Marine Management Organisation

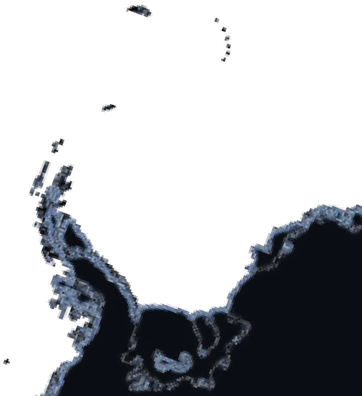
Centre for Environment Fisheries & Aquaculture Science

Funded by UK Government

Benthic biodiversity of the South Sandwich Islands

Results from the Blue Belt Programme

RRS *Discovery* Expedition DY99



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Blue Belt Programme
June 2021

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1. Summary

In 2012 the Government of South Georgia and the South Sandwich Islands (GSGSSI) declared a sustainable use Marine Protected Area (MPA) across more than 1 million km^2 of the Southern Atlantic and Scotia Sea within its maritime zone, this was further enhanced in 2013 and 2018. It is one of the largest marine protected areas in the World.

The South Sandwich Islands forms a significant proportion of the MPA. Despite this, very little was known about the region's benthic environment and the species that inhabit it, particularly the distribution of species and regional diversity. Funded by the UK Government Blue Belt Programme, the Cefas RRS *Discovery* 2019 survey (hereafter referred to as DY99) undertook a systematic survey of the region's benthic biodiversity.

Five islands along the South Sandwich Islands archipelago were sampled. At each island, a deep-water camera system and benthic trawls were used to survey epifaunal species distribution and diversity from 200m to 2,200m. The survey focused on determining trends in species distribution and diversity across both latitudinal and depth gradients to analyse the influence of topography and environment on benthic fauna species and community structure. The analysis presented here represents the first attempt to bio-physically characterise this region providing biogeographical context to the South Georgia and South Sandwich Islands Marine Protected Area.

The South Sandwich Islands are both diverse in benthic fauna and biogeographically distinct from neighbouring islands in the Scotia Arc. The benthic fauna changed from north to south along the archipelago with distinct north and south bioregions in both shallow and deep water. In terms of spatial protection therefore, the analysis supports the MPA objectives to conserve this marine environment along the full South Sandwich Islands latitudinal range.

A gradual reduction of benthic fauna with depth was recorded, punctuated occasionally by dropstones populated with characteristic species. Based on the analysis of the information collected by DY99 and historic surveys of the region's benthic environment, the current MPA design covers a 'representative' range of benthic habitats. The depth range currently open to licenced longline research fishery (700 - 2,250m) is not identified as a distinct bioregion.

Our results are synthesised below into key bullet points of relevance in understanding biogeographical trends across the region and their application in underpinning the current regional marine spatial planning and future design:

- The South Sandwich Islands are both diverse in benthic fauna and biogeographically distinct from neighbouring islands in the Scotia Arc. This is particularly notable given the islands' small shelf area, its young geological age, and that novel species discovery remains high.
- Compositional changes in benthic fauna were observed from north to south along the archipelago: high species diversity was recorded at the northern-most island of Zavodovski and high functional diversity across the south of the archipelago. Consequently, protection along the full latitudinal range is important to include the distinct north-south differences.
- Drop-camera observations suggest a marked change in abundance, faunal composition and vulnerable marine ecosystem (VME) indicator taxa abundance with depth and substrate type. Soft sediment dominates the environment at depths greater than 700m, where low faunal abundance, but distinct faunal diversity, is recorded.
- Mapping outputs show that VME indicator taxa are largely confined to waters shallower than 700m. As such, the current zoning of the MPA (restricting longline research fishing activity to between 700m – 2,250m) provides protection to the majority of the VME species distribution.
- Based on drop-camera observations of areas in which fishing has occurred, benthic communities, and the seabed itself, would not be significantly impacted by the current longline research fishery in the areas surveyed by the expedition.

The data acquired through the DY99 survey contributes to addressing several of the key objectives of the UK Government Blue Belt Programme. These were to improve scientific understanding of the marine environment at South Georgia and the South Sandwich Islands (SGSSI) and to use this information to support the GSGSSI objectives for long-term, sustainable, and evidence-based management of their MPA.

Through more detailed taxonomic identification, the material collected by the survey has the potential to greatly enhance knowledge regarding the diversity and ecology of the marine benthos of the South Sandwich Islands. A series of research studies, within three UK universities, have been realised as part of the survey and will lead to future collaborations and peer reviewed publications. Benthic samples collected during the DY99 survey have been donated to the Natural History Museum to provide a legacy collection that is available to the wider scientific community to improve the knowledge and understanding of the natural history of these remote islands.

2. Project details

Project title: Blue Belt Programme RRS *Discovery* Expedition 99

Personnel: Chris Darby (scientific lead), Caroline Whybrow, Ramon Benedet, Rodney Brash, Anna Downie, Maria Luiza De Carvalho Ferreira, Clement Garcia, Jessica Gordon, Gemma Kiff, Paul McIlwaine (survey scientist in charge), Bill Meadows, Georgia Robson, Christopher Roterman, Marta Soeffker, Rui Vieira, the Officers and Crew of the RRS *Discovery* and their shore-based support staff.

Funding: This report is part of the Blue Belt Programme, funded through the UK's Conflict, Stability and Security Fund (CSSF). The Blue Belt Programme is delivered by the Centre for Environment, Fisheries and Aquaculture Science (Cefas) and the Marine Management Organisation (MMO) with the UK Overseas Territories (UKOTs) on behalf of the Foreign, Commonwealth and Development Office (FCDO) and the Department for Environment, Food and Rural Affairs (Defra).

Framework: The GSGSSI MPA monitoring and development requires scientific information to describe the ecological processes at several key sites; including the data poor area around the South Sandwich Islands. Consequently, in 2019, Cefas chartered the RRS *Discovery* to undertake a survey around the South Sandwich Islands examining the biodiversity and distribution of benthic invertebrate species, and their potential vulnerability to impacts of the licensed longline research fisheries.

License: All survey activities were permitted by the GSGSSI through a Restricted Activity Permit (RAP 2019/003), including sampling within the no-take zones of the MPA.

3. Introduction

3.1 The Blue Belt Programme

The UK's Overseas Territories are home to over 90% of the UK's biodiversity and are of fundamental importance to regional and international marine conservation. The Blue Belt Programme supports the delivery of the UK Government's commitment to enhance marine protection of over four million square kilometres of marine environment across the UK Overseas Territories (UKOTs). The Blue Belt Programme will assist the UKOTs to sustainably manage human activities, based on best scientific evidence and governance structures.

The Blue Belt Programme objectives are to:

- Improve scientific understanding of the marine environment.
- Develop and implement evidence-based, tailored marine management strategies, including novel and effective approaches to surveillance and enforcement across these very remote and sparsely populated areas.
- Ensure management is sustainable and long term.

The Programme is a partnership managed by two agencies of the UK Government, the Centre for Environment, Fisheries and Aquaculture Science (Cefas) and the Marine Management Organisation (MMO). These partners support the UKOTs in sustainably developing their local economies whilst protecting the vulnerable ecosystems which sustain rich marine life. The design of the marine protection measures will be science-based and in accordance with the views of Territory governments and administrations.

3.2 South Georgia and the South Sandwich Islands

South Georgia and the South Sandwich Islands (SGSSI) form a UKOT in the South Atlantic Ocean. South Georgia is a mountainous island, located around 1,300km south-east of the Falkland Islands. The South Sandwich Islands are a chain of 11 volcanic islands positioned 550 - 800km south-east of South Georgia on a roughly north-south axis between 56°S to 60°S (Figure 3.1).

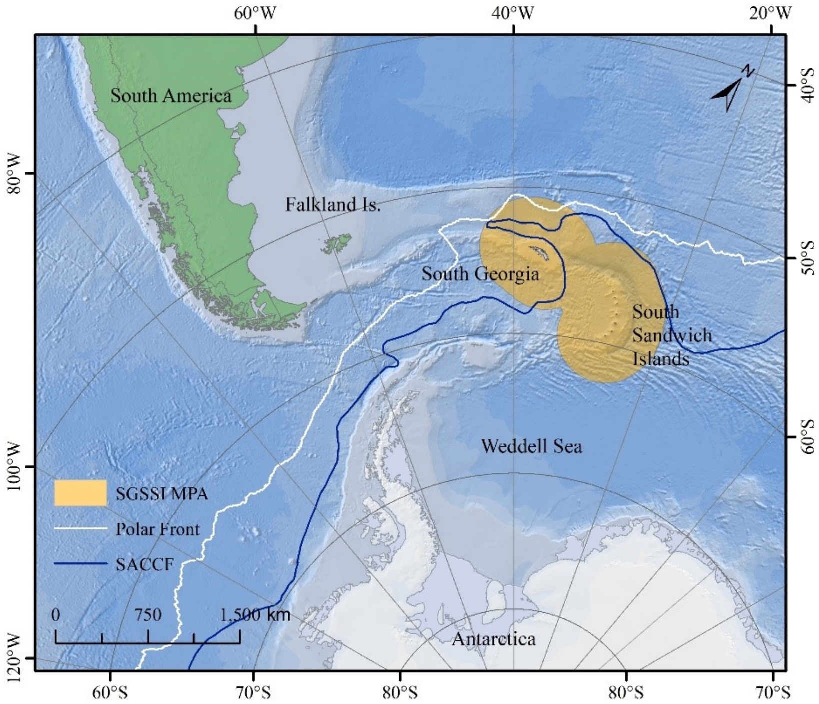

Figure 3.1. The geographical and oceanographic setting of the South Georgia and South Sandwich Islands marine protected area (orange polygon) relative to the Polar Front (white line) and the South Antarctic Circumpolar Current Front (SACCF) (blue line).

Both the South Sandwich Islands and South Georgia are internationally important sites for higher predators, hosting some of the largest populations of seabirds and marine mammals on Earth (Atkinson et al., 2001; Murphy et al., 2007; Clarke et al., 2012; Rogers et al., 2012; Trathan et al., 2014; Rogers et al., 2015). At the South Sandwich Islands this includes the Zavodovski Island Chinstrap Penguin (*Pygoscelis antarctica*) colony estimated to number over one million pairs of birds, or 7.5% of the World population (Convey et al., 1999). Furthermore, South Georgia is recognised as an internationally important site due to its abundant, diverse and unique benthic fauna (Barnes et al., 2011; Hogg et al., 2011). This diversity is thought to be driven by the age of the continental shelf (45 – 20 million years), its geographical isolation, large shelf area and proximity to powerful, nutrient rich currents (Hogg et al., 2011). The South Sandwich Islands zone constitutes over half of the total area of the MPA, yet in contrast to South Georgia, relatively little is known about the benthic biodiversity of the island's waters. This represents a significant gap in our understanding of the region.

At less than 5 million years old (Hawkesworth et al., 1977; Thomson, 2004), the South Sandwich Islands are, in geological terms, relatively young. The volcanoes that form the archipelago developed in situ through the subduction of the South American tectonic plate under the South Sandwich plate (Leat et al., 2016). The region is geographically remote, with

South Georgia and the South Orkney Islands, 800km to the west-south-west, the nearest land masses. Continental shelf area around the islands is limited, with steep-sided volcanic slopes. Small, young and remote, the South Sandwich Islands do not appear predisposed to high benthic diversity.

The South Sandwich Islands marine environment is one of extremes. Volcanic activity creates both disturbed environments resulting from volcanic eruptions and lava flows (e.g., Southern Thule; Griffiths et al., 2008; Rogers, 2015) and highly productive chemosynthetic environments such as the high-temperature black smokers at Kemp Caldera (Rogers et al., 2012; Rogers and Linse, 2014). Bathymetrically the waters range from shallow coastal environments to deep-sea trench (i.e., Meteor Deep – 8,266m). The deep sea is punctuated by seamounts rising to relatively near-surface and providing additional topographic complexity to the region. The archipelago exhibits pronounced environmental gradients with strong latitudinal gradients in seasonal pack ice cover (and thickness), sea-surface temperatures and productivity. Furthermore, the southern boundary of the powerful Antarctic Circumpolar Current (ACC) which flows close to the islands (Figure 3.1) represents a region of ecological importance centred around the upward flux and entrainment of high concentrations of macronutrients (Tynan, 1998). Despite its small size, remoteness, and young age therefore, this spatial and temporal heterogeneity in habitat across the archipelago coupled with regions of high productivity could act as catalysts of a diverse and distinct fauna.

Understanding the structure and function of biodiversity at this potentially important, yet poorly understood sub-Antarctic archipelago is important to identifying the potential ramifications for future environmental change such as regional warming (Whitehouse et al., 2008) and to ensure the representative nature of protection afforded by the MPA. Furthermore, understanding the differences in communities across the MPA can highlight important or distinctive biogeographical zones, providing a framework to effectively manage the region’s benthic environment.

3.3 The Government of South Georgia and the South Sandwich Islands MPA

In 2012 the Government of South Georgia and the South Sandwich Islands (GSGSSI) declared a sustainable use Marine Protected Area across more than 1 million km^2 of the Scotia Sea within its maritime zone (Figure 3.2); the protections were further enhanced in 2013 (Trathan et.al., 2014). As part of the management process of the MPA, the GSGSSI committed to undertake a review of the effectiveness of the SGSSI MPA against its objectives every five years. The first review occurred during 2017 and 2018 (Clubbe, 2018).

Following recommendations arising from the review, GSGSSI designated additional protections across the territory in 2018 (GSGSSI, 2018[1]). The objectives of the SGSSI MPA are to:

- conserve marine biodiversity, habitats and critical ecosystem function.
- ensure that fisheries are managed sustainably, with minimal impact on associated and dependent ecosystems.
- manage other human activities including shipping, tourism and scientific research to minimise impacts on the marine environment.
- protect the benthic fauna from the destructive effects of demersal (bottom) trawling.
- facilitate recovery of previously over-exploited marine species.
- increase the resilience of the marine environment to the effects of climate change.
- prevent the introduction of non-native marine species.

The management plan (see Figure 3.2) comprises complete no-take zones (both benthic and pelagic) extending 30km offshore from South Georgia; 12km exclusion around Shag Rocks and Clerke Rocks; the South Sandwich Trench; and all areas of the MPA south of 60°S.

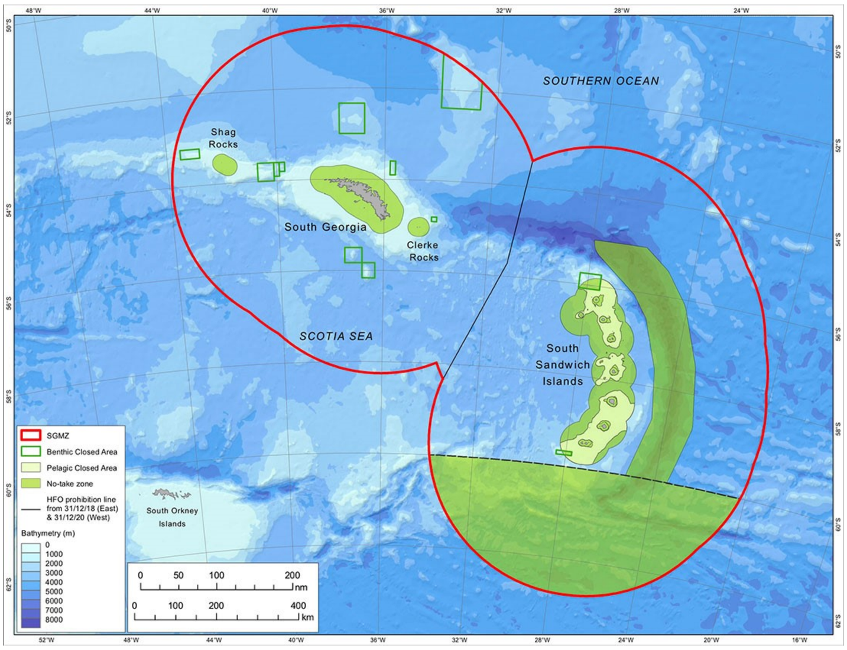

Figure 3.2. The South Georgia and South Sandwich Islands Marine Protected Area (SGSSI MPA). Figure obtained from the SGSSI MPA document[1].

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[1] http://www.gov.gs/32110-2/

At South Georgia and Shag Rocks only the benthic zone between 700m and 2,250m depth outside of benthic closed areas (BCA) is open to a licenced longline toothfish fishery. At the South Sandwich Islands, a no-take zone extends 50km offshore. In this zone the pelagic environment is a closed area, but the benthic environment between 700m and 2,250m depth is open to a licenced research longline toothfish fishery.

3.4 Discovery Expedition DY99 to the South Sandwich Islands

In 2018, having identified a significant gap in understanding of the benthic environment of the South Sandwich Islands, Cefas chartered the RRS *Discovery* to undertake a benthic survey around the archipelago in 2019 (RRS *Discovery* Expedition DY99, hereafter referred to as DY99). The survey set out to examine the biodiversity and distribution of benthic invertebrate species and their potential vulnerability to impacts of the licenced longline research fisheries. The research survey forms part of a wider Blue Belt multi-disciplinary research approach, using a variety of deep-water camera techniques, to establish a monitoring programme to determine the impact of longlines on the benthic environment (Darby, 2019; Darby, 2021).

The objectives of DY99 were supported by the GSGSSI MPA review (Clubbe, 2018), which highlighted that a significant amount of scientific research has been undertaken within the MPA since 2013. This research had greatly increased the knowledge of the biodiversity of South Georgia and the South Sandwich Islands. However, due to their remoteness, there is substantially less information available for the South Sandwich Islands than South Georgia. This was particularly the case for the benthic ecosystem.

The overall aim of the DY99 was to gain a wider understanding of the regional benthic ecosystem at the South Sandwich Islands and thereby provide advice to GSGSSI that would enable it to determine the effectiveness of current management measures and to further enhance its management of the region. The specific DY99 survey objectives were:

Seabed imagery
Collect high-resolution seabed imagery of the benthic environment at the South Sandwich Islands at increasing depth along the length of the archipelago.

Acoustic data collection

Acquire acoustic data throughout the survey transit and from areas of interest to improve information on (i) bathymetry, and (ii) of the pelagic biomass, through the passive collection of water column acoustic data.

Specimen collection

Deploy the Agassiz trawl and / or benthic dredge, following the deployment of the deep-water camera, to enable species identification, collection of samples to determine the genetic connectivity of the region's benthic species and to conduct geochemical analysis of coral skeletons to examine past ocean conditions, growth and biomineralization rates.

Marine mammal observations

Use the opportunity to collect supplementary information on location and abundance of marine mammals to improve understanding of their distribution during the time period of the survey.

The Blue Belt Programme also provided the opportunity to collaborate with research teams in other UK research institutes and universities, with typically more limited access to ship-based research platforms such as RRS *Discovery*. This opportunity was taken up by benthic specialists from the University of Essex, University of Bristol and University of Oxford, working alongside Cefas scientists.

4. Survey narrative

The DY99 survey cruise report (CR146, 2019) provides full details of the survey deployment and logistics.

Scientific staff participating in DY99, joined the vessel on the 14th February 2019, in Stanley Harbour, Falkland Islands. After installation of the survey deep-water camera system, the vessel sailed on the 16th February to the BAS research station at King Edward Point, South Georgia to collect additional equipment and conduct a trial camera deployment in the calm waters of Cumberland Bay. Following these tests, the vessel sailed to the South Sandwich Islands.

After arrival, to the west of Zavodovski Island, South Sandwich Islands, on the 23rd February 2019, ships operations followed, where possible, a standard operational format in each survey area, transiting from the north to south along the island chain (Figure 4.1):

1. After an acoustic assessment of the preliminary bathymetry, the results were used to inform the placement of target stations for the camera deployment.
2. The deep-water camera was deployed to conduct transects, of approximately 30 minutes seabed time, at depths of 200, 500, 750, 1,000 and 1,500m.
3. An Agassi trawl or benthic dredge were then deployed to collect specimens of benthic species in areas and depths determined from a review of the camera footage.

Seabed imagery was acquired from a total of 36 stations and six survey areas during 38 deployments. Operations were curtailed at two stations due to poor weather and equipment failure, resulting in shorter tows and fewer still images.

More than 3,000 specimens were collected from dredge and trawl samples at six stations covering four survey areas in the South Sandwich Islands chain. Of a total 12 deployments (four dredges and eight Agassiz trawls), ten were successful.

Observers undertook a total of 67 hours of marine mammal observations, covering a total of 1,486km (803 nautical miles). A total of 567 marine mammals were counted during these observations.

The vessel departed Cook Island (Southern Thule) and commenced transit back to Stanley Harbour, Falklands Islands on the 3rd March arriving on the 8th March. The scientific team disembarked on the 10th March 2019.

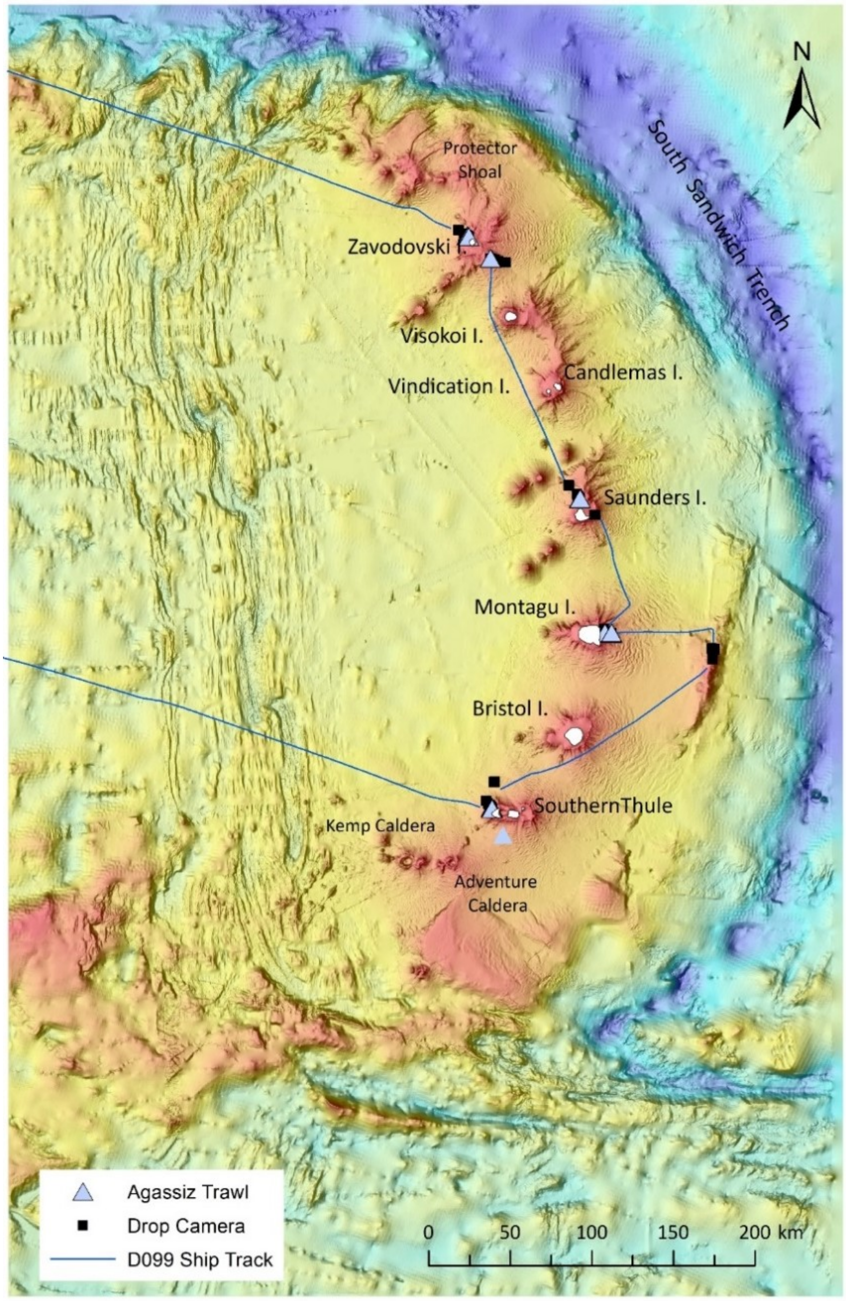

Figure 4.1. The DY99 survey track and sampling locations at the South Sandwich Islands. The base map uses bathymetry data from Leat et al. (2014).

5. Sampling

5.1 Multibeam echosounder bathymetry and backscatter

Multibeam echosounder (MBES) bathymetry and backscatter were acquired using a Kongsberg EM122 operated through the SIS (Seafloor Information Systems) acquisition software. At each of the South Sandwich Islands visited, one (or more) acoustic survey transects were run at 1-6 knots on each side of the island to achieve a depth profile for the area of interest. Bathymetry data were processed using CARIS HIPS and MBES backscatter data with the QPS FMGT software package.

Preliminary bathymetry outputs were produced onboard the ship for survey planning using (e.g., Figure 5.1). Stations were identified and selected to incorporate at least five depth contours: 250, 500, 750, 1,000 and 1,500m, with consideration given to the operational capability of the vessel in prevailing weather conditions and the specific requirements for the safe deployment of drop camera, trawls and dredges. Drop camera deployments, for instance, were restricted to either down-slope orientated run lines or within regions of topographically similar seabed, the latter allowing acquisition in any direction, as the weather and bathymetry permitted. Finalised bathymetry and backscatter grids were processed after the survey and exported as 5m cell-size floating point geotiff files for further analysis (Figure 5.2).

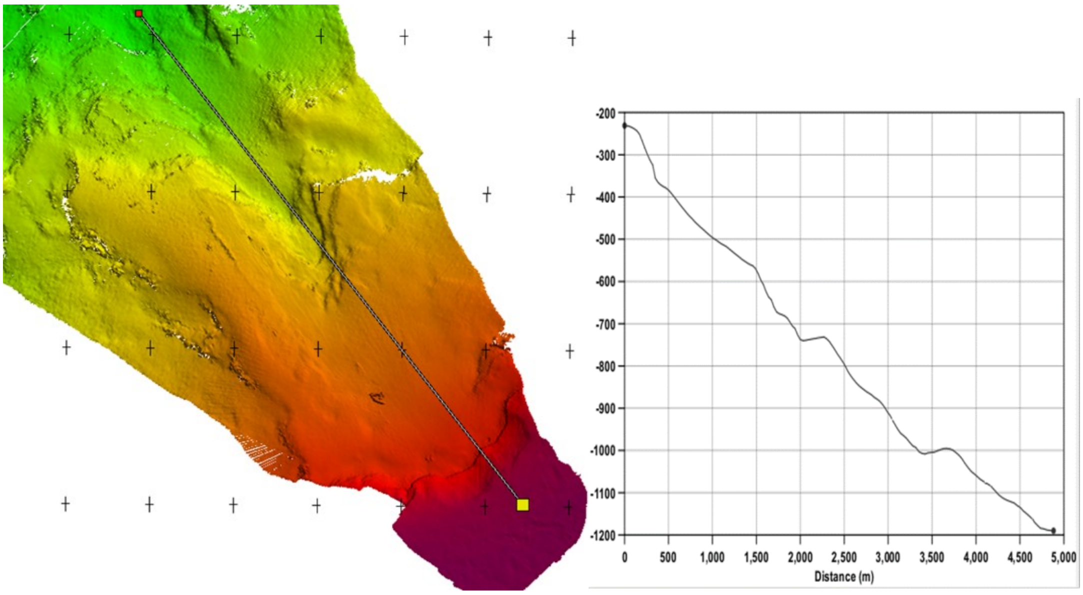

Figure 5.1. Bathymetry of the Saunders Island (west) area of interest, showing the depth profile between two points, generated from the preliminarily cleaned acoustic data from the acoustic processing software, CARIS.

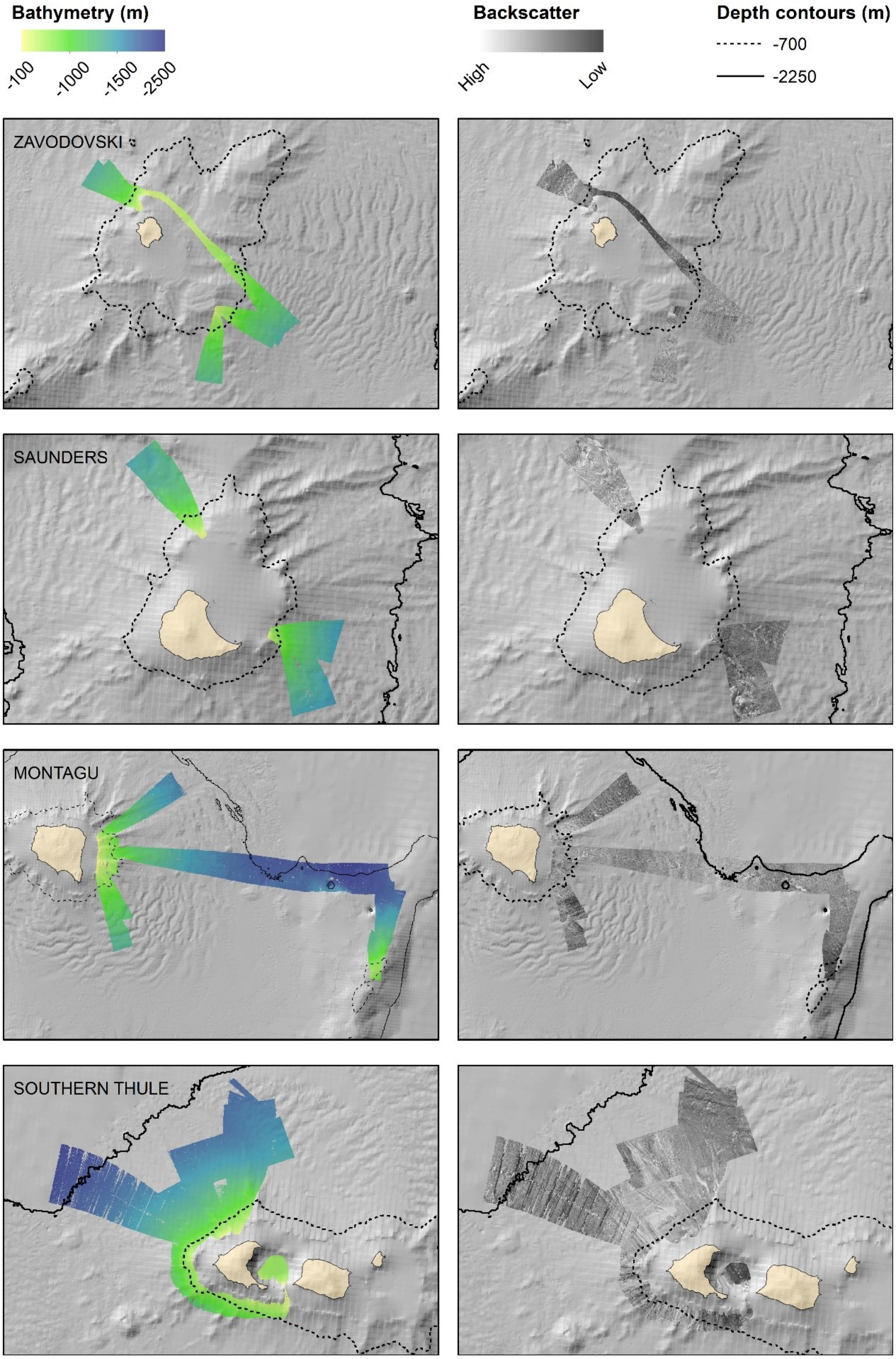

Figure 5.2. Bathymetry and backscatter layers from multibeam echosounder (MBES) data collected at each island. Bathymetric contours shown correspond to the depth range of the SSI longline research fishery with the 700m contour denoted by a dashed black line and 2,250m denoted by a solid black line. Background bathymetry and shorelines from https://www.sggis.gov.gs/ [accessed 29/08/2019].

5.2 Seabed imagery

Video observations were made with a deep-water capable drop-frame camera system (STR Telemetry), which has a separate video camera and still images system. Illumination was provided by four high powered Light Emitting Diodes (LED) and a separate high-powered synchronised flash. The high definition 1080p/25/30fps subsea video camera and 18-megapixels digital stills camera were oriented to provide a forward oblique view of the seabed. The frame also comprised an integrated 250khz precision altimeter, combined compass and depth sensor and was fitted with four dual scaling lasers spaced at 215mm.

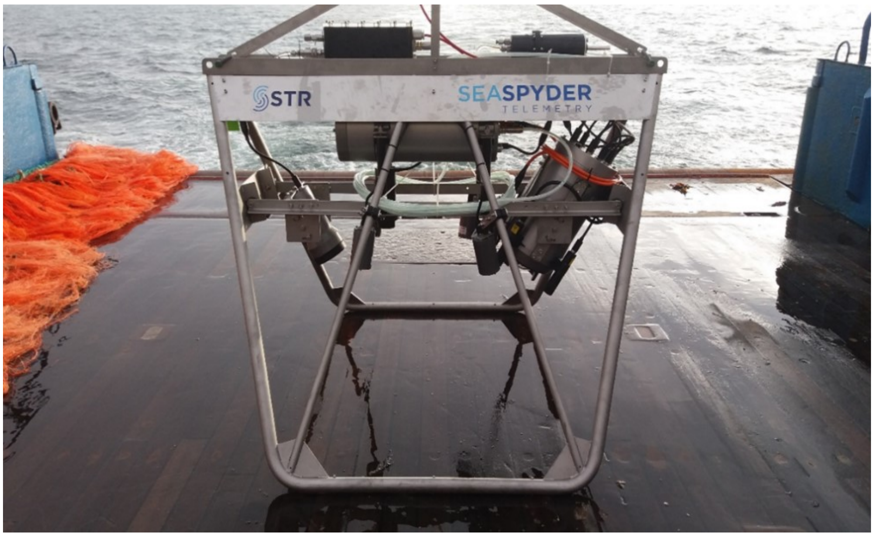

Figure 5.3. The deep-water video and still camera system deployed during DY99. The still and video camera system and laser pointers are mounted on the right with the flash system on the left.

Figure 5.4. Trial deployment of the deep-water video and still camera system from the RRS *Discovery*.

Set-up and operation followed the ‘Mapping European Seabed Habitats’ (MESH) ‘Recommended Operating Guidelines (ROG) for underwater video and photographic imaging techniques’ (Populus et al., 2015). Video and stills data were collected along 30-45 min transects with the vessel moving at a velocity of 0.3-0.5 knots. The transect was centred on the proposed sampling station.

Video was recorded simultaneously to two video capture top side units: one logging Central Reference Point (CRP) and telemetry data and one logging Ultra Short Base Length (USBL) position (as a backup). Recording commenced when the altimeter showed the camera was 30m from the seabed and continued until the end of the tow and arrival back at 30m altitude.

Still images were acquired every 30 seconds (or as close as possible), with the camera positioned no more than 2m off the seafloor, thus maximising the number of high-quality images available for subsequent analysis. At the beginning of each camera transect tow the focus of the stills camera was checked, this was done whilst on or as close as possible to the seabed.

USBL and/or CRP position data, altimeter data and combined compass and depth sensor data were combined to one file. Each still image was linked to coordinates and telemetry data through matching the time stamps in the image Exif file, allowing each individual image to be associated with depth and plotted in space (with an associated position error of between 10-50m).

In total, 28 successful drop-frame camera transects were completed during the survey at the South Sandwich Islands: six at Zavodovski Island, six at Saunders Island, seven at Montagu Island, four at Montagu Bank and five at Southern Thule (Annex 1). A total of 31 hours of video and 4,124 still images were collected (Table 5.1). Transects ranged in depth from approximately 200-2,150m, covering a mix of topography from flat seabed to slopes descending 250m in depth over the 650m of horizontal distance covered. Figure 5.5 shows the depth profiles for each camera transect, derived from combining the depth and altitude data recorded from the sensors on the camera frame.

Table 5.1. Total duration of video footage and number of stills collected from drop camera transects at each of the surveyed areas including two test sites at Cumberland Bay, South Georgia. Further details are provided in Annex 1.

Survey area	Video footage (hh:mm:ss)	Total stills	Deployments
Cumberland Bay	00:58:00	110	2
Montagu Bank	03:15:00	633	4
Montagu Island	05:11:00	760	7
Saunders Island	05:50:00	743	6
Southern Thule	04:43:00	715	5
Zavodovski Island	10:13:00	1,163	6
Totals	**31:10:00**	**4,124**	**30**

5.3 Targeted seabed imagery

The deep-water camera system enables focused research targeting specific areas and questions, collecting detailed and high-quality information, for example, the potential impact of fishing on the seabed substrate and biodiversity. Data on the location of historic longline fishing on Montagu Bank was used to set out two camera transects crossing the locations at which longlines had been deployed and recovered prior to the DY99 survey. After deployment of the camera, the dynamic positioning system on board the RRS *Discovery* was successfully used to transit between the known endpoints where the fishing lines had been deployed.

5.4 Global Navigational Satellite System and corrections

Position fixes were recorded on paper log sheets using the ship-based display, noting both time (UTC) and Central Reference Position (CRP) position as a minimum. The drop camera was deployed from the aft starboard crane. During camera operations, the position of the gear on the seabed was recorded using a USBL positioning beacon. An offset of up to ~10m may occur and the USBL position can be lost entirely in deep water and when the vessel is operating using dynamic positioning. Comparison of the USBL position and the CRP allowed for UBSL accuracy to be determined and a decision made on which was preferable/available for use with georeferencing seabed imagery. Positional data were recorded every second between the start and end of each tow on the top side acquisition suite. Still images were matched, based on embedded Exif time stamps within the renamed '.jpg' file, to the corrected positional data to provide geo-referenced still images.

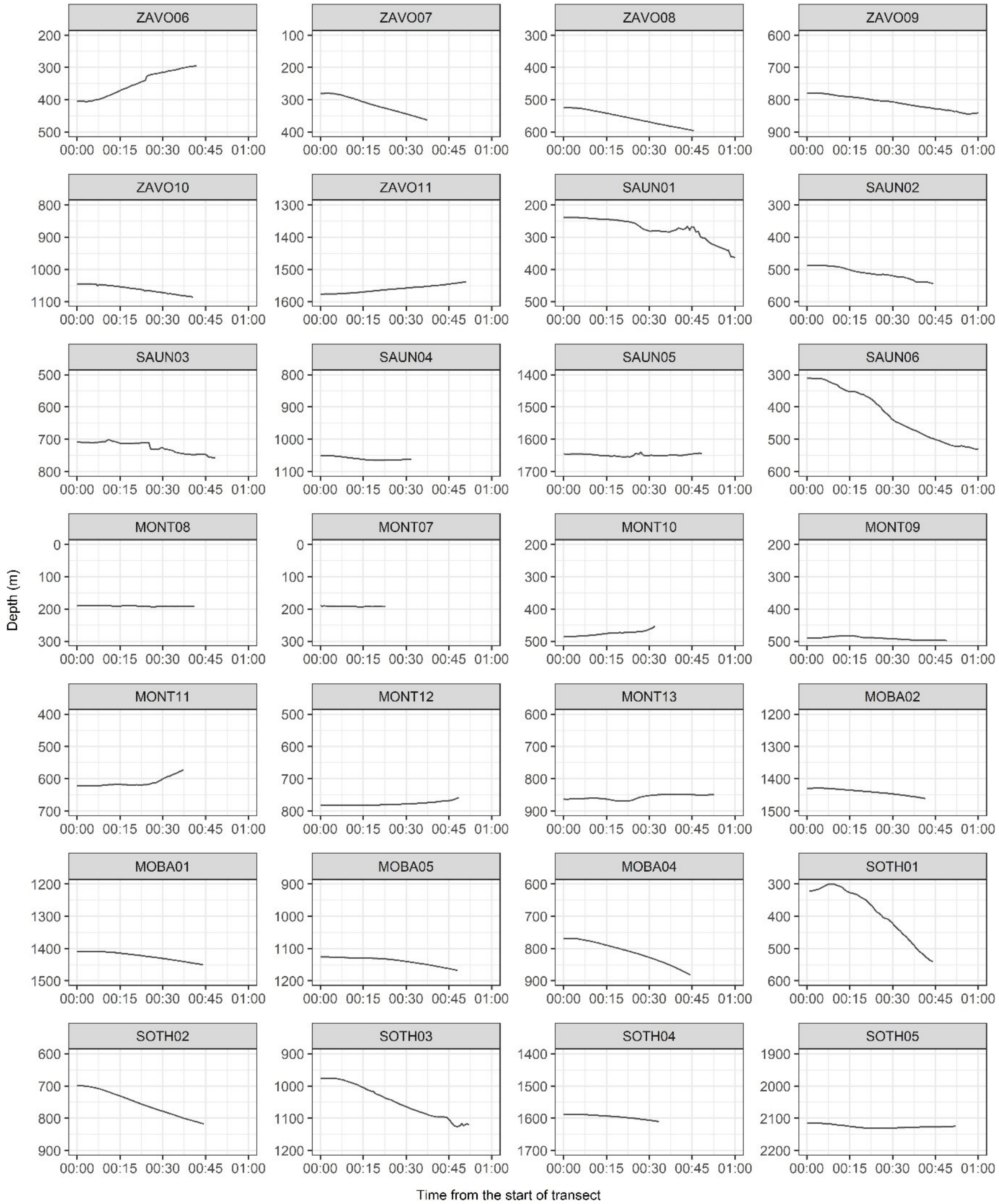

Figure 5.5. Depth profiles for each drop-frame camera transects at Zavodovski Island (ZAVO), Saunders Island (SAUN), Montagu Island (MONT), Montagu Bank (MOBA) and Southern Thule (SOTH).

5.5 Benthic Sampling

A total of 12 trawl deployments were conducted, in 10 locations at different depths ranging from 182 - 843m, four using a benthic dredge and eight using an Agassiz trawl. Of the 12 trawls, ten were considered valid; two were repeat trawls due to fouled gear. The Agassiz trawl is a benthic sampler designed to collect benthic invertebrates and is suitable for application in deep-water environments as the orientation of the gear as it lands on the seabed is not critical for successful specimen collection. The Agassiz trawl comprised 2m x 5mm inner and 40mm outer netting, wire sling bridle and a 5-tonne weak link in case of fouling. The benthic dredge construction was based on the “Hein” dredge design. This robust design is intended for use on coarse sediments and areas of flat bedrock where damage to other towed gears would limit haul success. The benthic dredge comprised a 1m x 2m box frame with steel mesh top and base. The operation of both the Agassiz and dredge involved deployment from a stationary vessel. A 500m pennant wire was used (in water greater than 500m) and the sampler deployed to the seabed. Winch wire was paid out while the vessel manoeuvred to a location between 200 and 500m from the starting location. The gear was recovered to the stationary vessel using the winch wire and the catch assessed and processed accordingly. The position of the dredge and the Agassi trawl deployments were determined using the CRP at the time of deployment and recovery.

Figure 5.6. Recovery of the Agassiz trawl (left) and dredge (right) from the aft deck of the RRS *Discovery* during DY99 showing the bridles, weak links and recovery bridle (dredge).

Specimens were collected from the sampler (muddy samples were sieved over a 5mm mesh) and brought into a constant temperature environment (4°C) and stored in ambient (sea surface temperature) seawater. Individuals were sorted, counted and identified to the lowest possible taxonomic level, provided a unique identification code and ordered for processing.

A representative image of each taxon was taken, along with tissue subsamples, stored in both 100% ethanol and RNA later, for subsequent genetic analysis. Specimens were sorted into major groups and fixed in 4% formaldehyde. After 24 hours, specimens were transferred to 70% ethanol.

Live corals, with a calcium carbonate skeleton deemed suitable for geochemical analysis, were rinsed in fresh water and placed in a 10% bleach solution for approximately 24 hours. After 24 hours they were rinsed to remove bleach and tissue residues. Dead/fossil corals did not require bleaching. Specimens were then air dried, placed in labelled containers and catalogued.

Table 5.2. Sampled stations off South Sandwich Islands during DY99. Stations 7 and 8 were invalid trials with no samples achieved.

