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Megabenthos habitats influenced by nearby hydrothermal activity on the Sandwich Plate, Southern Ocean

Authors

Katrin Linse[a,*], Miriam Römer[b], Crispin T.S. Little[c,d], Yann Marcon[b], Gerhard Bohrmann[b]

[a]British Antarctic Survey, High Cross, Madingley Road, Cambridge, CB3 0ET, UK

[b]MARUM – Center for Marine Environmental Sciences, Department of Geosciences, University of Bremen, Klagenfurter Str, 28359 Bremen, Germany

[c]School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK

[d]Life Sciences Department, Natural History Museum, London, SW7 5BD, UK

*Corresponding author: kl@bas.ac.uk

ORCID IDs

Katrin Linse	0000-0003-3477-3047
Miriam Römer	0000-0003-2540-9286
Crispin T.S. Little	0000-0002-1917-4460
Yann Marcon	0000-0002-1686-8045
Gerhard Bohrmann	0000-0001-9976-4948

Keywords

Abyssal lobsterette, bathyal octocoral assemblages, chimney structure, OFOBS, MTL miniaturized temperature data-logger, micro-bathymetry

Highlights

- Unknown areas of hydrothermal activity detected by locally raised temperature
- Local-scale bathymetric mapping of hydrothermal active sites
- Presence of chimney structures and bacterial mats at Quest Caldera
- Megabenthic epifauna comprising known Southern Ocean elements

Abstract

The Sandwich Plate is known as one of the tectonically most active regions in the Southern Ocean and Antarctica, characterised by a subsurface chain of active volcanic islands (the South Sandwich Arc), submarine volcanic features, an earthquake rich area along the South Sandwich Trench and hydrothermal vents on segments of the East Scotia Ridge. In 2013 and 2019 we investigated eight potential hydrothermally active sites in the forearc, island arc and back arc of the Sandwich Plate from shallow (60 m) to abyssal (3886 m) depths. All Protector Seamounts sites, Protector Shoal, Quest Caldera, and an unnamed submarine volcano, showed thermal anomalies, as did the East Scotia Ridge segment E5 back arc site. At Quest Caldera, chimney structures, bacterial mats and mineral precipitates were observed in a depression on the caldera rim. The investigated forearc sites showed hydroacoustic, but not temperature anomalies. None of the sites showed evidence of megafauna associated with hydrothermal venting or hydrocarbon seep sites, but did have evidence of both unexpectedly dense and sparse communities of Southern Ocean taxa in the vicinities of the anomalies. Overall, our investigations showed that the benthic habitats and communities of the Sandwich Plate are still barely known.

1. Introduction

Discoveries of hydrothermal activity in the waters around Antarctica and confined by the Polar Front (defined as Southern Ocean in Talley et al., 2011), have been made along Antarctic mid-ocean ridges and back-arc spreading centres since the early 2000s (e.g., German et al., 2000; Rogers and Linse, 2014; Hahm et al. 2015; Park et al., 2021), the West Antarctic Rift System (e.g., Bohrmann et al., 1999, Van Wyk der Vries et al., 2017) and the South Sandwich Island arc (e.g., Leat et al. 2000; Cole et al., 2014; Linse et al., 2019). More recently influence of hydrothermal activity in the Southern Ocean has been reported on not only bathyal chemosynthetic ecosystems (Rogers et al., 2012; Linse et al., 2019) but also pelagic ecosystems via massive surface phytoplankton blooms (e.g., Ardyna et al., 2019; Schine et al. 2021). Submarine hydrothermal activity in the Southern Ocean seems to affect the biogeochemical cycling and biological ecosystems more than previously thought and therefore research to discover and investigate these hydrothermal active sites gains increasing importance.

An area known for hydrothermal activity is the Sandwich Plate (55° – 60° S, 24° – 30° W), an oceanic microplate of about 180,000 km^2, surrounded by the Scotia Plate to the west, the Antarctic Plate to the south and the South American Plate to the west (Larter et al., 2003; Leat et al., 2013; 2016). The western boundary is the East Scotia Ridge (ESR), a back-arc spreading ridge, and the eastern boundary the South Sandwich Trench, where the South American Plate is subducting (Leat et al., 2004; 2016). The curved South Sandwich volcanic arc spans, from the north, the Protector Seamounts, through eleven islands, of which seven are volcanically active, to seamounts in the south (Leat et al 2013). Submarine explosive eruptions have been reported from Protector Shoal in 1962 (Gass et al., 1963; Holdgate, 1963) and submarine calderas at Southern Thule (Smellie et al., 1998) and Kemp Caldera (Linse et al., 2019).

