: Silt %: 3-79 (mean 32), MGS 95-186 (mean 140 µm). The green species had a length of 14-73 mm, was found at 12 stations with a highest density of 200 ind./m². Sediment characteristics: Silt %: 9-83 (mean 35), MGS 96-176 (mean 131 µm).

Family Nephtyidae (Catworm) - These worms often have a dirty yellow colour, the head is rather indistinct, without eyes and long tentacles. The parapodia are clearly divided into two parts. Length 4-83 mm. It was found at 162 stations. Highest density was 280 ind./m². Sediment characteristics: Silt %: 3-99 (mean 23), MGS 95-298 (mean 153 µm).

Family Glyceridae (two species) (Glycerid bristle worm) - These worms look similar to the Lumbrineridae, but the cone shaped head is long and slender. Besides, at the end of the cone it has four small antennae,

that can only been seen under a high magnification. Another peculiar feature is that every segment can be divided into 2 or 3 pseudosegments, only one of these having a pair of parapodia. These worms burrow actively through the sediment looking for prey. The black jaws, which can seen through the body wall and are situated far behind the mouth, can be protruded completely during grabbing prey. The larger species had a length of 10-100 mm, was found at 41 stations with a highest density of 80 ind./m². Sediment characteristics: Silt %: 3-83 (mean 27), MGS 95-187 (mean 137 µm). The greenish species had a length of 3-31 mm, was found at 205 stations with a highest density of 920 ind./m². Sediment characteristics: Silt %: 3-94 (mean 37), MGS 94-284 (mean 135 µm).

Family Goniadidae - Length 8-10 mm. The only major difference to the former family Glyceridae are the jaws. The glycerids have four jaws at the end of the proboscis, while the Goniadidae only have two large jaws at the end, and a pair of rows of small V-shaped teeth along the sides of the proboscis. It was found at 2 stations. Highest density was 40 ind./m². Sediment characteristics: Silt %: 4-14 (mean 9), MGS 173-187 (mean 180 µm).

Family Spionidae - The head is small and elongated and sits on the dorsal side of the first segment(s). It has no antennae. However, behind or at the sides of the head are two big grooved tentacles. Unfortunately, these tentacles break off easily in the process of collecting. The parapodia are clearly divided into two parts. Mostly all the anterior parapodia have dorsal cirri. Length 3-30 mm. It was found at 26 stations. Highest density was 280 ind./m². Sediment characteristics: Silt %: 4-77 (mean 26), MGS 96-210 (mean 135 µm).

Family Chaetopteridae (Plastic worm) - The main characteristic of these worms is their strong horny tube. The length can be over 30 cm, while the width is only a 1 mm. The tubes are positioned vertically in the sediment and only the upper millimetre is exposed. The animal itself is even more slender, and is only detected by looking at the brown-yellow transparent tube under a high magnification. The animals can form dense aggregations, and sampling these areas produced a sample of "spaghetti". Length 3-170 mm. It was found at 235 stations. Highest density was 15,200 ind./m². Sediment characteristics: Silt %: 3-88 (mean 37), MGS 95-284 (mean 135 µm).

Family Chaetopteridae (Brown Club worm) - This species was at first not recognised, because mostly we only found the abdomen. This has very peculiar parapodia. The main feature of the parapodium is a dorsal, club-like fleshy extension, supported by an internal bristle (aciculum). This species is much bigger, though not longer than the previous species. And it

was never collected with a tube. Length 5-53 mm. It was found at 13 stations with a highest density of 200 ind./m². Sediment characteristics: Silt %: 5-79 (mean 39), MGS 96-180 (mean 129 µm).

Family Cirratulidae - Long cylindrical worms with a pointed or rounded head. The parapodia mainly consist of two bundles of setae that seem to arise directly from the sides of the body. Often many segments have a pair of long cirri that easily break off. Length 4-22 mm. It was found at 16 stations. Highest density was 80 ind./m². Sediment characteristics: Silt %: 8-65 (mean 29), MGS 101-186 (mean 149 µm).

Family Paraonidae - Rather similar to the family Spionidae, but the large conspicuous dorsal cirri (branchiae) only start at segment 4 to 18 and do not continue until the very end of the animal. Length 7-92 mm. It was found at 16 stations. Highest density was 160 ind./m². Sediment characteristics: Silt %: 4-71 (mean 18), MGS 96-184 (mean 153 µm).

Family Opheliidae - Polychaetes with a rather stiff spindle-like body, often with a longitudinal groove along the ventral side of the body. The head is pointed and has no appendages. Length 6-30 mm. It was found at 83 stations. Highest density was 440 ind./m². Sediment characteristics: Silt %: 3-79 (mean 17), MGS 95-298 (mean 154 µm).

Family Capitellidae - Reddish worms without obvious parapodia. The thorax segments (around 10) have mostly four bundles of short setae, while the abdomen has rows of hooked setae that barely protrude from the body wall. The small pointed head looks like a nose-like knob. Length 3-80 mm. It was found at 98 stations. Highest density was 200 ind./m². Sediment characteristics: Silt %: 3-99 (mean 27), MGS 95-284 (mean 151 µm).

Family Maldanidae (Bamboo worm) - These worms are characterised by greatly elongated segments, hence the English name. The head has no appendages, but often has a more or less circular oblique shield. Parapodia mainly represented by setae. Length 5-60 mm. It was found at 67 stations. Highest density was 240 ind./m². Sediment characteristics: Silt %: 3-85 (mean 29), MGS 95-188 (mean 150 µm).

Family Sternaspidae - Animals with a short swollen body. The last segments are covered by a large flat bi-lobed shield. The worm digs in mud with the head down, the shield at the back is to close off the burrow. Length 3-11 mm. It was found at 24 stations. Highest density was 720 ind./m². Sediment characteristics: Silt %: 5-49 (mean 26), MGS 99-178 (mean 136 µm).

Family Oweniidae (Owenid bristle worm) (Plate 6.2) - The thorax of the animal has greatly elongated segments like in the family Maldanidae. Numerous minute hook-like setae form conspicuous transverse bands on the thorax segments. Around the head is a

crown of short, branched tentacles. These tiny worms are very abundant at places, and conspicuous because of their flexible sand-encrusted tubes that taper on both ends. With their tentacular crown they can filter-feed or pick up small particles from the substrate. They can, superficially, be confused with the Phoronida. Length 2-150 mm. It was found at 192 stations. Highest density was 9,600 ind./m². Sediment characteristics: Silt %: 3-88 (mean 35), MGS 95-284 (mean 138 µm).

Family Flabelligeridae - The surface of the body of these worms is mostly covered with lots of fine papillae. The setae are often as long as the segments are wide, and the head often has a crown of very long setae. Length 9-45 mm. It was found at 15 stations. Highest density was 120 ind./m². Sediment characteristics: Silt %: 6-88 (mean 32), MGS 99-181 (mean 149 µm).

Family Sabellariidae - These worms live in tubes made of sandgrains. These tubes do not have the neat conical form of the family Pectinariidae. The head has a mostly circular shield of golden thick setae. These animals mostly live attached to hard objects or together form reefs. Length 5-10 mm. It was found at 3 stations. Highest density was 40 ind./m². Sediment characteristics: Silt %: 26-30 (mean 28), MGS 150-186 (mean 168 µm). .

Family Ampharetidae - These animals live in a fragile tube that is mostly destroyed during collection. The abdomen of the animal has paddle like parapodia, that seem to be devoid of setae. Under a high magnification, however, many short hooked setae can be discovered. The head has many retractable tentacles near the mouth. Length 8-28 mm. It was found at 9 stations. Highest density was 40 ind./m². Sediment characteristics: Silt %: 5-46 (mean 22), MGS 102-185 (mean 157 µm).

Family Terebellidae (Plate 6.2) - These animals are very similar to the family Ampharetidae, but the mouth tentacles are not retractable. Besides, the segment 2 to 4 often have branched gills or lobes, and the anal part of the body does not have appendages. Among the different species a large bristleworm of the genus *Amphitrite* was found. *Amphitrite* mostly lives in a tube under rocks on sandy sediment. The many long tentacles are projected over the bottom and work like conveyor belts to transport small food particles to the mouth. It also has many branched gills. Length 20-80 mm. During the sampling it was only found at 3 stations. Highest density was 40 ind./m². Sediment characteristics: Silt %: 5-22 (mean 11), MGS 165-176 (mean 169 µm).

Family Sabellidae - These worms have a large feather like crown around the mouth. The animals live in rather strong flexible tubes made out of mud and/or mucus. Length 8-21 mm. It was found at 11 stations.

Highest density was 40 ind./m². Sediment characteristics: Silt %: 5-42 (mean 18), MGS 102-242 (mean 158 µm).

Arthropoda

Subphylum Chelicerata
Class Pycnogonida

Pycnogonida spec. (Seaspider) - The animal consist for the larger part of the 8 slender legs. It is not an infaunal animal, but a predator of mostly Hydrozoa (polyps) or Anthozoa (sea anemones). Length 5 mm. Only one specimen was found. Sediment characteristics: Silt %: 5, MGS 182 µm.

Subphylum Crustacea
Class Copepoda

Copepoda spec. - Shell length 1 mm. Only one specimen was found at 1 station. Sediment characteristics: Silt %: 9, MGS 170 µm.

Class Ostracoda (Mussel shrimps)

Blue flashing ostracod - These animals mostly had a rounded bivalve shell. They are rapid swimmers and it was hard to catch them with forceps in the sorting trays. At night upon disturbance they left a short trail of blue light. Length 1-4 mm. It was found at 129 stations. Highest density was 800 ind./m². Sediment characteristics: Silt %: 3-88 (mean 27), MGS 95-210 (mean 147 µm).

Class Amphipoda

Gammaridae spec. 1 - Length 2-10 mm. It was found at 49 stations. Highest density was 400 ind./m². Sediment characteristics: Silt %: 3-71 (mean 18), MGS 95-284 (mean 151 µm).

Gammaridae spec. 2 - Length 10 mm. It was found at 5 stations. Highest density was 80 ind./m². Sediment characteristics: Silt %: 4-14 (mean 9), MGS 125-189 (mean 167 µm).

Corophiidae spec. 1 - Length 2-3 mm. It was found at 6 stations. Highest density was 160 ind./m². Sediment characteristics: Silt %: 4-11 (mean 6), MGS 118-186 (mean 168 µm).

Class Isopoda

Anthura spec. - Family Anthuridae. Length 2-12 mm. It was found at 16 stations. Highest density was 1,280 ind./m². Sediment characteristics: Silt %: 3-66 (mean 20), MGS 102-182 (mean 159 µm).
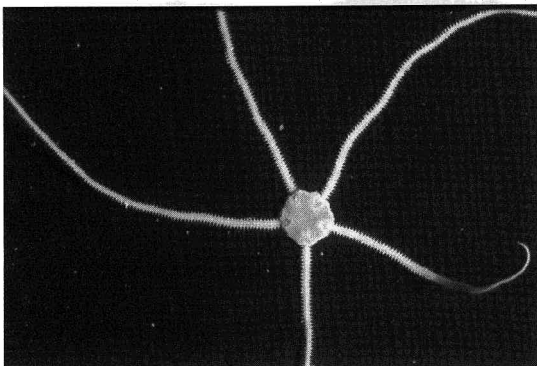
Eurydice spec. – Family Cirolanidae. These animals are swift swimmers, and therefore actually belong more to the pelagic fauna, than to the benthic fauna. They are carnivorous, and some species even

Plate 6.3: Crustaceans, brachiopods and brittle stars of Roebuck Bay
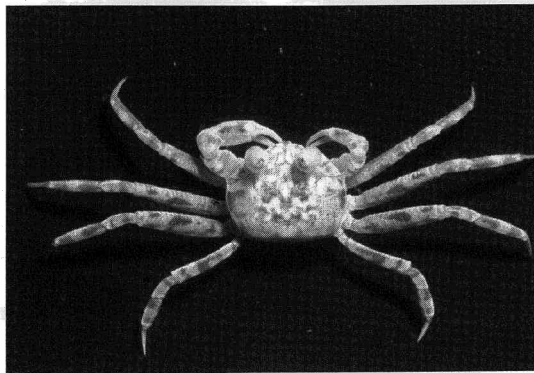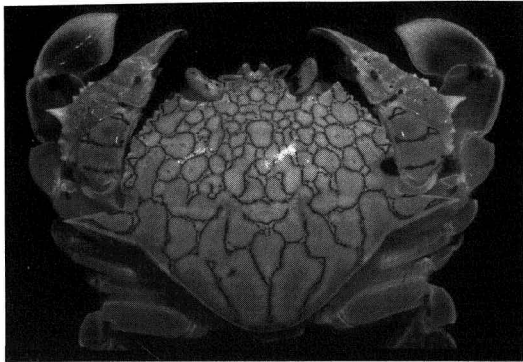
A few examples of the diverse macrofauna of Roebuck Bay:

Top left: *Matuta planipes*, a burrowing sand crab, which was found in a tidal creek bed in the sandy areas near Dampier Creek. This species is especially adapted to swimming, as can be seen by the paddle-like leg structures. Characteristic for the genus is the long, sharp spine on each side of the carapace, and usually several smaller teeth on the edges in front of their eyes.

Top right: *Uca flammula*, one of the most colourful and conspicuous of the many species of fiddler crabs occurring in Roebuck Bay. The large claw is used during courtship and combat in such a way that it appears to be playing a fiddle.

Middle: *Scopimera*, the sand bubbler crab. Like decapods of the genus *Uca* also an ocypodid crab typical for the highest parts of the intertidal and the beaches. Both claws are equal in size and bigger on males than on females. At low tide the crab leaves characteristic star like patterns of feeding pellets on the beach, radiating from the opening of its burrow.

Bottom left: A long-armed species of the brittle star family Amphiuridae. The arms are practically solid and break off at the slightest touch. The animals are typically buried into the sediment with their long arms sticking out into the water column to catch food particles.

Bottom right: *Lingula* spec., a brachiopod especially adapted to muddy substrates.

All photographs by Marc Lavaleye.

attack human legs. Length 8 mm. Only one specimen was found at 1 station. Sediment characteristics: Silt %: 9, MGS 174 µm.

Class Malacostraca
Order Tanaidacea

Tanaidacea spec. - Length 4-17 mm. It was found at 25 stations. Highest density was 120 ind./m². Sediment characteristics: Silt %: 3-44 (mean 12), MGS 99-193 (mean 158 µm).

Order Cumacea (Comma shrimps)

Cumacea spec. - Length 2-20 mm. It was found at 17 stations. Highest density was 120 ind./m². Sediment characteristics: Silt %: 3-48 (mean 15), MGS 103-205 (mean 159 µm).

Order Mysidacea

Mysidacea spec. - These little shrimps belong to the plankton, and normally are not found in benthic samples. Length 6-9 mm. Only two specimens were found at one station. Sediment characteristics: Silt %: 6, MGS 186 µm.

Order Stomatopoda

Squilla spec. (Mantis shrimp) – Family Squillidae. Most of the large perpendicular holes on the mud flats are made by this shrimp. During high tide they leave their burrow to look for prey. Their folded claws are spear like and can be stretched with an enormous speed to pierce their victim. So watch out to put your hand in these burrows. Length 6-35 mm. The larger specimens sit to deep in the sediment to be reach by our sampling method. It was found at 22 stations. Highest density was 80 ind./m². Sediment characteristics: Silt %: 6-99 (mean 42), MGS 96-186 (mean 138 µm).

Order Decapoda, Infra-order Caridea (shrimps)

Family Palaemonidae (two species) - These small shrimps (length 2-25 mm) often hover in small pools over the sediment surface. Although not belonging to the benthic infauna these shrimps were found at 14 stations. Highest density was 120 ind./m². Sediment characteristics: Silt %: 3-94 (mean 18), MGS 98-298 (mean 168 µm). Once by accident another large species with a length of 85 mm was caught with the sampling core.

Family Alpheidae (Pistol shrimps) - Length 2 cm. This shrimp lives in burrows, especially near mangrove trees. If you walk between these trees you often here a clicking noise. These shrimps can make this noise with the enlarged nipper, to scare of predators. During the quantitative sampling it was not found.

Gourretia coolibah (Poore & Griffin, 1979) - Family Callianassidae. Identified with Poore & Griffin (1979). This is a burrowing shrimp, which is a rather helpless and easy prey when extracted from its burrow. Length 3 mm. Only one specimen was found. Sediment characteristics: Silt %: 4, MGS 194 µm.

Order Decapoda, Infra-order Anomura (Hermit crabs)

Hermit crabs - At least 21 species of hermit crabs of three families can be found in NW Australia (personal compilation of Crustacea). Only small species were encountered during the survey. Length 2-9 mm. It was found at 93 stations. A few times very high densities were encountered with up to 3,520 ind./m². It is known from hermit crabs that they can aggregate for some reason (to rest until the water is returning). Another possibility is that a food source attracted these scavengers. Sediment characteristics: Silt %: 3-85 (mean 23), MGS 96-284 (mean 155 µm).

Family Porcellanidae. Many species (23) of this family are known from this region. These small crabs mostly hides under rocks, and are normally not found at the mud- or sandflats. Therefore it was not surprising that during the quantitative sampling it was not found. A few specimens were found near rocks.

Order Decapoda, Infra-order Brachyura (Crabs)

Megalopa larvae (juvenile crabs) - These crabs must have settled recently from the watercolumn. Length 2-3 mm. It was found at 3 stations. Highest density was 40 ind./m². Sediment characteristics: Silt %: 6-75 (mean 43), MGS 97-114 (mean 104 µm).

Dorippe cf *australiensis*. (Umbrella crab) – Family Dorippidae. Carapace width 2cm. This soft shelled crab carries a shell on its back to protect and hide itself. The four hind legs have special hooks to hold the shell. It slowly walks over the mud, and holds the shell very firmly even when you pick it up. This crab was not found in the quantitative samples. But at the mudflats near BBO 3 specimens were found at different occasions.

Matuta planipes (Fabricius,1798) (Plate 6.3) – Family Callapidae. Carapace width 7-25 mm. This beautiful colored crab has paddles on all its walking legs. With these it can swim as well as quickly bury in the sand. Sometimes larger specimens (up to 47 mm) were found in the small creeks on the sand flats. During the quantitative sampling only two specimens were found at two stations. Identified with Galil & Clark (1994). Sediment characteristics: Silt %: 4-33 (mean 19), MGS 181-189 (mean 185 µm).

Cf. *Myrodes eudactylus* (Bell, 1855) - Family Leucosiidae (Helmet crab, *Leucosia* spec. A.). Small hard shelled crabs (Pebble Crabs) which bury in the mud

and sand. The carapace of this species is granulated, and has posteriorly two short spines and a dorsal blunt one. Carapace width 5-10 mm. It was found at 4 stations. Highest density was 40 ind./m^2. Sediment characteristics: Silt %: 8-85 (mean 51), MGS 97-176 (mean 136 μm).

Nursia abbreviata (Bell, 1855) - Family Leucosiidae (Angel crab, *Leucosia* spec. B.). Identified with Campbell & Stephenson (1969). This genus is not mentioned in the key of Tyndale-Biscoe & George (1962) for Western Australia. The carapace is more or less circular with wavy edges. Regions of the carapace are a bit concave. The rim of the carapace has a lighter colour. Carapace width 4-16 mm. It was found at 7 stations. Highest density was 80 ind./m^2. Sediment characteristics: Silt %: 14-80 (mean 50), MGS 96-162 (mean 128 μm).

Ebalia spec. - Family Leucosiidae. (*Leucosia* spec. C). Carapace more or less circular with the anterior and posterior part straight. Carapace width 6 mm. It was found at 2 stations. Highest density was 40 ind./m^2. Sediment characteristics: Silt %: 22-27 (mean 25), MGS 107-116 (mean 112 μm).

Leucosia spec. D. - Family Leucosiidae. This is a typical representative of the genus *Leucosia* with a polished carapace and large granules on the arm of the nippers. Carapace width 3-14 mm. It was found at 9 stations. Highest density was 40 ind./m^2. Sediment characteristics: Silt %: 5-84 (mean 29), MGS 97-185 (mean 145 μm).

Nursia plicata (Herbst, 1883) - Family Leucosiidae (*Leucosia* spec. E). Identified with Campbell & Stephenson (1969). The granulated carapace is more or less broadly triangular with several blunt lateral and posterior angles. Carapace width 5 mm. Only one specimen was found. Sediment characteristics: Silt %: 84, MGS 97 μm.

Leucosia spec. F. - Family Leucosiidae. Carapace width 8 mm. Only one specimen was found. Sediment characteristics: Silt %: 5, MGS 185 μm.

Halicarcinus cf *australis* - Family Hymenosomatidae (Mud spider crab). Small crab, abundant, but hardly visible on the mud flats, as it is buried in the upper layers. Nice food for waders. Carapace width 1-7 mm. It was found at 71 stations. Highest density was 280 ind./m^2. Sediment characteristics: Silt %: 3-94 (mean 39), MGS 96-284 (mean 140 μm).

Scylla serrata (Mud crab). Family Portunidae. Carapace width 10cm. The largest crab on the mud flats. Makes shallow pits in the mud to hide. The nippers can be very powerful. Only one specimen was found near BBO on the mudflat. Parts of a large dead male were also found at the high water line.

Thalamita spinimana (Blue swimming crab) – Family Portunidae. Identified with Stephenson (1972).

These colorful large crabs were often seen near rocks, especially at night when the water was coming in, and they could swim about.

Family Xanthidae - Not found during the quantitative sampling. But some large specimens (over 5 cm carapace length) of these Stone Crabs, probably the species *Atergatis floridus* (see Jones & Morgan, 1994), were found near rocky patches at the tidal flats.

Family Pilumnidae (three species: Marmored claw, Hairy crab and another). Two species were only found at one station only. The last species was not found during the quantitative sampling. Carapace width varied from 6-12 mm.

Family Goneplacidae – Carapace width 1cm. Small crab living in the mud. When touched it stiffens to a peculiar posture, and will relax only after some minutes. Carapace width 2-8 mm. It was found at 41 stations. Highest density was 120 ind./m^2. Sediment characteristics: Silt %: 6-88 (mean 37), MGS 95-242 (mean 137 μm).

Neosarmatium cf *meinerti* (De Man) – Family Grapsidae. In the forest (Pindan), up to hundreds of metres away from the beach, large, dead, and already bleached out specimens of this crab were often found. They probably live in the deep burrows at a plain near Little Crab Creek (southern part of Roebuck Plains), which is only flooded by the sea once or twice a year (during cyclones). During their migration for mating and/or shedding the eggs some specimens get lost in the forest, dry out and die.

Mictyris longicarpus (Soldier crab) – Family Mictyridae. A few hours after the tide is out these crabs appear out of the sandy sediment and aggregate to form large herds that wander over the flats (hence their name). They eat tiny food particles. Carapace width 9-13 mm. It was found at 2 stations. Highest density was 40 ind./m^2. Sediment characteristics: Silt %: 3-6 (mean 4), MGS 149-184 (mean 166 μm).

Pinnotheres cf *cardii* - Family Pinnotheridae (Pea crab). Length 1 cm. These soft shelled crabs live commensally in bivalves. The males are much smaller than the females, and also can move from one shell to another to visit the females. Carapace width 3 mm. Only one specimen was found. Sediment characteristics: Silt %: 78, MGS 95 μm).

Scopimera inflata (Sand bubbler crab) (Plate 6.3) - Family Ocypodidae. Carapace width 10 mm. This crab lives rather high on the beach in sandy areas. During low tide it picks up sand from the surface with both its claws, and filters the palatable bits by its mouth parts. The filtered sand is discarded as little balls. Each ball takes about 1 minute. As no samples were taken from the sandy beach (near hightide level), this species was not found during the quantitative sampling.

Uca flammula (Fire fiddler crab) (Plate 6.3) - Family Ocypodidae. Length 3 cm. The most colourful of the fiddler crabs. The male claw and the front of the carapace is bright orange, the posterior part of the carapace is black. It is common in front of the BBO and along creeks through mangroves (Little Crab Creek). One of the claws (either the left or right one is enlarged). When the tide is coming in they close their burrow with a plug of mud behind them.

Uca mjobergi - Family Ocypodidae. The male claw is yellow. The small claws do not have teeth, but only some hairs on the inside of the nippers. Only found in front of the BBO on a small patch of mudflat with some rocks, enclosed by the sandy beach.

Uca polita (Shiny fiddlercrab) – Family Ocypodidae. Length 3 cm. The male claw is orange to rose, but with white fingers. The legs are brown except for the orange merus. The carapace is dark blue, the posterior part almost black with 2 dirty white blotches. The small nippers have only two teeth or thorns. One of the six species of fiddler crabs in Roebuck Bay. They were also only encountered in the same muddy area as the other *Uca* species. The males have one large claw to impress females and scare off other males, but is not used for feeding and protection. They only wave with it. They are deposit feeders. During high tide they hide in their burrow, which they close off with a patch of mud.

Uca seismella - Family Ocypodidae. Male claw orange rose with white fingers, but the colours are not as bright as of the previous species. The small claws have several teeth that enlarge towards the distal end. The merus of the legs has a brown spot. The carapace is mottled brown. Only found in front of the BBO on a small patch of mudflat with some rocks, enclosed by the sandy beach.

Uca dampieri - Family Ocypodidae. The male claw is white except for the orange fixed finger. The small claws have no teeth. The distal part of the merus of the legs has an orange dot. Only found in front of the BBO on a small patch of mudflat with some rocks, enclosed by the sandy beach.

Uca spec. (juvenile Uca) - Family Ocypodidae. Length 1.5cm. These bright blue crabs with yellow eyes were for while thought to be a new species, but ? Jones (WAM) helped me out of that idea. The juveniles of several species of fiddler crabs look the same, but are completely different in colouring from the adult stage. Only found in front of the BBO on a small patch of mudflat with some rocks, enclosed by the sandy beach.

Macrophthalmus spec. (Sentinel crab) - Family Ocypodidae (different species). Very similar to the fiddler crabs, and they have the long stalked eyes in common. They are, however, much flatter, have both claws of the same size and live lower on the mud flats in oblique burrows. Very often clear tracks are visible dispersing from these oblique holes. The male is recognisable by the small triangular abdomen and the more developed nippers. We encountered several species, but I had trouble identifying these animals with the key of Barnes (1967, 1971). Carapace width 2-44 mm. It was found at 129 stations. Highest density was 160 ind./m^2. Sediment characteristics: Silt %: 3-96 (mean 36), MGS 94-242 (mean 139 μm).

Ocypode spec. - Family Ocypodidae (different species). Some large animals were seen at night high on the beach. Among them was *O. cerathophtalma*, readily recognizable by their pointed projection above the eyes (George & Knott, 1965; Jones & Morgan, 1994). I also heard the stridulation noise that they produce by rubbing the stridulation organ on their claws against their body. During the quantitative sampling only once two juvenile specimens were found at one station. Carapace width 2-5 mm, but the species grows much larger and we caught specimens with a carapace length of 3 cm.

Echinodermata

The species of this group were kindly identified by Loisette Marsh (WAM). For some of the remarks about the species I am also indebted to her.

Subclass Ophiuroidea (brittle stars)

Amphiura (Ophiopeltis) tenuis (H.L.Clark,1938) (Plate 6.3) – Family Amphiuridae. Long armed brittle stars. Body 0.5cm, arms 10cm. This animal is burrowed deep into the sediment. Its very long arms stick out of the sediment in the water column, to catch tiny food particles that are then transported to the mouth. This species and the following two species were not recognised as different species during the survey. So the data of these three species were mixed. Amphiuridae were found at 209 stations. Highest density was 1,200 ind./m^2. Sediment characteristics: Silt %: 3-99 (mean 36), MGS 94-255 (mean 138 μm).

Amphiura sp. aff. *catephes* (H.L.Clark,1938) - Family Amphiuridae. See remarks for previous species.

Amphioplus (Lymanella) depressus (Ljungman,1867) - Family Amphiuridae. See remarks for *Amphiura tenuis*.

Ophiotrix (Placophiotrix) melanosticta (Grube,1868) (Large brittle star) – Family Ophiotrichidae. It was found at 6 stations. Highest density was 120 ind./m^2. Sediment characteristics: Silt %: 5-37 (mean 21), MGS 102-193 (mean 150 μm).

Dictenophiura stellata (Studer,1882) (Short-armed brittle star) - Family Ophiuridae. It was found at 12 stations. Highest density was 280 ind./m². Sediment characteristics: Silt %: 3-24 (mean 12), MGS 109-189 (mean 158 µm).

Ophiocnemis marmorata (Lamarck,1816) - Family Ophiotrichidae. The upper part of the body is covered with smooth shiny warts except for the smooth dorsal plates. This species can be very abundant in Roebuck Bay according to Clark (1946). He noted that they live so closely together that the arms more or less overlap one another. An interesting feature of this species is that it was found to "hitch-hike" on a jellyfish (Marsh 1998). This species was mixed up with *Ophiotrix melanosticta*, but was never found in the high abundance reported by Clark (1946).

Subclass Asteroidea (starfishes)

Astropecten granulatus (Muller & Troschel,1842) – Family Astropectinidae. These starfishes were common at certain areas, but were mostly seen an hour or so before dark when they suddenly emerged out of the mud. These fairly large animals were mostly missed by the quantitative sampling, but nevertheless found at two stations. Length 20-75mm. Sediment characteristics: Silt %: 9-21 (mean 15), MGS 127-179 (mean 153 µm).

Class Echinoidea

Peronella tuberculata Mortensen,1918 (Sand dollar) – Family Laganidae. Shallow burrower in fine sand. It devours large amounts of sediment to extract and digest the labile organic material. The white skeletons without the short spines are often seen in the small creeks in the sandier areas. Though it is common in a sandy area, it was only found once in the quantitative samples. Length 40 mm. Sediment characteristics: Silt %: 58, MGS 135 µm.

Class Holothuroidea

Leptopentacta grisea (H.L.Clark,1938) (Digging seacucumber) – Family Cucumariidae. The most common of the seacucumbers. Length 8-90 mm. It was found at 20 stations. Highest density was 240 ind./m². Sediment characteristics: Silt %: 4-70(mean 38), MGS 96-185 (mean 137 µm).

Stolus buccalis (Stimpson,1855) (Purple surface seacucumber) – Family Phyllophoridae. Length 25-65 mm. It was found at 3 stations. Highest density was 40 ind./m². Sediment characteristics: Silt %: 11-63 (mean 35), MGS 96-156 (mean 120 µm).

Cercodemas anceps (Selenka,1867) - Family Cucumariidae. Not found in the quantitative samples.

Protankyra verrelli (Théel,1886) (Naked seacucumber) - Family Synaptidae. Length 20 mm. Only found once. Sediment characteristics: Silt %: 5, MGS 185 µm.

Thone cf *micra* (H.L.Clark,1938) - Family Phyllophoridae. Not found in the quantitative samples.

New species and genus? - Family Phyllophoridae. This is a very strange seacucumber with huge plates in the skin, like a tiled roof. Marsh (personal communication) could not fit this species in a known genus and is sure that it is an undescribed species. Material was send to the holothurian specialist Frank Rowe.

Class Crinoidea

Heterometra crenulata (P.H.Carpenter,1882) - Family Himerometridae. This large species was collected between rocks on the mudflat. It is not an infaunal species, and was not found in the quantitative samples.

Hemichordata

Class Enteropneusta (Acorn worms)

Balanoglossus spec. – Family Balanoglossidae. Length 15-70 mm. It was found at 6 stations. Highest density was 80 ind./m². Sediment characteristics: Silt %: 4-77 (mean 29), MGS 96-189 (mean 122 µm).

Chordata

Subphylum Tunicata

Rooted Tunicate – Family Ritterellidae or Protopolyclinidae. Sandy sea squirt. Length 3cm. This animal forms circular colonies in the sandier areas. They are not easily noted because they are at the same level as the sediment surface and the body is encrusted with sand. The animals have a tough sand encrusted skin, have two openings, and are filterfeeders. Length 11-25 mm. It was found at 11 stations. Highest density was 720 ind./m². Sediment characteristics: Silt %: 5-40 (mean 23), MGS 109-185 (mean 154 µm).

Furthermore at least four other species were encountered on the flats. Probably they all had as a base some kind of firm substrate like the tube of an onuphid polychaet, and therefore are not specific for a mudflat as the previous species. We invented the following names: sandy colonial tunicate, colonial tunicate on tube, big colonial tunicate, transparent colonial tunicate.

Subphylum Vertebrata, Class Agnatha

Branchiostoma spec. (Lancet fish) – This species is mostly characteristic for sandy areas with a certain grain size.

Subphylum Vertebrata, Class Osteichthyes (Bony fish)

Family Periophthalmidae (mudskipper) - Two species. These fishes graze off the surface of the sediment with their broad mouth. These grazing traces together with imprints made by the walking or leaping activities of their pectoral fins are a common sight. They hide in deep burrows, often made by other animals, during disturbance or during high tide. They have a territorium that they defend, often just by raising their dorsal fin to scare off intruders. Very common close to the beach in very soft mud. Rarely found in the quantitative samples, because they easily escape by their swiftness or hide too deep in burrows. Of the blue spotted mudskipper, *Scartelaos histiophorus* (Valenciennnes, 1837) only two specimen were found at one station. Length 45-60 mm. Sediment characteristics: Silt %: 69, MGS 95 μm. The other species, *Periophthalmus cf argentilineatus* (Valenciennnes, 1837) was found in single specimens at 4 stations. Sediment characteristics: Silt %:.18-94 (mean 59), MGS 96-180 (mean 118 μm). A third different species was seen by the birders of BBO, but not collected. In the fish book of Allen & Swainston (1988), which is useful for this area, this family is included in the family Gobiidae.

Family Gobiidae. This small species (length 8-27 mm) was found at 10 stations. Maximum density 400 ind./m². Sediment characteristics: Silt %: 4-94 (mean 73), MGS 95-181 (mean 124 μm).

Family Soleidae. Only one fish was caught by accident by stepping on it.

Some large dead fishes were found on the beach of the family Mugilidae. A large sting ray was also seen dead on the beach. We often encountered small pools near the low water line that were probably made by stingrays while digging up food.

Plantae (Plants)

Halophila ovalis (R. Br.) J.D. Hook. (Oval seagrass). - Family Hydrocharitaceae. Identified with Kenneally (1996). This species is common in Roebuck Bay, though inconspicuous. The small ovate leaves are lying flat on the mud and are mostly the only visible parts of this plant. They have an extensive root system.

Halophila "lineata" (Linear seagrass) – Family Hydrocharitaceae. This species was normally found at the same spots as the previous species. It has small linear leaves.

A most surprising find on the mud flats of Roebuck Bay were these Mud Sponges. The cones are about 5 cm high and are anchored with a massive root system in the sediment. Only one patch of a few hundred individuals was found in an area with soft mud.

6.2 Ecology and distribution of the most abundant taxa in Roebuck Bay

Introduction

The various macrozoobenthic taxa described below were selected on account of their sheer abundance in the samples and observations during the sampling program. The high diversity in Roebuck Bay makes a complete revision of all taxa virtually impossible, not to mention the fact that the ecology of many tropical groups is only poorly known. The general ecology of all taxa is described on the family level, except for Ostracoda, Gammaridea, Paguridea and Ophiuroidea, which had to be treated on higher taxonomic levels. The distribution of the different taxa is illustrated by graduated pie chart maps. The area of the symbols is proportional to the square root of the numbers of individuals per square meter. This is a good representation of the overall picture, but has the disadvantage that sample points with low densities are hidden by neighbouring stations with higher numbers. The patchiness of the distribution of many species is therefore veiled to some extend. The lines shown on the map demarcate the approximate levels of Mean Low Water Spring (MLWS) and Mean High Water Spring (MHWS), the shaded area in between the neap tidal range between Mean Low Water Neap (MLWN) and Mean High Water Neap (MHWN). These levels were taken from the model of the intertidal surface, developed by Hickey and Ross (1998) (Ch. 4) and which are based on two Landsat images taken in 1994 and 1995. The MLWS level was adjusted in the north-western part of the bay to correct for shifts in sediments that must have taken place between 1994/1995 and the time of sampling (1997). The area in the north-west was sampled during spring tides and the sample points farthest offshore should therefore be a good approximation of the MLWS waterline.

The taxa described represent close to 85 % of all the individuals sampled. Many rare species, which might still play key roles in the ecology of this intertidal region, might be missing. We nevertheless hope to have introduced the most important characters of this unique intertidal environment.

Bivalvia

Solemyidae (Order Solemyoida)
Solemyids are elongate, ovoid, thin-shelled protobranchs, in which the periostracum extends beyond the calcified valve margins. Secretion of anterior and posterior oil glands give the valves a hydrofuge surface that sheds the sticky mud found in the usual environment of these organisms (Beesley et al. 1998). Solemyids are active burrowers in anoxic silts, making U-shaped, V-shaped, or Y-shaped burrows. The foot lines the burrow with mucus from the large pedal gland. *Solemya* species can swim actively by extending the foot, and relaxing the valves to take water into the mantle cavity through the anterior gape. The mantle margin then forms a seal around the foot, and when the valves are rapidly adducted, water is jetted out through the exhalant aperture, propelling the animal forward. This swimming cycle may be repeated frequently for up to a minute or more.

Availability in the environment of both oxygen and sulphide is important for the symbiosis between the bacteria in the ctenidia (gill-like organ, which is used to different degrees for both respiration and food filtering by many bivalves and gastropods) and the bivalve. It is likely that the bivalves have chemoreceptors sensitive to both of these metabolic constituents. Bacteria in the ctenidia of *Solemya reidi*, from the north-eastern Pacific, and *S. velum*, from the south-western Atlantic, have enzymes that are characteristic of the Calvin-Benson cycle, and fix carbon dioxide. The bacteria provide the bivalve with carbohydrates. The ATP which provides energy to drive the cycle is derived from the oxidation of environmental sulphide by the mitochondria of the bivalves. The bacteria also appear to convert nitrates to amino acids that become available to the bivalves. The sulphide may come from various sources: the anaerobic decomposition of organic molecules by bacteria in the sediment; from sulphide bound to sediment; or, in the case of animals inhabiting hydrothermal vents, from volcanic activity. Like all bivalves with sulphide-oxidising symbionts, solemyids require oxygen for normal respiration. Oxygen and sulphides have to be actively partitioned before they reach the target cells to prevent interaction of the two constituents (Beesley et al. 1998). In addition to the energy derived from the above described symbiosis solemyids depend to some extent on deposit-feeding.

In Roebuck Bay members of the genus *Solemya* attained highest densities in the lower intertidal (MLWN to MLWS) in the north-western part of the embayment between Quarry Beach and Dampier Creek (Fig. 6.1). Densities reached up to 360 ind. /m². Quite conspicuous is the co-occurrence of solemyids, the tube building chaetopterid polychaete and seagrass beds. In Western Australia solemyids presently assigned to *S. australis* and *S. terrareginae* occur in fine

benthic silt and also intertidally in association with eelgrass (personal observation S. Slack-Smith). A similar association was observed between Lucinidae, bivalves that also depend on sulphide oxidation, and seagrass and it is assumed that seagrass roots might supply oxygen to these bivalves. A similar commensalism might exist between solemyids, seagrass and chaetopterids, since the tubes of the latter are lined with a layer of oxidised sediment in an otherwise anoxic environment. An alternative explanation for the above mentioned correlation is that the trapping of finer particles by the worm tubes modifies sediment characteristics and offers the deposit-feeding solemyids a suitable habitat.

Cultellidae (Order Veneroida)

This family is also known under the name Pharidae. About 65 species are known world-wide. Shells normally have a narrow rectangular shape, are laterally compressed, and they gape widely at each end. The umbones are situated subterminally. The right valve

has two cardinal teeth and the left valve has only one. Often the shells are reinforced internally with calcareous rays emanating from beneath the umbones. The foot is laterally compressed and obliquely truncate. The elongated shape and smooth surface of the shell together with the well developed foot enables cultellids to burrow rapidly and thus to escape predation. The siphons are segmented and break off easily when grabbed by a predator and can be regenerated thereafter. All members of the superfamily Solenoidea are non-selective suspension-feeders living vertically or slightly obliquely in the substratum in more or less permanent tubes, in which they can ascend or descend (Beesley et al. 1998).

Two species were found in the samples, *Siliqua cf. winteriana* and *Cultellus spec.*, with the former being more abundant (Fig. 6.2). Highest densities of *Siliqua* were attained around neap tide range in the northeastern part of the embayment between Fall Point and Crab Creek. Here the substrate is very muddy with silt contents exceeding 60 %. Still lower in the intertidal
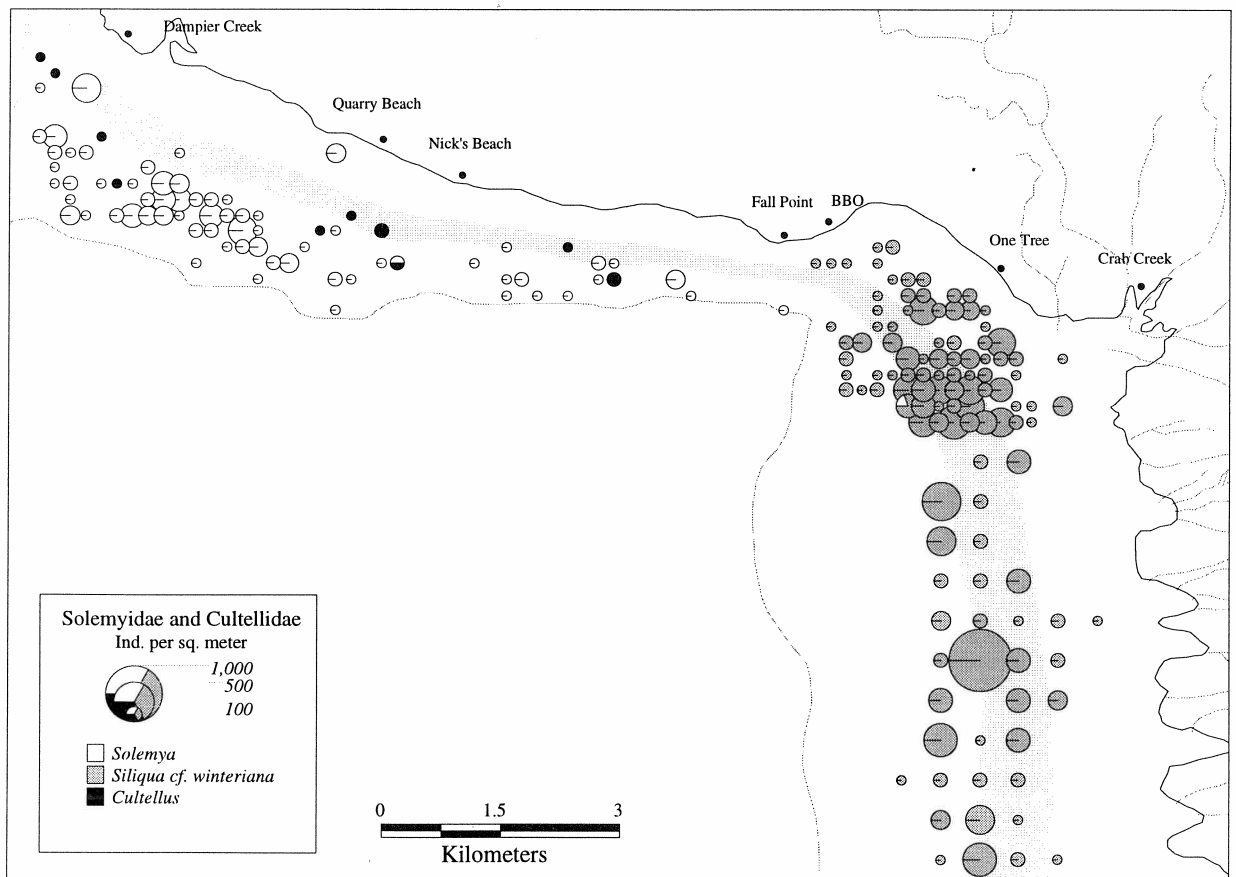

Fig. 6.1: Distribution of *Solemya* spec., *Siliqua* cf. *winteriana* and *Cultellus* spec. in Roebuck Bay (June 1997).

densities were somewhat lower. When the tide rushed in we observed a feeding frenzy on shell-fish, mainly by skates and flatfish. So the lower densities closer to MLWS might be explained by predation pressure.

The other species of cultellids we found in the samples belonged to the genus *Cultellus*, the razor shells. The general shape of the shell is similar to *Siliqua*, but even more elongated in relation to width. The surface is smooth and shows characteristic colour patterns of brown dots and lines on the otherwise whitish shell. The specimens we found were rather big with a maximum length of 50 mm. Similar to *Siliqua* they occured near the neap tide range but mainly in the sandier parts west of Fall Point.

Lucinidae (Order Veneroida)

Lucinids are small to medium-sized, thick, suborbicular, ovate or trapezoidal shaped bivalves. In all Lucinidae symbiotic bacteria that can fix carbon dioxide and contribute to a sulphide-oxidising symbiosis are present, usually in large vacuoles in bacteriocytes in the subfilamental tissues of the gills. Stored sulphur may constitute an energy store, capable of further oxidation to sulphate. Lucinidae usually occur intertidally or in shallow benthos and are commonly found in environments with low nutritive qualities, and often with high sulphide content (Beesley et al. 1998). The universality of sulphide-oxidising symbiosis in the Lucinidae validates the argument that the morphology of the family has been dictated by the symbiosis, perhaps since its emergence.

Four species of this family were found in Roebuck Bay, i. e. *Divaricella ornata*, *Divaricella spec.*, *Anodontia cf. omissa* and *Ctena spec.* with *Anodontia cf. omissa* being the most abundant bivalve. Highest densities of *Anodontia* were found in the lower intertidal zone below MLWN in front of Crab Creek in a zone of high silt content and long immersion times (Fig. 6.2). *A. cf. omissa* is globose in shape and has little ornamentation. The life specimens found in the samples had a median length of 5 mm and a maximum length of 15 mm, though larger shells were found on the
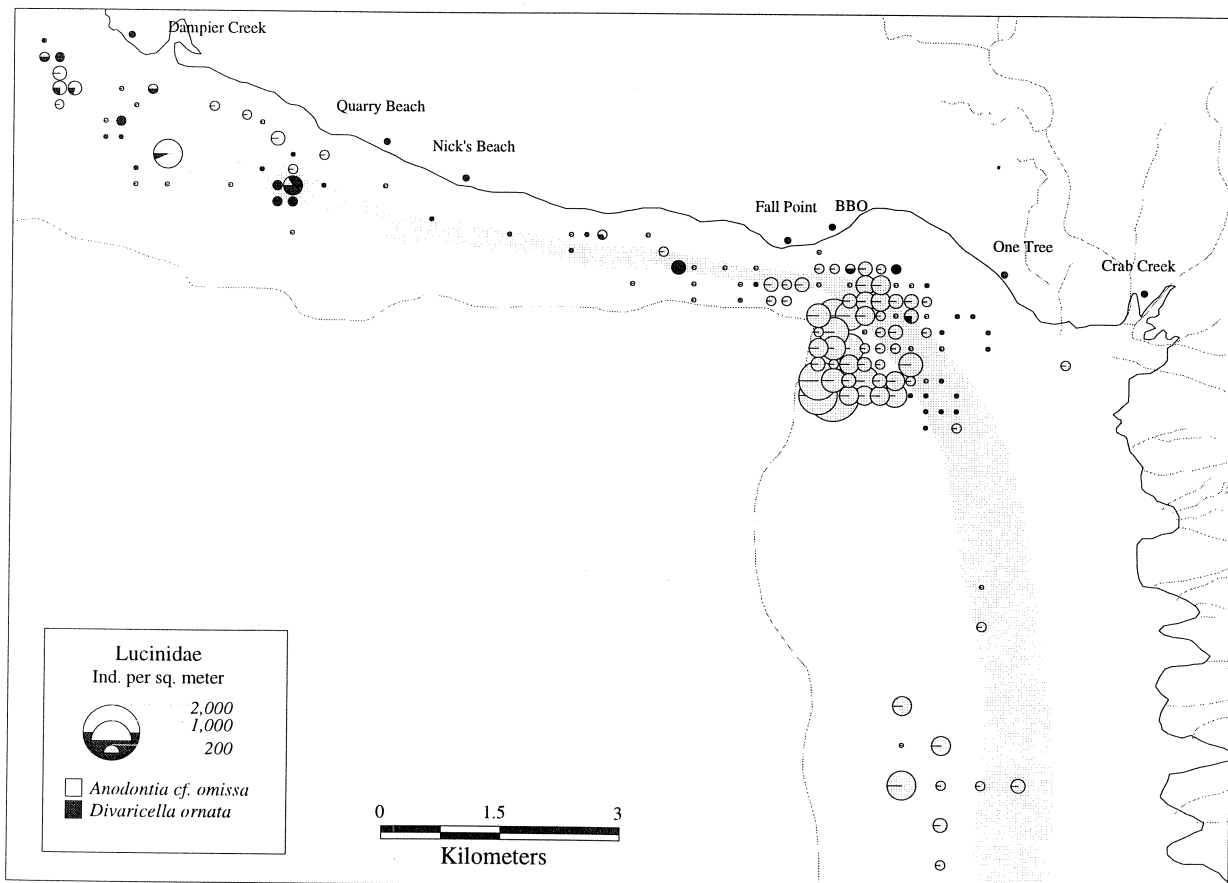

Fig. 6.2: Distribution of *Anodontia* cf. *omissa* and *Divaricella ornata* in Roebuck Bay (June 1997)

beach. *Divaricella ornata* occurs patchily in low densities throughout the whole area. With a shell length of up to 20 mm and a median length of 9 mm they are slightly bigger than *A. omissa* and thicker shelled. Compared to the former *Divaricella* is found slightly higher in the intertidal and within a wider range of sediments. The species name is derived from the divaricate ornamentation of the shell, which may facilitate burrowing in sandy substrates.

Tellinidae (Order Veneroida)

Tellins are bivalves with markedly laterally compressed and thin shells, with a distinct flexure and corresponding narrow gape posteriorly. Shells of different tellins vary in length between 5 and 125 mm for adults. Live animals lie obliquely within the substratum on their left valve, and thus the right valve has become accordingly more inflated and convex. The shell surface is usually smooth but some species display low, commarginal ridges, a few have prominent radial ribs and others have file-like scales. These morpho-

logical adaptations might help the animal to grip the sand during shell-rocking movements thus aiding sediment penetration. Most species belonging to the family are capable of rapid burrowing, which is achieved by the shell morphology and the enlarged foot.

Tellins are dioecios and spawning is tied to seawater temperature. Larvae are always planktonic but some species are lecithotrophic (development in which larvae do not feed and are relying solely on egg yolk) and have a shortened swimming stage. Larval settlement can be postponed if no suitable substratum is available. In life tellins bury deeply (up to 400 mm) and rest obliquely with their siphons pointing upwards. The siphons extend to the sediment surface where the inhalant one rotates with its tip touching the substratum to ingest organic material and sand grains. The exhalant siphon expels faeces and water while extended more or less horizontally below the surface. In suitable substrata, tellins can attain high population densities and may render them a dominant species
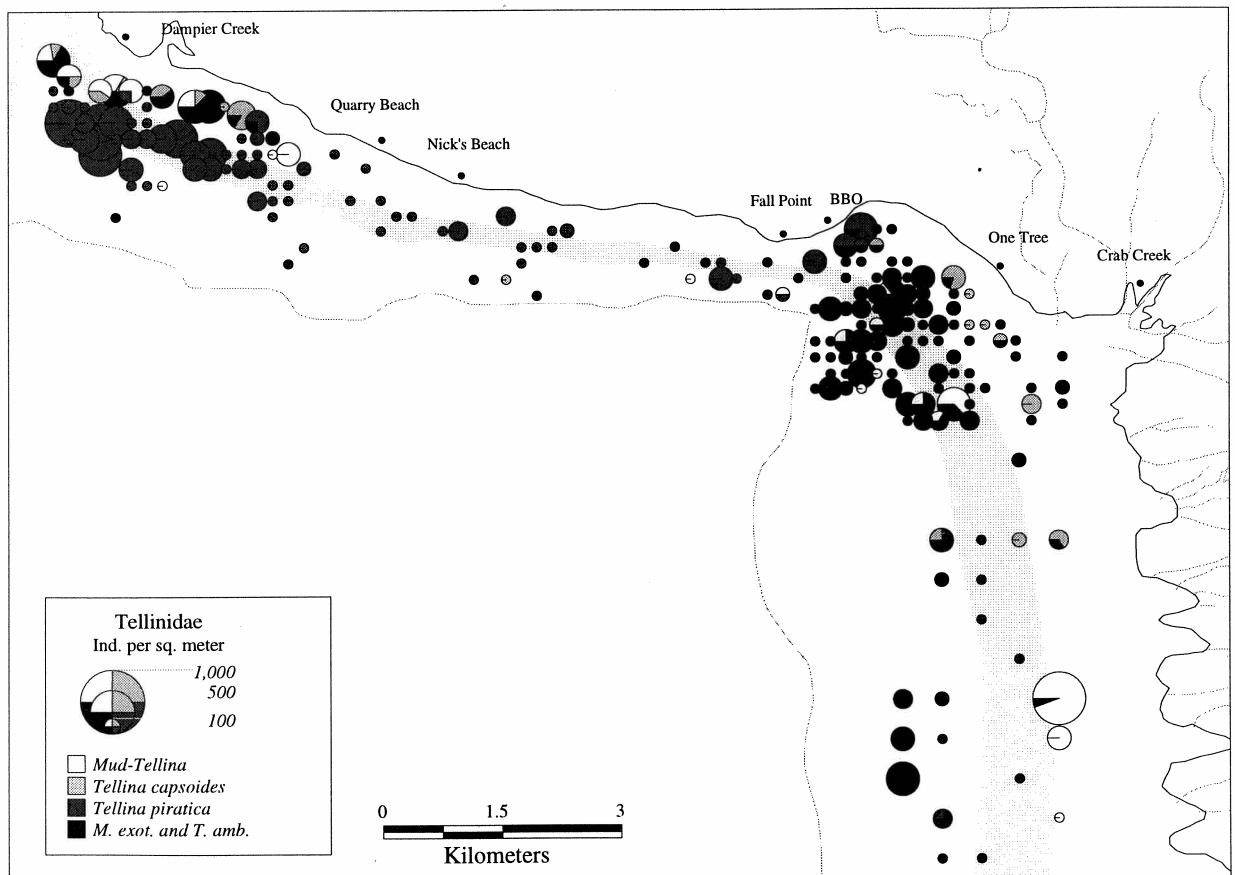

Fig. 6.3: Distribution of various tellinid bivalve species in Roebuck Bay (June 1997).

status in many soft substratum communities (Beesley et al. 1998).

The highest densities of tellins in the sampling area occur in the north-western part of Roebuck Bay near Dampier Creek and in the north-eastern region in the muddy substrates between Fall Point and Crab Creek (Fig. 6.3). They are virtually absent in the north-central part of the bay between Quarry Beach and Fall Point. This is somewhat curious because it cannot be explained by sediment characteristics, immersion times or the presence of a shallow impenetrable shell grit layer. An explanation could be a higher predation pressure by waders since high tide roosts are nearby and the intertidal region is here rather narrow, possibly resulting in higher densities of foraging waders (ch. 10). Tellins are by far the most diverse bivalve family with a total of 15 species encountered, some of which differed markedly in size and morphology and occupied different habitats. The most abundant species were *T. piratica*, *T. amboynensis*, *T. capsoides*, *Macoma exotica* and the so called 'Mud-Tellina'. Due to their ability to dig deeply into the substrates they are

well protected against desiccation and occur throughout the whole tidal range from MHWS to MLWS.

The centre of distribution of *T. piratica* is in the Dampier Creek area, in the sandy regions around MSL. Further offshore the limit of their distribution coincides with high densities of chaetopterid tube-worms, be it through competition for space or the alteration of sediment characteristics by these worms. *T. piratica* is thinner compared to the other tellins we found and the shell is more strongly ornamented with a rough, almost emery paper-like surface. This morphology might represent an adaptation to living in sandier substrates.

T. capsoides is found mainly near the mangrove fringe around Dampier Creek where the sediment is siltier and richer in organic material. They are associated with other tellins, mainly *T. amboyensis, M. exotica* and the mud-tellin.

T. amboynensis and *M. exotica* are very similar in shape and general shell morphology and the distinction between these two species was somewhat difficult, especially with younger specimens. Both have an
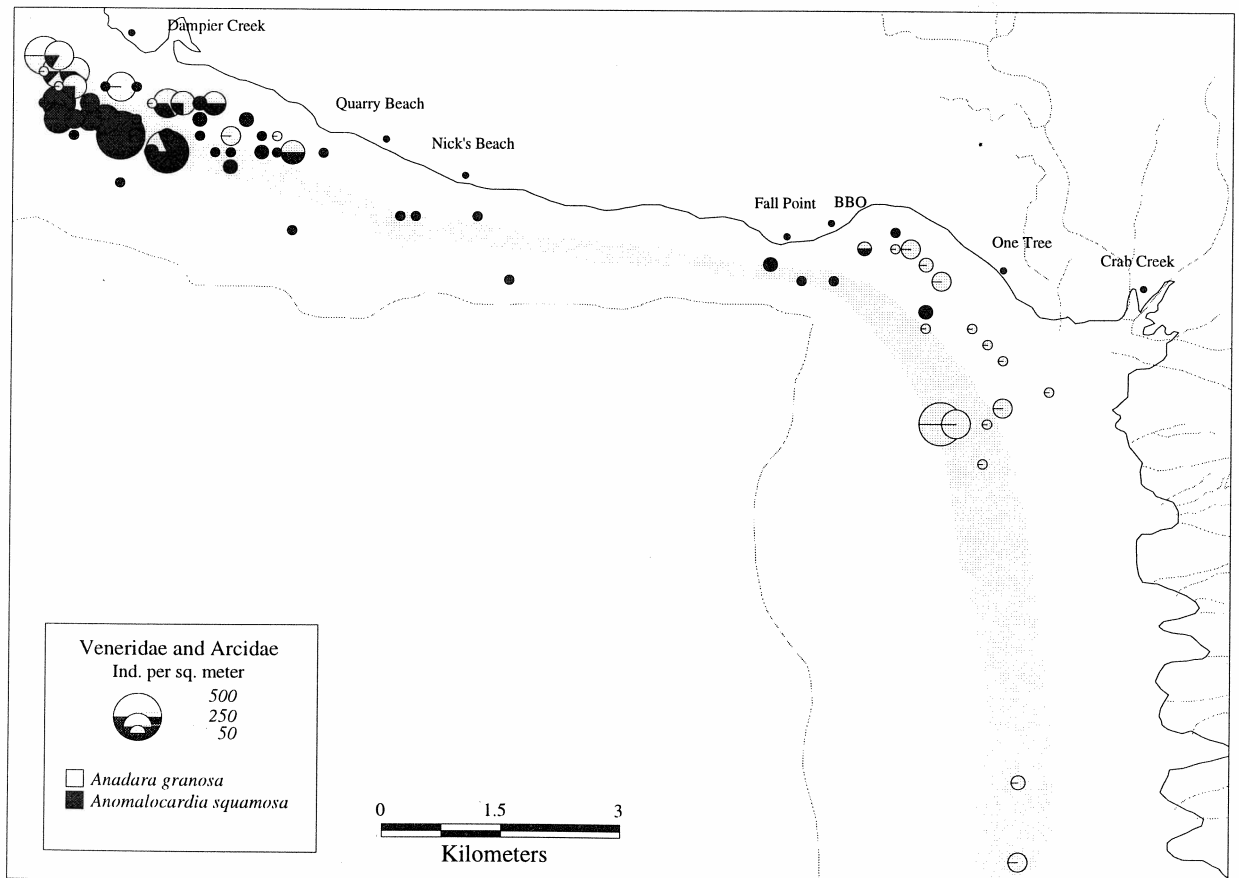

Fig. 6.4: Distribution of *Anadara granosa* and *Anomalocardia squamosa* in Roebuck Bay (June 1997).

almost triangular shape with rounded posterior and anterior ends and a very smooth surface. The shells are thin and very easy to crush, making these tellins an excellent prey for knots and godwits. Since it can be expected that their ecology is very similar, they are here treated together. Both species attain highest densities in the silty muds between Fall Point and Crab Creek with densities around 300 ind./m². The high water-holding capacity of the substrate enables these tellins to occupy the whole tidal range from the edge of the mangroves to MLWS.

Veneridae (Order Veneroida)

Venerids are shallow burrowing, marine and estuarine bivalves that are infaunal filter-feeders. The shells range in size from 4 mm to over 100 mm, and vary in shape from circular, ovate, subquadrate or trigonal to elongate; they usually have a pallial sinus. Shells are smooth or strongly sculptured; the sculpture is mainly commarginal, but can be cancellate, or with radial or divaricate ribbing, commarginal lamellae and, in some rare cases, posterior spines.

The large, wedge-shaped, compressed, heeled foot is not grooved and is used mainly for burrowing. The family Veneridae is one of the largest bivalve group in Australia, with more than 150 species in the fauna (Beesley et al. 1998). The family can be divided into two sections, roughly, but not exclusively characterised as follows: those clams with generally weak surface ornamentation, smooth margins, well-developed pallial sinuses, and well-developed anterior lateral teeth and those with pronounced surface ornamentation, crenulate margins, little or no pallial sinus, and little or no anterior lateral teeth. This diversity of morphology amongst species of the family results in a variety of habitats occupied by venerids.

The most abundant venerid found in the samples was *Anomalocardia squamosa*, a shallow burrowing, hard-shelled and strongly ornamented bivalve with commarginal and radial ribs and a very asymmetric shell. They occured in highest densities in the Dampier Creek area below MSL (Fig. 6.4). *A. squamosa* is a slow and shallow burrower, but the thick shell offers larger specimens some protection against predation by shorebirds and other predators (ch. 9). Five other venerids were identified in the samples: *Placamen gilva*, *P. gravescens*, *Tapes spec.*, *Grafrarium dispar* and *Dosinia spec.* Out of these only *Grafrarium dispar* was moderately common. They show small and less striking commarginal ribs which are intersected by very fine divaricate ribs near the umbone. *G. dispar* was most common near the mangrove fringe of the Dampier Creek area.

Arcidae (Order Arcoida)

Commonly known as arc shells, Australian members of this large and diverse family of marine bivalves range from minute (length 4-5 mm) to large (100 mm), living in nearly all marine environments, but are most common in the intertidal and shallow sublittoral zones. Most species have heavy, elongate, inequilateral shells, with a well-defined radial sculpture and dense periostracum. The taxodont hinge and the broad ligament are elongate, with the umbones well separated. Living arcoids show very little specialisation of their inner anatomy, but have an extensive array of shell forms which reflect adaptations to a wide variety of habitats (Beesley et al. 1998).

Anadara granosa, the only member of the family found in the samples, has a very thick shell which is further reinvorced by strong radial ribs and thus offers good protection against predators once a critical size is reached. In Roebuck Bay *A. granosa* shows a very limited distribution and is found mainly higher up in the intertidal close to the mangrove fringe in the Dampier Creek and Crab Creek area. Here the upper layer of the sediment is a lot siltier than farther offshore due to the trapping of finer particles by the proproots of *Avicennia marina*, the dominant mangrove species, and outwelling of fine organic material from the extensive mangals. Typical for the Dampier Creek area a shell grit layer, impenetrable for most burrowing species, was found in a depth of approximately 10 - 20 cm which may give shallow burrowing and heavily shelled bivalves like *A. granosa* and *Anomalocardia squamosa* a competitive advantage against deep burrowing species with thin shells. Between Fall Point and Crab Creek, where sediments are very fine, *A. granosa* occurs patchily. Adult specimens were only found in the upper intertidal region, whereas newly settled juveniles of less than 10 mm were also present farther offshore (Fig. 6.4). In the sandy region between Dampier Creek and Fall Point, *A. granosa* was missing completely.

Gastropoda

Amphibolidae (Order Eupulmonata)

Pulmonates are air-breathing gastropods that lack gills but use the mantle cavity as a lung. This method of respiration is more efficient in air than water, and so virtually all species are associated with the intertidal zone or found on land (Edgar 1997). The subclass consists essentially of land and freshwater molluscs, but representatives of a few genera, recognised as amongst the most primitive, live intertidally.

The mantle cavity lacks a ctenidium, but secondary gills or pseudobranchs may be developed in some ma-

rine and freshwater forms, although not in the family Amphibolidae. The shell is globose with a depressed spire and an inflated last whorl. The aperture is large and most species have an open umbilicus. Shell height is usually less than 30 mm, and shell sculpture varies from fine to coarse. The tentacles are very short with eyes at their bases. The broad central tooth of the radula bears five sharp denticles, the two lateral teeth are unicuspidate and tricuspidate, respectively, and the marginals are dagger-shaped.

In Australia the gastropod family Amphibolidae is represented only by species of the genus *Salinator*, which lives in the higher regions of intertidal mud flats and mangrove habitats, sometimes partially buried in the substratum. They feed unselectively by passing large quantities of sediment through their gut and retaining organic particles. Species of the genus are hermaphroditic and male and female genital systems are separate. Amphibolids lay egg strings on the surface of the mud which become covered with a fine coating of silt. Details of reproduction are widely un-

known.

The specimens found in Roebuck Bay had a very smooth shell surface and a large, open umbilicus. The maximum shell length was around 10 mm. Colours varied from creamy white, light grey to a light brown colour. The highest densities of amphibolid gastropods in the sampling area were found near the extensive mangals along the eastern coastline of the bay (Fig. 6.5).

Potamididae (Order Sorbeoconcha)

Potamidids are marine gastropods that inhabit mangroves and estuarine mudflats in tropical and subtropical regions of the world. In Australia 9 species in 3 genera are known (Beesley et al. 1998). *Cerithidea cingulata* was the only species of this family that was found in the quantitative samples. It can be confused with members of the family Cerithiidae and Batillariidae. The main difference with the Cerithiidae is the round, corneous, multispiral operculum with central nucleus. The shell is multi-whorled turreted and
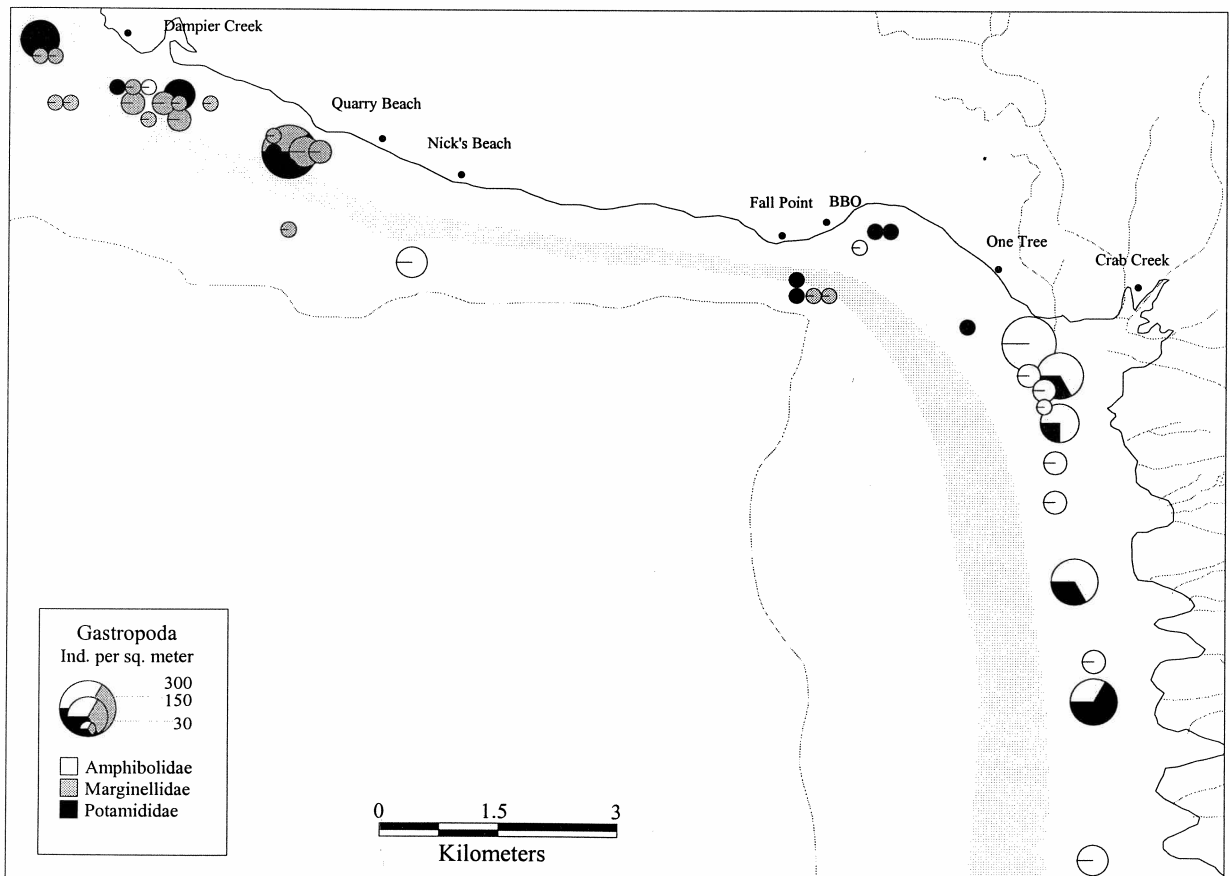

Fig. 6.5: Distribution of specimens of the gastropod families Amphibolidae, Marginellidae and Potamididae in Roebuck Bay (June 1997).

sculptured with strong spiral ridges crossed with heavy axial ridges. A short siphonal canal is clearly present. *C. cingulata* occurs on tropical mudflats near mangroves, but rarely lives among the trees, also. They crawl on the sediment surface and are detritivores.

Potamidids were found patchily in the upper intertidal regions of the embayment close to the mangrove fringe (Fig. 6.5). They were missing entirely from the region of clear washed sands in the north-central part of Roebuck Bay. The biggest specimens were up to 30 mm long, but the median size was with 13 mm much smaller.

Marginellidae (Order Sorbeoconcha)

These small marine snails typically have a shell with a short to sunken spire, a large last whorl and a smooth, polished surface. The sometimes brightly coloured mantle is usually capable of covering all or part of the shell and the large foot lacks an operculum. The shells of Australian species are less than 20 mm in length, although some marginellids reach 120 mm. Sculpture,

if present, is usually limited to axial plications restricted to the shoulder, although a few species have surface granulation. The aperture is flaring to narrow. The foot is broad and usually longer than the shell. Details about the carnivorous feeding habits of marginellids are not well known. Some feed on bryozoans, others are known to feed on ascidians. In all probability they feed on a wide range of animal food, although each group may feed selectively on one type of food. Marginellids range from the lower intertidal zone to more than 1000 m in depth, and from rocky reefs to soft shores (Beesley et al. 1998).

The marginellids found in the samples had a median length of only 5 mm. The shell of life specimens had a glossy, white colour. The lip was denticulate internally. The centre of distribution for this family was in the north-western part of the bay between Dampier Creek and Quarry Beach, where they were associated with cerithiids (Fig. 6.5). With a few exceptions all the specimens were found within 500 m of the shoreline.
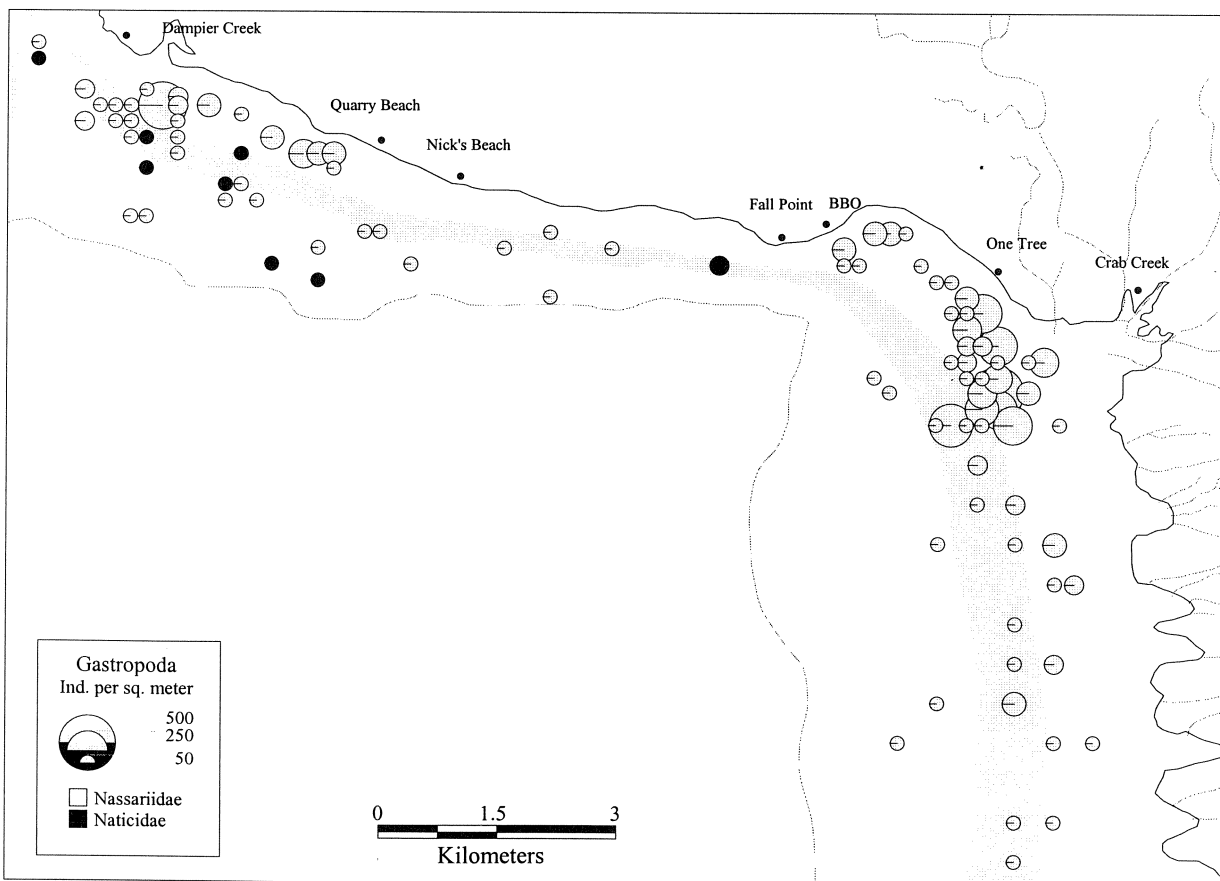

Fig. 6.6: Distribution of specimens of the gastropod families Nassariidae and Naticidae in Roebuck Bay (June 1997)

Nassariidae (Order Sorbeoconcha)

Species of the marine family Nassariidae are characterised by having a small (4-75 mm), high-spired, ovate to fusiform, strongly to indistinctly shouldered shell with a dorsally reflected siphonal notch. The shell surface may be smooth, or have axial and/or spiral sculpture. The shell aperture is strongly to weakly ovate, the outer lip is usually thickened and frequently forms a varix, denticulate within, with short spines along the anterior edge in some species. The columella is short and twisted, smooth or denticulate, with a pronounced siphonal fold. The operculum is thin and reduced in size, and often has serrated margins.