Station no.	Station ID	Gear	SOL Lat	EOL Lat	SOL Long	EOL Long	Min depth (m)	Max depth (m)	Date
7	ZAVO02	DGR	-56.2598	-56.2608	-27.6213	-27.6186	490	550	23/02/2019
8	ZAVO01	DGR	-56.2660	-56.2661	-27.6108	-27.6075	234	336	23/02/2019
15	ZAVO07	AGT	-56.3856	-56.3861	-27.3945	-27.3897	280	354	24/02/2019
15	ZAVO07	AGT	-56.3862	-56.3858	-27.3891	-27.3939	279	352	24/02/2019
16	ZAVO07	DGR	-56.3856	-56.3852	-27.3877	-27.3941	262	358	24/02/2019
18	SAUN01	AGT	-57.7076	-57.7051	-26.4910	-26.4863	228	235	25/02/2019
32	MONT07	AGT	-58.4431	-58.4414	-26.2119	-26.2139	182	188	28/02/2019
32	MONT07	AGT	-58.4428	-58.4414	-26.2122	-26.2134	185	190	28/02/2019
33	MONT13	AGT	-58.4462	-58.4420	-26.1451	-26.1452	811	843	28/02/2019
43	SOTH02	AGT	-59.4012	-59.4037	-27.4152	-27.4144	565	646	02/03/2018
44	SOTH01	DGR	-59.4086	-59.4100	-27.4133	-27.4110	295	369	02/03/2019
45	SOTH01	AGT	-59.4085	-59.4101	-27.4133	-27.4109	292	357	02/03/2018

6. Benthic communities of the South Sandwich Islands: drop camera observations and acoustic data

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6.1 Introduction and aims

This chapter presents the outputs from analysis of multibeam echosounder (MBES) acoustic data and drop camera imagery data collected during DY99. The high-resolution video and still imagery from all drop camera tows were used to gain an overview of the epibenthic communities at the South Sandwich Islands. Presence of taxa commonly associated with Vulnerable Marine Ecosystems (VMEs) were recorded for each still image. These VME records were overlaid with bathymetry, topographic features and seafloor acoustic reflectivity (an indicator of substrate hardness), extracted from the MBES data. The distribution of observed VME indicator taxa across bathymetric and topographic gradients were used to quantify the environmental range limits of VME groups. The spatial distribution of the VME indicator taxa was then extrapolated to the extent of the MBES data). This was achieved by applying decision rules based on the observed habitat preferences of VME indicator taxa and using GIS layers of MBES bathymetry and topography to map locations which fell within the known ranges of environmental suitability.

6.2 Analysis of drop camera imagery

A total of 31 hours of video and 4,124 still images were collected on 38 transects. To ensure data quality, the useable area within each still image was defined, to allow the exclusion of dark and blurred edges, and to reduce bias by the camera angle. The use of camera imagery is subject to several challenges, predominantly the identification of taxa within the images without associated physical specimens. Therefore, benthic biodiversity was assessed by means of operational taxonomic units or morphotaxa (Howell et al., 2019). A morphotaxon identification was given, where possible, to each individual observed and later categorised based on morphology. Identifications were based on Rauschert and Arntz (2010), CCAMLR VME Taxa Classification Guide (2009), Benedet (2017), Hogg and Collins (unpublished), Taylor (2011), SCAR Biogeographic Atlas (De Broyer et al., 2014), MBARI online deep-sea species guide (Jacobsen Stout et al., 2020) and by direct consultation with taxonomic experts.

Imagery was analysed in two steps:

1) A qualitative analysis of the conspicuous macrofauna in video and stills was conducted to record a list of the most common taxa on each drop camera tow, as well as notes on where rarely encountered large or sensitive taxa were observed.
2) A subset of taxa was selected for a more detailed analysis of still images, to record the presence of each selected taxon per image.

Selection of taxa for step 2 analysis was based on VME indicator taxa listed in the CCAMLR VME Taxa Classification Guide (2009), with morphologies that are potentially vulnerable to being caught as bycatch or damaged by demersal (bottom) longline fishing.

6.3 Bathymetry and seabed topography from MBES acoustic data

Seabed topography is known to influence the distribution of marine species. Fauna found in muddy basins is very different from sediment banks, or steep outcropping rock. Many commonly used terrestrial topographic attributes calculated using elevation and channel networks can also be used as proxies for attributes of seabed topography. The MBES bathymetry was resampled to 10m resolution and used to generate several derivative layers of relevance to the conditions experienced by marine fauna, using SAGA GIS tools for QGIS (v. 3.2). LS-factor is a combination of slope gradient and length, which predicts erosion potential (Desmet & Govers, 1996). Both slope gradient and LS-factor reflect the likelihood of exposed hard substrata. Steeper slopes are more likely to host attached fauna, which require hard substrata and food-rich currents. Relative slope position (Boehner & Selige, 2006) can be interpreted as a proxy for different current conditions dependent on proximity to the top or bottom of the slope. Positive and negative topographic openness (Yokoyama et al., 2002) provide information on how prominent or sheltered an area is in relation to surrounding topography. Similarly, the wind effect index indicates how exposed an area is (Boehner & Antonic, 2009). In the marine context, instead of wind, the exposure relates to currents and tides. The topographic layers, their units of measure and the tools used to produce them are summarised in Table 6.1. Examples are shown for the west side of Zavodovski Island in Figure 6.1.

Table 6.1. Description of topographic derivative layers calculated from MBES bathymetry

Variable	Measure	Tool
Slope	Radians	SAGA for QGIS – basic terrain analysis
LS-factor	Index value	
Relative slope position	From 0 (bottom) to 1 (top)	
Positive / negative topographic openness	Radians	SAGA for QGIS – topographic openness
Wind effect index	Sheltered < 1 > exposed	SAGA for QGIS – wind exposition index

6.4 Observations of epibenthic fauna

Although analysis is limited to selected epibenthic macrofaunal taxa, observations from deep-water camera deployments provide an insight into changes in faunal composition along latitudinal and depth gradients. The steep slopes of the South Sandwich Islands were dominated by a mixture of suspension and deposit feeders, and organisms living on rock or in sediment. Results from the photo-transects suggest a marked change in abundance and faunal composition correlated with depth and substrate, where hard substrates seem to show a higher number of individuals, taxa and possibly biomass. Benthic epifauna included hard and soft corals, bryozoans and sponges attached to dropstones, and ophiuroids, sea stars and holothurians dominating the soft sediments. Zavodovski and Saunders islands exhibited a larger variety of taxa, dominated by suspension feeding fauna, while the southern region seems to be dominated by generalist deposit-feeders. A summary description of the habitats present at each island is detailed below. Examples of the main benthic epifauna and features of interest observed at each station are also included.

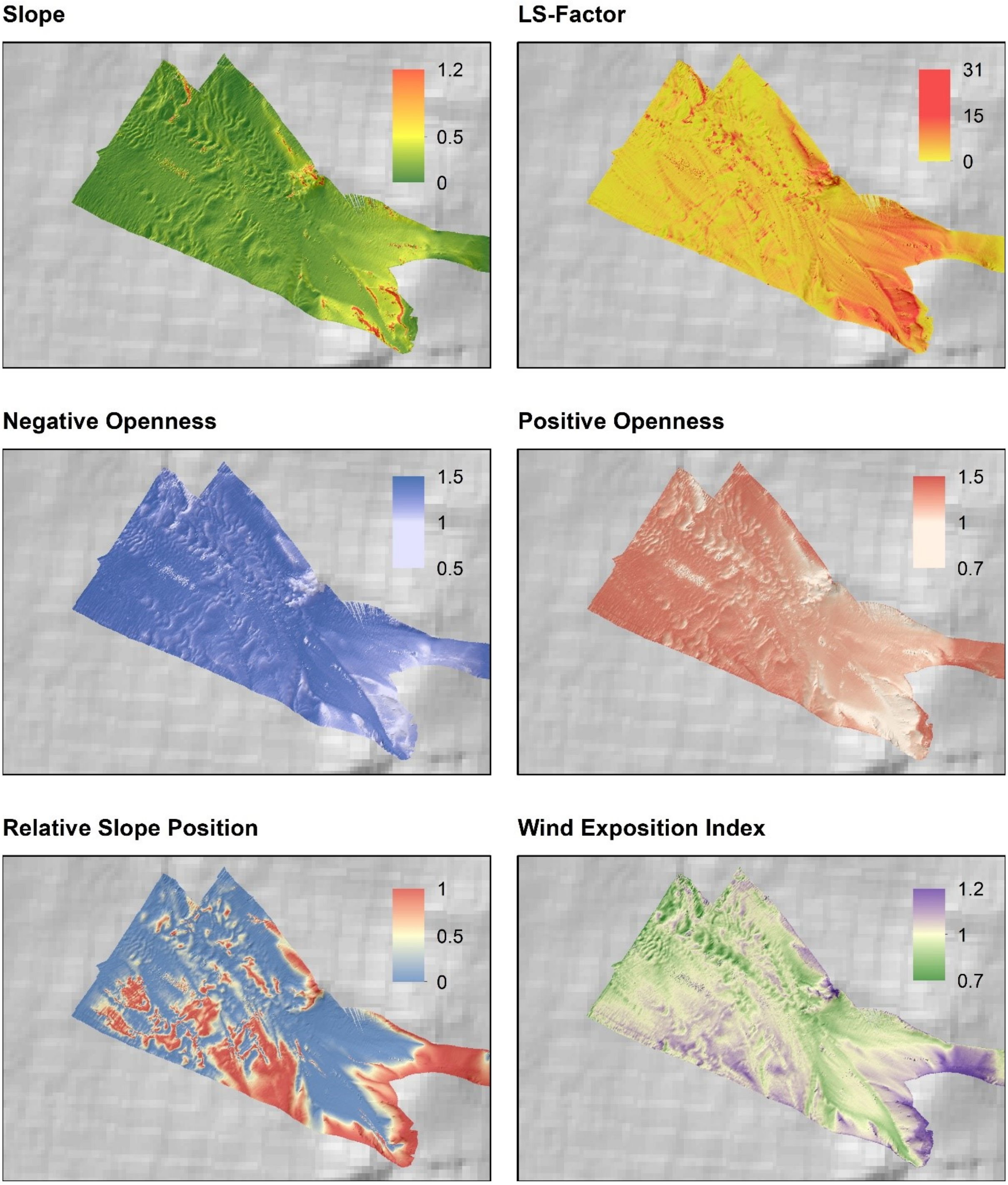

Figure 6.1. Examples of topographic layers derived from MBES bathymetry for the western side of Zavodovski Island.

6.4.1 Zavodovski Island

The island's topography shows evidence of mass-wasting and slope instability. Erosional gullies were seen on island flanks with down-slope, mass-flow transport of volcanic sediments was also evident from MBES data (Figures 6.2 and 6.3). Occasional drop stones and very steep vertical walls covered by corals, sponges and bryozoans were observed at the shallower stations (ZAVO01, ZAVO02, ZAVO06 and ZAVO07). Crinoids were also particularly abundant at between 250 and 300m depth.

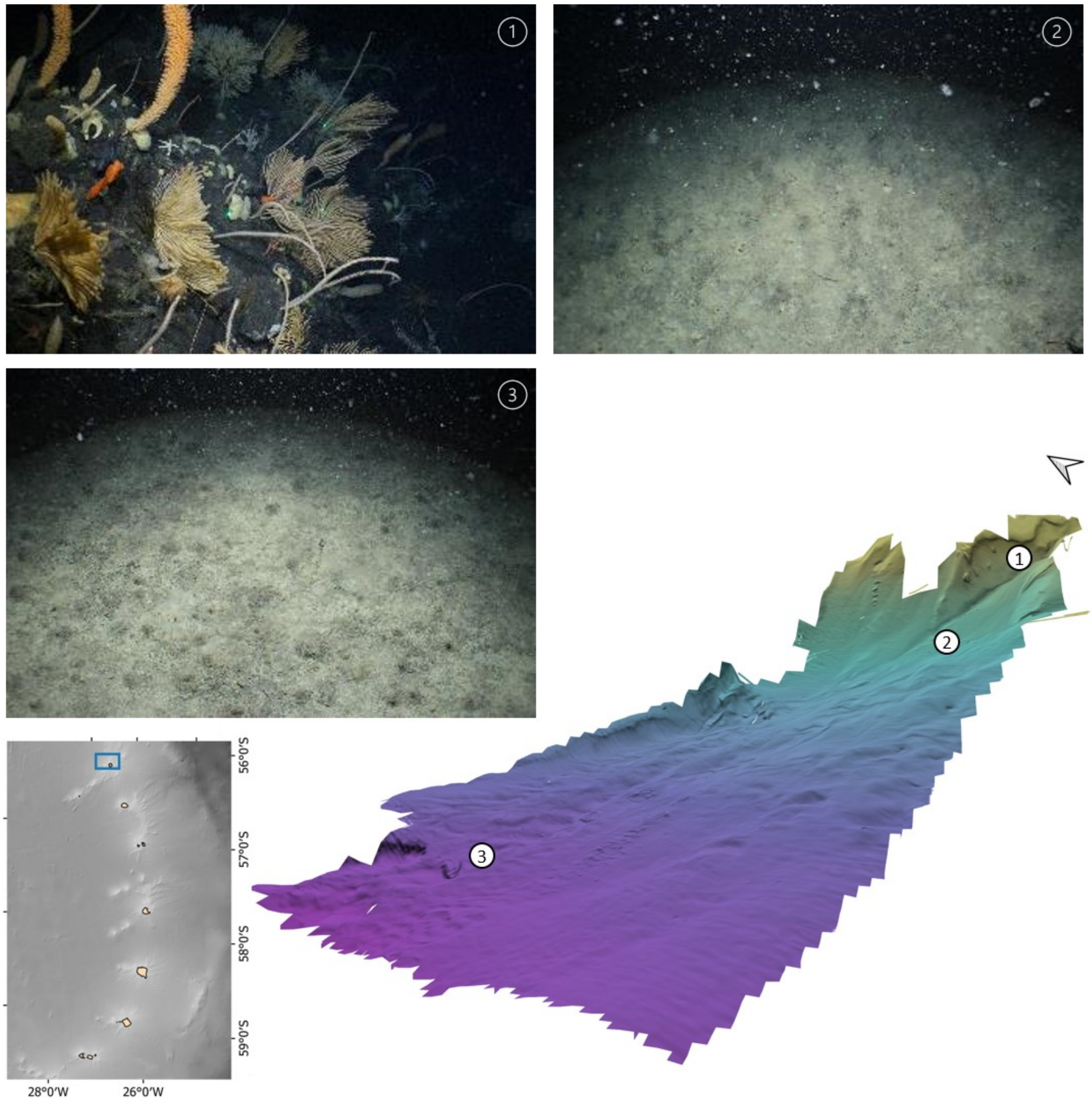

Figure 6.2. MBES bathymetry for the western side of Zavodovski Island, showing main benthic habitats observed on the camera tows.

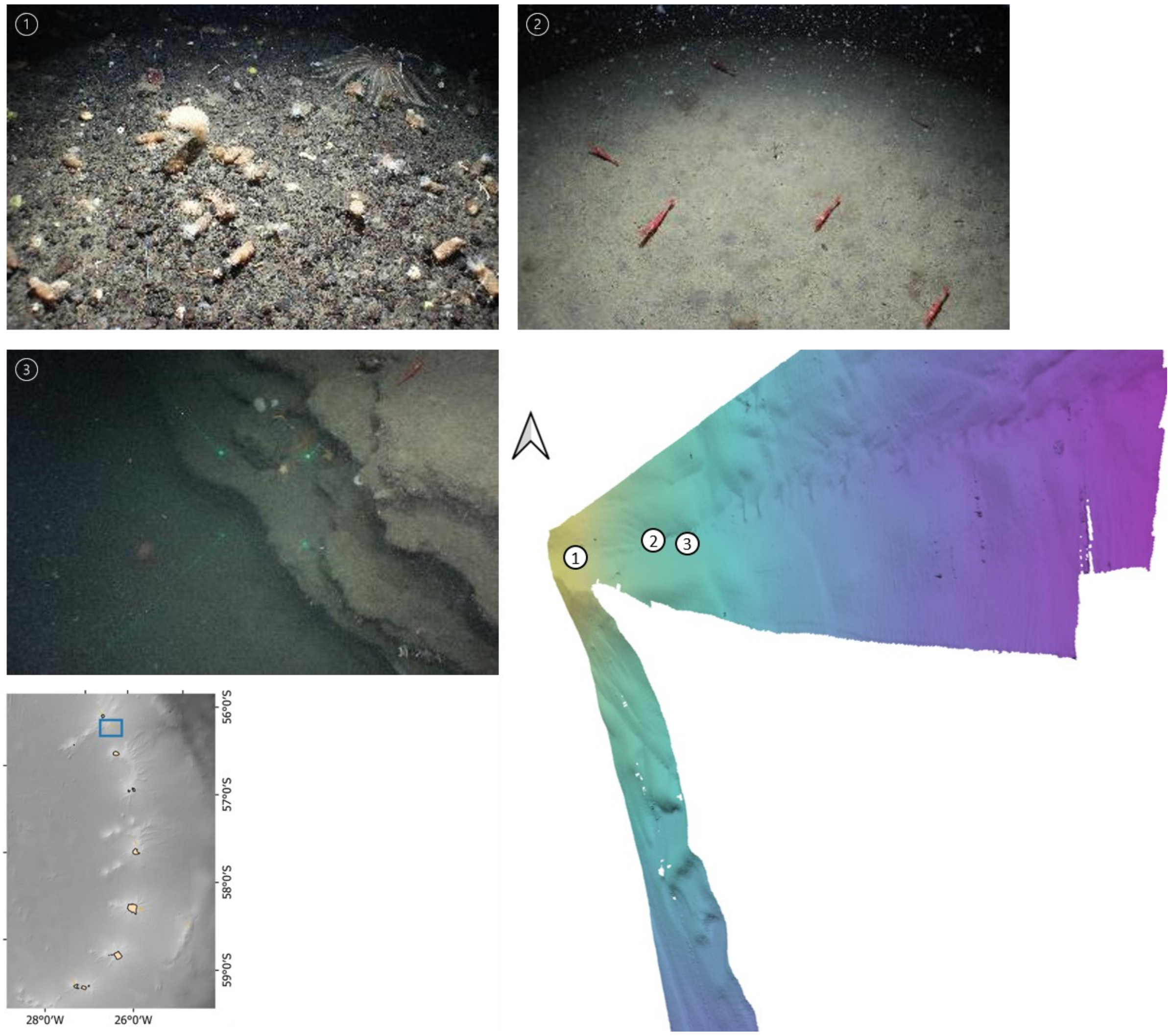

Figure 6.3. MBES bathymetry for the eastern side of Zavodovski Island, showing main benthic habitats observed on the camera tows.

The occurrence of corals and sponges reduced dramatically below 350m depth. Abundance of benthic epifauna was low but included occasional anemones and a holothurian. Small swarms of shrimps (Figure 6.4i) and some crabs (*Paramolis* spp.) were commonly observed at greater depths along with lebensspuren (biologically formed sedimentary structures) in the form of infauna burrows (Figure 6.4f).

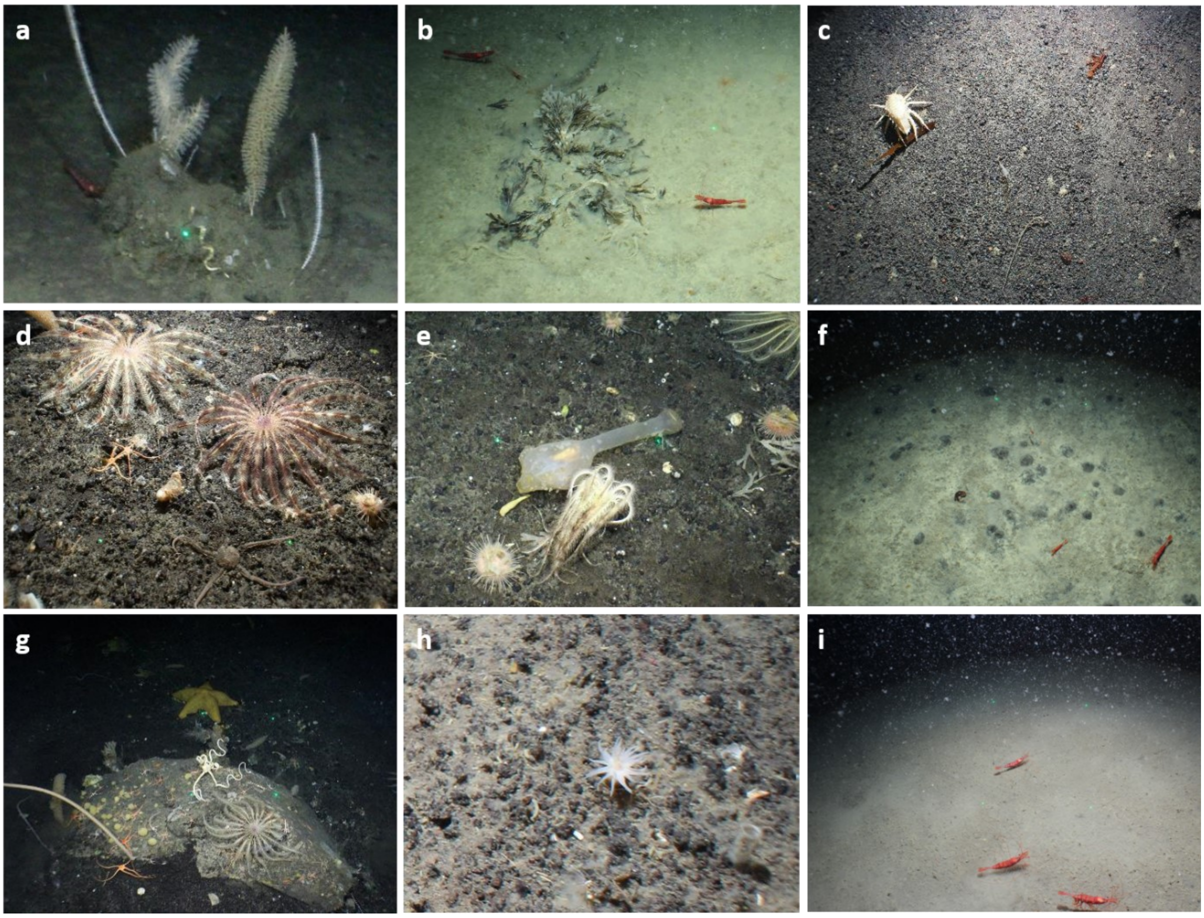

Figure 6.4. Photographs showing examples of epibenthic fauna observed at Zavodovski Island. (a) primnoid corals; (b) bryozoans; (c) large isopod; (d) crinoids; (e) large ascidian and crinoids; (f) several infauna burrows; (g) dropstone megafaunal communities, including basket stars (*Astrotoma agassizii*), crinoids, several ophiuroids and small sponges; (h) small anemone; (i) decapod shrimps.

6.4.2 Saunders Island

A complex assemblage of benthic fauna was observed along the first camera deployment between 220 and 390m depth. Alcyonaceans including whip and bottlebrush corals, non-stalked crinoids, sponges, sea anemones, holothurians and large sea stars were notably abundant at this site (Figures 6.5 and 6.6). Bedrock outcrops, covered with small-sized fauna, were common on steeper slopes (Figure 6.7), while flatter areas were covered by fine-grained sediments. One deployment was carried out on the eastern slope, between 300 - 580m depth, where abundance of benthic epifauna was low, but included rare and little-known hydroids (e.g. *Candelabrum* sp., Figure 6.6i), alcyonacean corals, soft corals, sponges and anemones populating moderately-large dropstones (Figure 6.8).

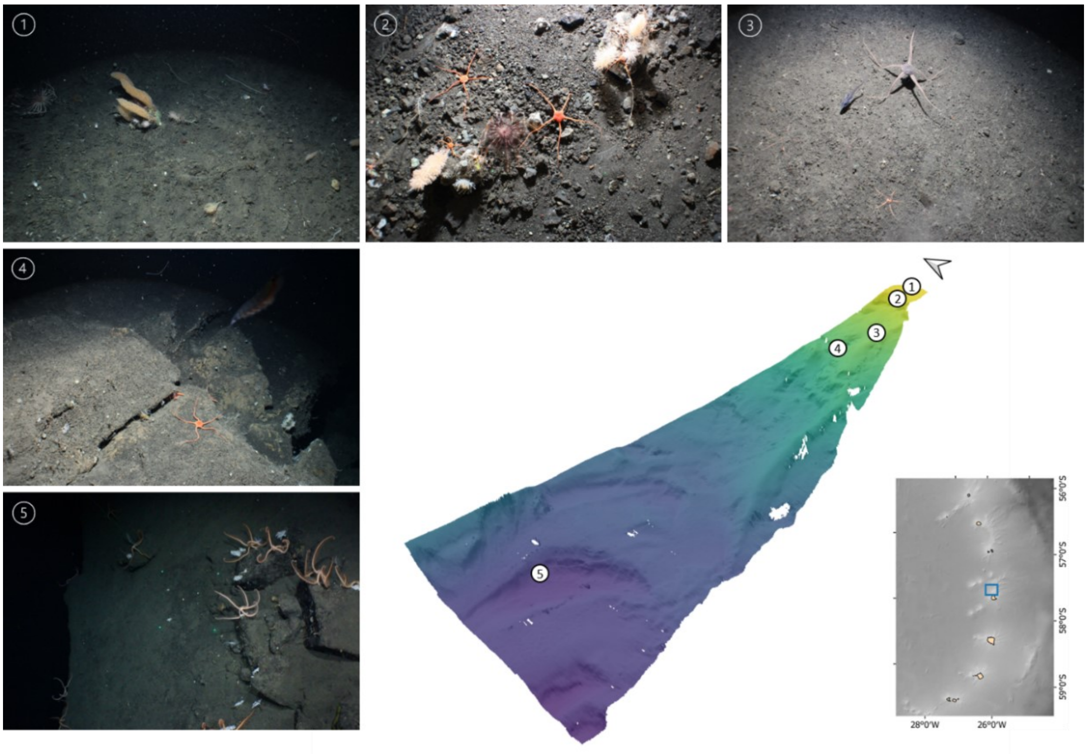

Figure 6.5. MBES bathymetry for the northern side of Saunders Island, showing the main benthic habitats observed during the camera tows.

Figure 6.6. Photographs showing examples of epibenthic fauna observed at Saunders Island. (a-c) examples of primnoid corals and associated communities; (d) a crinoid and a grenadier with parasitic fauna; (e) large ophiuroid (cf *Ophionotus* sp.); (f) large unidentified seastar; (g) holothurian (probably *Bathyplotes gourdoni*); (h) a large seastar (cf. *Solaster* sp.) and a holothurian (probably *Bathyplotes gourdoni*); (i) hydroids (*Candelabrum* sp.).

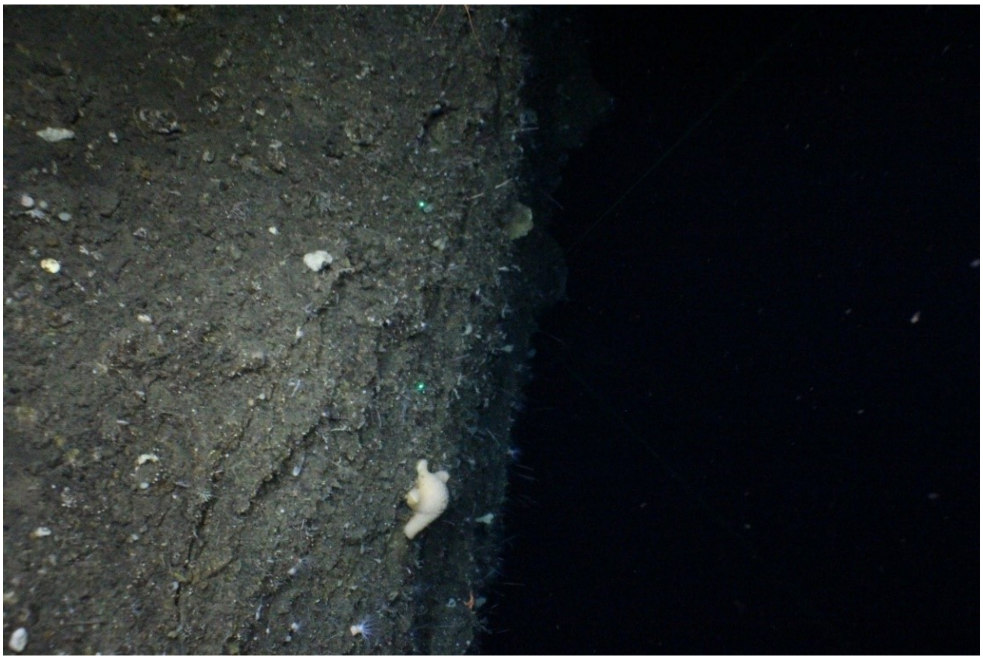

Figure 6.7. Steep slope populated with small benthic fauna, including a seastar, bryozoans and a holothurian (probably *Psolus* sp.).

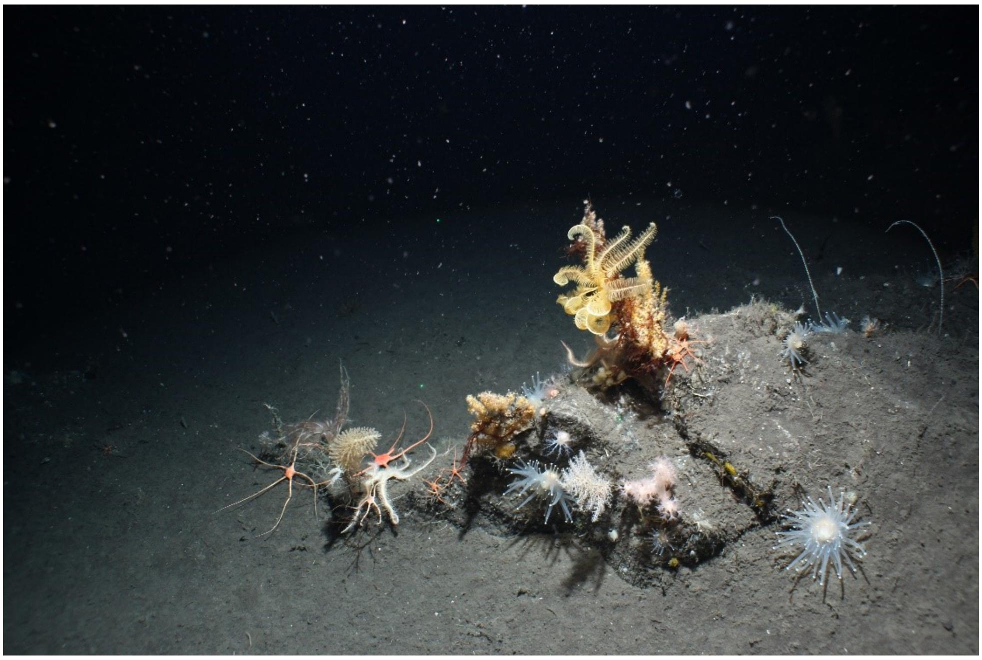

Figure 6.8. Diverse assemblage on a dropstone observed at Saunders Island including two species of crinoids, primnoid corals, several soft corals, anemones and several ophiuroids.

6.4.3 Montagu Island

Faunal diversity and abundance were very low along the flanks of Montagu Island, where soft sediment dominated the landscape (Figure 6.9). Extensive aggregations of tubed polychaetes were encountered at the two shallowest camera deployments, at approximately 180m depth (Figure 6.10a-c). Some anemones of considerable size were also recorded along these transects. Lebensspuren in the form of infauna burrows and feeding mounds were evident at greater depths, as were numerous large ophiuroids and burrowing holothurians (Figure 6.10e-f). Sea pens, an important VME indicator, although not particularly prevalent, were recorded along the deepest transect between 810 and 830m depth (Figures 6.9 and 6.10g-h).

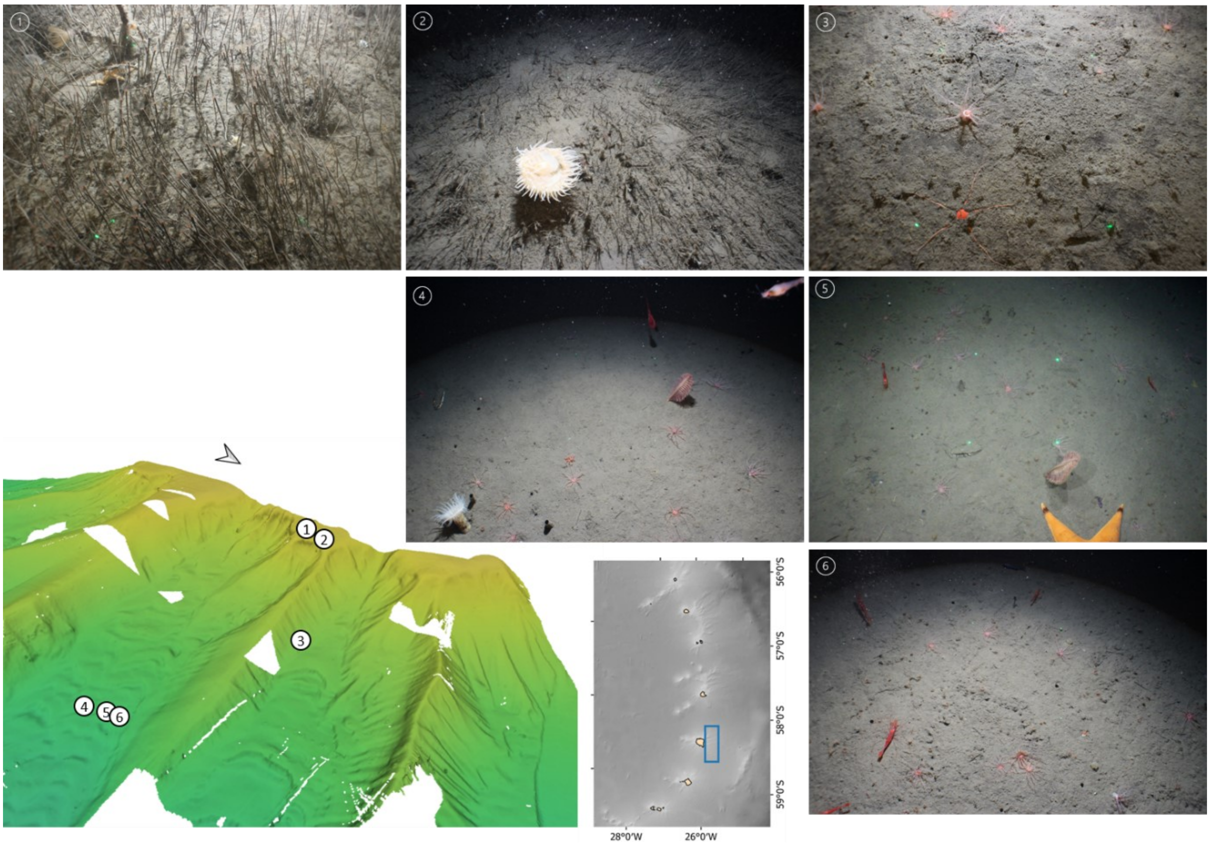

Figure 6.9. MBES bathymetry for the eastern side of Montagu Island, showing main benthic habitats observed during the camera tows.

Figure 6.10. Photographs showing examples of epibenthic fauna observed at Montagu Island. (a-c) aggregations of tubed polychaetes; (d) a seastar; (e-f) burrowing holothurians; (g-h) sea pen (*Pennatula* sp.); (i) several shrimps, burrowing holothurians and an unidentified anemone resembling a *Bolocera* sp.)

6.4.4 Montagu Bank

The habitat in Montagu Bank is predominantly formed of small rocks and gravel. Faunal diversity and abundance were very low (Figure 6.11). However, high abundances of holothurians (*Psolus* sp., Figure 6.12a-c), brachiopods and crinoids were notable in two of the four camera deployments.

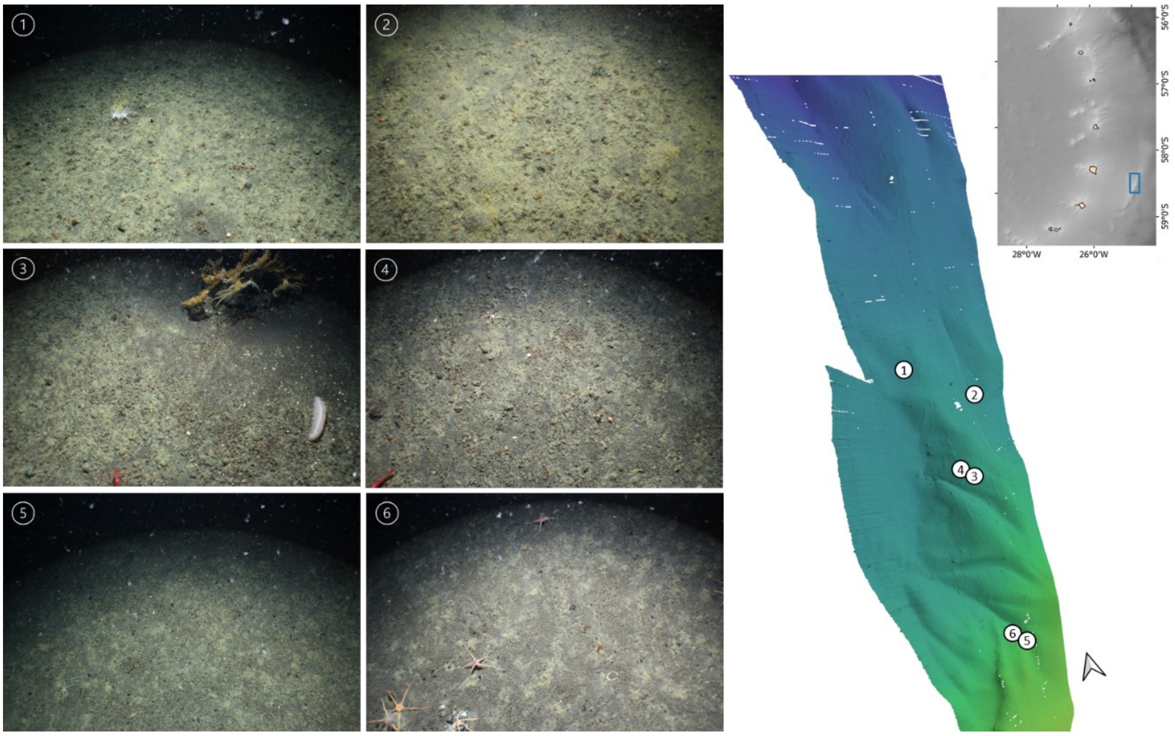

Figure 6.11. MBES bathymetry for Montagu Bank, showing main benthic habitats observed during the camera tows.

Figure 6.12. Photographs showing examples of epibenthic fauna observed at Montagu Bank. (a-b) holothurians (*Psolus* sp.); (c) seastar, probably genus *Pteraster*; (d) decapod shrimp; (e) sea mice (*Laetmonice producta*); (f) brachiopod; (g) unidentified holothurian; (h-i) small grenadier fish and unidentified ophiuroids.

6.4.5 Southern Thule (Cook Island)

Five sites were surveyed at Southern Thule, between 235 and 2,050m depth. Soft sediment was the dominant substrate (Figure 6.13), which exhibited low diversity and abundance of benthic epifauna. The benthic communities seem to be dominated by ophiuroids (as seen in Figure 6.14e-g), while large anemones were commonly observed populating occasional dropstones (Figures 6.13; Figure 6.14c and h). Sea pigs (probably *Laetmogone violacea*, Figure 6.14d) were common at Southern Thule and ascidians, although not abundant, were recorded growing to remarkable sizes (Figure 6.14b).

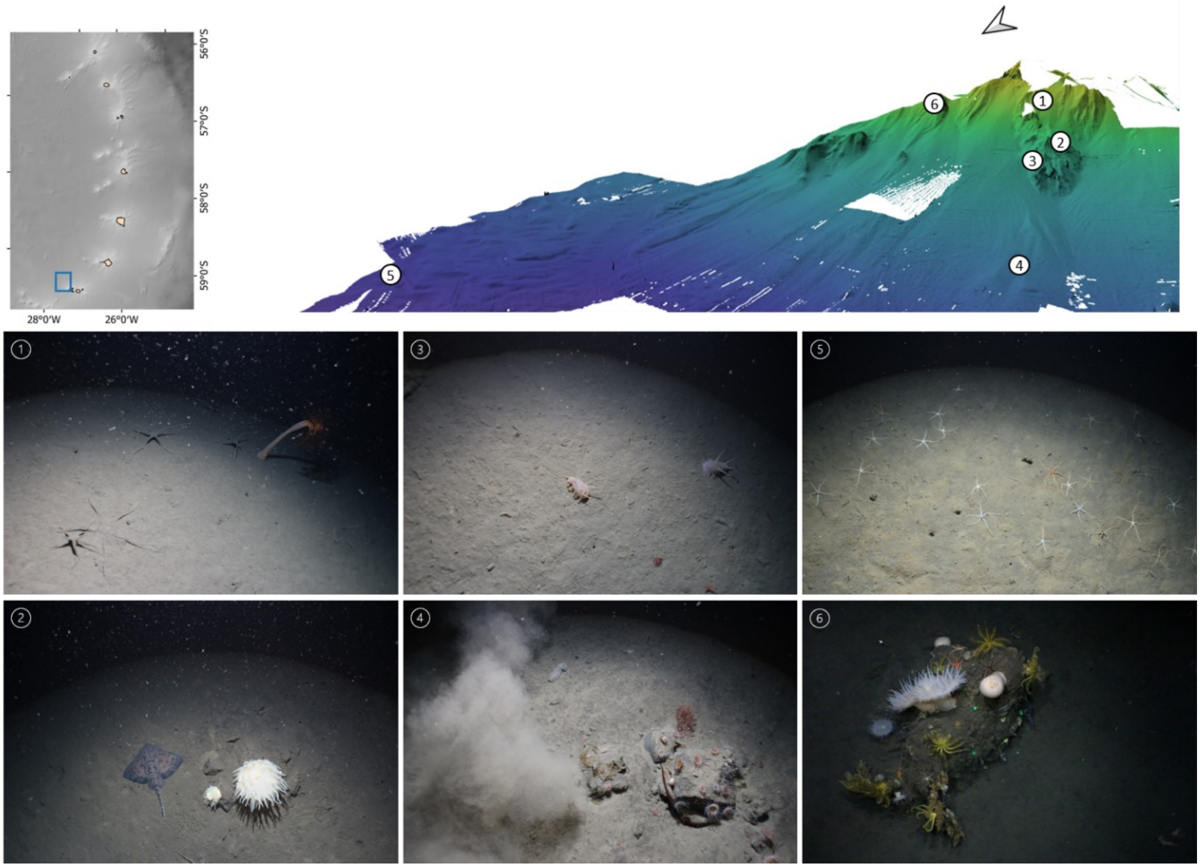

Figure 6.13. MBES bathymetry for the Southern Thule, showing main benthic habitats observed on the camera tows.

