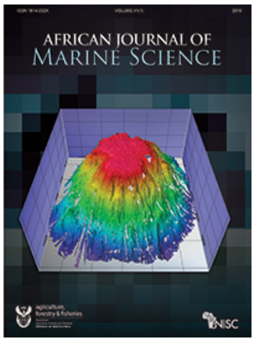

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Bathymetry, substrate and fishing areas of Southeast Atlantic high-seas seamounts

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Most of the Southeast Atlantic Ocean is abyssal, and global bathymetries suggest that only ~3.2% of the areas beyond national jurisdiction (ABNJ; also known as the high seas, as defined in the United Nations Convention on the Law of the Sea [UNCLOS]) are shallower than 2 500 m. This study mapped bathymetry and characterised substrates in selected seamount summit areas, including several that have been or may become fishing areas. The southernmost location, the Schmitt-Ott Seamount, has exposed volcanic bedrock with surrounding flats covered by thin biogenic sediments and/or coral rubble that appears ancient. At Wüst, Vema, Valdivia and Ewing seamounts the basaltic base appears to be overlain by coral caps and other coral substrates (sheets, rubble). Adjacent summit plains have biogenic sediments of varying thickness. Vema has a flat, roughly circular summit, <100 m deep, with the shallowest point being a 22-m-deep summit knoll; the upper slopes have ancient coral framework, but the summit has a mixture of coralline and volcanic rock and coarse sediments, including extensive areas with coralline algae and kelp forests. Valdivia Bank is a 230-m-deep, flat, rocky area (~11 × 5 km), protruding steeply from the extensive multi-summit Valdivia subarea of the Walvis Ridge. The distribution of past fisheries in the Convention Area of the South East Atlantic Fisheries Organisation (SEAFO) was considered in relation to the new information on bathymetry and substrate.

Keywords: areas beyond national jurisdiction, biogenic sediment, deep sea, echosounder mapping, fisheries, geomorphology, marine regions, seamount habitat, substrate

Introduction

The oceanic South Atlantic is deep and understudied, and, given that most data have been collected by remote-sensing techniques rather than mapping with modern ship-based technology, the bathymetry, geomorphology and substrate distributions of the area are not fully described. Maps and geomorphologies can be readily generated based on global databases and descriptions (e.g. Harris et al. 2014), and by this means maps and reliefs of many seamounts in subareas such as the Walvis Ridge have been produced (e.g. https://earthref.org/ERESE/projects/MV1203/dredges.htm). However, the spatial resolution remains relatively coarse, and the available global bathymetric datasets and geomorphologies have limited utility at a local scale—that is, the scale of individual seamounts.

This fine scale, however, is the resolution most relevant for studies of habitats and biota, including investigations of benthic and benthopelagic ecosystems utilised as a source of harvestable resources of fish and invertebrates. Improved bathymetries and geomorphologies at relevant spatial resolution are therefore required to enhance the quality of both basic scientific studies and applied science underlying assessments of human impacts on habitats and resources. Seamounts are regarded as ocean features that may require special attention by environmental and fisheries management (e.g. FAO 2009; Thompson et al. 2016; also see United Nations General Assembly Resolution 61/105 in 2006, http://www.un.org/Depts/los/general_assembly/general_assembly_resolutions.htm), and the multitude of seamounts in the Southeast Atlantic makes gathering new information in this extensive area especially pertinent.

The need for improved data on seamounts that are potentially or actually impacted by human activity thus formed the motivation for this study and was the basis for our selection and prioritisation of study sites. The aim was to provide detailed information on bathymetry and geomorphology of selected seamounts in the Sutheast Atlantic using multibeam echosounder mapping and *in situ* video

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exploration. The study was international and supported by the Food and Agriculture Organization of the United Nations (FAO) and was intended to supplement databases used by the intergovernmental fisheries management organisation known as the South East Atlantic Fisheries Organisation (SEAFO), which is mandated to regulate fisheries in marine areas beyond national jurisdiction (ABNJ), also known as the high seas, as defined in the United Nations Convention on the Law of the Seas (UNCLOS).

Previous mapping exercises in the relevant area included early explorations of Vema Seamount, where mapping with single-beam echosounders and various benthos samplers was conducted in the 1960s (Simpson and Heydorn 1965; Mallory 1966), but the maps generated were not very detailed. In 2010, on a contract with SEAFO, Jacobs and Bett (2010) compiled all the regional bathymetry data that were available from the General Bathymetric Chart of the Oceans (i.e. the GEBCO_08 Grid, http://www.gebco.net) and provided a bathymetric map for the entire SEAFO Convention Area (SEAFO CA) (Figure 1). Shortly prior to this, limited subareas were mapped in a Spanish–Namibian research effort (López Abellán and Holtzhausen 2011,

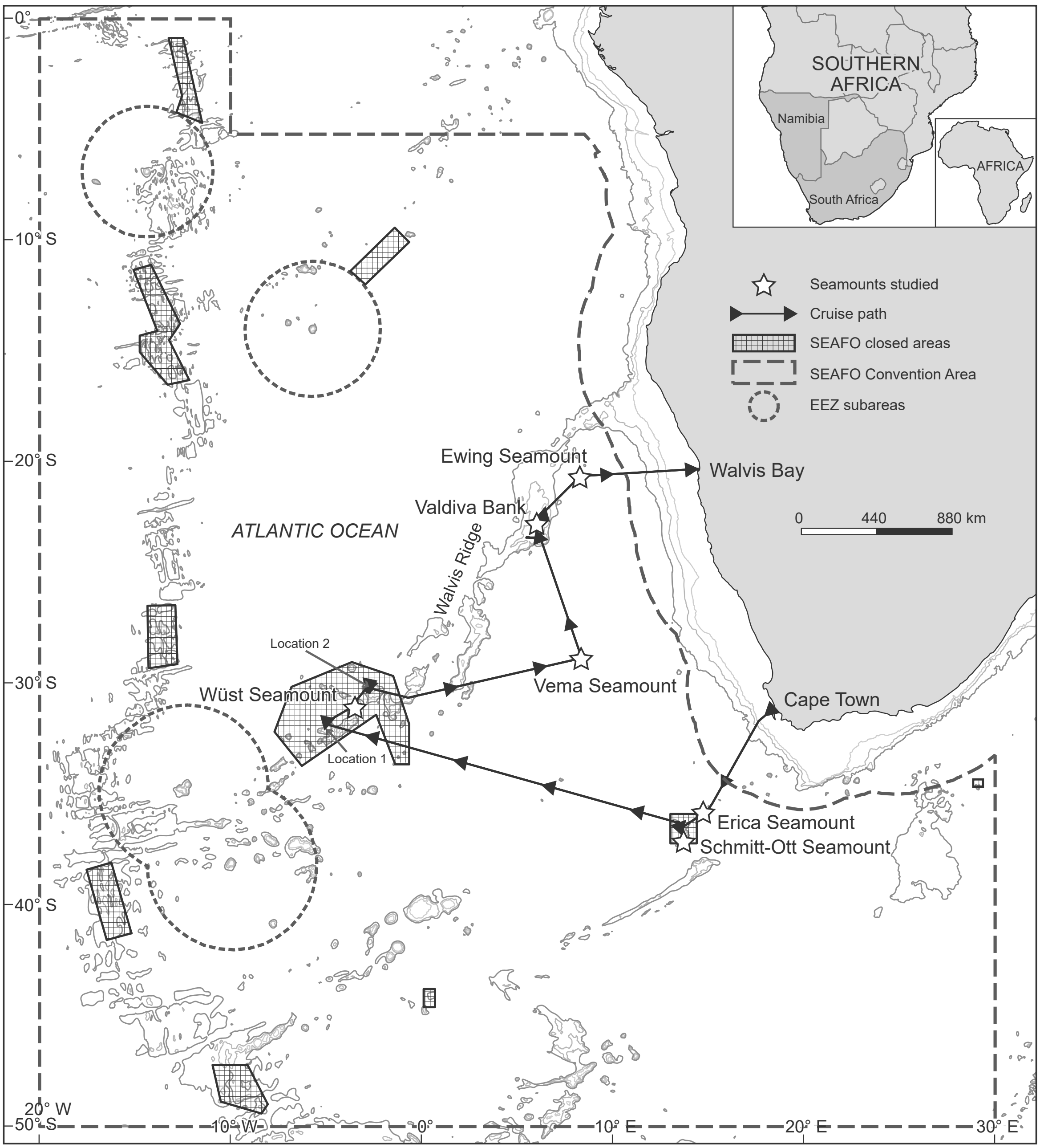

Figure 1: Track of the RV *Dr Fridtjof Nansen* off southern Africa during the 2015 study of seamounts in the SEAFO Convention Area. Encircled subareas inside the Convention Area are exclusive economic zones (EEZs) of UK Overseas Territories. All elements are superimposed on bathymetry obtained from the General Bathymetric Chart of the Oceans (GEBCO)

http://www.ideo-namibia.ieo.es), and detailed maps were generated for the Valdivia and Ewing seamounts on the Walvis Ridge. The results from the latter study were at a level of resolution much more useful for local and regional assessments and management.

Almost all fishing managed by SEAFO is associated with seamounts and seamount complexes, and the availability of good and relatively detailed knowledge of bathymetry is important because the organisation requires assessments of the distribution and spatial scale of actual and potential fishing areas within the Convention Area. The deepest recorded fishery in the SEAFO CA (the longline fishery for Patagonian toothfish) extends to approximately 2 500 m, but most of the fishing effort targets resources inhabiting the shallowest seamount summits and slopes, at depths of <1 000 m. Since 2006, SEAFO has implemented and refined a conservation measure specifying subareas that are closed to all fishing activity in order to protect vulnerable marine ecosystems (VMEs, *sensu* FAO 2009). In the absence of good data on the distribution of VMEs, fishing closures are based on best-available bathymetry data and comprise seamounts within the depth range of current fisheries deemed likely to have VMEs. The map of areas shallower than 2 000 m generated from GEBCO data was the primary basis of the selection, and more-detailed data on geomorphology and bathymetry would benefit further assessments of the appropriateness of current closures.

This investigation, initiated in 2014, included a 29-day research cruise on the RV *Dr Fridtjof Nansen* conducted in January–February 2015 (Figure 1). In addition to biological studies (Bergstad et al. 2019 [this issue], https://doi.org/10.2989/1814232X.2019.1571439), the effort comprised bathymetry mapping and visual substrate recording at the following five seamounts: Schmitt-Ott, Wüst (two summits), Vema, Valdivia (four locations), and Ewing (Figure 1). The vessel operated single- and multibeam echosounders to explore and map seamount summits in the depth range 0–1 500 m. Previous compilations of bathymetry data from global datasets provided a foundation, and here we present the local data generated in 2015 together with a wider regional analysis of bathymetry patterns for the entire SEAFO CA. The study also benefited from access to the Spanish–Namibian data collected in 2008–2009 (López Abellán and Holtzhausen 2011) and Norwegian data collected during a partial survey of Vema Seamount in 2008 (unpublished data curated by the Norwegian Marine Data Centre at the Institute of Marine Research [IMR], Norway). To analyse potential fishing areas, bathymetry data were combined with depth and location data from current and past fisheries records available in SEAFO observers' logbooks.

Materials and methods

Observations at sea in 2015

The RV *Dr Fridtjof Nansen* (since replaced by a new vessel of the same name) was a 57-m custom-designed research vessel used for fisheries research and oceanography. The vessel had a full complement of Simrad multibeam (EM710) and single-beam (EK60) echosounders, which were used in this SEAFO study to map bathymetry. Since the focus of the effort was on the main potential fishing areas, mapping was restricted to depths shallower than 1 500 m. Bathymetry data were stored continuously for further post-processing.

Raw data from the EM710 were imported to Fledermaus 7.4.1 (64-bit) for post-processing and generation of graphical output. Prior to production of bottom reliefs and maps, the raw input data were scrutinised, and obvious erroneous records were removed.

At each seamount, vertical hydrographic profiles were sampled with a Sea-Bird Electronics (SBE) conductivity–temperature–depth (CTD) profiler, to 1 000 m. Before running acoustic surveys on a new location, the sound–velocity data derived using the CTD data were used to adjust the sound–velocity profile settings of the echosounders.