Since 2012, the South Sandwich Islands and the wider Sandwich Plate are included in the South Georgia and South Sandwich Islands Marine Protected Area (SGSSI-MPA) based on their global importance for abundant and unique marine fauna, including benthic fauna at South Georgia and marine mammal and seabird populations in both areas (Trathan et al., 2014; Hogg et al., 2011, 2016, Clubbe, 2018). The benthic habitats of the South Sandwich Islands region range from the shallow intertidal around the islands to hadal depth in the South Sandwich Trench, down to 8266 m at Meteor Deep (Griffiths & Waller, 2016; Bongiovanni et al. 2021). The benthic diversity for this habitat-diverse region is poorly known and under sampled. The deeper sublittoral (>100 m) and upper bathyal (>1500 m) depths have been investigated during the LAMPOS (Arntz et al., 2005a, b), BIOPEARL I (Kaiser et al. 2008; Griffith et al. 2009), IceFish (Lockhardt and Jones, 2008) and BlueBelt expeditions (Downie et al., 2021; Hogg et al. 2021). These studies indicated that the South Sandwich Islands combine benthic faunal elements of the Antarctic and sub-Antarctic faunas and there also seemed to be a boundary for distributions of some species within the island arc (Arntz et al., 2004b, Hogg et al., 2021). Knowledge for the deep bathyal, abyssal and hadal depth is based on the Russian deep-sea investigations in the middle of the last century (Malyutina, 2004 and references therein), the Antarctic benthic Deep-Sea Biodiversity Project ANDEEP II expedition in 2002 (Brandt et al. 2004, 2007) and, more recently, the Five Deeps Expedition to the hadal part of the South Sandwich Trench (Stewart and Jamieson, 2019; Jamieson et al. this issue), as well as from the Biogeography of Deep-Water Chemosynthetic Ecosystems in the Southern Ocean (ChEsSO) expeditions, which investigated hydrothermal active habitats specifically (e.g. Rogers et al., 2012; Linse et al., 2019). The three ChEsSO expeditions discovered and investigated hydrothermal vents at the ESR segments E2 and E9, and at the southern island arc sites of the Kemp Caldera and Adventure Crater (Rogers et al. 2012; Tyler, 2011; Linse 2019), and described their megabenthic fauna and communities (e.g., Marsh et al., 2012; Reid et al. 2013; Mah et al., 2015; Thatje et al., 2015).

The aims of the RV Polarstern expeditions PS81 in 2013 and PS119 in 2019 were to investigate likely sites of hydrothermal activity on the Sandwich Plate, including locations in the back-arc, forearc and at the Protector Seamounts, by in-situ imagery, and to describe the examined habitats and to assess their faunal elements for chemosynthetic and Southern Ocean connections.

2. Material and Methods

2.1. *Study Area and expeditions*

The RV Polarstern expeditions PS81 in 2013 and PS119 in 2019 investigated locations on the Sandwich micro-plate for hydrothermal activity (Bohrmann, 2013; 2019). Particularly in the northern area of the arc, acidic volcanic cones reach up to 400 – 50 m below sea level (Leat et al., 2013; 2016). Based on preliminary results of previous hydroacoustic seafloor and water column surveys indicating potential hydrothermal activities on the microplate (German et al., 2000; Frenzdorff et al., 2002; Leat et al., 2004), eight locations in the northern arc area, the forearc and the ESR segment E5 were investigated (Figure 1).