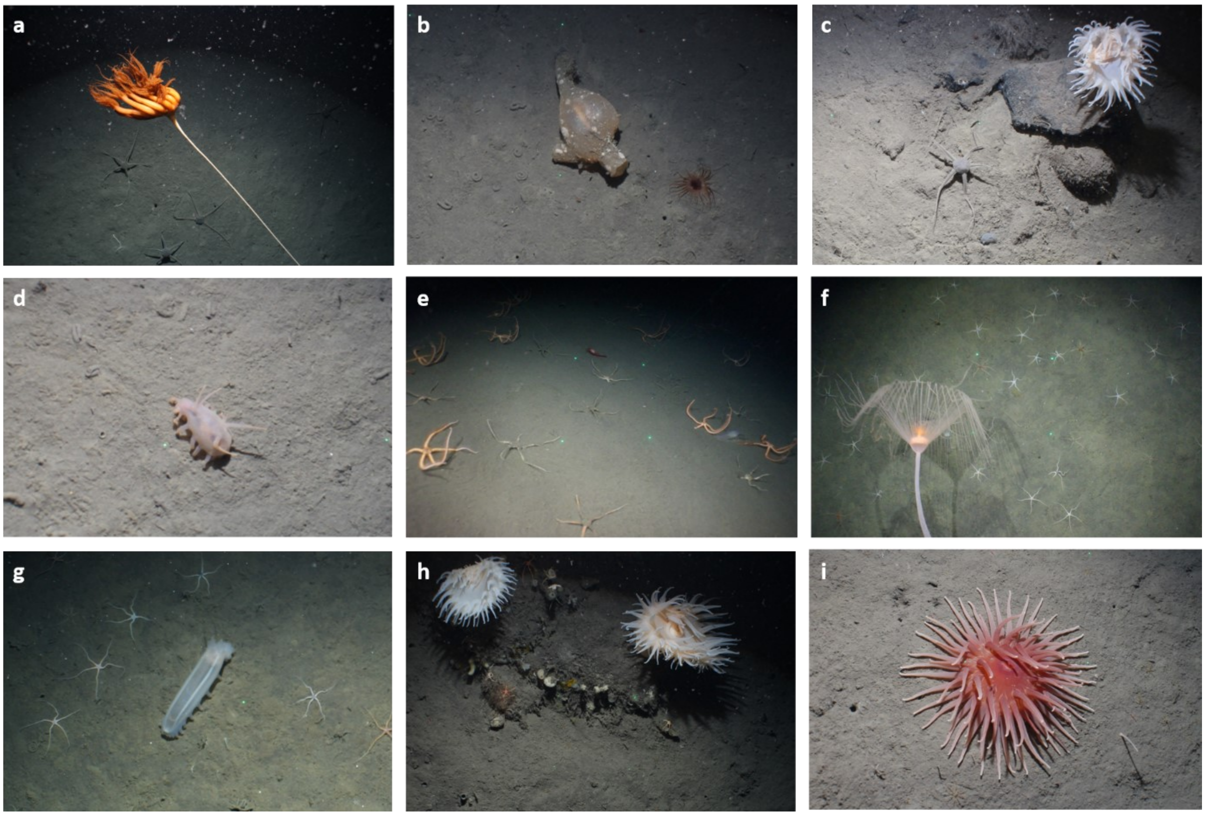

Figure 6.14. Photographs showing examples of epibenthic fauna observed at Southern Thule. (a) sea pen (*Umbellula* sp.); (b) ascidian; (c) anemone and unidentified ophiuroid; (d) holothurian (probably *Laetmogone violacea*); (e) several unidentified ophiuroids; (f) hydroid, possibly *Corymorpha*; (g) holothurian and several unidentified ophiuroids; (h) large anemones populating a large dropstone; (i) anemone.

6.5 VME indicator taxa

6.5.1 VME taxa observed at the South Sandwich Islands

The CCAMLR VME classification list was adopted for the purpose of this report. CCAMLR VME indicators are defined according to their ecological traits including uniqueness, functional significance, life-history characteristics and susceptibility to degradation by human-induced activities (Parker and Bowden, 2010).

VME indicator taxa observed at the South Sandwich Islands include alcyonacean corals with several distinct growth forms including bottlebrush corals, whip corals and branching corals (Figure 6.15a-j). Bottlebrush corals consist of multiple species in the families Isididae and Primnoidea (e.g. *Thouarella* cf.). Whip corals consist of Primnoidea species (e.g. *Primnoella* cf.) and branching corals are a collection of primnoid and isidid seafans. Other

VME associated taxa that were included in analysis consist of various species of sea pens (e.g. *Pennatula* spp., *Umbellula* spp. and Virgulariidae) (Fig. 6.15k-m), stalked crinoids (Figure 6.16a-c) and sponges (Porifera) (Figure 6.16d-g). Other VME indicator taxa, including Actiniaria, Alcyonacea, Zoantharia and Scleractinia, which are likely to be less susceptible to bycatch by longline fisheries (Benedet, 2017), were recorded in images, but were not included within the provisional analysis.

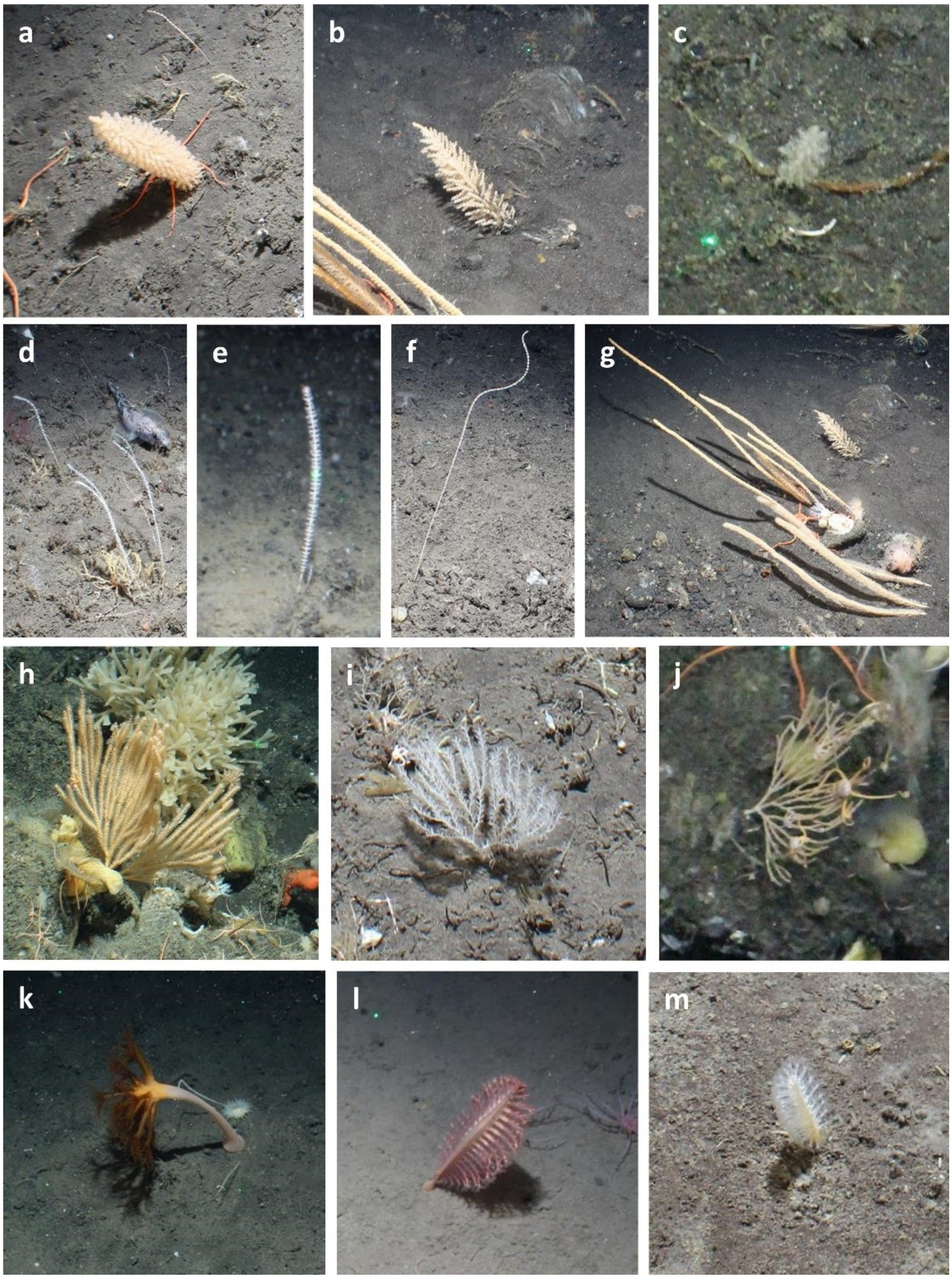

Figure 6.15. Photographs showing examples of selected VME taxa observed at the South Sandwich Islands. (a-c) bottlebrush corals; (d-g) whip corals; (h-j) branching corals; (k) sea pen, *Umbellula* sp.; (l) sea pen, *Pennatula* sp.; (m) sea pen, Virgulariidae.

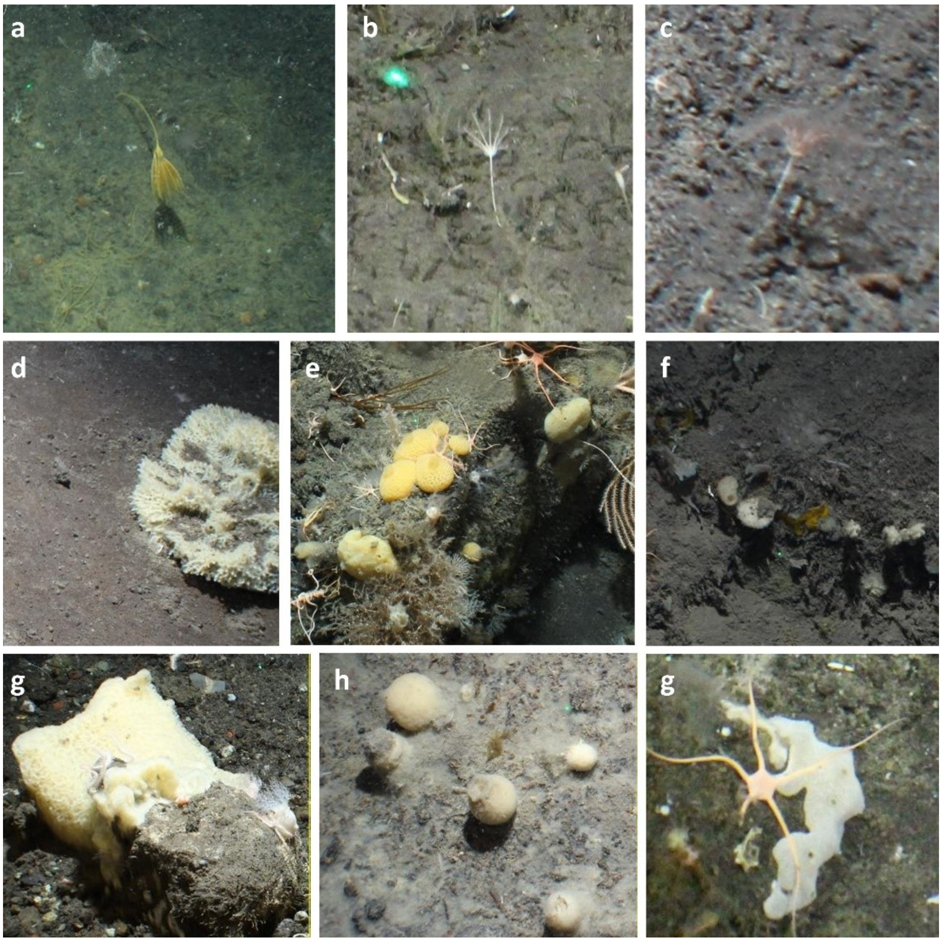

Figure 6.16. Photographs showing examples of selected VME taxa observed at the South Sandwich Islands. (a-c) stalked crinoids; (d-g) sponges.

6.5.2 Island specific trends in observations of VME taxa

The VME indicator taxa most commonly observed on the drop-camera transects were the bottlebrush and whip morphologies of Alcyonaceans. Whilst Porifera were frequently observed, they had very low percent coverage. The largest concentration of images including these taxa were collected at Zavodovski and Saunders Islands. Branching Alcyonaceans were less frequently encountered, and observations were more evenly distributed between islands. Although individual corals and Porifera were observed down to ~1,570m, the majority occurred in waters shallower than 700m. Sea pens (Pennatulacea) were observed in low numbers at each island but were most common at Montagu Island. The species of sea pen observed differed between the islands. Species of the family Virgulariidae were recorded at Zavodovski, *Umbellula* spp. at Saunders Island, Montagu Bank and Southern Thule, and *Pennatula* spp. at Montagu Island (Table 6.2). Of the sea pens the Virgulariidae were observed at ~530m depth, *Umbellula* spp. between ~290m and 1,100m, and *Pennatula* spp. between ~820 - 1,010m. Stalked crinoids were observed in very few images and only at Saunders Island and Montagu Bank at ~290 and ~1,360m, respectively.

The differences in taxa observed between islands are likely due to a combination of local topography and changes in environmental conditions along a north-south gradient. Environmental conditions at the islands were compared by extracting values from raster layers of relevant variables at each still image location. Depth and slope were extracted from the MBES bathymetry collected during the survey. Values for annual mean net primary productivity (NPP), number of sea ice days, summer bottom temperature and current velocity were extracted from modelled layers described in Section 9. Southern Thule demonstrated the lowest primary productivity and bottom temperature, and the longest duration of sea ice of the South Sandwich Islands. This may, in part, explain the comparatively low number of VME associated morphotaxa observed. The locations sampled at Montagu Island, whilst experiencing similar ranges of annual sea ice duration, productivity and temperature as Zavodovski and Saunders Islands, had much flatter topography, with less suitable habitat for the hard substratum associated corals.

Table 6.2. Number of images for which key VME indicator species were recorded at each study site.

			Bottlebrush	**Whip**	**Branching**	***Umbellula* spp.**	***Pennatula* sp.**	**Virgulariidae**	**Porifera**	**Stalked crinoids**
ISLAND	**Depth (m)**	**Tot. img.**	**Number of images where taxon present**							
ZAVO	0 - 700	499	138	111	37	0	0	2	118	0
	700 - 1,400	395	0	0	0	0	0	0	9	0
	1,400 - 2,100	269	0	0	0	0	0	0	0	0
SAUN	0 - 700	531	164	148	16	5	0	0	67	1
	700 - 1,400	95	0	0	0	0	0	0	2	0
	1,400 - 2,100	117	5	0	0	0	0	0	4	0
MONT	0 - 700	447	8	6	10	0	0	0	3	0
	700 - 1,400	305	0	1	1	1	29	0	3	0
	1,400 - 2,100	0	0	0	0	0	0	0	0	0
MOBA	0 - 700	0	0	0	0	0	0	0	0	0
	700 - 1,400	633	3	1	4	2	0	0	0	1
	1,400 - 2,100	0	0	0	0	0	0	0	0	0
SOTH	0 - 700	205	2	1	21	4	0	0	3	0
	700 - 1,400	265	0	2	3	1	1	0	1	0
	1,400 - 2,100	245	0	0	1	0	0	0	0	0

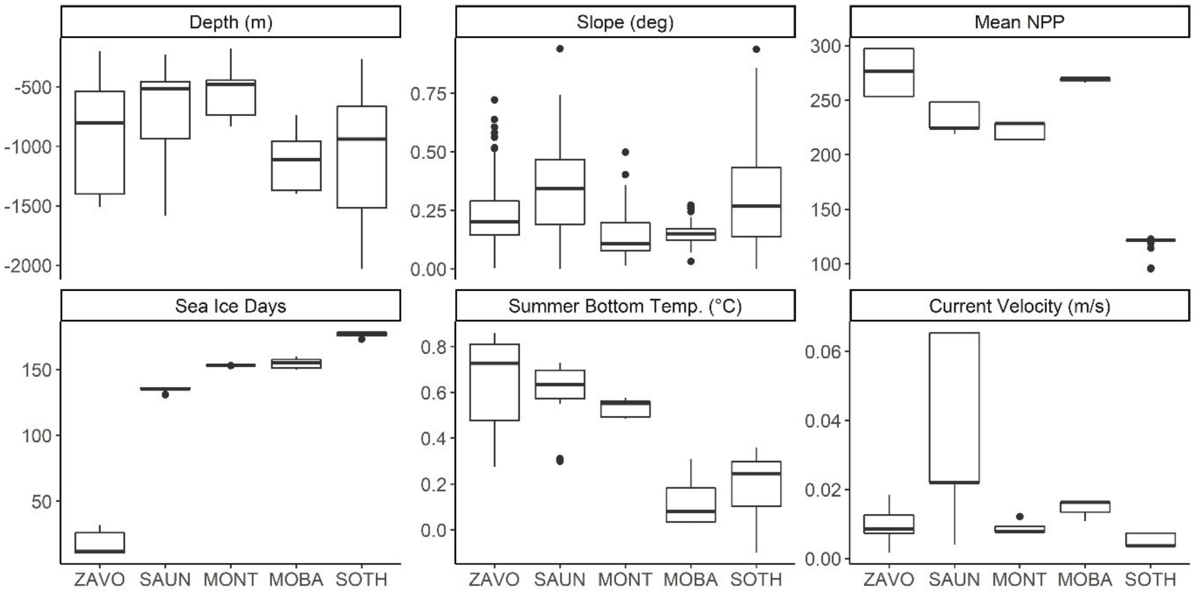

Figure 6.17. The range of depth, slope, annual mean net primary productivity (NPP), number of sea ice days, summer bottom temperature and current velocity at drop camera sampling stations at Zavodovski Island (ZAVO), Saunders Island (SAUN), Montagu Island (MONT), Montagu Bank (MOBA) and Southern Thule (SOTH). Depth and slope are extracted from MBES bathymetry collected during the survey. Mean NPP, sea ice days, summer bottom temperature and current velocity are extracted from modelled layers described in Section 9.

6.6 Modelling VME indicator taxa

6.6.1 Data preparation and methodology

Maps estimating the potential extent of the VME indicator taxa were produced to estimate the distribution of suitable habitat across the wider study area (delineated by the area covered by acoustic data collection). Maps were produced using Object Based Image Analysis (OBIA), a two-step approach consisting of segmentation and classification based on environmental data layer values (Blaschke, 2010). OBIA works on stacks of raster bands (layers) representing colour channels (e.g. red, green, blue). When working with environmental data instead of images, each layer represents a comparable band. In this way, the acoustic and topographic derivative spatial layers were used as components of the image. Segmentation creates spatial units called ‘objects’ by identifying and placing boundaries around sections of the image with homogeneous characteristics across the environmental data layers. These objects can then be classified based on their similarities and differences using various characteristics, including summary statistics (mean, standard deviation, skewness) of the pixel values of each layer as attributes of the objects. The object-based approach identifies uniform areas with similar attributes, whilst filtering out noise from single pixels in the data layers. Hence, it can be used to represent real-world objects of the underwater landscape.

For the segmentation step, bathymetry, backscatter and topographic layers were imported into eCognition (vs. 9.3) for each island separately and segmentation carried out in two steps, using the multi-resolution segmentation tool. Multi-resolution segmentation builds objects by consecutively merging neighbouring pixels until an *a priori* threshold for variability allowed in the objects is reached. This threshold is determined by the scale parameter. For a fixed value of the scale parameter, a homogeneous area of seabed will have larger objects than a heterogeneous area. Likewise, for a fixed seabed heterogeneity, larger values of the scale parameter produce larger objects than smaller values. The first segmentation step used LS-factor, Positive Openness and Relative Slope Position, with equal weight for each layer. A scale parameter of five produced the best fit of object boundaries to the topographic features of interest. The layers for the first step were selected to represent different aspects of topography, in this case substratum stability, topographic prominence and placement on the hill-trough continuum. In the second step, the objects delineating topographic features were further subdivided into smaller objects based on backscatter strength, which is a proxy for seafloor hardness. The scale parameter was again set at five. Figure 6.18 shows an example area of the segmentation of the benthic environment into multiple objects overlaid on top of the environmental layers used in the algorithm. These objects were exported and combined in a polygon shapefile, with object mean values of all input layers as attributes.

A decision-rule approach using environmental envelopes around known presences of each species or habitat of interest was used for the classification part of OBIA. Whilst more sophisticated modelling methodologies, including numerous classification and regression based statistical approaches, are available, they require more input data to provide robust outputs. As such, potential habitat presence was determined based on the environmental envelope, classifying a location based on whether the values of environmental variables fall within the range for observed values for presence of the species or habitat of interest. The approach is broad-brush, does not consider the prevalence of presence observed over absence and, hence, does not assign probability of presence or give an indication of goodness-of-fit. Therefore, the results must be interpreted with these limitations in mind.

Classification rules for applying the environmental envelope were derived from the mean environmental values of each of the segmentation objects. In QGIS, objects intersected by a drop-camera transect were identified and the percentage of the intersecting images that included a presence of each distinct VME indicator taxon was added as a data field to each object.

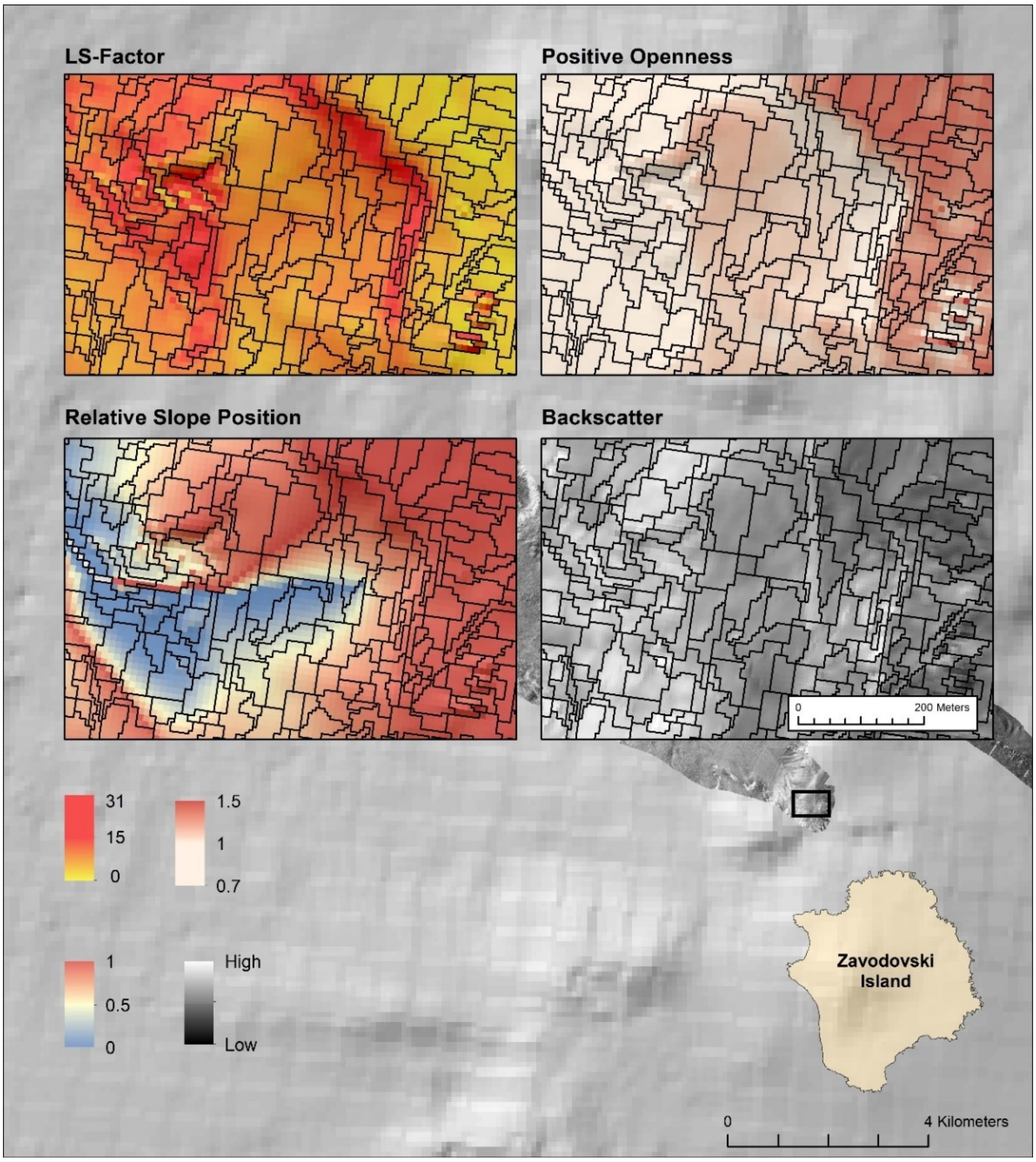

Figure 6.18. Close-up example of the results of the OBIA segmentation used to create maps of potential VME distribution.

In the classification analysis Montagu Island and Montagu Bank were dealt with together and are represented by 147 objects with associated images. Zavodovski Island, Saunders Island and Southern Thule have 140, 122 and 76 objects, respectively. The number of camera images per object ranged from one to 48, with an average of six. Objects in which VME indicator taxa were observed were placed into five prevalence classes based on the proportion of images containing each VME taxon. These were 0, 1 - 25, 25 - 50, 50 - 75 or 75 - 100% of images. For each of the five prevalence classes of each taxon, the ranges of values for bathymetry, backscatter and the topographic derivatives were analysed using density plots and summary statistics.

Maps were produced for those combinations of taxa and islands with a minimum of ten objects containing VME records. This threshold helped ensure reliable summary statistics. The South Sandwich Islands demonstrates strong latitudinal gradients in environmental conditions with significant environmental differentiation between each of the islands. Consequently, understanding, for example, depth trends in the distribution of taxa is complicated by the confounding influence of island-specific temperature and current profiles. This means transferability of results between islands is potentially problematic. As such, each study location was mapped separately using island-specific cut-off values for environmental variables. The variables used in the final set of rules defining the environmental envelopes were backscatter strength, depth, LS-factor, relative slope position, slope and wind exposition index.

After the more detailed analysis using the five prevalence classes for each VME indicator taxon outlined above, the number of classes was reduced to ensure each class contained enough observations to calculate accurate environmental envelopes. To derive the set of classification rules used for mapping potential VME habitat, prevalence was combined into three categories: 0% (no images with observed presence), <50% (presence observed in less than half of the associated images) and >50% (presence observed in 50% or more of the associated images). For those taxa that had ten or more objects with a ≥50% presence frequency of key VME taxa (bottlebrush, whip corals and sponges), the cut-off values for backscatter, depth, LS-factor, slope and wind exposition index were taken from the ≥50% class, for the less common taxa any objects with a presence were used.

Minimum and maximum values for the occurrence of each mapped taxon at each island were taken from the full range of observations within 1.5 times the interquartile range. This acted to exclude outliers that would unduly exaggerate the mapped distribution. At several of the islands, deeper transects all fell on level soft ground, which made determining the true depth limit of the hard substrate-dependent taxa difficult. To address this, a second map class was included using the maximum depth for these taxa across all the islands. Stricter minimum slope, relative slope position and wind exposition index values (lower quartile) were assigned to these depth extensions, to limit it to the most likely locations only. The decision rules used to produce distribution maps are summarised in Table 6.3.

Table 6.3. Summary of the decision rules used to create the potential VME distribution maps based on the three prevalence classes. Different rules were used for the more common taxa (bottlebrush and whip corals and sponges) and sparse taxa (sea pens and branching corals). Min/Max 0.5 = minimum/maximum of objects with 50% or more images with presence; Min/Max All = minimum/maximum of all objects with a presence; LQ = lower quartile.

	Observed range (common/sparse)	**Extended range (common/sparse)**
Minimum backscatter	Min 0.5/ Min All	Min 0.5/ Min All
Minimum depth	Min All/ Min All	Min All/ Min All
Maximum depth	Max 0.5/ Max All	Max All Islands/ Max All Islands
Minimum LS-factor	Min 0.5/ Min All	Min 0.5/ Min All
Maximum LS-factor	Max 0.5/ Max All	Max 0.5/ Max All
Minimum relative slope position	Min 0.5/ Min All	LQ Al/ LQ All
Minimum slope	Min 0.5/ Min All	LQ 0.5/ LQ All
Minimum wind exposition index	Min 0.5/ Min All	LQ 0.5/ LQ All

6.6.2 Modelling the spatial distribution of VME

There was a tendency of Alcyonaceans and Porifera to be more prevalent in shallower depths (<700m, Figure 6.19), higher up the slope (Figure 6.20) in more exposed conditions (Figure 6.21), particularly at Zavodovski Island, Saunders Island and Southern Thule. These environments are more likely to have exposed hard substrata, which provide the attachment surfaces required by Alcyonaceans and some Poriferans. The resulting maps of the areas of interest at Zavodovski (Figures 6.23 and 6.24) and Saunders Islands (Figures 6.25 and 6.26) show that suitable habitat for bottlebrush, branching and whip Alcyonacean corals and sponges occurrs predominantly on the slopes surrounding the islands between 200 and 700m depth. At Montagu Island and Bank the drop camera transects generally crossed much more gently sloping terrain (Figure 6.9 and 6.11) and consequently the bottom substrates largely consist of soft sediment. As a result, Alcyonaceans and sponges were scarce at the Montagu Island and Bank transects with bottlebrush and whip type morphologies present in <10 of the area’s 147 objects and in each case observed in <25% of the images per object. This sample size was too small therefore to extrapolate distributions of bottlebrush and whip coral habitats to the wider region. The distribution of suitable habitat for branching Alcyonaceans was mapped for the area of interest (Figures 6.28 and 6.29), though it must be noted that decision rules used to extrapolate the potential distribution were based on values derived from just 11 objects. The resulting mapped distribution should therefore be treated with caution. At Southern Thule there were very few observations of any of the VME indicator taxa. Presence of Alcyonaceans and Porifera were too few to extrapolate the distributions of their preferred habitats to the area of interest. Although branching Alcyonaceans were observed in 22 images, they were all located in just six objects. The locations where VME indicator taxa were observed at Southern Thule are presented in Figure 6.30.

Sea pens generally occurred in very low numbers of objects, and mainly in single images per object. The only exception was Montagu Island where a field of *Pennatula* spp. was encountered on one drop camera tow at ~820m depth. The sea pens at other islands consist mainly of scattered observations of individual *Umbellula* spp, occurring at depths shallower than 500m (Figure 6.19). At Saunders and Montagu Islands sea pens occurred in moderately sheltered to moderately exposed conditions, whereas observations at Southern Thule were from more exposed environments (Figure 6.21). This divergence is likely due to the drop camera transects at Southern Thule mainly covering exposed areas, whilst the Saunders and Montagu Island transects cover a wider range along the exposure gradient. The extrapolated distribution of habitat suitable for sea pens at Montagu Bank is shown in Figure 6.28 and 6.29. There were not enough objects with presence observations of sea pens at the other islands to extrapolate the distribution of suitable habitat spatially, but observed *Umbellula* sp. sea pens have been plotted at point locations for Saunders Island in Figure 6.27, and *Umbellula* sp. and *Pennatula* spp. for Southern Thule in Figure 6.30.

Stalked crinoids were only observed on two transects, one at Saunders Island (3 images at ~290 m) and one at Montagu Bank (1 image ~1360 m). The point locations of the transects are shown in Figure 6.31.

The mapped potential distributions of VME indicator taxa shown in Figures 6.23 – 6.26 and Figures 6.28 - 6.29 indicate the extent of environmental conditions suitable for the species to occur, based on the variables used. There are factors, such as fine-scale variability in substate type that is not captured in the MBES data that will affect the presence of the taxa, which cannot be captured at the resolution of the maps. Consequently, the maps should be interpreted with the understanding that they show areas where the taxa may be observed to be present given suitable substrate conditions. Similarly, it cannot be ruled out that VME indicator taxa may occur outside the depth limits observed in this survey. The acoustically surveyed area includes some locations with topographically suitable conditions that were not sampled during the survey, and consequently cannot be discounted as potential habitat without additional sampling. These areas are indicated in green in the distribution maps in Figures 6.23 - 6.26 and Figures 6.28 - 6.29, delimited by the deepest depth the VME taxa were observed across all islands.

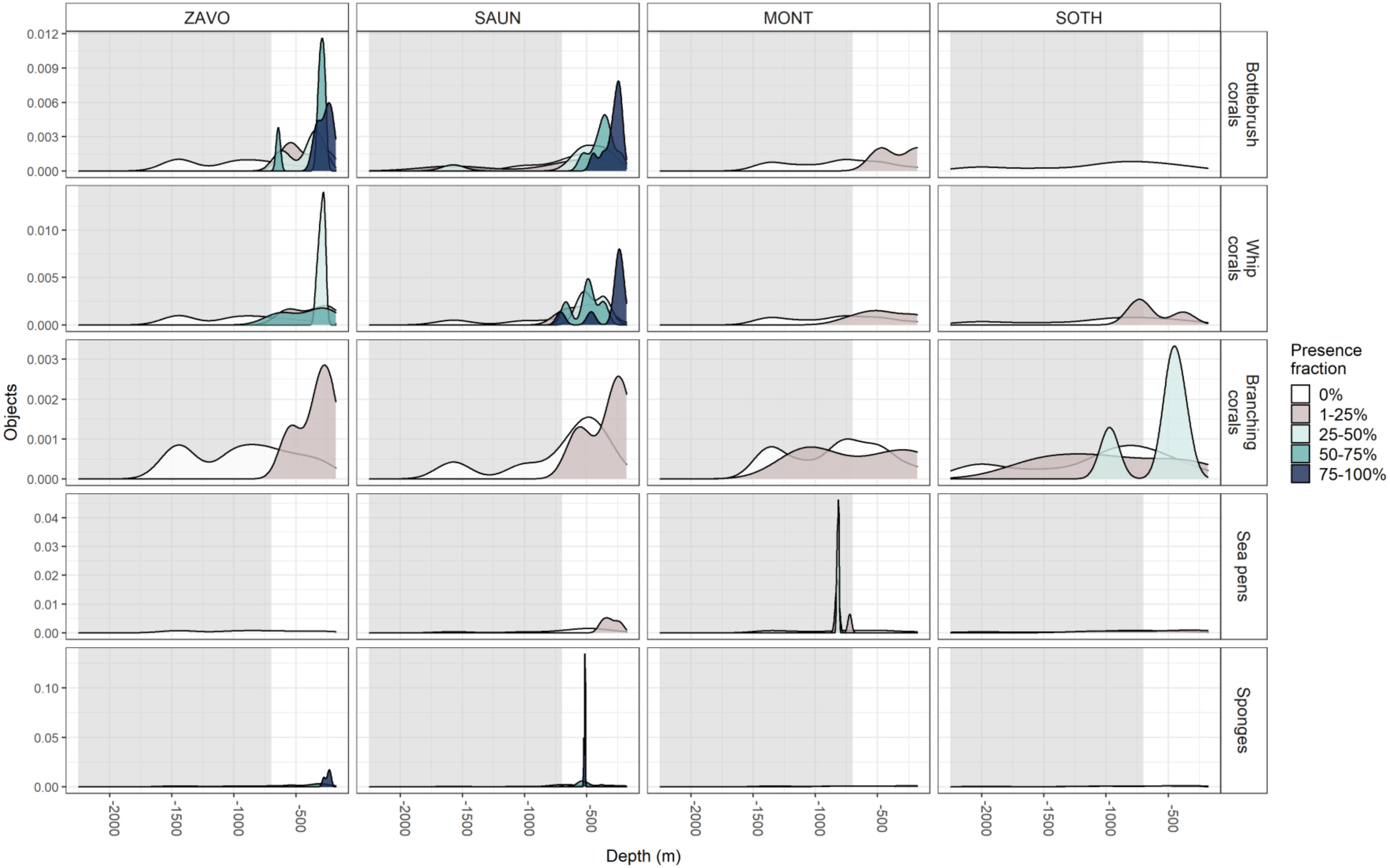

Figure 6.19. Prevalence of VME groups by depth at Zavodovski Island (ZAVO), Saunders Island (SAUN), Montagu Island and Bank (MONT) and Southern Thule (SOTH). Plots show the density distribution of VME for each of the five VME prevalence classes (i.e. taxon observed in 0% of drop camera images per OBIA object, 1 - 25, 25 - 50, 50 - 75 and 75 - 100%). The shading indicates depths between 700 - 2,250 metres, which are open to the licenced longline fishery.

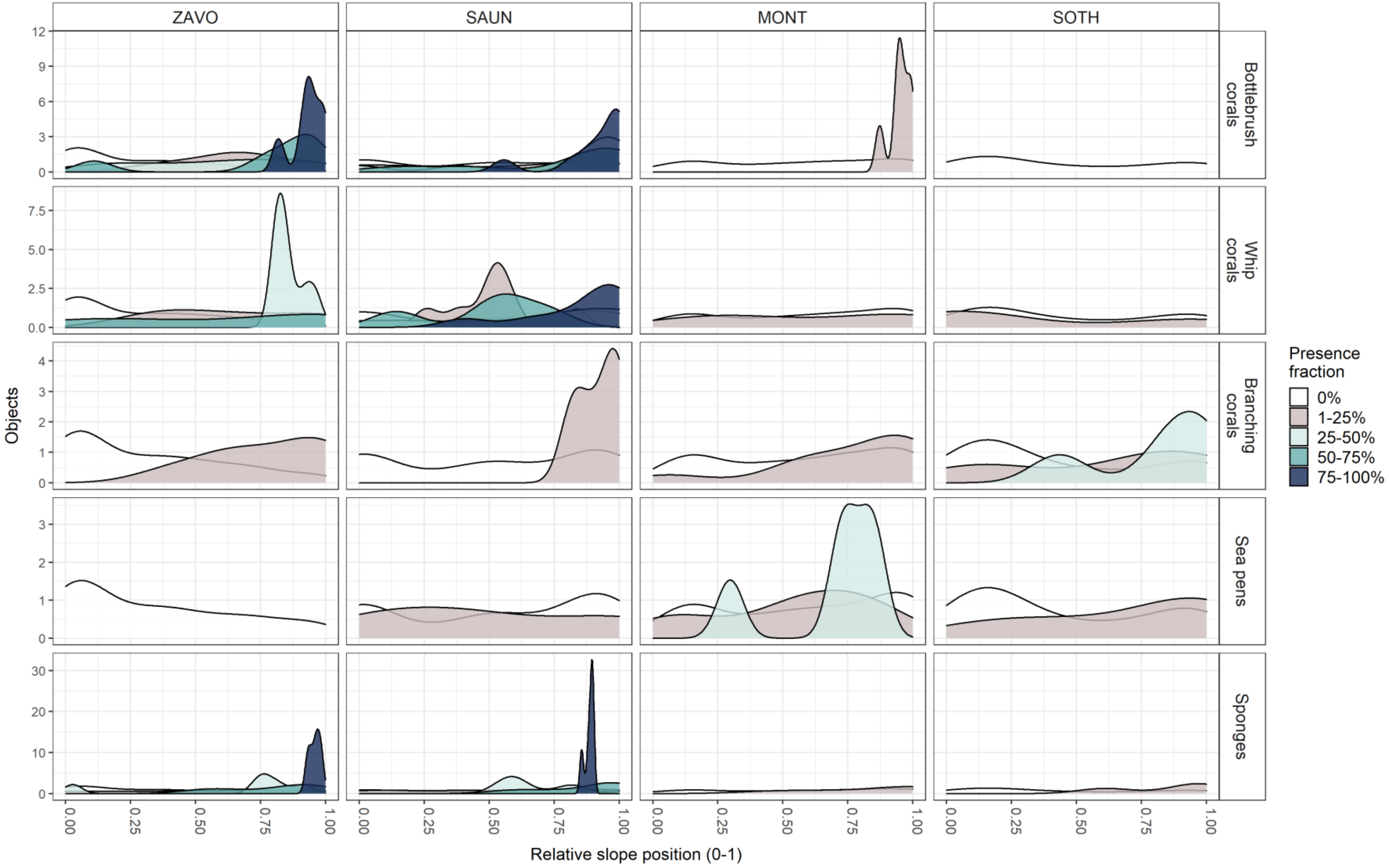

Figure 6.20. Prevalence of VME groups by relative slope position at Zavodovski Island (ZAVO), Saunders Island (SAUN), Montagu Island and Bank (MONT) and Southern Thule (SOTH). Plots show the density distribution of VME for each of the five VME prevalence classes (i.e. taxon observed in 0% of drop camera images per OBIA object, 1 - 25, 25 - 50, 50 - 75 and 75 - 100%).

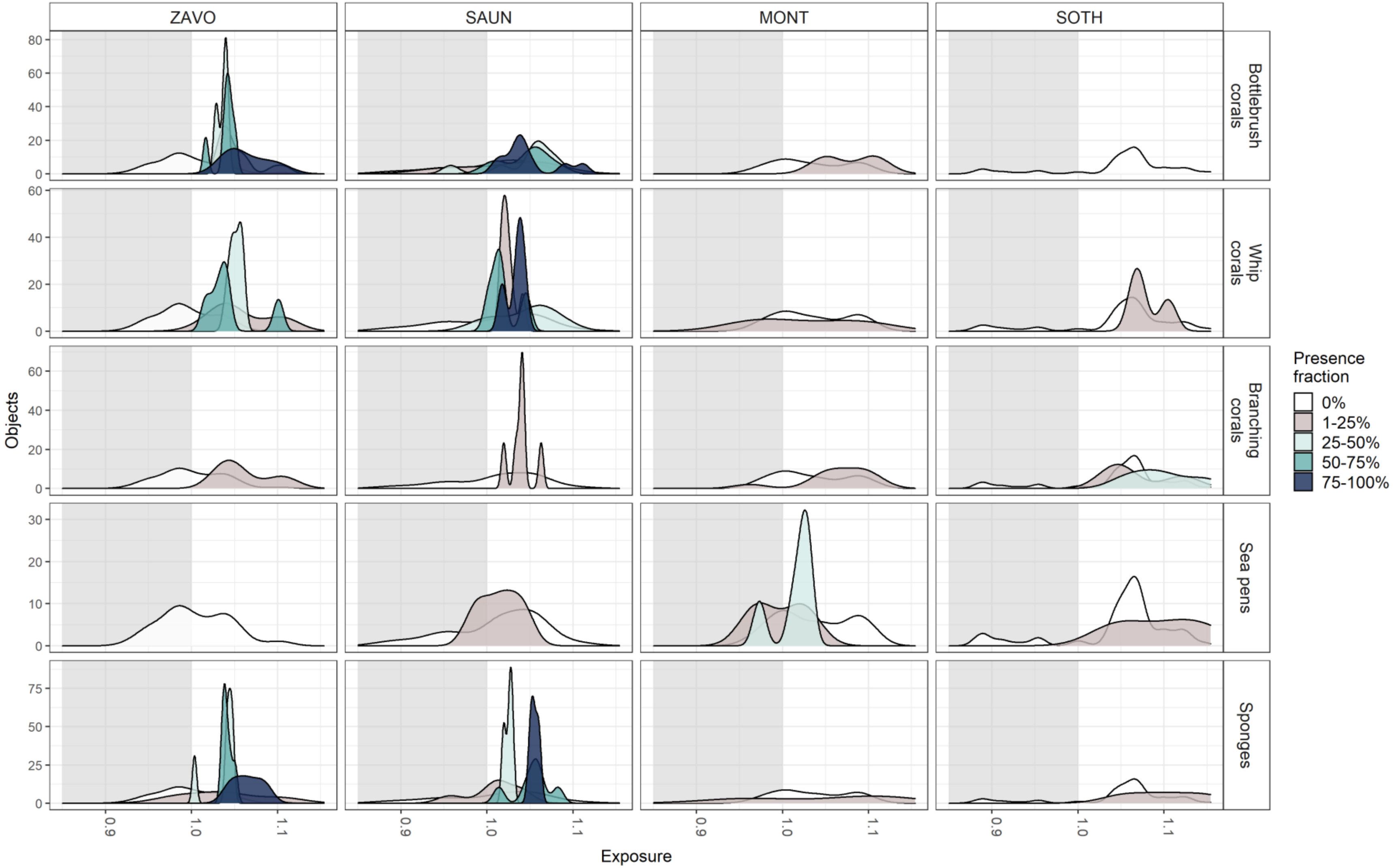

Figure 6.21. Prevalence of VME groups by exposure at Zavodovski Island (ZAVO), Saunders Island (SAUN), Montagu Island and Bank (MONT) and Southern Thule (SOTH). Plots show the density distribution of VME for each of the five VME prevalence classes (i.e. taxon observed in 0% of drop camera images per OBIA object, 1 - 25, 25 - 50, 50 - 75 and 75 - 100%). The shaded grey area indicates sheltered conditions (exposure index values <1).

