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Bioregionalization of the George V Shelf, East Antarctica

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Abstract

The East Antarctic continental shelf has had very few studies examining the macrobenthos structure or relating biological communities to the abiotic environment. In this study, we apply a hierarchical method of benthic habitat mapping to Geomorphic Unit and Biotope levels at the local (10s of kilometers) scale across the George V Shelf between longitudes 142°E and 146°E. We conducted a multi-disciplinary analysis of seismic profiles, multibeam sonar, oceanographic data and the results of sediment sampling to define geomorphology, surficial sediment and near-seabed water mass boundaries. Geographic information system models of these oceanographic and geophysical features increase the detail of previously known seabed maps and provide new maps of seafloor characteristics. Kriging surface modeling on data includes maps to assess uncertainty within the predicted models. A study of underwater photographs and the results of limited biological sampling provide information to infer the dominant trophic structure of benthic communities within geomorphic features. The study reveals that 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 waters within the direct influence of glacial ice (depths <500 m) on the banks, scouring by icebergs is a strong limiting factor in the distribution of macrobenthos. 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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1. Introduction

If marine ecosystems are to be managed to ensure rational use of resources or protected from

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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 characterization schemes now recognize 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 bioregionalization 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 kilometers in extent (regional scale); and (3) Geomorphic Units, such that within each Biome, there are areas characterized by similar geomorphology and which usually have distinct biota. These units may be up to 10s of kilometers 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 data sets to define each level.

This study aims to present a bioregionalization 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 data sets. 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 position datum and reanalyzed to provide new maps of seafloor characteristics.

This paper 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 kilometers) scale, and a description of each unit is given. We present a new bioregionalization, which provides insights into general environmental and biological relationships across the George V Shelf.

2. Materials and methods

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. 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 10s of kilometers (Domack and Anderson, 1983; Holdsworth, 1985).

Sediment-laden icebergs calved from the Mertz and Ninnis Glaciers have dimensions of up to several 10s of kilometers (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. 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. 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.

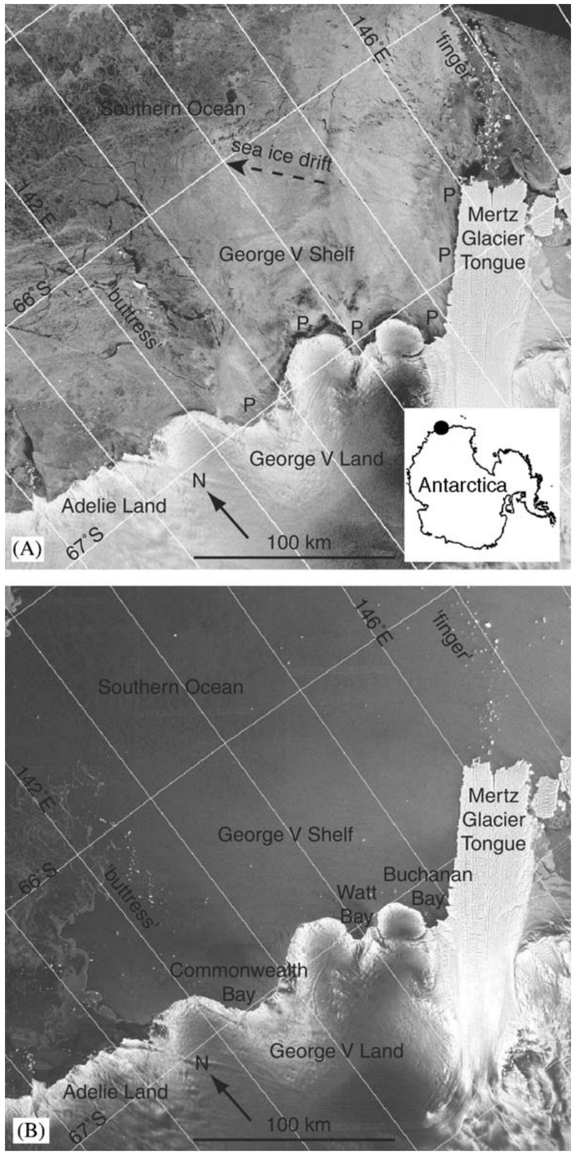

Fig. 1. Radarsat ScanSAR images of the George V Land and Shelf area from (A) 7 August 1999—winter and (B) 17 December 1999—summer. P denotes Mertz Polynya along the coast and west face of the Mertz Glacier Tongue. The 'buttress' and 'finger' refer to grounded icebergs and fast ice extending across the 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.

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). 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 toward 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 the southern side of the Mertz Bank, and interpreted as a lateral moraine (Barnes, 1987).

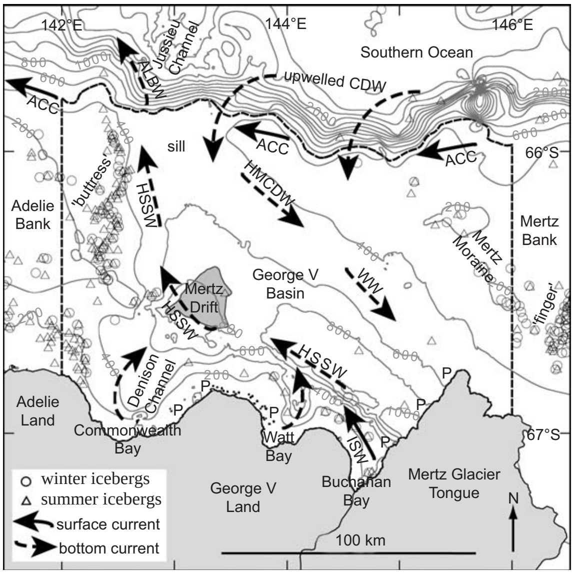

Fig. 2. Mercator projection map of the George V Shelf. A dashed line shows the study area bounded to the north by the depth contour 500 m, and to the west and east by longitudes 142–146°E. Bathymetry is in meters from Porter-Smith (2003). HSSW, high salinity shelf water; ACC, Antarctic Coastal (surface) 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. 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.