The main vehicle for visual exploration of benthic habitats and substrates was a towed 'CAMPOD' video rig, consisting of a tripod frame with a centrally placed pan-tilt HD camera, two 400-W strobe lights, 10×10-cm laser pointers, and a backward-looking camera intended mainly to help monitor performance and avoid snagging. The vehicle was towed at 0.5–1.5 knots, preferably uphill, and kept at a preferred height of 1–2 m off the seabed by the winch operator, who constantly monitored the video stream. Uphill transects of lengths ranging from 0.5 to 0.9 nautical miles (0.9–1.7 km) were run along paths determined after bathymetry mapping had been conducted with the multibeam echosounder system. The maximum depth range of the CAMPOD rig is 2 000 m, but the operating range in this study was restricted to approximately 1 000 m. In total, 41 CAMPOD dives were completed on the five seamounts investigated. The full list of dives is provided in Table 1 of Bergstad et al. (2019, this issue). At a given location, most dives started at the base of summit slopes and ended at the summit or plateau (shallowest point). On conical seamounts, an effort was made to distribute the transects so as to approach the summit from the north, south, east and west. Additional dives were made within narrower depth ranges—for example, on summits and level plains—to investigate particular features. For each dive a continuous HD video record corresponding to the dive duration was generated.

To sample bottom habitats, a Van Veen grab was used at selected sites. Grabs were mainly deployed at sites first explored with the towed video system. In total, 60 grabs were deployed, but many were replicates in roughly the same position. Many grabs came up empty, presumably either because the grab hit hard ground or because stones lodged in the grab caused leakage of the sample. Only 11 of the grabs generated biological and/or substrate samples. All raw data, including echosounder data, video records and metadata, were deposited with SEAFO as the data owner, and the Institute of Marine Research (IMR), Norway, as data custodian. Access is regulated in accordance with the data policy of the Ecosystem Approach to Fisheries (EAF)–Nansen Project.

Data available from previous multibeam mapping

In March 2008, the Norwegian RV *G.O. Sars* visited the Vema Seamount and mapped the slopes with Simrad EM300 and EM1002 multibeam echosounders. The raw data from that effort were made available (IMR unpublished data) and post-processed together with the 2015 data gathered in the present study.

Also included were extensive bathymetry data collected in Spanish–Namibian investigations. Between 2008 and 2010, three multidisciplinary research cruises were conducted by the Instituto Español de Oceanografía (IEO) on board the RV *Vizconde de Eza* on the Walvis Ridge, specifically on Ewing Seamount and Valdivia Bank and associated seamounts, where a total of 1 381 km^2 on Ewing Seamount and 14 442 km^2 on Valdivia Bank were surveyed using a Simrad EM300 multibeam echosounder (López Abellán and Holtzhausen 2011).

Analyses using global bathymetries

The general bathymetric data used for this analysis are contained in the General Bathymetric Chart of the Oceans (GEBCO) dataset, available from http://www.gebco.net. In particular, the GEBCO global 30 arc-second interval grid bathymetric data were used to plot bottom depth for the areas beyond national jurisdiction (i.e. the SEAFO CA). All geodetic datums used for area and length calculations were projected to the UTM Zone 32S conformal projection.

SEAFO fishing areas

Logbook data from fishing vessels deposited in the SEAFO logbook database for 2003–2016 were available and were used to derive spatially resolved fishing-activity records for individual trawl tows and sets of longlines and pots. Vessels fishing in the SEAFO CA are required to have a scientific observer on board (see SEAFO System, available at www.seafo.org). The observer data collected include information on set-by-set/tow-by-tow depth, and start and end locations. The SEAFO observer database contains complete information on 1 625 longline sets (LLS), 797 pot sets (FPO), and 301 bottom otter trawls (OTB). The database also includes 42 hauls identified as midwater otter trawls (OTM); however, the OTMs were omitted from this analysis, which focused on depth distributions of bottom fishing. Actual fishing areas were mapped on the high-resolution bathymetries compiled, based on sources given above. In order to derive depths for individual records of different fishery target species, tow-by-tow or set by-set data were assigned depths using the high-resolution bathymetry. The depth distribution analyses also included catch records of the same species from this survey and the previous Spanish–Namibian research surveys (see above).

Results

Observations of bathymetry and substrates at selected seamounts

The track of the RV *Dr Fridtjof Nansen* voyage from Cape Town, South Africa, to Walvis Bay, Namibia, over the period 15 January to 12 February 2015 is shown in Figure 1. Detailed vessel tracks from each of the locations studied are provided here and in the official cruise report (FAO 2016).

Erica and Schmitt-Ott seamounts

The Erica and Schmitt-Ott seamounts are neighbouring features located southwest of Cape Town, South Africa, and both are surrounded by abyssal depths (3 000–5 000 m). Erica was not studied in any detail, but en route to Schmitt-Ott the vessel passed across the summit to determine the summit depth. The shallowest point observed was ~770 m and was surrounded by a wider area of 800–850 m depth.

For Schmitt-Ott, Figure 2 shows the relief map and selected depth profiles generated. The seamount is elongated in the southeast to northwest direction, with a distinctive summit and a shallowest point of 923 m at the northwestern end. There are, however, deeper knolls in other locations of the surveyed area, as also shown in the depth profile running southeast to northwest across the summit. The indication from the echosounders' 'hardness index' is that the seamount had little sediment, particularly along the shallowest ridge leading up to the summit. The main, single summit is located at 38°41.662′ S, 13°24.618′ E.

Two upslope CAMPOD dives were made on the shallowest summits (Figure 3). The substrate was bare basaltic rock (Figure 4) and the plains had variable but apparently limited cover of unconsolidated biogenic sediment. A prominent feature was coral rubble, occurring at all depths across wide areas (Figure 4). On Dive 2 the sediment cover appeared especially thin, and extensive areas of bare rock were observed, including mushroom-shaped basaltic structures (Figure 4).

Wüst Seamount complex

The very extensive Wüst Seamount complex lies on the Walvis Ridge. The two presumed shallowest summits were selected for this study, Locations 1 and 2 (Figures 1, 5 and 7). Plateau depths of the summits of Wüst Locations 1 and 2 were approximately 1 000 m and 600 m, respectively.

Figure 5 shows the bathymetry results from Wüst Location 1 (34°30.134′ S, 5°01.867′ W). The central, almost circular, flat summit with a diameter of 4.6 km has a depth of 1 050 m. On the western edge of the plain, a group of shallower rugged knolls occur, and summit depths of these are ~950 m. Two CAMPOD dives (Figure 5) were carried out up the slope from the main plateau towards the summits of two of the adjacent knolls. At the start of the dives on the near-level plateau the substrate was fine white sand with ripples (Figure 6). The ripples, occurring well below wave-base depths, appeared to be symmetrical, and bifurcating ripple-crests were also observed. The sedimentary layer was superficial on hard rock. On the slopes of the knolls the same sediments were found but often only as a thin, uneven cover on top of basaltic rock. In the troughs of the sand ripples and in depressions on the slope, coarser particles were observed (Figure 6), probably primarily pteropod shells.

Wüst Location 2 (32°57.753′ S, 2°43.390′ W) is rather flat-topped with a few plateau knolls peaking at 550–600 m (Figure 7). At the plateau depth of 650 m, the summit is roughly ellipsoidal, measuring 27.8 × 18.5 km. In the depth profile shown in Figure 7, there are indications of marginal shallower features that may reflect ridges along the outer perimeter of the plateau. Location 2 was too large to map completely within the time available. In total, five CAMPOD dives were made. Three dives were upslope transects starting on the slope at 708–890 m and approaching the main plateau from the southwest, west and north, respectively, reaching plateau depths of ~600 m. The remaining two dives were transects up the slopes of two central summit knolls, the shallowest points of the seamount. Sandy and

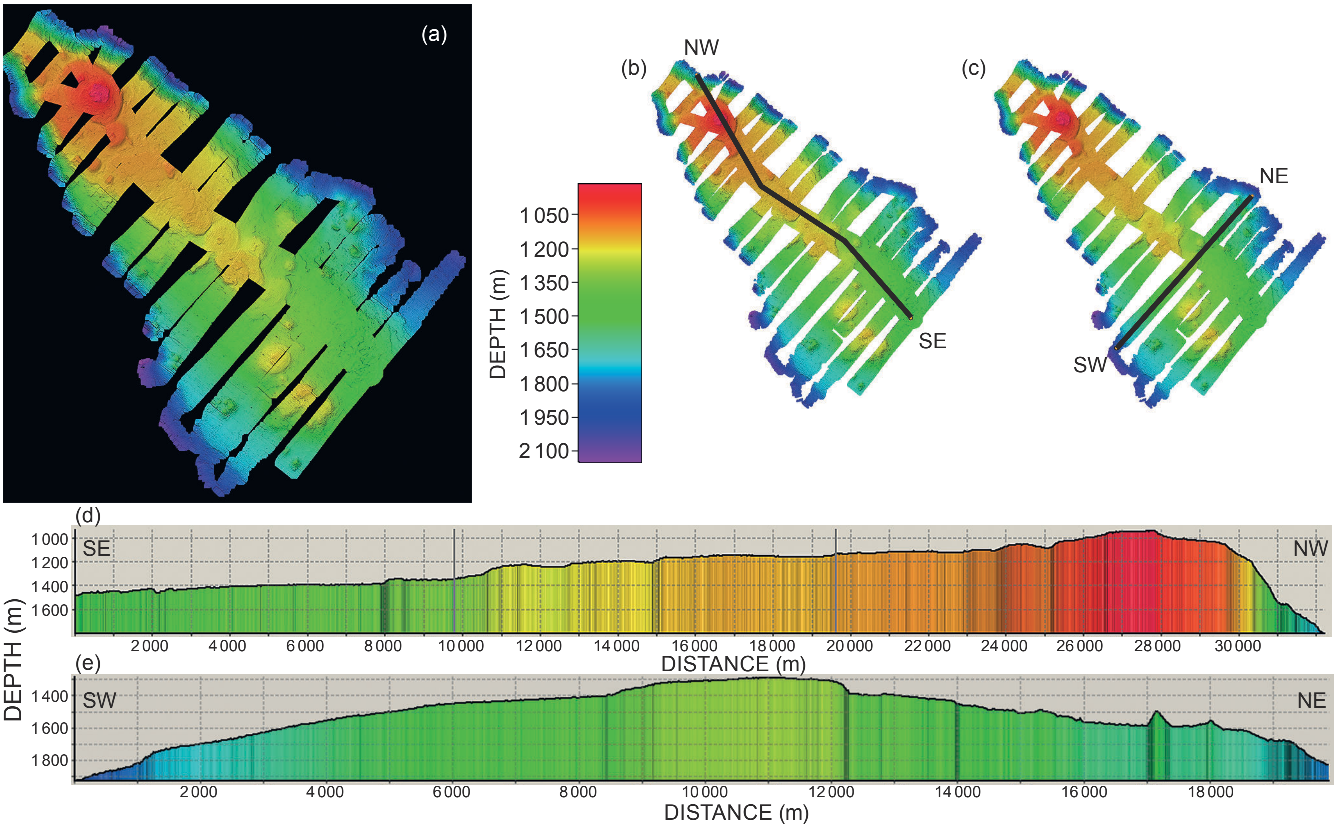

Figure 2: (a) Relief of Schmitt-Ott Seamount and (d, e) two depth profiles across the seamount, corresponding to the tracks shown as black lines in (b, c), respectively. Observations are from the multibeam echosounder survey by the RV *Dr Fridtjof Nansen* in January 2015

gravelly sediment on the lower western slope, at depths of 775–755 m, formed large, sharply crested dunes, rippled in some areas. Further up the slope, hard substrate occurred and appeared as a mixture of consolidated coral framework (sheets, broken-up fragments) and coral rubble (Figure 8).

The two knoll dives were used to explore the shallowest areas of Wüst Location 2, and the transect depths ranged from approximately 620 to 550 m. At the base the substrate consisted of hard patches (provisionally regarded as relict coral framework) and large flats of coral rubble (i.e. unconsolidated dead scleractinian coral). The terrain became very rugged in shallower parts. Three grabs were operated on the plateau and upper slope, at depths of 700, 630 and 560 m. These grabs produced a range of samples, including coral rubble identified as dead *Enallopsammia rostrata* (observations further documented in Bergstad et al. 2019, this issue).

Vema Seamount

In contrast to the Wüst seamounts on the Walvis Ridge, Vema Seamount lies isolated in the middle of a deep abyssal plain at 31°38′ S, 08°20′ E. It is a conical feature rising from the abyssal plain. The multibeam echosounder mapping by the RV *Dr Fridtjof Nansen* complemented mapping that was conducted in 2008 by the RV *G.O. Sars* (IMR unpublished data). The seamount summit, now fully mapped (Figures 9 and 10), was determined to be rather flat with depths less than 100 m. The relief map (Figure 9) illustrates the subareas shallower than 150 m and shows several summit hills, with the shallowest estimated to be at a depth of 21.5 m. The flat summit is ~11 km across in the E–W direction, and 8.5 km across in the N–S direction. Figure 10 shows the currently observed bathymetry of the seamount from different angles. Observations by video and acoustics suggested mostly hard substrate across the summit and on the upper slopes.