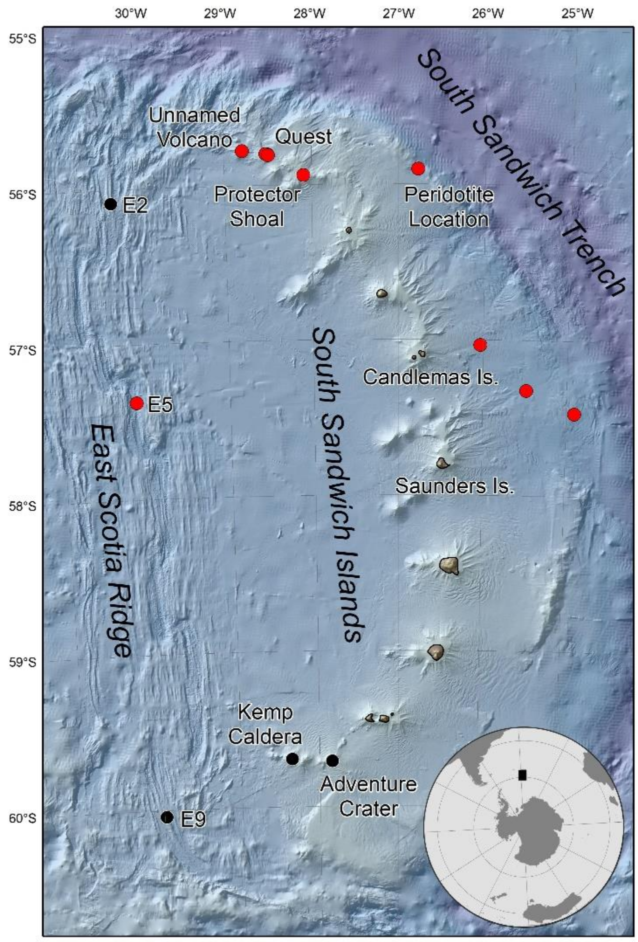

Figure 1. Positions of the investigated locations in the vicinity of the South Sandwich Islands on the Sandwich Plate. Inset map shows the position of the South Sandwich Islands in relation to Antarctica.

Black dots – known hydrothermal sites, red dots – investigated sites. Bathymetry based on dx.doi.org/10.5285/b8143952-421c-4544-8437-58f339253d30.

2.2. *Towed camera platform systems*

During the RV Polarstern expeditions PS81 and PS119, three types of towed camera systems were deployed to image and survey the deep-sea seafloor (Table 1): OFOS (ocean floor observation system), OFOBS (ocean floor observation and bathymetry system) and TV-sled.

Table 1. Geographic positions of camera deployments in the vicinity of the South Sandwich Islands on the Sandwich Plate. MAPR – miniature autonomous plume recorder; MTL – miniaturized temperature data-logger

Area	Station	Date	Gear	Latitude (S)		Longitude (W)		Depth (m)		Attachments
Location				Start	End	Start	End	Start	End	
Protector Seamounts										
Quest Caldera	PS81/268-1	31.03.2013	OFOS	55°48.219	55°48.724	28°30.144	28°30.029	731	744	4 MTLs
	PS81/268-2	31.03.2013	OFOS	55°48.008	55°49.366	28°31.488	28°32.136	731	950	4 MTLs
	PS81/276-1	08.04.2013	TV-sled	55°48.542	55°48.652	28°29.687	28°29.516	716	717	5 MTLs
Protector Shoal	PS81/275-1	08.04.2013	TV-sled	55°56.426	55°57.097	28°05.728	28°06.693	60	526	5 MTLs
Unnamed volcano	PS81/278-1	09.04.2013	TV-sled	55°46.711	55°46.873	28°47.601	28°47.459	618	779	5 MTLs
Forearc										
off Saunders Island I	PS81/270-1	02.04.2013	OFOS	57°28.190	57°28.285	24°54.174	24°55.174	3659	3681	2 MTLs*
off Saunders Island II	PS81/274-3	08.04.2015	TV-sled	57°19.605	57°19.536	25°29.072	25°29.178	3723	3725	3 MTLs
off Candlemas Island	PS81/273-1	07.04.2013	TV-sled	57°02.028	57°02.063	26°02.221	26°02.225	3025	3026	3 MTLs*
Peridotite Location	PS119/046-1	16.05.2019	OFOBS	55°54.159	55°54.429	26°46.530	26°47.041	2500	2313	3 MTLs, MAPR
East Scotia Ridge										
Segment E5	PS119/032-1	10.05.2019	OFOBS	57°22.567	57°27.705	30°07.266	30°07.326	3886	3649	3 MTLs, MAPR
* no data aquisition										

2.2.1. OFOS

During PS81 in 2013, the Alfred Wegener Institute (AWI) towed underwater camera system OFOS with a high-resolution digital camera (iSiTEC, CANON EOS 1Ds Mark III) was used. The three main components are a deck unit, a single-mode-optical fiber cable and an underwater unit. The underwater unit is mounted in a steel frame with dimensions of 140L X 92W X135H cm. The camera, two flashlights (iSiTEC UW-Blitz 250, TTL driven), three red laser pointers (Oktopus, Germany) at 50 cm to each other, four LED lights and a Tritech Altimeter are attached to the frame. The camera footprint at 1.5 m above seafloor encompasses 3–4 m^2. The deployment is controlled by the deck unit and five different software modules installed on a laptop computer control the operation of the components and save the images and positions.