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 toward the Mertz Glacier Tongue (Fig. 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 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 super-cooled 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 westward 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 ACC, driven by polar easterly winds (Whitworth III et al., 1998).

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 (WEGA) expedition on the R.V. *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 recognized on Admiralty charts (IHO, 2001).

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, 1988), the 1984 United States Geological Survey (USGS) cruise (Hampton et al., 1987), and 2000 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 1.

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 modeling 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, 1988; Domack and Anderson, 1983; Dunbar et al., 1985; Hampton et al., 1987; 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. 3).

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–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 (data available on request).

Table 1
Sediment sample locations, water depths, gravel, sand and mud data

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

Table 1 (*continued*)

Sample number	Source	Latitude	Longitude	Water depth (m)	Gravel (%)	Sand (%)	Mud (%)
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

Note: 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).

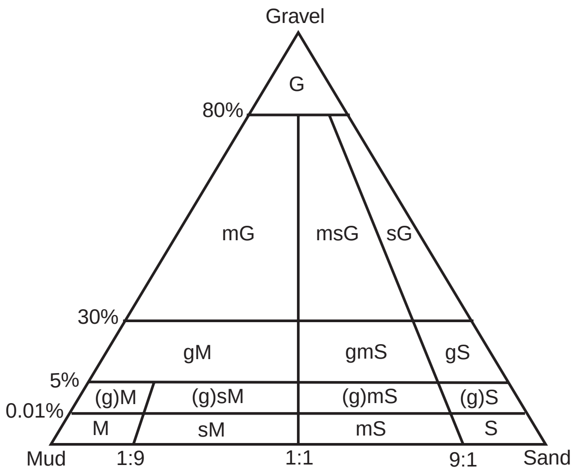

Fig. 3. Surficial sediment classification based on Folk (1954). Sediments are classified into textural groups based upon the relative proportions of gravel (>2 mm), and the ratio of sand (2–0.0625 mm) to mud (<0.0625 mm). Uppercase letters indicate largest proportion; lowercase letters indicate qualifiers; brackets indicate 'slightly', e.g. (g)mS is slightly gravelly, muddy sand.

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 meters of the seabed, to describe near-seabed hydrology conditions. Salinity (psu) and temperature (°C) values were obtained for the 45 summer samples (data available on request).

Maps of winter and summer temperature and salinity were 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) and a classification of water masses based upon the temperature vs. salinity boundaries of Bindoff et al. (2001), shown in Fig. 4.

2.6. Biological data

The limited biological data presented in this paper were mostly collected opportunistically from marine geological cruises to the region. In the absence of a dedicated benthic ecologist/taxonomist, the macrobenthos were categorized 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

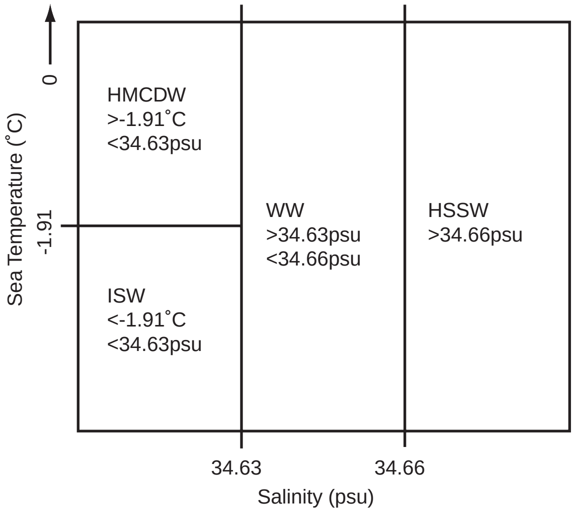

Fig. 4. Water mass classification. HMCDW, highly modified circumpolar deep water; ISW, ice shelf water; WW, winter water; HSSW, high salinity shelf water. The classifications of water masses are based upon temperature vs. salinity boundaries of Bindoff et al. (2001).

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, non-polychaete worm, gastropod, bivalve and bryozoa (Table 2). This category list reports only those taxa actually found in the WEGA grab and core samples. Data were standardized by calculating the percentage weight of taxa categories in each sample. Statistical analysis was carried out on the WEGA data set 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. The resulting similarity matrix was analyzed using group-averaged cluster analysis, displayed as a dendogram and a two-dimensional, multi-dimensional scaling (MDS) ordination plot.

Three rock dredges were deployed for approximately 30 min 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, non-polychaete worm, amphipod, pycnogonid, gastropod, bivalve, scaphopod, cephalopod, brachiopod, bryozoa, crinoid, asteroid, ophiuroid, holothuroid, echinoid and tunicate (Table 3). This category list reports only those taxa actually found in the NBP0101 dredge and grab samples. Data were standardized 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.

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

Table 2
Grab and core sample locations, water depths and macrobenthos percentage weight data

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		

Note: Source data are from the 2000 WEGA expedition (Brancolini and Harris, 2000).

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, non-polychaete worm, barnacle, amphipod, isopod, decapod, pycnogonid, gastropod, bivalve, brachiopod, bryozoa, crinoid, asteroid, ophiuroid, holothuroid, echinoid and tunicate (Table 4). 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.

The aim of this study was to bioregionalize the George V Shelf to the Geomorphic Unit and Biotope levels at the local (10s of kilometers) 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 data sets within a GIS. Qualitative

Table 3
Dredge and grab sample locations, water depths and macrobenthos percentage volume data

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

Note: Source data are from the 2001 NBP0101 cruise (Leventer et al., 2001).

consideration was conducted on the models and to assess their agreement or disagreement with each other. Geomorphic features were emphasized as the basis for the boundaries of the Biotopes, and then other data sets 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 data sets 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 digitized 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 WW masses, and inferred primary and secondary disturbances.

