Integrating multibeam sonar and underwater video data to map benthic habitats in an East Antarctic nearshore environment

Jodie Smith a,*, Philip E. O’Brien a,1, Jonathan S. Stark b, Glenn J. Johnstone b, Martin J. Riddle b

a Geoscience Australia, GPO Box 378, Canberra, ACT 2601, Australia
b Australian Antarctic Division, 203 Channel Highway, Kingston, Tasmania 7050, Australia

ARTICLE INFO

Article history:
Received 2 December 2014
Received in revised form
5 June 2015
Accepted 26 July 2015
Available online 29 July 2015

Keywords:
Benthic habitats
Multibeam sonar
Vestfold hills
Benthic communities
Video transects

ABSTRACT

An integrated analysis of biological and geoscientific data collected from the nearshore marine environment of the Vestfold Hills was used to identify benthic habitats and associated communities and examine relationships between benthic community composition and environmental characteristics. A 48 km² area was surveyed using a multibeam echosounder system (MBES) to produce high-resolution bathymetry and backscatter intensity maps of the seabed. Epibenthic community data and in situ observations of substrate composition and seafloor bedforms and features were obtained from towed underwater video.

A comparison of top-down and bottom-up approaches to defining benthic habitats was used to improve understanding of the applicability of mapping methodologies. On a broad scale, both approaches produced habitat classes distinguished largely by geomorphic features, with substrate and depth identified as the main controls of benthic community composition, however, the relationship between benthic community composition and environmental characteristics is complex with many variables contributing to differences in community composition.

The top-down approach was based on geomorphic units defined using abiotic characteristics and the assemblages identified within the geomorphic were very broad with only weak distinction between assemblages. Conversely, the bottom-up approach generated additional habitat classes, identified clear defining taxa for each class, greater distinction between the benthic communities, and allowed identification of additional environmental factors (i.e. sea ice cover) that influence benthic community distribution that are not discernible from geomorphic information alone. The habitat types identified and mapped using the bottom-up approach include shallow boulder fields and exposed bedrock which are dominated by dense macroalgae communities, and steep slopes, muddy basins and sandy plains which are dominated by invertebrate communities.

The results indicate that a bottom-up approach is preferable for benthic habitat mapping, however, where detailed information is not available, geomorphic information provides a reasonable indication of the distribution of benthic habitats and communities. This study highlights the utility of multibeam sonar for interpretation of seafloor morphology and substrate and the multibeam data provide a physical framework for understanding benthic habitats and the distribution of benthic communities. This research provides the scientific context and spatial framework for managing the Vestfold Hills nearshore marine environment and provides a baseline for assessing environmental change.

1. Introduction

In general, small human population and coastal watershed size predict light human impact in Antarctica but do not ensure it, as shipping, fishing, and climate change affect even remote locations (Halpern et al., 2008). In fact, Antarctic nearshore marine...
ecosystems are considered to be particularly susceptible to anthropogenic-associated threats, including localised threats around Antarctic stations (e.g. pollution and the introduction of alien species), as well as from global climate change on a broader scale (Aronson et al., 2011; Clark et al., 2013). Despite this, the seafloor environments and associated benthic communities in these nearshore areas remain largely undescribed and unmapped, particularly in East Antarctica.

Mapping seafloor habitat is the fundamental first step necessary for monitoring environmental change and for assessing the impact of anthropogenic disturbance on benthic organisms (Kostylev et al., 2001). Further, maps characterising and representing the distribution and extent of benthic habitats are valuable tools for improving understanding of ecosystem patterns and processes, promoting scientifically-sound management decisions and establishing environmental baselines (Hewitt et al., 2004; LaFrance et al., 2014).

The utilisation of multibeam echosounder systems (MBES) coupled with underwater video has led to a significant improvement in the scale to which seafloor habitats can be identified and in describing their relationships with associated biota (Lucieer et al., 2013). MBES provide continuous coverage of large swathes of seafloor and have an additional advantage of collecting high-resolution bathymetric and backscatter intensity data simultaneously which provides a means to map large areas of the seafloor and delineate them into geological and geomorphological regions (Kostylev et al., 2001; Micaleff et al., 2012). Seabed geomorphology is commonly associated with particular benthic habitats and is known to influence benthic community structure and ecological processes at many spatial scales (Harris and Baker, 2012; Micaleff et al., 2012).

Towed underwater video surveys provide the opportunity to collect fine scale in situ observations over large areas of seabed, with the advantage of simultaneously collecting information on organisms and habitat variables (Anderson et al., 2008). High-resolution datasets are imperative for examining heterogeneity of benthic habitats due to the importance of small-scale processes and interactions in shaping population dynamics and local diversity (Clarke, 1996; Gutt et al., 2013a). Further, these techniques are non-destructive which is particularly valuable when surveying in sensitive areas such as Antarctica where marine benthic assemblages develop at rates many times slower than those in lower latitudes (Bowden, 2005).

Integrating in situ biological and physical data with continuous environmental data layers for the purpose of benthic habitat mapping can be achieved through various approaches (Brown et al., 2011). The location of boundaries between and composition of habitats is highly dependent on the approach taken to integrate abiotic and biotic information (Shumchenia and King, 2010). Traditionally, benthic habitat mapping has employed a “top-down” approach which is based on abiotic characteristics. Full-coverage geophysical data is delineated into geological or geomorphological map units which are then used to identify benthic community patterns (Brown et al., 2011; Hewitt et al., 2004; LaFrance et al., 2014; Shumchenia and King, 2010). This approach is based on the concept that geologic or geomorphic environments contain distinct biological assemblages, however, habitat units which are geophysical in origin may not be biologically meaningful or appropriate for representing biotic–abiotic relationships.

The alternative “bottom-up” approach examines benthic assemblages based on biological similarity, and then establishes statistical relationships with associated environmental parameters (LaFrance et al., 2014; Shumchenia and King, 2010). These relationships are then used to describe and delineate habitat map units. This approach is used to identify discrete biotopes, i.e. a particular physical environment (habitat) and its distinctive biological assemblage (Olenin and Ducrotot, 2006). This approach is more resource intensive, however, it preserves biotic–abiotic relationships and therefore generates habitat maps that are ecologically meaningful and further our understanding of the benthic ecosystem (Brown et al., 2011; Rooper and Zimmermann, 2007; Shumchenia and King, 2010).

The present study aimed to examine the relationship between the seafloor environment and benthic communities in the nearshore marine environment of the Vestfold Hills using an integrated analysis of high-resolution acoustic and biological data. This study focuses on epibenthos communities, i.e. communities of larger plants and animals living on the seabed. From an ecosystem perspective, epibenthic organisms are important in recycling and redistributing organic matter deposited from the pelagic zone, and they also are key members of the local food web. A comparison of top-down and bottom-up approaches for integrating biotic and abiotic data and defining benthic habitats was used to improve understanding of the applicability of the different mapping methodologies, particularly in the data-poor Antarctic nearshore environment. In the top-down approach, benthic habitats were based on the abiotic characteristics of the datasets which were delineated into geomorphic units (O’Brien et al., 2015). In the bottom-up approach, benthic habitats were based on the physical characteristics of discrete biotopes identified from the biota data. Abiotic attributes were derived from the MBES and underwater video, whereas biotic data was obtained from the underwater video observations.

2. Regional setting

The Vestfold Hills are an area of mainland rock and offshore islands on the eastern side of Prydz Bay, East Antarctica (Fig. 1). They cover approximately 400 km² and form one of the largest ice-free areas of the East Antarctic coast. These ice-free areas are rare along Antarctica’s coast, yet constitute important breeding and haul-out areas for many birds and mammals (e.g. Lake et al., 1997; Whitehead and Johnstone, 1990) and represent important sources of shallow-water benthic production (Gillies et al., 2013). Consequently, the Vestfold Hills region represents an important geographic location amongst the coastal regions of East Antarctica. Additionally, the nearshore waters of the Vestfold Hills are adjacent to Davis station, one of the three Australian research stations in Antarctica, and therefore lie within an area of relatively high use.

The nearshore marine environment is a complex of small rocky islands, shallow embayments, narrow fjords, submerged rocks and shoals. The coastline is aligned approximately north-east to south-west. Depressions, infilled with soft, biogenic-rich sediments, are interspersed with outcrops of bedrock or till reflecting an extension of onshore geomorphic environments (O’Brien et al., 2015).

The nearshore waters are covered with sea ice for most of the year. Annual sea ice breakout occurs any time from early December to late January. Break-out occurs progressively from south to north in response to prevailing winds from the north-east and the geometry of the coast (see Fig. 1). The sea ice between the mainland and the islands offshore from Davis often breaks out within a single day (Gibson, 1998). The study area is relatively ice free from January to March. Tides are small, with a mean tidal range of 1.5 m. Water speed and direction has an important influence on nearshore currents when there is no sea ice. The general current offshore runs parallel to the coast from the north-east to the south-west and is part of the East Wind Drift which flows around the coastline of Antarctica. Gibson (1998) suggests water enters the
inshore waters near Davis from between Gardner and Anchorage Islands and exits to the south of Gardner Island, and reports the presence of strong currents flowing through the area. Recent current meter measurements taken near Davis station were strongly correlated with prevailing wind conditions and indicate flow is in a south-westerly direction (unpublished data).