Nassariids occur primarily in estuarine to shallow marine soft substrata, usually in tropical and temperate regions, and attain their greatest diversity in the tropical Indo-Pacific. Many species are colonial, sometimes occurring in high densities of up to 5,000 ind./m². Although most are carnivores feeding on carrion, at least some species can become facultative herbivores, developing a crystalline style in the stomach during such periods (Beesley et al. 1998).

Nassariids (at Broome Bird Observatory hysterically called 'Ingrid Eating Snails', due to their habit to start eating on any small wounds on human parts that remain stationary near the mud surface for some time) were by far the most abundant gastropod family representing more than 45 % of all the specimens sampled within this class. Three different species of the subfamily Nassariinae were found in Roebuck Bay. Only one, *Nassarius dorsatus*, could be identified to species level. The largest adults had a size of 30 mm, though the median size was with only 7.5 mm markedly smaller. *N. dorsatus* has a glossy, smooth shell surface without any sculptures. Adults of one of the other two species, the so called "Small Ingrid Eating Snail", were markedly smaller than *N. dorsatus*, had axial sculptures on the last whorl and in relation to size a much thicker lip.

Both species occured in a variety of substrates and were observed almost within the entire tidal range between MHWS and MHWN. Since nassariids are quite mobile and may even be capable of swimming ("surfing") for short distances by exposing their expanded foot to the surf, the distribution patterns may reflect the time of sampling and the water level at the specific sampling time. Nevertheless nassariids were most abundant between MSL and MHWS in the northwestern part of the embayment and in the siltier region to the east of Fall Point (Fig. 6.6). Field observations during the sampling program suggest that compared to their larger relatives the range of distribution of 'Small Ingrids' is narrower, and they seem to prefer slightly finer sediments and a habitat higher up in the intertidal.

Naticidae (Order Sorbeoconcha)

The Naticidae, commonly known as moon shells, are a family of carnivorous, burrowing marine gastropods. They are best known for their shell-boring predation using an accessory boring organ on the proboscis, and for the production of egg collars impregnated with sand or a gelatinous substance.

Moon shells have globose to pyriform shells that are usually smooth and often have colour patterns. The outer lip of the aperture is not sculptured, and the inner lip is usually thickened with umbilical and parietal calluses that may partially or completely fill the umbilicus. The last whorl and aperture are greatly enlarged. All naticids are predatory. The molluscan prey is captured with the dilated foot, and the radula is used in combination with the acid-secretory proboscoideal accessory boring organ to bore or drill a countersunk hole in the prey shell through which the prey flesh is consumed. Naticids are dioecious and fertilisation is internal. The embryos are either laid in a diagnostic sand collar (egg case), an agglutinated circular mass of sand, mucus, and egg capsules, or in a gelatinous, almost transparent, coiled up egg case, that remain on the sandy sublittoral surface until hatching occurs. Planctotrophic, lecithotrophic, and direct developmental modes all occur in this family. Naticids are common in the sandy and muddy areas of the intertidal and sublittoral zones, actively burrowing through the substratum in search of molluscan prey. Their chief predators are bottom-dwelling fish (especially small sharks and skates), crabs and other naticids (Beesley et al. 1998).

Three different species of naticids could be distinguished: *Polinices conicus* and two species of the genus *Natica*. *P. conicus* was by far the most abundant representative of the family and could be identified by the amber coloured operculum. Field observations indicate that they occupy a wide range of habitats and they could be found patchily throughout the bay. Although naticids were found only in a few samples (Fig. 6.6) and they comprise little more than 2 % of the collected gastropods, they seem to play an important role in the ecology of the embayment. Many of the empty bivalve shells found in the samples had a hole in the shell, indicating predation by naticids. In addition to that egg collars were observed frequently during sampling.

Polychaeta

Chaetopteridae (Order Spionida)

Chaetopterids are tubicolous polychaetes common in shallow water. The highly characteristic morphology of the widespread *Chaetopterus variopedatus* led to an

early interest in its structure and life history. Gut contents for this species include planktonic skeleta, unicellular algae and protozoans, small metazoans, and detritus. Food is captured by a mucuous net, which is produced from the edges of the aliform parapodia in *C. variopedatus*. The net is suspended from the edge of these parapodia to the cupule which is centrally placed on the dorsal side. At the cupule the net can be rolled up, formed into a food bolus and transported to the mouth along a ciliated groove. The necessary water current is set up by three fan-shaped notopodia immediately posterior to the cupule. Under some conditions especially with heavy particle loads, shreds of mucus containing food material are produced from the aliform parapodia, rather than the complete net.

Filter feeding seems to be the general feeding mode for the family. In some instances a single net is formed; in others several nets are formed on successive segments. In these chaetopterids, the current is set up by notopodial cilia rather than by muscular motion. Open canals are left between the notopodia and the tube-wall making a series of filter-nets useful. Deposit-feeding was only observed in chaetopterids other than the genus *Chaetopterus*. Surface deposit feeding is likely to be important for the few species living in bathyal and abyssal regions (Fauchald & Jumars 1979).

Chaetopterids are numerically the most abundant benthic family in Roebuck Bay. The highest density encountered was 15,200 individuals/m². The median abundance for all stations where chaetopterids were present was 320 ind./m². The tubes had a length of up to 10 cm and were much longer than the specimens living in it. The material is semi-transparent, very flexible, has a high tensile strength and has lead to the common name "plastic worms". The distribution of chaetopterids is patchy and it was not uncommon to find densities exceeding 3000 ind./m² in one sample and no specimens in the sample station next to it. In areas with high densities of tube-building worms the sediment is altered significantly because the tubes trap finer particles. In the north-western part of the em-
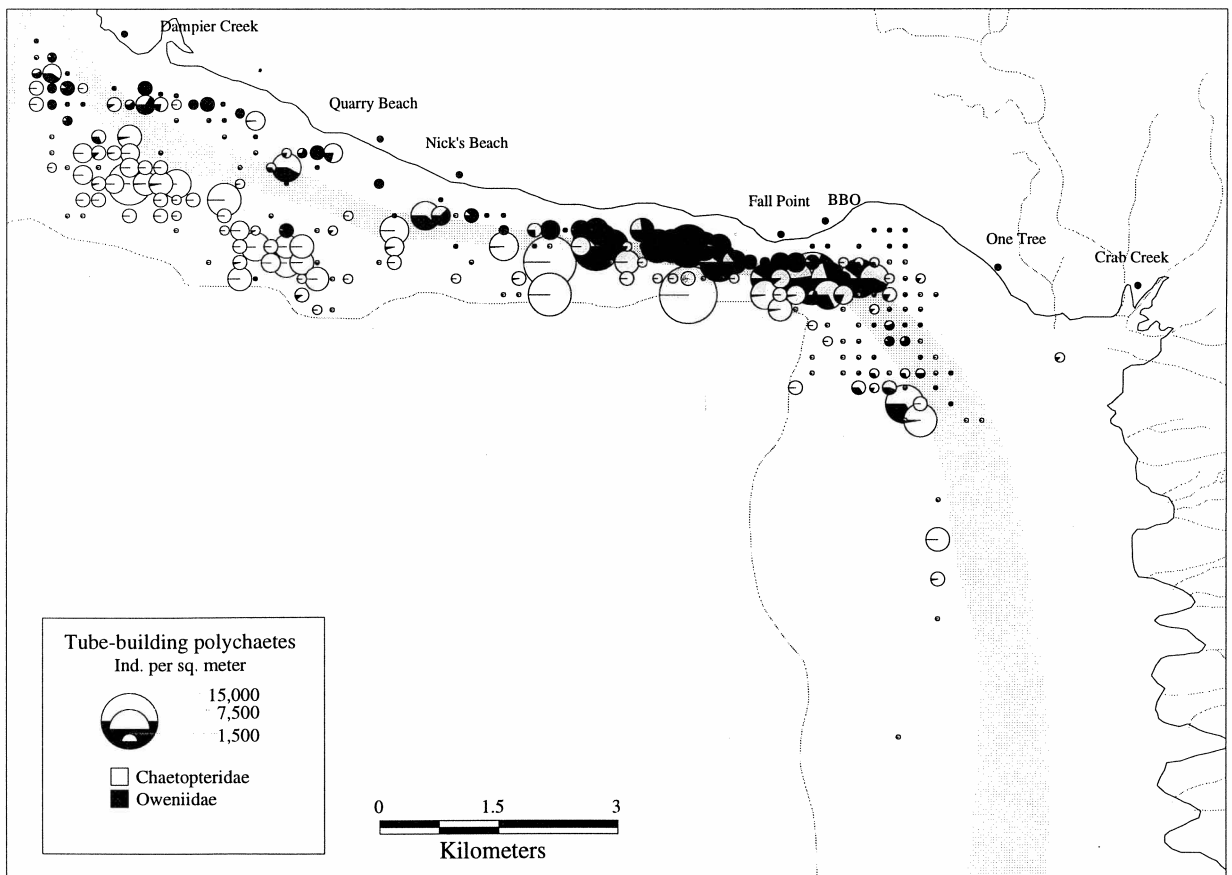

Fig. 6.7: Distribution of the tube-building polychaetes Chaetopteridae and Oweniidae in Roebuck Bay (June 1997).

bayment between Dampier Creek and Quarry Beach, where colonies of chaetopterids are most common, the silt content was markedly higher (up to 30 %) than in unpopulated areas nearby (silt content less than 5 %) (Fig. 6.4). Plastic worms occur in a variety of substrata and cover almost the whole tidal range, though densities are highest in regions below MLWN and with a silt content less than 50 %. It is quite interesting to compare the distribution patterns of chaetopterids and oweniids, both colonial tube building bristle worms, because they seem to be mutually exclusive (Fig. 6.7). The competition for space might be the dominant factor and chaetopterids seem to have a competitive advantage in the lower intertidal region.

Oweniidae (Order Oweniida)

The only oweniid so far investigated is *Owenia fusiformis*, but it can be assumed that the ecology is similar for all species within the family. *O. fusiformis* has a shallow, lobed tentacular crown. The flat marginal lobes have raised ridges with lateral cilia and with cili-

ary paths leading to the mouth, which is guarded by paired lips. These tubiculous worms will project the tentacular crown from one end of the tube. They can feed in an upright position or bent over the substratum; thus they are capable both of filter-feeding and of surface deposit-feeding. While doing the latter the lips are used to pick up particles directly. Considering the size of the tube in relation to the size of the contained specimen, they probably do not move around and stay in a permanent position once they are settled (Fauchald & Jumars 1979). The rather stiff tubes of the observed species in Roebuck Bay were incrusted with sand grains and shell debris and should offer a good protection against possible predators.

Similarly to chaetopterids, oweniids occured in a wide range of substrata but had their centre of distribution above MLWN. By far the highest densities were reached within the neap tide range near Fall Point (Fig. 6.7). The silt content showed a wide range between 10 and 60 %, indicating an alteration of sediment characteristics by the tube building colonies.
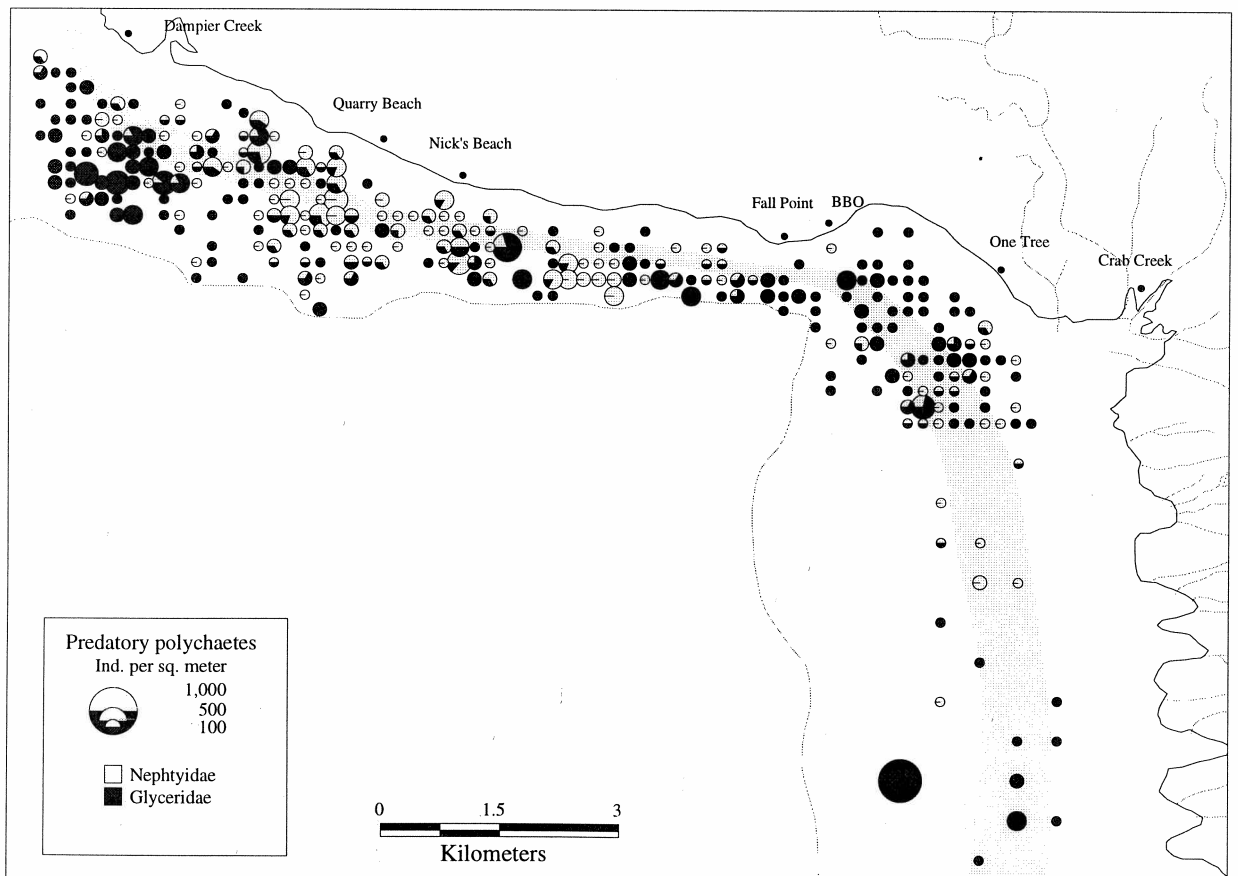

Fig. 6.8: Distribution of the predatory polychaetes Glyceridae and Nephtyidae in Roebuck Bay (June 1997)

Since they are capable of both filter- and deposit-feeding, oweniids seem to have a competitive advantage against chaetopterids when immersion times are lower. Filter-feeding is only possible with an overlying water column and thus only during high tide in the upper intertidal region. Therefore feeding times in this region should be longer for oweniids because they are capable of both feeding modes.

Glyceridae (Order Phyllodocida)

Glycerids are slender, long-bodied polychaetes with enormous eversible pharynges tipped by four jaws. The jaws are penetrated by a canal connected basally to a gland. In *Glycera convoluta* the secretion from this gland is toxic to small crustaceans. The jaws are made of tanned proteins impregnated with iron and copper compounds. Some glycerids form semi-permanent burrow systems in soft substratum, other species are free-living under rocks and crawling on algae. The ecology of glycerids is not well investigated and seems to change between species. Carnivory seems to be the primary feeding mode among the glycerids, but an unknown, probably small number of species have become detrivores. In nutrient rich environments either feeding mode may be supplemented by direct uptake of dissolved organic matter. The construction of a semi-permanent burrow system in soft substrata seems to be associated primarily with a carnivorous feeding habit and secondarily with the uptake of dissolved organic matter (Fauchald & Jumars 1979).

The carnivorous habit of glycerids is described for *G. alba*. This glycerid has a complex burrow system with several openings on the substratum surface. The worm is sensitive to small changes in water pressure such as created by an animal moving around. The glycerid will track the moving prey in its burrow system and will move to the opening that gives the best angle of attack and the easiest possibility of cutting off the path of the prey. The prey is grasped by a rapid eversion of the pharynx. *G. alba* seems to prefer moving prey, such as small polychaetes and amphipods; it is less interested in sessile prey and will not attack animals encased in tubes.

In the study area glycerids were found in a variety of substrata, in the sandy areas around Dampier Creek as well as in the muddy regions to the east of Fall Point. The life habit of glycerids seems to be more susceptible to changes in moisture content within the substrate than to sediment characteristics alone. In the sandy regions around Dampier Creek they are more or less restricted to areas below MLWN, whereas in the muddy areas near One Tree characterised by a high water capacity the range of distribution is extended towards regions above MHWN (Fig. 6.8).

Nephtyidae (Order Phyllodocida)

Nephtyids have very large eversible pharynges with a pair of small jaws internally, consisting of tanned protein. They are common in soft, mainly sandy sediments from the intertidal to abyssal depths and may be extremely abundant. All are free-living burrowers which may periodically form poorly agglutinated burrows. Nephtyids are usually considered vagile carnivores, feeding on small invertebrates including molluscs, crustaceans, and other polychaetes. Some species have taken up other feeding types as well and are described as subsurface deposit-feeder. Nevertheless carnivory seems to be the dominant feeding type (Fauchald & Jumars 1979).

Highest densities in Roebuck Bay with a maximum of 320 ind./m^2 were found in the sandier region between Dampier Creek and Fall Point. To facilitate movement in the substrate, interstitial water is essential, which could explain the higher abundance below the MHWS level. Being both free-living predators, Nephtyids and Glycerids occupy a similar ecological niche and might even prey on each other. In most sample stations either one or the other polychaete dominates and in many areas they even seem to exclude each other (Fig. 6.8). Whether this is due to predation on each other or the scarcity of shared resources is unclear.

Crustacea

Ostracoda

The ostracods are a sub-class of small crustaceans that occur in practically every aquatic environment. They may be free-swimming for all or part of their life-cycle, or, more commonly, are benthonic, living among aquatic plants or crawling on or through the sediment. A number of interstitial forms are known. Ostracods display a variety of feeding habits; some are filter-feeders, others are scavengers, detritivores, herbivores or predacious carnivores. A few species are parasitic or commensal on other crustaceans, polychaetes and echinoderms.

The most distinctive feature of the ostracods is the calcareous bivalved carapace that can totally envelop the body and limbs, but from which various appendages are protruded for locomotion, feeding and reproduction. The body is not noticeably segmented and has a reduced complement of limbs compared to other crustaceans. They have two large antennae, three pairs of mouthparts and two pairs of trunk limbs, with the end of the abdomen often developed into a claw-like structure (Athersuch, Horne & Whittaker 1989).

The benthonic ostracods found in the samples had a maximum size of 4 mm, but most of the specimens

were smaller than 2 mm. The carapace had an inconspicuous, almost opaque white colour and it was almost impossible to distinguish immobile ostracods from shell debris and coarse sand-grains in the samples. The only way to detect them was by the tracks they left in the thin layer of silt on the sorting plates. Sampling on the mudflats at night on the other hand was quite spectacular because when agitated by our movements through the pools of standing water, ostracods capable of bioluminescence emitted a bright violet light for several seconds. Ostracods were present throughout the bay but reached highest densities below MSL in the sandier areas between Dampier Creek and Fall Point (Fig. 6.9). With a few exceptions they were absent close to the shoreline and from the muddy eastern parts of the embayment.

Gammaridea (Order Amphipoda)

Gammaridea is the largest suborder of the order Amphipoda. Like all amphipods they are laterally compressed crustaceans without a carapace. They typically have two pairs of clawed limbs behind the head, followed by five pairs of walking legs, the first two or three of which have the tips directed backwards. Under the abdomen are three pairs of flattened, forked pleopods for swimming, followed by three pairs of spine-like appendages (the uropods). A small leaf-like telson is attached to the top of the last segment. About 20 families are adapted for living in sediments. Gammarideans are consumed in great quantities by larger animals and are an important component in the diets of small inshore fishes (Edgar 1997).

Gammarids are mainly restricted to the sandier regions in Roebuck Bay and show the highest densities between Dampier Creek and Quarry Beach (Fig. 6.9). In the muddy eastern parts of the embayment they were found only occasionally.

Paguridea (Order Decapoda)

Members of the superfamily Paguroidea, the hermit crabs, are characterised by their long, soft, coiled abdomen which is protected inside a gastropod shell or,
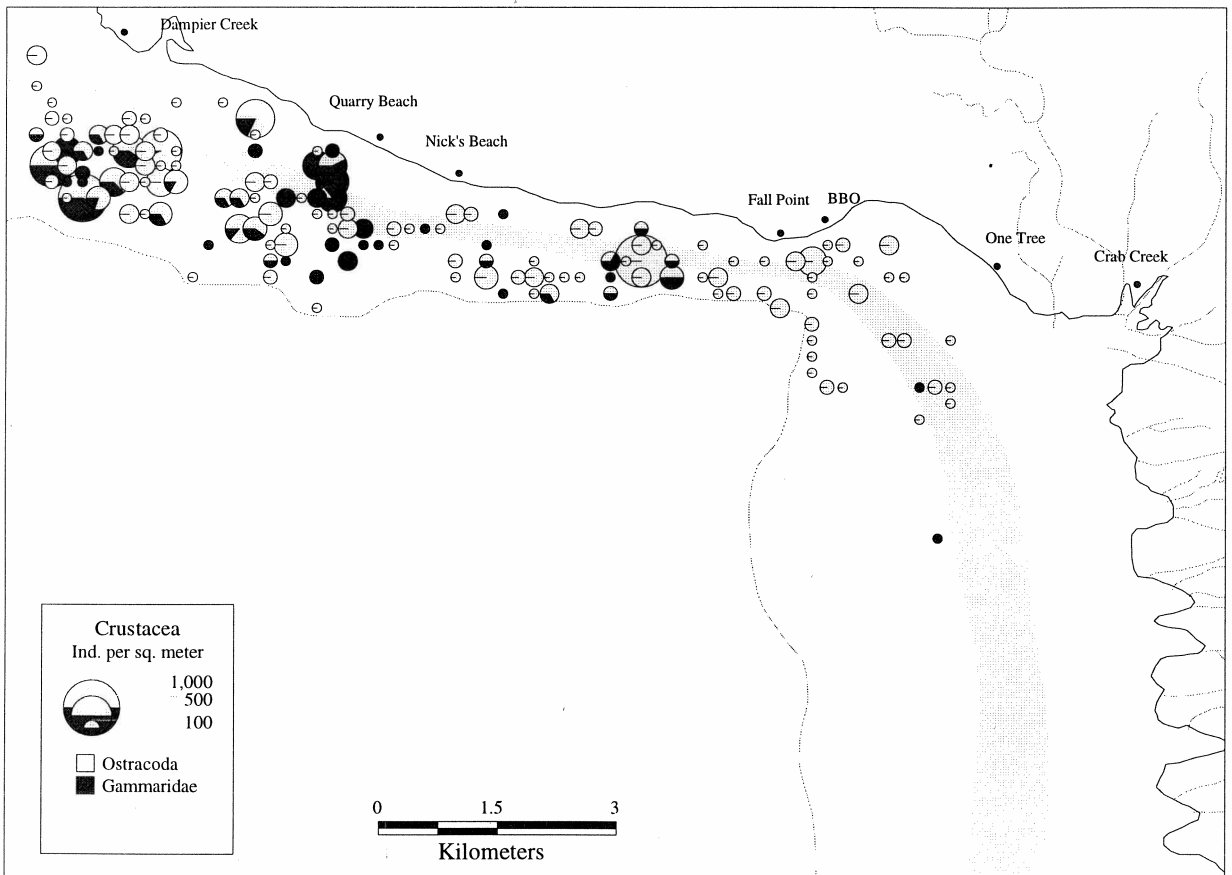

Fig. 6.9: Distribution of Ostracoda and Gammaridea in Roebuck Bay (June 1997)

more rarely, in a sponge, a piece of worm tube, or an hollow rock. Shells are replaced periodically as the hermit crab grows. Hermit crabs are primarily algal feeders but they are also scavengers; some are predatory and some filter feed with their antennae. The superfamily consists of four families, the Diogenidae, the Coenobitidae, the Paguridae and the Parapaguridae. The latter comprises only deep water species and will not be further described. Diogenids and Coenobitids can be recognised by having the left claw equal in size or larger than the right. Diogenids include nearly all the large and colourful hermit crab species. Coenobitids are terrestrial hermit crabs. They have gill chambers which are kept moist and act as a type of lung, permitting the crabs to live inland, some distance from the sea.

The pagurid hermit crabs differ from these two families by having the right claw larger than the left. Most pagurids are small and inconspicuous, and a number of species remain to be scientifically named (Jones & Morgan 1994).

Members of the superfamily were found patchily all over the intertidal flats except for the muddy east-ern parts (Fig. 6.10). Some of the larger specimens were diogenids and coenobitids, living in large gastropod shells like *Nassarius* or *Polinices*. Still larger hermit crabs were found higher up in the intertidal within the mangals, but here again numerical data is missing. The smaller pagurids represented the bulk of the specimens sampled and occupied smaller shells, mainly those of cerithiids. They were locally very abundant and attained densities of up to 3,000 ind./m² in two sample locations. Hermit crabs are quite mobile and can occasionally be seen feeding gregariously in high numbers on different kinds of food. One day we saw a torn bag of flour on the beach and hermits virtually covered the ground around it.

Hymenosomatidae (Order Decapoda)

Hymenosomatids are closely related to majid spider crabs but have smooth, flat-topped to almost concave carapaces. The rostrum is usually short and sometimes divided into prongs with the eyes sitting on very short stalks. The legs are long and thin. Left and right claws are equal in size, but are normally bigger in males than in females. The size varies between species but all are
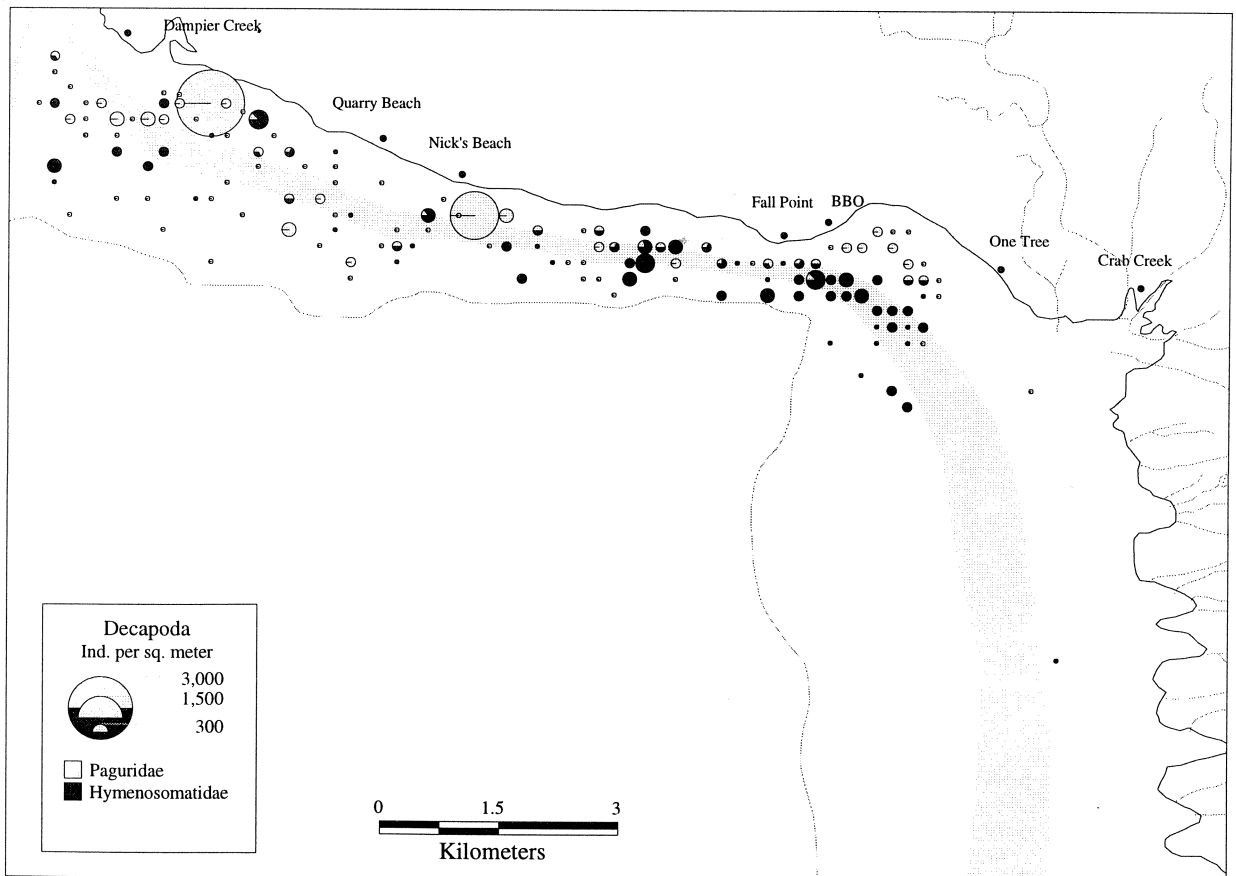

Fig. 6.10: Distribution of Paguridea and Hymenosomatidae in Roebuck Bay (June 1997)

smaller than 20 mm in carapace width. Most species live among marine plants and some occur in estuaries, where they may occur in large numbers (Jones, Morgan 1994). Members of the family found in Roebuck Bay had a maximum carapace width of 7 mm with a median size of 4 mm. The claws of some males are enormous compared to body size. The highest densities were found within the neap tide range around Fall Point (Fig. 6.10) with up to 560 ind./m². Due to their high abundance and the fact that they live close to the sediment surface, hymenosomatids may be an important prey item for smaller waders (ch. 10).

Ocypodidae (Order Decapoda)

Crabs of this family inhabit sand-dunes above high water mark, sandy beaches, mangrove-muds and muddy estuarine flats. Ecology and habitat differ significantly within the family and should be treated on lower taxonomic levels.

Sandbubbler crabs, genus Scopimera, live on more sheltered and tropical ocean sand-beaches. When the tide is in these crabs rest at the bottom of a vertical chimney-like burrow. When the tide ebbs and the sand is exposed the crab comes to the surface and feeds on the layer of organic matter that is left on the sand surface. In doing this it makes almost straight and shallow trenches radiating out from the opening of the burrow, leaving round pellets of sand in its way. These pellets comprise the sand that is rejected after the organic matter has been sifted out from it by the mouth appendages (Dakin 1952).

Ghost crabs, genus Ocypode, are swift-footed crabs of sand beaches and dunes above the high water mark. They make diagnostic holes in the dry sand which usually have characteristic crab-tracks leading to it over the sand, with numerous marks around the entrance. During the daytime they normally stay in their burrows which may be up to a meter deep. Night-time is the preferred hunting period when the crabs leave their burrows and move down to the water line. They are aggressive predators on small animals, as well as being scavengers. Ghost crabs can be identified by
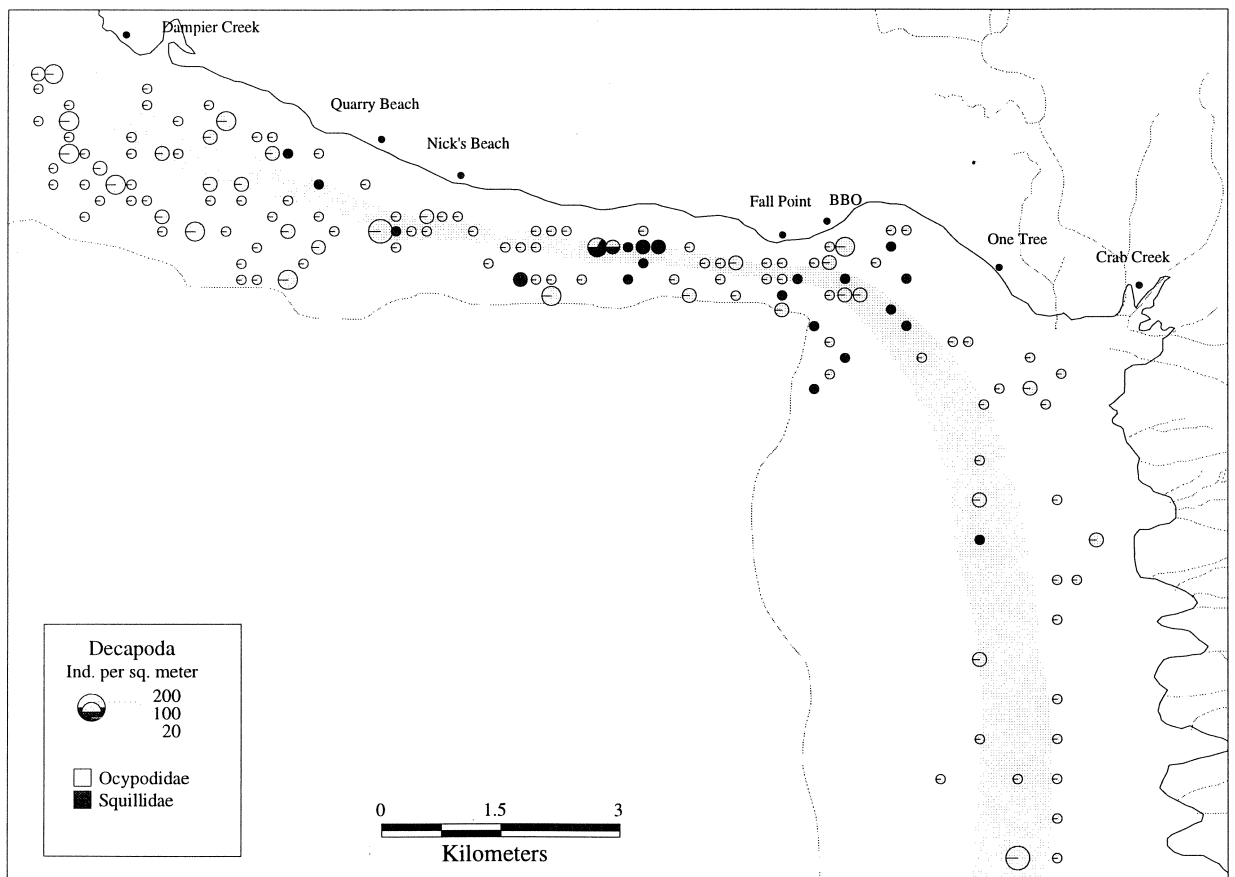

Fig. 6.11: Distribution of Ocypodidae (*Macrophthalmus*) and Squillidae in Roebuck Bay (June 1997)

their long and movable eye stalks and the nippers, which are unequal in size (Dakin 1952).

The fiddler-crab, genus *Uca*, is easily recognised by one of the claws in the male specimens being relatively enormous. It can be larger than all the rest of the body. Moreover the claw is often brightly red or orange in colour, and is brandished freely in a strange waving manner. It is not used for the uptake of food or defence against predators, but rather to defend the territory against male competitors and during courtship (Jones & Morgan 1994). Female specimens have two small claws and are duller and darker than the males. Similar to the genus *Macrophtalmus*, *Uca* species can protect their long eyestalks by flapping them sideways into a protective groove. The highest densities of fiddler-crabs in the study area was found directly in front of the bird observatory in the upper intertidal. Here the sediment was siltier due to the protection by a sandbank farther offshore. Like all ocypodids, fiddler-crabs also dig burrows. When the tide is coming in they close these with a plug of mud behind them. The diversity within the genus was astonishing and not less than 6 species were found in a small area in front of the bird observatory. The fire fiddler crab, *Uca flammula*, has a bright red colour and was by far the most colourful of the fiddler crabs encountered.

Species of the genus *Macrophthalmus*, commonly called 'Sentinel Crabs', are identifiable by reason of their shape and their exceedingly long eye-stalks, which flap down sideways into a protecting groove if touched. The carapace is square or rectangular and flattened. Some species reach 60 mm in carapace width, but most are smaller than 40 mm. Males can be distinguished from females by their larger claws. The crab has no striking colours, being a muddy olive over all and is thus difficult to detect, although they might be quite abundant. They make oblique burrows in the muddy sediment from which they leave to pick up small particles from the sediment surface (Jones & Morgan 1994). *Macrophthalmus* was by far the most dominant and diverse genus of ocypodid crabs in the samples. An identification to species level was not always possible and some species may still be undescribed. Sentinel crabs were found almost throughout the whole tidal range from MLWS to MHWS and in a variety of substrates from pure sands in the north-west to silty muds in the eastern parts of the bay (Fig. 6.11). The size ranged from 2 mm to 44 mm with a median of 7 mm. Since larger specimens can be expected to burrow deeper into the sediment the sampling results may not represent the actual size/frequency distribution.

Squillidae (Order Stomatopoda)

The general appearance of these animals is rather prawn-like, as the body is elongated and flattened. There are eight thoracic appendages, the first five pairs being clawed, and the second very large and curved back on themselves, with grasping spines. They are further distinguished by having eyes and first antennae attached to separate movable segments of the head, filamentous gills attached to the limbs under the abdomen, and a carapace that covers but is not attached to most of the thorax.

Common names for the genus are "Mantis shrimp" on account of the simmilarity of the second leg pair with the front limbs of a preying mantis or 'Prawn Killer' because they are quite often found in crab or prawn nets. As a matter of fact they probably very rarely kill commercial crabs or prawns because these prey items are to big. Some species exceed 30 cm in body length but the common species are less than 15 cm long. They are usually found in the intertidal region and in shallow, coastal marine waters, burrowing into soft sediments or sheltering in crevices and holes in the rocks or coral. Numerous species are found in Australian waters. The animals are predatory, feeding mainly on small fish and other crustaceans which are caught by the large second legs. These legs are either grasping, with sharp spines on the inside face of the movable finger, or they have a swollen, hammer-like structure, used to batter the prey. Large species with the latter have been known to break the glass walls of aquaria (Jones & Morgan 1994).

The Mantis shrimp found in our samples had a maximum body length of 55 mm, although they grow to larger sizes than that. During high tide they leave their burrow to look for prey. Their folded claws are spear like and can be stretched with an enormous speed to pierce the victim. Most of the large perpendicular holes on the tidal flats are probably made by this shrimp. Attempts to dig out the animal failed because the burrows were too deep. This is also the reason why only few and relatively small Mantis shrimp were found in the samples (Fig. 6.11). The burrows are simply deeper than the length of the cores we used for sampling (50 cm). From the sheer number of large holes in the sediment, members of the family Squillidae must play a very important role in the ecology of the tidal flats, not only as a predator of small fish and crustaceans but also because the burrowing activity modifies the sedimentary characters extensively and offers habitats to other animal groups. The highest number of large burrows, which we think are made by Squillidae, occurs in the silty muds in the northeastern part of the embayment from the mangrove fringe to MLWS level. Because of the high water holding capacity of the substrate and the depth of the

burrows the shrimp are well protected against desiccation at low tide and the burrows are at least partially filled with water at all times. This is also the area were mudskippers, Family Periophtalmidae, were observed in high densities, and which use the burrows as a refuge when disturbed or during high tide.

Ophiuroidea

Ophiuroidea
The class Ophiuroidea is one of the five classes of the phylum Echinodermata. They received their common name brittle-star because living specimens, on the slightest provocation, tend either to break off pieces of their arms, or throw them off altogether (to all our frustration while sorting the benthos samples). Like all Echinodermata they have an amazing faculty of regenerating lost parts. Some species reproduce asexually by splitting themselves deliberately in half. In contrast to starfishes, class Asteroidea, brittle-stars have a defi-

nite central disk from which usually five arms arise abruptly. They move more actively too, by the direct use of their arms, which push the creatures along the ground. The arms are practically solid, but a high degree of flexibility is achieved in their construction, for each arm is composed of a series of little limy rings or ossicles, held together by muscles (Dakin 1952). Most brittle star species feed on small organic particles, which are transported by tube feet along the arms. Some of the larger species capture worms and other bottom-dwelling prey. A few filter-feeding brittle stars are also known, which feed by raising their arms into the current and capturing planktonic organisms using the tube feet (Edgar 1997).

The long armed brittle stars of the family Amphiuridae were most common in the samples. The central disc had a diameter around 5 mm and long, slender arms up to 100 mm long (Plate 6.3). The animal is buried into the sediment with its long arms sticking out in the water column to catch tiny food particles, which are then transported to the mouth. These ophi-
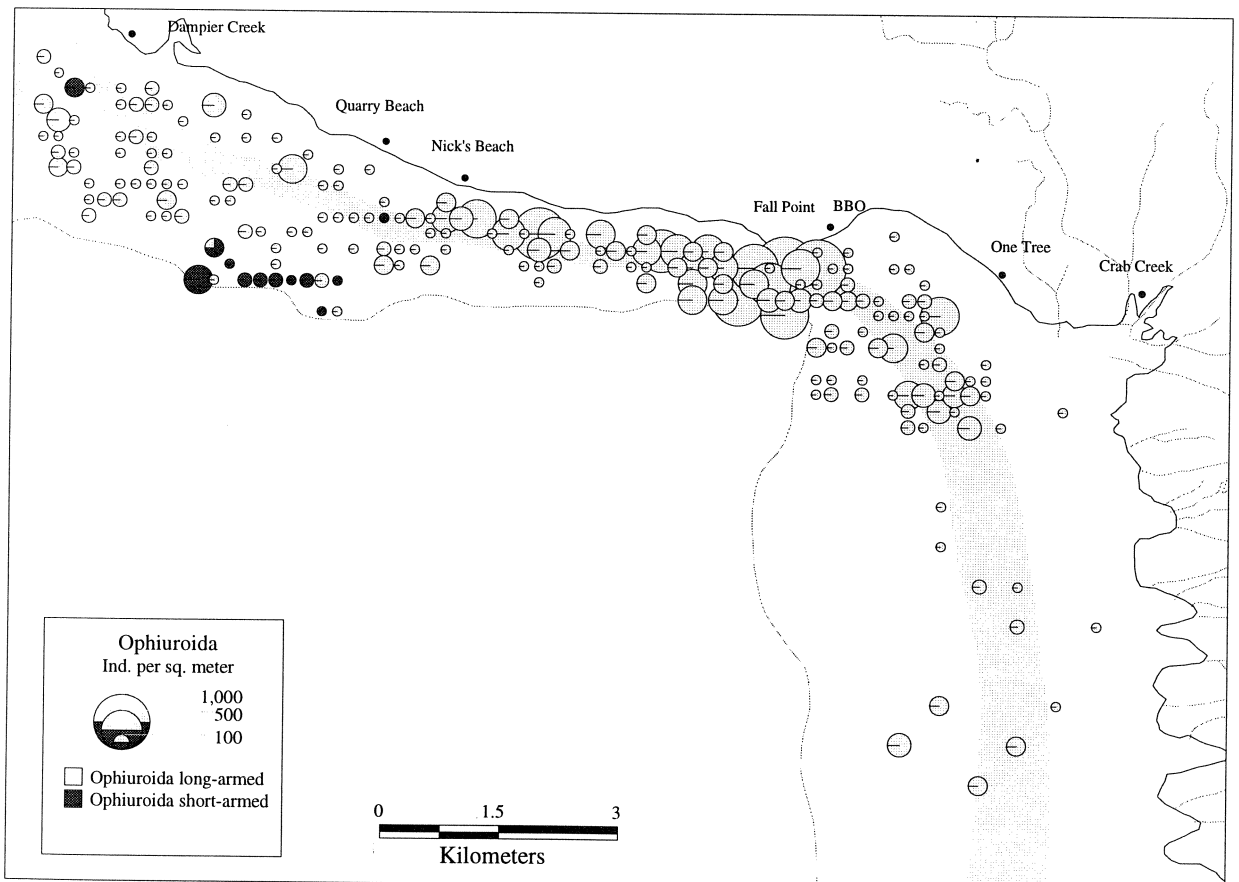
Fig. 6.12: Distribution of the large-armed species of brittle stars (Ophiuroidea) in Roebuck Bay (June 1997)

urids were found all over the intertidal area but reached highest densities within the neap tide range between Nick's Beach and Fall Point (Fig. 6.12).

Little Crab Creek, one of the many smaller tidal creeks of the Crab Creek system. The banks of the creeks consisted of very fine muds. In 1998 a cyclone hit the area and completely filled the creek – an impressive proof of the big influence these rare events have on the morphology of the coastal and intertidal areas and on the benthic community.
Photograph by Marc Lavaleye.

6.3 Symbiotic Coral

Several of the samples yielded button-shaped corals with a hole on the under side in which a worm had lived (Fig. 6.13). None of the specimens collected had either living corals or living worms. Marc Lavaleye called our attention to these and described the symbiosis, the worm receiving a protected place to live and the coral being moved about by the worm, thus avoiding being smothered by the soft sediments. The examples we found ranged in size from 6 mm to 15 mm in their greatest dimension.

The coral partner in the relationship may be one of three different genera in the waters around Australia, all of which show this same symbiosis; *Heterocyathus*, *Heteropsammia* or *Psammoseris*. The worm always is the sipunculid *Aspidiosiphon corallicola*. (Similar symbioses, involving different genera, occur in European and American waters.)

Whichever the coral of these samples may be, the life story is the same. The coral's larval stage is free-swimming and must settle on a very small abandoned shell of a gastropod. For the symbiotic relationship to occur, this same empty shell must be found and occupied by the worm. Now growth of the coral and the worm keep pace with each other. The coral soon covers the gastropod shell completely, save for the opening where the worm lives. The worm grows longer and bulkier and the coral increases the calcium deposit both upwards and outwards. The worm tube forms an arc just inside the perimeter of the lower surface of the coral, with pores in the coral surface, which may aid in the respiration of the worm. The coral we found was smaller (13 mm) than the 25 mm which one of the genera may reach.

The coral and worm live on soft substrate at a

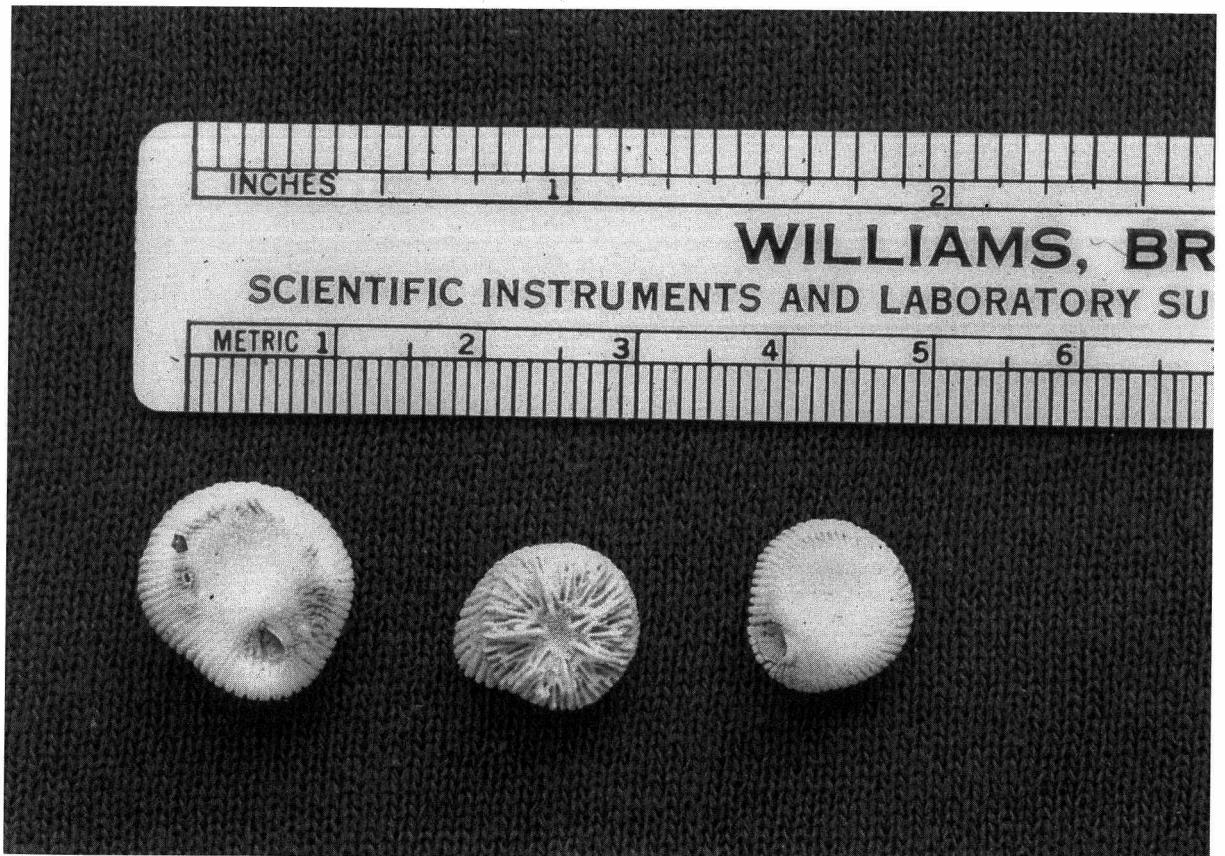Fig. 6.13: Corals living in symbiosis with the sipunculid *Aspidiosiphon corallicola*. To the left and the right a view of the lower surface is shown with the opening of the worm's tube and the location of that tube within the coral around the outer edge. The coral in the centre is shown from the upper side. The radiating septa that would have supported the coral polyp(s) can still be recognized. Photograph by Grant Pearson.

minimum depth of 20 meters. The coral benefits by being moved from place to place by the worm's extending and anchoring its proboscis by a terminal swelling and then pulling the rest of its body toward the proboscis. Work done on a similar coral/worm symbiosis from the Great Barrier Reef showed that the worm could move 10 cm in an hour and was capable of righting a coral that was upside down. If the coral were to remain in place, it would undoubtedly be suffocated by the soft sediments.

Corals frequently have algae living within their body tissues, and at least one of these three Australian genera is said to have such zooxanthellae. Corals with associated algae must live in water shallow enough for light to penetrate. Whether these specimens were associated with algae cannot be known. A depth of 20 meters in water with soft sediment might well be so turbid that little light would reach the algal cells to power photosynthesis. Since the corals we found were all dead, the questions arise as to where they came from and how they got to where we found them. If Roebuck

Bay has depths of 20 metres or more, they could live in the bay and be brought into shallow water by tidal currents or storm currents. If the water of the bay is not deep enough, then the coral must have lived farther from shore.

All three possible genera of coral, *Heterocyathus*, *Heteropsammia* and *Psammoseris*, are said to live in northwest Australian waters and all at depths of 20 meters or more. Although all form disk-like buttons on soft substrates, they may form reefs in appropriate conditions. *Heteropsammia* disks may be extremely numerous, 300 or more individuals in a square meter. At times *Heteropsammia* is also said to have a parasitic mussel, *Lithophaga lessepsiana*. We found no evidence of this.

Evidently these coral-worm symbioses are not a part of the intertidal area when alive, thus they are not available to feeding birds. Nevertheless, they are of interest for themselves and add a further dimension to our understanding of Roebuck Bay.
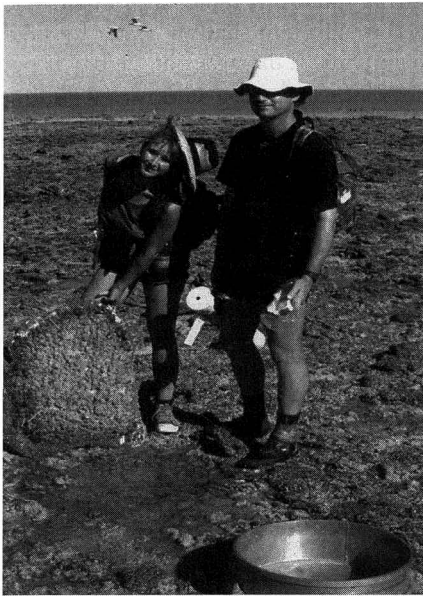
Different habitats in Roebuck Bay:
Top left: Rocky habitat in the north-western part of the bay. Erosion exposed the underlying mud- and sandstone. Colourful sponges and ane-mones were frequently found underneath the rocks, which offered protection against high sedimentation rates that would otherwise smother these animals. Other common animals of the rocky intertidal were barnacles, sea squirts and octopi, which use the rocks as holdfasts or hiding place. Soft and hard corals were present in a reef like structure farther offshore.
Top right: Sandy habitats near Dampier Creek. For the sampling teams a more than welcome relief after sampling in knee-deep muds in the eastern regions of Roebuck Bay. The outer fringe of the Dampier Creek mangals is visible in the background.
Bottom: Upper intertidal area close to Crab Creek. The sediment consisted of very fine carbonate muds. In the centre and to the left *Avicennia marina*, the dominant mangrove species of the region, with its characteristic cable roots and pneumatophores.
Photographs by Marc Lavaleye.

7 INTERTIDAL BENTHIC COMMUNITY STRUCTURE

Markus Pepping

Methodology

Feeding modes

Assigning feeding modes to the different taxa was problematic, both because of the fact that the ecology of many groups is only poorly investigated, and because different categories were used in the literature. Some authors using feeding mode as a category, others the trophic level. In this paper a classification based on the mode of food uptake is used. The following categories were used:

D:	Deposit Feeders
SF:	Suspension Feeders
P:	Predators
SC:	Scavengers
PA:	Parasites
G:	Grazers

In a number of taxa more than one feeding mode is present and these are then listed in the order of decreasing importance. Feeding modes of polychaetes are taken from Fauchauld & Jumars (1979), molluscs from Beesley et al. (1998) and crustaceans from Jones & Morgan (1994). The feeding modes for the remaining taxa were assigned with the help of Marc Lavaleye.

AFDM

The high diversity of the area and the low numbers of most taxa made experimental calculations of AFDM unfeasible. Most of the studies about tropical mudflats based their biomass figures on wet weight rather than AFDM and formulas based on regression of body length against AFDM are rare.

An earlier study by Tulp & de Goeij (1994) provided formula for five species of bivalves based on laboratory experiments (Table 7.1). The computation of AFDM (mg/m²) for the remaining bivalve species is based on morphological similarities to one of these species, i. e. either *Modiolus micropterus*, *Anodontia* cf. *omissa*, *Tellina piratica*, *Anomalocardia squamosa* or *Macoma exotica*.

For the other taxa the estimates of biomass had to be even rougher. Zwarts (1996) gives equations for the Wadden Sea gastropod *Hydrobia ulvae*, the polychaete

Nereis diversicolor, the crustacean amphipod *Corophium volutator* and the crab *Carcinus maenas*. Johannesson (1986) provided the regression formula for the gastropod *Littorina saxatilis*. We applied these equations to the remaining taxa using the principle of best fit, but a few problems arose. For the brittle star family Amphiuridae, the tube building polychaete families Chaetopteridae and Oweniidae and pagurid hermite crabs no length was recorded, either because it was too tedious to extract the animals from their tubes and shells or because only bits and pieces of echinoderms were found in the samples. For chaetopterids and oweniids an average size of 10 and 15 mm was assumed and equation (H) was applied, for the pagurids 5 mm and equation (I), respectively. For brittle stars an average of one milligram AFDM per individual was assumed, disregarding the actual size of the specimens

In the few cases where body length was not recorded accidentally, the median length of the species was taken. All Echinodermata (except Amphiuridae) and Cordata were excluded from the biomass estimates because their size would have swamped the figures.

Sampling

For a series of 12 successive days at almost every low tide benthic and sedimentological sampling took place, covering as much of the intertidal area of Roebuck Bay as possible. The sample locations were based on a pre-determined grid with intersections every 200 m north of Crab Creek and every 500 m south of Crab Creek (Fig. 7.1). Stations were located according to their geographical coordinates using a hand-held GPS. At each station 3 PVC cores with a diameter of 10.2 cm covering 3 times 1/120 m² were taken to a maximum depth of 50 cm. The sediment was sieved on the spot over a 1 mm mesh, with sieved samples carried ashore for sorting and processing. Each station yielded a list of invertebrate species, along with their number and sizes. Bivalves were identified to species level when possible, the other benthic animals to family level at best (polychaetes, crabs) or phylum level at worst (Porifera, Platyhelminthes, Nemertea, Sipuncula, Echiuroidea, Brachiopoda and Phoronida).

Table 7.1: Formulas used for computing AFDM, using the measurements on body lengths that were recorded during the sorting and identification process. Based on gross similarities in morphology it was tried to fit these formulas to the sampled animals.

A	*Modiolus micropterus*	$AFDM\ (mg) = 0.071\ L^{1.93}$
B	*Anodontia* cf. *omissa*	$AFDM\ (mg) = 0.193\ L^{1.65}$
C	*Tellina piratica*	$AFDM\ (mg) = 0.235\ L^{1.63}$
D	*Anomalocardia squamosa*	$AFDM\ (mg) = 0.154\ L^{1.73}$
E	*Macoma exotica*	$AFDM\ (mg) = 0.106\ L^{1.818}$
F	*Nereis diversicolor*	$AFDM\ (mg) = 2.455\ (0.1\ L)^{2.208}$
G	*Hydrobia ulvae*	$AFDM\ (mg) = 0.029\ L^{2.14}$
H	*Littorina saxatilis*	$AFDM\ (mg) = 0.027\ L^{2.73}\ 0.9\ (*)$
I	*Corophium volutator*	$AFDM\ (mg) = 0.005\ L^{2.8}$
J	*Carcinus maenas*	$AFDM\ (mg) = 0.054\ L^{2.871}$

*Johannesson's formula computes DM instead of AFDM. The factor 0.9 is used to subtract the 10 % of ash that the samples contain on average.

In addition to these cores, a sediment sample of the first 10 cm was taken for grain size analysis and analysis of total carbon. In total 537 stations were sampled covering the northern part of Roebuck Bay and about half of the eastern side, the strip of soft mud that stretches towards Bush Point along the mangroves of Thangoo Station. At all stations field observations were made about morphological features (creeks, pools, sandbars), sediment characteristics (core depth, layering, colour, presence of beach rock), fauna (esp. mobile, surface dwelling or deep-burrowing species that were under-represented in the samples and the number of burrows), flora and the depth of the shell-grit layer.

Sediments
The sediment samples were first wet-sieved over a 63 μm mesh. A chemical treatment of the sediment to break down aggregates was not necessary. The residue bigger than 63 μm was then dry-sieved over a stack of sieves with mesh sizes of 125, 250, 355, 500 and 1000 μm, respectively. The following parameters were computed to describe the sedimentology of the area: Silt content (fraction < 63 μm), median grain size, the sorting coefficient S_0 (only for the sand fraction between 63 and 1000 μm) and the percentage of the coarse fraction (> 1000 μm). Median grain size and the sorting coefficient S_0 were determined graphically by plotting cumulative weight percentages against size classes and reading the grain size for the different quartiles (25 %, 50 % and 75 %) off the x-axis. The sorting coefficient S_0 is here defined as: $S_0=(Q_1/Q_3)^{0.5}$.

Checking the raw data file revealed some inconsistencies in the weights. If the added weight of the sieved fractions differed more than 5 % from the total dry weight after wet sieving, the samples were excluded from further grain size analysis. For these sam-

ples it was assumed that the figures for the silt content were correct and that the mistakes happened during the dry sieving process.

Inundation times
Inundation times were modelled using a satellite image, heights and depth relative to chart datum (Indian Springs Low Water) of the area and local tidal charts. The times are hours of inundation per spring tide. For neap tide, basically, the points between 5 and 7 hours spring are the range for neap tides. Less than 5 hours, the area is completely dry; more than 7 (spring) and the area is under water.

For a number of sample stations more than 12 hours of inundation were computed, which is impossible for a semi-diurnal tide. More than 12 hours means, that the location is permanently under water, which would have made sampling impossible. The satellite image was taken years before, so the problem might be shifting of sediments and a net accumulation of sediment in these areas over the last years. Thus, the quality of the inundation times is a bit variable. The closer to the high tide line, the better the times; the closer to the low tide line, the worse. For the statistical analysis and possible correlations between biota and inundation times only relative values are important, so slight errors in the absolute values are of minor consequence.

The calculations of the relative inundation times in percentages are based on the values for hours of inundation during MHWS. Whereas these values were calculated as a linear function of height relative to chart datum, the true inundation times for a whole cycle of spring and neap tides are a non-linear function of it. As an approximation the tidal curve was assumed to be symmetrical with a sinusoidal shape. The relative time of inundation for any location with a given height
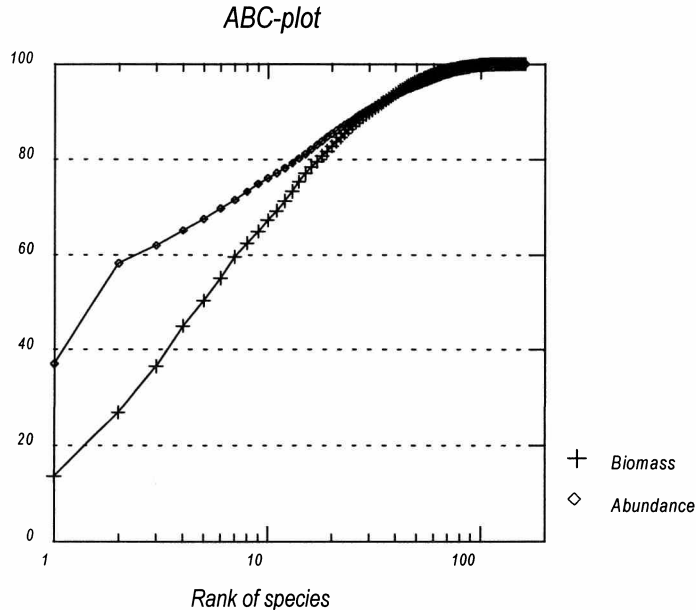
ABC-plot

Fig. 7.1: Abundance/Biomass plot. The plot shows cumulative relative abundance and AFDM of ranked species.

above chart datum may then be approximated by the formula: h (%)=sin (h/h_{max} x 1,571) x 100.

Classification and ordination

The benthic community structure was analysed following the 'Practical Strategy for Analysing Multispecies Distribution Patterns' by Field et al. (1982). In the following chapters, the term 'community' is used in its broadest sense, meaning an 'assemblage of macrobenthic taxa. In its strictest sense a community is defined as 'all the organisms living and coevolving in a particularly defined habitat'. This does not apply to our study because we concentrate on a few macrobenthic groups.

A low pass filter was applied to the original data set, averaging the abundance data within a square of 3 x 3 sampling stations in the north (200 m grid) and 2 x 2 stations in the south-eastern parts (500 m grid). Only those figures were taken into account that resulted from the average of at least 6 stations on the 200 m grid and 3 station on the 500 m grid respectively. The abundance data were then double square-root transformed to normalise the data and to down-weigh the influence of the most abundant species. All benthic fauna was included into the statistics and treated on the lowest taxonomic level the animals could be identified to. Bivalves were identified to species level, gastropods, polychaetes and decapod crustaceans to family level and the remaining taxa to suborder at best and phylum level at worst. Similarities between stations

were computed using the Bray-Curtis association measure. The resulting similarity matrices were then used as input to hierarchical agglomerative clustering with group-average linking. Station similarities were ordinated by using non-metric multi-dimensional scaling (MDS).

To find out which species were responsible for similarities within and dissimilarities between station groups, the similarity percentage procedure (SIMPER) of the PRIMER package was used. It was then tried to link environmental variables to community analysis. This was done by representing the values of the environmental variable in question as symbols of differing sizes and superimposing these symbols on the biotic ordination of the corresponding sample. To find out which combination of environmental variables best explains the biotic structuring of the community the BIO-ENV procedure of the PRIMER program was used (see Clarke & Warwick 1994 for details).

Abundance, biomass and diversity

All in all 537 stations were sampled during a period of twelve successive days. At each site three cores were taken to a maximum depth of 50 cm. Sorting and identification of the 17,105 animals retrieved on the 1 mm sieve yielded a total of 161 taxa. Bivalves were identified to species level, the other taxonomic groups were identified to family level (gastropods, polychae-
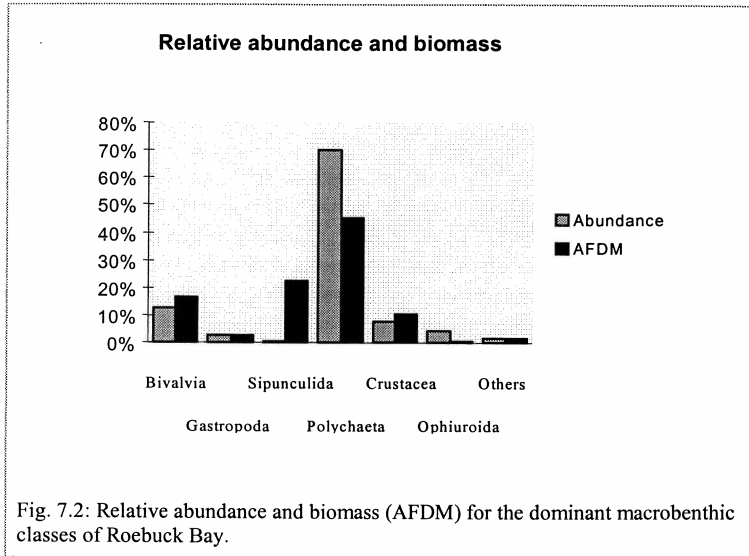
Relative abundance and biomass

Fig. 7.2: Relative abundance and biomass (AFDM) for the dominant macrobenthic classes of Roebuck Bay.

tes, decapod crustaceans), order (Amphipoda, Tanaidacea, Mysidacea), sub-class (Copepoda, Ostracoda) or phylum level (Nemertini, Tentaculata, Sipunculida, Echiurida, Porifera). The 161 taxa identified belonged to 114 families, 20 classes and 12 phyla (Ch. 6.1). Polychaetes were the most diverse class with 29 families, followed by crustaceans (23), gastropods (22) and bivalves (16).

With 161 taxa found, the area seemed to be rather diverse. As a matter of fact very few taxa dominate the fauna numerically and the distribution of individuals amongst taxa is extremely uneven. Plotting rank of species against the accumulated relative number of individuals shows that the two most abundant families make up 58 % of the total number of individuals found (Fig. 7.1). These are the colonial tube building polychaetes Chaetopteridae and Oweniidae, which occur locally in very high densities. 20 families, representing 17.3 % of all families found, account for almost 90 % of the sampled fauna. At the other extreme of the spectrum many rare species are present, which were found in only a few samples. 18 families out of the total of 114 families were found only once and with 52 families almost half of the total number of families occurred at less than 2 % of the sampled stations. The well defined trends in abundance across the bay therefore largely mirror the distribution patterns of the numerically dominant species, primarily chaetopterid and oweniid tubeworms. The average number of individuals per square meter is 1,287 with a range from 40 to 16,280. Since the frequency distribution is very uneven and inclined towards the stations with lower individual numbers, the median abundance of 560 macrobenthic individuals is therefore a more suitable parameter to describe the density per square meter.

Total benthic biomass was very patchy and differed from trends in abundance, except for regions with mass occurrence of oweniid tubeworms. This was due to the occasional inclusion of large individuals at various positions in the bay, namely large specimens of sipunculids, polychaetes of the families Lumbrineridae, Sigalionidae, Glyceridae and Paraonidae and decapods of the genera *Macrophthalmus* and *Squilla*. The average biomass value for the study area was 12.46 g/m² AFDM with a range from 0.07 to 167 g/m². The contribution of the different taxa to the biomass in the bay was more evenly distributed than to the numerical abundance. Here the seven most important taxa made up 60 % of the biomass. Spatial trends of biomass values within the study area did become discernible when looking at the distribution of AFDM within benthic classes, as will be discussed below.

On the class level polychaetes were most abundant, representing 70.2 % of the infauna and epifauna. These were followed by bivalves (12.5 %), crustaceans (7.9 %), gastropods (2.5 %) and brittle stars (4.2 %). All other taxa amounted to only 2.7 % (Fig. 7.2). Polychaetes also showed the highest biomass values with 45.4 % of the total AFDM, but here the dominance was not as conspicuous as for mere numbers of individuals. Sipunculids, though very low in numbers, followed next with 22.7 % of the biomass. Most sipunculids sampled had lengths exceeding 40 mm, which explains their high individual biomass. Bivalves contributed 16.3 % to the total AFDM, crustaceans 10.5 % and gastropods 3 %. The biomass of brittle stars is with 0.4 % quite insignificant. Most of the numbers within this class were made up by tiny specimens of the long-armed brittle star and AFDM
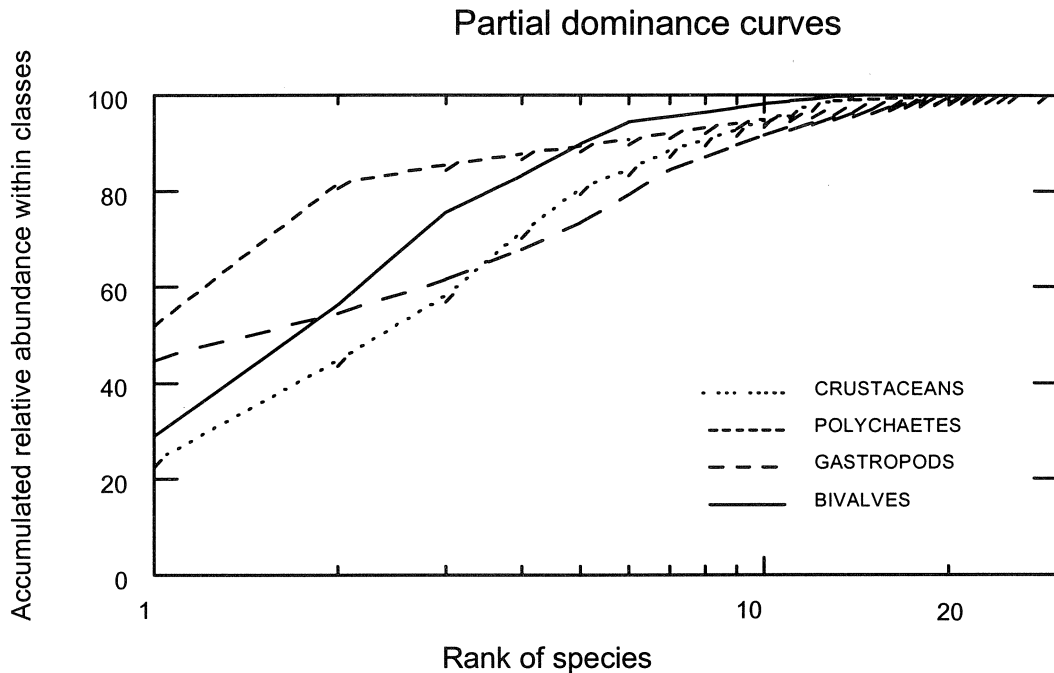
Partial dominance curves

Fig. 7.3: Partial dominance curves for the classes Gastropoda, Bivalvia, Polychaeta and Crustacea

per individual was accordingly low. The remaining taxa together made up 1.9 % of the total biomass.

The evenness of the distribution of individual numbers differed between classes, though a dominance of relatively few families was a common feature (Fig. 7.3), especially in the class Polychaeta. The class Crustacea showed the most evenly spread distribution of the mayor classes present.

Bivalves

The most common bivalves belonged to the families Lucinidae (29 %), Tellinidae (27 %), Cultellidae (20 %), Solemyidae (7.6 %), Veneridae (6.6 %) and Arcidae (4.6 %). The remaining ten families together made up only 5.7 % of the individuals within this class. Tellins were the most diverse family with twelve species. Most of these had to be given preliminary names and an identification to species level was not possible, indeed, there may be species among the tellins that are new to science. The highest numbers of individuals in the study area were found in the sandy areas around Dampier Creek and in the siltier eastern parts of the embayment between Fall Point and One Tree. Numbers were largely made up by *Tellina piratica*, *Solemya*, *Anomalocardia squamosa* and *Anadara granosa* in the Dampier Creek area and an assemblage of *Anodontia* cf. *omissa*, *Tellina amboyensis*, *Macoma* cf. *exotica* and *Siliqua* cf. *winteriana* in the east. Quite

striking was the fact that at Dampier Creek numbers tended to be higher in the upper intertidal whereas the opposite was true for the region around Fall Point and One Tree.

The distribution of AFDM across the bay largely reflected the patterns of mere abundance with one important exception. The high numbers of individuals in the lower intertidal in the eastern parts of the bay were made up of rather small specimens of the lucinid bivalve *Anodontia* cf. *omissa* and biomass values were accordingly low. Few rather big specimens of *Anadara granosa* and various tellins in the upper intertidal were responsible for a week trend of biomass values being higher close to the mangrove fringe between Fall Point and One Tree. The highest AFDM value found was 46 g/m² in one location in the south eastern part of the intertidal, where fifteen specimens of *Siliqua* cf. *winteriana* of various lengths were sampled resulting in a total number of 600 ind./m² (Fig. 7.4).

