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A GIS Study of Australia's Marine Benthic Habitats

by

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Declaration

This thesis contains no material that has been accepted for the award of any other degree or diploma in any other tertiary institution, and to the best of my knowledge contains no copy, paraphrase or material previously published or written by another person, except where due reference is given in the text.

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Supporting Publications

Some of the work presented in this thesis appears in peer-reviewed publications. Where substantial parts of these papers are reproduced in this thesis, it is in all cases my own original contribution to those papers that is transposed into the thesis. The papers directly related to the project work of this thesis are:

Beaman, R.J., Daniell, J., Harris, P.T., 2005. Geology-benthos relationships on a temperate rocky bank, eastern Bass Strait, Australia. Marine and Freshwater Research 56, 943-958.

Beaman, R.J., Harris, P.T., 2003. Seafloor morphology and acoustic facies of the George V Land shelf. Deep-Sea Research Part II 50 (8-9), 1343-1355.

Beaman, R.J., Harris, P.T., 2005. Bioregionalisation of the George V Shelf, East Antarctica. Continental Shelf Research 25, 1657-1691.

Beaman, R.J., Harris, P.T., in review. Geophysical variables as predictors of megabenthos assemblages from the northern Great Barrier Reef, Australia. In: B.J. Todd and H.G. Greene (Editors), Marine Geological and Benthic Habitat Mapping. Special Publication. Geological Association of Canada, St John's, Canada.

Harris, P.T., Beaman, R.J., 2003. Processes controlling the formation of the Mertz Drift, George Vth continental shelf, East Antarctica: evidence from 3.5 kHz sub-bottom profiling and sediment cores. Deep-Sea Research Part II 50 (8-9), 1463-1480.

Harris, P.T., Brancolini, G., Armand, L., Brusetti, M., Beaman, R.J., Giorgetti, G., Presti, M., Trincardi, F., 2001. Continental shelf drift deposit indicates non-steady state Antarctic bottom water production in the Holocene. Marine Geology 179 (1-2), 1-8.

Quotes

Il faut aller voir - We must go and see.

Jacques-Yves Cousteau

The real voyage of discovery does not consist of seeking new landscapes, but in having new eyes.

Marcel Proust

The very deep did rot: O Christ!
That ever this should be!
Yea, slimy things did crawl with legs
Upon the slimy sea.

Samuel Coleridge

Abstract

Continental shelf waters are subject to the greatest impact by humans. If marine ecosystems are to be efficiently managed and protected from the adverse effects of human activities, then identification of the types of marine habitats and the communities they contain is required. Research cruise data and existing data were collected at three diverse study sites on polar, temperate and tropical continental shelves within Australia's Exclusive Economic Zone (EEZ). This project conducted a multi-disciplinary analysis of satellite imagery, multibeam sonar, seismic profiles, oceanographic data, underwater video, and the results of sediment sampling. A Geographic Information System (GIS) was utilised to model the spatial boundaries of the physical and biological datasets. Spatial and multivariate statistical analyses were conducted on the GIS models and datasets to explore the relationships between abiotic and biotic patterns. GIS was used to map the spatial distribution of benthic habitats at each study site within a hierarchical context.

The East Antarctic continental shelf has had few studies examining the macrobenthos structure or relating biological communities to the abiotic environment. On the George V Shelf, GIS was used to map the geomorphology, surficial sediment and near-seabed water mass boundaries. A study of underwater photographs and the results of biological sampling provided information to infer the dominant trophic structure of benthic communities within geomorphic features. A hierarchical method of benthic habitat mapping was applied to the Geomorphic Unit and Biotope levels at the local (10s of km) scale. The study revealed that mud content, iceberg scour, and oceanic currents are the likely dominant abiotic factors in the broad-scale distribution of macrofauna on the George V Shelf.

To better understand the relationships between the geology of the seabed and associated biological communities, a multibeam sonar survey was conducted over New Zealand Star Bank, eastern Bass Strait, Australia. Through spatial and multivariate analyses of surficial sediment composition and underwater video, the biological assemblage patterns were related to the variation in geomorphology and substrate. A hierarchical method of benthic habitat mapping was applied to the Secondary Biotope and Biological Facies levels at the site (<10 km) scale. The major differences which control the distribution of biological communities in the New Zealand Star Bank area appear to be related to variations in substrate.

To help answer the question whether geophysical data from habitats can be used to predict the occurrence of benthic biodiversity, a multibeam sonar survey was conducted in the northern Great Barrier Reef - Gulf of Papua region. Multivariate statistical analyses were applied to the biological and physical datasets to determine patterns in the distribution of megabenthos, and the relationship with abiotic variables. A hierarchical method of benthic habitat mapping was applied to the Secondary Biotope and Biological Facies levels at the site (<10 km) scale. The combination of substrate type, sedimentary dynamics and physical processes related to near-seabed currents appear to be a dominant control on the benthic communities in the northern Great Barrier Reef - Gulf of Papua region.

Benthic habitat mapping plays a vital part in understanding marine ecosystems and the processes which influence the spatial distribution of benthos. The results of this research have made significant in-roads in the development of a framework for ecosystem-based management of the study areas, the contribution to the ongoing bioregionalisation of Australia, and through an examination of the use of geophysical proxies for the occurrence of biological assemblages, which are fundamental to the establishment of Marine Protected Areas.

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A PhD is not undertaken in isolation and there are many people to thank for the varied contributions they have made on both professional and personal terms. This PhD project involved three research cruises to very different parts of the world, and could not have been possible without the exceptional abilities of my research supervisor and colleague Peter Harris from Geoscience Australia. I am truly grateful that he gave me the opportunity to take part in these cruises and present the results in this thesis.

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The tropical case study was conducted as Geoscience Australia Survey 234 on the *RV Franklin*. I would like to offer special thanks to Captain Ian Taylor and crew of the *Franklin* for helping make the survey such as productive one. Thanks go to James Daniell for processing the multibeam data, and to James Cook University - Cairns Campus for the use of the media laboratory to process underwater video.

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Chapter 1 Introduction

1.1 Overview

This study is concerned with the application of geophysical, oceanographic and biological data to map marine benthic habitats of Australia's continental shelf. In particular, a Geographic Information System (GIS) is utilised to model the benthic habitat boundaries from three study sites on polar, temperate and tropical continental shelves within Australia's Exclusive Economic Zone (EEZ). The three regions were chosen to give a broad and diverse coverage of benthic habitats within different geophysical and oceanographic settings in the search for relationships between seabed biological assemblages and the physical environment. Essential datasets utilised in this project were high-resolution bathymetric data obtained through multibeam sonar. The digital elevation models of the bathymetry reveal far more complex seabed morphology than have been previously known. For this study, 'habitat' can be defined as the place, or type of site, where an organism or population occurs naturally (NOO, 2002). As all places in the ocean are occupied by living organisms, this study is concerned with distinguishing areas on the seabed that are somehow different due to a combination of physical, chemical and biological characteristics related to a given area. Mapping of benthic habitats are fundamental for scientific fisheries management, monitoring and assessing anthropogenic disturbance, and the delineation of Marine Protected Areas (Kostylev et al., 2001). For environmental management to be conducted on the ocean, what is required is an understanding of the physical and biological structure, and the processes that link the variables together. A GIS is a most indispensable tool for modelling the spatial boundaries of environmental and biological data at a variety of scales, and exploring the spatial relationships between the abiotic and biotic variables. GIS can then be used to interpolate across areas where data are scarce, based upon knowledge of the functional links between biological assemblages and physical habitats. In this project, GIS was utilised to model the spatial boundaries of the physical and biological datasets using satellite imagery, multibeam sonar, seismic profiles, oceanographic data, underwater video, and the results of sediment sampling. Spatial and multivariate statistical analyses were conducted on the GIS models and datasets to explore the relationships between abiotic and biotic patterns. Benthic habitat boundaries are derived which reflect conceptual models of the known relationships between the physical environment and biological assemblages for study sites on: (1) the George V Shelf, East Antarctica; (2) New Zealand Star Bank, eastern Bass Strait, Australia; and (3) the northern Great Barrier Reef - Gulf of Papua, Australia.

1.2 Environmental management

The continental shelves are the primary focus for a wide range of activities, especially shipping, fisheries production and tourism. Increasingly, the seabed and overlying waters are becoming degraded due to the over-harvesting of wildlife, and pollution and sedimentation from coastal development. Management responses to these environmental issues have tended to be reactive, ad hoc and non-integrated across all levels of government and stakeholders (Harris and Heap, 2003). In recent years, a significant shift has occurred in managing the human use of the environment, through ecosystem-based management. It recognises that ecosystems are: (1) complex, interconnected and dynamic, and we rely upon these ecosystems for essential resources; (2) our ability to accurately predict the outcomes of human use of resources is imperfect; and (3) there is a need to develop precautionary and adaptive management to reduce the risk of irreversible change to ecosystems (NOO, 2002). Ecosystem-based management requires a move away from boundaries based upon jurisdictions and towards planning based upon the characteristics of the ecosystem. Ecosystem-based boundaries are a way to identify areas that have recognisable differences from adjacent areas, and allow predictions for how those areas will respond to human uses and management (NOO, 2002).

To assist in environmental management of the ocean, a number of levels of a knowledge-based hierarchy are required (Table 1.1). At the first level are the fundamental descriptive variables of the ecosystem structure (Harris, 2001). Information at this level may be derived from a wide variety of environmental datasets. Available environmental data may take the form of oceanic climate data, such as water temperature and salinity or current and wave movement. Other environmental data include seabed characteristics, such as sediment grainsize distribution and composition as well as bathymetry and backscatter geophysical data. Biological datasets may consist of benthic ecology data relating to species composition and biomass. At the second level of the knowledge-based hierarchy are the physical, biological and chemical processes that are linked to and are characteristic of different marine ecosystems. Processes might include knowledge on food webs, life-history strategies for fish and invertebrates, dispersal and migration (NOO, 2002). An important process which determines the range of habitats available for plants and animals is the structural complexity of an ecosystem (Greene et al., 1999; Malatesta and Auster, 1999). Examples of physical processes which may influence community patterns are the variation in geology on the seabed or the influence of storms and waves. Ecosystem models are the third level of knowledge as they are based upon a synthesis of the descriptive data and processes specific to a given marine ecosystem. Environmental management of marine ecosystems requires knowledge of all three levels (Harris, 2001).

Level 3 - modelling	Ecosystem models Conceptual models of how the ecosystem functions, describing the links between biological assemblages and habitat			
Level 2 - processes	Ecosystem processes Physical, biological and chemical processes, such as energy flow and food webs, life histories, dispersal and migration, and structural complexity			
Level 1 - descriptive	Ecosystem structure			
	Oceanic climate: temperature salinity current energy wave energy etc.	Seabed characteristics: bathymetry morphology sediment grainsize sediment composition etc.	Benthic ecology: species composition presence/absence abundance biomass etc.	Chemical environment: nutrients light availability carbon dioxide oxygen etc.

Table 1.1 The levels of a knowledge-based hierarchy related to work required for benthic habitat studies (after Harris, 2001). Environmental management requires knowledge derived from all three levels.

Within each of the three study areas of this project, GIS is used to identify the spatial boundaries of available environmental and biological datasets to provide baseline descriptions of the various seabed habitats. GIS and statistical analysis is used to explore the relationships between abiotic and biotic datasets, with emphasis placed upon exploring the influence of geomorphology and geology as a key process for determining biological assemblage patterns on the seabed. Conceptual model diagrams are developed which sythesise the known relationships between the physical environment and biological assemblages. These three levels of knowledge are derived through a study of available scientific literature of the study areas and from data gathered directly from research cruises to the three study sites. *Therefore, this study contributes to greater knowledge of the physical and biological structure of the seabed and some of the key processes which drive ecosystem function. Such knowledge is essential for environmental management of these areas.*

1.3 Bioregionalisation of Australia

In 1998 during the International Year of the Ocean, the Australian Government launched Australia's Oceans Policy, which has the vision of 'Healthy oceans: cared for, understood and used widely for the benefit of all, now and in the future' (NOO, 2000). A key initiative of the Oceans Policy is the introduction of regional marine planning, which draws upon the principles of ecosystem-based management. Regional Marine Plans will be developed for each major region of Australia's marine jurisdiction, and seeks to integrate the use, management and conservation of marine resources at the broad ecosystem level (NOO, 2004). The major regions are based upon Large Marine Domains of broadly similar marine ecosystems within Australia's Marine Jurisdiction (some 16 million square kilometers; Fig. 1.1). The first Regional Marine Plan has been completed for the Southeast Marine Region, which includes the waters off

Victoria, southern New South Wales, eastern South Australia, Tasmania, and around Macquarie Island (NOO, 2004). However, for this area and indeed much of Australia's Marine Jurisdiction, the form and nature of the seabed is poorly known. Fundamental to the efficient development of Australia's offshore industries, exploration, defence and conservation is knowledge of the seabed communities, and understanding the ecosystem structures and processes at and below the seabed (NOO, 1999). High-resolution bathymetric maps and seafloor characterisation such as sediment distribution and benthic habitats are critical for developing the framework for regional marine planning.

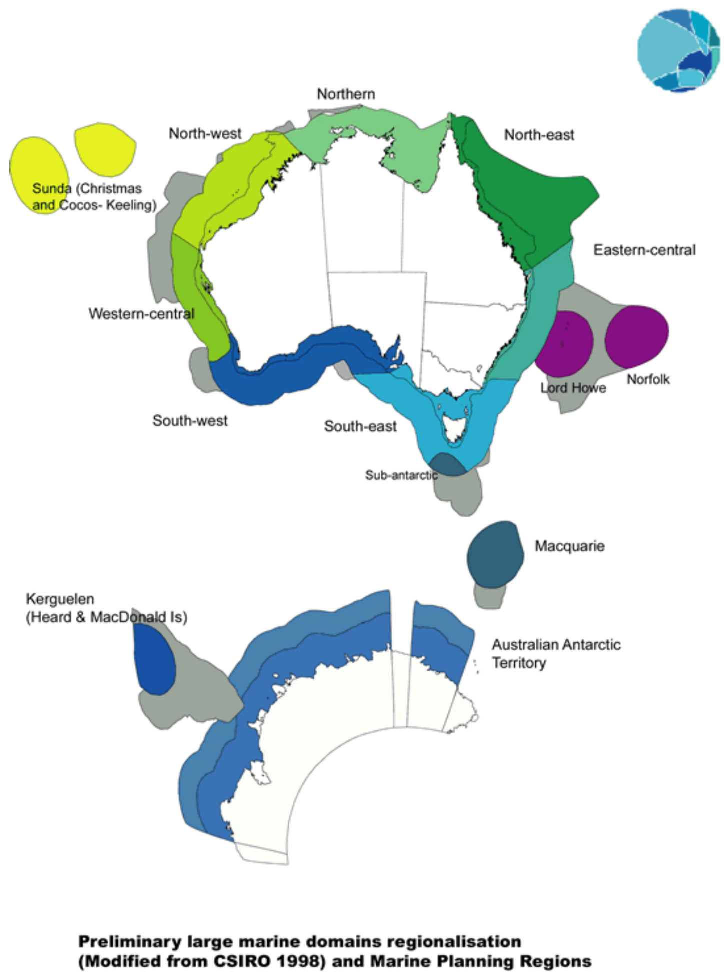

Fig. 1.1 Large Marine Domains of Australia's Exclusive Economic Zone (EEZ).
(Neptune Data Directory http://neptune.oceans.gov.au/index.html).

A key input to developing Regional Marine Plans is the bioregionalisation of Australia's Marine Jurisdiction, which identifies the spatial boundaries of bioregions based upon ecological attributes, such as geology, ocean currents and biota (NOO, 2002). The process of bioregionalisation recognises that marine ecosystems can be viewed as a hierarchy with natural

regions that vary at a range of nested spatial scales, i.e. each ecosystem contains finer-scale levels of organisation, each contained within a broader-scale context (Roff and Taylor, 2000; NOO, 2002). For this thesis, 'broader-scale' and 'finer-scale' are relative terms, and mean the scales of observation cover larger areas versus smaller areas respectively. Habitats should be thought of as a surrogate for ecological structure in a hierarchical context, and requires a classification scheme that can accommodate the diversity of habitats which occur in the marine ecosystem (Butler et al., 2001; NOO, 2002). Many seabed characterisation schemes recognise the importance of a hierarchical view, and have classification schemes to compare habitats and associated communities across geographic regions (Greene et al., 1995; Bax et al., 1999; Greene et al., 1999; Allee et al., 2000; Roff and Taylor, 2000). One such scheme has been developed by Butler et al. (2001) for the marine bioregionalisation of Australia (Table 1.2). At the highest level are Provinces, based upon broad-scale geology and the evolutionary history of fish ranges. At the lowest level are Microcommunities, which are species that depend on Biological Facies, the next level up the hierarchy. While size is not a criteria for levels in the hierarchy, scale does typically reduce for the area observed, and there is a transition in the use of geophysical to biological datasets to define each level (Butler et al., 2001).

Level	Name	Scale (approx. size)	Examples
1	Provinces	province (1000s of km)	Broad-scale geological units such as continental blocks, basins and abyssal plains. May include distribution data of fish assemblages.
2	Biomes	regional (100s of km)	Broad-scale gross geomorphology nested within Provinces, e.g. continental shelf, slope, abyssal plain and offshore continental blocks.
3	Geomorphic Units	local (10s of km)	Areas with similar seabed geomorphology and usually with distinct biotas, e.g. seamounts, canyons, rocky banks, submarine canyons and sand wave fields.
4	Primary Biotopes	local (10s of km)	Nested within Geomorphic Units are soft, hard or mixed substrate-based units, together with their associated biological communities.
5	Secondary Biotopes	site (<10 km)	Generalised types of biological and physical substrate within the soft, hard or mixed substrate, e.g. limestone, granite, shelly sand and muddy sand.
6	Biological Facies	site (<10 km)	Biological indicator or suite of species used as a surrogate for a community, e.g. species of seagrass, group of hardcorals or sponges.
7	Microcommunities	site (<10 km)	Assemblages of species that depend on member species of the Biological Facies, e.g. holdfast communities in giant kelp.

Table 1.2 Hierarchical seabed classification scheme modified from Butler et al. (2001).

Within each of the three study sites of this project, GIS is used to identify the spatial boundaries of benthic habitats using the Butler et al. (2001) seabed classification hierarchy used for the bioregionalisation of Australia. For brevity within this thesis, only the lowest levels of the hierarchy are mapped and described, based upon the resolution of the physical and biological datasets available for each study area. The first case study on the polar George V Shelf, East Antarctica is a shelf-wide bioregionalisation to level 4 Biotopes. Bioregionalisation of the East Antarctic shelf has not been documented previously within the scientific literature. For the

second case study on the temperate New Zealand Star Bank, the eastern Bass Strait has previously been included within the bioregionalisation for the Southeast Regional Marine Plan (NOO, 2004), albeit at a broader-scale and incorporating an earlier effort at classifying Australia's demersal and pelagic provinces of Australia's continental shelf (IMCRA, 1998). The survey of New Zealand Star Bank provides a high-resolution study of benthic habitats over a relatively small area to level 6 Biological Facies, and so complements knowledge of the variety of marine ecosystems in this area. For the third case study in the northern Great Barrier Reef - Gulf of Papua region, high-resolution geophysical and biological datasets are used to derive habitats to level 6 Biological Facies. Regional marine planning has not been conducted on this area and so the models produced in this study will help in understanding the links between the seabed and associated biological assemblages in this poorly-mapped northern part of Australia. *Therefore, this study contributes to the ongoing bioregionalisation of the marine ecosystems of Australia through the detailed examination of the structure and processes at the three study sites. Such information is vital for the regional marine planning of Australia.*

1.4 Geophysical proxies

Continental shelf waters are subject to the greatest impact by humans but also where the highest level of conservation of marine ecosystems occurs (Roff and Taylor, 2000). If marine environments are to be systematically managed and protected from the adverse effects of human activities, then identification of the types of marine habitats and the communities they contain, and delineation of their boundaries within a consistent classification is required (Roff et al., 2003). For this thesis, 'community' is defined as a species assemblage at any scale (Roff and Taylor, 2000). A classification of marine habitats and their associated communities can be used as the framework to delineate a system of representative marine conservation areas, and to enable interpolation of habitat-community relationships across similar areas (Roff and Taylor, 2000). Around the world, there is growing recognition of the importance and need to protect marine biodiversity for both conservation and economic reasons (IMCRA, 1998; Pauly et al., 2002). Australia has committed to the establishment of a representative system of Marine Protected Areas (MPAs), with no-take reserves at their core, which is widely regarded, nationally and internationally, as one of the most effective mechanisms for protecting biological diversity and maintaining ecological processes (ANZECC, 1998).

Due to the lack of good comparative biological information on the seabed, attempts at classifying seabed habitat at a range of scales relevant to management have tended to rely on more easily available geophysical and oceanographic data as proxies for biological distributions (Roff and Taylor, 2000; Stevens, 2002). The use of abiotic data is clearly important and in some

cases has been used to successfully predict the distribution of biological communities (Long et al., 1997; Zacharias et al., 1999). The trend towards marine reserve selection for protecting areas of high biodiversity, critical habitats or simply representative areas of typical habitats, requires a detailed knowledge of benthic habitats and their associated biological communities. In the absence or paucity of biological data to base decisions on benthic habitat boundaries, MPAs rely upon abiotic or geophysical factors to characterise the seabed and water column, and thus provide a basis for reserve selection (Zacharias et al., 1999; Roff et al., 2003). There is often an assumption that surrogates predict or correlate with biological distributions reasonably well. This assumption is not often tested (Stevens and Connolly, 2004).

Within this project, GIS and multivariate analysis has been used where possible to explore the relationships between the abiotic patterns and the distribution of biological assemblages. For the polar case study, the lack of biological data precluded quantitative analysis of the relationships to abiotic data. However, within the broader-scale focus of the bioregionalisation of the George V Shelf, qualitative consideration is conducted on the available datasets linking geomorphology, surficial sediment and near-seabed oceanography to the trophic levels of shelf benthos. The temperate case study at New Zealand Star Bank also qualitatively links the patterns of biology, revealed through surficial sediment composition and video analysis, against geomorphology and the substrate variation. The tropical case study in the northern Great Barrier Reef has higher-resolution datasets and dense groundtruthing, and was ideal for a quantitative study using multivariate analysis as an exploratory tool to link key environmental variables with benthic assemblage patterns observed in the video transects. For each study area, the relationships explored between abiotic and biotic datasets help in understanding the processes underlying the observed biological patterns. *Therefore, a major PhD research question was 'Can abiotic data on the seabed environment be used to predict the nature of benthic communities?' This project contributes information on the use of geophysical variables to predict the occurrence of biological assemblages. Such information is very useful in the use of abiotic proxies as surrogates for marine reserve selection.*

1.5 Aims and objectives

The aim of this thesis is to present an interdisciplinary study through the use of GIS techniques and mapping of available datasets to derive benthic habitats for three study sites on polar, temperate and tropical continental shelves. A wide range of equipment and data were utilised, including multibeam sonar, seismic profiles, near-seabed oceanographic sampling, biological and sediment sampling of the seabed, and optical techniques such as underwater photography and video (Table 1.3). Extensive use is made of published scientific information on ecosystem

structure and processes from the study areas to complement the data collected from the research cruises.

Technology	Types of data	Spatial resolution	Polar	Temperate	Tropical
1. Remote sensing					
Radarsat satellite	iceberg concentration, ice shelf boundary	100m	x		
Landsat satellite	shallow water geomorphic features	80m		x	
singlebeam echosounder	low-res bathymetry, contours etc.	1-100m	x		
multibeam sonar	high-res bathymetry, surficial sediment etc.	1-100m	x	x	x
Chirp seismic profiler	acoustic facies, geomorphic features	1-100m	x		x
2. Groundtruthing					
underwater video	megabenthos diversity, fauna patterns	1-10m		x	x
underwater camera	megabenthos diversity, fauna patterns	1-10m	x		
grab/core sampler	sediment type, macrobenthos diversity	1-2m	x	x	x
benthic trawling	macrobenthos diversity, biomass etc.	1-10m	x		
CTD profiler	temperature, salinity etc. vs. depth	1-5m	x		x
acoustic current meter	water mass flow vs. depth	1-10m	x		x

Table 1.3 The assessment technology and types of data used in the polar, temperate and tropical case studies of this project.

Objectives were to: (1) define the physical environment of the study sites using GIS maps of geomorphology, surficial sediments and near-seabed oceanography; (2) discriminate assemblages of macrobenthos through the use of multivariate statistical analysis where possible; and (3) explore the possible relationships between the geophysical environment of the seabed and the associated biological communities. An important question this project seeks to answer is whether geological data can be used to predict the occurrence of assemblages of benthic organisms. Benthic habitat boundaries are derived, which reflect conceptual model diagrams of the known relationships between the physical environment and biological assemblages. The benthic habitats for each study area are described in terms of the levels and scales within the ecosystem hierarchy described by Butler et al. (2001) for the bioregionalisation of Australia. A flowchart of the general methodology used in this project is presented in Fig. 1.2. For example, the physical and biological datasets were obtained from research cruises and the published literature. Various GIS techniques were used to model the spatial distribution of these datasets, such as (but not limited to): interpolate, contour, slope, hillshade, cut/fill, reclassify, buffer, merge, clip, intersect, union and edit. ArcGIS and the multivariate statistical program Primer were then used to qualitatively and quantitatively explore the relationships between the datasets. Conceptual model diagrams were developed which reflect the known relationships between the

abiotic and biological datasets. ArcGIS was used to map the spatial boundaries of these relationships as benthic habitats within a hierarchical context.

Note that it is not the intention of this thesis to describe in detail the many GIS analysis techniques used in this project, as GIS was considered simply as a tool to conduct scientific research and seabed mapping. Nor are all the GIS maps, derived from the many datasets available in this project, illustrated within this thesis except where useful for conveying the objectives of the project. Within the thesis, each case study comprises an individual chapter with a description of the study area setting, the materials and methods used, results, discussion, conclusion and references. The layout of each case study therefore follows the structure and scientific findings of the peer-reviewed publications relating to each chapter.

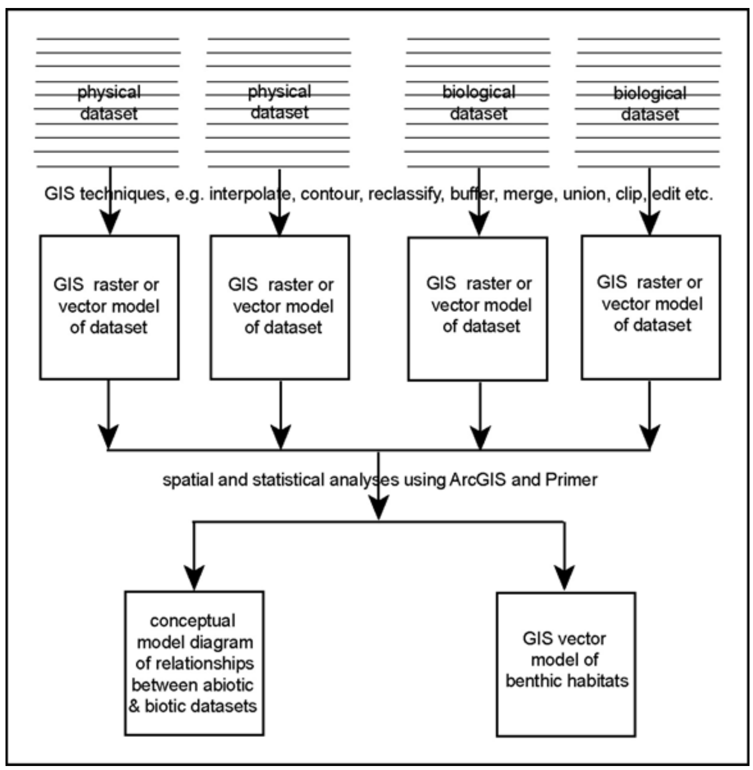

Fig. 1.2 The methodology used in this project. Physical and biological datasets were compiled from research cruises and published scientific literature. Various GIS techniques were used to model the spatial distribution of the datasets. Spatial and statistical analyses were conducted on the GIS models and datasets to explore the relationships between abiotic and biotic patterns. Conceptual model diagrams reveal the known associations between the abiotic patterns and biological assemblages. GIS is used to model the spatial distribution of benthic habitats within a hierarchical context.

1.6 Structure of thesis

Chapter 1 has outlined the importance of this work in terms of environmental management, the contribution to the ongoing bioregionalisation of Australia, and an examination of the use of geophysical proxies for the occurrence of biological assemblages, which are important for the establishment of MPAs.

Chapter 2 provides the polar case study for the George V Shelf, East Antarctica. This chapter follows the publication:

Beaman, R.J., Harris, P.T., 2005. Bioregionalisation of the George V Shelf, East Antarctica. Continental Shelf Research 25, 1657-1691.

Chapter 3 describes the temperate case study from New Zealand Star Bank, eastern Bass Strait, Australia. This chapter follows the publication:

Beaman, R.J., Daniell, J., Harris, P.T., 2005. Geology-benthos relationships on a temperate rocky bank, eastern Bass Strait, Australia. Marine and Freshwater Research 56, 943-958.

Chapter 4 contains the tropical case study of the northern Great Barrier Reef - Gulf of Papua region. This chapter follows the publication:

Beaman, R.J., Harris, P.T., in review. Geophysical variables as predictors of megabenthos assemblages from the northern Great Barrier Reef, Australia. In: B.J. Todd and H.G. Greene (Editors), Marine Geological and Benthic Habitat Mapping. Special Publication. Geological Association of Canada, St John's, Canada.

Chapter 5 provides a conclusion describing the key findings in terms of the project objectives. Recommendations are made about issues raised during the study, followed by a discussion of links between the science of this project and ocean management. The chapter finishes with a summary of this research.

Appendix A is an overview of the multivariate statistical analysis software Primer with descriptions of the statistical tests used in this project.

Appendix B is an attached CDROM of extra material from this project. These include: (1) flythrough movies; (2) images from research cruises; (3) peer-reviewed publications; (4) seminars from research; and (5) viewing software.

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Chapter 2 Polar Case Study

2.1 Introduction

If marine ecosystems are to be managed to ensure the rational use of resources or protection from adverse human activities, then identifying the different types of marine habitats and their associated biological communities is required (Kostylev et al., 2001; Roff et al., 2003). Understanding marine habitats and communities provides us with a way to identify the boundaries of the ecosystem, which accounts for some of its complexity and provides a base for developing ecosystem-based plans (NOO, 2002). Habitats should be thought of as a surrogate for ecological structure in a hierarchical context, with natural regions that vary at a range of nested spatial scales (Roff and Taylor, 2000; Butler et al., 2001). Many seabed characterisation schemes now recognise the importance of a hierarchical view and have standard classification schemes to compare habitats and associated communities across geographic regions (e.g. Greene et al., 1995; Bax et al., 1999; Greene et al., 1999; Allee et al., 2000; Roff and Taylor, 2000).

One such scheme has been developed by Butler et al. (2001) for the marine bioregionalisation of Australia (DEH, 2003). This scheme defined benthic habitats by: (1) Provinces, on the order of ~1000 km in extent (province scale); (2) Biomes, such as the coast, continental shelf, slope and abyssal plain, which are nested within Provinces and are typically several 100s of km in extent (regional scale); and (3) Geomorphic Units, such that within each Biome, there are areas characterised by similar geomorphology and which usually have distinct biota. These units may be up to 10s of km in extent (local scale) and, on the continental shelf, include sand banks, coral and rocky reefs, submarine plains and valleys. Within a geomorphic level and with targeted biological and environmental sampling, one may increase the levels of the scheme to include (4) Biotopes of soft, hard or mixed substrate-based units, together with their associated biological community. While size is not a criterion for level in the hierarchy, size does typically decrease and there is a transition from the use of geophysical to biological datasets to define each level (see Table 1.2 in Chapter 1 for further description).

This study aims to present a bioregionalisation of the George V Shelf, East Antarctica to the Geomorphic Unit and Biotope levels through the use of Geographic Information System (GIS) techniques and mapping of available datasets. The area of study, between longitudes 142°E and 146°E, has been the focus of a number of important marine geological and oceanographic cruises in recent years (Brancolini and Harris, 2000; Bindoff et al., 2001; Leventer et al., 2001;

Vaillancourt et al., 2003). The earliest detailed maps for the George V Shelf arose from extensive seabed and water column sampling during Operation Deep Freeze 79 (Domack and Anderson, 1983). This expedition resulted in a number of diverse studies: oceanographic influences on sedimentation (Dunbar et al., 1985), biogenic facies maps (Domack, 1988), diatom (Leventer, 1992) and benthic foraminifer (Milam and Anderson, 1981) distribution. In the years since this major expedition, data from geophysical surveys have added considerably to the knowledge of this remote and hostile part of the world. However, it is now through the use of GIS that data collected over many years can be put within a database using a common map datum and reanalysed to provide new maps of seafloor characteristics.

This chapter presents an interdisciplinary study based upon seismic profiles, multibeam sonar, oceanographic sampling, underwater photographs and the results of limited biological and sediment sampling. Our objectives were to: (1) define the physical environment of the shelf using geomorphology, surficial sediments and near-seabed oceanography; (2) discriminate assemblages of macrobenthos where possible; and (3) infer the dominant trophic structure of benthic communities within geomorphic features. The shelf is spatially defined to the Geomorphic Unit and Biotope levels at the local (10s of km) scale, and a description of each unit is given. We present a new bioregionalisation, which provides insights into general environmental and biological relationships across the George V Shelf.

2.2 Materials and methods

2.2.1 Study area - glacial and sea ice setting

The George V Coast is dominated by the edge of an ice-covered plateau. Most of the coastline consists of ice cliffs that are mostly sediment free (Domack, 1982). Glacial drainage along the ice cliffs is probably sufficiently slow that wave erosion keeps pace with the rate of advance (Domack and Anderson, 1983). Most of the ice drainage occurs through a relatively small segment of the coastline as the Mertz and Ninnis Glaciers. Within the study area, the Mertz Glacier Tongue extends in a southwest to northeast direction over 100 km into the ocean (Fig. 2.1A), and is probably grounded on the relatively shallow seafloor to the north (Domack, 1982; Berthier et al., 2003). Comparisons between various coastline surveys reveal that the calving front of the Mertz Glacier Tongue fluctuates by tens of kilometres (Domack and Anderson, 1983; Holdsworth, 1985).

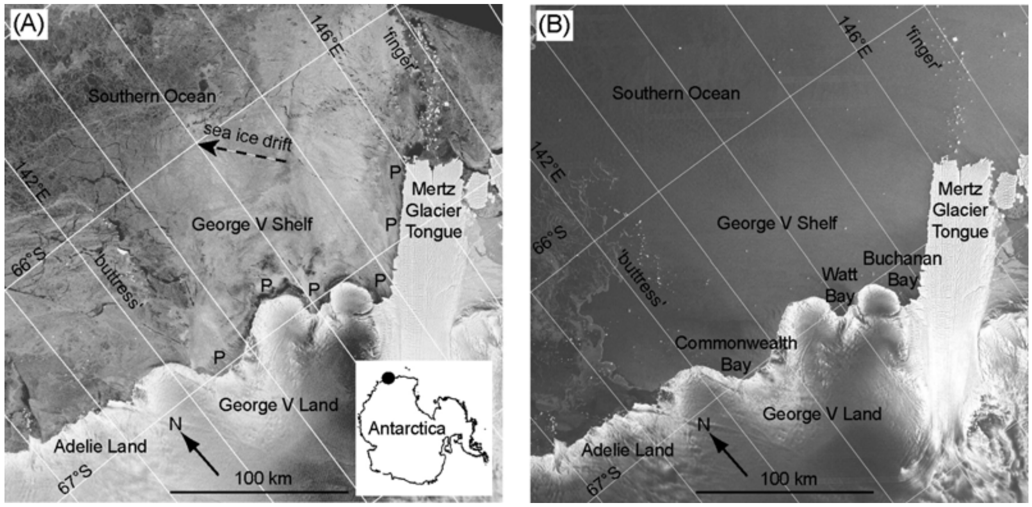

Fig. 2.1 Radarsat ScanSAR images of the George V Land and Shelf area from (A) 7 August 1999 - winter (B) 17 December 1999 - summer. P denotes Mertz Polynya along the coast and west face of the Mertz Glacier Tongue. The 'buttress' and 'finger' refer to grounded icebergs and fast ice extending across the shelf forming blocking features to westward advection of sea ice (Massom et al., 2001). Dashed arrow is the general direction of sea ice drift. Inset shows the location of the George V Shelf region in Antarctica. ©Radarsat International 2001.

Sediment-laden icebergs calved from the Mertz and Ninnis Glaciers have dimensions of up to several tens of kilometres (Domack and Anderson, 1983). The observed drift of icebergs is to the west caused by the westerly-flowing Antarctic Coastal Current (ACC). A line of grounded icebergs with a southwest to northeast orientation extends seaward from the Mertz Glacier Tongue. Radarsat images also reveal numerous grounded icebergs and fast ice up to 100 km offshore north of Commonwealth Bay (Fig. 2.1B). During austral winter, March-April to October-November, fast ice is pinned in place by the lines of icebergs to create a continuous zone of ice from the coast to the shelf break, and named the 'finger' and 'buttress' (Massom et al., 2001).

Between the zones of fast ice is an outlet zone for the westward advection of sea ice, formed within a polynya extending along the coast from Commonwealth Bay to Buchanan Bay and the western margin of the Mertz Glacier Tongue, collectively called the Mertz Polynya (Fig. 2.1A; Massom et al., 1998). The formation of the polynya is related to the persistent katabatic winds that channel down ice drainage valleys, resulting in high rates of sea ice production and then removal away from the coast (Parrish, 1981; Massom et al., 2001). These winds remove sea ice as quickly as it forms and mostly maintain regions of open water or low sea ice concentration as the Mertz Polynya.

2.2.2 Study area - bathymetric and oceanographic setting

The George V Shelf is deep with an average shelf break depth of 500 m and is approximately 130 km wide (Fig. 2.2). The shelf is dominated by the deep George V Basin, and is also called the Adélie Depression or the Mertz-Ninnis Trough (Porter-Smith, 2003). The deep basins and valleys of East Antarctica are believed to have a broad structural control, related to rifting of Australia from Antarctica during the Tertiary period, followed by erosion from successive ice advances during the Pleistocene (Hampton et al., 1987). The George V Basin reaches its deepest point of over 1300 m adjacent to the Mertz Glacier Tongue. The basin axis trends parallel to the coast, shoaling gently to depths of about 800 m, before swinging north towards a U-shaped sill connecting the basin to the shelf break at a depth of approximately 450 m. Within the west arm of the basin, a sediment drift deposit of about 400 km^2 was mapped and named the Mertz Drift (Harris et al., 2001). The George V Basin is bounded to the northeast by the flat-topped Mertz Bank, and to the west by the Adélie Bank, shoaling to depths of about 200 m (Domack, 1982). The Mertz Moraine is an approximately 50 m high ridge forming a rim on the southern side of the Mertz Bank, and interpreted as a lateral moraine (Barnes, 1987).

Oceanographic research indicates that the George V Basin is an important source of Adélie Land Bottom Water (ALBW), which is an integral component of global thermohaline circulation (Rintoul, 1998). The search for ALBW found four distinct water masses over the basin (Williams and Bindoff, 2003). A warm, fresh and oxygen-depleted Highly Modified Circumpolar Deep Water (HMCDW) upwelled through the sill connecting the basin to the shelf break and also over the shallow banks, then flowed towards the Mertz Glacier Tongue (Fig. 2.2). Over the basin to depths of about 500 m was found a large body of weakly-stratified Winter Water (WW). The WW was derived from HMCDW when it was cooled by the atmosphere and gained brine through interaction with the Mertz Polynya. Relatively cold and dense water, from brine rejected during sea ice formation, spills down the sides of the basin to accumulate below the WW as High Salinity Shelf Water (HSSW). A supercooled and freshened Ice Shelf Water (ISW), formed by the interaction of WW and HMCDW under the Mertz Glacier Tongue, is restricted to surface waters shallower than 500 m in the vicinity of the glacier, and flowed westwards along the coast (Bindoff et al., 2001). When the combination of HSSW and WW reaches a critical point in temperature and salinity, it becomes dense enough to spill over the sill as ALBW (Bindoff et al., 2000). Along the outer shelf and upper slope is a westerly-going surface current called the Antarctic Coastal Current (ACC), driven by polar easterly winds (Whitworth III et al., 1998).

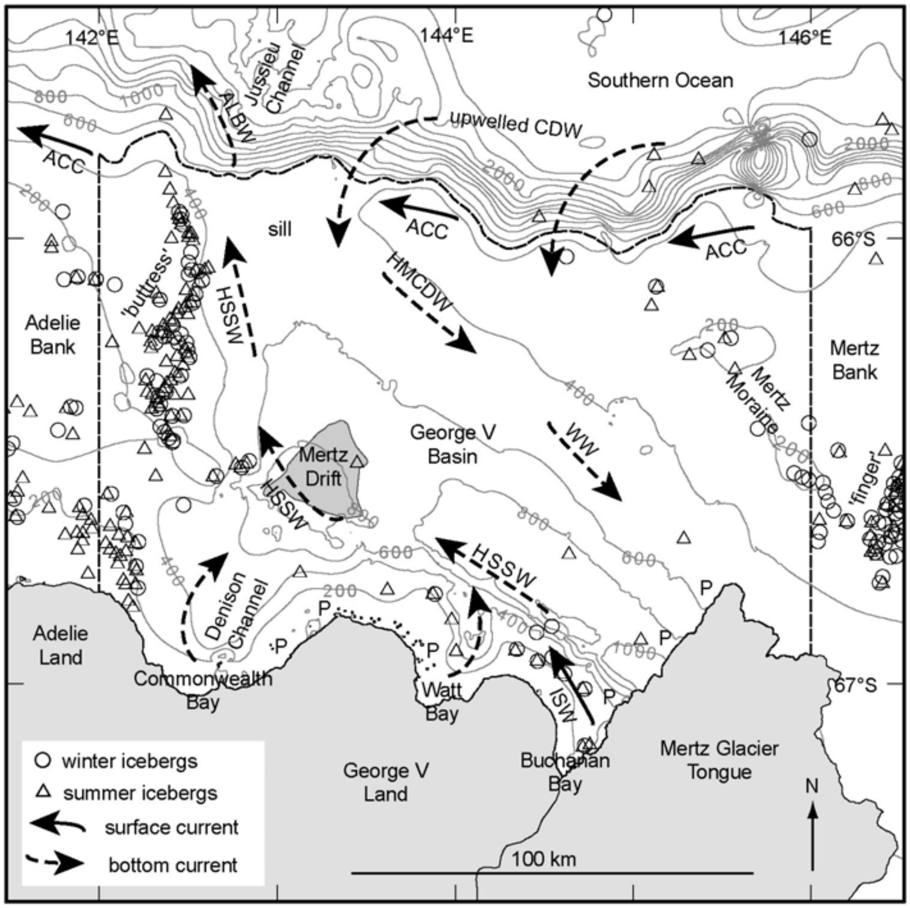

Fig. 2.2 Mercator projection map of the George V Shelf. A dashed line shows the study area bounded to the north by the depth contour 500 m, and to the west and east by longitudes 142°E to 146°E. Bathymetry is in metres from Porter-Smith (2003). HSSW denotes High Salinity Shelf Water; ACC Antarctic Coastal (surface) Current; CDW Circumpolar Deep Water; HMCDW Highly Modified Circumpolar Deep Water; WW Winter Water; ISW Ice Shelf Water; ALBW Adélie Land Bottom Water; P Mertz Polynya. Open circles and triangles are positions of winter and summer icebergs obtained from Figs. 2.1A and B respectively. Note the numerous grounded icebergs on the Adélie Bank north of Commonwealth Bay, and on the Mertz Bank north of the Mertz Glacier Tongue, named the 'buttress' and 'finger' respectively (Massom et al., 2001). The outline of Mertz Glacier Tongue is not accurate as the ice shelf currently extends further northwest onto the Mertz Bank.

2.2.3 Bathymetry data

The bathymetric model used in this study has a horizontal resolution of 0.001° (approximately 110 m) with depths referenced to mean sea-level (MSL). The model combined the Scientific Committee on Antarctic Research (SCAR) coastline (ADD, 1998) and General Bathymetric Chart of the Oceans contours (GEBCO, 1997), and supplemented with depths obtained from a number of recent expeditions to the region (Porter-Smith, 2003). In addition, Sea Beam™ 2112 multibeam sonar data from the 2001 *RVIB Nathaniel B. Palmer* expedition to East Antarctica (Leventer et al., 2001) was processed using MBSystem Ver. 4.6 (Caress and Chayes, 2004) to display 0.001° horizontal resolution bathymetry (depths referenced to MSL) and backscatter (gray-scale sidescan) of the Mertz Bank and George V Basin. The multibeam backscatter and bathymetric models were horizontally referenced to the WGS84 datum and mapped in ESRI™ ArcGIS as grid files.

Seismic data were collected during the Wilkes Land Glacial History expedition on the *RV Tangaroa* in 2000 using a hull-mounted ORE Model 140 3.5 kHz transceiver printing to an EPC Model 9802 thermal printer (Brancolini and Harris, 2000). Hard copies of the approximately 2000 km of seismic profiles were classified into acoustic facies types based upon Damuth (1980), and a map of acoustic facies distribution was constructed in ArcGIS as a polygon shapefile. The acoustic facies, bathymetric and backscatter maps were compared to define boundaries for a map of geomorphology over the shelf between longitudes 142°E and 146°E, from the coast to the shelf break at 500 m. Previous geomorphic studies (Vanney and Johnson, 1979; Barnes, 1987; Barnes and Lien, 1988; Beaman and Harris, 2003) were used to refine the boundaries. Geomorphic feature names made use of hydrographic terms recognised on Admiralty charts (IHO, 2001).

2.2.4 Sediment data

The use of GIS in this project allowed data from a number of previous studies from the shelf to be included for surficial sediment analysis. Grab and core top data were obtained from the Operation Deep Freeze 79 (DF79) expedition (Domack, 1980; Domack, 1988), the 1984 United States Geological Survey (USGS) cruise (Hampton et al., 1987), and 2000 Wilkes Land Glacial History (WEGA) expedition (Brancolini and Harris, 2000). All 66 samples were classified into percentage gravel (>2 mm), sand (2-0.0625 mm) and mud (<0.0625 mm), shown in Table 2.1.