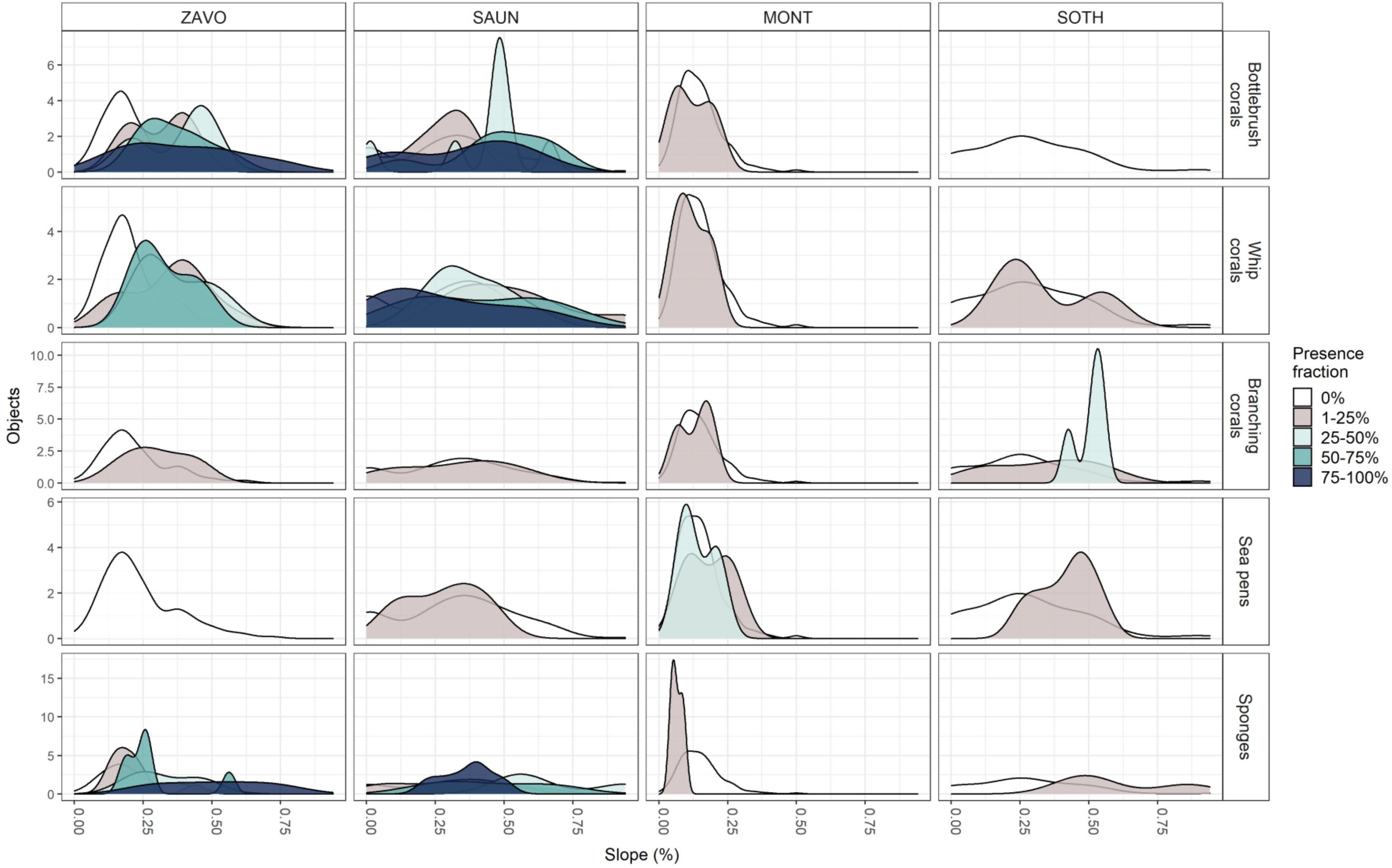

Figure 6.22. Prevalence of VME groups by slope gradient at Zavodovski Island (ZAVO), Saunders Island (SAUN), Montagu Island and Bank (MONT) and Southern Thule (SOTH). Plots show the density distribution of VME for each of the five VME prevalence classes (i.e. taxon observed in 0% of drop camera images per OBIA object, 1 - 25, 25 - 50, 50 - 75 and 75 - 100%).

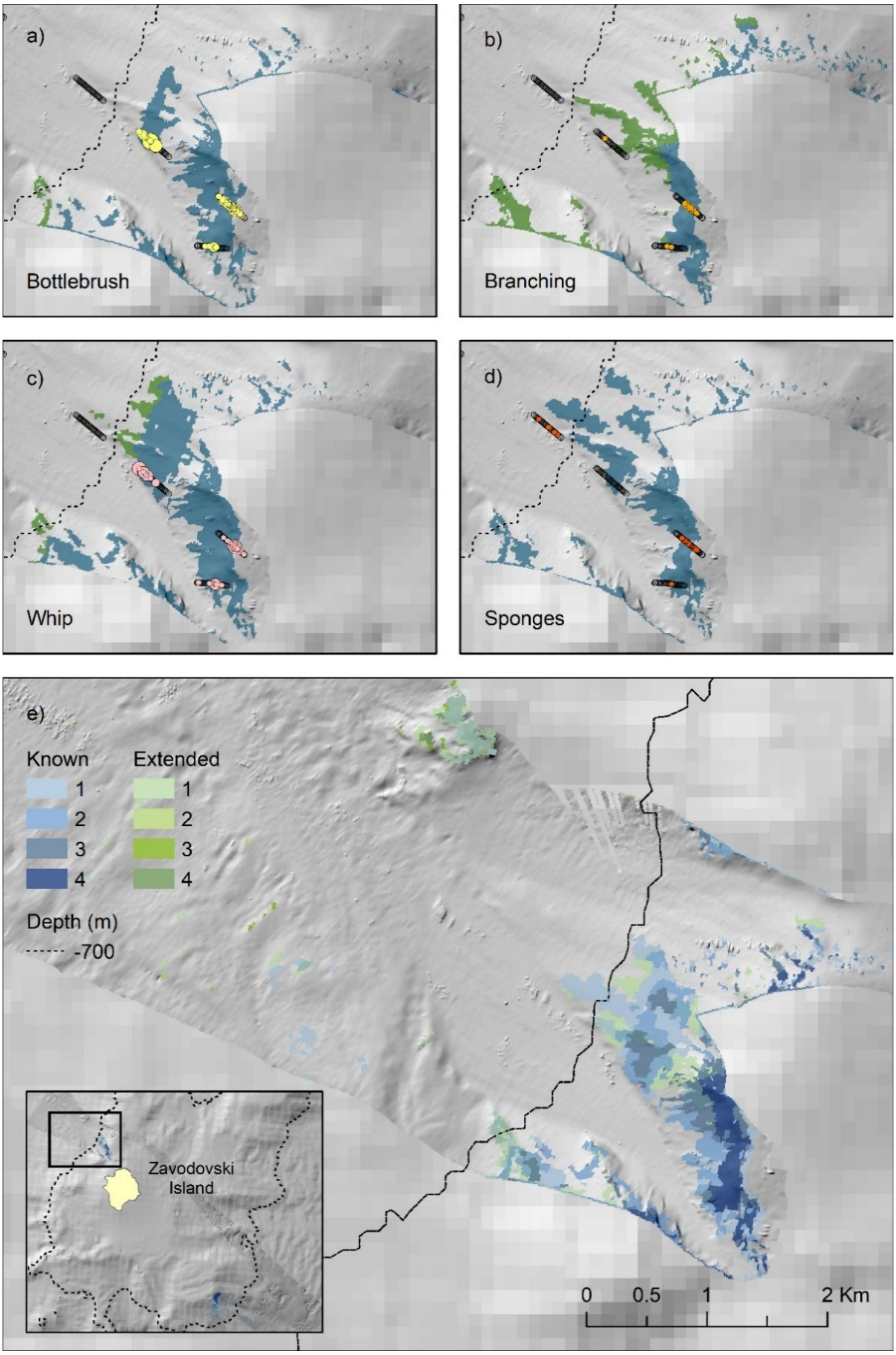

Figure 6.23. Occurrences of VME indicator taxa observed in still images at the survey location north-west of Zavodovski Island, with distribution of suitable habitat extrapolated through OBIA to cover the MBES extent for (a) bottlebrush corals, (b) branching corals, (c) whip corals, and (d) sponges. Camera transects are denoted by circles, with filled circles indicating the presence of VME. The bottom panel (e) shows the number of co-occurring VME taxa predicted. Blue colours indicate the extent within the observed depth limit for Zavodovski Island, green colours indicate topographically suitable habitat extended below the observed depth (see Section 6.5.3). The size of circles denotes the prevalence of taxa within images.

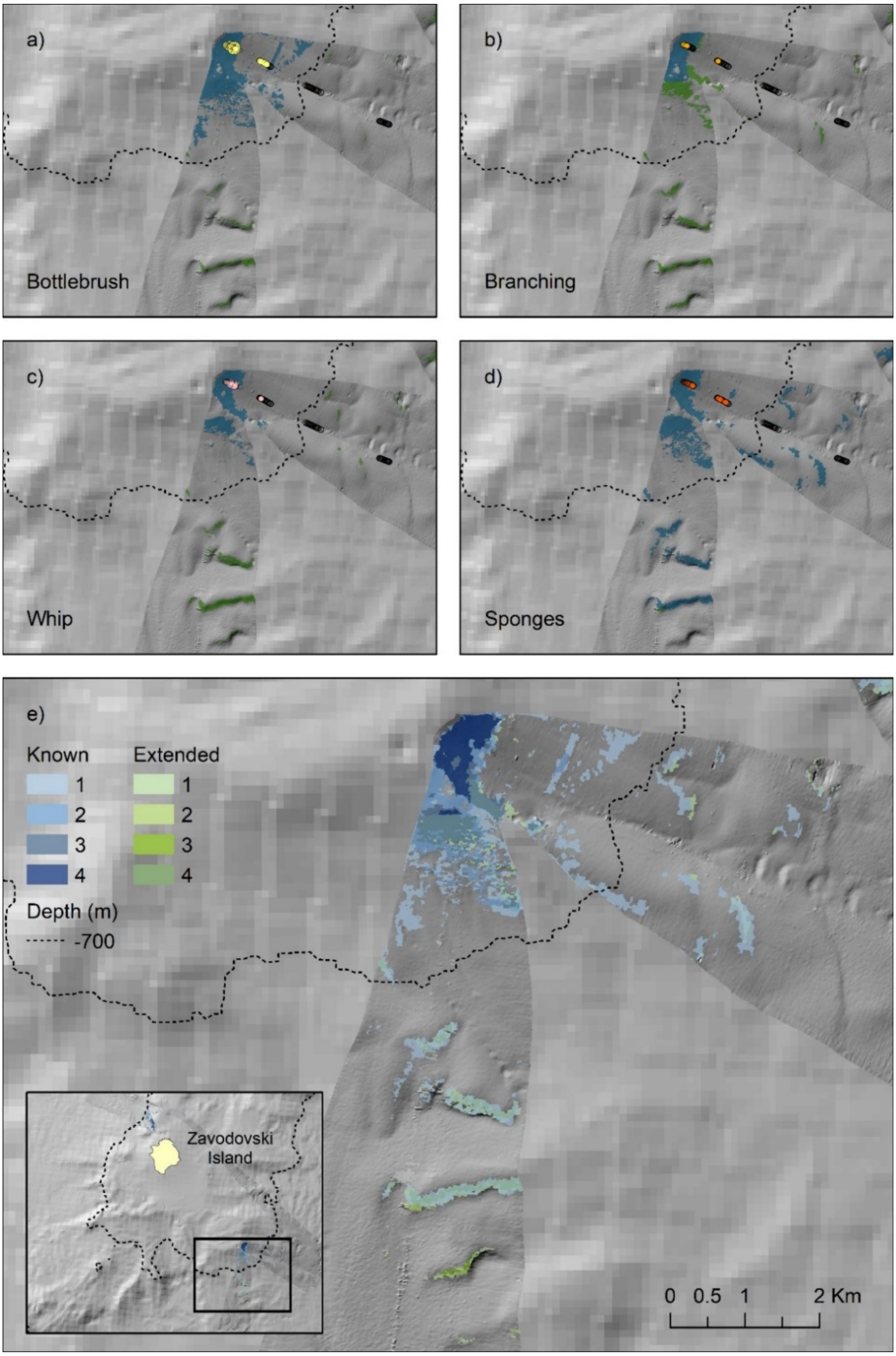

Figure 6.24. Occurrences of VME indicator taxa observed in still images at the survey location south-east of Zavodovski Island, with distribution of suitable habitat extrapolated through OBIA to cover the MBES extent for (a) bottlebrush corals, (b) branching corals, (c) whip corals, and (d) sponges. Camera transects are denoted by circles, with filled circles indicating the presence of VME. The bottom panel (e) shows the number of co-occurring VME taxa predicted. Blue colours indicate the extent within the observed depth limit for Zavodovski Island, green colours indicate topographically suitable habitat extended below the observed depth (see Section 6.5.3). The size of circles denotes the prevalence of taxa within images.

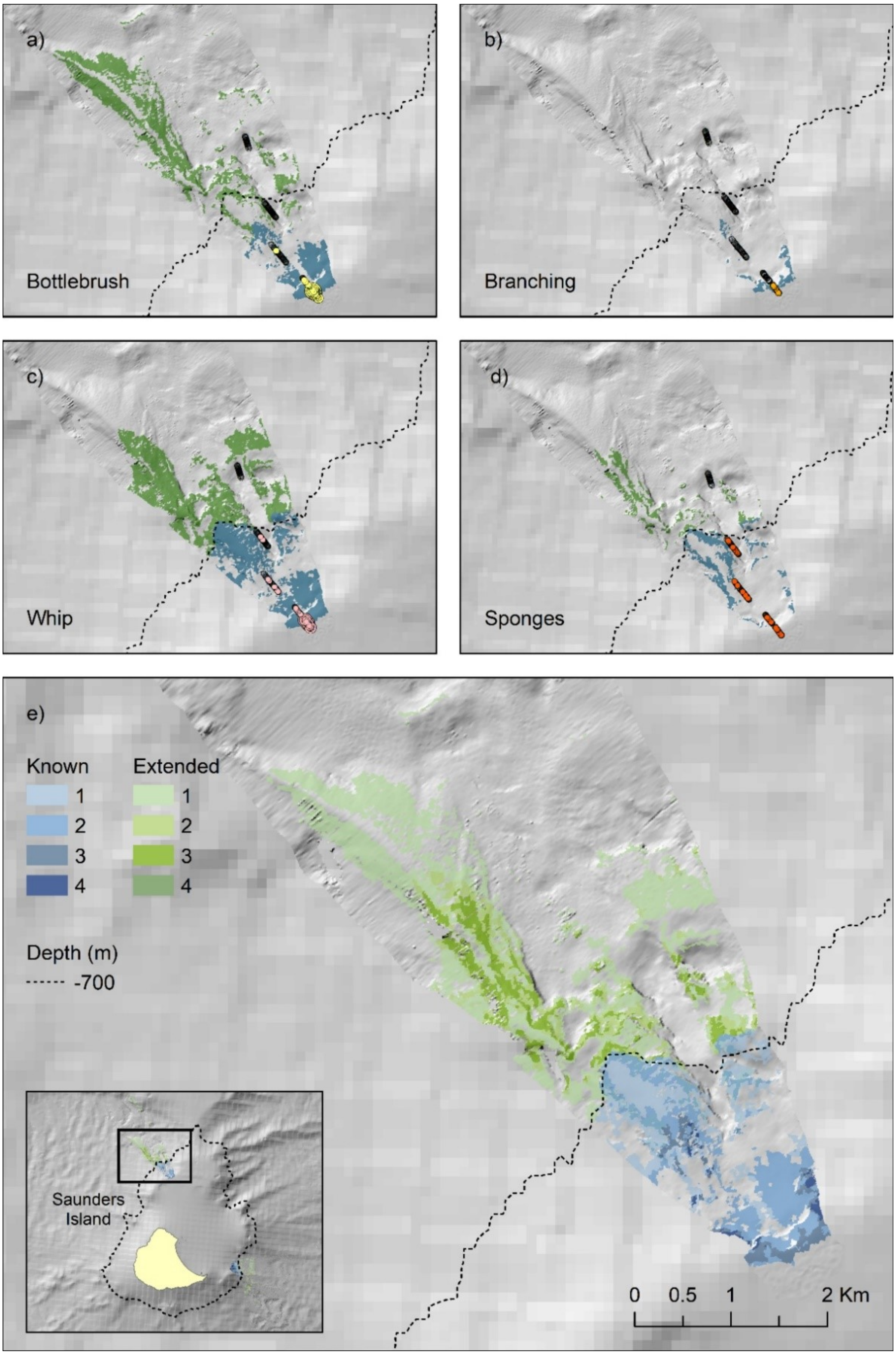

Figure 6.25. Occurrences of VME indicator taxa observed in still images at the survey location north-west of Saunders Island, with distribution of suitable habitat extrapolated through OBIA to cover the MBES extent for (a) bottlebrush corals, (b) branching corals, (c) whip corals, and (d) sponges. Camera transects are denoted by circles, with filled circles indicating the presence of VME. The bottom panel (e) shows the number of co-occurring VME taxa predicted. Blue colours indicate the extent within the observed depth limit for Saunders Island, green colours indicate topographically suitable habitat extended below the observed depth (see Section 6.5.3). The size of circles denotes the prevalence of taxa within images.

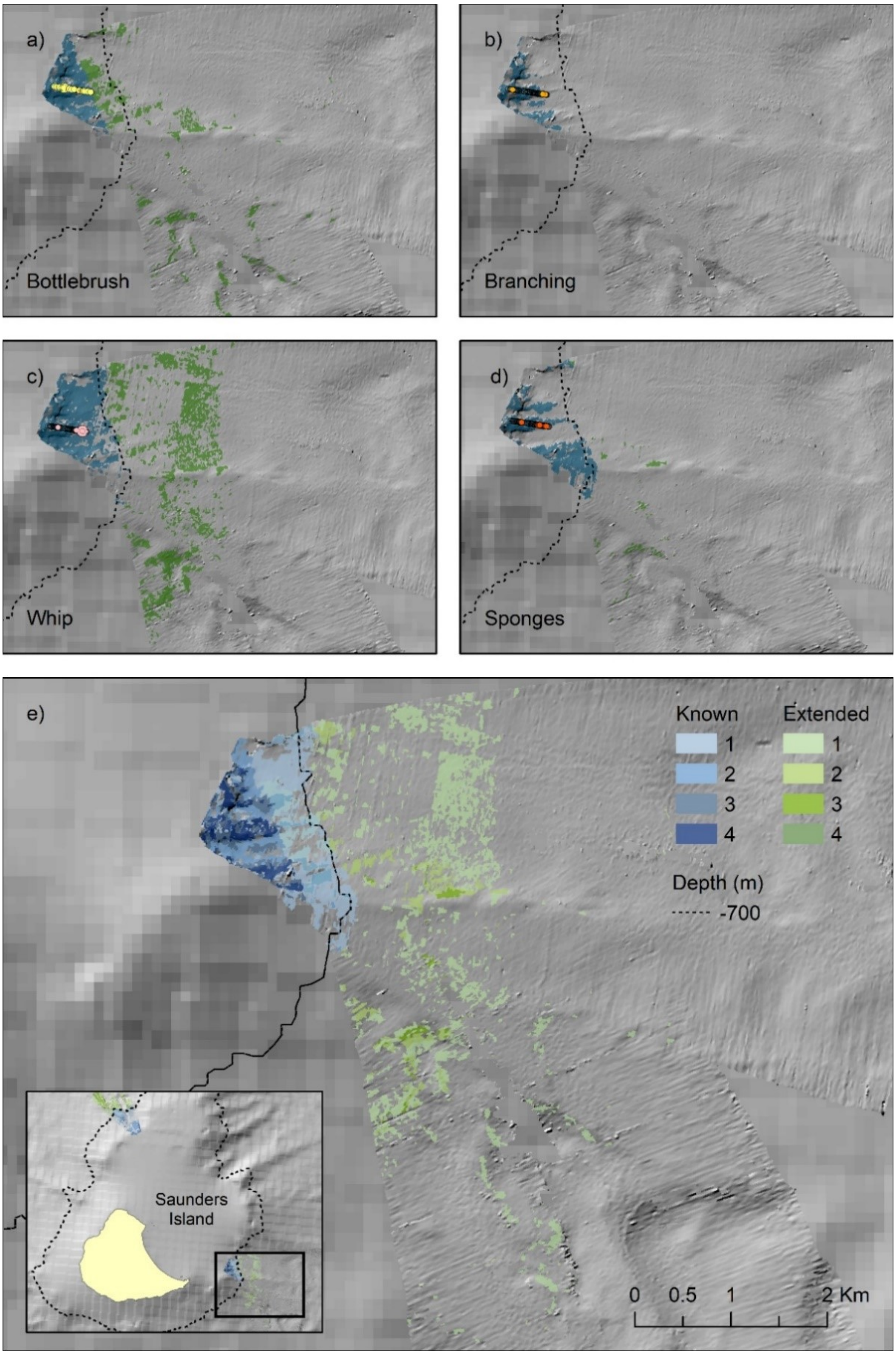

Figure 6.26. Occurrences of VME indicator taxa observed in still images at the survey location west of Saunders Island, with distribution of suitable habitat extrapolated through OBIA to cover the MBES extent for (a) bottlebrush corals, (b) branching corals, (c) whip corals, and (d) sponges. Camera transects are denoted by circles, with filled circles indicating the presence of VME. The bottom panel (e) shows the number of co-occurring VME taxa predicted. Blue colours indicate the extent within the observed depth limit for Saunders Island, green colours indicate topographically suitable habitat extended below the observed depth (see Section 6.5.3). The size of circles denotes the prevalence of taxa within images.

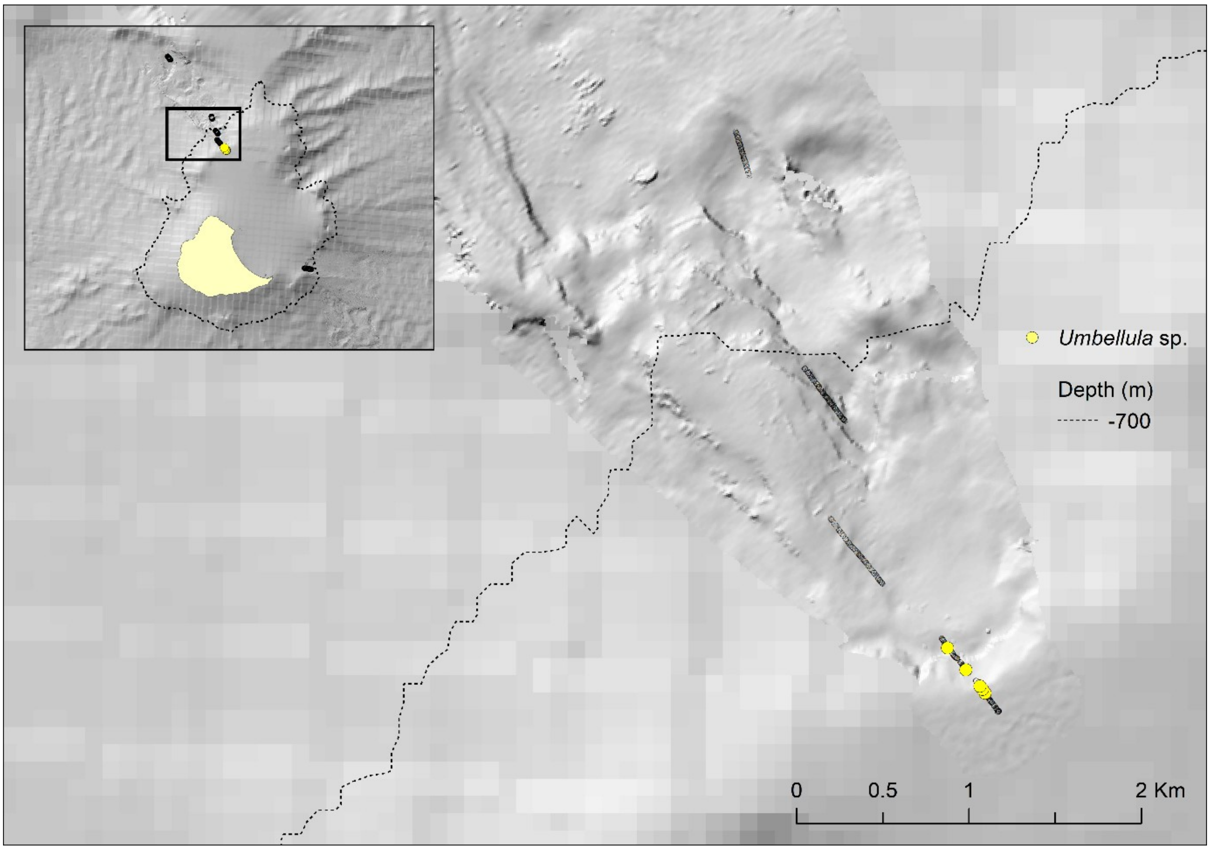

Figure 6.27 Location of still images with *Umbellula* sp. sea pens observed at Saunders Island. The size of circles denotes the prevalence of taxa within images.

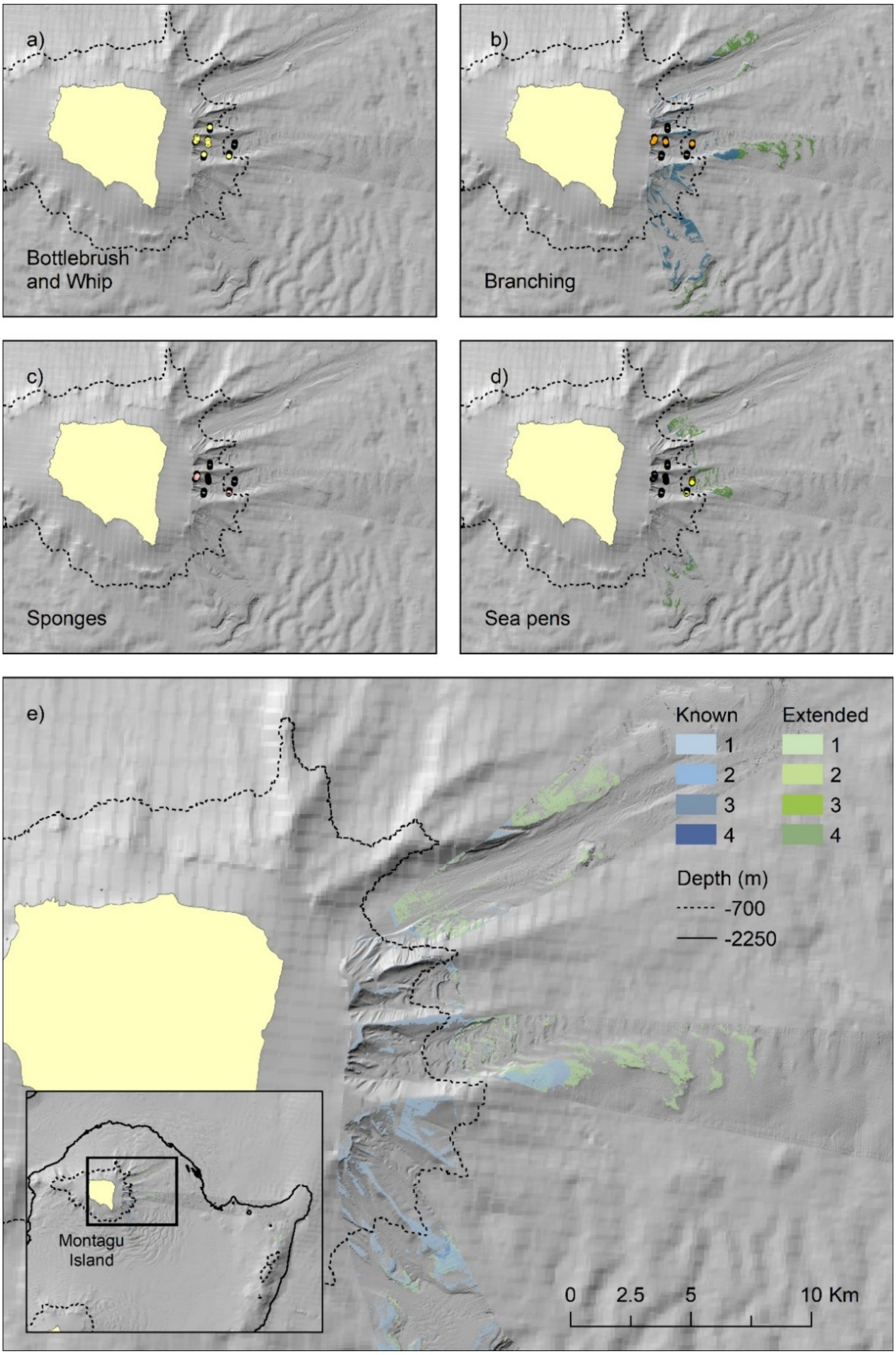

Figure 6.18. Occurrences of VME indicator taxa observed in still images at the survey location on Montagu Island, with distribution of suitable habitat extrapolated through OBIA to cover the MBES extent for (a) bottlebrush corals, (b) branching corals, (c) whip corals, and (d) sponges. Camera transects are denoted by circles, with filled circles indicating the presence of VME. The bottom panel (e) shows the number of co-occurring VME taxa predicted. Blue colours indicate the extent within the observed depth limit for Montagu Island, green colours indicate topographically suitable habitat extended below the observed depth (see Section 6.5.3). The size of circles denotes the prevalence of taxa within images.

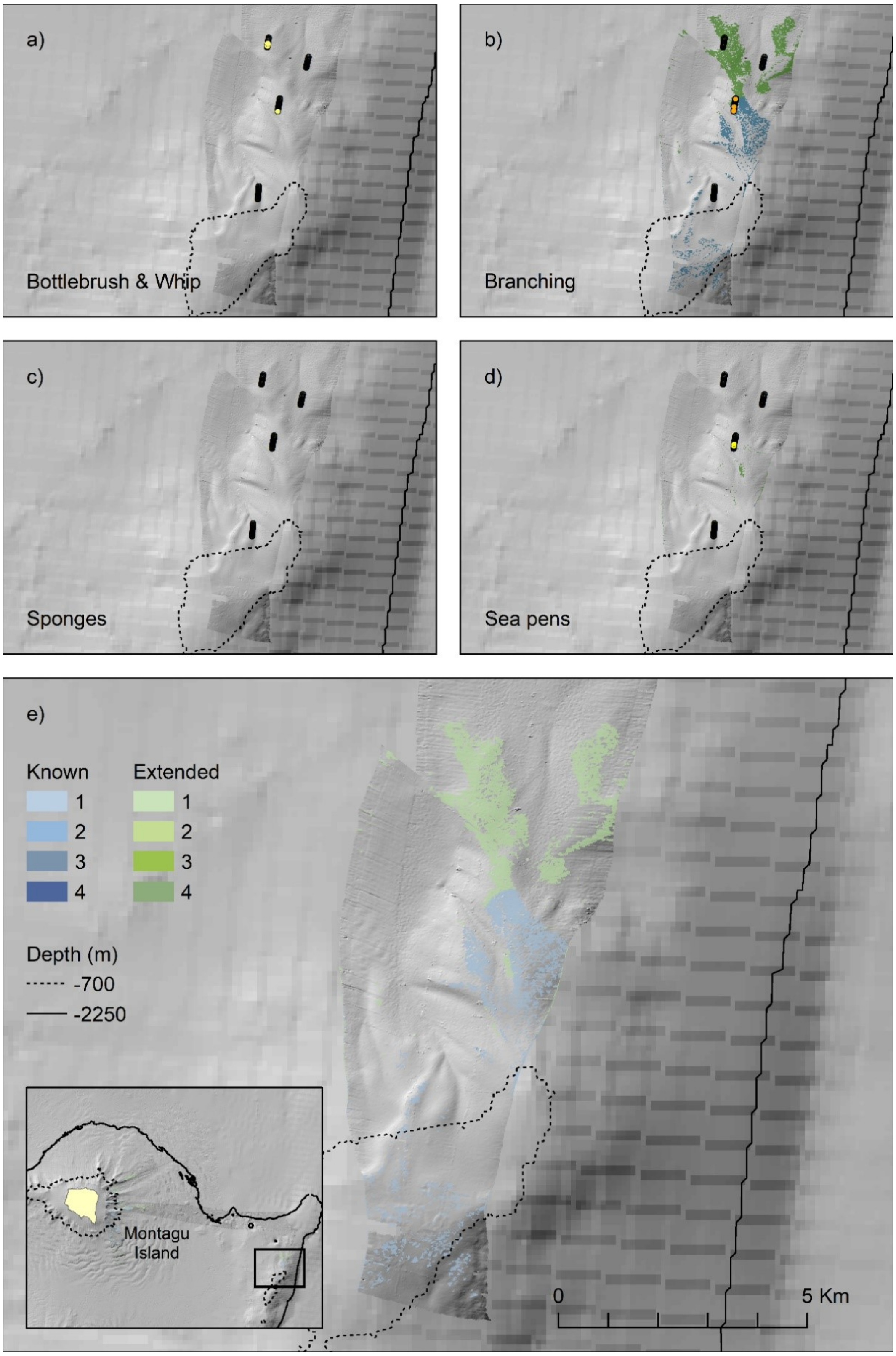

Figure 6.29. Occurrences of VME indicator taxa observed in still images at the survey location at Montagu Bank for (a) the bottlebrush and whip corals, (b) sponges, (c) branching corals, and (d) sea pens, with distribution of suitable habitat extrapolated through OBIA to cover the MBES extent shown for branching Alcyonacea and sea pens. The bottom panel (e) shows the number of co-occurring taxa predicted. Blue colour indicates the extent within the observed depth limit for Montagu Island, green colour indicates topographically suitable habitat extended below the observed depth (see Section 6.5.3). The size of circles denotes the prevalence of taxa within images.

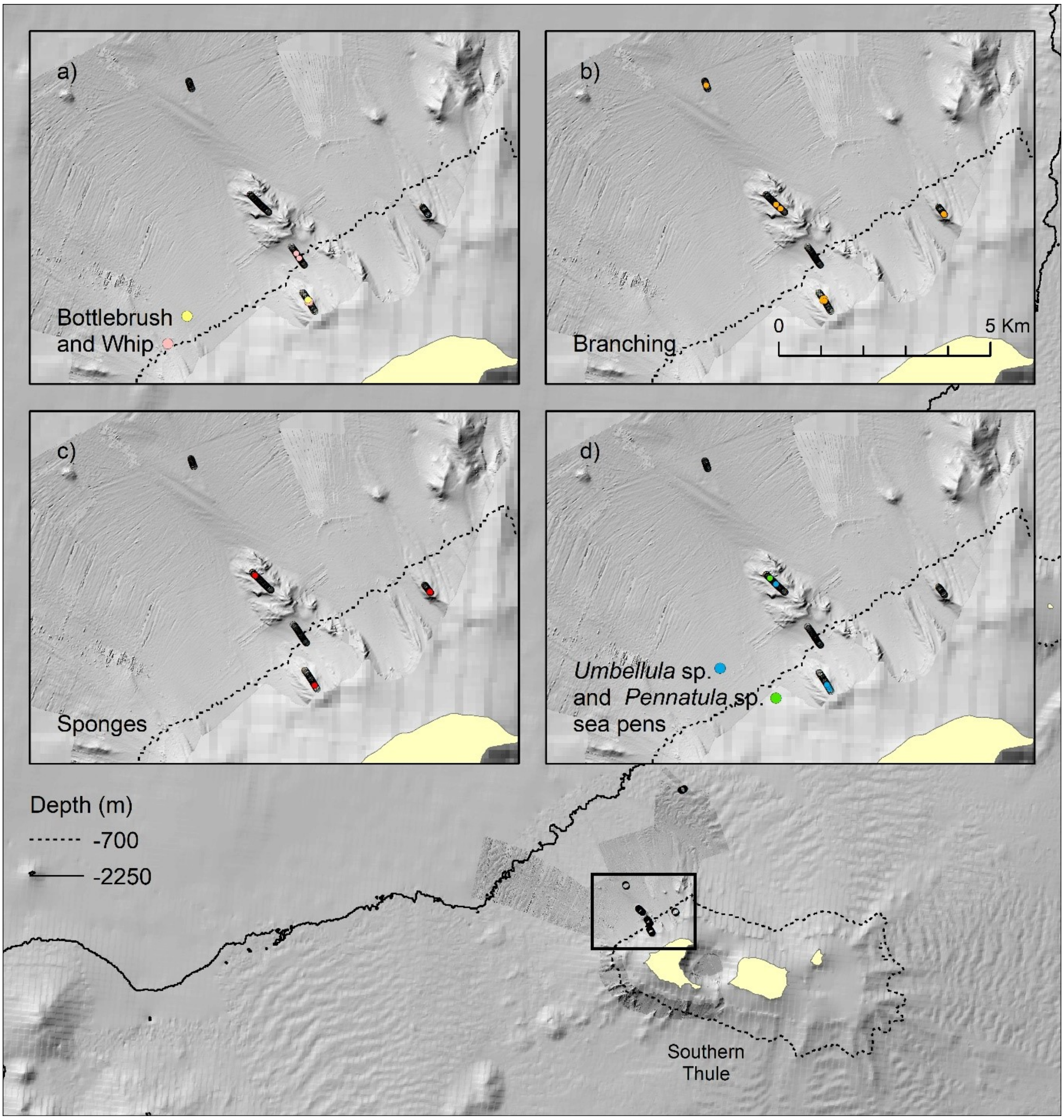

Figure 6.30. Occurrences of VME indicator taxa observed in still images at the survey location at Southern Thule for (a) bottlebrush and whip corals, (b) sponges, (c) branching corals, and (d) *Umbellula* sp. and *Pennatula* sp. Sea pens. The size of circles denotes the prevalence of taxa within images.

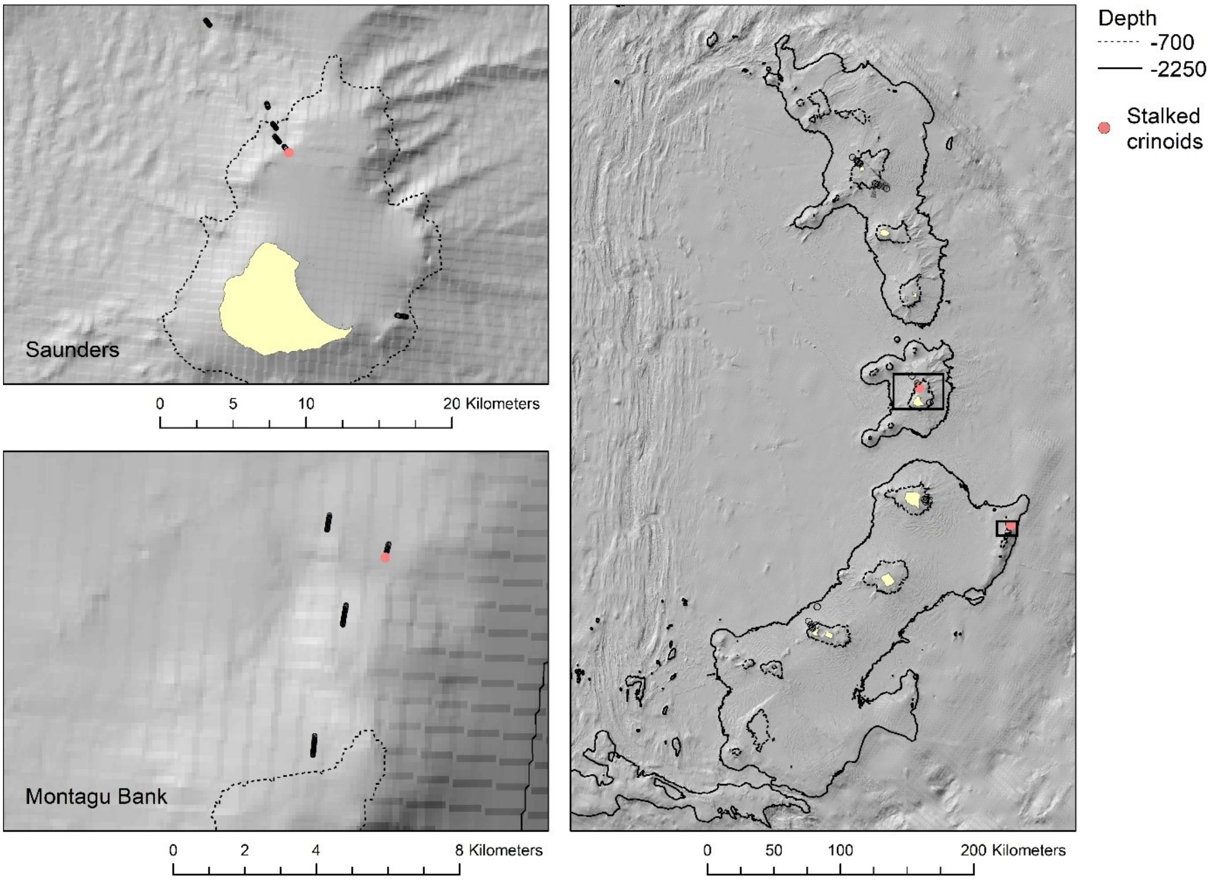

Figure 6.31. Occurrences of stalked crinoids (denoted in pink) in still images at the survey locations at Saunders Island and Montagu Bank. Survey sites for which crinoids were not recorded are denoted in black. The size of circles denotes the prevalence of taxa within images.

6.7 Drop camera analysis discussion and highlights

Deep-water camera operations have allowed the collection of high-resolution imagery of the seabed at the South Sandwich Islands to investigate the regions benthic fauna and its potential vulnerability to licensed longline research fisheries. At each surveyed island, the Blue Belt Programme's deep-water camera system was deployed to record the distribution and diversity on the seabed at different depth strata.

Whilst the analysis presented in this report is qualitative, the photographic studies undertaken nevertheless provide a significant insight into the biogeography of the region. The benthic fauna of the South Sandwich Islands shows variation in faunal composition both along the north-south gradient and by depth, corresponding with variations in topographic and oceanographic parameters.

A total of eight VME indicator taxa were mapped along the slopes of the South Sandwich Islands and a distinction, both in taxon composition and abundance, was visually observed between different bathymetric zones. Local-scale variations in distribution of benthic fauna were apparent, and the high-resolution multibeam echosounder acoustic data suggests a high dependency of topographic features (e.g. slope, exposure and depth). At Zavodovski and Saunders Islands the most commonly observed coral morphotypes were the bottlebrush and whip forms, whilst at Southern Thule, most corals were of the branching morphotype. The branching corals that were observed at the two northern islands were also different taxonomically from Southern Thule, being represented mostly by primnoid sea fans at Zavodovski and Saunders Island and by branching Isididae at Southern Thule. The differences in distribution between VME indicator taxa suggest that they respond differently to environmental conditions.

In situ observations included a wider range of taxa, including VME indicator species, occurring in higher numbers, at Zavodovski and Saunders Islands. Southern Thule showed lower, but distinct diversity of benthic fauna compared with the northern sites. The results suggest most of the VME taxa at the South Sandwich Islands occur in waters shallower than 700m depth. The vast majority of observed presence is limited to this range and no observations of significant aggregations were made below this depth, bar one. The only VME indicator taxon observed in deeper waters coinciding with the depths where the research longline fishery is permitted were *Pennatula sp*. sea pens in a continuous, albeit sparse, sea pen field at eastern Montagu Island at a depth of ~820m. The current map of sea pen distribution for the island is based mainly on this one transect, which limits the extrapolated distribution to a very narrow depth range and as such, the extent of their distribution could warrant further investigation with sampling targeted based on suitable ground (soft sediment, low reflectivity) to confirm their depth range and extent of distribution.

7. Benthic communities of the South Sandwich Islands: results from trawl surveys

7.1 General objectives

The epibenthic macrofauna at the South Sandwich Islands was sampled during the DY99 survey. The provisional identification and classification provide a basis for biogeographical analysis of the region (sections 9) and the samples collected, in future, will allow researchers to conduct more detailed taxonomic investigations using traditional classification and genetic methods (sections 10 and 11).

7.2 Taxonomic standards

Provisional species identifications were based on Rauschert and Arntz (2010), Benedet (2017) and Hogg and Collins (In Prep.); with taxonomic identifications matched to the World Register of Marine Species (WoRMS) to ensure a consistent and up-to-date taxonomic description. Where species identification was inconclusive, the lowest conclusive taxonomic level was recorded.

7.3 Data analysis

Statistical analysis was conducted to investigate the relationship between faunal composition and habitat distribution with individual station data grouped by island and depth. Latitudinal and depth patterns were investigated based on abundance data using Bray-Curtis similarities and ordination by multi-dimensional scaling (MDS) using a fourth-root transformation of the abundance data to down-weight highly abundant species. In addition, similarity and dissimilarity within and between islands and depth zones were tested using SIMPER analysis (Primer-e v7; Clarke and Gorley, 2015).

7.4 Faunal composition

The epibenthic faunal dataset comprised of 541 individuals, accounting for over 3,643 specimens belonging to 12 phyla, including: corals (Actiniaria, Alcyonacea, Hydrozoa, Pennatulacea, Scleractinia, Zoantharia), sponges (Desmospongiae), crinoids, sea stars, brittle stars and sea cucumbers, bryozoans, crustaceans (Amphipoda, Decapoda, Euphausiacea, Isopoda, Mysida, Pycnogonida), polychaetes and nematodes. A taxonomic summary is provided in Table 7.1. In total, 81 preliminary taxa were recorded across the sampled areas. Of these, 19 were provisionally identified to species level, belonging to 18 distinct families. The remaining taxa were identified to higher taxonomic levels, whilst seven taxa could only be identified to phylum level. Malacostraca and Anthozoa were the most diverse class comprising six and five taxa respectively.