Seven CAMPOD dives were made on Vema (Figure 9). Four marginal dives were upslope transects approaching the summit from different directions, and the remainder were comparatively short transects on the summit plateau and on summit knolls. Since Vema is shallow, the slope transects starting at 708–935 m spanned a wider depth range than dives in the other locations described thus far.

At the deeper end of all the slope transects, the substrate was white to yellow sand and gravel, but in many cases covered with coarse near-spherical pebbles with diameters of 5 cm or less (Figure 11). These pebbles were patchily distributed near rocky outcrops that appeared as consolidated coral framework (Figure 11c) and were most probably coralline-algal oncolites that had originally grown in shallower water within the photic zone, as earlier observed by Simpson and Heydorn (1965). On the western slope, coral framework was the dominant habitat on the

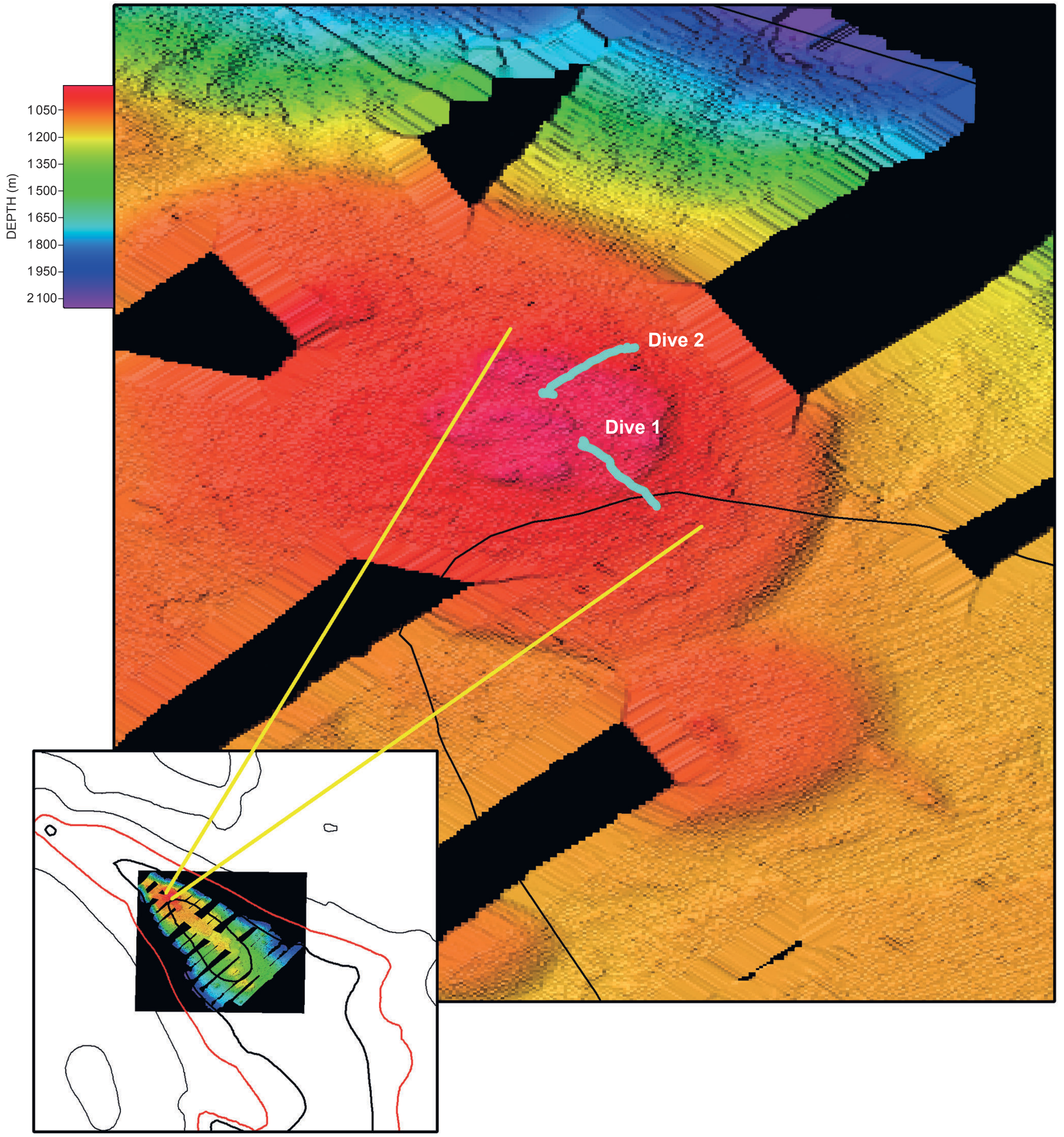

Figure 3: Relief of the summit of Schmitt-Ott Seamount, showing the tracks of the two upslope dives with the CAMPOD towed video vehicle (turquoise lines). Observations are from the RV *Dr Fridtjof Nansen* survey in January 2015

upper slope, whereas on the other slopes exposed black bedrock, likely basalt (Simpson and Heydorn 1965), was also present. At the summit of the plateau the substrate was rocky outcrops and sandy and gravelly plains, the latter also with coralline algae (Figure 11), as recorded in early explorations, for example by Mallory (1966). The knolls were rugged and rocky, with intervening plains covered in coralline algae, sometimes overgrown with green and/or brown macroalgae, in places forming kelp forests.

Valdivia Seamount

The Valdivia Seamount complex lies on the northeastern part of the Walvis Ridge. Four widely spaced subareas, including the shallowest summits, were visited (Figure 12). The extensive Spanish–Namibian exploration of the same area in 2007 and 2010 on the RV *Vizconde de Eza* generated multibeam acoustics data that were available to SEAFO and the *Dr Fridtjof Nansen* cruise. Only supplementary bathymetry data were collected in 2015.

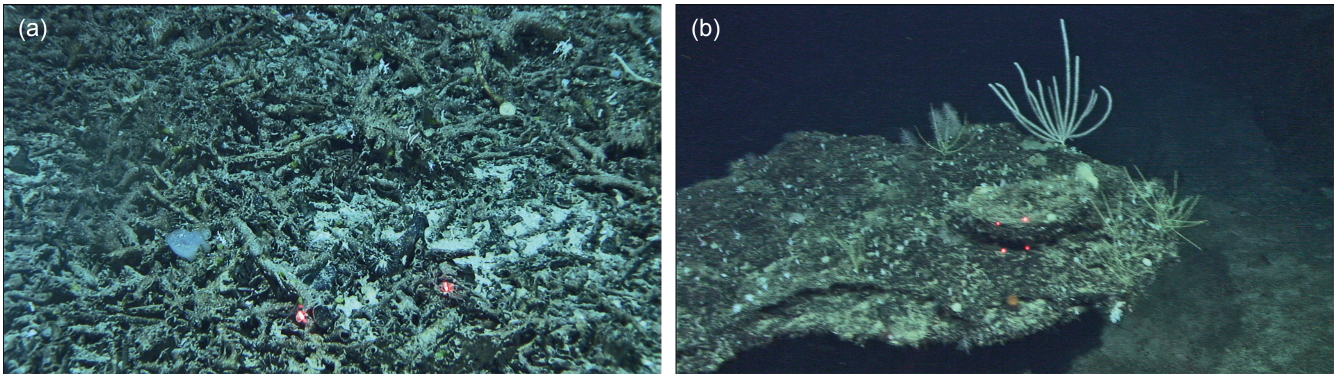

Figure 4: Summit of Schmitt-Ott Seamount, showing (a) scleractinian coral rubble and (b) a mushroom-shaped basaltic outcrop. Images are frame grabs from the CAMPOD towed video vehicle on the RV *Dr Fridtjof Nansen* in January 2015. Red dots from laser pointers indicate a 10-cm distance or 10×10-cm square

The subarea denoted Valdivia Central (Figures 12 and 13) comprises the prominent, nearly flat Valdivia Bank, with a plateau depth of 227–235 m, surrounded by complex areas of small knolls and extensive deep, flat areas (to the northwest). The elongate Valdivia Bank plateau is about 46.3 km long and 5.8 km wide. Valdivia West (Figure 12) is smaller and more complex, and the shallower hills are ~470 m deep. Valdivia Middle and North (Figures 12 and 14) are elongate in the north–south direction, with single, more-or-less circular summits in the north and south. Both have adjacent, broad plains ~1 000 m deep.

Valdivia Central was explored with seven CAMPOD dives up the slope of the flat bank (Figure 13) and on smaller and deeper knolls to the southeast and southwest of the bank. The slope dives started on adjacent sedimentary flats, at 800–900 m on the northern side and 550 m on the southeast side of the bank, and ended at the top of the bank, at 230–240 m deep. At the base the sediment was rippled sand and coral rubble (Figure 16c, d). Up the steep slopes and on the flat plateau the substrate was bare rock (Figure 16a, b), likely consolidated coral framework. The dives on the deeper knolls to the south of Valdivia Bank revealed a rather different habitat. On all the lower slopes of the knolls, coral rubble (i.e. dead scleractinian fragments) was common. Up the slopes the density of live corals of several taxa increased, and particularly in two knoll dives south of Valdivia Bank, the abundance was so high that the entire substrate was covered in live corals (for details, see Bergstad et al. 2019, this issue).

Three CAMPOD dives were made in the subarea denoted Valdivia West (Figure 15a). All were upslope dives, but only one reached as far as the shallowest summit, at 460 m. The substrate patterns were similar to those observed on the Valdivia Bank slope dives, with soft sediments at the base of the hills, increasing coral rubble on the slopes, and exposed coral framework/bedrock towards the summit.

Valdivia Middle (Figures 12 and 14a) is elongate in the north–south direction, with the shallowest subarea at the northern end (Figure 14a). The northerly shallow area has several knolls, of which the shallower is ~415 m. To the west of the elongate shallowest area, there is a large plain with a plateau depth of 875–880 m. Five CAMPOD

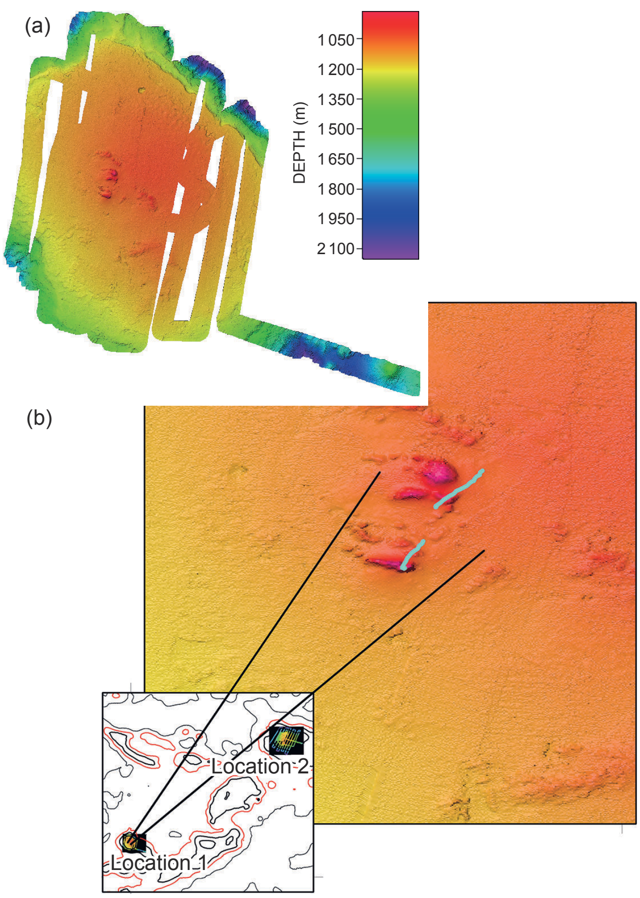

Figure 5: Results of multibeam echosounder mapping of Wüst Seamount Location 1, on the Walvis Ridge in the Southeast Atlantic. (a) Overview relief of entire summit, and (b) detail of the summit knolls showing the tracks of the CAMPOD dives (turquoise lines). Inset shows the position of the two separate locations on Wüst, observed by the RV *Dr Fridtjof Nansen* in January 2015