Sample number	Source	Latitude	Longitude	Water depth (m)	Gravel (%)	Sand (%)	Mud (%)
3GB	DF79	65°45.00'S	141°43.00'E	741	18.0	98.00	2.00
4GB	DF79	65°47.00'S	141°29.00'E	472	0.0	95.00	5.00
5GB	DF79	65°59.00'S	141°32.00'E	234	4.0	59.00	41.00
6GB	DF79	66°15.00'S	141°36.00'E	280	7.0	69.00	31.00
7GB	DF79	66°32.00'S	141°32.00'E	229	0.0	22.00	78.00
8GB	DF79	66°44.00'S	141°42.00'E	124	7.0	43.00	57.00
9GB	DF79	66°44.00'S	141°42.00'E	95	11.0	55.00	45.00
10GB	DF79	66°47.00'S	142°34.00'E	622	0.0	35.00	65.00
12GB	DF79	66°34.00'S	143°21.00'E	807	0.0	17.00	85.00
13GB	DF79	66°19.00'S	143°19.00'E	683	0.0	5.00	95.00
14GB	DF79	66°05.00'S	143°13.00'E	503	7.0	25.00	75.00
15GB	DF79	65°52.00'S	143°20.00'E	412	24.0	79.00	21.00
24GB	DF79	66°08.00'S	145°13.00'E	201	10.0	97.00	3.00
25GB	DF79	66°16.00'S	145°11.00'E	423	16.0	96.00	4.00
26GB	DF79	66°23.00'S	145°12.00'E	714	3.0	59.00	41.00
27GB	DF79	66°32.00'S	145°07.00'E	393	0.0	24.00	78.00
28GB	DF79	66°38.00'S	145°06.00'E	445	3.0	44.00	56.00
29TC	DF79	66°41.00'S	145°12.00'E	558	0.0	54.00	46.00
30GB	DF79	67°00.00'S	145°13.00'E	1080	11.0	35.00	65.00
31GB	DF79	66°53.00'S	146°22.00'E	399	7.0	53.00	47.00
32GB	DF79	66°33.00'S	147°00.00'E	534	0.0	24.00	76.00
35GB	DF79	67°03.00'S	146°50.00'E	540	15.0	32.00	68.00
37GB	DF79	67°33.00'S	147°00.00'E	582	1.0	65.00	35.00
38GB	DF79	67°44.00'S	146°51.00'E	1274	14.0	24.00	76.00
53GB	DF79	66°08.00'S	147°06.00'E	445	0.0	53.00	47.00
A2GC2	USGS	66°08.00'S	147°05.00'E	458	10.9	59.00	41.00
11GC02	WEGA	66°31.20'S	143°23.04'E	792	0.0	18.40	81.61
11GC03	WEGA	66°31.19'S	143°23.07'E	791	0.0	16.54	83.45
12GC04	WEGA	66°32.52'S	143°12.65'E	837	0.0	23.11	76.86
13GB02	WEGA	66°33.37'S	143°04.15'E	864	0.0	31.62	68.37
13GC06	WEGA	66°33.50'S	143°04.18'E	878	0.0	23.36	76.63
14GC07	WEGA	66°34.03'S	143°01.19'E	866	0.0	44.07	55.91
14GB03	WEGA	66°34.07'S	143°01.07'E	866	0.0	38.58	61.40
15GC08	WEGA	66°33.98'S	143°00.29'E	880	0.0	13.78	86.24
15GC09	WEGA	66°33.98'S	143°00.28'E	880	0.0	30.15	69.86
16GB04	WEGA	66°34.46'S	142°57.81'E	861	0.0	35.14	64.85
16PC01	WEGA	66°34.46'S	142°57.81'E	861	0.0	17.74	82.27
17GB05	WEGA	66°32.95'S	143°14.65'E	825	0.0	14.20	85.81
17PC02	WEGA	66°32.95'S	143°14.65'E	825	0.0	21.47	78.54
18GB06	WEGA	66°36.18'S	143°20.03'E	815	0.0	23.27	76.74
18PC03	WEGA	66°36.18'S	143°20.03'E	815	0.0	23.17	76.83
19GB07	WEGA	66°36.81'S	143°21.12'E	808	0.0	31.98	68.04
19PC04	WEGA	66°36.81'S	143°21.12'E	808	0.0	21.89	78.13
20GB08	WEGA	66°37.63'S	143°22.67'E	800	0.0	29.02	71.01
20PC05	WEGA	66°37.63'S	143°22.67'E	800	0.0	24.63	75.35
21PC06	WEGA	66°50.25'S	144°53.63'E	942	0.0	20.71	79.31
22GB09	WEGA	66°50.77'S	144°51.12'E	934	0.0	15.43	84.57
22PC07	WEGA	66°50.77'S	144°51.12'E	934	0.0	20.99	79.01
23GB10	WEGA	66°29.97'S	143°10.32'E	827	0.0	27.56	72.45
23GB11	WEGA	66°30.18'S	143°08.86'E	840	0.0	30.56	69.45
23PC09	WEGA	66°30.18'S	143°08.86'E	840	0.0	27.53	72.48
24GB12	WEGA	66°28.89'S	143°08.18'E	815	0.0	59.72	40.27
24PC10	WEGA	66°28.89'S	143°08.18'E	815	0.0	50.96	49.07

25GB13	WEGA	66°33.98'S	143°00.32'E	879	0.0	41.72	58.28
25PC11	WEGA	66°33.98'S	143°00.32'E	879	0.0	17.65	82.36
26GB14	WEGA	66°33.92'S	143°00.88'E	872	0.0	48.76	51.23
26PC12	WEGA	66°33.92'S	143°00.88'E	872	0.0	30.19	69.82
27GB15	WEGA	66°31.22'S	143°22.94'E	793	0.0	16.80	83.20
27PC13	WEGA	66°31.22'S	143°22.94'E	793	0.0	18.99	80.99
28GB16	WEGA	66°23.42'S	143°19.31'E	739	0.0	10.13	89.88
28GB17	WEGA	66°23.57'S	143°19.15'E	735	0.0	15.05	84.98
28PC15	WEGA	66°23.57'S	143°19.15'E	735	0.0	11.74	88.29
29GB18	WEGA	66°20.97'S	143°18.46'E	709	0.0	16.22	83.79
29PC16	WEGA	66°20.97'S	143°18.46'E	709	0.0	11.08	88.91
30PC17	WEGA	66°12.20'S	142°54.06'E	554	0.0	40.51	59.50
32GC11	WEGA	66°11.97'S	143°29.07'E	560	0.0	29.63	70.40

Table 2.1 Sediment sample locations, water depths, gravel, sand and mud data. DF79 denotes Operation Deep Freeze 79 (Domack, 1980); USGS is from 1984 USGS cruise (Hampton et al., 1987); WEGA refers to expedition Wilkes Land Glacial History (Brancolini and Harris, 2000).

Using the available sediment data, maps of percentage gravel, sand and mud were defined using kriging interpolation across the shelf and clipped to the study area. Kriging surface modelling on data was conducted with the ArcGIS Geostatistical Analyst extension, generally using nil transformation with a first order of trend removal, and interpolated using a spherical variogram model with anisotropy and a 1% measurement error. The benefits of kriging interpolation using Geostatistical Analyst include generation of prediction standard error maps for checking how well the model predicted values at unknown locations. A map of surficial sediment boundaries across the shelf was derived using the maps of percentage gravel, sand and mud, and available surficial sediment information of the study area (Domack, 1982; Domack and Anderson, 1983; Dunbar et al., 1985; Hampton et al., 1987; Domack, 1988; Anderson, 1999; Harris and Beaman, 2003; Presti et al., 2003). Surficial sediment classification followed Folk (1954), based upon the relative proportions of gravel and the mud:sand ratio (Fig. 2.3).

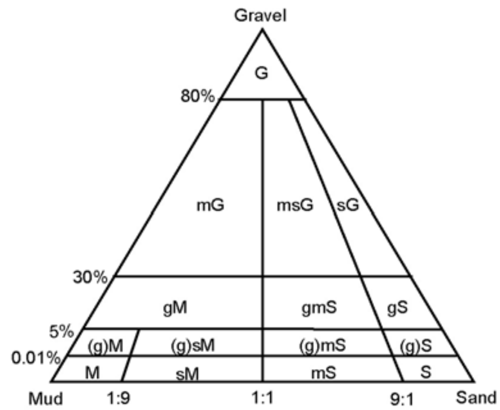

Fig. 2.3 Surficial sediment classification based on Folk (1954). Sediments are classified into textural groups based upon the relative proportions of gravel (>2 mm), and the ratio of sand (2-0.0625 mm) to mud (<0.0625 mm). Upper-case letters indicate largest proportion; lower-case indicate qualifiers; brackets indicate 'slightly', e.g. (g)mS is slightly gravelly, muddy sand.

2.2.5 Oceanographic data

The variation in oceanographic conditions from winter to summer required oceanographic data to be separate for each season. Winter oceanographic data were collected during July to September 1999 on the *RSV Aurora Australis* (AU9901) expedition (Bindoff et al., 2001; Rosenberg et al., 2001). Data were recorded from samples obtained from the deepest depth of each cast, at or within 50 m of the seabed to record near-seabed hydrology. The 87 winter samples record salinity (psu) and temperature (°C) values (Table 2.2).

Sample number	Latitude	Longitude	Water depth (m)	Salinity (psu)	Temperature (°C)
1	66°14.64'S	143°17.41'E	608	34.711	-1.894
2	66°40.25'S	143°48.10'E	831	34.688	-1.891
3	66°54.13'S	144°21.98'E	249	34.648	-1.906
4	66°49.54'S	144°27.33'E	977	34.716	-1.886
5	66°45.14'S	144°32.77'E	873	34.712	-1.891
6	66°40.30'S	144°36.88'E	819	34.723	-1.895
7	66°36.33'S	144°41.14'E	607	34.693	-1.901
8	66°32.08'S	144°45.58'E	499	34.688	-1.902
9	66°27.58'S	144°50.10'E	440	34.658	-1.899
10	66°23.12'S	144°54.26'E	407	34.607	-1.886
11	66°18.54'S	144°58.28'E	391	34.564	-1.753
12	66°21.70'S	145°07.45'E	367	34.548	-1.556
13	66°24.65'S	145°16.52'E	350	34.543	-1.632
14	66°27.60'S	145°26.17'E	321	34.535	-1.867
15	66°30.45'S	145°34.97'E	334	34.604	-1.898
16	66°33.21'S	145°43.77'E	306	34.576	-1.891
17	66°35.95'S	145°53.02'E	299	34.577	-1.892
18	66°39.56'S	145°45.87'E	379	34.603	-1.893
19	66°43.54'S	145°37.87'E	438	34.696	-1.902
20	66°46.87'S	145°31.16'E	532	34.661	-1.898

21	66°50.80'S	145°23.48'E	618	34.701	-1.899
22	66°54.51'S	145°16.04'E	812	34.695	-1.892
23	66°58.04'S	145°08.64'E	1121	34.718	-1.882
24	67°02.00'S	145°01.09'E	690	34.669	-1.897
25	67°05.62'S	144°53.81'E	487	34.634	-1.918
26	67°09.24'S	144°45.83'E	470	34.632	-1.911
27	66°54.11'S	144°22.70'E	251	34.637	-1.904
28	66°49.77'S	144°26.29'E	954	34.696	-1.886
29	66°45.20'S	144°32.02'E	868	34.716	-1.890
30	66°40.95'S	144°36.84'E	830	34.712	-1.892
31	66°36.39'S	144°40.33'E	616	34.681	-1.898
32	66°32.18'S	144°45.37'E	505	34.675	-1.899
33	66°27.82'S	144°50.11'E	430	34.647	-1.896
34	66°23.43'S	144°54.25'E	405	34.627	-1.895
35	66°19.02'S	144°58.51'E	382	34.556	-1.652
36	66°21.84'S	145°07.70'E	366	34.509	-1.726
37	66°24.72'S	145°16.57'E	351	34.514	-1.694
38	66°27.60'S	145°26.15'E	318	34.515	-1.684
39	66°30.61'S	145°34.96'E	334	34.549	-1.722
40	66°33.68'S	145°44.94'E	303	34.557	-1.876
41	66°36.29'S	145°54.36'E	285	34.662	-1.902
42	66°39.98'S	145°44.83'E	382	34.635	-1.897
43	66°43.79'S	145°37.74'E	438	34.672	-1.901
44	66°47.70'S	145°30.87'E	539	34.679	-1.899
45	66°51.69'S	145°23.47'E	645	34.673	-1.894
46	66°55.26'S	145°17.31'E	820	34.698	-1.893
47	66°58.90'S	145°09.68'E	1114	34.721	-1.882
48	67°02.67'S	145°02.08'E	678	34.669	-1.893
49	67°05.65'S	144°54.12'E	487	34.671	-1.898
50	67°09.46'S	144°46.80'E	509	34.632	-1.951
51	67°09.66'S	144°39.58'E	296	34.579	-1.998
52	66°19.49'S	143°45.99'E	533	34.710	-1.898
53	66°11.58'S	143°15.00'E	568	34.717	-1.899
54	66°02.25'S	144°10.79'E	397	34.543	-0.901
55	66°01.09'S	144°46.26'E	461	34.531	-1.657
56	66°04.03'S	145°25.43'E	300	34.542	-1.875
57	66°07.00'S	146°01.55'E	388	34.550	-1.813
58	66°10.62'S	146°40.75'E	230	34.589	-1.888
59	66°16.53'S	146°28.88'E	236	34.623	-1.896
60	66°54.35'S	144°23.92'E	238	34.647	-1.902
61	66°49.77'S	144°27.75'E	1013	34.704	-1.886
62	66°45.21'S	144°32.21'E	857	34.713	-1.890
63	66°40.82'S	144°36.62'E	818	34.730	-1.892
64	66°36.29'S	144°40.75'E	616	34.707	-1.899
65	66°31.87'S	144°44.88'E	493	34.677	-1.900
66	66°27.43'S	144°49.51'E	431	34.679	-1.900
67	66°23.15'S	144°54.16'E	405	34.673	-1.900
68	66°18.53'S	144°58.38'E	386	34.534	-1.772
69	66°21.47'S	145°07.11'E	369	34.519	-1.808
70	66°24.37'S	145°16.45'E	353	34.491	-1.848
71	66°27.24'S	145°25.57'E	320	34.510	-1.722
72	66°30.07'S	145°34.77'E	324	34.577	-1.891
73	66°33.03'S	145°43.53'E	306	34.589	-1.885
74	66°36.05'S	145°52.77'E	297	34.591	-1.893

75	66°39.70'S	145°45.12'E	372	34.670	-1.900
76	66°43.38'S	145°38.03'E	442	34.703	-1.902
77	66°47.29'S	145°31.02'E	538	34.681	-1.900
78	66°50.80'S	145°23.46'E	624	34.708	-1.898
79	66°54.66'S	145°16.36'E	816	34.713	-1.892
80	66°58.62'S	145°08.32'E	1117	34.719	-1.881
81	67°01.68'S	145°00.60'E	651	34.676	-1.895
82	67°05.88'S	144°53.89'E	483	34.623	-1.901
83	67°09.75'S	144°46.33'E	463	34.622	-1.981
84	67°10.20'S	144°39.33'E	373	34.559	-1.972
85	66°22.72'S	146°17.56'E	247	34.633	-1.895
86	66°29.28'S	146°06.35'E	228	34.621	-1.898
87	66°35.49'S	145°54.26'E	289	34.566	-1.888

Table 2.2 Winter near-seabed oceanographic sample locations, water depths, salinity and temperature data. Source data from expedition AU9901 (Rosenberg et al., 2001).

Summer data were obtained from CTD casts and water samples collected during DF79 (Domack, 1980; Domack and Anderson, 1983; Jacobs, 1989) and the 2000 WEGA expedition (Brancolini and Harris, 2000; Rosenberg et al., 2001). Despite the years between collections, the five data values from the WEGA expedition were in close agreement to those of proximal DF79 samples. Only deepest depth values from each cast were used, within 50 metres of the seabed, to describe near-seabed hydrology conditions. Salinity (psu) and temperature (°C) values were obtained for the 45 summer samples (Table 2.3).

Sample number	Source	Latitude	Longitude	Water depth (m)	Salinity (psu)	Temperature (°C)
1	DF79	65°30.50'S	141°32.00'E	1954	34.649	-0.820
2	DF79	65°33.30'S	141°31.70'E	1094	34.631	-0.990
3	DF79	65°39.00'S	141°45.00'E	886	34.631	-0.891
4	DF79	65°46.80'S	141°27.60'E	472	34.606	-1.740
5	DF79	66°15.70'S	141°35.80'E	279	34.579	-1.770
6	DF79	66°43.70'S	141°42.80'E	75	34.431	-1.184
7	DF79	66°30.80'S	143°11.60'E	808	34.703	-1.888
8	DF79	66°18.90'S	143°18.80'E	670	34.687	-1.892
9	DF79	66°05.90'S	143°12.70'E	490	34.698	-1.886
10	DF79	65°52.00'S	143°23.90'E	411	34.667	-1.460
11	DF79	65°47.10'S	143°23.30'E	1153	34.633	-0.420
12	DF79	65°44.40'S	143°24.80'E	1974	34.662	-0.381
13	DF79	65°37.10'S	143°08.50'E	2558	34.668	-0.383
14	DF79	65°47.50'S	145°12.70'E	2642	34.709	-0.167
15	DF79	65°58.45'S	144°52.40'E	1238	34.612	-0.503
16	DF79	65°59.90'S	144°58.10'E	360	34.550	-0.878
17	DF79	66°40.90'S	145°11.70'E	567	34.673	-1.895
18	DF79	67°00.00'S	145°14.00'E	1072	34.727	-1.886
19	DF79	66°52.90'S	146°21.50'E	391	34.563	-1.896
20	DF79	66°33.40'S	147°00.60'E	527	34.590	-1.915
21	DF79	66°49.50'S	146°58.80'E	604	34.604	-1.915
22	DF79	67°03.00'S	147°00.00'E	536	34.598	-1.918
23	DF79	67°16.60'S	146°58.80'E	499	34.597	-1.923

24	DF79	67°42.30'S	146°54.50'E	1380	34.705	-1.869
25	DF79	67°36.00'S	148°15.00'E	486	34.597	-1.917
26	DF79	67°23.10'S	149°01.00'E	582	34.602	-1.931
27	DF79	67°10.10'S	148°13.70'E	435	34.587	-1.921
28	DF79	66°54.10'S	148°19.40'E	536	34.625	-1.916
29	DF79	66°39.69'S	148°44.00'E	472	34.583	-1.914
30	DF79	66°24.00'S	148°36.00'E	353	34.517	-1.816
31	DF79	66°08.70'S	148°35.40'E	337	34.511	-1.746
32	DF79	66°04.10'S	148°33.40'E	353	34.518	-1.706
33	DF79	66°07.70'S	147°02.60'E	384	34.593	-1.902
34	DF79	65°53.20'S	146°51.40'E	690	34.577	-1.550
35	DF79	65°51.90'S	146°40.10'E	990	34.598	-1.099
36	DF79	65°40.90'S	146°32.60'E	2365	34.705	-0.157
37	DF79	67°33.12'S	147°00.06'E	545	34.582	-1.913
38	DF79	66°23.04'S	145°10.14'E	346	34.637	-1.493
39	DF79	66°08.04'S	145°10.08'E	178	34.506	-0.946
40	DF79	66°44.16'S	143°19.08'E	445	34.595	-1.891
1	WEGA	66°42.08'S	145°17.40'E	540	34.645	-1.870
2	WEGA	66°57.20'S	144°57.49'E	1093	34.703	-1.882
3	WEGA	66°11.57'S	143°28.71'E	557	34.625	-1.680
4	WEGA	66°11.96'S	143°10.18'E	606	34.622	-1.838
5	WEGA	66°12.05'S	142°54.35'E	553	34.579	-1.744

Table 2.3 Summer near-seabed oceanographic sample locations, water depths, salinity and temperature data. DF79 denotes Operation Deep Freeze 79 (Domack, 1980); WEGA refers to expedition Wilkes Land Glacial History (Rosenberg et al., 2001).

Maps of winter and summer temperature and salinity were each defined using kriging interpolation across the shelf. Maps of winter and summer water masses were derived from available oceanography of the area (Domack, 1980; Milam and Anderson, 1981; Domack and Anderson, 1983; Dunbar et al., 1985; Rintoul, 1998; Bindoff et al., 2001; Williams and Bindoff, 2003), based on a classification of water masses using the temperature vs. salinity boundaries of Bindoff et al. (2001), shown in Fig. 2.4.

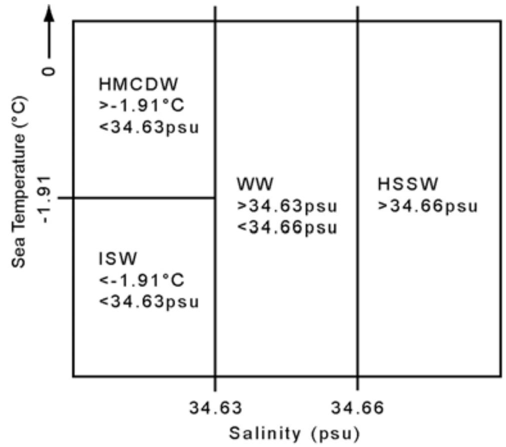

Fig. 2.4 Water mass classification. HMCDW denotes Highly Modified Circumpolar Deep Water; ISW Ice Shelf Water; WW Winter Water; HSSW High Salinity Shelf Water. The classification of water masses are based upon temperature vs. salinity boundaries of Bindoff et al. (2001).

2.2.6 Biological data

The limited biological data presented in this chapter were mostly collected opportunistically from marine geological cruises to the region. In the absence of a dedicated benthic ecologist/taxonomist, the macrobenthos were categorised to phylum or class to the best of our ability. We assumed that a simple measure of the number of taxa categories at each site would provide a crude proxy for biodiversity, in the absence of more rigorous analysis such as Shannon diversity indices which require lower taxonomic classification. No samples were retained onboard. Despite the paucity of biological data, some patterns emerge and the findings do reveal the general nature of benthic assemblages on the continental shelf for classification into Biotopes.

Grab and gravity core samples were obtained from the 2000 WEGA expedition, which mostly sampled the deep (below 700 m) west George V Basin in proximity to the Mertz Drift (Brancolini and Harris, 2000). The 19 samples were wet-sieved to 1 mm; biological material sorted to the appropriate taxa and weight (g) measured. The taxa categories were: benthic foraminifera, sponge, hydroid, polychaete worm, nonpolychaete worm, gastropod, bivalve and bryozoa (Table 2.4). This category list reports only those taxa actually found in the WEGA grab and core samples. Data were standardised by calculating the percentage weight of taxa categories in each sample. Statistical analysis was carried out on the WEGA dataset as the numbers of samples were considered sufficient to obtain meaningful results, the sampling technique was the same and stations were from a similar habitat, i.e. deep basin. Using Primer Ver. 5 statistical package (Clarke and Warwick, 2001), a Bray-Curtis similarity was conducted on the untransformed percentage weight data from Table 2.4. The resulting similarity matrix

was analysed using group-averaged cluster analysis, displayed as a dendogram and a two-dimensional, multidimensional scaling (MDS) ordination plot.

Sample number	GB01	GB02	GB03	GB04	GB05	GB06	GB07
Latitude	66°32.01'S	66°33.37'S	66°34.07'S	66°34.46'S	66°32.95'S	66°36.18'S	66°36.81'S
Longitude	143°38.00'E	143°04.15'E	143°01.07'E	142°57.81'E	143°14.65'E	143°20.03'E	143°21.12'E
Water depth (m)	761	864	866	861	825	815	808
Foram (%)	48.67	0.16	9.51	0.00	7.47	0.35	0.00
Sponge (%)	2.67	88.89	74.05	99.64	88.78	97.60	72.37
Hydroid (%)	0.00	0.03	0.00	0.00	0.00	0.02	0.00
Polychaete (%)	48.67	10.75	16.37	0.35	3.23	1.56	20.56
Nonpoly (%)	0.00	0.00	0.07	0.00	0.52	0.22	7.07
Gastropod (%)	0.00	0.00	0.00	0.00	0.00	0.25	0.00
Bivalve (%)	0.00	0.16	0.00	0.00	0.00	0.00	0.00
Bryozoa (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sample number	GB08	GB09	GB10	GB11	GB12	GB13	GB14
Latitude	66°37.63'S	66°50.77'S	66°29.97'S	66°30.18'S	66°28.89'S	66°33.98'S	66°33.92'S
Longitude	143°22.67'E	144°51.12'E	143°10.32'E	143°08.86'E	143°08.18'E	143°00.32'E	143°00.88'E
Water depth (m)	800	934	827	840	815	879	872
Foram (%)	0.00	41.79	44.53	40.28	69.47	0.00	0.01
Sponge (%)	99.95	0.00	19.86	7.29	0.00	99.95	99.84
Hydroid (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Polychaete (%)	0.05	32.68	35.60	45.30	30.53	0.05	0.15
Nonpoly (%)	0.00	25.52	0.01	0.00	0.00	0.00	0.00
Gastropod (%)	0.00	0.00	0.00	7.13	0.00	0.00	0.00
Bivalve (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Bryozoa (%)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sample number	GB15	GB16	GB17	GB18	GC11		
Latitude	66°31.22'S	66°23.42'S	66°23.57'S	66°20.97'S	66°11.97'S		
Longitude	143°22.94'E	143°19.31'E	143°19.15'E	143°18.46'E	143°29.07'E		
Water depth (m)	793	739	735	709	560		
Foram (%)	23.36	0.00	6.20	1.56	6.26		
Sponge (%)	40.58	98.48	93.42	96.20	0.00		
Hydroid (%)	0.00	0.00	0.00	0.00	0.00		
Polychaete (%)	36.06	1.52	0.38	2.24	1.77		
Nonpoly (%)	0.00	0.00	0.00	0.00	0.00		
Gastropod (%)	0.00	0.00	0.00	0.00	0.00		
Bivalve (%)	0.00	0.00	0.00	0.00	0.00		
Bryozoa (%)	0.00	0.00	0.00	0.00	91.97		

Table 2.4 Grab and core sample locations, water depths and macrobenthos percentage weight data. Source data is from the 2000 WEGA expedition (Brancolini and Harris, 2000).

Three rock dredges were deployed for approximately 30 minutes in the vicinity to the western calving face of the Mertz Glacier Tongue during the 2001 *RVIB Nathaniel B. Palmer* expedition (NBP0101) to the region (Leventer et al., 2001). Samples were wet sieved onboard to 1 mm and biological material was classified to phylum or class and wet volume (ml) obtained. Four grab samples were also obtained near the Adélie Coast, from Watt Bay, Mertz Bank and in the

deepest part of George V Basin. Samples were wet sieved to 1 mm, classified to phylum or class and the wet volume (ml) measured. Taxa categories were: sponge, seapen, anemone, polychaete worm, nonpolychaete worm, amphipod, pycnogonid, gastropod, bivalve, scaphopod, cephalopod, brachiopod, bryozoa, crinoid, asteroid, ophiuroid, holothuroid, echinoid and tunicate (Table 2.5). This category list reports only those taxa actually found in the NBP0101 dredge and grab samples. Data were standardised by calculating the percentage volume of taxa categories in each sample. The percentage volume was used to simply identify dominant and secondary macrofauna within each sample. No statistical analyses were carried out on the NBP0101 data due to the dissimilarity between sampling techniques and the low number of samples.

Sample number	3DR03	4DR04	5DR05	7GR07	8GR08	14GR14	15GR15
Latitude	66°53.99'S	66°48.98'S	66°42.49'S	66°56.14'S	66°44.06'S	66°37.23'S	67°03.67'S
Longitude	145°09.90'E	145°21.79'E	145°36.73'E	144°04.50'E	141°41.75'E	146°07.60'E	145°10.47'E
Water depth (m)	858	592	442	948	158	117	1276
Sponge (%)	25.82	34.89	13.74	1.64	39.88	1.56	0.00
Seapen (%)	0.36	0.00	1.53	0.00	0.00	0.00	0.00
Anemone (%)	2.55	0.31	0.00	0.00	0.00	0.00	0.00
Polychaete (%)	62.18	4.03	16.79	98.36	45.48	6.26	0.00
Nonpoly (%)	3.64	0.00	0.00	0.00	0.31	0.00	0.00
Amphipod (%)	0.00	0.39	0.00	0.00	0.16	0.00	0.00
Pycnogonid (%)	0.00	0.31	0.00	0.00	0.00	0.00	0.00
Gastropod (%)	0.00	0.39	0.00	0.00	0.16	0.23	0.00
Bivalve (%)	0.00	0.16	3.05	0.00	0.93	0.39	100.00
Scaphopod (%)	1.45	0.00	0.00	0.00	0.00	0.00	0.00
Cephalopod (%)	0.00	0.00	0.00	0.00	0.31	0.00	0.00
Brachiopod (%)	0.00	0.05	3.05	0.00	0.16	0.00	0.00
Bryozoa (%)	1.45	45.13	24.43	0.00	5.61	86.07	0.00
Crinoid (%)	0.00	0.70	0.00	0.00	0.00	0.00	0.00
Asteroid (%)	0.00	1.86	0.00	0.00	0.00	0.00	0.00
Ophiuroid (%)	0.00	0.93	4.58	0.00	0.31	0.39	0.00
Holothuroid (%)	2.55	0.00	8.40	0.00	0.16	0.00	0.00
Echinoid (%)	0.00	3.41	0.00	0.00	6.23	5.09	0.00
Tunicate (%)	0.00	7.44	24.43	0.00	0.31	0.00	0.00

Table 2.5 Dredge and grab sample locations, water depths and macrobenthos percentage volume data. Source data is from the 2001 NBP0101 cruise (Leventer et al., 2001).

The only dedicated biological sampling conducted on this region of the Antarctic shelf is from the 1911-1914 Australasian Antarctic Expedition (AAE), led by Sir Douglas Mawson. Four hand dredges were conducted in shallow waters around Commonwealth Bay, and three ship-operated trawls on the Adélie Bank, a submarine canyon and beside the west calving face of the Mertz Glacier Tongue (Mawson, 1940). The geographical positions of stations reported in Mawson (1940) are suspect, however, the relative positions to known coastal features were also quoted so we adjusted the geographic positions to conform as close as possible to the relative

positions and the depth of water quoted. The reports give only an indication of the presence of taxa at each station and no biomass data. The taxa categories were: sponge, hydroid, softcoral, anemone, polychaete worm, nonpolychaete worm, barnacle, amphipod, isopod, decapod, pycnogonid, gastropod, bivalve, brachiopod, bryozoa, crinoid, asteroid, ophiuroid, holothuroid, echinoid and tunicate (Table 2.6). The category list reports only those taxa actually reported in AAE dredge and trawl samples. No statistical analysis was carried out on the AAE macrobenthos table due to the lack of quantitative data.

Sample number	DR1	DR4	DR4A	DR5	TR21	TR22	TR23
Latitude	66°59.42'S	66°59.25'S	66°59.00'S	66°57.50'S	66°51.60'S	66°47.40'S	66°32.00'S
Longitude	142°39.50'E	142°38.33'E	142°38.33'E	142°40.80'E	142°28.80'E	145°28.80'E	141°37.00'E
Water depth (m)	8	41	106	7	644	551	285
Sponge	x	x	x	x	x	x	x
Hydroid			x		x	x	
Softcoral			x		x	x	x
Anemone		x			x	x	x
Polychaete	x	x	x	x	x	x	x
Nonpoly		x	x		x	x	x
Barnacle							x
Amphipod	x	x	x	x	x	x	x
Isopod			x		x	x	x
Decapod			x		x	x	x
Pycnogonid	x	x		x	x	x	x
Gastropod	x	x	x	x	x	x	x
Bivalve		x	x		x	x	x
Brachiopod						x	x
Bryozoa	x		x	x	x	x	x
Crinoid					x	x	x
Asteroid	x	x	x	x	x	x	x
Ophiuroid			x		x	x	x
Holothuroid	x	x		x	x	x	x
Echinoid		x	x				x
Tunicate		x	x		x	x	x

Table 2.6 Dredge and trawl sample locations, water depths and macrobenthos presence. Source information is from 1911-14 Australasian Antarctica Expedition (Mawson, 1940).

2.3 Results

The aim of this study was to bioregionalise the George V Shelf to the Geomorphic Unit and Biotope levels at the local (10s of km) scale. Our procedures were to use statistical analyses to identify patterns in the data where possible, and to overlay the interpolation models produced by various datasets within a GIS. The various models included: bathymetry, geomorphology, gravel, sand/mud, surficial sediment type, near-seabed temperature and salinity, near-seabed water masses and macrobenthos distribution. Qualitative consideration was conducted on the models and to assess their agreement or disagreement with each other. Geomorphic features

were emphasised as the basis for the boundaries of the Biotopes, and then other datasets were used to corroborate the patterns identified. For example, we asked whether the patterns within the maps of depth, sediment and oceanographic data were in accordance with the patterns of geomorphic features, or provided the basis to further subdivide geomorphic features. Information from the biological datasets provided the trophic structure of the dominant macrobenthos believed to be within each Biotope. Where available, underwater photos confirmed the general seabed sediment and dominant macrobenthos within the Biotopes. The boundaries of each unit were digitised as a shapefile within ArcGIS. A table was compiled which lists each Biotope against parameters such as depth, dominant and secondary macrofauna, epifauna scale, geomorphic feature, surficial sediment, summer and winter water masses, and inferred primary and secondary disturbances.

2.3.1 Geomorphology

Eight Geomorphic Units are recognised in the bathymetric and acoustic facies maps, highlighting the diversity of 'landscape' on this glacially-carved shelf (Fig. 2.5). The dominant feature of the shelf is the George V Basin, defined as seabed below the 400 m isobath and bounded by the Mertz and Adélie Banks, and sharing a southern boundary with inner shelf canyons at approximately 800 to 1000 m water depth. The sediment drift, Mertz Drift, lies in the western part of the basin and is characterised by mounded, parallel, sub-bottom reflectors up to 35 m in thickness (Harris and Beaman, 2003). Sediment cores obtained from the Mertz Drift show numerous layers of siliceous mud and diatom ooze (SMO) believed to be annual varves (Domack, 1988; Harris et al., 2001). In the eastern part of the basin, smaller drape- or fill-style deposits with similar parallel sub-bottom reflectors up to 16 m thickness occur at three locations below 800 m water depth. The combined deposits are labeled as drifts in Fig. 2.5. The sediment deposits thin at the edges to an approximately 30 cm layer of SMO overlying a grey, muddy diamicton (Domack, 1982) within the remainder of the basin.

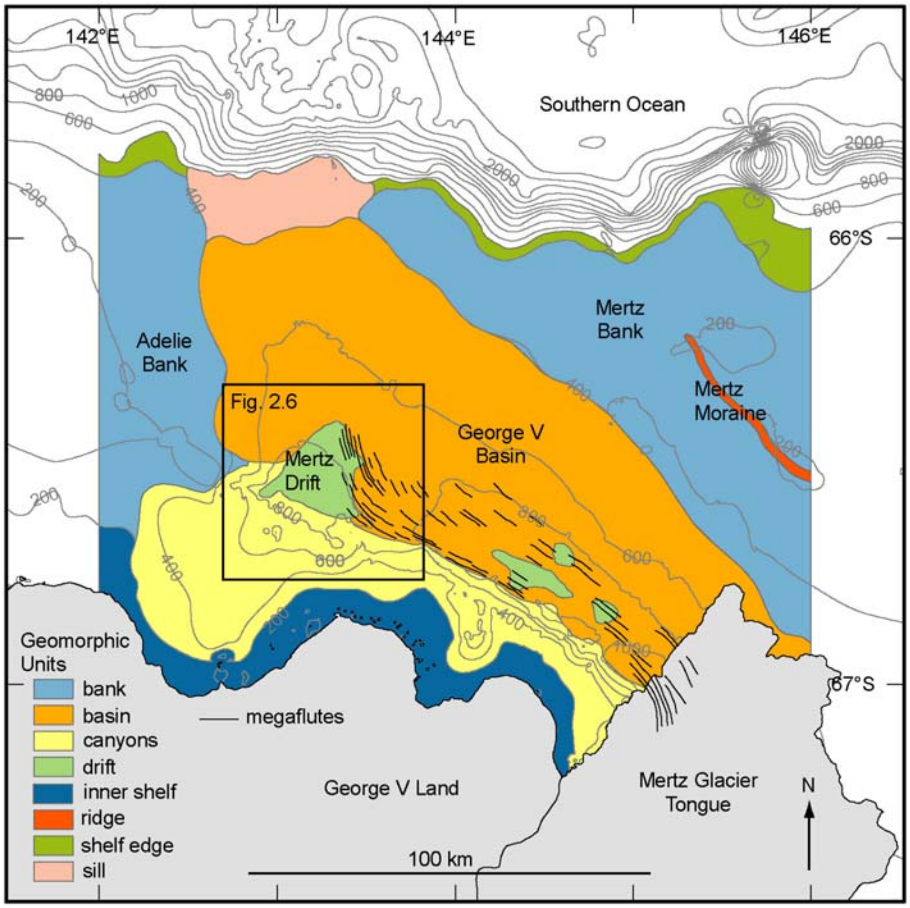

Fig. 2.5 Map of George V Shelf Geomorphic Units. Names are based upon hydrographic terms recognised on Admiralty charts (IHO, 2001). Megaflute lines are basin-parallel lineations resulting from sub-glacial molding of till by the glacier sole during glacial expansion. The box shows the location of Fig. 2.6.

Multibeam swath bathymetry revealed megaflutes or megascale lineations 10s of km long, a few 100 m wide, and up to approximately 30 m between trough and crest (indicated by parallel black lines in Fig. 2.5). The megaflutes can be clearly traced along the axis of the George V Basin back to the outlet of the Mertz Glacier Tongue, and record the subglacial molding of soft deformation till by the glacier sole during glacial expansion (Anderson, 1999). A hill-shaded relief of swath bathymetry of the western George V Basin shows megaflutes veering northward towards the sill that connects the basin to the shelf edge (Fig. 2.6). A thin layer of SMO (approximately 30 cm) is believed to overlie the megaflutes as elsewhere within the basin. Unfortunately, the multibeam swath mapping coverage was unable to resolve the full extent of the megaflutes, due to the limited time of the vessel on survey in the area.

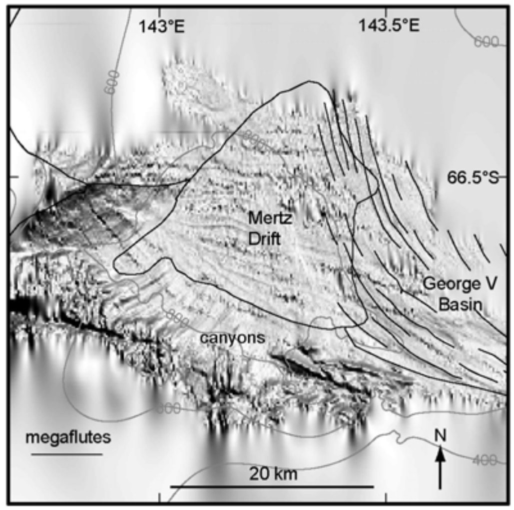

Fig. 2.6 Hill-shaded relief map of swath bathymetry in western George V Basin. Geomorphic Unit boundaries reveal the limits of the Mertz Drift and inner shelf canyons. Megaflute lines show the veering northward of sub-glacial molding of the seabed during glacial expansion by the Mertz Glacier.

Bounding the northeast and west of the George V Basin are the Mertz and Adélie Banks respectively. These extensive geomorphic features lie in water depths of less than 400 m and are generally flat-topped. Their shallow upper surface are ploughed by grounded icebergs and winnowed by oceanic currents (Fig. 2.2). In places, localised knolls occur on the bank tops which have yet to be fully resolved in the bathymetric model. One significant geomorphic feature is a ridge, named the Mertz Moraine (Eittreim et al., 1995), which rims the southern margin of the Mertz Bank at approximately 200 m depth, and appears to be a lateral moraine relating to ice shelf advance onto the shelf during the Last Glacial Maximum (Barnes, 1987; Domack et al., 1989). Radarsat images show grounded bergs following the approximate Mertz Moraine position, confirming that a shallow underwater ridge exists.

At the northern limit of this study area is the shelf edge, defined as below 400 m water depth and marking the upper part of the steep continental slope north of the Adélie and Mertz Banks. The shelf edge is swept by the westerly-going, shallow Antarctic Coastal Current (ACC) as well as flows of Highly Modified Circumpolar Deep Water (HMCDW). At longitude 143ºE, a sill connects the George V Basin to the continental slope. This gently sloping feature forms a transition zone between the shelf and deep ocean as the conduit for inflow of HMCDW into the basin and outflow of HSSW onto the slope (Williams and Bindoff, 2003). Depths range from 400 m to approximately 450 m in the centre of the sill (Eittreim et al., 1995).

Forming the inner shelf boundary of the George V Basin are two geomorphic feature types: submarine canyons, and high-relief ridges and depressions. The combined features are labeled

as canyons in Fig. 2.5. The submarine canyons are amongst the least-well studied features of the shelf, and yet are believed to be the conduit for brine spilling into the basin (Williams and Bindoff, 2003). Seismic profiles reveal canyons with varying vertex elevations of up to 150 m between crest and trough. Canyons and smaller gullies occur close to the coast and descend steeply to the floor of the George V Basin in over 800 m of water (see Fig. 2.6). In at least one place along the George V Coast, the head of a large canyon starts almost at the coastline, e.g. the Denison Channel (Fig. 2.2) in Commonwealth Bay (AHO, 2002). The canyons are believed to be formed by the eroding action of numerous small glaciers along the George V Coast, advancing over crystalline basement outcrop during previous glaciations (Beaman and Harris, 2003).

Also largely unexplored is the inner shelf, defined as seabed shallower than 200 m to the coast. An indication of the rough seabed morphology along the George V Coast can be found further west along the Adélie Coast. Seabed mapping reveals a hillocky inner shelf, heavily dissected by rocky ridges and ledges, separated by depressions with depths from 100 m to 200 m (Vanney and Johnson, 1979). The extreme contrasts of ridges and depressions on the seafloor manifests as over a hundred small islands and islets along the George V Coast, e.g. Mackellar and Stillwell Islands, and Way Archipelago west of longitude 144°E.

2.3.2 Surficial sediment

The map of interpolated gravel distribution (Fig. 2.7A) shows a distinct trend across the shelf. Gravel percentage is highest offshore along the shelf edge (20-25 %), decreasing within the George V Basin (0-5 %). The winnowing action of oceanic currents is likely responsible for the higher percentage of gravel offshore (Dunbar et al., 1985). Finer-grained sediments are proportionally increased within the basin, although underwater photography reveals the presence of ice-rafted debris (IRD) even in the deeper part of the basin. With limited sampling along the majority of the inner shelf in waters shallower than 200 m, the interpolation is least accurate in this zone. The few samples taken at Stations 8GB and 9GB, from inner shelf seabed west of Commonwealth Bay, indicates gravel percentage as 5-10% and is assumed to be indicative of bioclastic gravel along the remainder of the shallow coast. The increase in gravel percentage (5-10 %) around the Mertz Glacier Tongue is probably the result of glacial dropstones from the floating ice shelf.

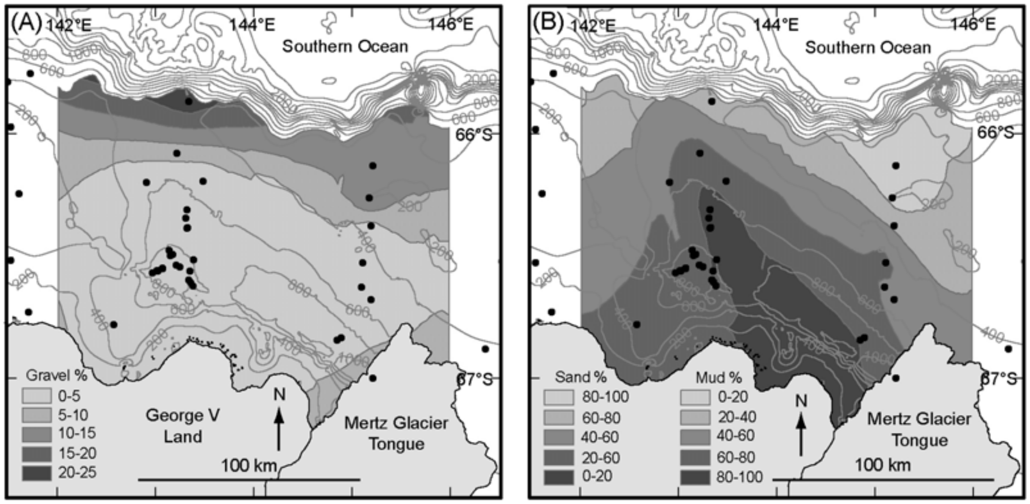

Fig. 2.7 Surficial sediments on the George V Shelf as (A) gravel percentage and (B) sand/mud percentage. Dots indicate the positions of sediment samples. Note that the lack of sampling along the coast decreases model accuracy in this area.

Mud percentage is highest (80-100 %) within the main part of the George V Basin and towards the sill below about 600 m (Fig. 2.7B). Mud percentage reduces closer to the Mertz Glacier Tongue in depths over 1000 m and in the western part of the basin in the vicinity of the Mertz Drift. Due to the lack of sampling along the George V Coast, it is unlikely that mud percentage is within the range 80-100 % as indicated by the interpolation, but possibly lies in the range 40-60 % from the mud percentages obtained at the shallow Stations 8GB and 9GB off the Adélie Coast. Sand percentage is greatest on the outer shelf (80-100 %), particularly over the Mertz Bank seaward of the relatively shallow (approximately 200 m) knolls. The high sand percentage here is likely to be the result of oceanic currents over the shallow banks winnowing finer-grained sediments and increasing the proportion of sand in relation to mud (Dunbar et al., 1985).

Distinguishing between different sediment types on the Antarctic shelf such as glacial-marine sediments and various diamictons is difficult (Anderson, 1999). Therefore, we applied a surficial sediment classification based upon the proportion of gravel and sand:mud ratios (Folk, 1954) at each station and interpolated across the shelf (Fig 8). Six classes of surficial sediment are found, with distribution generally conforming to the deep basin, the shallow inner shelf and offshore banks. A sandy mud characterises the lower basin, extending towards the sill and deeper than 600 m water depth. It does not extend into the deepest part of the basin below 1000 water depth. This sediment type contains terrigenous, medium-sized sand, rich in quartz and mica, arenaceous foraminifera and benthic diatom frustules (Presti et al., 2003). Sedimentation occurs in the basin when oceanic water masses, such as HMCDW, cool, sink and flow

landward, entraining and transporting finer-grained, terrestrial and biogenic sediments into the basin (Harris and Beaman, 2003).

In the upper basin, slightly gravelly, sandy mud is found between 500 to 600 m on the northern side and between 200 to 1000 m depth on the landward side. Again, mud is dominant within samples but with a slight increase in proportion of gravel compared to the deeper lower basin. Future sampling in the canyon region may reveal greater diversity in surficial sediment types than is depicted in Fig. 2.8 due to the steep slope of the canyon area between depths of 200 to 1000 m. Within the inner shelf shallower than 200 m, gravel dominates the surficial sediment. The two sediment samples taken in the area contain calcareous gravel and sand consisting of barnacles, bryozoans, ostracods, pelycepods, gastropods, foraminifera and calcareous algae (Domack, 1988).