Water temperatures undergo a general cycle of increase from the winter minimum of \(-1.9^\circ C\) to a summer maximum of \(0-1^\circ C\), followed by a rapid cooling in autumn. Salinity exhibits a similar but inverted cycle, reaching a maximum of 34.2–34.5 psu at the end of winter before falling to about 33–33.5 psu in summer as a result of freshwater input from the melting of the sea ice, icebergs and ice shelves (Gibson, 1998).

Complex physical and biological factors drive considerable inter-annual variations in phytoplankton biomass in the inshore waters of the region (Roden et al., 2013). High levels of biological activity are initiated in October with dramatic increases in biological production occurring in early December with peak production occurring from December to February, followed by a decline in March when sea ice forms and light availability diminishes (Roden et al., 2013). The intensity of the bloom in the inshore region is often significantly greater than at sites further offshore. The biological activity results in increased pH and decreased nutrient concentrations in summer (Gibson, 1998).

3. Methods

3.1. Data collection and processing

3.1.1. Multibeam acoustic data

Multibeam bathymetric data were collected by Geoscience Australia from February to March 2010 using the Australian Antarctic Division workboat Howard Burton equipped with a Kongsberg EM 3002D 300 kHz multibeam sonar system. Motion referencing and navigation data were collected using an Applanix Position and Orientation system (PosMV 320), coupled with a C-Nav Differential Global Positioning System (2050R), providing positional accuracy of \(\pm 0.2\) m. A total area of 48 km\(^2\) was surveyed, with coverage of the swaths between 150 and 200% in the main survey area in the shallow waters closest to Davis station. Additional survey lines were run to Long Fjord in the north and to Crooked Fjord and the Sørsdal Glacier in the south (Fig. 1).

The data were processed using Caris HIPS/SIPS v7.1 software. Initial processing of the multibeam data to account for tides, using tidal predictions provided by the Australian Antarctic Data Centre, and vessel motion (pitch roll and heave), and to remove erroneous values was completed during the survey. Final processing was completed after the survey at Geoscience Australia, where more complex artefacts were removed, data were converted to mean sea levels.
level (MSL), and an interpolated bathymetry surface was exported as a 2 m resolution grid for mapping purposes into ESRI ArcGIS 10.0 (Spinoccia and O’Brien, 2013). A slope grid was derived from the bathymetry grid using the Surface tool in the Spatial Analyst Toolbox in ArcGIS.

In addition to the bathymetric data, backscatter intensity data was recorded by the multibeam sonar system. The backscatter intensity data were processed using CMST-GA MB Process v.8.11.02.1, a multibeam backscatter toolbox co-developed by Geoscience Australia and Centre for Marine Science and Technology (CMST), Curtin University for Technology. Backscatter intensity values are calculated following correction for transmission loss and area and removal of angular dependence (see Lucieer et al., 2013 for further details). The final backscatter intensity grid was exported as a 2 m resolution grid (Fig. 2) (Siwabessy, 2013).

3.1.2. Underwater video

A total of 16 underwater video transects (Fig. 1) were surveyed in water depths ranging from 4 to 73 m using a shallow-water Raytech towed-video system during the 2010 multibeam survey (Geoscience Australia, 2010). The camera system consisted of a forward-facing video camera and associated lights and was deployed from the stern of the Howard Burton and towed at 0.5 to 3 knots. A small electro-hydraulic winch was used to maintain the video system at an altitude of 0.5–2 m above the seabed. A live video feed transmitted via a coaxial cable to a monitor on the vessel was used to guide winch operations in maintaining a consistent height above the seafloor. The video feed was recorded to mini DV tapes which were later copied to digital format. The UTC time stamp overlay on the imagery allowed correlation to the workboat position data.

Seabed habitat and biota were characterised using the 3-tiered characterisation scheme of Anderson et al. (2008) that records substrate composition, bedforms and features, and biota presence. The video was evaluated for a 10 m segment to characterise the seabed, with a 10 m interval between each segment. Substrate composition was categorised by primary and secondary percent-cover, while all other parameters were recorded as presence/absence within the segment. All observations were entered into a Microsoft Excel spreadsheet via a programmable keyboard. Video quality was variable and affected by abundant phytodetritus in the water column, therefore biota categories were taxonomically simple (e.g. sponge, sea star, gastropod). One infaunal bivalve species (Laternula elliptica) was also included as a discrete category as it was both easily identified in the video (unlike other infaunal species) due to its large siphons, and it was clearly a large biomass, as is commonly found in Antarctic coastal environments (Ahn, 1994; Philipp et al., 2011; Urban and Mercuri, 1998). Similarly, the brown macroalgae Himantothallus grandifolius was assigned to a discrete category because it was easily distinguishable and was
abundant throughout whereas differentiation of red macroalgae species was not possible based on video observations so these were grouped.

Underwater photos were taken by divers at a number of sites during this study, and although not analysed and presented in this paper, they were used to assist with benthos identification and provide supporting evidence for some of our findings.

Data from the video were analysed as single observations from each 10 m segment, with a total of 644 discrete observations. Each observation contained presence/absence values for all taxa recorded as well as presence/absence values for each primary (>50%) and secondary (>20%) substrate (rock, boulders, cobbles, pebbles, gravel, sand, mud), biological cover (barren, low, moderate or high) and bedforms and features (dropstone, hummocky, ripples, recent iceberg scour, relict iceberg scour, mound, ridge, shell hash, bioturbation). The primary and secondary substrate variables were converted to single continuous variables for each substrate type. Iceberg scour-related bedforms (recent scour, relict scour, mound, ridge, shell hash) were combined into a single variable (‘scour feature’). Taxa richness was calculated as the total number of different taxa per observation.

Latitude and longitude values for each observation were extracted from the workboat positioning system and were plotted in ArcGIS. The 2 m bathymetry, slope and backscatter intensity grids, and the geomorphic map produced by O’Brien et al. (2015), were added into the ArcGIS map. The mean depth, backscatter intensity and slope were calculated within 10 m neighbourhoods to coincide with the video characterisation using Block Statistics tool in the Spatial Analyst Toolbox in ArcGIS. A 10 m neighbourhood was chosen as an appropriate scale at which major geophysical changes and boundaries across the study area were still visible in the acoustic data. The depth, backscatter intensity and slope, as well as geomorphic unit, were then extracted for each observation. The final data were compiled into biota (taxa presence/absence) and environmental datasets containing 27 and 16 variables respectively for multivariate analysis. Additional variables including overall biological cover, taxa richness, bioturbation and geomorphic unit were used as exploratory variables only.

3.2. Integration of datasets

In this study, we used two methods to integrate the biological and environmental datasets, assess biotic–abiotic relationships and map habitat units. In the top-down approach, the environmental data was summarised into geomorphic units and biological community patterns within these units identified. In the bottom-up approach, we identified benthic assemblages based on biological similarity and then identified relationships with associated environmental parameters to determine habitat boundaries.

Multivariate statistical analyses were applied to the datasets using PRIMER v.6 (Clarke and Gorley, 2006) unless otherwise noted. Prior to statistical analysis, rare taxa (<2% occurrence) were removed from the biota dataset to reduce the variability caused by these infrequently occurring taxa. A matrix of similarity between observations of biota was constructed using the Bray–Curtis similarity coefficient. The environmental data were checked for normality and skewed data was log-transformed, then the data
were normalised and a Euclidean distance matrix constructed between observations.

3.2.1. Top-down approach

The first step in the top-down process is to establish geologically or geomorphologically-derived map units. In this study, we used geomorphic map units previously defined for this study area by O’Brien et al. (2015). We then determined if the geomorphic units contained distinct benthic assemblages. The analysis of similarities (ANOSIM) test on the Bray–Curtis similarity matrix of biota data was used to test the null hypothesis that there were no significant differences ($p < 0.05$) between benthic assemblages among the geomorphic map units (Clarke, 1993). Pairwise R values derived from these analyses indicate the degree of segregation between groups. Then the similarity percentages (SIMPER) routine was used to characterise the assemblages within each geomorphic unit by the taxa that contribute most to within-environment similarity and among-environment dissimilarity (Clarke, 1993).

To visualise the distribution of biota amongst the geomorphic units, an ordination of biota was performed by means of non-metric multidimensional scaling (MDS) and the observations plotted according to their respective geomorphic units.