Bivalves were encountered in 412 out of 538 stations. The average number of individuals for the entire study area was 155 ind/m², of biomass 2 g/m² AFDM, respectively. The upper intertidal region around Dampier Creek showed higher values both for numbers and AFDM with an average around 250 ind/m² and 4.8 g/m² AFDM. For the upper intertidal region between Fall Point and One Tree values were 200 ind/m² and 4.9 g/m² AFDM, respectively.
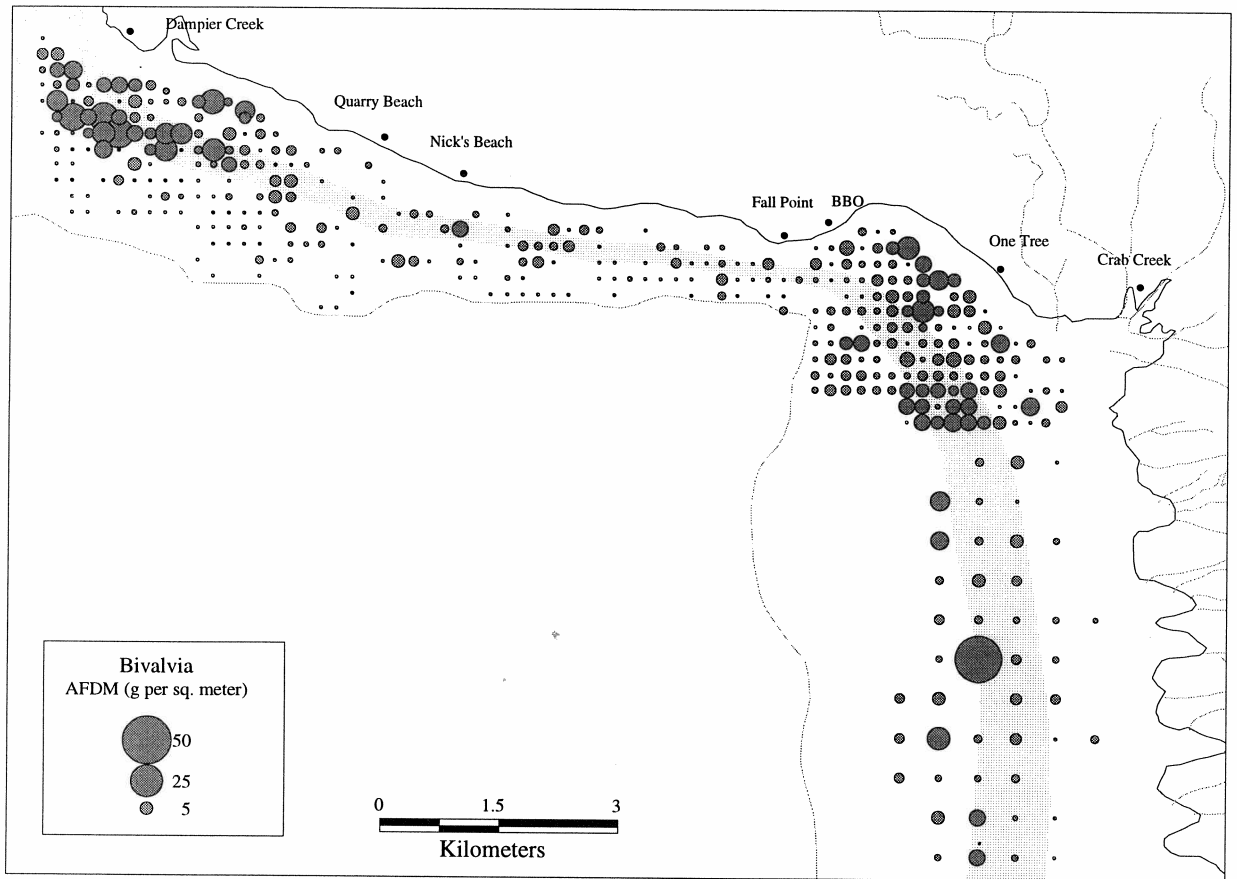
Fig. 7.4: Distribution of AFDM (g/m²) within the class Bivalvia. Highest biomass values were recorded in the very fine sands of the Dampier Creek area and the silty muds of the north-eastern parts of Roebuck Bay.

Gastropods

The most frequent gastropod in the samples belonged to the family Nassariidae (45,1 %), followed by members of the family Amphibolidae (9.4 %), Cerithidae (7 %), Marginellidae (6.2 %), Eulimidae (5.8 %), Columbellidae (5.8) and Costellaridae (5.3 %). Although nassariids were by far the most abundant taxon within the gastropods, numbers of individuals summed over all gastropod taxa were swamped by other species. This was due to the fact that nassariids occurred in low numbers all over the embayment, whereas most of the other gastropod families like Eulimidae or Amphibolidae had a very restricted distribution but reached higher densities per station.

Similar to the distribution of bivalves highest numbers of gastropods occurred in the Dampier Creek area in the north western part of Roebuck Bay and in the area between Fall Point and Crab Creek to the east. The rather narrow stretch of intertidal between Quarry Beach and Fall Point showed a very patchy distribution and gastropods were completely missing from most stations. The largest specimens of gastropods belonged to the families Nassarius and Naticidae and a plot of AFDM for all gastropods across the embayment largely reflected the distribution pattern of the dominant species *Nassarius dorsatus*. Gastropods were found in 164 out of 538 stations. Averaged over all stations the number of individuals was 30 with a maximum of 840.

The average biomass was 0.34 g/m² with a range from 0 to 9.6 (Fig. 7.5). In contrast to bivalves, highest values of AFDM within the class Gastropoda were made up by single, large specimens of snails that occured patchily. Due to this fact distribution patterns of AFDM were not perceivable and did not mirror patterns of abundance. This is backed up by correlation statistics. Although a correlation of AFDM with abundance (two-way Pearson correlation, both variables log-transformed) yielded significant results at the 1% level for both bivalves and gastropods, the correlation coefficients were a lot higher for bivalves than for
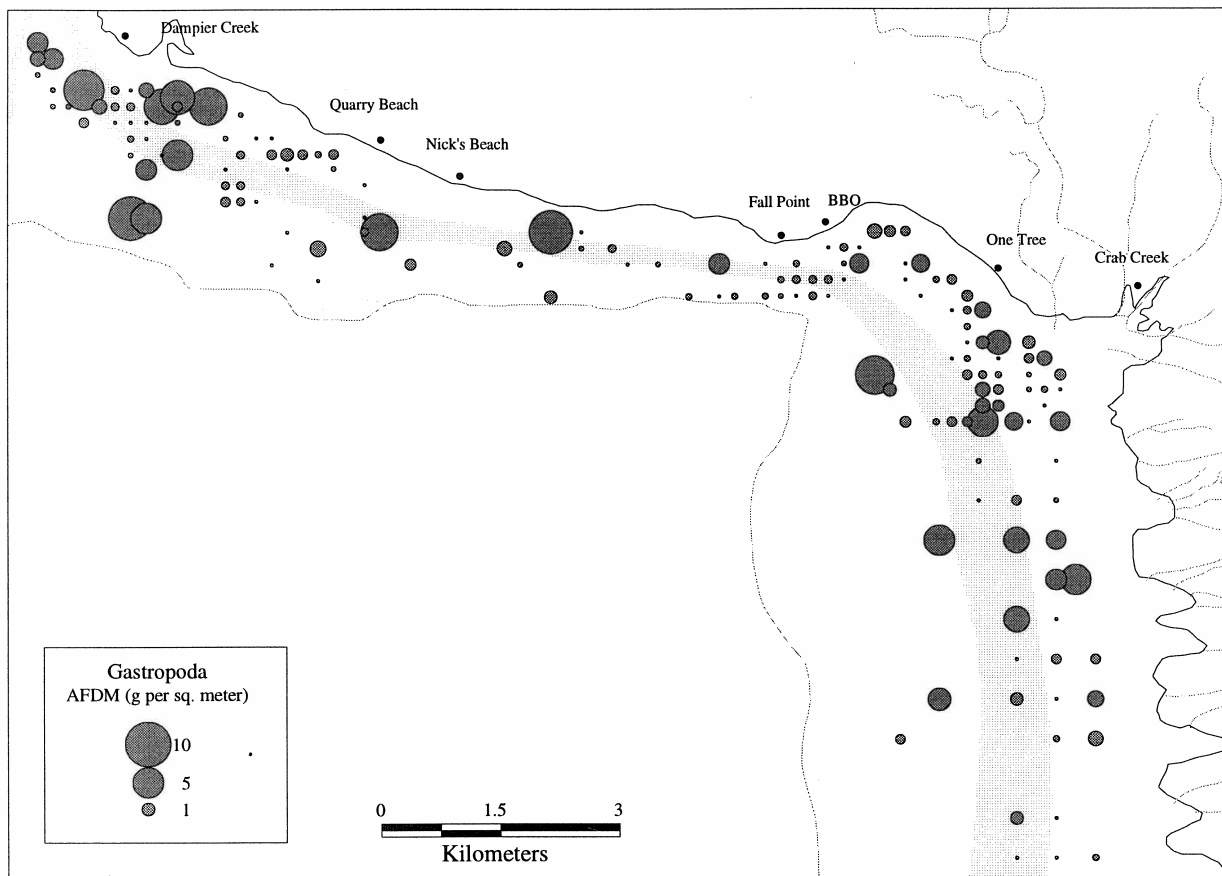
Fig. 7.5: Distribution of AFDM (g/m²) within the class Gastropoda. High values of AFDM are almost randomly distributed due to the occasional sampling of large nassariid snails that largely determined the figures.

gastropods (0.672, DF=410 compared to 0.358, DF=162).

Polychaetes

Amongst the polychaetes the two above mentioned tube building bristleworms Chaetopteridae (51.83 %) and Oweniidae (30 %) dominated the fauna. These were followed by the families Glyceridae (3.8 %), Nephtyidae (2.4 %), Opheliidae (1.54 %), Onuphidae %). Even though the relative abundance of the latter polychaete families seemed to be small compared to the numbers of the colonial tube building families Chaetopteridae and Oweniidae, this does not necessarily mean that their ecological role is of minor significance. The above mentioned families belong to different guilds, occupy different niches and are thus difficult to compare. Moreover the reader has to bear in mind that the sampled fauna includes both epifaunal and infaunal species of various sizes and a comparison of mere abundance would certainly give a wrong picture of their ecological importance.

The numbers of individuals ranged from 40 to 15,680 ind./m² with an average of 903 individuals. The range for biomass was 0.003 to 70 g/m² AFDM, respectively, with an average of 5.55 g/m² (Fig 8.6). As already mentioned numbers of abundance were swamped by chaetopterid and oweniid tubeworms. Excluding these two families resulted in accordingly lower figures, which are more suitable when it comes to evaluating the study area as a feeding ground for waders. First of all chaetopterids and oweniids do not seem to be a preferred prey item for shorebirds, and secondly the estimation of AFDM for these tubeworms was only a very inaccurate guess because body mass data were not available. The average abundance without these two families was 165 ind./m² and mean biomass 2.77 g/m² AFDM. The maximum values encountered were 1,520 ind./m² and 51.4 g/m² AFDM, respectively.

The highest numbers of individuals were found in the lower intertidal in front of Dampier Creek and in the sandy regions between Nick's Beach and Fall
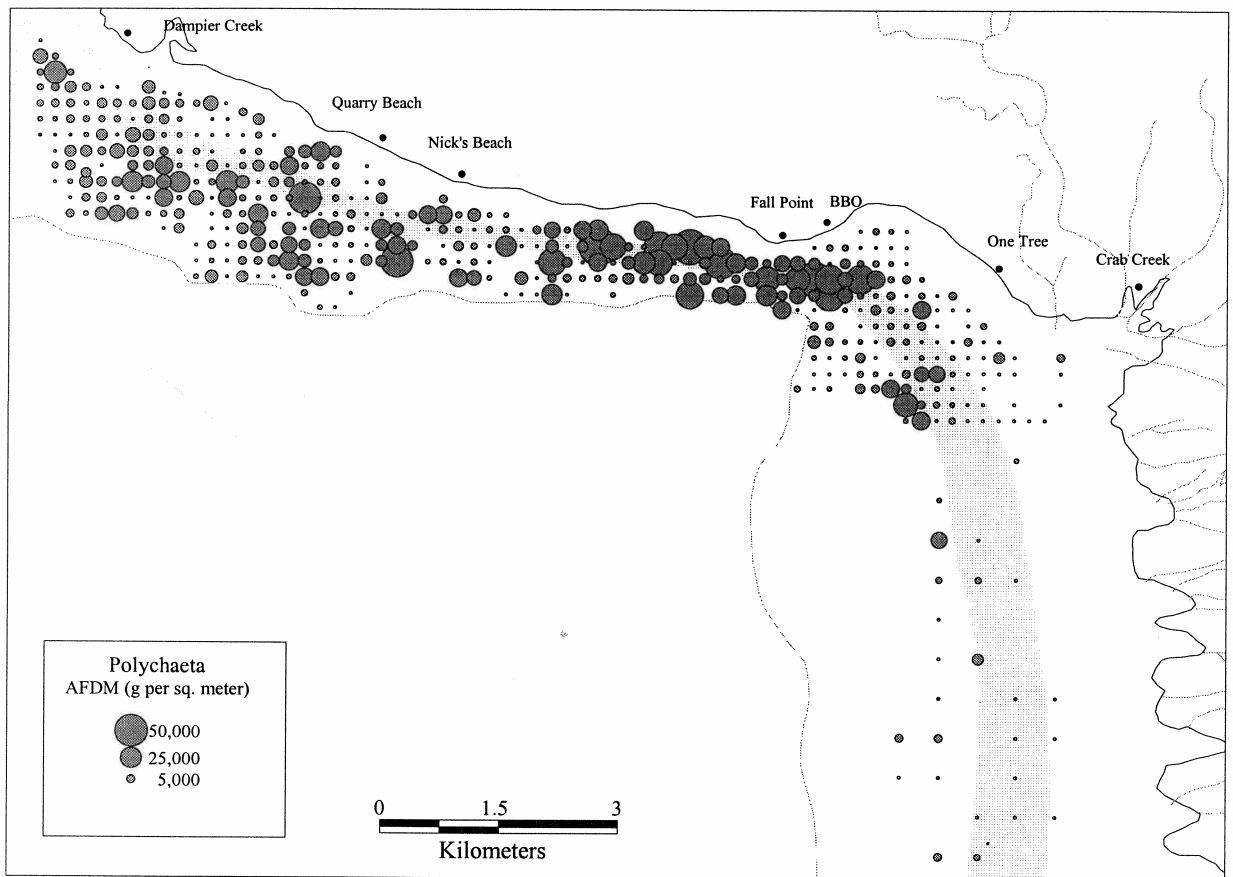
Fig. 7.6: Distribution of AFDM (g/m²) within the class Polychaeta. High values of AFDM largely reflect the distribution patterns of the dominant families Chaetopteridae and especially Oweniidae. Large biomass figures outside the distribution centres of these two families are mainly due to the inclusion of large individuals of a few polychaete families (see text for details).

Point. In the south eastern part of the study area both abundance and biomass values were very low. Quite a few stations showed high biomass values due to the occasional inclusion of large free living polychaetes, mainly of the families Sigalionidae, Lumbrineridae and Paraonidae, sometimes exceeding 10 cm in length. These large specimens were encountered randomly in the northern part of the embayment but were widely missing from the siltier, south eastern parts.

Crustaceans
Within the crustaceans, decapods and isopods were identified to family level, the other taxa to subclass (Ostracoda, Copepoda), order (Mysidacea, Cumacea, Tanaidacea, Isopoda), or suborder (Gammaridea). The order Decapoda was the most abundant with 58.8 % of all crustaceans sampled. Within the decapods the family Paguridae (21.03 %) was the most numerous, succeeded by the families Hymenosomatidae (13.31 %),

Ocypodidae (13.31 %) and Goneplacidae (3.9 %). Ostracods represented 23.7 % of the counts, the suborder Gammaridea 9.3 %, and the isopod Anthuridae 3.9 %.

Crustaceans were found at 344 out of the total of 537 sample stations. The abundance of crustaceans in the study area ranged from 0 to 3,560 ind./m² with an average of 100 individuals, biomass from 0 to 113 g/m² with an average of 1.2 g/m².

The figures of abundance were controlled by the distribution of the numerically dominant taxa Paguridae, Ostracoda, Hymenosomatidae and Gammaridea, and highest numbers were encountered in the upper intertidal region of the northern parts of the embayment. High biomass figures were almost entirely made up by large specimens of decapods, mainly of the genera *Squilla* and *Macrophthalmus*. At one site each, large individuals of the families Callapidae and Palaemonidae (Fig. 6.7) were responsible for high biomass figures.
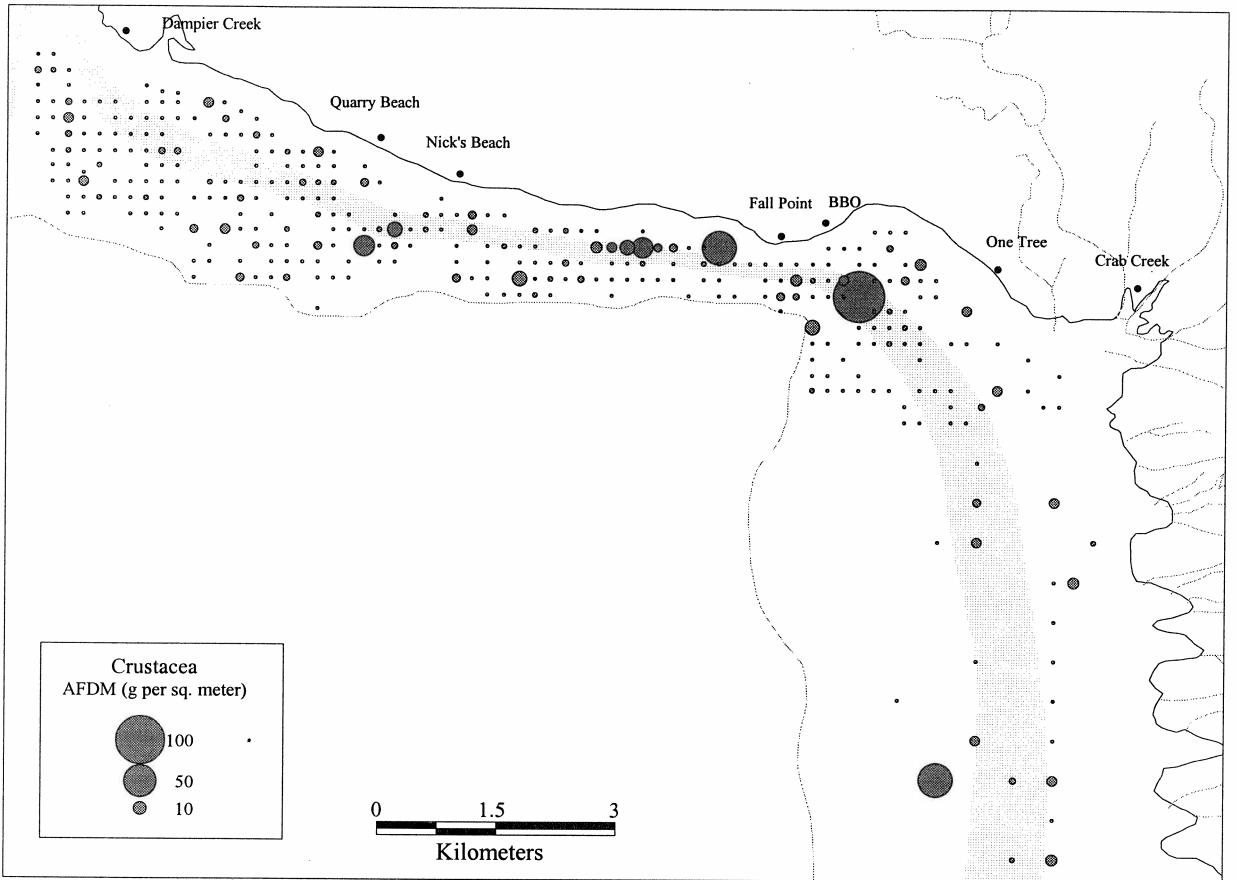
Fig. 7.7: Distribution of AFDM (g/m²) within the class Crustacea. Few, very large specimens of mainly Macrophthalmus crabs are responsible for the very high figures in different parts of the embayment.

The wide range of body sizes was extremely conspicuous within the crustaceans (Plate 5.1), and the relative abundance of the different taxa may therefore be misleading. Sizes ranged from 1 mm for the subclass Ostracoda to about 8 cm for the largest representatives of the family Squillidae. Especially the bigger, more mobile or deep digging crustaceans were clearly underrepresented in the samples, and numerical data has to be treated carefully. *Squilla* and *Macrophthalmus* dig deep into the sediment and the highest number of burrows was observed in the eastern parts of the embayment. The actual biomass of crustaceans in this part of Roebuck Bay can therefore be expected to be a lot higher than the figures calculated from the samples.

Diversity and eveness
The Shannon-Wiener Diversity Index H' and Pielou's evenness were computed using natural log as a base. The average values for H' for all stations was 1.41 (range 0 to 2.69), and for evenness 0.77 (range 0.08 to

1). It is important to notice that these diversity indices are only relative values, in as far as they depend on the taxonomic level the individuals were identified to. It is thus not possible to compare H' values of the study area with other locations. They are only adequate to describe differences in diversity within this particular area.

Diversity and evenness changed on a small scale and often differed drastically between adjoining stations. There was a weak trend of H' being higher in the northern parts of the bay than in the intertidal area along the eastern coastline. Evenness was generally high except for the sampling stations dominated by tubeworms.

Correlation analysis

On the 1 % significance level, the Shannon Wiener Diversity was not correlated with grain size parameters or inundation times. There was a weak negative cor-

relation between silt content on the one hand and the total number of species present (-0.164**), Richness (-0.178**) and the total number of individuals (-0.124**) on the other, showing a trend of diversity indices being slightly higher in sandier substrates (Table 7.2).

Correlations between these parameters were computed after Pearson, and the results need to be treated with caution. First of all the correlation after Pearson requires a normal distribution of the parameters. Stem and leaf plots of the data sets revealed that this is hardly the case. To approach normality the number of individuals per sampling unit and AFDM were henceforth log-transformed. Secondly, bivariate statistics are not sufficiently adequate to describe the distribution of the various taxa. A combination of many biotic and abiotic parameters must be taken into account to explain perceptible distribution patterns, still disregarding erratic events like spat-fall which make the picture even more complicated. Multivariate statistics are a more suitable means to approach this problem and will be applied below. Last but not least, correlating the abundance of the different taxa is problematic and the results must not be used to distinguish between species. For the correlation, cases were excluded pairwise and this bears the danger that completely different subsets of samples were investigated. For most species the numbers of observations were very low and the rather weak correlations can therefore hardly reach significance.

Nevertheless, bivariate statistics can give an idea about the preferred habitat of some taxa. Correlating species abundance with median grain size (MGS) and inundation hours yielded significant results on the 1 % and 5 % level for a few taxa that were widely in agreement with their distribution maps (Ch. 7).

Anodontia omissa was positively correlated with inundation hours (0.395**) and silt content (0.431**), and negatively to the median grain size (-0.412**), showing that this species tended to be more common in the lower intertidal environment and in finer substrates.

In contrast to this, the other abundant lucinid bivalve *Divaricella ornata* was negatively correlated with silt content (-0.366*), apparently thriving better in coarser substrates.

The distribution of *Siliqua* cf. *winteriana* could be partially explained with sediment characteristics (-0.264** with MGS) but seemed to be independent of inundation times.

The gastropod *Nassarius dorsatus* showed a significant correlation with inundation times (-0.377**) but not to MGS, making it a species of the higher intertidal with the ability to live in and on a variety of substrates.

The predatory polychaetes Nepthyidae and Glyceridae showed different susceptibilities to changes in abiotic parameters. Glycerids were more common in the lower intertidal (0.194** with inundation hours) irrelevant of MGS, whereas specimens of the family Nephtyidae seemed to prefer coarser substrates (0.278** with MGS) and numbers were not significantly correlated with inundation times.

The abundance of the tube building polychaetes Chaetopteridae and Oweniidae followed different gradients as well. Chaetopterids were positively correlated with inundation times (0.204**) and negatively with silt content (-0.185**). The latter correlation seemed somewhat strange, because the tubes trap finer particles and a positive correlation was expected.

This result shows the limits of bivariate statistics because here the fact is overlooked that the sediment characteristics are not independent of inundation times. The lower intertidal is a more dynamic environment than the higher intertidal, resulting in coarser substrates. The rather high correlation between inundation times and silt content (-0.322**) influenced the correlation between chaetopterids and sediment parameters and the interpretation of the latter dependency needs to be revised: Chaetopterids are adapted to living in the lower intertidal where sediments are coarser due to higher energy input.

Another interesting field observation, namely the co occurrence of chaetopterid polychaetes and seagrass, could also be backed up by bivariate statistics. The application of the Spearman-Rho correlation coefficient showed a significant correlation between the abundance of chaetopterids and both oval and lancet leafed seagrass (0.215** and 0.175**, resp.). The even stronger correlation between both seagrass species, silt content (-0.325**, -0.387**) and inundation times (0.484**, 0.418**) suggests that in this case flora and fauna flourished along the same kind of gradients, that is both being more abundant towards the lower intertidal where sediments tend to be coarser. Oweniids were negatively correlated with inundation times on the 5 % significance level (-0.172*). They lived higher up in the intertidal compared to chaetopterids, thus avoiding competition for space, which is essential for these colonial tube worms.

Finally, there was a very strong correlation between the occurrence of large burrows made by either mantis shrimps, *Macrophthalmus* crabs or mudskippers on the one hand, and silt content (Spearman-Rho, 0.700**), inundation times (Spearman-Rho, -0.301**), the depth to which the cores were taken (Spearman-Rho, 0.503**) and the degree of sorting (-0.378**) on the other hand. The permanent burrows, that may reach down to a depth exceeding one meter, were most numerous in silty, cohesive substrates and

Table 7.2: Correlations of fauna densities, feeding modes, diversity indices and biomass with habitat parameters. Indicated is the use of normalisation of the parameters, the significance of the observed correlation (* for p < 0.05 and ** for p < 0.01), the number of observations N (pairwise exclusion of variables) and which correlation coefficient is used. The Pearson product moment correlation (P) is used for normally distributed parameters (after transformation if necessary) and Spearman rank correlation (S) for the others. Blank cells denote insignificant correlations.

	Coeff. / Transf.	inund. hours	silt content (%)	MGS (µm)	Sorting coeff. (S_0)	seagrass oval	seagrass linear
	Coeff.	P	P	P	P	S	S
	Transf.	none	none	none	none	n.a.	n.a.
Anodontia cf. omissa	log	0.395** N=112	0.431** N=112	-0.412** N=112		-0.285** N=112	-0.268** N=112
Divaricella ornata	log		-0.366* N=43				
Siliqua cf. winteriana	log			-0.264** N=113	-0.219* N=113		
Nassarius dorsatus	log	-0.377** N=81	0.222* N=81				
Nephtyi-dae	log		-0.261** N=161	0.278** N=161			
Glyceridae	log	0.194** N=231					
Chaetop-teridae	log	0.204** N=235	-0.185** N=234	0.131* N=234	0.214** N=234	0.215** N=234	0.175** N=234
Oweniidae	log	-0.172* N=192			0.143* N=191	-0.179* N=192	
D.-feeders (%)	none		-0.217** N=535	0.181** N=533			
F.- feeders (%)	none	0.300** N=536	0.160** N=535	-0.180* N=533	-0.085* N=533		
No. of species	none	0.087* N=538	-0.164** N=536	0.092* N=534	0.199** N=538		
No. of ind.	log	0.146** N=538	-0.124** N=536		0.168** N=538		
Richness	none		-0.178** N=536	0.098* N=534	0.177** N=538		
AFDM	log	0.099* N=538	0.115** N=538		0.123** N=538		

in the upper intertidal where energy input is low. A shell grit layer or underlying sandstone, typical for the western parts of the bay, and which prevented sampling to greater depths, would have been unpenetrable for these burrowing species. Finally, the reworking of the sediment by the burrowing activity of these species is responsible for the lower degree of sorting.

The correlation of the relative abundance of individuals within different feeding guilds with abiotic parameters showed some results that were unexpected at the first sight. The numbers of deposit feeders proportionally and absolutely increased along a gradient of decreasing silt content (-0.217**, -0.213**), independent of height relative to chart datum. The opposite was true for suspension feeders. Here the relative abundance was positively correlated to silt content (0.160**). Absolute numbers on the other hand showed no significant correlation with sediment texture. This seems to contradict the conventional wisdom of benthic ecology that the abundance of deposit feeders in a community increases as grain size decreases (Gray, 1974).

These results require careful examination because, although significant on the 1 % level, correlations are rather weak. A rigid assignment of species to feeding guilds is problematic and may be misleading. Many species are capable of more than one mode of food uptake and especially the distinction between feeding guilds is somewhat artificial. Typical for the study area is the dominance of few species within taxonomic

groups and also within feeding guilds. The correlations between feeding modes and other parameters may therefore reflect the individual ecology of the few abundant species rather than generalised characteristics of feeding groups.

In unison with theory was the rather strong negative correlation between the relative abundance of deposit feeders and suspension feeders (-0.554**). According to Rhoads (1974) an extensive reworking of the silt-clay environment, deposit-feeders live in, produces an uncompacted surface of faecal pellets of low density. This instability inhibits the suspension-feeders by clogging their filtering structures. But here again figures might be swamped by the mass occurrence of the suspension feeding polychaete Chaetopteridae and decreasing numbers of deposit feeders in its natural habitat could be explained by the competition for space and food.

Multivariate analysis

Plots of abundance for the various taxa found in Roebuck Bay revealed that patchiness of distribution was a common feature throughout the benthic fauna. Neighbouring stations often differed remarkably in both the assemblage of species and the absolute numbers of individuals. The mudflats, which at the first glimpse seemed to stretch out for miles and miles without a change in appearance, must therefore possess a spatial heterogeneity of habitats and animal communities on large and small scales. With the kind of sampling program we undertook, i. e. sampling on a 200 and 500 m grid, small scale variations could not be satisfactorily described. However, just by looking at the distribution maps of the most important species, it becomes evident that many taxa do show distinct distribution patterns and that different regions of the embayment harbour characteristic assemblages of species.

The sediment characteristics in Roebuck Bay changed both along a shore normal and a shore parallel gradient, grading from coarse sands in the lower intertidal in the north-western parts of the bay to fine muds close to the mangrove fringe along the eastern coastline. Sediment parameters together with immersion times are predicted to affect the species composition and abundance and it might be assumed that the faunal assemblage in the north-west is markedly different from the eastern parts.

The main problem, like so often, was to delineate these regions. Both species composition and abiotic parameters changed along a continuum, and every borderline decision must therefore be artificial. This has to be kept in mind when looking at the results of the cluster analysis presented below. The hierarchical clustering procedure dictates that, once a sample is grouped with others, it will never be separated from them at a later stage of the process. Thus, early borderline decisions, which may be somewhat arbitrary are perpetuated through the analysis and may sometimes have a significant effect on the shape of the final dendrogram. Such situations are certain to arise if, as here, one is trying to force what is essentially a steadily changing pattern into discrete clusters.

Multi-Dimensional Scaling (MDS) can offer a more realistic picture of station similarities than a dendrogram because it can display similarities as distances on a two-dimensional plane. The problem with MDS is that a two dimensional picture cannot be a perfect representation of the station similarities computed from a multi-dimensional n x m species/samples matrix. The goodness-of-fit of the representation can be described by a stress value, which is basically a formula to describe the scatter of values around a fitted, non-parametric regression of distances in the 2-dimensional MDS against Bray-Curtis Similarity values (see Clarke & Warwick 1994 for further discussion). A rough rule-of-thumb for 2-dimensional ordinations is as follows: Stress values under 0.1 correspond to a good ordination with no real prospect of misleading interpretation. Stress between 0.1 and 0.2 still gives a potentially useful 2-dimensional picture, though for values at the upper end of this range too much reliance should not be placed on the details of the plot. A cross-check, e.g. the superimposition of cluster groups on the ordination is advisable to validate the results. Values in the range 0.2 to 0.3 should be treated with a great deal of scepticism and certainly discarded in the upper half of the this range, especially for a small to moderate number of points. Another drawback of MDS is that it is computationally demanding. Processor time increases roughly proportional to n^2 and increasing sample size generally brings increasing complexity of the sample relationships. A 2-dimensional representation of the sample relationships of much more than 100 stations is then very unlikely to be adequate.

An MDS ordination using a subset of the original species\samples matrix as input resulted in high stress values around 0.25 and had to be discarded. The samples taken on the grid locations were too dissimilar regarding their species composition and absolute numbers to find any patterns. The reasons for this are twofold. One is the small-scale heterogeneity typical for the embayment, the other reason is connected to the sampling scheme itself. The three cores taken per station covered only 1/40 of a square meter and especially the rarer and larger species are poorly represented. For a study on the macrozoobenthos a sam-

Roebuck Bay Macrofauna
Dendrogram of stations
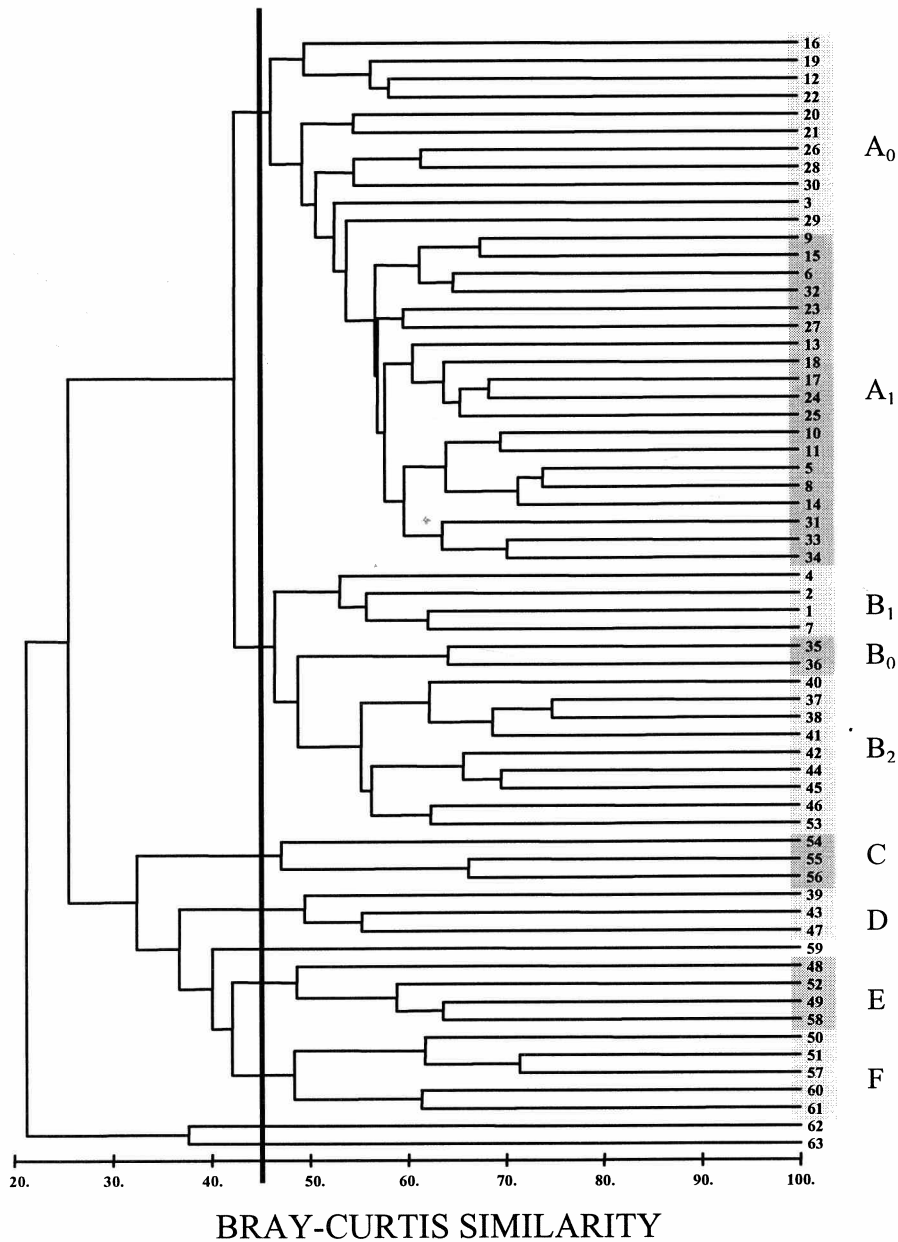
Fig. 7.8: Dendrogram showing the station clusters cut off at 45 % similarity. Stations 59, 62 and 63 showed a very dissimilar species composition and were excluded henceforth.

pling design with less stations, but more replicates and material per site would have been advisable.

To make up for these deficits a 3 x 3 low pass filter was applied to the stations sampled on the 200 m grid and a 2 x 2 filter on the 500 m grid, respectively. On the resulting 600 m grid in the north only groups containing at least 6 out of possible 9 stations were used for further statistics, on the 1,000 m grid in the south-

west groups with 3 out of 4 stations, respectively. The remaining stations (86), mainly situated at the lower or upper end of the intertidal, were grouped together as miscellaneous and excluded from multivariate analysis. The filtering process left a total of 63 aggregated stations. Two of these, stations 62 and 63, are located at the extreme southern end of the embayment and therefore not shown on the maps (Fig. 7.9). It would have been desirable to find a scheme that aggregated the same number of stations, but this was not possible due to the shape of the embayment.

The biotic and abiotic data was averaged over the filtered stations and used as input for further statistics. Inherent in this filtering process is a loss of valuable data, but it has the advantage that general patterns of species assemblages become discernible and that the data of most stations rather than just of a small subset flow into the calculations.

Cluster analysis of stations

Fig. 7.8 is a dendrogram showing station affinities,

based on the mean root-root transformed abundance of all 163 species found in the study, using the Bray-Curtis measure of similarity and group average sorting. The similarity between the jth an kth samples, Sjk, is computed using Eq. 7.1.

$$\delta_{ik} = 100 * \frac{\sum_{i=1}^{p}|y_{ij} - y_{ik}|}{\sum_{i=1}^{p}(y_{ij} + y_{ik})}$$

Eq. 7.1

Here y_{ij} represents the entry in the ith row and jth column of the data matrix, i.e. the abundance for the ith species in the jth sample (i =1,2,...,p; j = 1,2,...,n). Similarly, y_{ik} is the count for the ith species in the kth sample.

A line drawn at the arbitrary similarity level of 45 % delineates six major groups of stations, representing 60 out of 63 stations. Station number 59 and the two southern stations 62 and 63 were grouped together
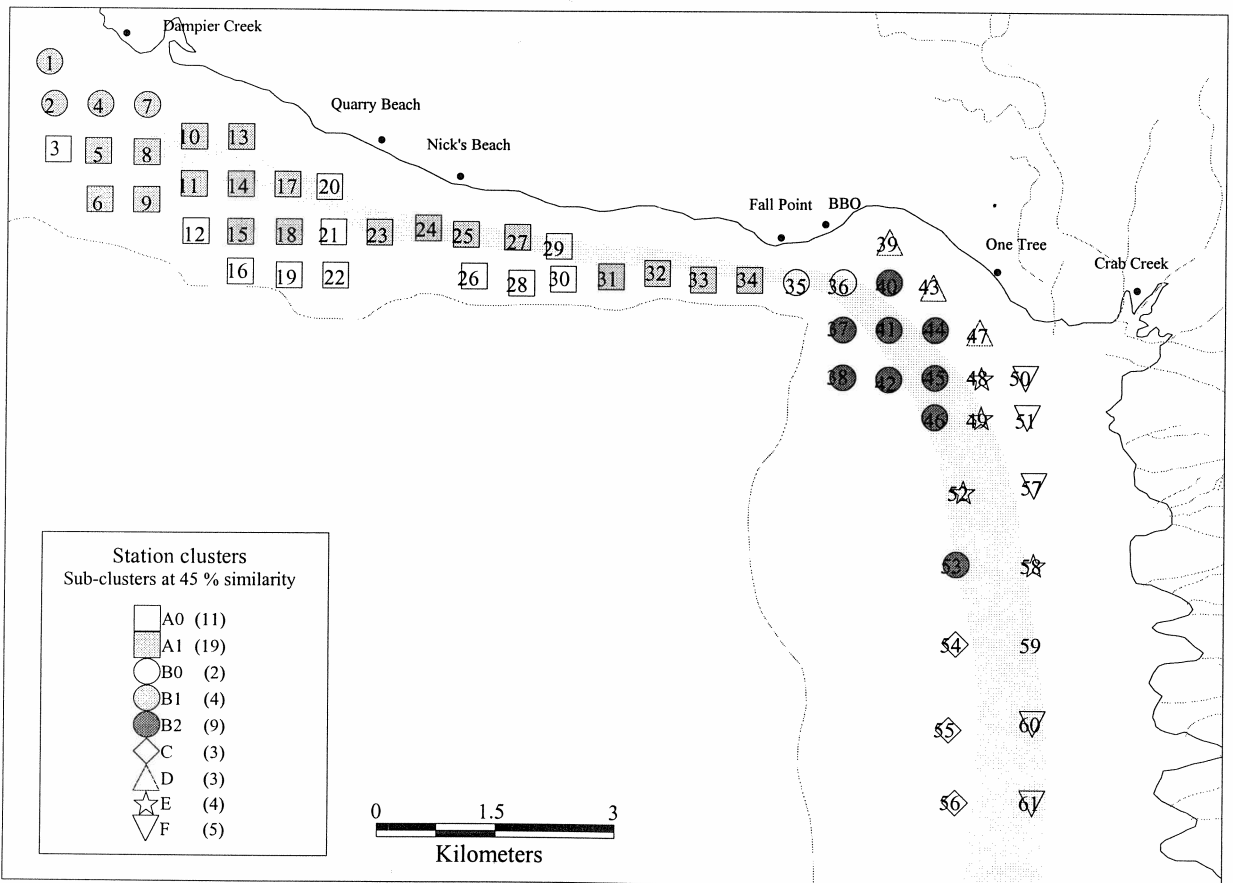

Fig. 7.9: Map showing the station clusters resulting from cluster analysis. The cut-off level was chosen arbitrarily at 45 % similarity. Stations 59 and the two stations 62 and 63 to the far south (not shown on the map) were grouped together with other stations at lower similarity levels and are henceforth excluded from further analysis.

with these clusters at lower similarities and are excluded from further analysis. The clusters differ significantly in size. Clusters A and B are the by far the largest clusters, comprising a total of 30 and 15 stations, respectively. The others are smaller, with five stations grouped together in cluster F, four in cluster E and three stations each in cluster D and C.

A more detailed look at the results shows that the sequence of clustering groups together is not very clear-cut. Even after the filtering process stations are still very dissimilar and the first clustering of stations occurs at only 74.8 % similarity (stations 37 and 38). After that the grouping together to continuously bigger units proceeds very rapidly until the six clusters A to F show at 45 % similarity. So except for a few outlying stations, most similarities are within a narrow range of 50 to 75 %. The inherent problem of clustering analysis, i. e. that early borderline decisions are perpetuated throughout the rest of the analysis affecting the final shape of the dendrogram, reaches higher significance. The two large clusters A and B can be further subdivided. Within cluster A a rather tightly clustered sub-group, labelled A_1, emerges at 57.8 %. The other stations of cluster A are then combined with this cluster at consecutively lower similarity levels until the small subgroup containing stations 16, 19, 12 and 22 is finally linked at 46 % similarity. Cluster B divides into three homogeneous sub-groups that have been designated B_0, B_1 and B_2.

Plotting the station groups on the map of Roebuck Bay (Fig. 7.9) shows that the 9 clusters form discrete geographical units, except for station number 3, which is separated from the other stations of cluster A_0. Fig. 7.10 shows the ordination for the 63 stations, using MDS as an ordination technique. The group labels from the cluster analysis are superimposed on the corresponding stations. As expected from the narrow range of similarity values, most stations form a rather tight cluster on the ordination plot. Although some degree of overlap in the cluster groups on the MDS plot exists, segregation is evident. Stations of cluster A_1 form a rather tight cluster within the cloud of stations made up by groups A_0, A_1, B_0, B_1 and B_2. The other groups are clearly separated from these and appear
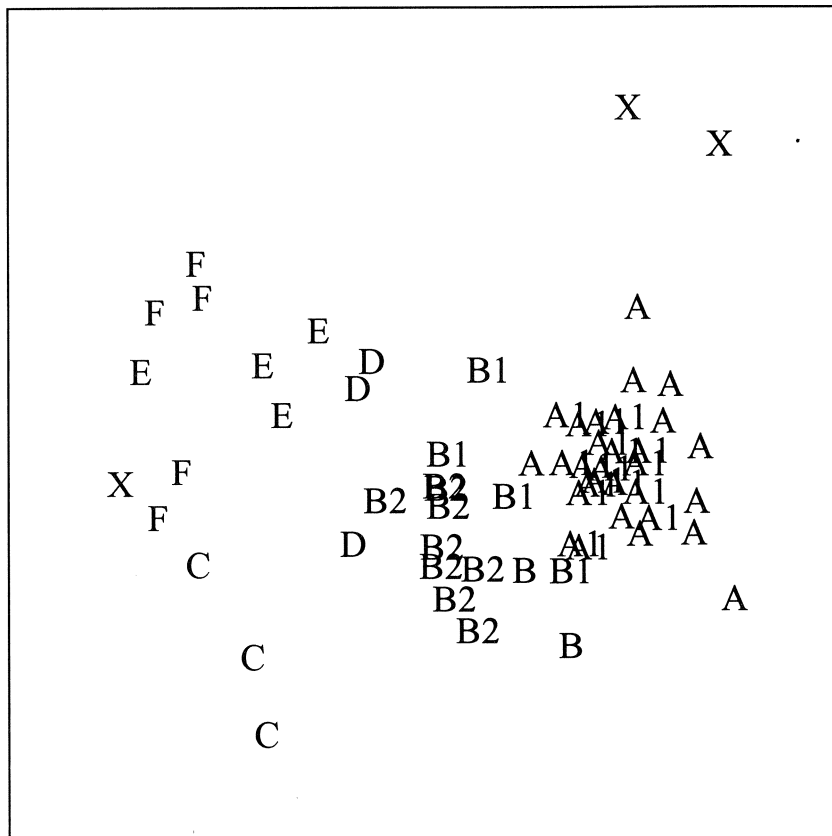
Ordination of stations

Fig. 7.10: Ordination of stations, using Multi-Dimensional Scaling as ordination technique. Cluster labels are superimposed on the corresponding stations. Note that in this plot the group label A corresponds to sub-cluster A_0 in the text, B to B_0, respectively.

more diffusely clustered on the MDS-plot. he stress value of the ordination is with 0.17 rather high, indicating a rather poor adequacy of the 2-dimensional representation. In some cases, stations within groups are ordinated farther apart from each other than stations belonging to different groups. A representation in more than two dimensions would have given better results. Nevertheless, the plot seems to be widely in unison with the results from the cluster analysis and no severe contradictions are obvious.

Linking community analyses to environmental variables

It may be assumed that the observed biological pattern is matched by a suite of environmental variables that define the distinct habitats found in the bay. The objective is to find out which variables, taken either singly or in combination, explain the community structure best. The relation of the biotic data, as summarised by the MDS ordination, to a univariate environmental measure can be visualised by representing the values of this variable as symbols of differing size and superimposing these symbols on the biotic ordination of the corresponding stations. These simple plots can be an effective means of noting any consistent differences in the environmental variable between biotic clusters or observing a smooth relationship with ordination gradients.

For each station averages for the relative time of immersion, silt content, median grainsize, sorting coefficient and the depth to which the cores could be taken were computed. These variables were then superimposed on the corresponding stations, with the size of the cluster labels representing the value of the variable. All sedimentological parameters and the core depth were highly correlated which each other and the patterns are similar, so only the MDS plots using silt content and relative time of immersion are presented (Fig. 7.11).

Stations of cluster A were clearly typified by a sandy substrate and long immersion times. The subdivision into clusters A_0 and A_1, as seen in the dendrogram, cannot be explained by either one of these variables. Cluster B is also made up of stations with long immersion times, but the substrate is a lot finer. The difference in the biotic structure between subclusters B_0, B_1 and B_2 can partly be explained by different sediments. Stations of cluster B_2 showed a very high silt content as compared to sub-clusters B_0 and B_1. Clusters C, D, E and F are all characterised by high to very high silt contents but differ significantly regarding inundation times. The three stations of cluster D are situated higher up in the intertidal and have accordingly shorter immersion times than the other stations.

Just from looking at the two plots it becomes obvi-

Ordination of stations with environmental variables superimposed on stations

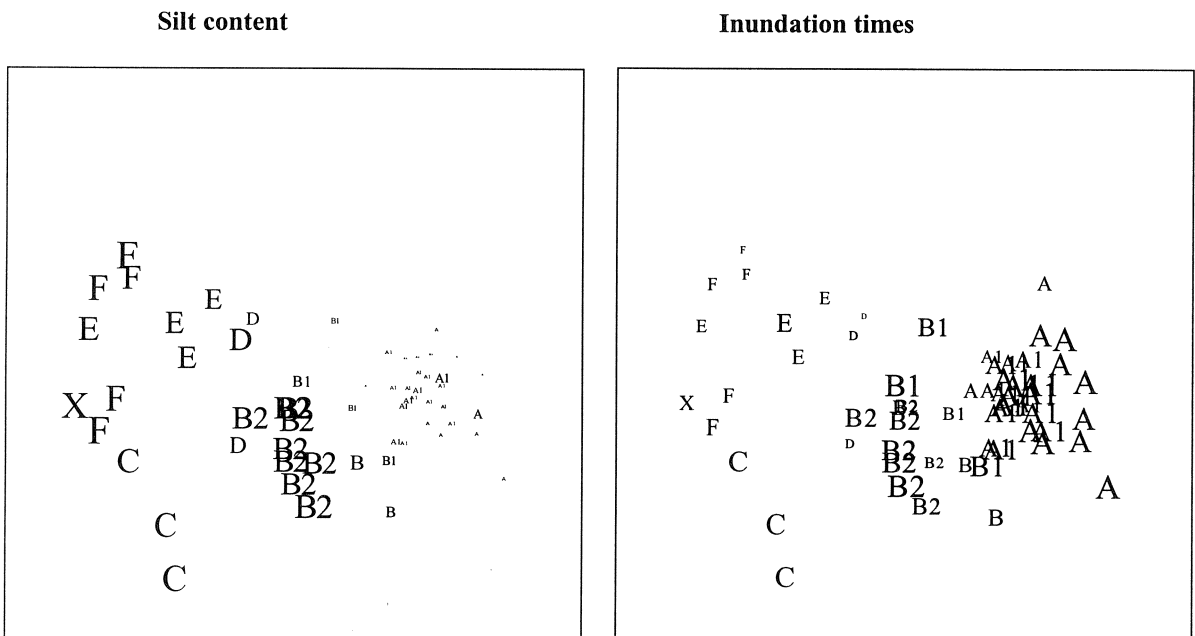### Silt content

Inundation times

Fig. 7.11: Ordinations of stations with superimposed environmental variables. The size of the letters is proportional to the value of the environmental variable in questions. Label A corresponds to A_0 in the text, B to B_0, respectively.

ous that a combination of environmental variables might explain the biotic structure better than just one variable taken singly. To link the biota to multivariate environmental patterns, the procedure suggested by Clarke & Warwick (1994) is applied. The intuitive premise adopted there is that if the suite of environmental variables responsible for structuring the community were known, then samples having rather similar values for these variables would be expected to have rather similar species composition, and an ordination based on this abiotic information would group sites in the same way as for the biotic plot. If key environmental variables are omitted or irrelevant data is added, the match between the two plots would deteriorate.

Quantifying the match between the two plots is accomplished by comparing the similarity matrices underlying both biotic and abiotic ordinations. The similarity matrices are chosen differently to account for the different form of the data, i.e. the Bray-Curtis measure for the biological data and Euclidean distance for the environmental variables. Both ordinations will be scaled in a different way but the rank of similarities can be compared by using the Spearman coefficient or a modified form of it, the weighted Spearman rank correlation (Eq. 7.2).

$$\rho_w = 1 - \frac{6}{N(N-1)} \sum_{i=1}^{N} \frac{\left(r_i - s_i\right)^2}{r_i + s_i}$$

Eq. 7.2

The constant terms are defined such that ρ lies in the range (-1,1), with the extremes corresponding to the cases where the two sets of ranks are in complete opposition or complete agreement. Values of ρ around zero correspond to the absence of any match between the two patterns, but typically ρ will be positive. Combinations of environmental variables are now considered at steadily increasing levels of complexity, (k=1, 2, 3.....6) until all six variables recorded are taken into account. Table 7.3 displays the outcome of this analysis.

The single abiotic variable that best groups the sites, in a manner consistent with the faunal patterns, is the silt content, followed by the depth of cores and the median grainsize. Inundation time taken on its own is only weakly correlated with faunal patterns (0.151) and not listed here. Knowledge of the silt variable alone does distinguish stations from cluster A from the remaining stations but fails to explain the patterns found between clusters C to F. The best possible combination of variables is silt content together with times of immersion, resulting in a maximum correlation coefficient of 0.557. Adding more variables to this combination only deteriorates the picture. Other combinations with three or four variables follow close by, but always a combination of inundation times with one or two sediment parameters.

Taken at a time the here tested environmental variables cannot explain the biological structure adequately. The combination of the variables silt content and inundation times explain at best 25 % ($0.557^2 = 0.25$) of the composition of the macrozoobenthic communities in Roebuck Bay. This suggests that other abiotic parameters, e.g. organic content, interstitial salinity or the redox potential together with biotic interactive factors play a decisive role in the ecology of the embayment.

Similarity percentage breakdown

The next step was to find out which species were responsible for similarities of stations within groups and dissimilarities between groups. To achieve this the average dissimilarity between all pairs of inter-group samples (i.e. every sample in group A paired with every sample in group B) was computed and this average then broken down into the separate contributions from each species (Clarke & Warwick 1994). Dissimilarities (δ) can easily be computed from similarities (S) by the formula $\delta = 100 - S$, which, together with Eq. 7.1, gives the Bray-Curtis coefficient (Eq. 7.3) which has limits $\delta = 0$ (no dissimilarity) and $\delta = 100$ (total dissimilarity).

Table 7.3: Correlation coefficients (weighted Spearman) of subsets of environmental variables with biotic data. Si: Silt content, I: Immersion times, M: Median grain size, S₀: Sorting coefficient, D: Depth of cores, G: Mass-percentage of shell grit > 1 mm.

k	1st best fit	2nd best fit	3rd best fit	4th best fit
1	Si (0.553)	D (0.365)	M (0.314)	So (0.166)
2	Si, I (0.557)	Si, D (0.513)	Si, M (0.456)	Si, So (0.438)
3	Si, I, D (0.553)	Si, I, M (0.539)	Si, I, So (0.511)	I, M, D (0.509)
4	Si, I, M, D (0.551)	Si, I, So, D (0.524)	Si, I, M, So (0.514)	I, M, So, D (0.497)
5	Si, I, M, So, D (0.532)	Si, I, M, So, D (0.453)	Si, I, So, G, D (0.436)	Si, I, M, So, G, (0.435)
6	Si, I, M, So, G, D (0.457)			

For Bray-Curtis dissimilarity δ_{ik} between two samples j and k, the contribution from the ith species, $\delta_{ik}(i)$, could simply be defined as the ith term in the summation of Eq. 7.3, which results in Eq. 7.4. $\delta_{jk}(i)$ is then averaged over all pairs (j,k), with j in the first and k in the second group, to give the average contribution δ'_i from the ith spcies to the overall dissimilarity δ' between the two groups.

$$\delta_{ik} = 100 * \frac{\sum_{i=1}^{p}|y_{ij} - y_{ik}|}{\sum_{i=1}^{p}\left(y_{ij} + y_{ik}\right)}$$

(Eq. 7.3)

$$\delta'_{jk}(i) = 100 * \frac{|y_{ij} - y_{ik}|}{\sum_{i=1}^{p}\left(y_{ij} + y_{ik}\right)}$$

(Eq. 7.4)

Typically, there are many pairs of samples (j, k) making up the average δ'_i and a useful measure of how consistently a species contributes to δ'_i across all such pairs is the standard deviation SD(δ_i) of the $\delta_{jk}(i)$ values. If δ'_i is large and SD(δ_i) small and thus the ratio δ'_i / SD(δ_i) is large, then the ith species not only contributes much to the dissimilarity between groups but it also does so consistently in inter-comparisons of all samples in the two groups; it is therefore a good discriminating species. The same applies to similarities (S) within groups.

To minimise the computational effort, only the 30 most abundant species were taken into account. Table 7.4 shows the species that contributed most to the similarity within cluster groups A-F. Listed are the average similarity of stations within the cluster, the average abundance of the respective species per square meter, the ratio S'$_i$ / SD(S$_i$), the average contribution of a species to the total similarity within the cluster and the cumulated similarity over the species. Ratios that were very typical for the groups and that contributed consistently to the overall similarity are marked with an asterisk. It is important to note that these results say nothing about whether that species is a good discriminator of one group from another; some of the more abundant species may be very typical of a number of communities. Although the data was root-root transformed to down-weigh the most abundant species, similarity percentages were still dominated by a few species with mass occurrence, namely chaetop-

Table 7.4: Breakdown of average similarity within groups A-F into contributions from each species. The abbreviation 'l. a'. behind the taxon Ophiuroida signifies that here the long armed species of brittle stars is meant.

Cluster	Avg. Simil.	Species	Avg. Abund.	Ratio	Sim. Perc	Acc. Sim. Perc.
A	63.59	Chaetopteridae	1,560	2.71	17.61	17.61
		Glyceridae	89	5.74	10.70	28.31
		Ophiuroida l. a.	93	2.33	8.77	37.08
		Opheliidae	81	1.85	8.37	45.45
B	66.56	Chaetopteridae	680	5.21	14.61	14.61
		Oweniidae	500	5.33	12.68	27.29
		Anodontia	143	4.49	10.41	37.70
		Ophiuroida l. a.	109	6.28	10.29	47.99
C	62.77	Siliqua	217	17.36*	35.31	35.31
		Anodontia	156	14.17*	29.91	65.22
D	58.30	Siliqua	98	7.73	14.15	14.15
		Nassarius dors.	82	4.20	13.23	27.38
		Anadara granosa	73	16.09*	12.85	40.23
		Oweniidae	86	13.79*	12.55	52.78
E	67.73	Siliqua	207	6.91	19.66	19.66
		Nassarius dors.	97	10.9	18.79	35.45
		Dentalium rib.	90	31.36*	14.89	50.35
		Ophiuroida l. a.	66	11	13.96	64.31
F	54.66	Siliqua	118	7.57	25.37	25.37
		Nassarius dors.	112	6.63	25.12	50.49
		Glyceridae	60	13.86*	22.45	72.94

terid and oweniid tubeworms and the long-armed brittle stars. These three species contributed most to the similarities within the large clusters A and B, even though their distribution was patchy and the contribution very inconsistent in inter-comparison of all samples within the clusters.

A few trends were nevertheless obvious. Much of the overall similarity within cluster A was made up by polychaetes. Nine taxa contributed to 80 % of the overall similarity and six of these belonged to aforementioned class. The contributions to the overall similarity were very inconsistent and the ratio S'_i / $SD(S_i)$ was low for all taxa. The picture offered by cluster B was basically the same, with the one difference that the input of the class Bivalvia to the overall similarity was higher. Eight species added up to 80 % of the total similarity and among these were three bivalve species (*Anodontia* cf. *omissa, Tellina amboyensis* and *Siliqua* cf. *winteriana*).

Clusters A and B are by far the largest clusters and stations within clusters differed markedly both in abundance and diversity. The smaller clusters C-F were more homogeneous and fewer species were responsible for most of the total similarity within clusters. Cluster C was typified by two bivalve species, namely *Siliqua* cf. *winteriana* and *Anodontia* cf. *omissa*. Cluster D, E and F had with *Nassarius dorsatus* and *Siliqua* cf. *winteriana* two mollusc species with high similarity percentages in common. A very typical taxon for cluster D was *Anadara granosa*, and for cluster E *Dentalium*.

More interesting than to look at the contribution of species to the overall similarities within groups is to find out the species that discriminate one site from the other and therefore have an indicator function for a certain area. Table 7.5 is a cross-tabulation showing the species that contributed most to the dissimilarity between all possible pairs of cluster groups. More often than not there were many taxa contributing almost evenly to the overall dissimilarity between groups, but only the top four species are shown. The regions most dissimilar from each other regarding their overall species composition were areas A compared to F with an average dissimilarity of 80 % and A to C with 78 %, respectively. Polychaetes, mainly chaetopterids, oweniids and opheliids, were typical for cluster A and absent in cluster F, whereas the opposite was true for *Siliqua* cf. *winteriana*, a bivalve species occurring frequently in cluster F, but that was absent from cluster A. A rather similar picture resulted from comparing A to C, with tubeworms dominating the fauna in A and bivalves, here *Siliqua* and *Anodontia*, characteristic for cluster C. The clusters most similar to each other were clusters D and E with an average dissimilarity of 43.52, and then the two large clusters A and B with

47.62 dissimilarity. In both cases there were no highly discriminating species that were very characteristic of one area but missing from the other. These results need some refinement and it is worthwhile to look at the two large clusters A and B in more detail.

Cluster A, cut off at 45 % similarity, was by far the largest cluster, covering almost the entire northern part of the embayment between Dampier Creek and Fall Point. In the dendrogram (Fig. 7.8), a rather tight cluster, subsequently called A_1, appeared at approximately 55 %. The remaining stations of cluster A were than added to this cluster at continuously lower similarities. Comparing sub-cluster A_0 with A_1 gave a very low average dissimilarity between groups of 39.49 %. The breakdown into species showed no highly discriminating species distinguishing A_0 from A_1. Both sub-clusters were characterised by the numerical dominance of chaetopterid tubeworms. Oweniids were more abundant in cluster A_1, its stations comprising a region which lay higher up in the intertidal and had a higher silt-content compared to cluster A_0. *Anomalocardia squamosa*, a shallow digging venerid bivalve, was also more frequent in sub-cluster A_1. Differences in inundation times and possibly predation pressure resulting from it seemed to be the dominant reasons for the slightly different species pool.

At the 50 % cut-off level cluster B could be subdivided into sub-cluster B_0, B_1 and B_2. Sub-cluster B_1, comprising stations within the Dampier Creek area, was geographically separated from B_0 and B_2, which formed adjacent areas between Fall Point and One Tree. All sub-clusters had a dominance of chaetopterid tubeworms in common and differed mainly in the composition of bivalve species. Sub-cluster B_0 and B_2, though situated right next to each other , showed different sediment characteristics. The median silt content of the 'B_0' stations was 40 %, while 75 % for sub-cluster B_2. Oweniid tubeworms had an average density of more than 2,000 individuals per square meter in region B_0 compared to only 180 in B_2. These polychaetes need coarser substrates and a more stable substratum for their rather stiff and sand encrusted tubes. They are clearly not adapted to an environment of water-logged and semi-fluid mud, typical for the south-eastern part of the embayment. With *Anomalocardia squamosa* and *Tellina piratica* two more species adapted to sandy substrates are found in B_0 that are virtually missing in area B_2. The sub-region B_1 at Dampier Creek shows a median silt content of 25 % and still more animals adapted to sandy environments were found. A smooth-shelled species of the scaphopod genus *Dentalium* and the bivalves *Anadara granosa, Tellina piratica* and *Anomalocardia squamosa* were typical representatives of this sandy environment. *Siliqua* cf. *winteriana* on the other hand is

adapted to muddy environments and became more abundant in the south-eastern parts of the embayment.
    The relatively high dissimilarity indices comparing cluster A with other clusters can partially be explained with the size of the areas in question. The total number of species of a region is a function of its area and ac-

Table 7.5: Breakdown of average dissimilarity between cluster groups into contributions from each species. Species that might have an indicator function are marked with an asterisk.

δ_{ik} x	y	Avg. δ_{ik}	Species	Avg. A x	Avg. A y	Ratio $\delta'_i / SD(\delta_i)$	$\delta'_i(i)$	$\Sigma\delta'_i(i)$
A	B	47.62	Anodontia cf. omissa	35	143	1.60	6.59	6.59
			Tellina amboyensis	5	75	2.10	6.39	12.97
			Siliqua cf. winteriana	0	72	1.54	5.97	18.94
			Solemya	56	27	1.47	5.28	24.23
A	C	78.14	Chaetopteridae	1559	53	1.99	9.88	9.88
			Siliqua cf. winteriana	0	217	4.96*	8.70	18.58
			Oweniidae	346	0	1.75	6.83	25.42
			Anodontia cf. omissa	35	156	1.78	6.28	31.69
A	D	63.04	Chaetopteridae	1559	98	1.69	7.52	7.52
			Siliqua cf. winteriana	0	98	4.92*	6.59	14.11
			Tellina capsoides	1	80	4.08*	5.77	19.88
			Anadara granosa	7	73	3.54	5.76	25.65
A	E	63.73	Siliqua cf. winteriana	0	208	5.09*	8.87	8.87
			Chaetopteridae	1559	110	1.50	7.80	16.67
			Dentalium	12	90	2.40	6.13	22.80
			Nassarius dorsatus	13	97.02	1.71	5.41	28.21
A	F	77.99	Chaetopteridae	1559	0	3.09	11.55	11.55
			Siliqua cf. winteriana	0	118	4.12*	6.78	18.34
			Oweniidae	346	0	1.75	6.39	24.73
			Opheliidae	81	0	2.41	5.58	30.31
B	C	55.15	Oweniidae	501	0	3.99	12.95	12.95
			Chaetopteridae	680	53	1.86	11.01	23.96
			Polynoidae	50	0	1.88	6.87	30.83
			Hymenosomatidae	64	0	1.59	6.85	37.68
B	D	47.91	Chaetopteridae	680	98	1.46	7.32	7.32
			Anodontia cf. omissa	143	27	1.5	6.71	14.03
			Tellina capsoides	16	80	1.88	6.06	20.09
			Polynoidae	49.87	0	1.87	5.99	26.08
B	E	52.34	Anodontia cf. omissa	143	0	3.42	9.18	9.18
			Oweniida	501	30	1.56	7.94	17.12
			Dentalium	12	90	2.63	7.50	24.61
			Chaetopteridae	680	110	1.25	6.79	31.40
B	F	66.45	Chaetopteridae	680	0	4.52*	11.40	11.40
			Oweniidae	501	0	3.98	10.06	21.46
			Anodontia cf. omissa	143	32	1.97	6.75	28.21
			Tellina amboyensis	75	0	3.04	6.67	34.88
C	D	63.99	Oweniidae	0	87	5.79*	8.87	8.87
			Anadara granosa	0	73	18.91*	8.63	17.50
			Tellina capsoides	0	80	10.74*	8.49	25.99
			Anodontia cf. omissa	156	27	1.53	7.88	33.87
C	E	55.74	Anodontia cf. omissa	156	0	6.78*	14.24	14.24
			Dentalium	0	90	14.41*	12.26	26.50
			Nassarius dorsatus	13	97	1.74	9.4	35.90
			Chaetopteridae	53	110	1.24	8.42	44.32
C	F	66.03	Anodontia cf. omissa	156	32	2.12	11.65	11.65
			Tellina amboyensis	60	0	10.22*	11.18	22.83
			Nassarius dorsatus	13	112	1.66	9.63	32.46
			Retusa	0	48	1.91	8.96	41.42
D	E	43.52	Tellina capsoides	80	20	2.19	8.01	8.01
			Dentalium	13	90	1.64	7.98	15.99
			Nassarius small	67	0	1.20	7.68	23.67
			Chaetopteridae	98	110	1.15	6.51	30.18
D	F	53.44	Oweniidae	87	0	5.97*	9.86	9.86
			Tellina capsoides	80	24	2.58	7.91	17.77
			Chaetopteridae	98	0	1.35	7.08	24.85
			Nassarius small	67	8	1.15	6.43	31.28
E	F	50.98	Chaetopteridae	110	0	1.54	9.67	9.67
			Ophiuroida	66	20	2.35	9.48	19.15
			Retusa	0	48	1.88	9.13	28.28
			Dentalium	90	32	1.51	8.20	43.00

cordingly more species are encountered in areas A and B compared to the other regions. Moreover areas A and B encompass a wide variety of habitats with a great range of sediment characteristics and immersion times. This heterogeneity adds to the total species richness of the area. A lot of these species are patchily distributed and the ratio $\delta'_i / SD(\delta_i)$ is accordingly low, but due to their sheer numbers they still contribute to the overall similarity within groups and the dissimilarity between groups. The probability, that a species occurs in all stations of a cluster decreases with an increasing number of stations. For the same reason it is also more likely to find species that occur exclusively in one cluster when the respective areas of the clusters that are compared with each other are small. This explains in part the high dissimilarity values between cluster A and the smaller clusters as well as the low figures comparing A to B.

Another means to point out the taxa that are characteristic for each cluster is to compute a ratio between the average abundance within a cluster and the average of all stations. Taxa with a ratio > 1 are overrepresented in a sub-area compared to all other areas, taxa with a ratio < 1 underrepresented. A ratio of zero means that the taxon is completely missing from a sub-area. Table 7.6 summarises these ratios for a few

taxa, which might have an indicator function according to the results from the similarity percentage breakdown. It is interesting to see that most of the highly discriminating species belong to the class Bivalvia. This could be explained by the fact that most of the bivalve species found in the bay are specialist which are highly adapted to a particular habitat and that opportunistic species are rare. The other classes, especially the polychaetes, seem to have more opportunistic taxa, adapted to living in a wider range of environments. Other reasons might be important as well. Bivalves were identified to species level whereas most of the other taxa only to family level or higher. So if, like within the class Bivalvia, the ecology and preferred habitats differed between species of the same family, this could not have become evident on account of the taxonomic levels the other benthic classes were identified to.