Table 7.1. Summary of total number of specimens sampled by site and taxa from Zavodovski Island (ZAVO), Saunders Island (SAUN), Montagu Island (MONT) and Southern Thule (SOTH).

Phylum	**Station**						**Total**
	ZAVO07	**SAUN01**	**MONT07**	**MONT13**	**SOTH01**	**SOTH02**	
Annelida	211	147	153	206	94	15	826
Arthropoda	36	185	233	104	7	91	656
Brachiopoda	28	10	5				43
Bryozoa	318	100	2				420
Cephalorhyncha					1		1
Chordata	7	5	3	5			20
Cnidaria	43	192	3	209	2	7	456
Echinodermata	190	474	25	80	10	16	795
Mollusca	6	20	10	158	1	2	197
Nematoda			100		5		105
Porifera	18	103			1		122
Sipunculida						2	2
Total	857	1,236	534	762	121	133	3,643

The most dominant taxa, in terms of numbers of samples, were Annelida, Echinodermata and Arthopoda. The least common taxa were Cephalorhyncha, Sipunculida, and Chordata. The highest number of individuals from any given trawl was from Saunders Island (station no. 18), accounting for 34% of the total collected samples. The southern region (Southern Thule) had the lowest abundances, with only 121 individuals collected at the shallower station (SOTH01) and 133 at the deeper site (SOTH02).

The composition of benthic epifauna changed with latitude from north to south along the South Sandwich Islands chain. Sampling at different depths however represented a potentially confounding influence on these results. Sampling at Southern Thule, for example, demonstrated a shift in faunal composition with depth from a dominance of annelids (polychaetes) in shallower waters to arthropods (mostly mysids and pycnogonids) at the deeper stations. To isolate the influence of latitude on faunal composition, stations were grouped into two depth categories (< 400m and > 400m). In the depth range > 400m two samples were collected at Montagu Island and at Southern Thule. Significant differences were noted in species composition and abundances between the two islands. Notably in terms of abundances, there was a dominance of zoanthids at Montagu Island in contrast to mysids at Southern Thule.

Samples collected during DY99 include a wide range of taxa, which require further taxonomic examination for a more detailed biogeographical description. A summary description of each taxonomic group is presented below.

7.4.1 Annelida, Nematoda, Sipunculida and Cephalorhyncha

The Agassiz trawl sampled small-sized epibenthic fauna, such as polychaetes and other unsegmented worms, recording a high abundance, with some taxa such as members of the family Phyllodocida, occurring in most samples. In contrast, some annelids, notably of the taxa Clitellata, Sabellida and Terebellida, only occurred in one sample each. Identification of most annelids to lower taxonomic levels was not possible onboard. Nematodes occurred in high abundances at Montagu Island, while sipunculids and cephalorhynchs were infrequent and restricted to Southern Thule.

7.4.2 Arthropoda

Benthic sampling revealed diverse assemblages of epibenthic crustaceans. Mysids and amphipods had a wide range across latitudinal and depth gradients, whilst Isopods were only collected in Saunders Islands. Sea spiders of the families Nymphonidae and Colossendeidae had distinct geographical ranges, at Southern Thule, and Saunders and Montagu Islands, respectively.

7.4.3 Echinodermata

Echinoderms represented the second most recorded taxa, of which brittle stars were the most abundant. This was particularly notable at Saunders Island, where over 315 individuals were recorded. In general, sea cucumbers and crinoids were also recorded in nearly every Agassiz trawl deployed, with the exception of the deep station at Southern Thule. Several large sea stars were also collected, particularly the cold-water sea star (*Labidiaster* sp.) and an unidentified Asteroidea (Figure 7.1). Sea urchins were less common, with samples only recorded at Zavodovski and Montagu Islands.

7.4.4 Mollusca and Brachiopoda

Relatively low numbers of molluscs were recorded. Five molluscan classes were collected (Bivalvia, Cephalopoda, Gastropoda, Polyplacophora and Scaphopoda), of which bivalves were the most ubiquitous group, absent only at Southern Thule. Cephalopods were sampled at Saunders Island, Montagu Island and Southern Thule, with one specimen collected at each location. Eighty percent of the molluscan samples were collected at the deeper station off Montagu Island, with these samples primarily dominated by scaphopods. Gastropods were present at Saunders and Montagu Islands, with more than 50% sampled at about 830m depth off Montagu, whilst the small number of chitons (Polyplacophora) recorded were restricted to the muddy bottom of Saunders Island. Samples of brachiopods were restricted to the shallower stations off Zavodovski, Saunders and Montagu Islands.

7.4.5 Bryozoa and Porifera

A diverse range of bryozoans were collected, including branching and encrusting colonies. These samples were restricted to the northern sampling locations, mainly at Zavodovski and Saunders Islands, with an additional two specimens sampled in the shallow station of Montagu Island (185m depth).

The diversity and abundances in sponges were universally low across samples. This was likely on account of trawling occurring largely in the predominant soft sediment environments whereas greater diversity would be expected to occur in hard substrate environments. In total ~120 specimens (or fragments) were collected during DY99, with samples geographically restricted to Zavodovski and Saunders Islands. Though some samples remain unidentified, the collection predominantly consisted of the class Desmospongiae.

7.4.6 Cnidaria

Cnidaria, including corals and hydroids, were a ubiquitous group throughout the South Sandwich Islands samples. In total, 456 specimens were collected, with zoanthids and small stony corals representing the largest constituent groups. Zoanthids were the dominant taxa at the deep station at Montagu Island, whilst stony corals were dominant at Saunders Island. Few anemones or hydroids were caught at Southern Thule. Few cnidarians sampled were collected at Montagu Island. The shallower depths of Zavodovski and Saunders Islands appear more diverse and with higher abundances than deeper waters. One sea pen, provisionally identified as *Pennatula phosphorea,* was collected in Montagu Island (830m) which corresponded with observations made during drop-camera deployments in the region (see Section 6).

7.4.7 Chordata

Few ascidians were recorded from trawl samples. Those that were, were caught at Zavodovski and Saunders Islands, and in the deep station at Montagu Island. Salps were caught at Zavodovski Island and six small nototheniid fish (*Nototheniops larseni*) were caught at Saunders (230m) and Montagu islands (185m). These samples were most likely collected during the decent or ascent of the gear.

7.5 Community analysis

7.5.1 Zavodovski Island

Three hauls were conducted at the same depth (350m) at Zavodovski Island. The benthic assemblages (presented in Figure 7.2 for each island) were dominated by bryozoans (37.1%) and polychaetes (24.6%). A wide range of echinoderms (seastars, sea urchins, crinoids, sea cucumbers and brittlestars) accounted for 22.2% of samples, of which 65% were brittlestars. Other taxa collected, included those classified as VME: corals (4%, Alcyonacea), brachiopods (3.3%), sponges (2.1%), and hydroids (0.6%). Mysids and seaspiders were the dominant crustaceans, although both recorded low relative abundances (1.9% and 1.4% respectively).

7.5.2 Saunders Island

Benthic fauna collected from 330m at Saunders Island demonstrated a more even representation of taxonomic groups in comparison to that from Zavodovski Island. Six species of Echinoderms were recorded, dominated by brittlestars and sea cucumbers belonging to the order Dendrochirotida. These represented 25.6% and 8.3% of the total assemblage, respectively. Bryozoans and sponges represented 8.3% of samples at Saunders Island, whilst corals, and in particular the stony corals (scleractinians), were also common at this site, with 125 (10.1%) samples recorded. Other taxa included polychaetes (11.9%), mysids (8.3%), seaspiders (4%) and amphipods (1.6%).

7.5.3 Montagu Island

Two locations were sampled at Montagu Island from 185m and 830m depth. A shift in the dominant species was observed with depth. Seaspiders (22.8%) and mysids (19.7%) were the most abundant taxa collected in the shallower station, with sabellid worms and nematodes also contributing considerably to the assemblage (19.5% and 18.7%). Polychaetes (27%), zoanthids (26.4%), scaphopods (13.1%) and decapods (10.5%) were more abundant in the deeper sample.

7.5.4 Southern Thule (Cook Island)

Two sites were sampled at Southern Thule, at depths of 325 and 605m. A third station was sampled at 332m using the epibenthic dredge. The shallow sites were dominated by polychaetes (77.7%), with brittlestars, sea cucumbers and one sea star contributing a further 8.3% of the assemblage. Crustaceans (predominantly seaspiders and amphipods), and nematodes accounted for 5.8% and 4.1% of samples, respectively. Corals and sponges were rare (3 specimens, ca. 2% in total).

At 605m, trawl samples were characterised by mysids and seaspiders (68.4%), brittlestars (11.3%) and polychaetes (11.3%). The polychaetes belonged to the order Terebellida, which were only found at this station. Sea anemones and hydroids were also found, but in lower proportions (3.8% and 1.5% respectively).

Figure 7.1. Examples of epibenthic fauna collected during the Blue Belt RRS *Discovery* Expedition 99. (a) primnoid coral; (b) assorted polychaetes; (c) unidentified ophiuroid; (d) unidentified sea star, probably belonging to Genus *Labidiaster* (Class Asteroidea); (e) unidentified coral; (f) assorted holothurians; (g) sea pig (probably *Laetmogone violacea*); (h) assorted sea spiders (Class Pycnogonida); (i) unidentified sea star (Class Asteroidea); (j) assorted amphipods; (k) decapod shrimp, provisionally identified as *Nematocarcinus lanceopes*; (l) unidentified sea star (Class Asteroidea).

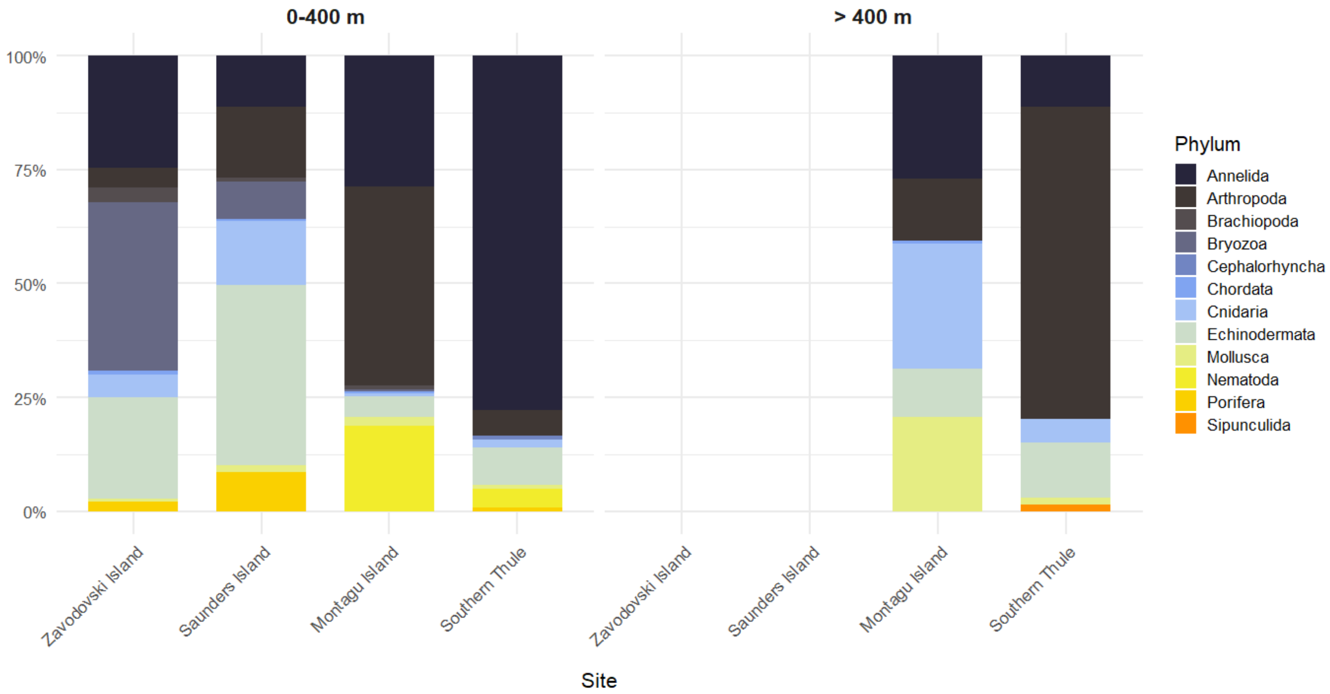

Figure 7.2. Proportion of samples recorded by phylum for each island.

7.6 Multivariate analysis

Multivariate statistical techniques were applied to determine the factors driving the benthic community composition along the South Sandwich chain; although the analysis is confounded by the low number of samples taken, the different depths sampled and the sampling efficiency of the two trawl gears.

Multidimensional scaling (MDS) demonstrated a clear similarity between the benthic fauna of Zavodovski and Saunders Islands, and, to some extent, the shallow depth communities of Montagu Island. Conversely, Southern Thule showed a low similarity with the northern region. The deeper station (830m) sampled at Montagu Island was dissimilar to all other stations (Figure 7.3).

Similarity in the faunal composition between samples measured using Bray-Curtis demonstrated minor differences between Zavodovski and Saunders (37.24%), between Montagu and Saunders (44.10%) and Montagu and Zavodovski (47.96%). High dissimilarity was shown between Southern Thule and the other sampled regions. Of this dissimilarity, SIMPER analysis demonstrated that 65-66% can be explained by distinct taxon sampled at the deep station (SOTH02), namely Sipunculida and Nymphonidae. However, this interpretation should be taken with caution as a better taxonomic resolution of the specimens sampled in other locations is likely to refine this preliminary analysis.

The clusters among taxa seem to separate the northern stations (Zavodovski and Saunders Islands) from Southern Thule. The northern stations were dominated by bryozoans, sponges and echinoderms (brittle stars and sea cucumbers), whilst Montagu and Southern Thule exhibited higher abundances of polychaetes, nematodes, mysids, pycnogonids and, at the deep station of Montagu Island, zoanthids (Figure 7.4).

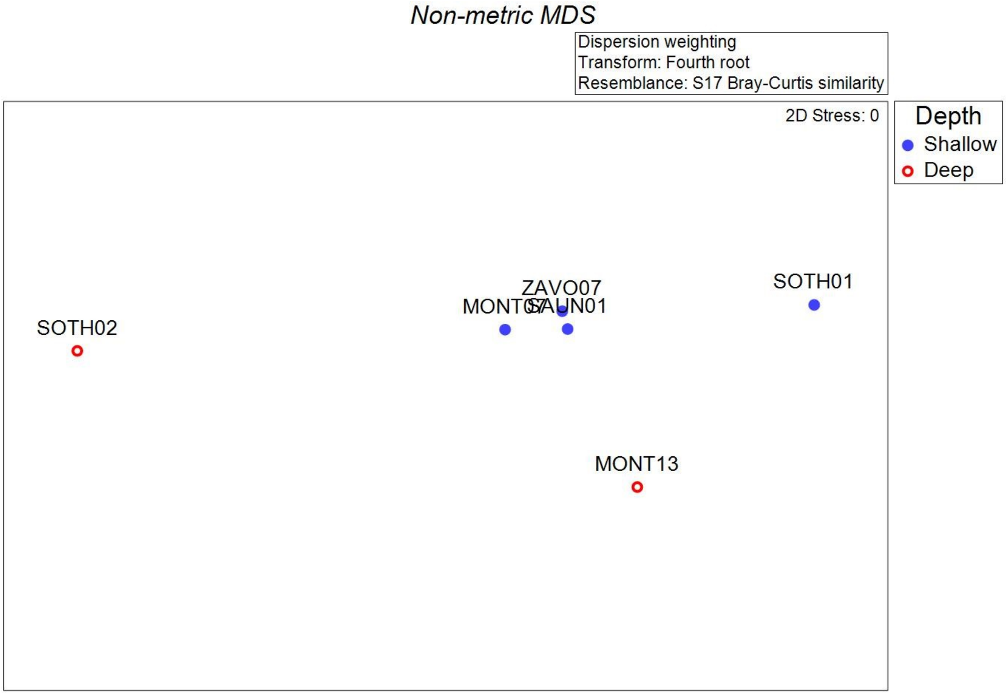

Figure 7.3. Multidimensional scaling plot of the epibenthic assemblages by depth.

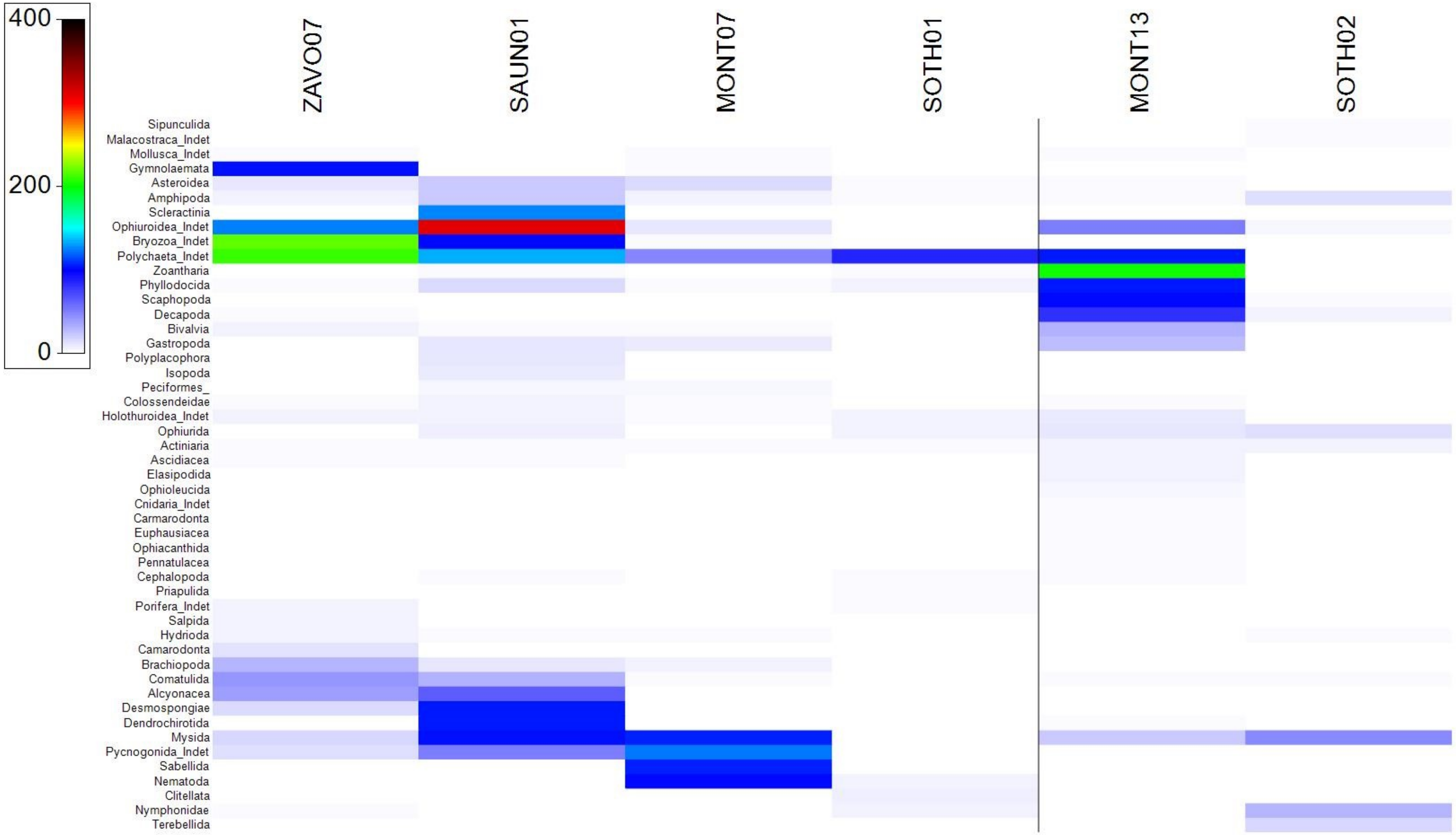

Figure 7.4. Comparative shade plot showing abundances of epibenthic fauna collected during DY99, at each site. ZAVO07-SOTH01 represent the shallow sampling sites at Zavodovski Island and Southern Thule, and MONT13 and SOTH02, the deeper sampling sites at Montagu Island and Southern Thule. Species abundance was transformed to down-weight dominant species that were observed in the raw data.

7.7 Discussion

Biodiversity data collected during DY99 has contributed to an improved understanding of benthic biogeography across the South Sandwich archipelago and the wider Scotia Sea. The collection includes 81 taxa, belonging to 12 phyla; providing opportunities for taxonomic biodiversity studies and predictive modelling of the distribution of benthic communities in the region.

The dominance of generalist deposit-feeders, active predators and scavengers (e.g., polychaetes, sea spiders, brittlestars and sea cucumbers) suggests food availability and depth are important factors explaining the community structure along the South Sandwich Islands (Ramos, 1999; Lockart & Jones, 2008). The communities benefit from inputs of organic matter from the pelagic realm, and thus the observed differences in community composition along the latitudinal gradient could be a result of variations in sea ice cover and primary productivity, associated with the low sea surface and seabed temperature (Gutt et al., 2021).

Trawl survey results demonstrate substantial faunal variability between sampling sites. SIMPER analysis identified suspension feeders such as corals, bryozoans and sponges as contributing most to this observed variability. Notably, suspension feeders were mostly sampled at Zavodovski and Saunders Islands, whereas trawl samples from higher latitude stations consisted predominantly of generalist deposit-feeders, predators, and opportunists. Low occurrences of sessile fauna at Southern Thule were evident from both trawl samples and camera surveys. This trend could be indicative of a scarce food supply owing to the increased duration of sea ice coverage at these latitudes (Ramos, 1999). Another plausible explanation could be the frequent passage of icebergs. The effects of small-scale disturbance regimes, such as iceberg scouring, is thought to enhance sedimentation and disrupt the settlement and feeding of sessile fauna (Smale et al., 2008; Barnes, 2017).

The slopes of the South Sandwich Islands vary in age, topography and sediment type, as described in Sections 6 and 9. Water-masses and primary productivity are also important factors in driving faunal composition (e.g., Hogg et al., 2018). Analysis of the composition of trawl samples suggests differences in taxa between sampled stations are likely due to a combination of local topography and changes in environmental conditions along a north-south gradient. These results, although based on a limited number of sampled stations, support results from the deep-water camera observations (see Section 6), in that benthic fauna present on the island’s slopes differ along a depth gradient, as observed in other locations from the Scotia Sea and Weddell Sea (Lockart & Jones, 2008; Kaiser et al., 2011).

The trawl samples have provided important species presence information allowing taxonomic validation of the deep-water camera observations. The data collected represents a further development in the understanding of deep-water communities at the South Sandwich Islands. For example, the sea pen collected at 830m depth (provisionally identified as *Pennatula phosphorea antarctica*), at Montagu Island confirmed the species identity in video observations. Other taxa, such as gorgonian and scleractinian corals, are currently being identified in more detail and analysed under the scope of research projects, linked to DY99, to provide information on genetic connectivity and paleoecology of deep-sea corals (see sections 10 and 11).

8. Monitoring the behaviour and benthic impact of longline gears

8.1 Longline fishing

Research fishing is permitted along the South Sandwich Islands archipelago, to monitor the local biomass of Patagonian toothfish (*Dissostichus eleginoides*) and Antarctic toothfish (*Dissostichus mawsoni*) which are linked to the South Georgia and Antarctic populations. Two vessels are licensed annually by GSGSSI to use benthic longlines (either Spanish or autoline systems, Figure 8.1). The vessels are allocated research fishing positions, from a random stratified spatial distribution of known locations (historic viable fishing locations). This ensures samples are collected and tagged toothfish are released throughout the species distributions rather than at vessels' favoured fishing locations. Fishing is restricted within the GSGSSI MPA to depths between 700 - 2,250m (Section 3.3). The majority of the lines are set by the vessels between 1,000 – 1,700m.

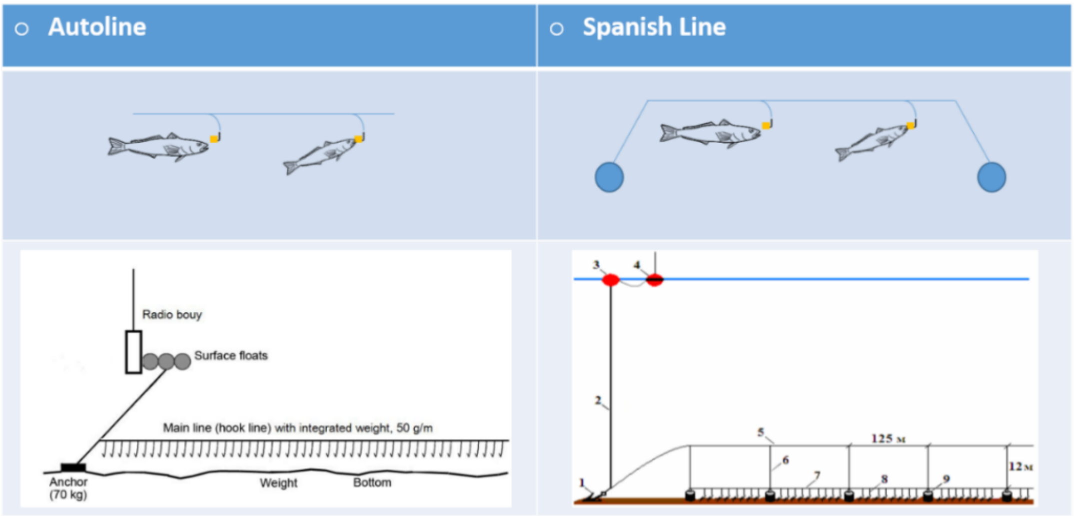

Figure 8.1. Overview of the two gears used in the SGSSI fishery: autoline and Spanish line longlines. Schematic drawings provided by CCAMLR fishing gear library (https://www.ccamlr.org/en/publications/fishing-gear-library). Although drawn above the seabed, both hook lines generally lie on the seabed.

8.2 Benthic impact of longline gears

The impact of a longline fishery on benthic fauna is difficult to quantify. There has been no common agreement on the actual impact of bottom longlines, but general agreement that it is substantially less than that resulting from bottom trawling (Pham et al., 2014; Welsford et al., 2014).

Observations that in some areas gorgonians and other corals were caught on longlines hauled around South Georgia, raised concerns regarding the potential impact on such vulnerable species. This led to the establishment of Benthic Closed Areas (BCAs, originally called Reduced Impact Areas, RIA, Agnew et. al. 2007, Collins et. al. 2012) in areas identified as having relatively higher levels of bycatch. However, the observation and recording of benthic diversity at the surface, of species hooked on a longline, is a highly uncertain process (Parker and Bowden 2011, Benedet 2017). In addition, aside from bycatch caught on hooks, longlines have the potential to damage without actually catching the benthic fauna, through lateral movement of the lines, particularly for soft bodied species which may not get hooked but may be damaged or fall from the hooks during line retrieval.

To identify areas of vulnerable species which may be susceptible to the impact of longlining, the deep-water camera system was developed to conduct benthic surveys of fishing areas such as the camera trials conducted at South Georgia by the *Pharos* (Vieira et al., 2021) and the South Sandwich Islands RRS *Discovery* DY99 survey. These surveys enable focused research, targeting specific areas, depths, and structures to provide detailed and high-quality information from an area from which to model the spatial distribution of vulnerable species in relation to depth, substrate, and topography to map areas of potential risk from a fishery (Section 4).

8.3 DY99 longline targeted transects.

In addition to the presence of benthic structures and species, another key piece of information required to provide advice on the risk from fishing, is the impact of fishing gears on the seabed. This was addressed on the DY99 survey by adding a secondary camera transect objective in locations where research fishing has occurred to determine:

1) the substrate and benthic species abundance and diversity;
2) whether historic longline interactions with the seabed could be detected.

Where possible, camera transect location and transit direction were specified to intersect positions at which longlines had been previously deployed. Of the thirty-seven camera deployments, seventeen were conducted within the 700 – 2,250m permitted range for longline fishing at Zavodovski Island, Montagu Bank, Saunders Island and Southern Thule, with potential intersection across ten lines (Table 8.1).

Table 8.1. DY99 South Sandwich Islands camera transects which intersected historic longline fishing sets.

	Station	Potential longline intersections	Year set	Gear	Depth (m)
Zavodovski	ZAVO05	1	2016	Autoline	1,450
Zavodovski	ZAVO09	1	2008	Autoline	750
Zavodovski	ZAVO11	1	2009	Autoline	1,500
Saunders	SAUN05	2	2009, 2010	Autoline, Spanish	1,500
Montagu Bank	MOBA02	2	2010, 2016	Autoline, Spanish	1,400
Montagu Bank	MOBA01	2	2010, 2016	Autoline, Spanish	1,400
Southern Thule	SOTH04	1	2009	Autoline	1,550

8.4 Substrate and benthic diversity

The seventeen camera transects conducted within the permitted fishing depths covered a depth range from 700 – 1,561m. All of the substrates were mobile volcanic sediments and/or silt, with the only structure observed occurring where iceberg released dropstones had fallen or where earthquake and landslide subsidence had created breaks or ridges in the more stable sediment layers (Figure 8.2). The transects revealed no substantial boulder reefs or rocky substrates that would provide the structure to support extensive benthic assesmblages, such as those recorded at South Georgia (Darby, 2021, Vieira et al., 2021).

One area to the east of Montagu Island recorded an area of sparsely distributed sea pen individuals that are potentially at risk of interaction with longlines. Apart from the sea pen area, no other benthic species or structures were observed at fishing depths which would be considered at risk. This is not surprising given the highly mobile substrates on the slopes of the South Sandwich Islands.

Figure 8.2. Example images from six of the DY99 camera transects conducted at the depths at which research fishing lines are deployed (700 - 2,250m). The image bottom left shows one of the scattered sea pen individuals.

8.5 The benthic impact of longline fishing

Seven camera transects were undertaken at locations which potentially intersected with ten fishing line positions, that were set between the years 2008 – 2016 (Table 8.1). Site selection was based on potential longline positions, because although the endpoints of each line are known and the transect crossed between each, longlines are not usually set in straight lines between the endpoints, instead they are dependent on tide, wind, and currents.

Of the ten potential interactions only one camera transect, Montagu Bank station 02, recorded a longline imprint (Figure 8.3), in an area where two lines had been set; an autoline in 2010 and a Spanish longline in 2016, nine and three years prior to the DY99 survey. There was no indication of disturbance at any of the other nine sites where longlines had been set.

The Montagu Bank longline impression is a linear furrow in an area of silt, sand and gravel, with raised sides, approximately 10cm across the external edges (estimated from the known distance between the laser pointers). Darker, settling, sedimentation is gradually filling the furrow such that it will eventually be obscured. The images show no disturbance of benthic species, neither is interaction seen within the video. No VME species or structures were recorded in the surrounding area, which would have been susceptible to interaction.

The type of gear that formed the imprint cannot be determined. Observations using miniature wildlife cameras attached to longlines have shown that autolines and Spanish lines can produce similar footprint impressions during recovery (Darby, 2021). Autolines have been recorded as having a very limited interaction with the seabed when settling, no lateral movement while deployed has been observed and during hauling only a stretching movement along the length of the line recorded to date. The miniature cameras show that the lateral footprint of the autolines is likely to be in the region of tens of centimetres, consistent with the observed Montagu Bank imprint. Spanish line settlement exhibits limited movement. While deployed lines move in the currents but the weights are generally stationary. When hauling weights are dragged along the seabed in the direction in which the lines are being hauled, generating furrows. Consequently, distinguishing the type of longline gear from the imprint is not possible. The Spanish line was deployed three years prior to the survey and due to the sedimentation observed, this was the most likely the origin of the furrow.

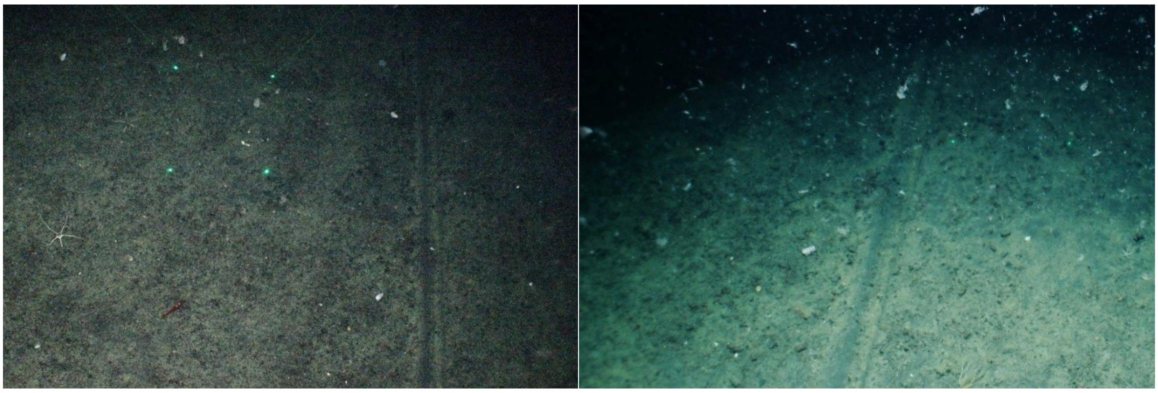

Figure 8.3. Consecutive still camera images of a longline interaction with the seabed taken at Montagu Bank during DY99. The four green laser points (top left and top right) are 27cm apart indicating a longline footprint of ~ 10cm.

8.6 Discussion

The Blue Belt deep water camera system has proven to be an extremely appropriate method to determine the characteristics of the deep-water benthic habitat where longline fishing occurs. In the dynamic sea conditions experienced at the South Sandwich Islands the stability of the vessel and in particular the dynamic positioning of the RSS *Discovery* allowed deployment across most subsea terrains to collect high-definition images of the sea floor in the fishing areas. The transect areas were selected to cover locations where longlines have been previously deployed. All seventeen camera transects conducted at the depths where longline fishing is permitted recorded soft substrate with a high degree of mobility due to the topography and type of volcanic substrate or sedimentation rate. This will, to some extent, have been a result of the choice of the transect positions, in that challenging underwater features were not surveyed. However, the bathymetry profiles (Figure 5.1 and 5.2, section 5), recorded prior to deploying of the camera, established that these areas were infrequent and most of the topography was similar to that surveyed.

No areas were recorded in which VME indicator species occurred in densities that would be considered at risk from disturbance by benthic longlines. In one area, to the east of Montagu Island on a plateau region, sea pens were recorded which would be vulnerable to lines moving in a lateral sweeping movement, however, to date this type of movement has not been recorded during observations of the longline fishing process by a second Blue Belt funded research programme (Darby, 2021; see also Kilpatrick et. al., 2011 and Ewing and Kilpatrick, 2014 for work undertaken at Heard Island and MacDonald Island region). The benthic footprint of lines has been recorded by miniature cameras to be linear, along the length of the line, with a lateral extent limited to tens of centimetres, similar to that confirmed by the Montagu Bank transect images. Apart from the Montagu Bank transect which located a linear impression of a line, most likely from a Spanish line weight three years earlier, no other longline disturbance was recorded by any other camera transect. The risk associated with the fishing process in the South Sandwich Islands, at the depths and in the areas surveyed, is considered to be low, due to a combination of:

- the mobile nature of the substrate which does not support significant benthic structures and diversity in densities that would be impacted by longline fishing;
- a consequently low abundance of sparsely distributed benthic species and structures;
- the limited longline footprint, primarily extending along its length and 10cm either side;
- the low frequency of research lines set along the island archipelago.

9. Biophysical profile of the South Sandwich Islands

An abridged version of this chapter has been submitted to the Frontiers in Marine Science Blue Belt Special Issue. Its use, distribution or reproduction should cite:

Hogg, O.T., Downie, A-L., Vieira, R.P., and Darby, C. (2021) Macrobenthic Assessment of the South Sandwich Islands Reveals a Biogeographically Distinct Polar Archipelago. Manuscript submitted for publication.

9.1 General objectives

The overall aim of this analysis was to create a baseline measure of marine biodiversity at the South Sandwich Islands and thus provide a framework from which to identify ecologically sensitive areas and species, identify conservation priorities and monitor future biogeographical changes. As such five key questions were addressed: 1) How is the biodiversity of the South Sandwich Islands structured spatially and taxonomically? 2) What environmental factors drive this structuring? 3) Can priority areas around the South Sandwich Island be identified which are anomalously rich, vulnerable, or important to investigate due to paucity of knowledge? 4) How does the archipelago fit in to its broader biogeographical setting (i.e., is it a distinct biogeographical realm or is its population a subset of that of one of its neighbouring regions)? 5) How can this information inform marine spatial planning in the region?

9.2 Methodology

9.2.1 Study area

The greater South Sandwich Islands region, which forms the focus of this section, is defined here by a bounding box of ~510 km (32°W to 24°W) by ~790 km (55°S to 62°S), covering an area of 405,270 km^2. The region covers the South Sandwich volcanic arc which includes the South Sandwich Islands and associated seamounts extending from Protector Shoal in the North to the waters south of Herdman and Tyrell Banks in the south (Figure 9.1). To the east, the region includes the South Sandwich Trench and to the west, the East Scotia Ridge back-arc spreading centre (Larter et al., 2003, Leat et al., 2003). The region covers a bathymetric range from coastal waters to >8,000m. The rationale for this geographical delimitation was based on the spatial extent of bathymetric datasets compiled for the region (Leat et al., 2014).

9.2.2 Biological data

Biodiversity data were collected as part of the DY99 expedition which assessed the diversity and distributions of epibenthic macro- and megafauna biological communities at the South Sandwich Islands and their vulnerability to fishing impact. During DY99, 28 drop-camera transects, and twelve sampling deployments were conducted. Camera transects ranged in depth from 200 - 2,150m and were undertaken at Zavodovski Island, Saunders Island, Montagu Island, Montagu Bank and Southern Thule. Sample deployments were undertaken in ten locations at depths ranging from 182 to 843m. Four deployments used a benthic dredge, and eight employed an Agassiz trawl. DY99 data were assimilated with data collated from the Global Biodiversity Information Facility open-access database (GBIF.org; accessed 11th April 2019). This data included materials collected during the Discovery expeditions (1925 - 1938), Islas Orcadas 575 (1975) and USNS Eltanin (1968 - 1982), along with more recent research in the region led by the British Antarctic Survey (e.g. BIOPEARL expedition, 2006).

The scientific cruises, from which the data was drawn, differed in collection techniques. Most commonly Agassiz trawl and epibenthic sledges were used, but benthos was also collected using camera lander systems, ROV video footage and fisheries longline. This report summarises these findings in a standardised format classifying all samples, where reconcilable, to species level, depth at which specimens were recorded, and the geo-reference at which the specimens were found. Inconsistencies in species classification were reconciled using the World Register of Marine Species match taxa tool (http://www.marinespecies.org) thus avoiding synonymies, which were especially prevalent in some of the older collections. In instances where data were collected using trawls, the start and end location was recorded along with maximum and minimum depths.

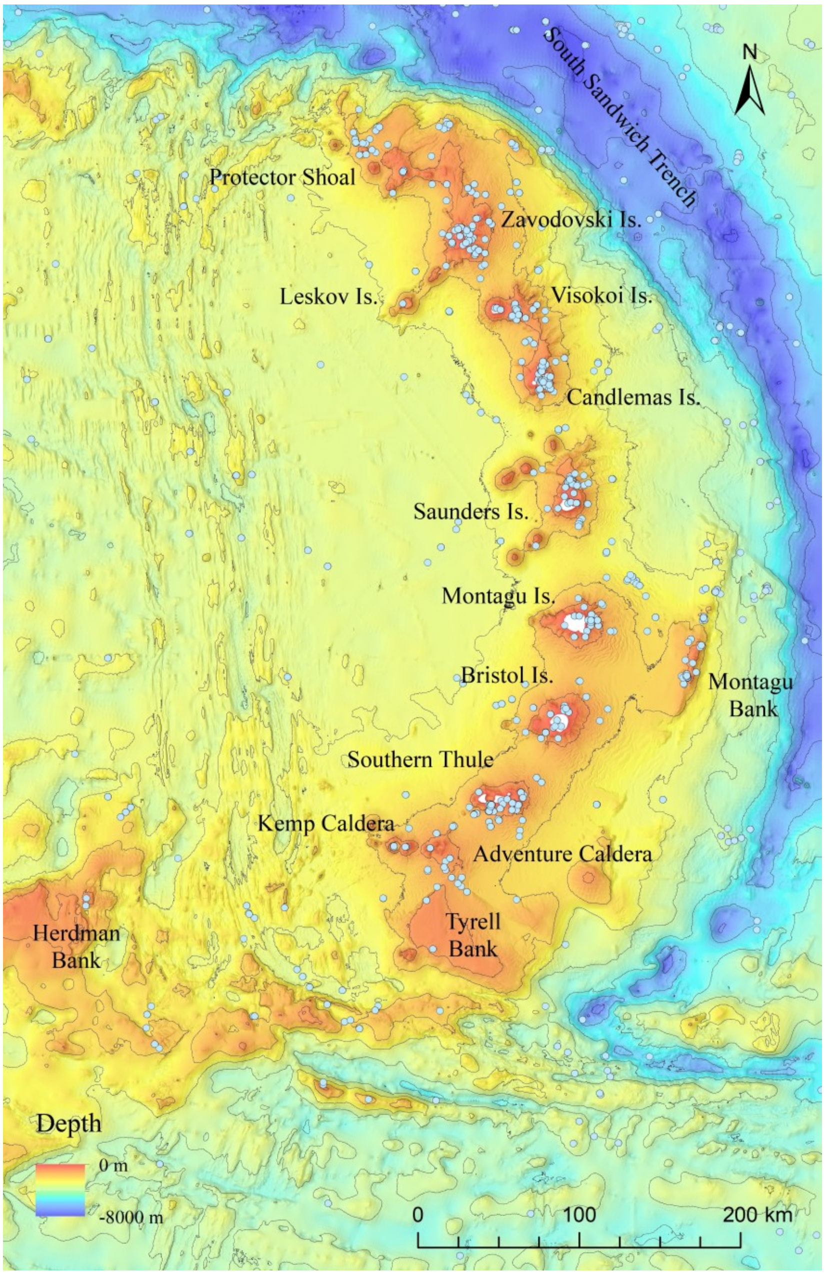

Figure 9.1. The study region showing the island chain and neighbouring South Sandwich Trench. Sampling locations are shown blue. The base map uses bathymetry data from Leat et al. (2014).

9.2.3 Environmental data

Twenty one environmental data layers were included in the analysis, to characterise physical geomorphology (depth, slope, rugosity, topographic position, channel networks and curvature), surface productivity (net and peak surface chlorophyll), physical oceanography (temperature, salinity and current velocity) and sea ice extent. All input variables are summarised in Table 9.1.

Bathymetry data was obtained from a 200m resolution digital elevation model compiled for the region (Leat et al., 2014; 2016) and was used to calculate eight bathymetry derivative datasets - slope angle, seabed rugosity, topographic position, valley depth, channel network base level, channel network distance, LS-Factor and curvature.

Slope was calculated using LandSerf (version 2.3) multi-scale analysis. To 'smooth out' sampling artefacts and noise in the data, the effective resolution of the slope was reduced by introducing a window scale of 10 grid cells (i.e. 2,000m) with an inverse linear distance decay, whereby the analysis takes into account the slope value of surrounding cells (in this case with a diameter of ten) to give greater importance to cells closer to the target cell. The effect of this is to remove finer-scale variation in slope morphology but retain larger topographic features.

Topographic position index (TPI) was calculated using Land Facet Corridor Tools extension for ArcGIS. TPI provides a measure of whether a cell is positioned on a peak, in a depression, or in a region of constant gradient (flat or constant slope) relative to the surrounding cells. It can account for local scale topography versus broader-scale features by changing the size of the window of reference. For this analysis two separate window sizes (ten and 100) were used.

Terrain ruggedness index (TRI) was calculated at broad (1,000m) and fine (200m) scales using SAGA GIS Terrain Analysis Morphometry tools as a measure of rugosity. TRI is calculated as the square root of the sum of squared difference between the bathymetric value of a cell and its eight surrounding cells.