The OFOS was deployed from the side of the Polarstern and towed at a speed of ~0.5 – 0.7 knots at a minimum distance of 1.5 m above the seafloor. The target altitude of 1.5 m varied considerably as a winch operator manually adjusted the cable length and adapted to varying bottom topography and sea state and ranged from 1.4 m to 15 m above the seafloor. If the distance to the seafloor is too far, the laser pointers are not visible on the image and only images below an altimeter depth of 10 m were analysed. To determine the position of the OFOS and to locate the positions of the images taken, a ship's ultra-short baseline system (USBL) Posidonia transponder was fixed to the frame of the OFOS.

2.2.2. TV-sled

The MARUM TV-sled was used during PS81 when technical problems did not allow for OFOS deployments. The TV-sled is a towed camera system transmitting an analogue video signal from the sled through the ship's coax cable to the deck unit. The main components are the video-data telemetry system consisting of a deck unit and an underwater system with a black-and-white camera system and a high intensity discharge light. The black-and-white video signal transmitted by the video-data-telemetry system is displayed in real time on monitors and recorded by a VCR.

The underwater system is mounted in a steel frame with dimensions of 120L x 80W x 120H cm. The sled was also towed at a speed of 0.5 to 1 knots at a distance of about 3 m above the ground. This distance is maintained by a winch operator manually adjusting the cable length, such that a weight suspended 3 m below the sled is flying just above the seafloor. The length of the weight is ~25 cm and can be used for size estimation on the seafloor when visible in the image. A USBL Posidonia transponder was attached to the frame during deployment for underwater positioning.

2.2.3. OFOBS

During PS119 in 2019, the AWI ocean floor observation and bathymetry system (OFOBS) was used for visual inspection (Purser et al., 2019). The system is deployed with a continuous direct communication through the ship's fiber optic cable and operational at depths up to 6,000 m. The OFOBS frame is equipped with a deep-sea underwater telemetry system including 4 LED lamps, 2 flashes, 3 laser pointers, a high-resolution digital camera (iSiTEC, CANON EOS 5D Mark III) for still pictures and a HD colour video camera (Sony FCB-H11). A USBL Posidonia transponder and a Tritech altimeter are mounted for underwater positioning and depth control. However, the altimeter did not function during the dive of station PS119/032-1, therefore, a safe distance to the seafloor was maintained suitable for the 3-dimensional topography of the site. At station PS119/046-1 the altimeter range for images varied between 4 m and 14.1 m. If the distance to the seafloor was too far away, the laser pointers were not visible on the image.

2.2.4. Additional sensors

Miniaturized temperature data-logger (MTL, Pfender and Vilinger, 2002), autonomous high-precision thermometers for deep-sea application rated to 6000 m depth, were connected to the camera system frames to measure near-seafloor temperatures along the survey paths. Their accuracy is within the range of 5 – 1 mK, depending on the temperature range and precision up to 1 mK. Between two and five MTLs were mounted on OFOS, OFOBS and TV-sled and sampled bottom water temperatures at a 1 Hz frequency during all dives. Mounted diagonally across the bottom and top of the frames they successfully registered bottom water anomalies.

A miniature autonomous plume recorder (MAPR; Walker et al. 2007), built by the Pacific Marine Environmental Laboratory (PMEL), Seattle, was connected to the OFOBS deployed during the PS119 cruise in 2019. The MAPR contains the following probes: 1) a pressure gauge with a range of 0-400 bars to record the water depth; 2) a thermistor with a resolution of 0.001°C mounted in a titanium probe; 3) a light back scattering sensor (LBSS, or "nephelometer") that senses scattered light from a small volume within centimetres of the sensor window; and 4) an oxidation-reduction potential (ORP) sensor that responds to reduced hydrothermal chemicals in the water column. ORP detects hydrothermal discharge of all temperatures, including low-temperature diffuse venting as well as higher-temperature but particle-poor sources. It responds immediately, with decreasing potential values (E(mV)), to the presence of nanomolar concentrations of reduced hydrothermal chemicals such as Fe^{+2}, HS^{-}, H_2 that are out of equilibrium with the oxidizing ocean (Walker et al., 2007). These chemicals rapidly oxidize or metabolize near their seafloor source.