The taxa marked with an asterisk have ratios bigger than two, i.e. they were at least twice as abundant in the particular sub-area compared to the overall average. Bivalves of the genus Solemya were found in clusters A_0, A_1 and B_1 (Fig. 7.12), all located in the north-western part of the bay and were completely absent from the rest of the regions. The highest abundance was reached in B_1, near Dampier Creek, and the

Table 7.6: Abundance ratio for selected species. The ratios given are the average abundance within an area divided by the average abundance for all stations. Ratios above two are marked with an asterisk.

| SPECIES	A_0	A_1	B_0	B_1	B_2	C	D	E	F
Solemya	1.83	2.50*	0.00	4.68*	0.00	0.00	0.00	0.00	0.00
Anadara granosa	0.00	1.32	0.00	2.12*	3.00*	0.00	0.97	0.79	0.79
Anodontia cf. omissa	0.37	0.82	1.10	0.82	2.29*	1.40	0.74	0.00	1.47
Cultellus spec.	2.40*	4.20*	0.00	2.40*	0.00	0.00	0.00	0.00	0.00
Siliqua cf. winteriana	0.00	0.00	0.47	0.00	1.36	2.50*	1.26	2.18	1.24
Tellina capsoides	0.88	0.00	0.00	1.41	0.88	0.00	1.41	1.76	2.65*
Tellina piratica	0.97	2.47*	2.03*	2.73*	0.00	0.81	0.00	0.00	0.00
Tellina amboyensis	0.69	0.69	0.69	1.56	1.56	1.04	1.61	1.15	0.00
Mud Tellina	0.00	0.65	0.65	1.70	0.98	0.00	0.00	0.00	5.01
Anomalocardia sqamosa	0.89	2.16*	0.89	2.38*	1.78	0.00	0.89	0.00	0.00
Nassarius dorsatus	0.57	0.57	0.57	1.37	1.05	0.57	1.34	1.56	1.42
Nassarius small	1.38	1.38	0.00	1.38	0.00	0.00	3.46*	0.00	1.38
Dentalium (smooth)	2.69*	2.54*	1.88	1.88	0.00	0.00	0.00	0.00	0.00
Sipunculida	1.25	1.93	1.09	1.45	2.18*	1.09	0.00	0.00	0.00
Nephtyidae	1.91	1.20	0.00	1.47	1.01	0.73	0.98	0.98	0.73
Glyceridae	0.98	1.55	1.23	0.89	1.11	0.62	0.69	0.88	1.05
Chaetopteridae	1.99	2.60*	2.11*	0.88	0.70	0.25	0.26	0.21	0.00
Oweniidae	0.79	1.32	4.96*	1.00	0.50	0.00	0.29	0.14	0.00
Gammarus	5.01*	2.61*	0.00	0.00	1.38	0.00	0.00	0.00	0.00
Paguridae	0.93	2.41*	0.79	1.70	1.31	0.00	1.08	0.00	0.79
Hymenosomatidae	1.53	1.87	2.33*	1.39	1.19	0.00	0.69	0.00	0.00
Macrophthalmus	1.19	1.08	1.15	1.31	0.80	0.80	0.80	0.97	0.89
Ophiuroida	0.64	1.28	2.35*	0.73	0.86	1.10	0.49	0.65	0.91
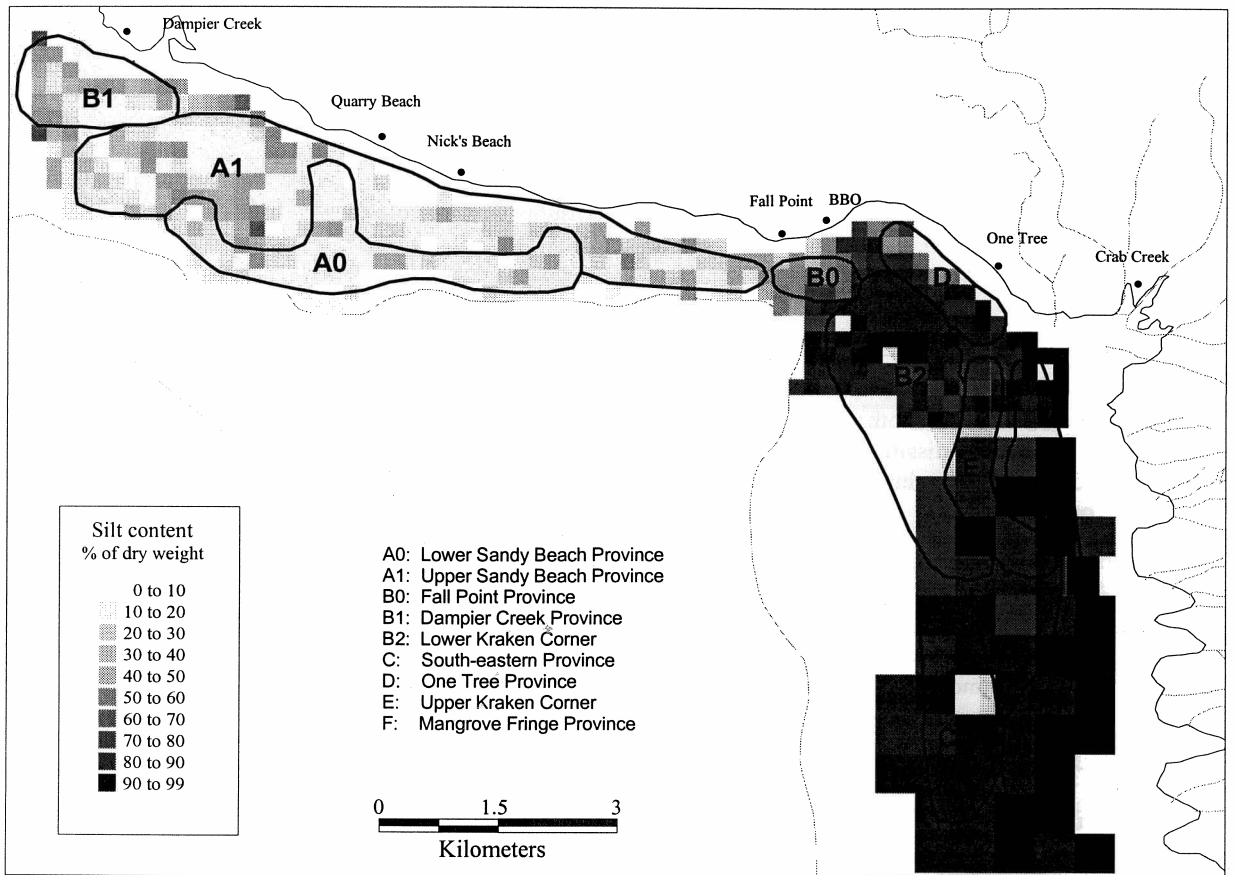
Fig. 7.12: Map of the faunal provinces resulting from cluster analysis. Superimposed is the silt content of the sample stations. The delineation of the provinces is artificial, since there are no such sharp gradients present on the mudflats. The filter-stations clustered together in the analysis (see also Fig. 6.9) were simply encircled by hand to show the position of the provinces.

mean density was with 200 individuals per square meter almost five times higher than the average of the other areas taken together. Areas A_0, A_1 and B_1 all shared substrates of fine to very fine sand as opposed to the more silty areas to the east. Other taxa typical for this environment were the bivalves *Cultellus*, which showed highest numbers in cluster A_1 and *Anomalocardia squamosa*, most abundant in A_1 and B_1.

A smooth-shelled scaphopod species of the genus *Dentalium* was also typical for the sandy regions and equally well represented in A_0, A_1, B_0 and B_1, but missing from all other areas. The amphipod *Gammarus* was mainly found in the very sandy areas A_0 and A_1. Highest numbers were found in A_0, which lies lower in the intertidal compared to A_1. Chaetopterid tubeworms were found everywhere in the intertidal except in cluster F, which is very silty, but reach highest densities in A_0, A_1 and B_0. Oweniids were missing in cluster C and F for similar reasons and by far the

highest numbers were reached in cluster B_0 with 2,125 individuals per square meter on average.

Representatives of the muddy regions of cluster C, E and F were *Siliqua* cf. *winteriana*, *Tellina capsoides*, and another tellinid bivalve, preliminary named Mud-Tellina. With the very sandy areas A and A1 to the north-west and the muddy provinces C, E and F to the very east the two extremes of the spectre were taken out. The gradients, both for sediment characteristics and immersion times, are shallow, though, and most of the stations showed intermediate conditions.

To compare all the sub-regions with each other regarding their species composition and their abiotic parameters is beyond the scope of this paper. Rather than putting the figures presented in the tables into words again it will be tried to synthesise the results and to portray each region by describing the physical characteristics of the habitat and the species association typical for it.

Dampier Creek Province

B_1, the 'Dampier Creek Province', is the cluster at the western end of the study area. It is located at the mouth of a big tidal creek system, which influences the physical environment of most of the province. Habitat parameters change on a small scale and contribute to the heterogeneity of the province. The levees of the ever shifting tidal creeks are muddy, probably consisting of silt and clay particles derived from the big catchment area of Dampier Creek and then recycled within the creek system. In the Dampier Creek area the embankments are only weakly sloped as opposed to the Crab Creek area, where the substrate is finer and more cohesive. The creek beds itself are sandy with layers of dead shells arranged in a way to offer minimum resistant to the strong currents during falling and rising tides. In between the tidal creeks and gullies are slightly elevated sandbanks showing small ripple structures with a wavelength of approximately 5 cm and occasional depressions with puddles of water. The sediment typically showed a thin layer of light grey silt of approximately 1.5 cm grading into anoxic sands. At a depth of 10 to 20 cm a dense shell grit layer was typically found which was almost impenetrable for our cores and certainly for most of the larger benthic animals as well. As was to be expected from observations, sediment parameters differ significantly between sample stations. The silt content shows a wide range of values between 5 % and 62 % with a median of 24 %. Values of the median grainsize are also highly variable with extremes of 99 to 371µm and a median value of 119 µm. The sediment is poorly sorted and the median sorting coefficient (1.39) is the highest of all areas (Table 7.7). The 'Dampier Creek Province' covers an area from the mangrove fringe in the north to the low water line and is typified by morphological features like sandbanks and tidal creeks. Immersion times, computed using satellite images and interpolation techniques, are based on the assumption of a linear slope between the high and low water line and small scale morphological features are neglected. Especially for this particular area it is therefore misleading to give absolute values of immersion times because the assumption of a linear slope certainly doesn't apply for the 'Dampier Creek Province'. It is only important to know that immersion times are highly variable and that pools and creeks offering protection against desiccation are common features.

The biological indices AFDM, total number of individuals per square meter, total number of taxa and the Shannon-Wiener Diversity Index reflect the patchiness of the faunal distribution patterns. To compare the different provinces regarding the different sedimentological and biological parameters the median is used, because it is less sensitive to extreme values (Table 7.7). In the 'Dampier Creek Province' the median AFDM was quite high (10.8 g/m^2), surpassed only by the 'Fall Point Province' (17.6 g/m^2). Diversity, measured by the total number of species per station and the Shannon-Wiener Diversity Index, is one of the highest in Roebuck Bay. The low numbers of individuals per square meter can be explained by the relative paucity of gregarious tubeworms, especially chaetopterids, which decrease in numbers towards the mayor creek system and the mangrove fringe.

Due to the heterogeneity of the area and the multitude of different habitats it is difficult to find an assemblage of species characteristic for the area. The bivalves *Solemya, Cultellus, Anadara granosa, Tellina piratica, Anomalocardia squamosa* and the scaphopod *Dentalium* spec. are typical for the area. The shell morphology of these molluscs either offers good mechanical protection or allows quick burrowing into the sandy substrates (Ch. 8).

The Sandy Beach Province

The 'Upper' (A_1) and 'Lower Sandy Beach Province' (A_0) are quite similar in their overall species composi-

Table 7.7: Median values of sedimentological and faunal parameters. The median was preferred to the mean because it is less sensitive to extreme values.

Province	Silt content	MGS (µm)	S_0	AFDM (g/m^2)	Number. of ind.	Number of spec.	H'
Dampier Creek (B_1)	24.3 %	119	1.39	10.8	920	9	1.63
Upper Sandy Beach (A_1)	11.9 %	164	1.32	9.3	640	7	1.50
Lower Sandy Beach (A_0)	7.8 %	173	1.27	4.5	480	6	1.55
Fall Point (B_0)	41.3 %	156	1.38	17.6	3,180	12	1.49
One Tree (D)	66.2 %	97	1.19	6.4	360	6	1.58
Lower Kraken Corner (B_2)	74 %	97	1.19	6.1	760	8	1.64
Upper Kraken Corner (E)	74.4 %	96	1.19	5.2	420	4	1.27
Mangrove Fringe (F)	89 %	96	1.19	1.8	220	3	0.95
South-eastern Province (C)	82.8 %	96	1.19	7.1	400	4	1.05

tion and sedimentological characteristics and can therefore be treated together. The former of the two experiences a higher energy input through tidal currents and sediments are accordingly coarser. The sediment of the lower region has a silt content of 7.8 %, of the upper region 11.9 %, respectively (Table 7.7). The higher energy input near the low water mark is also responsible for the fact that the sediments are better sorted compared to the upper region. The colour of the near surface sediments is slightly different, too. In the upper intertidal area of A_1 the surface colour was grey and the transition into the anoxic layer gradual. The light grey colour is indicative of a higher silt content near the surface, probably lag deposits left behind at slack tide. In the lower intertidal area of A_0 the colour of the surface sediments was a light brown and at around 1 cm depth a sharp transition into anoxic conditions could be observed by the darker colour of the sediments. Below MSL large patches of seagrass were present in both provinces. Two tiny species of seagrass mostly occurring together were found, one with oval, the other with lancet shaped leaves. The single plants are widely spaced and show a poor coverage of the ground, but may still play an important role in the ecology of this particular region.

The diversity indices for both regions were likewise comparable, although the median number of individuals was a little higher in the upper region. Especially in these two provinces numbers were swamped by the mass occurrence of chaetopterid tubeworms, which reached local densities of up to 16,280 individuals per square meter. Typical for both regions was an assemblage of *Solemya*, *Cultellus*, *Dentalium* and chaetopterid tubeworms. The Upper Sandy Beach Province' borders both the 'Dampier Creek Province' and the 'Lower Sandy Beach Province' and the species composition was somewhat intermediate. A1 and B1 shared some taxa adapted to a medium silt content, e.g. *Anomalocardia squamosa*, *Tellina piratica*, glycerid polychaetes, the crustacean family Hymenosomatidae, and animals that live high up in the intertidal like *Anadara granosa* and pagurid crabs. In contrast to this, the very sandy sediments of the lower region offer suitable habitats for some specialists of coarser substrates, namely gammarid amphipods and predatory polychaetes of the family Nephtyidae.

Fall Point Province
The 'Fall Point Province', formerly called cluster B_0, also showed an intermediate character, this time between the sandier province of A_1 and the siltier province B_2. It is around Fall Point that the intertidal area widens out and tidal currents diverge. Whereas the provinces so far described were all dominated by erosional processes, now deposition becomes more

prominent and sediments grade quite abruptly into silty, carbonate-rich muds.

The 'Fall Point Province' was by far the smallest of all provinces and showed quite unique characteristics. Most notably was the increase in biomass, the median number of individuals and the median number of species found per sample site. The high biomass values and densities of individuals could be explained by the mass occurrence of oweniid tubeworm and 'long-armed brittle stars', which reached highest densities within the neap tidal range between Nick's Beach and One Tree. This centre of distribution also stretched into the 'Lower Sandy Beach Province', but here median densities were 'diluted' by the many stations with lower individual numbers. The 'Fall Point Province' on the other hand fell fully into these distribution centres with the resulting high median values of biomass and absolute numbers of individuals. More interesting was the high number of taxa found per sample site (12), which was the highest of all provinces, followed by the 'Dampier Creek Province' with nine species per station (Table 7.7). Characteristic for both provinces, although for different reasons, were the highly variable sediment parameters. On the one hand it was the influence of a mayor tidal creek system, on the other hand the bathymetry of the embayment and the sudden change of current velocities. Taxa typical for the 'Fall Point Province' were oweniid tubeworms, long-armed brittle stars and spider crabs of the family Hymenosomatidae. *Tellina piratica* was still found in the sandier regions, slowly being replaced by the smooth-shelled tellins *Tellina amboynensis* and *Macoma exotica*. Another smooth shelled bivalve typically found in muddy substrates, the lucinid *Anodontia cf. omissa*, also showed an increase in numbers.

One Tree Province
All the areas that still await description were characterised by fine to very fine muddy sediments. Cluster D, the 'One Tree Province' is located in the upper intertidal region of the north-eastern corner of Roebuck Bay, comprising stations from the sandy beach to about 500 m offshore. With 66 % the median silt content was lower than in the provinces farther to the south and the different sample stations displayed a broader range of substrates. Generally there were two gradients observable. Sediments were getting finer from north to south and from the lower intertidal towards the mangrove fringe to the east.

The total abundance of individuals dropped towards the south and the numerical dominance of tubeworms lessened. Either it is the physical environment of the fine muds that does not offer conditions stable enough for the establishment of large tubeworm colonies or it is the high suspension load that clogs the

filtering organs of these polychaetes. In the 'One Tree Province' they were still frequent with chaetopterids representing 9 % of all individuals found and oweniids 12 %, respectively. Farther south numbers decreased until both families of tubeworms completely disappeared in cluster F.

Characteristic for all areas to the east of Fall Point was the high number of large burrows made by crustaceans of the genus *Squilla* and *Macrophthalmus* and possibly mudskippers. These deep burrowing crustaceans are especially adapted to the muddy and cohesive substrate and seem to posses a key function in the ecosystem of the south-eastern part of the embayment. The burrowing activities must rework huge amounts of sediment and the deep holes, which are at least partly filled with water at all times, offer protection against predation and desiccation for other animals of the intertidal. Unfortunately for us, the holes offered good protection against being sampled as well and judged by the omnipresence of holes in this area the genera *Macrophthalmus* and *Squilla* must have been underrepresented in our figures. The few large specimens we sampled still contributed a lot to the overall biomass of the area and they dominated the figures in the 'South-eastern Province'.

A few species, either adapted to living high up in the intertidal or in sediments with intermediate silt content, distinguished the 'One Tree Province' from other areas of the silt dominated eastern part. More abundant in this province compared to the adjoining 'Lower' and 'Upper Kraken Corner Provinces' were the bivalve *Tellina amboynensis* and especially the so-called 'Small Ingrid-eating Snail' of the gastropod family Nassariidae. Typical for the area was that numbers of individuals were low for all classes and that the five most abundant classes, i.e. Bivalvia, Gastropoda, Polychaeta, Crustacea and Ophiuroida were equally well represented. The provinces to the west were generally dominated by polychaetes and towards the south bivalves became relatively more abundant.

Lower Kraken Corner Province

This province was the largest of the provinces in the eastern half of the study area. Compared to the just described 'One Tree Province' the median silt content was higher (74 %) and the sediment seemed to be more homogeneous throughout the entire province. The microtopography of the muddy areas to the east was very different from the sandier regions to the west. Ripples were missing or were at least not as prominent as in the sandier provinces and most of the small scale topography was created by the interaction of animal and plant activity. Plants, especially algae films, tend to stabilise the sediment while the burrowing activity of benthic animals, predominantly crabs,

disrupts original sediment structures. The high water holding capacity of the fine muds prevents the sediment from drying out and puddles in small depressions around crab holes were frequent. The upper layer of the sediment was usually very fine and had a light grey colour. At a depth of one to one and a half centimetres it slowly graded into darker, more anoxic muds. A well established shell grit layer, common to the northwestern parts of the bay, was missing within the first 50 cm.

The entire 'Lower Kraken Corner' lies below MHWN, which means that the stations are immersed at least once every 12 hours throughout the year. Almost half of the area is below MLWN and the stations farthest offshore are inundated most of the time.

Taxa typical for the area were chaetopterid and oweniid tubeworms, though less numerous than in the western provinces, the bivalves *Siliqua* cf. *winteriana*, *Anodontia* cf. *omissa* and *Tellina amboyensis* and sipunculids. What seemed strange at the first sight is the fact that the arcid bivalve *Anadara granosa* is also found in densities above average. A look at the raw data revealed that their distribution is very patchy. At two neighbouring sample stations, located around MLWN, *A. granosa* showed very high densities of 400 and 240 individuals per square meter. All specimens were very small, though, with a shell length between 3 and 9 mm. It must have been a fairly recent spatfall and it is unlikely that the presence of this species adapted to the higher intertidal will be a permanent feature.

Upper Kraken Corner Province

The ordination of stations (Fig. 7.10) indicates that the overall species composition of cluster E, the 'Upper Kraken Corner Province' is more similar to clusters F and D than to the adjoining 'Lower Kraken Corner'. The median silt content of both 'Kraken Corner Provinces' was almost identical (74 %) and the other sedimentological parameters were of the same order of magnitude, too (Table 7.7). So apparently other parameters were responsible for the dissimilarity of both provinces. One reason for sure is the position relative to chart datum. While most of the sample stations that were grouped together into cluster B_2 were below the mean sea level, stations of cluster E are found farther up in the tidal regime, mostly above MLWN. Another reason, though hypothetical at the moment, might be the influence of Crab Creek, the second mayor tidal creek system of the study area. The dominating class for this province, both regarding the total number of individuals as AFDM, was the class Bivalvia. Bivalves made up 40.17 % of the total abundance of benthic macrofauna and 55.22 % of the biomass.

Almost 80 % of these belonged to just one species, the cultellid bivalve *Siliqua* cf. *winteriana*, which reached mean densities of more than 200 individuals per square meter. Occasionally found, and in abundance slightly above average, were furthermore the tellins *Tellina capsoides* and *Tellina amboyensis*.

The nassariid gastropod *Nassarius dorsatus* was with 18.41 % of all individuals sampled the second most abundant taxon. Nassariids are very mobile and found in all provinces of the bay. Highest numbers were found in the mid- to upper intertidal region of the muddy eastern part of Roebuck Bay, namely in the 'One Tree", 'Upper Kraken Corner' and 'Mangrove Fringe Province'. Mean densities were 82, 97 and 112 individuals per square meter. Towards the lower intertidal the numbers decrease rapidly and nassariids were only occasionally sampled.

Another typical mollusc of the area is the ribbed *Dentalium*. In our samples we found two species of this scaphopod genus, one with a smooth and entirely white shell, the other one with a shell that showed numerous, very fine longitudinal ribs and an orange coloured tip. The former dentaliid, the larger of the two species, occurred in low numbers throughout the bay, the latter was restricted to the muddy environment of the 'Upper Kraken Corner' and 'Mangrove Fringe Province'. According to the results from the similarity percentage breakdown, the ribbed *Dentalium* is a highly discriminating species and very characteristic for the 'Upper Kraken Corner Province'.

Mangrove Fringe Province
Like the name already entails, the 'Mangrove Fringe Province' covers the upper intertidal region close to the mangals in the east of Roebuck Bay. The median silt content was with almost 90 % the highest of all provinces (Table 7.7). The total abundance as well as diversity indices on the other hand were the lowest of the study area. Per average only three species were found at the sample stations, adding up to a mean density of 200 individuals per square meter. Tubeworms, otherwise abundant, were completely missing and the only polychaetes that were found in decent numbers were glycerids. Abundance and biomass figures for the province were clearly controlled by molluscs, which comprise 72 % of all individuals and 66 % of the biomass. The most abundant species is *Siliqua* cf. *winteriana* with 19.3 % of all specimens sampled, followed by the so-called 'Mud Tellina' (13.9 %) and the gastropod *Nassarius dorsatus* (12 %). Mature specimens of *Nassarius* and *Siliqua* were found in consistent numbers at almost all station within the cluster, the mudtellin only at two station with densities of 680 and 200 individuals per square meter. Here again these were juvenile specimens with a size range from two to five

millimetres, and they are an exception rather than typical faunal elements of the area.

Although the absolute numbers of *Macrophthalmus* crabs found in the samples were not higher than in other provinces, they now become relatively more important due to the paucity of both species and individuals. Some of the specimens sampled were quite large with a maximum carapace width of 44 mm. These large specimens of the genus *Macrophthalmus* and, to a lesser extent, of the genus *Squilla*, contributed most to the total biomass of the 'Mangrove Fringe' and the 'South-eastern Province'. In the former *Macrophthalmus* is responsible for 24.5 %, within the latter even for 46.7 % of the total AFDM.

Two very characteristic species of the 'Mangrove Fringe Province' were the gastropod families Retusidae and Amphibolidae. The eupulmonate family Amphibolidae was the more common one and we encountered these snails frequently close to the mangals to the south of Crab Creek. Specimens of the family Retusidae were found patchily in the same region, but the distribution was not as restricted to the vicinity of the mangals and extended a little farther into the mudflats.

South-eastern Province
The last of the areas to be described is the 'South-eastern Province', located at the southern end of the study area. Compared to the 'Mangrove Fringe Province' it lies lower in the intertidal and the sediment are not quite as muddy. The median silt content was 83 % and both the number of species and individuals per sample station are higher on average. The numerical dominance of the class Bivalvia was with 76 % of the retrieved animals the highest in the bay. The density of *Siliqua* cf. *winteriana* had its peak in this province with a mean value of 217 individuals per square meter. This species alone comprised more than half of the macrofauna sampled. Another very common bivalve was the lucinid *Anodontia* cf. *omissa*, with an average density of 156 specimens. The macrofauna of this particular region seemed to be typified by a very low diversity and the occurrence of a few species that are highly adapted to their environment.

Species associations

A closer look at the different provinces revealed that the species composition differed markedly between regions. A simple vertical zonation pattern, typical for some rocky shores or sand beach ecosystems, apparently does not exist in the study area. Unfortunately the data on abiotic parameters was scarce, but at least two gradients could be observed. In addition to the

vertical gradient just mentioned, which is just a function of the height relative to chart datum, there was a second gradient with respect to the sedimentological parameters. Sediments did become finer towards the upper intertidal and towards the eastern parts of Roebuck Bay. The coarsest substrate was found in the upper intertidal of the north-central part of the embayment, which falls together with the 'Lower Sandy Beach Province'. The degree of sorting followed a similar trend and was generally increasing towards the east. The combination of parameters best explaining the biological patterns was silt content together with

inundation times. It will now be tried to find typical species associations for some combinations of these two variables. The division of the intertidal into an upper, middle and lower intertidal is based on the position relative to the local chart datum. The upper intertidal is the region above MHWN, the lower intertidal the area below MLWN and the middle intertidal the area in between. Sediments are referred to as sandy when the silt content was below 20 %, as muddy when it was above 70 % and otherwise classified as intermediate.

Most of the common faunal elements of Roebuck

Table 7.8: Distribution centres for the most common taxa of Roebuck Bay. Sediments in this context are considered sandy when the silt content was below 20 %, muddy when it was higher than 70 % and otherwise classified as intermediate. The upper intertidal is defined as the region between MHWN and MHWS, the lower intertidal as the region between MLWN and MLWS. The mid intertidal encompasses the neap tidal range.

	sandy sediments	*intermediate sediments*	*muddy sediments*
Upper intertidal	*Modiolus micropterus* →	*Anadara granosa* → *Tellina capsoides* → *Cerithidea cingulata* → Columbellidae * Marginellidae *	Nassariidae ← Retusidae ↓ Amphibolidae *
Mid-intertidal	Costellariidae → ↓ *Dentalium* (s.) → ↕ Onuphidae → ↕ Nephtyidae ↕ Oweniidae → ↕ *Gammarus* ↕ *Anthura* → ↕ Tanaidacea ↓ *Lingula* ↕	*Nucula* ↕ *Anomalocardia squamosa* ↓ *Divaricella ornata* ↔ ↕ *Macoma* cf. *exotica* → ↕ *Tellina amboyensis* → ↕ *Tellina* mud → ↕ *Tellina piratica* ← Naticidae ← *Dentalium* (ribbed) → ↕ Nemertini ↔ ↕ Sipunculida ↔ ↓ Ophiuroidea (l.-a) ↔ ↕ Polynoidae → ↕ Phyllodocidae ↔ ↕ Lumbrineridae ↔ ↓ Maldanidae ↔ ↓ *Squilla* → ↕ Paguridae ← ↕ Hymenosomatidae ↔ *Macrophthalmus* ↔ ↕ Goneplacidae → ↕	*Siliqua* cf. *winteriana* ↕ Pyramidellidae ↕ Pilargidae ←
Lower intertidal	*Cultellus* spec. → Opheliidae → ↑ Sternaspidae * Flabelligeridae → Cumacea * Ophiuroidea (s.-a.) *	*Solemya* ← Orbiniidae ← ↑ Sigalionidae ↔ Nereidae ↔ ↑ Glyceridae ↔ ↑ Chaetopteridae ↔ ↑ Ostracoda ← ↑	*Anodontia* cf. *omissa* ↑

Bay seem to be generalists, adapted to a wide range of sedimentological conditions and abundant from the lower to the upper intertidal. The concept of niche width bears some problems with it, because we describe distribution patterns of benthic animals on different taxonomic levels. Polychaete families, which seem to occupy fairly wide niches, might in reality consist of a number of species, each of which is highly adapted to a particular environment. Table 7.8 groups the most abundant taxa of Roebuck Bay into associations of species typical for different substrates and regions of the tidal regime. Taxa are grouped according to their centre of distribution. This doesn't necessarily mean that they are entirely restricted to it. The arrows next to the taxon signify that the distribution extends into the direction the arrow is pointing to. The bivalve *Tellina piratica* for example had its centre of distribution in the mid-intertidal and in sediments of intermediate silt content but the distribution extended into sandier regions as well. This is indicated by the arrow pointing to the left and towards sandier substrates. Generalist, like *Divaricella ornata*, are indicated by arrows pointing into all four directions, specialist like the eupulmonate gastropod Amphibolidae by an asterisk behind their name.

Most of the intertidal fauna exhibited a wide range of distribution that is centred around intermediate conditions both regarding the position within the tidal regime and sedimentological characteristics. Very opportunistic taxa, like *Divaricella ornata*, nemertins, long-armed brittle stars, the polychaete family Phyllodocidae and *Macrophthalmus* crabs extended their range into all directions from here and are found almost everywhere in the intertidal. Most other species seem to follow a gradient into either sandier or siltier substrates. The bivalves *Macoma* cf. *exotica*, *Tellina amboyensis* and the mud-tellin are also common in finer substrates, *Tellina piratica* on the other hand extended its range from regions of intermediate silt content into sandier regions. Quite conspicuous was the fact that certain classes seemed to play the dominant role in the different habitats. The upper intertidal appeared to be the domain of molluscs, especially of gastropods. The mussel *Modiolus micropterus*, the arcid *Anadara granosa* and the tellin *Tellina capsoides* were commonly found in this region and amongst the gastropods the genus *Cerithididea* and the families Columbellidae, Marginellidae, Nassariidae, Retusidae and Amphibolidae.

The mid- and lower intertidal, and here especially the regions with moderate to low silt content, were numerically dominated by polychaetes. In the very sandy parts of the mid-intertidal molluscs were virtually absent. Only *Tellina piratica*, *Divaricella ornata* and the gastropod family Costellariidae extended their

range into these parts of the bay. Predatory polychaetes of the family Nephtyidae and gammarid amphipods showed highest densities in this environment. Towards finer sediments bivalves increased in numbers and in the very muddy parts to the east of Roebuck Bay the two species *Siliqua* cf. *winteriana* and *Anodontia* cf. *omissa* clearly dominated the figures of abundance and biomass. The only polychaete adapted to this muddy environment belonged to the family Pilargidae and was found in moderate numbers.

A few taxa seemed to be restricted to the lower regions of the intertidal. In the sandier parts these were the razor shell *Cultellus* spec., the polychaete families Sternaspidae and Flabelligeridae, comma shrimps and the short-armed brittle star. *Solemya*, the polychaete families Chaetopteridae and Sigalionidae and benthic ostracods reached highest densities in the lower intertidal region with intermediate silt content. Last but not least the lucinid bivalve *Anodontia* cf. *omissa* was the most typical representative of the very muddy parts of the lower intertidal.

In summary, gastropods are mainly found in the upper intertidal regions with medium to high silt content. Bivalves reach peak densities in the muddy parts of the lower intertidal, although each of the different habitats in the bay shows at least one bivalve species adapted to it. Polychaetes taken as a class seemed to be more opportunistic, and were found everywhere except in the upper intertidal and the very muddy parts of the bay. The few polychaetes that were found there were all epibenthic species. The fine carbonate muds offer little interstitial space and are not a suitable habitat for infaunal species. Tube building polychaetes face different problems. Once the muds are waterlogged they become semi-fluid and unstable in the upper layers. The species most common in these muds are deep burrowing bivalves and crustaceans. The thixotropic properties of the mud enable quick burrowing bivalve species to escape predation. The cohesiveness properties of the muds, on the other hand, allow crustaceans to build semi-permanent burrows, which protect them from predation and desiccation. The highest numbers of crustaceans were nevertheless found in regions with a moderate to low silt content. *Macrophthalmus* crabs seem to be very opportunistic and were found in all parts of the bay, although the larger specimens were mostly found in the muddy eastern parts. Two other crustacean families, pagurid hermit crabs and spider crabs of the family Hymenosomatidae, are responsible for the higher densities of crustaceans in the sandier parts of the embayment. Since both families show epi-benthic life forms, they need a more stable substrate than the shifty muds to the east.

Although this study is about benthic communities of the intertidal, a few words should be said about typical faunal elements of the supratidal. Numerical data is not available, since we only sampled on the mudflats and not on the beach and within the mangals, so the following description is based entirely on personal observations.

Crustaceans seemed to be especially adapted to living in the supratidal and among these especially members of the family Ocypodidae and the superfamily Paguroidea, the hermit crabs. The most conspicuous inhabitant of the sandy beaches were ocypodid crabs of the genus *Scopimera*, the 'Sand bubbler crab', which left their diagnostic traces all over the beach. Other common representatives of the family were 'ghost crabs' (genus *Ocypode*), and 'fiddler crabs' (genus *Uca*). Ghost crabs were seen frequently on the beach while the fiddler crabs were only encountered in a few places, generally with higher silt contents and slightly lower down in the tidal regime.

Hermit crabs, belonging to different families, were found almost everywhere from the lower intertidal to the supratidal and here both on sandy beaches and within the mangals. The superfamily Paguroidea consists of four families. Most of the hermit crabs found in the samples belong to the family Paguridae and were generally small and inconspicuous. Species of the family Coenobitidae on the other hand are well adapted to living on land, and we found members of this family in the mangals and on the beach.

Discussion

In the previous chapters it was tried to describe the study area in terms of the physical environment and the species assemblages typical for the different parts of the embayment. After pointing out some general characteristics of tropical soft-bottom benthic ecosystems in general (Alongi 1990), and our study area in particular, it will then be tried to compare Roebuck Bay with other tropical intertidal environments. Most of the benthic studies in the tropics were conducted on exposed beaches, whereas literature on tropical mudflats is very scarce. The temporal and spatial scales of these studies as well as the sampling designs are all different and the results thus hardly commensurable. It will nevertheless be attempted to compare at least qualitatively the results of these few studies with our findings

The last part of the discussion focuses on the topic of diversity. Which factors are generally increasing diversity within an area and which factors decrease it? Which of these factors are at work in Roebuck Bay and contribute to the very diverse benthic fauna in the

embayment? And what is it exactly that make Roebuck Bay the unique place we think it is?

Ecology of tropical soft-bottom benthic ecosystems

There is no simple definition of the tropics. At least concerning intertidal habitats it is not, as commonly supposed, a benign and uniform region of the earth. The ecological boundaries of the tropics are somewhat fluid as tropical climatic conditions may reach well beyond the Tropics of Cancer and Capricorn. In the review by Alongi (1990) the delimitation of the tropics as suggested by Deshmukh (1986) is accepted, being defined on land by the ecological boundaries between the tropical and extratropical vegetation types, and on the sea by the 18°C mean isotherm at sea level for the coolest month.

Variations in temperature and rainfall are large in the tropics. Over the tropical seas, climatic variations are smaller than within the continental masses, but rainfall patterns differ greatly. The western boundaries of the oceans are warmer, wetter, and more stable climatically than the eastern margins. The diversity of marine habitats peaks in the tropics. Many are dominant or unique, such as mangroves, coral reefs, stromatolites, and hypersaline lagoons.

Little benthic work has been conducted in the tropics, and the few studies that have been done focused on sandy beaches. Especially the literature on tropical mudflats is scarce, mainly because field work in muddy substrates under a tropical climate is extremely strenuous. Reviewing these studies reveals a few patterns, nevertheless. Although discontinuities exist in the latitudinal distribution of benthic invertebrates, similarity is greater between tropical and subtropical faunas than between the subtropical and the higher latitude faunas. Ekman (1953) noted that within the warm-water benthic fauna there is a considerable degree of longitudinal homogeneity, attributed to the origins of most benthic life-forms in the circumtropical Téthis Sea and their eventual radiation to more marginal, high latitude environments. An Indo-West Pacific and an Atlantic-East Pacific fauna are the two principal elements of the zoogeography of the benthic warm water fauna, with the former region faunistically more diverse.

More than 6,000 species of molluscs, 800 species of echinoderms, 500 species of hermatypic corals, and 4,000 species of fishes are described. Despite a basic homogeneity caused by the occurrence of many wide-ranging species, there are great differences in species diversity among the various parts of the region. The majority of tropical marine families have their greatest

concentration of species within a comparatively small triangle formed by the Philippines, the Malay Peninsula, and New Guinea. There seems to be a decrease in species richness that is negatively correlated with distance form the East Indies. On average it contains the youngest genera and is the evident place of origin for several groups whose dispersal tracks into peripheral regions has been traced. It appears to be the focal point for the initiation of extinction processes and its populations tend to possess a greater genetic diversity than those in peripheral areas. For these reasons it can be assumed that the East Indies has been operating as a centre of evolutionary radiation (Briggs 1999).

Within regions the western margins appear to have a more diverse fauna than the eastern margins, underscoring the long-term, but frequently overlooked, importance of climatological and environmental variations of the world oceans.

Environmental characteristics

When discussing tropical environments in general a distinction between the wet and dry tropics has to be made. On the basis of climate, the tropics are divided into four regions:

- Africa,
- tropical South and Central America, including the Caribbean islands,
- tropical regions of the Indian, Atlantic and Pacific Oceans,
- Southeast Asia and northern Australia.

Patterns of monsoon rainfall in Africa vary greatly with the vast expanse of the continent within the tropics. In northern Australia and south-east Asia, three monsoonal patterns control the climate:

- Equatorial monsoons where winter and summer monsoons are wet (Papua New Guinea and Indonesia),
- dry and wet monsoons where one season is wet and one dry (dry winter and wet summer in Thailand and Australia; wet winter and dry summer in eastern Philippines, eastern India and Bay of Bengal),
- the dry tropics (where rainfall is less than 400 mm per year) in Pakistan, central Australia, north-west India and Saudi Arabia, where monsoons are rare because large-scale disturbances are inhibited by short ocean distances between land masses.

Due to the regional variability of precipitation and solar insulation there are very sharp gradients in temperature, salinity, and some other properties, such as dissolved nutrients. Lower salinities are characteristic of surface waters in the humid tropics, and conversely, surface waters in arid tropical seas are very salty. Surface water masses in the tropics are greatly influenced by river run-off and dilution by monsoonal rains, particularly on most continental shelves (estuarisation), in which the inner portions of continental shelves consist of low salinity waters or exhibit discrete plumes of discharged river water (e.g. Brazilian shelf and Bay of Bengal). Changes in water mass characteristics induced by excessive evaporation may lead to changes in faunal distributions and abundances or to the development of a unique fauna such as in the hypersaline lagoons of the Red Sea.

Also common in the tropics are strong tidal currents in tropical coastal waters that frequently lead to the formation of tidal fronts, where tidal mixing overcomes buoyancy. In some shallow areas, particularly during the dry season, vertical gradients of buoyancy develop, inhibiting vertical mixing and resulting in the formation of a lutocline (fluid mud layer) separating clear surface waters from sediment-laden bottom waters.

Coastal upwelling is another major feature in the tropical oceans. Such events occur in all latitudes, but within subtropical and tropical latitudes, physicochemical differences between upwelled and surface water masses are greatest. Upwelling is dominant along the subtropical-tropical boundary coasts of Peru-Chile (Peru Current), Morocco-Mauritania (Canary Current), Angola-Namibia (Benguela Current), and California-Mexico; minor upwelling occurs on the Malabar coast of India, off the Andaman Islands, off western Australia, the Gulf of Panama, the Gulf of Nicoya and Tehuan-tepec, off north-east Venezuela and Brazil south of Cabo Frio, from Ghana to Togo, on the Somali coast, and off southern Arabia.

Between-year variations are generally greater than within-year variations within the tropical oceans. ENSO-events (El Niño Southern Oscillation) emphasise the fact that atmospheric variations can mediate changes in the environment on a global scale with major biological consequences.

Sedimentary patterns

The distribution of sediment types on the inner continental shelves reflects the influence of sediment runoff from the continents. Hayes (1967) compiled the available sedimentary data and correlated coastal climate with sediment type indicating that the major climatic factors responsible for the global patterns were weathering, the presence or absence of major rivers, glaciation, and ice-rafting. Mud and coral are most abundant in the tropics, whereas sand is globally abundant, decreasing with higher latitudes to be proportionally displaced by gravel and rock. The distribution of relict shell is not related to climate. Muddy sediments are predominantly found near the mouths of the major river systems. Excluding these areas, most tropical shelves are sand-dominated, several by car-

bonates and in many instances, bordered landward by mangroves or fringed seawardly by coral reefs.

In summary, wide variations in tropical rainfall lead to the formation of many sedimentary facies and habitats peculiar to the tropics. Mudbanks, green and blue anoxic mud regions, mixed terrigenous-carbonate bedforms, hypersaline lagoons, stromatolites and, more generally, mangroves, coral reefs, and extensive carbonate shelves are characteristic of shallow, tropical seas.

Organic carbon and nitrogen

The global distribution of sedimentary organic carbon and nitrogen is not related to latitude, but dependent upon water depth, grain size, terrestrial run-off, and hydrography (Romankevich 1984). The highest concentrations of organic matter in sediments are in regions of upwelling and in proximity to rivers, and more generally, relate to the patterns of pelagic primary production. It is interesting to note, however, that while there are no clear latitudinal trends in the distribution of sedimentary organic carbon and nitrogen, the lowest and highest values yet recorded are found in the tropics. The highest concentrations, particularly of carbon, in intertidal sediments have been found in mangroves on Cape York Peninsula in Australia.

Seasonal variations in particulate organic matter, particularly in estuaries, are greatly influenced by monsoonal rains. High river discharge during the rainy season can scour surface silts and clays and associated organic matter. In dry tropical areas, organic matter concentrations do not appear to vary seasonally (Alongi 1987). Lowest organic nutrient concentrations recorded in the tropics are found mainly in carbonate sediments, where organic sedimentation is frequently low and concentrations are generally lower than in quartz sand and mud of equivalent grain size in temperate areas. C/N and N/P ratios vary greatly in tropical sediments as in other latitudes. Variations in these ratios reflect the relative importance of terrestrial compared with marine origin of the deposited organic matter as C/N ratios generally less than 8 indicate a marine origin, whereas higher values suggest some terrestrial input.

Concentrations of the principal dissolved inorganic nutrients (NH_4^+, NO_2^-, NO_3^-, $Si(OH)_4$, PO_4^{3-}) are normally lower in tropical interstitial waters than in pore waters of sediments in higher latitudes. One characteristic of tropical sediments is the frequent presence of nitrite (NO_2^-) in the pore waters, which is an intermediate product of nitrification and generally an indication of moderate anaerobic conditions.

Regeneration of nutrients across the sediment-water interface is significantly lower in the tropics than in temperate sediments of identical grain size and at similar temperatures (Ullman & Sandstrom 1987), despite a sharp gradient in nutrient concentrations between the overlying waters and sediment. As in terrestrial ecosystems in the tropics, it is likely that nutrients in tropical marine systems are tied up in living plant and microbial biomass.

Benthic standing stocks, distribution and community structure

Sandy beaches (quartz, carbonate or mixed), mud- and sandflats, seagrass beds, salt marshes, mangroves, and coral reefs comprise the great variety of littoral habitats found along tropical and subtropical coastlines. In this study we concentrate on the benthic community structure of sandy beaches and mud- and sandflats, since these are the prevailing habitats in Roebuck Bay.

In his review on the ecology of tropical soft-bottom benthic ecosystems, Alongi (1990) compiled data about the community structure of macrofauna of 35 different study sites. The mean density per square meter and the mean number of species varied greatly between sites of similar habitat types as did the species dominating the faunal abundance. Mean densities ranged from 100 to 17,000 individuals per square meter and the number of species from 5 to 35. The numerically dominant organisms within the various study sites belong to different groups as well and general patterns are not evident. Isopods, amphipods, polychaetes, bivalves, gastropods and crustaceans are the most important taxonomic groups and either one of these dominates in each of the listed studies. The quantitative data presented in his review are hardly comparable considering the different sampling techniques and sieve sizes used, different sediment depths, and the general lack of season and site replication. Nevertheless he concludes that faunal densities in tropical intertidal regions are not greatly different from those in analogous temperate habitats; highest faunal densities generally occur in moderately exposed and sheltered habitats, whereas lowest densities are found on exposed, coarse sandy beaches, where most tropical intertidal studies have been conducted.

Piersma et al. (1993) evaluated 19 intertidal areas worldwide as feeding habitats for shorebirds. The total biomass figures varied between 5 and 80 g AFDM per m^2. No latitudinal trend was apparent in total biomass. On the other hand, tropical areas contain a greater variety of the major taxonomic groups compared to north-temperate intertidal flats. Whereas molluscs seem to dominate the macrofauna in temperate regions, other groups, e.g. crustaceans, echinoderms or brachiopods become relatively more important in the tropics.

Seasonality

Temporal patterns of intertidal populations depend greatly upon distance from the Equator, and whether or not the habitat in question lies in the wet or dry tropics. In the wet tropics, most populations suffer increased mortality or migrate during monsoons to escape sediment erosion and decreased salinities. In the dry tropics, densities of most benthic organisms vary in response to seasonal changes in temperatures, high salinity and desiccation.

Epibenthic and infaunal macrobenthic communities generally respond negatively to the onset of monsoonal rains and species richness peaks in the pre-monsoon months, when environmental conditions are most stable. Beach erosion takes place during the heavy monsoonal rainfalls and only species capable of migrating can persist. During the monsoon, densities of some opportunistic species (e. g. oligochaetes, capitellid polychaetes) reach maxima. In other regions, where erosion is of minor importance, faunal responses are in general species specific, and the total community response is dependent upon the frequency and intensity of climatic disturbance as well as the time of year in which it occurs. There is evidence of some seasonality on mudflats in Malaysia, where spawning of the dominant arcid bivalve *Anadara granosa* is triggered by seasonal depressions of salinity in interstitial waters.

In regions where rainfall is sporadic, high temperatures and desiccation are the major factors influencing seasonality of intertidal benthos. In summer, temperatures of intertidal sediments in north Queensland were shown to increase from 27°C at daybreak to 40°C at noon (Alongi 1990). Especially protozoan and meiofaunal abundances decreased significantly over a tidal cycle during summer. In the winter, when the range of temperatures is less, the densities did not change drastically. Lowest faunal densities generally occurred during the hottest months of the year.

Heat stress and desiccation also effect the macrofauna and the different taxa respond to it with different morphological, physiological, and behavioural adaptations to resist or compensate for rapid changes in temperature. Organisms of the upper intertidal are subjected to more heat stress than those lower in the intertidal zone and should therefore be more resistant to thermal stress. It is beyond the scope of this study to describe all the adaptations organisms evolved in respond to high temperatures and long periods of emersion. Behavioural adaptations (esp. among molluscs and crustaceans) include deep burrowing, hiding (passive phases under rocks or dense canopy during the hottest hours of the day and active phases when the tide comes in) and hybernation (crabs of the supratidal). Morphological adaptations include evapora-

tive cooling (e.g. the gastropod *Nerita*) and for hard shelled forms like barnacles or molluscs the sealing off of the shell to minimise the loss of body fluids.

Zonation

The zonation of intertidal sand fauna was first popularly conceived by Dahl (1953) who described the crustacean fauna inhabiting sandy beaches in Europe and South America. He divided sandy shores into three horizontal belts:

- The subterrestrial fringe ("Talitrid-Ocypodid belt"), which harbours mainly talitrid amphipods on temperate beaches and ocypodid crabs on beaches in lower latitudes,
- the midlittoral fringe ("Cirolana belt"), of which cirolanid isopods are the most common inhabitants,
- the sublittoral fringe, which is the most diverse belt, having a rich and varied fauna with members typical of other sandy shores as well as dominant subtidal dwellers.

Many subsequent workers on tropical and subtropical shores have followed this classification, basing the zonation of beach fauna on species "belts" or "associations". Depending on the local and regional species pool, different taxa dominate each belt. Many differences within regions may be attributable to minor variations in exposure and beach slope.

Reviewing some of these classifications reveals that the high intertidal, here defined as the region between equinoctial high water spring (EHWS) and mean high water spring (MHWS) is generally dominated by ocypodid crabs. The mid and lower intertidal regions are less well defined.

The dominance of ocypodid crabs in the high intertidal is easily observable just by walking along the beach and should therefore be quite independent of the sampling techniques and the spatial and temporal scales of the studies. In the lower regions, figures of densities largely depend on the sampling design and the sieve sizes used. Smaller meshes bias the results in the direction of smaller organisms (e. g. polychaetes, amphipods, isopods, ostracods etc.), whereas larger and deep burrowing species, like some crustaceans, are proportionally underrepresented.

According to Alongi (1989), tropical intertidal areas are usually dominated by decapod crustaceans, isopods, and bivalve molluscs of the genus *Donax*. Species of the latter genus are extremely successful inhabitants of most tropical and subtropical sandy beaches and shallow subtidal sandflats and are the dominant bivalves in high energy, warm-water habitats. In colder climates, more sheltered habitats, and on beaches with more carbonate than quartz they are displaced by other species. Temperate sandy habitats on the other hand are inhabited mainly by gastropod

molluscs and polychaetes. The apparent success of crustaceans and bivalves in the tropics can be attributed to their motility and ability to escape or avoid high temperatures and salinity or desiccation.

However, there are many exceptions to these generalisations. In intertidal mudflats of Malaysia and South America polychaetes are conspicuously absent (Broom 1982), whereas they dominate the figures of abundance of Costa Rica mudflats (Vargas 1988). Broom (1982) suggested that although different phyla dominate in different latitudes, the various trophic types (deposit-feeders, scavengers, suspension-feeders, algal grazers, predators) are well represented worldwide, with different but similar genera filling identical niches.

Characteristics of the Roebuck Bay ecosystem

Mudflat typology

The most striking feature of the study area is the heterogeneity of habitats and the associated faunal assemblages within the embayment. If similar habitats in different studies on tropical intertidal communities are to be compared it is therefore necessary to precisely describe the habitats of the study area. Habitat types in most studies are defined very roughly and usually only classified according to substrate and various degrees of exposure.

Using the typology of intertidal mudflats by Dyer (1998), Roebuck Bay can be classified as a macrotidal, low energy environment. In the northern parts the intertidal is only a narrow stretch of approximately two kilometres width and erosion seems to be the dominant process (Type 2a). In the wider eastern parts deposition is prevailing and the tidal flats are accordingly wider (Type 2b).

The substrate in the northern parts consists of fine to very fine sands. The coarsest sediments are found in the 'Sandy Beach' provinces in the north-central part of the embayment (Ch. 5). The median grain size is with 170 µm still quite small and the sediments contain on average around 10 % silt. Even after a few days of emersion during neap tides the sediments were still moist, so the fine sands must possess a rather high water holding capacity or capillary forces in the sand matrix are high enough to transport water from the water table to the surface. So except for the narrow sandy beach, which will only be inundated during spring tides, the sediments do not dry out completely. This bears important consequences for the biota, because the very high heat capacity of water compared to air and the additional effect of evaporative cooling dampen the temperature extremes between daybreak and noon and therefore decrease the danger of heat stress and desiccation at least for the infauna.

Climate and currents

The monsoonal climate of north-western Australia is characterised by a dry winter and a wet summer. During the wet season rainfalls are highly sporadic and the average precipitation in the wettest months is with 150 mm for the month of January still quite low. The average evaporation exceeds precipitation for any one month. Rare events of cyclones hitting the area can bring torrential rainfalls for a few days, but in comparison to the wet tropics these events are short termed.

Since there is no mayor river system entering the embayment it can be assumed that salinity changes during the wet season are of minor importance. Large seasonal variations in salinities, as can be observed on lower latitude mudflats or in tropical estuaries, are absent. This has implications on the faunal structure, because relatively few species are adapted to drastic salinity changes. At least in this regard Roebuck Bay can be considered a more stable environment compared to intertidal areas in the wet tropics. The consequences this has on the diversity of the area will be discussed later.

Even though the environmental conditions within the study area seem to be quite stable compared to the wet tropics, temporal variations in the faunal assemblages have been observed. During a previous field trip (1991) that was aimed at evaluating Roebuck Bay as a springboard for the northbound migration of waders (Tulp & de Goeij 1994), the mussel *Modiolus micropterus* was locally found in high densities of up to 260 individuals per square meter. Hinges of *M. micropterus* could be identified in droppings of Great Knots and it was assumed that mussels were an important prey item for these waders. In 1997, when we conducted our field work, *Modiolus* was conspicuously absent and was only found in 13 out of 537 samples. The specimens had an average length of 15 mm with a range from 4 to 30 mm, so they must have been recruited in different years. Settlement of larvae apparently takes place every year, but spatfall and survival rates seem to vary significantly between years. Many invertebrate species of the tropics show an extended planctotrophic larval development and can live for several months in the water column (Scheltema 1971). Thus they are capable of long distance dispersal through oceanic currents. This already shows that any attempt to explain local species assemblages has to include processes operating at larger temporal and spatial scales.

The overall density and biomass of macrofaunal species in 1991 was with 1,017 ind./m² and AFDM of

15.5 g/m³ within the range calculated for 1997 (1,287 ind./m² and 12.5 g/m³ AFDM, respectively). Unfortunately, there are no data on temporal variations of species abundances. A few species, like the edible arcid bivalve *Anadara granosa*, are known to be permanent features of the intertidal fauna because they constitute an appreciated food item and have been collected by Aborigines for a long time. The settlement of other species with long distance larval dispersal may well be erratic and dependent on oceanic currents, spawning success in remote source areas, and the survival rate during the planctonic stage.

Organic carbon and nitrogen

As mentioned before, high concentrations of organic matter are not correlated with latitude but depend on grain size, water depth, terrestrial run-off, and hydrography. The study area is not affected by upwelling, and terrestrial run-off in the semiarid setting is low. This, together with the fact that soils of the catchment area are nutritionally poor and agriculture is only present in the form of extensive cattle breeding, insinuates that nutrient concentrations of the surface waters and within the pore water of the intertidal sediments are low. The colour of the sediments was a light grey within the top one to three centimetres, grading farther down into a slightly darker, bluish grey colour. Black anoxic layers and the stench of hydrogen sulphides, typical for sediments rich in organic matter, were not observed in the intertidal.

Well developed mangal soils are different with respect to organic carbon content and nutrient levels. It is not unusual to measure carbon concentrations greater than 5 % and nitrogen levels greater than 1 % by dry weight in some tropical mangal soils (Alongi 1990). At deeper levels, which are permanently moist, the soil becomes odorous with hydrogen sulphide and may be saturated with iron sulphide that is fixed by bacteria under reducing conditions. The extensive mangals of the Crab Creek and Dampier Creek system were not part of our investigations. However, they may influence intertidal communities by the outwelling of particulate and dissolved organic matter and nutrients. A review of the literature discussing exchange of materials between mangroves and offshore areas suggests that export is a feature of most tidally inundated mangroves (Lee 1995), mostly as dissolved forms of organic matter. The exact pathways are poorly investigated and the relative importance of groundwater flow, tidal flushing or as flux of assimilated mangrove-derived carbon in the form of animal biomass is still largely unknown. Mangrove litter is poor in nitrogen (high C/N ratio) and may only be assimilated at low efficiencies by estuarine consumers. The assimilation efficiency can be greatly enhanced by the colonisation of the detritus by bacteria. Such microbial enrichment action is probably required in order that most macro-detritivores can beneficially utilise mangrove detritus. An exception are grapsid crustaceans that consume fresh litter in great quantities.

Unfortunately, most past studies on the beneficial effects of mangrove outwelling were based on works carried out in the mangrove environment itself. By definition, however, outwelled detritus have their transformation and subsequent utilisation in the oceanic or intertidal environment with a different suite of physical and chemical characteristics as well as different communities of microbial organisms. To assess the importance of the outwelled matter to non-mangrove consumers, further studies have to be conducted in the receiving environments.

Benthic zonation patterns in Roebuck Bay

As already described in chapter 5, the distribution of most taxa is very patchy and changes on small scales. Nevertheless, a basic zonation is obvious that might serve as a base for comparisons with other tropical intertidal areas.

The supratidal, here defined as the region above MHWS and characterised by a narrow stretch of sandy beaches, is dominated by crustaceans, mainly ocypodid crabs of the genera *Uca*, *Scopimera* and *Ocypode* and hermit crabs. For the rest of the intertidal a rough distinction between sandy and muddy substrates has to be made. Sandy substrates in the upper intertidal (MHWS to MHWN) are rare within the embayment and the one species restricted to this kind of habitat is the mussel *Modiolus micropterus*. The mid intertidal (MHWN to MLWN) shows a greater variety of species and an assemblage of the gastropod family Costellariidae, the smooth-shelled *Dentalium*, gammarid amphipods, anthurid isopods, Tanaidacea, *Lingula* and the polychaete families Onuphidae, Nephtyidae and Oweniidae was typically found. The lower intertidal (MLWN to MLWS) was characterised by an assemblage of *Cultellus*, Cumacea, short-armed brittlestars and the polychaetes Opheliidae, Sternaspidae and Flabelligerida.

The muddy regions with silt contents in excess of 70 % exhibited an assemblage of the gastropod families Nassariidae, Retusidae and Amphibolidae in the upper intertidal. The mid intertidal was the centre of distribution for the bivalve *Siliqua* cf. *winteriana*, the gastropod family Pyramidellidae and the free living polychaete Pilargidae. In the lower intertidal the lucinid bivalve *Anodontia* cf. *omissa* dominated the figures of abundance. Most taxa of the local species pool seemed to prefer intermediate substrates and had their centre of distribution around the neap tidal range, extending their distribution from there into the upper

and lower intertidal and into finer and coarser substrates (Ch. 6). The higher diversity in intermediate substrates does not necessarily indicate a more benevolent or heterogeneous environment, but may as well be an area effect because most of the samples were taken in this kind of substrate.

Summarising the results even further, gastropods and bivalves seem to be characteristic of the upper intertidal areas independent of grain size characteristics. The mid and lower intertidal was numerically dominated by polychaetes in the sandier regions, whereas bivalves prevailed in the muddy substrates of the study area.

Comparisons with other tropical intertidal areas

Difficulties in comparing intertidal assemblages in different locations

Up to date few studies have been carried out in tropical intertidal environments and out of these most were conducted on coarse sandy beaches. If the structure of benthic communities is to be compared, then similar habitat types have to be chosen. However, perfectly matched sites are impossible to achieve a problem that lies at the heart of current arguments over the causes of diversity differences between continents in some groups. The best that one can do is to match sites as carefully as possible and admit that the true magnitude of the habitat component may be underestimated somewhat because of residual ecological differences between sites on different continents (Schluter & Ricklefs 1993). This problem is even enhanced in the field of intertidal community structure because very few studies have been done. Alongi (1990) reviewed the macrofaunal community structure of 35 intertidal sites. 26 out of these were beaches with varying degree of exposure, and three were seagrass meadows. Only six studies had been carried out on intertidal mud- or sandflats like our study in Roebuck Bay, and among these climatic conditions and sediment parameters vary greatly.

Ignoring variances of the abiotic environment between sites, another problem arises from methodological differences between studies. If similar habitats are to be compared, then the sampling design and the spatial and temporal scales of the studies have to be cognate as well.

Although most of the literature on intertidal environments purports to be about communities, the majority of such studies is, in fact, on taxocoenes or taxonomic assemblages and focuses on a relatively small subset of the organisms within a community. Studies on macrobenthic species commonly include many different phyla, but depending on requirements of logistics, the taxonomic status in an area, and simple choice of the researchers, decisions about how to deal with many species differ between studies and more often than not organisms are identified to different taxonomic levels, making comparisons difficult. Using the concept of functional groups or guilds instead of examining the fauna on a species-by-species basis would be reasonable in very diverse settings, but then the ecological relationships of different species in a group have to be known and not simply assumed.

Comparisons from one place to the other are also made difficult by the different spatial scales used by different investigators. Many processes (e.g. predation, competition, larval settlement etc.) work on different geographic scales and depending on the size of the quadrates or experimental plots the variability of these processes changes. Differences in faunal assemblages will be discernible when small quadrates are used, but much of the smaller scale variation will be averaged out in larger quadrates.

When it comes to assessing the diversity of a specific region, the size of the area sampled has to be taken into account. Plotting species numbers against the area sampled (species-area curves) is a good indicator of whether enough samples have been taken and if the ceiling of local diversity has been reached. Unfortunately, this has not been done in many studies and a low diversity may be an artefact just because not enough samples have been taken.

Another problem that frustrates biogeographical comparisons of local assemblages is the time scale over which many studies are done. Studies are often done at a single time of year, or in only one season, making comparisons from one place to another potentially confounded by the time of year, unless studies are done at similar times, or in the same season. Yet another problem is that studies are often short. For example, even though a long-term study may be available from each of two geographical areas, these can only be compared if it is known that the two periods studied are, in fact, equivalent. If one study had been conducted during times of exceptional whether, such as during ENSO events, and the other study in between these events, then the studies differ in two ways. Under these circumstances it is not possible to identify which components of difference are attributable to locality and which are due to prevailing weather conditions. Alternatively, a lack of differences between the two areas does not necessarily indicate a lack of geographical differences. Instead, the intrinsic differences due to geography and different locality may have been cancelled by concomitant differences between the two prevailing patterns of weather (Underwood & Petraitis 1993).

As already mentioned, identical sites cannot be found. Out of all the literature on the ecology of tropical soft-bottom benthic ecosystems, the five studies that appeared to be most comparable regarding habitats and sampling design were chosen. These studies are:

- Species richness and distribution of benthic tidal flat fauna of the Banc d'Arguin, Mauritania (Wolff et. al. 1993)
- Benthos structure on tropical tidal flats of Australia (Dittmann 1995)
- Structure and seasonality in a Malaysian mudflat community (Brown 1981)
- Numerical density and biomass of macrobenthic animals living in the intertidal zone of Surinam, South America (Swennen et al., 1982).

A detailed comparison between all studies is beyond the scope of this paper. Instead, after giving a short description of the habitat, it will only be tried to compare zonation patterns, overall densities and biomass figures, and the species richness of the respective areas with our study site.

Banc d'Arguin, Mauritania

The Banc d' Arguin in Mauritania, West-Africa, is an area of intertidal flats and shallow inshore waters bordering the sandy desert of the Sahara. The average tidal amplitude amounts to 1.61 m, with approximately 2.0 m at spring tides and 1.0 m at neap tides. An intertidal area of ca. 500 km² is exposed at spring tides. The climate is arid with an average monthly temperature of 18°C in winter and about 22°C in summer. Precipitation is rare at the Banc d'Arguin (< 50 mm/a); there is also no freshwater land drainage. Salinity of the inshore waters is higher than in the adjacent open ocean, with values of 38 – 42 psu in the larger part of the tidal flat area, but much higher values close to the shore and in land-locked bays. The larger part of the Banc d'Arguin area consists of soft sediments. Sandy and muddy areas alternate. In general the areas covered with seagrasses are muddy, whereas unvegetated areas are sandy.

During the study in 1993, 72 sites, randomly chosen, were sampled on the tidal flats with 5 replicates taken at each site. The corers used had a diameter of 10 cm and were pushed into the sediments to a depth of about 40 to 45 cm. The total area sampled in this way amounted to 2.8 m², compared to 12.65 m² sampled in Roebuck Bay. To compare the biodiversity of both study sites and to compensate for the area effect, 120 out of the total of 537 stations of the Roebuck Bay data set were randomly chosen and only the taxa present in these samples were taken into account. Taxa of both study areas were aggregated to the same taxonomic level for each group; family level for bivalves,

gastropods, polychaetes and decapod crustaceans, and for the remaining taxa the taxonomic levels used in the Roebuck Bay study. Although the comparison of diversity on higher taxonomic levels cannot be an adequate substitute for counts on the species level, the latter is almost impossible to achieve, bearing in mind that some groups are taxonomically difficult and that the accuracy of identification largely depends on the expertise available and the focus of the study.

However, assuming that the total number of species and the higher-taxon richness from different groups are positively correlated, it appears that the Roebuck Bay area is more diverse. A total of 77 taxa was found in the 120 subsamples of Roebuck Bay compared to only 56 taxa in the Banc d'Arguin. The number of families within the classes Bivalvia (13 families in Roebuck Bay, 10 families in the Banc d'Arguin), Gastropoda (12 vs. 14) and Polychaeta (27 vs. 20) were in the same range. The group that differed most in terms of diversity were decapod crustaceans, which were not found in any of the 360 cores taken in Mauritania. In contrast, 11 families of decapods were found in the Roebuck Bay samples.

The total densities cannot be compared easily because different mesh sizes were used. Macrofauna of the Banc d'Arguin study was defined as those animals retrieved on a 0.6 mm mesh, whereas a 1 mm mesh was used in our study. To make up for these differences, only the taxonomic groups with predominantly larger sized individuals were compared, namely bivalves, gastropods and decapod crustaceans. Biomass values on the other hand are not as much affected, since small specimens contribute very little to the overall AFDM.

The density of bivalves is with 152 ind./m² in Roebuck Bay and 173 ind./m² in the Banc d'Arguin very similar. In Roebuck Bay the families Lucinidae, Tellinidae and Cultellidae are the most abundant bivalves and together make up more than 75 % of the total counts. In the Banc d'Arguin the two species *Loripes lacteus* and *Abra tenuis* are most numerous with more than 85 % of all the bivalves sampled. Figures of AFDM are strikingly dissimilar in both regions. Large specimens of the West-African blood cockle *Anadara senilis* make up the gross of the macrobenthic biomass of the Banc d'Arguin. This species alone accounts for approximately 8.1 g AFDM/m². The estimated total for the class Bivalvia is 11 g/m² compared to only 1.9 g/m² in Roebuck Bay. The part of the biomass on the Banc d'Arguin available to waders will be a lot lower, since the rather large and thick shelled arcids are not a suitable prey item for most waders, and numbers of Oystercatchers, which are capable of handling these bivalves, are low in the Banc d'Arguin.

Note, however, that the biomass figures presented in our study must be treated with caution because they were not measured directly in the laboratory but computed from body lengths. For five different bivalve species AFDM was measured within different size groups and the mathematical relationship between body length and AFDM was calculated with regression analysis. The computation of AFDM for the remaining bivalve species was then based on morphological similarities to one of these five species and the respective formula was applied. The exponents in the formulae had all values between 1.63 and 1.93, which seem to be extraordinarily low. Usually volume and body mass increase with the third power of length and an exponent between 2.5 and 3 was expected. At least for the class Bivalvia the biomass figures calculated for Roebuck Bay are very conservative estimates and likely to be higher.

Densities and biomass values among the class Gastropoda are a lot higher in the West-African study site. In Roebuck Bay the average density was 31 ind./m², amounting to an AFDM of 0.35 g/m². The Banc d'Arguin showed 216 individuals and an AFDM of 1.9 g per square meter on average. The higher abundance of gastropods in the Banc d'Arguin might be explained by the extensive seagrass meadows and the higher organic content of the sediments, which offer a suitable habitat for deposit feeding and grazing snails. In Roebuck Bay the distribution of most gastropod families was restricted to the rather narrow upper intertidal close to the mangrove fringe.

Polychaetes were the most abundant class in Roebuck Bay with an average of more than 900 ind./m² and a mean biomass of 5.55 g AFDM/m². The high numbers were largely made up by the tube building families Chaetopteridae and Oweniidae, whereas *Capitella capitata*, *Euclimene oerstedii* and *Naineris laevigata* dominated the figures in the West-African site. At first sight the absolute numbers (900 ind./m² in Roebuck Bay vs. 789 ind./m² in the Banc d'Arguin) seem to lie in the same range. However, the use of sieves with a 0.6 mm mesh in the Mauritanian study biased the figures in the direction of the smaller and mostly opportunistic species, which locally occur in very high numbers. The differences in densities both studies should therefore be a lot higher than the figures suggest. The high abundance of *Capitella capitata* and other opportunistic infauna suggests an environment with a considerable amount of stress or disturbance, where pollution-indicator species can also occur. In Roebuck Bay these opportunists are conspicuously absent, either because they were not retained on the 1 mm mesh or because they are not able to compete with other more specialised taxa. The higher stress levels in the Mauritanian study site and the larger number of infaunal opportunistic species might be explained by the higher organic content in the sediments and anoxic conditions in the subsurface sediments.

The most noticeable difference between both study areas is the absence of decapod crustaceans in the Mauritanian samples. In Roebuck Bay the order Decapoda showed average densities of 56 ind./m² in the intertidal region and these numbers must be an underestimate judged by the numbers of crab burrows seen on the intertidal flats. Totalled for all crustaceans the densities are higher in the Banc d'Arguin (145 compared to 97 ind./m²) due to large numbers of small sized isopods and amphipods retained on the 0.6 mm mesh. However, the AFDM of these specimens is insignificant and the total biomass for the class Crustacea amounts to only 0.1 g/m² in the Banc d'Arguin compared to 1.2 g AFDM/m² in Roebuck Bay. Typical for both study sites is the dominance of ocypodid crabs in the upper intertidal, although fiddler crabs are more abundant in the West-African site, whereas *Scopimera* and *Ocypode* are more frequent in Roebuck Bay.

Haughton River Estuary, north-east Australia
The intertidal flat investigated lies in the mouth of the Haughton River, flowing into Bowling Green Bay (19° 25' S, 147° 5' E) and covers an area of approximately 5 km². The Haughton Estuary lies in the dry tropics and has a seasonal summer rainfall. The total precipitation is 1,152 mm/a and the average monthly rainfall is 181 mm in the summer and 11 mm in the winter. Average daily temperatures are 29°C in the summer and 26°C in the winter. The tidal range is quite small with 0.6 m during neap tides and 2.3 m during spring tides. Salinity is marine over most of the year and can vary between 25 and 41 psu. The sediments are fine muds with a median grain size of 120 µm. The organic content of the sediments was 2.37 % of the dry weight on average. In comparison, carbonate muds, as found in the eastern parts of Roebuck Bay, typically show contents of less than 1 % of the dry weight.

Five sites were sampled in April and September 1991 with 5 replicate samples each and for every benthos size. The sites lay along a transect from the high (mudflats) to the low intertidal (sandflats). Core sizes used were 177 cm² for macrofauna and they were taken to a depth of 20 cm. The actual area sampled in this manner amounted to 0.178 m². Macrofauna in this study was defined as all organisms retained on a 0.5 mm sieve.

The sampling design is exceedingly different from ours to permit any quantitative comparisons. Moreover, the study was focused on the benthos structure in general and detailed lists for the macrofaunal species were not included in the publication (Dittmann 1995). Due to this it is not possible to compare the biodiver-

sity of the Haughton Estuary with the diversity in Roebuck Bay.

A total of 96 species were identified in the samples taken in the Haughton estuary. A plot of species numbers against the area sampled indicated that the species stock of benthic organisms was not yet sufficiently sampled and that the actual diversity was a lot higher. All benthic organisms were identified to species level and the number of species was summed over macro- and mesofaunal taxa, i.e. they included all organisms retained on a 0.25 mm mesh. Crustaceans were the most diverse class with 32 species, followed by polychaetes (29), bivalves (13) and gastropods (10).

The total macrofaunal density was with 1,810 ind./m² in the same range as in Roebuck Bay (1,287), even though a much smaller mesh (0.5 mm) was used. In Roebuck Bay figures were dominated by gregarious chaetopterid and oweniid tubeworms, which together constituted almost 60 % of the total faunal abundance. In the fine muds of the Haughton Estuary bivalves were the most abundant class with an average density of 950 ind./m², followed by crustaceans (380), polychaetes (354) and gastropods (26). The very high score for bivalves in the Haughton estuary was due to a single sample taken in the sandflat in September 1991 containing 510 juvenile tellins. Bivalves did not attain sizes bigger than 1 cm and they did not aggregate to form beds. The high numbers of juveniles and the commonly very small sizes suggest that the estuary acts as a sink for dispersed larvae and that smaller opportunistic species prevail. But these are only guesses which need to be confirmed by a more extensive sampling program.

The predominance of the class Bivalvia in muddy substrates is a feature also found in Roebuck Bay, where highly adapted bivalves of the families Lucinidae and Cultellidae controlled the figures of benthic abundance in the muddy eastern parts of the embayment. Polychaetes in these muddy habitats were low in numbers and mostly free-living epibenthic forms were found. It appears that interstitial space and the stability of the substrate are the restricting parameters. The former is to small for macrobenthic infaunal polychaetes, the latter inhibits the construction of permanent or semi-permanent tubes and burrows.

The general zonation pattern Dittmann (1995) comes up with shows some broad similarities with the Roebuck Bay study site. The highest areas of the intertidal were dominated by ocypodid crabs in both study areas. Also present in the 'ocypodid belt' of the Haughton river estuary were soldier crabs (Myctyridae). Deep burrowing and high motility seem to be the evolutionary traits best adapted to this high stress environment in the tropics. For the remaining parts of the intertidal a well established vertical zonation was not

detected. Muddy substrates showed an assemblage of the crustacean genera *Macrophthalmus* and *Uca*, mudskippers, cerithid snails, polychaetes of the genus *Heteromastus* and sipunculids. Infaunal species only occupied the uppermost layers, probably because of anoxic conditions in the deeper layers of the sediments.

Muddy sandflats showed an increase of infaunal species. The larger interstitial spaces and the cohesiveness of the substrate allow the construction of permanent burrows, which in turn increases the environmental complexity and offers additional habitats to other species. The deep burrowing species in the Haughton Estuary are mostly callianassid shrimps. In Roebuck Bay this ecological niche seems to be filled by crustaceans of the genus *Squilla*. The typical assemblage found in the muddy sands of the Haughton Estuary consisted of the decapod crustacean *Callianassa australiensis*, different polychaetes families (Terebellidae, *Glycera*, *Nereis*, *Magelona*, *Prionospio*), the brachiopod *Lingula anatina*, the gastropod *Nassarius pullus* and various amphipods.

Sandflats typically comprised an assemblage of enteropneusts, small free-living and infaunal polychaetes, the gastropods *Nassarius* and *Polinices*, myctyrid crabs and tellinid bivalves.

The diversity seemed to be higher in the muddy sandflats and sandflats compared to mudflats. Observations in Roebuck Bay suggest that muddy environments in general tend to be more uniform and homogenous than sandier counterparts. In addition to that, life forms of muddy environments are mostly epibenthic, whereas slightly coarser substrates also show a diverse infauna and depth as the third dimension becomes increasingly important in structuring the benthic community.

Intertidal mudflats of the west coast of peninsular Malaysia

The intertidal mudflats which border much of the west coast of peninsular Malaysia cover an area of at least 400 km². In 1977 a study was initiated to examine the production of *Anadara granosa*, a commercially important arcid bivalve. The regular monitoring of the populations provided the basis for an examination of the general structure of the macrobenthic community (Broom 1982).

The work was carried out at two localities on the west coast of peninsular Malaysia, one in the estuarine mudflats at the mouth of the Selangor river termed Kuala Selangor (3° 20' N, 101° 14' E), the other on the mudflat that forms the south bank of the river Sungei Buloh at low tide (3° 15'N, 101° 18' E). The substrate characteristics of both sites were broadly similar. Water content was mainly between 55 and 65 % and organic matter (as loss on ignition at 475 °C for

7 h) between 6 and 11 %. Sediments consisted of fine muds with 80 to 90 % of the dry weight made up by particles < 53 μm. At both sites a black, sulphide-rich layer was to be found 3 - 4 cm below the surface of the substrate. The two study sites in Malaysia might serve as a good example for an organically rich mesotidal estuary of the wet tropics.

Samples of the fauna were taken from each of the study sites at intervals of 1 - 2 months using a hand-held dredge that sampled an area of 0.4 m². Usually five dredge samples were aggregated to make one fauna sample representing 2 m² and 10 - 20 of such aggregated sample were collected on each occasion. In addition to the dredge samples, at Kuala Selangor sediment samples were also collected on each occasion using a Birge-Ekmann box sampler of area 225 cm². These samples were passed through a sieve of mesh size 0.5 mm and the young of all species were collected, sorted and counted. Annelids occured in conspicuously low numbers and were excluded from the data. It seemed that they were only inefficiently sampled by the techniques employed.