3. Results

3.1. Geomorphology

Eight Geomorphic Units are recognized in the bathymetric and acoustic facies maps, highlighting the diversity of 'landscape' on this glacially carved shelf (Fig. 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 800–1000 m water depth. The sediment drift, Mertz Drift, lies in the western part of the basin and is characterized 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

Table 4
Dredge and trawl sample locations, water depths and macrobenthos presence

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

Note: Source information is from 1911–1914 Australasian Antarctica Expedition (Mawson, 1940).

at three locations below 800 m water depth. The combined deposits are labeled as drifts in Fig. 5. The sediment deposits thin at the edges to an approximately 30 cm layer of SMO overlying a gray, muddy diamicton (Domack, 1982) within the remainder of the basin.

Multibeam swath bathymetry revealed megaflutes or megascale lineations 10s of kilometers long, a few 100 m wide, and up to approximately 30 m between trough and crest (indicated by parallel black lines in Fig. 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 sub-glacial 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 toward the sill that connects the basin to the shelf edge (Fig. 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.

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 surfaces are ploughed by grounded icebergs and winnowed by oceanic currents (Fig. 2). In places, localized 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

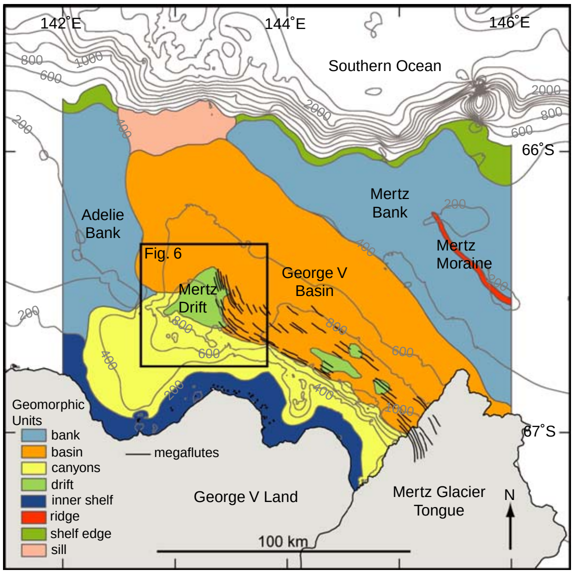

Fig. 5. Map of George V Shelf Geomorphic Units. Names are based upon hydrographic terms recognized on Admiralty charts (IHO, 2001). Megaflute lines are basin-parallel lineations resulting from sub-glacial molding of till by the glacier sole during glacial expansion. The box shows the location of Fig. 6.

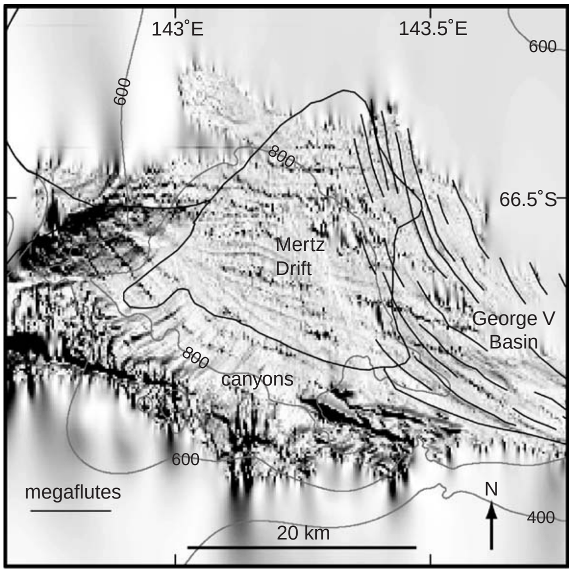

Fig. 6. Hill-shaded relief map of swath bathymetry in western George V Basin. Geomorphic Unit boundaries reveal the limits of the Mertz Drift and inner-shelf canyons. Megaflute lines show the veering northward of sub-glacial molding of the seabed during glacial expansion by the Mertz Glacier.

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 ACC as well as flows of HMCDW. At longitude 143°E, 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 center 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. 5. The submarine canyons are the among least-well studied feature 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. 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) in Commonwealth Bay (AHO, 2002). The canyons are believed to be formed by the eroding action by 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 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.

3.2. Surficial sediment

The map of interpolated gravel distribution (Fig. 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.

Mud percentage is highest (80–100%) within the main part of the George V Basin and toward the sill below about 600 m (Fig. 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

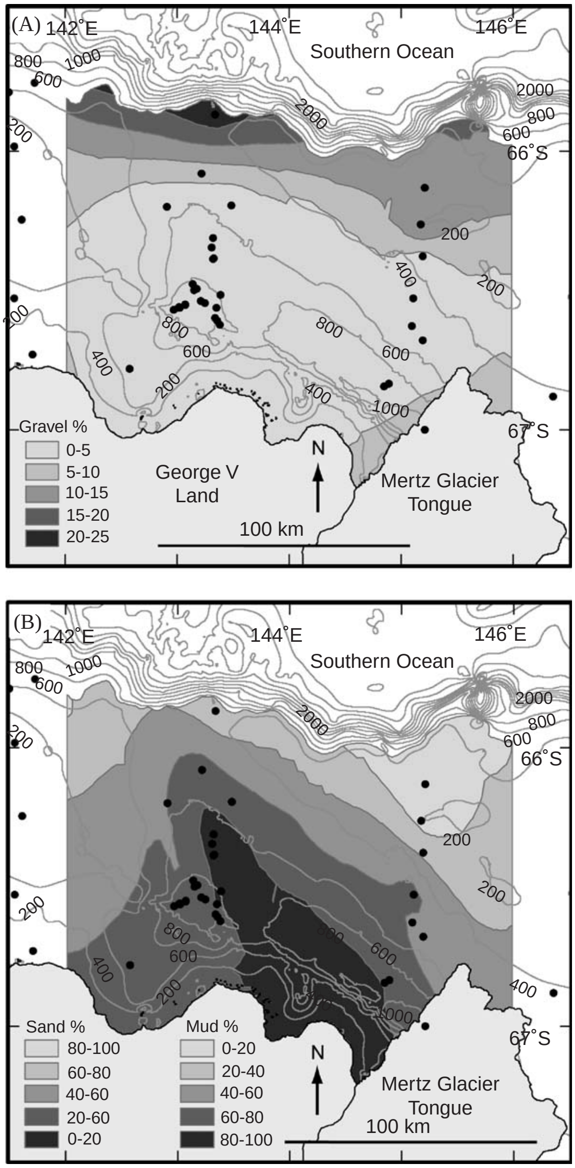

Fig. 7. Surficial sediments on the George V Shelf as (A) gravel percentage and (B) sand/mud percentage. Dots indicate the positions of sediment samples. Note that the lack of sampling along the coast decreases model accuracy in this area.

oceanic currents over the shallow banks winnowing fine-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 characterizes the lower basin, extending toward 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 fine-grained, terrestrial and biogenic sediments into the basin (Harris and Beaman, 2003).