SAGA GIS tools for QGIS (v. 3.2; Conrad et al., 2015) was used to calculate Channel Network Base Level, Channel Network Distance, Valley Depth and LS-Factor. The concept of the channel network base level is used to distinguish topographic highs and lows. The approach uses the Digital Elevation Model (DEM) to create a channel network attributed with a Strahler order. The channel network base level is an interpolated elevation surface connecting the channel elevations. The channel network distance is calculated as the vertical distance between the DEM elevation and the channel network base level elevation. Valley depth is calculated as the vertical distance to the lowest elevation of source flow. The LS-factor, a combination of slope length and steepness (gradient over the length) is applied in the marine environment to reflect the potential stability of sediment deposits and hence the likelihood of exposed hard substrata.

Profile curvature was calculated using the spatial analyst toolbox in ArcGIS. It is a second derivative index of bathymetry that measures the surface shape of the seabed in the steepest downhill direction quantifying the rate at which slope gradient changes. Regions with constant gradient return a value at or approaching zero, concave and convex slopes return large negative and positive values respectively.

Satellite derived primary productivity data (NPP) were accessed through Oregon State University (http://www.science.oregonstate.edu/ocean.productivity/). Here net primary productivity is defined as a function of chlorophyll, available light, and photosynthetic efficiency. The data are derived from the Vertically Generalized Production Model (VGPM) (Behrenfeld & Falkowsk, 1997), MODIS surface chlorophyll concentrations (Chlsat), MODIS 4-micron sea surface temperature data (SST4), and MODIS cloud-corrected incident daily photosynthetically active radiation (PAR). Euphotic depths are calculated from Chlsat. The data were extracted as monthly means over a five-year period (2010–2014) with a grid cell resolution of 1/12 degree of latitude (~9,275m) by longitude (~5,465m). R (version 3.1.2) was used to define the geographic region of interest, create a data matrix of each month's mean NPP, and transpose this into a raster dataset with the correct geographic projection and each grid cell pixel representing a mean and peak NPP for five-years of monthly data.

Sea ice data were obtained from the National Snow and Ice Data Centre's (NSIDC) online resource (https://nsidc.org/data/seaice_index/archives/). Sea ice cover was calculated as the mean number of days per year that an area is covered in sea ice based on the median extent of sea ice for each day between 1981 and 2010.

Oceanographic data on current velocity, seabed and sea surface temperature and salinity were obtained from the Operational Mercator global ocean analysis and forecast system based on the NEMO ocean model. Accessed through the E.U. Copernicus Marine Service Information. Data was extracted at a resolution of 1/12 degree of latitude (~9,275m) by longitude (~5,465m).

To standardise the spatial extent and resolution of each input variable, each raster was resampled using nearest neighbour analysis to the same spatial resolution. For the oceanographic and satellite primary productivity data which had coarser spatial resolutions (see Table 9.1), data were resampled to 200m using ArcGIS spatial analyst spline (with barrier) interpolation. Spline with barrier interpolation was selected based on its suitability for environmental variables that change over gradients. The spline barrier used was a polygon of the coastline of the South Sandwich Islands to prevent values being interpolated across the physical boundary of the island.

9.2.4 Biogeographical analysis

Data management and analysis was undertaken using dplyr (Wickman et al., 2019) and vegan (Oksanen et al., 2019) R packages (R Core Team, 2019) and ArcMap version 10.5 (ESRI, 2017). Species accumulation curves were constructed using the rarefaction method in vegan, calculated over 1,000 permutations. For comparative analysis between islands, each island was delineated using a 1,500m depth contour calculated using the Leat et al. (2014) digital elevation model. The South Sandwich Trench was delineated using the 4,000m depth contour. South Georgia data were obtained from a 2011 assessment of the region’s biodiversity (Hogg et al., 2011) combined with updated GBIF data for both South Georgia and the South Orkney Islands (GBIF.org; data accessed 13 November 2019). Similarity matrices comparing species composition between each island were computed using the Jaccard similarity index. The bathymetric profile was calculated from the Leat (2014) digital elevation model using the profile tool in ArcMap 3D Analyst.

Table 9.1. Summary of environmental variables included in landscape mapping and gradient forest analysis.

Environmental Variables	Description	Source	Unit	Original Scale
Depth	Digital elevation model (DEM) of the South Sandwich Islands, South Sandwich Trench and East Scotia Ridge.	Leat et al. (2014)	m	200m
Slope	A first derivative of DEM representing the rate of change in depth from one cell to its neighbours.	Derived from Leat et al. (2014)	°	200m
Rugosity	A measure of rugosity calculated as the ratio of the three-dimensional DEM surface area to the two-dimensional planar area of a cell.	Derived from Leat et al. (2014)	-	200m
Profile curvature	A second derivative of DEM measuring the rate of change in the slope gradient.	Derived from Leat et al. (2014)	-	200m
Topographic Position Index (TPI)	A measure of whether a cell is positioned on a topographic peak, in a depression on in a region of constant gradient.	Derived from Leat et al. (2014)	-	200m
Channel Network Base Level	Used to distinguish topographic highs and lows using a channel network attributed with a Strahler order. The channel network base level is an interpolated surface connecting the channel elevations	Derived from Leat et al. (2014)	m	200m
Channel Network Distance	The channel network distance is calculated as the vertical distance between the depth DEM elevation and the channel network base level elevation	Derived from Leat et al. (2014)	m	200m
Valley Depth	Valley depth is calculated as the vertical distance to the lowest elevation of source flow	Derived from Leat et al. (2014)	m	200m
LS-Factor	The LS-factor, a combination of slope length and steepness (gradient over the length). It reflects the potential stability of sediment deposits and hence the likelihood of exposed hard substrata.	Derived from Leat et al. (2014)	m	200m
Net primary productivity	5-year (2014–2018) mean net primary productivity calculated using VGPM, a global "chlorophyll-based" model that estimate net primary production from chlorophyll.	Behrenfeld and Falkowski (1997) Data available from Oregon State	mg C/m^2/day	1/12°
Maximum primary productivity	5-year (2014–2018) peak primary productivity calculated using VGPM.	Behrenfeld and Falkowski (1997) Data available from Oregon State	mg C/m^2/day	1/12°
Sea ice extent	Number of sea ice coverage days per year calculated from median daily sea ice extent between 1981 and 2010.	National Snow and Ice Data Centre (NSIDC).	Days/year	-
Sea surface mean temperature	Two-year mean sea surface temperature (2016-2019) for summer (Dec – Feb) and winter (Jun-Aug).	The Operational Mercator global ocean analysis and forecast system Accessed through the Copernicus.	°C	1/12°
Seafloor mean temperature	Two-year mean seafloor temperature (2016-2019) for summer (Dec – Feb) and winter (Jun-Aug).	The Operational Mercator global ocean analysis and forecast system	°C	1/12°
Seafloor annual temperature range	Two-year mean temperature differential between summer and winter seafloor temperature.	The Operational Mercator global ocean analysis and forecast system	°C	1/12°
Seafloor current speed	Two-year mean seafloor current speed (2016-2019) for summer (Dec – Feb) and winter (Jun-Aug).	The Operational Mercator global ocean analysis and forecast system	m/s	1/12°
Seafloor salinity	Two-year mean seafloor salinity (2016-2019) for summer (Dec – Feb) and winter (Jun-Aug).	The Operational Mercator global ocean analysis and forecast system	PSU	1/12°
Latitude	Decimal degrees recorded at the centroid of each raster	-	Decimal Degrees	Continuous

Table 9.2. Functional group categories modelled using gradient forest analysis. Descriptions adapted from Barnes & Sands (2017) with trait categorisation based on assessment in Hogg et al. (2018).

Functional Group	Record Count	Description	Example taxa
1A	109	Climax sessile suspension feeders	Brachiopods, some bryozoans
1B	141	Climax sessile suspension feeders	Demosponges, glass sponges
2	38	Sedentary suspension feeders	Basket stars, valviferan isopods, some polychaetes
3	76	Mobile suspension feeders	Some brittle stars, crinoids
4A	191	Epifaunal deposit feeders	Sea cucumbers
4B	185	Epifaunal deposit feeders	Some polychaetes
5	222	Infaunal soft-bodied deposit feeders	Echiurans, sipunculans, some polychaetes
6	207	Infaunal shelled deposit feeders	Bivalves, irregular sea urchins
7	109	Grazers	Regular sea urchins, limpets
8A	109	Soft-bodied, sessile scavenger or predators	Alcyonacea (soft corals)
8B	173	Soft-bodied, sessile scavenger or predators	Sea pens, anemones, hydroids
9	56	Hard-bodied, sessile scavenger or predator	Cup corals, whip corals, hydrocorals
10A	125	Soft-bodied mobile scavenger or predator	Some polychaetes, priapulids, nemerteans
10B	118	Soft-bodied mobile scavenger or predator	Octopus, nudibranchs
11A	321	Hard-bodied mobile scavenger/predator	Some brittlestars
11B	236	Hard-bodied mobile scavenger/predator	Sea stars
11C	203	Hard-bodied mobile scavenger/predator	Gastropods
11D	68	Hard-bodied mobile scavenger/predator	Isopods
12A	280	Jointed legged, mobile scavenger or predator	Amphipods
12B	178	Jointed legged, mobile scavenger or predator	Other peracarida
12C	353	Jointed legged, mobile scavenger or predator	Pycnogonids, decapods

9.2.5 Landscape mapping analysis

The statistical approach to mapping marine landscapes was based on an unsupervised mapping protocol described and discussed in detail in Hogg et al. (2016; 2018). This methodology can be summarised in four steps - (1) principal component analysis (PCA) of the gridded environmental variables; (2) determination of the optimal number of clusters using a combined calinski harabasz index and elbow plotting approach; (3) K-means clustering of the principal components; (4) plotting the optimal cluster solution as a landscape map and assigning environmental meaning to each cluster based on the relationship between the original environmental variables and each cluster. The resulting landscape map covers the entire study region (Figure 9.1), with regions delineated based on similar environmental conditions.

The landscape mapping clusters form a 2-level nested hierarchy with a top-level classification, hereafter referred to as level-1 cluster (or clusters 1-7), covering an area of 405,207 km^2 from coastal to abyssal environments, and level-2 cluster (clusters 5.1-5.7) which provides a sub-clustering of shelf environments (cluster 5) from level-1.

9.2.6 Gradient forest analysis

The statistical approach to gradient forest modelling was undertaken using the R Development Core Team (2019) package randomForest (Liaw & Wiener 2002) and gradientForest (Ellis, Smith & Pitcher 2012). The approach was based on the mapping protocol discussed and described in detail in Ellis et al. (2012) and Pitcher et al. (2012). This methodology can be summarised in four steps - (1) A random forest method quantifies the degree to which environmental variables can predict faunal distribution patterns and assigns importance to each predictor; (2) gradient forest analyses the shape and magnitude of changes in faunal composition along environmental gradients; (3) Critical values are identified along these gradients that correspond to changes in faunal composition; (4) Principal components of the transformed predictors provide a multidimensional representation of variation in combined faunal and environmental composition. This is mapped to show gradient clusters of the first two dimensions of biologically transformed environment space.

Taxa recorded at the South Sandwich Islands were categorised into functional groups for use in gradient forest analysis. To assign functional trait information data were collected on development types, reproductive modes, feeding strategies, mobility, lifestyle, affinity to specific substrata, reef-building capacity, whether they were considered habitat forming, whether they were associated with a certain stage of ecological succession and how fragile they are to physical impacts. A breakdown of this methodology is discussed in Hogg et al. (2018). A total of 21 functional groups were assigned based on these ten functional traits, in line with previous research on functional traits at South Georgia (Barnes & Sands, 2017). These groupings are summarised in Table 9.2.

9.3 Results

9.3.1 Biogeographical analysis

Marine benthic biodiversity at the South Sandwich Islands was rich across taxonomic levels (Table 9.3) and comparable to the neighbouring biodiversity hotspot of South Georgia in terms of richness in phyla (18), classes (45) and families (447). Species richness was lower (883), though notably this was based on far fewer records with 2,670 samples (c.f. South Georgia - 17,732) recorded to species level (Table 9.3). In total 4,887 distinct georeferenced samples were recorded at 773 sampling stations.

Table 9.3. Number of distinct taxa per taxonomic level and the taxonomic resolution of sampling records at the South Sandwich Islands. Taxonomic resolution is defined as the number of records identified to each taxonomic level.

	Distinct taxa	***Taxonomic Resolution***
Phylum	18	238
Class	45	396
Order	134	360
Family	447	301
Genus	758	922
Species	883	2670

Structured by depth, both species richness and record counts (Figure 9.3) were highest in shallower waters, with 58.3% of all records collected between 0 and 500m and 88% of South Sandwich Islands species represented in this depth range. Whist record counts dropped at depths greater than 1,000m, there was a secondary peak in record counts between 2,000m and 3,500m which accounted for 22.2% of records. This depth band had an even more pronounced peak in species with 30.8% (272) represented in this bathymetric zone. A distinct shallow-deep discontinuity was observed in species composition, with only 69 species shared between 0-500m and 2,000-3,500m. Beyond 3,500m, record counts and to a slightly lesser degree species richness, tapered to a maximum sampling depth of ~8,000m.

Non-structured sampling by depth at the South Sandwich Islands makes it difficult to interpret depth trends in benthic diversity. Firstly, sampling effort, calculated in terms of number of distinct sample gear deployments, varies with depth. Secondly, sampling methodology is not standardised and often not explicitly recorded from historic surveys. Regression analysis on species and station counts provided a crude means of adjusting for the confounding influence of variance in sampling effort across depth. Analysis of the regression residuals calculated in 250m depth bins between 0m and 8,000m (Figure 9.2B) identified a distinct discontinuity in standardised species richness at ~3,000m. Sampling stations deeper than 3,000m largely recorded negative residuals (i.e. low species richness relative to sampling effort), whilst shallower waters recorded mostly large positive residuals. The notable exception to this was seen in shallow water (<500m), which recorded negative residuals.

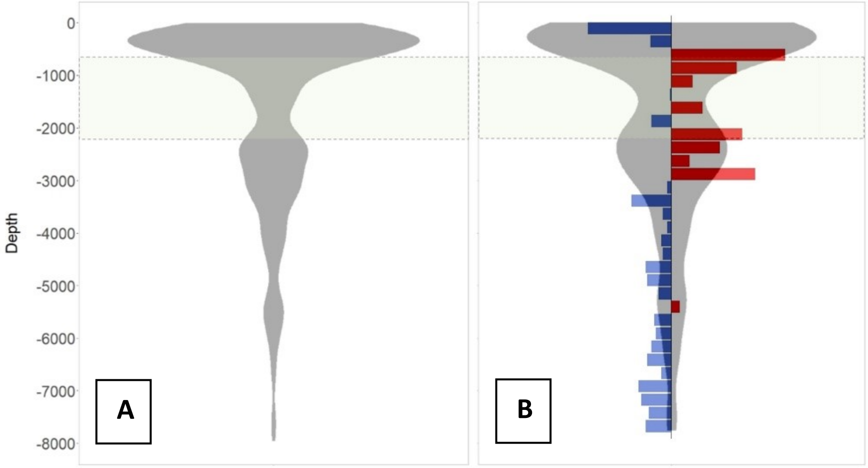

Figure 9.2. Density plot of (A) record counts and (B) species richness by depth. Species richness is calculated as number of distinct species per 250m depth bin. The species richness plot includes residuals for each 250m depth bin derived from a regression analysis on species and station counts. Blue bars denote negative residuals (relative species paucity), and red bars denote positive residuals (relative species richness). The light green shared zone between 700 and 2,250m denote the depth range open to licenced longline fishing.

Subdivision of the South Sandwich Islands region into 10km^2 grid squares (Figure 9.4) demonstrates a geographically uneven distribution of sampling effort in terms of number of distinct sampling stations per grid cell ($\bar{x}$ =20.6; σ=39.8). Sampling has focused primarily around the seven main islands, with sampling much reduced in offshore, deep-water regions. Most sampling has occurred at the northern-most islands of Zavodovski and Candlemas and the southern-most island of Southern Thule. Sampling effort across the rest of the archipelago is notably lower, especially at Montagu Island, Montagu Bank and Bristol Island.

Species richness was similarly uneven across the region ($\bar{x}$ =9.9; σ=19.8). Higher species richness corresponded with higher sampling effort in the northerly islands, but notably not at Southern Thule, where despite high sampling effort, species richness was comparatively low. Regression analysis on species and station counts was undertaken for each 10km^2 grid square. Analysis of the regression residuals identified four biodiversity hotspots with large, positive residuals (Figure 9.4A). These grids occurred nearshore at Zavodovski and Visokoi Islands. Potential biodiversity cold spots, identified by large negative residuals, were located nearshore at Southern Thule, Montagu Island and north of Zavodovski Island (Figure 9.4A). Family-level richness was also shown to be uneven across the region ($\bar{x}$ =10.1; σ=15.6). The spatial distribution of biodiversity cold spots was similar to that of species richness, primarily located at the three most southerly islands with a single grid cell north of Zavodovski Island also reporting large negative residual (Figure 9.4B). Highest family-level residuals were seen at Visokoi and Zavodovski, but notably moderately high residuals were recorded at all islands except Montagu Island, Montagu Bank and Candlemas Island.

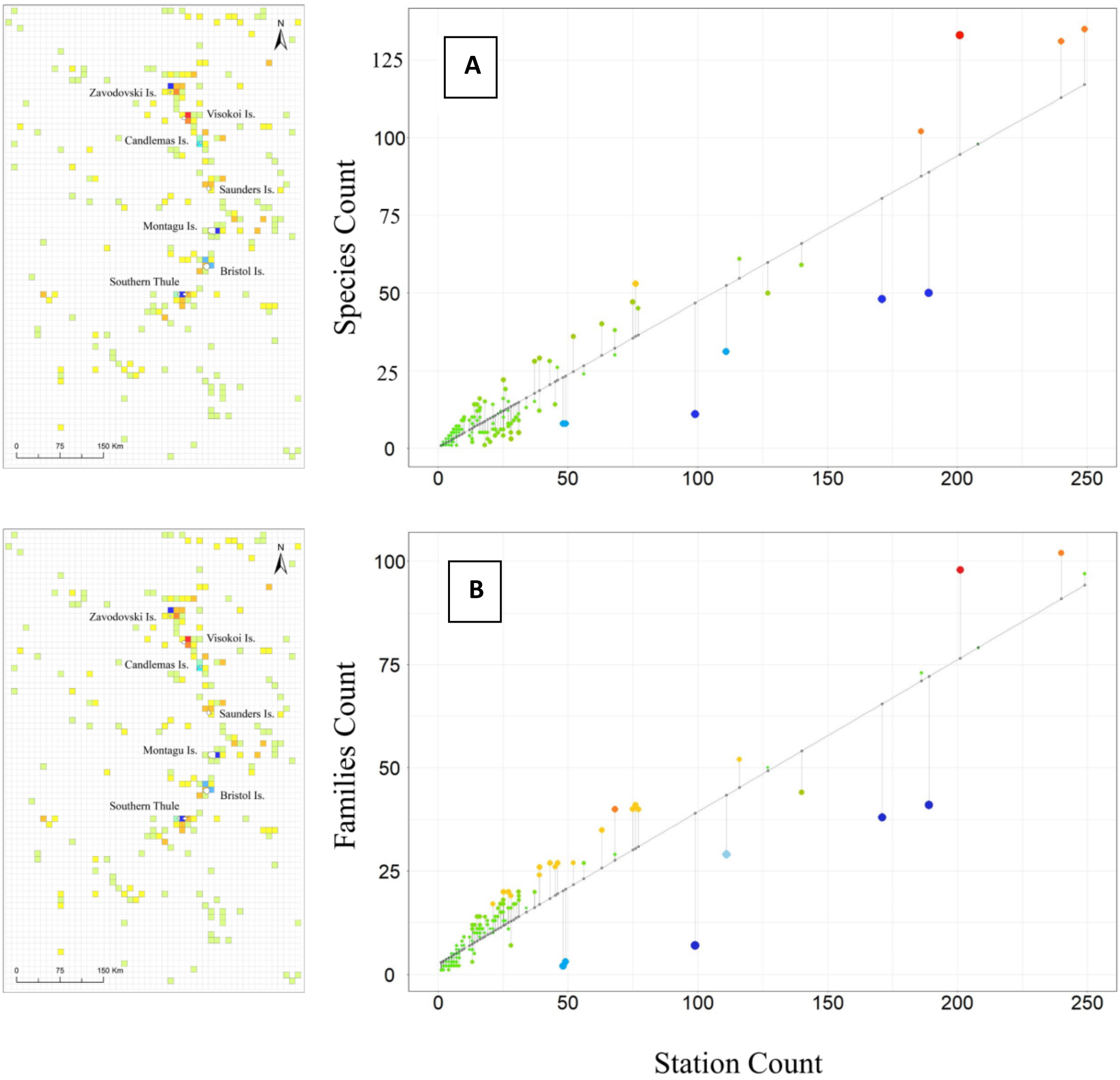

Figure 9.3. Relationship between sampling intensity and (A) species richness and (B) family richness. Each point corresponds to a single 10 x 10km grid square on the South Sandwich Islands map. The regression line is shown in black. Grid square residuals are scaled from large positive (denoted in red) to large negative (denoted in blue).

Taxonomically, arthropods were the dominant taxa constituting 27.5% of species and 31.9% of records (Table 9.3). 75.9% of species and 78.3% of records were recorded from the four most species rich phyla (arthropods, echinoderms, annelids and molluscs). At species level no single species was dominant, with the top 25 species accounting for 17.3% of records and the top 100 species for 42.6%. Most species were rare, recorded only once (46.4%) or twice (cumulatively 67.7%). Only 49 species (<1%) were recorded more than ten times. The ten most common species represented ~ 10% of total records. These species included four species of brittlestar, three species of sea spider, two species of polychaete, a crinoid and one squid species.

General taxonomic trends were shared across the archipelago, with arthropods and echinoderms representing the dominant taxa. Notable exceptions to this were a dominance of molluscs and echinoderms on Bristol Island; a notably larger proportion of corals on Saunders Island and both corals and sponges (key VME taxa) on Montagu Bank. The South Sandwich Trench was a clear outlier to the group with arthropods a significantly more dominant constituent in catches. At Southern Thule the proportion of annelid worms was significantly higher than elsewhere.

Table 9.3. Breakdown of species and record counts for each benthic taxa recorded at the South Sandwich Islands. Distinct species counts relate to specimens recorded to species-level.

Phylum	***Distinct Species***	***Distinct Records***
Arthropoda	243	1,558
Echinodermata	163	994
Annelida	148	558
Mollusca	112	641
Cnidaria	66	407
Bryozoa	58	176
Porifera	34	225
Chordata	33	106
Nematoda	8	21
Sipuncula	7	68
Brachiopoda	5	36
Nemertea	5	34
Cephalorhyncha	1	2
Chaetognatha	-	28
Platyhelminthes	-	13
Echiurida	-	9
Priapulida	-	9
Hemichordata	-	2
Total	***883***	***4,887***

9.3.2 Species accumulation

Rarefaction curves of all benthic species data (Figure 9.4) showed the rate of novel species discovery remains high across the region, with 0.75 new species recorded per new sample site. Novel species discovery was highest around the islands themselves (<1,500m depth) with species differentials ranging from 2.57 new species per new site at Saunders Island to 1.68 at Bristol Island (Table 9.4). Assessment of individual islands in the archipelago demonstrated significant variance in sampling effort and species richness along the archipeligo (Figure 9.4; Table 9.4). At the most northernly islands of Zavodovski and Candlemas the curves did not reach asymptote, with novel species discovery remining high. In contrast, the southerly island of Southern Thule recorded lower total species richness and a lower rate of novel species discovery, despite similar sampling effort. At Saunders Island sampling was lower, corresponding to fewer species records, but species discovery was amongst the highest in the region. The islands and banks that form the centre of the island chain (Bristol Island, Montagu Island and Montagu Bank) have few reported species but have also had very low sampling effort (at least sampling that has resolved specimens to species-level). The rarefaction curve for the South Sandwich Trench is shown to be levelling-off and reaching asymptote (Figure 9.4). With lower recorded species richness and lower species differential (0.62), it is likely the Trench region is not as speciose as the shallower waters of the neighbouring islands.

Table 9.4. Estimation of species richness for the South Sandwich Islands region extrapolated using Chao 1 and Jacknife 2 (based on eight key taxa). Species column represents actual records of distinct species for each location; Differential column represents the number of new species recorded per future sample site; bracketed numbers represent standard error associated with each species estimation.

Region	***Species***	***Chao 1***	***Jacknife***	***Differential***
South Sandwich Islands	**883**	**1317** (± 57.7)	**1286** (± 57.8)	0.75
Zavodovski Island	**288**	**449** (± 35.1)	**435** (± 54.6)	2.20
Candlemas Island	**242**	**388** (± 34.5)	**369** (± 45.8)	2.08
Saunders Island	**126**	**278** (± 45.4)	**214** (± 32.1)	2.57
Montagu Island	**73**	**105** (± 13.0)	**114** (± 21.2)	2.26
Montagu Bank	**31**	**104** (± 47.2)	**54** (± 13.7)	1.79
Bristol Island	**55**	**84** (± 12.9)	**88** (± 12.2)	1.68
Southern Thule	**150**	**310** (± 44.2)	**250** (± 30.9)	1.79
South Sandwich Trench	**143**	**249** (± 31.3)	**226** (± 14.7)	0.62

Figure 9.4. Rarefaction curve showing the rate of species accumulation with increasing sampling effort for each of the South Sandwich Islands. Islands are delineated by 1,500m depth contours. Zavodovski Island includes Protector shoal; Candlemas includes Visokoi Island and Southern Thule includes the Adventure and Kemp Caldera. Sample effort is defined by the number of sampling sites. Green ribbons denote standard deviation over 100 permutations. All island plot show species accumulation across the entire study region.

Species accumlation curves for key taxa across the region (Figure 9.5) demonstrated high rates of species discovery with no phylum reaching asymptote. Novel species discovery was highest in byozoans (0.9) and as such represents the phyla for which current biodiversity estimates are poorest. There was little variance in novel species accumation between all other key taxa ($\bar{x} = 0.47$; $\sigma = 0.07$). Chao 1 and Jacknife 2 species richness estimators indicate that across the eight major phyla summarised in table 9.4, 67.1% and 68.7% of probable species present at the South Sandiwch Islands are currently represented in our sampling. Extrapolations based on these eight phyla (representative of 97.1% of total species) place total South Sandwich Islands species richness at between 1,317 (Chao 1) and 1,286 (Jacknife 2). Relative variance in biodiversity between the major phyla remained relatively constant between observed and predicted richness estimates with rank order species richness remaining broadly unchanged (Table 9.5).

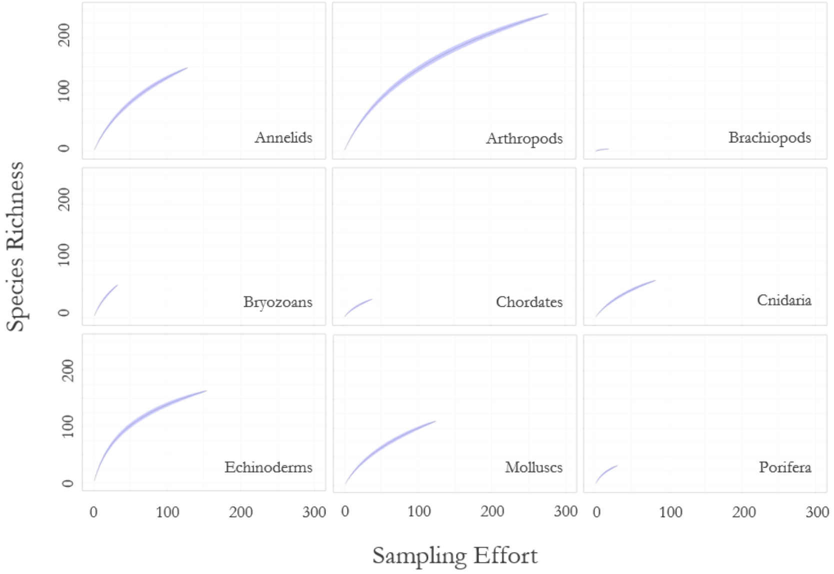

Figure 9.5. Rarefaction curve showing the rate of species accumulation with increasing sampling effort in nine major phyla. Sample effort is defined by number of sampling sites. Blue ribbons denote standard deviation over 1,000 permutations. Chordates excludes fish.

Table 9.5. Estimation of species richness for key phyla extrapolated using Chao 1 and Jacknife 2. Species column represents actual records of distinct species for each phylum; Differential column represents the number of new species recorded per future sample site; bracketed numbers represent standard error associated with each species estimation.

Phyla	***Species***	***Chao 1***	***Jacknife***	***Differential***
All Phyla	**883**	**1,317** (± 57.7)	**1,286** (± 57.8)	0.75
Annelida	**148**	**219** (± 22.5)	**218** (± 22.0)	0.55
Arthropoda	**243**	**359** (± 30.2)	**348** (± 15.8)	0.40
Bryozoa	**58**	**107** (± 23.1)	**92** (± 17.0)	0.90
Chordata	**33**	**55** (± 14.4)	**51** (± 7.1)	0.49
Cnidaria	**66**	**103** (± 17.0)	**101** (± 8.4)	0.48
Echinodermata	**163**	**213** (± 17.7)	**218** (± 10.7)	0.38
Mollusca	**112**	**176** (± 22.5)	**170** (± 17.9)	0.40
Porifera	**34**	**46** (± 8.2)	**49** (± 4.7)	0.56

9.3.3 Biogeographical setting

A large proportion of species (~58.2%) recorded at the South Sandwich Islands were recorded only from the islands and were not shared across the other Scotia Arc islands (Table 9.6). The South Sandwich Islands exhibits a stronger biogeographical link with South Georgia (sharing ~16.7% of SSI Species) than the South Orkney Islands (8.9% of SSI species). 16.2% are considered cosmopolitan across the whole Scotia region.

The proportion of species recorded only from the South Sandwich Islands varied by phyla (x̄ = 56.2%; σ = 10.6%). Considering just the major phyla (here definded as those with >30 species), annelids (71.6%), molluscs (62.5%) and ascidians (60.6%) had the highest proportion of species not recorded across the rest of the region. Bryozoan species conversely, were least likely to be restricted just to the South Sandwich Islands (36.2%).

Table 9.6. Faunal similarity between South Georgia (SG), South Orkney Islands (SOI) and the South Sandwich Islands (SSI). 'Island Only' species are recorded from just the island in question; 'All Scotia Species' were recorded as cosmopolitan across the Scotia Arc. Numbers in brackets indicate actual counts of species in each category.

	South Sandwich Is.	**South Georgia**	**South Orkney Is.**
Total Species	**883**	**1631**	**855**
Island Only	**58.2%** (514)	**69.3%** (1130)	**49.4%** (422)
All Scotia Species	**16.2%** (143)	**8.8%** (143)	**16.7%** (143)
SSI – SG Shared	**16.7%** (147)	**9.0%** (147)	-
SSI – SOI Shared	**8.9%** (79)	-	**9.2%** (79)
SG – SOI Shared	-	**12.9%** (211)	**24.7%** (211)

Subdivision of each of the South Sandwich Islands into distinct biogeographic zones (delineated by 1,500m depth contours) demonstrated low species-level similarity between individual islands and the continental shelf regions of South Georgia and the South Orkney Islands (Figure 9.6). Highest similarity was recorded between neighbouring Zavodovski and Candlemas/Visokoi Islands. This was followed by Saunders and Candlemas Islands and to a lesser degree Zavodovski Island and Saunders Island. There was low similarity between Saunders Island and any islands to the south. The South Sandwich Trench demonstrated high dissimilarity to all regions. Outside the South Sandwich Islands, the highest similarity (albeit still low) was seen between the South Georgia and South Orkney Islands.

At family level there was very little similarity between South Georgia, Shag Rocks and South Orkney Islands. At the South Sandwich Islands similarity appears a function of geographical proximity, with highest similarity between neighbouring islands (e.g., Southern Thule and Montagu/ Zavodovski and Candlemas/ Visokoi Islands), and similarity reducing between more distinct islands (e.g., Zavodovski and Southern Thule).

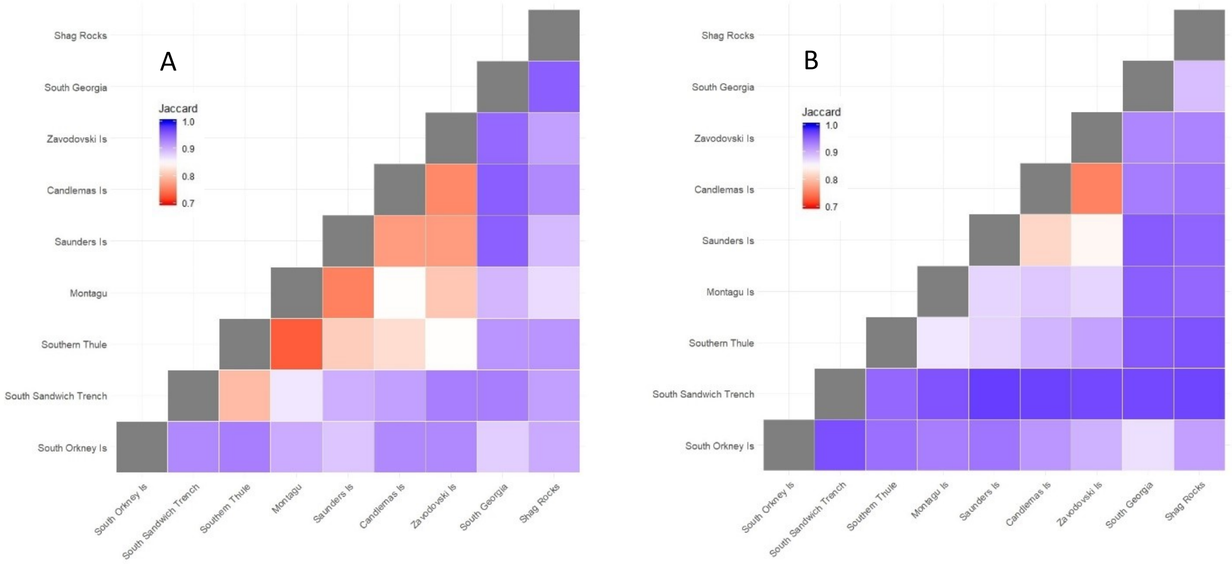

Figure 9.6. Jaccard dissimilarity matrix of the benthic faunal composition of (A) families and (B) species across the Scotia Arc. Islands are ordered from south (South Orkney Islands) to north (Shag Rocks). Islands are delineated by 1,500m depth contours. Zavodovski Island includes Protector shoal; Candlemas includes Visokoi Island and Southern Thule includes the Adventure and Kemp Caldera. Montagu Bank and Bristol Island were excluded from the analysis due to limited samples. The South Sandwich Trench was delineated by the 4,000m depth contour. South Georgia data were obtained from a biogeographic analysis by Hogg et al. (2011). South Orkney Islands data were sourced from GBIF (GBIF.org; accessed 11th April 2019).

9.3.4 Environmental analysis

The continental shelf around the South Sandwich Islands is limited, with steep-sided volcanic slopes dropping away to depths in excess of 3,000m within 10 km of the coastline (Figure 9.1). As such, the area of seabed under 1,000m depth is restricted to 13,270 km^2. In addition to the seabed surrounding the islands themselves, there are several seamounts and submarine banks which sit in <1,000m water. These include a group of seamounts that cluster around Protector Shoal (400 - 700m) at the northern extent of the archipelago; Montagu Bank (500 - 800m) to the east of the islands and adjacent to the South Sandwich Trench; Herdman Bank (at depths of 400 - 1,000m) in the far south-west of the study region and the non-volcanic Tyrell Bank (650 - 800m) at the southern end of the archipelago (Leat et al., 2016). Islands in the chain exhibit differing degrees of bathymetric connectivity with their neighbours. All are separated by regions of deeper water, typically between ~1,000 and 1,500m. Saunders Island is the most bathymetrically isolated of the archipelago, separated by Candlemas Island to the north and Montagu Island to the south by water depths of ~2,500m (Figure 9.7; Figure 9.8).

Slope, rugosity and topographic position (i.e. whether a site is on a topographic peak or in a trough) were all associated with the volcanic slopes of the islands and the tectonic spreading zone in deep water to the west of the island chain. Slope angles generally peaked at ~25° on steeper topographic features with gradients of 10° more generally associated with the flanks of the volcanoes.

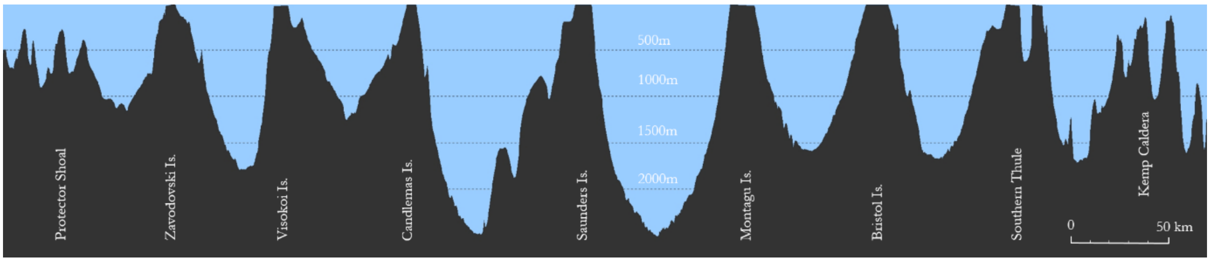

Figure 9.7. Bathymetric profile of the South Sandwich Islands from north (left) to south (right). Profile follows shallowest line between each island and is derived from the Leat et al. (2014) digital elevation model.

Positioned broadly on a north-south axis, the South Sandwich Islands exhibit a strong latitudinal sea-surface temperature gradient. During the summer months the region experiences a range of -1.4°C to 2.2°C, dropping to between 0°C and -1.85°C in Winter. The temperature range around the islands themselves is more constrained, ranging from 1°C at Protector Shoal to -0.8°C at Southern Thule in summer. In winter, sea-surface temperatures are more homogenous with a range of -1.4°C and -1.7°C across the island arc. Seabed temperature demonstrates collinearity with depth and little annual variance. The coldest region is the South Sandwich Trench with an annually stable temperature of ~ -0.6°C which changes little with latitude. The spreading zone to the west of the islands exhibits temperatures ~ -0.15°C. Seabed temperature around the islands ranges from 1°C (0.9°C winter) at Zavodovski to 0.6°C (0.45°C winter) at Southern Thule. Seabed salinity is also linked to depth with lower salinity in proximity to the islands (Figure 9.8).

Sea ice conditions varied considerably throughout the year and across the latitudinal gradient of the islands. In the north, Protector Shoal and Zavodoski Island experienced little or no sea ice, even during the height of winter. In contrast the southern-most island of Southern Thule had on average ~ 200 sea-ice coverage days per year. This sea ice longevity likely also influences sea ice thickness.

Mean sea-surface productivity demonstrated a distinct east-west discontinuity. Waters at, and to the east of, the island chain demonstrate higher productivity with a marked drop-off west of the islands. Highest mean productivity was recorded in the water to the east of Zavodovski, Visokoi and Candlemas Islands and on Montagu Bank. A second discontinuity was seen at Bristol Island, with all islands and Banks to the south demonstrating very low mean primary productivity. Primary productivity peaked in hotspots at Zavodovski, Visokoi and the seamount chain extending to Leskov Island. A localised area of peak productivity occurred at Montagu Bank. All other islands showed no peaks in productivity.

Regions of higher current velocities (peak average ~ 0.2m/s) appear linked to the topography of the lower flanks of the South Sandwich Trench (6,000m depth). Areas of higher current velocity were also seen along the eastern flank of Zavodoski and Saunders Islands and in deeper water (~2,500m) bisecting between Saunders and Montagu Island. All other islands in the arc including Protector Shoal, Southern Thule, Bristol Island and Montagu Island demonstrated low current velocities.

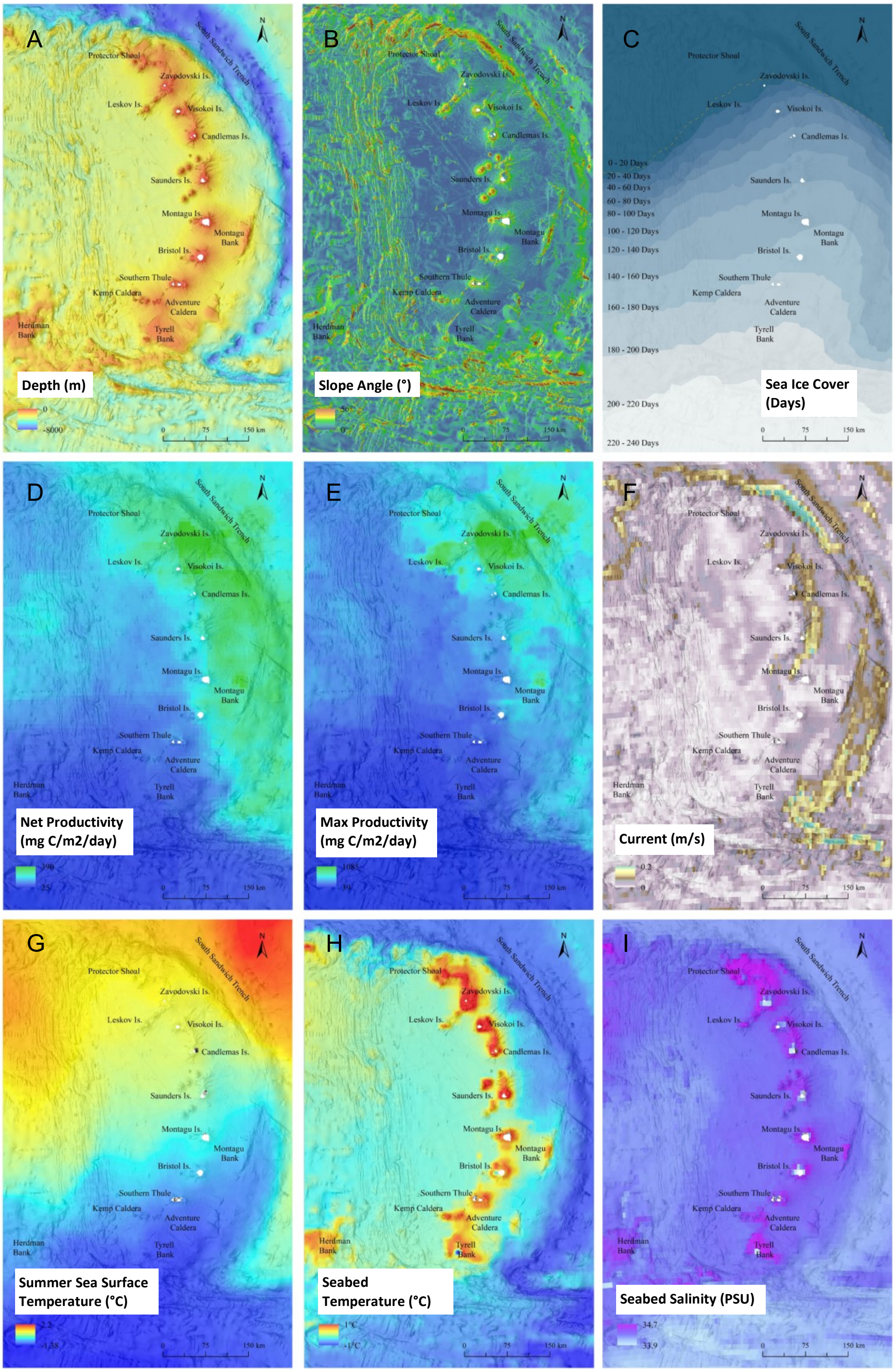

Figure 9.8. Summary of regional environmental datasets: (A) depth, (B) slope, (C) sea ice, (D) mean primary productivity, (E) peak primary productivity, (F) current speed, (G) sea surface temperature, (H) seabed temperature and (I) seabed salinity. A full description of the data including data sources are summarised in Table 9.1.