In terms of abundance molluscs dominated the figures, especially the bivalves *Anadara granosa* (Arcidae) and *Pelecyora trigona* (Veneridae) and the nassariid gastropod *Plicarcularia leptospira*. The biomass values are controlled by *Anadara granosa*, which contributes 80 % to the total biomass in Kuala Selangor and more than 95 % in Sungei Buloh. Molluscs are also the most diverse phylum of the area. In total 22 macrobenthic species were encountered, of which 8 were bivalves and 11 gastropods. The total number of taxa is definitively an underestimate because the sampling was designed for studies on the production and growth rate of *Anadara granosa* and not to investigate the benthic community as a whole. However, the estuarine mudflats seem to be very poor in species. This is consistent with other studies of tropical and temperate estuaries, where changing salinity levels and prevailing anoxic conditions in organically enriched sediments are the major stress factors limiting the diversity of the habitat.

One faunal feature shared by the Malaysian mudflats, the Haughton estuary and Roebuck Bay is the presence of predatory gastropods. In both Australian sites these were different species of the gastropod family Naticidae, in Malaysia in addition to the naticid moon snail *Natica maculosa* also the neogastropod *Thais carinifera*. In both study areas they only occurred in low densities but the frequency of empty shells showing the characteristic bevelled drill hole of a naticid (Ch. 5) indicate that these snails are important predators of bivalves.

The only non-molluscan organism which was present in appreciable numbers was the small hermit crab *Diogenes* sp., which is assumed to be a predator/scavenger. However, since it is very small, it is probably only important as a predator of the recently settled molluscs.

Intertidal zone of Surinam, South America
The rather inaccessible tropical sea coast of Surinam forms the staging ground of large numbers of birds of the Ciconiiformes and Charadriiformes, including millions of migrating and wintering North American waders (Swennen, Duiven & Spaans 1982). The study was performed to gain insight into the composition, numerical densities and the biomass of the macrozoobenthos in the intertidal habitats and to evaluate the area as a feeding ground for shorebirds.

The Surinam coast is situated at about 6° N and between 54° and 57° W. Geographically it forms the central part of the Guiana coast, which consists of almost 2,000 km of muddy and sandy shore of the Atlantic Ocean, between the mouths of the Amazon and Orinoco. The intertidal zone of the Surinam coast consists of a series of mudflats in accretion, alternating in space and time with sections in erosion. The rapid succession of accretion and erosion results in a rather unstable shore line.

The fine muds deposited along the Surinam coast originates from the Amazon; the sand and shells of the beaches, however, are of local origin. The mud discharged into the Atlantic Ocean by the Amazon and carried WNW by the Guiana current gives rise to a zone of very turbid water along the coast. The high load of suspended materials inhibits the primary production in the water column even though nutrient levels might be quite high. On the other hand many species of benthic diatoms were found in high densities on the mudflats; their production will be quite high. As a result of the admixture of fresh water from the Amazon and the Guiana rivers the salinity of the near-shore surface water is lowered. The tidal amplitude at neap tides is 1.0 m, at spring tides 2.8 m.

The study was carried out in September 1980 at five locations representing different habitat types, including a relatively stable part of a long existing mudflat, a still growing part of a recently settled flat, a mudflat along a creek, an eroded clay bank, tidal lagoons, and sandy beaches. Out of these only the mudflats will be discussed in detail.

Samples were taken along transects perpendicular to the coast. For biomass determinations cores with a surface area of 0.018 m² and a depth of 35 to 40 cm were used. Along each of the transects on the mudflats 30 cores were taken, but 10 successive cores were aggregated and considered as a sample. The sampled mud was then sieved through a 1 mm mesh. Species which contributed significantly to the total biomass

were identified to the species level, the other organisms were taken together as a group (polychaetes, nemerteans etc.).

In the upper intertidal zone the gastropod *Melampus coffea* and the burrowing decapods *Uca rapax* and *U. vocator* were numerous with local densities of up to 100 ind./m^2 and biomass values of more than 30 g/m^2.

On the intertidal mudflats three zones could be recognised. Aside from the zone above MHT level covered with mangroves, and the zone around MHT with *Uca maracoani* as a dominant species, a third zone of bare wet muds could be distinguished. Here the fauna was richer in species numbers than in the *Uca* zone, but the biomass was much lower. Characteristic for this zone was the high density of Tanaidacea, consisting exclusively of *Discapseudes surinamensis*, with numbers of up to 6,000 ind./m^2. Generally biomass values were higher in the relatively stable older muds compared to the fast growing and recently settled muds, and higher in the upper intertidal compared to the lower regions.

The number of invertebrate species seems to be quite low compared with the wealth of species usually occurring in tropical marine habitats. Crustaceans dominate among the benthic invertebrates, whereas polychaetes and molluscs were only poorly represented. The conclusion arrived at in the study, that the dominance of crustaceans may be a general characteristic of tropical intertidal areas whereas polychaetes and molluscs dominate in temperate areas, cannot be shared after looking in detail at the studies presented here. More likely, a dominance of crustaceans is typical for intertidal areas with a high degree of physical stress, to which they are adapted or from which they can escape due to their high motility. In case of the tidal flats of Surinam the instability of the tidal flats are probably the decisive factor that cause the low biomass of benthic invertebrates in the lower intertidal. The mud is so little consolidated that the upper 20 to 30 cm can be fluidised easily, which makes this habitat unsuitable for burrowing species and infauna.

Possible explanations of the high biodiversity in Roebuck Bay

The tropical intertidal studies here reviewed comprise examples of very different habitats, even though most of them would probably have been classified together as tropical intertidal mudflats. None of the sites are alike, some not even roughly similar. They differ in climatological, hydrographical and sedimentological aspects and the faunal assemblages are accordingly different as well.

The intertidal areas in Surinam and Malaysia are located in the wet tropics and show estuarine characteristics. In the Malaysian sites salinity levels change seasonally with the onset of the monsoons. In Surinam salinities are low year round due to the constant fresh water input by the Amazon. Both intertidal areas are rich in organic material and especially the Malaysian study sites are typified by anoxic conditions in the subsurface of the sediments. A characteristic of the Surinam coast are the unconsolidated and shifting mudbanks that represent a very hostile environment for most benthic species. The total number of species in both study areas are low compared to the studies in more arid settings.

The intertidal flats of the Haughton estuary shows estuarine conditions as well but the salinity levels are marine during most of the year. The organic content is intermediate with an average of 2 to 3 % of the dry weight. Even though very few samples were taken, more than 90 species were identified and the actual diversity of the area will be a lot higher. Although very few species occur in both sites, the faunal assemblages of similar substrates show some similarities with Roebuck Bay on higher taxonomic levels. Identical niches seem to be filled with different, but similar genera.

The Banc d'Arguin is the site most easily comparable to Roebuck Bay. Both areas are reversed estuaries and terrestrial run-off is low. The major stress factors for the fauna are heat and desiccation, compared to changing salinity levels, anoxic conditions and physical instability of the sediments in the South-east Asian and South American sites. Judging from the much higher diversity in more arid settings, adaptations to temperature changes were evolved independently in many different groups, whereas only few opportunistic species seem to thrive in estuarine conditions. The main difference between both areas seems to be that dense seagrass meadows cover extensive areas in the Banc d'Arguin, whereas in Roebuck Bay they are only locally found and coverage is generally poor. The higher proportion of deposit feeding and grazing gastropods in the Banc d'Arguin may be explained by these extensive seagrass habitats.

None of the areas investigated showed a diversity in terms of species numbers as high as Roebuck Bay. The sampling design of our study with more than 1,600 cores taken was by far the most extensive benthic mapping program undertaken. The species-area curve (Fig. 7.13) suggests that the ceiling of local species richness in the different habitats of the intertidal region is nearly reached and that enough samples have been taken. It has to be kept in mind that only bivalves were identified to species level and all other groups to higher taxonomic levels. Furthermore, the mesh size of 1 mm is too large for many polychaetes and micro-

Species-area curves for different habitats
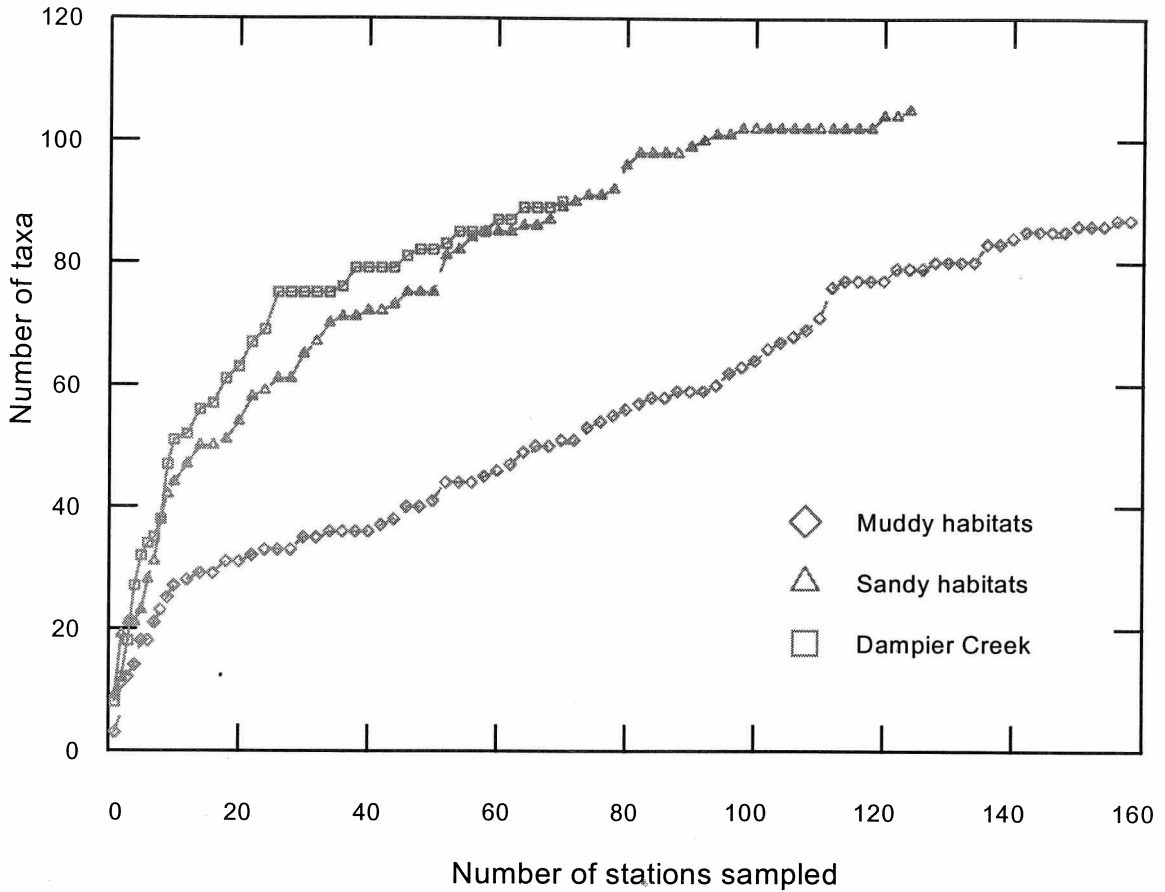

Fig. 7.13: Species-area curves for different intertidal habitats. Three different areas were selected:
1) An area of fine to very fine sands near Dampier Creek, characterised by tidal creeks and a very heterogeneous microtopography. The overall substrate was sandy, but muddy substrates were present near the tidal creeks.
2) The sandy regions on the north-central part of Roebuck Bay.
3) The muddy regions in the eastern and south-eastern parts of Roebuck Bay which seemed to be more homogeneous compared to the former regions.

crustaceans. So the actual number of species will be a lot higher than the 161 taxa identified in our study. From the few cores we took in the very southern parts of the embayment we expect yet another different assemblage of species again. Hydrographic conditions were more openly marine and the sediments accordingly coarser. A thorough study covering the entire embayment and including the mangals and rocky habitats would certainly have increased the species numbers substantially.

Comparing the species richness of the major sedimentological units showed that the very muddy habitats were less diverse than the environments characterised by fine and very fine sands. The shape of the curves on the other hand revealed that in muddy areas

with generally lower densities of macrofaunal species, larger areas have to be covered to reach the ceiling of local richness. Even after more than 150 stations sampled the number of taxa was still growing. This might be due to the fact that epibenthic forms are proportionally more abundant and are inefficiently sampled with small area cores taken to large depths. These findings suggest that the paucity of species found in muddy compared to sandy intertidal environments may to some extend be an artefact because the same sampling designs will show varying degrees of efficiency in different habitats.

It is generally accepted that diversity peaks in the tropics. The latitudinal diversity gradient is well established for most terrestrial and aquatic ecosystems.

Whereas studies on the diversity of terrestrial plants and vertebrates and some marine systems like coral reefs and even deep sea benthos abound, comparable studies of intertidal environments are rare. According to Thorson (1957), species richness increases markedly towards the tropics for epifauna, but not for infauna. This latter may hold true for deep-sea benthos, simply due to the fact that below the thermocline oceanic environmental conditions are very similar worldwide. In the case of intertidal flats this hypothesis cannot be accepted due to a lack of empirical evidence. A review of tropical intertidal studies by Alongi (1990) suggests that diversity of intertidal habitats varies just as much within latitudes as between latitudes, which is not surprising considering the variety of marine habitats in the tropics and the wide range of environmental conditions.

The high species diversity of Roebuck Bay cannot be explained solely by environmental characteristics of the study area. According to Schluter & Ricklefs (1993) the number of species in a community may be profitably described as having at least two components: one attributable to the local habitat, and another to the region in which the community is embedded.

Processes operating on the local habitat level
On the local level, here defined as the entire study area of Roebuck Bay, a combination of processes promoting biodiversity is at work. These are:

- Spatial heterogeneity
- Local population size
- Intermediate disturbance levels
- Productivity

Spatial heterogeneity
Much of the species richness of the study area may be explained by the suite of different habitats present. Soft bottom substrates range from coarse sands in the southernmost parts of the embayment to fine and very fine sands in the north and fine carbonate muds in the eastern parts. Even though many of the taxa found in Roebuck Bay seemed to be adapted to a wide range of sedimentological conditions and were found almost all over the intertidal, others showed very distinct distribution patterns and were only found in certain habitats (e.g. gastropods of the family Amphibolidae). So although some overlap of species is obvious, each sedimentological province seems to harbour its own characteristic assemblage of species. It must be assumed that on lower taxonomic levels the niche width is even smaller, so families that by their widespread distribution seem to be generalists might as well consist of many specialised species, each of which is highly adapted to certain environments.

Even within habitats the morphology of the tidal flats is not uniform. Especially the sandflats in the northern parts of Roebuck Bay have a very heterogeneous aspect and exhibit a micro-topography that changes on centimetre to metre scales. These features include ripple structures, tidal creeks and creeklets, water pools, animal burrows, and small scale changes of the substrate induced by tubeworm colonies, seagrass or other organisms. Other habitats of the study area include extensive mangals and local rocky habitats consisting of large slabs of beachrock, sand- and mudstone. Although the fauna of these systems has not been studied in detail, they still contribute to the species richness of the sand- and mudflats, especially where the different habitats meet. The small scale heterogeneity of the area in terms of resources and physical factors should therefore allow many different highly specialised species to coexist (Tilman & Pacala 1993).

Local population size
The finite size of habitats, and thus of population densities, should place a limit on species diversity. An important component of this finite limit is the random walk to extinction of rare species (May 1973). This theory predicts that in a finite environment containing competing species, the appearance of each new species would reduce the average number of individuals per species. This would increase the chance that some species would fall below the minimum population size required for long-term survival.

Roebuck Bay with its 150 km^2 of intertidal flats should therefore allow many more species to coexist above their minimum threshold   abundance than smaller sized disjunct areas (e. g. small estuaries or enclosed lagoons). This area effect is particularly important for larger sized animals. Based on allometric relationships of metabolic costs (Peters 1983), a 10-fold increase in the size of organisms (as represented by their length), should lead to about a 180-fold decrease in their population density. Expressed in a different way, an animal of 10 cm length would need 180 times the area to fulfil its metabolic requirements than its 1 cm counterpart. This is one of the reasons why some small scale ecosystems (e.g. small lakes) cannot sustain large predators; the numbers of individuals sustainable by the ecosystem are simply below the minimum viable population size.

Intermediate disturbance levels
Levin & Paine (1974) showed that habitats characterised by a colonisation-competition trade-off should have maximal diversity at intermediate rates of disturbance, given that there is a fixed pool of potential species. In his models, intermediate disturbance levels

generate the greatest spatial heterogeneity because they create the full range of successional habitats from newly disturbed to late successional, each with its typical assemblage of species. In contrast, at high disturbance levels only newly disturbed habitats would be present and the species assemblage would be dominated by r-strategists apt at colonising new patches rapidly. In a low disturbance environment only late successional stages would be present and the best competitors would dominate the fauna.

It is problematic to evaluate the degree of disturbance present in a study area. Tropical intertidal areas are in general not the benign and stable environments that most people think. Climatic disturbances may be due to seasonal variations in temperatures and precipitation, rare cyclonic events, or unusual global weather patterns (ENSO-events). Pollution and habitat destruction are a major threat to tropical ecosystems, especially in the often very densely populated coastal areas.

Compared to the wet tropics the environmental conditions in the semiarid setting of Roebuck Bay are quite stable. Salinity levels, at least in the interstitial waters, can be assumed to stay in the marine range all year round and shelf estuarisation and the widespread erosion of intertidal sediments during times of heavy rainfalls and high river discharge, as observed on the Brazilian shelf and the Bay of Bengal, do not take place. Torrential rainfalls may be experienced during rare cyclonic events, but because no major river system is entering the embayment, even these fresh water masses should not greatly affect the salinity levels, given that the bay is open to the ocean and marine waters can enter the bay freely.

The energy input by waves and currents is relatively low compared to open beaches or other macrotidal environments. High energy environments like King Sound are characterised by shifting sand banks and megaripples, which make it a very hostile environment for sessile and infaunal species. Shifting mudbanks are found in intertidal areas of the wet tropics with a high sediment input (e.g. Amazon basin). These unconsolidated muds fluidise easily and will be entrained at low current velocities. Compared to these terrigeneous muds the carbonate muds found in Roebuck Bay tend to be more consolidated and stable.

Most important, Roebuck Bay can still be considered a relatively pristine environment, although there is danger that this might change in the near future. The town of Broom is growing steadily and with it the environmental impact on the embayment. More detrimental to the fate of the intertidal flats are plans to irrigate the neighbouring Roebuck Plains and to grow cotton. The use of pesticides and fertilisers that might enter the bay via groundwater flow and terrestrial runoff is almost certain to have fatal consequences for the biology of the area.

Productivity

Empirical evidence suggests that biodiversity is greatest at intermediate productivity. The fact that diversity is a hump-shaped function of productivity is hard to explain. The increase phase is not so much the problem and felt to be on a firm theoretical background: A poor environment supplies too meagre a resource base for its would-be rarest species, and they become extinct. The decrease phase empirically observed presents the real problem: Why does diversity decrease after a certain productivity is exceeded? There are many different theories addressing this topic in the literature (see Rosenzweig & Abramsky 1993 for a detailed review), none of which can successfully explain the similar pattern in the different communities studied.

The hypothesis that at first sight looks most promising is that productivities past a certain point reduce environmental heterogeneity. This theory was based on observations of terrestrial plant communities and could be backed up empirically by nutrient enrichment studies. Under conditions of extreme low productivity, there is not much habitat or resource heterogeneity; the landscape is uniformly barren and the average spot will not contain any species. As productivity rises, the average variety of micronutrient combinations in fertile spots increases, or some fertile spots have more light with sparser nutrients while others have less light with more nutrients. In either case, plant diversity increases and plant physiognomies diversify, allowing animal diversity to increase also. Moderately productive areas have excellent mean habitats, but their variance also encompasses a wealth of different sorts of exploitable niche opportunities. Past a certain point, more productivity has the opposite effect. Very productive areas still offer excellent mean habitats, but their variance rarely presents significantly different challenges to life, thus reducing the variety of viable temporal specialisations. Diversity declines.

Although much evidence favours this hypothesis, it might well be a tautology. Habitat and resource heterogeneity partitioning are evolved responses of organisms. In order to survive, species in a highly diverse system are forced to subdivide the habitat more finely. Moreover, organisms influence their immediate environment and a high heterogeneity of habitats may just as well be the effect of a diverse fauna and flora.

Whereas competition for water, limiting nutrients and light seem to be the decisive mechanisms in structuring terrestrial plant communities, the analogous factors in intertidal soft bottom systems are

poorly understood. That diversity is a unimodal function of productivity also for these habitats is more than likely. Coarse sandy beaches with low nutrient levels and productivity are almost barren of life. At the other end of the spectre, studies of diversity before and after eutrophication revealed an increase in faunal abundances of some opportunistic species, but a general decrease in species numbers. The concentration of dissolved oxygen decreases with temperature and is therefore low in tropical surface waters. In organically rich sediments oxygen is quickly consumed by aerobic bacteria and anoxic conditions in the subsurface of the sediments are common. Although there are some organisms especially adapted to these anoxic environments (Ch. 5, *Solemya*), it nevertheless constitutes a hostile environment characterised by low diversity.

It is difficult to quantify 'medium productivity'. Productivity in 'sensu strictu' is the rate at which energy flows through an ecosystem, which is hard to measure. In most cases ecologists used an index of productivity rather than measuring it directly (e. g. precipitation or evapotranspiration for terrestrial ecosystems, depth as an indicator of light availability on the ocean floor etc.). In intertidal habitats such an index is hard to find. Biomass figures do not have to be strongly correlated with productivity, particularly not so in the tropics where high turnover rates may be responsible for high productivity even though the standing stock at any one time is low. Another interesting question arises in respect to the shape of the uni-modal function. Is the mode of highest diversity skewed towards more productive or less productive habitats? Using the organic content and nutrient levels as an index for productivity, the above comparison of the five intertidal study sites suggests that diversity is highest at the lower end of productivity. Roebuck Bay, the biologically most diverse site, is very poor in nutrients and organic carbon is low in the intertidal. Maybe the important factors are not nutrient levels and carbon content itself but the oxygen content within the sediments. As already mentioned highly anoxic conditions were not observed in the intertidal and the sediments seemed to be well aerated.

Taken one by one the above described local processes cannot sufficiently explain the high diversity of the area. Even taken together they may help to explain what promotes diversity on a local scale, but fail to explain differences in the diversity between similar habitats in different parts of the tropics. To explain these we must go a spatial scale higher and look at regional processes affecting biodiversity.

Regional processes affecting diversity

Roebuck Bay is embedded in the larger biogeographic region of the Indo-West Pacific. The shelf waters of this region encompass an enormous geographic area extending longitudinally more than halfway around the world and through more than 60° of latitude. The biota is incredibly rich, with a species diversity exceeding the total of the other three tropical regions (eastern Pacific, western Atlantic, eastern Atlantic). Diversity is not evenly distributed throughout the region but seems to peak within a comparatively small triangle formed by the Philippines, the Malay Peninsula, and New Guinea (Briggs 1999). From this centre there appears to be a decline in species numbers correlated with distance to the triangle.

The proximity to this centre of high diversity, assuming that the faunal patterns for the groups used in this study apply to most benthic groups, should therefore positively affect the biodiversity of our study area. The relative importance of local and regional processes vary between taxonomic groups. Unfortunately, the ecology and large scale distribution of most benthic species in the tropics is only poorly investigated.

Many tropical invertebrate species show an extended planctonic larval stage and are therefore capable of long distance dispersal through oceanic currents. The arcid bivalve *Anadara granosa* might serve as an example. In Malaysian mudflats the economically important bivalve *A. granosa* is the dominant species of the benthic community. Mass-spawning is thought to be triggered by salinity depressions at the time of the onset of the north-east monsoon between October and November. The synchronised spawning enhances the prospects for successful fertilisation in the water column. In Roebuck Bay *A. granosa* was found locally in low densities, predominantly close to the mangrove fringe of the north-western parts of the embayment and in the muddy eastern parts (Ch. 5). The distribution of size classes was bi-modal with high abundances in the size class from 0 to 10 mm (83 %) and a second lower peak in the size class from 35 to 45 (12 %) mm. Specimens with a length of 10 to 35 mm were only represented by 5 % of the individuals. The bi-modal distribution of size classes suggests that settlement of larvae is not continuous but happening at certain intervals. It is conspicuous that the size class between 10 and 35 mm is virtually absent. Either it is due to size selective predation and the higher abundance of larger specimens can be explained that a critical size limit was reached, protecting the bivalves against further predation. A different explanation would be that for unknown reasons settlement failed or was poor during some years and that therefore entire size classes are missing. The latter explanation would also explain the observed differences in abundance of the mussel *Modiolus micropterus* between the two studies conducted in 1991 and 1997. This would imply two things: first that Roebuck Bay is a sink area for some

species and second that the local species richness is governed by the regional species pool of the Indo-West Pacific and processes acting on larger geographical scales. It would also imply that the high diversity of the area cannot be sustained without protecting the source areas from where species are exported.

The problems of the research efforts so far

Trying to explain the local species richness of Roebuck Bay rendered more questions than answers. To really get an insight into population dynamics and the community structure of the ecosystem, longer termed and larger scaled studies are needed. A comparison of the few studies on tropical intertidal areas was difficult and could not explain the large differences in diversity and species assemblages between sites. Based on the few studies available it seemed that diversity of intertidal habitats was higher in the climatically more stable dry tropics compared to the wet tropics. The Surinam and Malaysian studies represent estuarine conditions and are therefore hardly comparable to Roebuck Bay and the Banc d'Arguin. To really understand global diversity patterns similar habitats have to be compared and the same methodology has to be used.

Coastal habitats, especially in the highly populated tropics, are threatened by human impact. If we want to understand the dynamics of these ecosystems in order to protect them as efficiently as possible we have to hurry up. So far the research was conducted independently by different groups, each having their own focus and each using their own methods. It is really time to combine scientific efforts world-wide and work interdisciplinary in order to get an understanding of intertidal ecosystems.

Much effort has been put into palaeoclimatic research and deep-sea drilling projects. The importance of shelf and intertidal areas in regulating the global climate is generally acknowledged, and yet surprisingly little effort has been undertaken to study these systems.

Such a study would imply an enormous effort. The studies would have to be long-term and would have to be conducted at the same time to entangle temporal from spatial phenomena. In addition, the widely different intertidal habitats have to be covered by the program with replicates among each habitat. Last but not least the methodology of the sampling programs and the analyses applied have to be standardised to allow valid comparisons. To the best of our knowledge, Roebuck Bay still represents a largely intact and pristine environment. Representing an intertidal area with a macrotidal, low energy environment of the semi-arid tropics, it would be an ideal study site for this type of habitats. Compared to most other countries, Australia does not experience high population pressure on coastal areas. It would be a disgrace if a unique coastal environment like Roebuck Bay would be lost to future generations for lack of knowledge and consciousness.
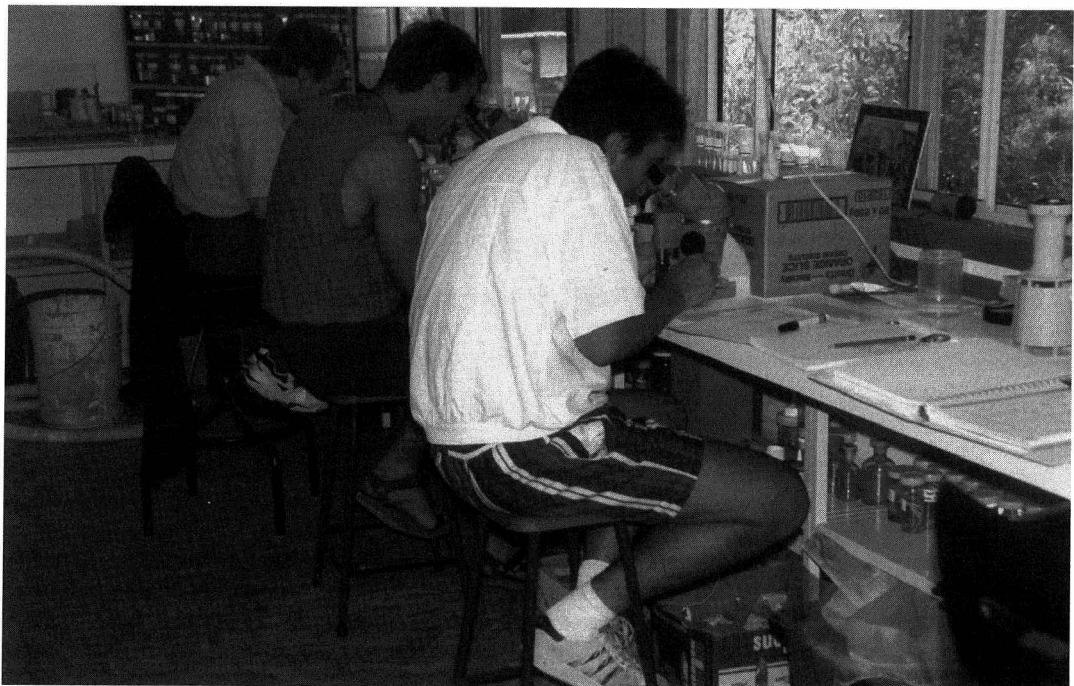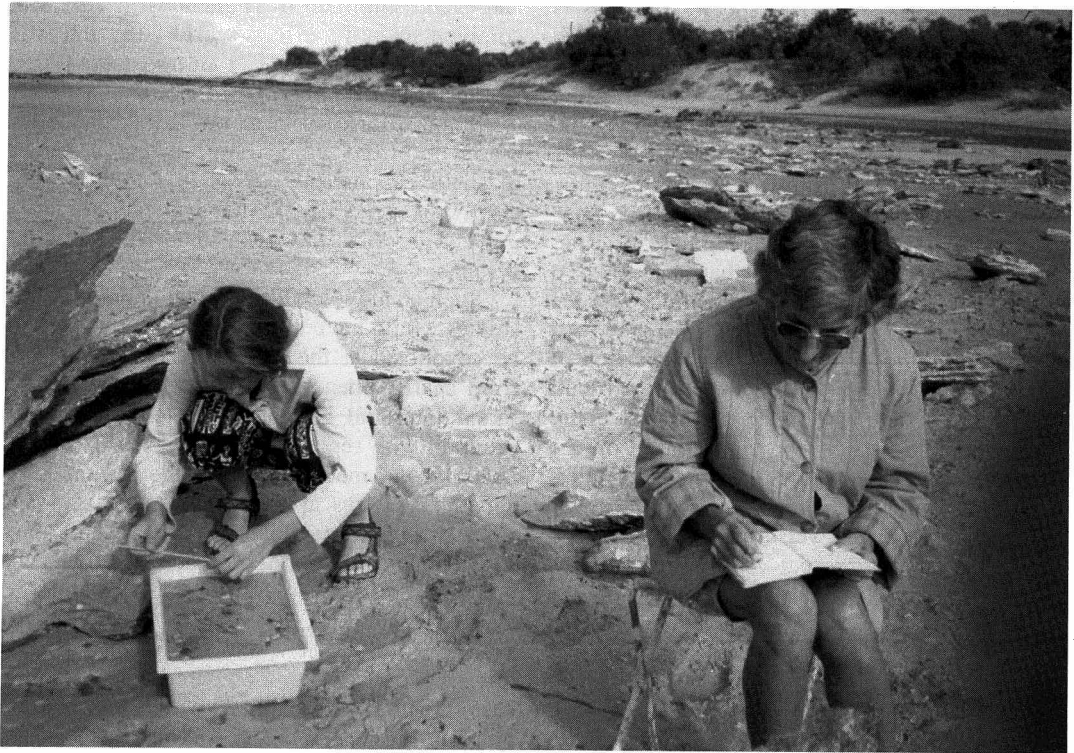
Field- and labwork in Roebuck Bay: Top: Petra de Goeij and Mavis Russell (taking notes) doing experiments on burying speeds of bivalves. Bottom: Pieter Honkoop, Markus Pepping and Danny Rogers (from front to back) trying to identify the macro-benthic animals sampled. Photographs by Theunis Piersma.

8 ANTI-PREDATOR ADAPTATIONS OF THREE BIVALVE SPECIES

Petra de Goeij

Introduction

Buried bivalves comprise important prey for at least two numerous shorebirds in Roebuck Bay, the Great Knot *Calidris tenuirostris* and the Red Knot *Calidris canutus rogersi* (Tulp & de Goeij 1994; D.I. Rogers this report). Finding them by touch with the very sensitive tip of the bill with which they probe in the mud, knots pull mollusc prey out of the sediment, swallow them whole, and crush the shells in their muscular stomach. Preferred bivalves should therefore not be buried too deeply, they should not be too big and they should not have a very thick shell (Zwarts & Blomert 1992, Piersma et al. 1993, Tulp & de Goeij 1994). Consequently, prey that aim to escape the attention of predators like knots should either be buried deeply or be able to move fast, or hide in a thick and uncrushable shell.

In March-April 1991, shell-fragments of the bivalves *Modiolus micropterus*, *Siliqua* cf. *winteriana*, *Tellina piratica*, and *Anomalocardia squamosa* were found in the faeces of knots which were feeding in Roebuck Bay (Tulp & de Goeij 1994). Of these species, only *Siliqua*, *Tellina* and *Anomalocardia* appeared to occur abundantly in Roebuck Bay in June 1997 (this report). *Siliqua* was found in the area where the silt content was highest (see Fig. 5.6 and 6.1; this report). Both *Anomalocardia* and *Tellina* were found near Dampier Creek, an area with a low silt content (see Fig. 5.6, 6.3 and 6.4; this report). As the shells of the three species are very different (Plate 8.1), the different species might reflect different solutions to the problem of detection, capture and ingestion by shorebird predators (Stanley 1970, Vermeij 1993). For example, the shell of *Siliqua* is very fragile, smooth and the shape is oblong. In complete contrast, *Anomalocardia* has a very solid rounded shell with strong ribs. *Tellina* is very different again, with their almost round shape, and the laterally strongly flattened shells with solid valves.

In this exploratory study, the different possible adaptations against probing predators like knots are described for each of the three bivalve species. In a field experiment burying behaviour was studied and in the laboratory I looked at morphological/physiological features related to this burying, as well as features of the protective (shell) armour. The first prediction was that the thin and smooth-shelled *Siliqua* would be the fastest burier, and that the thick-shelled and ribbed *Anomalocardia* would be the slowest. The second prediction was that the thin-shelled *Siliqua* would bury deepest and the thick-shelled *Anomalocardia* shallowest, according to Stanley (1970).

Methods

Experimental work

In an experimental set-up, the speed of burying was measured and also the resulting burying depth of the three bivalve species. The bivalves were collected in the bay on the same day as the experiment took place. We used 21 *Siliqua*, 14 *Tellina* and 15 *Anomalocardia*. Mean shell length of *Siliqua* was 18 mm (SD=1.9 mm), of *Tellina* 31 mm (SD=2.5mm) and of *Anomalocardia* 27 mm (SD=1.3 mm. A thin thread of known length was glued to the shell. At the end of the thread a numbered waterproof label was attached. By subtracting the part of the thread which was still visible on the sediment from the total length of the thread, depth could be calculated (see Zwarts 1986 for an illustration of this method).

The experiment was executed in a small basin (40*25*15 cm) buried in the intertidal just outside the laboratory at Broome Bird Observatory (ensuring realistic temperature and light conditions). The basin was filled with sediment (silt content 35%) which we saturated with ambient seawater. The bivalves were spread over the top of the sediment. Additional seawater was added after 116, 130, 185 and 210 minutes. The moment of the first burying movements of individuals was registered.

The eventual burying depth was recorded by measuring the length of the thread above the sediment surface. At the end of the experiment we took the bivalves out of the sediment. The basin was put on the top of the mudflat where we let the bivalves bury again. After 850 min (during which one high tide occurred) burying depth was measured again using the length of the labelled threads.

Laboratory work

Of each species 25 individuals were collected and stored in 70% alcohol. At the Netherlands Institute for Sea Research (NIOZ) the individuals representing a

Plate 8.1: Morphological adaptations of selected bivalves
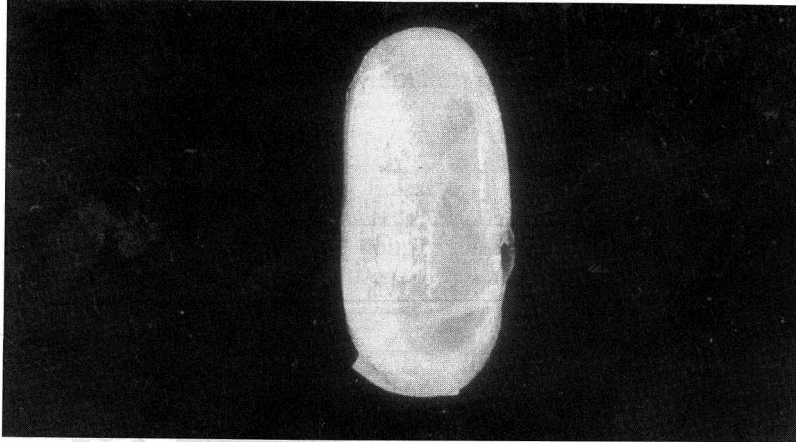
Three bivalve species that represent a range of morphological possibilities. From top to bottom: the thin-shelled, slender *Siliqua* cf. *winteriana*, the flat, round, but robust *Tellina piratica*, and the thick-shelled and round *Anomalocardia squamosa*. Photographs by Bert Aggenbach.

range in shell lengths were dissected and analysed for mass composition. Firstly we determined shell length, shell height and shell width, measured with vernier-calipers to the nearest 0.1 mm. Subsequently the foot and the inhalent siphon of the animals were dissected out, and dried with the separated shell and remaining flesh to constant mass in an oven at 60°C. This yielded the dry mass (DM_{sh}) of shells. Incineration in a furnace at 550°C of the other parts yielded the ash-free dry mass of the foot ($AFDM_{ft}$), the inhalent siphon ($AFDM_{sip}$), and the remainder of body ($AFDM_{meat}$).

Table 8.1: Composition of three bivalves with divergent survival strategies. For the three bivalve species the percentages of the total AFDM of the foot and the siphon of the total body mass are given with SD in brackets. The shell/ body mass ratio is the dry shell mass/ ash free dry mass of the body.

	n	perc. foot	perc. siphon	shell/body mass
Siliqua cf. *winteriana*	24	33.0 (4.7)	7.9 (2.1)	1.7 (0.9)
Tellina piratica	19	16.4 (4.1)	6.6 (3.4)	14.5 (2.4)
Anadara squamosa	15	28.8 (8.1)	5.8 (1.9)	26.7 (7.1)

Results

Siliqua buried very rapidly, the first animals disappeared in the sediment within one minute (Fig. 8.1).
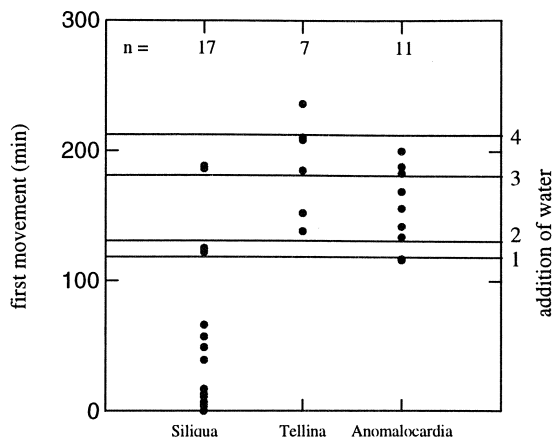
Fig. 8.1: Time to first movement of *Siliqua, Tellina* and *Anomalocardia*, when put on the surface of a sandy substrate.

Their burying behaviour is very powerful. The relatively big foot (Table 8.1) is stretched out of the shell and is used as an anchor, which is thrown out in the sediment. With a powerful jumping movement, the shell changes from a horizontal into a vertical position, and disappears within seconds shock wise in the sediment. In fact, in the laboratory the animals sometimes 'jumped' through the petri-dish. *Anomalocardia* was the next in burying speed, although we needed to add fresh seawater to get the animals to bury themselves (Fig. 8.1). The animals buried steadily, without jumping movements. It took the fastest burrower two minutes to disappear in the sediment. The first *Tellina* only
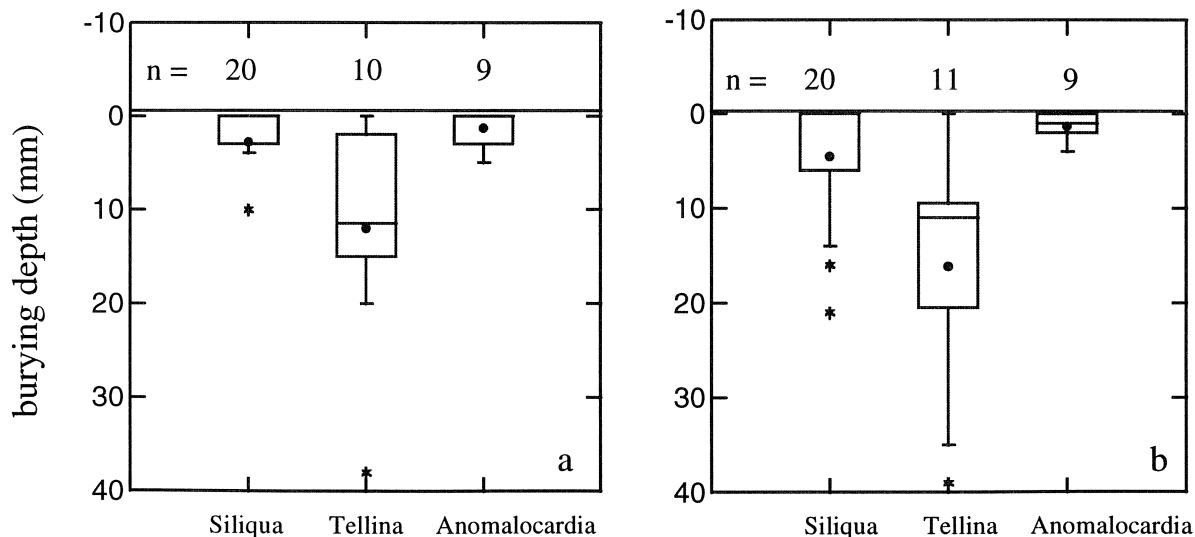
Fig. 8.2: Burying depth of *Siliqua* cf. *winteriana, Tellina piratica* and *Anomalocardia squamosa* 330 min (a) and 500 min (b) after being put on the surface of the sediment in the experimental setup. Note that more seawater was added between the first and second measurement. Presented as box-plots, with the box enclosing 50 % of the data points, and the vertical line representing the range. The midline of the box gives the median value, and the closed dot the average. The asterisks are outlying data points.

started to bury after water was added two times, but then it took the fastest burrower also two minutes to disappear in the sediment (Fig. 8.1). *Tellina* also buried steadily, without jumping movements.

The final burying depths in both parts of the experiment differed strongly. *Siliqua* buried in the first part on average 4.5 mm, while *Tellina* buried on average 16.2 mm, and *Anomalocardia* 1.5 mm (Fig 8.2). After the trial (850 minutes on the mudflats), the average burying depth of Siliqua and Tellina was about the same (Fig. 8.3).
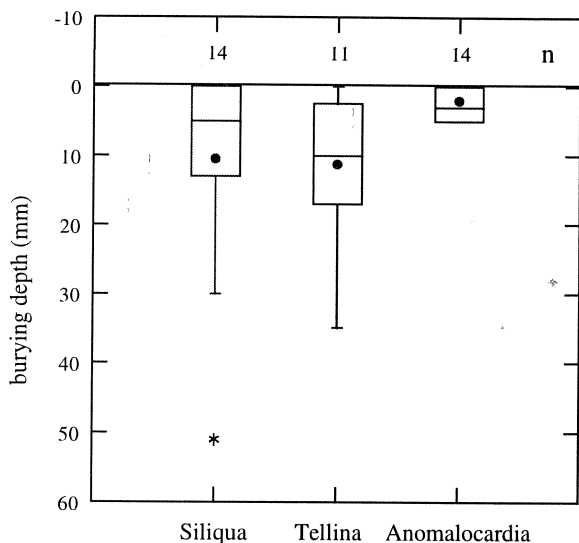
Fig. 8.3: Burying depth of *Siliqua* cf. *winteriana*, *Tellina piratica* and *Anomalocardia squamosa* 850 min (including a high tide period) after being put on the surface of the sediment for a second time. See captions of Fig. 8.2 for explanations on box-plots.

In Fig. 8.4 the size and body composition of the three bivalve species are given. The shell of *Siliqua* is very oblong compared to *Tellina* and *Anomalocardia*, which have almost the same length-width relationship (1). *Siliqua* and *Tellina* both have flattened shells, *Anomalocardia* is very round (2). *Siliqua* and *Tellina* have almost the same shell length-body mass relationship, but for the same shell length *Anomalocardia* has a higher body mass (3). In all three species, siphon mass increases with body mass (4). The variation in siphon mass is highest in *Tellina*. In all three species foot mass also increases with body mass (5).

The foot of *Siliqua* and *Anomalocardia* constitutes a big part of the body mass, but the shell/body mass ratio in *Siliqua* is much lower than in *Anomalocardia* (Table 8.1). *Anomalocardia* has to drag much more shell with it. It is a known phenomena that thick shelled bivalves are slow and shallow burrowers (Stanley 1970).

The foot is relatively smallest in *Tellina*. The shell/body mass ratio is lower than that of *Anomalocardia* but much higher than that of *Siliqua*. *Tellina* has very long thin siphons which enables them living at deeper depths.

Discussion

Three aspects of the methodology need discussion. First of all one type of sediment was used in the experimental basin. The choice was between the use of three different sediment types with the error of non-standardized methods, or one sediment type, one that would be unfamiliar to the species. The sediment which was used had a silt content which was intermediate between the locations where the bivalves were taken from. The second fact was that although I had saturated the sediment with water, I had to add water a few times to activate the burying of especially *Tellina* and *Anomalocardia*. The third experimental 'artefact' is the fact that I analyzed the bivalves in the laboratory after they had been stored in alcohol for some time. Although the relative mass values should be accurate, the absolute mass values would represent slight underestimates because part of the mass would have gone into solution.

High-relief sculptures, like knobs and spines on the shells are effective against predators. The three species I studied did not have such features, as is usual in burying bivalves. Burying bivalves have to rely on other anti-predator features. Burying speed is one of these features. Other features are shell shape and shell thickness (Stanley 1970).

Siliqua seem the ideal prey for knots. The oblong shape of the shell makes that they are easy to swallow. Red Knots *Calidris canutus rogersi* can swallow *Siliqua* with a length up to 29 mm and Great Knots *Calidris tenuirostris* up to 36 mm (Tulp & de Goeij, 1994). This includes all sizes used in this study. The shell/body mass ratio is very favourable; it does not cost a knot much energy to crush the shells in the stomach. The only disadvantage is that *Siliqua* bury very rapidly and can bury deep (up to 60 mm; Tulp & de Goeij 1994). In 1991 it was noticed that the knots followed the tideline with the outgoing tide. It seems likely that *Siliqua* live shallow during high tide to feed, but bury deeper with the outgoing tide to escape heat stress and/or desiccation . When they bury deeper they are more difficult to reach by the knots. So to reach the *Siliqua* knots have to follow the tideline! Red Knots can reach shells which are buried shallower than 35 mm and Great Knots can reach them when they are not buried deeper than 44 mm.
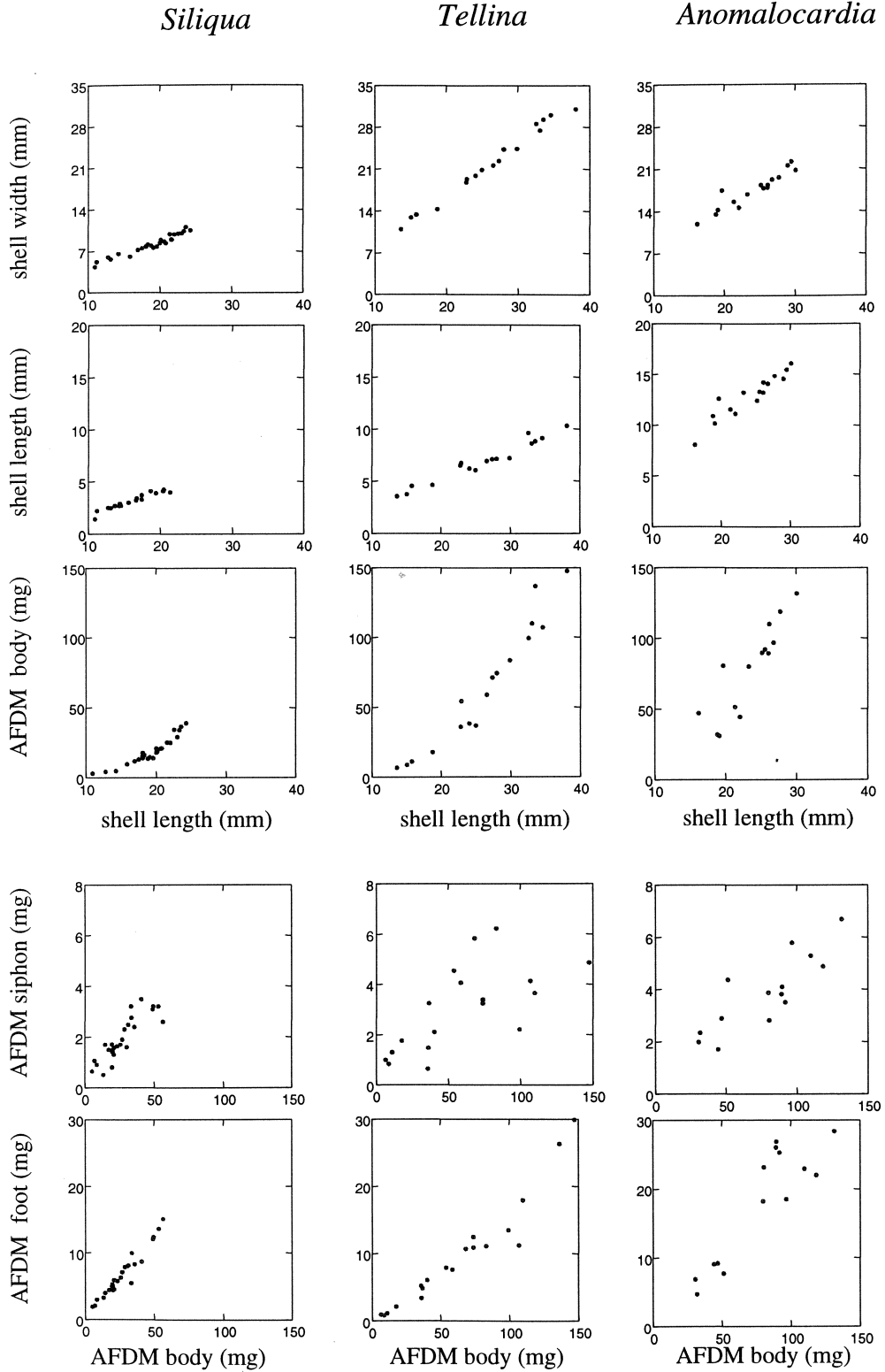
Fig. 8.4: Size and compositional relationships in *Siliqua* cf. *winteriana*, *Tellina piratica* and *Anomalocardia squamosa*. The numbers 1 to 5 in the text refer to the rows of graphs from top to bottom.

Tellina have thinner shells than *Anomalocardia*. Knots can swallow larger sizes (max. 19 mm for Red Knot and 24 mm for Great Knot) than of *Anomalocardia* because of the flattened shape. But with their long siphons *Tellina* can live very deep (up to 60 mm; Tulp & de Goeij,1994) and part of the population is therefore not available.

Due to their round shape only the small *Anomalocardia* can be swallowed by knots. Maximum shell lengths that can be swallowed are 15 mm (Red Knot) and 18 mm (Great Knot). Only very small *Anomalocardia* can be ingested. *Anomalocardia* are always available in the upper few centimeters of the sediment. However, the very small ones were rare and shell thickness makes them less attractive; it will cost a lot of energy to crush the shell in the stomach.

The average final burying depths in the experiments do not seem to give a realistic average when compared with the field data of 1991 (Tulp & de Goeij, 1994). Maximum burying depths probably give a better idea about the escape-chances for the different bivalves. By looking at burying speed, depth and morphology, it must be possible to do a prediction about the profitability (intake rate/ handling time) of different prey for predators like knots. To get better predictions, and to test the hypothesis that knots follow the tideline because of the rapid burying of *Siliqua* we want to continue this work in Roebuck Bay in March 2000. Following the knots on the mudflats in detail and following the burying behaviour of the most abundant bivalves in the field as well in the laboratory, we hope that it is possible to understand the behaviour of the predators through the behaviour of the prey.

Bird roost in the north-eastern parts of Roebuck Bay at high tide. Photograph by Marc Lavaleye.

9 WHAT DETERMINES SHOREBIRD FEEDING DISTRIBUTION IN ROEBUCK BAY?

Danny I. Rogers

Abstract

The foraging distribution of shorebirds on the northern intertidal flats of Roebuck Bay in October 1997 was mapped on a 200 m grid congruent with a 200 m grid that had been used to map benthos in June 1997. This report describes the mapping method used and summarises the intertidal distributions of the 35 bird species that were found feeding in reasonable numbers in the intertidal zone of Roebuck Bay. These birds were classified into seven guilds on the basis of their prey choice and method of foraging (arranged in order of abundance): (1) Tactile hunters of macrobenthos, feeding mainly in sea-edge flocks; (2) Tactile hunters of microbenthos, most of which fed along sandy sea-edges or near tidal creeks; (3) Visual hunters of slow, surface-dwelling prey, mostly feeding in 'closed' habitats such as reefs or mangrove fringes; (4) Visual hunters of small fast prey, mainly occurring in the sandier western parts of Roebuck Bay, often nearshore; (5) Visual hunters of fast large prey, most species occurring in the soft flats in the north-east of Roebuck Bay; (6) Kleptoparasites (Gull-billed Tern); (7) Pelagic hunters of nekton and neuston, mainly associated with creeklines in the east of Roebuck Bay which were south of the study area.

The distribution of most species of shorebirds was compared with the distribution of their preferred prey. On the basis of these comparisons I make the first attempt to identify the key intertidal areas for shorebirds in Roebuck Bay. Distribution of preferred prey did not explain foraging distribution of shorebirds perfectly, and in some cases did not explain it at all. These discrepancies suggest directions for further shorebird research in Roebuck Bay, including collection of more identification on the prey choice of shorebirds and investigating the role of roost location and prey behaviour in determining the foraging distribution of shorebirds.

Introduction

Roebuck Bay is one of the most important non-breeding grounds for migratory shorebirds in the East Asian-Australasian Flyway. This was not realised until the early 1980's, when high tide surveys showed the waders of Roebuck Bay to be both numerous and diverse: over 190,000 shorebirds of at least 35 species are estimated to occur there (Watkins 1993, Collins 1995) in addition to large populations of terns and other waterbirds. Roebuck Bay supports more than 1% of the East Asian-Australasian Flyway population of twenty species of shorebird and is considered internationally significant to their conservation (Watkins 1993).

Shorebirds have been counted and banded at Roebuck Bay since 1981 but only one study of shorebird ecology in its intertidal area has been done (Tulp & de Goeij 1993). Although it is clear that the intertidal flats of Roebuck Bay are crucial as feeding areas, virtually nothing is known of shorebird feeding distribution, how the 35 shorebird species of the bay divide resources between themselves, and whether some areas of the flats are more important than others. Without answering basic questions of this kind it is impossible to identify the key areas of the bay requiring most conservation attention, let alone to address more sophisticated questions such as whether shorebirds regulate numbers of various benthic species, or what the shorebird carrying-capacity of Roebuck Bay might be.

ROEBIM '97 has provided a beautiful background database on benthos distribution against which shorebird foraging distribution can be compared. In October 1997, while the ROEBIM'97 database was still 'fresh', I mapped shorebird distribution on the northern part of the intertidal flats using the 200 m grid previously used to map the benthos. In this report I describe the mapping method used and identify several distinct shorebird foraging guilds that feed on the intertidal flats of Roebuck Bay. The observed distributions of foraging shorebirds are described in a series of species accounts and distribution maps. These are compared

with the ROEBIM '97 dataset on the distributions of preferred prey of each shorebird species. On the basis of these comparisons I make the first attempt to identify the key intertidal areas for each foraging guild, and suggest directions for further research on the determinants of shorebirds distribution in Roebuck Bay.

Methods

Why map shorebird distribution in October?

At first glance, it may seem that the best time to map shorebird distribution in Roebuck Bay would have been during the course of the ROEBIM '97 expedition. This was not actually the case, for two reasons. For a start, we were simply too busy. Secondly, the ROEBIM '97 expedition was held in July, a period when adult migratory shorebirds are breeding in the northern hemisphere and numbers in Roebuck Bay are accordingly low.

A banding expedition to North-west Australia in 1998 confirmed that the return of migrating shorebirds to Roebuck Bay is a rather staggered event. Species such as Eastern Curlew and Greater Sand Plover, which nest on the steppes and grasslands of far northern China, Mongolia and southern Siberia, return much earlier than Arctic-breeding species such as Great and Red Knots. Even within species there is much variation in arrival times: birds which fail in their breeding attempts return earlier than adults that raise chicks, in many species there is a sexual difference in timing of southern migration, and juveniles typically arrive in Australia long after the adults. By October, when the shorebird mapping was performed, all shorebirds had probably arrived except for some juveniles; further it is thought that any passage migration through north-west Australia is largely complete by October (C.D.T. Minton, D.I. Rogers, unpubl.). Accordingly the great majority of shorebirds mapped in October were birds that had settled on Roebuck Bay as the site they planned to use for the non-breeding season. Moult and other banding data suggests that the majority of adult migratory shorebirds in Roebuck Bay in October have been there for at least a month, and one would therefore expect they had time to locate their favoured feeding areas.

The shorebird mapping method

Mapping was restricted to the northern parts of Roebuck Bay, which had been surveyed on a 200m grid during ROEBIM '97. The eastern and southern parts of Roebuck Bay (mapped on a 500m grid during ROEBIM '97) were too remote to be reached safely by a single worker on foot. The mapping method was based around the 200 m grid used on ROEBIM '97;

each ROEBIM sampling point was treated as the centre of a 200 m square in which shorebird numbers were counted.

A problem was posed by the fact that shorebirds are relatively mobile; they fly more readily than your average tubeworm and can move quickly around the intertidal flats in response to disturbance and changes in tide level. To some extent it was possible to control for these effects by mapping shorebird distribution in a series of transects performed in systematic fashion. Each transect was started after the high tide had ebbed sufficiently to expose 200–400 m of mudflats. I would walk due south across the flats - usually straight towards the sea, as I was mapping off an east-west coastline. At 200 m intervals I would stop at an observation point (located by handheld GPS) to record data; observation points were 200 m apart, and each lay 100m due west of a ROEBIM '97 sampling point, 100 m due east of another.

From each observation point, I would record shorebird numbers in four grid-squares: the one lying immediately to my west (0–200 m away), the one to the west of that (200–400 m away), and the two 'mirror-squares' to my east. The main reason for locating the observation points thus relative to the grid-squares was that it enabled me to walk between observation points without passing through the middle of grid-squares and scaring shorebirds away before they had been counted. Transects were timed so that I reached the sea-edge at the slack-water period of low tide. After recording data from the sea-edge grids, I quickly made my way 800 m to the east or west and started another transect, this time walking north from the sea-edge towards the coast on a rising tide. As with the transect made on the ebbing tide, shorebirds in the sea-edge grids were counted during the slack-water period at low tide. In general I walked into the sea to avoid disturbing birds in the sea-edge quadrats while moving from one transect to the next. My enthusiasm for this lengthy paddle in the sea diminished after several encounters with stingrays, jellyfish and puzzled fishermen in small boats.

For each grid-square I recorded the number of each bird species on the ground or wading in the sea, the time at which observations were made and the distance between my observation point and the sea-edge. Birds in flight were not recorded. Opportunistic notes were also taken on foraging behaviour and identified prey types; if the sea covered some of the grid-square the percentage left exposed was estimated, and if the count was affected by recent disturbance or by some of the search area being obscured (usually by rocks), this was also noted. Observations were made with Zeiss 10x40 dialyte binoculars and a Kowa TSN4 telescope with 20x and 40x eyepieces. In good light,

identification of shorebird species between 0–400 m away was straightforward. An inconvenience at Roebuck Bay is that during spring tides, low tides occured at dawn and dusk. This sometimes led to counting being performed in poor light conditions in which it was only possible to record the number of large and small shorebirds, and failing light sometimes led to counts being skipped for some grid-squares.

In effect, this sampling method was a rolling survey, with the most firmly fixed points relative to the tide being those at the sea-edge, which were always counted when the tide was at its lowest. For most of the survey area, shorebird distribution was mapped once on a spring low tide and once on a neap low tide. in the extensive and very soft north-eastern flats of Roebuck Bay (near Crab Creek) it was only possible to get to the sea-edge on foot during neapy tides - and even that involved extremely strenuous mudbashing in high temperatures. An attempt to get to the sea-edge using the hovercraft during a spring tide was of limited

success (see Box 9.1). The coverage managed is summarised in figure 9.1, which also shows the geographical locations referred to in the text.

In this report, distribution of the most commonly seen shorebirds is summarised in maps, which present the square root of the number of individuals in each grid-square; the size of the dots in the maps is thus proportional to the number of birds seen. All maps presented depict the distribution on spring tides for transects 1–6 and on rather neapy tides for transects 7–9 (see figure 2 for details of date and tide height of each transect). Similar data on neap tide distribution in transects 1–6 were also collected; maps for these neap tides are not presented, but the text mentions places where neap distribution differed strikingly from spring distribution.

Judging distances on the flats
Locating the boundaries of the shorebird grids on the flats of Roebuck Bay was problematic. In theory it

Box 9.1: Different perspectives on mudflats.

Different perspectives on mudflats

I've been asked to report on my attempts to get a different perspective on the mudflats of Roebuck Bay. Well, I've seen them from the underside of a moving hovercraft, so I guess everything is going to plan... What happened is this.

Broome Bird Observatory has a small hovercraft. It takes two small people, or one big one; travels quickly and smoothly over expanses of glutinous mud that take days to walk through; makes an awful noise but strangely enough, hardly scares birds at all. Dangerous? Not a bit of it. It was used for a couple of hundred hours during Roebim '97, and not a single person was killed.

I needed the machine in October to map wader distributions at low tide in some of the inaccessible parts of Roebuck Bay. Chris and Jan, the wardens of BBO, were very helpful here. In retrospect some of their actions may have been odd - they insisted that I took a mobile phone with me whenever I took the machine out, asked for details of my next of kin and so on. They also found me a pilot, Rob, and with his help we sorted out various maintenance problems. Apparently it isn't supposed to have fuel of similar colour and viscosity to vegemite.

All prepared, Rob and I headed out onto the flats. After ten minutes, we were some 6 km from where we started, out on the sea-edge at a point I could only reach otherwise with a three-hour walk (and from which I could only normally return by swimming). The hovercraft was going briskly and sideways (it isn't easy to steer in a strong breeze). Suddenly it gave a mighty lurch. Rob was holding on the handlebars and stayed in the craft. I had nothing to hang on to, so out I flew - landing in the path of the hovercraft, which went right over me. Seconds later I was on my feet again, completely unscathed; there was a neat Rogers-mould in the mudflats and Rob was wringing his hands and saying "whatever you do, don't tell Jan". In fact it wasn't his fault at all - the hovercraft had spontaneously developed a large tear in the skirt and the wind had caught under this. If Rob hadn't quickly gone to full throttle when I got thrown out, the hovercraft would probably have ground over me rather painfully instead of gliding over the top.

On the whole it was an instructive experience. There are rumours that hovercrafts crush lots of invertebrates but I no longer believe this; if they don't harm a person when they go over the top, the tough benthic inhabitants of the mudflats are probably immune to hovercraft damage. I've also developed a new theory about what the waders of Roebuck Bay eat - mud! It is a bit salty with a dash of hydrogen sulphide, but it must be nutritious. I only swallowed a mouthful, but I wasn't hungry for hours afterwards.

Sorry, I digress. Since the accident had happened in the area I had been aiming at anyway, I did an hour of mapping - the sea-edge is most exciting part of the mudflats when it comes to watching waders feed. We nursed the damaged hovercraft back to the launching point, and while Rob guarded the machine, I walked back to the observatory to fetch the trailer. Jan saw me, and took note of my mud-caked whole. "Hi Danny", she said. "You're looking very muddy. Did Rob run you over?" "Yes, he did", I replied.
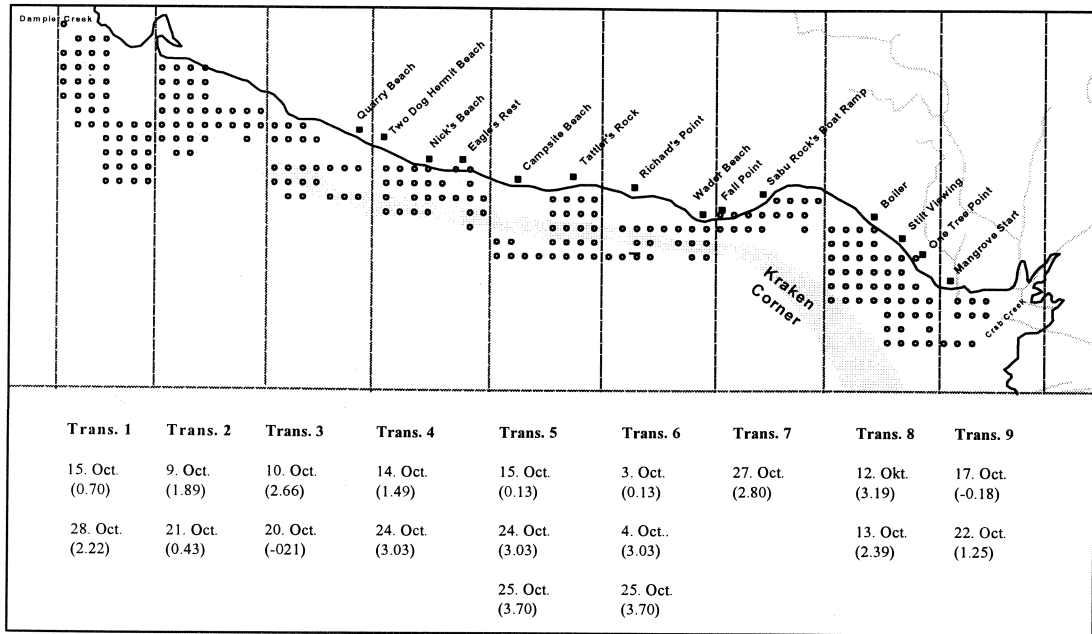
Trans. 1	Trans. 2	Trans. 3	Trans. 4	Trans. 5	Trans. 6	Trans. 7	Trans. 8	Trans. 9
15. Oct. (0.70)	9. Oct. (1.89)	10. Oct. (2.66)	14. Oct. (1.49)	15. Oct. (0.13)	3. Oct. (0.13)	27. Oct. (2.80)	12. Okt. (3.19)	17. Oct. (-0.18)
28. Oct. (2.22)	21. Oct. (0.43)	20. Oct. (-021)	24. Oct. (3.03)	24. Oct. (3.03)	4. Oct.. (3.03)		13. Oct. (2.39)	22. Oct. (1.25)
				25. Oct. (3.70)	25. Oct. (3.70)			

Fig. 9.1: Map showing the coverage of shorebird mapping transects, the dates and tidal heights when the mapping was performed and the positions of the main high tide roosts.

would be best to physically mark all quadrats, but that approach is extremely difficult on Roebuck Bay - the huge tides can dislodge pegs smaller than a star-picket, and if I had somehow found the time to plant 1000 or so star-pickets on the flats they would probably have been illegal, and would certainly have been a hazard to small fishing boats. Instead, I used an optical method to judge the distances between myself (location pinpointed with GPS) and the birds I was watching, and used these distances to work out which grid-square each bird was in.

Distances were measured with the technique described by Heinemann (1981). The method requires:
1. A flat study site
2. A set of callipers (my $3 set of plastic callipers were fine)
3. A piece of string.
The basis of the method is the formula:

$$c = \frac{bh(v - d)}{h^2 + vd}$$

where:

c = The reading obtained on the callipers (in m) when they are held at arms length with the upper jaw fixed on the horizon, the lower jaw fixed on the bird or landmark for which a distance-measurement is required.

b = the distance (in m) from the eye to the callipers (i.e. essentially arms length). In my case, that is 0.69m. To keep this distance consistent, I used a piece of string: one end was tied to the callipers, and at the other end there was a knot which I held in my teeth.

h = The height of the observers eye above the ground. In my case, that is about 1.6m (allowing for the fact that I'm usually ankle-deep in mud when in the field).

v = 3838 x $h^{0.5}$. This is the distance to the observers visual horizon (the constant includes corrections for curvature of the earth and refraction of light). In my case, my visual horizon at Broome comes out as 4855 m.

d = the distance, in metres, to the bird or landmark for which a distance-measurement is required.

The method works best for observers who happen to be more than 3 metres tall. For my purposes, it was reasonably accurate for objects less than 300m away, not so good for more distant things (tests on the repeatability of the method were performed on Roebuck Plains). It is quite likely that occasional errors were made as a result of this uncertainty, and because the readings obtained on a hand-held GPS are only accurate to about 30–50 m. Range-finding binoculars judge distances more accurately but such devices are expensive (c. $8000 for a high-quality, laser-based set). Nevertheless I do not consider the errors I made very serious, as there is unlikely to have been any system-

atic bias to my mistakes, and because there was little room for huge errors. Any misclassified birds were probably in a grid-square adjacent to the real one, a rather small error given the large distance shorebirds can cover while feeding.

Identification of preferred prey.
I originally started this work with the intention of finding the correlations between the distribution of each shorebird species with the benthos, expecting the most powerful correlations to occur with the benthic species that are preferred as prey. It didn't take me long to decide this approach was flawed, in large part because of the high benthic diversity in Roebuck Bay: significant correlations can be found between many hundreds of combinations of shorebird species and benthic species, but in isolation they tell one nothing about causality.

As the above method did not look promising, I approached the problem from the opposite angle: identifying the preferred prey of each bird species, and comparing the distribution of the preferred prey with that of the birds. At times this approach hardly seemed any better, mainly because so little is known about the prey choice of shorebirds in Roebuck Bay. Quantitative studies on the prey of shorebirds in Roebuck Bay have only been performed on two species, Great Knot and Red Knot (Tulp & de Goeij 1994; D.I. Rogers in progress). For other species it was generally necessary to rely on my own (qualitative) field experience, and published literature on their diet (usually from studies performed outside the tropics). In addition to identifying the species (or families) of benthos most likely to be preferred, I attempted (usually unsuccessfully) to assess the size limits of prey that could be taken profitably: shorebird prey choice is strongly size-dependent, with some potential prey being unavailable because it is simply too large to be swallowed or digested, and other prey being unprofitable because it is so small that it provides less energy when digested than was expended while it was being located (e.g. Zwarts & Wanink 1993). I assumed for all bird species that they did not eat two of the more common benthic animals in Roebuck Bay: "Ingrid Snails" (Nassariidae) and the green, surface-dwelling worms of the family Phyllodocidae. Both are abundant on the mud surface of Roebuck Bay and make no attempt to conceal themselves when potential predators approach. They would be easy to identify in a shorebirds bill if they were taken as prey, Phyllodocidae as they are bright green, Nassariidae as they poke their heads out of their shells and sway them around if picked up. I have only once seen a shorebird eat either (the one exception was a juvenile Great Knot trying an Ingrid Snail) and do not think they are a regular part of the diet of any

wader species; I strongly suspect them to be unpalatable or mildly poisonous. I also assumed that no bird species concentrated on tubeworms of the families Chaetopteridae and Oweniidae. Fewer data exist to back up this assumption but I suspect these worms are inaccessible to shorebirds while in their tubes; further, they are so brittle that a bird which did succeed in grabbing the head of a feeding Chaetopterid or Oweniid would probably end up with only a tiny fragment of ingestible worm, unlikely to be profitable as prey (except maybe for the smallest waders). Further, shorebirds rarely waded into the sea to forage and I suspect this would be the best way to catch feeding tubeworms. None of these arguments is conclusive proof that shorebirds do not eat tubeworms. It was nevertheless a convenient assumption to make, as Chaetopteridae and Oweniidae are so abundant in Roebuck Bay that when included, they swamped estimates of abundance of prey. The basis for all other decisions made about preferred prey is summarised in the respective bird species accounts.

Density of preferred prey is summarised in distribution maps. The number of individual benthic animals was not a sound currency in which to express this information, as this approach would give equal value to each animal, whether it was a fine meaty bivalve or a puny worm that provided almost no energy to a foraging wader. Accordingly the abundance of prey was expressed in terms of ash-free dry mass (AFDM) per ROEBIM sample (mg). Chapter 7 describes the procedures used to calculate AFDM.

The resultant maps of distribution of preferred prey are obviously crude, with much guesswork going into the assessment of the prey types preferred by each shorebird, and into the assessments of prey biomass. The maps should be seen merely as models of where prey is likely to occur in highest densities. Comparisons of these models with the observed feeding distributions of shorebirds may in fact shed more light on where the gaps of our knowledge of prey choice lie than they do on the ultimate causes of shorebird foraging distribution in Roebuck Bay.

Results

Fifty bird species were seen and mapped on the intertidal flats of Roebuck Bay. Eleven of these species fed at sea, only using the flats as a place to roost, and these are not considered further here; nor is much thought given to five species which were seen too infrequently to allow even brief descriptions of their ecology.