In the upper basin, slightly gravelly, sandy mud is found between 500 and 600 m on the northern side and between 200 and 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. 8 due to the steep slope of the canyon area between depths of 200–1000 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).

The area bordering the upper basin in depths shallower than 500 m and over the landward side of the Mertz and Adélie Banks is characterized by slightly gravelly, muddy sand (Fig. 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).

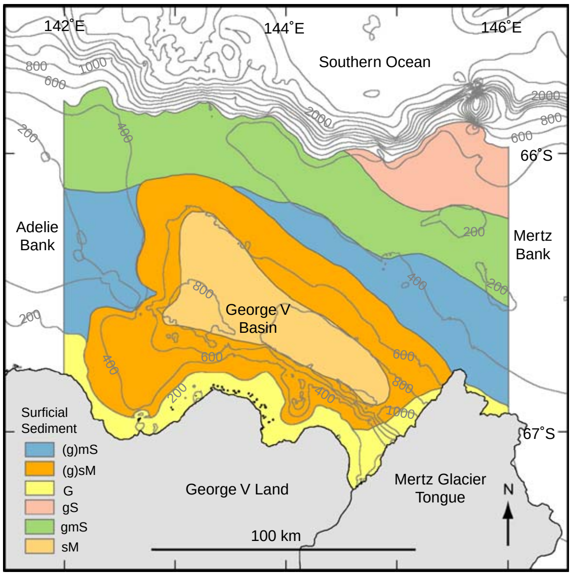

Fig. 8. Surficial sediment distribution on the George V Shelf using the Folk (1954) classification (see Fig. 3).

Sediments in this zone have been referred to as an ice-keel turbate, comprising a mix of reworked glacial till, IRD and marine biogenic material (Barnes and Lien, 1988).

Sediment on the majority of the outer banks and shelf edge is gravelly, muddy sand (Fig. 8). Sand dominates and the gravel proportion increases with proximity to the shelf edge. Grounded icebergs in this zone rework the seabed, and hydrologic 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.

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. 4) were also applied to the summer data set. 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. 9A) shows that the basin and part of the Mertz Bank, north of the Mertz Glacier Tongue, is bathed in very cold ($<-1.8\,^{\circ}$C) water. Important features detected during the 3-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 400–500 m over the bank and into the upper basin. A comparison against the summer temperature map (Fig. 9B) reveals the basin also with temperatures colder than $-1.8\,^{\circ}$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. 9B). At the shelf edge in summer, temperatures are warmer than $-1.2\,^{\circ}$C and cool toward 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.

Winter salinity measurements (Fig. 10A) reveal that the George V Basin is filled to approximately 500 m and toward the sill with very saline (>34.65 psu) HSSW. A small area of the seabed in the vicinity of the outlet of the Mertz Glacier

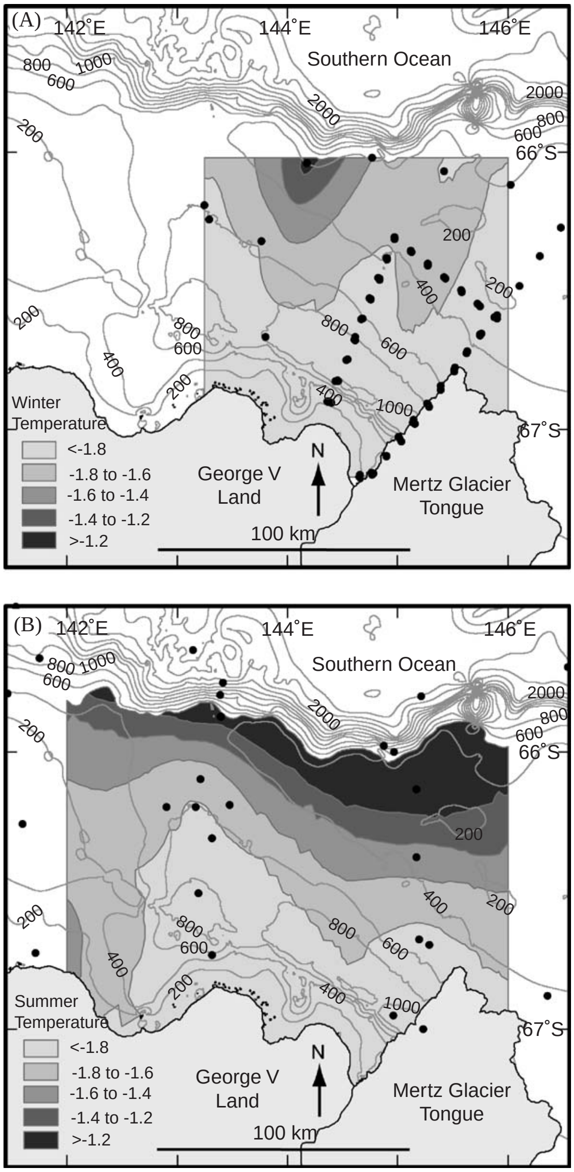

Fig. 9. Near-seabed temperature (°C) during (A) winter and (B) summer. Dots indicate positions of oceanographic stations. Note the winter model does not extend to the west side of the study area.

Tongue is influenced by relatively fresh (<34.55 psu) 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 400–500 m depth. The summer salinity distribution

(Fig. 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 (34.60–34.65 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.