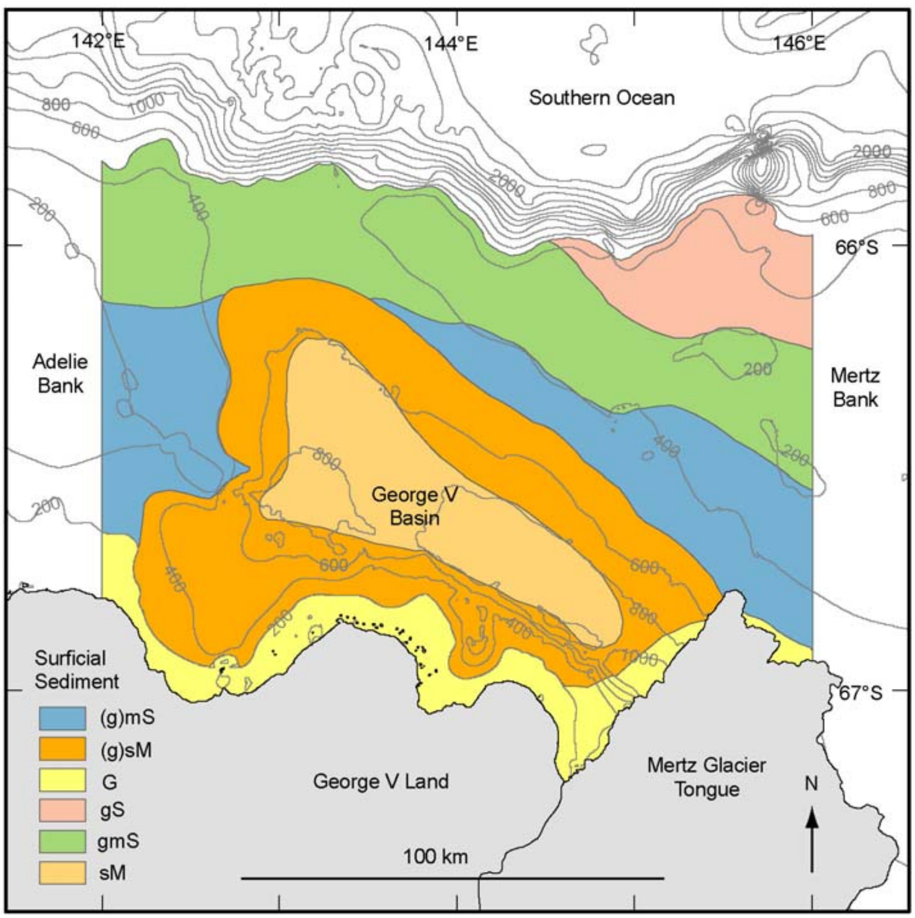

Fig. 2.8 Surficial sediment distribution on the George V Shelf using the Folk (1954) classification (see Fig. 2.3).

The area bordering the upper basin in depths shallower than 500 m and over the landward side of the Mertz and Adélie Banks is characterised by slightly gravelly, muddy sand (Fig. 2.8). In these shallower waters, we suggest the presence of icebergs and the influence of shelf currents result in an increase of the proportion of sand at the seabed. On the southern side of the Mertz Bank, the seabed is scoured by drifting icebergs to 500 m depth, being driven by westerly-going shelf currents and wind (Barnes and Lien, 1988). Sediments in this zone have been referred to as an ice-keel turbate, comprising a mix of reworked glacial till, ice-rafted debris and marine biogenic material (Barnes and Lien, 1988).

Sediment on the majority of the outer banks and shelf edge is gravelly, muddy sand (Fig. 2.8). Sand dominates and the gravel proportion increases with proximity to the shelf edge. Grounded icebergs in this zone rework the seabed, and oceanographic processes, such as upwelling water masses and shelf currents, winnow finer-grained sediments to further reduce the proportion of mud in relation to sand and gravel (Harris and O'Brien, 1996). Sampling on the outer shelf reveals bioclastic rich sand and gravel sediments with a carbonate component comprised primarily of foraminifera, ostracods, pteropods and bryozoa fragments (Domack, 1988). To the northeast of the study area, Domack (1988) described a zone of gravelly sand, reflecting the increased winnowing effect of oceanic currents flowing over the outer Mertz Bank. The shallow (approximately 200 m) knolls found on the bank coincide with the southern boundary of this zone and are possibly a restriction to oceanic currents in this area.

2.3.3 Near-seabed oceanography

The near-seabed hydrology characteristics were classified into the four water masses described over the shelf using the temperature vs. salinity boundaries by Bindoff et al. (2001). In the absence of published summer water mass boundary definitions using temperature and salinity, the same temperature vs. salinity classification for the winter water masses (Fig. 2.4) were also applied to the summer dataset. This assumption allows comparison of watermass boundaries between winter and summer within a GIS, however, it is likely that summer water mass boundary definitions do vary compared to winter water mass boundary definitions. Further, oceanographic measurements on the shelf were not taken in the same locations between winter and summer. Despite the winter cruise having more data points than summer (87 vs. 45 respectively), there are no winter data points in the western George V Basin, and hence the interpolated maps for winter oceanography do not cover the entire study area.

The map of winter temperature (Fig. 2.9A) shows that the basin and part of the Mertz Bank, north of the Mertz Glacier Tongue, is bathed in very cold (< -1.8°C) water. Important features

detected during the three week winter cruise were the intrusions of warmer water over the shelf break and onto the bank. These relatively warm water intrusions correspond to upwelled HMCDW, and the influence of these intrusions may be detected to depths of approximately 400 to 500 m over the bank and into the upper basin. A comparison against the summer temperature map (Fig. 2.9B) reveals the basin also with temperatures colder than -1.8°C, although apparently reduced in area (deeper than approximately 600 m) compared to the winter map for the same temperature range. A more even distribution of warmer temperatures occurs along the outer shelf in summer (Fig. 2.9B). At the shelf edge in summer, temperatures are warmer than -1.2°C and cool towards the continent, generally following the topography of the basin and banks. The lack of sampling along the George V Coast during summer does not allow interpolated temperatures in the shallow inner shelf region to be resolved with confidence.

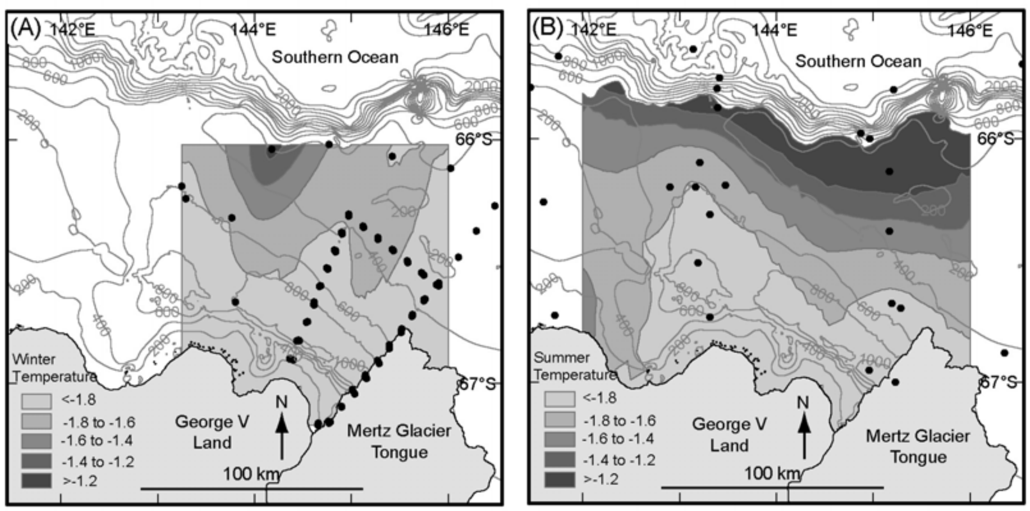

Fig. 2.9 Near-seabed temperature (°C) during (A) winter and (B) summer. Dots indicate positions of oceanographic stations. Note the winter model does not extend to the west side of the study area.

Winter salinity measurements (Fig. 2.10A) reveal that the George V Basin is filled to approximately 500 m and towards the sill with very saline (> 34.65 psu) High Salinity Shelf Water (HSSW). A small area of the seabed in the vicinity of the outlet of the Mertz Glacier Tongue is influenced by relatively fresh (< 34.55 psu) Ice Shelf Water (ISW) advected from beneath the ice shelf. Over the Mertz Bank, the influence of HMCDW is apparent due to fresher (< 34.55 psu) intrusions detected to approximately 400 to 500 m depth. The summer salinity distribution (Fig. 2.10B) reveals a body of highly saline water (> 34.65 psu) approximately filling the basin and extending up to the sill connecting the basin to the slope. Either side of the basin, near-seabed salinity generally becomes fresher approaching 34.55 psu on the bank tops. The interpolation indicates more saline water (34.60 to 34.65 psu) over the eastern limit of the

study area on the Mertz Bank. Lack of sampling along the George V Coast does not provide a confident interpolation of bottom salinity for that area.

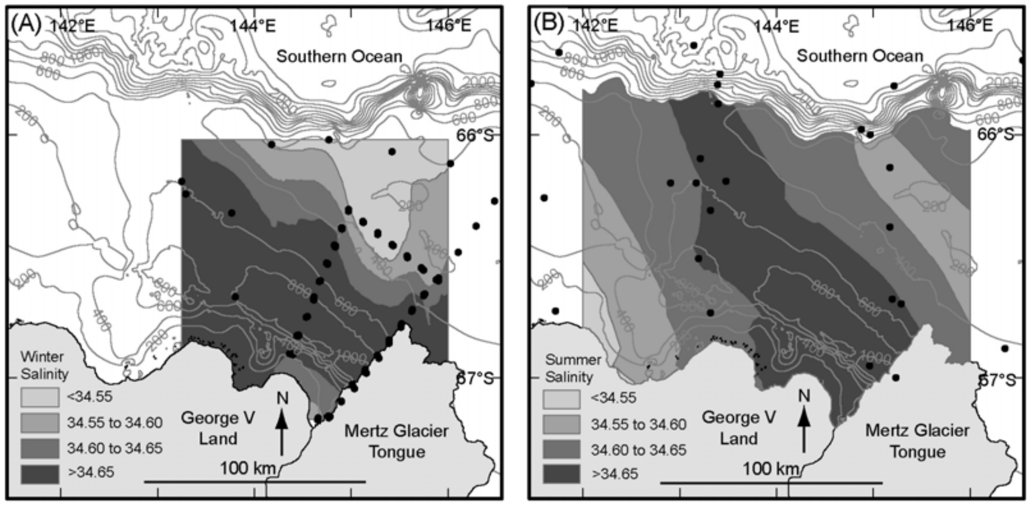

Fig. 2.10 Near-seabed salinity (psu) during (A) winter and (B) summer. Dots indicate positions of oceanographic stations. Note the winter model does not extend to the west side of the study area.

A striking feature of the near-seabed winter water masses compared to summer is the reduced areal extent of HSSW in the George V Basin (Figs. 2.11A and B). During winter, WW is correlated with and balanced by changes in area of upwelling HMCDW, and therefore found as a narrow layer at near-seabed depths between 400 to 500 m on the Mertz Bank and along the inner shelf (Fig. 2.11A). During summer, a stratified version of remnant WW fills most of the basin and overlies HSSW (G.D. Williams, pers. comm., 2002). In summer, HMCDW is found as large bodies of relatively warm and fresh water over the Mertz and Adélie Banks to depths of between 400 to 500 m (Fig. 2.11B). ISW is not detected at near-seabed in the summer map of water masses, but this may also be due to a lack of sampling.

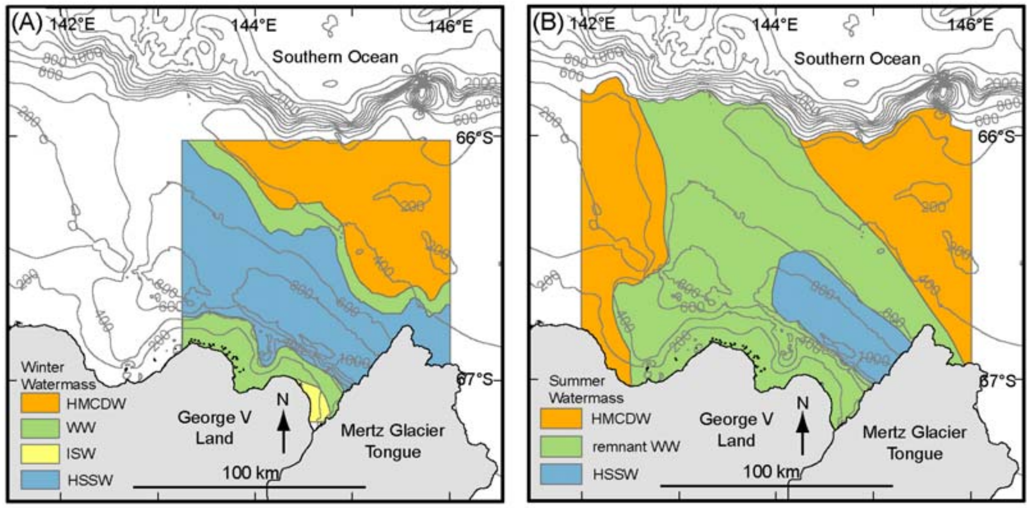

Fig. 2.11 Near-seabed water masses during (A) winter and (B) summer. HMCDW denotes Highly Modified Circumpolar Deep Water; WW Winter Water; ISW Ice Shelf Water; HSSW High Salinity Shelf Water. Note the winter model does not extend to the west side of the study area.

2.3.4 Macrobenthos

A map of the number of taxa at each station in Tables 2.4, 2.5 and 2.6, shows graduated symbols in a range from 1 to 20 taxa (Fig. 2.12). While caution needs to be taken when comparing the number of taxa due to the different sampling techniques across the shelf, some general patterns can be seen. Stations in proximity to the coast of Commonwealth Bay recorded increasing taxa numbers from 8 to 15 as sample depths increased from 7 m to 106 m. The one sample on the Adélie Bank (285 m) records the highest diversity of taxa with a value of 20. A sample taken from the upper part of a submarine canyon (644 m) in Commonwealth Bay also has a relatively high value of 18 taxa. In contrast, a sample from the base of a deep canyon in Watt Bay (948 m) has a low value of two taxa. Within the western part of the George V Basin, where most of the WEGA samples were obtained (709 m to 879 m), taxa numbers ranged from a relatively low two to six. The deepest sample obtained from the basin (1276 m) recorded only one taxa. Sampling along the west calving face of the Mertz Glacier Tongue reveals taxa numbers increasing as depths shoal. Taxa values increase from eight (858 m) to relatively high values of 14 and 20 (592 m and 551 m respectively). However, in the vicinity of the glacier grounding zone on the Mertz Bank (442 m), the taxa number decreases to 10. More shallow and in proximity to the Mertz Moraine (117 m), the taxa number is a relatively low value of 7.

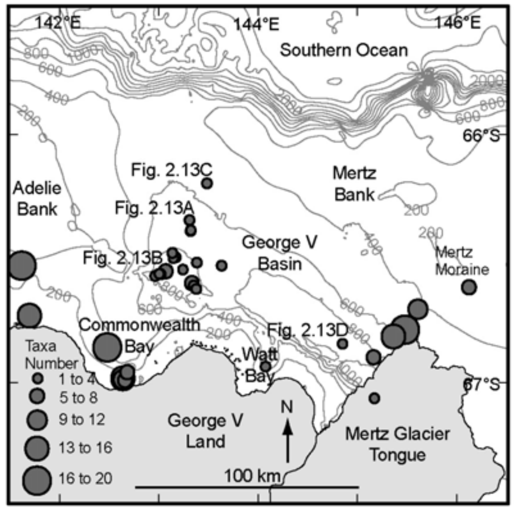

Fig. 2.12 Graduated symbols of macrobenthos taxa number in seabed samples taken from the George V Shelf. Note the positions of grab sample photographs displayed in Figs. 2.13A, B, C and D.

Focusing on the more comprehensive WEGA dataset in Table 2.4, polychaetes and sponges were the predominant taxa within samples taken from the seabed in depths below 709 m. Polychaete and nonpolychaete worms were thin, soft and clearly infaunal within the siliceous mud and diatom ooze (e.g. Sample GB18; Fig. 2.13A). Sponge material was mostly glass spicule mat although small (several cm diameter) whole hexactinellid sponges were found in some samples (e.g. Sample GB04; Fig. 2.13B). Arenaceous benthic foraminifera up to 15 mm long were also common in most samples, possibly *Reophax* sp., also found in a study by Milam and Anderson (1981) in a deep basin assemblage of benthic foraminifera. Sample GC11 was obtained at 560 m in the upper basin towards the sill, which has calcareous bryozoa as the dominant macrofauna and a higher proportion of gravel compared to the lower basin samples (Fig. 2.13C). The deepest sample obtained during the WEGA cruise was in 934 m from the eastern part of the basin. It also had a high proportion of polychaete and nonpolychaete worm material and arenaceous benthic foraminifera (e.g. Sample GB09; Fig. 2.13D).

Fig. 2.13 Photographs of macrobenthos taxa in WEGA seabed samples (A) GB18 - 709 m (B) GB04 - 861 m (C) GC11 - 560 m and (D) GB09 - 934 m.

Statistical analysis (cluster analysis and multi-dimensional scaling MDS) of the WEGA dataset reveals three groups of samples, distinguished both on the dendogram and the MDS plots of the untransformed data (Fig. 2.14). These were: a group dominated by sponges; a group with polychaetes as the dominant macrofauna; and a group of one sample with bryozoa as the dominant fauna. On the dendogram (Fig. 2.14A), the main divisions between the bryozoa, sponge and polychaete groups are made at a low level of similarity, not exceeding 20%. The bryozoa sample was obtained from north of the Mertz Drift in the upper basin (Figs. 2.14B and C). The samples in the sponge group are clearly clustered together in relative similarity, and were obtained from the southwestern part of the Mertz Drift and restricted to the area showing true drift-style of sedimentation (Harris and Beaman, 2003). Samples from the polychaete dominated group were obtained where the drape-style of deposition gradually thins away from the Mertz Drift and into the lower basin (Harris and Beaman, 2003). Underwater photos confirm

that the seabed in the western George V Basin is muddy with small quantities of ice-rafted debris cobbles clustered on the seabed. Most photos showed the water column of the seabed as quite turbid. Sessile macrobenthos are relatively rare except for the occasional stalked hexactinellid sponge and seapens.

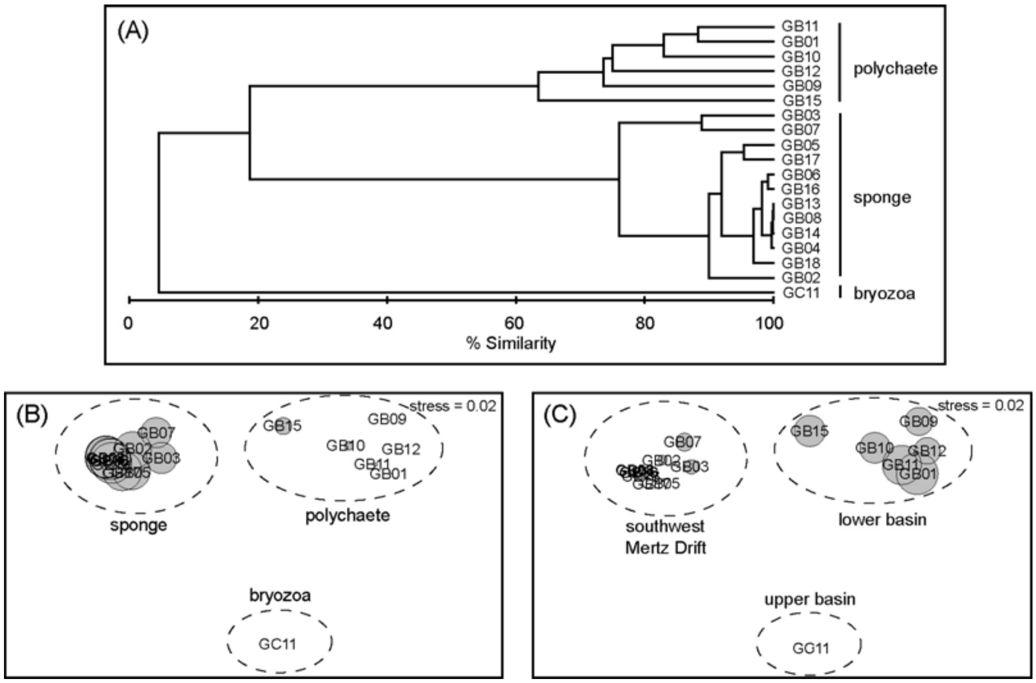

Fig. 2.14(A) Group-averaged dendogram of cluster analysis on untransformed percentage weight data from Table 2.4 (WEGA samples). (B) Two-dimensional ordination plot from non-metric multi-dimensional scaling (MDS) of Table 2.4 data showing the relative size of sponge percentage in samples, and the three macrobenthos groups. (C) MDS plot of the same Table 2.4 data showing the relative size of polychaete percentage in samples, and the general location of stations.

2.3.5 Biotopes

Qualitative examination of the available datasets resulted in the George V Shelf being divided into twelve Biotopes (Figs. 2.15 and 2.16). We believe that the patterns observed in the environmental and biological datasets support subdivision of the shelf into this number of units within the context and local (10s of km) scale of the hierarchical structured system proposed by Butler et al. (2001). Our classification seeks to define the benthic communities associated with Biotopes according to the trophic category of the inferred dominant macrofauna within a geomorphic feature, i.e. 'suspension-, detritus- or deposit-feeders' (Clarkson, 1989). Where diversity of macrofauna is high, such as in shallow inner shelf waters with a roughly equal mix of trophic category, then the benthic community is recorded as 'diverse'. In contrast, where macrobenthos is nearly absent, such as in the deepest part of the basin, the benthic community is

'barren'. As the shelf edge is swept regularly by deep ocean currents, the benthic community is defined as 'oceanic'. Similarly, the sill is a conduit for oceanic HMCDW upwelling onto the shelf and the outflow of HSSW off the shelf, and therefore the benthic community is defined as 'transitional' between oceanic and shelf macrobenthos. Table 2.7 summarises each Biotope against biological, geophysical and oceanographic features, and includes inferred primary and secondary disturbance regimes.

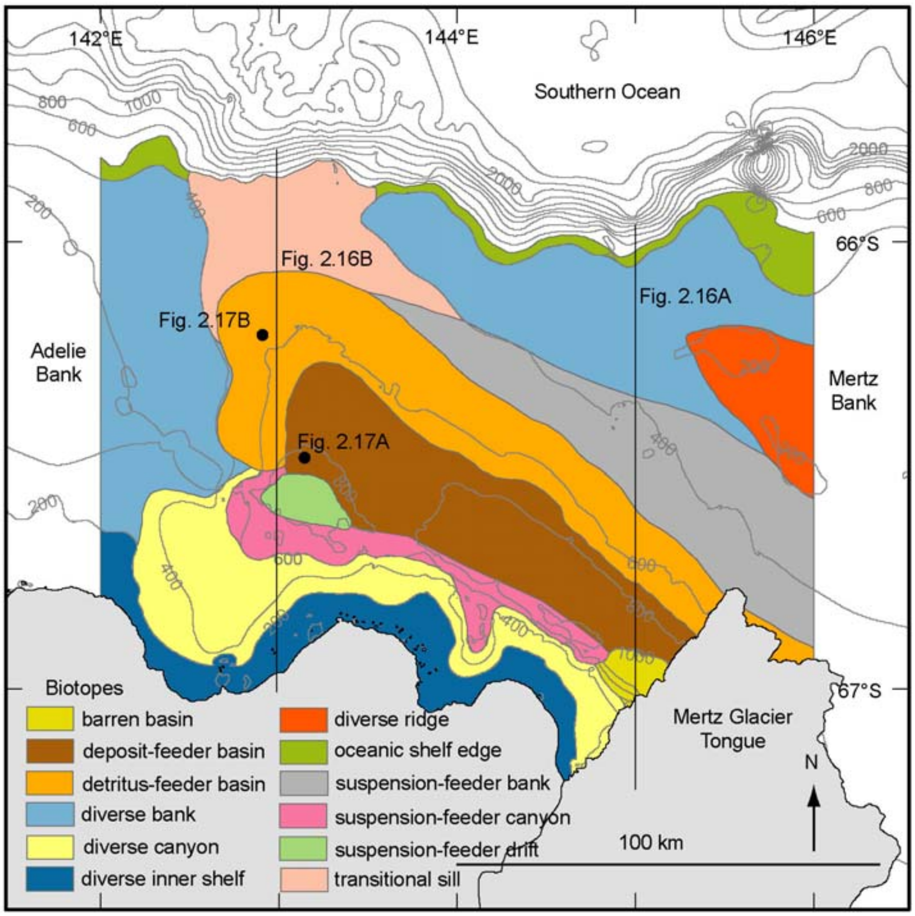

Fig. 2.15 Biotopes of the George V Shelf. North/south lines across the shelf at longitudes 145°E and 143°E mark the cross sections of the conceptual model diagrams in Figs. 2.16A and B respectively. Note the positions of underwater photographs in Figs. 2.17A and B.

2.3.5.1 'Diverse inner shelf'

The 'diverse inner shelf' Biotope is found in depths 0 to 200 m along the George V Coast. NBP0101 grab 8GR08 (Table 2.5) and AAE dredges DR1, DR4, DR4A and DR5 (Table 2.6) reveal a very diverse macrofauna with a high epifauna. Littoral waters are most disturbed by nearshore ice through fouling of epifauna in anchor ice or impact by loose sea ice (Barnes, 1999; Gutt, 2001). The effect of nearshore ice could possibly explain the increase in taxa

number from 8 to 15 as sample depths increased from 7 m to 106 m. Fauna in shallow water must also cope with a periodic sea ice cover throughout winter, restricting light available for photosynthesis of macroalgae stocks (Norkko et al., 2004). Nonetheless, rank growths of algae are recorded on the hard bottom and sandy seabed of Commonwealth Bay in depths to approximately 45 m (Mawson, 1940). However, samples taken at approximately 106 m in the bay recorded little macroalgae and were instead dominated by diverse sponges and bryozoans with high epifauna. The seasonal flow of brine over the inner shelf seabed would be another important disturbance to benthic communities as the dense brine sinks from the shallows into the deeper basin.

An important difference between the east and west inner shelf is the supercooled ISW found within Buchanan Bay (Williams and Bindoff, 2003). The macrobenthos would need to tolerate very cold temperatures, high currents and low productivity levels as waters originate from beneath the glacier. We predict the area to have increased populations of relatively motile infauna, such as polychaetes, with a structurally less complex sessile fauna of sponges and bryozoans compared to further along the coast towards Commonwealth Bay. Comparable oligotrophic waters found in the southwestern Ross Sea are derived from ISW advected under the Ross Ice Shelf (Barry and Dayton, 1988), and typically have higher numbers of polychaetes and reduced structural complexity compared to the eutrophic eastern Ross Sea (Barry and Dayton, 1988; Lenihan and Oliver, 1995).

In summer, the inner shelf seabed is bathed in a stratified and fresher remnant WW with the breakout of sea ice along the coast or a transient HMCDW whenever upwelling extends across the shelf. Surficial sediments are mostly gravel, although this zone would likely have a high variation of textures including sand and mud (Domack, 1988), and hard ground features similar to the rocky ridges and ledges found on the Adélie Coast (Vanney and Johnson, 1979).

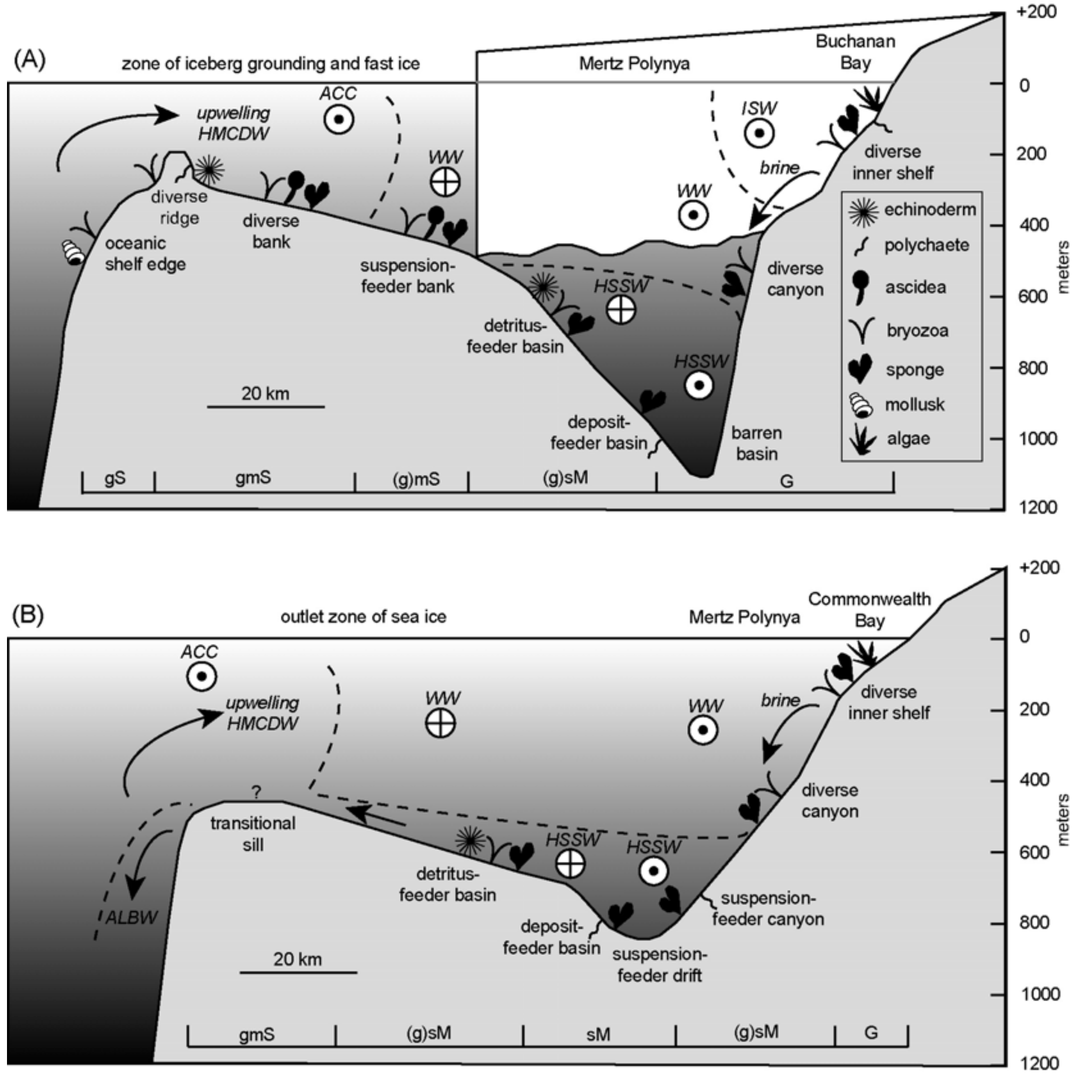

Fig. 2.16 Conceptual model diagrams of the Biotopes on the George V Shelf at longitudes (A) 145°E and (B) 143°E. Dashed lines show the approximate water mass boundaries for winter conditions. Circles with dots show current direction out of page (westerly). Circles with crosses show current direction into page (easterly). The macrobenthos symbols show the common taxa within each Biotope. The boundaries for surficial sediment types lie along the bottom of each profile.

2.3.5.2 'Diverse canyon'

In the upper submarine canyon area of the shelf is a 'diverse canyon' Biotope. Depths range from 200 m to approximately 600 m. Heads of canyons likely start close to the coast and plunge dramatically into the deep basin, e.g. Denison Channel (Fig. 2.2). AAE trawl TR21 (Table 2.6) records very diverse and abundant sessile macrofauna and epifauna. Bryozoans dominate over sponges compared to the inner shelf where sponges dominated. Depths of the upper canyons lie below the direct impact of sea ice and most icebergs, although the canyons are likely conduits for seasonal brine flows originating on the inner shelf. The steepness of this part of the shelf could result in debris flows as another localised disturbance (Domack, 1988).

Biotope	Water depth (m)	Dominant macrofauna	Secondary macrofauna	Epifauna	Geomorphic feature	Surficial sediment	Winter watermass	Summer watermass	Primary disturbance	Secondary disturbance
diverse inner shelf	0-200	sponge	bryozoa	high	inner shelf	G	WW/ ISW	remnant WW/ HMCDW	nearshore ice grounding	seasonal brine flow
diverse canyon	200-600	bryozoa	sponge	high	canyons	(g)sM/G	WW/ HSSW	remnant WW	seasonal brine flow	debris flows
suspension-feeder canyon	600-1000	polychaete	sponge	low	canyons/basin	(g)sM	HSSW	remnant WW/ HSSW	seasonal brine flow	debris flows
barren basin	>1000	bivalve?	foram	low	basin	G	HSSW	HSSW	deep shelf currents	ice-rafted debris
deposit-feeder basin	700-1000	polychaete	sponge	low	basin/drift	sM	HSSW	remnant WW/ HSSW	deep shelf currents	sediment deposition
suspension-feeder drift	750-850	sponge	polychaete	low	drift	sM	HSSW	remnant WW	deep shelf currents	sediment deposition
detritus-feeder basin	500-700	bryozoa	sponge	medium	basin	(g)sM	HSSW	remnant WW	deep shelf currents	sediment deposition
suspension-feeder bank	350-500	bryozoa/ascidea	sponge	medium	bank/basin	(g)mS	WW/ HMCDW	remnant WW/ HMCDW	ice-shelf grounding	iceberg scouring
diverse bank	200-400	bryozoa/ascidea	sponge	high	bank	gmS/gS	HMCDW	HMCDW	iceberg scouring	shallow shelf currents
diverse ridge	100-200	bryozoa	polychaete	high	ridge/bank	gmS	HMCDW	HMCDW	iceberg grounding	shallow shelf currents
transitional sill	400-500	bryozoa	mollusk	high	sill	gmS	HSSW/ WW	remnant WW/ HMCDW	deep shelf currents	oceanic currents
oceanic shelf edge	400-600	bryozoa	mollusk	high	shelf edge	gmS/gS	HMCDW	HMCDW	oceanic currents	shallow shelf currents

Table 2.7 Summary of the George V Shelf Biotopes, water depths, macrobenthos, geomorphology and surficial sediments, near-seabed seasonal water masses, and possible disturbance regimes.

Surficial sediments in the upper canyon are muddier than the inner shelf with slightly gravelly, sandy mud found here. Closer to the ice shelf, gravel is more common due to the presence of glacial dropstones. The rugged seabed in the upper canyon is comprised of crystalline basement outcrop (Beaman and Harris, 2003) interspersed with soft sediment, and probably has a patchy benthic community reflecting an increase in macrofauna diversity wherever sessile creatures can attach to a stable and hard surface (Barnes et al., 1996). The upper canyon area is under the influence of WW, becoming HSSW with depth as the basin fills with brine in winter. Currents close to the seabed are westerly-flowing away from the ice shelf (Williams and Bindoff, 2003). In summer, the seabed of the upper canyon lies above the influence of HSSW and benthos are likely bathed in remnant WW.

2.3.5.3. 'Suspension-feeder canyon'

In the lower reaches of the submarine canyon area is a 'suspension-feeder canyon' Biotope. Depths range from 600 m to approximately 1000 m as canyons merge into the relatively smooth floor of the George V Basin. One NBP0101 grab sample, 7GR07 taken in 948 m (Table 2.5), found a high proportion of infaunal, suspension-feeding polychaetes. Sponge spicule mats were present but few whole sponges were seen. Diversity of macrofauna is lower in this Biotope compared to the upper canyons, although the dominance of suspension-feeders requires that bottom currents must be sufficiently energetic to supply nutrients and food. Seasonal brine flows down the canyons in winter could be responsible for the bottom currents required by these suspension-feeders. In summer, this part of the shelf would be under the overall influence of remnant WW, becoming HSSW with depth and proximity to the eastern basin. Surficial sediment in this unit comprises slightly gravelly, sandy mud. However, within the canyons themselves, sediments may possibly become less muddy as fines are winnowed out by energetic seasonal brine flows.

2.3.5.4 'Barren basin'

In the deepest accessible part of the George V Basin (>1000 m) and within the shadow of the Mertz Glacier Tongue is a 'barren basin' Biotope. A single NBP0101 grab sample, 15GR15 (Table 2.5), revealed little mud with just some pebbles and sand. The only biota recorded were very small and fine, calcareous bivalve shells and arenaceous benthic forams. Milam and Anderson (1981) also record this part of the basin as comprising of low diversity arenaceous foraminifera. The lack of biota in the sample was not surprising but the bivalves were. It did not appear that they had died in situ and had possibly been laterally advected from shallow waters, as has sometimes been observed in other deep parts of the Antarctic shelf (Gili et al., 2001). The deepest basin is also the most environmentally constant, having no light and always bathed in cold HSSW regardless of season. However, acoustic doppler current profiler data reveal

relatively strong currents (up to 12 cm sec^{-1}) at the seabed, in part due to the proximity of a polynya along the west face of the Mertz Glacier Tongue (Williams and Bindoff, 2003). Other disturbances are likely to be the localised impact at the seabed by drop stones released from the calving ice shelf, as surficial sediments record abundant gravel in this zone.

2.3.5.5 'Deposit-feeder basin'

Within the George V Basin in depths approximately 700 m to 1000 m, is a 'deposit-feeder basin' Biotope. This Biotope is found in the floor of the basin and incorporates the northern part of the Mertz Drift as well as the drape and fill deposits in the eastern part of the basin (Beaman and Harris, 2003). Samples from this zone were the NBP0101 dredge 3DR03 (Table 2.5), and WEGA grab samples GB01, GB09, GB10, GB11, GB12, GB15, GB16, GB17 and GB18 (Table 2.4). Statistical analysis of the WEGA samples reveal a high proportion of infaunal, deposit-feeding polychaete and non-polychaete worms, within the siliceous mud and diatom ooze (SMO) draping the deep basin (Dunbar et al., 1985; Domack, 1988). Secondary macrofauna are sponges, typically as sponge spicule matting, and underwater photos also reveal stalked sponges concentrated on or near IRD cobbles, presumably as a stable and hard surface to settle and grow upon (Fig. 2.17A). Other photos show the presence of seapens upright in the soft mud. The glacial-molded megaflutes found on the basin floor may also provide preferential surfaces for macrobenthos to colonise as these geomorphic features are tens of km long and up to approximately 30 m between trough and crest. During winter, the basin floor is covered with a wedge of HSSW that thins on the northern side of the basin (Williams and Bindoff, 2003). However, as brine production reduces towards summer, the areal extent of HSSW reduces and becomes replaced with remnant WW in the western part of the basin. Current direction is a sporadic clockwise gyre, with HSSW and the overlying WW flowing towards the glacier on the northern side of the basin, to flow away from the glacier on the southern side of the basin (Williams and Bindoff, 2003).

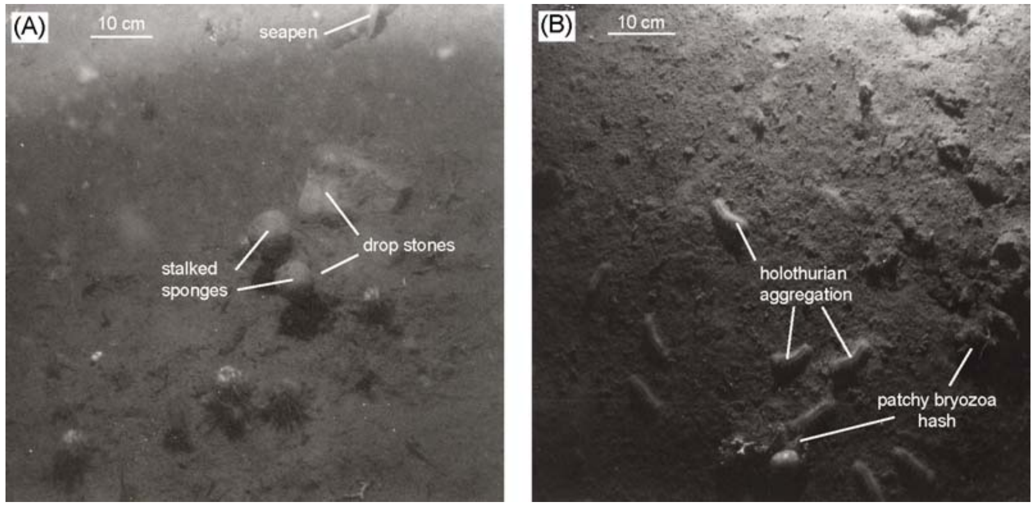

Fig. 2.17 Underwater photographs from WEGA stations in depths of (A) 814 m and (B) 556 m. Note the concentration of stalked sponges around glacial drop stones in the lower basin, and the holothurian aggregation amongst the patchy bryozoa hash in the upper basin.

2.3.5.6 'Suspension-feeder drift'

A 'suspension-feeder drift' Biotope lies in the western George V Basin between depths of approximately 750 m to 850 m. Statistical analysis reveals that WEGA grab samples GB02, GB03, GB04, GB05, GB06, GB07, GB08, GB13 and GB14 (Table 2.4) have a high proportion of sponge material with polychaetes as a secondary biomass by proportion. The limited extent of this unit encompasses only the southwestern Mertz Drift, where deep basin currents have created a mounded, depositional architecture (Harris et al., 2001), indicative of a true drift deposit (Faugères et al., 1999). The presence of suspension-feeding sponges, possibly taking advantage of the relatively higher flow rates (Gili et al., 2001), and increasing grain size at the periphery of the Mertz Drift (Harris and Beaman, 2003) appears to confirm the view that deep basin currents of HSSW are increased clockwise around the southwestern part of the drift where the seabed rises steeply from 850 to 750 m. Underwater photographs taken in this area during summer were not usable as all photos revealed a water column clouded by abundant marine snow. Surficial sediments in this zone are a sandy mud, with X-radiographs of core tops showing massively-bedded SMO with numerous sand grains and dark mottles of IRD gravel and sponge spicules (Beaman, 2000). During winter, this zone is covered in HSSW as the basin fills with this water mass, reverting to remnant WW in summer after the level of HSSW has been lowered.

2.3.5.7 'Detritus-feeder basin'

In the upper basin, between depths of approximately 500 m to 700 m, and following the contours of the George V Basin is a 'detritus-feeder basin' Biotope. WEGA sample GC11 (Table

2.4), NBP0101 dredge 4DR04 (Table 2.5) and AAE trawl TR22 (Table 2.6) reveal bryozoa as the dominant sessile macrofauna, followed by sponges as the next highest biomass by proportion. Epifaunal crinoids and ophiuroids were entwined in the bryozoa hash as well as crustaceans and large (14 cm) pycnogonids. In contrast to the lower basin, the diversity of macrofauna in this zone is much higher with taxa between 14 and 20 in this study. However, underwater photographs reveal that the seabed is not completely covered in bryozoa hash but is rather patchy on a soft seabed, which appears to favour detritus-feeding holothurians (Gutt, 1991; O'Laughlin et al., 1993). Fig. 2.17B shows a dense aggregation of approximately 10 cm long holothurians, possibly *Mesothuria bifurcata*, an Aspidochirotida sediment feeder (P.M. O'Loughlin, pers. comm., 2000). Similar dense aggregations of detritivore holothurians have been found below 500 m on patchy seabed in the Weddell Sea (Gutt and Piepenburg, 1991). Other photos taken of the upper George V Basin show patchy bryozoa hash, stalked anemones and occasional ophiuroids on the soft seabed.

This Biotope is just below the direct influence of modern iceberg keels at approximately 500 m (Barnes and Lien, 1988). Surficial sediments reflect a relative increase in gravel content in the upper basin as slightly gravelly, sandy mud. During winter, this unit lies on the northern slope of the basin within the thinning wedge of HSSW. Deep shelf currents are the primary disturbance due to the generally clockwise deep basin mixing during the formation of WW and HSSW. At various times during winter, the volume of HSSW does increase sufficiently to surge towards the sill and down the continental slope (Bindoff et al., 2001). During summer, this zone is bathed in remnant WW. Sediment deposition is a secondary disturbance and is possibly more noticeable in summer as the seasonal on/off shelf mass flux reduces during warmer months (Marsland et al., 2004).

2.3.5.8 'Suspension-feeder bank'

The 'suspension-feeder bank' Biotope is located along the landward side of the Mertz Bank and northern flank of the George V Basin. Seabed depths range from approximately 350 m to 500 m within the lower range of iceberg scour (Barnes and Lien, 1988). The NBP0101 dredge sample 5DR05 (Table 2.5) records bryozoa hash and colonial ascidians as the predominant sessile fauna, followed by sponges. Filter-feeding holothurians and polychaetes were also present within the bryozoa hash as epifauna. The dredge recovered a very stiff diamicton with many cobble-sized stones at a water depth of 442 m, with less mud compared to the nearby NBP0101 sample 4DR04 at a depth of 592 m (Leventer et al., 2001). The surficial sediment is slightly gravelly, muddy sand, where sand is the predominant component compared to the deeper basin where mud dominates. The relatively high sand content, the predominance of suspension-filter

feeders and reduction in taxa diversity to 10, is likely the result of increased shelf currents and the influence of icebergs scouring the seabed as depths reduce over the bank.

Sample 5DR05 was obtained very near the pinning zone of the Mertz Glacier Tongue, where the action of grounded ice and an extremely variable calving face (Holdsworth, 1985) would likely decrease the benthic diversity and abundance (Gutt, 2001). Within this zone along the landward side of the Mertz Bank, it is the action of icebergs swept along by shallow shelf currents that leave shallow (several metres deep), slope parallel, multiple-gouge tracks in the seabed (Barnes, 1987). Water masses within this zone during winter are WW, correlated with and balanced by changes in area of upwelled HMCDW flowing intermittently across the bank. In summer, remnant WW is the main water mass for this zone, again correlated with upwelled HMCDW.

2.3.5.9 'Diverse bank'

A large proportion of the shelf is classified as the 'diverse bank' Biotope. This zone falls over the majority of the shallow shelf banks in depths of approximately 200 m to 400 m. AAE trawl TR23 (Table 2.6) in 285 m on the Adélie Bank records a high diversity of 20 taxa with abundant bryozoa and colonial ascidians followed by large sponges. Epifaunal polychaetes, holothurians, ophiuroids and echinoids were numerous within the bryozoa hash. Surficial sediments grade from gravelly, muddy sand on both the Mertz and Adélie Banks to a reduced area of gravelly sand north of the Mertz Moraine. This relatively shallow zone is under the influence of the westerly-flowing ACC, which can drive icebergs into the 'finger' and 'buttress' large iceberg banks on the Mertz and Adélie Banks respectively (Fig. 2.2; Massom et al., 2001). The high density of grounded icebergs in these areas would clearly have a major localised impact on the biota (Gutt and Starmans, 2001).