3.2.2. Bottom-up approach

The first step in the bottom-up approach was to identify discrete benthic assemblages based on biological similarity. The observations were classified into groups using cluster analysis based on the group-average sorting algorithm. The similarity profiles (SIMPROF) procedure was used to identify significant clusters (Clarke et al., 2008). At a SIMPROF significance threshold of 0.15%, the
revealed that there were no significant differences in physical habitat characteristics between each of the benthic assemblages identified in the cluster analysis and pairwise R values derived from these analyses were used to indicate the degree of segregation between the clusters. An initial analysis revealed that there were no significant differences in physical habitat parameters between several of the assemblages, so several assemblages were combined. To test whether the assemblages within the final biotopes were still significantly different from each other, ANOSIM was used on the Bray–Curtis similarity matrix of biota data. The ANOSIM routine was used to examine the relationships between the benthic assemblages that occupy a unique physical environment. The SIMPER routine was used to characterise the benthic community composition within each of the clusters.

The next step was to examine the relationship between the benthic assemblages and the environmental variables. The aim was to identify discrete biotopes (i.e. distinctive benthic assemblages that occupy a unique physical environment). ANOSIM was used on the Euclidean distance matrix of environmental variables to test for significant differences in physical habitat characteristics between each of the benthic assemblages identified in the cluster analysis and pairwise R values derived from these analyses were used to indicate the degree of segregation between the clusters. An initial analysis revealed that there were no significant differences in physical habitat parameters between several of the assemblages, so several assemblages were combined. To test whether the assemblages within the final biotopes were still significantly different from each other, ANOSIM was used on the Bray–Curtis similarity matrix of biota data. The ANOSIM routine was used to examine the relationships between the benthic assemblages that occupy a unique physical environment. The SIMPER routine was used to characterise the benthic community composition within each of the clusters.

The next step was to examine the relationship between the benthic assemblages and the environmental variables. The aim was to identify discrete biotopes (i.e. distinctive benthic assemblages that occupy a unique physical environment). ANOSIM was used on the Euclidean distance matrix of environmental variables to test for significant differences in physical habitat characteristics between each of the benthic assemblages identified in the cluster analysis and pairwise R values derived from these analyses were used to indicate the degree of segregation between the clusters. An initial analysis revealed that there were no significant differences in physical habitat parameters between several of the assemblages, so several assemblages were combined. To test whether the assemblages within the final biotopes were still significantly different from each other, ANOSIM was used on the Bray–Curtis similarity matrix of biota data. The ANOSIM routine was used to examine the relationships between the benthic assemblages that occupy a unique physical environment. The SIMPER routine was used to characterise the benthic community composition within each of the clusters.

The next step was to examine the relationship between the benthic assemblages and the environmental variables. The aim was to identify discrete biotopes (i.e. distinctive benthic assemblages that occupy a unique physical environment). ANOSIM was used on the Euclidean distance matrix of environmental variables to test for significant differences in physical habitat characteristics between each of the benthic assemblages identified in the cluster analysis and pairwise R values derived from these analyses were used to indicate the degree of segregation between the clusters. An initial analysis revealed that there were no significant differences in physical habitat parameters between several of the assemblages, so several assemblages were combined. To test whether the assemblages within the final biotopes were still significantly different from each other, ANOSIM was used on the Bray–Curtis similarity matrix of biota data. The ANOSIM routine was used to examine the relationships between the benthic assemblages that occupy a unique physical environment. The SIMPER routine was used to characterise the benthic community composition within each of the clusters.

The next step was to examine the relationship between the benthic assemblages and the environmental variables. The aim was to identify discrete biotopes (i.e. distinctive benthic assemblages that occupy a unique physical environment). ANOSIM was used on the Euclidean distance matrix of environmental variables to test for significant differences in physical habitat characteristics between each of the benthic assemblages identified in the cluster analysis and pairwise R values derived from these analyses were used to indicate the degree of segregation between the clusters. An initial analysis revealed that there were no significant differences in physical habitat parameters between several of the assemblages, so several assemblages were combined. To test whether the assemblages within the final biotopes were still significantly different from each other, ANOSIM was used on the Bray–Curtis similarity matrix of biota data. The ANOSIM routine was used to examine the relationships between the benthic assemblages that occupy a unique physical environment. The SIMPER routine was used to characterise the benthic community composition within each of the clusters.

To visualise the distribution of biota amongst the final assemblages, the observations were plotted in the MDS ordination according to their respective assemblages. The SIMPER routine was then used to characterise each of the assemblages by the taxa that contribute most to within-assemblage similarity and to identify key taxa that contributed greatly to distinctions between assemblages. We then examined the relationships between the benthic assemblages and environmental parameters. A Spearman’s correlation of the biota and environmental matrices using the RELATE procedure, a non-parametric Mantel test, was used to test the null hypothesis of no relationship between multivariate patterns between the environmental and biota datasets (p < 0.05). The explorative BIOENV procedure was used to identify the combination of environmental variables which best explains the variability in the distribution of the taxa between observations (Clarke and Ainsworth, 1993). Spearman rank correlation was used to determine the strength of the relationships. Canonical Correspondence Analysis (CCA) using the CANOCO (v5.03) program (ter Braak and Smilauer, 2012) was used to determine the combinations of environmental variables that were most strongly associated with the benthic assemblages (ter Braak, 1986). An initial, exploratory CCA was performed using all 16 environmental variables. Rare taxa were down-weighted and Monte Carlo tests using 999 random permutations were carried out to test the significance of each index variable. Four of the variables (mud, scour, ripples and dropstone) were not significant in the ordination (p > 0.05) and were subsequently removed from the analysis. A second CCA with the 12 remaining variables was completed using forward stepwise selection to select the variables that best explain the variation in taxa composition. At each step, the analysis reviews all the variables and includes those which contribute most to the discrimination. The biotopes were summarised in terms of their biological characteristics, including key taxa, identified by the SIMPER analysis, overall biological cover, taxa richness and bioturbation; environmental characteristics, including depth, substrate type, slope, bedforms and features; and geographic location. For each biotope, box plots showing the range and distribution of abiotic variables were computed.

### 3.3. Benthic habitat mapping

A benthic habitat map was created in ArcGIS based on the physical habitat characteristics of the biotopes identified using the bottom-up approach. A map based on the geomorphic units used in the top-down approach is available in Fig. 6A and in O’Brien et al. (2015).
Due to inadequate spatial coverage, the environmental data from the video could not be interpolated across the study area. Therefore, the benthic habitat map was created using only full coverage acoustic and geospatial variables (bathymetry, backscatter intensity, slope, latitude, longitude). Thresholds in these environmental variables were derived from the box plots and used to define the initial habitat boundaries. Using just these boundary conditions, a large proportion (58%) of the study area could not be classified. Therefore, areas on the map where abiotic conditions were not representative of any of our video observations were manually interpolated and shaded to indicate a lower level of confidence. Areas to the north, south and deeper waters in the western part of the study area were mapped as undefined as underwater video observations in these areas were unavailable to adequately predict the habitat classes.

To simplify the map and remove small-scale irregularities produced as a result of the high-resolution datasets, small polygons (≤5000 m²) were merged with larger polygons to produce a final habitat map. The habitat classes were colour-coded and labelled to illustrate the biotic—abiotic relationships. Therefore, each class is described by the dominant physical habitat characteristics and benthic community.

4. Results

4.1. Seabed characteristics

The bathymetry data reveal the inshore waters along the Vestfold Hills coast are very shallow (<10 m). Immediately offshore from Davis station, water depths increase to approximately 60 m within 5 km of the coastline with deeper waters further offshore (Fig. 1). Water depths increase rapidly to >200 m at the mouths of Long and Crooked Fjords. The seabed displays heterogeneous bottom topography with shallow bedrock outcrops and shoals, steep escarpments and flat plains interspersed between large deeper basins. The backscatter intensity mosaic (Fig. 2) reveals substrate composition is also highly heterogeneous across the study area. Exposed bedrock and other hard substrates (e.g., boulders and cobbles) constitute a locally rough seabed that returns high-amplitude backscatter intensity values (typically −3 to −11 dB). By contrast, soft muddy substrate constitutes a locally smooth seabed and returns low-amplitude backscatter intensity values (typically −22 to −40 dB). Sand, or sand mixed with coarse unconsolidated material (pebbles or gravel), returns intermediate backscatter intensity values (typically −11 to −22 dB; Fig. 2). Areas of highest relief occur on the slopes of the bedrock outcrops. The coastal embayments, depressions and plains have flat or low relief. Hummocky terrain, identified from the underwater video, is common among boulders in the Airport Beach embayment. Further details of the relationships between the physical variables and geomorphic units are published in O’Brien et al. (2015).

Abundant iceberg scours are evident in the bathymetry image in areas of muddy basins. Recent and relict iceberg scours identified in the underwater video are distributed throughout the survey area in water depths ranging from 6 to 42 m. However, other seafloor features often associated with scours, including ridges, mounds, shell hash and barren cover were found to occur at depths ranging from 5 to 68 m.