2.3. *Hydro-acoustic data*

Multibeam surveys were conducted by the RV Polarstern's hull-mounted multibeam echo sounder systems, HYDROSWEEP DS3 (Teledyne RESON, formerly ATLAS) with water-column imaging capability. The multibeam echosounder had a nominal sounding frequency of 14–17 kHz, which enabled hydroacoustic recording below 30 mbsl down to full ocean depth. The swath width was set in the deep sea to a coverage of 3.5 times and in the shallower areas of 5 times the water depth. Multibeam data were processed using MB-System suite software (Caress & Chayes, 2017) and CARIS Hips & Sips (Teledyne) to produce seafloor bathymetry and backscatter grids with a resolution of 35 - 70 m grid cell size.

The hull-mounted single-beam echosounder Parasound P70 (Teledyne RESON, formerly ATLAS) is capable to act as a sub-bottom profiler and for water column investigations. The opening angle of the transducer array is 4° by 5°, which corresponds to a footprint size of about 7% of the water depth. The device utilizes the parametric effect based on the nonlinear relation of pressure and density during sonar propagation (Spiess and Breitzke, 1990). The primary high frequency (~19 kHz) allows imaging water column anomalies, whereas the secondary low frequency (~4 kHz) is used to image subsurface structures. The acquisition software ATLAS PARASTORE was used to store and display the echograms.

2.4. Qualitative assessment of megabenthic epifauna and habitats

The still images and video footage were assessed to describe the present megabenthic epifauna and seafloor substrate. During each deployment, digital and manual logs were written to document common, as well as rare fauna, and geological structures. Low quality images (too dark, too high altitude, extensive sediment clouds) were omitted from the analyses. To account for camera lens edge distortion effects, the images were split into 100 equal sized rectangles and the outer two rectangle layers were excluded, leaving 36 rectangles for analysis. Still images were analysed to assess percentage cover of abiotic and biotic substrate types following the sedimentary size classification of Tucker, 1991: mud, sand, gravel, pebbles, cobbles, boulders, or bedrock, with the addition of pillow lava and talus to note volcanogenic origin. Megafaunal taxa were counted. In-situ image-derived taxonomic identification to lower taxonomic levels is difficult, especially in low resolution or far-distant images. Additionally, recent molecular studies have shown high numbers of cryptic species complexes in the Antarctic benthic fauna (e.g., Grant and Linse, 2009; Brasier et al., 2016: Riuz et al. 2020). Therefore, we followed the recommendations of Horton et al. (2021) for identification of in-situ images. Hence, our identifications were based on established phylum and class levels, in selected compelling taxa family or genus levels. We used 'indet.' to denote an undetermined species, and Rauschert and Arntz (2015) and, if appropriate, taxon specific literature for identifications.

3. Results

3.1. Site descriptions

Eight potential hydrothermal active sites on the South Sandwich microplate have been investigated by still and video imagery during nine towed camera system deployments (Table 2). The sites varied from volcanic cones at the Protector Seamounts to potential seep sites in the forearc and venting sites in the back-arc ridge system. At all sites exposed rock, often of obviously volcanogenic origin, was present, with various amounts of sediment between the rock outcrops. The megabenthic epifauna observed on the still and video imagery varied in abundance and diversity within and between sites, independent of depth. Hard substrates served as habitat for suspension feeding taxa, like hard and soft corals, hydrozoans, bryozoans, crinoids and sponges, whilst ophiuroids and holothurians were more abundant at sites with more soft sediment.

Table 2. Number of images and seafloor temperatures per camera deployments.

Area	Station	Imagery	Altimeter	Depth range	Seafloor temperature	
Location		stills/ min VHS	range (m)	(m)	ambient	raised / depth
Protector Seamounts						
Quest Caldera	PS81/268-1	379/-	4.0-9.9	731-744	0.4°C	0.6-0.75°C / ~720 m
	PS81/268-2	499/-	1.3- 9.9	731-950	0.38-0.45°C	-
	PS81/276-1	-/127	-	716-717	0.5°C	0.6-2.7°C / ~716 m
Protector Shoal	PS81/275-1	-/126	-	60-526	0.25-0.4°C	0.6-0.85°C / ~460-520 m
Unnamed volcano	PS81/278-1	-/119	-	618-799	0.5°C	0.8-2°C / ~590-620 m
Forearc						
off Saunders Island I	PS81/270-1	55/-	1.4 - 8.8	3659-3681	nd	nd
off Saunders Island II	PS81/274-3	-/97	-	3723-3725	-0.4°C	-
off Candlemas Island	PS81/273-1	20/-	2.2 - 6.1	3025-3026	nd	nd
Peridotite Location	PS119/046-1	520/-	4 - 14.1	2500-2313	-0.2°C	-
East Scotia Ridge						
Segment E5	PS119/032-1	50/-	-*	3649-3886	0°C	0.5°C / ~3600 m
*altimeter did not function						