Away from the large iceberg banks, less intensive iceberg scouring can lead to greater between-habitat diversity at a broader scale (Gutt, 2000; Gutt and Piepenburg, 2003), which may be reflected by the higher diversity of the sample taken on the Adélie Bank. Icebergs are rarer on the bank tops because, in the case of the Mertz Bank, the rimming Mertz Moraine (100 to 200 m) blocks the passage of icebergs from the south and east (Barnes, 1987). During summer and winter, HMCDW is shown to upwell over this zone. The muddy component of the gravelly, muddy sand in this zone is thought to be derived from a small iceberg bank grounded on the Mertz Moraine and other shallow knolls (Barnes, 1987). Suspended, finer-grained sediment from grounded iceberg knick points is possibly transported landward by intruding HMCDW to blanket the seabed at greater depths.

2.3.5.10 'Diverse ridge'

A 'diverse ridge' Biotope lies on and around the knolls in depths of approximately 100 to 200 m on the Mertz Bank top. The Mertz Moraine forms the landward boundary of this zone as it rims the bank. NBP0101 grab 14GR14 (Table 2.5) taken in 117 m water depth on the side of the Mertz Moraine has a relatively low taxa diversity of seven, showing a high proportion of bryozoa and suspension-feeding polychaetes, and minor sponges. Grazing heart urchins and gastropods were found in the fine to coarse sand of the sample. Radarsat images show a concentration of icebergs in a line apparently grounded along this ridge (see Fig. 2.2), conforming to the definition of a small iceberg bank (Gutt and Starmans, 2001). The line of icebergs is likely to be the cause of reduced diversity of benthos in this zone, as has been seen in similar small iceberg bank environments in the Weddell Sea (Gutt and Starmans, 2001).

The relatively steep slope of the ridge and shallow water depth becomes an obstruction for icebergs of all sizes. Once aground, the seabed is disturbed but not as intensively as found on large iceberg banks, and individual scours are smaller (Gutt and Starmans, 2001). Wallowing of the icebergs then suspends sediment that is reworked into the knolls leeward of the knick point. The grounded bergs break up by calving and spalling to produce smaller icebergs, which then drift across the bank (Barnes, 1987; O'Brien and Leitchenkov, 1997). The other important disturbance is the westward flowing ACC which flows along the shallow banks and outer shelf, and the upwelling HMCDW which intrudes over the shelf edge and this zone year round. Barnes (1987) noted the lack of large clasts on the Mertz Bank top, and concluded that waves and currents, perhaps intensified around grounded icebergs, are transporting finer-grained sediment from the shoals to the inner-bank top, leaving a blanket of gravelly, muddy sand lacking coarse clasts.

2.3.5.11 'Transitional sill'

Linking the George V Basin to the continental slope is the 'transitional sill' Biotope in water depths 400 m to 500 m between the Mertz and Adélie Banks. This Biotope lies below the influence of icebergs. To our knowledge, no biological sampling has been conducted in this zone except for the DF79 core sample 15GB (Table 2.1) from 412 m. Forams analysed from this core concluded that the sample belonged to a 'transitional shelf assemblage' containing mixed calcareous and arenaceous foraminifera. This assemblage is a transition between a 'deep shelf calcareous assemblage' on the outer shelf banks, and the 'slope assemblage' from the steep continental slope (Milam and Anderson, 1981). Hydrographically, this zone is a dynamic part of the shelf. A winter oceanographic transect across the sill found that HSSW was the near-seabed water mass overlain by a layer of WW. ADCP records show a northward transport out of the sill for these two water masses (Williams and Bindoff, 2003).

During summer, remnant WW is the near-seabed water mass over the sill. However, water column temperature profiles also reveal a front where a shallower HMCDW is intruding over the remnant WW and southeast along the northern flank of the basin (Marsland et al., 2004). Surficial sediment in this zone is a gravelly, muddy sand, and a 360 cm core taken at DF79 Station 15 reveals a massive, muddy diamicton lacking the diatomaceous mud collected from the deeper George V Basin cores (Escutia et al., 2003). The sea surface in this zone is also the outlet area for drifting sea ice due to the 'buttress' of grounded bergs and fast ice along the eastern side of Adélie Bank (Massom et al., 2001). Thus the water column in this Biotope is quite dynamic and is probably reflected by a shelf/oceanic transitional macrobenthos. Macrobenthos are possibly high numbers of bryozoans and calcareous mollusks, similar to those found on the shelf edge at other sites in East Antarctica (Harris and O'Brien, 1996).

2.3.5.12 'Oceanic shelf edge'

Along the outermost part of the shelf lies the 'oceanic shelf edge' Biotope as a linear zone between the 'diverse bank' Biotope and the continental slope. Depths are approximately 400 m to 600 m before dropping steeply to the upper continental rise in 2000 m (De Santis et al., 2003), although for this study the shelf break is defined to be at a depth of 500 m. A number of significant valleys, e.g. Jussieu, WEGA and Buffon Channels, occur along this zone which direct the downslope transport of ALBW and suspended sediment in the form of turbidity currents (De Santis et al., 2003). No biological sampling has been conducted along this zone to our knowledge, except for benthic foraminifera analysis (Milam and Anderson, 1981). Similar to the sill, this Biotope is a transition between a 'deep shelf calcareous assemblage' and a 'slope assemblage', i.e. relative percentage of calcareous foraminifera decreasing with depth down the continental slope (Milam and Anderson, 1981). Macrobenthos are possibly bryozoans, and calcareous bivalves, gastropods and echinoderms, as has been found at other shelf edge and upper slope sites in East Antarctica (Harris and O'Brien, 1996).

The surficial sediments are mostly gravelly, muddy sand with gravelly sand on the northerly side of the Mertz Bank. Winnowing by the shallow ACC as it sweeps westerly along the shelf edge at velocities of up to 25 cm sec^{-1} is responsible for the gravel and sand lag (Dunbar et al., 1985). In winter, intermittent HMCDW intrudes over the shelf edge and onto the shallow banks. In summer, with sea ice melted, intrusions of HMCDW are still conspicuous over the shelf edge, and the ACC would likely increase in relative velocity (Harris and O'Brien, 1998), presumably due to the greater interaction between the atmosphere and sea surface. The biota living in this zone must be adaptable to the sudden inflow of the relatively warm and oxygen-depleted HMCDW, then to be swept by westward-flowing and colder, shallow shelf currents. The relatively fast currents would likely favour dense populations of suspension-feeders.

2.4 Discussion

2.4.1 Environment-benthos relationships

We consider that the Biotopes described for the George V Shelf address the objectives for this study. The twelve Biotopes are the synthesis of maps created to define the physical environment of the shelf using geomorphology, surficial sediments, near-seabed oceanography, and the inferred dominant trophic structure within geomorphic features based on limited macrobenthos data. In general, our study agrees with broad-scale benthic structure and distribution found in other parts of the high Antarctic (Gutt and Koltun, 1995; Gutt and Starmans, 1998; Starmans et al., 1999; Ragua-Gil et al., 2004). In the present study, by characterising marine benthic habitats and their associated biological assemblages at the Biotope level we can gain a better understanding of the controls on biodiversity. The aim is to systematically understand the coupling between seabed characteristics and associated benthic communities at the local (10s of km) scale. A number of environmental factors appear to control the Biotope distribution on the George V Shelf, including: (1) the depth of the seabed and the pattern of iceberg grounding on the shelf; (2) the influence of a variable Mertz Glacier Tongue grounding zone; (3) the distribution of substrate in the basin below the influence of icebergs; and (4) the oceanic and shelf current circulation patterns.

2.4.1.1 Depth of the seabed and the pattern of iceberg grounding on the shelf

Near the George V Coast where there are no ice shelves, anchor ice and ice scour have reduced the diversity of sessile benthos in intertidal and near-subtidal areas. Ice scour in shallow Antarctic waters results in patchy removal of whole communities from small areas, whereas anchor ice is largely a winter phenomena that results in fouling of epifauna in this zone (Barnes, 1999; Gutt, 2001). Severely disturbed areas are expected to have low infaunal abundance and colonised by motile species, such as polychaetes, gastropods and nemerteans with highly opportunistic life histories (Barnes et al., 1996; Clarke, 1996). In the present study, below the influence of anchor ice and ice scour on the inner shelf, diversity is high and increases with depth, with sponges and bryozoa dominating the sessile macrobenthos. A similar increase in biomass and diversity is found below the strong negative impact of ice in other near-shore environments in Antarctica (Arntz et al., 1994; Barnes, 1999). The rich and dense large-bodied demosponges and bryozoans in this zone have been described as a 'multi-storied assemblage' (Teixido et al., 2002), which provide a favourable habitat for epifauna to climb higher into the water column to feed off drifting particles and other animals (Gutt and Schickan, 1998).

The presence and density of iceberg grounding has a significant impact on biological communities (Gutt, 2001). The localised disturbance by ice will vary with depth, site exposure and local currents, producing a high degree of patchiness on the Antarctic shelf (Gutt and Koltun, 1995; Peck et al., 1999). On the George V Shelf, seabed within the influence of high iceberg scour or dense grounding zones is predicted to have a reduced diversity of benthos. These areas are typically found on the windward (eastern) edges of the Mertz and Adélie Banks and have high concentrations of grounded bergs, which are commonly referred to as large iceberg banks (Gutt and Starmans, 2001). At lower levels of iceberg scour on low-relief, planated bank tops, diversity tends to be higher, with scouring contributing to a high between-habitat diversity at broader scales (Peck et al., 1999; Gutt, 2001). In the present study, abundant bryozoa, colonial ascidians and sponges were common sessile macrofauna, as well as diverse epifauna found within the bryozoan hash on the bank tops, within the influence of low levels of iceberg scour. In areas experiencing higher iceberg grounding density, such as the small iceberg bank on the Mertz Moraine, the macrobenthos comprised a high proportion of suspension- and detritus-feeders, however, diversity of taxa overall appeared suppressed compared to the bank tops.

2.4.1.2 Influence of a variable Mertz Glacier Tongue grounding zone

The effect of a highly variable calving face on the Mertz Glacier Tongue may also lead to depauperate areas being exposed with the advance and retreat of glaciers (Barnes, 1999). In the present study, the area of the Mertz Bank close to the grounding zone of the ice shelf is where benthic diversity appeared to be suppressed, compared to stations in the upper basin and just below the depth of the ice shelf, which recorded increased macrobenthos diversity. Suppression of benthos may be due to past disturbance of ice shelf advance (Berthier et al., 2003) or from the numerous icebergs calved from the Mertz and Ninnis Glacier Tongues (Massom et al., 2001). At the end of the Last Glacial Maximum, the ice shelf is believed to have started retreating from its expanded position on the Mertz Bank from 11-10 kyr BP (Beaman and Harris, 2003). With many important Antarctic benthic fauna, such as hexactinellid sponges, having slow dispersion and slow growth life histories, the reduced macrobenthos diversity found near the Mertz Glacier Tongue grounding zone may show that not enough time has elapsed for all benthic groups to inhabit this location, even if environmental conditions are favourable (Gutt and Koltun, 1995).

2.4.1.3 Distribution of substrate in the basin below the influence of icebergs

In the upper George V Basin and below the influence of icebergs (>500 m), benthic life is quite rich and varied, with sufficient energy and particulate supply to sustain moderate amounts of suspension-feeders and dense aggregations of detritus-feeding holothurians between the patchy bryozoa hash. In similar environments in the Weddell Sea, large numbers of detritus-feeding

holothurians are found distributed on soft sediments between patches of sessile fauna such as bryozoa, sponges and hydroids (Gutt and Piepenburg, 1991). In the present study, the lower basin generally becomes muddier with depth where suspension-feeders are largely absent and is the preferred habitat of deposit-feeding polychaetes. Studies from the deep shelf of the Weddell Sea also describe a trench community where suspension-feeders are almost absent with low values for species numbers and diversity (Gutt, 1991). Our study agrees with results in the Weddell Sea in that there appears to be a gradient from suspension-feeders to detritus-feeders to deposit-feeders with depth in deep trenches on the Antarctic shelf (Gutt and Starmans, 1998; Starmans et al., 1999). Our study also found the presence of concentrated patches of live hexactinellid sponges attached to ice-rafted debris (IRD) in small areas of the deep basin. At a finer-scale, any roughness in the seabed, such as due to IRD from melting icebergs or low-relief features such as megaflutes, are predicted to be favourable surfaces for deep basin sessile benthos to colonise on (Malatesta and Auster, 1999).

2.4.1.4 Oceanic and shelf current circulation patterns

Within the George V Basin, near-seabed shelf circulation patterns follow a sporadic clockwise motion at up to 12 cm sec^{-1}, which decreases with depth (Bindoff et al., 2001; Williams and Bindoff, 2003). The presence and geomorphology of the Mertz Drift in the western part of the basin (Harris and Beaman, 2003) suggests that shelf currents are relatively increased in this area, and are probably bathymetrically controlled as the seabed rises steeply at the edge of the drift deposit. The water column over the drift was found to be turbid and sediments recorded a high proportion of hexactinellid sponge spicules. Away from the drift, near-seabed currents are relatively decreased and result in a muddy seabed favouring deposit-feeding polychaetes in the lower basin, as described above.

With proximity to the Mertz Glacier, the seabed (< 500 m) on the inner shelf is swept with super-cooled ISW at over 30 cm sec^{-1}, but does decrease rapidly away from the glacier to less than 12 cm sec^{-1} (Bindoff et al., 2001). The shallow inner shelf seabed proximal to the glacier mouth would likely experience the suppressing influence of oligotrophic waters on benthos (Barry and Dayton, 1988). The source of supercooled waters from beneath the ice shelf is predicted to result in sessile macrobenthos being poorer in comparison to seabed underlying more productive waters away from the glacier, as has been noted in similar environments in the Weddell and Ross Seas (Barry and Dayton, 1988; Lenihan and Oliver, 1995; Gutt and Starmans, 1998).

The outer shelf/upper slope area of the George V Shelf is a high-energy environment due to strong ocean currents of up to 25 cm sec^{-1} (Dunbar et al., 1985), and is similar to 'scalped shelf'

bank margins dominated by ocean currents in other areas of Antarctica (Barry and Dayton, 1988; Harris and O'Brien, 1996). The relatively strong and warmer oceanic currents winnow the outer shelf seabed into coarser sediments, and is predicted to favour dense populations of suspension-feeders, such as bryozoans, and calcareous mollusks (Harris and O'Brien, 1996). On the shallow planated bank tops (<400 m) which are regularly swept by the ACC and intruding HMCDW, benthic diversity is relatively high with abundant bryozoa, ascideans and large sponges, and a corresponding diverse epifauna.

2.4.2 Dominant abiotic processes on the George V Shelf

In the past, most studies of Antarctic shelf benthic fauna have been concentrated around the Antarctic Peninsula, Weddell and Ross Seas (Lenihan and Oliver, 1995; Arnaud et al., 1998; Piepenburg et al., 2002; Teixido et al., 2002; Gerdes et al., 2003). Fewer studies have been conducted in East Antarctica and most have been conducted in shallower waters (Arnaud, 1974; O'Laughlin et al., 1993; Stark, 2000; Stark et al., 2003). This study, therefore, provides a useful contribution to theories concerning factors that may determine the structure and functioning of marine ecosystems on the deep Antarctic shelf. Biotic factors that influence Antarctic benthos at finer-scales include predation, competition and recruitment (reviewed in Arntz et al., 1994). At the site (<10 km) scale, significant biotic factors identified on the Antarctic shelf have been the role of 'multi-storied assemblages' of large sessile suspension-feeders on epifauna (Gutt and Schickan, 1998), and how mats of hexactinellid sponge spicules accumulating over centuries have led to depauperate infaunal communities (Barthel, 1992; Gerdes et al., 2003). Both these biological substrates have been identified on the George V Shelf, although the exact boundaries of the macrobenthos structured by these biotic factors cannot be resolved without finer-scale surveys being undertaken.

A key question is 'What abiotic processes exert the dominant control over the distribution of macrobenthos on the George V Shelf at this scale?' Our findings can be summarised as in:
(1) Below the effects of iceberg scour (depths >500 m) and in the George V Basin, broad-scale distribution of macrofauna is largely determined by substrate type, specifically mud content in sediments, which generally increases with depth as shelf currents weaken in the basin. In the upper basin, macrobenthos diversity is relatively high and reduces with depth as the proportion of mud increases. There appears to be a gradient from suspension-feeders to detritus-feeders to deposit-feeders with depth. Relative increases in deep-basin currents due to rapid changes in bathymetry result in localised increases in suspension-feeders over deposit-feeders.
(2) In waters within the direct influence of glacial ice (depths <500 m) on the banks, scouring by icebergs is found to be a strong limiting factor in distribution of macrobenthos. Intense

iceberg activity on the windward (eastern) side of the relatively shallow Mertz and Adélie Banks, the Mertz Moraine and in the vicinity of the ice shelf grounding zone suppresses macrobenthos diversity. Reduced iceberg grounding on the flat, outer shelf bank tops coincides with a higher diversity of suspension- and detritus-feeders.

(3) In areas protected from iceberg scour disturbance, such as on the outer shelf banks and slope, the direction and speed of oceanic currents in and around shallow features are the likely dominant abiotic factor in the broad-scale distribution of macrofauna. Macrobenthos are predicted to be diverse with a high proportion of suspension-feeders and epifauna adapted to a dynamic hydrographic environment.

A number of other studies on the Antarctic shelf have concluded that substrate, the influence of icebergs and currents exert strong abiotic controls over broad-scale benthos distribution. On the eastern Weddell Sea shelf and slope, the major structuring agent for sponge associations was substrate condition, which is in turn influenced by sedimentation (Barthel and Gutt, 1992). Diverse 'multi-storied' sponge assemblages dominated on hard substrate in shallow waters then reduced in diversity on soft sediments in deeper waters. As in our study, Barthel and Gutt (1992) identified sponge species which make use of ice-rafted debris as a hard settling substrate and which later extend onto the surrounding soft substrate. In comparable deep basin and trench environments in the Weddell, Amundsen and Bellingshausen Seas, motile deposit-feeders were more abundant where bottom currents are slow and there is a soft bottom substrate (Starmans et al., 1999). We suggest that it is the increasing proportion of mud as currents reduce with depth, which becomes more influential as a food source, and results in an observed gradient from suspension-feeder dominated assemblages, such as bryozoans and sponges, to those with higher numbers of detritus- and deposit-feeders, such as holothurians and polychaetes (Gutt and Starmans, 1998; Starmans et al., 1999).

Within shallower waters, iceberg scouring is among the most significant disturbances that marine ecosystems can experience (Gutt and Starmans, 2001). However, the effects of iceberg scouring on benthic assemblages depend on the spatial scale of observation (Gutt and Piepenburg, 2003). At the localised site of impacts, diversity of megabenthos assemblages is indeed dramatically reduced, however, at broader scales (>1 km) habitat heterogeneity caused by iceberg scouring enhances between-habitat benthic diversity (Gerdes et al., 2003; Gutt and Piepenburg, 2003). Within the limits of the data observed on the George V Shelf, we also observe a similar increase in benthos diversity where low levels of iceberg scour occur on relatively shallow flat-topped banks. At even broader scales, iceberg grounding is determined more by bottom topography and currents than by sites of intense calving activity (Gutt and Starmans, 2001). In the case of the George V Shelf, we predict that the high concentrations of

icebergs driven onto the eastern sides of the Mertz and Adélie Banks and the Mertz Moraine by the westerly-flowing ACC, suppress macrobenthos assemblages as observed in the Weddell Sea where similar large and small concentrated iceberg banks also occur (Gutt and Starmans, 2001).

Another factor identified as an important influence on benthic distribution on the George V Shelf is the presence of oceanic and shelf currents in areas protected from iceberg scour. The variable bottom topography of shallow knolls on the outer shelf is expected to result in enhanced currents around these features. In the Weddell Sea, shallow banks within the influence of the westward-flowing coastal current had high numbers of suspension-feeders, such as hydroids and gorgonians, where variable and strong currents were able to supply them with food and keep the substratum clear of sediment (Ragua-Gil et al., 2004). Diverse and dense benthic suspension-feeder communities are found along the Weddell Sea outer shelf and slope which coincides with active hydrodynamic regions (Gutt and Starmans, 1998). Any substratum heterogeneity and biogenic structures interfere with the flow pattern, increasing turbulence which enhances particle capture by suspension-feeders (Gili et al., 2001). Thus the high flux of water masses over the outer George V Shelf and the combination of relatively fast shelf currents flowing over a topographically heterogeneous outer shelf would favour development of dense suspension-feeders in this area.

2.5 Conclusions

For this study, we have applied a hierarchical method of benthic habitat mapping to the Geomorphic Unit and Biotope levels across the George V Shelf at the local (10s of km) scale. Based upon the analysis of seismic profiles, multibeam swath bathymetry, oceanographic data and the results of sediment sampling, it has been shown that the George V Shelf can be characterised in terms of geomorphology, surficial sediment and near-seabed water mass boundaries. GIS models of these oceanographic and geophysical features increases the detail of previously known seabed maps and provide new maps of seafloor characteristics. Kriging interpolation was used for surface modelling of data, including maps to assess uncertainty within the predicted models. A study of underwater photographs and the results of limited biological sampling provided further information to infer the dominant trophic structure of benthic communities within geomorphic features. Twelve Biotopes were defined across the shelf and described in terms of biological features, such as the trophic categories of the dominant and secondary macrofauna, and physical features, such as depth range, geomorphology, winter and summer water masses, surficial sediment, and primary and secondary disturbances.

In general, our study agrees with broad-scale environment-benthos relationships found in other parts of Antarctica. The abiotic processes that exert dominant control over the distribution of macrobenthos at the local (10s of km) scale are: (1) Below the effects of iceberg scour (depths >500 m) in the basin, broad-scale distribution of macrofauna is largely determined by substrate type, specifically mud content in sediments. (2) In waters within the direct influence of glacial ice (depths <500 m) on the banks, scouring by icebergs is a strong limiting factor in distribution of macrobenthos. (3) In areas protected from iceberg scour disturbance, such as on the outer shelf banks and slope, the direction and speed of oceanic currents are the likely dominant abiotic factor in the broad-scale distribution of macrofauna.

This hierarchical method of benthic habitat mapping could be applied circum-Antarctic for comparison against other geographic areas, and would assist authorities responsible for developing ecosystem-based plans by identifying the different types of marine habitats and their associated biological communities at varying scales on the Antarctic shelf.

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Chapter 3 Temperate Case Study

3.1 Introduction

The southeastern Australian continental shelf and slope is the location of Australia's oldest fishery and has been the subject of extensive benthic and pelagic surveys to describe the fish-habitat associations (Bax et al., 1999; Bax and Williams, 2001; Kloser et al., 2001; Williams and Bax, 2001). Recently, this area was included as part of the Southeast Regional Marine Plan in support of Australia's Oceans Policy (NOO, 2004). A key step in the development of the plan was an assessment of the physical and biological structure of the area, and an examination of the processes that link the two components together (Butler et al., 2001). Previous efforts to classify the marine ecosystems of the southeastern Australian continental shelf were descriptions of bioregions at regional scales of 100s of km, based primarily upon the ranges of fish in conjunction with physical environmental attributes (IMCRA, 1998). At a finer-scale, a series of transects across the southeastern shelf, in combination with fishers' information and physical and biological sampling, defined the boundaries of seabed habitats at the local (10s of km) scale (Bax and Williams, 2001). Within these transects, (1) soft, (2) hard and (3) rough substrate features were examined, and generally related to unconsolidated sand or mud, low-relief limestone or sandstone slabs, and high-relief granite or limestone outcrops respectively (Bax and Williams, 2001).

In the present study, we undertook detailed seabed mapping of New Zealand Star Bank, a group of granite outcrops on the inner continental shelf of eastern Bass Strait and a noted shipping hazard off the Victoria coast. We defined the spatial boundaries of the benthic habitats and biological communities of the area at the site (<10 km) scale. Our study contributes habitat maps of the area, which has until now been poorly mapped, and provides a better understanding of the relationships between seabed geology and associated benthic communities. The study was conducted as part of a co-operative survey between Geoscience Australia and the Royal Australian Navy (RAN) aboard the Hydrographic Ship *HMAS Melville*, and utilised the shallow-water Atlas™ Fansweep20 multibeam sonar. Geophysical sampling and underwater video data collected in this study reveal a complex bathymetry and biological structure that complements the limited information of marine ecosystems and processes of the eastern Bass Strait. This survey is also timely as New Zealand Star Bank is included within the East Gippsland Broad Area of Interest within the Southeast Regional Marine Plan (NOO, 2004). Candidate marine protected areas are being investigated within Broad Areas of Interest to ensure a National Representative System of Marine Protected Areas (MPAs; DEH, 2003).

Because of the difficulty with mapping the distribution of benthic biodiversity, MPAs rely upon abiotic factors to characterise the seabed and water column, and therefore provide a basis for reserve selection (Stevens, 2002; Roff et al., 2003). Thus an important question to consider is whether geological data can be used as a proxy to predict the occurrence of assemblages of benthic organisms.

To make our results more applicable to the MPA process and help answer this question, we adopted a benthic habitat classification scheme used for the bioregionalisation of Australia (Butler et al., 2001). Habitat can be considered as the place, or type of site, where an organism or population occurs naturally, and can be used as a surrogate for ecological structure in a hierarchical context (NOO, 2002). Marine ecosystems vary at a range of nested spatial scales, and the classification scheme developed by Butler et al. (2001) defined: (1) Provinces, in the order of 1000s of km in extent, based upon broad-scale geological patterns, e.g. continental blocks and abyssal basins. (2) Biomes, nested within Provinces and at scales of 100s of km, which show broad-scale geomorphology, e.g. coast, continental shelf, slope and abyssal plain. (3) Geomorphic Units, within each Biome at the local (10s of km) scale, are areas of similar seafloor geomorphology and which usually have distinct biotas, e.g. seamounts, canyons, sand banks and coral reefs. (4) Primary Biotopes refer to soft, hard and mixed substrate-based units, together with their associated floral and faunal communities, also at the local (10s of km) scale. Maps to this level can generally be obtained by high-resolution acoustic surveys. (5) Secondary Biotopes are substructural units within Primary Biotopes, distinguished by the types of physical or biological substrate within soft, hard or mixed types at the site (<10 km) scale, e.g. limestone, granite, shelly sands or seagrasses. Maps to this level are provided by biological and physical groundtruth sampling. (6) Biological Facies are identifiable site (<10 km) scale units defined by a biological indicator, such as a species of seagrass, or group of corals, sponges or other macrofauna adherent to the facies (see Table 1.2 in Chapter 1 for further description).

This study aims to: (1) define the spatial boundaries of Secondary Biotopes and Biological Facies at the site (<10 km) scale on the basis of geomorphology, surficial sediment composition and the results of underwater video analysis; and (2) explore the possible relationships between the geology of the seabed and the associated biological communities.

3.2 Materials and methods

3.2.1 Study area

New Zealand Star Bank is positioned at latitude 37° 47'S, longitude 149° 43'E and lies approximately 10 km southeast of Little Rame Head on the Victorian East Gippsland coast (Fig. 3.1A). The bank is made of crystalline, high-relief (>1 m in vertical change) granite that outcrops on the seabed, rising to a minimum depth of approximately 10 m (RAN, 2002). The granite is an extension of the Lachlan fold belt consisting of a multitude of Silurian-Devonian granites found through eastern NSW and Victoria (Coney et al., 1990), and is likely lower Silurian (434 - 420 Mya) in age, inferred from the similar granite outcrops on the land (DNRE, 1999). The shelf in this area is known to contain other granite outcrops, e.g. Point Hicks Reef, however these banks are smaller and closer to the coast. New Zealand Star Bank also lies at the eastern end of an elongate, low-relief (<1 m in vertical change) sandstone outcrop, which parallels the East Gippsland coastline and is known as Broken Reef (Fig. 3.1B). These low-relief slabs of rock are likely Quaternary aeolian dune deposits of sand similar to dune deposits found along the present Gippsland shoreline (DNRE, 1999), and possibly formed as sand bodies along palaeo-coastlines (Bax and Williams, 2001). These hard substrate features contrast with the surrounding relatively flat seabed of mainly unconsolidated quartz sands with variable amounts of shell debris (Jones and Davies, 1983). Seaward of New Zealand Star Bank, the seabed drops steeply to a depth of over 120 m where muddy quartzose and calcareous sediments extend over the remainder of the shelf to the shelf break.

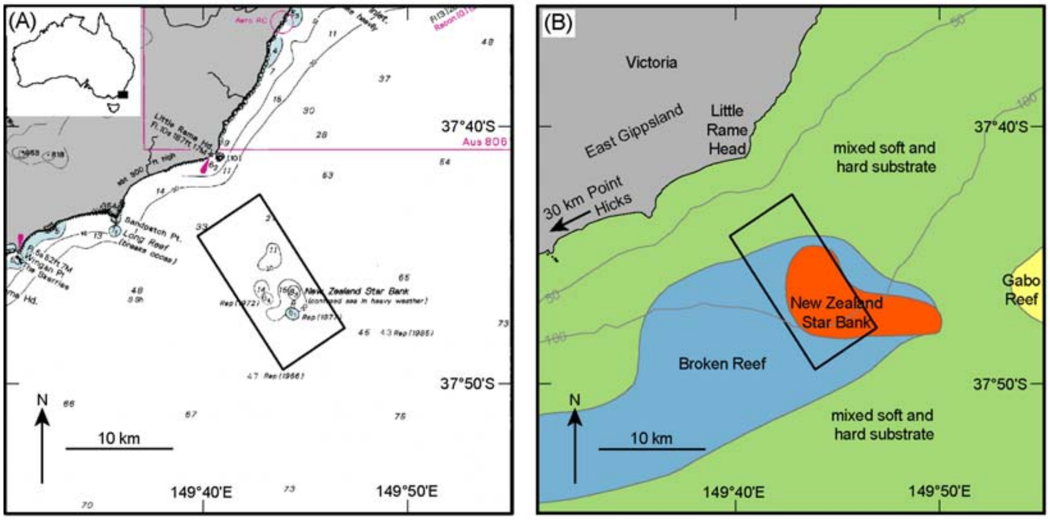

Fig. 3.1 Mercator projection maps of the study area in eastern Bass Strait off the East Gippsland coast. The box shows the multibeam sonar coverage over New Zealand Star Bank. (A) Continental shelf features from navigation chart AUS358 prior to the present survey (AHO, 1971). Spot depths and contours are in fathoms. The bank was not well defined in previous surveys and posed a significant hazard to shipping. (B) Primary Biotopes of the area modified from Bax and Williams (2001), showing the inferred extent of the high-relief granite New Zealand Star Bank next to the low-relief sandstone slabs of Broken Reef. These features lie within mixed soft and hard substrate across the shelf. Depth contours are in metres. Gabo Reef is a high-relief limestone outcrop on the outer shelf.

The bank lies within the Twofold Shelf bioregion where the climate is moist cool temperate with warm summers and a winter-spring rainfall (IMCRA, 1998). The near-seabed oceanography in the vicinity of the bank is influenced by coastal trapped wave (CTW) energy which is generated in Bass Strait and propagates northwards along the eastern Victorian and southern coast of New South Wales (NSW; Morrow et al., 1990; Harris et al., 1991). CTWs propagate along the East Gippsland shelf at a speed of about 3.1 m sec^{-1} (Morrow et al., 1990), and coincide with the northerly-flowing tongue of cool (~12° C) Bass Strait Water (Lavering, 1994; Bax et al., 2001). In addition, most of Bass Strait is well mixed vertically due to wind-induced currents and its shallow depths (< 80 m). These currents are locally produced and therefore flow in the direction of the wind down to water depths of approximately 60 to 70 m (Middleton and Black, 1994). Wave energy is relatively low, however stalled low pressure systems in the Tasman Sea during summer create higher wave energy along the coast (IMCRA, 1998), and will only reach the seabed in depths of 100 m under rare storm events (Harris et al., 1991). Surface water masses in the vicinity of the Gippsland Shelf are influenced by the southern extremity of eddies belonging to the East Australian Current with temperatures of 13° to 16° C, which intermittently intrude over the shelf (Bax et al., 2001; Young et al., 2001).

3.2.2 Bathymetry data

An Atlas™ Fansweep20, 100 kHz, multibeam sonar system was used to map the seabed over New Zealand Star Bank, initially with a survey line spacing at 140 m apart, and then interlined as the morphology of the seabed was revealed (Fig. 3.2). With swath width set at four times water depth, 100% coverage was achieved over the 100 km^2 area of the bank except for a small gap over the shallowest part of the bank where rising seas made surveying dangerous in this area. Soundings were reduced to Lowest Astronomical Tide (LAT) using predicted tides at Point Hicks. ASCII XYZ data were extracted from the raw files using Caraibes seafloor mapping software and interpolated using the ESRI™ ArcInfo program TOPOGRID to generate a 5 m resolution gridded bathymetric model. The resulting bathymetry model was analysed for artificial drainage flow and slope within ESRI™ ArcGIS, and viewed as a 3D digital terrain model (DTM). Caraibes was unable to extract the backscatter data from the raw files, and therefore only bathymetry data was used for this study.

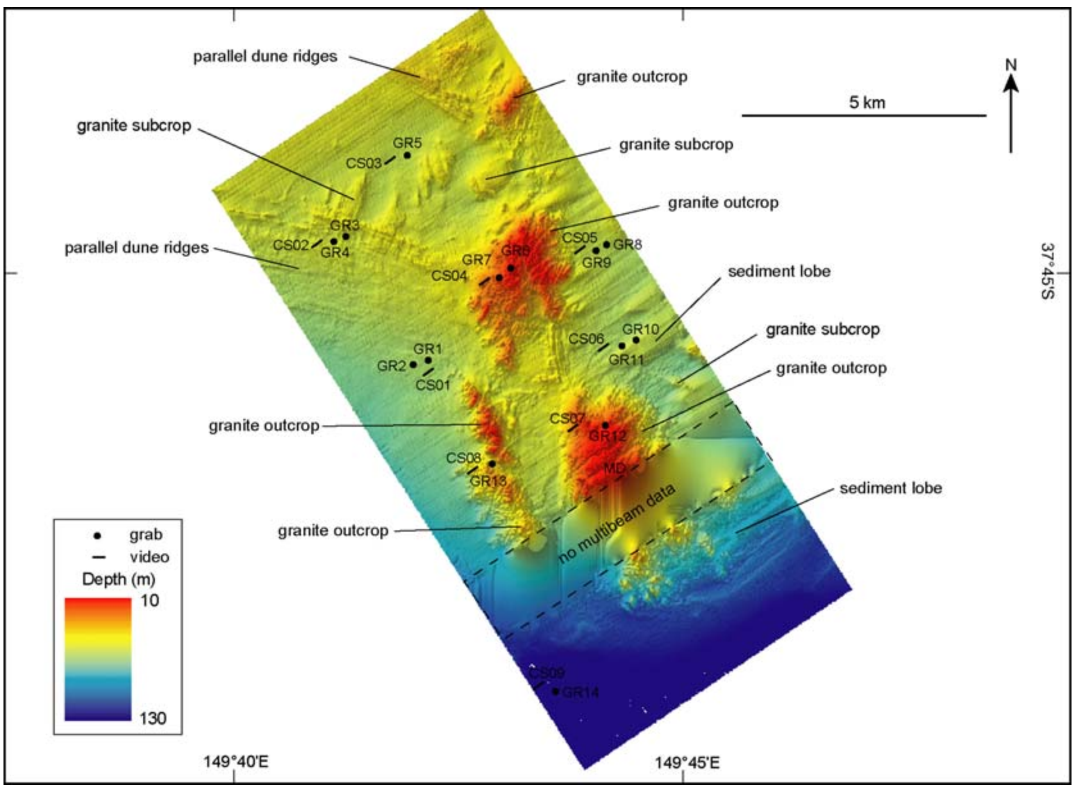

Fig. 3.2 Shaded relief map of the New Zealand Star Bank bathymetry model, at 5 m spatial resolution and with grab and underwater video transect locations. MD refers to the position of the minimum depth (approximately 10 m) on the largest granite outcrop.

3.2.3 Sediment data

Seabed samples were collected using a Smith-Macintyre grab at nine locations on and around the bank with most sites sampled twice (Fig. 3.2 and Table 3.1). Sediment recovery varied as the water depth increased and weather conditions worsened through the survey, but generally we obtained up to 200 g of material in each grab. The winnowing of finer-grained material out of the grab GR14, in the south of the survey area, led to a rejection of GR14 data for statistical analysis. The grabs GR4 and GR5, with a high sediment volume, were selected for wet sieving into gravel (>2 mm), sand (2 to 0.063 mm) and mud (<0.063 mm). The percentages of gravel, sand and mud were recorded as dry weight. The two sediment samples were analysed for mean grain size using a Malvern 2000 laser particle sizer and calcium carbonate content determined as per Harris et al. (2000). These values were compared against previous samples obtained in the vicinity of New Zealand Star Bank from the study by Jones and Davies (1983).

Sediment samples from all the grabs except GR14 were dry sieved and the composition of gravel (>2 mm) and very coarse sand (1-2 mm) fractions were examined under a stereo microscope. Where fragments could be clearly identified, they were assigned to various biogenic and lithoclast categories. When a fragment was biogenic but unable to be identified, then it was categorised as unknown bioclast. Composition categories were: coralline algae, coral, polychaete, decapod, gastropod, bivalve, bryozoa, echinoid, unknown bioclast and lithoclast. The weight of the various categories were calculated for each sample, and then standardised into the percentage weight of each sample. Multivariate statistical analysis of sediment composition was undertaken using the Primer Ver. 5 software package (Clarke, 1993; Clarke and Warwick, 2001). Bray-Curtis similarity coefficients were computed on the square root-transformed percentage weight data to reduce the emphasis on the dominant components. The resulting similarity matrix was analysed using group-averaged cluster analysis, displayed as a dendogram and a non-metric, multi-dimensional scaling (MDS) ordination plot to establish similarity in sediment composition between sites.

Grab number	Latitude	Longitude	Water depth (m)
GR1	37°45.8'S	149°42.1'E	74.79
GR2	37°45.89'S	149°41.91'E	76.21
GR3	37°44.71'S	149°41.23'E	67.39
GR4	37°44.74'S	149°41.08'E	68.01
GR5	37°43.99'S	149°41.91'E	70.49
GR7	37°45.06'S	149°42.93'E	41.23
GR8	37°44.73'S	149°44.21'E	70.14
GR9	37°44.76'S	149°44.13'E	70.69
GR10	37°45.62'S	149°44.47'E	71.39
GR11	37°45.67'S	149°44.33'E	72.99
GR12	37°46.37'S	149°44.15'E	36.92
GR13	37°46.79'S	149°42.86'E	50.87
GR14	37°40.83'S	149°43.51'E	125.96

Table 3.1 Grab sample locations and water depth (m) data. See Fig. 3.2 for locations.

3.2.4 Underwater video data

Underwater video transects were obtained at nine sites selected as being representative of the diverse seabed morphology revealed during the survey (Fig. 3.2 and Table 3.2). On average, two minutes was recorded at each site over a transect distance of 100 m at water depths of between 46 to 120 m. Differential GPS position was recorded automatically as an overlay on the video. At every two second interval, the video transects were classified into environmental descriptors of: (1) Substratum (mud, fine sediments, coarse sediments, gravel/pebble, cobble/boulder, igneous/metamorphic rock); (2) Geomorphology (unrippled, current rippled, wave rippled, irregular, debris flow/rubble, mounds/pits, subcrop, low (<1 m) outcrop, high (>1 m) outcrop); and (3) Fauna (none, large/dense sponges, small/sparse sponges, mixed gardens, octocorals, small encrusters/erect forms, sedentary, mobile, bioturbators). Not all environmental descriptors were observed in the underwater video. The resolution of the video data precluded identification of fauna to a lower taxonomic level. The descriptors were mapped within ESRI™ ArcGIS as point shapefiles for draping on the 3D DTM. Counts were made of each Substratum, Geomorphology and Fauna descriptor present, then standardised into the percentage occurrence within each transect. Using Primer Ver. 5, a Principal Component Analysis (PCA) was conducted on the untransformed descriptors to establish similarities in the environmental variables across the study area. PCA ordination using Euclidean distance to measure dissimilarity of samples is a suitable method of analysing relationship trends for environmental variables (Clarke, 1993).

Video number	Latitude start	Longitude start	Latitude end	Latitude end	Water depth	Description
CS01	37°45.89'S	149°42.12'E	37°45.91'S	149°42.09'E	74.88	gravel and shell hash, irregular seabed, fauna is sparse, occasional small erect sponge and bryozoa
CS02	37°44.78'S	149°40.86'E	37°44.78'S	149°40.83'E	66.92	gravel and shell hash, patchy fauna with initially little fauna then garden of large erect sponges on irregular seabed
CS03	37°44.04'S	149°41.75'E	37°44.04'S	149°41.71'E	70.33	gravel and shell hash, irregular seabed with pockets of New Zealand screw shell, fauna is sparse with small erect sponges
CS04	37°45.11'S	149°42.81'E	37°45.13'S	149°42.77'E	46.49	high-relief granite outcrop, dense gardens of erect and encrusting sponges, numerous crinoids and occasional urchins
CS05	37°44.80'S	149°43.94'E	37°44.81'S	149°43.90'E	69.69	shell hash and rubble, irregular seabed, large erect sponges occur on rougher seabed, isolated small sponges occur on sediment flat
CS06	37°45.73'S	149°44.11'E	37°45.74'S	149°44.06'E	73.12	shell hash and rubble, irregular seabed and granite boulders, large sponges on seabed, dense sponge gardens on granite boulders
CS07	37°46.45'S	149°43.82'E	37°46.48'S	149°43.71'E	49.83	low-relief granite outcrop and shell hash seabed, granite with small sponges and sea whips, or dense in Black sea urchins
CS08	37°46.78'S	149°42.70'E	37°46.81'S	149°42.64'E	62.92	high-relief granite outcrop and shell hash, dense sponge and octocoral gardens on granite, little sessile fauna on sediment
CS09	37°48.98'S	149°43.23'E	37°49.01'S	149°43.17'E	120.1	unrippled, coarse well-sorted sediment, shell hash, fauna very sparse, rare octocorals, occasional burrows in seabed

Table 3.2 Underwater video transect locations, water depth (m) and descriptions. See Fig. 3.2 for locations.

An examination of the geomorphology revealed by the bathymetry model and the results of statistical analysis of the sediment and video transect data were used to derive maps of the Secondary Biotopes and Biological Facies of the study area.

3.3 Results

3.3.1 Geomorphology

The geomorphic features shown in Fig. 3.2 are: (1) the high-relief granite outcrops of New Zealand Star Bank; (2) the low-relief parallel dune ridges of Broken Reef; (3) sediment lobes to the east of the granite outcrops; and (4) low-relief granite subcrop in patches around the high-relief granite outcrop. The five distinct outcrops of granite reveal a mostly high-relief (>1 m of vertical relief) and structurally complex surface of numerous fractures and joints that make up the rocky bank. The outcrops rise from a surrounding seabed of between 60 m to the north and 120 m to the south of the bank. The majority of the granite outcrop upper surfaces are between 30 to 40 m depth, while only the larger outcrop to the south rises to the minimum depth of approximately 10 m (marked as MD in Fig. 3.2).

To the northwest of the survey area are parallel dune ridges. These are the low-relief (<1 m vertical relief) features of Broken Reef, appearing as two discrete bands of linear, parallel dune ridges. One band is approximately 2000 m in width and the second is 400 m in width, and they abut the northern granite outcrops in depths of between 65 to 75 m. Dune ridge crests average

about 70 m apart and between 0.25 to 1.25 m from crest to trough in height. The ridge crests appear to be highly eroded and are structurally less complex than the high-relief granite outcrops, but most ridges can be followed continuously for over 5 km across the area surveyed.

On the eastern side of the granite outcrops are smooth and mounded features 2 to 3 m high that stretch linearly in a northeasterly direction away from the rocky bank. These appear to be sediment lobes of soft unconsolidated sediment forming in the lee of the granite outcrops. Clustered around the high-relief outcrops is granite subcrop, defined as low-relief (<1 m vertical relief) granite that influences the morphology of the seabed, which is composed of soft unconsolidated substrate. Granite subcrop appears as small areas of raised seabed between the high-relief granite outcrops and parallel dune ridges, and also amongst the sediment lobes. The remaining seabed around these geomorphic features appears as flat and unrippled unconsolidated soft substrate.

3.3.2 Surficial sediment

The results of the laser particle sizer on samples GR4 and GR5 show both are unimodal, medium to coarse sand, with less than 1% mud. The percentage gravel of GR4 and GR5 are 14.6% and 11.36% respectively. The gravel fractions are dominated by broken and abraded bioclasts, and rounded and iron-stained quartz granules. Minor bioclastic components are modern disarticulated bivalves, broken gastropods and bryozoa pieces. A comparison of the mean grain sizes of the samples GR4 and GR5 with the Jones and Davies (1983) samples BMR1785, BMR1786 and BMR1790, reveals a coarsening of sediments in proximity to the bank (Fig. 3.3). Despite the approximate 20 year difference between sample times, we do not believe that the hydrodynamic conditions have changed so much as to result in a uniform coarsening across the shelf, and so the coarse sediments found in the present study are more directly related to proximity to the rocky bank. Classification of the samples using the Folk (1954) scheme shows that both GR4 and GR5 are a gravelly sand, whereas BMR1785 and BMR1790 are slightly gravelly sand, and BMR1786 is slightly gravelly, muddy sand. The mean grain size for BMR1786 show an increase in finer-grained material seaward of the bank and in the deeper water found southeast of the survey area.

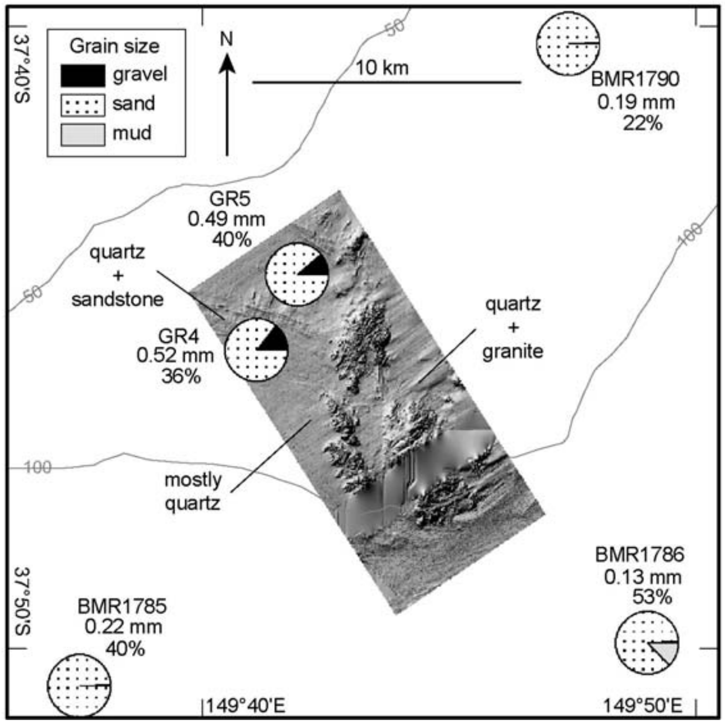

Fig. 3.3 Gravel, sand and mud proportions for GR4 and GR5, compared to previous samples obtained by Jones and Davies (1983). The samples names are followed by mean grain size (mm), then the calcium carbonate percentage of each sample.