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. 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 and 500 m on the Mertz Bank and along the inner shelf (Fig. 11A). During summer, a stratified version of remnant WW fills most of the basin and overlies HSSW (G.D. Williams, 2002, pers. comm.). 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 and 500 m (Fig. 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.

3.4. Macrobenthos

A map of the number of taxa at each station in Tables 2, 3 and 4 shows graduated symbols in a range from 1 to 20 taxa (Fig. 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 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,

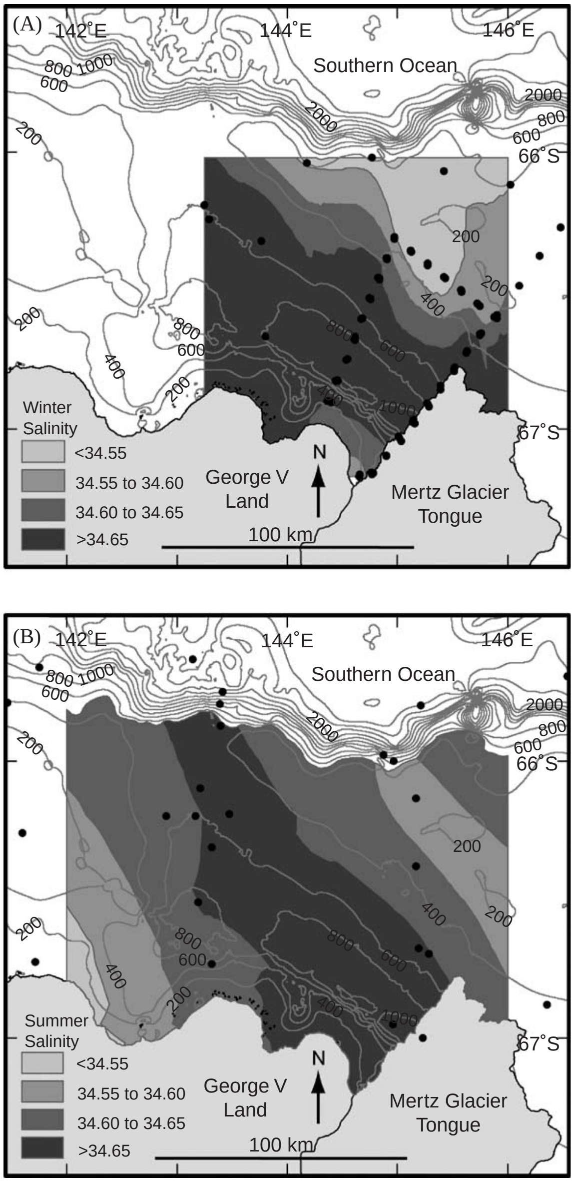

Fig. 10. Near-seabed salinity (psu) during (A) winter and (B) summer. Dots indicate positions of oceanographic stations. Note the winter model does not extend to the west side of the study area.

where most of the WEGA samples were obtained (709–879 m), taxa numbers ranged from a relatively low 2–6. 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

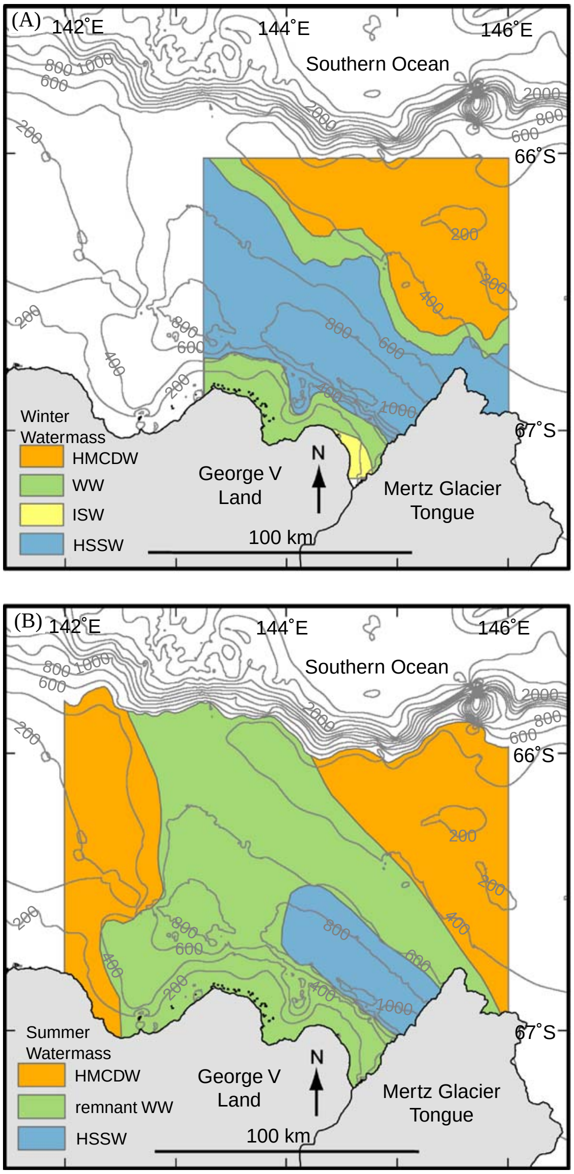

Fig. 11. Near-seabed water masses during (A) winter and (B) summer. HMCDW, highly modified circumpolar deep water; WW, winter water; ISW, ice shelf water; HSSW, high salinity shelf water. Note the winter model does not extend to the west side of the study area.