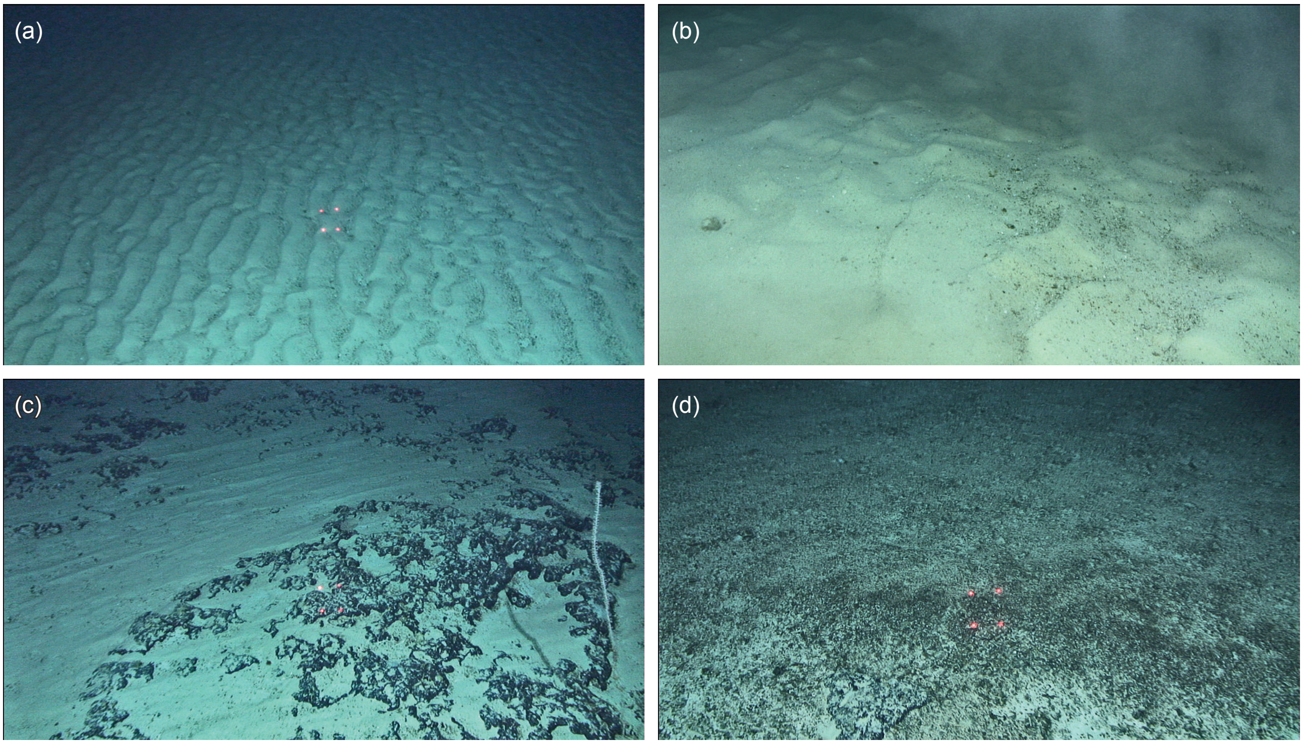

Figure 6: Substrates of Wüst Seamount, Location 1: (a, b) rippled sandy sediment, and (c) biogenic sand on (possibly basaltic) bedrock; (d) coarse sediment dominated probably by pteropod shells. Images are frame grabs obtained with the CAMPOD towed video vehicle on the RV *Dr Fridtjof Nansen* in January 2015. Red dots from laser pointers indicate a 10×10-cm square

dives were made on the shallower part of the seamount (Figure 15b), and one dive on the adjacent flat plateau, at 865 m. The plateau was sandy. The slope dives revealed sandy bases of the hills and hard substrates on the slopes, including much coral rubble and broken-up coral framework. The shallowest summit substrate was bare rock.

In Valdivia North (Figures 12 and 14b) the circular summit, with a diameter of ~4.7 km, lies to the southeast of a wide shallow area (Figure 14b). The shallowest knoll is at ~550 m. On the summit, three CAMPOD dives were carried out, of which two were upslope dives which revealed hard ground (Figure 15c). The third was a summit dive, within a narrower depth range than the slope dives. In addition, one dive was located in the flat deep area to the west of the circular summit, at ~890 m, and this plain had sandy sediment.

Ewing Seamount

Ewing Seamount lies on the northeastern section of the Walvis Ridge, at 23°14.7′ S, 08°16.0′ E (Figure 1). It has an irregular shape (Figure 17), and from the southeastern summit area there is a rather wide and elongate deep plateau running northwestward. This plateau is relatively deep (~1 000 m), and the shallower summit (780 m) is in the southeast. The reliefs shown in Figure 17 illustrate the shape and size of the summit area, including a depth profile across the summit and onto the northwestern plain. The deeper summit (<800 m) is ~2.3 km across.

Four CAMPOD dives (Figure 17) were made from different directions up the slope of the shallower parts of the seamount, from about 900–925 m, and a further one on the plain to the northwest. The latter dive confirmed that the plain is a flat sandy area. The base of the summits and lower slopes had rippled sandy sediment, but the sediment layer appeared thin and underlying rock was often exposed. On the summit slopes coral framework and dead scleractinian coral and rubble formed the dominant substrate. In some parts towards the summit, the terrain was very rugged.

Bathymetry based on data from GEBCO compared with the observations

Figure 18 compares data on summit plateau depths extracted from GEBCO with summit depths recorded with echosounders in the 2015 study by the RV *Dr Fridtjof Nansen*. In addition to the summits described in some detail above, another two summits on Wüst, plus the Erica Seamount, were included in the comparison. Those three summits were not fully mapped but the summit soundings were obtained during passage en route to other locations. For several of the selected seamounts there was a rather significant discrepancy in summit depths between GEBCO and the multibeam echosounder data. For five of seven summits the observed depths were several hundred metres greater than the summit depth extracted from GEBCO (mean depth difference: 579 m; range: 230–850 m). Even if small knolls protruding from the plateaus are taken into account, these discrepancies between GEBCO and the echosounder observations remain.

Only for Erica and Ewing seamounts was the case the opposite, as the discrepancy for those summits was not

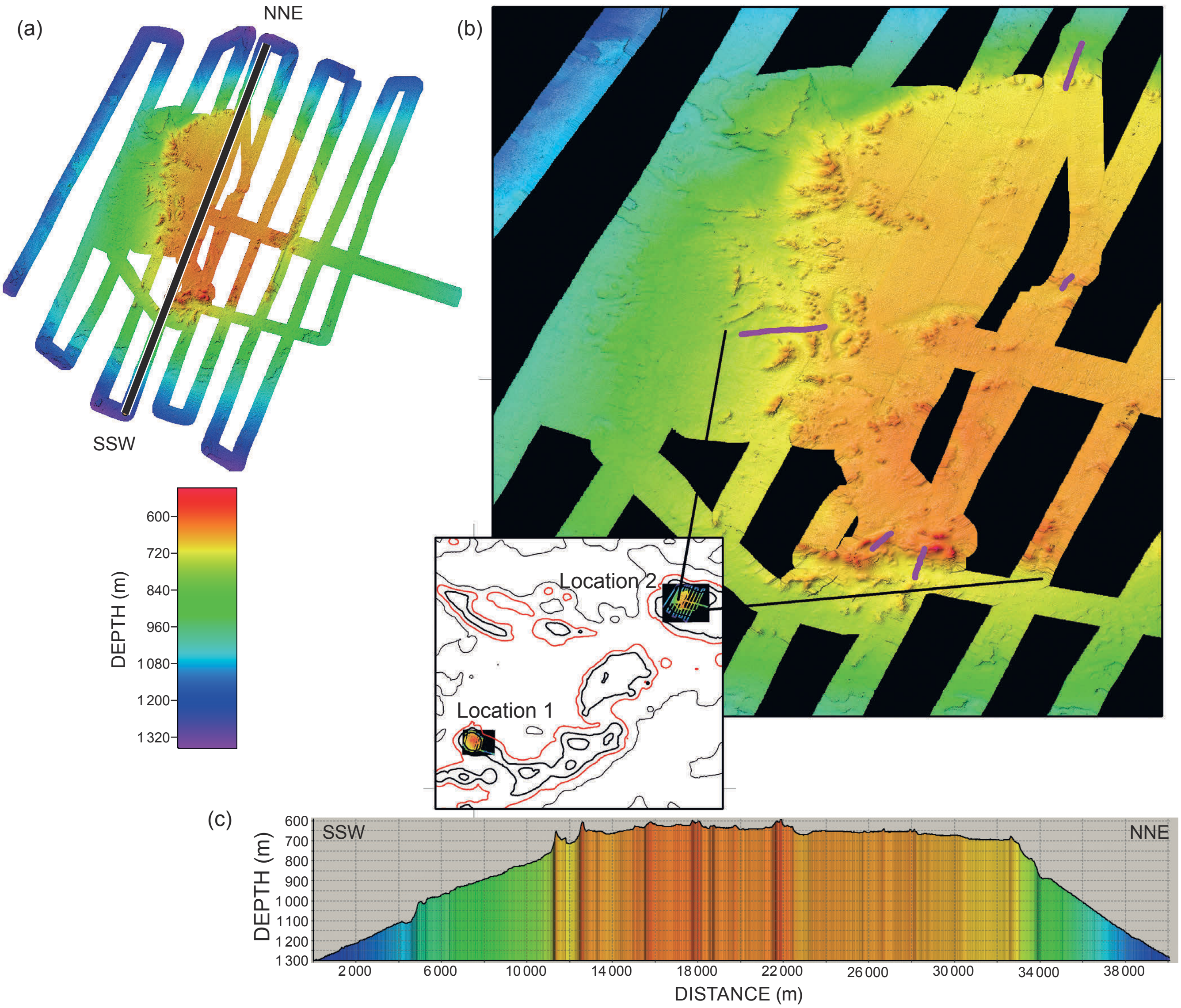

Figure 7: Results of multibeam echosounder mapping of Wüst Seamount, Location 2, on Walvis Ridge in the Southeast Atlantic. (a) Overview relief of the summit area; (b) detail of the summit area showing the five CAMPOD dive transects (purple lines); (c) depth profile across the seamount from SSW–NNE, along the track shown as a black line in (a). Inset shows the relative positions of Wüst Locations 1 and 2

very substantial (Figure 16). Valdivia was not included in these comparisons because previous multibeam mapping efforts had been extensive in that subarea.

Potential and actual fishing areas

A large proportion of the SEAFO CA of 15 546 309 km^2 (Figure 1) is considered to be non-conducive to fishing because many areas are too deep for normal fishing operations. Based on the GEBCO dataset, approximately 96.85% of the SEAFO CA is deeper than 2 499 m (Figure 19). The limited, comparatively shallow areas comprise numerous seamounts and seamount chains, guyots, banks and plateaus.

Figures 20 and 21 show records of the geographical distributions of the pot and trawl fisheries, respectively, obtained from the SEAFO observer database for the period 2003–2016. Accounts of the fisheries and evaluations of the development and state of the resources are available in the reports of the Scientific Committee of SEAFO (www.seafo.org/Science). The fisheries activity that is mapped here targets deep-sea red crab *Chaceon erytheiae* using pots, and trawl fisheries for fish species normally associated with seamounts. The trawl fisheries target pelagic armourhead *Pseudopentaceros richardsoni*, alfonsino *Beryx splendens*, and orange roughy *Hoplostethus atlanticus*, but they also take small catches of blackbelly rosefish *Helicolenus dactylopterus* and Oreosomatidae. Both the pot and trawl fisheries are essentially restricted to the Valdivia area (Figure 20). The exception is past trawl fishing for orange roughy on Ewing Seamount (Figure 21). After 2005, this fishery ceased and no landings were recorded as SEAFO banned targeted fishing in the traditional fishing area and only maintained a

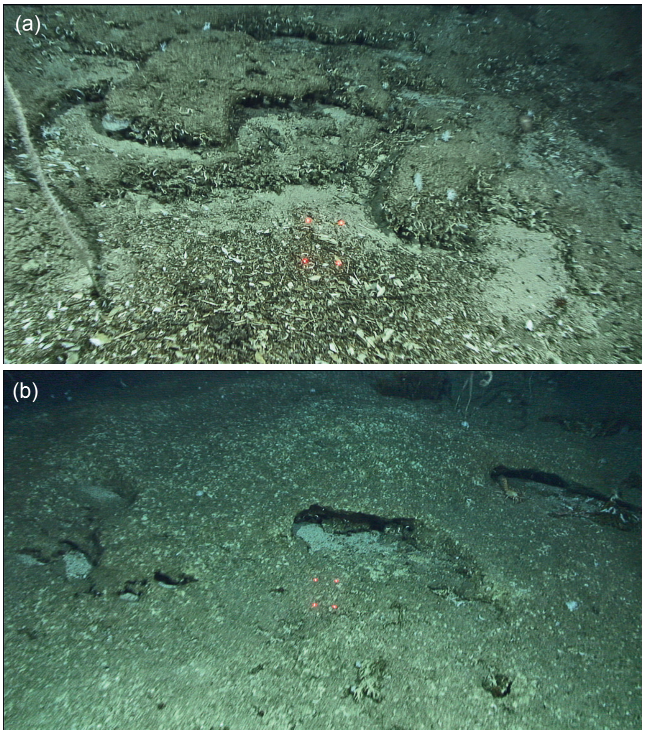

Figure 8: Substrates on the summit of Wüst Seamount, Location 2: (a) coral rubble and relict coral framework, and (b) rock provisionally classified as carbonate deposits. Images are frame grabs obtained with the CAMPOD towed video vehicle on the RV *Dr Fridtjof Nansen* in January 2015. Red dots from laser pointers indicate a 10×10-cm square

small total allowable catch (TAC) in the remainder of the Convention Area. In 2016 there was neither pot nor trawl fishing for any of the species, and hence no landings. The last year with significant trawl fishing was in 2013, when the landings had declined to a very low level after two years of unprecedented landings.