A comparison of the calcium carbonate content from GR4 and GR5 shows they are similar to, or slightly less than, the adjacent BMR samples (Fig. 3.3). Sample BMR1786 shows an increase in carbonate content southeast of the bank. In addition, a microscope examination of the sand and gravel fractions from all grab samples obtained in the present study revealed interesting patterns for the non-biogenic material across the survey area. In samples obtained on the parallel dune ridges to the northwest, the non-biogenic material is mostly rounded and iron-stained quartz grains with minor, medium-grained quartz sandstone fragments (Fig. 3.3). We believe the sandstone fragments confirm that Broken Reef was formed from aeolian coastal dunes (Jones and Davies, 1983), and that the sandstone is being eroded and reworked into the thin unconsolidated soft sediments overlying the dune ridges. In the southwest study area, only rounded and iron-stained quartz particles are found, whereas quartz and mafic mineral fragments commonly found in granite are found northeast of the granite outcrops. This pattern of mostly quartz to the southwest, and quartz and mafic mineral fragments to the northeast is consistent with sediment transport by the prevailing northeasterly-flowing current over New Zealand Star Bank, which deposit eroded granite particles and create the sediment lobes on the leeward side of the bank (Fig. 3.2).

The percentage weight of sediment composition in the combined gravel and very coarse sand fractions (>1 mm) are listed in Table 3.3. Multivariate statistical analysis of this dataset reveals division into two groups (Figs. 3.4A and B). The presence of coralline algae only within samples GR7 and GR12, results in the other samples appearing to cluster together (Fig. 3.4B). These two samples were obtained directly from the high-relief granite outcrops with a high coverage of benthos, with the remaining samples collected from mostly unconsolidated soft substrate around the bank. A solution to observing the trends in soft substrate composition around New Zealand Star Bank is to split the data and conduct ordination separately on just the soft substrate samples after square root-transformation (Figs. 3.4C and D). In Fig. 3.4D, most samples have a high level of similarity except for GR4 and GR13. Sample GR4 was obtained from the crest of the parallel dune ridges of Broken Reef in the northwest of the survey area and has high lithoclast content. Sample GR13 was obtained from a narrow channel between the two westerly granite outcrops, and has low lithoclast content, as might be expected for a sample obtained proximal to granite outcrop with a high coverage of benthos.

Grab number	GR1	GR2	GR3	GR4	GR5	GR7	GR8	GR9	GR10	GR11	GR12	GR13
Coral algae (%)	0.00	0.00	0.00	0.00	0.00	65.46	0.00	0.00	0.00	0.00	87.02	0.00
Coral (%)	0.00	0.00	0.00	0.00	0.00	0.00	1.75	0.00	0.00	0.06	0.00	0.00
Polychaete (%)	0.62	0.43	0.40	0.24	0.54	0.90	3.45	4.53	3.00	0.22	0.67	1.09
Decapod (%)	0.00	0.02	0.00	0.00	0.00	0.00	1.68	0.08	0.09	0.04	0.38	1.12
Gastropod (%)	11.62	4.13	4.95	2.11	2.25	0.00	3.16	2.23	2.93	3.48	3.24	6.32
Bivalve (%)	2.24	1.30	6.88	9.60	2.22	1.03	3.93	1.86	2.34	5.08	2.77	1.44
Bryozoa (%)	3.47	2.91	7.01	2.24	3.98	10.50	12.44	20.66	9.18	9.12	2.19	38.45
Echinoid (%)	0.32	0.17	1.12	0.28	0.00	0.00	0.05	0.48	1.18	2.30	0.00	0.90
Bioclast (%)	48.24	46.93	42.30	28.73	54.92	12.24	38.34	31.21	47.19	38.84	0.86	35.35
Lithoclast (%)	33.50	44.11	37.34	56.80	36.09	9.86	35.20	38.94	34.09	40.85	2.86	15.32

Table 3.3 The percentage weight of sediment composition for grains >1 mm.

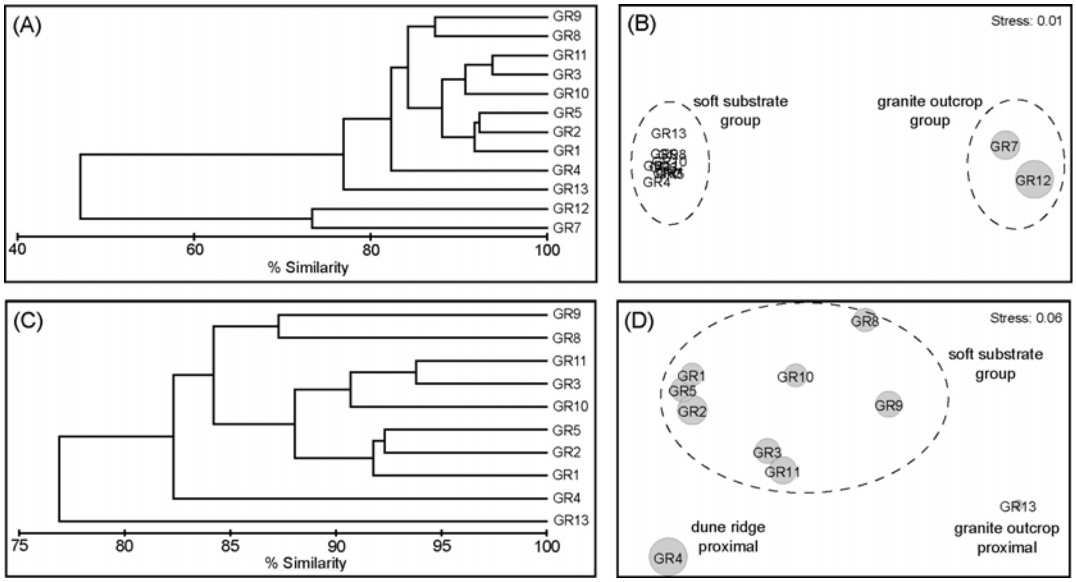

Fig. 3.4 (A) Group-averaged dendogram of cluster analysis on the square root-transformed percentage weight of sediment composition for the samples in Table 3.3. (B) Two-dimensional ordination plot from non-metric multi-dimensional scaling (MDS) of all samples, showing the relative size of coralline algae percentage weight. The samples are clustered into two groups due to the presence of coralline algae only in the two granite outcrop samples GR7 and GR12. The stress value is low, emphasising a good representation of the ordination. (C) Group-averaged dendogram of cluster analysis on the square root-transformed percentage weight of the composition from just the soft substrate samples, i.e. samples GR7 and GR12 removed. (D) MDS plot of just the soft substrate samples, showing the relative size of lithoclast percentage weight. Most samples are similar within the soft substrate group. GR4 was obtained over Broken Reef with a high lithoclast content. GR13 has low lithoclast content, obtained proximal to granite outcrop with a high coverage of benthos.

3.3.3 Environmental variables

The percentage occurrence of Substratum, Geomorphology and Fauna descriptors from the nine underwater video transects are listed in Table 3.4. PCA analysis of this dataset reveals division into three groups (Figs. 3.5A and B). There is a clear trend of transects separating a group comprising the granite outcrop sites (CS04, CS07 and CS08) from a group of sites collected over the soft substrate around New Zealand Star Bank (CS01, CS02, CS03, CS05 and CS06). The high proportion of gravelly sand observed in the latter group confirm that surficial sediments landward of New Zealand Star Bank are from the inner shelf (Jones and Davies, 1983). Seaward of New Zealand Star Bank, the transect CS09 was collected in approximately 120 m of water and is dissimilar to the other transects due to the increased presence of bioturbators (e.g. burrows) observed in the video. The high proportion of finer-grained sediments observed in CS09 compared to the other transects, confirms that this site lies in the middle shelf where muddy sand dominates (Jones and Davies, 1983).

	Substratum			Geomorphology				
Video number	Coarse sed (%)	Gravel/pebble (%)	Igneous rock (%)	Unrippled (%)	Irregular (%)	Low outcrop (%)	High outcrop (%)	
CS01	0.00	100.00	0.00	0.00	100.00	0.00	0.00	
CS02	0.00	100.00	0.00	72.41	27.59	0.00	0.00	
CS03	0.00	100.00	0.00	62.50	37.50	0.00	0.00	
CS04	0.00	0.00	100.00	0.00	0.00	58.18	41.82	
CS05	0.00	100.00	0.00	42.31	57.69	0.00	0.00	
CS06	0.00	88.89	11.11	20.00	68.89	0.00	11.11	
CS07	0.00	33.33	66.67	0.00	33.33	63.89	2.78	
CS08	0.00	39.06	60.94	34.38	4.69	14.06	46.88	
CS09	100.00	0.00	0.00	100.00	0.00	0.00	0.00	
	Fauna							
Video number	No fauna (%)	Large sponge (%)	Small sponge (%)	Mixed garden (%)	Octocoral (%)	Encruster (%)	Mobile (%)	Bioturbator (%)
CS01	73.68	0.00	21.05	0.00	0.00	5.26	0.00	0.00
CS02	6.90	37.93	55.17	0.00	0.00	0.00	0.00	0.00
CS03	65.00	5.00	30.00	0.00	0.00	0.00	0.00	0.00
CS04	0.00	58.18	0.00	5.45	0.00	10.91	25.45	0.00
CS05	57.69	13.46	25.00	0.00	0.00	0.00	3.85	0.00
CS06	26.67	17.78	53.33	0.00	0.00	2.22	0.00	0.00
CS07	2.78	0.00	0.00	64.81	0.00	0.00	32.41	0.00
CS08	34.38	37.50	3.13	25.00	0.00	0.00	0.00	0.00
CS09	84.21	0.00	0.00	0.00	3.51	0.00	0.00	12.28

Table 3.4 Underwater video transect Substratum, Geomorphology and Fauna descriptors for the nine video transects. Counts were made of the various descriptors at two second intervals along each transect and standardised into percentage occurrence.

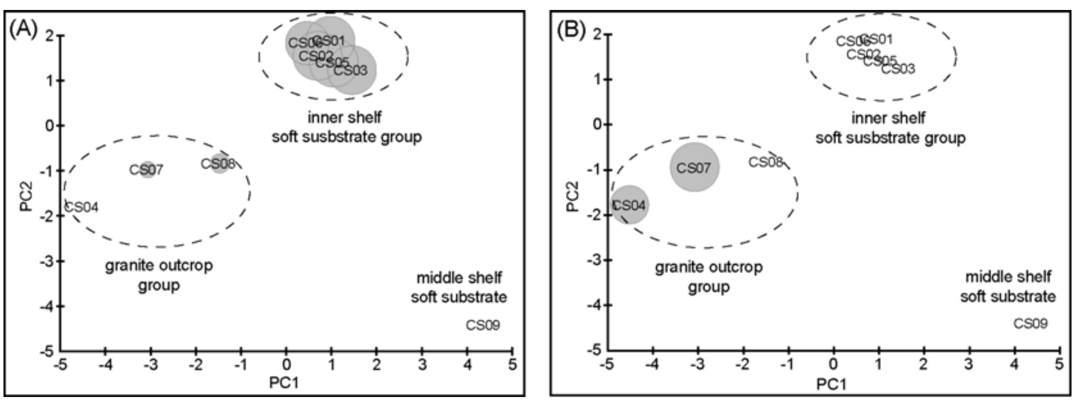

Fig. 3.5 (A) Ordination plot of principal component analysis (PCA) using Euclidean distance on untransformed Substratum, Geomorphology and Fauna descriptors in Table 3.4, showing the relative size of gravel/pebble percentage occurrence. (B) Ordination plot of PCA of the descriptors in Table 3.4, showing the relative size of mobile fauna percentage occurrence. The samples are clustered into three groups due partly to the high presence of gravel/pebble in the inner shelf soft substrate group and the presence of mobile fauna and igneous rock observed in the granite outcrop group.

This simplified visualisation of similarities (dissimilarities) between the environmental variables observed in transects belies the complexity of faunal-geologic relationships revealed by underwater video. For example, graphs of the numbers of small and large sponges, mobile fauna

(e.g. crinoids and Black sea urchins) and sea whips observed at two second intervals along soft substrate transects (Figs. 3.6A and B), and along granite outcrop transects (Figs. 3.6C and D), shows that the high-relief outcrops are associated with a relatively greater abundance and diversity of fauna than flat or low-relief habitats. Transect CS02 (Fig. 3.6A) was obtained over the parallel dune ridges to the northwest, and initially reveals a relatively flat seabed of shell hash with sparse large sponges as sessile fauna, which coincides with a trough. The video proceeds onto a shell hash-covered, rough and irregular seabed coinciding with a crest. At this point, a distinct patch of dense and erect large sponges appears. Transect CS06 (Fig. 3.6B) was obtained in the eastern part of the study area amongst a flat or irregular seabed covered in shell hash with the occasional rounded granite boulder protruding through the soft substrate. The majority of the flat seabed has a fauna of small erect sponges. However, wherever a boulder appears through the soft substrate, both large and small sponges cluster on the rock.

In contrast to transects obtained over flat or low-relief soft substrate environments, the fauna of the CS04 (Fig. 3.6C) transect obtained over a high-relief granite outcrop is a dense coverage of large and small sponges, and scattered individuals of mobile fauna, such as crinoids and urchins hiding in the numerous cracks and crevices. To show that not all granite outcrop is densely covered in sponges, the transect CS07 (Fig. 3.6D) reveals large numbers (approximately 10 to 14 per m^2) of the Black sea urchin (*Centrostephanus rodgersii*) apparently grazing low-relief granite outcrop so that few sessile fauna are present. Wherever urchins are absent or sparse, small sponges and sea whips (*Primnoella australasiae*) occur. Interspersed between the granite outcrops is a flat seabed of shell hash sediment, where fauna numbers typically drop. A pattern is repeated throughout the survey of sparse small sponges occurring on relatively flat seabed of unconsolidated soft sediments; with patches of large sponges appearing wherever the seabed has low-relief or where rounded granite boulders protrude through the sediment. Wherever the seabed comprises high-relief granite outcrop with a structurally complex surface, dense mixed sponge gardens appear.

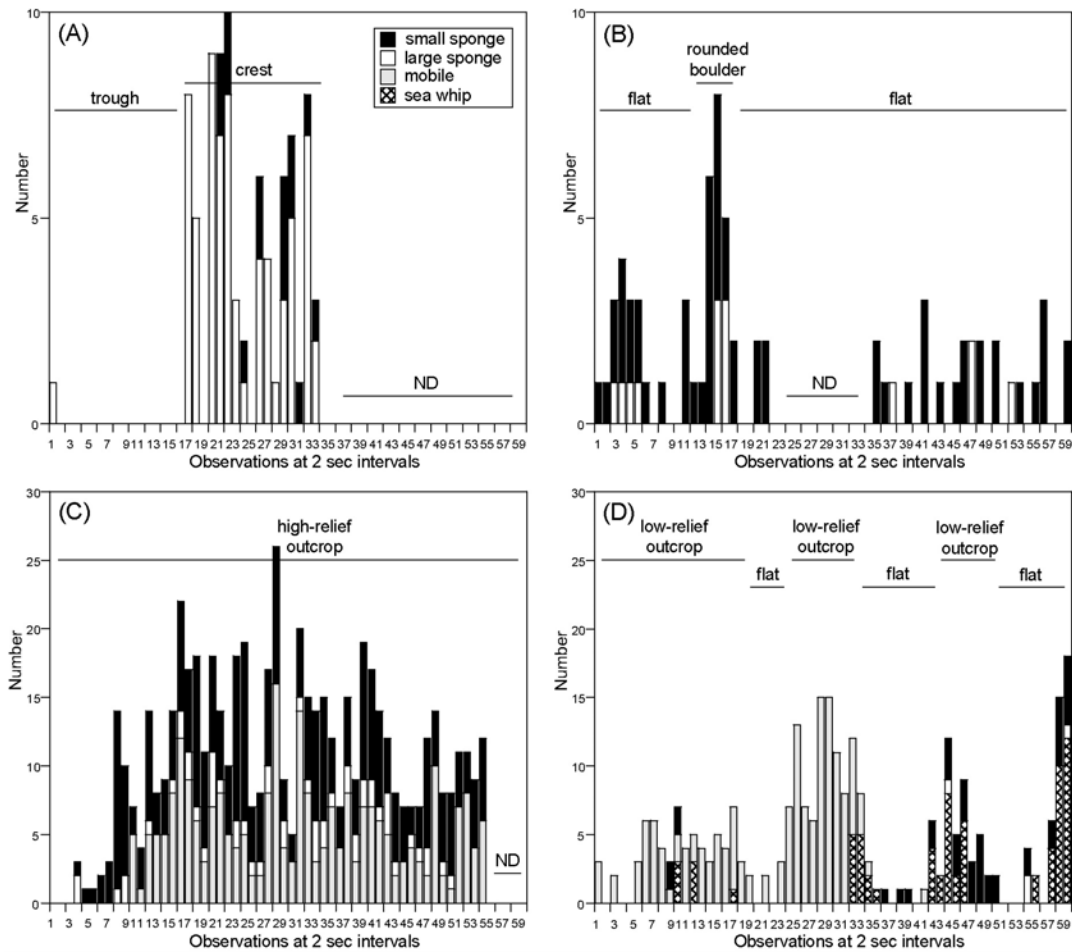

Fig. 3.6 Distribution of the numbers of small and large sponges, mobile fauna (e.g. crinoids and Black sea urchins) and sea whips observed at two second intervals along video transects. Soft substrate transects: (A) CS02 and (B) CS06. Granite outcrop transects: (C) CS04 and (D) CS07. See Fig. 3.2 for locations. ND denotes no data.

3.3.4 Secondary Biotopes and Biological Facies

Through an examination of the geomorphology, surficial sediment characteristics and results of the video transect analysis, the study area was divided into four Secondary Biotopes and four Biological Facies at the site (<10 km) scale, showing a high correlation between the predominant types of physical substrate observed and the biological communities associated with this substrate (Fig. 3.7). We believe that the patterns observed using the available datasets support the spatial boundaries of the mapped units within the context and scales of the hierarchical classification scheme developed by Butler et al. (2001). A description of each Secondary Biotope and the corresponding Biological Facies is given, which provides insights into the possible relationships between the geology of the seabed and the associated biological communities. A conceptual model diagram of New Zealand Star Bank area is shown in Fig. 3.8.

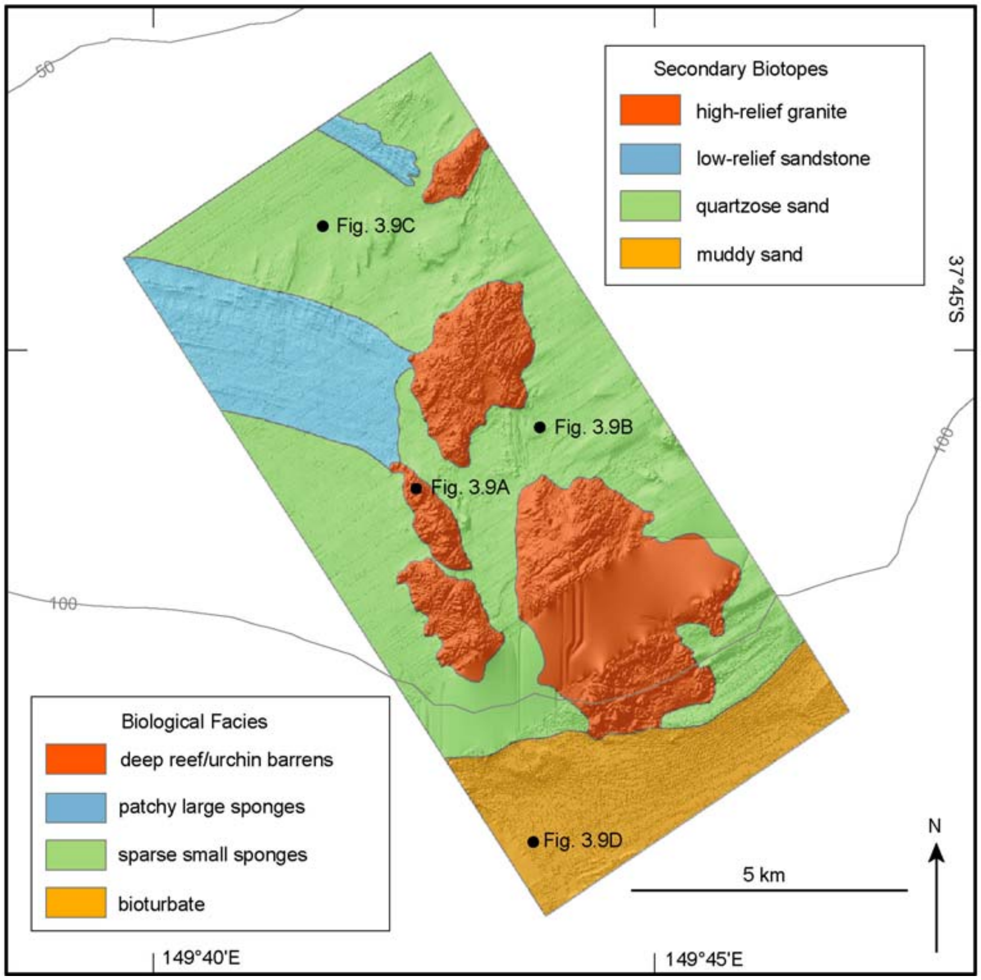

Fig. 3.7 Secondary Biotopes and Biological Facies of the study area. Note the positions of the underwater video images in Figs. 3.9A, B, C and D.

3.3.4.1 'High-relief granite' and 'deep reef/urchin barrens'

The 'high-relief granite' Secondary Biotope clearly stands out from the surrounding low-relief or flat seabed in the bathymetric model as five discrete outcrops (Fig. 3.7). The numerous fractures and joints give the granite outcrop surfaces a rough appearance in the model. These outcrops have upper surfaces of between approximately 30 to 40 m water depth, and the larger granite outcrop reaches a minimum depth of approximately 10 m. Underwater video reveals that not all the rocky bank outcrop is high-relief (>1 m in vertical change) granite. At the margins of the outcrops are found rounded granite boulders of low-relief (<1 m in vertical change) protruding through the soft substrate surrounding the rocky banks. Between the boulders at the margins and also observed accumulating in crevices on the high-relief granite is thin unconsolidated sand and gravel. The overall impression is a marine landscape of eroded granite often seen in

terrestrial environments where onion skin weathering creates a surface of domes in patterns related to joint spacing in the bedrock.

The 'deep reef' Biological Facies associated with the high-relief granite, derives its name from the Deep Reef habitat described in other hard-ground environments in southeast Australia (Underwood et al., 1991; Andrew and O'Neill, 2000). This consistent and recognisable habitat of subtidal rock substrate along the NSW coast is characterised by large sponges not found at shallower depths and by reduced densities of algae, particularly phaeophytes (Underwood et al., 1991). Other sessile fauna found on deep reef habitats, in waters deeper than 30m are ascidians, cnidarians and bryozoans (Andrew, 1999). Underwater video footage from the present study reveals a structurally complex surface of crevices and steep slopes, which is densely covered in erect large and small sponges, and encrusting calcareous red algae (Fig. 3.9A). Encrusting red algae are usually the greatest occupier of space due to tolerance of low light conditions (< 1% of surface) found at these depths (Andrew, 1999). Mobile benthos observed were crinoids within crevices and the Black sea urchin (*Centrostephanus rodgersii*) in low numbers on high slope surfaces.

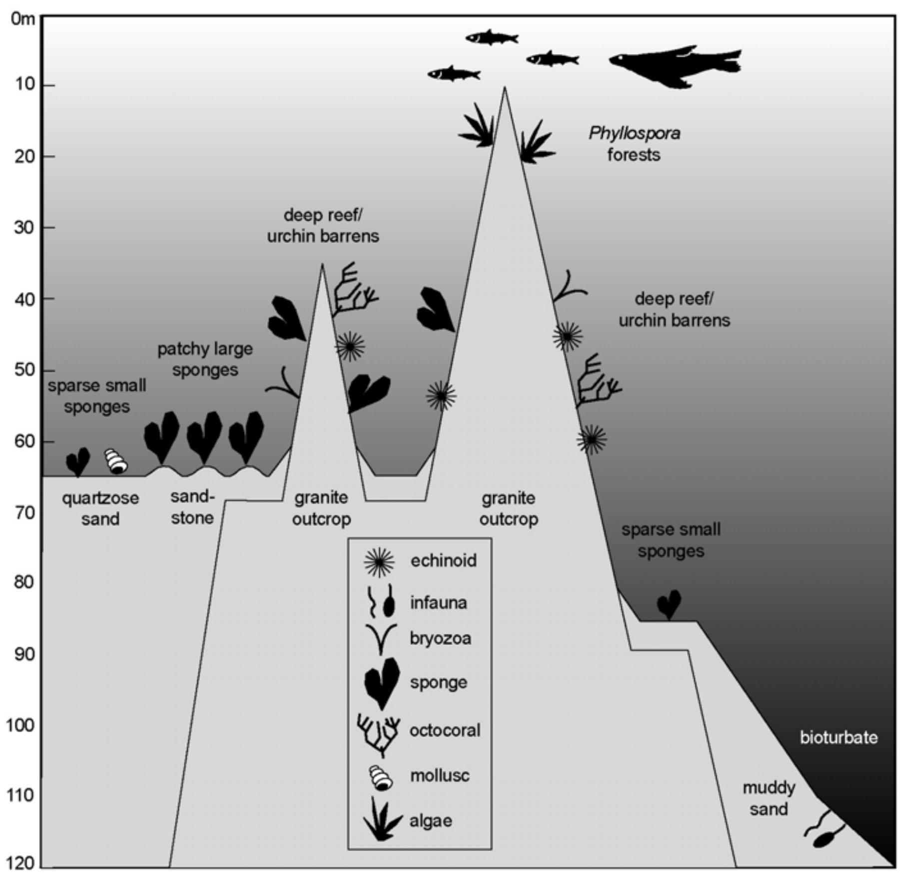

Fig. 3.8 New Zealand Star Bank conceptual model diagram.

The 'urchin barrens' Biological Facies is a biologically-modified 'deep reef' facies, also observed on the high-relief granite of New Zealand Star Bank. It too derives its name from a consistent habitat found on NSW subtidal rock substrate called a Barrens habitat (Underwood et al., 1991). This habitat is characterised by large numbers of the herbivorous Black sea urchin (*Centrostephanus rodgersii*), which graze the surrounding rock substrate (Underwood et al., 1991). Andrew and O'Neill (2000) state that the urchins are able to maintain their habitat clear of kelp and large macroalgae. The boundaries of urchin barrens are usually distinct, however they are patchy and are not depth related (Underwood et al., 1991). Underwater video footage from the present study revealed large numbers (approximately 10 to 14 per m^2) of *Centrostephanus rodgersii* on low-relief granite outcrop. Where urchins were concentrated, sessile fauna was rare or absent and the rock was mostly crustose red algae. In places where the numbers of urchins were low, small erect sponges and sea whips (*Primnoella australasiae*) were observed. This species of sea whip is common on deep rocky banks around southeastern Australia (Edgar, 1997). It is possible that where urchins do not graze heavily, sessile animals with small surface area attachment points, such as sea whips or small sponges, are able to maintain space (Andrew, 1999). The density of transects in our study could not differentiate the extent of the 'urchin barrens' within the 'deep reef' facies, but is expected to be patchy over the rocky substrate, as found in other surveys (Curley et al., 2002; Hill et al., 2003).

Another consideration of New Zealand Star Bank is the shallow minimum depth (approximately 10 m) that the largest granite outcrop rises to. No video footage was obtained at the shoalest area, however the physical environment may indicate the type of biological communities found there. Crevices and joints are evident in the shallow area that was ensonified by the multibeam sonar. The shallow depth is within the influence of wind-induced waves and relatively high light compared to surrounding deeper seabed. Off the southeast Australian coast, Crayweed (*Phyllospora comosa*) is the most common large algae in shallow water along exposed rock substrate (Edgar, 1997). In southern NSW waters, dense forests of Crayweed are recognised as a distinct habitat called *Phyllospora* forests (Andrew, 1999), and we predict that this biological community is found on New Zealand Star Bank in depths shallower than 20 m (Fig. 3.8).

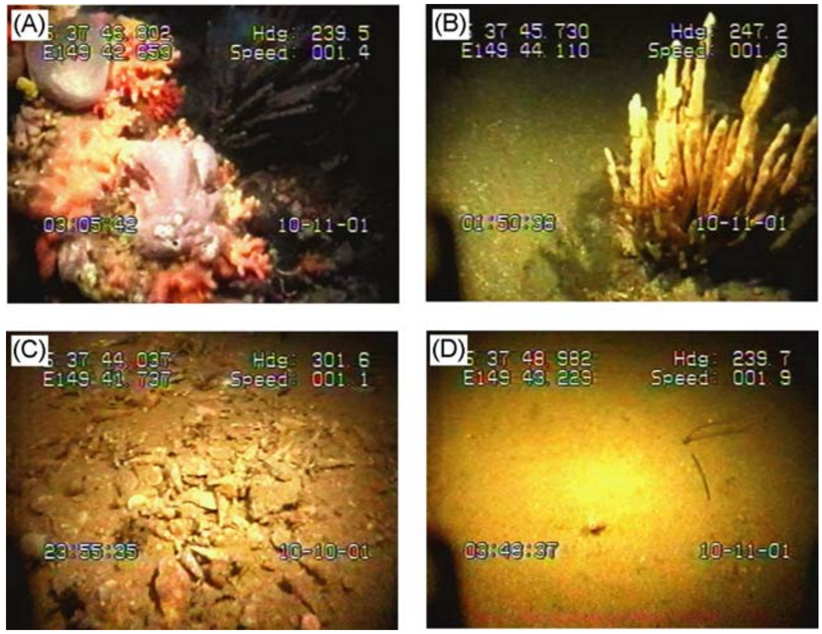

Fig. 3.9 Underwater video images of the study area. (A). Dense mixed gardens on high-relief granite outcrop. (B) Isolated large sponges on low-relief granite. (C) *Maoricolpus roseus* shells. (D) Octocoral and burrow in muddy sand. See Fig. 3.7 for locations.

3.3.4.2 'Low-relief sandstone' and 'patchy large sponges'

The 'low-relief sandstone' Secondary Biotope represents the two bands of the Broken Reef parallel dune ridges in the northwest of the survey area, which abut the northern granite outcrops. The presence of medium-grained quartz sandstone particles in sediment samples from this area is consistent with the idea that the dune ridges are a quartz arenite of aeolian origin (Jones and Davies, 1983). The overall impression is a marine landscape comprising linear ridges of sandstone approximately 70 m apart and about 1 m high, with crests that are eroded and which extend over 5 km beyond the limit of the survey area (Fig. 3.1B). The dunes are covered with a thin layer of quartzose sand with minor biogenic gravel.

If the parallel ridges are aeolian dunes formed along a palaeo-coastline (Jones and Davies, 1983; Bax and Williams, 2001), then the water depth at the base of the dunes is an indication of sea-level during the period when the dunes were formed if proximal to the shoreline. The water depth at the base of the dunes lies at approximately 65 m to 75 m, suggesting that the dunes were deposited when sea-level was at a maximum of between 65 to 75 m below present mean sea-level (MSL). An examination of eustatic sea-level curves shows that in the late Quaternary, a midstand occurs between 34 to 74 thousand years BP, when sea-level was between 65 to 75 m below MSL (Pillans et al., 1998). This time period represents approximately 40,000 years of possible coastal dune development. If we also include the period when sea-level fell below 65 m below MSL during the Last Glacial Maximum, when aeolian dunes may have developed distal

to the shoreline, then the time period for coastal dune development increases to approximately 60,000 years. Thus a substantial period of time is available for the coastal dunes to form along the edge of a midstand coastline.

The 'patchy large sponges' Biological Facies is strongly associated with this habitat. Underwater video reveals that the dune ridge crests are the preferred habitat of distinct patches of dense and erect large sponges. In contrast, the troughs or relatively flat seabed between the crests have only sparse large sponges growing on the unconsolidated soft substrate. The patches of large erect sponges found on the dune ridge crests are possibly taking advantage of a harder substrate afforded by the sandstone as an attachment surface, and/or increased water flow due to interference of near-seabed currents over the low-relief crests, thus providing favourable conditions for increased densities of these large suspension-feeders.

3.3.4.3 'Quartzose sand' and 'sparse small sponges'

The 'quartzose sand' Secondary Biotope correspond to the inner shelf quartzose sands of Ferland and Roy (1997). They comprise the majority of the seabed of the survey area and are found landward of the approximate 110 m depth contour, and also around the high-relief granite outcrops. Sediment grabs obtained from the predominantly flat and unrippled seabed contained a relatively high proportion of iron-stained, rounded quartz granules. Minor components were biogenic gravel of bryozoan and mollusc shell hash. The relatively mature quartz granules are a result of reworking during successive sea-level fluctuations in a high-energy, wave-dominated environment (Ferland and Roy, 1997). In the present survey, no ripples were observed on the flat seabed which is generally deeper than 65 m and at the limit of wave-induced mobilisation of sediment (Porter-Smith et al., 2004).

An examination of the bathymetry model revealed that the 'quartzose sand' biotope is slightly raised due to a variety of low-relief geomorphic features. On the eastern side of the granite outcrops are located sediment lobes 2 to 3 m high that stretch linearly away from the rocky bank. The sediment lobes are probably formed as a result of near-seabed currents sweeping over the bank in a northeasterly direction. Our interpretation is that the lobes are the result of a current-induced, bottom stress maxima around the prominent edges of the bank, such as occur in other current-scoured environments (Stride, 1982; Harris et al., 1995). The prevailing northeasterly flowing currents in the area are considered to be generated from coastal trapped waves (CTWs) propagating northward along the Gippsland coast (Morrow et al., 1990; Harris et al., 1991). Another geomorphic feature that influences the relief of the seabed in this biotope are the small areas of granite subcrop, which appear as raised seabed in between the high-relief granite outcrop and parallel dune ridges, and also amongst the sediment lobes. The seabed is

comprised of quartzose sand as a layer over the granite subcrop, and underwater video reveals an irregular seabed with low-relief, which is likely due to the morphology of the granite lying just below the seabed.

The 'sparse small sponges' Biological Facies is associated with the 'quartzose sand' Secondary Biotope. Video footage shows this facies to comprise mostly low numbers of individual small sponges. The flat seabed of the study area tends to have low densities of erect small fan sponges or rare large finger sponges that occur at an average distance of approximately 10 m apart. Encrusting sponges were not observed. An important variation to the predominantly sparse small sponges observed on flat seabed is that wherever the seabed became irregular or rises in low-relief, then these localised areas corresponded with an increase in numbers of large sponges (Fig. 3.9B). Similarly, wherever low-relief rounded granite boulders protruded through the quartzose sand then concentrations of large finger sponges dominated the sessile fauna on the irregular seabed. Another interesting feature of this facies were the accumulation of dead New Zealand screw shells (*Maoricolpus roseus*) observed in the underwater video taken in the north of the survey area in water depths of approximately 70 m (Fig. 3.9C). Numbers of these large (up to 87 mm in length) gastropods were approximately 30 per m^2, however living *M. roseus* were not observed in the video but may well have been infauna in this area. This introduced gastropod has a recorded expansion along the southeast Australian coast and is known for its ability to considerably modify the habitat that they live in (Allmon et al., 1994; Bax et al., 2003). We were unable to resolve the extent of the substrate covered by these gastropods with our video transects.

3.3.4.4 'Muddy sand' and 'bioturbate'

The 'muddy sand' Secondary Biotope is defined as seaward of the approximate 110 m depth contour where the seabed deepens rapidly away from New Zealand Star Bank and flattens out in depths of about 125 m. Interestingly, the 110 m depth contour is also the approximate lowstand for eustatic sea-level during the Last Glacial Maximum (Fleming et al., 1998). Therefore, at approximately 19,000 to 22,000 years ago when sea-level had dropped to about 110 m below MSL (Yokoyama et al., 2000), the coastline in this region would have been close to this biotope boundary. New Zealand Star Bank would have appeared as a prominent granite hill at the shoreline. Today, sediments in this biotope are more muddy with fine to very fine sand, and correspond to the mid-shelf muddy sands of Ferland and Roy (1997). The transition to finer-grained sand and increased mud content just seaward of New Zealand Star Bank was observed in the underwater video of the area, and from the results of Jones and Davies (1983). The proportion of mud is higher due to the seaward transport of finer-grained sediment from the high-energy inner to middle shelf (Morrow et al., 1990).

The 'bioturbate' Biological Facies associated with the 'muddy sand' biotope is quite different to the biological communities found on the inner shelf landward of the 110 m depth contour. Underwater video in the present survey revealed relatively few sessile fauna, except for rare octocorals, however burrows from infaunal biota were clearly more noticeable compared to the shallower transects (Fig. 3.9D). Despite the fact that we were unable to sample for soft-bodied infauna using grabs, this facies is named for the unseen infauna that were evidenced by the numerous burrows, and which appear to dominate seaward of the bank. In this deeper environment the light level is relatively low and the seabed is well below storm wave base (Porter-Smith et al., 2004).

3.4 Discussion

3.4.1 Geology-benthos relationships

We believe the descriptions and maps of the Secondary Biotopes and Biological Facies address the aims of this study, and provide insights into the possible relationships between the geology of the seabed and the associated biological communities on this temperate rocky bank. By characterising the benthic habitats at the Secondary Biotope and Biological Facies levels we can gain a better understanding of the controls on benthic biodiversity. The goal is to systematically understand the relationships between seabed characteristics and associated biological communities at the site (<10 km) scale. An important question asked earlier in this chapter, is whether geological data can be mapped as a proxy to predict the occurrence of assemblages of benthic organisms? The major differences which control the distribution of biological communities in the New Zealand Star Bank area appear to be related to variations in substrate: (1) hard-ground features related to granite outcrops; (2) unconsolidated sediment on a flat seabed; and (3) unconsolidated sediment on a low-relief seabed.

3.4.1.1 Hard-ground features related to granite outcrops

It is evident in the present study that there is a vast difference between communities that live on hard-ground features such as the granite outcrops of New Zealand Star Bank and those which exist on soft substrate surrounding the rocky bank. These granite outcrops support a diverse sessile fauna of large and small sponges, bryozoa, hydroids and ascidians which prefer stable attachment surfaces (Underwood et al., 1991; Andrew, 1999; Andrew and O'Neill, 2000). Finer-scale ecological niches of the granite outcrops are the high-relief fractures and joints that provide numerous microhabitats for the diverse mobile fauna observed in this study. Another important physical-biological relationship is the prey availability, which is dependent on broader-scale hydrodynamic conditions. Substratum heterogeneity which interferes with current

flow pattern will increase water turbulence and enhance particle capture by benthic suspension feeders (Gili et al., 2001). The dense cover of suspension-feeders suggests that the availability of food particles is sufficiently high within the relatively strong currents passing over these high-relief habitats to support a rich and colourful sessile fauna. At a finer-scale, biotic factors such as competition for space, predation and larval settlement would also influence the distribution of benthos on subtidal rocky substrate (Edgar, 2001).

Deep reef habitats can also be biologically-modified by grazing urchins to produce patchy urchin barrens. In the present study, dense aggregations of *Centrostephanus rodgersii* reduced the sessile fauna to low numbers of sea whips and small sponges. This resulted in granite outcrop covered in crustose red algae, and devoid of foliose algae and large sessile fauna. In temperate waters, large aggregations of these urchins can graze over extensive areas, sometimes in patches large enough to cover several hectares and with boundaries that are always clear (Andrew and O'Neill, 2000; Vanderklift and Kendrick, 2004). This urchin species has a preference for habitat complexity, occupying crevices during the daytime and emerge at night to graze, travelling up to 5 m from the crevice to forage (Hill et al., 2003; Vanderklift and Kendrick, 2004). Thus the fractures and joints of the granite outcrops of New Zealand Star Bank provide an ideal resting habitat for the Black sea urchin. Underwater video in this survey also shows urchins in the open during the day on the upper surfaces of granite outcrop, as has been observed in other studies (Andrew and O'Neill, 2000).

3.4.1.2 Unconsolidated sediment on a flat seabed

Unconsolidated sediment habitats in deeper water have not received the same research attention as shallow water hard-ground features (Malatesta and Auster, 1999). However, a number of habitat studies have been conducted over the soft substrate in southeastern Australia (Coleman et al., 1997; Bax and Williams, 2001; Kloser et al., 2001; Ferns and Hough, 2002). In the present study, unconsolidated sediments landward of the approximate 110 m contour are a quartzose sand with variable amounts of biogenic gravel of bryozoa and mollusc. The quartz grains are relatively mature, sub-rounded and the high iron-staining suggests reworking during successive sea-level fluctuations (Ferland and Roy, 1997). This sediment type covers the mostly flat seabed of the inner Gippsland Shelf (Jones and Davies, 1983; Bax and Williams, 2001). This habitat supports a biological community of sparse small bushy sponges and the occasional large finger sponge as sessile fauna. Rare solitary ascidians, infaunal anemones and small bryozoa were also present on the flat sandy seabed.

Mobile fauna observed in this habitat included hermit crabs and octopus, and in the north of the survey area, aggregations of dead *Maoricolpus roseus*. This gastropod was first recorded in

Tasmanian waters in the early 1960s and has subsequently spread across Bass Strait to the Victorian and NSW coasts to depths of 80 m (Bax et al., 2003). Museum of Victoria records show that this species was off East Gippsland by 1990 (Passlow et al., 2004). Bax and Williams (2001) also report occasional *M. roseus* beds of intermediate to sparse density within the soft substrate of the nearby Point Hicks Reef. Dense beds of these burrowing and suspension-feeding gastropods have the ability to dominate the benthic community in unconsolidated sediments within its geographic distribution, however it is unclear as to whether the beds of *M. roseus* are having a negative effect on native species on the southeast Australian shelf (Bax et al., 2003). The gastropod prefers a firm coarse substrate, and a moderate to strong current which provides available suspended food but does not have a large suspended terrigenous load (Allmon et al., 1994; Bax et al., 2003). The physical environment of the unconsolidated sediment and flat seabed landward of New Zealand Star Bank is therefore quite suitable for the occurrence of this species.

On the middle shelf and seaward of the approximate 110 m depth contour, the seabed becomes relatively flat and muddy. Sediments correspond to the mid-shelf muddy sands of Ferland and Roy (1997), and the higher mud component is due to the seaward transport of finer-grained sediment from the high-energy inner to middle shelf (Morrow et al., 1990). The carbonate content of the sediment is also higher on middle shelf compared to the inner shelf, and increases across the shelf due to the bioerosion of relict carbonate skeletal debris (Jones and Davies, 1983; Ferland and Roy, 1997). This finer-grained and flat habitat supports a community dominated by infauna, resulting in moderate bioturbation observed as numerous burrows. Animals that push through soft sediments with body widths up to 10 mm, which might result in burrows, include amphipods, callianassid shrimps, bivalves and polychaetes (Edgar, 2001). This study was unable to determine the infauna producing the burrows. Sessile fauna observed were rare individual octocorals upright on the flat seabed. This habitat is relatively stable in terms of low light and the lack of wave-induced currents at this depth, and clearly favours infauna over sessile fauna.

3.4.1.3 Unconsolidated sediment on a low-relief seabed

A striking observation in this study was the increase in density and sizes of sponges wherever any low-relief feature appeared on the relatively flat seabed. The 5 m pixel bathymetric model was able to resolve many low-relief features around New Zealand Star Bank. Underwater video confirmed the patches of large sponges occupying these features and helped explain the origin of the low-relief features. These features may take the form of sediment lobes which stretch linearly away from the rocky bank, raised seabed due to granite subcrop influencing the morphology of the overlying soft substrate, or long ridges of sandstone with a thin cover of

unconsolidated sediment. Within the limits of this study, there appears to be no difference in the preference of certain sponge morphologies to favour one type of low-relief feature over another, therefore we believe that the common factor is that the large sponges prefer areas which are elevated above the surrounding flat seabed. Again hydrodynamic factors are likely to be important. Interference in the flow of water caused by irregularities in the seabed leads to a concentration near the seabed of food and passively dispersing invertebrates (Edgar, 2001). These environmental conditions would favour the development of populations of sponges as the increased turbulence enhances particle capture by these suspension-feeders (Gili et al., 2001).

In the present study, the patchy distribution of large sponges on low-relief features is closely related to proximity to New Zealand Star Bank. Small areas of raised seabed due to granite subcrop are clustered around the high-relief granite outcrops, and do not appear to extend beyond several km of the bank before grading into the relatively flat seabed. Similarly, the 2 to 3 m high sediment lobes do not appear to extend for more than a km to the northeast of the bank, as the current scouring caused by near-seabed currents reduce in bottom stress with distance from the high-relief granite outcrops. Thus, patches of large sponges on unconsolidated soft substrate are likely to be more concentrated closer to the bank as the seabed becomes more irregular and raised. In contrast, the long ridges of sandstone comprising Broken Reef can be traced for many km across our study area, and is known to extend for 10s of km southwest along the East Gippsland shelf (Fig. 3.1B). Thus, the biological community of patchy large sponges associated with this biotope is predicted to cover a significant area of the shelf wherever Broken Reef can be mapped. Bax and Williams (2001) highlight the vulnerability of low-relief, fossiliferous sandstone banks, such as Broken Reef, to damage by bottom trawling. Once eroded these low-relief reefs may never recover their structural habitat.

3.4.2 Fish-benthos relationships

This study also provides provide useful links between fish and associated benthic habitats, and have been the subject of previous investigations on this shelf (Williams and Bax, 2001). Habitat-related patterns are usually the rule rather than the exception for temperate rocky reef fishes (Curley et al., 2002). Based on fish-benthos relationships found on the high-relief granite at the nearby Point Hicks Reef (Bax and Williams, 2001; Williams and Bax, 2001), New Zealand Star Bank should support planktivorous Butterfly perch (*Caesioperca lepidoptera*) and Eastern orange perch (*Lepidoperca pulchella*), and the carnivorous Port Jackson shark (*Heterodontus portusjacksoni*) and Draughtboard shark (*Cephaloscyllium laticeps*). Indeed, our underwater video showed a Draughtboard shark cruising above the crevices of high-relief granite outcrop as well as cloud-like schools of Butterfly perch feeding on plankton in the water

column above the bank. During the period of the survey, large numbers of seals were also observed feeding over the bank, presumably on the shoals of bentho-pelagic fish observed in the video. These seals were likely Australian fur seals (*Arctocephalus pusillus*) due to the proximity to a known haul-out site on nearby Gabo Island and their foraging distribution (Andrew, 1999). The presence of these higher-level predators demonstrates the importance of New Zealand Star Bank as a significant location for food in the eastern Bass Strait.