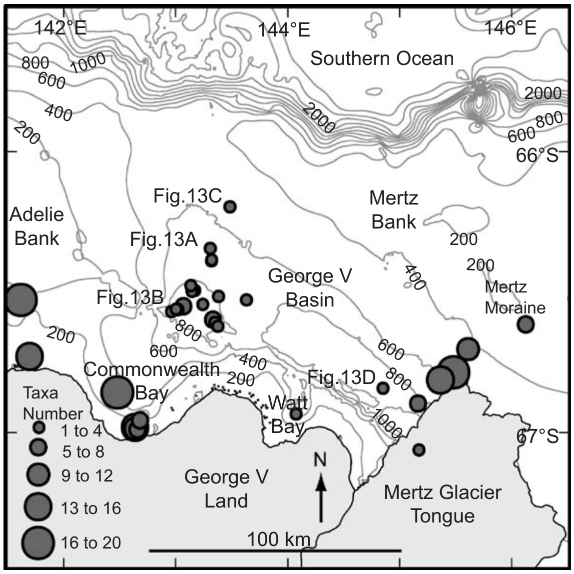

Fig. 12. Graduated symbols of macrobenthos taxa number in seabed samples taken from the George V Shelf. Note the positions of grab sample photographs displayed in Figs. 13A, B, C and D.

depths shoal. Taxa values increase from eight (858 m) to relatively high values of 14 and 20 (592 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.

Focusing on the more comprehensive WEGA data set in Table 2, polychaetes and sponges were the predominant taxa within samples taken from the seabed in depths below 709 m. Polychaete and non-polychaete worms were thin, soft and clearly infaunal within the siliceous mud and diatom ooze (e.g. Sample GB18; Fig. 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. 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 toward the sill, which has calcareous bryozoa as the dominant macrofauna and a higher proportion of gravel compared to the lower basin samples (Fig. 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 non-polychaete worm material and arenaceous benthic foraminifera (e.g. Sample GB09; Fig. 13D).

Statistical analysis of the WEGA data set reveals three groups of samples, distinguished both on the dendogram and the MDS plots of the untransformed data (Fig. 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. 14A), the main divisions between the bryozoa, sponge and

Fig. 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.

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. 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 IRD 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.

3.5. Biotopes

Qualitative examination of the available data sets resulted in the George V Shelf divided into 12 Biotopes (Figs. 15 and 16). We believe that the patterns observed in the environmental and biological data sets support subdivision of the shelf into this number of units within the context and local (10s of kilometers) 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'

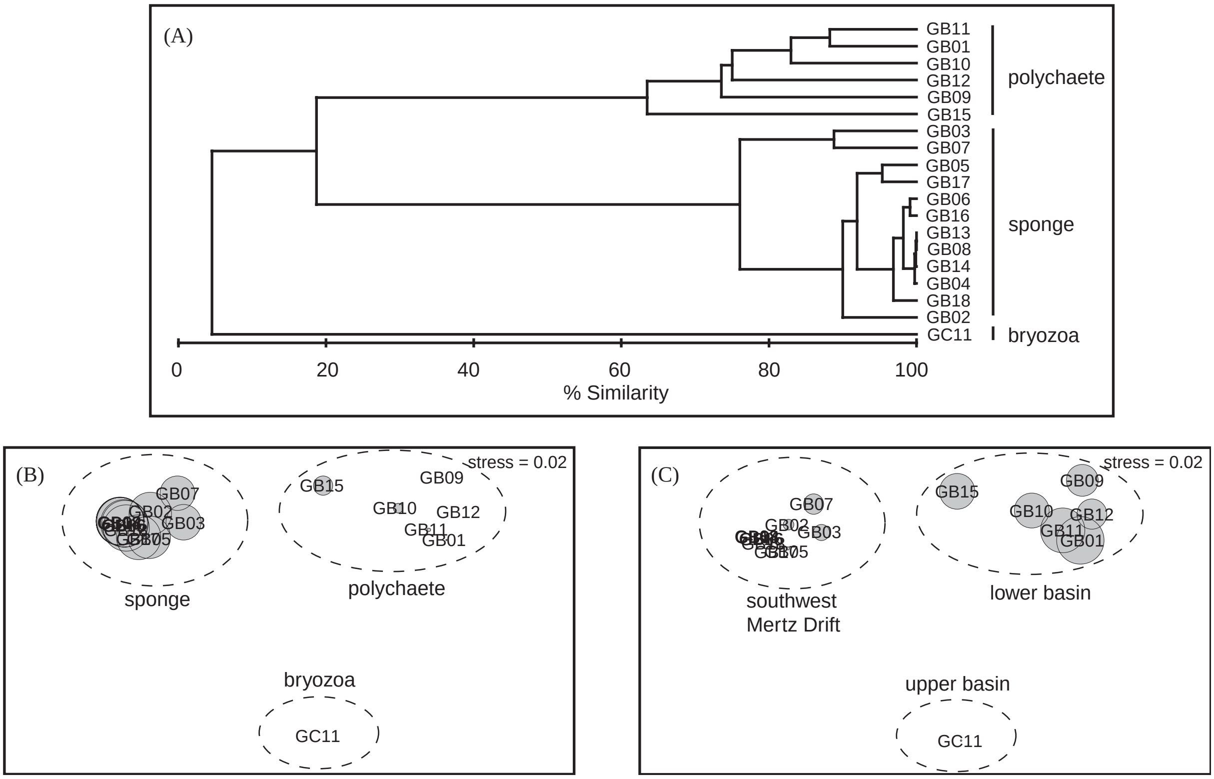

Fig. 14. (A) Group-averaged dendogram of cluster analysis on untransformed percentage weight data from Table 2 (WEGA samples). (B) Two-dimensional ordination plot from non-metric multi-dimensional scaling (MDS) of Table 2 data showing the relative size of sponge percentage in samples, and the three macrobenthos groups. (C) MDS plot of same Table 2 data showing the relative size of polychaete percentage in samples, and the general location of stations.

(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 5 summarizes each Biotope against biological, geophysical and oceanographic features, and includes inferred primary and secondary disturbance regimes.

3.5.1. Diverse inner shelf

The 'diverse inner shelf' Biotope is found in depths 0–200 m along the George V Coast. NBP0101 grab 8GR08 (Table 3) and AAE dredges DR1, DR4, DR4A and DR5 (Table 4) reveal a very diverse macrofauna with a high epifauna.