In addition to the Valdivia and Ewing fisheries, there is a longline fishery for Patagonian toothfish *Dissostichus eleginoides*. That fishery is restricted to southern seamounts in the Discovery and Meteor complexes, which are to the south of the present study area, and is thus not considered relevant here.

The pot-fishing area is rather extensive both in terms of depth range and spatial distribution (Figures 20 and 22), with pots being distributed in the entire Valdivia area, primarily within the depth range 900–1 100 m (mean depth 945 m). This depth range corresponds to the depths of sedimentary plains adjacent to the shallower, rugged summits and knolls at Valdivia. Trawl fishing was conducted in much shallower areas, and the concentration at ~250 m deep (Figure 22) and the map of the trawl tracks reflect the targeting of Valdivia Bank. Trawl fishing was geographically very restricted to that single feature, with few tows on other summits (Figure 20). Pot fishing and trawl fishing occurred in the same seamount complex but apparently without significant spatial overlap.

Discussion

There are hundreds of seamounts and guyots in the Southeast Atlantic high-seas area, and the sites mapped

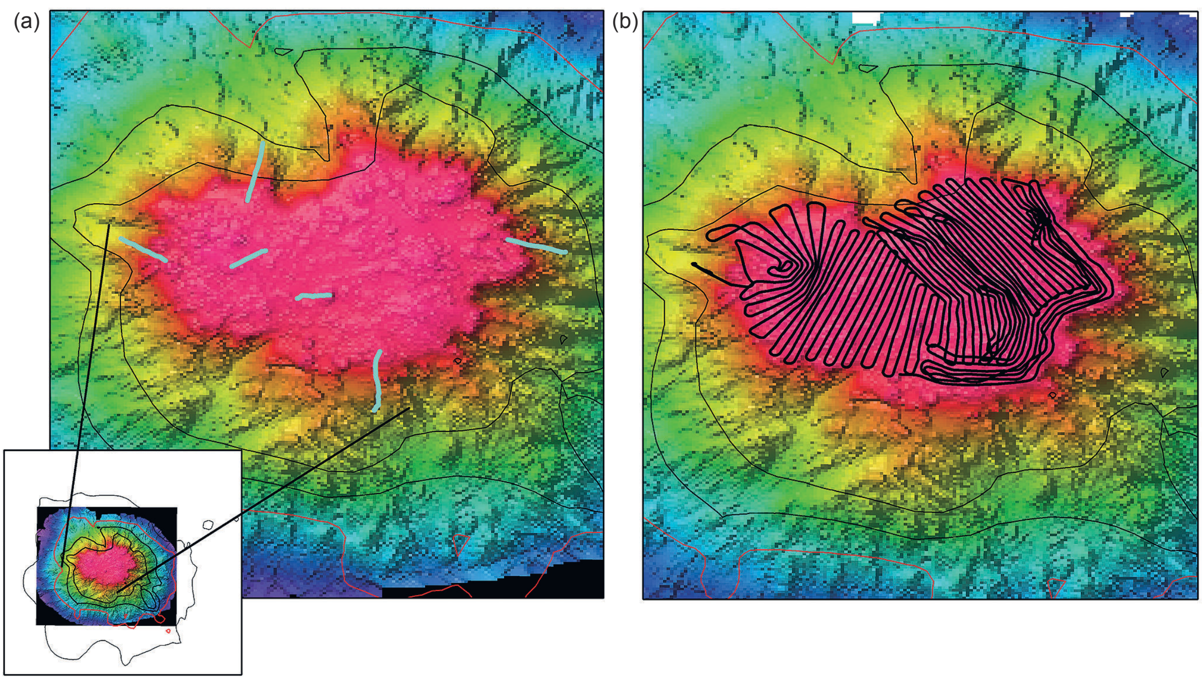

Figure 9: (a) Relief of the summit of Vema Seamount, from the multibeam echosounder survey by the RV *Dr Fridtjof Nansen* in January 2015, showing locations of the CAMPOD dives (turquoise lines), and (b) tracks of the survey; seven CAMPOD dives were conducted but one was interrupted and is not included in the diagram. The surrounding black and red lines on the slopes of the seamount denote survey lines of the RV *G.O. Sars* from 2008. Coloured depth scale is as in Figure 10

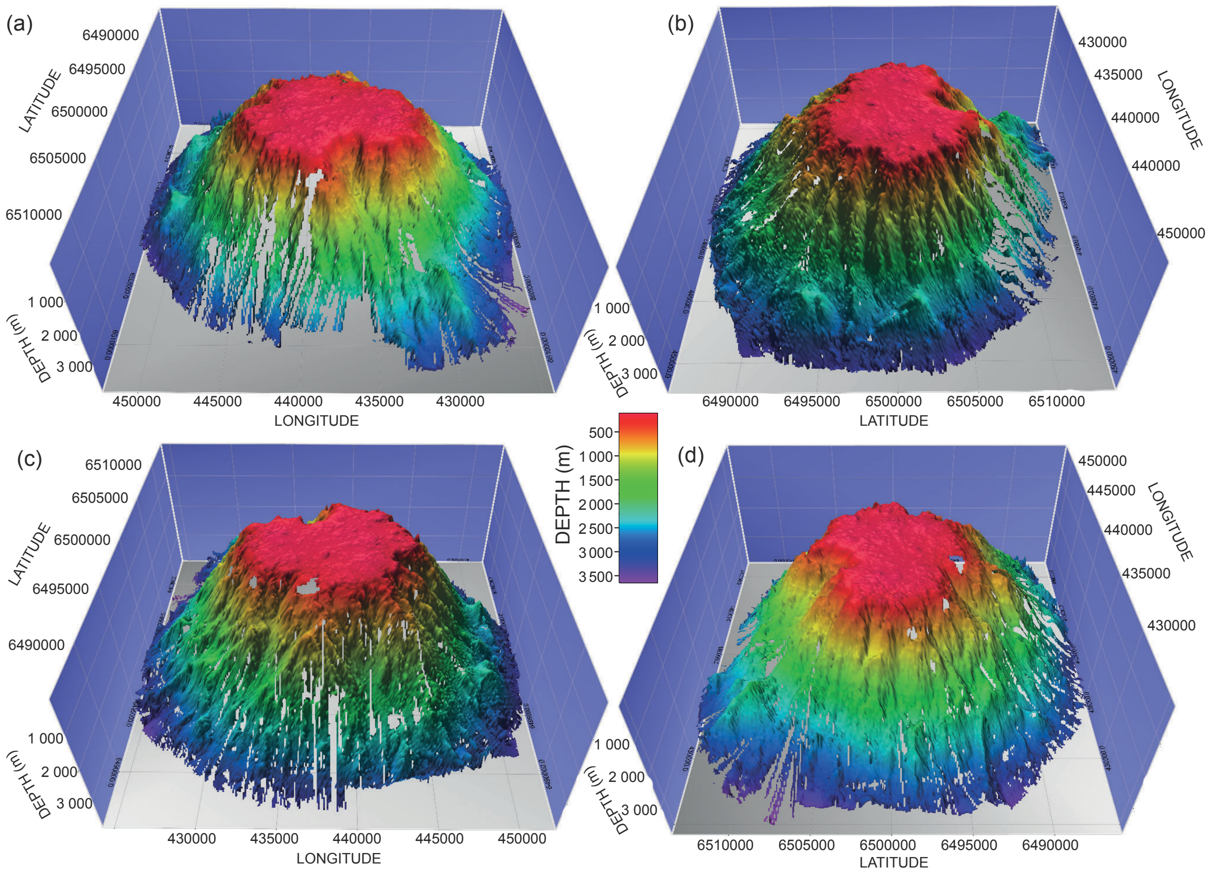

Figure 10: Relief of Vema Seamount, viewed from (a) north, (b) east, (c) south, and (d) west. Combined data from multibeam mapping conducted by the RV *G.O. Sars* in 2008 (Institute of Marine Research [Norway] unpublished data) and the RV *Dr Fridtjof Nansen* in 2015. The coordinates on the axes are UTM coordinates

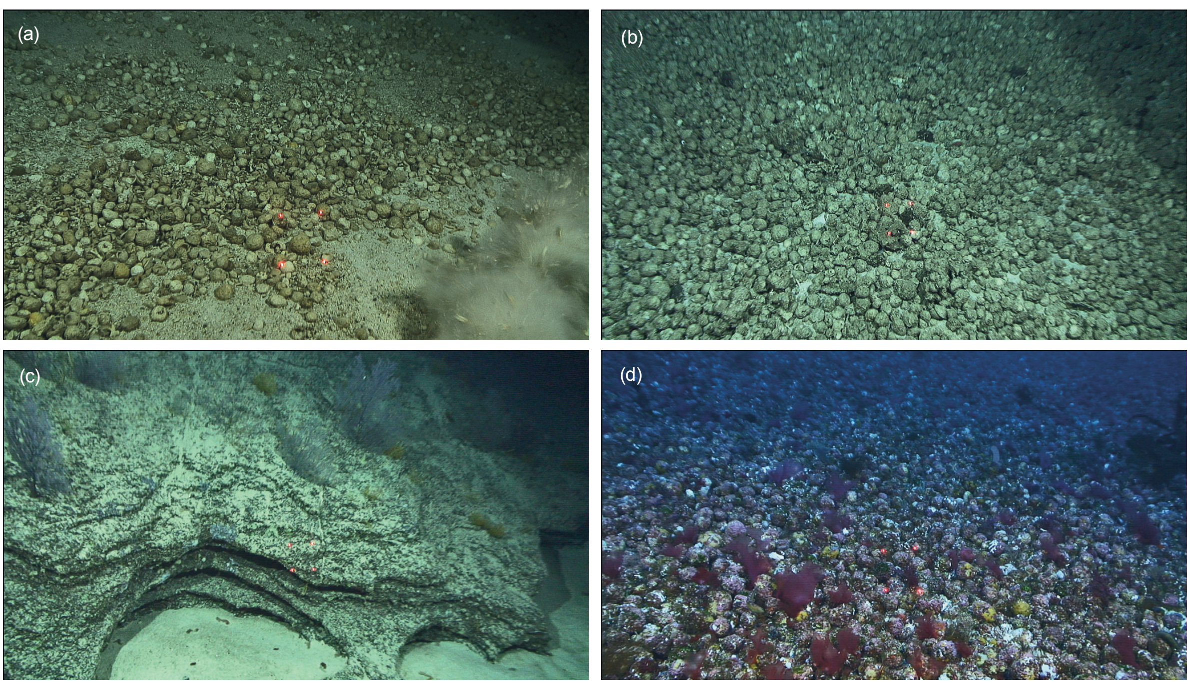

Figure 11: Substrates on the upper slope (a, b, c) and the summit (d) of Vema Seamount. Images are frame grabs obtained with the CAMPOD towed video vehicle on the RV *Dr Fridtjof Nansen* in January 2015. Red dots from laser pointers indicate a 10×10-cm square