To ease discussion of the remaining 34 species, I have classified birds of the intertidal flats of Roebuck Bay into guilds; a similar approach was used on wet-

lands in Ghana by Piersma & Ntiamoa-Baidu (1995). Guilds are defined as groups of species exploiting a common resource in a similar fashion (Root 1976). The following classification was performed *a posteriori* on the basis of observations of foraging behaviour, identified prey types and the sensory mechanism used to locate prey:

Guild 1: Tactile macrobenthos hunters
All these species feed to a large extent by 'blind' probing for prey items that they cannot actually see - though the tactile and olfactory mechanisms used to locate prey by at least some of these species are extremely sophisticated, and their choice of where to stick their beaks is far from uninformed (see Gerritsen *et al.* 1983; Gerritsen & Meijboom 1986; Piersma *et al.* 1998). This guild comprises Great Knot, Red Knot, Bar-tailed Godwit, Black-tailed Godwit and Asian Dowitcher.

Guild 2: Tactile 'microbenthos' hunters
Again, these species feed to a large extent by 'blind' probing for prey items that they probably cannot see. All these species ate extremely small prey items; it is not certain that their prey was microscopic, but their prey could taken in without opening their bills wide or lifting them from the mud and it was certainly too small for me to identify it in the field. Rubega & Obst (1993) and Rubega (1997) have described a feeding mechanism in fine-billed shorebirds which allows them to rapidly move tiny prey from bill-tip to mouth in water droplets held together and transported by surface-tension. The species identified as part of this guild - Curlew Sandpiper, Red-necked Stint, Broad-billed Sandpiper, Marsh Sandpiper and Sharp-tailed Sandpiper - all appeared to use this feeding mechanism frequently.

Guild 3: Visual surface-foragers: hunters of slow-moving prey
The species identified as part of this guild - Common Sandpiper, Sooty Oystercatcher, Pied Oystercatcher, Silver Gull and Ruddy Turnstone - forage by sight on prey which does not need much chasing; the challenge appears to lie more in detection. Of the birds in this guild, only the Silver Gull was restricted to the open flats; others often made use of more 'closed' habitats such as rocky reefs and mangroves. This is the most weakly defined of the shorebird guilds identified in Roebuck Bay and it is possible that some of the species will be re-assigned when a better understanding of their prey choice is attained.

Guild 4: Visual surface-foragers: hunters of small prey
All these species hunt small surface-dwelling prey (especially crabs and shrimps), and generally employ a stand-run-peck mode of foraging. The guild comprises Grey, Red-capped, Greater Sand and Lesser Sand Plovers, Grey-tailed Tattler and Terek Sandpiper.

Guild 5: Visual surface-foragers: hunters of large burrowing prey
The division between this guild and guild 4 (visual surface-foragers: hunters of small prey) may seem rather artificial. I consider the split justified as all species in this guild concentrate on large prey inaccessible to other shorebirds of Roebuck Bay. The prey taken (typically crabs, mudskippers and mantis shrimps) is probably large and strong enough to cause injury if handled incautiously and requires a rather lengthy handling time (making the birds susceptible to kleptoparasitism). Birds in this guild include Black-necked Stork, Eastern Curlew, Whimbrel, Greenshank and Striated Heron (other heron species in Roebuck Bay sometimes feed in this manner too, but seem to spend more of their time in water, hunting swimming prey).

Guild 6: Kleptoparasites
Only one bird species seems to be a habitual kleptoparasite on the flats of Roebuck Bay: the Gull-billed Tern, which robs large crabs from Whimbrels.

Guild 7: Pelagic hunters of nekton and neuston
The following species were seen in mapped quadrats, usually hunting swimming prey while wading in creeks or on the sea-edge: Reef Egret, Little Egret, Great White Egret, White-faced Heron, Royal Spoonbill, Black-winged Stilt and Red-necked Avocet.

Tide-related movements

High-tide distribution
At high tide, shorebirds are unable to feed on the inundated intertidal flats of Roebuck Bay, and move to beaches and other sites where they roost. Roosting birds on the northern beaches of Roebuck Bay have been watched (and counted and banded) regularly since the early 1980's by Broome Bird Observatory and AWSG expeditions. Specific roost choice on the northern beaches has varied a good deal in this time, perhaps partly as a result of disturbance; in some years one small beach will regularly hold large numbers of waders and in other years it will hardly be used at all. Despite these fluctuations, it is felt that there are specific patterns to where birds roost; for example Bar-tailed Godwits and the two species of Knot show a

preference for wide beaches, most of which occur in the north-east of Roebuck Bay; small waders such as Red-necked Stints and Red-capped Plovers are traditionally most numerous as Quarry Beach; Grey-tailed Tattlers, Ruddy Turnstones and Terek Sandpipers are characteristic of roosts on rock outcrops and enclosed beaches between Quarry Beach and Fall Point (pers. obs; C. Hassell, C.D.T. Minton pers. comm.).

It is obviously an advantage to a shorebird to roost close to its feeding grounds; this reduces the amount of energy it looses in flying between roost sites and feeding areas. This consideration may be more important to small waders, which in theory fly more slowly than large ones and consume a greater proportion of their reserves in covering the same distance (Alerstam 1993). Whether roost choice has an effect on the choice of feeding sites by shorebirds is debatable. I cannot rule the possibility out at Roebuck Bay, so in Table 9.1 I have presented my paltry data on high-tide roost choice of shorebirds in northern Roebuck Bay during October 1997. These data were collected opportunistically as I collected disturbance data at high tide, and as this was done from hides I could not always see the entire flock; absolute numbers of birds in Table 9.1 are probably underestimates in some cases but the data on flock composition should be sound.

Table 9.1: Species composition at high tide roosts.

Species	Quarry Beach		Nick's Beach		Wader Beach		Stilt Viewing		One-Tree Point	
	Avg. total	Avg.% of flock	Avg. total	Avg. % of flock	Avg total	Avg. % of flock	Avg. total	Avg. % of flock	Avg. total	Avg. % of flock
Bar-tailed Godwit	1281	26	130	22	503	22	670	63	2057	65
Great Knot	655	13	28	5	427	18	100	9	550	17
Red Knot	180	4	18	3	30	1	50	5	195	6
Black-tailed Godwit	0	0	0	0	141	6	5	0	370	12
Asian Dowitcher	0	0	1	0	2	0	0	0	0	0
Curlew Sandpiper	278	6	45	7	44	2	0	0	0	0
Red-necked Stint	1943	40	60	10	342	15	0	0	0	0
Broad-billed Sandpiper	0	0	0	0	2	0	0	0	0	0
Common Sandpiper	0	0	1	0	0	0	0	0	0	0
Ruddy Turnstone	2	0	63	10	2	0	2	0	0	0
Pied Oystercatcher	1	0	0	0	57	2	0	0	0	0
Grey Plover	5	0	25	4	10	0	190	18	0	0
Red-capped Plover	23	0	3	0	23	1	0	0	0	0
Greater Sand Plover	464	9	65	11	717	31	20	2	0	0
Lesser Sand Plover	4	0	1	0	6	0	0	0	0	0
Grey-tailed Tattler	6	0	155	26	2	0	0	0	0	0
Terek Sandpiper	8	0	8	1	7	0	22	2	0	0
Eastern Curlew	8	0	0	0	5	0	0	0	14	0
Whimbrel	1	0	4	1	0	0	0	0	0	0
Greenshank	44	1	0	0	0	0	0	0	0	0
SUM OF WADERS	4901	100	605	100	2318	100	1059	100	3186	100

The data in Table 9.1 were collected on tides between 5.8 and 8.3 m high. On lower high tides, birds do not usually roost on the northern beaches of Roebuck Bay; high mudbanks south of Crab Creek remain above the water and birds gather on those. On 11 Oct., I counted waders of this area from high ground on Fall Point, seeing a total of 35,700 shorebirds. On spring high tides, the northern beaches of Roebuck Bay are water-covered and most shorebirds fly to flooded saltflats behind the Crab Creek mangroves. A count performed from One-tree Point of shorebirds flying to the saltflats on 16 Oct. produced 29,000–33,800 waders, broadly similar to the total counted on neap tides. No complete count of shorebirds roosting on the northern beaches in October was performed, but Chris Hassell and I independently estimated that about 30,000 were regularly present. This compares with a total of 22,980 shorebirds mapped on the intertidal flats (using only spring-tide data for transects counted twice), suggesting that the roost sites of northern Roebuck Bay attract birds which feed in areas south of the area on which I mapped shorebird distribution.

Low-tide distribution

The area of intertidal flats available for feeding shorebirds in Roebuck Bay changes markedly with tide conditions. During spring low tides a large area is available (Fig. 4.1). During neap low tides the largest areas of exposed mudflats near the northern shores occur in the Kraken Corner between Broome Bird Observatory and Crab Creek. A reasonable area also remains exposed in the west on the sandy flats between Quarry Beach and Dampier Creek (although the overflow of Dampier Creek covers a large area) but the flats between Fall Point and Quarry Beach are largely inundated, becoming no more than 400 m wide.

Tulp and de Goeij (1994) found that feeding shorebirds in north-eastern Roebuck Bay occurred at higher densities during neap tides. Are shorebirds simply compressed into a smaller area, or do they undertake relatively lengthy movements in response to neaps? This is a difficult question to answer without a radio-tracking study (such a study is planned for 2000) but some light can be shed on the matter by comparing the spring tide and neap tide data on shorebird distribution collected in October. The shorebird totals obtained for the 6 shorebird transects performed on both a spring and neap tide are summarised in Table 9.2. These transects lie between Dampier Creek (transect 1) in the north-west of Roebuck Bay to Broome Bird Observatory (transect 6); unfortunately the extensive flats of the Kraken Corner could not be mapped on spring tides. The location of each transect is shown in Fig. 9. 1.

Table 9.2 shows that in general shorebirds occured at higher densities during neap tides. However the ab-

Table 9.2: Comarison of transect counts on spring and neap low tides. BARG = Bar-tailed Godwit, GKN = Great Knot, RKN = Red Knot, CS = Curlew Sandpiper, RNS = Red-necked Stint, SG = Silver Gull, RT = Ruddy Turnstone, GTT = Grey-tailed Tattler, GP = Grey Plover, RCP = Red-capped Plover, GSP = Greater Sand-Plover, TS = Terek Sandpiper, STRH = Striated Heron, WI = White Ibis, GANK = Greenshank, EC = Eastern Curlew, WHIM = Whimbrel, GBT = Gull-billed Tern, LE = Little Egret.

	S1	N1	N1/S1	S2	N2	N2/S2	S3	N3	N3/S3	S4	N4	N4/S4	S5	N5	N5/S5	S6	N6	N6/S6	Tot. S	Tot. N	N/S
BARG	225	49	22%	287	501	175%	236	268	114%	249	276	111%	557	238	43%	1484	420	28%	3038	1752	58%
GKN	333	58	17%	385	742	193%	208	434	209%	295	122	41%	139	69	50%	1461	324	22%	2821	1749	62%
RKN	56	7	13%	185	52	28%	62	138	223%	69	28	41%	40	30	75%	518	151	29%	930	406	44%
CS	120	33	28%	239	14	6%	82	334	407%	0	48	+	39	35	90%	48	259	540%	528	723	137%
RNS	254	101	40%	334	64	19%	286	708	248%	281	451	160%	457	512	112%	372	819	220%	1984	2655	134%
SG	45	2	4%	34	6	18%	2	6	300%	10	10	100%	375	0	0%	6	2	33%	472	26	6%
RT	60	23	38%	49	0	0%	23	12	52%	44	27	61%	41	12	29%	15	13	87%	232	87	38%
GTT	196	59	30%	125	72	58%	183	113	62%	139	145	104%	208	48	23%	77	87	113%	928	524	56%
GP	7	5	71%	16	5	31%	16	1	6%	9	4	44%	1	1	100%	11	6	55%	60	22	37%
RCP	5	6	120%	6	11	183%	20	19	95%	36	39	108%	3	1	33%	3	14	467%	73	90	123%
GSP	136	101	74%	130	101	78%	164	104	63%	69	56	81%	79	25	32%	135	28	21%	713	415	58%
TS	105	78	74%	55	17	31%	23	12	52%	6	12	200%	20	4	20%	7	2	29%	216	125	58%
STRH	5	4	80%	4	1	25%	1	0	0%	0	2	+	0	0	-	0	0	-	10	7	70%
WI	8	3	38%	6	1	17%	0	1	+	1	0	0%	0	1	+	1	2	200%	16	8	50%
GANK	34	5	15%	34	16	47%	15	24	160%	37	10	27%	33	5	15%	44	14	32%	197	74	38%
EC	10	4	40%	4	6	150%	0	0	-	1	6	600%	4	2	50%	13	0	0%	32	18	56%
WHIM	41	36	88%	39	56	144%	25	8	32%	26	10	38%	17	9	53%	61	8	13%	209	127	61%
GBT	7	2	29%	1	1	100%	0	0	-	1	0	0%	0	2	+	0	0	-	9	5	56%
LE	5	0	0%	0	1	+	0	1	+	5	4	80%	7	0	0%	0	0	-	17	6	35%
Others	197	10	5%	919	759	83%	64	118	184%	19	71	374%	298	5	2%	349	116	33%	1846	1079	58%
Total:	1849	586		2852	2426		1410	2301		1297	1321		2318	999		4605	2265		14331	9898	

solute number of shorebirds in many of the transects actually decreased during neap tides, suggesting that many birds were obliged to move to a completely different area of mud during neaps. The tendency for shorebird numbers to decrease was most clear in transects 1, 5 and 6, in which the area of exposed intertidal flats is most reduced during neaps. Tide related movements apparently differed between species. The large tactile-foraging shorebirds of Guild 1 showed a striking decrease in numbers during neap tides and were suspected to move to the large intertidal flats of the Kraken Corner. In contrast, the smaller tactile-foraging shorebirds of Guild 2 showed no such tendency and their numbers in the twice-mapped areas of northern Roebuck Bay may indeed have increased slightly during neaps. Likewise, in the visually-foraging guilds of shorebirds (Guilds 3–5) there is a suggestion that larger species such as Eastern Curlew, Whimbrel and Grey Plover were more apt to move elsewhere than small species such as Red-capped Plover.

Species Association

Species associations of the most common shorebird species on the intertidal flats of Roebuck Bay are summarised in Table 9.3. It shows shorebirds to be gregarious, most species co-occurring with others more often than would be expected if their distributions were random and independent. If the species within each foraging guild had a strong tendency to feed in the same places, a diagonal band would be expected across the species association matrix. In fact, such a trend is not particularly clear. The tactile foragers of large prey (Guild 1) show a strong tendency to feed together; this is not unexpected as all are sociable species with a strong tendency to feed in flocks near the sea-edge. The tactile foragers of smaller prey (Guild 2) are also sociable birds and also show rather strong species associations, both within the guild and with the tactile foragers of Guild 1. Within the guilds 3–5, comprising visually-foraging hunters of surface-dwelling prey, species associations are less often strong; even where species do show tendencies to feed in similar habitats, their relatively spaced distribution tends to obscure any patterns of species association. As would be expected, the foraging distribution of the kleptoparasitic Gull-billed Tern is closely correlated to that of the Whimbrels that they steal prey from.

Piersma *et al.* (1995) found the distribution of many shorebird species in a wetland complex in Ghana to overlap with that of the Greenshank and suggested that there may be a tendency for (roosting) shorebirds to associate with this notoriously wary spe-

cies as they act as good sentinels against disturbance. This trend may be hinted at the Geenshank data from Roebuck Bay, but the relationship is not clear, and there was no particular tendency for other shorebirds to associate with the even more wary Eastern Curlew.

Species accounts

Guild 1: Tactile macrobenthos hunters
The four commonest species in this guild all showed a strong tendency to follow the tide-edge, and typically fed in mixed flocks at the sea-edge (henceforth referred to as sea-edge flocks). Most birds in sea-edge flocks fed within 100 m of the sea, but few actually waded in it. In all of these species, tide-related movements appeared similar. As the tide receded they walked after it, occasionally catching up with it with a short leisurely flight in which they always remained very low (1–2m); this flight behaviour is easily identified, differing markedly from the towering flights they employ when disturbed. They also tried to walk ahead of the water as the tide rose, but were unable to keep this up for long, eventually undertaking an erratic flight to land in flocks several hundred metres from the sea. There seemed to be little pattern to where flocks settled to feed on rising tides, barring a tendency to stay well clear of humans or birds of prey. To some extent this behaviour prevents the distribution maps from fully reflecting the tide-following tendencies of these species, as birds mapped on rising tides could occur far from the sea-edge where they apparently preferred to feed. Nevertheless there were a few individuals which definitely did not follow the tide all the way out, perhaps because they had stumbled across profitable foraging patches which they were reluctant to leave.

Bar-tailed Godwit
Bar-tailed Godwits, the commonest shorebirds of Roebuck Bay, showed a strong tendency to follow the tide-edge (Fig. 9. 3). On transects performed on receding tides, about 80% of individuals mapped occurred in sea-edge flocks. The highest densities occurred on the muddy flats between Crab Creek and Fall Point; while also common on the sandy flats towards the western end of the bay they occurred in lower densities here and showed less of a tendency to form distinct sea-edge flocks. Although not documented thoroughly, in the field there appeared to be a tendency for the longer-billed females to feed closer to the sea-edge than males; a more detailed investigation of sexual selection of feeding areas would be worthwhile.

Table 9.3: Association of bird species. Each column presents the proportion of occasions that a particular species occurred in the same grid-square as a species in the left-hand column. Depth of shading indicates the significance of each association: darkest grey = combination where the probability of the observed co-occurrence was less than 5 %, lighter grey = combinations where this probability was between 5 and 10 % (working with the null hypothesis that bird distribution was random). Species within the thicker frames belong to the same guild.

| | GUILD 1 | | | | GUILD 2 | | | | GUILD 3 | | | |
	BARG	GKN	RKN	BLAG	CS	RNS	BBS	MS	SO	PO	SG	RT
BARG	1.00	0.89	0.88	1.00	0.86	0.84	0.88	0.87	1.00	0.95	0.85	0.82
GKN	0.63	1.00	0.87	0.57	0.70	0.71	0.88	0.78	1.00	0.70	0.54	0.63
RKN	0.37	0.52	1.00	0.29	0.51	0.45	0.75	0.48	0.50	0.55	0.35	0.44
BLAG	0.06	0.05	0.04	1.00	0.06	0.02	0.13	0.04	0.00	0.20	0.07	0.04
CS	0.43	0.49	0.59	0.50	1.00	0.58	0.75	0.61	1.00	0.50	0.57	0.53
RNS	0.54	0.65	0.68	0.21	0.76	1.00	1.00	0.78	0.75	0.50	0.57	0.65
BBS	0.03	0.04	0.06	0.07	0.05	0.05	1.00	0.04	0.25	0.15	0.04	0.03
MS	0.08	0.11	0.11	0.07	0.12	0.12	0.13	1.00	0.00	0.00	0.10	0.11
SO	0.02	0.02	0.02	0.00	0.03	0.02	0.13	0.00	1.00	0.05	0.01	0.02
PO	0.08	0.08	0.11	0.29	0.08	0.06	0.38	0.00	0.25	1.00	0.06	0.07
SG	0.24	0.22	0.24	0.36	0.33	0.25	0.38	0.30	0.25	0.20	1.00	0.29
RT	0.33	0.35	0.42	0.29	0.43	0.40	0.38	0.48	0.50	0.35	0.41	1.00
GTT	0.68	0.73	0.80	0.21	0.77	0.83	1.00	0.83	1.00	0.60	0.72	0.84
GP	0.15	0.16	0.22	0.21	0.19	0.17	0.38	0.13	0.25	0.10	0.24	0.15
RCP	0.21	0.22	0.24	0.14	0.25	0.29	0.50	0.09	0.50	0.40	0.18	0.28
GSP	0.70	0.71	0.77	0.36	0.75	0.79	0.88	0.91	0.50	0.75	0.68	0.73
LSP	0.08	0.10	0.10	0.07	0.13	0.13	0.50	0.17	0.50	0.35	0.06	0.11
TS	0.43	0.42	0.44	0.36	0.46	0.47	0.38	0.57	0.00	0.25	0.37	0.43
STRH	0.06	0.06	0.10	0.07	0.09	0.06	0.13	0.13	0.00	0.00	0.15	0.06
WI	0.07	0.05	0.08	0.21	0.08	0.05	0.13	0.09	0.50	0.05	0.15	0.07
GANK	0.54	0.61	0.61	0.57	0.64	0.63	0.75	0.96	0.50	0.70	0.57	0.64
EC	0.19	0.11	0.14	0.21	0.12	0.12	0.13	0.26	0.00	0.20	0.15	0.17
WHIM	0.55	0.52	0.62	0.50	0.44	0.50	0.38	0.70	0.50	0.60	0.47	0.53
GBT	0.10	0.05	0.10	0.36	0.09	0.06	0.00	0.09	0.00	0.00	0.13	0.14

| | GUILD 4 | | | | | | GUILD 5 | | | | WHIM | GUILD 6 |
	GTT	GP	RCP	GSP	LSP	TS	STRH	WI	GANK	EC.	WHIM	GBT
BARG	0.81	0.82	0.81	0.70	0.77	0.75	0.79	0.74	0.82	0.68	0.74	0.76
GKN	0.61	0.60	0.60	0.50	0.65	0.51	0.53	0.39	0.65	0.29	0.49	0.27
RKN	0.40	0.49	0.39	0.33	0.38	0.32	0.53	0.35	0.39	0.21	0.35	0.30
BLAG	0.01	0.07	0.03	0.02	0.04	0.04	0.05	0.13	0.05	0.05	0.04	0.15
CS	0.45	0.51	0.48	0.37	0.58	0.39	0.58	0.43	0.47	0.21	0.29	0.33
RNS	0.64	0.58	0.73	0.51	0.77	0.53	0.53	0.35	0.61	0.27	0.43	0.27
BBS	0.04	0.07	0.06	0.03	0.15	0.02	0.05	0.04	0.04	0.02	0.02	0.00
MS	0.09	0.07	0.03	0.09	0.15	0.09	0.16	0.09	0.14	0.09	0.09	0.06
SO	0.02	0.02	0.03	0.01	0.08	0.00	0.00	0.09	0.01	0.00	0.01	0.00
PO	0.06	0.04	0.13	0.06	0.27	0.04	0.00	0.04	0.09	0.06	0.07	0.00
SG	0.24	0.36	0.19	0.19	0.15	0.18	0.53	0.43	0.25	0.15	0.18	0.27
RT	0.40	0.31	0.44	0.29	0.42	0.30	0.32	0.30	0.39	0.24	0.28	0.39
GTT	1.00	0.78	0.76	0.66	0.73	0.71	0.63	0.61	0.70	0.45	0.62	0.33
GP	0.17	1.00	0.16	0.14	0.15	0.18	0.21	0.35	0.19	0.21	0.17	0.21
RCP	0.23	0.22	1.00	0.23	0.31	0.20	0.11	0.17	0.25	0.14	0.18	0.09
GSP	0.79	0.76	0.89	1.00	0.88	0.85	0.63	0.78	0.76	0.79	0.76	0.82
LSP	0.09	0.09	0.13	0.10	1.00	0.06	0.05	0.09	0.11	0.05	0.07	0.03
TS	0.49	0.56	0.45	0.49	0.31	1.00	0.63	0.65	0.46	0.56	0.49	0.55
STRH	0.06	0.09	0.03	0.05	0.04	0.09	1.00	0.09	0.06	0.08	0.06	0.15
WI	0.07	0.18	0.06	0.08	0.08	0.11	0.11	1.00	0.09	0.12	0.09	0.18
GANK	0.54	0.67	0.63	0.50	0.69	0.52	0.47	0.61	1.00	0.55	0.50	0.61
EC	0.15	0.31	0.15	0.22	0.12	0.27	0.26	0.35	0.23	1.00	0.29	0.58
WHIM	0.55	0.67	0.53	0.57	0.46	0.64	0.58	0.74	0.57	0.79	1.00	0.88
GBT	0.05	0.16	0.05	0.11	0.04	0.13	0.26	0.26	0.13	0.29	0.16	1.00

Bar-tailed Godwits took most of their prey by probing, often as deep as they could (80–120 mm); they were seen capturing large worms and bivalves by this method. Fig. 9. 2 also shows the distribution of their preferred prey; I have assumed for the purposes of this figure that they prefer:

- Any size of *Lingula* and thin-shelled bivalves: *Nucula, Cultellus, Siliqua, Tellina* (but not the rela-
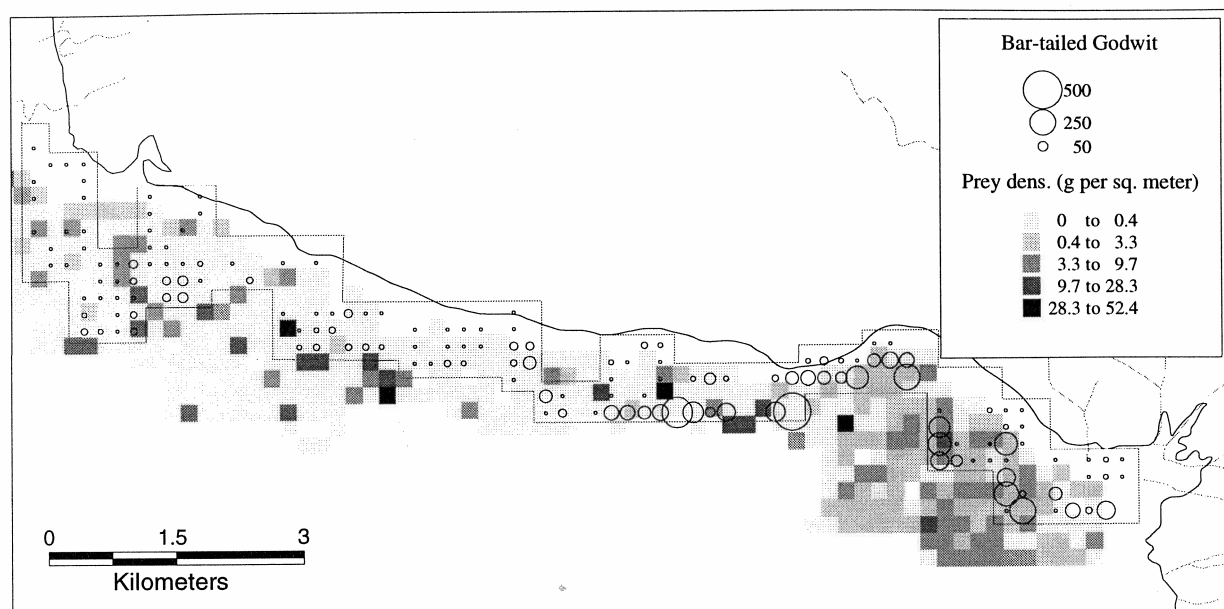
Fig. 9.2: Distribution map for Bar-tailed Godwit at spring tide and densities of the preferred prey items. Benthos samples covered a larger area than did the bird observations. The gray line in this and the following maps demarcates the area where bird counts were done.

tively hard-shelled *T. capsoides or T. piratica*), *Macoma* and *Ensis*.

• Large annelids, 50 mm or longer (but not Chaetopteridae, Oweniidae or Phyllodocidae).

On first glance, the distributions of Bar-tailed Godwits and their prey seem to have little in common. The prey shows no strong increase in abundance towards the sea-edge, though there may be a weak tendency in this direction. The strong tendency of Bar-tailed Godwits to follow the sea-edge probably has another cause; I suspect it is because prey is more easily detected near the sea-edge. Both Bar-tailed Godwits and their prey appear to be more common in the Eastern end of Roebuck Bay, though the relationship is far from perfect. This might be a result of the crude guesses made about what their preferred prey is; a more detailed breakdown (by species) would be well worth attempting if there was more detailed information about their prey choice. Another possibility worth investigating is that given similar prey availability in both ends of Roebuck Bay, Bar-tailed Godwits prefer the muddy substrates of the east where deep probing is easier.

Great Knot
Foraging distribution of Great Knots was similar to that of Bar-tailed Godwits; they followed the tide-edge closely and greatest densities occurred on the muddy flats from Crab Creek to (especially) Fall Point (Fig. 9.

3). Great Knots tended to feed in tighter flocks than Bar-tailed Godwits. A couple of days were spent watching their foraging behaviour off Fall Point, where Great Knots were most abundant; the birds here were feeding on small bivalves (see notes for Red Knot). Bivalves (sometimes large) formed a considerable part of their diet in other parts of the bay too, identified prey species including *Siliqua* in the Kraken corner, *Tellina* sp. and *Cultellus* on sandier flats. Shrimps and cumaceans are often taken too, most noticeably off Dampier Creek. Tulp & de Goeij (1994) provide a list of other items identified in the diet of Great Knots in Roebuck Bay; to this I can now make a few surprising additions: *Leucosia* crabs, tiny Hermit crabs, mudskippers and once, a large Ingrid Snail (taken by a juvenile which probably didn't know any better). A few juvenile Great Knots joined Red Knots in feeding on Mangrove Moonsnails near crab creek (see Red Knot account).

Fig. 9. 3 also shows the distribution of preferred prey of Great Knots, the assumptions being that they prefer:

• Bivalves, not exceeding the size limits identified by Tulp & de Goeij (1994): *Siliqua* and the similarly elongated *Cultellus* and *Ensis* if <36 mm long, *Macoma* (and most *Tellina*) if <28 mm, *Modiolus* (and *Ledella, Nucula* and *Anadara*) if <27 mm long, *Tellina piratica* (and *T. capsoides,*
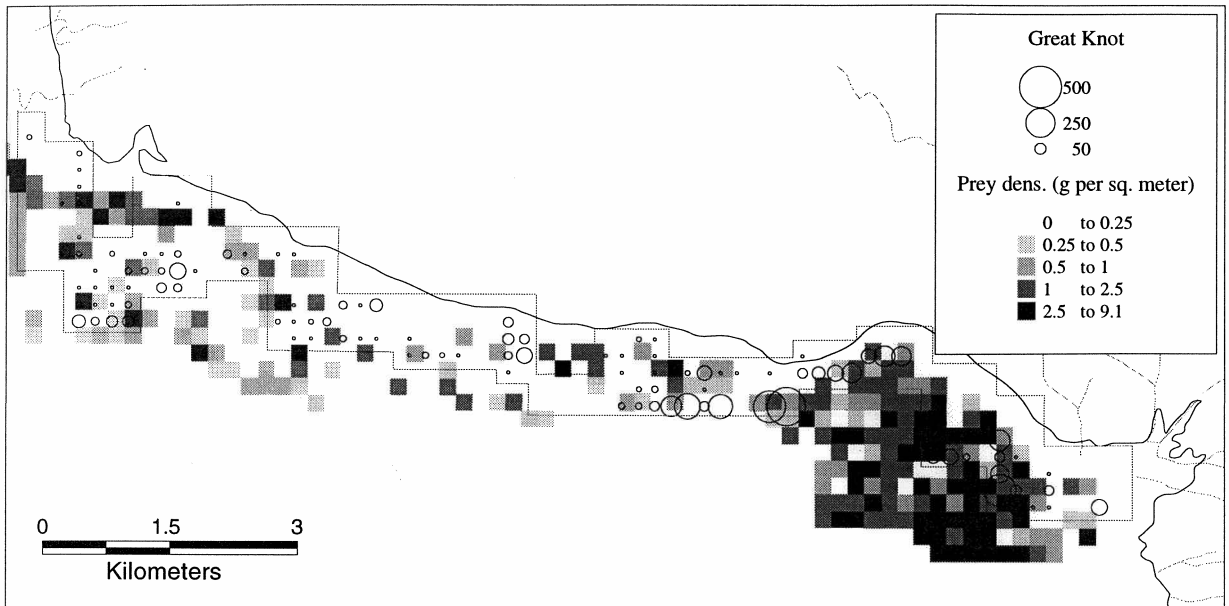
Fig. 9.3: Distribution map for Great Knot and densities of the preferred prey items.

Solemya, Donax, Gari, Laternula, all Mactridae, Semelidae, and most Veneridae) if <24 mm, *Anomalicardia* if <19 mm, and *Anodontia* (and *Divaricella, Ctena* and *Placamen*) if <16.

- Cumaceans, shrimps and *Lingula*
- *Leucosia* crabs if <16 mm. This may seem a surprising choice of prey for Great Knot but I have recorded several individuals consuming *Leucosia* crabs (and nothing else) on subsequent field-trips.

As with Bar-tailed Godwits, the links between the distribution of Great Knots and their preferred prey are not particularly obvious (Fig. 9. 4). There is no obvious tendency for their prey to be more common in the direction of the sea - if anything the opposite applies, particularly in the western end of Roebuck Bay. Nor did ROEBIM '97 sample a great deal of Great Knot prey on the flats off Fall Point where highest densities of Great Knots were seen. It is possible that much of the prey in this area (bivalve spats) had settled in the period between the ROEBIM expedition in June and the shorebird work in October. Another indication that Great Knot distribution may change with time comes from *Modiolus*. In 1991, Tulp & de Goeij (1994) found this bivalve to be common in the diet of Great Knots; indeed it dominated samples of droppings. In 1997, the distribution of *Modiolus* and foraging Great Knots were dissimilar, *Modiolus* differing from Great Knots in that it usually occurred in near-shore sites. Moreover, I found no evidence of Great Knots eating *Modiolus* in the course of four months of foraging observations in 1998, and never found *Modiolus* in the

core samples taken routinely at sites where Great Knots were observed foraging.

Red Knot

Another species showing a strong tendency to follow the tide-edge; the majority of Red Knots seen on receding tides were in sea-edge flocks (Fig. 9. 4). Much the highest densities were found on the sea-edge between Richards Point and Fall Point, where Red Knots fed with Great Knots on very small bivalves. There had been a reasonably recent spatfall, and high densities of the following species, nearly all between 1.5–6 mm long, were present at U47 (10 cores taken): *Anodontia* (384 animals per m^2), *Nucula* (108 per m^2), *Solemya* (24 per m^2) and *"Macoma" exotica* (84 per m^2). On the sea-edge elsewhere, Red Knots had a similar distribution to Great Knots, but a higher proportion of birds occurred on the sandy flats at the western end of the bay.

The sea-edge flocks of Red Knots consisted only of adults. Juveniles roosted with adults (principally on Crab Creek Beach between One-tree Point and Stilt Viewing) but were only found feeding in one area, far from the sea-edge on soft mud right next to the edge of the Crab Creek mangroves (mapping of this area was performed before most juveniles had arrived). In the flock watched most carefully in this area, there were 35 juveniles and only 3 adults; they were gorging on very high densities of mangrove moon-snails (4392 per m^2 at U65!) found within 10m of the mangrove edge. Two factors may have been involved in the clear
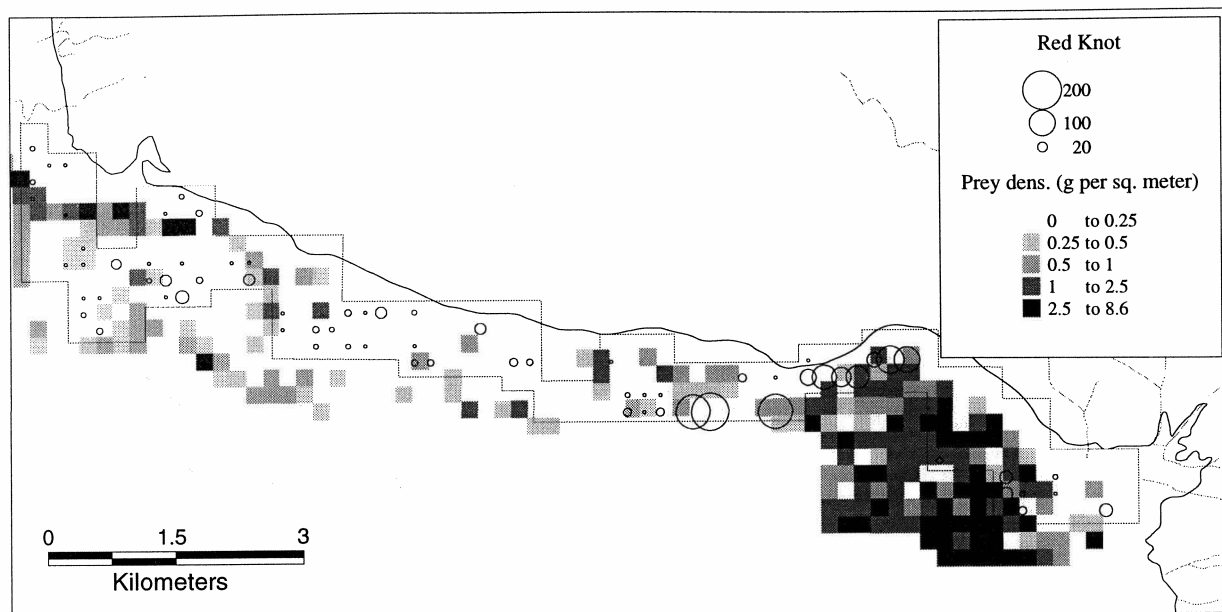
Fig. 9.4: Distribution map for Red Knot and densities of its preferred prey items.

age-segregation seen on October: adults may have disliked the dense cover near the mangrove edge, which made birds vulnerable to raptor predation (the Red Knot flocks here were extremely wary, often flying off in response to false alarms such as passing terns or woodswallows), while juveniles may have been less adept at finding bivalves on the sea-edge than adults (in a subsequent field-trip, Feb.–April 1998, juveniles fed in the same areas as adults but captured fewer bivalves). Other prey of Red Knots seemed similar to that of Great Knots, but smaller and hard to identify on the basis of field observations; they were occasionally seen eating tiny hermit crabs (shells and all).

Fig. 9. 4 also shows the distribution of preferred prey of Red Knots, the assumptions being that they prefer:

- Bivalves, not exceeding the size limits identified by Tulp & de Goeij (1994): *Siliqua* and the similarly elongated *Cultellus* and *Ensis* if <29 mm long, *Macoma* (and most *Tellina*) if <23 mm, *Modiolus* (and *Ledella, Nucula* and *Anadara*) if <22 mm long, Tellina piratica (and *T. capsoides, Solemya, Donax, Gari, Laternula*, all Mactridae, Semelidae, and most Veneridae) if <20 mm, *Anomalicardia* if <15 mm, and *Anodontia* (and *Divaricella, Ctena* and *Placamen*) if <14.
- Cumaceans, shrimps, hermit crabs, spider crabs and *Lingula*
- *Leucosia* crabs if <14 mm.

The distribution of the preferred prey of Red Knots was closely similar to that of Great Knot prey, and if anything showed a tendency to be less common towards the sea. The ROEBIM data does not imply particularly high prey abundance in the region off Fall Point where greatest numbers of Red Knots were seen - this may be a sampling problem or (as discussed in the Great Knot account) may be because the Red Knots were feeding on a spatfall that had settled after the ROEBIM expedition.

Black-tailed Godwit

Black-tailed Godwits almost always fed in sea-edge flocks on the very soft muds of the Kraken corner (Fig. 9. 5). Most birds roosted on Crab Creek Beach, the closest available roost to this area. At both roosts and on feeding areas, they were usually associated with Bar-tailed Godwits. The only prey adults were seen taking at the sea-edge were bivalves (thought to be *Siliqua*), though it is likely that they also eat many polychaetes, as they do in other parts of their range (e.g. Cramp & Simmons 1988). A few adult Black-tailed Godwits were seen feeding with Red Knots and Great Knots on the Mangrove Moonsnail bonanza near the Crab Creek mangroves, though they only seemed interested in using the area when the tide covered most of the flats elsewhere.

Fig. 9.5 shows the distribution of the preferred prey of Black-tailed Godwits. The assumptions about preferred prey were as for Bar-tailed Godwit (q.v.), but it was guessed that Black-tailed Godwits, being
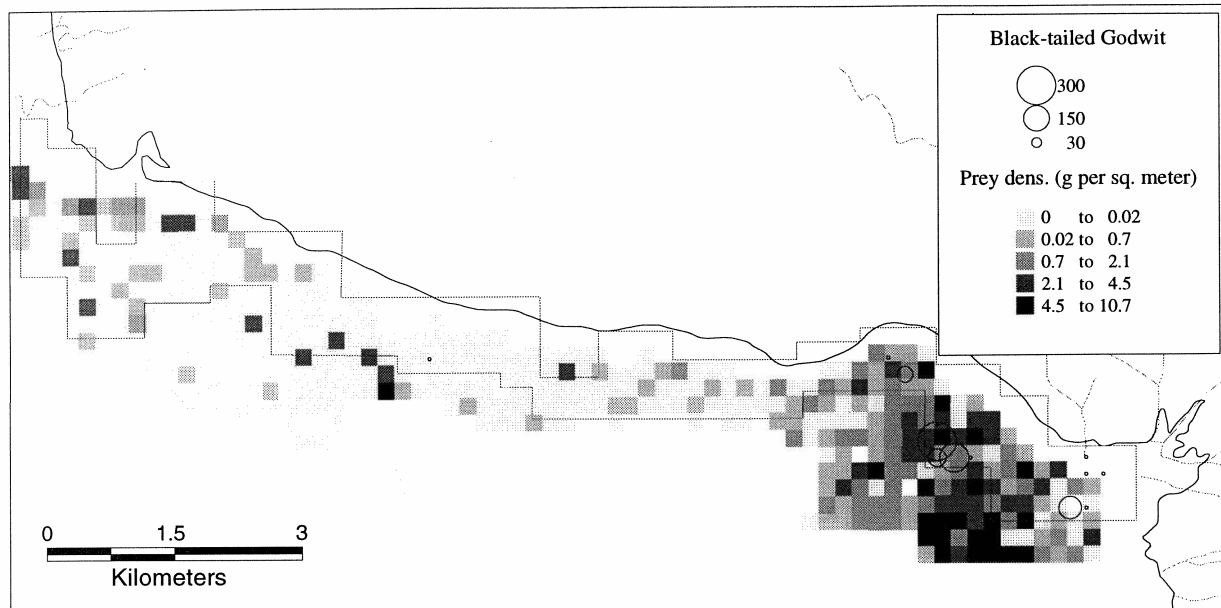
Fig. 9.5: Distribution map for Black-tailed Godwit and densities of its preferred prey items.

smaller than Bar-tailed Godwits, would find smaller worms profitable; accordingly polychaetes were included if >40 mm long. The predictions of preferred prey type clearly need refining, as they suggest that Black-tailed Godwits could feed in most parts of the bay whereas in reality they only occurred on the sloppy muds of the Kraken Corner. It is possible that bivalves are the key to the problem; *Siliqua* and *Tellina amboyensis*, both apparently highly suitable as prey, are common in the Kraken corner, are rare elsewhere and occurred in all quadrats which contained Black-tailed Godwits.

Asian Dowitcher

Only six Asian Dowitchers were seen, all on reasonably muddy flats between Nick's Beach and Broome Bird Observatory. All individuals watched on the flats were feeding by probing, and two were seen eating large worms. Asian Dowitchers are superficially similar to Bar-tailed Godwits and usually associate with them at high tide. The few records available suggest a slight difference in foraging distribution from Bar-tailed Godwits; only three were seen in sea-edge flocks, and none were seen in the Kraken corner.

Guild 2: Tactile microbenthos hunters

Curlew Sandpiper

Typically occurring in small 'pure' flocks, Curlew Sandpipers were often found on the landward border of sea-edge flocks (Fig. 9. 6). They were also partial to sediments bordering small tidal creeks, a habitat more common in the sandy western half of the bay than in the eastern half of the bay where very low relief and relatively soft and mobile sediments probably inhibit the development of clear creek-lines. The most important roost was at Quarry Beach, and many of the feeding Curlew Sandpipers seen were close to this area, especially on neap tides.

The prey of Curlew Sandpipers at Roebuck Bay is unknown. In preparing a map of the distribution of their preferred prey, a study of stomach contents in Tasmania (Thomas & Dartnall 1971) has been used as the basis of the assumptions that they would concentrate on:
- Polychaetes between 3 and 80 mm long;
- Soft-bodied crustaceans between 3 and 12 mm long;
- Bivalves and other hard-bodied animals (gastropods, hermit crabs and spider crabs) between 3 and 5 mm long.

Following these assumptions it would appear that the preferred prey of Curlew Sandpipers is widespread in Roebuck Bay but with relatively low densities occurring in the near-shore parts of the Kraken Corner. Paradoxically a reasonable number of Curlew Sandpipers were seen in this part of the bay, albeit mostly in only a few quadrats. There was no strong tendency for the preferred prey (predicted by the above criteria) to be more abundant close to the sea edge. There is however a reasonably strong superficial similarity between
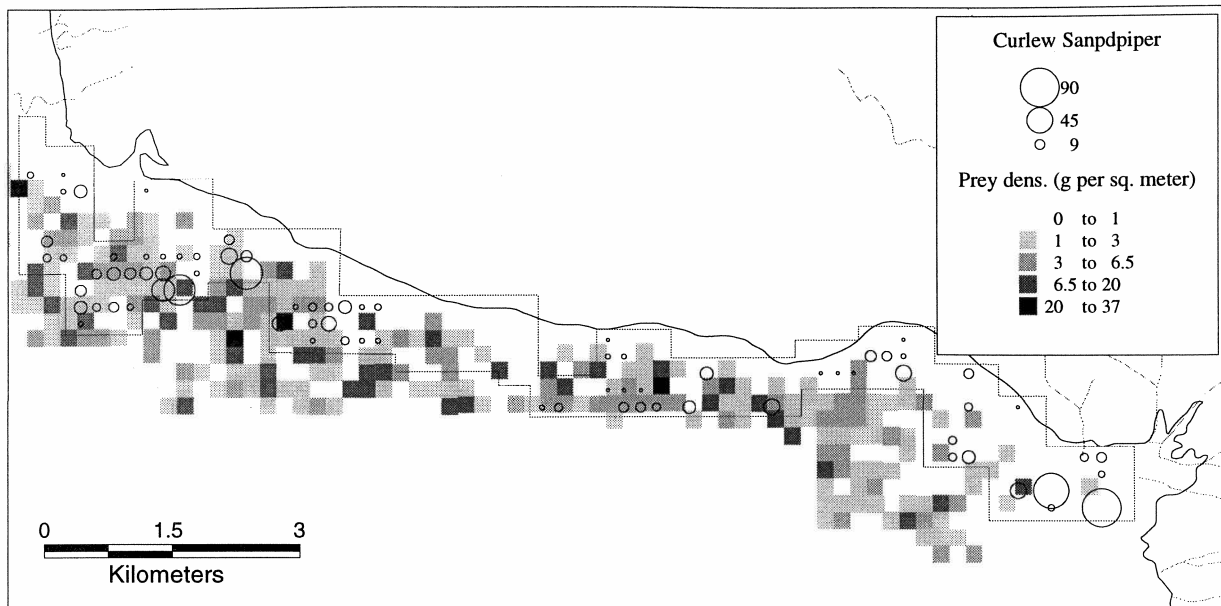
Fig. 9.6: Distribution map for Curlew Sandpiper and densities of its preferred prey items.

the foraging distribution of Curlew Sandpipers and that of Opheliidae, Capitellidae and *Solemya* (Fig. 6.1), all of which would probably be very suitable prey for this species. Direct work on the prey choice of Curlew Sandpipers in Roebuck Bay would be desirable.

Red-necked Stint

The traditional roosting stronghold of Red-necked Stints in Roebuck Bay is at Quarry Beach. Many occurred in this area at low tide as well, especially on rather small flats between rocky reefs (Fig. 9. 7). Red-necked Stints ventured into the sea-edge flocks on the mainly sandy flats west of Richards Point and were
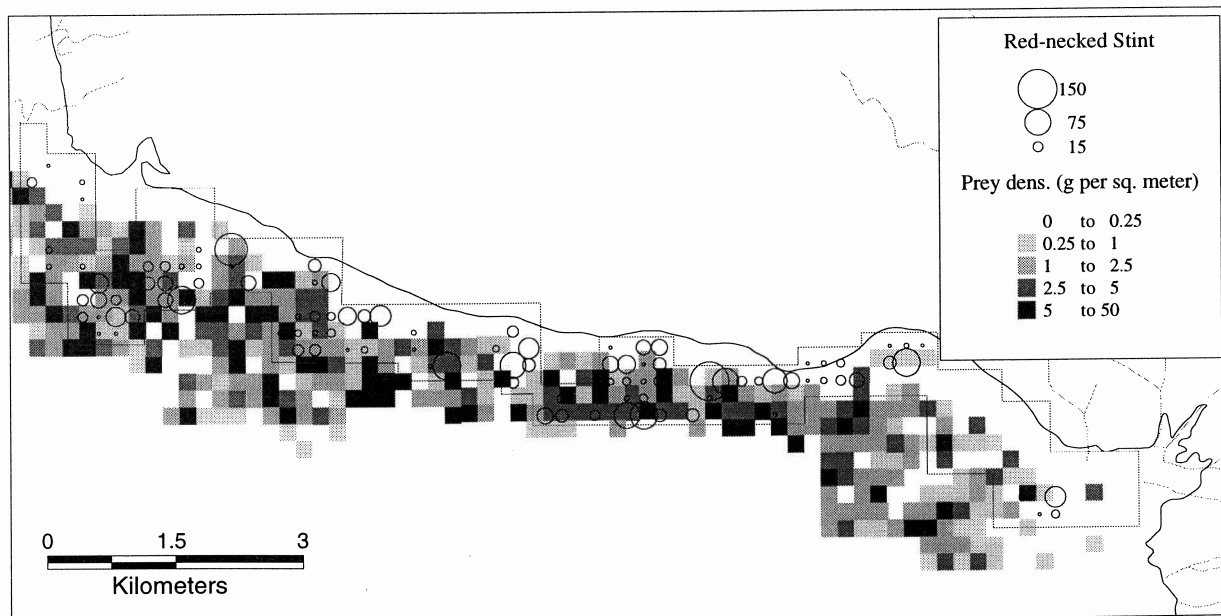
Fig. 9.7: Distribution map for Red-necked Stint and densities of its preferred prey items.

generally rather widespread, but very few occurred on the mushy flats of the Kraken Corner. In subsequent fieldtrips they have been watched in a regular feeding association with Silver Gulls (and Turnstones); the Silver Gulls were eating large Brittle Stars and the Red-necked Stints were picking at the overturned remains, though what they actually ate in this situation is unknown (for this reason large Brittle stars were not included in the map of preferred prey).

The prey of Red-necked Stints at Roebuck Bay is unstudied. In preparing a map of the distribution of their preferred prey, an investigation of stomach contents in Tasmania (Thomas & Dartnall 1971) has been used as the basis of the assumptions that they would concentrate on:

- Polychaetes and soft-bodied crustaceans between 3 and 12 mm long;
- Bivalves and other hard-bodied animals (gastropods, ostracods, hermit crabs and spider crabs) less than 5 mm long.

The resultant map of distribution of preferred prey of Red-necked Stints is rather similar to that for preferred prey of Curlew Sandpipers. Both Red-necked Stints and their preferred prey were rare in the Kraken corner - this could be a difficult place for Red-necked Stints to feed in any case, as the mud there is deep and Red-necked Stints have short legs. As with Curlew Sandpipers, it may be of relevance that three apparently very suitable prey types (Opheliidae, Capitellidae and *Solemya*) had superficially similar distributions to Red-necked Stints, being commonest towards the sea

edge on the flats off Dampier Creek and Quarry Beach.

Broad-billed Sandpiper
Usually seen around Wader Beach, both when roosting and feeding; they typically fed on muddy substrates, not particularly close to the sea-edge.

Redshank
Only five Redshanks were seen on the flats of Roebuck Bay, four on soft mud near the Crab Creek mangroves and one in a sea-edge flock in the Kraken Corner. Their prey choice in Roebuck Bay is unknown.

Sharp-tailed Sandpiper
Typically birds of freshwater wetlands, Sharp-tailed Sandpipers are rare on Roebuck Bay and it is likely that the 41 birds I saw were transients, destined to move on after the wet season had created suitable habitat inland. All were mapped in five adjacent quadrats on soft mud very close to the Crab Creek mangroves, where they joined juvenile Red Knots in feeding on small Mangrove Moonsnails.

Marsh Sandpiper
In most parts of the world, Marsh Sandpipers are typically associated with inland wetlands where they feed on small aquatic prey (e.g. Cramp & Simmons 1988; Piersma *et al.* 1996); exact prey choices are poorly known. In Australia, the largest numbers of Marsh Sandpipers arguably occur on intertidal mudflats of
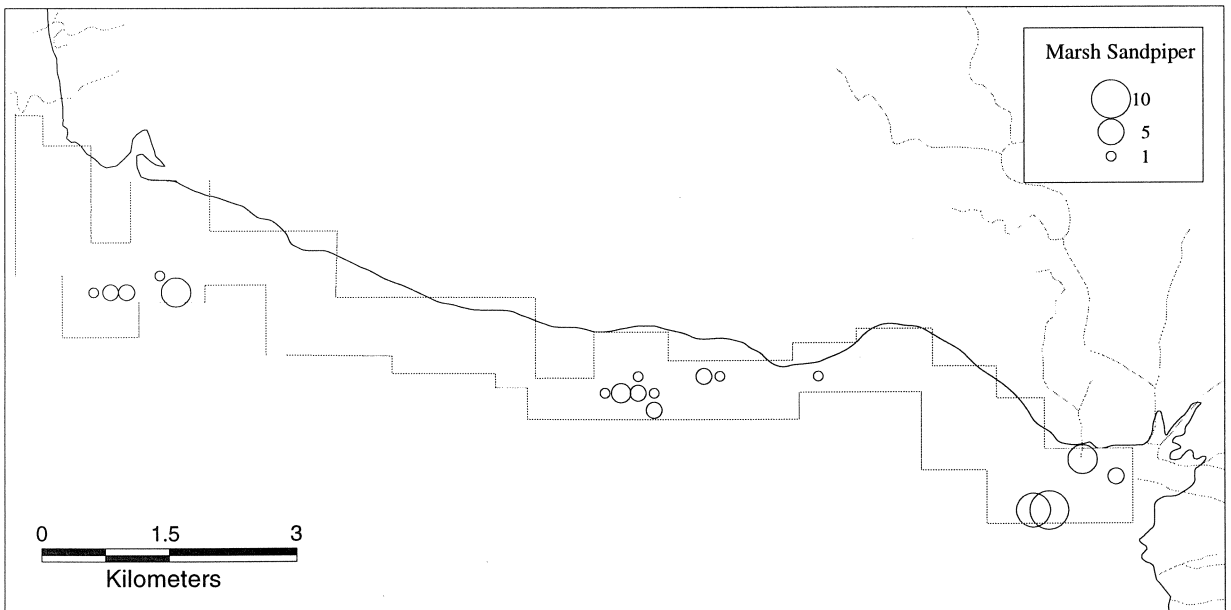
Fig. 9.8: Distribution map for Marsh Sandpiper.

northern Australia (Lane 1987; Higgins & Davies 1997). Only a few Marsh Sandpipers were seen feeding in Roebuck Bay (Fig. 9. 8). Most were feeding on very small prey in soft mud along creeklines from the Dampier Creek flats to Richards Point. Some were also seen in a sea-edge flock on the soft flats of the Kraken Corner and a few joined juvenile Red Knots in the hunt for Mangrove Moonsnails on the fringes of the mangroves of Crab Creek.

Guild 3: Visual surface foragers - hunters of slow-moving prey

Common Sandpiper

Common Sandpipers in Roebuck Bay often occurred near or in mangroves, especially near creeklines. They also foraged on and around rocky reefs and occurred on the 'lumpy' undulating flats near Broome Bird Observatory. At all intertidal sites they fed by picking small unidentified prey items from the surface; they often fed at high tide too, picking up flotsam from the surf line and perhaps catching sandflies on the beaches. Common Sandpipers fly more slowly than the other shorebirds of Roebuck Bay and are apt to avoid raptors by taking cover or manoeuvring through dense habitat such as mangroves; possibly this influences their choice of feeding area.

Silver Gull

Silver Gulls were rather irregularly scattered over the intertidal flats of Roebuck Bay, more commonly seen near the sea-edge (Fig. 9. 9). During the October bird-mapping I had the impression that most birds were roosting rather than feeding on the flats. Subsequent fieldwork has made me think I may have been mistaken, especially in the area off Campsite Beach to Tattler Rocks where largest numbers were seen (in October I mapped these transects in failing light, and didn't have time to watch the behaviour of the birds). In Feb–Apr. 1998 there was again an aggregation of Silver Gulls in the same area; in August 1998 numbers at the same site were so huge (>1,300) that I couldn't resist investigating what they were after. The answer was unexpected: just Large Brittlestars, not previously recorded in the diet of Silver Gulls (Higgins & Davies 1997) and a prey item I would have considered pretty unnutritious. The Brittlestars were picked from the surface of the mud by one leg; which would immediately fall off; the process would be repeated until enough legs had fallen off for the central disk of the Brittle-star to be swallowed. The brittle-stars were swallowed with difficulty; Silver Gulls which did not manipulate the prey sufficiently for it to loose most or all arms ended up with brittle-star legs wrapped round their head.

There is a rough correspondence between distribution of Silver Gulls and large Brittle Stars in Roebuck Bay. I suspect the relationship would look considerably stronger if large Brittle-stars were easier to census by core-sampling. In areas where I found feeding Silver Gull flocks in August 1999 there was an essen-

Fig. 9.9: Distribution map for Silver Gull.

tially continuous lattice-work of Large Brittle-Stars, none lying on top of each other but each with the tips of its arms just touching the tips of the arms of another Brittle Star. With this even spacing, the chances of obtaining a random core sample containing a large Brittle-star central disc are quite low; Large Brittle-stars were only recorded for each core-sample if a central disc (and not just a piece of arm) were found.

Ruddy Turnstone
The distribution of Ruddy Turnstones (Fig. 9. 10) was quite similar to that of Grey-tailed Tattlers: some fed on rocky reefs, some fed at the sea-edge though they rarely used the very soft flats of the Kraken Corner, and some were found mainly on the sandy flats towards Dampier Creek. The greatest numbers of roosting birds occurred on rocks and small beaches between Quarry Beach and Broome Bird Observatory. Turnstone prey on rocks was unidentified, but was often picked from small crevices. On the flats prey was picked from the surface; no confident identifications were made, but amphipods were suspected to be taken at times. In subsequent field-trips (Feb-Apr. and August 1998) Ruddy Turnstones on the sea-edge from Campsite Beach to Dampier Creek were often seen flipping over large Brittle Stars (often in association with Silver Gulls); I do not know whether they found something to eat within the Brittle Star, or were locating small prey underneath. Ruddy Turnstones have been seen turning over Sand-dollars in Roebuck Bay in similar fashion (Bornmann 1985).

A map of preferred prey distribution, based on the assumptions that Turnstones fed on amphipods or in sites with Large-Brittle Stars or Sand-dollars (Fig. 9. 10), showed a broad similarity to the observed foraging distributions of Turnstones but did not shed any light on why reasonable numbers were seen feeding near the Dampier Creek mangroves. The concentration of birds off Fall Point included many birds feeding on rocky reefs.

Pied Oystercatcher
Small concentrations of Pied Oystercatchers were seen in the sea-edge flocks of the Kraken corner, on reefs off Nick's Beach and Sabu Rocks, and in scattered localities elsewhere on the flats (Fig. 9. 11). No map of the distribution of their preferred prey is presented as the diet of Pied Oystercatchers in Roebuck Bay is a mystery; I have never seen a Pied Oystercatcher eating anything in Roebuck Bay. In general Oystercatchers are adept at opening very large mussels, thus exploiting a resource unavailable to other shorebirds. Apparently suitable large mussels do occur in Roebuck Bay - Oysters on the reefs, and *Anadara* sp. on the flats, but whether Oystercatchers eat them is unproven; such prey items are conspicuous and involve long handling times and it seems improbable that I would not have seen them being eaten if they were a regular part of the diet.

Sooty Oystercatcher
Only 7 Sooty Oystercatchers were mapped, all feeding
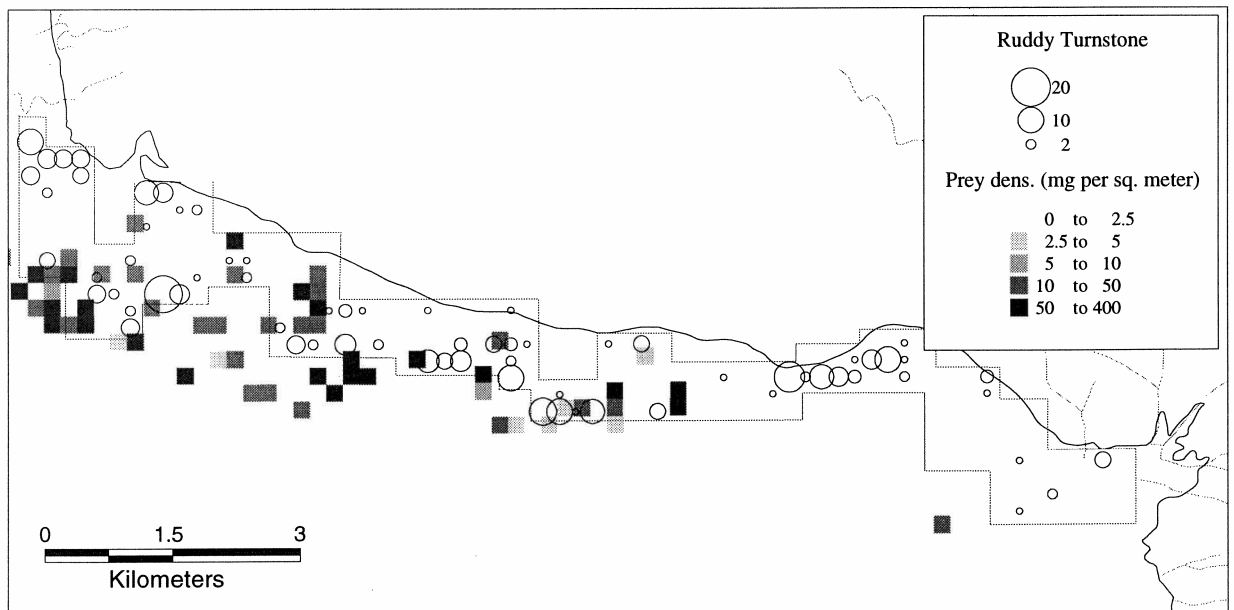
Fig. 9.10: Distribution map for Ruddy Turnstone and densities of its preferred prey items.
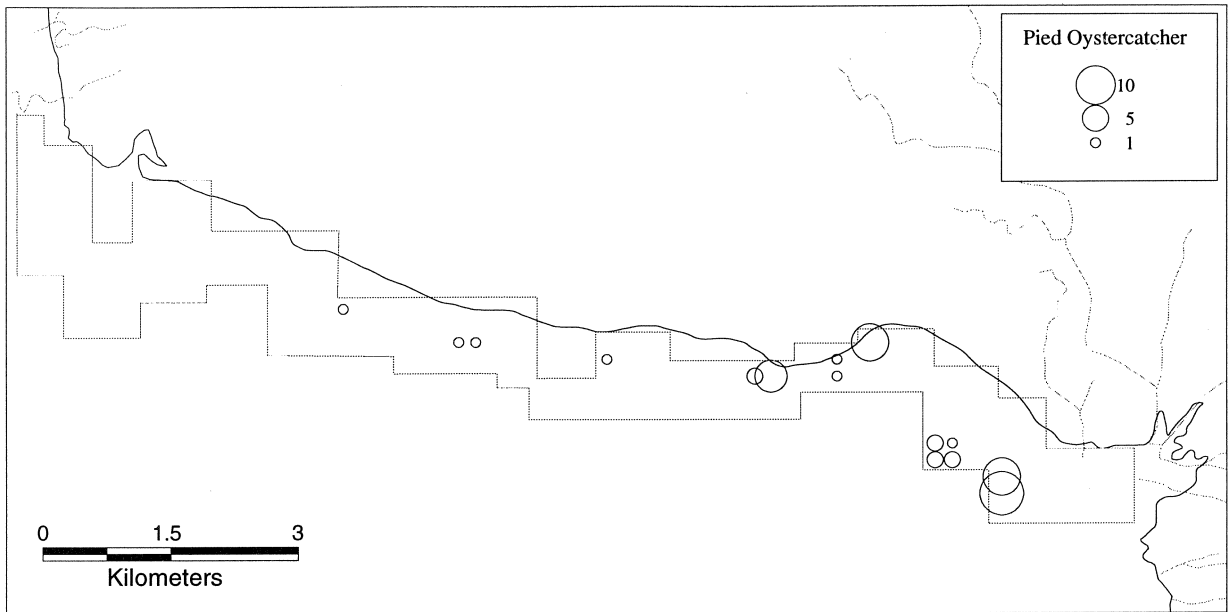
Fig. 9.11: Distribution map for Pied Oystercatcher.

on rocky reefs between Quarry Beach and Richard's Point. It is likely that some were concealed by the rocks and were overlooked; a systematic search for Sooty Oystercatchers on the reefs along this stretch of coast usually reveals 20-30 individuals (they are seldom seen in any other habitat on Roebuck Bay). Diet of Sooty Oystercatchers in Roebuck Bay is unknown but in other parts of Australia they concentrate on slow rock-dwelling prey such as large mussels and chitons (Marchant & Higgins 1993).

Guild 4: Visual surface-foragers: hunters of small prey

Grey Plover

Grey Plovers were fairly evenly scattered over the flats of Roebuck Bay, possibly with a tendency to be more numerous on sandy substrates (Fig. 9. 12). Several individuals were seen eating large polychaetes (family confirmed as Onuphidae in one case); this may be their preferred prey in Roebuck Bay, though they were also seen running after small surface-prey (crabs?) on some occasions. In studies overseas Grey Plovers have been shown to maintain feeding territories. Whether they do so at Roebuck Bay is debatable; their scattered distribution may appear to support this but of the 34 quadrats in which they were recorded, 18 contained 2–5 birds, sometimes with two individuals feeding very close to one another; no obvious territorial disputes between birds were seen.

Fig. 9. 12 also shows the distribution of what may be the preferred prey of Grey Plovers in Roebuck Bay: polychaetes >50 mm long and crabs (excluding hermit crabs) between 7.5 and 15 mm long. There is a broad correspondence between the distribution of these benthic animals and Grey Plovers - certainly not perfect, but both show quite a scattered distribution, mainly on the sandier flats of Roebuck Bay.

At high tide Grey Plovers were not widely dispersed: generally no more than 30 used the wader roosts between Quarry Beach and Broome Bird Observatory, but a flock of about 200 regularly roosted near the Boiler. The number of birds at this roost far exceeded the number seen feeding on the flats (n=74), although this tall stately plover is a conspicuous bird which is difficult to overlook. The feeding distribution of Grey Plovers using the Boiler roost cannot be confirmed without a study in which individuals are marked but it seems likely that it included birds which fed outside the area in which I mapped shorebirds (presumably on the western side of the bay) and birds which flew all the way to the Dampier Creek flats.

Red-capped Plover

This small plover is an Australian resident; numbers in Roebuck Bay decrease markedly in the wet season, when many inland wetlands become suitable for breeding. Although widely scattered in Roebuck Bay (Fig. 9. 13) they tended to avoid the wetter areas near the sea-edge and highest densities were on dry, near-beach flats where they feed on small, active surface-
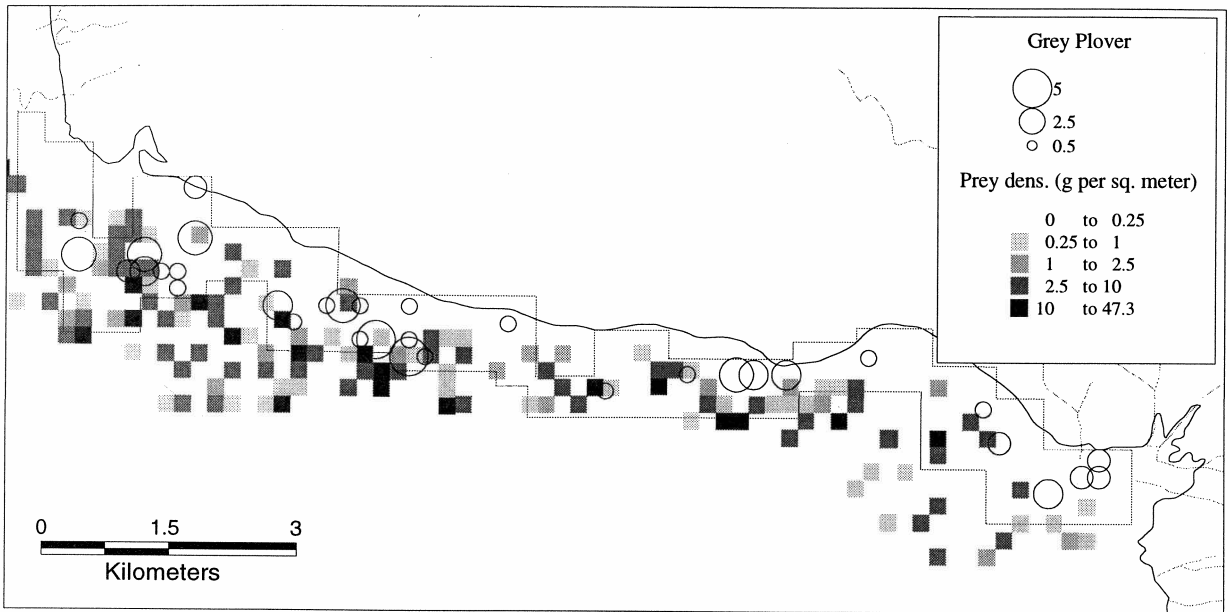
Fig. 9.12: Distribution map for Grey Plover and densities of its preferred prey items.

dwelling prey. These prey have not been identified but were most probably arthropods. The distribution of small arthropods (excluding hermit crabs) of 6 mm or less is also shown in Fig. 9.13; it shows no obvious relationship to the distribution of Red-capped Plovers.

Greater Sand Plover

Greater Sand Plovers were one of the most widely distributed shorebirds of the flats of Roebuck Bay. They did not show any tendency to be more common on the sea-edge than elsewhere (if anything densities were higher near the coastline) and tended to be more common on firm sandy flats than on soft muddy ones
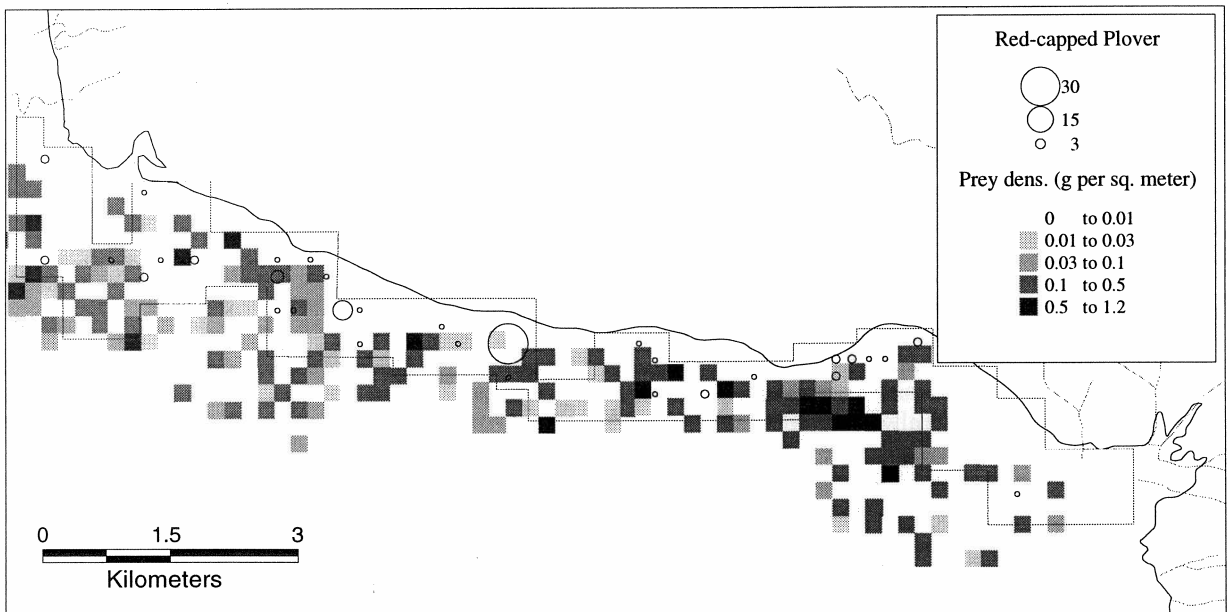
Fig. 9.13: Distribution map for Red-capped Plover and densities of its preferred prey items.
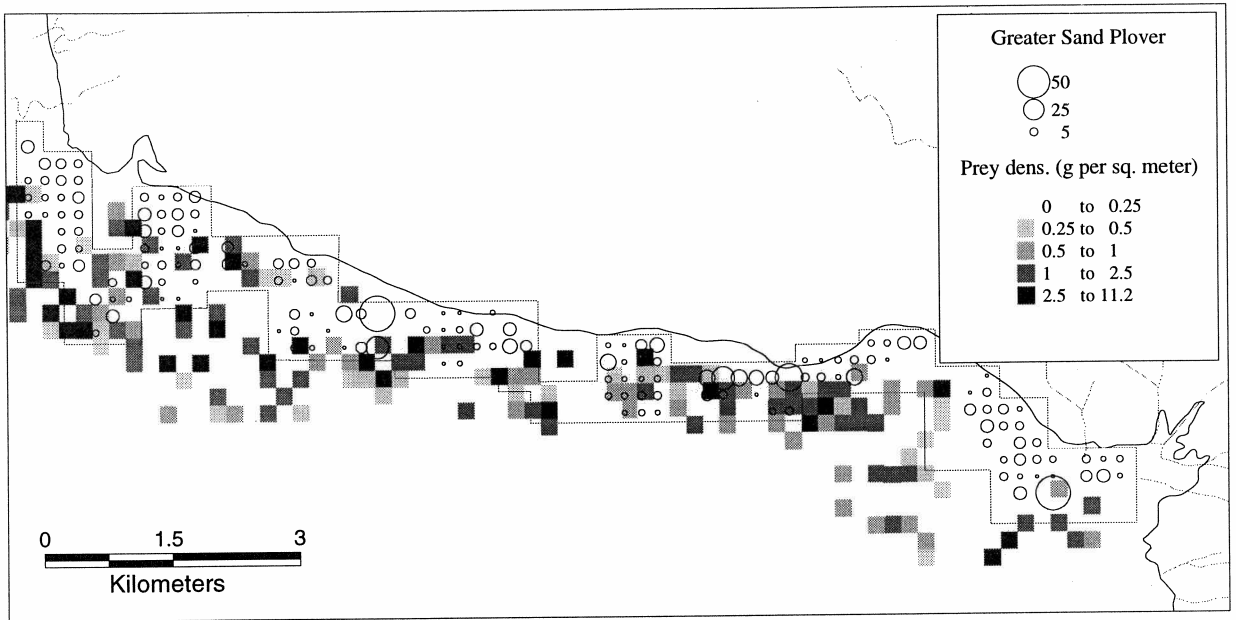
Fig. 9.14: Distribution map for Greater Sand Plover and densities of its preferred prey items.