9.3.5 Landscape mapping

Landscape mapping at the South Sandwich Islands delineated seven distinct environmental clusters (Figure 9.9). Cluster 1 was characterised by the deep water of the South Sandwich Trench. This region typically had fewer sea ice days per year and high maximum and mean primary productivity. Sea surface temperature was relatively high, whilst seabed temperature was constantly cold throughout the year with high salinity. Cluster 2 had a Northern geographic distribution with corresponding low sea ice, higher sea surface and bottom temperatures and lower salinity. Cluster 3 had a southern geographic distribution with corresponding high annual sea ice cover. Sea surface and seabed temperature was low, as was salinity and primary productivity. The benthic environment in cluster 3 was generally flat with low TPI and rugosity. Cluster 4 was a relatively shallow, flat environment with high sea ice, low sea surface temperature, low productivity and low current. Cluster 5 was a shallow, predominantly coastal environment, characterised by high temperature range, low salinity and a large range across other variables such as sea ice and productivity. Cluster 6 was a deep-sea environment, with high current speed, higher slope angles forming the flank of the South Sandwich Trench, lower sea ice and low temperature ranges. Cluster 7 was characterised by high slope angle, high rugosity and TPI.

Given much of the sampling undertaken during DY99 occurred within cluster 5, the statistical protocol was run again for this region in isolation. This created a series of seven hierarchical nested sub-clusters (Figure 9.10). Sub-clusters 5 and 7 were differentiated along latitudinal gradients, with 5 having an exclusively southern distribution and 7 exclusively northern. Consequently, sub-cluster 5 experiences high sea ice cover, low productivity and low surface temperatures. In contrast sub-cluster 7 exhibited low sea ice, higher surface temperatures and productivity. Both clusters represent relatively flat, mid to deep environments. Sub-cluster 1 were steep, highly rugose environments with high TPI and curvature values. Sub-cluster 1 occurred across the depth range but was predominantly found in deeper water. Sub-cluster 2 is a relatively deep environment with high sea ice cover, low sea bottom temperature and low rugosity. Sub-cluster 3 was principally characterised by high current speed. Sub-cluster 4 was a relatively shallow cluster with high TPI values (topographic peaks). It exhibits relatively high bottom temperature and annual temperature ranges. With a large latitudinal range, it experiences a range of sea ice conditions. Sub-cluster 6 was restricted to the coastal environment and consequently experiences low salinity, high temperature, and a high annual range in temperature.

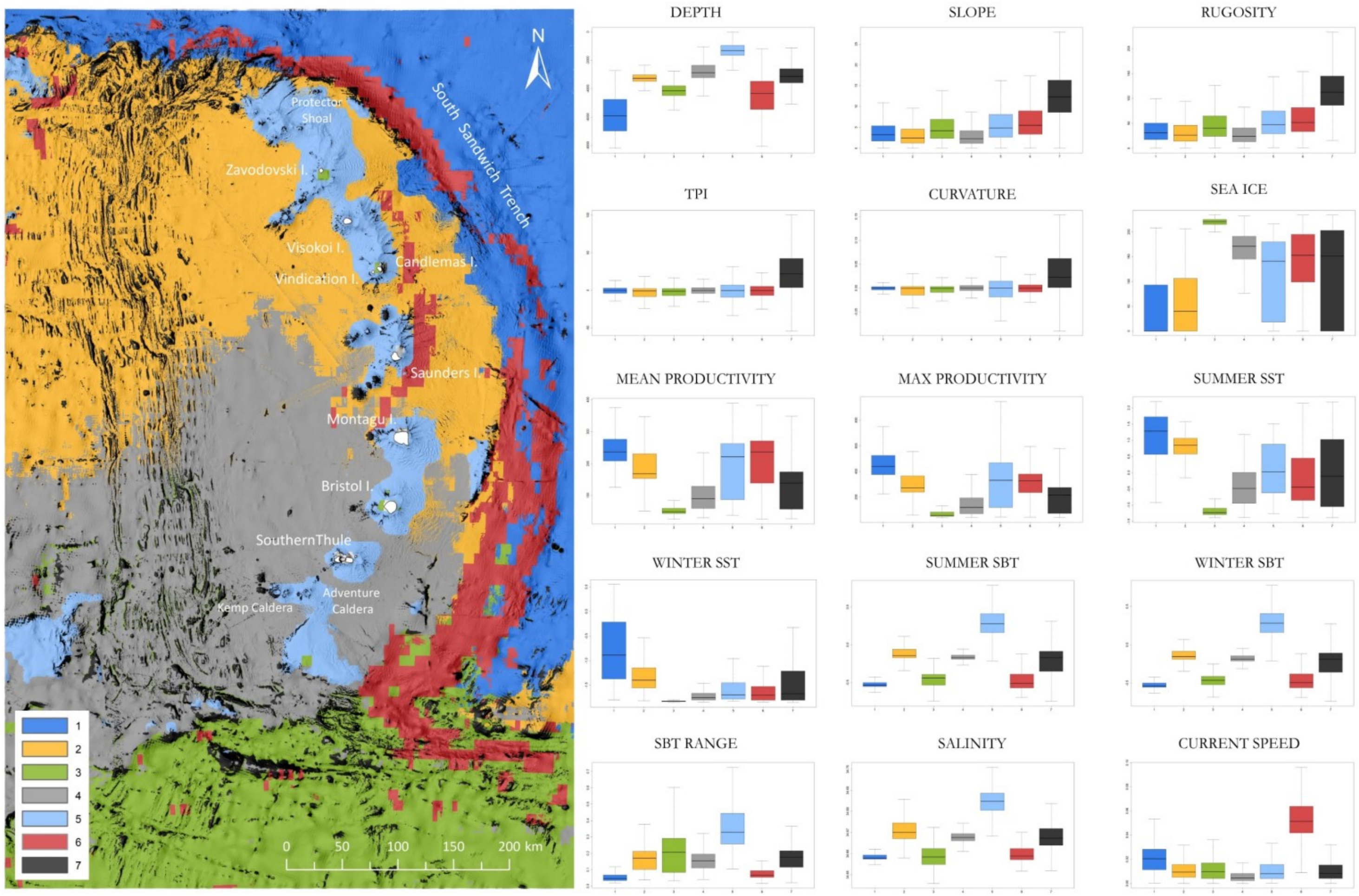

Figure 9.9. Marine landscape map showing the distribution of 7 cluster classes across the whole study region as defined by k-means cluster analysis Box plots of K-means derived clusters versus 17 original abiotic variables. Descriptions of each variable including their units are summarised in Table 9.1. In each box plot the middle line represents the median, the upper and lower extent of the box represent the first and third quartiles. The whiskers are the maximum and minimum observed values (excluding statistical outliers - values > 1.5 x the interquartile range). Box plot colours denote the corresponding landscape map.

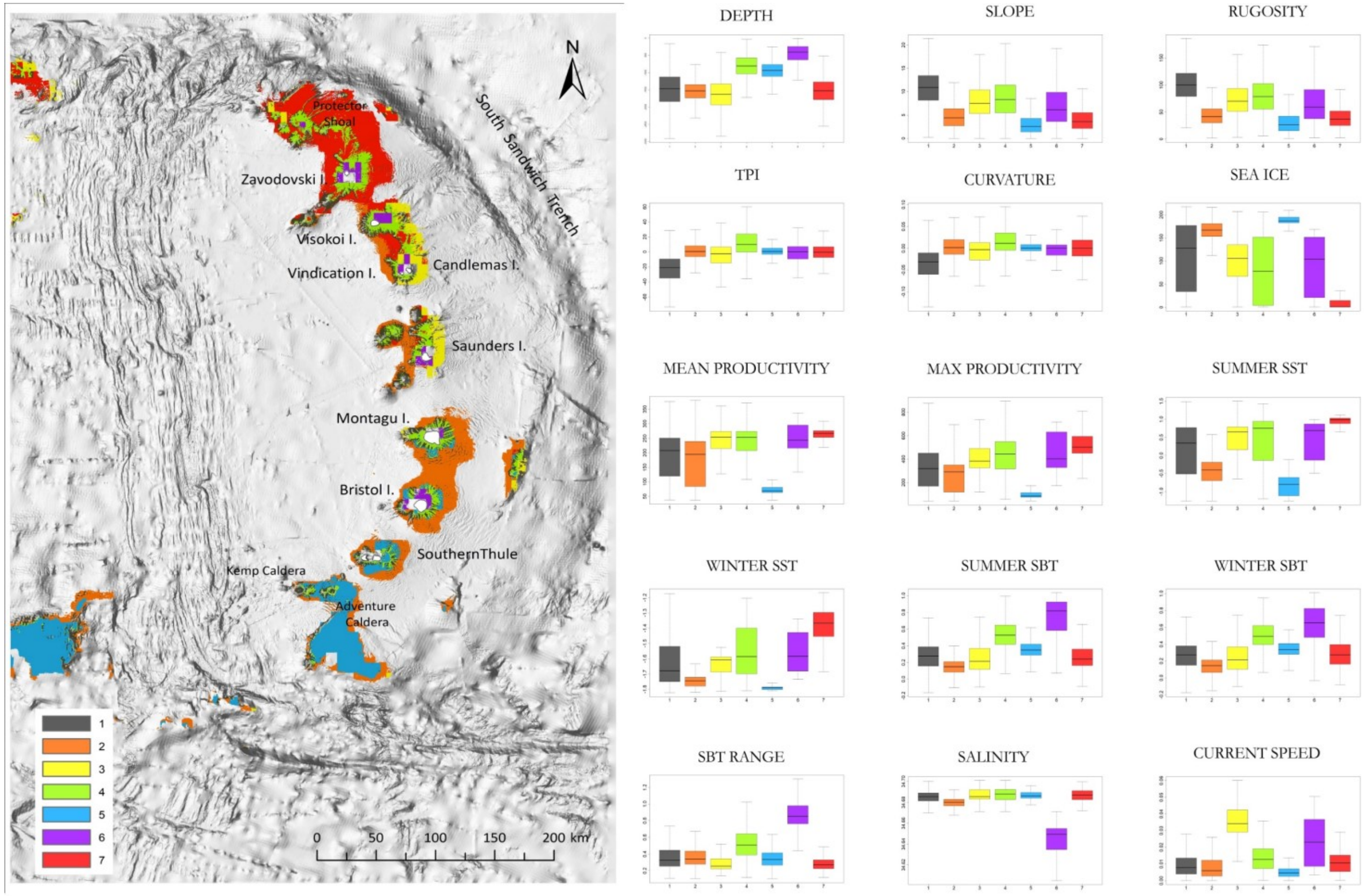

Figure 9.10. Hierarchically nested marine landscape map showing re-clustering of cluster 5 taken from first k-mean partition (Figure 9.9) whereby the shelf (previously a single cluster) is now split into 7 further sub-clusters. Box plots of K-means derived clusters versus 17 original abiotic variables. Descriptions of each variable including their units are summarised in Table 9.1. In each box plot the middle line represents the median, the upper and lower extent of the box represent the first and third quartiles. The whiskers are the maximum and minimum observed values (excluding statistical outliers - values > 1.5 x the interquartile range). Box plot colours denote the corresponding landscape map.

9.3.6 Gradient forest analysis

Gradient forest analysis was used to (i) assess the key environmental drivers of faunal composition at the South Sandwich Islands and quantify their degree of influence; (ii) interpret the shape and magnitude of compositional changes in faunal groups along these key environmental gradients; (iii) apply this information to spatially cluster the benthic environment at the South Sandwich Islands based density of splits in random forest models signifying relatively large changes in functional group composition; and (iv) characterise these clusters based on environmental and faunal descriptors.

Spearman's correlation was used to remove highly colinear environmental variables reducing predictor variables from 19 to 15. Those variables excluded were mean productivity (which correlated strongly with peak productivity), annual temperature range (which correlated with both bathymetry and bottom temperature), rugosity with a 5-cell neighbourhood (which correlated with slope angle and the standard measure of rugosity) and relative slope position (which correlated with channel network distance).

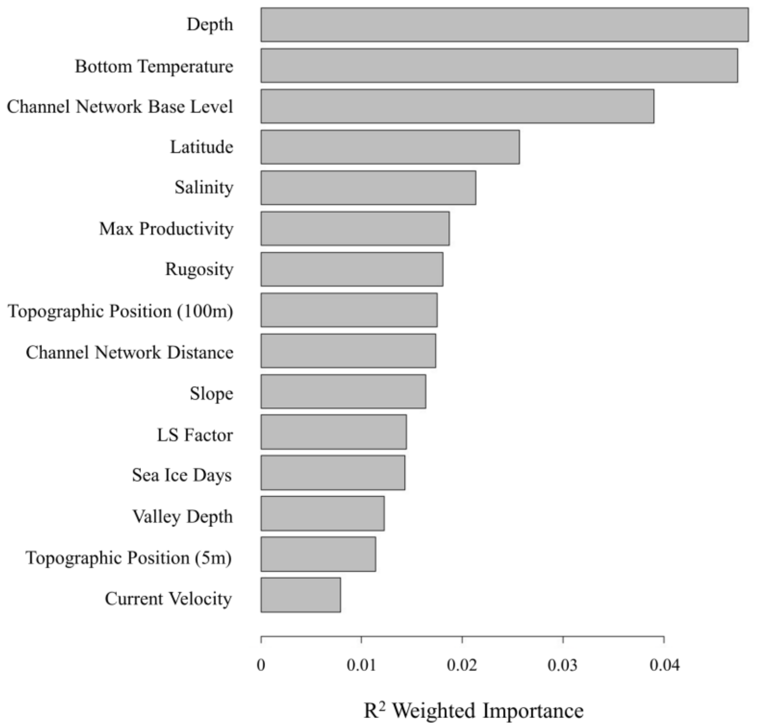

Figure 9.11. Importance of environmental variables for predicting distributions of 21 benthic functional groups (see Table 9.2). Importance was calculated by weighting the functional group-level predictor importance by the functional group R^2 and then averaging. For descriptions of environmental variables see Table 9.1.

The importance of each of the 15 environmental predictor variables to random forest model accuracy was assessed by quantifying the degradation in modelling performance when each variable was removed and replaced with a random permutation. The most important predictors for functional group distribution at South Sandwich Islands were depth, seabed temperature, channel network base level and latitude (Figure 9.11). Salinity and areas of peak primary productivity were of intermediate importance, as were measures of seabed topography such as slope angle, rugosity and broad scale topographic position. Fine-scale topographic position (i.e., location of topographic peaks and troughs) and current velocity were of least importance.

The frequency distributions of split importance (Figure 9.12) show that changes in the composition of functional groups (summarised in Table 9.2) along environmental gradients were non-uniform. Along the depth gradient, a large number of splits occurred in the range 0-1,000m, indicating that shallower waters were very heterogenous, with large changes in functional group composition. In contrast, across the rest of the bathymetric range (1,000 - 8,000m) samples splits had low importance, indicating relatively little compositional faunal change. Sampling at the South Sandwich Islands has been higher in shallower waters (see Figure 9.12 red line). To account for this bias, the ratio of densities (blue line) plots the expected density of splits had depth been sampled with uniform density. The ratio of densities plots supports the assertion that large changes in functional group composition are seen between 0-1,000m depth.

Along a gradient of sea bottom temperature, high relative rates of faunal assemblage change were seen in a bimodal distribution. These peaks were at ~0.9°C and 0.6°C. A series of distinct peaks in faunal assemblage change were shown along a latitudinal gradient. Most notably ~ 56.2°S, where highest compositional change corresponded with Zavodovski Island. Smaller peaks were seen at Saunders Island (57.7°S), Montagu Island (58.4°S) and Southern Thule (59.5°S). In contrast Candlemas Island (57°S) and Bristol Island (59.1°S) demonstrated little change in functional groups. A further two peaks were shown south of 60°S, these could correspond with sampling on and between Tyrell and Herdman Banks.

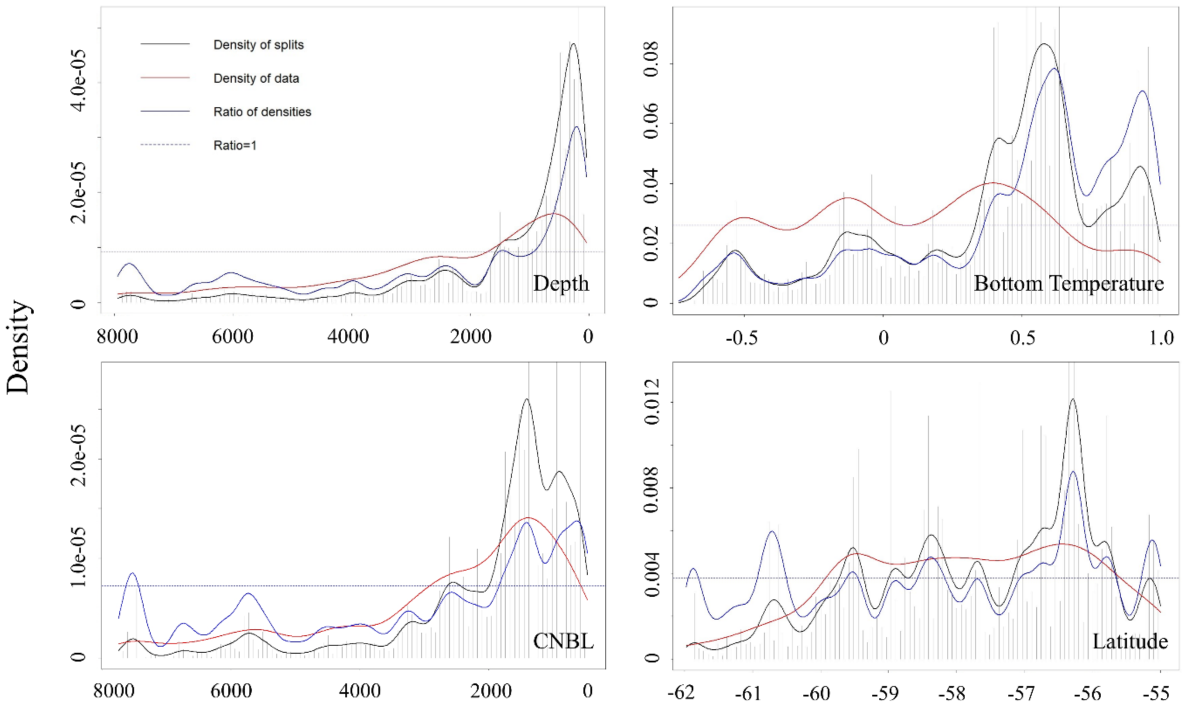

Figure 9.12. Kernel density plot of random forest tree splits across environmental gradients for the four most important predictors - depth, bottom temperature, channel network base level (CNBL) and latitude. A high density of splits indicates relatively large changes in functional group composition. Split density is denoted by the histogram and black line. Density of sampling is shown in red. The ratio of splits standardised by the sampling density is shown in blue, with ratios >1 (dashed blue line) indicating locations of relatively greater change in composition.

Gradient forest maps were created using a k-medoids approach which partitioned the region into 12 mapping clusters. K-medoids assigns clusters whilst attempting to minimise variability between data points within clusters.

The gradient forest map, along with the underlying discontinuities in environmental and faunal character are presented in Figures 9.13, Figure 9.14 and Figure 9.15. The most obvious divide was between shallow (Figure 9.13 clusters 8 and 10) and deep environments (all other clusters). The shallower water clusters 8 and 10 were then split along a latitudinal gradient with cluster 8 covering the northern regions of Protector Shoal, Zavodovski Island, Candlemas and Visokoi Island and cluster 10 covering the southern regions of Herdman and Tyrell Banks, Southern Thule, Bristol Island, Montagu Island and Bank and Saunders Island. The boundary between these two gradient forest clusters occurred at Candlemas Island. Environmentally clusters 8 and 10 were characterised by shallow water. Additionally, cluster 8 was characterised by low latitude, low sea ice cover and higher maximum productivity (Figure 9.14). Conversely cluster 10 was characterised by high latitude and longer sea ice cover.

Functional group composition between clusters also differed (Figure 9.15). The lower-latitude cluster representing the northernly islands of the archipelago demonstrated a higher dominance of soft-bodied sessile scavengers and predators such as Alycyocea (soft corals), sea pens, anemones and hydroids. The higher-latitude cluster 10 was notable for its high ratio of presences across all functional groupings including the presence of climax communities.

This distinct latitudinal discontinuity in fauna and environment was not restricted to shallow waters. The deep-sea environment, which covers much of the study region, was not a homogenous region but was sub-divided by gradient forest analysis into ten mapping clusters. Both environmentally and faunistically these zones were distinct. In contrast to the shallow-water clusters, these changes were more graduated, demonstrated in Figure 9.13 by the similarity in colours between neighbouring clusters denoting relatedness. The deep-sea clusters transitioned over gradients of sea ice cover, latitude and productivity. Faunistically, the northern-most deep-sea cluster was characterised by infaunal and epifaunal deposit feeders and mobile, jointed legged predators or scavengers such as sea spiders and decapod crustaceans. Further south, cluster 3 demonstrated representation across all functional groupings, though universally these were with low occurrences. In the deep sea surrounding Saunders Island, cluster 3 transitioned to cluster 4, the fauna of which was benthos not attached to the seabed. This included grazing species, infaunal deposit feeders and mobile predators. The most southerly cluster 12 was similar in faunal composition to cluster 4 with the addition of hard sessile species such as cup corals and whip corals. Other notable clusters included the South Sandwich Trench system (cluster 1) which was dominated by mobile predators and infaunal species. In contrast the upper flanks of the trench (cluster 2) had a higher proportion of climax communities (e.g., sponges) and sessile soft bodied predators and scavengers such as soft corals.

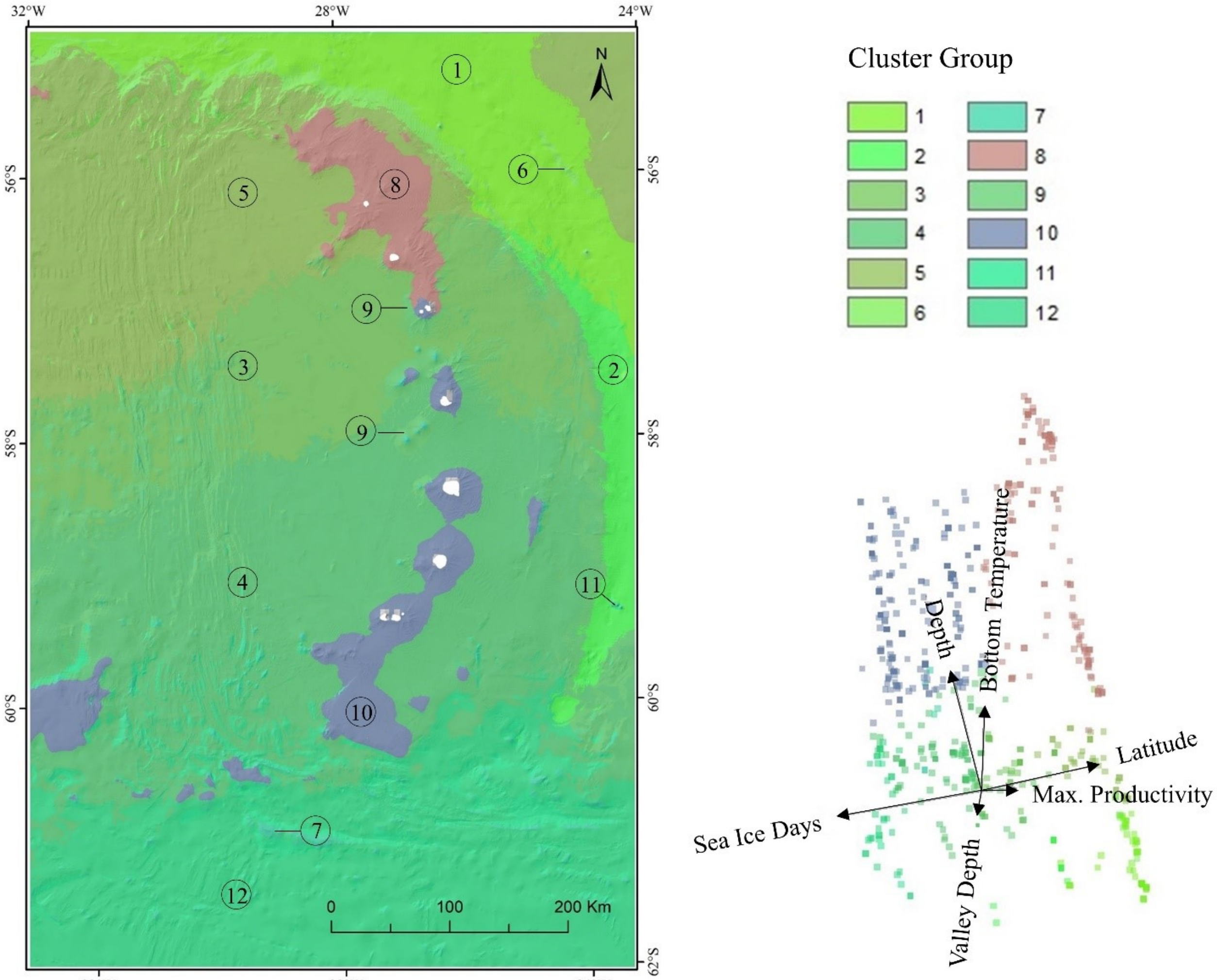

Figure 9.13. Gradient forest mapping clusters combining transformed environmental variables with benthic functional group data. Clusters represent the expected continuous patterns of composition for seabed biodiversity at the South Sandwich Islands with similarity in composition denoted by similarity in colour. The biplot shows the first two principal dimensions of the biologically transformed environment space with vectors indicating the direction and magnitude of major environmental drivers and colours corresponding to mapping clusters.

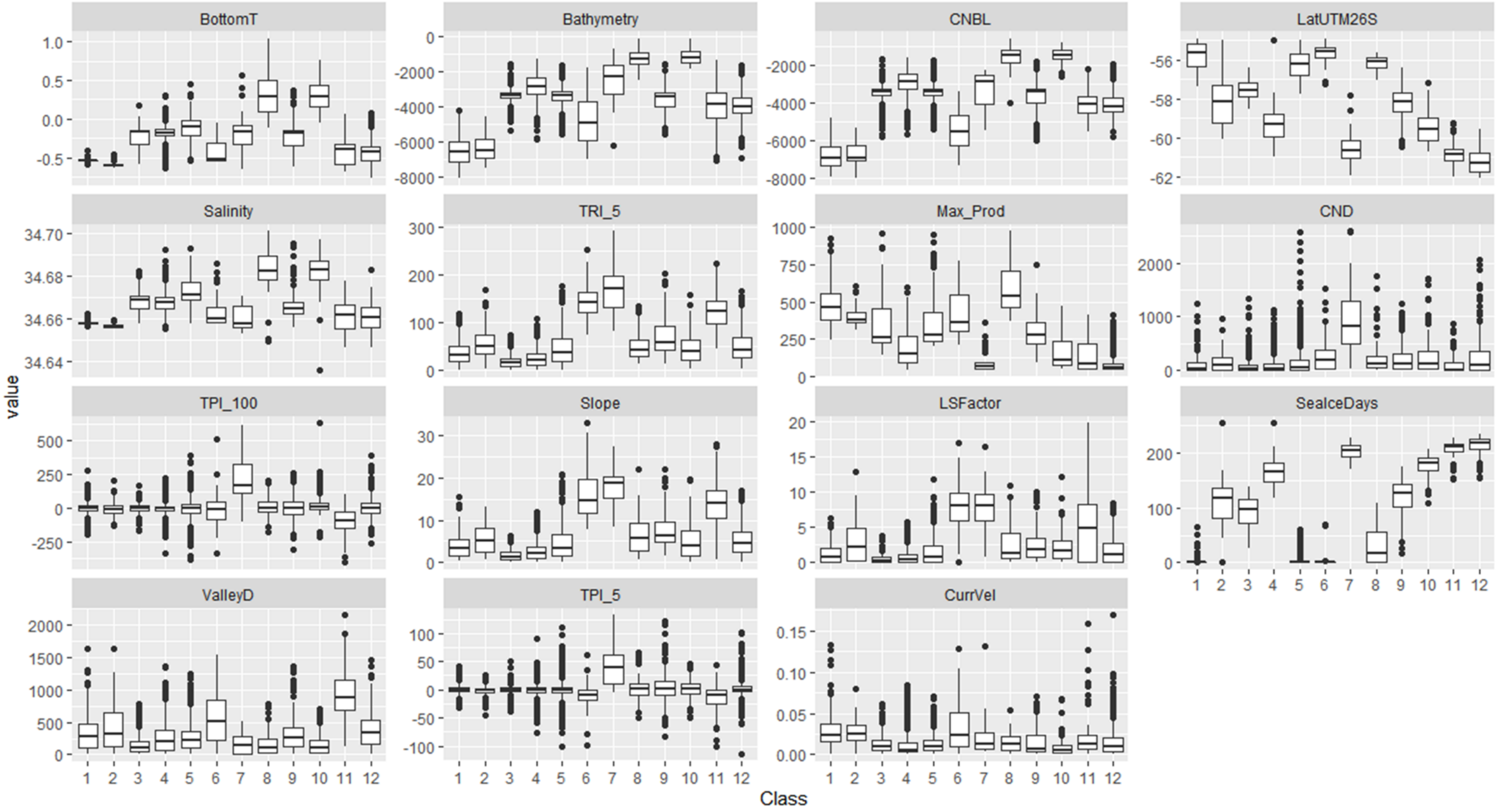

Figure 9.14. Environmental characterisation of the 12 mapping clusters shown in Figure 9.13. In each box plot the middle line represents the median; the upper and lower extent of the box represent the first and third quartile.

Figure 9.15. Faunal characterisation of the 12 mapping clusters shown in Figure 9.13. Plots show the ratio of presence (black) to absence (grey) of 21 functional groups (Table 9.2) for each mapping cluster.

9.4 Discussion

9.4.1 Biogeographical setting of archipelago

The Southern Ocean is delineated by the Polar Front, which represents a distinctive physical discontinuity between polar and temperate waters. This discontinuity is manifest in fast, eastward-flowing jets of water which extend to a significant depth (>1,000m) and form the largest temperature cline (3-4°C) in the Southern Ocean (Barker & Thomas, 2004; Thornhill et al., 2008). Consequently, the Polar Front also represents a biogeographical discontinuity, greatly limiting the exchange of epipelagic and benthic fauna (Clarke et al., 2005). The established paradigm of the Southern Ocean, therefore, is one of an isolated system (Dell, 1972; Angel, 1997; Longhurst, 1998). The same currents which limit latitudinal exchange between Antarctic and temperate waters, facilitate eastward dispersal within the Southern Ocean. The result is a general homogenising influence on Antarctic marine fauna (Barnes & Griffith, 2008; Chown et al., 2015), with very few barriers to dispersal across a single Antarctic province (Griffiths et al., 2009). As such, the South Sandwich Islands has typically been considered part of a ‘connected’ Antarctic/Scotia Arc biogeographical region.

Here we present the South Sandwich Islands as biogeographically linked to South Georgia ($\bar{x}$ = 16.6% shared species) and to a lesser extent the South Orkney Islands ($\bar{x}$ = 8.9%), with a further 16.2% of species recorded as cosmopolitan across the Scotia Region. Most notably however, a large proportion of species reported from the South Sandwich Islands ($\bar{x}$ = 58.2%) have not been recorded anywhere else in the Scotia Arc and species and family-level comparisons between the Scotia islands demonstrate near universal dissimilarity between the island groups (Figure 9.6). Within a Scotia Sea context, the 58.2% of species recorded only from the South Sandwich Islands mirrors high levels of species recorded only from South Georgia (69.3%) and only from the South Orkney Islands (49.4%). Species recorded only from the South Sandwich Islands include representation across all phyla recorded from the region. The proportions of each phyla that have only been recorded from the South Sandwich Island however varies considerably across the eight major phyla ($\bar{x}$ = 56.2%; $\sigma = 10.6$). Highest levels of South Sandwich exclusivity were seen in annelid worms (71.6%) and molluscs (62.5%), whilst bryozoans were shown to be the phyla most likely to be cosmopolitan in distribution (36.2%). This biogeographical characterisation support previous descriptions of specific phyla at South Georgia which reported 25 - 30% similarity in mollusc species between South Georgia, South Orkney Islands and the South Sandwich Islands (Linse, 2006) and high similarity in bryozoans (~40%) between South Georgia and the South Sandwich Islands (Barnes & Griffiths, 2008).

Where connectivity between regions is restricted (e.g. by deep water and strong currents), this is often reflected in the biogeography of the region's benthic fauna. Some taxa such as bryozoans for example, exhibit predominantly benthic larval stages. This limits their ability to proliferate into neighbouring regions and as such restricts their geographical distribution (Griffiths et al., 2009). The observation that bryozoans in the Scotia Arc seem to be amongst the most cosmopolitan of phyla implies that it may not be limited connectivity that restricts or fundamentally determines distribution, rather the suitability of habitats in geographically neighbouring, but environmentally dissimilar regions.

Looking at sea temperature as an example, South Georgia exhibits an annual range of ~5°C, with sea-surface temperatures ranging between 0 and −1°C in winter and between 3 and 4°C in summer. South Georgia is therefore amongst the warmest (Barnes et al., 2006), and most variable (Holeton et al., 2005) water masses south of the Polar Front. This wide range of environmental conditions, coupled with its geographical position as the most northerly continental shelf area within the Polar Front results in an island characterised by strong biogeographical links between both Antarctica and South America (Hogg et al., 2011). In contrast, the South Orkney Islands and the South Sandwich Islands are both environmentally Antarctic in character with colder, more annually stable water masses and the presence of season sea ice (Barnes et. al., 2009; Rogers, 2015). The waters around the South Sandwich Islands themselves range from -1.7°C at the south of the archipelago in winter to ~1°C at the north of the archipelago in summer, with a maximum local-annual range of ~ 2.4°C. The South Orkney Islands is reported as having a maximum range of around ~2.8°C (Clarke et al., 1988). If it is environment rather than connectivity that principally drives faunal discontinuity between the islands of the Scotia Arc, then based solely on temperature gradients, one might expect higher faunal similarity between the higher latitude archipelagos of South Orkney and the South Sandwich Islands than between South Georgia and either of the other two island groups. In contrast however, our analysis reports higher South Orkney Island - South Georgia species similarity (24.7% of South Orkney Island species shared) than South Orkney Island – South Sandwich Islands similarity (9.2% of South Orkney Island species shared).

The explanation for this is likely multifaceted, encompassing environmental suitability for species, oceanographic connectivity and geological factors such as island age, size and provenance. Southern Ocean-wide analyses has identified the steep-flanked, geologically young volcanic South Sandwich Islands archipelago as having distinct geomorphic features from the rest of the Southern Ocean (O'Brien et al., 2009). In contrast, the South Orkney Islands and South Georgia represent geologically older regions that once formed part of the same landmass (Livermore et al., 2007) and now represent topographically similar island groups with large continental shelf areas (Dickens et al., 2014; Hogg et al., 2016). In this context, South Georgia and the South Orkney Islands are more like one another than either is to the South Sandwich Islands. Furthermore, the South Sandwich Islands are also more oceanographically disconnected from the Scotia group with the clockwise flow of the ACC more directly connecting South Georgia to 'upstream' South Orkney Islands, but with the South Sandwich Islands somewhat offset away from the current's northward flow (see Figure 3.1). Indeed, considering regional currents more broadly, it is possible that the South Sandwich Islands exhibits stronger links with the Weddell Sea provinces, linked through the outer edge of the Weddell Gyre. There is evidence for such a link, for example in some fish species (Gon & Heemstra, 1990).

Our bio-physical assessment of the archipelago supports previous attempts to cluster the Southern Ocean into distinct provinces using environmental datasets. These assessments have typically identified a Scotia Arc province in which South Georgia, South Sandwich and South Orkney Islands are identified as three distinct sub-provinces (Spalding et al., 2007; Turner et al., 2014). Analysis of 'ecoregions' at South Georgia and South Sandwich Islands have delineated South Georgia and South Sandwich Islands as separate biogeographical provinces, with ecoregions aligning strongly with the environmental structuring of the ACC (Longhurst, 1998; Grant et al., 2006; Raymond, 2011). Given the combination of distinct environmental conditions and distinct benthic fauna reported here, the South Sandwich Islands should, we argue, be considered a distinct biogeographic province.

9.4.2 How is biodiversity structured spatially and taxonomically?

South Sandwich Islands is a biological rich archipelago. Here we report comparable biodiversity to the neighbouring biodiversity hotspot of South Georgia across taxonomic levels from phylum to family (Hogg et al., 2011). At species level, richness is lower than at South Georgia with 883 species currently recorded from the South Sandwich Archipelago (cf. 1,445 species from the South Georgia shelf region). South Sandwich Islands species richness is nonetheless notably high based on three key criteria – sampling effort, sampling focus and sampling area:

Sampling effort in terms of the number of distinct records (n = 4,887) has been lower at the South Sandwich Islands than neighbouring regions (e.g., South Georgia n = 17,732). This is largely on account of the absence of research bases such as with King Edward Point (U.K.) and Bird Island (U.K.) at South Georgia, and Orcadas Base (Argentina) and Signy station (U.K.) at South Orkney Islands which act as regional logistical hubs for research vessels to operate from.

There has been far less focus on certain species-rich, yet typically underreported taxa such as, for example, nematodes which were the second richest phyla reported from South Georgia (Hogg et al., 2011) but for which only 21 records (8 species) have been recorded at the South Sandwich Islands. Furthermore, in contrast to both South Georgia and the South Orkney Islands, there has been no sampling undertaken in inter-tidal communities (see Barnes et al., 2009; Hogg et al., 2011). These taxonomic and spatial gaps in the South Sandwich Islands dataset considered, our analysis likely represents a significant under-reporting of regional diversity across the South Sandwich Islands Archipelago. For the regions and taxa that have been sampled, we projected regional species count of between 1,286 and 1,317 based on the current rate of novel species discovery (See Figure 9.4 and Table 9.3) (c.f. between 1,627 and 1,760 species at South Georgia).

Finally, unlike its neighbouring islands, the South Sandwich archipelago does not have a broad continental shelf area. Instead, the benthic environment consists of steep-sided volcanic flanks, with a limited relatively shallow zone restricted to narrow bands around the islands and the tops of submarine seamounts. As shelf area increases so to do the number of species (Richness-area relationship: MacArthur & Wilson 1967; Williamson, 1988; Rosenzweig, 1995). As such, benthic species richness at the South Sandwich Islands should be considered high given only 13,270 km^2 of its seabed is shallower than 1,000m. To place this in a regional context, this is roughly 25% the area of either South Georgia (Hogg et al., 2011) or South Orkney Island’s (Dickens et al., 2014).

Biogeographic distribution patterns are difficult to interpret at the South Sandwich Islands because: (i) historic sampling effort has been both non-uniform and patchy (see Figures 9.1 – 9.4); and (ii) most South Sandwich Islands species were rare - 67.7% of species recorded a maximum of twice. Whilst this is not necessarily problematic when considering broad-scale ecosystem level comparisons, such as between the South Sandwich Islands and other polar archipelagos, it does limit our understanding of how biodiversity is structured spatially across the South Sandwich region itself.

Spatial biases can, in part, be accounted for by factoring in levels of sampling effort (see Figure 9.3). In doing so, biodiversity was shown to vary across the region. Sampling decreased as a function of distance from the archipelago's islands. As such, paucity in sample was too high away from the islands to formulate an informative overview of distribution patterns. Around the islands themselves, species and family richness adjusted for variance in sampling effort demonstrated biodiversity 'hotspots' at Visokoi island, Saunders Island and parts of Zavodovski. Conversely biodiversity 'coldspots' were recorded predominantly towards the southern end of the island chain at Bristol Island, Montagu Island and Southern Thule. Sampling at Bristol Island and Montagu Island has been low however (Figure 9.4) so there is a higher degree of uncertainty with this assessment. Southern Thule, in contrast, has received relatively higher rates of sampling and reports relatively low rates of species accumulation. This assessment of the southernmost island of the archipelago is supported by previous observations which report the island to be species poor (Griffith et al., 2008).

Species diversity also demonstrated a depth gradient, though as with spatial assessment, it was difficult to account for the confounding influence of non-structured sampling across depth. The highest levels of sampling have occurred in the waters shallower than 500m (58% of sampling). Within these waters, 88% of species recorded at South Sandwich Islands are represented. A secondary peak in sampling effort between 2,000 and 3,500m revealed a change in species composition with depth, with few shared species between sub-500m samples and samples collected deeper than 2,000m. Adjusting species richness by factoring in levels of sampling effort (Figure 9.2B) identified deeper waters (>3,000m) as relatively species poor. Highest species richness (adjusted for sampling effort) was shown in depth ranges 500 - 1,000m and 2,000 - 3,000m, with notably low adjusted richness recorded in waters shallower than 500m. One explanation for low shallow-water residuals is the rate of species accumulation will be different across depth strata. As waters shallower than 500m, have been sampled most extensively (Figure 9.2A), it is likely they record a lower rate of novel species discovery per new sample. Therefore, the large overall sampling effort in this depth range may correspond to fewer species per sampling effort than other depths ranges, resulting in the shallow-water negative residuals reported in Figure 9.2B. Previous research has highlighted that abundances recorded in samples was heavily depth dependent, with a marked decline from 200 to 500m in demersal trawl samples (Griffiths et al., 2008) and from 300 to 1,500m in epibenthic samples (Kaiser et al., 2008). Rogers et al. (2015) also reported seamount summits as covered in large abundances of brittlestars, with scattered sea pens, large anemones and the seastar *Labidiaster sp*. In deeper waters around the seamount, Rogers et al. (2015) reported an abundance of octocorals and brachiopods.

The South Sandwich Islands are unique in a Southern Ocean context in that they represent a long chain of islands extending almost 400km on a north-south axis. As such, they bisect a broad gradient of environmental conditions. Whilst Lockhart and Jones (2008) and Roberts (2012) reported differences in the dominant phyla between the islands, this analysis is the first to attempt to assess changes in faunal composition across the archipelago. As mentioned, most species recorded in the region are rare and subsequently species (and family) composition is highly dissimilar between islands (Figure 9.6). Similarity was however shown to correspond geographical proximity with highest species and family-level similarity recorded between neighbouring islands (e.g. Zavodovski and Visokoi and Candlemas Islands) and similarity reducing as a function of distance. A potential discontinuity in species-level faunal composition was identified at Saunders Island which demonstrated little similarity with any of the islands to the south (Figure 9.6). In contrast Zavodovski, Visokoi/Candlemas and Saunders Islands demonstrate relatively higher species similarities. This species compositional divide between north and south, centred on Saunders Island has also been reported in toothfish species and bycatch invertebrate species (Roberts, 2012). Roberts demonstrated an abrupt transition between an ‘Antarctic’ and ‘sub-Antarctic’ bioregions around Saunders Island, characterising these two bioregions by differences in sea temperature with depth, hydrographic characteristics and biological productivity.

9.4.3 Environmental drivers of biogeography

Environmental conditions at the South Sandwich Islands were predominantly linked to latitudinal gradients (e.g., sea ice, temperature and productivity) and depth gradients (e.g., temperature and salinity). Sea-surface productivity also demonstrated an east-west divide. Saunders Island was again identified as the most bathymetrically isolated island of the archipelago (Figure 9.7), separated by deep water (2,500m) with oceanographic currents bisecting the water between Saunders Island and Montagu Island to the south (Figures 9.8 and 9.9).

The topography of archipelago's islands shows evidence of mass-wasting and slope instability (Leat et al., 2010; 2013; 2016). Collapse scars, slump structures, embayments and erosional gully systems can be seen on all the volcanic island flanks (Figure 9.16). Wave-like structures, particularly on the eastern, trench-facing side of the islands, are thought to be formed by down-slope, mass-flow transport of volcanic sediments (Leat et al. 2010). This instability of the archipelago's slopes was also evidenced in drop camera deployments conducted during DY99 which demonstrated significant down-slope sediment flows creating what is likely a heavily perturbated benthic environment (e.g. Section 6.4; Figures 6.2 and 6.3). These conditions will influence the fauna that colonises these environments, potentially selecting against slow growing sessile communities in favour of faster-growing pioneer communities (e.g., encrusting bryozoans and ascidians) or mobile scavengers and predators. It also seems logical to expect a discontinuity in faunal composition between the more stable environment of the shallow shelves around the islands (shown in Figure 9.16) and the slope. To the west of the island chain is a large plain at a relatively uniform 3,000m depth. Here large amounts of volcaniclastic sediment, transported down-slope, have formed a thick (up to 1km) layer of turbidite overlaying the bedrock (Vanneste et al., 2002; Leat et al., 2016). Though there is limited benthic sampling of this environment (Figure 9.1), it is likely completely restricted to infaunal, epifaunal and mobile deposit feeders or scavengers (e.g. polychaete worms and holothurians). This region transitions into the tectonic spreading zone and East Scotia Ridge, an area characterised by tectonically uplifted regions of topographic complexity. These hard-rock islands in the deep sea may represent oases for sessile suspension feeding communities, though connectivity across a vast plain of turbidite mud may limit this diversity. Running 100km to the east and parallel to the Islands, the South Sandwich Trench reaches depths of over 8,000m, with water depths commonly >7,000m.