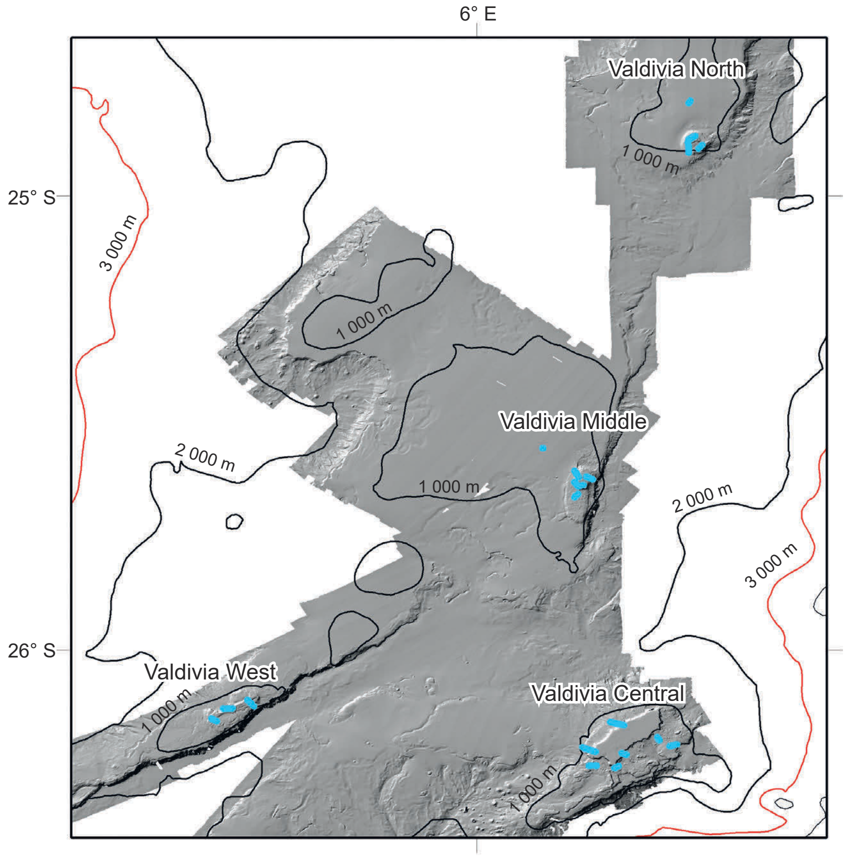

Figure 12: Relief of the Valdivia Seamount complex, on the Walvis Ridge in the Southeast Atlantic, noting the four summits sampled by the RV *Dr Fridtjof Nansen* in January–February 2015. Locations of dives made with the CAMPOD towed video vehicle on the shallower summits are shown in blue. The relief (grey area) is based on bathymetry data gathered by Spanish–Namibian cruises (López Abellán and Holtzhausen 2011) and in this study

in 2015 represent but a small subset, even of the summits expected to be shallower than 2 500 m. As expected, the study revealed considerable geomorphological variation among study sites, from single-summit conical features, such as Vema Seamount, to multiple summit features with large adjacent plains. Major subareas not surveyed were the Discovery and Meteor complexes in the south, and these are the primary seamounts targeted by the longliners fishing for Patagonian toothfish.

The study provided mainly two datasets: echosounder data and visual data from the CAMPOD vehicle. Unfortunately, the technology for collecting rock samples to verify the identity and age of the rocks observed visually was not available. References to rock identities are somewhat uncertain and are based on past descriptions from the region (e.g. Simpson and Heydorn 1965; Dingle and Simpson 2013; Perez et al. 2018) or on their appearance in images.

Approximate ages of seamounts of the Walvis Ridge range between 40 and 60 million years (https://earthref.org/ERESE/projects/MV1203/dredges.htm, accessed 15 December 2016). Summits of the seamounts may be younger; for example, Simpson and Heydorn (1965) dated the shallowest knoll on Vema to be 11 million years. The morphological patterns observed conform with general theory on formation of off-ridge seamounts, as was described by Wessel (2007). The provisional conclusion that many of the seamount summits and slopes explored also had widespread carbonate presence, in the form of consolidated carbonate rock, coral framework and fossil coral rubble, also conforms with descriptions from similar features elsewhere, such as the Emperor seamount chain in the Pacific Ocean (US Geological Survey 1978). The light rock that was observed, for example on the Vema slopes (Figure 11) and Valdivia Bank (Figure 16), appears very similar to the carbonates observed and verified on Rio Grande Rise in the SW Atlantic (Perez et al. 2018). The presumed coral fringe or cap was particularly well developed at Vema, Valdivia, and Wüst Location 2, and the flat-topped Valdivia Bank appeared as a very prominent guyot.

A summary of the substrate habitat observations across the entire area investigated is provided in Table 1. All the Southeast Atlantic seamounts visited in 2015 had coral rubble, including the southernmost site of Schmitt-Ott, where the density of live scleractinians was very low and where gorgonian corals are presently the prominent coral taxon (Bergstad et al. 2019, this issue). The widespread scleractinian coral rubble was weathered and relict (Figure 4), but no samples were collected for age

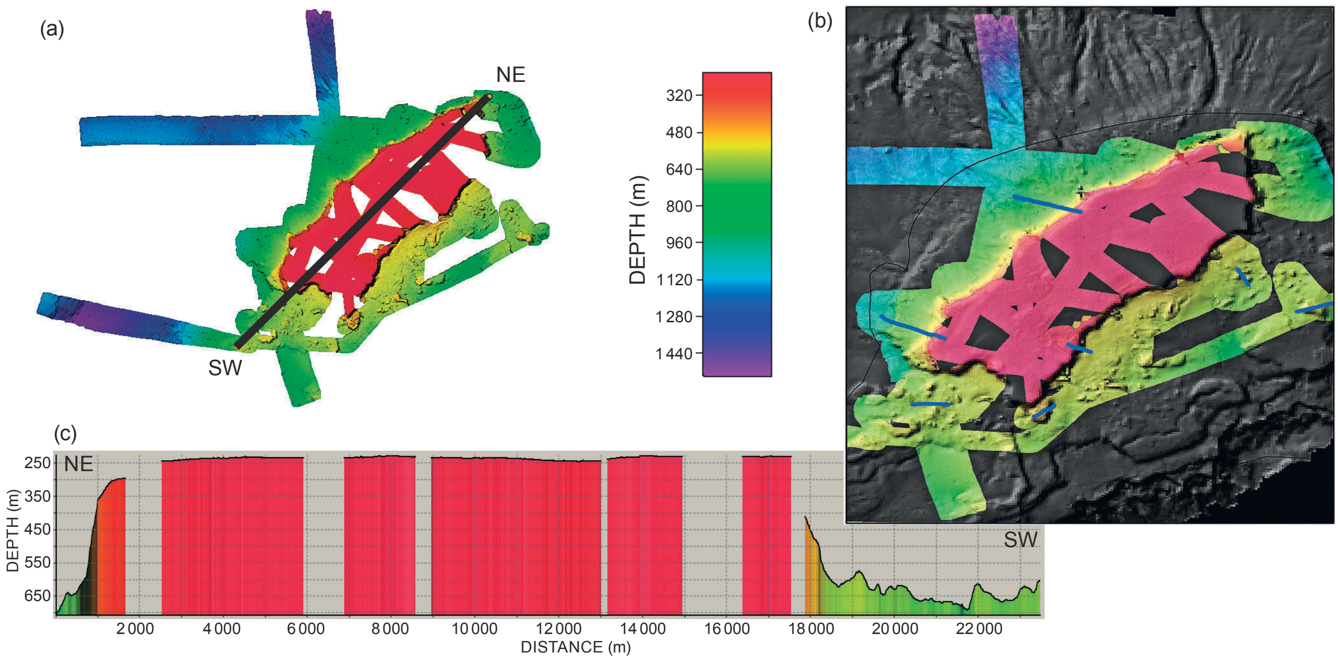

Figure 13: Valdivia Bank and adjacent knolls within the Valdivia Central subarea of the Valdivia Seamount complex on the Walvis Ridge in the Southeast Atlantic. (a) Relief mapped by the RV *Dr Fridtjof Nansen* in 2015, and (c) depth profile along a track from NE to SW, indicated as the black line in (a). (b) Diagram showing the entire bank as mapped by Spanish–Namibian surveys (grey area, López Abellán and Holtzhausen 2011) together with new data from the RV *Dr Fridtjof Nansen* (colour overlay); tracks of the CAMPOD dives are indicated as blue lines

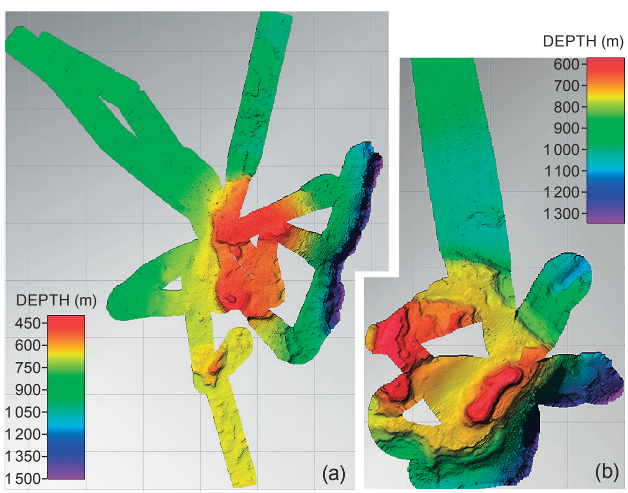

Figure 14: Reliefs of the subareas denoted (a) Valdivia Middle and (b) Valdivia North, features of the Valdivia Seamount complex (see Figure 12); results from multibeam echosounder mapping by the RV *Dr Fridtjof Nansen* in 2015. Note the difference in the depth scale between (a) and (b)

determination. While live colonies of stony corals were common in several of the study sites, the density was generally low and unlikely to be high enough to account for the extensive coral-rubble occurrence. The masses of rubble presumably reflect past mortality events in periods of unfavourable environmental conditions combined with long-term accumulation of persistent skeletons. Several of the summits visited are shallow (e.g. Vema and Valdivia Bank) and will have been strongly influenced by dropping sea levels during quaternary glaciations, affecting the morphology, substrates and biota of the summits and upper slopes.

While discrepancies between the summit depths derived from GEBCO data and those observed by echosounders were not unexpected, it was surprising that the differences were as much as several hundred meters at about half the sites studied, and essentially for all the least-known sites. This observation suggests that the GEBCO bathymetry overestimates the size (area) of summits and underestimates the summit depth. Jacobs and Bett (2010) found that, compared with more richly surveyed areas, relatively few good echosounder records were available for the relevant waters. Discrepancies may result from the way in which GEBCO models the terrain and draws depth contours using both old echosounder records and other sources such as satellite data; however, an analysis of the possible explanations is beyond the scope of this article. These observations have several potential implications, if the GEBCO bathymetry or similar data are used to study and quantify the potential distribution areas (habitat suitability) of organisms that are associated with limited depth ranges. In a related study of benthic megafauna and fish in the same area, Bergstad et al. (2019, this issue) show that live corals (scleractinians, gorgonians and antipatharians) decline in abundance to very low levels deeper than 800–1 000 m. If the seamount summits are generally deeper than previously assumed, this may mean that coral distribution areas are

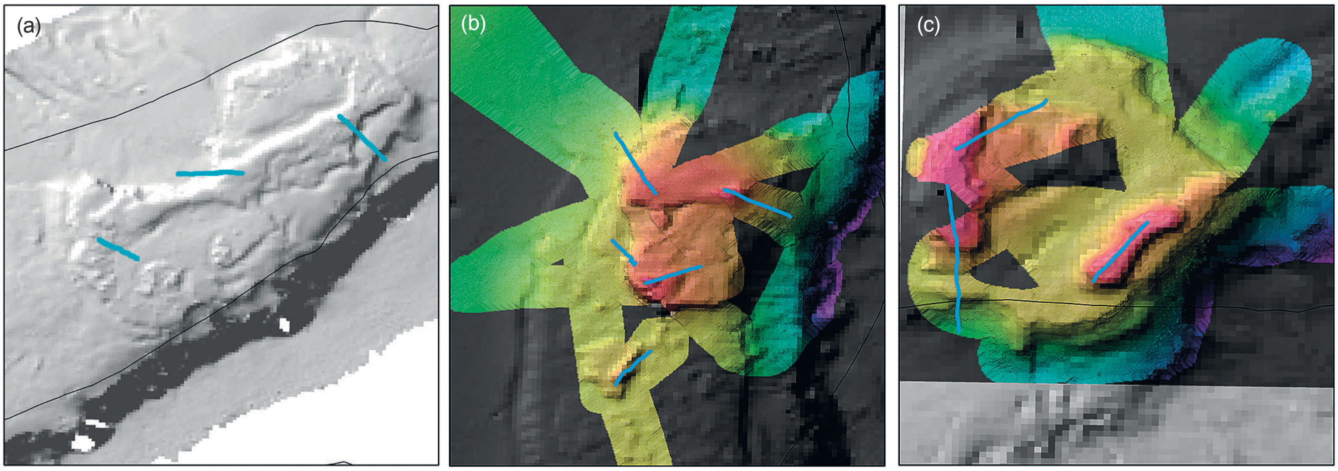

Figure 15: Tracks of dives with the CAMPOD towed video vehicle (blue lines) on (a) Valdivia West, (b) Valdivia Middle, and (c) Valdivia North, features of the Valdivia Seamount complex (see Figure 12.) The underlying reliefs (grey areas) are from Spanish–Namibian survey data (López Abellán and Holtzhausen 2011) and are combined with new data from this study (colour overlays)