3.4.3 Assessment techniques

The assessment techniques shown in this survey reveal quite different levels of spatial resolution (1 cm up to 5 m), and making the link between these various spatial scales and the differing technologies is difficult (Malatesta and Auster, 1999). It is only through the use of GIS techniques that oceanic themes of varying scale can be mapped within a common map datum and easily compared with each other. The ability of GIS to present high-resolution bathymetric models as a 3D digital terrain model, which can then be draped with thematic layers representing physical and biological datasets, is indispensable for scientists and managers of marine environments. Similarly, a new age of ocean exploration is underway with the use of multibeam sonar systems that can fully ensonify the seabed and provide us with an unprecedented view of the true complexity of the seafloor (Exon and Hill, 1999; Kostylev et al., 2001; Harris et al., 2004). In this study, the real-time mapping of the seabed with multibeam sonar permitted considered and targeted groundtruthing so that we could add value to what was primarily a safe navigation survey by the RAN.

The assessment techniques used in this study are recommended for future ocean mapping studies. Multibeam sonar data were most useful for revealing the high-resolution geomorphic features of the seabed. Co-registered backscatter data and bathymetry models alone can provide most of the information to characterise the geomorphology of the seabed. In the present survey, slope models derived from the bathymetric model were also useful for helping delineate the boundaries of various features. However, only underwater video, at the resolution of cm to metres, could provide the groundtruthing to observe the contrast between a diverse and colourful benthos on high-relief granite and the relatively sparse small sponges on unconsolidated soft substrate. Single long video transects are recommended as biological assemblages can be very patchy on the seabed (Starmans and Gutt, 2002; Stevens, 2005). In this study, the composition of sediment grabs, at the resolution of cm, were not able to discriminate benthic assemblages at this scale because of the disconnect between the environment for existing biota and the hydrodynamic sorting of their skeletal remains until equilibrium is

reached (Jones and Davies, 1983). Nevertheless, the examination of sediment composition was useful in helping to explain the environment of deposition.

Therefore, each technique by themselves has their merits and disadvantages. However, the combination of assessment techniques using multibeam sonar mapping, underwater video and sediment grabs complement each other and provide powerful tools to characterise the seabed. The integration of high-resolution bathymetry and dense and well-targeted groundtruthing was the key to understanding the relationships between seabed characteristics and associated biological communities at the site (<10 km) scale. As MPAs often rely upon abiotic or geophysical factors to map the distribution of benthic biodiversity, our findings add confidence for the use of high-resolution geological datasets to provide a basis for reserve selection.

3.5 Conclusion

Multibeam sonar mapping has revealed approximately 100 km^2 of complex physiography on and around New Zealand Star Bank in the eastern Bass Strait at a detail not observed previously. Extensive groundtruthing of the area obtained grab samples and underwater video transects. In this study, we have characterised the seabed of the study area adopting the benthic habitat classification scheme used for the bioregionalisation of Australia (Butler et al., 2001). The spatial boundaries of Secondary Biotopes and Biological Facies at the site (<10 km) scale were defined on the basis of geomorphology revealed by the bathymetry model and the results of statistical analysis of the sediment and video transect data. Four Secondary Biotopes were observed: (1) high-relief granite; (2) low-relief sandstone; (3) quartzose sand; and (4) muddy sand. The Biological Facies associated with these biotopes were: (1) deep reef/urchin barrens; (2) patchy large sponges; (3) sparse small sponges; and (4) bioturbate.

This study also explored whether geological data can be mapped as a proxy to predict the occurrence of assemblages of benthic organisms. The major differences which control the distribution of biological communities in the New Zealand Star Bank area appear to be related to variations in substrate: (1) Hard-ground features related to high-relief granite outcrops are associated with diverse and abundant sessile and motile fauna. These faunal communities may be biologically-modified to patchy barrens habitat by grazing urchins. (2) Unconsolidated sediment on a flat seabed is associated with sparse small sponges on the inner shelf. On the middle shelf and seaward of bank, the flat and muddy seabed supports a community dominated by infauna. (3) Unconsolidated sediment on a low-relief seabed is associated with an increase in the density and sizes of sponges concentrated on any low-relief feature raised above the surrounding flat seabed.

The successful management of the East Gippsland shelf environment requires that decisions are made based upon an understanding of the characteristic physical and biological structure and processes. We have provided habitat maps of the seabed around New Zealand Star Bank at a high-resolution and examined the possible relationships between the geology of the seabed and the associated biological communities on this temperate rocky bank. New Zealand Star Bank and the adjacent Broken Reef is representative of a diverse range of habitats supporting prolific benthic and pelagic communities in apparently pristine condition, and may provide a useful example for the selection of habitats suitable for inclusion in a marine protected area.

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Chapter 4 Tropical Case Study

4.1 Introduction

One of the major obstacles posed for managers of marine environments has been knowledge of benthic biodiversity. The vastness of the continental shelf seabed, let alone the deep abyssal seas, and the high cost of data collection is a huge impediment for even developed countries. Over the majority of the continental shelf, there is an absence of biological data of the required quality and scale to map biological distributions (Stevens, 2002). Yet the trend towards Marine Protected Areas (MPAs) as zones of conservation of biodiversity demands a detailed knowledge of benthic habitats and associated biological communities. In the absence or paucity of biological data to base decisions on benthic habitat boundaries, MPAs rely upon abiotic or geophysical factors to characterise the seabed and water column, and thus provide a basis for reserve selection (Zacharias et al., 1999; Roff et al., 2003). Such questions as whether, and to what extent, the geophysical data from habitats can be used to predict the occurrence of assemblages of benthic organisms, will become increasingly important. However, there are few studies on the quantitative associations between habitats and the biological communities which depend on these habitats (Zacharias et al., 1999).

A number of studies have attempted to answer this vexing question, often using multivariate or regression analysis to make quantitative associations: (1) on soft substrate (Schlacher et al., 1998; Edgar and Barrett, 2002; Stark et al., 2003; Giberto et al., 2004; Rodil and Lastra, 2004); or (2) hard/complex substrate (Wilkinson and Cheshire, 1989; Schoch and Dethier, 1996; Bourget et al., 2003). Typically, results show the patchiness of biological communities and habitats, and conclude that there is no single correct scale at which ecosystems can be described. In addition, each study must be clearly defined as to the scale of interest in order for comparisons to be made against similar areas (Shin and Ellingsen, 2004). At the broader-scale, a number of studies have been made which successfully link regional (100s of km) scale physical processes to biological patterns. For example, seabed current stress was used as a predictor of benthos distribution in the Torres Strait (Long et al., 1995), and sediment type was found to be an important factor in the distribution of prawn species in the Gulf of Carpentaria (Somers, 1987). Zacharias and Roff (2001) were able to show that a combination of physical factors, related to environmental stability and disturbance, could explain patterns of intertidal species richness in coastal British Columbia.

Importantly, habitat should be considered as a surrogate for ecological structure within a hierarchy of scales (Greene et al., 1999; Roff and Taylor, 2000). One such scheme used for the bioregionalisation of Australia (Butler et al., 2001), defined six levels: (1) Provinces, based upon broad-scale geological patterns and 1000s of km in extent, e.g. continental blocks and abyssal basins. (2) Biomes, nested within Provinces and at the regional (100s of km) scale, which show broad-scale geomorphology, e.g. coast, continental shelf, slope and abyssal plain. (3) Geomorphic Units, within each Biome at the local (10s of km) scale, are areas of similar seabed geomorphology and which usually have distinct biotas, e.g. seamounts, canyons, rocky banks and coral reefs. (4) Primary Biotopes are soft, hard and mixed substrate-based units, together with their associated biological communities, also at the local (10s of km) scale. Maps to this level can generally be obtained by high-resolution acoustic surveys. (5) Secondary Biotopes are substructural units within Primary Biotopes that are distinguished by the types of physical or biological substrate within soft, hard or mixed types at the site (<10 km) scale, e.g. limestone, granite, shelly sands or seagrasses. Maps to this level are obtained by biological and physical groundtruthing. (6) Biological Facies are site (<10 km) scale units defined by a biological indicator, such as a species of seagrass, or group of hardcorals, sponges or other macrofauna linked to the facies (see Table 1.2 in Chapter 1 for further description).

To better understand the relationship between sediment, geomorphology and biological communities, we undertook a cruise to the northern Great Barrier Reef - Gulf of Papua region in January to February 2002 (Geoscience Australia Survey 234; Harris et al., 2002). In this study, we adopted the Butler et al. (2001) habitat classification scheme to map a series of areas along a transect from the Fly River delta to the northern end of the Great Barrier Reef at the Secondary Biotope and Biological Facies levels. We utilised multibeam sonar and a sub-bottom profiler, and then collected underwater video footage and grab samples at selected sites. This study contrasts two diverse areas within: (1) an inner shelf, low-relief, distal deltaic zone; and (2) a high-relief, mid-shelf, incised valley zone (Harris et al., 1996). These areas were selected from previous surveys to the area by Dr P.T. Harris, and were considered typical of inner shelf and mid-shelf areas in the northern Great Barrier Reef. The aim of the present study was to determine whether, in common with both areas, there is a combination of environmental variables which may be useful to quantitatively predict the distribution of megabenthos assemblages at the site (<10 km) scale in the northern Great Barrier Reef - Gulf of Papua region. The objectives of this study were to: (1) describe the physical environment of the two areas; (2) determine the dominant megabenthos assemblage patterns; (3) examine which geophysical variables are the best predictors for megabenthos assemblages; and (4) derive maps of the Secondary Biotopes and Biological Facies of the two areas.

4.2 Materials and methods

4.2.1 Study areas

Area A (Fig. 4.1) is located on the distal-delta of the Fly River along the western margin of the Gulf of Papua. The Fly River is rated as the 17th largest river in the world based upon a pre-industrial sediment discharge of 85 million tonnes $year^{-1}$, due to abundant rainfall in the Papua New Guinea highlands (Harris et al., 1993). The distal-delta lies in 20 to 50 m water depth, and is deep enough to escape reworking except by the largest wind-driven waves (Harris et al., 1993). Wind-driven currents in the area reflect the seasonal variation in winds, from the northwest during the monsoon period, November to April, and from the southeast during the trade-wind season, May to October (Wolanski et al., 1988). The distal-delta sediment facies are millimetre- to decimetre-thick sand/mud alternations occurring with a limited amount of bioturbation (Harris et al., 2004b). Despite the proximity to the Fly River mouth, the distal-delta experiences a slow rate of sediment accumulation at the present time (Harris et al., 2002; Walsh et al., 2004). Brackish water plumes derived from the Fly River are known to extend over this area (Wolanski et al., 1984; Davies, 2004).

Area B (Fig. 4.1) lies on an incised valley zone on the middle shelf, just north of the Great Barrier Reef (Harris et al., 1996). The seabed shows a complex, east-west valley-dominated bathymetry of approximately 50 to 130 m water depth. The area experiences the same seasonal variation in winds as the distal-delta region. A branch of the South Equatorial Current gives rise to a clockwise rotating current within the Gulf of Papua called the Coral Sea Coastal Current, which sweeps north along the outer shelf but reduces towards the coast (Wolanski et al., 1995). Oceanographic observations in Area B indicate that the valleys provide a conduit onto the shelf for cool and saline upwelled Coral Sea water (Harris et al., 2002). The surficial sediment reflects a Great Barrier Reef shelf facies with a calcium carbonate content that increases towards the south, and which contain less than 50% mud (Harris et al., 1993).

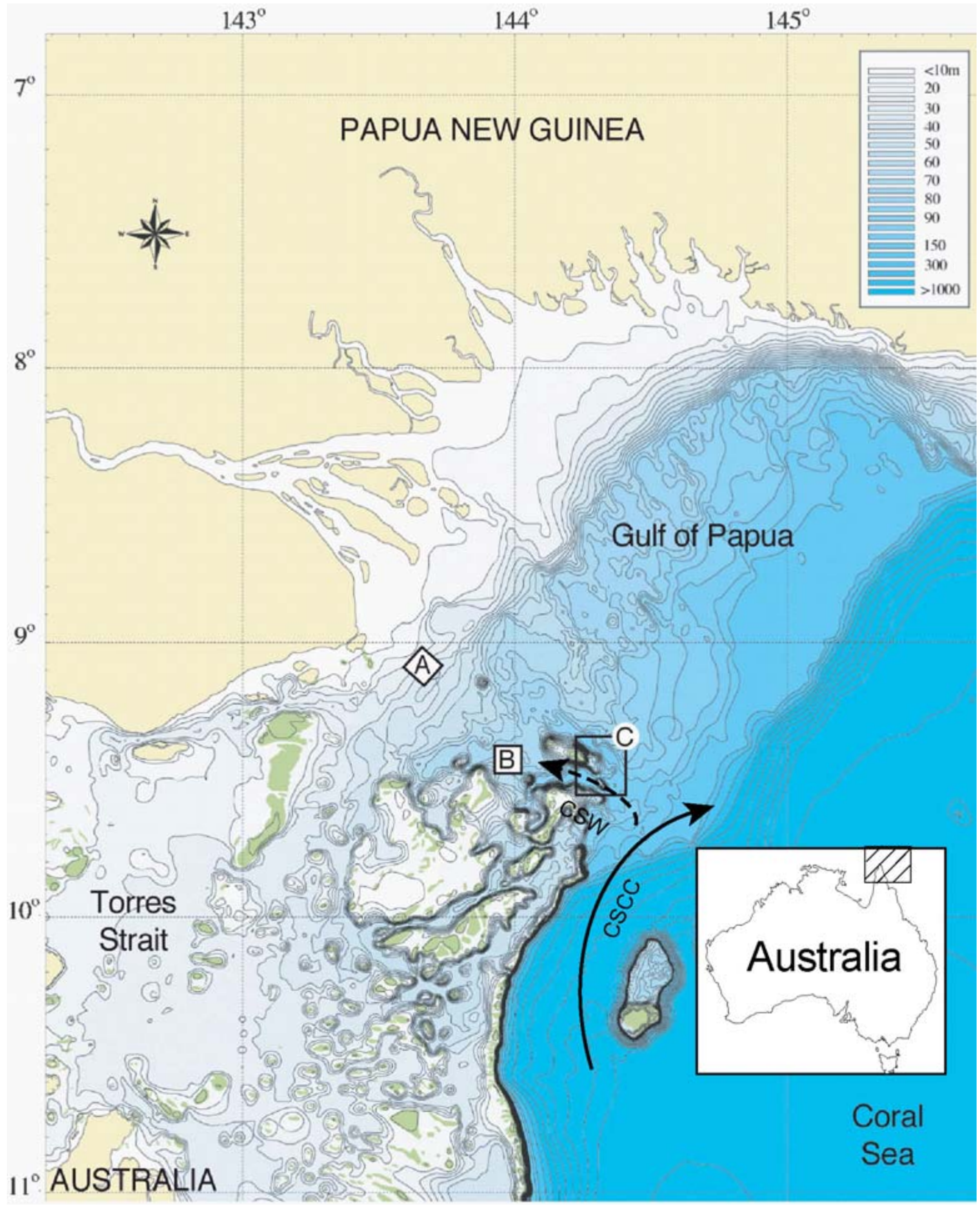

Fig. 4.1 Regional bathymetric map of the Gulf of Papua, Torres Strait and northern Great Barrier Reef based upon a new compilation of digital data provided by the CSIRO Division of Marine Research and the Royal Australian Navy Hydrographic Office. Reefs are shaded green. Boxes show the location of surveys in Areas A and B reported in this chapter from Geoscience Australia Survey 234 (Harris et al., 2002). CSCC, Coral Sea Coastal Current; CSW, upwelling Coral Sea water.

4.2.2 Bathymetry data

A Reson™ SeaBat 8101 240 kHz multibeam sonar recorded bathymetry and sidescan backscatter using a line spacing of 250 m in both Areas A and B. Navigation was maintained with a differential GPS to a horizontal accuracy of better than 5 m. Tidal corrections were performed at Geoscience Australia using predicted tidal heights provided by the National Tidal

Facility at Flinders University, South Australia. The tidal heights were derived from a computer tidal model and related to the centre positions of Areas A and B. ASCII XYZ (easting/northing/depth) point data at 10 metre intervals were extracted from the raw files using Caraibes seafloor mapping software (http://www.ifremer.fr/fleet/equipements_sc/logiciels_embarques/caraibes/) and interpolated using the ESRI™ ArcInfo program Topogrid to generate a 5 m resolution bathymetric model of each area. The resulting bathymetry grids were analysed for artificial drainage flow and slope within ESRI™ ArcGIS, and viewed as a 3D digital terrain model. The slope model was created by fitting a plane with a 3 x 3 cell neighborhood around each processing or center cell. Thus slope was averaged over a distance of 15 m for each cell of the bathymetry model to derive a 5 m resolution slope model for each area.

In conjunction with the multibeam sonar, a Datasonics™ DSP 661/66 3.5 kHz Chirp sub-bottom profiler and tow fish TTV170S recorded high-resolution seismic data throughout the cruise with a trigger interval of 0.25 seconds. The high-resolution sub-bottom profiles were recorded as CGM images for each survey line, then examined in the viewing program ZEHPlot-PE™ for echo-character types based upon Damuth (1980). At each one minute interval (about 150 metres equivalent distance), an echo-character type was assigned within a spreadsheet. The resulting spreadsheet was converted to an ArcGIS point shapefile, and then polygon boundaries digitised to match the spatial distribution of echo-character types, which was used to help create a GIS model of the geomorphology for each study area.

4.2.3 Underwater video data

Within each study area, 21 sites were selected for groundtruth sampling based upon variation observed in bathymetric and sub-bottom profiles. The aim was to groundtruth as much seabed surface and sub-bottom diversity as possible to observe the variation in geomorphology and any associated biological communities. A sled-mounted analog video camera was towed along the seabed for about five minutes at each station to obtain a transect averaging approximately 75 m long. A scaled ruler was mounted on the sled within view of camera to obtain a crude size of features on the seabed. Real-time video images were fed to the vessel and recorded onto VHS tape through a monitor, with the differential GPS position and time recorded automatically on the video. Underwater video footage was viewed frame by frame (approximately every two seconds or an equivalent 0.5 metres distance range) and a megabenthos category assigned based on the predominant assemblage in the frame. Megabenthos is defined as organisms readily visible in photographs (Solan et al., 2003). Categories were: no fauna, small sponge, mixed garden, softcoral, mobile, bioturbator. The category softcoral included softcorals, gorgonians

and sea whips (Alcyonacea). The category mixed garden comprised both softcorals and sponges, and other dense fauna. Mobile megabenthos were typically echinoderms and excluded fish. The category bioturbator comprised mounds or burrows as indicators of the indirect presence of infauna.

The resolution of the analog video precluded lower taxonomic classification of individual organisms, and so these broad categories were considered detailed enough to capture the variation of biological assemblages associated with benthic habitat at the scale of this study. For each transect, counts were made of the number of times a megabenthos category was recorded, and then standardised into the percentage occurrence. Thus each transect had a ratio of the megabenthos categories observed and provided the data to conduct multivariate statistical analysis. Using the statistical program Primer Ver. 5 (Clarke and Warwick, 2001), Bray-Curtis similarity coefficients were computed on the square root-transformed percentage megabenthos data, the purpose of the transformation being to reduce the emphasis on dominant components. The resulting similarity matrix from each study area was analysed using group-averaged cluster analysis and displayed as a non-metric, multi-dimensional scaling (MDS) ordination plot to establish the similarity in megabenthos occurrence between transects.

4.2.4 Environmental data

While in position at each station, a Sea-Bird Electronics™ SBE911 conductivity/temperature/depth (CTD) profiler was deployed along with a SeaTech transmissometer, calibrated to measure suspended sediment concentration in the water column. At each station, surficial sediment grabs were obtained by Smith-McIntyre grab, collecting approximately 10 litres of sediment. Sediments from grab samples were analysed for percentage gravel, sand and mud content by the wet sieve method, using nested 2 mm and 63 µm analytical sieves. The carbonate content of the gravel fraction was estimated visually, within approximately +/- 5%. The carbonate content of the sand and mud fractions were determined separately in a carbonate bomb where a known weight of dried and crushed sediment is placed in a sealed chamber (Müller and Gastner, 1971). Dilute hydrochloric acid is released inside the chamber and the dissolution of the calcite produces CO_2 gas. The mass of calcium carbonate was then determined by a calibration curve.

In order to test which environmental variables were the best predictors for the megabenthos assemblage patterns observed in video transects at each station, a spreadsheet was compiled with the following categories: depth (m), slope (°), gravel weight (%), sand weight (%), mud weight (%), gravel $CaCO_3$ (%), sand $CaCO_3$ (%), mud $CaCO_3$ (%), total $CaCO_3$ (%),

temperature (ºC), salinity (psu), and transmission (%). The data for the oceanographic variables of temperature, salinity and transmission were obtained from near-seabed at each cast. Because of the requirement to obtain a single depth and slope value at each sample site for comparison against the megabenthos data, the video transect lines were overlaid on the slope and bathymetry grid models within a GIS. The cell values from the depth and slope models intersected by each transect were examined in a histogram and the mean was used to derive the single depth and slope value at each sample site. The resulting spreadsheet of environmental variables of each area provided data for multivariate statistical analysis.

Using the statistical program Primer, a principal component analysis (PCA) was conducted on the untransformed environmental data to establish trends in environmental variables across the sites. PCA ordination using normalised Euclidean distance to measure dissimilarity of samples is a suitable method of analysing relationship trends for environmental variables (Clarke, 1993). The BIO-ENV procedure in Primer was then used to explore the subset of environmental variables which best matches the observed megabenthos patterns. The BIO-ENV routine simply calculates a measure of agreement between the two (dis)similarity matrices. For each survey area, the Bray-Curtis similarity matrix of square root-transformed megabenthos data was compared against the normalised Euclidean distance (dissimilarity) matrix of untransformed environmental data. Spearman rank correlation coefficients quantifies the match between the biotic and abiotic matrices, and chooses the subset of environmental variables which maximise the correlation coefficient. This subset of environmental variables were given priority for overlay in a GIS, and in conjunction with models of the geomorphology and bathymetry, assisted in deriving the spatial boundaries of the Secondary Biotopes and Biological Facies of each area. These boundaries were then digitised as polygon shapefiles within ArcGIS for overlay on the 3D digital terrain models.

4.3 Results

4.3.1 Geomorphology

Approximately 68 km^2 of seabed was mapped for Area A to 100% coverage. The bathymetry of Area A shows a gradual seaward-dipping ramp forming the distal section of the Fly River delta (Fig. 4.2A). Water depths range from 22 to 38 m over a flat seabed with isolated knolls and pockmarks (Fig. 4.3A). The knolls are up to 4 m above the surrounding seabed and the pockmarks are less than 1 m deep. Knolls and ridges with a similar relief above the surrounding flat seabed have been recognised in other studies within the distal delta, which are generally flat-topped and described as 'mesa-like' in profile (Harris et al., 1996). There are seabed surface

expressions of two shallow channels trending normal to the general slope of the area, which average approximately 550 m in width (Fig. 4.3B). Sub-bottom profiles reveal these features to be infilled channels (Figs. 4.4A and B). The channels are now infilled to approximately 10 to 15 m deep. A third infilled channel with little surface expression was detected across the middle of the survey area. Seismic profiles revealed that isolated knolls lay either side of the infilled channels, and look much like relict versions of the ridge and channel morphology characteristic of modern tide-dominated deltas (Walker, 1984). Pockmarks are located around the base of a number of these low-relief knolls.

Approximately 165 km^2 was mapped for Area B to nearly 100% coverage. The survey confirmed the presence of a submarine valley system, trending east-west across the shelf dividing the survey area into three platforms (Fig. 4.2B). Depths in the valleys are about 130 m in the south valley and 90 m in the north valley (Fig. 4.3C). Multibeam survey results show that the two valleys are separate limbs of the Darnley Valley, which branches around an unnamed live reef in the west-central study area. These valleys are considered to have been formed by high-energy, tidal current scour during mid-stand sea-levels in the late Quaternary and are now relict features (Harris et al., 2005). In the north of the survey area is a relatively flat and channel-incised platform averaging about 55 m depth. On the central platform, sub-bottom profiles also reveal numerous meandering channels (Fig. 4.3D), and now infilled to maximum depths of approximately 20 m with little or no seabed surface expression (Fig. 4.4C). A large seabed surface feature of the central platform is an active dune field in depths of approximately 40 to 70 m (Fig. 4.3E), with crest to trough heights averaging 2 m, and a wavelength of approximately 180 m (Fig. 4.4D). Dune crests are sinuous, often sharp, and in cross section the lee slope faces west, suggesting net westerly-going current flow (Harris et al., 2005). A live reef on the south platform extends to approximately 6 m below the water surface from platform depths of about 50 m. Scattered around the southern and central platforms are numerous submerged or relict reefs showing karst-erosion surfaces in sub-bottom profiles between depths of 30 to 42 m, and averaging 36 m water depth (Fig. 4.3F).

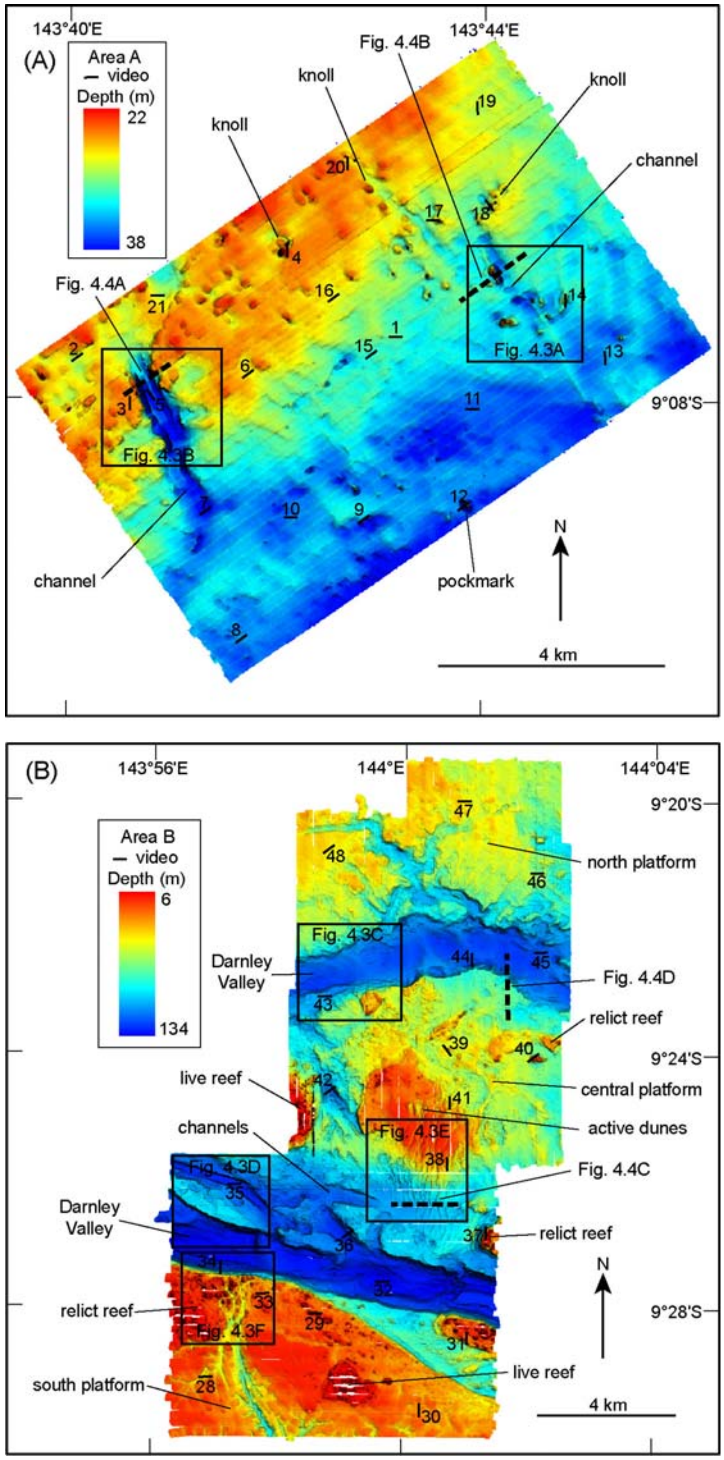

Fig. 4.2 Sun-shaded bathymetric maps of the survey areas. (A) Area A on the Fly River distal-delta. Note the shallow channels aligned normal to the isobaths and the numerous low-relief knolls. (B) Area B on the northern Great Barrier Reef shelf. Note the presence of deep submarine valleys as two limbs of the Darnley Valley separated around a live reef in the west-central platform. Numbers refer to the video transect stations. Boxes refer to close-up images of bathymetry in Fig. 4.3. Dashed lines refer to the positions of the sub-bottom profiles in Fig. 4.4.

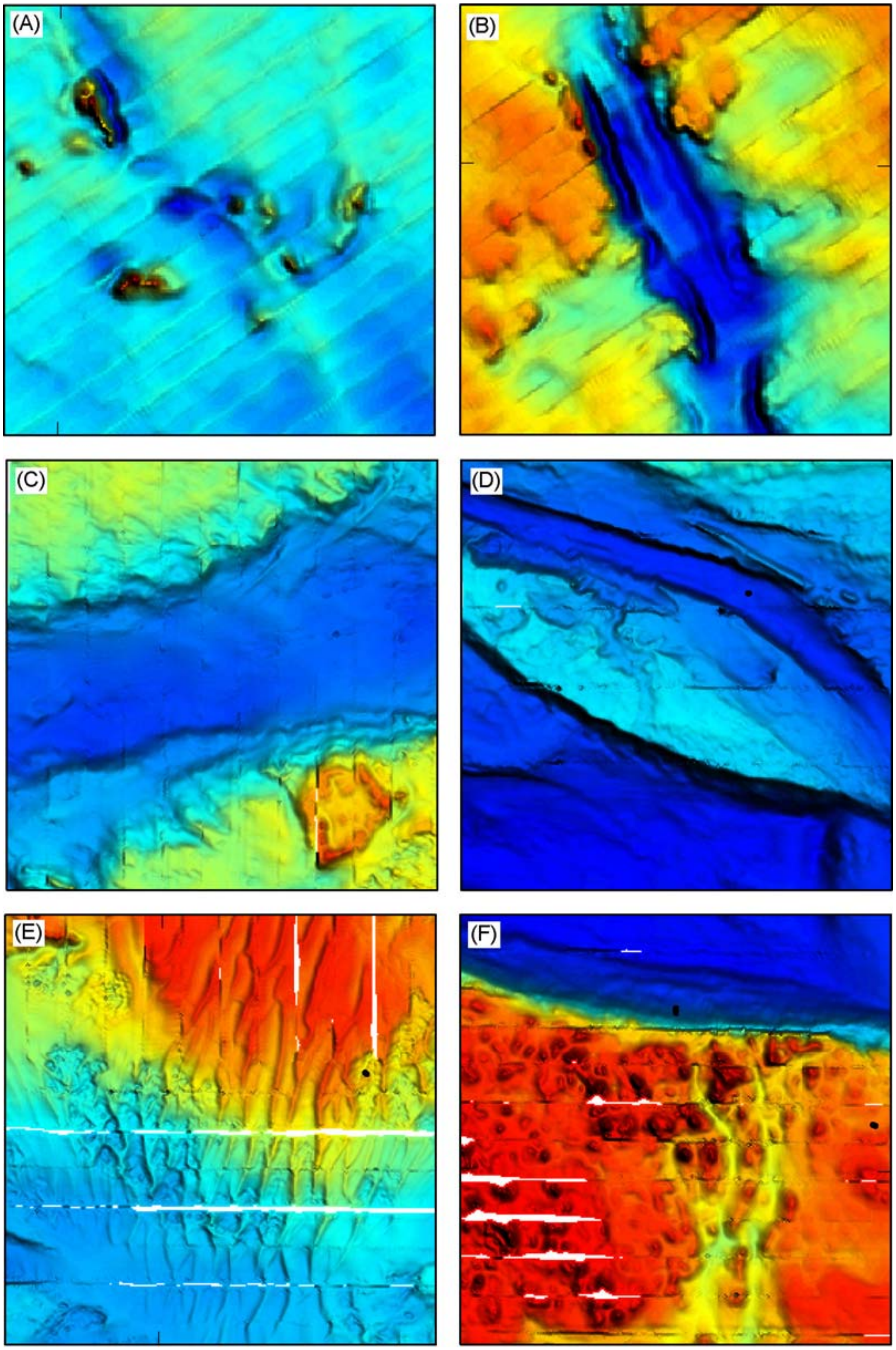

Fig. 4.3 Close-up images of bathymetry. (A) Area A limestone knolls. (B) Area A palaeochannel. (C) Area B Darnley Valley. (D) Area B shallow channels. (E) Area B dune field. (F) Area B relict reefs.

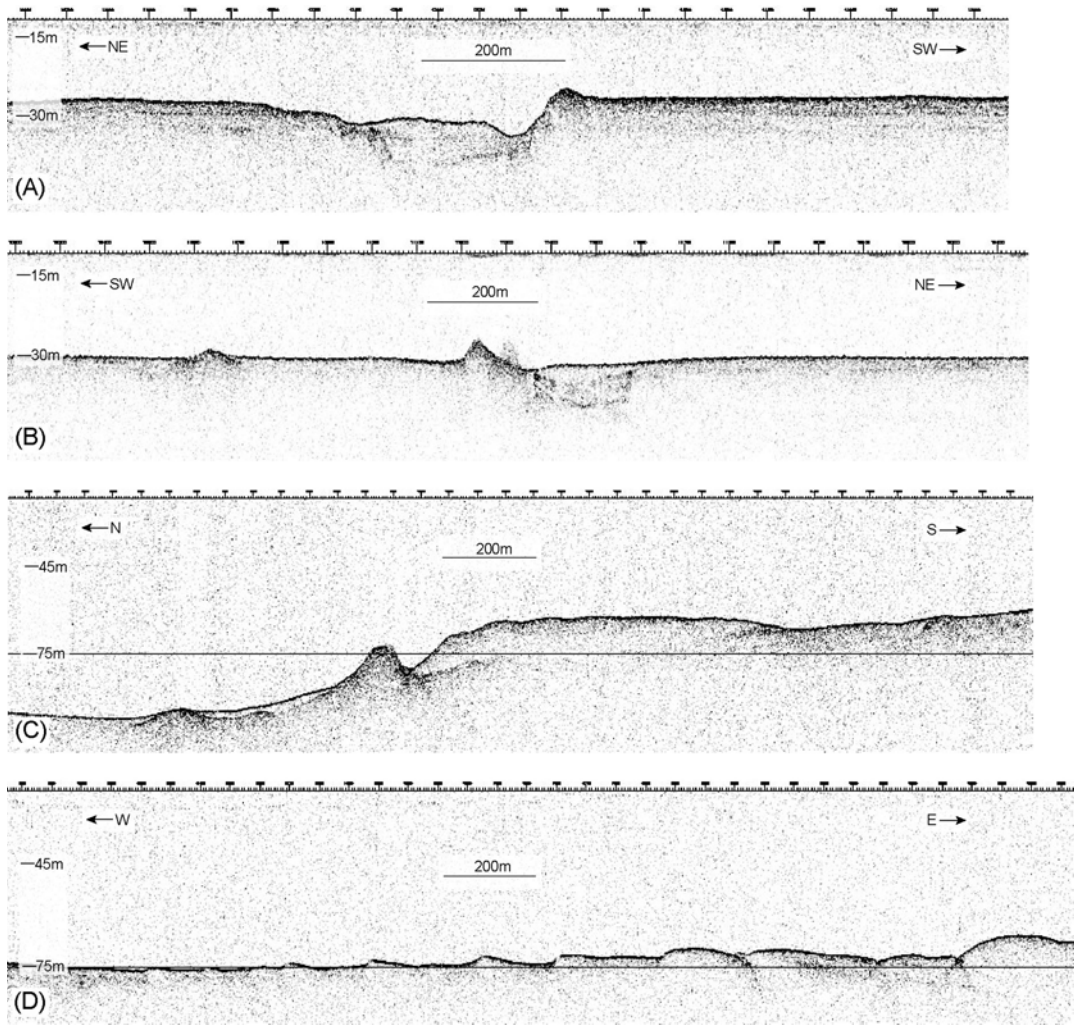

Fig. 4.4 Example Chirp sub-bottom profiles. (A) Area A, showing an infilled channel. (B) Area A, showing sub-surface reflectors and infilled channel. (C) Area B, showing sub-surface reflectors on the margin of the north arm of the Darnley Valley. (D) Area B, showing an active dune field. See Fig. 4.2 for locations.

4.3.2 Megabenthos

Table 4.1 gives the percentage occurrence of megabenthos categories for Area A transects 1 through 21 (Fig. 4.2A). For 19 out of the 21 video transects, the substrate appears as a muddy sand, and mostly flat to undulating. Only the occasional small bushy softcoral or small tube sponge was observed as sessile megabenthos. Rare holothurians or asteroids were the only mobile megabenthos observed on the sand flat, however, there were moderate to abundant burrows and mounds. These were likely the result of Ghost shrimps (Callinassidae) biogenically working the seabed. In contrast to the predominantly flat seabed, the seafloor at Stations 4, 14 and 18 (Fig. 4.2A) was noticeably more gravelly and revealed low-relief (<4 m in vertical change) knolls above the surrounding flat seabed. Cores targeting the knolls obtained a

compacted grey mud with scattered shell debris. Wherever the low-relief limestone knolls were observed in video transects, prolific mixed gardens of fan-shaped sponges, gorgonian fan corals, large bushy softcorals and sea whips appeared as sessile fauna attached to the hard surface of the knolls. Soldier fish (Holocentridae) and large cod (Serranidae) congregated around the low-relief knolls. Station 12, which targeted a pockmark adjacent to a knoll, recorded the substrate becoming coarse and with a prominent change in gradient as the video sled travelled into the depression. Only the occasional small bushy softcoral was observed with no bioturbation on the seabed.

Video number	No fauna (%)	Small sponge (%)	Mixed garden (%)	Softcoral (%)	Mobile (%)	Bioturbator (%)
1	52.48	0.00	0.00	0.71	0.00	46.81
2	81.58	0.00	0.00	0.00	0.00	18.42
3	71.11	0.74	0.00	9.63	0.00	18.52
4	17.28	0.62	35.19	46.91	0.00	0.00
5	95.00	0.00	0.00	0.00	0.00	5.00
6	62.73	0.00	0.00	0.91	0.00	36.36
7	72.22	0.00	0.00	2.78	0.00	25.00
8	78.26	1.09	0.00	1.09	1.09	18.48
9	80.58	1.94	0.00	4.85	0.97	11.65
10	88.78	0.00	0.00	0.00	0.00	11.22
11	84.38	1.04	0.00	0.00	0.00	14.58
12	97.30	0.00	0.00	2.70	0.00	0.00
13	89.51	0.70	0.00	0.00	0.00	9.79
14	75.74	0.37	6.99	9.56	0.37	6.99
15	89.25	0.00	0.00	0.00	0.00	10.75
16	85.84	0.00	0.00	0.00	0.00	14.16
17	91.23	0.00	0.00	0.88	0.00	7.89
18	78.13	1.25	9.38	9.38	0.00	1.88
19	90.40	0.00	0.00	0.80	0.00	8.80
20	83.48	0.00	0.00	0.87	0.00	15.65
21	95.58	0.00	0.00	0.00	0.00	4.42

Table 4.1 Underwater video transect megabenthos descriptors for Area A. Counts were made of the various descriptors at two second intervals along each transect and standardised into percentage occurrence. See Fig. 4.2 for locations.

Table 4.2 gives the percentage occurrence of megabenthos categories for Area B transects 28 through 48 (Fig. 4.2B). The majority of stations sampled the flat to gently undulating extensive platforms. On the seabed was sparse sessile benthos, with the just the occasional small bushy softcoral observed. Only infrequent mounds or burrows were recorded, in contrast to the more heavily bioturbated seabed of Area A. Rare individual ophiuroids and echinoids were seen moving along the seabed. On the central platform, transects obtained at Stations 38 and 41 on the active dune field showed a seabed of mostly sand with few gravel clasts. Small ripples about 10 cm apart were superimposed on the stoss slope of the dunes. Burrows and sessile megabenthos were rarely observed in this dynamic area. Transects at Stations 34 and 44

sampled the sides of the valleys and found the high-gradient seabed to have abundant cobbles and boulders scattered on the gravelly sand. Sessile benthos was moderate to abundant, with the scattered boulders providing the attachment substrate for large softcorals and sea whips.

Video number	No fauna (%)	Small sponge (%)	Mixed garden (%)	Softcoral (%)	Mobile (%)	Bioturbator (%)
28	89.50	0.00	0.00	0.00	0.00	10.50
29	72.45	0.51	22.45	0.00	0.00	4.59
30	97.95	0.00	0.00	1.37	0.68	0.00
31	95.00	0.00	0.00	5.00	0.00	0.00
32	97.06	0.00	0.00	0.00	1.18	1.76
33	95.83	0.00	0.00	2.78	0.00	1.39
34	63.00	2.00	0.00	35.00	0.00	0.00
35	90.55	0.00	0.00	4.72	0.00	4.72
36	86.33	0.72	0.00	10.07	0.00	2.88
37	39.33	0.00	52.81	7.87	0.00	0.00
38	99.28	0.00	0.00	0.72	0.00	0.00
39	93.81	0.00	0.00	0.00	0.00	6.19
40	28.06	0.00	38.13	33.81	0.00	0.00
41	96.55	0.00	0.00	2.76	0.00	0.69
42	99.51	0.00	0.00	0.49	0.00	0.00
43	95.51	0.00	0.00	3.37	1.12	0.00
44	75.63	0.00	3.13	20.63	0.00	0.63
45	93.03	1.00	0.00	5.97	0.00	0.00
46	91.12	0.00	0.00	5.92	2.37	0.59
47	98.44	0.00	0.00	0.52	0.00	1.04
48	93.96	0.00	0.00	4.70	0.00	1.34

Table 4.2 Underwater video transect megabenthos descriptors for Area B. Counts were made of the various descriptors at two second intervals along each transect and standardised into percentage occurrence. See Fig. 4.2 for locations.

Transects at Stations 32 and 45 (Fig. 4.2B) sampled the valley floors at approximately 129 m and 88 m respectively, and the seabed became notably more muddy, indicating an increase in finer-grained sediment in these deeper areas. In contrast to the valley sides, the flat valley floors were much reduced in biota. Scattered around the south and central platforms were high-relief (>4 m in vertical change) submerged or relict reefs. When video transects ran directly over the relict reefs at Stations 29, 37 and 40 (Fig. 4.2B), the karst-style erosion was obvious. Weathered limestone outcrop revealed numerous holes and caves, providing a favourable habitat for dense gardens of large softcorals, sponges and sea whips to attach to. Within Area B, two unnamed live reefs were surveyed in the south platform and western-central platform. Both these two reefs came within approximately 10 m of the water surface and had abundant live hardcorals observed from the deck of the vessel, however, neither reef was sampled by video or grab sample and so were excluded from statistical analysis.

The non-metric, multi-dimensional scaling (MDS) ordination plots of square root-transformed percentage megabenthos occurrence data in Tables 4.1 and 4.2 show distinct groups of samples. In Area A (Fig. 4.5A), dense mixed gardens of softcorals, sponges and sea whips occur only on the limestone knolls observed at Stations 4, 14 and 18, with the latter two stations also having bioturbate due to flat seabed also being in the transects. Station 12 has no bioturbation and only softcorals, and appears dissimilar compared to the other stations. In contrast, the majority of stations in Area A are grouped together showing a similar high bioturbate assemblage, reflecting the presence of abundant infauna in the muddy sand. The MDS plot for megabenthos in Area B (Fig. 4.5B) shows a group of mixed garden assemblage at Stations 29, 37 and 40, which were sampled over the relict reefs. Softcorals dominate at Stations 44 and 34, obtained on the relatively steep valley sides. Fig. 4.5B shows a group of the remaining stations as predominantly sparse fauna. These stations included the infilled channel sites, active dune field, valley floors and on the extensive platforms.

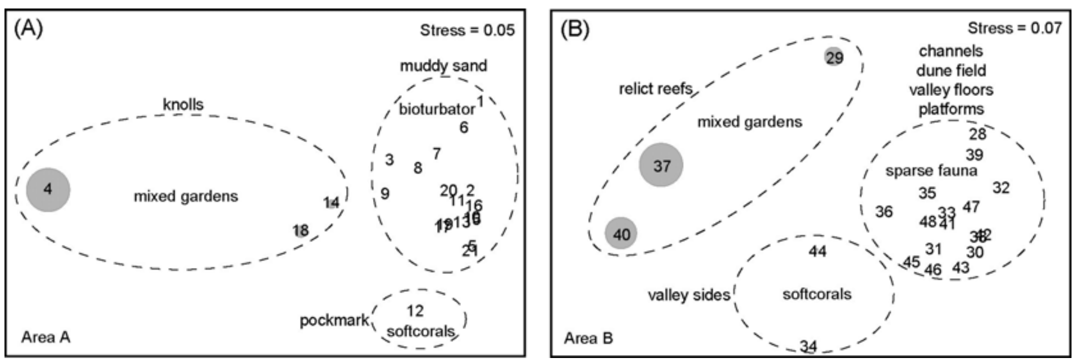

Fig. 4.5 Two dimensional ordination plots using non-metric multi-dimensional scaling (MDS) on Table 4.1 and Table 4.2 megabenthos data, showing circles of the relative size of mixed garden percentage at sites. (A) Area A transects are clustered into three groups: mixed gardens, softcorals, and predominantly bioturbator. (B) Area B transects are clustered into three groups: mixed gardens, softcorals, and predominantly sparse fauna.

4.3.3 Environmental variables

Tables 4.3 and 4.4 show the environmental data for Areas A and B respectively. In Area A, slope ranged from nearly 0º to 3º, highlighting the generally flat study area. Gravel percentage ranged from approximately 2% to as high as 70% (Fig. 4.6A). Total calcium carbonate varied from 37% to 92%. In Area B, slope varied from nearly 0º to over 11º, reflecting an increase in relief and gradient compared to Area A. Gravel percentage ranged from less than 1% to nearly 32% (Fig. 4.6B). The total calcium carbonate ranged from approximately 34% to greater than 95%.