3.1.1. Protector Seamounts - Quest Caldera

The Quest Caldera, a volcanic structure with an outer and inner caldera, was investigated during 3 camera dives from the outer top and rim of the structure, to the inner caldera and down a chute-like structure (Table 1,2, Figure 2A). The upper rim of the structure is at about 720 m water depth, while the central part of the caldera is at 1075 m, about 340 m deeper than the rim. The distance from the rim to the centre is ~1.8 km. After discovery of thermal anomalies on the north-east rim during dive PS81/268-1 the site was further investigated during dive PS81/276-1 and chimney structures with microbial mats and/or whitish precipitates about 1 m in extent were observed in a steep-walled depression, roughly 10 m deep of about 12 x 24 m across. In this depression, the water temperature reported by the MTLs on the camera frame was raised 2.7°C above the ambient temperature of 0.5°C outside the depression (Figure 2B). Neither shimmering water, nor vent-endemic megafauna known from the East Scotia Ridge vents (e.g., *Kiwa* crabs, stalked barnacles, peltospirid gastropods or vesicomyid clams) were seen.

The upper rim of the caldera was covered by volcanic blocks with aged appearance. These had sizes ranging from several centimetres to few meters and had sediments between them (Figure 2 C-E). A diversity of suspension-feeding organisms in abundance was observed during the entire deployment, especially on the elevated blocks. There were scattered areas with many a white, branched octocoral, which in turn served as habitat for other organisms, such as suspension feeding brittle stars and sponges. Other common fauna on the volcanic blocks were elongated *Primnoella*-like octocorals, orange *Thourella*-like bottlebrush octocorals, yellow sponges, bryozoans, yellow stalked crinoids and red brisingid starfish (Figure 2 C-E). Occasional red lithodid spider crabs of the genus *Paralomis* were observed (Figure 2 H), representing a typical sub-Antarctic faunal element, as well as macrourid fish (rattails) and red *Nematocarcinus* shrimps (Figure 2 F-H), which are also found in the Southern Ocean and in deep-sea habitats.

The suspension feeding fauna was less abundant on the inner caldera slope of Quest Caldera. On the floor of the first caldera plateau the sediment included colourful gravel near to the slope, which gradually decreased in grain size and volume with increasing distance from the slope (Figure 2 F). The gravel served as attachment sites for a variety of sessile suspension feeding animals, including primnoid and white, branching fan-like isidid octocorals, some sponges, bryozoans and serpulid worms. There were also a few white infaunal anemones and orange epifaunal anemones. Rattails, *Paralomis* and *Nematocarcinus* were present and increased in abundance where the gravel gave way to finer sediments. The wall of the inner caldera was abrupt with a talus slope descending into the inner caldera structure. Only a few animals were observed on the slope. The floor of the inner caldera was like that of the outer caldera plateau, with gravel and finer sedimented areas. The deepest part of the caldera had fewer suspension feeding epifauna, with occasional primnoid octocorals and soft corals, while *Nematocarcinus* was still abundant. Occasionally larger, mobile fauna like rattails and holothurians were seen (Figure 2G). The floor of the chute-like structure that runs south-west from the nested caldera varied from sandy areas with scattered blocks to talus slopes. The blocks were settled by occasional white branched, fan-like octocorals and stalked crinoids; *Paralomis* and *Nematocarcinus* were also present (Figure 2 H).