4.2. Data integration — relationship between physical and biological data

4.2.1. Top-down approach

The top-down classification separated the study area into six geomorphic units (basin, bedrock outcrop, pediment, embayment, valley, scarp; Table A.1) and video observations occurred within five of these units. The analysis of similarity (ANOSIM) shows that overall, there are weak but significant differences in benthic community composition between the five geomorphic units (Global R = 0.304; p = 0.001). Pairwise comparisons revealed there were only very weak differences in benthic community composition between bedrock outcrop and valley (R = 0.129, p < 0.05) and pediment and valley (R = 0.135, p < 0.05), however, there were only 8 observations recorded in the valley unit. All other pairwise combinations showed significant differences in benthic community composition (p = 0.001) with the greatest degree of segregation in benthic community composition between embayment and valley (R = 0.853). However, the overall degree of segregation in benthic community composition between assemblages was typically moderate to low (R < 0.552).

The SIMPER output indicates the within-environment similarities in benthic assemblages was relatively low (33.63–51.52%; Table 1), indicating there is a high level of variation in community structure between observations within each geomorphic unit. The SIMPER output also indicates which taxa contribute the most towards the benthic community similarity within each geomorphic unit. Key taxa that typify a community have a high similarity/standard deviation ratio (Sim/SD > 1). Only three of the five assemblages identified within the geomorphic units had key taxa that typify the community.

In the basins, bivalves are the most common taxa and are the only key taxa in this unit. Himantothallus grandifolius is common on bedrock outcrops but there are no key taxa in this geomorphic unit; however, Himantothallus grandifolius and red macroalgae combined explain over 51% of the within-group similarity. Similarly, there are no key taxa in the pediment unit, and these areas contain a mix of macroalgae, infaunal bivalves and motile invertebrates. The embayments are dominated by red macroalgae and amphipods, whilst the valleys are dominated by invertebrates, with polychaete tube worms and hydroids the distinguishing taxa (Table 1).

The MDS ordination, plotted by geomorphic unit (Fig. 3A), shows an overall clustering of observations. The high stress value (0.2) for the ordination is due to the high-dimensional dataset and the large number of observations included in the analysis, but indicates the MDS provides a satisfactory representation of the relationship between observations. The plot does reveal some separation in benthic composition between the basin, embayment and bedrock outcrop units, however there is a large degree of overlap. Observations from pediment and valley units show no distinct separation from other units with observations from the pediment unit plotting across the entire ordination and observations from valley typically plotting across the same area as bedrock outcrop. Overall, these results indicate a weak relationship between geomorphology and benthic community composition.

4.2.2. Bottom-up approach

The 644 video observations were initially grouped to form 8 benthic assemblages at a significance level of 0.15%. The initial SIMPER output indicated three of the assemblages were macroalgae-dominated (Algae1; Algae2; Algae3); three of the assemblages were invertebrate-dominated communities (Invert1; Invert2; Invert3); one is dominated by benthic diatoms (diatoms) and one was a relatively barren community with few taxa (barren). Overall, there were significant differences in physical habitat characteristics between these assemblages (ANOSIM Global R = 0.368, p = 0.001); however, pairwise comparisons revealed there was no significant differences in physical habitat parameters between Algae2 and Algae3, Invert3 and Barren, Invert3 and Diatom, and Barren and Diatom. As the purpose was to identify discrete biotopes, the ANOSIM and SIMPER results were used to
combine several assemblages. The Algae2 and Algae3 communities are both dominated by *Himantothallus grandifolius* and are found on shallow, rocky substrates with no significant difference in habitat characteristics, so these were combined into Algae2. Additionally, benthic diatoms were common in both the Diatom and Invert3 communities, and these both occurred in areas of soft substrate in the northern part of the study area, so these were combined into Diatom.

An analysis of similarity of the biota data revealed significant differences in benthic community composition between the final six benthic assemblages (*ANOSIM* Global $R = 0.666, p = 0.001$) and strong and significant segregation in benthic community composition between all assemblages (Pairwise $R$ values range from 0.45 to 0.89, $p = 0.001$). The final six benthic assemblages also had significantly different physical habitat characteristics (*ANOSIM* Global $R = 0.387$, $p = 0.001$), and pairwise comparisons revealed there were significant differences in physical habitat parameters between all assemblages ($p = 0.001$). These results confirm that six discrete biotopes were identified.

The MDS ordination, plotted by the six assemblages (Fig. 3B), reveals distinct groupings within the overall clustering of observations and indicates a continuous change rather than a sharp discontinuity between assemblages. The algae (*Algae1, Algae2*) and invertebrate (*Invert1, Invert2*) communities plot separately on opposite sides of the ordination. Additionally, there is little overlap within these algae and invertebrate communities. Whilst the Barren and Diatom communities appear to overlap with observations from the other communities, a 3-dimensional ordination indicates they plot separately (data not shown) and therefore the six assemblages are distinct from each other.

The SIMPER output indicates the within-assemblage similarities in biota ranged from 43.87 to 56.79% (Table 2), indicating that there is a moderate level of variation in community structure between observations within each assemblage. Each assemblage contained key taxa (i.e. taxa with a Sim/SD ratio $>1$) that typify each community. The inter-assemblage dissimilarity was high ($>61.8\%$) which reflects significant differences in taxa between assemblages.

Results from the RELATE analysis indicate correlation between the taxa and environmental matrices is highly significant ($p = 0.001$). The combination of depth, backscatter intensity, rock, mud, and longitude had the best correlation with the biological data ($pw = 0.404$). Backscatter intensity and depth are the variables with the best result when each environmental variable is considered separately ($pw = 0.297$ and $0.293$ respectively), and substrate-related variables (backscatter intensity, rock, mud and sand) frequently prove useful for discriminating different benthic habitats (Table 3).

Canonical Correspondence Analysis provided a combined ordination of benthic taxa and environmental variables. CCA of the 644 observations produced eigenvalues of 0.272 ($p = 0.001$) and 0.175 ($p = 0.001$) for axes 1 and 2 respectively (Table 4). Both axes capture 16.1% of the cumulative variation in the benthic data and 68.8% of the variance in the benthic–environment relationship. This high level of unexplained variation is typical of ecological gradient analysis and is attributable to (unknown) factors not included in the analysis, as well as the tendency for CCA to explain less variation with an increasingly large number of samples and taxa, an inherent feature of data with a strong presence/absent aspect (ter Braak and Verdonschot, 1995).

The importance of depth, backscatter intensity and longitude is again shown by their long vectors in the CCA plot (Fig. 4). The first canonical axis was negatively correlated with backscatter intensity ($-0.88$) and depth ($-0.69$) and conceptually, these variables describe a gradient of observations belonging to shallow hard substrates on the negative end of axis 1 to deeper muddy basins at the positive end. The second axis was positively correlated with rock (0.68) and slope (0.66) and negatively correlated with longitude ($-0.85$). The gradient along axis 2 represents observations

---

**Table 1**

SIMPER analysis results for benthic assemblages within geomorphic units, defined using the top-down approach. Average abundance values represent the percent of observations within each unit that each taxa is present. Key taxa that typify an assemblage (high similarity/standard deviation (Sim/SD) ratio) are highlighted in bold. A cut-off at a cumulative similarity of 75% was applied. Overall average similarity between observations from each unit is included.