Station number	Depth (m)	Slope (º)	Gravel weight (%)	Sand weight (%)	Mud weight (%)	Gravel CaCO3 (%)	Sand CaCO3 (%)	Mud CaCO3 (%)	Total CaCO3 (%)	Temp (ºC)	Salin (psu)	Trans (%)
1	29.66	0.11	2.92	77.76	19.32	95.00	47.00	13.00	41.83	28.32	34.51	83.66
2	28.60	0.17	2.68	63.66	33.66	95.00	63.00	9.00	45.68	28.94	34.45	83.42
3	27.13	0.38	18.33	55.84	25.83	60.00	75.00	14.00	56.49	28.86	34.49	83.87
4	22.27	2.91	69.60	26.73	3.68	97.50	89.00	12.00	92.09	28.93	34.48	83.10
5	32.50	1.25	3.03	62.18	34.79	95.00	70.00	12.00	50.58	28.91	34.46	81.21
6	27.90	0.26	5.45	73.74	20.81	75.00	70.00	14.00	58.62	28.93	34.44	81.24
7	32.37	0.32	2.53	71.80	25.66	95.00	75.00	15.00	60.11	28.85	34.46	83.62
8	31.42	0.37	2.09	83.26	14.65	85.00	63.00	22.00	57.45	28.77	34.51	85.21
9	30.72	0.19	4.93	83.10	11.97	85.00	60.00	21.00	56.56	28.70	34.53	85.66
10	31.65	0.28	3.98	80.22	15.80	90.00	63.00	23.00	57.75	28.72	34.53	85.56
11	31.85	0.15	9.77	72.27	17.97	85.00	57.00	17.00	52.55	28.56	34.56	84.60
12	32.72	2.33	18.13	75.05	6.83	95.00	88.00	18.00	84.49	28.44	34.58	81.72
13	30.96	0.61	3.77	77.59	18.64	90.00	56.00	14.00	49.45	28.27	34.61	81.21
14	29.32	2.33	7.52	82.56	9.92	85.00	73.00	14.00	68.05	28.24	34.62	78.70
15	30.04	0.07	2.73	77.28	19.99	90.00	68.00	16.00	58.20	28.51	34.58	81.27
16	28.23	0.15	8.73	64.08	27.19	70.00	61.00	12.00	48.46	28.65	34.55	82.46
17	28.88	0.49	5.20	62.42	32.38	85.00	68.00	9.00	49.78	28.79	34.52	79.53
18	27.55	2.72	5.81	82.75	11.45	95.00	81.00	10.00	73.69	28.84	34.51	77.25
19	28.71	0.11	3.86	52.91	43.23	95.00	61.00	7.00	38.97	29.07	34.37	65.75
20	27.50	0.31	2.50	53.19	44.31	90.00	61.00	6.00	37.36	29.14	34.33	71.26
21	28.14	0.05	1.98	64.41	33.61	95.00	59.00	7.00	42.23	29.15	34.31	77.67

Table 4.3 Environmental data for Area A. See Fig. 4.2 for locations.

Station number	Depth (m)	Slope (º)	Gravel weight (%)	Sand weight (%)	Mud weight (%)	Gravel CaCO3 (%)	Sand CaCO3 (%)	Mud CaCO3 (%)	Total CaCO3 (%)	Temp (ºC)	Salin (psu)	Trans (%)
28	51.08	0.87	5.92	64.61	29.47	75.00	67.00	77.00	70.42	27.78	34.81	86.68
29	38.93	8.74	22.83	74.12	3.05	97.50	96.00	75.00	95.70	27.83	34.81	88.42
30	48.01	0.43	6.32	84.89	8.79	90.00	57.00	80.00	61.11	27.66	34.83	88.98
31	46.46	2.27	5.31	84.32	10.37	80.00	89.00	77.00	87.28	27.69	34.86	90.02
32	128.64	1.83	0.25	73.61	26.15	97.50	63.00	76.00	66.48	27.60	34.88	89.19
33	46.86	0.96	5.77	82.57	11.66	60.00	63.00	76.00	64.34	27.66	34.87	89.88
34	83.02	11.54	27.57	55.54	16.89	55.00	78.00	76.00	71.32	27.72	34.85	89.41
35	100.31	0.28	5.70	74.07	20.23	80.00	62.00	67.00	64.04	27.67	34.82	88.29
36	81.03	11.08	23.04	55.31	21.64	65.00	47.00	63.00	54.61	27.67	34.86	90.28
37	144.89	4.22	31.90	65.49	2.60	95.00	91.00	70.00	91.73	27.73	34.89	89.87
38	50.70	3.44	1.16	96.58	2.26	90.00	21.00	63.00	22.75	27.61	34.91	88.27
39	53.23	1.84	3.27	83.98	12.75	75.00	37.00	63.00	41.56	27.53	34.92	87.02
40	51.45	6.19	22.35	60.58	17.07	75.00	75.00	63.00	72.95	27.55	34.93	86.59
41	51.82	4.67	7.37	78.88	13.75	40.00	41.00	24.00	38.59	27.57	34.93	88.74
42	72.82	5.79	25.69	52.00	22.31	70.00	35.00	66.00	50.91	27.55	34.91	88.96
43	75.37	2.67	4.39	75.12	20.49	70.00	64.00	60.00	63.44	27.50	34.94	89.70
44	86.31	9.82	13.80	66.53	19.67	75.00	38.00	47.00	44.88	27.51	34.93	89.65
45	88.37	2.09	1.39	80.37	18.23	60.00	49.00	42.00	47.88	27.59	34.93	90.81
46	58.02	1.16	7.50	81.27	11.23	80.00	51.00	54.00	53.51	27.45	34.91	89.83
47	51.96	1.35	3.50	91.36	5.14	70.00	32.00	54.00	34.46	27.37	34.90	89.25
48	51.66	0.09	7.40	76.47	16.13	85.00	60.00	59.00	61.69	27.45	34.88	89.57

Table 4.4 Environmental data for Area B. See Fig. 4.2 for locations.

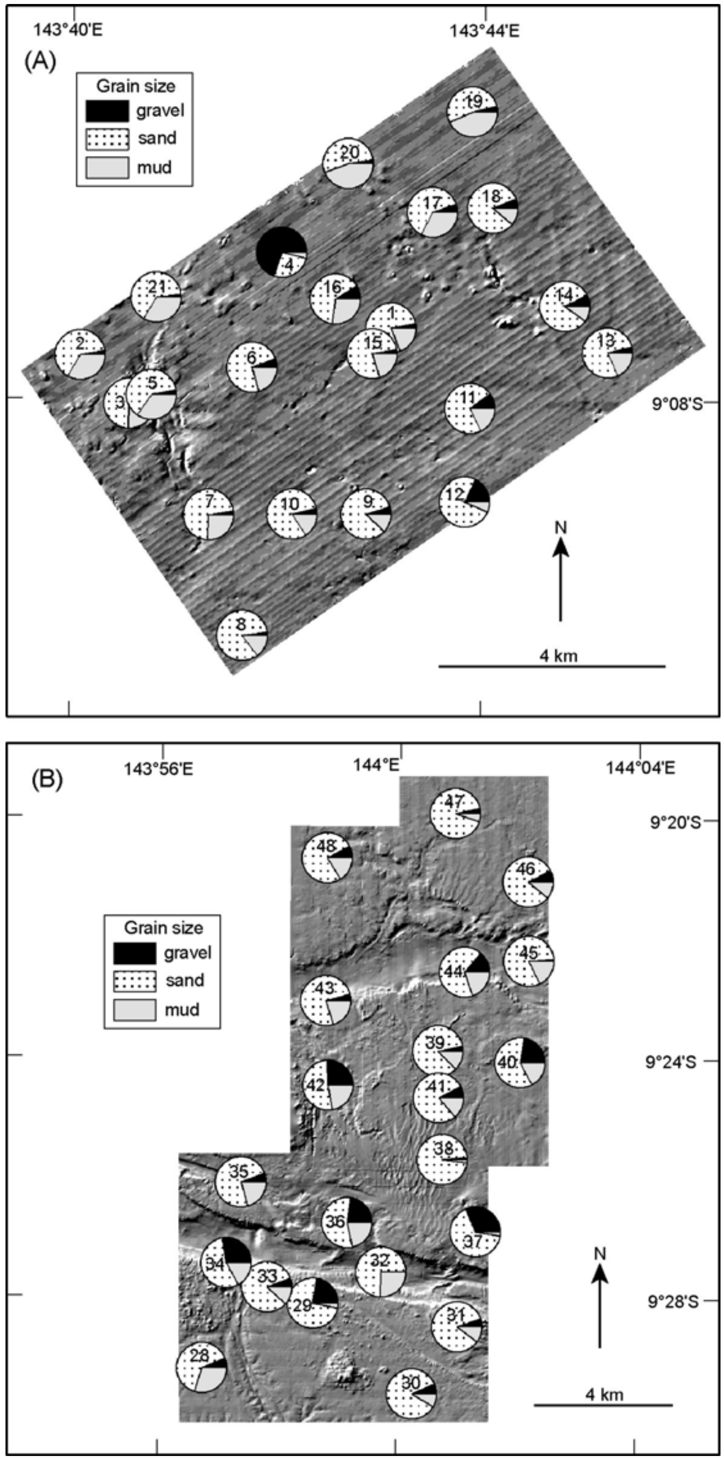

Fig. 4.6 Gravel, sand and mud weight proportions from grab samples. (A) Area A. (B) Area B. Numbers refer to station numbers in Tables 4.3 and 4.4. There is a pattern of higher gravel proportions in samples obtained from low-relief limestone and pockmarks in Area A; and relict reefs, valley sides and channels in Area B.

Ordination plots of principal component analysis (PCA) on the untransformed environmental descriptors in Tables 4.3 and 4.4 show distinct groups of similarity. In Area A (Fig. 4.7A), a group of Stations 4, 12, 14 and 18 shows relatively higher slope and were obtained at knoll and pockmark sites. A second group of the remaining stations were obtained from the predominantly flat muddy sand of Area A. In Area B (Fig. 4.7B), there are three groups of similarity. One group, with relatively high slope are the relict reef samples at Stations 29, 37 and 40. Another group of relatively high slope are the valley sides and adjacent channel samples at Stations 34, 36, 42 and 44. The remaining stations are grouped into samples obtained from the predominantly flat platforms, dune field and valley floors.

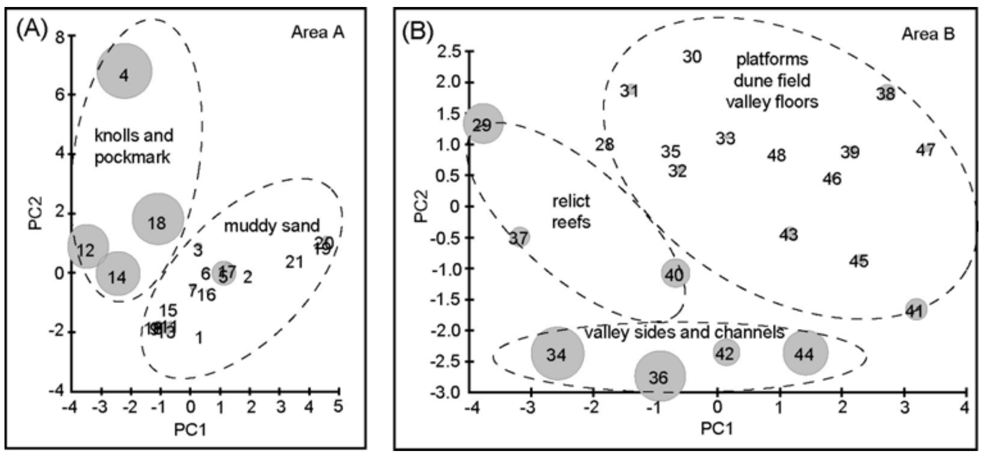

Fig. 4.7 Ordination plots of principal component analysis (PCA) using Euclidean distance on Table 4.3 and Table 4.4 environmental data, showing circles of the relative size of slope at each station. (A) Area A variables are clustered into two groups: knolls and pockmarks; and muddy sand. (B) Area B variables are clustered into three groups: relict reefs; valley sides and channels; and platforms, dune field and valley floors.

4.3.4 BIO-ENV procedure

To explore the subset of environmental variables which best matches the observed megabenthos patterns in Area A, the BIO-ENV procedure was applied to the biotic data in Table 4.1 and abiotic data in Table 4.3. Reducing the environmental variables to a manageable subset of three, the best combination is slope, gravel weight and sand $CaCO_3$ at a Spearman Rank correlation of 0.747. For Area B, the BIO-ENV procedure on biotic data in Table 4.2 and abiotic data in Table 4.4 results in a best combination of slope, gravel weight and transmission at a Spearman Rank correlation of 0.62. Both correlation coefficients are relatively high (1.0 would be a perfect match) suggesting that these subsets of abiotic variables are good matches for the patterns of megabenthos assemblages observed in the MDS plots of Fig. 4.5.

Of interest in the BIO-ENV results is the inclusion of the environmental variables, slope and gravel weight, from both survey areas despite the obvious contrast in marine landscapes. The relatively high correlations indicate that these two environmental variables, slope and gravel weight, are potentially useful as predictors for megabenthos assemblage patterns in this study. For example, sites with high slope and gravel weight values appear to correlate with the presence of relatively dense mixed gardens of softcorals, sponges and sea whips on both the knolls of limestone in Area A and the relict reefs in Area B. Sites with low slope and gravel weight values correlate with bioturbated muddy sand in Area A and the sparse fauna on the platforms, dune field and valley floors in Area B.

4.3.5 Secondary Biotopes and Biological Facies

Through an examination of the patterns of the megabenthos assemblages and environmental variables, the results of the BIO-ENV procedure and in conjunction with models of the geomorphology and bathymetry, Area A was divided into three Secondary Biotopes and three Biological Facies at the site (<10 km) scale, showing a high correlation between the predominant substrate and the types of biological assemblages associated with this substrate (Fig. 4.8A). Area B was divided into four Secondary Biotopes and four Biological Facies, and includes the live reefs observed, but not sampled for quantitative analysis (Fig. 4.8B). We believe the spatial boundaries of these units reflect the patterns observed using the available datasets, and are consistent within the context and scales of the hierarchical habitat classification scheme of Butler et al. (2001).

The construction of these maps was assisted by raster reclassification of the high-resolution bathymetric and slope models using GIS. For instance, an examination of the histograms of slope and depth grid values found that the limestone knoll features in Area A were greater than 1º slope and less than 4 m above the surrounding seabed. The relict reefs of Area B were greater than 4º slope and generally over 4 m above the surrounding seabed. Therefore, reclassification of the slope and depth raster grids using these limits highlighted the exact boundaries of these significant geomorphic features. A description of each Secondary Biotope and the corresponding Biological Facies is given for each survey area. Conceptual model diagrams of the association between the Secondary Biotopes and Biological Facies of Areas A and B are shown in Fig. 4.9.

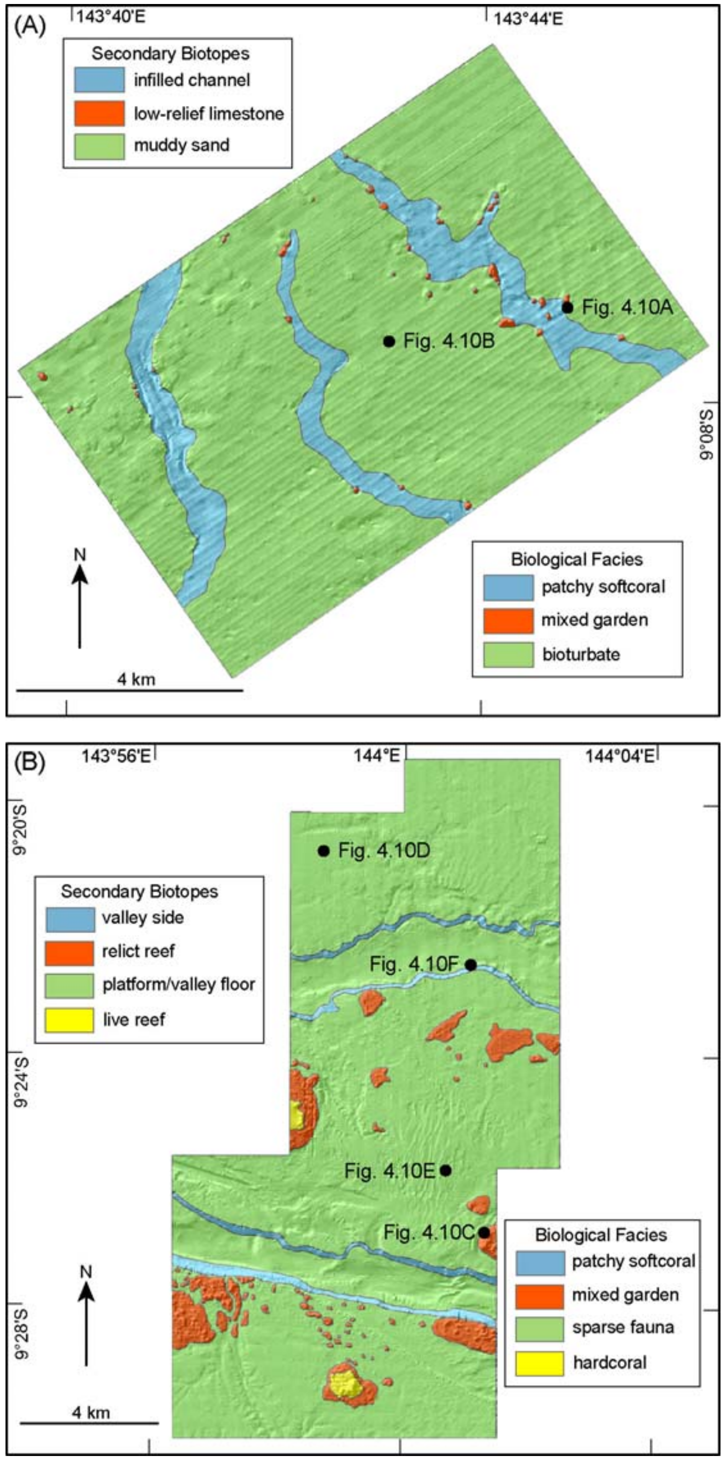

Fig. 4.8 Secondary Biotopes and Biological Facies of the study areas. (A) Area A. (B) Area B. Note the positions of the underwater video images in Figs. 4.10A, B, C, D, E and F.

4.3.5.1 Area A - 'low-relief limestone' and 'mixed garden'

The 'low-relief limestone' Secondary Biotope stands out from the predominantly flat distal-delta zone as numerous (at least 30) small knolls. There is a distinct pattern of knolls located along the edges of the shallow infilled channels. Even channels filled and showing little seabed surface expression had knolls located at the edges, confirming the strong link between the knolls and palaeochannels. The low-relief features are interpreted to be relict Pleistocene deltaic deposits (Harris et al., 2005), and may have originally been levee banks deposited while draining the Fly River during lower sea-levels. After transgression, the levee banks were drowned and compacted into a hard limestone substrate, and the scattered knolls are now the eroded remnants of these levees. Underwater video reveals a 'mixed garden' Biological Facies strongly associated with this biotope (Fig. 4.10A). The hard substrate has a structurally complex surface with overhangs and small crevices. Dense fauna covered the limestone knolls and comprised a mixed garden of fan-shaped sponges, gorgonian fan corals, large bushy softcorals and sea whips. The knolls also provide favourable habitats for reef- and rocky bottom-dwelling fish such as invertebrate/fish-feeding soldierfish and cod (Randall et al., 1990).

4.3.5.2 Area A - 'infilled channel' and 'patchy softcoral'

The 'infilled channel' Secondary Biotope represents the three palaeochannels which trend across Area A. They are similar to palaeochannels observed elsewhere on the distal-delta that once drained part of the Fly River (Crockett et al., 2005). Surficial sediments in the channels are a dark grey muddy sand with calcareous gravel similar to the predominantly flat seabed either side of the channels (Harris et al., 2002). However, the present study found localised pockmarks closely associated with the knolls and channels, and surficial sediment that became relatively coarser. The 'patchy softcoral' Biological Facies is named after the occasional small bushy softcoral observed in pockmarks. Because of the lack of bioturbation and increase in gravel content compared to the surrounding flat muddy sand, we interpret the pockmarks are the result of near-seabed currents, inducing a local bottom-stress maxima and associated zone of bottom scour around the knolls. In this area, tidal currents up to approximately 50 cm sec^{-1} were observed during the duration of the survey (Harris et al., 2002). The current scour around the knolls and channel edges favours suspension-feeding sessile fauna over deposit-feeding infauna.

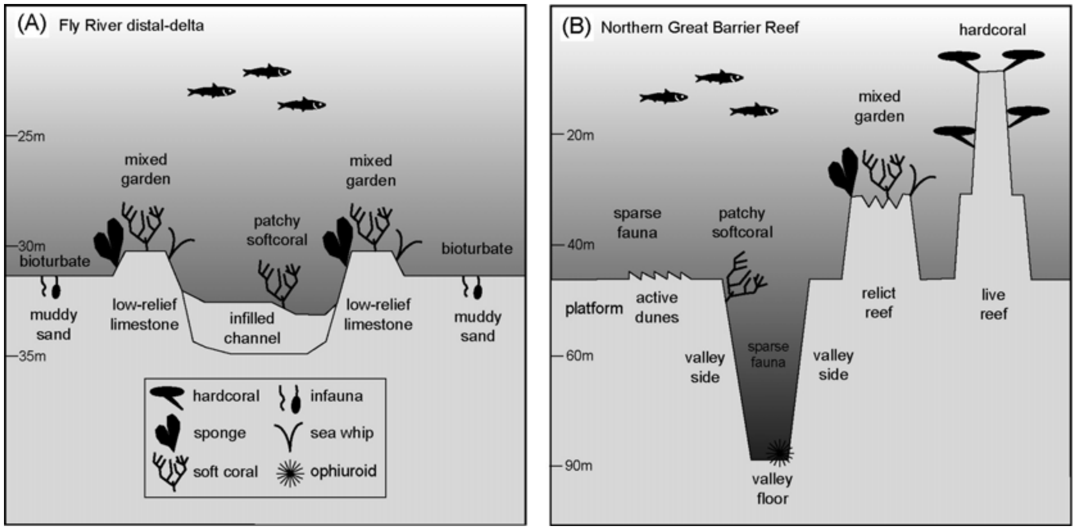

Fig. 4.9 Conceptual model diagrams of the association between the Secondary Biotopes and Biological Facies. (A) Area A on the Fly River distal-delta. (B) Area B on the northern Great Barrier Reef shelf.

4.3.5.3 Area A - 'muddy sand' and 'bioturbate'

The majority of Area A is a 'muddy sand' Secondary Biotope. The seabed is predominantly flat, interrupted only by the presence of low-relief limestone knolls and the infilled channels. Surficial sediments are dark grey muddy sand with calcareous gravel. The mud content is highest in the northern corner and generally decreases to the east and south, reflecting the Fly River delta as the source of terrigenous material (Harris et al., 2002). The 'bioturbate' Biological Facies is strongly associated with this habitat, showing moderate to abundant burrows and mounds as evidence of an environment favouring infauna (Fig. 4.10B). An earlier survey on the inner to middle shelf of the Gulf of Papua using a variety of cores found that the macroinfauna was dominated generally by small seabed surface deposit-feeding polychaetes, followed by amphipod crustaceans (Aller and Aller, 2004). The presence of relatively high bioturbation seaward of the Fly River delta clinoform is also consistent with the bioturbation observations of Alongi et al. (1992) and Walsh et al. (2004). Sessile fauna, such as small softcorals and tube sponges, are present but were few in number in comparison to a seabed dominated by deposit-feeding infauna.

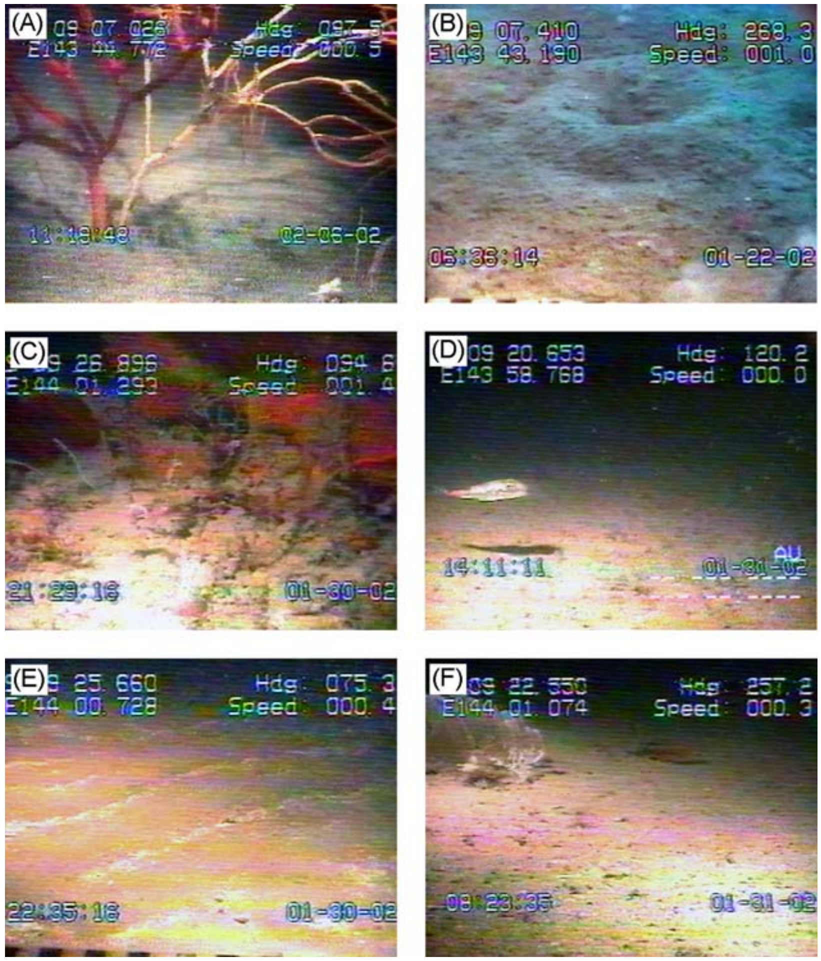

Fig. 4.10 Underwater video images of the study areas. (A) Area A softcorals on low-relief limestone knolls. (B) Area A infaunal burrows in muddy sand. (C) Area B dense mixed gardens of softcoral on relict reef. (D) Area B sparse fauna on platform. (E) Area B ripples on active dunes. (F) Area B patchy softcoral on valley side. See Fig. 4.8 for locations.

4.3.5.4 Area B - 'relict reef' and 'mixed garden'

The 'relict reef' Secondary Biotopes of Area B were a surprising discovery in this study. They appear as numerous (at least 50) submerged reefs of various sizes across the southern and central platforms. Underwater video reveals a structurally complex surface with high-relief and karst-type erosion into holes and caves. The 'mixed garden' Biological Facies is strongly associated with this habitat. The limestone provides a hard stable substrate for the attachment of a dense mixed garden comprising softcorals, sponges and sea whips (Fig. 4.10C). It is interesting that the dense softcoral is now mostly found on the relict reefs because these were once sites of hardcoral growth when sea-level was between 30 to 42 m below present sea-level, which is the approximate range of upper surface depths. An examination of the eustatic sea-level curve over the past 140 kyr BP (Pillans et al., 1998; Lambeck and Chappell, 2001), reveals a sea-level at or less than 30 to 42 m below present sea-level for approximately 38 kyr during

the last glacial/interglacial cycle, when hardcorals may have lived. When sea-level dropped more than 42 m below present sea-level (approximately 90 kyr of the past 140 kyr BP) reefs would be exposed to karst-type erosion. When eustatic sea-level rose through the Holocene, reef growth lagged the rapid rate of sea-level rise, growth ceased and the reefs drowned (i.e. 'give-up reefs'; Neumann and MacIntyre, 1985).

4.3.5.5 Area B - 'live reef' and 'hardcoral'

In Area B, two unnamed 'live reef' Secondary Biotopes were mapped in the west-central platform and in the centre of the southern platform. The seabed rises nearly to the water surface and was clearly associated with a 'hardcoral' Biological Facies, typical of fauna found on other northern Great Barrier Reef platform reefs (Veron, 1993). Bathymetric data shows that these live reefs rose from the upper surfaces of relict reefs. The limited extent of the live reefs in comparison to the relict reefs show that only two live coral reefs were able to grow and track Holocene sea-level rise, or later catch-up to the water surface (i.e. 'keep-up' and 'catch-up reefs' respectively; Neumann and MacIntyre, 1985). The majority of Torres Strait platform reefs grow on an antecedent foundation of Pleistocene reefs (Davies et al., 1989; Woodroffe et al., 2000), and further dating of coral framework from the relict and live reefs is required to establish the exact timing of reef growth or demise.

4.3.5.6 Area B - 'platform/valley floor' and 'sparse fauna'

The majority of Area B is the 'platform/valley floor' Secondary Biotope, which is predominantly flat and divided by some of the deepest submarine valleys found on the northeast Australian shelf (Harris et al., 2002). Surficial sediments on the platforms range from gravelly muddy sands to gravelly sands, and a moderate to high carbonate content in the mud fraction, showing a gradual increase from the north to south platforms (Harris et al., 2002). A localised variation in surficial sediments on the central platform occurs in the active dune field. Surficial sediments are slightly gravelly sand, with a lack of mud, indicating winnowing of finer-grained sediments by relatively stronger currents in this area (Fig. 4.10E). This biotope also includes the predominantly undulating to flat valley floors, and surficial sediments are slightly gravelly, muddy sand. The increased depth reflects a slight increase in mud content compared to the relatively shallower platforms. The 'sparse fauna' Biological Facies corresponds with this predominantly flat habitat. Underwater video reveals a seabed with sparse sessile benthos, with the occasional individual small bushy softcoral (Fig. 4.10D). Mobile fauna were mostly ophiuroids and echinoids. In contrast to the high bioturbation in Area A, the platforms of Area B show limited mounds or burrows.

4.3.5.7 Area B - 'valley side' and 'patchy softcoral'

Thin, linear 'valley side' Secondary Biotopes are found on the sides of the two limbs of the Darnley Valley and show a high gradient environment. Underwater video reveals the seabed to have abundant cobbles and boulders scattered on the gravelly sand, presumably as a result of debris flows down the steep slope of the valley sides. The 'patchy softcoral' Biological Facies is clearly associated with this habitat as moderate to abundant large softcorals and sea whips are attached to the cobbles and boulders (Fig. 4.10F). The preference for soft fauna on the valley sides may also be due to the Coral Sea water upwelling through the deep shelf valleys and these suspension-feeders taking advantage of the increased nutrients and food particles.

4.4 Discussion

This study has shown a quantitative association between geophysical data from seabed habitats and the biological communities which depend on these habitats. Such findings are helpful when asking whether geophysical data can be used to predict the occurrence of benthic biodiversity, particularly with the increase in Marine Protected Areas as tools for marine conservation. In this study, the geophysical variables, slope and gravel weight, were highlighted as useful predictors for megabenthos assemblages, and in conjunction with models of the geomorphology and bathymetry, were used to derive the spatial boundaries of benthic habitats at the site (<10 km) scale. These findings add confidence to the use of abiotic or geophysical factors, such as geology, sediment and high-resolution geomorphology, as predictors for benthos distribution and thus provide a basis for reserve selection. We recommend that future studies be conducted which prioritise the collection of these geophysical variables, to explore whether they are potentially useful as universal predictors or are relevant only to the northern Great Barrier Reef - Gulf of Papua region under study.

4.4.1 Limitations of BIO-ENV procedure

It should be noted that the use of the BIO-ENV procedure is best thought of as an exploratory tool, and that more detailed statistical analyses (beyond the scope of this study) are required to accurately assess how well biological community data are predicted by environmental variables. However, within this study, slope and gravel weight distribution alone provided a useful 'first cut' approximation of megabenthos patterns. An important consideration for the use of gravel weight as a predictor of megabenthos assemblages is the sampling density of the sediment samples. In the present study, a high density of groundtruth sites across the study areas resulted in gravel data points located for comparison against every underwater video transect. Sediment samples are rarely collected at such high densities, and so an interpolation of widely-spaced

gravel data points, in order to derive a map of the gravel content of the seabed, is therefore unlikely to correlate well to the patchy distribution of megabenthos. Ideally, sediment grabs should be collected at a density which matches the scale of the geomorphic feature being investigated and co-located with optical groundtruthing sites.

Another limitation in the use of the BIO-ENV procedure was the low resolution of the biological data. With the biological variables restricted to broad megabenthos categories, Bray-Curtis similarities could only detect gross variations between assemblages. Yet, the variation between biological assemblages was sufficient to confidently predict the spatial distribution of assemblages, when related to the 5 m horizontal resolution of the underlying slope and depth grids. These results show that it is not necessary to categorise benthos to genus and species for Bray-Curtis similarity coefficients when the spatial distribution of broad assemblages over these scales is quite sufficient. An additional limitation for the BIO-ENV procedure was the horizontal resolution of the important slope and depth grids. Ideally, for the slope and depth data to be of use for comparison against the biological data observed in the relatively short video transects, they should be at the highest resolution possible. Reducing these slope and depth grids to lower resolution, say 10 m and larger, would decrease the effectiveness of the BIO-ENV procedure to detect similarities between biotic and abiotic datasets.

4.4.2 Geology-benthos relationships

The results of this study reinforce knowledge of the contrast between biological assemblages living on hard substrate and those in soft unconsolidated substrate. In the present study, there is a pattern of zooxanthellate hardcorals within the photic zone and suspension-feeding softcorals on hard substrate features, compared with detritus- and deposit-feeding fauna, such as echinoderms, crustaceans and polychaetes, on soft unconsolidated sediment. The variation in substrate is therefore an important factor in controlling the distribution of biological communities. Finer-scale positive bathymetric features are also known to influence hydrodynamic processes, whereby the complex seabed surfaces interferes with current flow patterns to increase water turbulence and enhance particle capture by benthic suspension feeders (Gili et al., 2001). The dense cover of suspension-feeders on the limestone knolls and relict reefs suggests that the availability of food particles is sufficiently high within the near-seabed currents passing over these seabed habitats to support such a rich and colourful sessile fauna. Table 4.5 is a summary of area (km^2) and percentage of the Secondary Biotopes in Areas A and B. Given the strong relationship between the mixed garden assemblage and low-relief limestone or any hard substrate feature projected above the surrounding seabed in Area A, it is likely that the area of low-relief limestone at 0.54% is an underestimate. This small percentage of

limestone knolls belies the fact that even in this predominantly flat deltaic zone, life does thrive, albeit in small patches associated with hard substrate. The strong association between low-relief limestone knolls and the mixed gardens of sessile fauna on the distal-delta adds to knowledge of the fate of buried river channels in tropical shelf environments (Johnson et al., 1982; Woolfe et al., 1998; Fielding et al., 2003; Crockett et al., 2005). In Area B, the hard substrate is limited primarily to the relict limestone reefs and live reefs. It is worth noting that the surface area of the relict reefs is over an order of magnitude greater than the area of live reefs surveyed (6.18% versus 0.53%), and suggests that the development of coral reefs in the northern Great Barrier Reef was more extensive in the past. Similarly, the strong relationship between sessile soft fauna and relict reefs contributes to a greater understanding of the fate of drowned reefs (MacIntyre, 1972; Adey et al., 1977; Lightly et al., 1978; Vora and Almeida, 1990; Grigg et al., 2002; Harris et al., 2004a).

Area A Secondary Biotopes	Area km^2 (%)
infilled channel	9.24 (13.64)
low-relief limestone	0.37 (0.54)
muddy sand	58.13 (85.82)
total	*67.74 (100)*
Area B Secondary Biotopes	**Area km^2 (%)**
live reef	0.88 (0.53)
platform/valley floor	148.02 (89.51)
relict reef	10.22 (6.18)
valley side	6.24 (3.77)
total	*165.36 (100)*

Table 4.5 Area in km^2 (percentage) for the Secondary Biotopes of Areas A and B.

In the present study, the spatial boundaries between unconsolidated soft substrate habitats and their associated biological assemblages is not as sharp as the boundaries between hard substrate features and the associated dense sessile benthos. Yet there are distinct patterns unique to each area which relate to physical processes in addition to substrate type. On the inner shelf, distal deltaic zone, the predominantly flat seabed is the preferred habitat of deposit-feeding infauna within the muddy sand. Localised variations in this relationship occur with the presence of shallow pockmarks, possibly due to near-seabed currents scouring around knolls bordering the palaeochannels, similar to the scour pits found around shipwreck obstacles (Stride, 1982). The pockmarks are the preferred habitat of suspension-feeding softcoral at the expense of deposit-feeding infauna, therefore the dominant process is believed to be an increase in current strength on the seabed at this finer-scale.

On the mid-shelf, incised valley zone, the unconsolidated soft substrate of the extensive platforms and valley floors are the preferred habitat of sparse sessile fauna. The presence of the active dunes and ripples between the two shelf valleys, points to strong near-seabed currents as the dominant process controlling benthos in the dune field. In this case, high disturbance by mobile sand over a large area would be an important limiting factor to settlement by sessile benthos or infauna maintaining burrows, and is likely to favour mobile infauna such as errant polychaetes, heart urchins and sand-dwelling molluscs. The relative increase in sessile benthos on the valley sides may be a function of both a suitable substrate and upwelling Coral Sea water flowing through the valleys, taking advantage of an increased supply of food particles. In contrast to the valley sides, the flat valley floors were much reduced in sessile biota. No boulders or cobbles were observed on the seabed. The environment is relatively constant with little light and with reduced disturbance as the near-seabed currents decrease with depth. This habitat appears to favour detritus-feeding echinoderms over suspension-feeders. These physical processes are consistent with the observation by Aller and Aller (2004) that sedimentary dynamics and physical processes related to near-seabed currents, in addition to substrate type, appear to be a dominant control on the benthic communities in the northern Great Barrier Reef - Gulf of Papua region.

4.4.3 Assessment techniques

The utility of high-density bathymetric data to image the seabed points to a new age of discovery of the oceans. Full ensonification of the seabed by multibeam sonar presents us with an unprecedented view of the true nature of the morphology of the seafloor and the variation in seabed sediment texture (Kostylev et al., 2001). In addition, the ability to overlay a wide variety of physical and biological datasets as models using GIS now provides us with new insights to interpret the structure of benthic habitats and the processes influencing these patterns. The capability to examine the seabed as a 3D digital terrain model at high-resolution is invaluable as other GIS models can then be draped and viewed at different scales of resolution and viewed at any angle. Where once we saw contours, we now see complexity. And the complexity of the seabed, revealed by multibeam sonar, is the key to making links between the benthos and the dominant processes affecting the distribution. Because many benthic habitats are defined by substrate (sediment or rock), the new generation of bathymetric and geological maps derived from multibeam sonar provide a framework for remotely mapping the distribution of benthos or to accurately target distinct geomorphic features for groundtruth sampling (Greene et al., 1995; Kostylev et al., 2001).

The assessment techniques used in this study are recommended for future surveys requiring benthic habitat mapping. In priority, multibeam sonar data, with co-registered sidescan, is the most useful remote-sensed acoustic data. It produces high-resolution bathymetric and backscatter models to reveal geomorphology and sediment textural attributes of the seabed. Slope models, derived from bathymetry, are shown to be quite useful as predictors of megabenthos assemblage patterns. Another recommended remote-sensed acoustic technique is a sub-bottom profiler, in order to put into geological context the morphology of the seabed. As shown in this study, the events of the geological past have a profound influence on the present seabed, and an understanding of the long-term processes on a geological scale which have controlled the form of the seabed are very useful for interpreting benthic habitats.

Seabed groundtruthing priorities include optical techniques such as video, followed by physical sampling using sediment grabs, cores or water sampling devices. Single long video transects can give an indication of the composition and spatial arrangement of megabenthos on the seabed, which may be quite patchy. Sediment grabs and cores cannot provide the sampling area to discriminate megabenthos assemblages at this scale, and other than gravel weight as a potential proxy, are probably more useful to help describe the environment of deposition. Similarly, oceanographic variables such as temperature and salinity, which vary over broader-scales, are probably more useful to help describe the hydrodynamic environment. The combination of both acoustic seabed classification methods and optical and physical groundtruthing is very effective in delineating the spatial patterns of seabed habitats and their associated biological assemblages.

4.5 Conclusion

This chapter described the physical environment and megabenthos assemblage patterns of two study areas on the Fly River distal-delta and northern Great Barrier Reef of Australia. We utilised multibeam sonar and a sub-bottom profiler data, and then collected underwater video footage and grab samples at selected sites. Multivariate statistical analysis (cluster, multi-dimensional scaling and BIO-ENV procedure) of the physical and biological datasets from both areas, determined that the geophysical variables, slope and gravel percentage, were the most useful predictors for megabenthos assemblage patterns. In this chapter, we gave the slope and gravel percentage models priority for overlay in a GIS, and in conjunction with models of the geomorphology and bathymetry, derived maps of the Secondary Biotopes and Biological Facies using the Butler et al. (2001) benthic habitat classification scheme. By characterising the seabed at the Secondary Biotopes and Biological Facies levels we gain a better understanding of the association between the physical environment and the megabenthos assemblage patterns of the two study areas at the site (<10 km) scale.

The variation in substrate was an important factor in controlling the distribution of biological communities in the study areas. Hard substrate habitats in both areas were associated with a dense and colourful sessile fauna of predominantly suspension-feeders. Soft substrate on the inner shelf, distal deltaic zone, was the preferred habitat of deposit-feeding infauna. Shallow pockmarks, possibly due to near-seabed currents scouring around low-relief limestone knolls, were the preferred habitat of sessile suspension-feeders. On the mid-shelf, incised valley zone, the unconsolidated soft substrate was the preferred habitat of sparse sessile fauna. A relative increase in suspension-feeding sessile fauna on the steep valley sides may be a function of both a suitable substrate and upwelling Coral Sea water flowing through the valleys. The combination of substrate type, sedimentary dynamics and physical processes related to near-seabed currents appear to be a dominant control on the benthic communities in the northern Great Barrier Reef - Gulf of Papua region. We recommend future surveys combine high-resolution acoustic methods with optical assessment techniques to delineate seabed habitats and their associated biological assemblages.

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Chapter 5 Conclusions

5.1 Key findings in terms of the project objectives

The objectives for this project were to: (1) define the physical environment of the study sites using GIS maps of geomorphology, surficial sediments and near-seabed oceanography; (2) discriminate assemblages of macrobenthos through the use of multivariate statistical analysis where possible; and (3) explore the possible relationships between the geophysical environment of the seabed and the associated biological communities. The following paragraphs summarise the key findings in terms of these objectives.

5.1.1 Physical environment of the study sites

Habitat can be defined as spatially recognisable areas where the physical, chemical and biological environment is distinctly different from surrounding environments (Kostylev et al., 2001). This definition places emphasis on benthic habitats which can be readily mapped using remotely-sensed geophysical techniques, such as used in this project. The identification of representative habitats using oceanographic and physiographic characteristics is a vital first step in developing hierarchical classifications of ecosystems for marine conservation and management (Roff and Taylor, 2000). This project has revealed a variety of physical variables which describe seabed environments at the local (10s of km) scale - polar case study, and site (<10 km) scale - temperate and tropical case studies. Further, these study areas were conducted in vastly different physical environments. Unique physical factors for the George V Shelf were the very deep continental shelf and the impact of glacial and sea ice. New Zealand Star Bank lies within the influence of seasonal storm events and has a varied geological history which includes aeolian dune systems. The northern Great Barrier Reef - Gulf of Papua survey is within a climatically-stable region but which is influenced by wind-induced currents and ocean upwelling. The geological history is also distinct with palaeochannels and relict reefs. As geophysical processes were used as surrogates for habitat, a challenge for this project was to find the processes which have a natural range of variation within the scale of observation.

The broad-scale and remoteness of the George V Shelf study necessitated remotely sensed imagery to locate icebergs, ice shelf boundaries and sea ice variation from winter to summer. These features were mapped in GIS with the existing bathymetric model to highlight the likely areas of grounded icebergs and Mertz Glacier Tongue across the approximately 130 km wide shelf. Within the limits of our present knowledge, the general flow of shelf surface and bottom

currents were also mapped. The low-resolution bathymetric model, with a grid size of approximately 110 m, was supplemented with multibeam sonar data to discern the ruggedness of the inner shelf submarine canyons and megascale lineations along the axis of the basin. The bathymetric model and results of extensive sub-bottom profiling were the basis for the geomorphic features recognised on the shelf. Due to the difficulty in sampling the benthos over such as wide area, it was important to map the surficial sediment in order to characterise the sedimentary environment and relate it to the limited biological samples. The use of GIS was very useful to interpolate grain size data and show the general variation of gravel, sand and mud, then to derive a sediment classification over the shelf. Similarly, the distribution of the near-seabed oceanographic variables, temperature and salinity, defined the spatial boundaries of water masses, highlighting the seasonal flux in water masses over the shelf.

The New Zealand Star Bank case study was a smaller survey of approximately 7 x 14 km in extent. Primarily a multibeam bathymetric survey, the 100% seafloor coverage at a grid size of 5 m, revealed the structurally complex, high-relief granite outcrops, and the subtle details of the parallel dune ridges and sediment lobes in the lee of the outcrop. This high-resolution representation of morphology highlights the revolution in geological mapping of the seabed and the finer-scale mapping of habitats using multibeam sonar. Groundtruthing of the seabed around the bank utilised sediment grabs and underwater video. GIS was useful to map the locations and granulometric descriptions of sediment grabs from this survey, for comparison against the gravel, sand and mud content, the mean grain size and $CaCO_3$ component of previous sediment samples in the area. Unfortunately, no oceanographic data were collected during this survey, however, it is unlikely that any measurements of oceanographic variables, such as temperature and salinity, would have varied sufficiently within the scale of observation to be useful as a surrogate for habitat. Nonetheless, examination of the high-resolution seabed morphology and the patterns of non-biogenic sediment around the bank allowed the interpretation of the current flow direction over New Zealand Star Bank.

The tropical case study also utilised multibeam sonar to provide 100% coverage of approximately 7 x 10 km on the Fly River distal delta and about 9 x 19 km on the northern Great Barrier Reef . Bathymetric models with a grid size of 5 m revealed previously unrecognised seabed morphological structure, providing the framework for mapping the distribution of habitats in these two areas. Extensive groundtruthing resulted in a high density of surficial sediment and oceanographic samples. GIS was used to interpolate the gravel, sand and mud, and $CaCO_3$ distribution across the survey areas to help interpret the environment of deposition. Similarly, the interpolation of oceanographic variables, such as temperature and salinity, were useful to describe the hydrodynamic environment but did not vary sufficiently to

provide useful proxies for habitats within the scale of observation. Despite the lack of direct seabed current measurement, the high-resolution representation of seabed morphology and dense sediment sampling allowed interpretation of the strong near-seabed currents responsible for pockmarks around the limestone knolls on the inner shelf, and the active dune field on the middle shelf.

Overall, the datasets required to characterise the physical environment of the seabed need to be carefully selected if they are to be used as surrogates of habitat within the scale of observation. Physiographic features, such as morphology and sediment distribution, are vital datasets at any scale to provide the framework of benthic habitats. Multibeam bathymetric data are very useful for revealing high-resolution geomorphology and the dynamic characteristics of seabed currents as important physical processes controlling the distribution of benthic habitats.

5.1.2 Macrobenthos assemblages

The use of multivariate statistical analysis has widespread use in helping discriminate benthic community structure (Somerfield and Gage, 2000; Kostylev et al., 2001; Stark et al., 2003). During this project, a range of groundtruthing techniques were utilised to obtain biological data, and an objective was to discriminate assemblages of macrobenthos through the use of multivariate statistical analysis where possible. Qualitative and quantitative comparison could then be made against the maps and datasets of the physical environment to define the significant physical processes which influence the distribution of benthos. When using multivariate analysis to distinguish trends in faunal assemblages, analysis is typically conducted on large datasets with biological classification at the lowest taxonomic level possible. Yet a major limitation of this project was that biological classification to genus and species levels were beyond the scope of the study, particularly as this usually requires preservation of samples and expert advice. However in this project, even with the coarse resolution of taxonomic classification to phylum or class levels, or a simple list of faunal groups, multivariate analysis was able to distinguish biological assemblage trends and the general relationships with the physical environment.