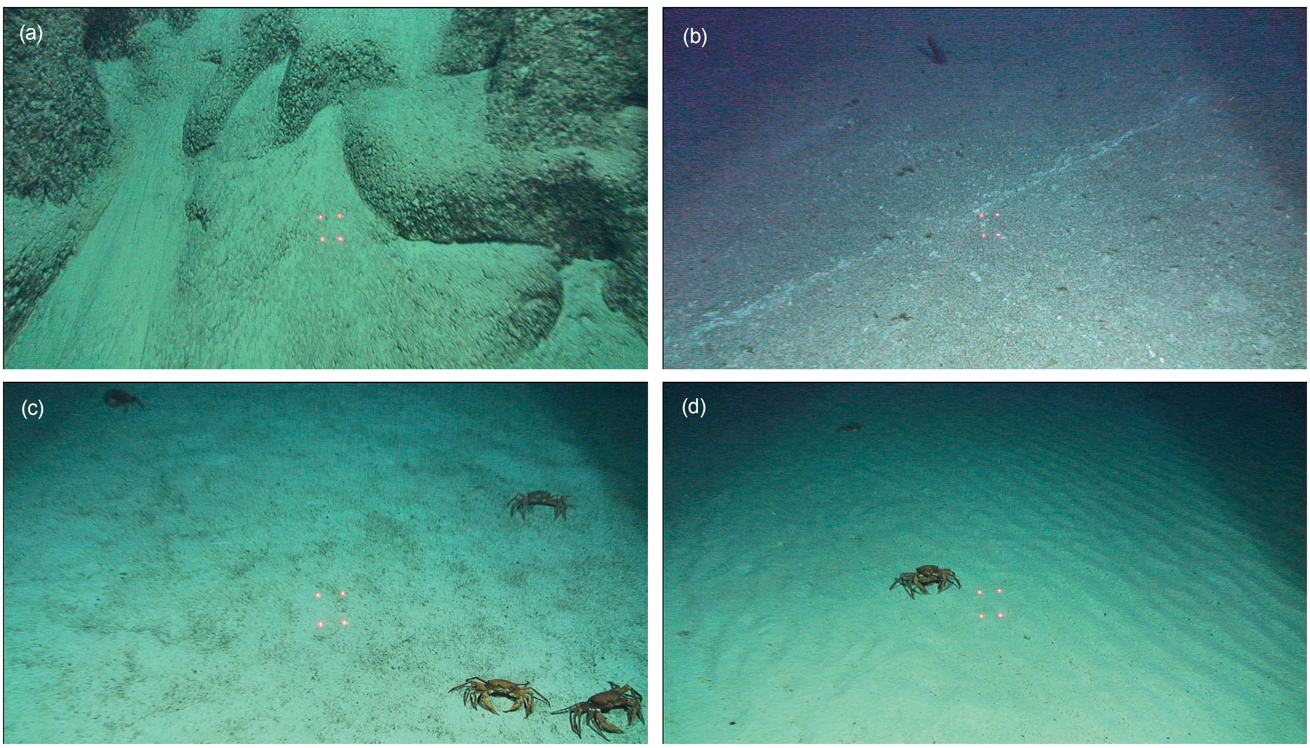

Figure 16: Images from Valdivia Bank (see Valdivia Central in Figure 12) showing (a) the rocky slope, (b) 230-m-deep summit plateau, and (c, d) sandy flats adjacent to Valdivia Bank. Images are frame grabs obtained with the CAMPOD towed video vehicle on the RV *Dr Fridtjof Nansen* in 2015. Red dots from laser pointers indicate a 10x10-cm square

substantially smaller than anticipated and predicted by, for example, habitat suitability models. This may also be the case for some fish species that are primarily associated with seamount summits.

Analyses of depth distribution for the entire SEAFO CA suggest that approximately 2% of the area is 2 000 m or shallower. This estimate is based on GEBCO bathymetry, and may, if the GEBCO generally overestimates summit areas and underestimates depths, be rather an overestimate of the collective comparatively shallow subareas of the SEAFO CA. Further estimation of this probable overestimation was not pursued but would seem to be a task for future study.

The available observer logbook records from commercial pot and trawl fisheries from 2005 until 2015 (no fishing was recorded in the pot and trawl areas in 2016) show that actual fishing operations were restricted to depths much

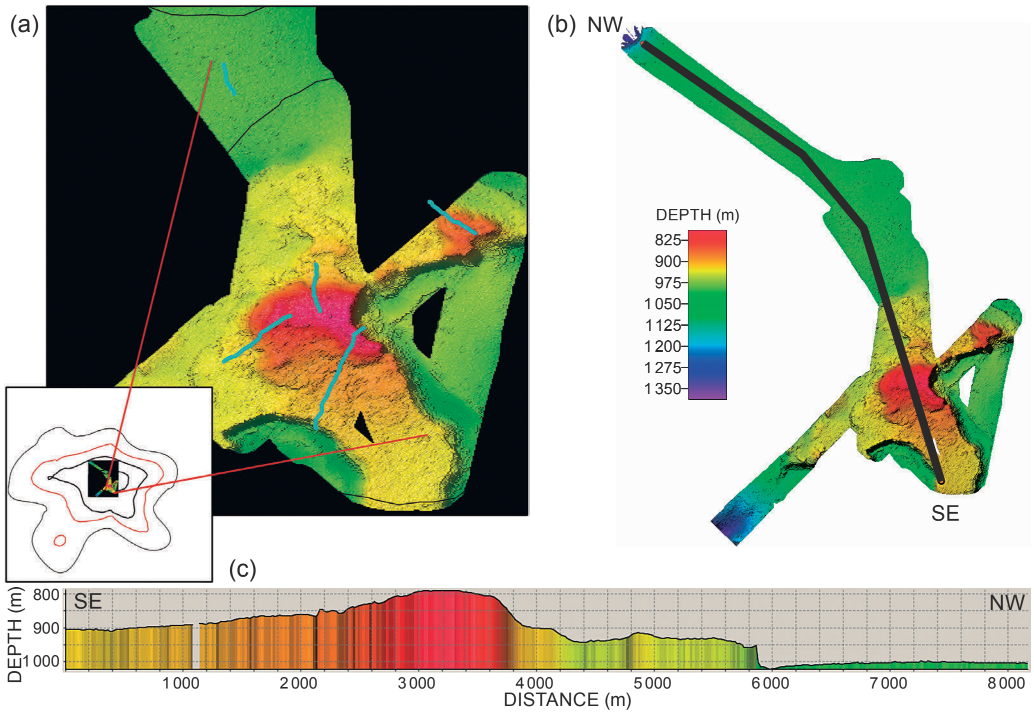

Figure 17: Observations of Ewing Seamount on the Walvis Ridge, made by the RV *Dr Fridtjof Nansen* in February 2015. (a) Relief of the seamount showing the CAMPOD dive transects (blue lines); (b) summit area; and (c) depth profile along the transect shown as a black line in (b), from SE across the summit and onto a flat area to the NW

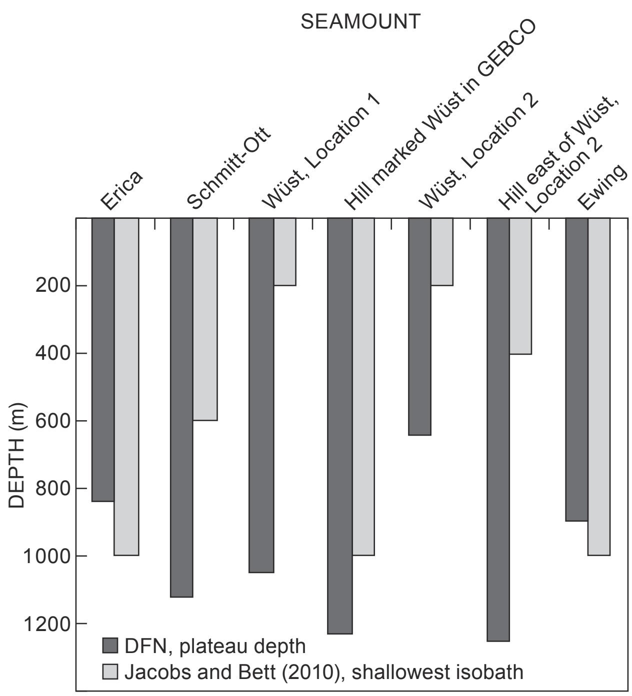

Figure 18: Comparison of the summit plateau depth at individual Southeast Atlantic seamounts, observed by the RV *Dr Fridtjof Nansen* (DFN) in 2015 using multibeam echosounders, and the summit depths derived from GEBCO data compiled by Jacobs and Bett (2010). Plateau depth is the depth of the main flat summit for flat-topped seamounts even though somewhat shallower minor summit knolls may occur

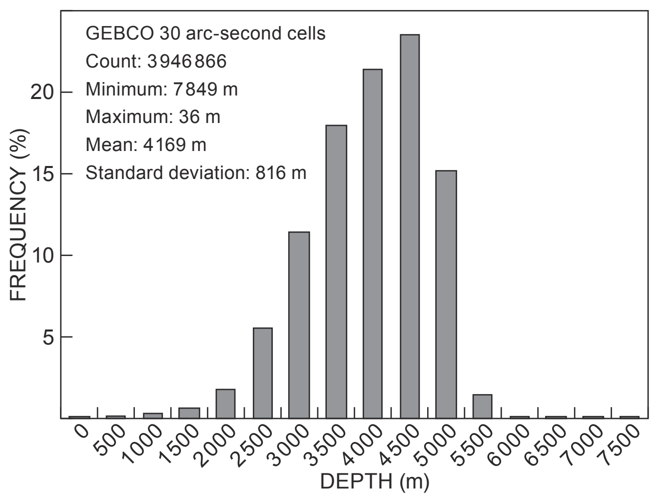

Figure 19: Frequency distribution by depth zone of GEBCO 30 arc-second grid cells for the SEAFO Convention Area (see http://www.seafo.org)

shallower than 2 000 m. Trawl fishing was essentially only conducted shallower than 250 m on Valdivia Bank, whereas pot fishing for deep-sea crabs was conducted on the Valdivia plains to a maximum depth of ~1 200 m, but mostly significantly shallower. SEAFO regulations did not limit expansions into deeper waters, and deeper areas may have been explored without revealing attractive resources.