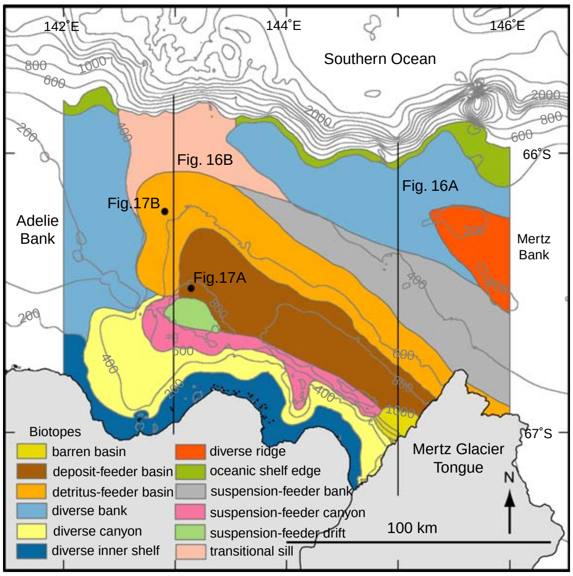

Fig. 15. Biotopes of the George V Shelf. North/south lines across the shelf at longitudes 145°E and 143°E mark the cross sections in Figs. 16A and B, respectively. Note the positions of underwater photographs in Figs. 17A and B.

Littoral waters are most disturbed by near-shore ice through fouling of epifauna in anchor ice or impact by loose sea ice (Barnes, 1999; Gutt, 2001). The effect of near-shore ice could possibly explain the increase in taxa number from 8 to 15 as sample depths increased from 7 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 super-cooled 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 toward 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

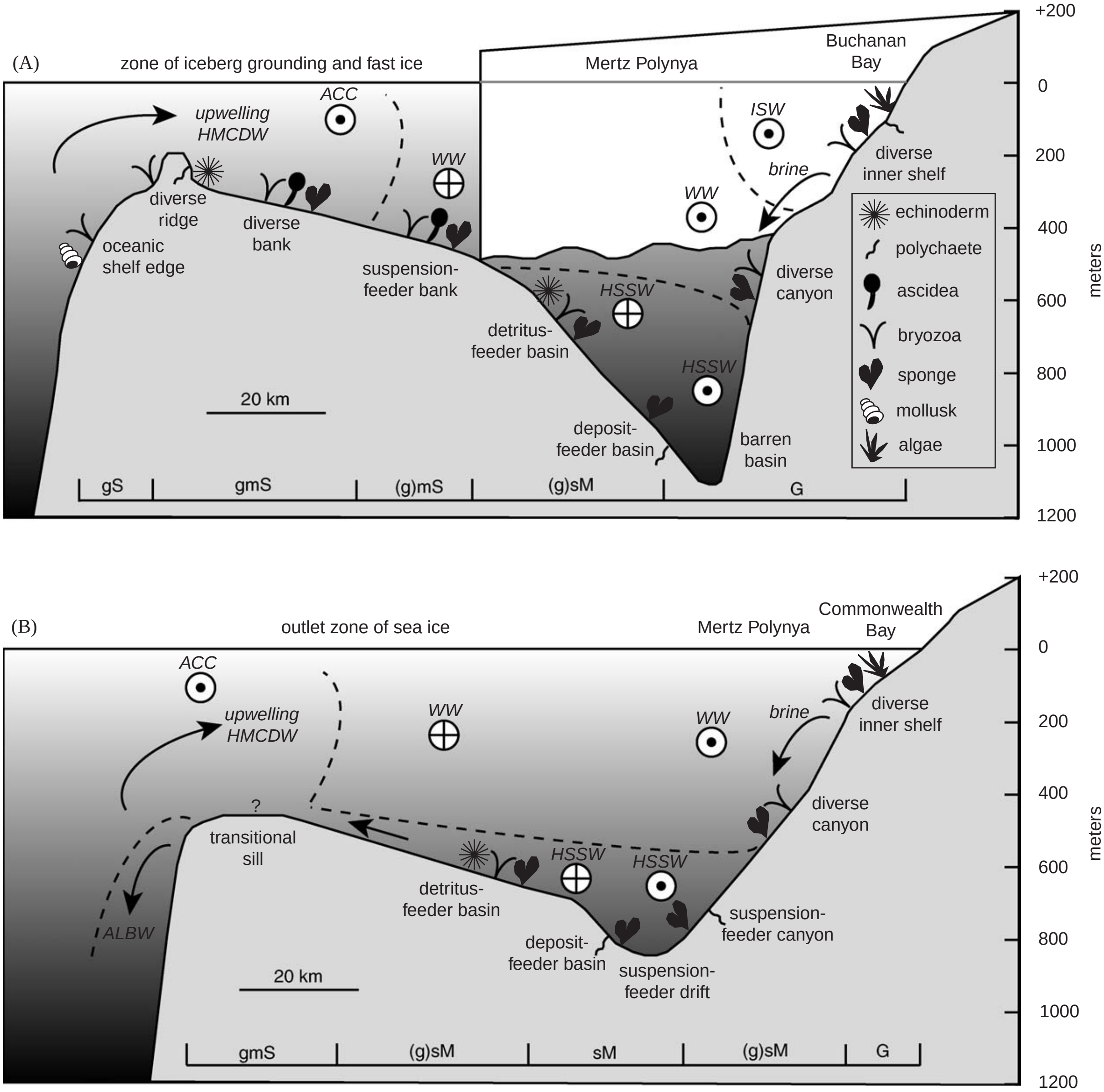

Fig. 16. Summary cross sections of the George V Shelf at longitudes (A) 145°E and (B) 143°E. Arrows and circles show the direction of water masses, with approximate boundaries separated by dashed lines for winter conditions. The macrobenthos symbols show the common taxa within each Biotope. The boundaries for surficial sediment types lie along the bottom of each profile.

to the rocky ridges and ledges found on the Adélie Coast (Vanney and Johnson, 1979).

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). AAE trawl TR21 (Table 4) records very diverse and abundant sessile macrofauna and epifauna. Bryozoans dominate over sponges

Table 5
Summary of the George V Shelf Biotopes, water depths, macrobenthos, geomorphology and surficial sediments, near-seabed seasonal water masses, and possible disturbance regimes

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

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 localized disturbance (Domack, 1988).