(Fig. 9.14). In October, the best roosts for Greater Sand Plovers were Quarry Beach and Wader Beach. Both are traditional roosts for this species and were close to flats where reasonably large numbers of feeding birds were seen.

Greater Sand Plovers in Roebuck Bay feed on small active prey picked from or just below the surface. Most of these are probably arthropods of some kind, and I have seen them pick up small crabs up to half a bill length long. I have also seen them abandon their usual stand-run-peck mode of foraging to pick up numerous small prey items from just below the surface, next to a creekline near Dampier Creek; identity of this prey was not confirmed but I suspected them to be 'Mickey Mouse' worms (Sternaspidae) as these were common in the area. The distribution map of preferred prey in Fig. 9.14 assumes they concentrate on arthropods and Sternaspidae less than 12 mm (half a bill-length) long. It does not suggest prey to be more common close to shore, but does indicate a relative paucity of prey on the extensive muddy flats of the Kraken corner. Neither trend is particularly consistent with the observed distribution of the Greater Sand Plover, suggesting there is much to be learned about its prey choice. It is possible that the feeding distribution of Greater Sand Plovers is affected by numbers of other shorebirds. Rather few Greater Sand Plovers were seen near the sea-edge where the presence of large numbers of tactile-foraging waders might discourage potential Greater Sand-Plover prey from feeding conspicuously on the surface of the flats.

Lesser Sand Plover
Much less common than Greater Sand Plovers at Roebuck Bay, but they seemed to have similar foraging habits and feeding distribution.

Grey-tailed Tattler
Large roosts of Grey-tailed Tattlers occur on boulders lying off the cliffs between Nick's Beach and Richard's Point; Tattlers are one of the few shorebird species in Roebuck Bay that will roost on mangroves, and limited data suggest that reasonable numbers do this in the Dampier Creek system. Grey-tailed Tattlers were widespread at low tide, but avoided the very soft flats of the Kraken Corner (Fig. 9. 16). The densest concentrations were seen in two areas: (1) On the rather narrow intertidal area between Nick's Beach and Richard's Point, where Grey-tailed Tattlers picked up prey (including small crabs) from the surface of silty to sandy flats, and also hunted for prey in crevices of rocky reefs; (2) On the broad sandy flats between Quarry Beach and Dampier Creek, where Grey-tailed Tattlers hunted crabs on open flats, and also occurred in sea-edge flocks. They picked prey from the surface while in sea-edge flocks but it is not clear what this was; while not large enough to be easily identified, it was not usually tiny either, and I considered Grey-tailed Tattlers rather clumsy in their attempts at handling very small prey. In the map of distribution of preferred prey (Fig. 9.15) I have therefore assumed that Grey-tailed Tattlers aim to find soft-bodied arthropods more than 5 mm long; I have also assumed
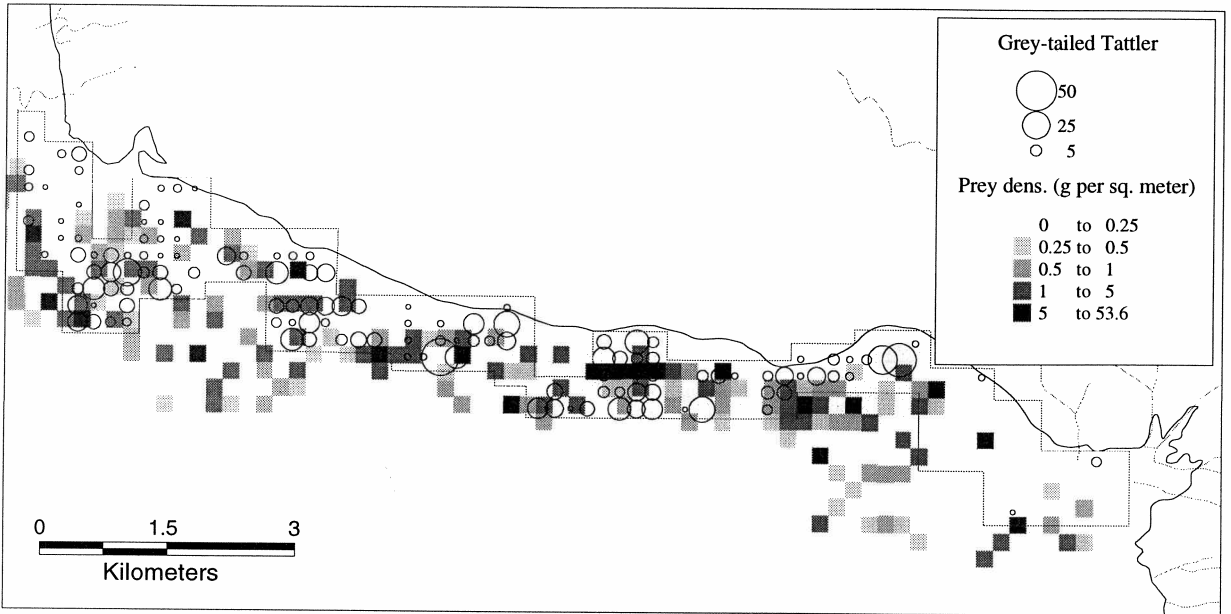
Fig. 9.15: Distribution map for Grey-tailed Tattler and densities of its preferred prey items.

they eat crabs, but not if they are longer than 16 mm (about half a bill-length). The total dietary range of Grey-tailed Tattlers is probably much broader and I have seen them experiment with more improbable food sources - most memorably a juvenile tattler which spent 20 minutes on an ambitious and unsuccessful attempt to swallow an 8 cm Sole. The map of preferred prey corresponds well with the observed distribution of Grey-tailed Tattlers in that it shows little reason for them to feed in the Kraken corner, but in the west of the Bay it shows only a slight increase in abundance of prey towards the sea-edge.
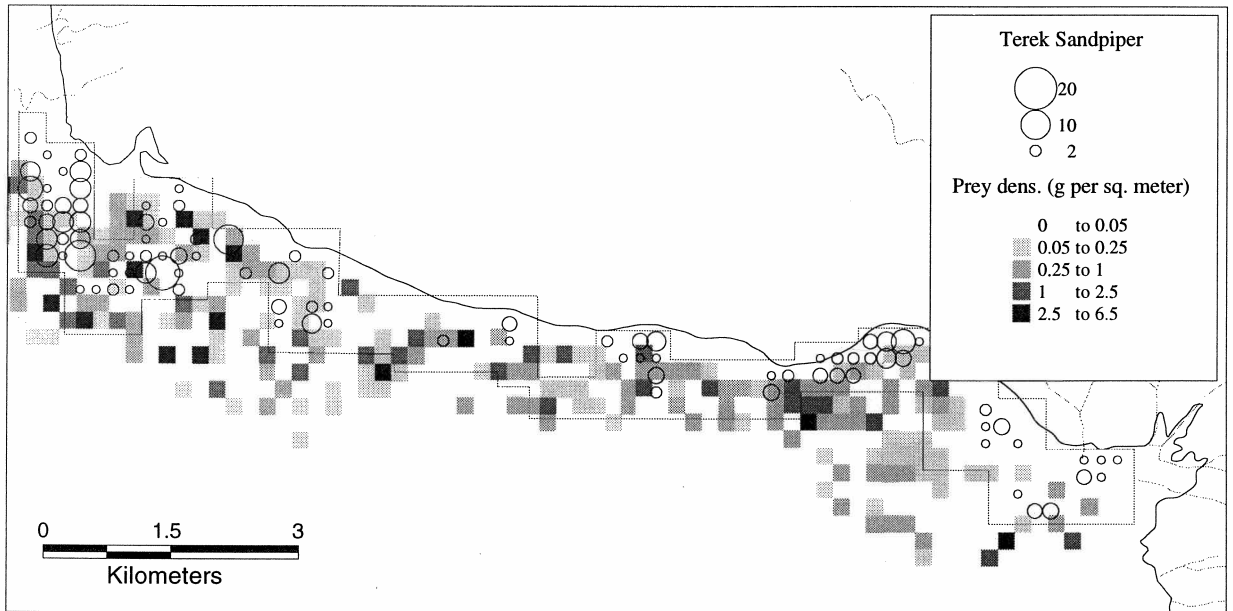
Fig. 9.16: Distribution map for Terek Sandpiper and densities of its preferred prey items.

Terek Sandpiper

Although widely distributed on the flats of Roebuck Bay there were clearly two areas where Terek Sandpipers were concentrated on both springy and neapy tides (Fig. 9.16). The most important of these was the sandy flats near Dampier Creek; reasonable numbers also occurred on the narrow flats from Wader Beach to about Broome Bird Observatory, where the flats are gently undulating, with relatively firm and sandy ridges separated by muddier swales. Roosting preferences are similar to those of Grey-tailed Tattler; they use boulders lying off the cliffs between Nick's Beach and Richard's Point and some certainly roost on mangroves, especially in the Dampier Creek system. An unexpected flock of 700 (far exceeding the numbers mapped on the intertidal flats) seen at a pre-roost near Crab Creek suggests that the northern part of the bay is used as a roost by Terek Sandpipers which feed south of the area mapped.

Terek Sandpipers are swift-running crab-catchers in South Korea (Piersma 1986a), and their foraging style in Roebuck Bay is consistent with this diet. In the map of preferred prey density (Fig. 9.16) I have assumed they concentrated on eating crabs with a carapace diameter less than 12 mm (gape diameter in Terek Sandpipers is about 11.2 mm; Piersma 1986a). This map corresponds with the observed distribution of Terek Sandpipers in that it shows preferred prey to be most common on the sandy flats near Dampier Creek, and on the narrow flats from about Wader Beach to Broome Bird Observatory.

Guild 5: Visual surface-foraging waders: hunters of large prey

Eastern Curlew

Widespread but rather sparsely distributed over most of the flats, Eastern Curlews were most concentrated on the soft flats of the Kraken Corner (Fig. 9.17). This has been a favourite area for them ever since the establishment of Broome Bird Observatory (they are easy to see by telescope from Observatory Beach). One attraction of that part of the bay may be its isolation; it is seldom visited by people in boats and never by sensible people on foot, which probably suits the notoriously wary Eastern Curlew rather nicely.

Eastern Curlews feed mainly on large crabs in South Korea (Piersma 1986b) and in Roebuck Bay (K. Hodder pers. comm.; pers. obs.). I have also seen them catch mantis shrimps and chase mudskippers. In the map of preferred prey distribution, I have assumed that Eastern Curlews concentrate on crabs larger than 5mm wide, mudskippers and mantis shrimps; they are very large shorebirds so I have assumed they could manage to swallow any of benthic animals we captured in core samples. The resultant map (Fig. 9.18) showed no particular tendency for prey to be more abundant in the Kraken corner (where most Curlews occurred). My impression is that the core-sampled ROEBIM data for these large species is not particularly representative of the abundance of large crabs and mantis shrimps, which are quick and clever enough to avoid an approaching corer. The distribu-
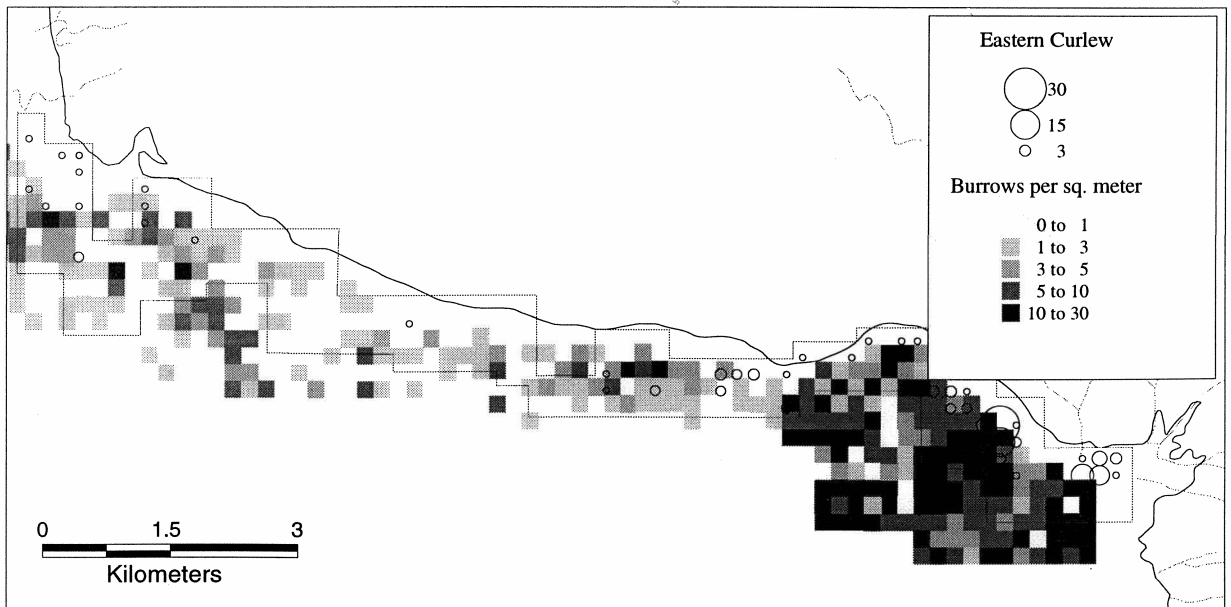
Fig. 9.17: Distribution map for Eastern Curlew and densities of large crab burrows.

tion of big holes,most of which are made by mantis shrimps or large crabs, is more closely correlated to that of Eastern Curlews (Fig. 9.17).

Whimbrel

Whimbrels are widespread in Roebuck Bay (Fig. 9.18); the largest numbers were seen on the muddy flats of the Kraken corner. Another concentration occurred on the muddy flats between Richards Point and Sabu Rocks. Whimbrels are one of the only two shorebird species that feed in mangroves in Roebuck Bay; they seem more common in the Dampier Creek mangroves than in the denser ones of Crab Creek, and reasonably large numbers were seen along the mangrove fringe there. The full number of Whimbrels feeding in the mangroves of Roebuck Bay is unknown (they are difficult to count in this habitat); it is possible that this is their preferred feeding habitat, for in the mangroves they are not subject to kleptoparasitism from Gull-billed Terns.

Like Eastern Curlews, Whimbrels in Roebuck Bay feed mainly on large crabs (P. Collins & R. Jessop pers. comm.; pers. obs.). In the map of preferred prey distribution I assumed that they ate crabs between 5 and 30 mm (size limits based on Zwarts 1985 and Dann 1993), mudskippers and mantis shrimps (any size). Whether the Whimbrels of Roebuck Bay are unable to kill and eat crabs >30mm is debatable - I have seen them tackle some pretty big ones - but the assumption that there is an upper limit to the size of crab they concentrate on is probably reasonable, as the

larger the crab, the longer the handling time - and in Roebuck Bay, the greater the risk that it will be stolen by a Gull-Billed Tern. Whether or not there is an effective size limit to they prey they eat in Roebuck Bay, the diet of Whimbrels overlaps a great deal with that of Eastern Curlews. The distribution of Whimbrels is therefore also more neatly related with the distribution of big holes (Fig. 9.18). I suspect these two species divide resources between themselves by feeding in different ways: Whimbrels chase crabs and grab them from the surface or as they are entering or leaving a burrow; the very long-billed Eastern Curlew is a bit more sedate, and tends to stalk crabs before probing well down a burrow to pull them out.

Greenshank

Greenshanks have a rather broad diet overseas (e.g. Cramp and Simmons 1988) but in Roebuck Bay most seem to concentrate on catching fish. This preference has been noted at other intertidal sites too (e.g. Nethersole-Thompson & Nethersole-Thompson 1979). Reasonably large numbers of Greenshanks occur on the muddy flats of the Kraken Corner (Fig. 9. 19), where several individuals were seen eating mudskippers up to 10 cm long and the foraging behaviour of most individuals (stalking and then pouncing on a large, fast-moving prey) seemed reasonably consistent with this diet. Elsewhere, greenshanks were widespread and were usually found along creeklines, typically standing in water and picking up swimming prey which included small fish.
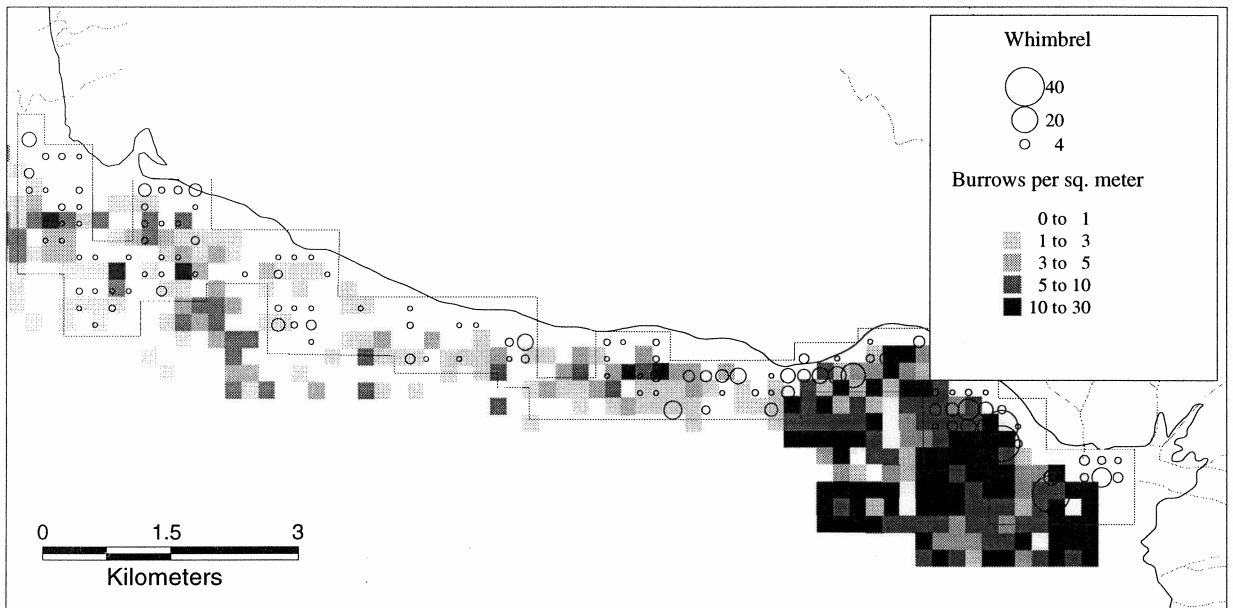
Fig. 9.18: Distribution map for Whimbrel and densities of large crab burrows.
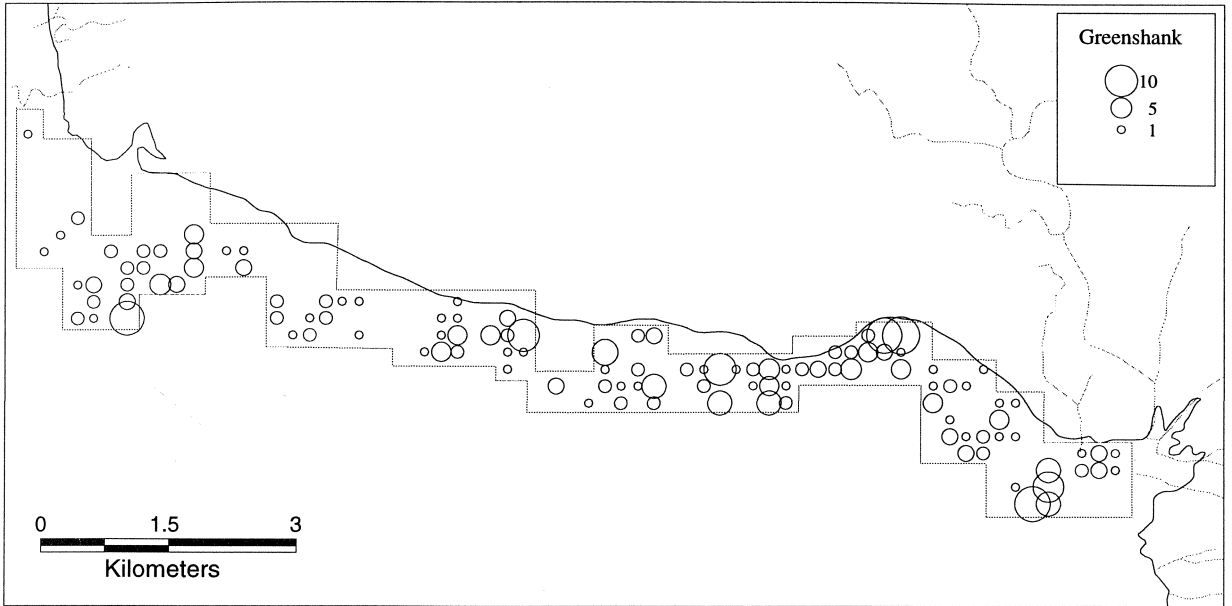
Fig. 9.19: Distribution map for Greenshank.

Black-necked Stork
Very small numbers of the huge Black-necked Stork occur regularly on the remoter intertidal flats of Roebuck Bay, walking deliberately while inspecting the mud very closely. Prey captures are rarely seen, suggesting that the prey items they capture are large (so they do not need many to satisfy energetic requirements). I suspect that in Roebuck Bay they usually seek Sole - this was the only prey item I saw a Black-necked Stork take (once) and their foraging style seems well suited to locating this large, sluggish and extremely cryptic flatfish.
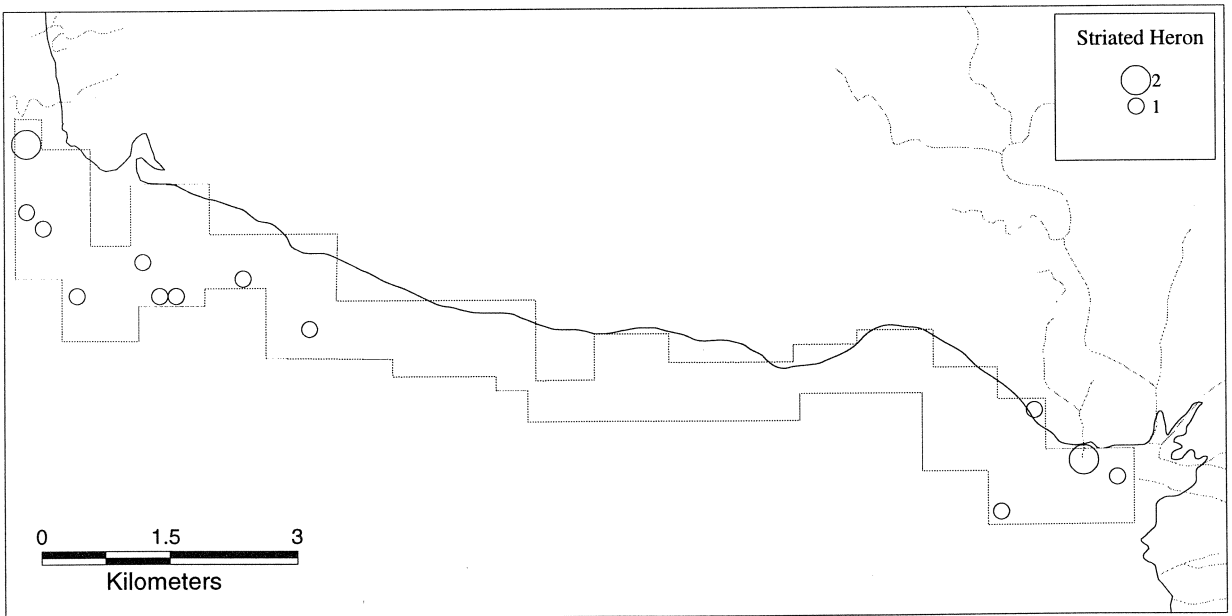
Fig. 9.20: Distribution map for Striated Heron.

Striated Heron

This bird used to be called the Mangrove Heron, and the name is certainly apt in Roebuck Bay. At Roebuck Bay they only feed in mangroves (probably their core habitat though they were not counted within mangroves) and in front of them; some individuals will follow creeklines up to 2km from the nearest mangroves but none were seen on the long expanse of flats (from Quarry Beach to One-tree Point) which are not backed by mangroves (Fig. 9.20). About equal numbers of Striated Herons were seen stalking mudskippers on open muddy flats and wading through creeklines while hunting fish; Striated Herons could equally well be classified in Guild 7 (hunters of nekton and neuston).

White Ibis

Most White Ibis mapped in Roebuck Bay were feeding on intertidal flats in front of the Mangroves of Dampier Creek or Crab Creek (Fig. 9.21). Their diet in Roebuck Bay has not been studied. In Westernport Bay (Victoria), White Ibis fed mainly on *Macrophthalmus* crabs and shrimps (Marchant & Higgins 1990). The distribution of these organisms in Roebuck Bay has little in common with the distribution of White Ibis.

Guild 6. Kleptoparasites

Gull-billed Tern

In much of their range, Gull-billed Terns are birds of inland wetlands which hawk insects in flight. In Roebuck Bay I was initially surprised to see a fair number of Gull-billed Terns loafing on the flats (most often in the Kraken corner) and still more surprised when it transpired that their distribution was almost perfectly correlated with that of Whimbrels (Fig. 9.22). The penny started to drop one day on the Kraken flats, when I saw a Gull-billed Tern fly at a Whimbrel which had just captured a large *Macrophthalmus* crab; it beat up the Whimbrel, stole the crab carapace and ate it, while the resigned Whimbrel swallowed some of the legs that remained. Since then I have seen this kind of interaction occur almost every time I have watched a Whimbrel on the flats for long enough; sometimes the Whimbrel manages to complete its meal, sometimes the Gull-billed Tern gets the lot and often they end up sharing the spoils. Further, once I had worked out what was going on, I realised that every Gull-billed Tern I saw on the flats had positioned itself within 50 to 200 m of at least one Whimbrel, and spent all of its time watching them closely and waiting for an opportunity to rob prey.

Kleptoparasitism by Gull-billed Terns does not appear to have been recorded before, although the species occurs through much of the Old World. It is possible that only the Australian subspecies *macrotarsa* robs Whimbrels. This is much the largest subspecies of Gull-billed Tern, and it can hold its own in a fight with a Whimbrel (the battles can be quite physical, with pecks exchanged). An indication that Gull-billed Terns are not keen on tackling opponents larger than themselves comes from the fact that I have never seen one
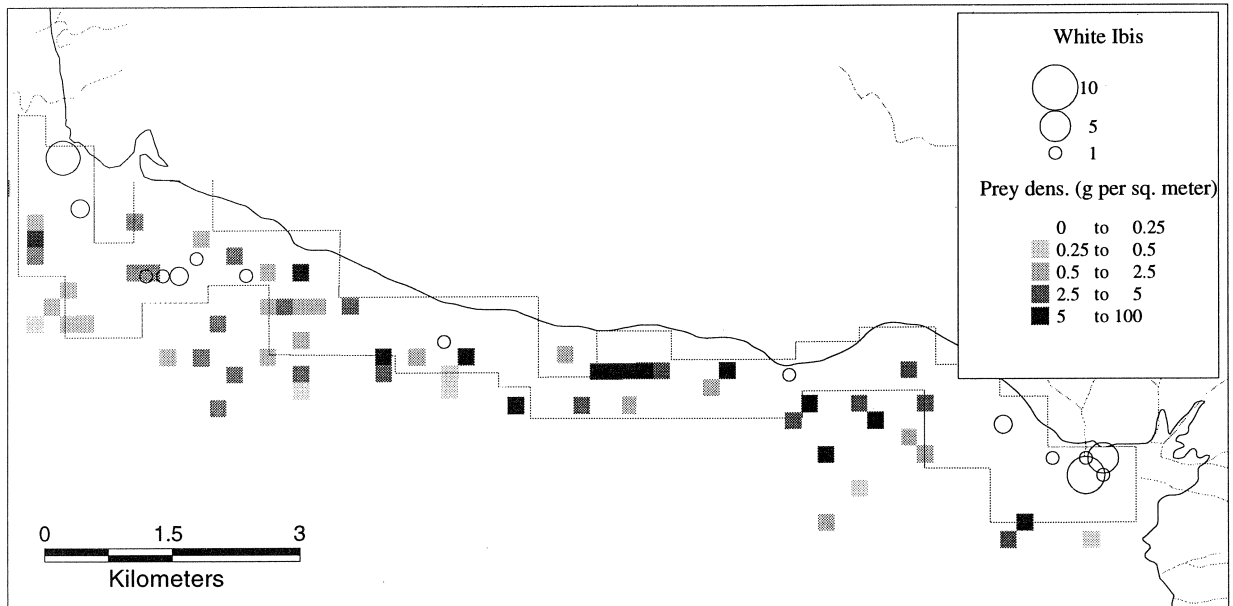
Fig. 9.21: Distribution map for White Ibis and its preferred prey items.
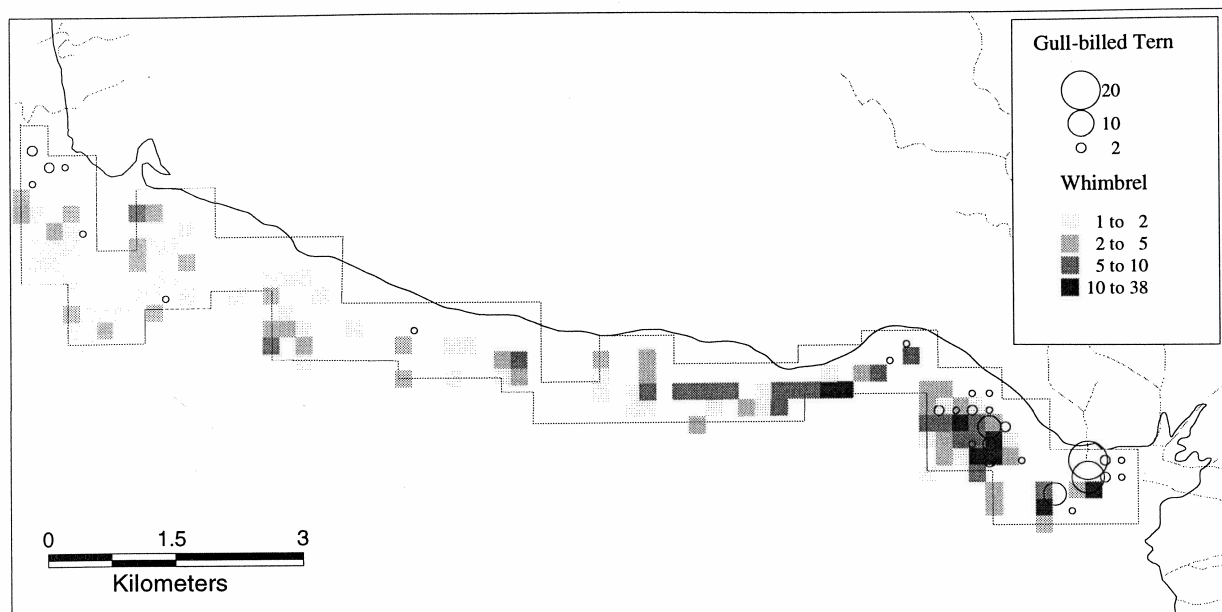
Fig. 9.22: Distribution map for Gull-billed Tern and Whimbrels (see text for details on the kleptoparasitic behaviour of the terns).

attempt to rob food from an Eastern Curlew (though they certainly watch crab-hunting Curlews with some interest).

Guild 7: Pelagic hunters of nekton and neuston

Most species in this guild were only mapped rarely on the northern flats of Roebuck Bay; for at least the egrets and Royal Spoonbill, the stronghold appeared to lie on the eastern side of the bay (many birds could be seen in this area, but I could not cross Big Crab Creek to do any mapping). ROEBIM '97 was not directed at mapping their swimming prey, so only brief notes follow:

Reef Egret
Only four individuals were mapped, three feeding on rocky reefs between Nick's Beach and Tattler Rocks, and one feeding on a flat bed of coral near to Quarry Beach; all were hunting apparently fast-moving prey that hid in rock pools.

Little Egret
Most were seen feeding along the large creek systems of Dampier and Crab Creek (1–15 birds per 200 m grid) and a few birds feeding (usually alone) in small creeklets or at the sea-edge between Nick's Beach and Tattler Rocks. All were wading in shallow water, apparently hunting swimming prey.

Great White Egret
Less common than Little Egret but apparently identical in foraging distribution.

White-faced Heron
Only mapped in creeklets near 'the Crab Creek mangroves.

Royal Spoonbill
Most (n= 9) were mapped in creeklets near the Crab Creek mangroves, two were mapped near Sabu Rocks.

Black-winged Stilt, Red-necked Avocet
Only seen on mudflats near Crab Creek, where neither species was actually feeding. Black-winged Stilts have been seen feeding in creeklines or on very soft creekside mud in this area on subsequent fieldtrips, but Red-necked Avocet is rare and irregular at Roebuck Bay.

Discussion and conclusions

On first glance the intertidal flats of Roebuck Bay look uniform and almost featureless. On closer inspection though, they turn out to be beautifully diverse, and this is reflected well by the species composition of shorebirds in different areas. On this basis, the flats of Roebuck Bay can be roughly subdivided into the following habitats:

The Sea-edge

This is the clearly defined stronghold for tactile hunters of macrobenthos (knots and godwits; Guild 1). Within this narrow habitat, there is some species segregation in feeding distribution: Black-tailed Godwits feed exclusively along muddy sea-edges in the east of Roebuck Bay; Red Knots feed mainly on sandy sea-edges of the west; Great Knots and Bar-tailed Godwits feed in both, but seem more partial to the muddy areas. Specific prey choice could well contribute to these differences. Two bivalves which may have an especially large effect on the differences in distribution of knots and Godwits are *Siliqua* and *Tellina amboyensis*; both are common in the muddy Kraken corner and rare elsewhere. Their burrowing depth may make most of them inaccessible to Red Knots, but still available to long-billed species. In the western half of the bay, the sea-edge also holds a large proportion of the tactile hunters of microbenthos (guild 2) and locally high numbers of Silver Gulls (guild 3) and Grey-tailed Tattlers (Guild 4).

The position of the sea-edge varies a great deal according to tide height, so it is not really surprising that no benthic species is restricted to this habitat. More surprisingly, for most bird species that were commonest near the sea-edge, there was no strong indication that the abundance of their preferred prey increased with distance from shore. It is likely that for the benthic prey sought at the sea-edge, prey abundance (as measured by core sampling) and prey availability are quite different things. Presumably much benthic prey (especially that exploited by tactile hunters of macrobenthos) behaves in a way that makes it more easily detected near the sea-edge than elsewhere. Experiments are needed to confirm this. Whatever the causes for the sea-edge preferences of foraging knots and godwits may be, they lead to the birds spending relatively little time foraging in any one place between the neap low and spring low tide-marks, and this probably reduces the chances of them 'over-harvesting' their benthic prey. Nevertheless, I suspect that the foraging distribution of shorebirds (especially knots) at the sea-edge can fluctuate a good deal with time. In October the highest densities of Red Knots, Great Knots and possibly Bar-tailed Godwits (but not Black-tailed Godwits) occurred off Fall Point where Red and Great Knots were feeding on a bivalve spatfall. This spatfall was not detected in the sampling done during June in ROEBIM '97; by Feb.–Apr. 1998, numbers of both birds and bivalves in the same area had decreased markedly.

The Dampier Creek Flats

The sandy flats between Quarry Beach and Dampier Creek are characterised by relatively large numbers of visual hunters of small active prey (guild 4), and are the stronghold for Terek Sandpipers and several species of plover. The flats here are crossed by many small tidal creeks, a preferred feeding area for tactile hunters of microbenthos (guild 2) and greenshanks (guild 5). The eastern boundary of this habitat type is not easily defined (there is a rather gradual and patchy transition to more muddy flats) and most of the bird species found on the Dampier Creek flats also occur quite commonly on some of the relatively narrow flats backed by cliffs between Quarry Beach and Broome Bird Observatory. A broadly similar distribution pattern is found in many of the benthic taxa surveyed during ROEBIM '97: e.g. *Tellina piratica*, Opheliidae, *Solemya*, Spionidae, *Anomalicardia*, Orbinidae, *Gammarus* and Sternaspidae.

The visual hunters of small running prey (Guild 4) characteristic of the sandy flats did not a show a strong tendency to follow the sea-edge, and they did not occur at the very high densities characteristic of the guilds that detect prey with tactile mechanisms. The preferred prey of each bird species in this guild (chiefly small crabs and other arthropods) was generally uncommon in the muddy eastern part of the survey area, corresponding with the distribution of the birds in this respect. At a finer level though, distribution of what was perceived to be the preferred prey did not explain the subtle differences in distribution that seemed to exist between most· bird species on the Dampier Creek flats. Quantitative data on prey choice of these species would be desirable, and to interpret distribution of various benthic species in the area it would help to have a better understanding of how their numbers were related to the proximity of nearby creeks.

The flats between Quarry Beach and Dampier Creek do not have Ramsar listing and are not included in the region that has been proposed for marine park status. The lack of formal protection for this area is a matter of concern, as the species composition of both shorebirds and benthos in the area are distinctive. Moreover, the Dampier Creek flats are close to the town of Broome and are more often disturbed by people (mainly anglers and bait-hunters) than any other part of the intertidal area of Roebuck Bay. To develop a better understanding of the conservation value of this area it would be desirable to add a Dampier Creek transect to the benthos monitoring program (MONROEB) currently in progress in the northeastern half of Roebuck Bay.

The Kraken Corner

The very soft and broad flats in the north-eastern corner of Roebuck Bay (between Broome Bird Observatory and Crab Creek) attained their name because ex-

hausted mudbashers who walked across these flats began to develop an irrational feeling that a subterranean beast was trying to suck them under the surface of the mud. The Kraken Corner is characterised by low numbers of most small waders, but is the stronghold for Eastern Curlews, Whimbrel and Greenshank (all hunters of large crabs and mudskippers; guild 5) and for Gull-billed Terns (which steal food from Whimbrels). Benthos data collected during ROEBIM was consistent with these trends, showing prey abundance in the Kraken corner was low for most small shorebird species; judging by the abundance of holes, the area has high numbers of large crabs, mudskippers, and mantis shrimps. The Kraken Corner is also used by a number of other large wader species on neap low tides when most other intertidal flats of Roebuck Bay are inundated. As a result, the benthos of this area is exposed to longer periods of shorebird predation than other areas of the bay; it would be interesting to learn if this influences the amount or type of prey available there.

Rocky Reefs
The rocky reefs of northern Roebuck Bay lie mainly between Quarry Beach and Fall Point. They do not hold huge numbers of birds, but are the only areas where Reef Egrets and Sooty Oystercatchers (guild 3) feed, and also hold reasonably large proportions of Roebuck Bay's foraging Ruddy Turnstones, Pied Oystercatchers (both guild 3) and Grey-tailed Tattlers (guild 4). Although they do not forage on rocks, large number of Red-necked Stints and Red-capped Plovers forage on the sandy flats between rocky reefs, an area used sparingly by other waders. It is possible that their preference for this area is based not on the benthic prey available (which is not obviously distinctive), but upon its proximity to traditionally preferred roosts on Quarry Beach and Wader Beach.

Mangroves
The only shorebirds which forage in the mangroves of Roebuck Bay are Common Sandpipers (Guild 3) and Whimbrels (Guild 4). The numbers of these species occurring in mangroves are difficult to assess, but are certainly quite small compared to the numbers of shorebirds that use the open intertidal flats. More shorebirds forage near the fringes of mangroves, especially at Crab Creek. Many of the birds mapped in this area in October were feeding on high concentrations of Mangrove Moonsnails which had disappeared by Feb. 1998. While not used as feeding habitats by many shorebirds, the mangroves of Roebuck Bay may be of considerable indirect importance in terms of nutrient input into Roebuck Bay (is there another chapter to cite here?), and because the saltflats that form behind

them are favoured as roosts at night and on very high tides.

Big Crab Creek
Although this area was south of the area covered in the shorebird surveys, it deserves brief mention as the stronghold of most bird species in guild 7, hunters of nekton and neuston. The high banks on the south of Big Crab Creek are the last area of mudflat to be covered by rising tides in northern Roebuck Bay; huge numbers of waders (over 30,000 birds) can gather there on rising or neap high tides, using the site as a pre-roost rather than as a feeding area.

Conclusions
This report has presented snapshots of the distribution of shorebirds (in October 1997) and their benthic prey (in July 1997) on the intertidal flats of Roebuck Bay. It is quite possible that the distribution of both changes with time and only further studies can elucidate what these effects might be. Some such studies are in progress. I have repeated the shorebird mapping survey twice (Feb. 1998 and Aug. 1998) and plan to do so several more times. The shorebird surveys performed so far indicate that temporal changes in distribution do occur but the changes have not (yet) been enormous, and the broad trends apparent from the data described in this work are likely to hold true most of the time.

Sharp-eyed readers will have noticed the untrendy absence of significance tests in this report. Much more sophisticated analyses are possible but they alone will not provide us with a thorough understanding of what determines shorebird foraging distribution in Roebuck Bay. More research is needed, perhaps focusing on the following issues:

1. There is dearth of data on the prey choice of most waders in Roebuck Bay. Even very brief studies supplemented by collection of droppings can be informative (see Piersma 1991 for an example of how brief and inexpensive such a study can be).

2. We still do not know why many shorebirds in Roebuck Bay show a powerful inclination to feed by the sea-edge. The answer is almost certainly related to benthos behaviour, but working out the details would be most desirable.

3. In the western half of Roebuck Bay, the ROEBIM data generate rather patchy distribution maps for most benthic species. It is not clear if this patchiness is real or related to our sampling methods. I suspect that the presence of many small creeks in this part of the bay may have very localised effects on the benthic species captured in core samples; this possibility would be easy to test.

4. Identification of crabs, especially from the genus *Macrophthalmus*, has not yet been sorted out in

Roebuck Bay. Without making more progress on this problem it will not be possible to work out whether or not the rather patchy distribution of most crab-eating shorebirds in Roebuck Bay is related to differences in the species of crabs they prefer to eat.

5. The best currency with which to describe prey abundance in Roebuck Bay would be biomass. The ROEBIM data could produce much sounder estimates of biomass if some work was done to establish the relationships between body length and AFDM in the commonest benthic taxa of Roebuck Bay.

6. The extent of temporal variation in benthos abundance and biomass in Roebuck Bay is being followed in a benthos monitoring project (MONROEB) based on monthly samples from two sites in north-eastern Roebuck Bay. It would be desirable to extend this survey to the Dampier Creek flats, where the species composition of benthos is quite different.

7. Radio-tracking studies for selected species would establish the precise movements of individual birds in relation to tide changes, the relationship between choice of feeding and roosting area, and the unstudied feeding distribution of Roebuck Bay's waders at night.
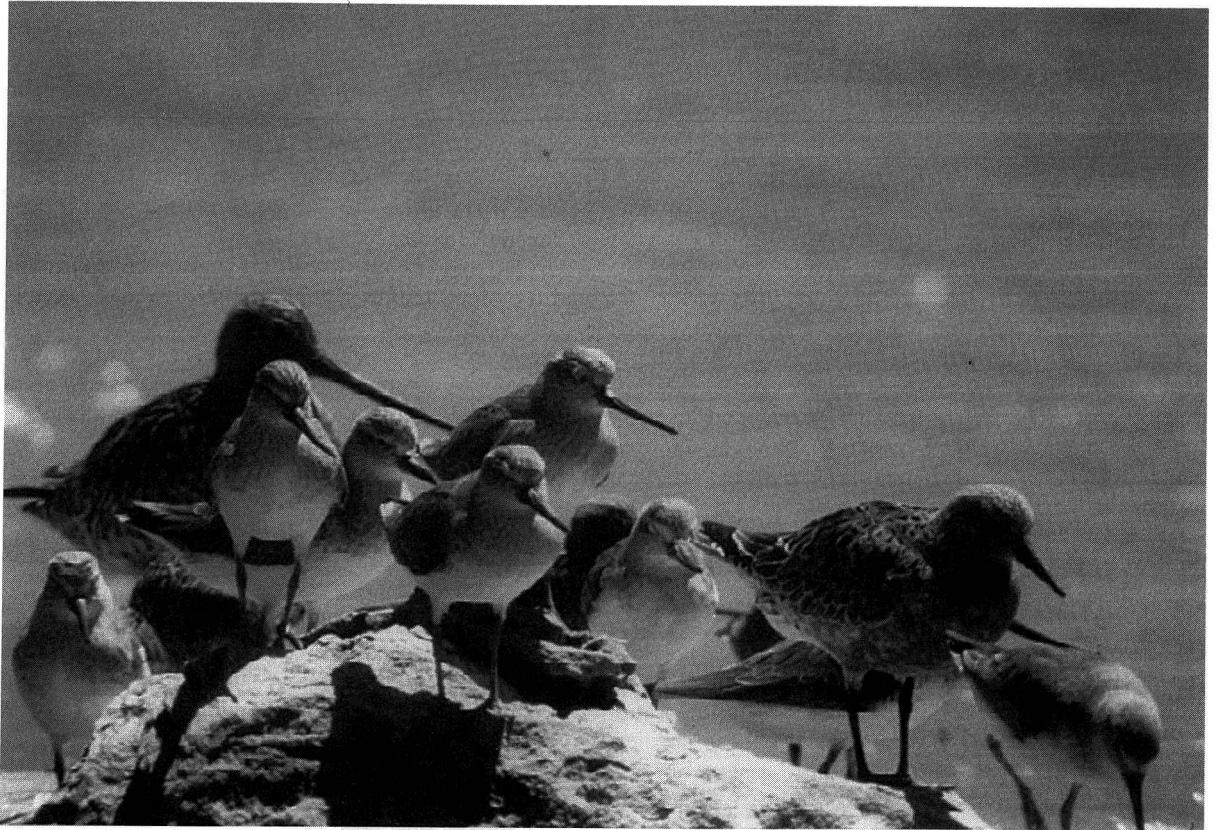
Fig. 9.23: Mixed flock of waders in Roebuck Bay with Grey-tailed Tattlers, Red Knots (rather stout bird to the right) and Bar-tailed Godwit (large bird with long beak in the left-hand corner). Photograph by the Broome Bird Observatory.

10 MANAGEMENT IMPLICATIONS FOR ROEBUCK BAY FROM ROEBIM'97

Grant Pearson, Allen Grosse & Tim Willing

The results of ROEBIM'97 have identified Roebuck Bay as containing intertidal mudflats with a benthic bio-diversity comparable with any in the world. It is unlikely that this richness has changed much in the past 100 years but the potential for change in the short to medium term is considerable. This is due in part to the rapid development of the metropolis of Broome and the concomitant increase in industrial and residential pollutants, and to the impact of the burgeoning physical human presence on the intertidal flats and its hinterland.

The Roebuck Bay intertidal flats and parts of its hinterland are among the most important migratory shorebird feeding grounds and roosts on the East Asian - Australasian Flyway (Watkins 1993). Roebuck Bay is listed under the Ramsar Convention (The Convention on Wetlands of International Importance) under criteria 1: 2(c), 3(a) and 3(c), as a Wetland of International Importance.

Apart from this international recognition of the need for protection of important wetlands, Australia is signatory to two international bird agreements, (JAMBA - Japan Australia Migratory Bird Agreement and CAMBA -China Australia Migratory Birds Agreement). As signatory to these agreements there is a commitment to ensure the protection of migratory bird habitat.

Roebuck Bay is the first landfall in Australia for tens of thousands of migratory shorebirds. The site supports more than 1 % of the national population of 20 species of shorebird (Watkins 1993). The extensive mangal fringing the bay is an important nursery area for marine life (Watkins 1993). Our report has shown a diversity of benthic invertebrate biota with over 200 taxa (species, families or larger taxonomic groupings) and the possibility of no less than 500 intertidal invertebrate species. Most taxa are possibly quite limited in their distribution.

The conservation area recommended in a report on conservation and management concerns for Roebuck Bay by Watkins (1993) has four major units (Fig. 10.1):

• The waters of Roebuck Bay - from near East Rocks in an arc of 3 km radius around the Port to Mangrove Point, along the high water mark in front of the town site, around Dampier Creek, Fisherman's Bend, Fall Point, Crab Creek then south around the coast past Bush and Sandy Points to Yardoogarra Well, then north to East Rocks.
• The Common around the east side of Dampier Creek and the Vacant Crown Land extending towards Fall Point. This would exclude Reserve 30906 (For the use and benefit of Aborigines) and Reserve 35493 (Gravel).
• The Vacant Crown Land already excised from Roebuck Plains Station for the specific purpose of conservation. This includes Reserve 41066 (Bird Observatory).
• An area of land along the seaward margin of Thangoo Station to ensure protection of the mangroves and adjacent vegetation."

Our work also indicates that these are the main areas of concern for management to maintain the integrity of the Roebuck Bay ecosystem. Our study was limited to the intertidal area of the Bay with reference to the sedimentology and hydrogeology of the region. It is, however, necessary to also look farther afield and include aspects of recent development proposals around Broome and the Roebuck Plains in consideration of implications for proper management for the Bay.

Mineral exploration and the development of Broome as a base for North-west shelf gas exploration will accelerate expansion of human activity in and around Roebuck Bay

It is worth noting that the Broome Port Authority and native title issues may have significant impact on Marine Park proposals.

In the case of Thangoo Station, if the lessee is unwilling to have the area excised from the lease then a joint-management agreement between the lessee and the Department of Conservation and Land Management could be pursued for this area
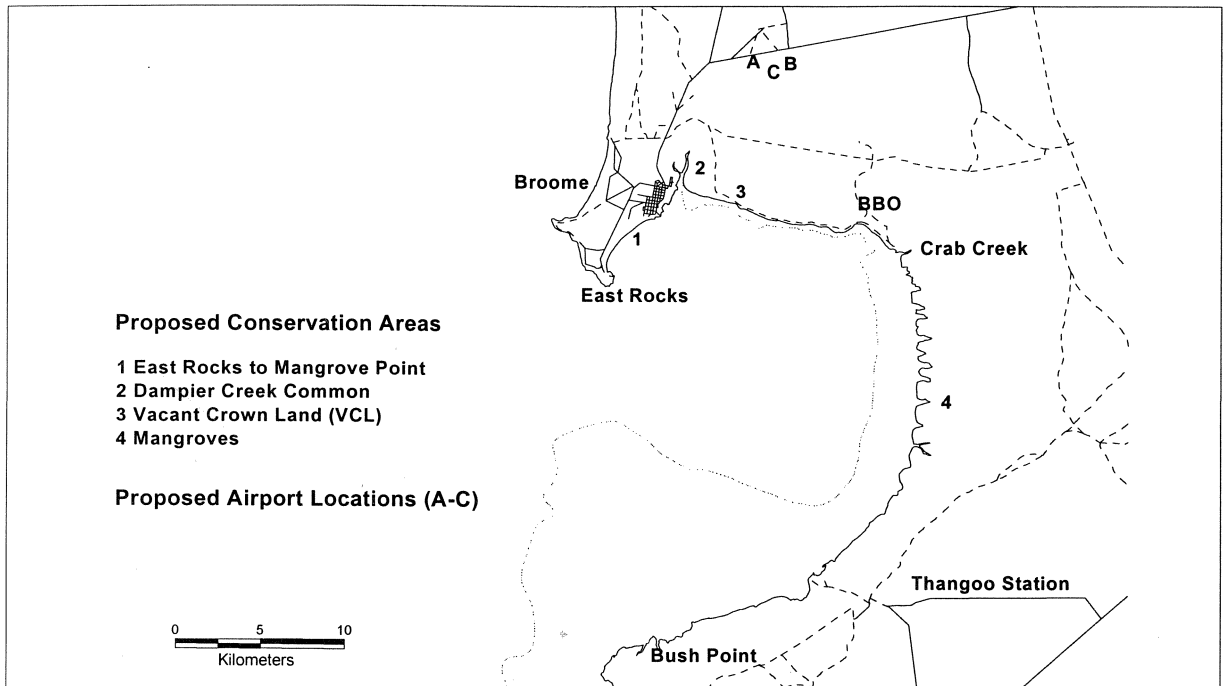
Fig. 10.1: Map showing the proposed conservation areas and preferred sites for the new airport.

The conservation area suggested above (Watkins 93) is more extensive than the original proposal made by the Department of Conservation and Land Management for the Roebuck Bay Marine Park (1987). Proposed extensions include the important shorebird roosting areas between Fall Point and Fisherman's Bend, the mangrove stands of Dampier Creek and additional marine areas in Roebuck Bay. A larger conservation area is also seen as a more comprehensive approach to natural resource management in the Broome area."

Management of the Conservation Area

Our study has shown that Roebuck Bay is close to a pristine marine environment. The complexity of the ecosystem is considerable and the management of the system will need to reflect that complexity but be pragmatic enough for managers to implement.

Management Objectives

The following management objectives are also drawn from Watkins (1993):
1. "Conserve native species, habitats and natural processes." Our report has revealed that some benthic communities occur in patches and are thus vulnerable to disturbance. Over grazing has damaged natural stands of grass plains and salt marsh habitats landward of the extensive mangrove communities of the Bay. This needs to be monitored and managed with primary consideration for the maintenance of the marine and terrestrial ecosystems.
2. "Promote an appreciation and understanding of the marine environment and sites of cultural significance in the Park, through information, interpretation and education."
3. "Provide recreational opportunities and facilities which maximise the quality of experience sought by visitors."
4. "Provide for tourism, to the extent consistent with maintenance of resources" (but recognise the potential for increased human activity to cause serious disturbance of high tide wader roosts).
5. "Manage recreational and commercial fishing to ensure that the fish populations are not adversely affected."
6. "Provide for pearl oyster farming without adversely affecting the ecological character of the Park." It may be possible to identify indicator species of bivalves that, through on-going monitoring, will provide early warning of increases in levels of pollutants in the Bay. The extent to which a viable pearl industry is dependent upon the maintenance of pristine waters of the Bay is unclear but probably important.

7. "Integrate management and development of the Park with that of adjacent areas of land to achieve maximum effectiveness and optimum allocation of management resources."

8. "Ensure that all development and activities are consistent with the maintenance of species, populations, habitats, natural features, and cultural and scenic values."

9. "Conduct research programs aimed at understanding how impacts of use and natural processes affect the maintenance and management of the Park."

Management issues

It is clear that the areas most in need of management attention are those with the highest levels of human interaction. Of particular concern are issues relating to beach access for vehicles and pedestrians. High tide roosts are vulnerable along much of the northern shore of the Bay from off-road vehicles and passive pedestrian traffic and demand special attention. There is an increasing amount of tourist pressure on the southern parts of the bay around Bush and Sandy Points.

Watkins (93) identifies concerns for impact from boat launching facilities, tourism, recreational use, landscape management fire management, shellfish collecting, public education.

Further research is required to investigate the impact of pollutants on the benthic invertebrate fauna of Roebuck Bay, the potential for those pollutants to enter the Bay through run-off, ground water inflows, airborne mechanisms or physical chemical spills and the impact of ground water abstraction on the water table. Watkins (93) reports that "the Broome Coastal Management Plan (1987) has recommended a number of policies specifically for the Dampier Creek to Crab Creek coast. These include the need to:

a) establish a conservation area (At the time of writing this report, affirmative action has been taken by the Broome Shire Council and Rubibi, through liaison and grant applications).

b) rationalise the gravel quarrying operations along the coast and rehabilitate the existing pits.

c) realign Crab Creek Road to minimise erosion of the cliffs.

d) prevent illegal camping and shack construction.

e) control the movements of off-road vehicles.

f) close all tracks around Dampier Creek tidal flats to ensure protection of the tidal flat and mangrove system.

g) formalise car-parking areas.

h) close tracks along the coast that provide access to important roosting areas for shorebirds."

At the time of writing this report pre-emptive action has been taken on items b) to h)).

POTENTIAL IMPACTS

Location of Industry

Roebuck Bay contains intertidal flats in the north and east of the bay covering approximately 200 km² at spring low tides. There is a large variation in tidal range, varying from 10 m at the full and new moon spring tides, down to half a meter during the neap tides occurring in between.

There needs to be adequate recognition of the potential for infrastructure development north of the shoreline of Roebuck Bay to impact upon the bay. A large amount of data has been collected in the past 17 years on some aspects of the shorebirds and benthic invertebrate populations of Roebuck Bay. However the information about marine flora and fauna is limited. It is precisely this limitation that demands that proper research is carried out on Roebuck Bay. There is potential for industry to impact on the Bay where land within 15 km of Western Australia's most biologically diverse Bay is earmarked for development for heavy industry purposes.

The recent Waterbank Structure Plan refers to the development of heavy industry in association with a new airport. It is unclear if the term refers to heavy industry in a typical sense or what heavy industry could be suitable for a remote area with limited resources such as the Broome area.

The Plan identifies land on the corner of the Broome to Derby Road and Cape Leveque Road as being suitable for development as a sewage treatment site. Ground water and surface water flows must not be allowed to carry the pollutants from this site into the Bay. The proposal to establish two PhD students to work on sediments and hydrogeology of the Bay (operating from the Broome Bird Observatory) will enhance the understanding of the potential for pollutants from industry to impact upon the Bay.

Groundwater harvesting

This report has shown that many of the life forms in the benthos occur patchily throughout the bay. The reasons for this patchiness are unclear but one hypothesis may involve eruptions of groundwater from the substrate that encourage certain species (Lavaleye, pers comm). The protection of this resource must be included in the management of the Bay. There should also be consideration for the potential for these features to transport pollutants onto the intertidal zones of areas such as Roebuck Bay.

The requirement for potable water for the expansion of Broome and its industry needs consideration. Proper environmental impact studies must precede any development of this resource that may cause stress to the benthic or avian fauna of the Bay. These studies should consider the potential for the increased demand for water created by the progressive expansion identified in the Plan to encourage the development of water from a dam on the Fitzroy River. The resultant horticultural development along the coastline east and south east of Broome could have significant impact on the natural ecosystems of Roebuck Bay. In particular the development of the area for production of cotton is of concern. The potential development of up to 500,000 hectares for horticulture (probably mainly cotton) would be deleterious for the natural systems of the region. Surface expressions of the ground water (such as mound springs) could disappear with the increased demand for ground water. Systems dependant on aquifer levels being maintained, could also be threatened by increased abstraction from a large scale horticultural industry.

The possible intrusion of seawater from reduced head pressures as a result of excessive abstraction could affect coastal communities. Sea grass beds of Roebuck Bay (and along the 80 Mile Beach) could be adversely affected with the reduction in fresh water flows eventuating in damage to sea grass communities and their dependant fauna.

Pollutants can change species composition and density

Sediments exposed to stress from either low dissolved oxygen events or contamination are characterised by:
- reduced community biomass
- reduced species richness
- possibly less biomass consisting of deep dwelling species and equilibrium species
- more biomass consisting of opportunistic species (Dauer 1993).

Ecological stress is best measured by multiple methods or analyses with different assumptions. Biological measurement supplements other measurements of the state of the biota (Dauer 1993).

Estimates of the benthic macrofaunal community (organisms retained on a 1 mm screen) are often used to indicate environmental health (Piersma pers comm). Dauer (1993) classified benthic animals as:
- relatively sedentary (cannot avoid deteriorating water/sedimentary quality conditions),
- relatively long living (indicate and integrate water/sediment quality conditions),

- likely to consist of different species that exhibit different tolerances to stress (can be classified into functional groups),
- commercially important or are important food sources for economically or recreationally important species,
- likely to have an important role in cycling nutrients and other chemicals between the sediments and the water column.

The potential for pollutants to impact upon the invertebrate fauna of Roebuck Bay, and consequently threaten the shorebird population is not well understood (Piersma, pers comm). Before any industry is developed along the hinterland of Roebuck Bay, in particular the area between Dampier Creek and Crab Creek and the Roebuck Plains floodplain, the planners should be confident that there is no risk of alteration to the benthic ecosystems. No level of increased stress to the wildlife of the intertidal areas should be countenanced. The following excerpts highlight the potential for pollutants to alter the integrity of environments such as Roebuck Bay.

Dauer (1993) draws from work by Pearson and Rosenberg (1978) and Rhoads et al. (1978) in formulating a description of highly stressed macrobenthic communities being dominated by species that are shallow dwelling, short lived and primarily annelids. Dauer postulates that it is likely that high mortalities of benthic communities associated with periodic hypoxic or anoxic events will have several predictable effects. Longer-lived benthos is generally deeper dwelling within the sediment and cannot survive long enough to become either biomass dominant or established in the deeper depth intervals. Therefore such a community becomes dominated by short-lived shallow dwelling species (Dauer (1993), Biological Criteria).

"Species richness as measured by the number of species per replicate is lower due to the smaller number of species with the physiological adaptations, behavioural characteristics or spatiotemporal recruitment patterns necessary to overcome hypoxic or anoxic stress.

Contaminated sediments present a diversity of stresses for benthic communities and result in patterns of biomass with lower species richness and shifts in community composition to a dominance by shallow dwelling species. Contaminants are diverse chemical compositions and have cumulative effects on the macrobenthos as well as consumers of the macrobenthos. Contamination of marine and estuarine sediments is therefore a serious threat to both living resources and human health" (Dauer 1993).

Pollution Pathways

The Waterbank Structure Plan identifies a number of sites as being preferred sites for a new airport and associated industry. A, C and D are preferred sites and are less than 20 km north of the Bay.

Further work is required to ensure that the site selection is made on the basis of sound scientific principles. Although this topic is outside the scope of this report the impact of a new airport located in a major flyway of the migrating shorebirds may have ramifications on the long-term management strategies devised for the intertidal areas. This study has, however, shown that Roebuck Bay has many near pristine qualities that must be protected from potential contaminants from developments such as those associated with large airports.

The Broome Bird Observatory has evidence showing large numbers of shorebirds migrate out of Roebuck Bay across the proposed airport sites at A, C and D (Fig. 10.1). This is also true for the existing airport location but there is insufficient evidence to confirm whether the risk is higher or lower. The Broome Airport Relocation Taskforce should ensure that the airport is relocated to an area that has a demonstrably lower bird strike risk.

There are concerns that there is insufficient consideration for the potential for a major chemical/pollutant/ oil spill at any of the proposed sites to impact upon Roebuck Bay and its dependant fauna. The location of a new airport at site A, C or D would place the facility "downstream" from the Town Water Reserve and "upstream" of Roebuck Bay.

Further research is required to determine the potential for pollutants to reach the intertidal flats of Roebuck bay through airborne, underground water flows, or physical means. The Werribee Sewage Farm near Melbourne has contributed to large quantities of organic waste being deposited in the intertidal areas (Lane 1987). In this case the succession of a few species of deposit feeding invertebrates has provided shorebirds with a rich feeding ground of extremely high density and demonstrates a case where organic pollution has favoured some migratory shorebirds. However the downside is that there appears to have been a decrease in diversity of benthic fauna and shorebird species.

Summary

Roebim-97 has identified Roebuck Bay to be a truly exceptional natural habitat - a wilderness in many aspects. The study revealed a bio-diversity of world class standards and high conservation value that demands special consideration. It has provided an insight into the nature and distribution of the biomass. And revealed that some of the communities are vulnerable due to their patchy occurrence in the benthos.

The ability of shorebirds to adapt to polluted or disturbed habitats has been demonstrated in a number of locations around the world. The degree to which these locations have changed from the original species composition is less clear but it can be demonstrated that there have been real changes to water quality and faunal structure(Port Phillip Bay, Delaware Bay, Chong Ming Dao).

Adaptability is not the real issue when it comes to management of intertidal marine habitat. Maintaining the integrity of the ecosystem is the real issue. The measure by which we may be judged in the future is the degree to which we have been able to maintain species diversity in unique environments such as Roebuck Bay. The rest will follow automatically as a consequence.

Recommendations

1. Apply the "Precautionary Principle" to the proposed development of any new airport, industry or water resources in the West Kimberley, that the project should only proceed when there is sufficient information on the possible ecological effects of the development.
2. Identify through proper Environmental Impact Studies and then protect, important ecological values and processes that rely on the near pristine water and sediment qualities of Roebuck Bay.
3. Apply the principles of Adaptive Environmental Management to any future industrial or water resource development(s) in the West Kimberley.
4. Recognise the Council of Australian Governments' water resource policy reforms and National Competition Council competition policy reforms, that investment in water infrastructure may only be undertaken if it is economically viable and ecologically sustainable.
5. Recognise all other International (Ramsar, CAMBA, JAMBA), National (National Estate, COAG; ANZECC Principles) and State (National Parks and Nature Reserve policies) obligations for sustainable management of the Roebuck Bay system, it's floodplain and associated wetlands.
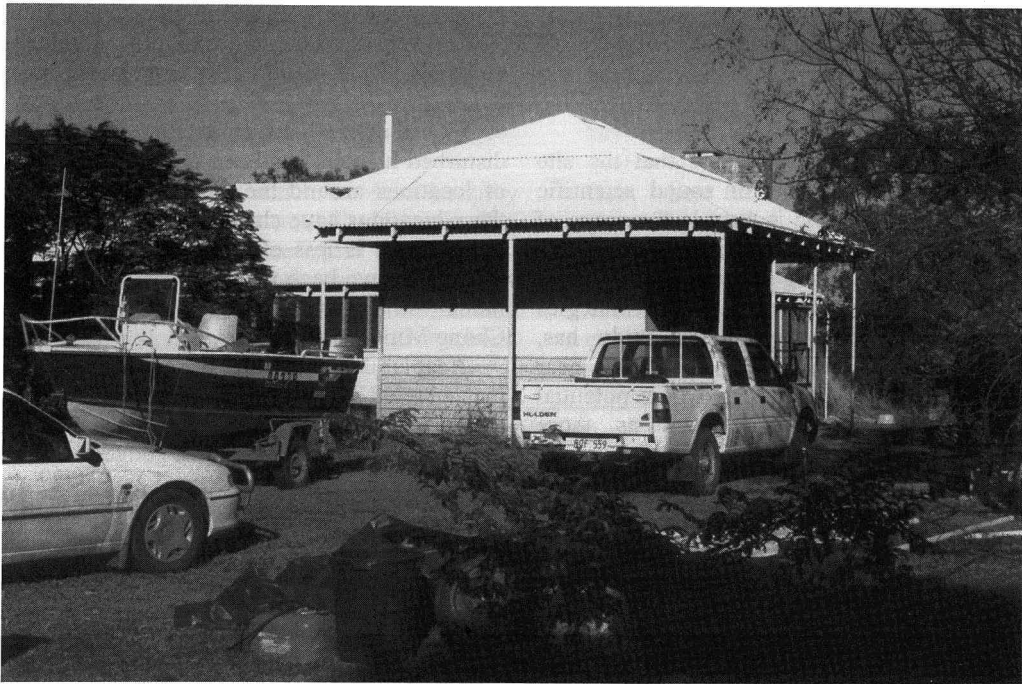
Top: The old Derby Leprosarium, now called Bungerun. The facility provided accommodation and laboratory space during the field work.

Bottom: Wallis Hovercraft, which provided a safe platform for 4 to 6 people from which to sample. Without it, access to remote sites of King Sound would have been impossible. Further, sampling on sandbanks would have been too dangerous because the incoming tides with speeds in excess of 3 m/s can easily cut off the way back to the shore. The hovercraft proofed to be quite untroubled by tidal currents and was suited for all terrain except for areas with very high sand ripples. Photographs by Marc Lavaleye.

11 BEYOND ROEBIM'97: REPORT ON DERBIM'98 PRELIMINARY REPORT

Markus Pepping, Marc Lavaleye & Grant Pearson

Introduction

Shorebird studies in the North-west of Western Australia have primarily been concerned with Roebuck Bay and a portion of 80 Mile Beach between Cape Missiessy and Mandora Station. An aerial survey conducted in the mid 1980s of the coastline from Wyndham to Broome failed to identify any significant shorebird roosts or concentrations of shorebirds. However, Walcott Inlet and King Sound were identified as likely to contain suitable habitats. A bird survey of Doctors Creek, 20 km north of Derby, was carried out in November 1997 by Chris Hassell from the Broome Bird Observatory. This was on behalf of the proponents of a tidal power station and revealed shorebird numbers in moderately high density around the Creek.

The potential and extent that King Sound may support large populations of shorebirds remained, however, unsubstantiated. In the event of shorebirds being displaced from their traditional habitats at Roebuck Bay and 80 Mile Beach it has been suggested that other sites - such as King Sound - may provide suitable alternative sites for feeding and roosting.

In 1997 an intensive survey of the northern and part of the eastern shores of Roebuck Bay was carried out by a collaborative group from CALM, Curtin, NIOZ and the Broome Bird Observatory. This survey enabled a close examination of why Roebuck Bay is so important to shorebirds. Over a period of 14 days 800 stations were visited. 550 of these were sampled and analysed quantitatively for macrobenthic animals. Sediment samples were analysed for colour and texture in the field and retained for further laboratory analysis. A total of 17,000 individual animals were collected during the process from more than 160 different taxa yielding probably more than 500 intertidal invertebrate species (Ch. 7). This biodiversity places Roebuck Bay among the richest known intertidal areas in the world.

In July a smaller pilot study comprising the same team of researchers from Curtin, CALM, NIOZ and the Broome Bird Observatory took place in King Sound. The WA Museum also participated with assistance with taxonomy from Shirley Slack-Smith. 59 stations were visited and core samples for benthic animals and sediments were taken. Shorebird numbers were noted when possible. The preliminary results of these are discussed later on in this chapter.

Participants for the survey were based at the old Derby Leprosarium, now named Bungerun. This excellent facility provided a quality of accommodation and laboratory space quite unexpected. Access to the edge of King Sound was, generally, not difficult but the logistics of traversing the large distances across the Sound was daunting. Several methods were tried, including:

- Small BBO Hovercraft - generally not successful due to the condition of the skirt, engine and the high sand ridges formed on the bed of the Sound which created substantial obstacles for the small craft.
- 6 wheel drive Argo amphibious craft. - this was unsuccessful in the thick, deep or loose substrates. It has considerable use on the harder sand flats on the Sound bed but even with tracks required lengthy detours to avoid boggy areas of deep silt.
- Wallis Hovercraft - an excellent if expensive way to cover large areas of soft mud, high sand ridges and open water. It provided a safe platform from which to sample and carried substantial loads of 6 passengers plus sediment samples, spare fuel and personal gear and was untroubled by tidal movement except during launching and retrieval.
- Foot traverse - the most reliable method of covering short distances between tides. Nevertheless it required consideration for protection from crocodiles and the unknown aspects of tidal movements and tidal bores.
- Local Derby resident participation level was low but important. The local knowledge provided by local interest groups was helpful.

Objective
The fieldwork was aimed to do a pilot survey on the distribution, diversity and biomass of the benthic intertidal fauna of the mud- and sandflats, in combina-
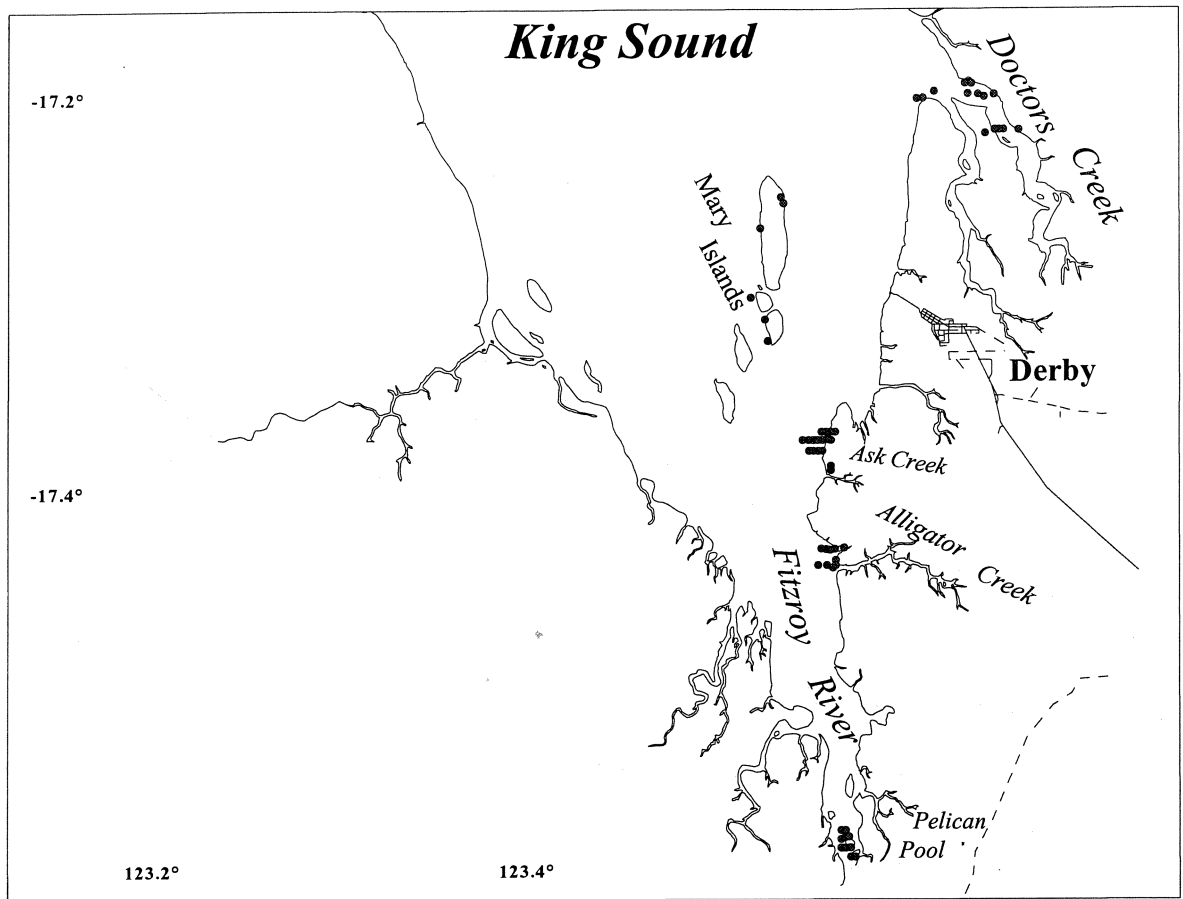
Fig. 11.1: Map of the southern parts of King Sound and the positions of the sample stations.

tion with sedimentological and geological investigations. This survey will provide data with which a comparison with the data of Roebuck Bay (ROEBIM'97) and an assessment of the suitability of the intertidal area for foraging birds, especially migratory waders, can be made.