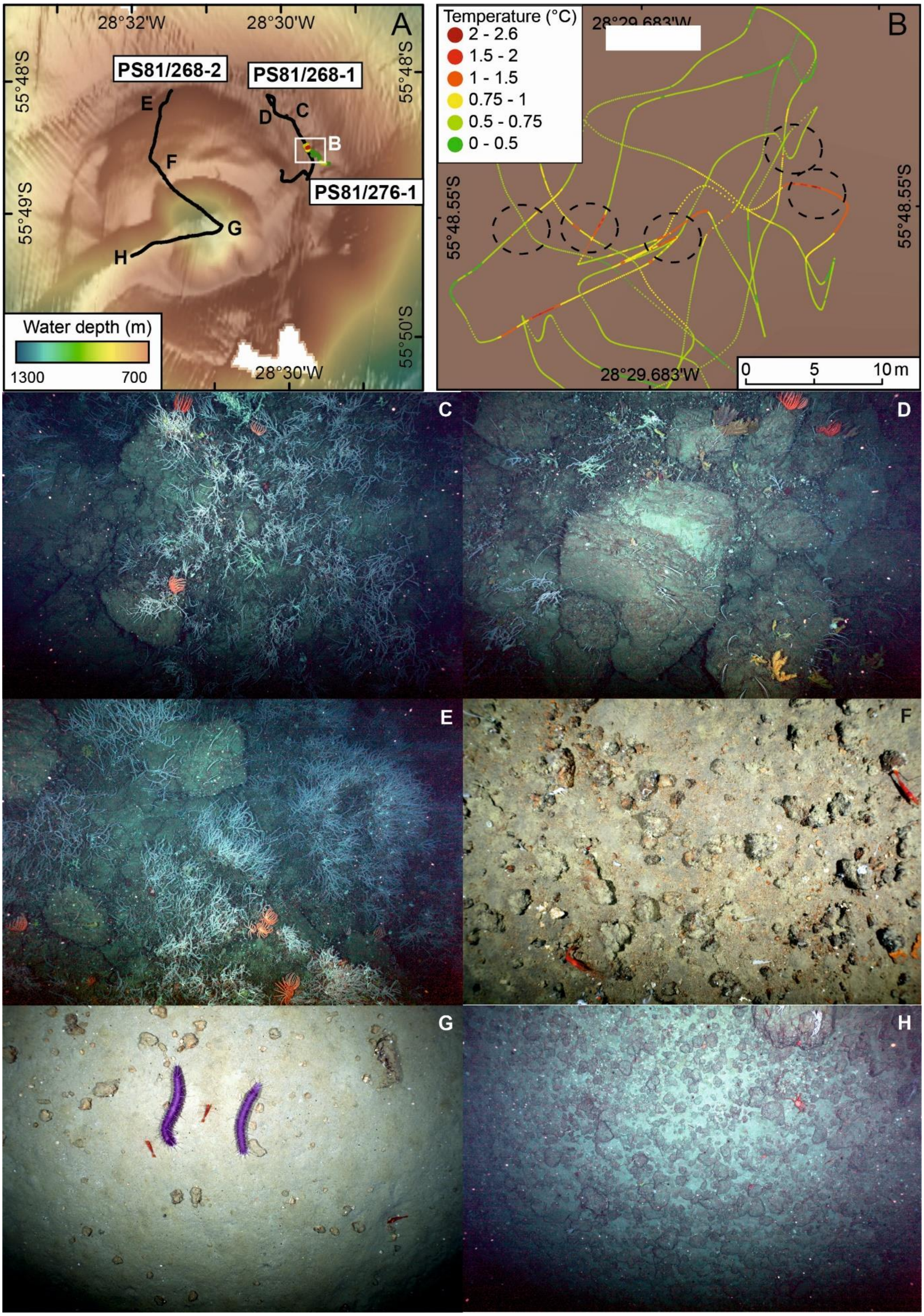

Figure 2. Positions of OFOS and TV-sled dives and in-situ habitat images at the Quest Caldera. A) Dive transects of PS81/268-1, PS81/268-2 and PS81/276-1; B) Position of temperature anomalies on the

outer rim of the Quest Caldera during PS81/276-1. Observed hydrothermal activity indicators, such as microbial mats or chimney structures are circled; C) Dense suspension feeding epifauna including soft corals and brisingid star fish on the top of the caldera 250 m away from hydrothermal anomalies and chimney structures ; D) Suspension feeding epifauna including soft corals and brisingid star fish on the outer rim of the caldera 400 m away from hydrothermal anomalies and chimney structures ; E) Dense suspension feeding epifauna including soft corals and brisingid star fish on the outer rim of the caldera 2500 m away from hydrothermal anomalies and chimney structures ; F) Decapod (*Nematocarcinus* indet.) and mysid shrimps on the talus slope to the inner caldera rim; G) Decapod shrimps *Nematocarcinus* indet. and holothurian *Bathyplotes* indet. on the soft and gravel sedimented inner caldera floor; H) Decapod shrimps *Nematocarcinus* indet. and spider crab *Paralomis* indet. on talus slope of the chute-like structure.