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.

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 3), 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.

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 3), 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, ADCP data reveal relatively strong currents (up to $12\,\mathrm{cm\,s^{-1}}$) 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 localized impact at the seabed by drop stones released from the calving ice shelf, as surficial sediments record abundant gravel in this zone.

3.5.5. Deposit-feeder basin

Within the George V Basin in depths approximately 700–1000 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 3), and WEGA grab samples GB01, GB09, GB10, GB11, GB12, GB15, GB16, GB17 and GB18 (Table 2). 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. 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 colonize as these geomorphic features are 10s of kilometers 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 toward 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 toward 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).

3.5.6. Suspension-feeder drift

A ‘suspension-feeder drift’ Biotope lies in the western George V Basin between depths of approximately 750–850 m. Statistical analysis reveals that WEGA grab samples GB02, GB03, GB04, GB05, GB06, GB07, GB08, GB13 and GB14 (Table 2) 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 photo-

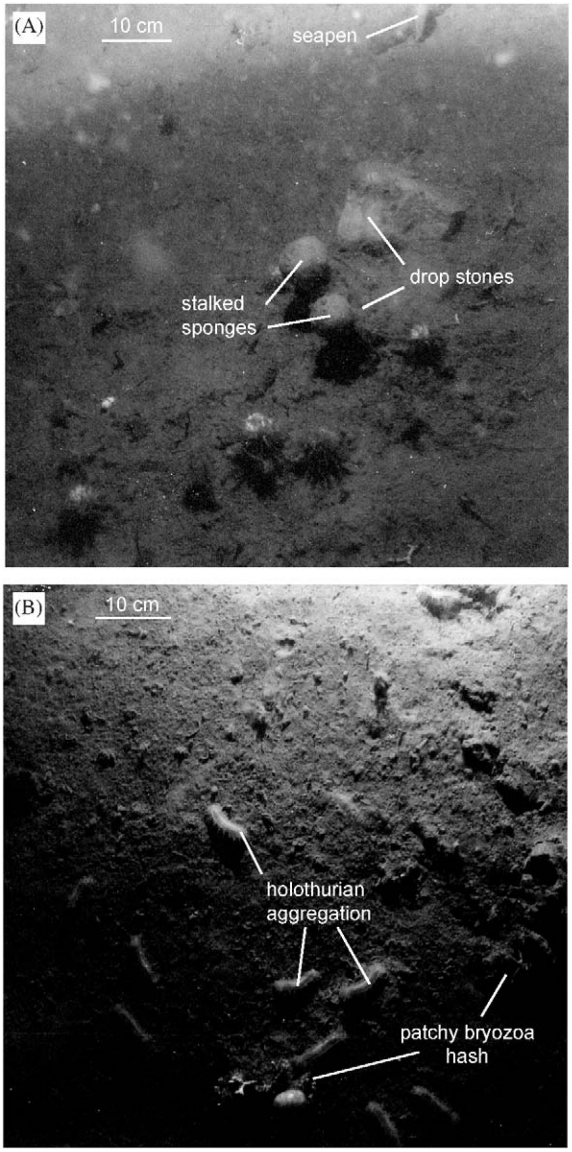

Fig. 17. Underwater photographs from WEGA stations in depths of (A) 814 m and (B) 556 m. Note the concentration of stalked sponges around glacial drop stones in the lower basin, and the holothurian aggregation amongst the patchy bryozoa hash in the upper basin.

graphs 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.

3.5.7. *Detritus-feeder basin*

In the upper basin, between depths of approximately 500–700 m, and following the contours of the George V Basin is a 'detritus-feeder basin' Biotope. WEGA sample GC11 (Table 2), NBP0101 dredge 4DR04 (Table 3) and AAE trawl TR22 (Table 4) 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 favor detritus-feeding holothurians (Gutt, 1991; O'Laughlin et al., 1993). Fig. 17B shows a dense aggregation of approximately 10 cm long holothurians, possibly *Mesothuria bifurcata*, an Aspidochirotida sediment feeder (P.M. O'Loughlin, 2000, pers. comm.). 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 toward 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).

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 to 500 m within the lower range of iceberg scour (Barnes and Lien, 1988). The NBP0101 dredge sample 5DR05 (Table 3) 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 meters 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.

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 200–400 m. AAE trawl TR23 (Table 4) 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; Massom et al., 2001). The high density of grounded icebergs in these areas would clearly have a major localized 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 (100–200 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, fine-grained sediment from grounded iceberg knick points is possibly transported landward by intruding HMCDW to blanket the seabed at greater depths.

3.5.10. Diverse ridge

A 'diverse ridge' Biotope lies on and around the knolls in depths of approximately 100–200 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 3) 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), 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.

3.5.11. Transitional sill

Linking the George V Basin to the continental slope is the 'transitional sill' Biotope in water depths 400–500 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 1) from 412 m. Forams analyzed 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).

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 400–600 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 s^{-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 favor dense populations of suspension-feeders.

4. Discussion

4.1. Environment–benthos relationships

We consider that the Biotopes described for the George V Shelf address the objectives for this study. The 12 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 characterizing 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 kilometers) 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.

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 colonized 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 favorable 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 localized 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.

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 to 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 favorable (Gutt and Koltun, 1995).

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 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 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 favorable surfaces for deep-basin sessile benthos to colonize on (Malatesta and Auster, 1999).

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 s^{-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 favoring 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 s^{-1}, but does decrease rapidly away from the glacier (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 super-cooled 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 s^{-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 favor 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.

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. However, at the local (10s of kilometers) scale of the bioregionalization conducted, the results of the present study are useful for a wide range of applications.

A key question is what abiotic processes exert the dominant control over the distribution of macrobenthos on the George V Shelf at this scale? (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 localized 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 IRD 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 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 localized 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 favor development of dense suspension-feeders in this area.

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 kilometers) 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 characterized 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 surface modeling on data included maps to assess uncertainty within the predicted models. A study of underwater photographs and the results of limited biological sampling provide 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 kilometers) 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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