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Characterising taxa</th>
<th>Average abundance</th>
<th>Average similarity</th>
<th>Sim/SD %</th>
<th>Cumulative %</th>
<th>Average similarity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basin</td>
<td>Bivalve</td>
<td>0.78</td>
<td>10.4</td>
<td><strong>1.21</strong></td>
<td>24.21</td>
<td>24.21</td>
</tr>
<tr>
<td></td>
<td>Macroalgae fragments</td>
<td>0.66</td>
<td>7.3</td>
<td>0.84</td>
<td>17</td>
<td>41.21</td>
</tr>
<tr>
<td></td>
<td>Seapen</td>
<td>0.54</td>
<td>5.41</td>
<td>0.63</td>
<td>12.59</td>
<td>53.8</td>
</tr>
<tr>
<td></td>
<td>Urchin</td>
<td>0.52</td>
<td>4.64</td>
<td>0.59</td>
<td>10.79</td>
<td>64.59</td>
</tr>
<tr>
<td></td>
<td>Ribbon worm</td>
<td>0.47</td>
<td>3.43</td>
<td>0.52</td>
<td>8</td>
<td>72.59</td>
</tr>
<tr>
<td></td>
<td>Benthic diatoms</td>
<td>0.4</td>
<td>3.08</td>
<td>0.42</td>
<td>7.17</td>
<td>79.77</td>
</tr>
<tr>
<td>Bedrock</td>
<td>Himantothallus</td>
<td>0.7</td>
<td>11.59</td>
<td>0.87</td>
<td>31.77</td>
<td>31.77</td>
</tr>
<tr>
<td>outcrop</td>
<td>Red macroalgae</td>
<td>0.51</td>
<td>5.85</td>
<td>0.56</td>
<td>16.04</td>
<td>47.81</td>
</tr>
<tr>
<td></td>
<td>Urchin</td>
<td>0.45</td>
<td>3.54</td>
<td>0.47</td>
<td>9.71</td>
<td>57.52</td>
</tr>
<tr>
<td></td>
<td>Polychaete tube worm</td>
<td>0.46</td>
<td>3.41</td>
<td>0.5</td>
<td>9.35</td>
<td>66.88</td>
</tr>
<tr>
<td></td>
<td>Holothurian</td>
<td>0.41</td>
<td>2.53</td>
<td>0.43</td>
<td>6.95</td>
<td>73.83</td>
</tr>
<tr>
<td></td>
<td>Gastropod</td>
<td>0.33</td>
<td>1.85</td>
<td>0.33</td>
<td>5.06</td>
<td>78.89</td>
</tr>
<tr>
<td>Pediment</td>
<td>Macroalgae fragments</td>
<td>0.62</td>
<td>7.09</td>
<td>0.74</td>
<td>21.08</td>
<td>21.08</td>
</tr>
<tr>
<td></td>
<td>Bivalve</td>
<td>0.62</td>
<td>6.69</td>
<td>0.76</td>
<td>19.9</td>
<td>40.99</td>
</tr>
<tr>
<td></td>
<td>Gastropod</td>
<td>0.57</td>
<td>5.97</td>
<td>0.66</td>
<td>17.75</td>
<td>58.74</td>
</tr>
<tr>
<td></td>
<td>Red macroalgae</td>
<td>0.36</td>
<td>2.72</td>
<td>0.37</td>
<td>8.08</td>
<td>66.81</td>
</tr>
<tr>
<td></td>
<td>Himantothallus</td>
<td>0.33</td>
<td>2.25</td>
<td>0.32</td>
<td>6.69</td>
<td>73.5</td>
</tr>
<tr>
<td></td>
<td>Holothurian</td>
<td>0.29</td>
<td>1.27</td>
<td>0.29</td>
<td>3.77</td>
<td>77.27</td>
</tr>
<tr>
<td>Embayment</td>
<td>Red macroalgae</td>
<td>0.97</td>
<td>15.38</td>
<td>2.7</td>
<td>27.17</td>
<td>56.61</td>
</tr>
<tr>
<td></td>
<td>Amphipod</td>
<td>0.84</td>
<td>11.45</td>
<td>1.38</td>
<td>20.23</td>
<td>47.41</td>
</tr>
<tr>
<td></td>
<td>Holothurian</td>
<td>0.74</td>
<td>7.87</td>
<td>1.05</td>
<td>13.9</td>
<td>61.3</td>
</tr>
<tr>
<td></td>
<td>Benthic diatoms</td>
<td>0.72</td>
<td>7.34</td>
<td>0.98</td>
<td>12.97</td>
<td>74.27</td>
</tr>
<tr>
<td></td>
<td>Himantothallus</td>
<td>0.5</td>
<td>3.44</td>
<td>0.56</td>
<td>6.08</td>
<td>80.35</td>
</tr>
<tr>
<td></td>
<td>Polychaete tube worm</td>
<td>1</td>
<td>15.11</td>
<td><strong>2.71</strong></td>
<td>29.32</td>
<td>51.52</td>
</tr>
<tr>
<td>Valley</td>
<td>Hydroid</td>
<td>0.88</td>
<td>11.17</td>
<td><strong>1.64</strong></td>
<td>21.67</td>
<td>71</td>
</tr>
<tr>
<td></td>
<td>Bivalve</td>
<td>0.63</td>
<td>5.81</td>
<td>0.73</td>
<td>11.28</td>
<td>62.28</td>
</tr>
<tr>
<td></td>
<td>Holothurian</td>
<td>0.63</td>
<td>5.38</td>
<td>0.72</td>
<td>10.44</td>
<td>72.72</td>
</tr>
<tr>
<td></td>
<td>Urchin</td>
<td>0.65</td>
<td>5.05</td>
<td>0.72</td>
<td>9.81</td>
<td>82.53</td>
</tr>
</tbody>
</table>
from offshore, sloped rocky areas on the positive end of axis 2 to nearshore flat areas on the negative end of axis 2. The forward stepwise selection procedure shows that the best variables related to biota were backscatter intensity, longitude, sand, depth, latitude and slope, contributing 33.6, 23.7, 9.8, 8.3, 6.4 and 5.7% of the model variation respectively and were highly significant (p = 0.001; Table 5). Boulders, rock, pebbles, gravel, cobbles and hummocky were also significant (p < 0.05) but each contributed less than 5% to the model variation of the benthic—environment relationship.

As both the BIOENV procedure and CCA separately identified depth, backscatter intensity and longitude as major environmental variables in influencing the taxa distribution, the results obtained
with the two different techniques can be viewed with a reasonable degree of confidence.

The biological and physical habitat characteristics of the six biotopes are outlined below and summarised in Table 6. The community composition and key taxa are from the SIMPER analysis (Table 2). The typical environmental characteristics are derived from box plots (Fig. 5) and the spatial distribution of the habitats is shown on the benthic habitat map (Fig. 6).

4.2.2.1. Biotope A: Boulder/Algae1. The Algae1 community is dominated by red macroalgae which occur in dense patches with high overall cover across large areas. Holothurians are commonly found amongst the macroalgae (Fig. 7a) whilst amphipods are commonly found in dense patches on the seafloor. In some areas, benthic diatoms form mats on the unconsolidated sediments. Overall biological cover is moderate, with relatively high richness compared to other communities.

The habitat for this macroalgae-dominated community occurs in shallow water depths (typically <8.1 m; Fig. 5) with mixed substrate (mainly sand and boulders with some cobbles). High backscatter intensity values (>12 dB) indicate a hard substrate which suggests the sand forms a thin veneer over the harder boulder/cobble substrate. The seafloor is typically flat and hummocky, and ripples are common in sandy areas. Large boulders (2 m diameter) are common and sit proud of the seafloor. Sandy areas are bioturbated with abundant pits and tracks and shells are commonly observed on the surface. This habitat predominantly occurs in the coastal embayments and in shallow waters in between the islands and bedrock outcrops closest to shore (Fig. 6).

4.2.2.2. Biotope B: Rock/Algae2. The Algae2 community is a mixed algal assemblage with both Himantothallus grandifolius and red macroalgae common (Fig. 7b). Spirorbid polychaetes are commonly found attached to the macroalgae and encrusting algae and a variety of invertebrates (urchins, gastropods, polychaete tube worms) on rocks in the understory. Biological cover is moderate to high and richness is low.

The habitat for this community is characterised by shallow (<16 m), gently sloping (<5°), exposed bedrock (Fig. 5). This habitat has a broad geographical distribution which typically coincides with the tops of the bedrock outcrops identified in the geomorphic map, as well as shallow areas of exposed bedrock in the pediment and embayments (Fig. 6).

4.2.2.3. Biotope C: Slope/Invert1. The Invert1 community is a mixed invertebrate community dominated by suspension-feeding sessile invertebrates (Fig. 7c) including hyroids, polychaete tube worms and sponges, as well as motile invertebrates such as ribbon worms, holothurians andurchins. Bivalves are also found in areas with softer substrate. Overall, biological cover is moderate and richness is high.

This habitat occurs in the sloped (>3°; Fig. 5) transition zone between muddy basins and bedrock outcrops (Fig. 6B). Video observations reveal a mixed substrate of sand and mud as well as exposed rock and cobbles and this is supported by the intermediate backscatter intensity values (−14 to −24 dB).

4.2.2.4. Biotope D: Basin/Invert2. The Invert2 community is dominated by infaunal bivalves (Laternula elliptica) (Fig. 7d) with macroalgal fragments also common. Biological richness is moderate, with a range of deposit and suspension-feeding invertebrates (e.g. seapens, urchins, gastropods, holothurians and ribbon worms) relatively common, but overall biological cover is low.

This habitat occurs in the muddy basins (backscatter intensity < −20 dB; Fig. 5) both inshore and further offshore (Fig. 6B). Parts of the seabed are bioturbated with pits, mounds and tracks and impacted by iceberg scours.

4.2.2.5. Biotope E: Plains/Barren. The Barren community consists of very few taxa. Macroalgal fragments are common (Fig. 7e) and were often observed drifting rapidly across the seafloor suggesting these are areas of high current activity. Overall, biological cover and richness is low and invertebrates are sparse but predominantly motile (e.g. gastropods).

This habitat predominantly occurs on shallow (<20 m), flat plains such as south of Gardner Island, in the sandy boulder-free areas of the basin.