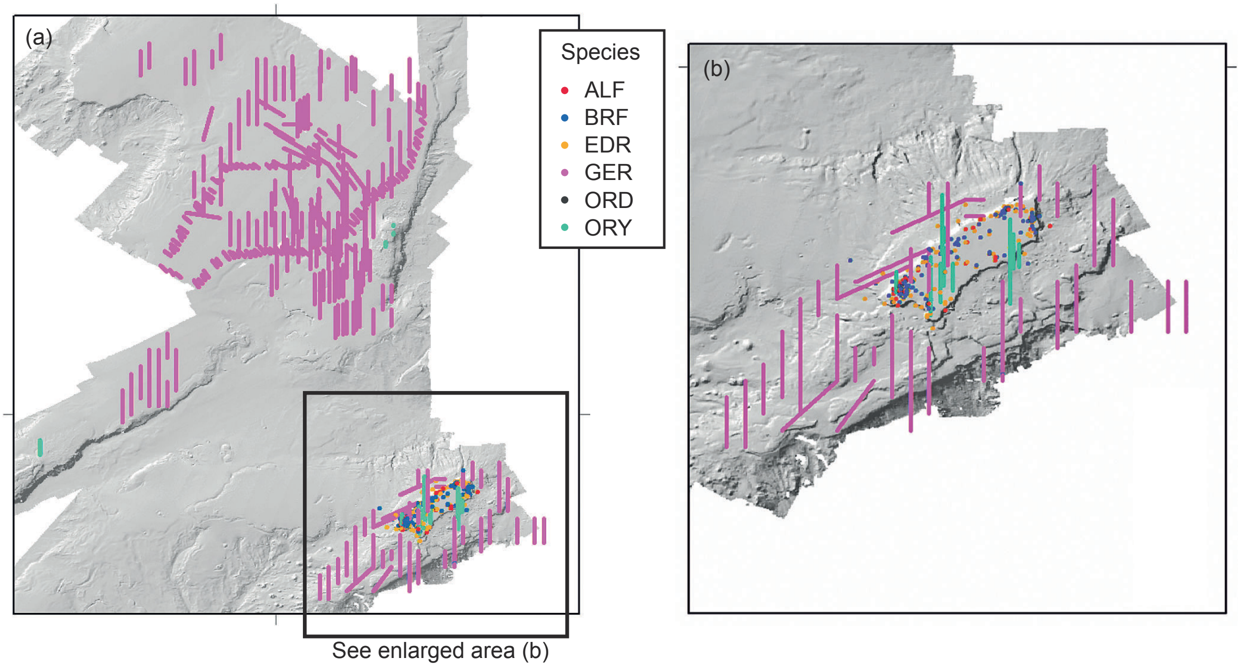

Figure 20: Records of fishing in the Valdivia area (a), including on the Valdivia Bank (b). Colour-coding represents set-by-set data for pot fisheries for deep-sea red crab (GER) and haul-by-haul data for trawl fisheries for slendid alfonsino (ALF), blackbelly rosefish (BRF), pelagic armourhead (EDR), oreo dories (ORD) and orange roughy (ORY). Data from SEAFO observer records for the period 2003–2016; when only points are shown, these are the start positions of tows

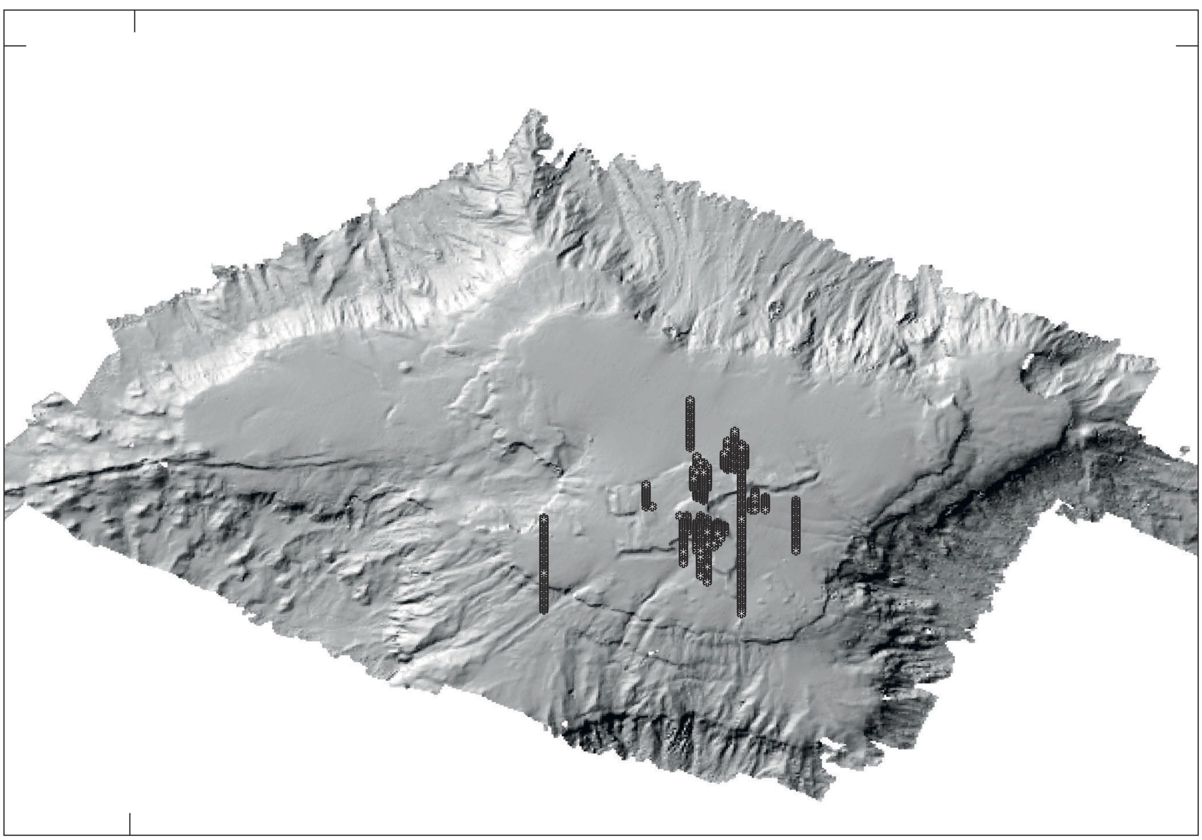

Figure 21: Records of trawl sets during fisheries for orange roughy on Ewing Seamount, from SEAFO observer records for 2003–2016

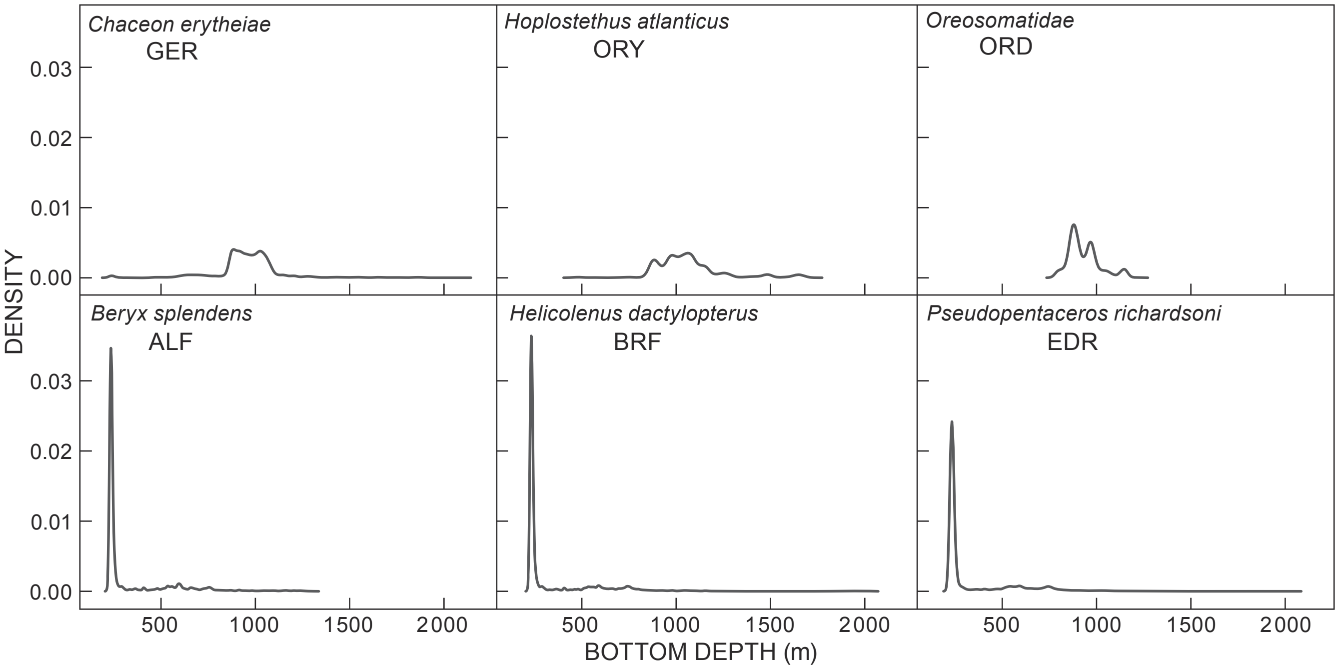

Figure 22: Observed distribution by depth of pot sets targeting deep-sea red crab (GER), and trawl sets targeting various fish species (ORY = orange roughy; ORD = oreo dories; ALF = slendid alfonsino; BRF = blackbelly rosefish; EDR = pelagic armourhead). Density functions were derived by kernel smoothing, with observer and survey catch data as input

Table 1: Summary of substrate-habitat observations on the Southeast Atlantic seamounts visited by the RV *Dr Fridtjof Nansen* in 2015. Substrate types were assessed as: * = present, *** = abundant, or ***** = very abundant

Substrate type and location		Seamount							
		Schmitt-Ott	Wüst	Vema	Valdivia				Ewing
					Central	West	Middle	North	
Biogenic sediment (sandy and gravelly)	Base	***	***	*	*****	*****	*****	*****	***
	Slope	***	–	*	–	–	–	–	***
	Summit	***	–	*	–	–	–	–	–
Coral rubble (dead coral)	Base	*****	–	–	*	*	–	*	–
	Slope	*****	***	–	*	*	*****	*	–
	Summit	*****	***	–	–	–	–	–	***
Basaltic rock	Base	***	–		–	–	–	–	–
	Slope	***	–	–	–	–	–	–	–
	Summit	***	–	–	–	–	–	–	–
Consolidated hard sediment	Base	*	–	–	–	–	–	–	*****
	Slope	*	***	*	*****	*****	***	*****	*****
	Summit	*	***	*	*****	*****	***	*****	–
Kelp forest	Base	–	–	–	–	–	–	–	–
	Slope	–	–	–	–	–	–	–	–
	Summit	–	–	*****	–	–	–	–	–

Considering the restricted depth range of trawl fishing on Valdivia and the bathymetry distribution for the entire SEAFO CA (Figure 19), it is likely that the actual maximum depth of trawl fishing is instead 500 m or at most 1 000 m. The only fishery that ventures to 2 000 m deep in the SEAFO CA is the longline fishery for Patagonian toothfish conducted on the Discovery and Meteor complexes in the southernmost subareas of the SEAFO CA, and logbook data suggest that this fishery has a wide depth range of 600–2 000 m. However, the distribution area of toothfish is restricted to these southernmost areas, and it is unlikely that longline fishing will expand towards the northern seamounts that were studied here. Similarly, it is unlikely that crab fishing will expand much beyond traditional fishing areas on Valdivia. Trawl fishing essentially ceased after 2013 and is unlikely to resume with current fishing opportunities, even if SEAFO offers fishing opportunities for all of the former target species: alfonsino, pelagic armourhead, and even orange roughy.

Should trawl fisheries reappear, there is a high likelihood that such fisheries will target the shallowest available seamount summits (i.e. those shallower than 1 000 m). The depth distribution shown in Figure 19 suggests that less than 1% of the SEAFO CA is shallower than 1 000 m, and that may be an overestimate. If the actual potential trawl fishing depth is less than 500 m, then the available area is less than 0.5% of the SEAFO CA and is essentially restricted to very few summits and knolls (e.g. Valdivia Bank and Vema Seamount). Even if trawling were to be conducted to 1 000 m, the available fishing areas would only be expanded to include summit knolls at Wüst and Schmitt-Ott and a few seamounts outside the present study area. However, this study has shown that the knolls are very small and significantly smaller than previously envisaged. The actual potential trawl-fishing area is thus highly restricted. It should be noted that some areas that are potentially trawlable are currently closed to fishing (Figure 1).

The character and limited sizes of the seamount habitats in the SEAFO CA probably explain why the actual and estimated production potential in the high-seas demersal fisheries appears very low as compared with in the vast ocean area available. Not only is the collective shallow area small, but the area is also oligotrophic, with very low primary productivity (Longhurst 1998). This low potential is reflected in the low landings and correspondingly low level of fishing opportunity (see total allowable catches maintained by SEAFO: www.seafo.org). Past experience from target fisheries for orange roughy and pelagic armourhead furthermore shows that the resources were reduced to low levels in short periods (Clark et al. 2007). In the most recent years, the fisheries for previously targeted fish resources exploited by trawling ceased following declines in catch per unit of fishing effort, an indication that the target stocks are commercially extinct.

Tasks for the future would be to expand exploration of the bathymetry and habitats to include the seamounts to the north, west and south of the area studied in this investigation. Of particular interest and relevance to SEAFO is to map the actively fished subareas of the SEAFO CA, including the target area of longline fishing for Patagonian toothfish on the Discovery and Meteor complexes.

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