Description of the area

King Sound, located roughly between 123 and 124° E, and 16° 15' and 17° 45' S in the Kimberley region of north-western Australia, is a large, shallow (6-18 m deep) marine embayment of approximately 5,000 km² (Fig. 11.1). The climate is very similar to that of Roebuck Bay (Ch. 5), which lies approximately 150 km to the east. Approximately 620 mm of rain falls in the short wet period in summer between December and March. Precipitation during the winter is negligible. There are two wind seasons corresponding to the wet and dry season. In the dry season trade winds from the

east and southeast are dominant in strength and frequency. An afternoon sea breeze is developed from the northwest and west. During the wet season winds from the northwest and west are dominant, and sea breezes are subordinate. The wet season is also the period of tropical cyclones. Analysis of cyclone tracks over the past 60 years show that on average every two years a cyclone passes within 100 km of Derby, and every 5 to 6 years within 50 km. Winds are important for the study area because they generate small waves, which together with tidal currents are responsible for the erosional processes in King Sound (Semeniuk 1982).

During the wet season King Sound is the estuary of the Fitzroy River, during the dry season King Sound essentially is a marine embayment. Geologically, King Sound is a Quaternary depositional embayment within the Canning Basin.

The main King Sound embayment delineated by mangroves that occur at mean sea level is funnel-shaped, narrowing to the south towards the Fitzroy River. However, its shape at the high spring tide mark

Plate 11.1: Perspectives of Mary Island, King Sound, Western Australia
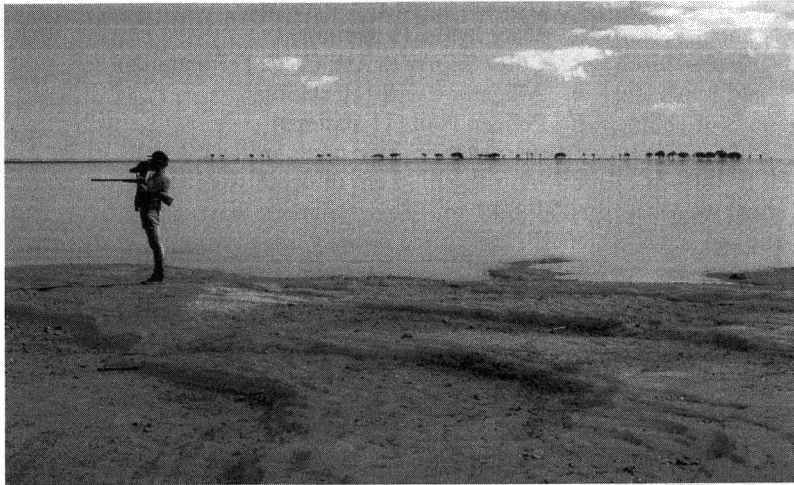
Exposed intertidal flats of Mary Island during low tide. Most of the intertidal areas consist of coarse sands that are almost barren of life. What looks like a Fata Morgana in the background are the crowns of open mangals, shown in detail below.

Open mangals on the weather exposed side of Mary Island in King Sound. The landscape has an aspect of an African tree savanna rather than a mangal. A closer look reveals that erosion is responsible for this formation. Strong tidal currents expose the root systems of the trees and prevent the establishment of saplings. The viviparous seedlings are swept away before they can anchor themselves firmly to the ground. Only the older trees, here probably *Sonneratia alba*, can resist the currents. Towards the sea the trees space out even more until they totally disappear.

Extensive mangal on the leeward side of Mary Island at low tide. While the landward and seaward sides of mangals in Western Australia mostly consist of pure *Avicennia* stands or paired associations, the interior often exhibits mixed formations of up to 6 species.

Photographs by Marc Lavaleye.

tends to be more irregular to sub-rectangular. The coastline of King Sound has large semidiurnal tides. Equinoctial spring tide range recorded at Derby is up to 11.5 m; the mean spring tide range is about 9.4 m; the mean neap range is 4.5 m. Tidal currents reach velocities of 1.5 – 2 m/s in open waters, and 3 m/s and greater in narrow tidal creeks during periods of ebbing spring tide. Wave action overall is negligible. The embayment is protected from oceanic swell by islands of the Buccaneer Archipelago. However, small waves are generated for a short period by afternoon sea breezes and by periodic summer storms. The waves are responsible for local coastline erosion and some shoreward transport of sand and debris. In the main, however, the embayment may be viewed as tide dominated.

The waters of King Sound and creeks that drain high tidal flats are turbid throughout the year. Turbidity is especially marked during spring tides, when fine muds from the surrounding salt flats are suspended and washed into the sound. Aerial observations show that these turbid waters extend out of King Sound as a plume and are finally deposited in deeper waters offshore.

Erosion and local sedimentation are taking place concurrently along parts of the King Sound coastline, or are alternating along other parts (Semeniuk 1980). However, erosion today is the obvious and dominant process. Aerial photographs taken over the past 28 years show a steady retreat of the coastline. The dominant erosional processes are cliff, sheet and tidal creek erosion. Rates of erosion are variable in space and time, depending on current velocities, wave action, and the underlying foundation material. Cliff erosion in the southern parts of the embayment is estimated to be in the order of 30 to 50 m/a. Even faster rates of about 90 m/a occurred between 1949 and 1967 in the Alligator creek area near the mouth of the Fitzroy River (Fig. 11.1). On the other hand, erosional rates of up to 2 m/a, which were directly measured, were more typical of most cliffs in the southern parts of King Sound. These unequal rates of erosion result in a very scalloped coastline. The extent of erosion is most clearly visible where the root systems of mangroves are undercut along tidal creeks and slopes (Plate 12.1). Erosion seems to have been the dominant process for the last 5,000 years. Before that, during three mayor transgressions in the Quaternary (2 Pleistocene, 1 Holocene), sediments were accreting until they formed the shore-fringing platform of wedge upon which modern geomorphic processes act.

Biology

Macrofauna was sampled at 59 stations within King Sound (Fig. 11.1 and Plate 11.1 for Mary Island). All stations were intertidal. The sampled stations were distributed over the following five areas:

1. Doctors Creek (15 stations)
2. Mary Island (6 stations)
3. Colac Shoals to Ask Creek (17 stations)
4. Alligator Creek (10 stations)
5. Pelican Pool (11 stations)

At every station three cores with a diameter of 10.2 cm down to about 30 cm of depth were taken, covering in total 1/40 m². This sediment was sieved over 1-mm mesh, and sorted directly after sampling at the temporary installed wetlab in the Leprosarium. This had the advantage that most animals were still alive. This helped detection in the sorting trays because of their movements and on the other hand made identification easier. Of each sample the name and number of the species was noted, as well as the lengths of each animal.

Further notes of the visible fauna (including birds) within about 50 meters of each sampling site were made, as were notes on grain size, surface colour, current ripples, etc. To get an exact figure for grain size and porosity a 10 cm deep sediment sample, taken with a core of a diameter of 6 cm was taken, to be worked out later by the geologists of Curtin University.

Results

Species diversity and overall abundance of macrozoobenthic species in King Sound are very low, indicating a very hostile environment especially for sessile animals. The total number of species we found in the samples were 19 out of the following taxonomic groups:

- Crustaceans (5)
- Gastropods (3)
- Bivalves (1)
- Polychaetes (4)
- Isopods (1)
- Amphipods (1)
- Nemertines (1)
- Actiniaria (1)
- Echinoderm (1)
- Insect larvae (1)

The most abundant taxa were *Scopimera* (Sand bubbler crab), with 29 individuals in 14 out of 59 sites, and *Corbula* spec., with 66 individuals in 10 out of 59 sites. High numbers of individuals were found only in one or two sites, indicating that habitats with a more suitable environment do exist. Samples from one location at Alligator Creek contained 23 Hydrobiidae, 13 Pyramidellidae, 8 Corbuliidae and one Insect larvae, making it the 'richest' site that was sampled. (For density per square meter multiply the figures by 40).

Apparently these locations are exceptions, representing one of the few areas where current velocities are lower and animals are not swept away by the tidal currents. 31 out of 59 stations didn't contain any living macrozoobenthic species, the poorest area being sampled was Pelican Pool (Fig. 11.1), where only 3 out of 11 sites showed living animals in small numbers. This is probably due to strong currents and the height of the sandbanks, which are well above MWS (Mean Water Spring).

Discussion

The low diversity and biomass can be explained by a combination of some of the following features of King Sound:

a)   High tidal current velocities of up to 1.5 – 2 m/s in open waters and 3 m/s and greater in deep, narrow tidal creeks during spring tides (Semeniuk, 1981). The currents rework the upper layers of the sediment constantly, making it impossible for sessile animals like most of the bivalves and polychaetes to survive. The finer sediments are washed out into the open ocean, leaving only clear washed, medium to coarse-grained sands, which are an unsuitable environment for most species. This is because coarse sands have a low water capacity and therefore dry out quickly, have little pore space and little organic content. Current velocities are highest in tidal creek systems and in the southern parts of the embayment due to its funnel shaped bathymetry. Coarse sediments are therefore deposited near the mouth of the creeks and in the southern parts of the bay, building up high, often megarippled sandbanks, which form an especially unsuitable habitat for most species (Fig. 11.2).

b)   High sediment load in the water column. The waters in King Sound are very murky, carrying a high load of small particles (clay/silt) that may clog the gills of filter feeding animals. The fine sediment load in the water column can be explained by erosion processes along the coastline of King Sound and the neighbouring tidal flats, and, to a lesser extent, by sediment input from the Fitzroy River during the wet season. Sheet, cliff and tidal creek erosion are the dominant processes that are shaping the geomorphology of King Sound for the last 5000 years. Older stratigraphic units (2 Holocene, 4 Pleistocene), comprising sand, interlayered sand and mud deposits, muddy sands and mud, are readily eroded (Fig. 11.3) and the current veloci-

Fig. 11.2: Sandbank in a high energy environment of King Sound. Megaripples with their long axis perpendicular to the current direction and with wavelengths of more than 5 m were common. The crests consisted of coarse sands, while the troughs showed a thin veneer of finer substrate that is deposited during slack tide. Photograph by Marc Lavaleye.

Fig. 11.3: Erosion of mudbanks. The mangal soils consist of interlayered mud and sand. These soils developed during former times of transgression when the sea level was approximately 2 m higher and are now eroded by tidal currents. The roots are undercut and the trees are dying. The whole mangal system moves progressively farther inland, keeping pace with the erosional processes in most parts of the embayment. The fine muds are carried in suspension until they are finally deposited in deeper waters offshore.
Photograph by Marc Lavaleye.

ties lead to differential settlement of the particles. Gravel and coarse sands stay in the bay, while finer sediments are washed into the open sea. Only during slack tide is there a deposition of finer particles (ephemeral sediment veneer), which are stripped off again by spring tides and storms.

c)   Changing levels of salinity. During the dry season the salinity of King Sound is basically that of the open ocean (32-35 psu). During the wet season salinity changes drastically because of fresh water input from the Fitzroy River and groundwater aquifers. Salinities as low as 6 psu have been recorded in the southern part of King Sound and Doctors Creek. This might be another reason for the low diversity of sessile animals, since very few species are adapted to drastic changes in salinity.

d)   Macrotidal range and slope gradients. For a macrotidal environment with a tidal range of up to 11.5 m during EHWS (equinoctial high water spring) surprisingly little surface area is exposed during nor-

mal tides. This is due to the steep gradient of the inclined slope, which is typical for the geomorphology of King Sound. Within the lower-lying tidal flats only sandbanks and shoals, consisting of coarse-grained sands and gravel, are exposed regularly. Vast areas in between the sandbars are exposed only during spring tides. This is another mayor difference between King Sound and Roebuck Bay, the slope gradients of the latter being a lot shallower, thus exposing more surface area at a given change of the water level and offering a larger feeding ground for shore birds.

The animal best adapted to this harsh environment seems to be the very mobile crab *Scopimera* (sand bubbler crab) of the family Ocypodidae. At some places they showed a density of up to 240 individuals per square meter. They rework vast amounts of sediment, feeding on the little organic matter the sandflats have to offer. This explains the dominance of this species in King Sound. Out of the class Bivalvia only the Corbuliidae seem to be sufficiently adapted. This may

Fig. 11.3: Erosion of mudbanks. The mangal soils consist of interlayered mud and sand. These soils developed during former times of transgression when the sea level was approximately 2 m higher and are now eroded by tidal currents. The roots are undercut and the trees are dying. The whole mangal system moves progressively farther inland, keeping pace with the erosional processes in most parts of the embayment. The fine muds are carried in suspension until they are finally deposited in deeper waters offshore.
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be due to their shell shape, which is very rounded and offers little resistance to currents, and their small size.

Summary

It is clear that the substrates in the parts of King Sound that we sampled are significantly different to those at Roebuck Bay. King Sound is dominated by the high tidal current velocities, the periodic flooding of the Fitzroy River and the high sediment loads in the water column. These factors combine to restrict suitable habitat for benthic invertebrates and, consequently, shorebirds.

Further work is justified to properly quantify the shorebird use of the Sound during the summer migration period and to extend the biological and geological fieldwork to the whole of the Sound. An integrated survey of Stokes Bay and Walcott Inlet to the north should also be carried out to complete the picture of potential shorebird sites north of Roebuck Bay.
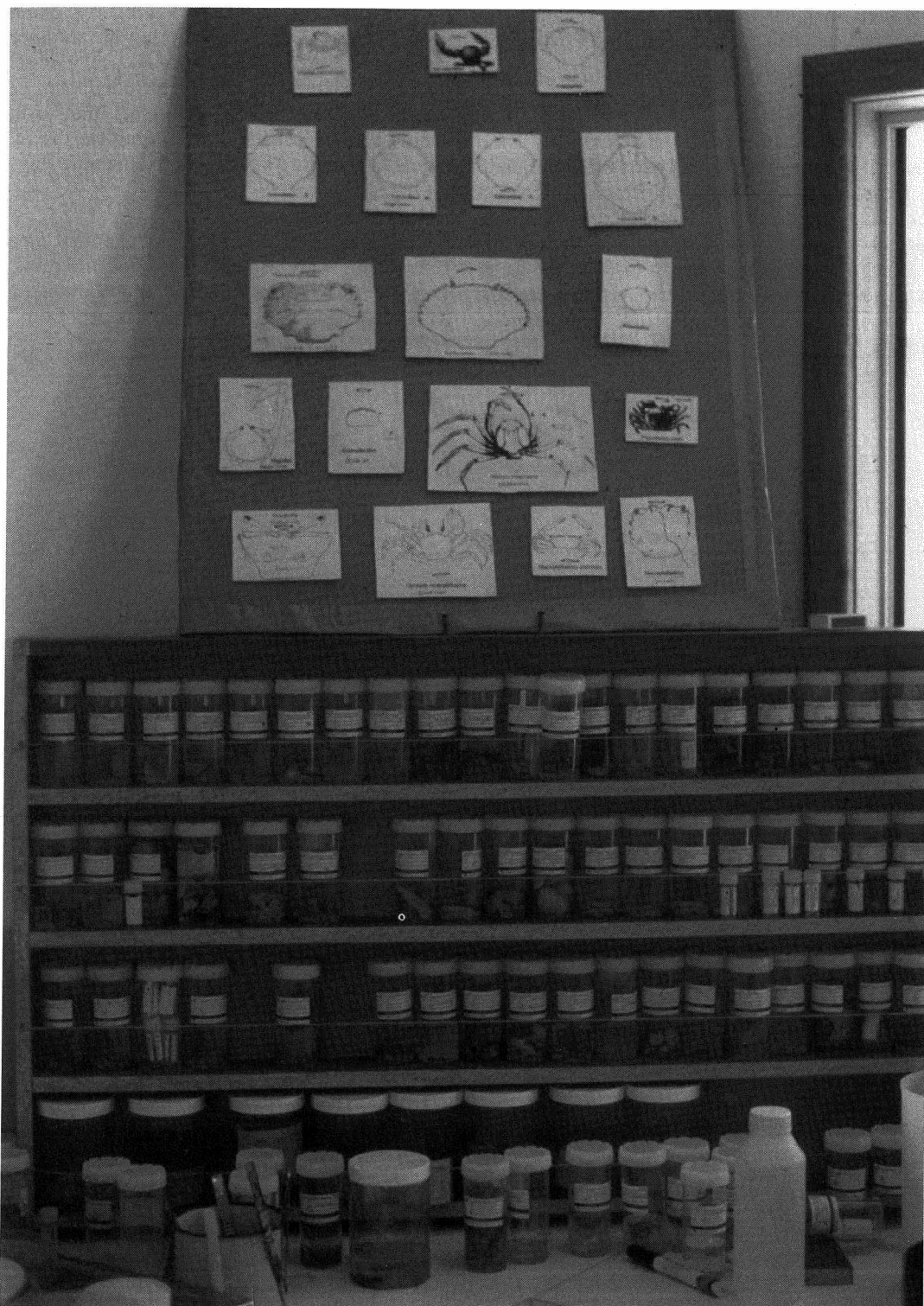
Reference collection and poster of common crabs to help with identification. Most of the taxa found and later on preserved in alcohol so far have not been identified to species level. The complete reference collection will be donated to the Western Australian Museum after completion of the scientific work at NIOZ. Photograph by Marc Lavaleye.

12 GENERAL DISCUSSION

Theunis Piersma, Markus Pepping & Grant Pearson

Most natural environments of the world are in the process of being heavily affected by modern humankind. Often there remains little hope that we can even assess the extent of the changes taking place. This is especially so in tropical areas where biodiversity is high (and the task of description thus daunting), where human pressure on the environment is often high as well, but where academic expertise is often low (Wilson 1992). In the tropics of Northwest Australia there are two large areas of intertidal habitat that, without any doubt, carry clear distinction in a global context in view of the large migrant shorebird populations that occur there: 80-Miles Beach and its intertidal forelands, and Roebuck Bay. Both appear relatively pristine. As yet, they appear to have been largely unaffected by the presence of humans' ever more powerful tools to modify natural environments. Obviously, these intertidal lands have undergone changes in connection with worldwide changes in sea-level, and the aborigine populations have used resources such as the bloody-cockles (*Anadara*), fish and dugongs for many thousands of years. But, by and large, the 80-Miles Beach and Roebuck Bay areas may well provide two important and beautiful examples of rare undisturbed tropical intertidal ecosystems. Ecosystems that are being encroached by expanding modern human populations. Ecosystems that urgently require detailed description in order to be able to assess what may be lost, what will have been lost if changes would take place, and, indeed, what could be done to avoid any such losses in the first place.

Such were the main reasons to organise the first comprehensive survey of the benthic animals of Roebuck Bay's intertidal in June 1997. That so many shorebirds utilise these resources provided an additional attraction, and also inspired the design of the survey. Mapping benthic resources on a scale typical of the daily movements of shorebirds would enable us to compare the distribution of benthic animals with that of the shorebirds feeding on them. Although hardly explored in the present report, the degree of patchiness in the occurrence of benthic animals (Thrush et al. 1989, Legendre et al. 1997), and the way that this affects the distribution of their predators

(Hines et al. 1997, Cummings et al. 1997), is something of great scientific interest. For all we know, it is also an issue that had never been addressed for tropical intertidal communities. Indeed, there is very little comparative material at hand to place our findings in context as far as the tropics are concerned (Alongi 1990, Piersma et al. 1993). The results of this survey may therefore be put to good use as a reference-point for several years to come.

We hope that the report that you have just gone through showed the impressive intertidal biodiversity of Roebuck Bay and laid out some of the possible sedimentological, biological and paleohistorical explanations for to this diversity. The results demonstrated also how much can be achieved in less than two weeks of fieldwork by a relatively small, dedicated team. Of course, most people usually worked far beyond the point of exhaustion, and the work was only possible due to a happy combination of scientific and logistic expertise, and the proper logistics themselves. In extensive featureless landscapes like intertidal mudflats it would have been impossible to sample a 200 m grid without GPS. Equally, it would have been impossible to carry out as extensive a survey as the present one without a hovercraft in combination with a more stationary support-boat. Instant data-entry was possible by the availability of three personal computers. We would never have been able to sort all the samples in time if we had not had access to the dust- and mosquito-poor and relatively cool laboratory that was newly built at BBO. Successful sorting depended on the availability of many pairs of hands and able eyes, and the identifications depended on having a world-class taxonomist in our midst. Having said this, we also should acknowledge the fact that we were poorly prepared for the aftermath of this survey, for the analyses of the many thousands of data-points, the thinking about their meaning and the writing of this report. Due to good fortune, the basic data could be used by some of the participants for their undergraduate and graduate theses. Quite outside the context of the expedition-proper, these people put in the many months behind the desk that are necessary to come up with a report like the present.
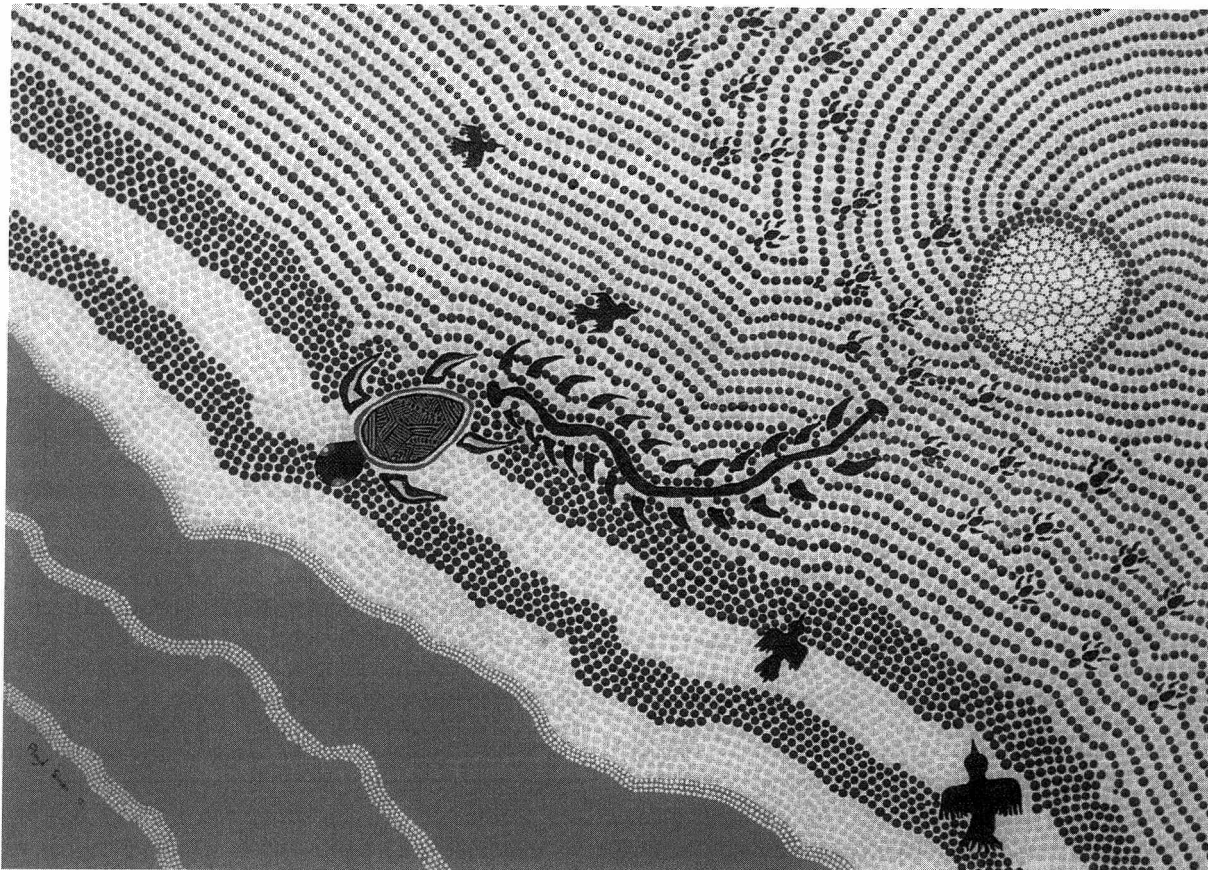
Koo Wa Nee by Floyd Simon (© Towabba Art)

Let us go through the new knowledge generated directly and indirectly by the ROEBIM-97 efforts. Using a combination of the processing of specific satellite images (one being taken in 1994 during high tide, another being taken in 1995 during low tide) and grid-based modelling efforts derived from geographical information system theory, a model of the tidal inundation regime of the northern shores of Roebuck Bay was developed (Ch. 4). The basic outputs of this model (times of tidal exposure and inundation) could be put to good use in the studies of the factors explaining the distribution patterns of intertidal benthos as well as shorebirds.

Based on sediment samples taken with a 5 cm diameter core to a depth of 10 cm from 530 locations, a detailed description of the spatial distribution of different kinds of sediments in the northern part of Roebuck Bay could be presented (Ch. 5). Most important for the description of the sediments was a detailed granulometric analysis yielding grain size distributions and median grain size values. In addition, the origin of the sediment was studied, e.g. by doing a carbon

analysis of 36 samples representing the range in sediment types for total carbon. Three main sediment types were recognized. The soft muds in the northeast and the east are composed of fine silty material mainly composed of carbonate-rich material of biogenic origin. The other extreme is formed by sediments along the northern shore that are composed of fine-grained sediments mainly consisting of nonbiogenic spheroid quartz particles which appear characteristic of sediments transported in moderate to high energy marine conditions. A third sediment type found in the northwest near Dampier Creek and also in an area between the two earlier types, was called "very fine grained sand" and seems to be comprised of a mix of the two previous sediment types. It is clear that not only physical processes are responsible for the kind of sediments found at certain places, but that the presence of tubeworms, seagrasses and algae, as well as burrowing animals, are important factors. Many invertebrates in Roebuck Bay may thus play roles as 'ecosystem engineers' (Giblin et al. 1995, Jones & Lawton 1995, Levinton 1995).

The importance of oceanography and geomorphology to the biological richness of an area became abundantly clear in July 1998 with a similar survey of the King Sound area near Derby (DERBIM'98), the efforts which are briefly reported on in chapter 11. In this area with its huge tides and very course sediments, benthic invertebrates were very sparse, which would explain the paucity of shorebirds known from this region.

With an overall average density of 1,287 macrobenthic invertebrate animals (retained on a 1 mm sieve) per square meter, and an average estimated biomass value of 12.46 g AFDM/m^2 (Ch. 6 and 7), benthic invertebrates are about as abundant in Roebuck Bay as they are in the one other well-studied tropical intertidal area, the Banc d'Arguin on the west coast of Africa in Mauritania, where comparable values for animals retained on 0.6 mm sieves were respectively 1,404 n/m^2 and 17.0 g AFDM/m^2 (Wolff *et al.* 1993). However, with a minimum of 161 taxa, compared with slightly over a 100 species on the Banc d'Arguin, macrobenthic biodiversity of Roebuck Bay is far larger. In both areas particular groups contribute disproportionally to the numerical and biomass values. At the Banc d'Arguin, a large arc-shell (*Anadara senilis*) that occurs over a limited range in low densities nevertheless makes up almost half of the benthic biomass (Wolff *et al.* 1993). In Roebuck Bay two families of tube-building polychaete worms (Chaetopteridae and Oweniidae) account for almost 60 % of the numbers, although 'only' about 20 % to the biomass. Two sipunculid species, though low in absolute numbers,

take a similar high proportion of the AFDM due to their very large size. It is important to note, however, that these figures do not take into account the big animals that live deep in their burrows, such as mantis shrimps (*Squilla*), sentinel crabs (*Macrophthalmus*) and mudskippers. The distribution of all taxa was very patchy, a phenomenon often observed in intertidal studies.

There were large distributional differences between taxa. The substrate and associated physical and chemical parameters, and the position within the tidal regime seemed to be mainly responsible for these patterns. Some taxa can be characterised as generalists and exhibited a wide range of distribution that was centred around intermediate conditions both regarding the position within the tidal regime and sedimentological characteristics (*Macrophthalmus* crabs, some free-living polychaetes). In contrast, other taxa are very specialised to certain habitats, e. g. some snails of the upper intertidal, or cumaceans, which were restricted to sandy regions of the lower intertidal.

In summary, gastropods were mainly found in the upper intertidal regions with medium to high silt content. Bivalves reached peak densities in the muddy parts of the lower intertidal, but different species were found in virtually all habitats of the intertidal area. Polychaetes taken as a class seemed to be more opportunistic and were found everywhere except in the upper intertidal and the very muddy parts of Roebuck Bay. Crustaceans were found all over the intertidal. *Macrophthalmus* crabs and crabs of the family Hymenosomatidae were characteristic for the mid- and

Seabirds by Terry Johnstone (© Towabba Art)

lower intertidal, while crabs of the genera *Uca*, *Ocypode* and *Scopimera* dominated in the upper intertidal and the beaches.

With 12 phyla, 20 classes, 114 families and almost 200 different taxa, the macrobenthic invertebrate fauna is as diverse as one would expect from an area of tropical marine sediments in the Indo-Pacific region (e.g. Roy et al. 1998, Douglas 1998). Obviously, this huge biodiversity is a great asset to Australia. However, the fact that only 10 % (ten percent!) of the taxa could be confidently assigned a species name within the three months of volunteer specialist's work allotted to this aspect, presents us with a rather grandiose problem. It actually means four things.

The marine invertebrates of Northwest Australia desperately need the full attention of expert taxonomists to describe the huge biodiversity of the local coastal habitats. That even of well-known groups such as the bivalves (which, incidently, are a critical food resource for the shorebirds) only a small fraction can presently be identified confidently to species level is disturbing, and calls for action at both scientific and conservation managerial levels.

The large numbers of specimens unidentified to species imply that we have only scratched the surface of describing true biodiversity in Roebuck Bay. A survey using 0.5 mm in stead of 1 mm mesh sieves would yield even higher diversity estimates (Coleman et al. 1997).

With the rather limited taxonomic refinement of our description we may have to pay the price of perhaps not being able to detect some important changes in macrobenthic community structure in the future, should they take place at taxonomic levels below those that we have been able to distinguish during the present survey.

It may also be a problem that predator prey-interactions take place at the level of species and populations (e.g. Piersma 1987b). Failure to distinguish the right entities may thus constrain the analyses that can be carried out using the present dataset.

The shorebirds feeding on the benthic resources of Roebuck Bay were surveyed over the same grid as soon as they were all back from their arctic breeding grounds in October 1997 (Ch. 9). For some abundantly occurring shorebirds it was rather difficult to find associations between their occurrence and the densities of their preferred prey species. This was especially so for the shorebird species following the waterline and feeding mainly along the sea-edges such as the two knot species (Red Knot *Calidris canutus* and Great Knot *Calidris tenuirostris*) and the two godwit species
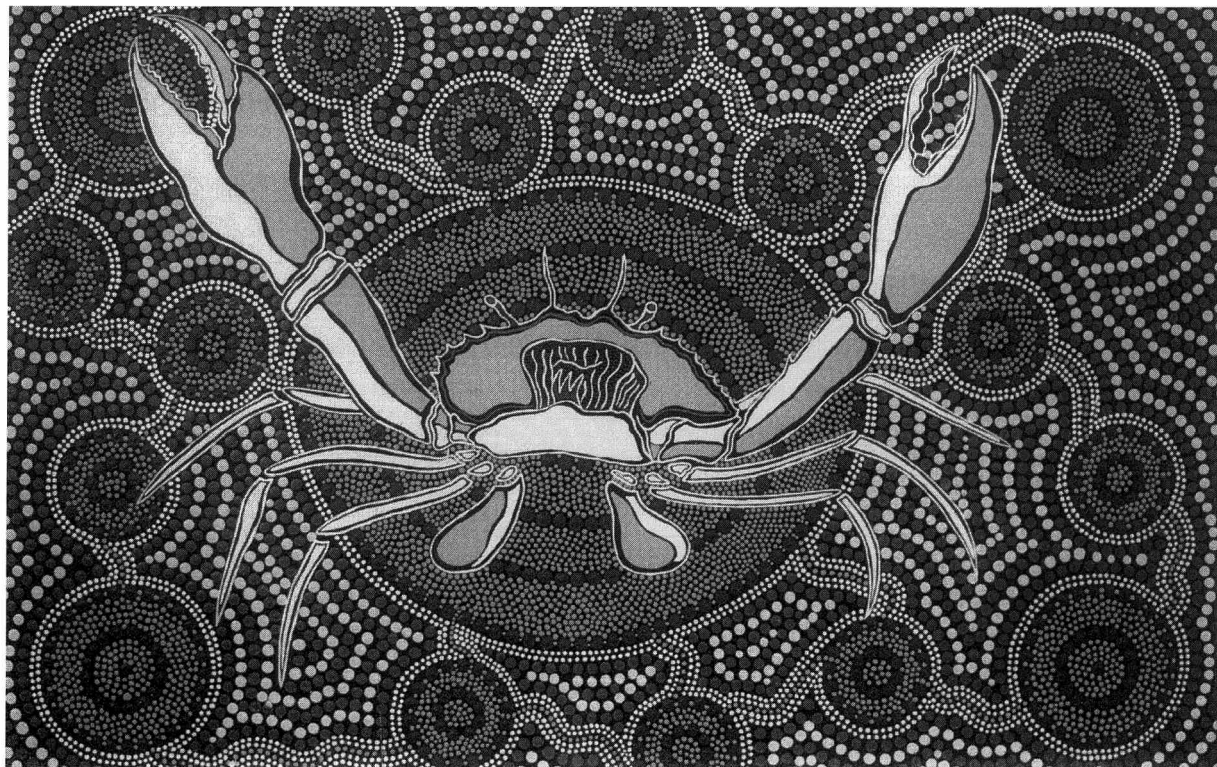
Crab on the Defense by Graham Ridgway (© Towabba Art)
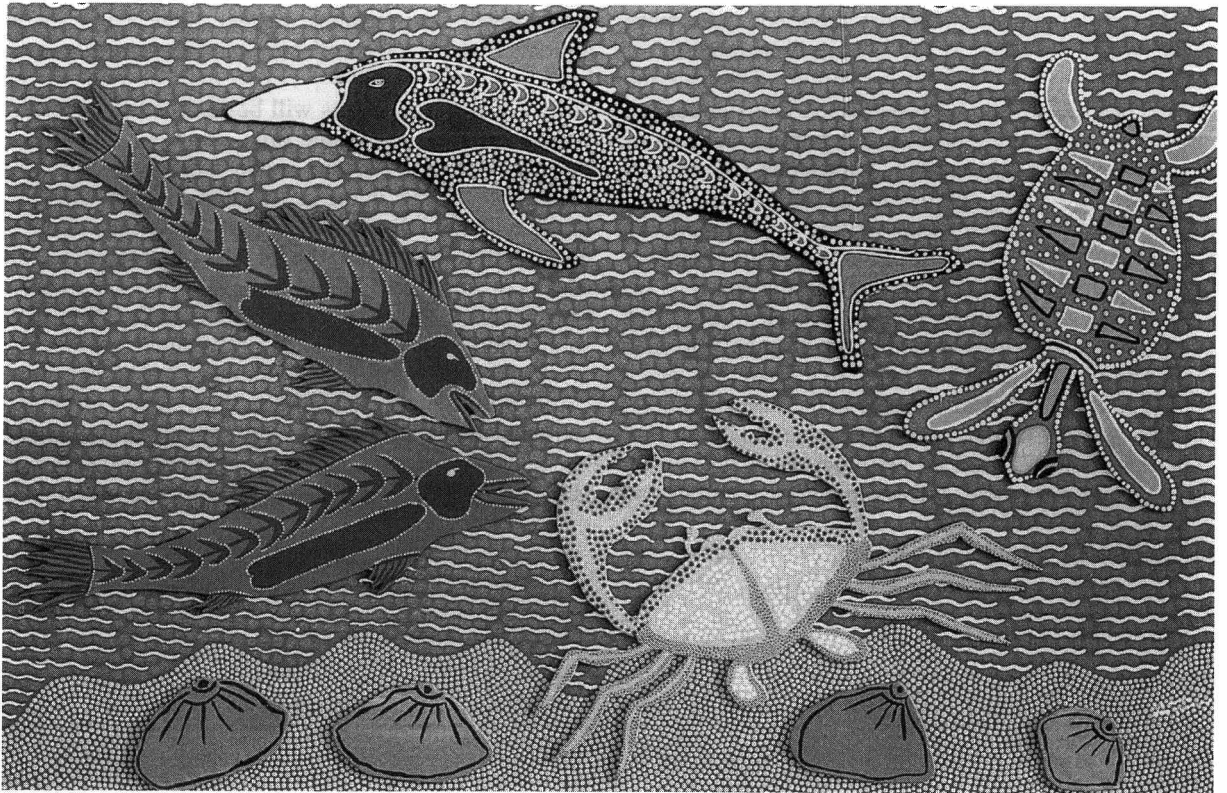
Forster Seascape by Lisa Omara and Terry Johnstone (© Towabba Art)

(Bar-tailed Godwit *Limosa lapponica* and Black-tailed Godwit *Limosa limosa*). All four species are known as specialised tactile hunters, and have been used as model predators to understand shorebird-benthos interactions (Piersma et al. 1993). Nevertheless, their outspoken habit of following the tidelines strongly suggest that measures of availability (notably size and depth of living) commonly used to describe prey abundance on temperate flats (e.g. Ens et al. 1994), are inadequate to completely capture the features that make bivalves and other prey harvestable for the knots and the godwits. Presumably such prey behave in ways that make them more easily detectable near the sea-edge than elsewhere. Indeed, preliminary studies on the burying behaviour of three bivalve species carried out during ROEBIM'97 (Ch. 8), demonstrates how important behavioural features linked to seawater movements may be for shorebird predators. Whereas it was not so easy to match the distribution of the tactile hunting knots and godwits with that of their presumed prey types, the concentration of species specialised in feeding on large crabs and mudskippers (Eastern Curlew *Numenius madagascariensis*, Whimbrel *Numenius phaeopus*, and to a lesser extent Greenshank *Tringa nebularia*) on the soft and muddy sediments in the north-east corner of Roebuck Bay coincided nicely with the distribution of their presumed prey.

The flats close to the town of Broome, just east of Dampier Creek, are characterised by mixed sediments (i.e. the category of "very fine grained sand") and harbour quite distinct benthic communities as well as a very distinct assemblage of shorebirds (especially visual hunters for small active prey, including the rather rare and quite specialised Terek Sandpiper *Xenus cinereus*; Piersma 1986a). After reviewing the various infrastructural works that are in the books for the Broome area (Ch. 10), we come to the conclusion that the management of a unique area as Roebuck Bay should not allow for the macrobenthic communities and the species higher in the food-chain to adapt to changing conditions, but that the maintenance of the present integrity of the ecosystem is the real issue. We believe that the measure by which this generation will be judged in the future, is through the degree to which we have been able to maintain species diversity in unique and irreplaceable environments. In this context, the visit of part of our team to the Rubibi Aboriginal Land Heritage and Development Commission was very heartening. We share their concerns for an unspoiled Roebuck Bay.

Having completed this report, there lay major tasks ahead when it comes to the proper dissemination of the results. Although the interpretation of the satellite images has meanwhile been published in a symposium volume (Hickey et al. 1998) and a popular account of ROEBIM'97 has appeared in Landscope (Piersma et al. 1998), the basic sedimentological and biological data and data-analyses await writing up as papers in the refereed literature. The latter especially requires placing our results in the context of the existing literature (e.g. Thomas 1997, Roy et al. 1998). For analyses of community structure we may have to play with additional statistical tools (e.g. van der Meer 1991). A major point of concern is the desperate present state of taxonomic expertise in general (Cotterill & Dangerfield 1997), and as we have discussed above, for Australian tropical soft-sediment invertebrates in particular. Most of the material collected, even after the fieldwork, could not be identified to taxonomic levels lower than families. In fact, quite a few of the animals that we have collected (and that are presently held in storage at NIOZ, Texel) may be new to science. All type specimens will be returned the Western Australian Museum in due time, and very much hope that the incentive for this move will be provided by major investments in the description and identification of the unique biological material at hand (any offer for help in this regard will be gladly considered by the editors of this report!). The benthic survey planned for the 80-Miles Beach intertidal area in October 1999 should add importantly to the collections. All this material and the distributional data that goes along with it could thus help to establish a new level of understanding of, as well as to help safeguard, Northwest Australia's amazing marine biodiversity, the importance of which cascades down into the tundras of north-eastern Asia!

13 CONCLUSIONS

1. Roebuck Bay near Broome is one of the foremost internationally important sites for shorebirds in the Asia-Pacific flyway system. It is home to 150,000 shorebirds (or 'waders') in the non-breeding season. The thousands of shorebirds that occupy Roebuck Bay from August to April come from a huge breeding range in the north, spanning an arc of about 130 longitudinal degrees, from western Siberia to arctic Canada. The very fact that so many shorebirds fly 30,000 km per year to get to and away from Roebuck Bay, suggests that the bay has much to offer, particularly abundant food.

2. Roebuck Bay presents a macrotidal, low energy environment in a semi-arid tropical setting. Most of the rainfall occurs between November and April. Averaged over the years, evaporation exceeds precipitation for any one month. Torrential rainfalls are experienced during rare cyclonic events. Water exchange with the ocean is not restricted and salinity levels in the pore water of the sediments should stay in the marine range most of the time.

3. To answer the question why and how so many birds are able to make a living in the mud of Roebuck Bay, to evaluate the food stocks for migratory shorebirds, and to provide the groundwork for future environmental impact assessments in the Roebuck Bay area, the intertidal area of Roebuck Bay was quantitatively sampled for benthic animals in June 1997, when a team of about 30 volunteers and professionals joined forces during ROEBIM'97, the 'Roebuck Bay Intertidal benthic Mapping programme'. For a series of 12 successive days at almost every low tide 2-4 three-person teams walked parts of the study area. In addition there was a two-person Hovercraft team working the outlying sites. To the best of our knowledge, this is the first detailed mapping of benthic biodiversity on tropical intertidal mudflats.

4. Representing 45 km², or about a quarter of the intertidal area of Roebuck Bay, and covering the entire northern shore of Roebuck Bay, benthos and sediment cores were taken at 537 suitable stations laid out in a grid-like fashion with intersections every 200 m. Each sampling station yielded a list of invertebrate species, along with their number and sizes, and a value for median grain size and silt content of the sediment.

Most molluscs and many crustaceans were sorted to species (even though some of these species are presently unknown to science and need formal description). All worms (including the polychaetes, but also groups such as phoronids, nemertines and sipunculids) were sorted and counted to family level at best (polychaetes) or phylum level at worst (phoronids and nemertines, for example).

5. Sediments of the intertidal largely reflect the hydrographical conditions present. Fine sands are typical for the narrow intertidal area in the north-central part of the embayment, where current velocities are highest. In the Dampier Creek area, fine and very fine sands alternate on small scales. Muddy substrates are typical for the banks of the tidal creek systems. The large intertidal areas to the east are characterised by carbonate muds of predominantly marine origin.

6. Small scale variations in the sedimentology are due to organism/sediment interactions. Stabilising agents include tube-building polychaetes, root systems of mangroves and sea grass, and mucus-excreting lower algae. Important destabilising agents are burrowing crabs, suspension and deposit feeding organisms, and other taxa that physically disturb the sediments. Organic content and nutrient levels of the intertidal can be assumed to be very low. Subsurface sediments are only weakly anoxic, and black sulphide rich layers are not present. The rather well aerated sediments thus offer a relatively benign habitat for infauna compared to oxygen depleted subsurface sediments of organically rich intertidal areas.

7. A total of 161 taxa were identified from the quantitative samples; another 30 taxa were observed opportunistically. Only bivalves were identified to species level, the other taxa to family (gastropods, polychaetes, decapod crustaceans) or even higher taxonomic levels. The total densities were with 1,287 ind./m² in the range reported in other macrobenthic studies. The polychaete families Chaetopteridae and Oweniidae dominated the fauna in terms of abundance and biomass. The 20 most abundant taxa make up more than 90 % of the total numbers. On the other hand many rare species were present and almost half of the taxa occurred at less than 2 % of the stations sampled. On the class level polychaetes were most abundant with 70 % of the individuals, followed by

bivalves (12.5 %), crustaceans (8 %), brittle stars (4.2 %), and gastropods (2.5 %). All the remaining taxa amounted to only 2 %. In respect to biomass, the dominance of the class Polychaeta was not as conspicuous (45.4 %). Few, but very large sipunculids amounted to 23 % of the total biomass, followed by bivalves (16.3 %), crustaceans (10.5 %), and gastropods (3 %). Brittle stars, though high in numbers, make up only 0.4 %. The distribution of biomass did not follow any trends and was very patchy due to the occasional inclusion of large crustaceans or sipunculids.

8.   With 12 phyla, 20 classes, 114 families, and over 160 different taxa, the macrobenthic invertebrate fauna is very diverse, a feature quite typical for biota in the Indo-Pacific region. However, only 10 % of the taxa could be confidently assigned a species name within the three months of volunteer specialist's work allotted to this aspect. Thus, the marine invertebrates of north-western Australia desperately need the full attention of expert taxonomists to describe the huge biodiversity of the local coastal habitats. The large numbers of specimens that could not be identified to species level imply that we have only scratched the surface of describing true biodiversity in Roebuck Bay. This may make it impossible to detect some important changes in macrobenthic community structure in the future, should they take place at taxonomic levels below those that we have been able to distinguish during the present survey.

9.   The distribution of the major taxa was very patchy and densities differed significantly at neighbouring stations. Nevertheless, a few patterns emerged and a rough zonation of faunal assemblages could be discerned. Clear vertical zonation patterns of faunal assemblages were not obvious and were probably veiled by other factors. The supratidal showed the typical ocypodid belt described in most other tropical studies. The most abundant genus here was the sand bubbler crab Scopimera. Lower regions were only vaguely defined. In summary, gastropods and bivalves seem to be characteristic of the upper intertidal areas independent of grain size characteristics. The mid- and lower intertidal was numerically dominated by polychaetes in the sandier regions, whereas bivalves prevailed in the muddy substrates of the study area.

10.   A comparison with four other tropical intertidal areas was attempted. These were the Banc d'Arguin in Mauritania, the Haughton estuary in north-eastern Australia, intertidal mudflats of the west coast of peninsular Malaysia, and an intertidal zone of

Surinam. The least diverse in terms of species numbers were the Malaysian and Surinam mudflats, both located in the wet tropics. Salinity changes, anoxic conditions and unstable sediments seem to be the main reason for the low diversity. The Haughton estuary in North Queensland has a semiarid climate. Salinities stay in the marine range throughout most of the year. Species numbers are higher compared to the former sites. The zonation patterns revealed some similarities with Roebuck Bay, and different, but similar genera fill identical niches. The Banc d'Arguin in Mauritania seemed to be most similar to Roebuck Bay in terms of its abiotic environment. Species numbers were lower than in Roebuck Bay, suggesting larger scaled geographical and historical processes to be at work. None of the mentioned sites, though for different reasons, was as diverse in terms of species numbers as Roebuck Bay

11.   Diversity of an area has two components: one attributable to the local habitat, the other to the region in which the community is embedded. The high diversity in Roebuck Bay may be explained on the local level by a combination of habitat heterogeneity, a relatively large population size, intermediate disturbance levels, and a low to intermediate productivity. Regional processes include the faunal exchange with other areas of the Indo-West Pacific and source/sink effects associated with long-distance larval dispersal.

12.   For some abundantly occurring shorebirds it was rather difficult to find correlations between their occurrence and the densities of their preferred prey species. This was especially so for the shorebird species following the waterline and feeding mainly along the sea-edges such as the two knot species (Red Knot Calidris canutus and Great Knot Calidris tenuirostris) and the two godwit species (Bar-tailed Godwit Limosa lapponica and Black-tailed Godwit Limosa limosa). All four species are known as specialised tactile hunters. In contrast, the concentration of species specialised in feeding on large crabs and mudskippers (Eastern Curlew Numenius madagascariensis, Whimbrel Numenius phaeopus, and to a lesser extent Greenshank Tringa nebularia) on the soft and muddy sediments in the north-eastern corner of Roebuck Bay coincided nicely with the distribution of their presumed prey.

13.   The outspoken habit of tactile feeding waders to follow the tidelines strongly suggest that measures of availability (notably size and depth of living) commonly used to describe prey abundance on temperate flats are inadequate to completely capture

the features that make bivalves and other prey harvestable for the knots and the godwits. Presumably such prey behave in ways that make them more easily detectable near the sea-edge than elsewhere. Studies on the burying behaviour of three bivalve species demonstrate that behavioural features linked to seawater movements may indeed be important in determining their availability for shorebirds.

14. There is urgent need to standardise the methodology of intertidal studies world-wide. So far, the few studies that have been conducted are hardly comparable, either due to differences in spatial or temporal scales or due to the accuracy and focus of the sampling itself. Methodologies developed in temperate regions need to be refined and adjusted for use in tropical regions. Limited access to study sites, strenuous environmental conditions, inadequate laboratory facilities, and a poor taxonomic and ecological knowledge of the sometimes very diverse intertidal fauna are common problems encountered in the tropics.

15. Coastal habitats, especially in the highly populated tropics, are threatened by human impact. It is high time to combine scientific efforts worldwide and work interdisciplinary in order to get a better understanding of intertidal ecosystems. The taxonomic description of tropical soft-sediment invertebrates, even though currently not regarded as a very fashionable trade, needs to be high on the research agenda.

14 ACKNOWLEDGEMENTS

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16 APPENDIX

Species list

Appendix 1: List of species observed at the tidal flats of Roebuck Bay with their average density (ind./m²) and biomass (mg AFDM/m²) calculated over the 537 stations sampled in June and July, 1997. Feeding modes are abbreviated as follows: SF = Suspension feeder, D = Deposit feeder, P = Predator, G = Grazer, Pa = Parasite. AFDM Type refers to the formulae used for biomass calculations (see Ch. 6). Frequency denotes the percentage of stations the taxon was found at. If feeding mode was not known or AFDM not included in the analysis, the fields are left empty. At the end of the list species are enumerated, which were not retrieved in the samples but found elsewhere.

Taxon	Family	Tax. group	F. mode	AFDM Type	Dens.	AFDM	Freq.
Chaetopteridae indet.	Chaetopteridae	Polychaeta	SF	H (L = 10)	469.20	1152.15	43.76%
Oweniidae indet.	Oweniidae	Polychaeta	D/SF	H (L = 15)	268.45	1613.36	35.75%
Amphiuridae indet.	Amphiuridae	Ophiuroidea	SF	1 mg/ind.	48.49	43.64	38.92%
Anodontia cf. *omissa*	Lucinidae	Bivalvia	SF	B	38.96	113.98	20.86%
Glyceridae (small)	Glyceridae	Polychaeta	P	H	31.06	134.04	38.18%
Siliqua cf. *winteriana*	Cultellidae	Bivalvia	SF	E	27.78	531.59	21.04%
Nephthys spec.	Nephtyidae	Polychaeta	P	H	21.53	273.93	30.17%
Paguridae indet.	Paguridae	Decapoda	D	I (L = 5)	20.71	37.07	17.32%
Tellina piratica	Tellinidae	Bivalvia	D/SF	E	14.82	294.97	13.04%
Opheliidae indet.	Opheliidae	Polychaeta	D	H	13.93	57.33	15.46%
Onuphidae indet.	Onuphidae	Polychaeta	P/SC/D/G	H	12.74	242.21	16.57%
Macrophthalmus spec.	Ocypodidae	Decapoda	D	J	12.74	641.03	24.02%
Hymenosomatidae indet.	Hymenosomatidae	Decapoda	D	J	12.51	32.45	13.22%
Nassarius dorsatus	Nassariidae	Gastropoda	SC	G	12.29	243.28	15.08%
Solemya cf. *terraereginae*	Solemyidae	Bivalvia	D	A	11.69	36.08	12.48%
Polynoidae indet.	Polynoidae	Polychaeta	P	H (2L)	11.69	71.57	17.13%
Tellina amboynensis	Tellinidae	Bivalvia	D/SF	E	11.10	147.84	14.15%
Capitellidae indet.	Capitellidae	Polychaeta	D	H	10.95	104.53	18.25%
Gammarus spec.	Gammaridae	Amphipoda	D	I	8.72	4.79	9.12%
Anomalocardia squamosa	Veneridae	Bivalvia	SF	D	7.67	243.66	8.75%
Lumbrineridae indet.	Lumbrineridae	Polychaeta	P/SC	H	7.67	560.53	16.39%
Anadara granosa	Arcidae	Bivalvia	D	D	7.00	105.23	6.15%
Maldanidae indet.	Maldanidae	Polychaeta	D	H	7.00	128.93	12.48%
Macoma cf. *exotica*	Tellinidae	Bivalvia	D/SF	E	6.85	52.95	10.24%
Orbiniidae indet.	Orbiniidae	Polychaeta	D	H	6.70	146.61	10.80%
Sternaspidae indet.	Sternaspidae	Polychaeta	D	H	6.18	4.88	4.47%
Sipunculida indet.		Sipunculida	D	H (2L)	5.36	1585.78	8.57%
Polychaeta indet.		Polychaeta		H	4.99	54.20	8.94%

Taxon	Family	Tax. group	F. mode	AFDM Type	Dens.	AFDM	Freq.
Sigalionidae indet.	Sigalionidae	Polychaeta	P	H (2L)	4.62	347.37	8.01%
mudTellina	Tellinidae	Bivalvia	D/SF	E	4.47	23.81	4.28%
Divaricella irpex	Lucinidae	Bivalvia	SF	B	4.32	39.67	8.01%
Phyllodocidae indet.	Phyllodocidae	Polychaeta	P/SC	H	4.10	71.26	8.57%
Spionidae indet.	Spionidae	Polychaeta	D	H	4.02	12.96	4.84%
Anthura spec.	Anthuridae	Isopoda	D	I	3.87	2.47	2.98%
Goneplacidae indet.	Goneplacidae	Decapoda	P	J	3.80	19.81	7.64%
Dentalium cf. *lubricatum*	Dentalidae	Scaphopoda	D	F (L/2)	3.65	20.84	7.08%
rooted Tunicate		Tunicata (S-Ph)	SF		3.65		2.05%
Ringed Sipunculid		Sipunculida	D	H (2L)	3.20	1011.11	6.33%
Glyceridae (large)	Glyceridae	Polychaeta	P	H	3.13	206.55	7.64%
Salinator cf. *burmana*	Amphibolidae	Gastropoda	D	G	2.91	9.18	2.79%
Lingula spec.		Brachiopoda	SF	E (L/2)	2.83	5.12	3.54%
Leptopentacta grisea	Cucumariidae	Holothurioida	SF		2.83		3.72%
Dentalium cf. *bartonae*	Dentalidae	Scaphopoda	D	F (L/2)	2.68	3.77	3.35%
Tellina capsoides	Tellinidae	Bivalvia	D/SF	E	2.46	77.95	3.54%
Tanaidacea indet.		Tanaidacea	D	I	2.23	9.80	4.66%
Cerithidea cingulata	Potamididae	Gastropoda	G/D	F	2.16	19.78	2.79%
Nemertini indet.		Nemertini	P	H	2.16	51.79	4.28%
Marginellidae indet.	Marginellidae	Gastropoda	P	F	1.94	1.97	3.35%
Squilla spec.	Squillidae	Decapoda	P	I	1.94	231.69	4.10%
Dictenophiura stellata	Ophiuridae	Ophiuroidea	D/P		1.94		2.23%
Flabelligeridae indet.	Flabelligeridae	Polychaeta	D	H	1.86	31.52	2.79%
Nucula cf. *astricta*	Nuculidae	Bivalvia	D	D	1.79	7.29	3.72%
Eulimidae indet.	Eulimidae	Gastropoda	PA	F	1.79	1.02	0.56%
Amphinomidae indet.	Amphinomidae	Polychaeta	P/PA	H	1.79	9.60	3.35%
Cumacea indet.		Cumacea	SF	I	1.79	2.37	3.17%
Paraonidae indet	Paraonidae	Polychaeta	D	H	1.71	63.23	2.98%
Vexillium radix	Costellariidae	Gastropoda	P	F	1.64	6.07	2.79%
Gobiidae indet.	Gobiidae	Pisces			1.64		1.86%
small Ingrid	Nassariidae	Gastropoda	SC	G	1.56	31.45	2.79%
green Phyllocidae	Phyllodocidae	Polychaeta	P/SC	H	1.56	124.92	2.23%
Shrimps	Caridea	Decapoda	D	I	1.56	16.09	2.61%
Modiolus micropterus	Mytilidae	Bivalvia	SF	A	1.49	24.05	2.42%
Columbellidae indet.	Columbellidae	Gastropoda	SC/P/D	F	1.49	3.82	2.79%
Edwardsia spec.		Anthozoa	P		1.49		2.61%
Corbula spec.	Corbulidae	Bivalvia	SF	B	1.42	5.00	2.05%
Nereidae indet.	Nereidae	Polychaeta	P/SC/D/G	H (2L)	1.42	76.07	3.35%

Taxon	Family	Tax. group	F. mode	AFDM Type	Dens.	AFDM	Freq.
Phoronida indet.		Phoronida	SF	H	1.34	33.14	2.05%
Cirratulidae indet.	Cirratulidae	Polychaeta	D	H	1.34	5.99	2.98%
brown Clubworm	Chaetopteridae	Polychaeta	P	H	1.12	9.37	2.42%
Cultellus spec.	Cultellidae	Bivalvia	SF	E	0.97	46.03	1.86%
Donax spec.	Donacidae	Bivalvia	SF	B	0.82	0.81	0.19%
Stenothyra spec.	Stenothyridae	Gastropoda	D	F	0.82	0.21	0.56%
Pilargidae indet.	Pilargidae	Polychaeta	P	H	0.82	3.75	1.68%
Syllidae indet.	Syllidae	Polychaeta	P/PA	H	0.82	8.77	2.05%
Sabellidae indet.	Sabellidae	Polychaeta	SF	H	0.82	3.41	2.05%
Retusa spec.	Retusidae	Gastropoda	P	F	0.74	0.37	1.49%
Ledella spec.	Ledidae	Bivalvia	D	A	0.67	2.08	1.12%
Tellina oval	Tellinidae	Bivalvia	D/SF	E	0.67	20.32	1.30%
Gari lessoni	Psammobiidae	Bivalvia	SF	B	0.67	19.16	1.68%
Tapes spec. 1	Veneridae	Bivalvia	SF	D	0.67	11.91	1.30%
Grafrarium dispar	Veneridae	Bivalvia	SF	D	0.67	20.17	1.30%
Balanoglossus spec.	Balanoglossidae	Enteropneusta		H	0.67	44.32	1.12%
Ampharetidae indet.	Ampharetidae	Polychaeta	D	H	0.67	5.24	1.68%
Corophium spec.	Corophiidae	Amphipoda	D	I	0.67	0.07	1.12%
Leucosia D	Leucosiidae	Decapoda	P	J	0.67	20.27	1.68%
Leucosia B	Leucosiidae	Decapoda	P	J	0.60	29.41	1.30%
Ophiotrichidae indet.	Ophiotrichidae	Ophiuroida	D/P		0.60		1.12%
Ctena spec.	Lucinidae	Bivalvia	SF	D	0.52	0.46	1.30%
Phasiolion spec.		Sipunculida	D	H (2L)	0.52	44.27	1.30%
Heterocardia gibbosula	Mactridae	Bivalvia	SF	C	0.45	10.13	1.12%
Mactra grandis	Mactridae	Bivalvia	SF	C	0.45	16.18	1.12%
Ensis spec.	Solenidae	Bivalvia	SF	E	0.37	9.32	0.56%
Polinices conicus	Naticidae	Gastropoda	P	G	0.37	13.03	0.93%
Porifera indet.		Porifera	SF		0.37		0.19%
Tellina pointed	Tellinidae	Bivalvia	D/SF	E	0.30	2.88	0.74%
Macoma Roebuck	Tellinidae	Bivalvia	D/SF	E	0.30	2.24	0.74%
Veneridae indet.	Veneridae	Bivalvia	SF	D	0.30	0.76	0.19%
Placamen gilva	Veneridae	Bivalvia	SF	D	0.30	7.55	0.74%
Clanculus spec.	Trochidae	Gastropoda	SF	G	0.30	0.43	0.74%
Brown Columbellidae	Columbellidae	Gastropoda	SC/P/D	F	0.30	0.60	0.74%
Terebridae indet.	Terebridae	Gastropoda	P	F	0.30	2.36	0.56%
Haminoea indet.	Haminoeidae	Gastropoda	P	F	0.30	0.26	0.56%
Leucotina spec.	Amathinidae	Gastropoda	PA	F	0.30	0.63	0.74%
cf. *Myrodes eudactylus*	Leucosiidae	Decapoda	P	J	0.30	6.53	0.74%

Taxon	Family	Tax. group	F. mode	AFDM Type	Dens.	AFDM	Freq.
Mudskipper indet.	Periophthalmidae	Pisces			0.30		0.74%
Divaricella Bushpoint	Lucinidae	Bivalvia	SF	B	0.22	3.58	0.19%
Placamen gravescens	Veneridae	Bivalvia	SF	D	0.22	3.24	0.37%
Laternula creccina	Laternulidae	Bivalvia	SF	D	0.22	3.76	0.56%
Littorinidae indet.	Littorinidae	Gastropoda	G	G	0.22	0.25	0.37%
Epitoniidae indet.	Epitoniidae	Gastropoda	P/PA	F	0.22	0.73	0.56%
Natica spec 2	Naticidae	Gastropoda	P	G	0.22	0.47	0.56%
Cassidula indet.	Ellobiidae	Gastropoda	D	F	0.22	0.42	0.37%
Echiurus spec.		Echiura	D	H (2L)	0.22	54.43	0.56%
Sabellariidae indet.	Sabellariidae	Polychaeta	SF	H	0.22	0.41	0.56%
Terebellidae indet.	Terebellidae	Polychaeta	SC	H	0.22	18.88	0.56%
Decapoda indet.	Crustacea	Decapoda		J	0.22	0.15	0.56%
Stolus buccalis		Holothurioidea	SF		0.22		0.56%
Mactra spec. 3	Mactridae	Bivalvia	SF	C	0.15	0.11	0.19%
Tellina spec. 1	Tellinidae	Bivalvia	D/SF	E	0.15	3.10	0.37%
Tellina mysia	Tellinidae	Bivalvia	D/SF	E	0.15	1.92	0.37%
Dosinia spec.	Veneridae	Bivalvia	SF	D	0.15	4.45	0.37%
Mitridae indet.	Mitridae	Gastropoda	P	F	0.15	0.48	0.37%
Turridae indet.	Turridae	Gastropoda	P	F	0.15	1.76	0.37%
Pyramidellidae indet.	Pyramidellidae	Gastropoda	PA	F	0.15	0.08	0.37%
Hirudinea indet.		Hirudinea		H	0.15	1.32	0.37%
Goniadidae indet.	Goniadidae	Polychaeta	P	H	0.15	0.29	0.37%
Mysidacea indet.		Mysidacea	SF	I	0.15	0.25	0.19%
Matuta planipes	Callapidae	Decapoda	P	J	0.15	42.43	0.37%
Ebalia spec.	Leucosiidae	Decapoda	P	J	0.15	1.38	0.37%
Mictyris longicarpus	Mictrydae	Decapoda	D	J	0.15	8.54	0.37%
Pilumnidae indet. 2	Pilumnidae	Decapoda	P	J	0.15	7.24	0.19%
Ocypode spec.	Ocypodidae	Decapoda	D	J	0.15	0.44	0.19%
Astropecten granulatus	Astropectinidae	Asteroidea	P		0.15		0.37%
Blue spot mudskipper	Periophthalmidae	Pisces			0.15		0.19%
Montacutidae spec.	Montacutidae	Bivalvia	SF	C	0.07	0.17	0.19%
Mactra spec. 1	Mactridae	Bivalvia	SF	C	0.07	3.77	0.19%
Mactra spec. 2	Mactridae	Bivalvia	SF	C	0.07	0.87	0.19%
Corbula (heavily ribbed)	Corbulidae	Bivalvia	SF	B	0.07	0.44	0.19%
Tellina bushpoint	Tellinidae	Bivalvia	D/SF	E	0.07	4.30	0.19%
Tellina cf. *remies*	Tellinidae	Bivalvia	D/SF	E	0.07	0.27	0.19%
Nerita spec.	Neritidae	Gastropoda	G	G	0.07	1.78	0.19%
Natica spec. 1	Naticidae	Gastropoda	P	G	0.07	0.27	0.19%

Taxon	Family	Tax. group	F. mode	AFDM Type	Dens.	AFDM	Freq.
Muricidae indet.	Muricidae	Gastropoda	P	G	0.07	4.60	0.19%
Nassarius C	Nassariidae	Gastropoda	SC	G	0.07	0.27	0.19%
Actaeon spec.	Actaeonidae	Gastropoda	P	F	0.07	0.30	0.19%
Turbonilla spec.	Pyramidellidae	Gastropoda	PA	F	0.07	0.02	0.19%
Little red polynoid	Polynoidae	Polychaeta	P	H (2L)	0.07	0.84	0.19%
Eurydice spec.	Cirolanidae	Isopoda	P	I	0.07	0.13	0.19%
Palaeomonidae indet.	Palaemonidae	Decapoda	D	I	0.07	99.71	0.19%
Gourrretia coolibah	Callianassidae	Decapoda	D	I	0.07	0.01	0.19%
Nursia plicata	Leucosiidae	Decapoda	P	J	0.07	0.41	0.19%
Leucosia F	Leucosiidae	Decapoda	P	J	0.07	1.57	0.19%
Pinnotheres cf. *cardii*	Pinnotheridae	Decapoda	-99	J	0.07	0.09	0.19%
Pilumnidae indet. 1	Pilumnidae	Decapoda	P	J	0.07	0.69	0.19%
Pycnogonida indet.		Pycnogonida	P	J	0.07	0.41	0.19%
Peronella tuberculata	Laganidae	Echinoida	D		0.07		0.19%
Protankyra verrelli	Synaptidae	Holothurioida	SF		0.07		0.19%
Montacuta spec.	Galeommatidae	Bivalvia					
Mactridae indet.	Mactridae	Bivalvia					
Mactra pura	Mactridae	Bivalvia					
Tellinidae indet.	Tellinidae	Bivalvia					
Tellina orange	Tellinidae	Bivalvia					
Tapes spec. 2	Veneridae	Bivalvia					
Venus spec.	Veneridae	Bivalvia					
Dosinia spec.	Veneridae	Bivalvia					
Calliostoma spec.	Trochidae	Gastropoda					
Niso spec.	Eulimidae	Gastropoda					
Onchidium spec.	Onchidiidae	Gastropoda					
Chrysallida spec.	Pyramidellidae	Gastropoda					
Arabellidae indet.	Arabellidae	Polychaeta					
Alpheidae indet.	Alpheidae	Decapoda					
Dorippe spec.	Dorippidae	Decapoda					
Procellanidae indet.	Porcellanidae	Decapoda					
Xanthidae indet.1	Xanthidae	Decapoda					
Xanthidae indet.2	Xanthidae	Decapoda					
Hairy Pilumnidae	Pilumnidae	Decapoda					
Mud sponge		Porifera					
Cerianthus spec.		Ceriantharia					
Stoichactis spec.		Actiniaria					
Mangrove anemone		Actiniaria					

Taxon	Family	Tax. group	F. mode	AFDM Type	Dens.	AFDM	Freq.
Shell anemone		Actiniaria					
Tunicata indet. 1		Tunicata					
Tunicata indet. 2		Tunicata					
Tunicata indet. 3		Tunicata					
Tunicata indet. 4		Tunicata					
Branchiostoma spec.		Pisces					
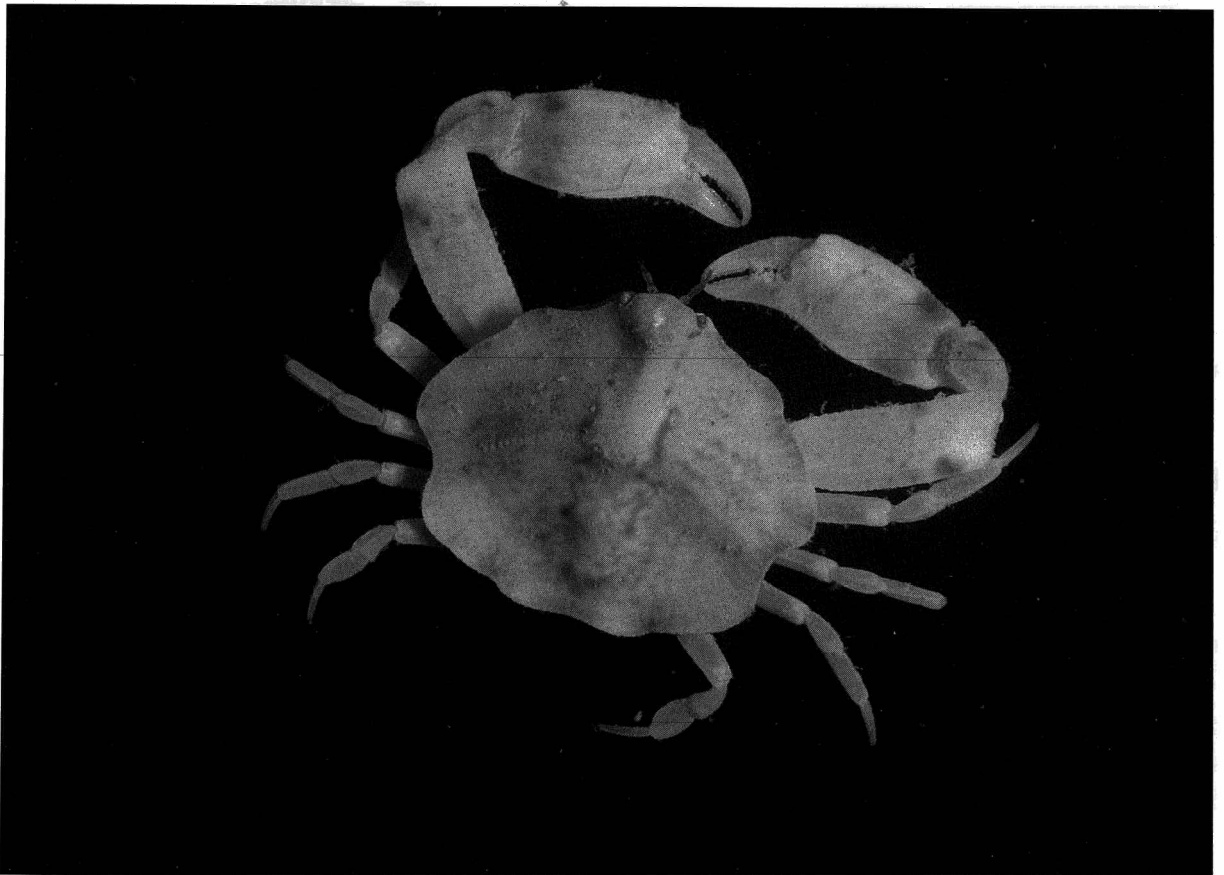
The Angel Crab, *Nursia abbreviata* is not rare on the tidal flats of Roebuck Bay. This beautiful crab was found at seven stations. Carapace length 10 mm.

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The front cover shows a satellite photograph of Roebuck Bay (Landsat Thematic Mapper). The town of Broome is next to Dampier Creek in the upper left of the picture, the core study side in the upper part and Bush Point and surrounding sandflats are in the low part of the cover picture. The mangroves around Dampier Creek, and those bordering the lower parts of Roebuck Plains (at right in the picture), stand out by their dark colours. The animal portraits illustrate a little of the huge benthic biodiversity that we encountered in the intertidal of Roebuck Bay. From left to right there are portraits of a polychaete worm of the family Glyceridae, a pebble crab of the genus *Leucosia*, a polychaete worm of the family Onuphidae, and the sanddollar *Peronella tuberculata*.

The back cover shows one of the editors on a mudsledge, and also, from left to right and from top to bottom the mussel *Modiolus micropterus*, a brittlestar of the family Amphiuridae, a sentinel crab *Macrophthalmus* spec., the bivalve *Siliqua* cf. *winteriana*, a tiny spider crab of the family Hymenosomatidae, the Ingrid eating snail *Nassarius dorsatus*, a polychaete worm of the family Onuphidae, the bivalve *Tellina amboynensis*, a pebble crab of the genus *Leucosia*, the sanddollar *Peronella tuberculata*, and a mantis shrimp of the family Squillidae.