### Table 5

Summary from CCA forward stepwise selection process.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Explains %</th>
<th>Contribution %</th>
<th>Pseudo-F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backscatter intensity</td>
<td>7.8</td>
<td>33.6</td>
<td>54.7</td>
<td>0.001</td>
</tr>
<tr>
<td>Longitude</td>
<td>5.5</td>
<td>23.7</td>
<td>41</td>
<td>0.001</td>
</tr>
<tr>
<td>Sand</td>
<td>2.3</td>
<td>9.8</td>
<td>17.3</td>
<td>0.001</td>
</tr>
<tr>
<td>Depth</td>
<td>1.9</td>
<td>8.3</td>
<td>15</td>
<td>0.001</td>
</tr>
<tr>
<td>Latitude</td>
<td>1.5</td>
<td>6.4</td>
<td>11.8</td>
<td>0.001</td>
</tr>
<tr>
<td>Slope</td>
<td>1.3</td>
<td>5.7</td>
<td>10.6</td>
<td>0.001</td>
</tr>
<tr>
<td>Boulders</td>
<td>1</td>
<td>4.2</td>
<td>8</td>
<td>0.001</td>
</tr>
<tr>
<td>Rock</td>
<td>0.6</td>
<td>2.7</td>
<td>5.2</td>
<td>0.001</td>
</tr>
<tr>
<td>Pebbles</td>
<td>0.5</td>
<td>2.2</td>
<td>4.1</td>
<td>0.001</td>
</tr>
<tr>
<td>Gravel</td>
<td>0.3</td>
<td>1.3</td>
<td>2.4</td>
<td>0.004</td>
</tr>
<tr>
<td>Cobbles</td>
<td>0.3</td>
<td>1.3</td>
<td>2.5</td>
<td>0.002</td>
</tr>
<tr>
<td>Hummocky</td>
<td>0.2</td>
<td>1</td>
<td>1.9</td>
<td>0.011</td>
</tr>
</tbody>
</table>

### Table 6

Summary of biotopes identified using the bottom-up approach, including the physical and biological characteristics of the benthic habitat and associated biological communities. Median values are provided for depth, backscatter intensity, slope and number of taxa. Primary/secondary (plus minor) substrate types are indicated. Note: shells indicates intact or large fragments of shell material (predominantly Laternula elliptica shells), shell hash indicates abundant small loose shell fragments.

<table>
<thead>
<tr>
<th>Habitat/Community</th>
<th>Depth (m)</th>
<th>Substrate</th>
<th>Backsc. Intensity (dB)</th>
<th>Slope (◦)</th>
<th>Bedforms and features</th>
<th>Cover</th>
<th>Taxa richness (n)</th>
<th>Dominant benthic community</th>
<th>Major geomorphic unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boulder/Algae1</td>
<td>7</td>
<td>Sand/boulders (cobbles)</td>
<td>−10</td>
<td>1</td>
<td>Hummocky, ripples, shells, bioturbation</td>
<td>Mod 6</td>
<td>4</td>
<td>Macroleg, motile invert.</td>
<td>Embayment</td>
</tr>
<tr>
<td>Rock/Algae2</td>
<td>14</td>
<td>Rock (sand/cobbles)</td>
<td>−10</td>
<td>2.6</td>
<td>Shell hash, shells</td>
<td>Mod 4</td>
<td>7</td>
<td>Macroleg</td>
<td>Bedrock outcrop</td>
</tr>
<tr>
<td>Slope/Invert1</td>
<td>25</td>
<td>Mud/sand (rock/cobbles)</td>
<td>−19</td>
<td>4.8</td>
<td>Scours, shells, dropstones</td>
<td>Mod 7</td>
<td>1</td>
<td>Sessile &amp; motile invert.</td>
<td>Basin, Pediment Bedrock outcrop</td>
</tr>
<tr>
<td>Basin/Invert2</td>
<td>23</td>
<td>Sandy mud</td>
<td>−25</td>
<td>1.5</td>
<td>Scours, shell hash, shells, dropstones, bioturbation</td>
<td>Low 5</td>
<td>4</td>
<td>Infaunal, motile &amp; sessile invert.</td>
<td>Basin</td>
</tr>
<tr>
<td>Plains/Barren</td>
<td>17</td>
<td>Sand (pebbles)</td>
<td>−13</td>
<td>1.7</td>
<td>Scours, shell hash, shells, bioturbation</td>
<td>Low 4</td>
<td>4</td>
<td>Motile invert.</td>
<td>Pediment</td>
</tr>
<tr>
<td>Ice/Diatoms</td>
<td>17</td>
<td>Sandy mud</td>
<td>−23</td>
<td>1.7</td>
<td>Scours, bioturbation</td>
<td>Low-high 4</td>
<td>4</td>
<td>Benthic diatoms</td>
<td>Basin</td>
</tr>
</tbody>
</table>

J. Smith et al. / Estuarine, Coastal and Shelf Science 164 (2015) 520–536
areas of Airport Beach embayment, and at the mouth of Heidemann Bay (Fig. 6B). The intermediate backscatter intensity values (Fig. 5) support the video observations which show the substrate is primarily comprised of sand, with pebbles occurring in some areas. Scour features are also found in some places.

5. Discussion

5.1. Integrated sampling approach

High-resolution multibeam bathymetry and backscatter intensity datasets in the nearshore marine environment of the Vestfold Hills reveal previously unrecognized seafloor morphological and substrate attributes and provide a framework for understanding the distribution of benthic communities. The integration of these acoustic datasets with physical and biological data from underwater video has enabled identification of important biotic–abiotic relationships. The acoustic and underwater video data reveal a diverse and heterogeneous seabed environment with a complex mosaic of benthic habitats. Geomorphic and topographic complexity of the seabed is the result of glacial and modern processes. The complex coastline and underlying topography contributes to the patchiness of benthic communities.

The nearshore ecosystem of the Vestfold Hills is by no means unique in Antarctica with relatively similar communities found in comparable habitats of other Antarctic coastal regions. The macroalgal communities in the Vestfold Hills nearshore environment
are dominated by *Himantothallus grandifolius* and red macroalgae. *Iridaea cordata* is the most common and widespread red macroalgae found in the study area but other algae species including *Phyllophora Antarctica*, *Palmaria decipiens*, *Desmarestia menziesii*, *Chaetomorpha spp.*, *Monostroma spp.*, and *Gymnogongrus spp.* are also present. Benthic diatoms are found in the study area and often form dark mats on the substrate. The invertebrate communities identified in this study resemble the mixed assemblages defined by Gutt (2007) where a considerable proportion of sessile fauna coexists with mobile and infauna.

A number of previous studies have attempted to identify and explain distribution trends in benthic assemblages and habitats in Antarctic coastal regions (see Clarke, 1996; Gutt, 2007; Gutt et al., 2013b; Knox, 2007 for an overview of these studies), however, there have been very few quantitative studies in nearshore areas of East Antarctica relating benthic communities to the abiotic environment. Several studies (e.g. Hamada et al., 1986; Nakajima et al., 1982; Tucker and Burton, 1988) have reported a relationship between benthic communities and substrate or depth, but these conclusions have been based on observations from very few sites and limited information on the physical environment. Studies by Propp (1976) and Gruzov and Pushkin (1970) involved extensive dive programs but their findings are descriptive in nature with no quantitative data provided. Other studies have provided quantitative data and tested biological relationships, however they have been restricted in their scope by examining only one particular substrate type (Johnston et al., 2007; Stark, 2000) or limited environmental parameters (Everitt et al., 1980). This is the first study that has investigated benthic assemblages across a range of habitats in a nearshore marine environment in East Antarctica and related benthic communities to a number of environmental parameters using high resolution datasets and multivariate statistics.

This study used a comparison of top-down and bottom-up mapping approaches to integrate the environmental and biological data and define benthic habitats. The two approaches produced habitat classes with distinct benthic assemblages, however, the assemblages identified within geomorphic units using the top-down approach were very broad (ANOSIM Global R = 0.304) with few characterising taxa, and showed weak segregation between assemblages. This indicates that broad-scale geomorphic features likely influenced the composition of benthic assemblages, but did not reflect the more fine-scale abiotic and biotic factors affecting habitat preferences. Some of the geomorphic units encompass a range of different habitat types, potentially grouping distinct biological assemblages. For example, the bedrock outcrops include areas of relatively flat, exposed bedrock as well as steep-sided slopes with coarse unconsolidated material. These two habitats support different benthic communities (Algae2 and Invert1 respectively) but these are combined in the top-down approach into a single geomorphic unit (i.e. bedrock outcrop), thereby losing key biological information.

Overall, the results indicate the geomorphic units only provide a broad representation of benthic habitats, with additional environmental factors likely to be important. This is similar to other studies (Brown et al., 2002; Eastwood et al., 2006; Hewitt et al., 2004; Shumchenia and King, 2010; Todd and Kostylev, 2011) which have found mixed results establishing strong biotic-abiotic connections using the top-down approach. In general, the top-down approach often over-simplifies habitat classes and creates classes with a higher level of biological variability, indicating the biological communities are influenced by environmental factors not captured in the broad-scale habitat units used in this approach (LaFrance et al., 2014).