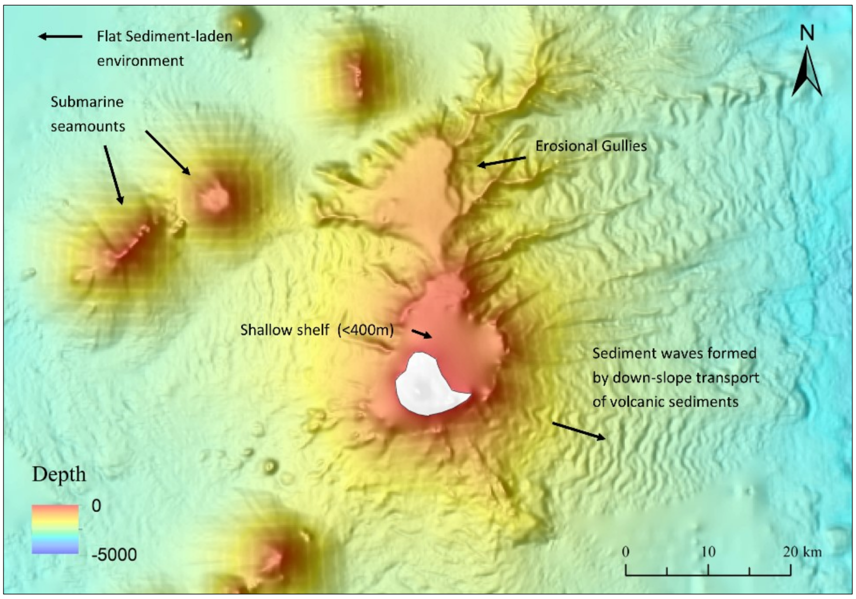

Figure 9.16. Seabed topography around Saunders Island showing shelf and seamounts and mass-wasting processes such as waves of down-slope sediment movement on the volcanic flanks and erosional gully features. Bathymetry and topographical interpretations adapted from Leat et al. (2016).

Given most species are recorded rarely at the South Sandwich Islands, it is difficult to assess how environmental conditions drive species-level composition. In this analysis we categorised the region's benthic fauna into 21 functional groups based predominantly on mobility, feeding strategies and lifestyle and then subdivided again based on taxonomy (see Table 9.2). This functional grouping provided a means of categorising benthic fauna in an ecologically meaningful way, whilst retaining enough sampling records per grouping to allow statistical significance when assessing their correlation with environmental covariates.

The importance of 15 environmental predictor variables (Figure 9.11) was assessed using a random forest modelling approach in which variables were sequentially removed to assess their influence on the accuracy of modelling outputs. Depth, bottom temperature, channel base network level (a derivative of bathymetry) and latitude were identified as the most important drivers of benthic functional group composition. Spatial variation in marine biodiversity over gradients of latitude, depth and temperature are well documented (reviewed in Gaston, 2000; Gaston and Spicer, 2013), with depth and temperature commonly cited as environmental drivers of habitat mapping models (reviewed in Harris & Baker, 2012). Seemingly of less importance in our study region were measures of geomorphology (e.g. slope angle, rugosity and topography) and variance in oceanographic current velocities. Measure of slope and topography are often useful predictors of faunal composition, notably with measures of geomorphology often employed as surrogates of hard substrate communities (Harris & Baker, 2012). One explanation for their lack of importance here could be that the resolution at which they were gridded (200m) did not correspond with faunal compositional change. This mismatch in spatial scale may be even more pronounced in modelled oceanographic data for the region constraining only very broad-scale oceanographic currents (1/12°).

9.4.4 Gradient forest and landscape classifications

There are certain features in the marine environment such as coral reefs (Andrefouet et al., 2006), canyons (Huvenne et al., 2011), gullies (Gales et al., 2016) and continental shelf breaks (Harris & Macmillan-Lawler, 2016), for which sharp discontinuities in environmental conditions, notably depth and substrate, delineate a boundary between consolidated habitats. Most marine habitats however, depending on the spatial scale at which they are observed, are not clearly delineated by abrupt boundaries. Instead, conditions that define habitats change over gradients and biological communities transition, with a degree of turnover between regions. As such there is a fundamental inconsistency between this continuum of environmental variables and categorical classification systems (Wallace, 1876), which will always make analysis and mapping of marine habitats problematic (e.g. see Hogg et al., 2018).

Gradient forest provides a nonlinear and flexible methodology in constraining, quantifying and interpreting compositional changes in fauna along environmental gradients. It is particularly applicable to datasets such as at the South Sandwich Islands, because its use of dimensionless R^2 to quantify change allowing the use of amalgamated datasets, even if such data include disparate sampling methodologies (Pitcher et al., 2012).

Of the four most important drivers of faunal composition (Figure 9.11), latitude and depth proved the most spatially informative (Figure 9.12). The largest changes in functional group composition occurred along a latitudinal gradient and coincided with specific islands in the archipelago, most notably were threshold changes in faunal composition at Zavodovski and to a lesser extent Saunders Island, Montagu Island and Southern Thule. This trend was also evident in similarity matrices of species and family-level composition (Figure 9.6) where similarity was shown to be a function of distance. With depth, most compositional changes in fauna were shown to occur in relatively shallow waters (depth <500m). This corresponded with the small, restricted shelf areas of the islands. Beyond this depth, turnover in species composition was not marked by definitive thresholds (Figure 9.12).

Gradient forest maps demonstrated clear latitudinal delineations in environment and fauna. Most notable was a north-south divide in shallow-water environments. This bio-physical classification of the South Sandwich Islands supports previous interpretations of distinct northern and southern bioregions at the archipelago (Roberts, 2012). The analysis by Roberts identified a clear discontinuity in toothfish species with Patagonian toothfish (*Dissostichus eleginoides*) reported north of Saunders Island and Antarctic toothfish (*Dissostichus mawsoni*) reported to the south. In slight contrast, here we show a transition in bioregion one island further north at Candlemas Island, with Saunders Island representing the most northernly island solely within the southern bioregion.

This distinct biogeographical cut-off in finfish was suggested to relate to temperature as the key range-limiting factor (Roberts, 2012). In this case Saunders Island represented a discontinuity because it exhibited the most northerly location at which mean winter surface temperatures dropped below -1°C. This is of physiological significance in fish because it represents the freezing point of blood plasma and so tolerance requires physiological adaptations (i.e., antifreeze proteins) which are only present in certain specifically Antarctic species (Roberts, 2012). Other environmental factors suggested as possible drivers of a north-south divide in fauna have been sea ice associated productivity (Perissinotto et al., 1992) and seafloor substrate (Roberts, 2012). In our assessment the latitudinal discontinuity is less clear as there are no obvious abrupt clines in environmental gradients at either Candlemas or Saunders Island (Figures 9.8 and 9.12). Instead, it seems likely to result from a composite influence of a variety of physical and biological factors.

Landscape mapping conducted over the same area employs a different approach to clustering the marine environment. Here biological data is not considered in the analysis, with clustering undertaken objectively based on shared environmental conditions. This analysis is not directly comparable given its differing methodology and the number of partitions created in environmental space. Broadly however the landscape mapping results validate the gradient forest mapping outputs (Figure 9.10 and Figure 9.15) with distinct environmental clusters for the northern and southern islands. Landscape mapping identified a more gradual transitional change in physical habitat types with co-occurrences of multiple clusters in several locations such as Saunders and Candlemas Islands. This is however logical given that landscape mapping attempts to create ‘hard boundaries’ in its analysis so more clusters are needed to characterise change over gradients.

9.4.5 Marine protection in a changing climate

With South Sandwich Island fauna linked to latitudinal gradients in temperature, sea ice and productivity, temporal changes in the marine environment resulting from climate change are of fundamental importance in understanding possible ramifications for future trends in diversity and distribution. Positioned south of the South Antarctic Circumpolar Current Front ACC (Figure 3.1), environmentally, the South Sandwich Islands are distinctly Antarctic in character with lower temperatures and seasonal sea-ice. Consequently, the region’s benthic fauna is likely characterised by slow growth rates, increased longevity, morphological gigantism and deferred sexual maturity (Peck, 2002). As such, many species may have poor ability to cope or adapt to warming oceans compared to species at lower latitudes (Convey & Peck, 2019).

The Southern Ocean has undergone substantial warming since the 1930s (Gille, 2008; Swart et al., 2018) and is forecast to continue this trend (Turner et al., 2016). Regionally, observations at South Georgia demonstrate an average sea-surface (0 - 150m) warming of 2.3°C over 81 years (Whitehouse et al., 2008). This warming exhibited interannual variation, with the warming twice as strong during the winter months. Furthermore, the waters of the ACC have, since the 1960s, also demonstrated more significant warming than the Southern Ocean as a whole (Turner et al., 2013). Most notable the Circumpolar Deep Water (150 - 500m) on the southern edge of the ACC has demonstrated decadal increases up to 0.17°C (Gille 2002; Böning et al., 2008). Model projections suggest above average future changes near the ACC (Sokolov & Rintoul 2009), with poleward displacement of the ACC frontal features combined with a strengthening and/or warming of the southernmost jet (Turner et al., 2013).

These changes have significant implications on the capacity of the South Sandwich Island’s fauna to adapt to or tolerate a future marine environment with higher temperatures.

Sea ice is known to be important to the structure and dynamics of the South Sandwich Island's marine ecosystems (Rogers et al., 2015). In spring, melting sea ice is associated with the release of algae and iron incorporated into the sea as it is formed (Massom & Stammerjohn, 2010). Ice-edge spring melting corresponds with seasonal phytoplankton blooms which form the basis of higher predator food chains (Murphy et al., 2007). Climate-driven changes to sea ice distribution and duration will likely impact the onset and duration of seasonal plankton booms and productivity fluxes. Furthermore, it could lead to potentially greater seabed disturbance from earlier and more extensive sea ice breakup and iceberg scouring (Barnes, 2016).

Given our assessment of latitudinal and temperature gradients in bioregions and a north-south discontinuity in environment and faunal character, changing climate is a key consideration in future-proofing MPA design through assessing potential range-shifts in benthic fauna under different climate scenarios. Furthermore, given the region's unique setting in the Southern Ocean (i.e., an island chain extending across latitude), the islands provide a good natural laboratory in which to assess biogeographical changes in relation to climate change in the Southern Ocean more broadly.

The South Sandwich Islands are typical of many Southern Ocean locations, which due to their isolation, and the associated logistical and financial limitations of accessing the region, there remains significant paucity in our understanding of the region. We recognise that compilations of diversity data, like reported here, are ultimately limited by the fact that they have been assimilated from different sources. As such, though the data may be presented in the same format, the means by which the data has been obtained varies considerably. An improved understanding of the South Sandwich Islands' biogeography must therefore ultimately come from the kind of structured sampling effort presented by the research undertaken during DY99.

10. Geochemical analysis of deep-sea corals from the South Sandwich Islands

In the past decade, the use of deep-sea corals as an oceanographic proxy to determine the dynamics of chemical concentrations in the World's oceans has been investigated. The corals incorporate chemical elements from seawater into their calcium carbonate skeletons and, by measuring the levels of these elements, it is possible to infer information about the past environment in which they lived (Tittensor et al., 2009). Sub-fossil deep-sea corals can be precisely dated using uranium series decay, allowing determination of the historic spatial distribution and trends in oceanic and atmospheric conditions. The collection of living and fossil corals and their analysis to extract the geochemical time series is contributing towards a worldwide database of information for use in climate studies to which the DY99 South Sandwich coral samples will be added.

Seventy-six deep-sea corals of the genus Flabellum (*F. thouarsii* and *F. curvatum*) were collected during DY99 at Saunders Island from approximately 235m depth. They were all small (approx. 5cm long), presented a thin skeleton and were collected alive, therefore no dating was required. Twenty-five of them were subsampled for DNA analysis and two for RNA. These two species had previously been reported from the Falkland Islands and South Georgia from a depth range of 71 to 305m and 115 to 1,513m, respectively (Cairns, 1982; Cairns and Polonio, 2013). Therefore, the occurrence of these corals at the South Sandwich Islands was not completely unexpected.

The University of Bristol hosts a collection of sub-fossil deep-sea corals from the Drake Passage region and these new South Sandwich Islands' samples will be analysed there to help expand an ever-increasing deep-sea coral database.

11. Genetic connectivity of deep-sea corals from the South Sandwich Islands

The data acquired during DY99 allowed the aims set out under a Darwin Plus-funded Project (DPLUS089)[1] to be addressed. The aim of the benthic sampling was to record the diversity and distribution of epibenthic macro- and megafauna, and to collect samples for genetic analysis linked with the project.

All benthic material was preliminarily identified on board the ship; coral specimens and genetic tissue was preserved and subsequently transported to the University of Essex for further analysis under the ongoing Darwin Plus project. Project staff are collaborating with taxonomic experts for species identification and biodiversity data analysis is currently ongoing.

Collected specimens will be combined with previously collected samples (200+) from across the sub-Antarctic. The mixed quality of specimens, from varied sources and preservation methods (e.g., bycatch, museums, formalin-preserved specimens), means a targeted DNA library preparation methodology is desirable to ensure standardisation and the quality of analysis. One such method uses Non-coding Ultra-Conserved elements (UCEs); these are sections of DNA distributed throughout the genome that are highly conserved, yet have variable flanking regions, making them useful for addressing questions across a range of evolutionary scales, including population genomics. Using a probe library of existing UCEs variable sections of the genome will be extracted as single-nucleotide polymorphisms (SNPs). This data will allow the examination of population structure and gene flow within and between sampled populations across the Atlantic sector of the Southern Ocean.

As part of this research, an Advanced Research and Innovation in the Environmental Sciences (AIRES) Doctoral Training Partnership (DTP) proposal entitled "*Seascape genomics of Antarctic deep-sea corals*" has been successful and these outputs will contribute to the ongoing Darwin Plus project. The selected candidate started the PhD project in October 2020.This research will continue to increase the outputs from DY99, further demonstrating the value and ongoing importance of this expedition.

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[1] https://www.darwininitiative.org.uk/project/DPLUS089/

12. Opportunistic surface sightings of marine mammals

12.1 Introduction

The distribution of marine mammals around South Georgia and the South Sandwich Islands is well studied for some species of marine mammals, however there are no regular transect surveys in place to determine overall trends in occurrence and abundance. The South Sandwich Islands, in particular, have limited information on marine mammal sightings, currently limited to annual information from the SGSSI Scientific Observer Data Collection during the fishing season, using fishing vessels as platforms of opportunity. Blue Belt therefore used the opportunity of two consecutive surveys under its banner to collect information on marine mammal distribution in this region (Fielding et. al., 2019). During DY99 the transition time between stations was used by DY99 survey staff to collect information on location and abundance of marine mammals to improve understanding of their distribution during the time period of the survey.

12.2 Methodology

Marine mammal observations were carried out in two modes. Firstly, vessel transit was used as the basis for transects using distance sampling with two observers with separate viewing points on a single vessel (Buckland et al., 2001). Observers were located on the bridge deck on the port and starboard side, and during observation effort periods, observations were made from -10 degrees to 90 degrees on the starboard side, and from -90 degrees to 10 degrees on the port side, thus ensuring a 20 degree overlap in observation sector at the bow of the ship. Distance sampling is part of a group of data collection methods for estimating animal densities or abundances, based on the assumption that (in most cases) detection probability decreases with increasing distance from the observation transect (Buckland et al., 1993). In addition to conventional presence (number)/absence data, the method also relies on collecting information on the height of the observation position, the distance, the angle to the observed target, and factors that may affect detectability, such as weather or sea conditions (Figure 12.1). This allows a detection function to be calculated, which models the probability of detecting a target depending on its distance from the observation point.

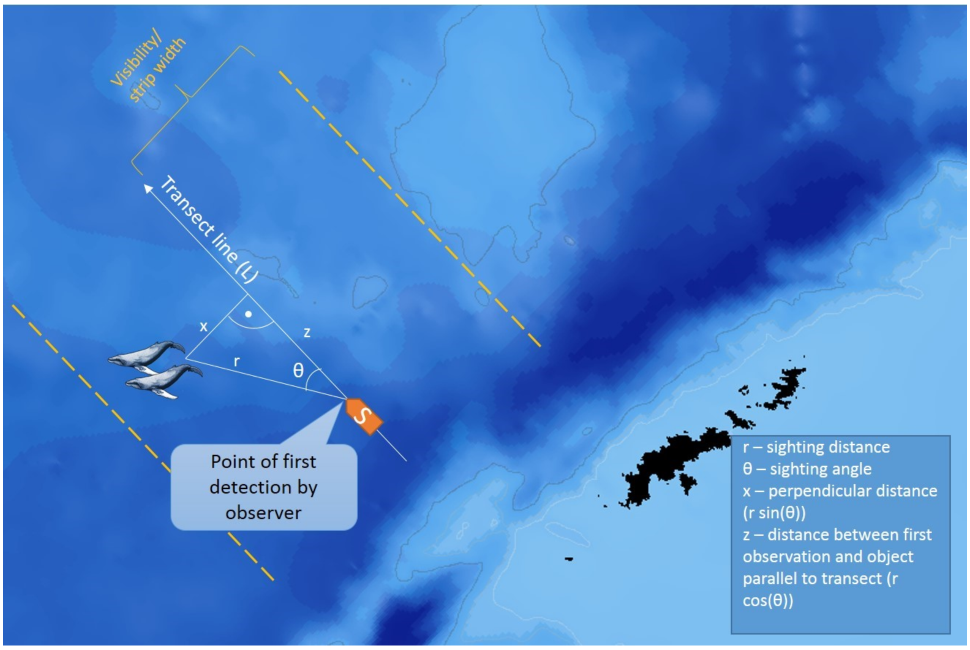

Figure 12.1. Schematic representation of data collection under distance sampling

Secondly, outside of scheduled observation periods, marine mammals were recorded opportunistically when observed, either by observers or by bridge crew. These data were presence-only records, treated as supplemental information of species occurrence to the distance sampling dataset.

12.3 Marine mammal observation summary

Observers completed 67 hours of marine mammal observation in total, covering a total of 1,486 kilometres or 803 nautical miles. The black lines in Figure 12.2 show the locations of observation effort. A total of 567 marine mammals were counted during these observation effort sessions. The most frequent marine mammals were fur seals, seen in abundance approaching South Georgia and towards the South Sandwich Islands. Humpback whales were also seen frequently and throughout the entire survey, followed by hourglass dolphins, groups of pilot whales, and fin whales. Other less frequently sighted species included blue whales, sei whales, minke whales, sperm whales, and beaked whales. Closer to the Falkland Islands several dolphin species were recorded, including dusky dolphins, hourglass dolphins, Commerson’s dolphins, and Peale’s dolphins. A total of 15 species were identified, as well as unidentified records of seals, whales, and dolphins. In addition to observations during scheduled effort periods, an estimated 156 marine mammals were recorded as opportunistic sightings outside of scheduled effort periods. These included fur seals, humpback whales, hourglass dolphins, minke whales, and fin whales.

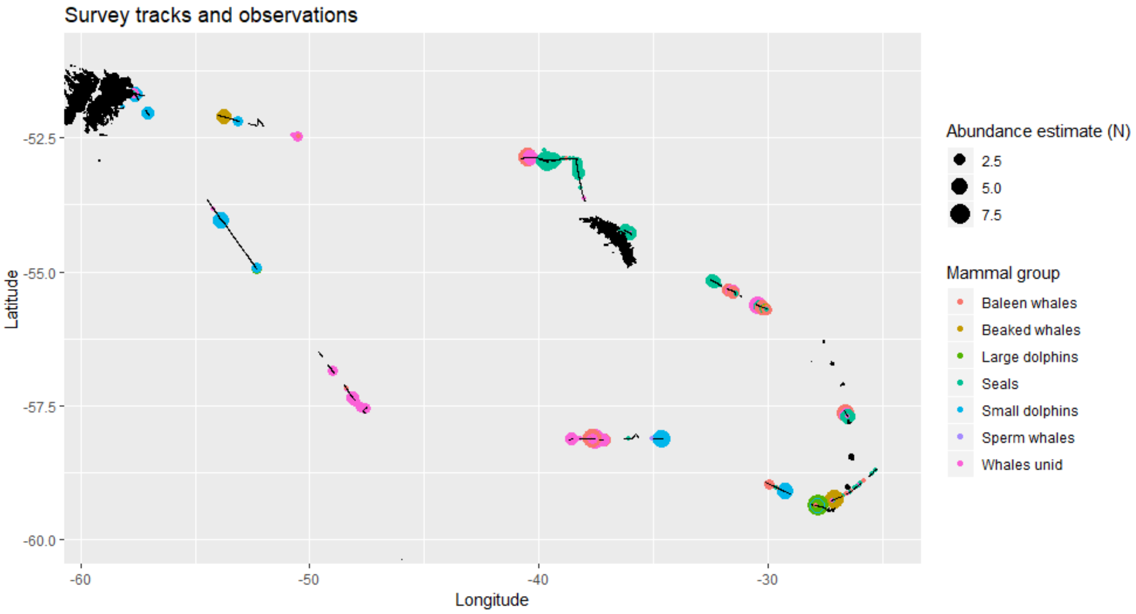

Figure 12.2. Scheduled effort of marine mammal observations around South Georgia and the South Sandwich Islands. Observation effort tracks are shown as black lines. Species groups are shown as centroids on the line (not at angle/distance), with the point size indicating sighting abundance.

13. General conclusions

In 2012 the Government of South Georgia and the South Sandwich Islands declared a sustainable use Marine Protected Area (MPA) within its maritime zone, covering more than 1 million km^2 of the Scotia Sea (Collins et al., 2012). The MPA was further enhanced in 2013 and 2019 to include additional spatial and seasonal protection (GSGSSI, 2018). It is one of the largest marine protected areas in the World, with the South Sandwich Islands forming a significant proportion of the area protected.

Very little was known about the benthic environment of the South Sandwich Island archipelago, particularly the distribution of species and regional diversity. What was known of the regions' benthos typically comes from toothfish fisheries bycatch data (Roberts, 2012), and limited scientific demersal sampling (Ramos, 1999; Lockhart & Jones, 2008; Griffiths et al., 2008; Kaiser et al., 2008). Amongst mobile fauna, biodiversity is known to be at least partially shared with South Georgia (Roberts & Agnew, 2008). Knowledge of the distribution and diversity of less mobile and sessile benthic fauna however was considerably patchier.

Funded by UK Government Blue Belt Programme, the Cefas RRS *Discovery* 2019 survey (DY99) undertook a systematic survey of the region's benthic biodiversity, to address this information gap and to enable management advice to be provided on the potential impact of demersal (bottom) longline fishery within the region. Four islands and one bank along the South Sandwich Islands archipelago were selected for sampling. At each site, a deep-water camera system and benthic trawls were used to survey epifaunal communities from 200 to 2,100m. The survey focused on determining trends in species distribution and diversity across both latitudinal and depth gradients to determine the influence of topographic and environmental variables on benthic fauna and community structure.

13.1 Logistics

The RRS *Discovery* proved eminently suited to the deployment of the camera system and the collection of data in the dynamic conditions experienced at the South Sandwich Islands. The vessel's stability and dynamic positioning allowed the camera system to be deployed across the majority of subsea terrains and in, at times, challenging seas conditions. The Blue Belt survey team commented particularly on the excellent experience and facilities provided by the vessel and all on board. The support and encouragement provided by the RRS

Discovery crew, was excellent and all staff enjoyed the atmosphere and working with the crew as a collaborative team.

The Blue Belt deep-water camera system proved to be an extremely successful approach to determining the characteristics of the South Sandwich Islands benthic species, substrate, and habitats. Seabed imagery was acquired from a total of 36 stations at six survey areas during 38 deployments, including over 4,000 images and 30 hours of video footage. In addition, over 500 samples and 3,600 specimens were collected from the benthic trawl stations conducted at four survey areas.

Towards the end of the DY99 survey, failure in a cable seal of both the primary and then the back-up camera housings resulted in the termination of the survey and lost research capability. This is being further addressed with the manufacturer of the camera housing. Fortunately only a few days were lost to this setback, as the failure terminated the survey.

Despite the short time available for the DY99 survey (nine days), the extensive amount of data collected has resulted in substantial improvements in the scientific understanding of the marine environment at the South Sandwich Islands. This data will underpin short and long-term research projects, leading to the provision of evidence-based management advice for the region for many years.

13.2 Benthic composition and diversity

This report has summarised the data collected by the DY99 survey and, with the addition of data recorded by previous expeditions to the region, presents the first attempt to holistically map and bio-physically characterise the benthic environment of the South Sandwich Islands region, providing biogeographical context to the South Georgia and South Sandwich Islands Marine Protected Area.

The South Sandwich Islands are both diverse in benthic fauna and biogeographically distinct from neighbouring islands in the Scotia Arc. This is particularly notable given the islands' small shelf area, young geological age, and that novel species discovery remains high. Combining biological observations with multibeam backscatter and derived topography data enabled determination of the location and extent of benthic habitat types and prediction of likely VME habitats throughout the survey area.

Community composition, diversity and large-scale zonation of benthic fauna along the South Sandwich chain are influenced by the interaction of environmental conditions and geographical setting, notably seabed temperature, topography and latitude. High species diversity was recorded at the northern-most islands of Zavodovski and Saunders, comprising mainly of suspension feeding fauna. Lower species richness, but high functional diversity of generalist deposit-feeders and opportunistic fauna, was recorded in the southern islands. Analysis of species composition, diversity, and distribution of benthic epifauna in relation to environmental variables highlighted depth, latitude and temperature, as primary drivers.

The effects of small-scale disturbances, such as iceberg scouring and volcanic substrate instability, on these distribution patterns are likely to be locally important. The slope environment of the South Sandwich Islands is characterised by geomorphological instability and mass sediment transport (Leat et al., 2016). This is likely to be limiting faunal composition, favouring colonisation of opportunistic fauna, fast-growing pioneer communities or species with mobile life stages. Most of the sessile fauna such as corals, sponges and bryozoans, were concentrated on consolidated substrates, while unconsolidated substrates hosted a wide range of deposit-feeding fauna (e.g. brittle stars, sea stars, sea cucumbers).

Analysis of camera surveys, DY99 trawl samples and historic sampling demonstrated a change in benthic fauna from north to south across the archipelago. This was manifest in distinct north and south bioregions in both shallow and deep-water habitats. Notably however, even the islands of the northern bioregion demonstrated limited shared species with neighbouring sub-Antarctic South Georgia.

13.3 VME species distribution

Epibenthic VME groups identified from camera images were correlated with bathymetry, topographic features, and seafloor acoustic reflectivity to quantify the environmental range limits of VME taxa. These limits were used to extrapolate the spatial distribution of VME indicator taxa across the entire acoustic study region to produce maps showing areas where VME taxa are likely to occur given suitable substrate conditions.

The output generated allow the risk of encountering VME species to be mapped to provide advice on where interactions with fisheries, in the surveyed regions, would be likely to impact key species. In all of the survey regions, the VME taxa were located almost exclusively at depths shallower than 700m, the upper depth limit for longline fishing. Only in one area, to the east of Montagu Island, were VME indicator species (sea pens) recorded, in sparse densities, within the permitted longline fishing depths at ~820m.

The drop-camera observations demonstrated that soft sediment dominates the environment at depths greater than 700m. The acoustically surveyed area did however include some locations with topographically suitable conditions for VME that were not sampled during the camera survey. This includes, for instance, depths greater than 2,200m that consequently cannot be discounted as potential VME habitat without additional camera sampling. If bathymetry and reflectivity data become available for other areas these maps can be extended to include areas outside of the survey area, providing a basis for risk analysis advice across the South Sandwich Islands region of the MPA.

13.4 The benthic impact of longline fishing gears

Research fishing using benthic longlines is permitted along the South Sandwich Islands archipelago, to monitor the local biomass of Patagonian toothfish (*Dissostichus eleginoides*) and Antarctic toothfish (*Dissostichus mawsoni*), which are linked to the South Georgia and Antarctic populations. Two vessels are annually allocated research fishing positions, from a random stratified spatial distribution of known locations. In addition to the distribution of benthic structures and species, another key piece of information required to provide advice on the ecosystem effects of fishing to managers, is quantifying the physical impact of fishing gears on the seabed.

A total of 17 camera transects were conducted at the depths where longline fishing is permitted. All transects recorded soft substrate with a high degree of mobility due to the slope and type of volcanic substrate or sedimentation rate. Transect positions were selected such that any benthic impacts from ten longlines, set between 2008 – 2016, could be observed. Only one shallow impression from a longline was recorded, most likely from a Spanish line weight on a line set three years earlier. No other longline disturbance was detected in any other camera transects throughout the survey.

Based on the drop-camera observations, it can be expected that communities, and the seabed itself, would not be significantly impacted by the longline fishery. The risk associated with the fishing process at the depths and in the areas surveyed, is considered to be low, due to a combination of:

- a low abundance of sparsely distributed benthic VME species and structures;
- a restricted longline footprint, primarily extending along its length and 10cm either side;
- the low frequency of research lines set within each area surveyed.

The Blue Belt Programme is conducting a series of research studies investigating the impact of longlines on the benthic environment, such that risk strategies can be developed for management and the results from the DY99 survey inform that process.

13.5 Informing MPA management

Analysis presented here, based on the data collected by DY99 and other surveys that have preceded it, present the first attempt to holistically map and bio-physically characterise the region's benthic environment, providing biogeographical context to the South Georgia and South Sandwich Islands Marine Protected Area. The results of the survey are synthesised into points of relevance to the GSGSSI MPA management:

- VME indicator taxa are largely confined to waters shallower than 700m. Only in one area, to the east of Montagu Island, were VME indicator species (sea pens) recorded, in sparse densities, within permitted longline fishing depths at ~820m. As such, the current zoning of longline fishing to within 700 – 2,250m appears to offer effective protection for the majority of the VME indicator taxa.

- Fishing effort is limited. Research fishing locations are mostly distributed randomly along the island chain, in low density, and longlines have a benthic footprint which extends a short distance to either side and along their length. Based on the drop-camera observations, it can be expected that communities, and the seabed itself, would not be significantly impacted by a longline fishery in the areas surveyed by the expedition.

- The depth range currently open to licenced longline fisheries is not identified as a distinct bioregion in either gradient forest of landscape mapping analyses. As such, based on our current understanding of the region's benthic environment, as currently established, the MPA protections cover a 'representative' range of benthic habitats.

- The current regional extent of the spatial protection within the MPA for benthic species is considered appropriate. Due to the variation in species and functional diversity along the archipelago, the protection along the full latitudinal range is important in conserving distinctly different bioregions from the north to the south along the island chain.

14. The RRS Discovery Expedition 99 legacy

The overall aim of the Blue Belt Programme RRS *Discovery* Expedition 99 was to gain a wider understanding of the regional benthic ecosystem at the South Sandwich Islands and thereby provide advice to the Government of South Georgia and the South Sandwich Islands that would enable it to determine the effectiveness of current management measures and to further enhance its management of the region. This ambition has been achieved despite the expedition only being able to achieve nine full working days at the South Sandwich Islands archipelago.

The results presented within this report are just the first stage in the scientific analysis of the data available within the gigabytes of acoustic bathymetry and backscatter data, 30 hours of video, 4,000 images, 3,600 preserved benthic specimens and 67 hours of marine mammal observation.

The digital information will be archived and made available to the Government of South Georgia and the South Sandwich Islands for researchers to use on request. Cefas particularly, as part of the Blue Belt Programme, will be continuing to use the data collected to conduct research on predicting species and biodiversity distributions within the region.

Cefas and the Natural History Museum also have a Memorandum of Understanding in place to encourage, develop and extend cooperation in the natural sciences. The Discovery 99 collections have been donated to the Natural History Museum who will ensure the curation, long-term storage, and access sharing of biological collection resources. These materials include representative sample of the invertebrate species and molecular voucher specimens. They are housed as a collection at the Natural History Museum in London and will be available to the wider scientific community to undertake further studies to improve our knowledge of these remote habitats.

The genetic samples collected also included material contributed to the Natural History Museum biobanking and The Darwin Tree of Life Project, an ambitious initiative to sequence the genomes of all life on the British Isles and, where possible, within the UK Overseas Territories.

The data collected by the RRS *Discovery* Expedition 99 will form the basis of a series of published papers from the research team based on their work conducted on board the vessel and analysing the information presented within this report. This will hopefully be the start of a legacy to scientific research lasting for a further 100 years.

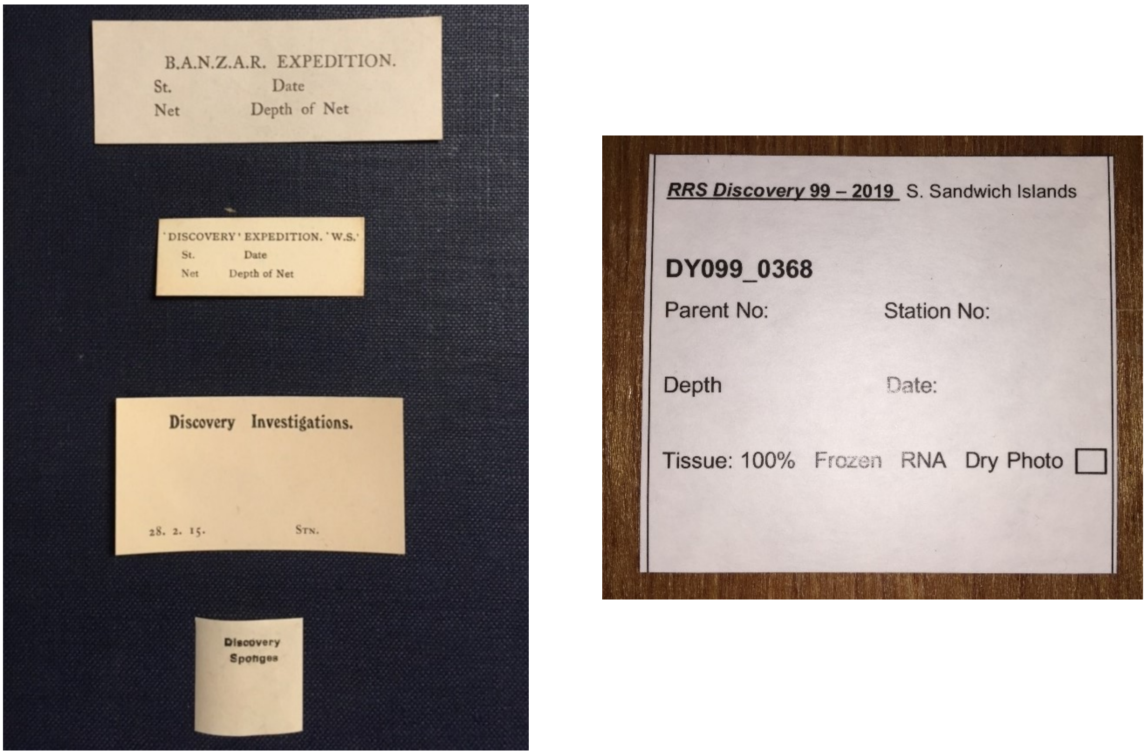

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Figure 15.1. One hundred years of Discovery labels. The left image shows historical labels used during the RRS *Discovery* Expeditions. On the right, an example of the labels used to identify samples collected during the Blue Belt Programme RRS *Discovery* Expedition 99. © Natural History Museum.

15. Acknowledgements

We would like to sincerely thank the captain, crew and scientists of the RRS *Discovery* Expedition 99. The foresight and pre-planning by Cefas project managers Caroline Whybrow, Gemma Beard and Blue Belt Programme Office team provided all of the necessary support needed to make DY99 a success. Our thanks also go to Jennifer Lee (GSGSSI) for her invaluable assistance with arranging the export permits.

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17. Annex 1: Station metadata for DY99

Station metadata for DY99. Station number is a sequential event number for the cruise, so changes each time a new gear is used, or a new location is sampled. Station code identifies the sampling locations at Cumberland Bay, South Georgia (CUB); Zavodovski Island (ZAVO); Saunders Island (SAUN); Montagu Island (MONT); Montagu Bank (MOBA) and Southern Thule (SOTH) Latitude and Longitude are recorded in degrees and decimal minutes.

Station number	Station code	Date	Gear	Sample acquired	Replicate Attempt	Start of line Latitude		Start of line Longitude		Number of stills	Duration of video footage
1	CUBA01	21/02/2019	Drop Camera	TRUE	A1	54	16.0176	36	26.1356	84	01:02
1	CUBA01	21/02/2019	Drop Camera	TRUE	A2	54	15.8995	36	25.872	26	00:33
2	ZAVO01	23/02/2019	Drop Camera	TRUE	A1	56	15.931	27	36.275	127	00:53
3	ZAVO02	23/02/2019	Drop Camera	TRUE	A1	56	15.65	27	37.115	115	01:16
4	ZAVO03	23/02/2019	Drop Camera	TRUE	A1	56	15.387	27	37.837	116	02:02
5	ZAVO04	23/02/2019	Drop Camera	TRUE	A1	56	14.998	27	38.946	95	01:21
6	ZAVO05	23/02/2019	Drop Camera	TRUE	A1	56	13.918	27	42.099	146	01:31
7	ZAVO02	23/02/2019	1.5m Benthic Dredge	FALSE	A1	56	15.588	27	37.28	-	N/A
8	ZAVO01	23/02/2019	1.5m Benthic Dredge	FALSE	A1	56	15.959	27	36.646	-	N/A

Station number	Station code	Date	Gear	Sample acquired	Replicate Attempt	Start of line Latitude	Start of line Longitude	Number of stills	Duration of video footage
9	ZAVO06	23/02/2019	Drop Camera	TRUE	A1	56 16.1148	27 36.672	91	01:03
10	ZAVO07	24/02/2019	Drop Camera	TRUE	A1	56 23.138	27 23.674	100	00:57
11	ZAVO08	24/02/2019	Drop Camera	TRUE	A1	56 23.303	27 22.739	66	01:04
12	ZAVO09	24/02/2019	Drop Camera	TRUE	A1	56 23.565	27 21.38	93	01:28
13	ZAVO10	24/02/2019	Drop Camera	TRUE	A1	56 23.935	27 19.283	81	01:08
14	ZAVO11	24/02/2019	Drop Camera	TRUE	A1	56 24.556	27 14.588	133	01:30
15	ZAVO07	24/02/2019	2m Agassiz Trawl	TRUE	A1	56 23.137	27 23.67	-	N/A
15	ZAVO07	24/02/2019	2m Agassiz Trawl	TRUE	A2	56 23.169	27 23.344	-	N/A
16	ZAVO07	24/02/2019	1.5m Benthic Dredge	TRUE	A1	56 23.138	27 23.266	-	N/A
17	SAUN01	25/02/2019	Drop Camera	TRUE	A1	57 42.347	26 29.311	210	01:47
18	SAUN01	25/02/2019	2m Agassiz Trawl	TRUE	A1	57 42.457	26 29.457	-	N/A
19	SAUN02	25/02/2019	Drop Camera	TRUE	A1	57 42.0052	26 30.095	87	01:05

Station number	Station code	Date	Gear	Sample acquired	Replicate Attempt	Start of line Latitude	Start of line Longitude	Number of stills	Duration of video footage
20	SAUN03	25/02/2019	Drop Camera	TRUE	A1	57 41.5189	26 30.4605	126	01:12
21	SAUN04	25/02/2019	Drop Camera	TRUE	A1	57 40.8213	26 31.2339	60	01:00
22	SAUN05	25/02/2019	Drop Camera	TRUE	A1	57 38.1253	26 36.0142	117	01:36
23	SAUN06	26/02/2019	Drop Camera	TRUE	A1	57 47.685	26 20.319	143	01:34
24	MONT08	27/02/2019	Drop Camera	TRUE	A1	58 26.702	26 12.658	77	01:19
25	MONT07	27/02/2019	Drop Camera	TRUE	A1	58 26.5138	26 12.7426	57	00:34
26	MONT06	27/02/2019	Drop Camera	FALSE	A1	58 25.2137	26 13.581	8	00:17
27	MONT10	27/02/2019	Drop Camera	TRUE	A1	58 27.392	26 11.6971	79	00:46
28	MONT09	27/02/2019	Drop Camera	TRUE	A1	58 26.5684	26 11.5701	138	01:04
29	MONT11	27/02/2019	Drop Camera	TRUE	A1	58 25.7973	26 11.5347	96	00:55
30	MONT12	28/02/2019	Drop Camera	TRUE	A1	58 27.156	26 9.069	147	01:26
31	MONT13	28/02/2019	Drop Camera	TRUE	A1	58 26.51	26 8.669	158	00:26

Station number	Station code	Date	Gear	Sample acquired	Replicate Attempt	Start of line Latitude	Start of line Longitude	Number of stills	Duration of video footage
32	MONT07	28/02/2019	2m Agassiz Trawl	TRUE	A1	58 26.572	26 12.734		N/A
32	MONT07	28/02/2019	2m Agassiz Trawl	TRUE	A2	58 26.584	26 12.711		N/A
33	MONT13	28/02/2019	2m Agassiz Trawl	TRUE	A1	58 26.774	26 8.705		N/A
34	MOBA02	01/03/2019	Drop Camera	TRUE	A1	58 31.0919	25 5.547	116	01:24
35	MOBA01	01/03/2019	Drop Camera	TRUE	A1	58 31.396	25 3.77	145	01:26
36	MOBA05	01/03/2019	Drop Camera	TRUE	A1	58 32.457	25 4.63	196	01:28
37	MOBA04	01/03/2019	Drop Camera	TRUE	A1	58 34.471	25 4.854	176	01:34
38	MOBA03	01/03/2019	Drop Camera	FALSE	A1				00:00
39	SOTH01	01/03/2019	Drop Camera	TRUE	A1	59 24.6585	27 24.5412	90	00:59
40	SOTH02	02/03/2019	Drop Camera	TRUE	A1	59 24.0833	27 24.9565	124	01:02
41	SOTH03	02/03/2019	Drop Camera	TRUE	A1	59 23.481	27 26.024	178	01:26
42	SOTH04	02/03/2019	Drop Camera	TRUE	A1	59 22.063	27 28.341	89	01:18

Station number	Station code	Date	Gear	Sample acquired	Replicate Attempt	Start of line Latitude		Start of line Longitude		Number of stills	Duration of video footage
43	SOTH02	02/03/2019	2m Agassiz Trawl	TRUE	A1	59	24.07	27	24.91		N/A
44	SOTH01	02/03/2019	1.5m Benthic Dredge	TRUE	A1	59	24.515	27	24.796		N/A
45	SOTH01	02/03/2019	2m Agassiz Trawl	TRUE	A1	59	24.508	27	24.796		N/A
46	SOTH05	02/03/2019	Drop Camera	TRUE	A1	59	15.865	27	23.4853	156	01:43
47	SOTH09	02/03/2019	Drop Camera	TRUE	A1	59	23.247	27	22.12	78	00:43

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We are the government’s marine and freshwater science experts. We help keep our seas, oceans and rivers healthy and productive and our seafood safe and sustainable by providing data and advice to the UK Government and our overseas partners. We are passionate about what we do because our work helps tackle the serious global problems of climate change, marine litter, over-fishing and pollution in support of the UK’s commitments to a better future (for example the UN Sustainable Development Goals and Defra’s 25 year Environment Plan).

We work in partnership with our colleagues in Defra and across UK government, and with international governments, business, maritime and fishing industry, non-governmental organisations, research institutes, universities, civil society and schools to collate and share knowledge. Together we can understand and value our seas to secure a sustainable blue future for us all, and help create a greater place for living.

Pakefield Road, Lowestoft, Suffolk, NR33 0HT

The Nothe, Barrack Road, Weymouth DT4 8UB

www.cefas.co.uk | +44 (0) 1502 562244

For more information about the Blue Belt Programme:

Web: www.gov.uk/government/publications/the-blue-belt-programme

Email: Bluebelt@cefas.co.uk

Twitter: @UKGovBlueBelt

Blog: marinedevelopments.blog.gov.uk/category/blue-belt

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