Within the George V Shelf case study, multivariate analysis was restricted to the WEGA sediment grabs due to the large number of samples collected in the deep basin. Even though grabs typically under sample benthos and give little indication of the patchiness of sessile fauna, the multi-dimensional scaling (MDS) ordination plot of the infauna from the deep basin provided the basis to differentiate trends, such as areas dominated by deposit-feeding polychaetes and those with a high proportion of suspension-feeding sponges. The variation in

benthic community provided more information about the physical environment of the deep basin than could be obtained from the sediment data alone. Unfortunately, the remoteness and large area of the George V Shelf resulted in disparate biological datasets collected over large temporal scales using different techniques, which are difficult to compare. In this case, GIS proved useful for simply presenting the locations of biological samples, without statistical analysis, for qualitative comparison against the spatial distribution of the physical datasets.

The New Zealand Star Bank survey provided sufficient groundtruthing data through sediment grabs and underwater video to conduct multivariate analysis, and help determine whether the biogenic composition of sediment could indicate benthos distribution. Much time and effort went into determining the coarse taxonomy of skeletal components from grabs. MDS plots of the sediment composition were able to establish gross trends in the physical habitat where the samples were obtained, e.g. granite outcrops, soft substrate and dune ridge proximal. Sediment composition therefore proved useful to help establish variations in the environment of deposition. However, it was only through closely studying the megafauna-substrate relationships observed in the underwater video that links could be made between the various habitats and the megafauna distribution. Sediment composition on its own would not be a good proxy for benthos unless one was only studying just the infauna.

The northern Great Barrier Reef - Gulf of Papua survey provided a high density of good quality groundtruth data, sufficient to conduct multivariate analysis on the biotic datasets. In this case study, the underwater video transects were used to derive the biotic datasets using a coarse classification of the megabenthos observed along transects. The use of underwater video to categorise benthos instead of sediment grabs improved the speed of analysis. However, the resolution of underwater video precluded detailed taxonomic description of megabenthos, and infauna could only be deduced by the indirect presence of mounds or burrows. MDS plots of biotic datasets were able to establish distinct trends in benthic assemblage composition, e.g. mixed gardens, softcoral only and predominantly bioturbate. Data on megabenthos obtained from underwater video proved better at being able to distinguish patterns in benthos compared to sediment grabs as video transects were able to 'capture' the patchiness of fauna at a range of scales.

Overall, multivariate analysis of sediment composition and underwater video proved useful for distinguishing trends in benthic fauna. Underwater video transects are very useful for revealing the patchiness of fauna at all scales. Analysis of underwater video proved faster and more effective than sediment composition in establishing the trends in benthos distribution.

5.1.3 Geophysical and biological community relationships

An objective of this project was to explore the possible relationships between the geophysical environment of the seabed and the associated biological communities. Finding such relationships would provide understanding of the processes that are linked to and characteristic of the diverse marine ecosystems under study. As structural complexity of the seabed is an important determinant of the range of habitats available for flora and fauna (NOO, 2002), this project focused on understanding the influence of geology in controlling the distribution of benthos. An important question posed in this project is whether geological data can be used as a proxy for the occurrence of assemblages of benthic organisms. To help answer this question, a range of techniques were used, such as qualitative spatial analysis in GIS to quantitative comparisons between biotic and abiotic datasets using multivariate statistical analysis.

On the George V Shelf, geomorphic features were emphasised as the basis for the boundaries of benthic habitats at the Biotope level. GIS models of other physical datasets, such as bathymetry, surficial sediment and oceanographic variables distributions, were used to corroborate the boundaries of the Biotopes. The lack of comprehensive biological sampling across the shelf was a problem when trying to find the relationships between the physical environment and benthic distribution. Yet, GIS proved a most useful tool for the spatial comparison between the locations of widely-spaced biological samples and models of the physical structure across the shelf. Information from biological datasets provided the trophic structure of the dominant macrobenthos inferred to be within each of the twelve Biotopes. Due to the large area considered in this bioregionalisation, a number of environmental factors appear to control the Biotope distribution on the George V Shelf, including: (1) the depth of the seabed and the pattern of iceberg grounding on the shelf; (2) the influence of a variable Mertz Glacier Tongue grounding zone; (3) the distribution of substrate in the basin below the influence of icebergs; and (4) the oceanic and shelf current circulation patterns.

For the New Zealand Star Bank survey, underwater video transects were used to describe the physical environment at the seabed. Coarse environmental descriptors of the substrate, geomorphology and megafauna types observed along each transect were of sufficient quantity to conduct multivariate analysis in order to determine trends in seabed habitat. The mixed measurement scales of the environmental descriptors required principal component analysis (PCA) as a suitable multivariate analysis for this dataset. PCA plots were able to distinguish distinct trends in habitat, such as granite outcrop, inner and middle shelf soft substrate. The study used spatial analysis in GIS to qualitatively link the gross trends in habitat distinguished by sediment composition, the geomorphology and the megafauna-substrate relationships

observed in the underwater video. The variation in substrate appears to be a major control on the distribution of biological communities in the New Zealand Star Bank area. These variations are: (1) hard-ground features related to granite outcrops; (2) unconsolidated sediment on a flat seabed; and (3) unconsolidated sediment on a low-relief seabed. Benthic habitats were derived to Secondary Biotope and Biological Facies levels, which reflect the strong relationships between the substrate and benthos.

The northern Great Barrier Reef - Gulf of Papua survey resulted in a high density of groundtruth data, sufficient to conduct multivariate analysis on both the abiotic and biotic datasets to establish trends, then quantitatively link them through the BIO-ENV procedure. This was to explore whether environmental variables could be useful to predict megabenthos assemblage patterns observed in underwater video. PCA conducted on the abiotic datasets established distinct trends in similarity, such as groups of samples obtained from knolls and pockmarks, muddy sand, relict reefs, valley sides and channels. There was a close correlation between the patterns of megabenthos and the variety of habitats distinguished by multivariate analysis. Spearman Rank correlation was used to quantify the measure of agreement between the subset of abiotic variables which best matches the megabenthos patterns in the biotic datasets. Slope and gravel weight were the most useful predictors for megabenthos assemblage patterns. Again, the variation in substrate was considered an important factor in controlling the distribution of biological communities. The study reinforced the knowledge on the contrast between biological assemblages living on: (1) hard substrate; and (2) those in soft unconsolidated substrate. Benthic habitats were derived to Secondary Biotope and Biological Facies levels, which highlight the contrast between benthos living on the hard and soft substrates.

Overall, there are strong relationships observed between the geophysical environment of the seabed and the associated biological communities. This study confirms that physiographic features of the seabed, such as substrate type and morphology, greatly influence the distribution and range of benthic communities at all scales.

5.2 Recommendations

This project presented the author with three wonderful opportunities to travel to remote parts of the Australian and Antarctica continental shelves, with the challenge of mapping the benthic habitats from select sites. Apart from the great variation in the physical environment of the study sites, the scales of observation and assessment techniques used were also vastly different. With the benefit of the experience gained through this project, the following issues are raised,

some with recommendations, and others with predictions of the future use of certain technologies for marine benthic habitat mapping.

5.2.1 Multibeam sonar

An essential technology used in this project was multibeam sonar. The high-resolution 100% sea floor coverage has revolutionised bathymetric and geological maps of the ocean. This technology is the key to linking the traditional geological and biological approaches to benthic habitat mapping. Yet it can come at a large cost in time and money. The huge leap in the amount of data collected, taxes post-processing time if applied line by line. Area-based editing is by far a quicker method to clean the data of outliers, however, this software is expensive and is not easily available for students. Another impediment for using this technology is the predominant use of proprietary-formatted survey data. This project used three different expensive multibeam sonar systems and each had a different output data format. Big delays were experienced in obtaining post-processing software which could view the data, then convert it into simple XYZ format for viewing in a GIS. One can only hope that multibeam manufacturers realise that making their data formats accessible on open-source processing packages, such as MBSystem and Caraibes, will encourage more use of their equipment.

5.2.2 Underwater video

Underwater video is considered the priority tool for groundtruthing marine habitats. Single long transects are recommended to image the patchiness of benthic communities, which occurs at all scales. In contrast, still cameras are limited in their ability to 'capture' the patchiness of benthos. The resolution of underwater video is becoming closer to the image quality of still cameras with the development of digital video, and improved processing techniques will enable better taxonomic identification of megabenthos. Analogue video should be avoided as it usually requires conversion to digital for analysis and loses resolution in the process. Statistical analysis of video imagery is time consuming, however, this project benefited greatly from the megabenthos patterns revealed by multivariate analysis of the video data. In the future, we will see greater use of video imagery within a GIS, whereby screenshots of video imagery are mosaiced and then georeferenced for overlay on multibeam data. This technique will greatly enhance interpretation of geophysical data and the relationship with biota.

5.2.3 Sediment grabs

Sediment grabs are a traditional method of sampling the seabed to detect patterns in macrobenthos distribution. Certainly grabs are a low-impact technique compared to benthic trawls for collecting infauna. In this project, much use was made of sediment samples for trying to determine whether the biogenic composition of sediment could indicate macrobenthos distribution. Sediment composition did also prove useful in helping to establish the variation in environments of deposition. However, much time and effort was spent looking at skeletal components under a microscope, and underwater video was found to be a far better groundtruthing technique to establish benthos distribution. As gravel weight was found to be a useful proxy for benthos, analysis should focus on the size classification of sediments. Classifying the detailed biogenic components of sediment is not recommended.

5.2.4 GIS

GIS is indispensable to scientists and managers to provide a comprehensive view of the ocean's natural processes. Yet it does present some problems. Again, propriety-formatted data formats cause large delays in converting from one format to another for viewing in the GIS of choice. One should not underestimate the time needed to convert data formats, particularly if dealing with raster datasets from different sources. Any GIS chosen for ocean modelling should, ideally, view both raster and vector data together from a large variety of data sources. In addition, quality metadata is important if one is to share GIS models between colleagues or to present maps to the public on the internet. Care should be taken to keep detailed notes of how each GIS map was produced so as to compile the metadata. It is also important that the verbal descriptions of processes acting on the seabed match the spatial distributions of benthic habitat boundaries in a GIS. In this project, the author found the use of conceptual model diagrams to be useful in describing the geology-benthos relationships, and for communicating other processes acting on the seabed. In the future, we will see greater use of interactive 3D models of seabed bathymetry and benthic habitats through the internet as the next step from traditional 2D mapping in a GIS.

5.2.5 Proxies

Finding geophysical proxies for benthos distribution was an important objective of this thesis. Amongst the benthic habitat mapping fraternity, there are many projects looking for the right proxy so as to automate datasets and derive benthic habitats. This project found that slope and gravel weight were useful physical variables to predict megabenthos patterns, but these variables may be relevant only to the northern Great Barrier Reef - Gulf of Papua region under

study. We recommend that future benthic habitat mapping studies are conducted which prioritise the collection of these two geophysical variables, to explore whether they are potentially useful as universal proxies in other marine environments. However, it is unlikely that there is actually a single 'Rosetta Stone' proxy, which can automatically predict all benthos assemblage patterns. In this project, the author found that the use of proxies can only be taken so far and should only be used as a guide for characterising the seabed. One should then stand back and consider all physical and biological patterns in light of what one knows about the processes, asking questions, such as 'Do the patterns make sense?' As this project found, it takes a wide view, considering all information on the geology, oceanography and biology to derive benthic habitats.

5.2.6 Habitat definition

The concept of 'habitat' means many things to many people. Scientists and managers appear to spend a lot of time and effort trying to define a 'one-size-fits-all' definition. Similarly, there are many different schemes to classify marine benthic habitats. It is generally accepted that habitats should be viewed within a hierarchy at progressively finer-scales of observation. For this project, a classification scheme was used which is being developed for the bioregionalisation of Australia. This author found the scheme quite user-friendly as the finer-scales of observation described the seabed habitats in terms of the Secondary Biotopes (the geology type) and the Biological Facies (the biological assemblages associated with the geology). Even though this is a top-down hierarchy, it is important to note that the boundaries of the lower levels define the boundary limits of the upper levels. However, this author believes that one should not get too pedantic about which scheme is used for interpreting benthic habitats of study areas. A recommendation is to select a scheme, modify it for ones own use, and make the definitions and scale of each level clear for the reader to understand.

5.2.7 Maps

This project has raised questions about how should one report the scale and resolution of electronic maps produced in a GIS. The traditional method of map making involved the production of paper hard copies where reporting scale is quite standard. Scale for GIS is a very dynamic because it can be changed in an instant. When dealing with raster imagery in a GIS, knowing the resolution of the grid size is probably as important as knowing the scale. For this project, the resolution of gridded data in the digital elevation models were reported in the text, however, for screen shot images of bathymetric maps produced in a GIS, it may be of use to also include the grid size along with a distance scale within a legend on the map. To enable

people to understand the uncertainties and the technology used in collecting and interpreting benthic habitat maps, a reliability diagram could be attached to images. The diagram could be a matrix of the technology used, line-spacing, age of survey etc. for users to judge the quality of the data behind the interpretations. This author believes that hard copy paper maps of fixed scale are quite limiting in their ability to communicate the spatial distribution of benthic habitats. In the future, greater use will be made of the internet for users to access GIS data, and to interactively change the presentation, scale and colours of electronic maps.

5.3 Linking science and management

Since 1998, when the Australian Government launched Australia's Oceans Policy, a substantial amount of public funding has been committed to scientific cruises for the rapid assessment and mapping of seabed habitats to obtain the information needed for regional marine planning. This PhD project has been fortunate to have had the luxury of time to explore-in-depth the data collected from some of these voyages. The results show that much information can be extracted which have a variety of uses.

Australia is committed to a policy of ecosystem-based management of its marine jurisdiction. Presently, there is an Exclusive Economic Zone declared offshore Australia's territorial claim in Antarctica. While a Regional Marine Plan for this zone is probably some way in the future, as a signatory to the Antarctic Treaty, Australia is also a member of the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR). The Convention underpinning CCAMLR has as its basis ecosystem-based management. Collecting baseline ecological information within the CCAMLR region is vital to establishing catch quotas for the krill fishery, and determining the relationships between the physical environment and biological processes. In this regard, the results of the polar case study are an important baseline contribution to understanding ecosystem processes on the East Antarctic shelf where much of the productivity occurs. These results will be of interest to managers at the Australian Antarctic Division (AAD) to relate the physical environment of the George V Shelf with known distributions of krill, seabirds and marine mammals. In addition, the International Polar Year in 2007-2009 provides the context for a Census of Antarctic Marine Life (CAML) study. The AAD is coordinating the census, and the results of the polar case study are important as a potential framework around which benthic marine life may be targeted for sampling.

Around the Australian mainland, the Southeast Marine Region has recently had a Regional Marine Plan completed. The temperate case study falls within this zone and also lies within the location of Australia's oldest fishery, which has much line and trawl fishing pressure. The

survey over the bank was relatively small in area, however, the results highlighted the diversity of the benthic habitats around New Zealand Star Bank. In particular, the low-relief sandstone of Broken Reef has been identified as vulnerable to trawling, and this project showed the sessile biota which could be removed by over-fishing. Presently, personnel in the Department of the Environment and Heritage (DEH) are coordinating efforts to identify Marine Protected Areas (MPAs) within the East Gippsland Broad Area of Interest, identified during the regional marine planning process. The results of this study will be of interest to these managers as New Zealand Star Bank and the adjacent Broken Reef is representative of a diverse range of habitats supporting prolific benthic and pelagic communities in apparently pristine condition, and may provide a useful example for the selection of habitats suitable for inclusion in a MPA.

The northern part of Australia's marine jurisdiction is the current focus of Australian government scientific agencies to identify the physical and biological characteristics for a Regional Marine Plan. The results of the tropical case study are a timely contribution to knowledge of the ecosystems in this area. The survey targeted little known areas of the shelf and the results highlighted the complexity of habitats and close biological associations, even on the relatively flat and muddy inner shelf. The survey also discovered the deepest known valleys on the northern Australian shelf and a number of live coral reefs which had never been surveyed. These features will be of great interest to the Royal Australian Navy who are responsible for producing the nautical charts for Australia. In this study, the examination of the use of geophysical variables to predict the occurrence of biological assemblages produced results which are likely to be very useful to managers when considering areas with little biological information. As the Australian continental shelf is mostly poorly surveyed, knowledge of the usefulness of geophysical proxies will assist in decisions for spatially defining areas for the purposes of ecosystem-based management and MPA planning.

5.4 Summary of research

Continental shelf waters are subject to the greatest impact by humans. If marine ecosystems are to be efficiently managed and protected from the adverse effects of human activities, then identification of the types of marine habitats and the communities they contain is required. This demands an understanding of the physical and biological structure of marine ecosystems, and the processes which link the variables together. A GIS is an indispensable tool for mapping the spatial boundaries of environmental and biological data, and exploring the spatial relationships between the abiotic and biotic variables. GIS can then be used to model benthic habitats, which are critical for developing the framework for ecosystem-based management and the establishment of marine reserves.

The aim of this research was to present an interdisciplinary study through the use of GIS techniques and mapping of available datasets to derive benthic habitats for three diverse study sites on polar, temperate and tropical continental shelves within Australia's Exclusive Economic Zone. Research cruises to collect data were conducted on: (1) the George V Shelf, East Antarctica; (2) New Zealand Star Bank, eastern Bass Strait, Australia; and (3) the northern Great Barrier Reef, Australia. The objectives were to: (1) define the physical environment of the study sites using GIS maps of geomorphology, surficial sediments and near-seabed oceanography; (2) discriminate assemblages of macrobenthos through the use of multivariate statistical analysis where possible; and (3) explore the possible relationships between the geophysical environment of the seabed and the associated biological communities. GIS was then used to map the spatial distribution of benthic habitats within a hierarchical classification for each study area.

The East Antarctic continental shelf has had few studies examining the macrobenthos structure or relating biological communities to the abiotic environment. An analysis of seismic profiles, multibeam sonar bathymetry, oceanographic data and sediment sampling, defined the geomorphology, surficial sediment and near-seabed water mass boundaries across the George V Shelf. A study of underwater photographs and the results of limited biological sampling provided information to infer the dominant trophic structure of benthic communities within geomorphic features. A hierarchical method of benthic habitat mapping was applied to the Geomorphic Unit and Biotope levels at the local (10s of km) scale. The study revealed that mud content, the limiting effect by iceberg scour, and the direction and speed of oceanic currents are the likely dominant abiotic factors in the broad-scale distribution of macrofauna on the George V Shelf.

To better understand the possible relationships between the geology of the seabed and the associated biological communities, a multibeam sonar survey was conducted over New Zealand Star Bank in the eastern Bass Strait, Australia. Through spatial and multivariate analyses of surficial sediment composition and underwater video, the biological assemblage patterns were related to the variation in geomorphology and substrate. A hierarchical method of benthic habitat mapping was applied to the Secondary Biotope and Biological Facies levels at the site (<10 km) scale. The major differences which control the distribution of biological communities in the New Zealand Star Bank area appear to be related to variations in substrate.

To help answer the question whether geophysical data from habitats can be used to predict the occurrence of benthic biodiversity, a multibeam sonar survey was conducted in the northern

Great Barrier Reef - Gulf of Papua region. Multivariate statistical analyses (cluster, MDS and BIO-ENV) were applied to biological and physical datasets to determine patterns in the distribution of megabenthos, and the relationship with abiotic variables. The geophysical variables, slope and gravel percentage, were useful to predict megabenthos assemblage patterns. A hierarchical method of benthic habitat mapping was applied to the Secondary Biotope and Biological Facies levels at the site (<10 km) scale. The combination of substrate type, sedimentary dynamics and physical processes related to near-seabed currents appear to be the dominant control on the benthic communities in the northern Great Barrier Reef - Gulf of Papua region.

Benthic habitat mapping plays a vital part in understanding marine ecosystems and the processes which influence the spatial distribution of benthos. The results of this research have made significant in-roads in the development of a framework for ecosystem-based management of the study areas, the contribution to the ongoing bioregionalisation of Australia, and through an examination of the use of geophysical proxies for the occurrence of biological assemblages, which are fundamental to the establishment of Marine Protected Areas.

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Appendix A Primer

A.1 Introduction

The statistical package of choice for conducting multivariate analysis on abiotic and biotic datasets was Primer Ver. 5 (Clarke and Gorley, 2001). This software package is used by benthic ecologists worldwide to investigate the similarities and patterns of biological communities and environmental variables: (1) on soft substrate (Somerfield and Gage, 2000; Parry et al., 2003; Stark et al., 2003; Wlodarska-Kowalczuk and Pearson, 2004); or (2) hard/complex substrate (Gutt and Starmans, 1998; O'Hara, 2001). In this project, multivariate (multiple variable) analysis was successfully used to detect trends in samples and explore the relationships between different datasets. In all three case studies, extensive use was made of Bray-Curtis similarity coefficients to derive similarity matrices of biological data, then clustering dendograms and non-metric, multi-dimensional scaling (MDS) ordination plots to detect trends in similarity. In the temperate and tropical case study, principal component analysis (PCA) was also conducted on environmental data to detect trends between environmental varibles collected across the study sites. And in the tropical case study, the BIO-ENV procedure was used to explore the subset of environmental variables which best 'matches' the biological patterns observed between the two study areas.

Readers should be aware that multivariate analysis is best considered an exploratory tool and that more rigorous experimental design is necessary, such as the use of univariate (single variable) data and field manipulative experiments, before significant conclusions can be drawn to the results. The data collected for the case studies in this project were never part of a rigorous experimental design, and care was made not to 'over analyse' the data beyond the various statistical tests used. The following procedures are the steps used in Primer for this project, and to give the reader some background on how various decisions were made using statistical tests.

A.2 Bray-Curtis similarity

A real dataset is used for an example. As part of the northern Great Barrier Reef - Gulf of Papua survey, sediment grabs were obtained across Area A in conjunction with underwater video transects and oceanographic samples (see Fig. 4.2A in Chapter 4 for locations). Ideally, the soft-bodied infauna collected within the sediment grabs would be analysed within Primer, however, for this example the skeletal biogenic composition of the sediment was analysed to explore whether there are trends in the data, and if there is a relationship with environmental variables in

Area A. The skeletal biogenic and lithic composition of the gravel (>2 mm) component of each sample was examined by eye and then compiled into Table A.1 as an estimate of the percentage. Categories were: bivalve, gastropod, bryozoa, benthic foraminifera, echinoid, soft coral, other echinoderm, hard coral, serpulid, arthropod, coralline algae, ostracod, other bioclast, intraclast and lithics.

Grab number	1	2	3	4	5	6	7	8	9	10	11
Bivalve	60	60	35	22	60	50	40	40	50	50	58
Gastropod	12	10	5	5	2	5	10	18	10	8	7
Bryozoa	4	2	4	5	20	3	12	12	6	10	5
BenthicForam	8	8	4	0.1	0.5	5	15	7	10	12	6
Echinoid	5	1.5	1	0.2	1.4	2	7	2.5	1.5	1	1.5
SoftCoral	0	0	0	0.05	0.2	0	0	0	0	0	0
OtherEchino	0	0	0	0	0.1	1	1	0	0	0	0.5
HardCoral	0	0	0	1	0.5	0	0	1.5	3.5	0	2
Serpulid	0	0	0.8	0.05	0.2	1	0	0	0	0.25	0.5
Arthropod	4	5	1	1	5	5	10	5	2	6.75	8
CoralAlgae	5	1	6	0.1	0	0.5	0	0	0	0	0
Ostracod	0	0	0.2	0	0	0	0	0	0	0	0
OtherBioclast	0	2	5	0.5	0.1	2.5	1	4	2	7	0.5
Intraclast	1	8	1	0	0	0	0	0	0	0	0.5
Lithics	1	2.5	37	65	10	25	4	10	15	5	10.5

Grab Number	12	13	14	15	16	17	18	19	20	21
Bivalve	20	45	50	50	40	35	35	40	35	37
Gastropod	44	8	8	10	5	2.5	5	5	12	7.5
Bryozoa	0.7	12	8	4	0	15	5	2.5	8	20
BenthicForam	1	5	10	20	10	5	5	8	5	4
Echinoid	4	2	4	2	0.5	1	2.5	1.5	4	0.4
SoftCoral	0	0	0	0	0	0.1	0.1	0	0	0
OtherEchino	0	0.5	1	0	0	0.5	0	0	0.8	0
HardCoral	0.3	3.5	1.3	0.8	0.5	1	9.5	3	2.5	4
Serpulid	0.1	0	0.9	0.2	0	0.4	1	0	1.3	0.1
Arthropod	3	10	3.3	3	4	2.5	0.7	4	7.5	7.5
CoralAlgae	0	0	0	0	0	0	0	0	0	0
Ostracod	0	0	0	0	0	0	0	0	0	0
OtherBioclast	21	10	5.5	7	15	22	20	19	4	17
Intraclast	0	0	0	0.5	0	2.5	1	5	15	0.5
Lithics	6	4	8	2.5	25	13	15	12	5	2

Table A.1 Composition of gravel (>2 mm) in sediment grabs from Area A. Visual estimates were made of the various skeletal biogenic categories and standardised into percentage. See Fig. 4.2A for locations.

The first step is to conduct a Bray-Curtis similarity on the sample data in Table A.1 to result in a similarity matrix, which can then be used for further statistical tests (Fig. A.1). This similarity measure is an appropriate coefficient for exploring biological community similarities (Clarke and Warwick, 2001), as the data matrices usually have the same units of measure, such as abundance or biomass (in this example - the percentage volume). A number of transformations

may be conducted on the data matrix before the similarity measure (Fig. A1). No transformation results in similarity patterns dominated by a few, very common taxa. With each successive transformation of the data matrix, the less common and rare taxa are taken into account, up to an analysis with presence/absence data, which takes into account all taxa regardless of their abundance in a sample (Clarke, 1993). For this example, a Bray-Curtis similarity is conducted on the data matrix without transformation, and results in a similarity matrix which can then be examined using cluster analysis dendograms and non-metric, multi-dimensional scaling (MDS) ordination plots.

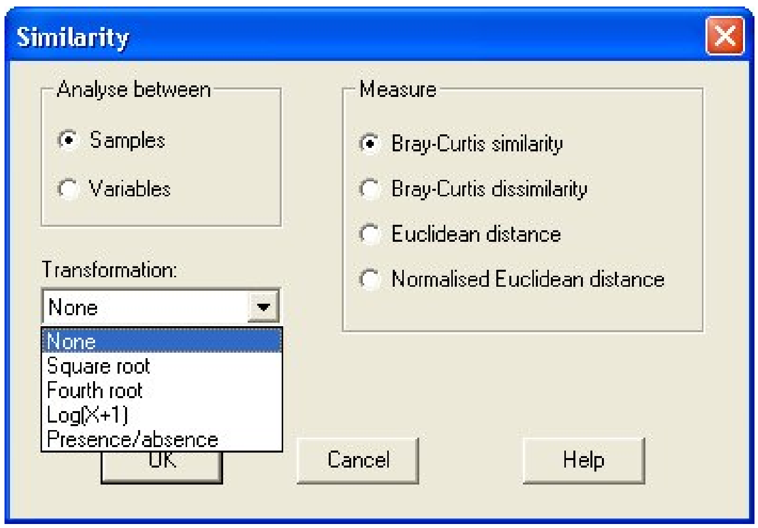

Fig. A.1 First step is to conduct a Bray-Curtis similarity on the data using a variety of transformations.

A.3 Cluster analysis

The clustering method used in this example is a hierarchical clustering with group-average linking (Fig. A.2). This method takes the similarity matrix as the starting point and successively fuses the samples into groups and the groups into larger clusters, starting with the highest mutual similarities then gradually lowering the similarity level at which groups are formed (Clarke and Warwick, 2001). The result is a tree diagram or dendogram plot (Fig. A.3).

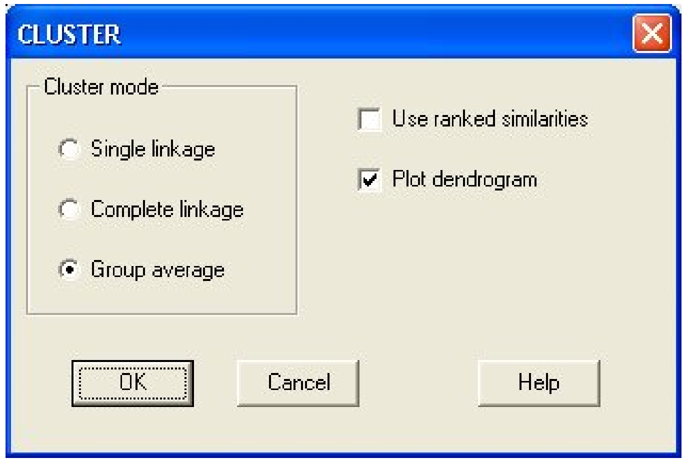

Fig. A.2 Second step is to conduct a cluster analysis on the similarity matrix.

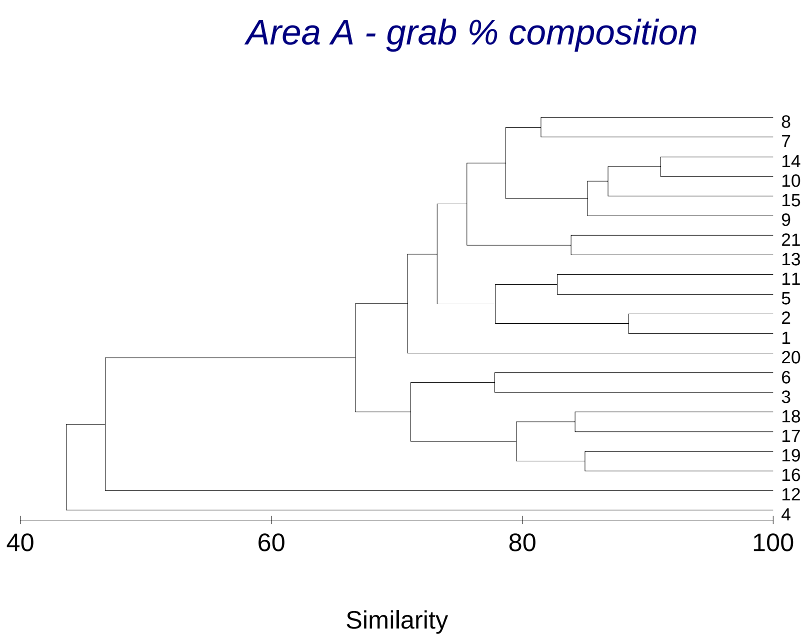

Fig. A.3 Cluster analysis results in a dendogram showing the linkages between samples.

In Fig. A.3, there is clearly a low level of similarity between samples 4 and 12, and the remainder of the samples (<50 % similarity). The majority of samples (except samples 4 and 12) appear to have high levels of similarity (>65 % similarity). So trends in the samples compositions can now be observed.

A.4 Non-metric, multi-dimensional scaling

The next step is to conduct non-metric, multi-dimensional (MDS) scaling on the similarity matrix into an ordination plot to explore trends between samples (Fig. A.4). MDS uses an algorithm which successively refines the positions of the points until they satisfy, as closely as possible, the dissimilarity between samples (Clarke and Warwick, 2001). The result is a two-dimensional ordination plot where points that are close together represent samples that are very similar in composition. Points that are far apart correspond to samples with very different composition. Figs. A.5 and A.6 show non-metric, MDS ordination plots of sediment composition, and bubbles showing the relative size of gastropod and lithics percentages respectively.

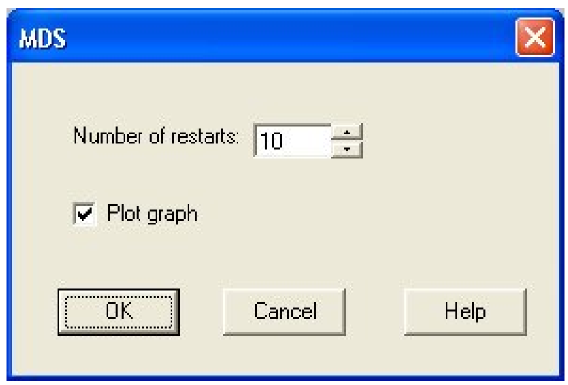

Fig. A.4 Third step is to conduct a MDS analysis on the similarity matrix.

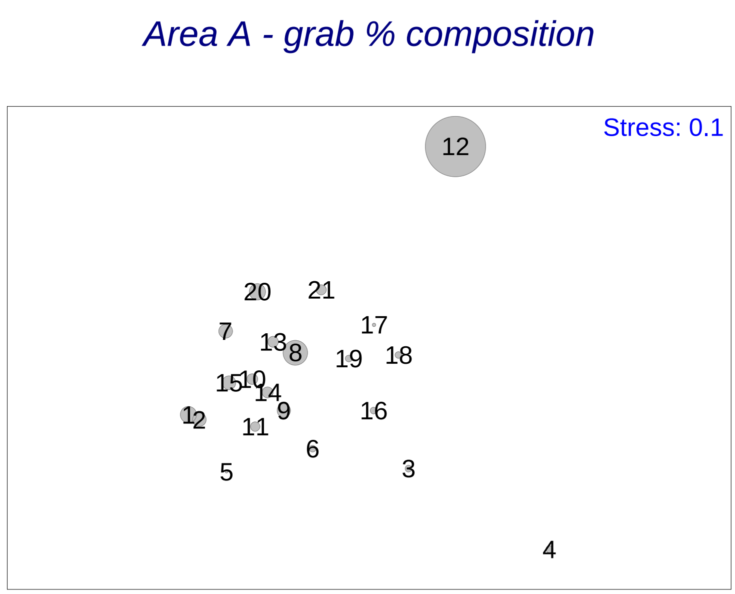

Fig. A.5 A non-metric, MDS ordination plot showing similarities between samples with no transformation. Bubbles show the relative size of gastropods in samples.

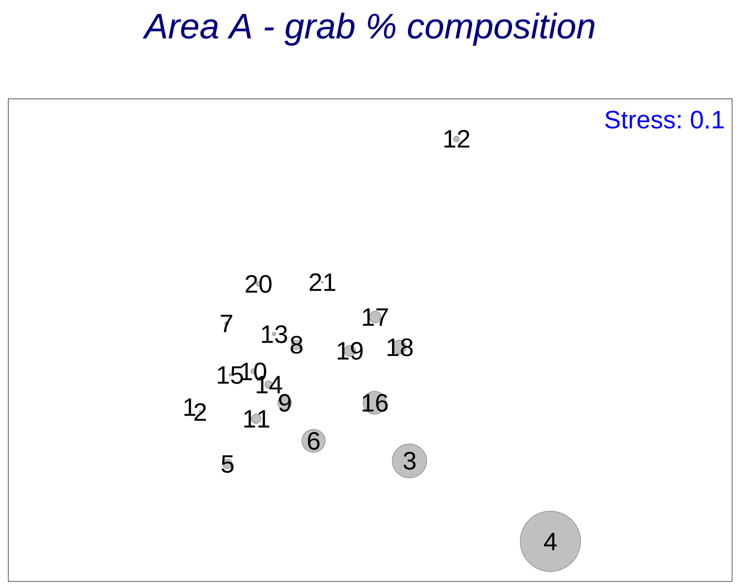

Fig. A.6 A non-metric, MDS ordination plot showing similarities between samples with no transformation. Bubbles show the relative size of lithics in the samples.

In Figs. A.5 and A.6, there are clearly a majority of samples grouped as similar in composition, with samples 4 and 12 quite dissimilar. The use of bubbles to explore the relative sizes of variables assists in exploring the trends in variables between samples. For example, sample 12 (collected from a pockmark) has a high gastropod component (Fig. A.5), and sample 4 (collected from a limestone knoll) has a high lithic component (Fig. A.6). The stress values in Figs. A.5 and A.6 are used to estimate the adequacy of the MDS representation. In these examples, stress values of 0.1 correspond to a good ordination with no real prospect of a misleading interpretation (Clarke and Warwick, 2001). As an example of how transformation of the original data matrix affects ordination plots, a square root transformation was conducted on Table A.1 data and plotted in Fig. A7.

Area A - grab % composition

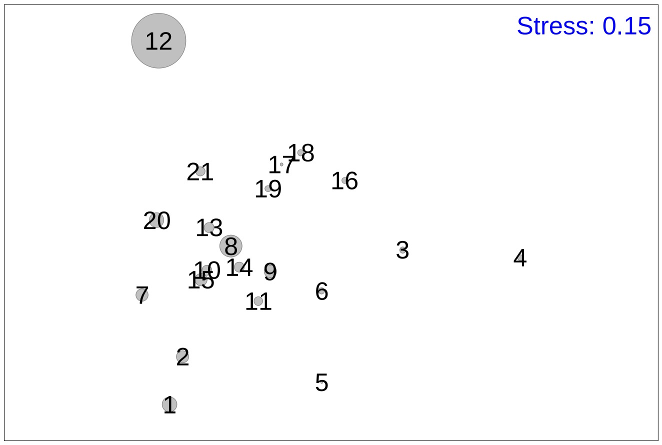

Fig. A.7 A non-metric, MDS ordination plot showing similarities between samples after square root transformation. Bubbles show the relative size of gastropods. Compare against Fig. A.5.

A square root transformation of the Table A.1 data results in greater spreading of samples in Fig. A.7, as the less common components of the samples become more important in the Bray-Curtis similarity. However, it also results in a plot with a higher stress value (0.15) and could suggest that transformation of this data is not appropriate. One needs to experiment with transformations and the various plots to find what is suitable for interpretation of the data.

A.5 Principal component analysis

For this example, a principal component analysis (PCA) is conducted on environmental data collected in Area A from the tropical case study (Table A.2). The variables were: depth (m), slope (º), gravel weight (%), sand weight (%), mud weight (%), gravel $CaCO_3$ (%), sand $CaCO_3$ (%), mud $CaCO_3$ (%), total $CaCO_3$ (%), temperature (ºC), salinity (psu), and transmission (%). PCA also uses an ordination plot to project the points of greatest similarities closer together while samples more dissimilar are further apart (Figs. A.8 and A.9). Unlike biological data, environmental data usually have mixed measurement scales, and similarity methods, such as normalised Euclidean distance used in PCA, are more appropriate for environmental data (Clarke and Warwick, 2001). A useful exercise before conducting PCA is to examine the environmental data in a draftsman scatter plot to ascertain whether there are variables that are highly correlated with one another, which may then be omitted from the PCA.

Station number	Depth (m)	Slope (º)	Gravel weight (%)	Sand weight (%)	Mud weight (%)	Gravel CaCO3 (%)	Sand CaCO3 (%)	Mud CaCO3 (%)	Total CaCO3 (%)	Temp (ºC)	Salin (psu)	Trans (%)
1	29.66	0.11	2.92	77.76	19.32	95.00	47.00	13.00	41.83	28.32	34.51	83.66
2	28.60	0.17	2.68	63.66	33.66	95.00	63.00	9.00	45.68	28.94	34.45	83.42
3	27.13	0.38	18.33	55.84	25.83	60.00	75.00	14.00	56.49	28.86	34.49	83.87
4	22.27	2.91	69.60	26.73	3.68	97.50	89.00	12.00	92.09	28.93	34.48	83.10
5	32.50	1.25	3.03	62.18	34.79	95.00	70.00	12.00	50.58	28.91	34.46	81.21
6	27.90	0.26	5.45	73.74	20.81	75.00	70.00	14.00	58.62	28.93	34.44	81.24
7	32.37	0.32	2.53	71.80	25.66	95.00	75.00	15.00	60.11	28.85	34.46	83.62
8	31.42	0.37	2.09	83.26	14.65	85.00	63.00	22.00	57.45	28.77	34.51	85.21
9	30.72	0.19	4.93	83.10	11.97	85.00	60.00	21.00	56.56	28.70	34.53	85.66
10	31.65	0.28	3.98	80.22	15.80	90.00	63.00	23.00	57.75	28.72	34.53	85.56
11	31.85	0.15	9.77	72.27	17.97	85.00	57.00	17.00	52.55	28.56	34.56	84.60
12	32.72	2.33	18.13	75.05	6.83	95.00	88.00	18.00	84.49	28.44	34.58	81.72
13	30.96	0.61	3.77	77.59	18.64	90.00	56.00	14.00	49.45	28.27	34.61	81.21
14	29.32	2.33	7.52	82.56	9.92	85.00	73.00	14.00	68.05	28.24	34.62	78.70
15	30.04	0.07	2.73	77.28	19.99	90.00	68.00	16.00	58.20	28.51	34.58	81.27
16	28.23	0.15	8.73	64.08	27.19	70.00	61.00	12.00	48.46	28.65	34.55	82.46
17	28.88	0.49	5.20	62.42	32.38	85.00	68.00	9.00	49.78	28.79	34.52	79.53
18	27.55	2.72	5.81	82.75	11.45	95.00	81.00	10.00	73.69	28.84	34.51	77.25
19	28.71	0.11	3.86	52.91	43.23	95.00	61.00	7.00	38.97	29.07	34.37	65.75
20	27.50	0.31	2.50	53.19	44.31	90.00	61.00	6.00	37.36	29.14	34.33	71.26
21	28.14	0.05	1.98	64.41	33.61	95.00	59.00	7.00	42.23	29.15	34.31	77.67

Table A.2 Environmental data for Area A. See Fig. 4.2A for locations.

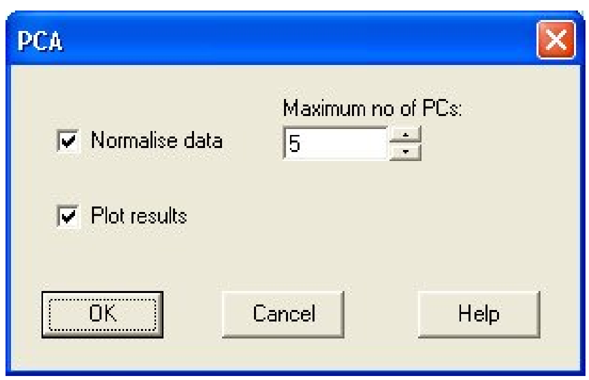

Fig. A.8 PCA is conducted on Table A.2 data using normalised Euclidean distance.

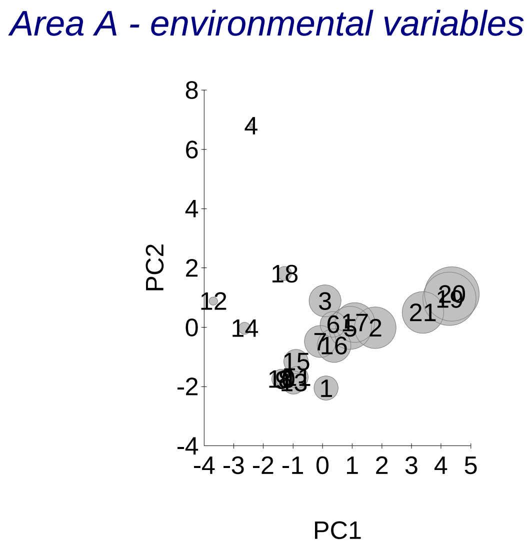

Fig. A.9 PCA ordination plot of environmental data, showing bubbles of the relative size of mud % at each station.

When conducting PCA, Primer outputs useful information on the variance explained by each axis and, like the MDS plots, bubbles of the relative sizes of variables can be used to show the trends in environmental variables across the survey area. For example in Fig. A.9, the mud % increases across PC1 from left to right, which can then be compared with the positions of samples in a GIS to explore spatial trends across the survey area.

A.6 BIO-ENV

The last statistical test used in this project was the BIO-ENV procedure to link biological community analyses to environmental variables (Fig. A10). In other words, the requirement is to examine the extent to which environmental data, such as physical-chemical data, is related to or 'explains' the observed biological pattern (Clarke and Warwick, 2001). The approach is firstly to analyse the biotic data and then to ask how well the information on environmental variables, taken either singly or in combination, matches this community structure. The BIO-ENV procedure simply calculates a measure of agreement between the two similarity matrices: the fixed biotic similarity matrix (using Bray-Curtis similarity on the biotic data) and each of the possible abiotic matrices (PCA on combinations of the abiotic data). This is done by Spearman rank correlation, which ranks the subsets of variables that best 'matches' the biological patterns.

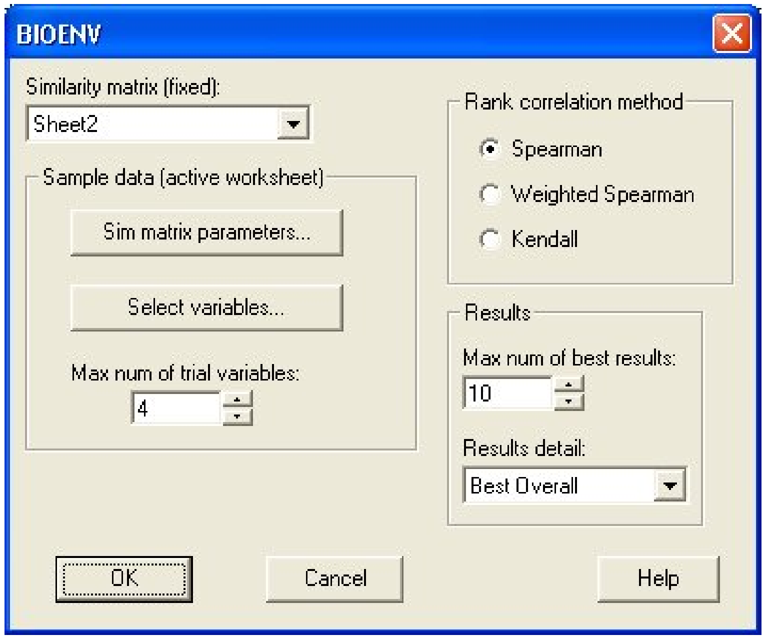

Fig. A.10 The BIO-ENV procedure to link abiotic variables to the biological patterns.

In this example, the BIO-ENV procedure results in a list of variables which show a subset of four variables: Depth, GravelWt, GravelCaCO3 and SandCaCO3, have the highest correlation (0.675) to the biotic pattern. One can then speculate as to significance of these correlations, however, it is stressed that the subset of variables do not imply causality, and only manipulative field experiments can prove causal links. However, the BIO-ENV procedure is a useful exploratory tool, and in the tropical case study, was utilised to find the variables: slope and gravel weight, were useful as predictors of megafaunal assemblage patterns.

A final note regarding Primer is that when compiling biotic datasets, the taxonomic classification of biota should always be to the lowest level possible. However, this author found that it was possible to use multivariate analysis to detect trends in coarse categories of megabenthos. This means that one can survey the seabed without having specialist taxonomic knowledge of the benthos. Basic biological knowledge and some good field guides can suffice when classifying underwater video. A recommendation when using coarse taxonomic classifications, however, is not to transform the data using presence/absence transformations on the original biological data, as experience shows that this further reduces the effectiveness of detecting trends in coarse categories. In time, we will see more use of Primer as a tool to bridge the disciplines of geology and biology, which is needed if we are to successfully map benthic habitats and their associated communities.

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