The bottom-up approach, based on multivariate statistics, discerned finer-scale habitat characteristics and was biologically-driven. This approach produced a more well-defined set of assemblages compared with the top-down approach (ANOSIM Global R = 0.666), with key characterising taxa identified in each assemblage and greater segregation between assemblages (Pairwise R values: 0.45–0.89). On a broad-scale, the bottom-up approach produced habitat classes largely distinguished by geomorphic characteristics (i.e. substrate and depth), however, the bottom-up approach generated additional habitat classes and enabled identification of additional environmental factors at a finer spatial scale that influence benthic community distribution that are not discernible from geomorphic information alone. Using the bottom-up approach, six discrete benthic habitats were identified, including boulder fields, gently sloping exposed bedrock, slopes with mixed substrate, flat sandy plains and muddy basins. Areas of hard substrate, including the shallow boulder fields and exposed bedrock, form a habitat suitable for macroalgae-dominated communities whilst soft-sediment basins form suitable habitats for invertebrate-dominated communities. Sloped transition areas containing exposed bedrock, often with a sediment drape, and coarse unconsolidated material, form suitable habitat for a range of attached invertebrates with sandy plains are relatively barren except for drifting algal fragments and a few motile invertebrates. Importantly, macroalgae do not inhabit all areas of hard substrate where sufficient light is available for growth. Available slopes, exposed bedrock is dominated by attached invertebrates.

This study has demonstrated that there is a relationship between geomorphology and benthic communities and therefore physical and acoustic datasets are useful for characterising benthic communities across broad scales. Where detailed information is not available, as is often the case in data-poor areas such as the Antarctic nearshore environment, geomorphic information provides a reasonable indication of the distribution of benthic habitats and communities. This type of approach has been used around the world (see Harris and Baker, 2012 for examples) and across large areas of the Antarctic shelf (e.g. Beaman and Harris, 2005). However, the bottom-up approach is valuable in its ability to more clearly define macrofaunal assemblages among habitats, discern finer-scale habitat characteristics, and directly assess the degree of benthic assemblage variability captured by the environmental parameters (LaFrance et al., 2014). This study has shown a number of additional environmental factors are important in controlling the composition and distribution of benthic communities, and to fully capture this information, a bottom-up approach to benthic habitat mapping is needed.

5.2. Factors controlling benthic communities

No single factor alone structures benthic communities and in this study the distribution of the nearshore epibenthos could be best explained by a combination of several of the environmental variables measured, the best being backscatter intensity (i.e. substrate) and depth. Geographic location is also important with longitude identified in the BIOENV analysis and CCA, and latitude identified as significant in the CCA. The fact that so many environmental variables contributed to explaining the benthic assemblage patterns illustrates the complexity of the relationship between habitat characteristics and benthos.

Many of the various factors reported as being important for structuring benthic communities in shallow nearshore Antarctic waters, including sea ice cover (spatial extent and duration), light availability, currents, salinity, ice disturbance, primary production, organic matter flux to the sediments (i.e. food availability), sediment grain size and resuspension, are interrelated (Knox, 2007; Teixidó et al., 2002). All of these factors are of ecological relevance for benthic communities and this illustrates the complexity of relationships between habitat characteristics and benthic
communities. Integrated sampling approaches measuring a variety of variables at high resolution over a broad spatial scale are therefore ideal for understanding benthic community structure and their relationship to habitat characteristics.

According to the BIOENV analysis, only 40% of the variation in the biota dataset could be explained by the environmental variables. This suggests other factors may play an important role in determining benthic community composition in the Vestfold Hills. Indeed, depth itself may not be relevant to the biota but is likely a proxy for other, unmeasured parameters, such as light availability, frequency of disturbance by icebergs or sea ice, currents and food availability. The fact that depth has strong correlation with both the x and y axes on the CCA plot suggests it is representative of several unmeasured depth-dependent parameters. Further, latitude and longitude may also be proxies for other environmental variables which show geographical trends, such as sea ice cover (Clark et al., 2013). Biological factors, such as predation, competition and dispersal, will also account for some of the variability in benthic community composition that abiotic factors cannot account for.

5.2.1. Substrate

This study examined benthic communities across a number of different substrate types. Substrate is important in structuring the benthic communities with backscatter intensity (and the correlated variable mud) and sand, as well as boulders, rock, pebbles, gravel and cobbles to a lesser extent, all significant in the CCA. Discrete differences between benthic assemblages based on substrate characteristics is commonly reported for Antarctic marine environments (Gutt, 2007) and the importance of substrate in this study is consistent with previous studies in the Vestfold Hills area in which similar benthic communities and habitats are described. For example, Everitt et al. (1980) identified species-rich areas with abundant macrophytes; deep anoxic muddy basins with deposit-feeding species, and poorly sorted sands with mainly motile fauna. Tucker and Burton (1988) found flat sandy substrate with motile epifauna; flat muddy substrate dominated by Laternula elliptica; and sloping rock with a diverse invertebrate community. A correlation between sediment and the benthic fauna was also found by Kirkwood and Burton (1988) in nearby Ellis Fjord. This study has confirmed these earlier findings on a broader spatial scale using quantitative datasets rather than field observations at a limited number of sites. Additionally, while this study supports the earlier findings that substrate drives patterns in benthic communities, we also found that other environmental drivers are also important.

5.2.2. Sea ice cover and light availability

Two of the habitats identified in this study were characterised by muddy basins supporting mixed invertebrate communities (Invert2 and Diatoms). The habitat characteristics were very similar in terms of morphology and substrate, however the Diatom community is unique in that it is mostly found in the north-eastern part of the study area (Figs. 5 and 6) where sea ice is known to break out later in the summer season. Dense benthic diatom mats are also common in other ice-covered coastal areas in East Antarctica (McMinn et al., 2004). The invertebrates comprising these two communities also differ with infauna (Laternula elliptica) and motile taxa common in Invert2, and sessile taxa common in the Diatom community. Given the limited multibeam and video coverage in this area, the broad distribution patterns of the Diatom community are less known, however, observations from this and previous studies suggest the habitat of the Diatom community is likely to occur more broadly in areas with extended sea ice coverage.

Sea ice cover also largely defines the underwater light environment (Clark et al., 2013) which plays an important role in regulating interactions between macroalgae and invertebrates, thereby affecting the spatial distribution of different communities. In areas receiving adequate light, sessile invertebrates are often outcompeted by algae. Consequently, macroalgal beds are generally found in areas where sea ice breaks out early in summer and conversely, areas where sea ice remains for most of the year are often inhabited by diverse shallow-water invertebrate communities (Johnston et al., 2007). The annual breakout of ice is usually rapid across the study area so differences in benthic communities as a result of duration of sea ice cover are difficult to distinguish. However, photos taken by divers during this study and observations by Kirkwood and Burton (1988) indicate the north-eastern part of the study area around Long Fjord, where sea ice is known to persist for longer periods, is dominated by sessile, filter-feeding invertebrates and is mostly devoid of macroalgae.

Sea ice cover, and subsequently light availability, may be a dominant factor in controlling benthic communities and this suggests that latitude and/or longitude may be a proxy for sea ice cover in this study. Cummings et al. (2006) also suggested latitude may be a surrogate for broader scale environmental factors such as sea ice cover in a study of shallow water locations in the Ross Sea.

5.2.3. Currents and exposure

Gutt (2007) suggests near bottom currents are one of the most relevant environmental conditions when examining biophysical relationships. Currents up to 0.1 ms⁻¹ have been measured (unpublished data) and there is further evidence of strong currents in the study area. For example, channels resembling drainage features occur south of Gardner Island and suggest this is an area of high current activity (O’Brien et al., 2015). Video observations in this area reveal a relatively barren underwater landscape with sandy sediments, limited biota and large macroalgal fragments drifting rapidly across the seafloor. In other areas, such as immediately offshore from Davis station and in shallow waters in the north of Airport Beach embayment, phytodetritus was commonly observed deposited on the sediment surface and on the thalli of macroalgae, indicating a low current velocity. Soft sediments may also be a proxy for currents with sediment accumulation typically greater in areas of reduced currents (Johnston et al., 2007). Therefore, low backscatter intensity values, indicative of soft sediments, may also indicate areas of reduced currents.

The complex coastline and bottom topography likely contributes to variability of currents across the study area. Major wind events play an important role in the advection of water into the area and sea ice will protect the water from wind and reduce current flow (Gibson, 1998). However, the role of currents in structuring benthic communities in the nearshore waters of the Vestfold Hills remains unclear and represents an area of future research.

5.2.4. Disturbance

Disturbance by ice, including sea ice which directly affects the intertidal zone, scouring by icebergs and the formation of anchor ice, has been proposed as the single most important physical variable influencing the ecology of the benthic flora and fauna in the shallow water marine environment in Antarctica (Clarke, 1996). The multibeam bathymetry image reveals abundant iceberg scours in the muddy basins offshore from Davis (Fig. 1), and the predominate direction of larger iceberg scours reflects the current direction (Gibson, 1998; O’Brien et al., 2015). However iceberg scour features were not a significant factor in benthic community structure in this study (Fig. 4) and there are a number of possible reasons for this. The numerous offshore islands and shallow nature of the inshore environment likely prevents larger icebergs from entering the coastal area and any icebergs are likely to be small and only affect localized areas. Icebergs are reported to rarely enter the
bay east of Gardner Island (Tucker and Burton, 1988) and whilst this contrasts with the abundant scour marks visible in the multibeam image, these scours are of unknown age and it is likely the sediments maintain a long term record with many of these features quite old. Further, these scours are often only low-relief bedforms (<1 m) and may have been re-colonised and are therefore not identifiable in the video. Overall, these factors result in a poor relationship between scour features and benthic communities in this study. This is in contrast to other areas where larger icebergs have caused massive disturbance to benthic communities on the continental shelf in waters up to several hundred metres deep (Barnes and Conlan, 2007; Post et al., 2010).

5.3. Benthic habitat mapping approach

The purpose of the mapping effort was to synthesise all available information resulting from the multibeam mapping and underwater video and to create a map that best represented the relationships between physical and biological components of the benthic environment. Habitat units were designed to reflect statistically valid biotic–abiotic relationships. The benthic habitat map created using the bottom-up approach likely reflects the natural gradations in habitat characteristics and, although more complex, likely represents a more ecologically realistic portrayal of the study area compared to the more generalised geomorphic map.

A major disadvantage of the bottom-up approach was the inability to include all significant variables in a full-coverage benthic habitat map. While full-coverage acoustic and point-coverage video datasets were successfully integrated into the statistical analysis in this study, the spatial distribution of the point-coverage video dataset prohibited the inclusion of video-derived environmental variables into full-coverage maps. However, the BIOENV and CCA results show that the acoustic and geospatial variables (backscatter intensity, longitude and depth) explain the majority of the biotic–abiotic relationship, with other video-derived substrate variables (e.g. rock, sand) adding little additional information. Therefore, using only the acoustically-derived variables resulted in a full-coverage habitat classification map that was able to denote the geospatial distribution of habitat classes.

The spatial distribution of the benthic habitats extends beyond the immediate study area. In particular, it is likely the coastal embayment habitat identified in this study extends to other unmapped areas nearby such as Heidemann Bay. Multibeam data and underwater video were not collected there because of the very shallow water depths (<5 m) and visible boulders breaking the surface at low tide. However, Everitt et al. (1980) and Tucker and Burton (1987) sampled shallow sites in or at the mouth of Heidemann Bay and found macroalgae and crustacean-rich (e.g. amphipods) communities on mixed substrate. Photos taken by divers during this study within Heidemann Bay also reveal red macroalgae communities on a mixed sand/cobble substrate. This suggests Heidemann Bay and the Airport Beach embayment have similar substrates and benthic communities.

Both the top-down and bottom-up approaches were found to be suitable for mapping benthic habitats at a broad scale and the most suitable approach depends primarily on mapping objectives and data availability and coverage. The benthic habitat map produced using the bottom-up approach is essentially a model of benthic biotic–abiotic relationships that can be further tested and ground-truthed, and expanded into adjacent areas. Future work should also aim to examine some of the unexplained variability in benthic community composition by incorporating additional environmental variables such as oceanographic parameters, light availability, and nutrient and food supply.

5.4. Environmental management

Maps characterising and representing the distribution and extent of benthic habitats are valuable tools for improving understanding of ecosystem patterns and processes, and promoting scientifically-sound management decisions (LaFrance et al., 2014). The benthic habitat map of the Vestfold Hills nearshore environment provides the scientific context and spatial framework for managing this high-use and vulnerable nearshore environment. Broad-scale mapping is required for marine management and conservation in order to monitor and predict the ecosystem response to potential localised human-disturbances around Davis station, as well as large-scale environmental changes, such as climate-change. This community-level study provides important information on spatial patterns in benthic habitats and provides the basis for further studies on representative components of the ecosystem. Our research provides a baseline for assessing change in the Vestfold Hills nearshore environment and highlights the importance of using biological community data where available to inform management decisions.

Climate-driven shifts in benthic communities are likely to occur in Antarctica. In particular, significant increases in light could potentially switch shallow Antarctic marine ecosystems from invertebrate to algae-dominated states (Clark et al., 2013) and there are already reports of macroalgal colonisation of newly ice-free areas along the Western Antarctic Peninsula (Quartino et al., 2013). Widespread shifts from invertebrate to algal-dominated states in shallow Antarctic waters will reduce coastal biodiversity and alter ecosystem stability and function (Clark et al., 2013). In the Vestfold Hills, macroalgae is currently excluded from areas with extended sea ice cover, e.g. in the northern areas around Long Fjord, and within Ellis Fjord. Therefore, mapping the extent of macroalgal cover and monitoring over time will be an important step for assessing the potential shifts in the dominant benthic communities in the Vestfold Hills. The use of high resolution multibeam datasets enables the spatial distribution of benthic habitats defined in this study to be extrapolated across broader areas and also provides an appropriate mechanism to gather benthic information when sampling is not always available. For example, it is likely that areas of shallow, hard substrate across the broader Vestfold Hills area, excluding areas with extended sea ice cover, support macroalgal communities.

6. Conclusions

This study has demonstrated the utility of multibeam sonar and underwater video for the interpretation of benthic habitats and associated biological communities in an Antarctic nearshore environment. By using an integrated sampling approach, we have significantly enhanced the resolution and spatial coverage of data collection in the Vestfold Hills nearshore marine environment and have greatly increased the scope of marine benthic studies in the shallow coastal waters of East Antarctica.

The acoustic data and observations of the physical environment have enhanced our understanding of the physical habitat characteristics across the nearshore region, including detailed information on morphology, substrate and bedform features. Benthic assemblages have been described across a range of different habitats, with their distribution largely controlled by substrate type and depth. However, the role of other environmental factors such as sea ice cover is clearly important. The region supports a rich benthic community comparable with that of similar habitats from other parts of Antarctica.

The top-down approach to integrating the biotic and abiotic data characterised broad-scale habitats while the bottom-up
approach provided a more detailed and accurate representation of discrete benthic habitats and associated benthic communities. The benthic habitat map summarises the present understanding of the nearshore ecology and represents a first attempt at integration of high resolution geoscientific and biological data over the region. The map provides information to support marine spatial planning efforts and future ecological research and importantly, our research provides a baseline for assessing environmental change in the nearshore region.

Acknowledgements

We thank Ian Atkinson (GA), Ross Bowden, Dean Forrest, Jared Padddison and Steven Swanson (RAN) who assisted with the survey. We also thank Michele Spinoccia, Olivia Wilson and Dr Justy Siwabessy (GA) for assistance processing the multibeam datasets. Thanks also to Dr Alix Post (GA) who assisted with the interpretation and analysis of the underwater video data, and Dr Rachel Przeslawski and Dr Andrew Carrol (GA) for assistance with biological identifications. This research was a component of Australian Antarctic Science (AAS) Project 2201 Natural Variability and Human Induced Change on Antarctic Nearshore Marine Benthic Communities (CI: Martin Riddle). The bathymetry data collection was also under the auspices of the Australian Antarctic Division non-science Project 3259 Hydrographic Charting of Antarctic Waters. We thank Dr Alix Post (GA) and Dr Rachel Przeslawski (GA) for their critical reviews of the original manuscript. We would also like to thank two anonymous reviewers for their useful comments. This paper is published with the permission of the Chief Executive Officer, Geoscience Australia.

Appendix

Table A.1

<table>
<thead>
<tr>
<th>Geomorphic unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basin</td>
<td>Broad, flat to slightly undulating depressions between islands and bedrock outcrops; covered with muddy sediment</td>
</tr>
<tr>
<td>Valley Embayment</td>
<td>Shallow areas close to shore enclosed by peninsulas, islands and shallow silts</td>
</tr>
<tr>
<td>Pediment</td>
<td>Broad flat to gently sloping surface between bedrock outcrops and sediment-filled depressions</td>
</tr>
<tr>
<td>Bedrock Outcrop</td>
<td>Rounded hills and knolls standing higher than the surrounding seafloor</td>
</tr>
<tr>
<td>Scarp</td>
<td>Elongated steep slopes separating areas of relatively flat surfaces</td>
</tr>
</tbody>
</table>

References


Todd, R.J., Kostylev, V.E., 2011. Surficial geology and benthic habitat of the German Bank seabed, Scotian Shelf, Canada. Cont. Shelf Res. 31 (2, Suppl. ment), S54–S68.