3.1.2. Protector Seamounts - Protector Shoal

Protector Shoal, a shallow, submarine volcano with a collapsed flank, was investigated from its top at around 60 m depth to 526 m depth at circular depression on the flank (Figure 3A, B). Elevated temperatures of 0.4-0.6°C above ambient were recorded on the inner slope of the circular depression. The top of Protector Shoal showed north-south running low ridges, about one metre apart, of pale coloured lava and within the ridges darker, coarse sediment. Towards the rim the substrate changed to pitted lava with lava collapse structures, which were densely colonised (~10 per m^2) by broad, single bladed seaweeds, which disappeared below 66 m depth. The slope of the flank deeper than 100 m consisted of sand, gravel, and isolated lava boulders. Large cidarid urchins were commonly observed as well as occasional *Paralomis* specimens, anemones and macrourid fish. At 500 m depth the gravel changed briefly to pitted lava, indicating an area that may correspond to the recorded temperature anomaly, before continuing to 526 m at the end of dive.

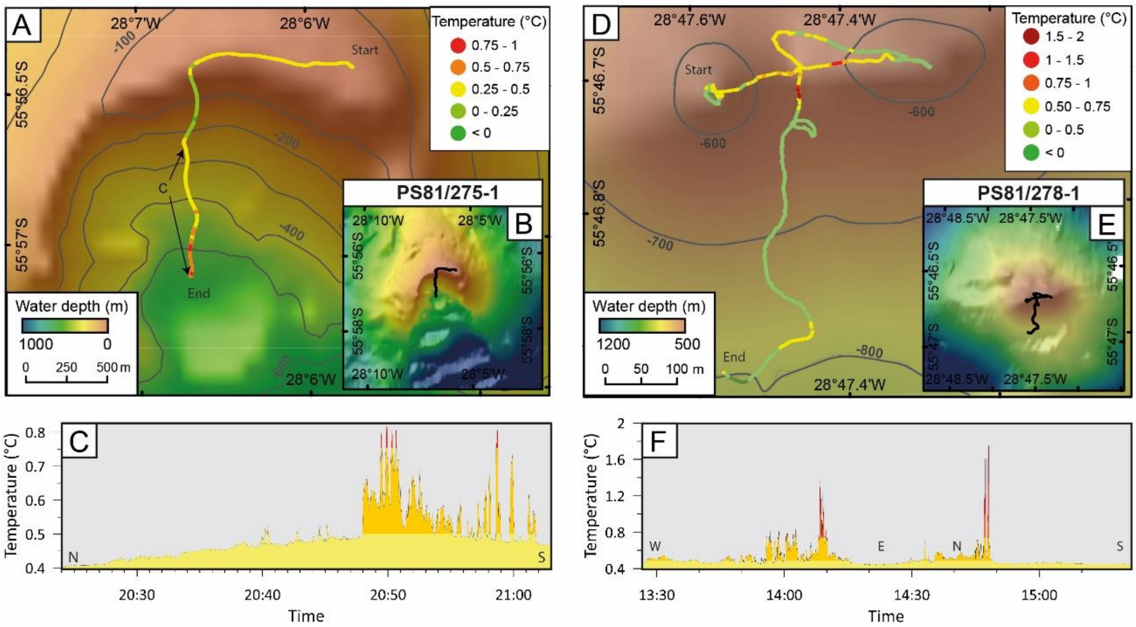

Figure 3. Positions of TV-sled at Protector Shoal and an unnamed volcano. A) Dive transect and temperature anomalies of PS81/275-1 at Protector Shoal; B) Overview map of Protector Shoal; C) Temperature anomalies along PS81/275-1 dive track; D) Dive transect and temperature anomalies of

PS81/278-1 at an unnamed volcano; E) Overview map of the unnamed volcano; F) Temperature anomalies along PS81/275-1 dive track.

3.1.3. Protector Seamounts - Unnamed volcano

The unnamed volcano (55°46 S 28°47 W, 618 m) was initially investigated by an hydroacoustic survey based on its double-peaked structure, and a high raising plume-like anomaly was detected in the saddle area between the peaks (Figure 3D, E; 4A)). The two peaks and the flanks were formed of gravel and larger volcanic rock outcrops. Numerous lithodid crabs were seen on the gravel on top of the peaks, but no other megabenthos was visible. No fauna was observed on the deeper gravel flanks between the peaks where thermal anomalies of 0.-1.5°C above ambient were recorded (Figure 3F; Table 2). On the flank of the eastern peak large rock outcrops and steeps scarps of exposed lava were seen. These were colonised by suspension feeding brisingid starfish, large isidid octocorals and stalked anemones. The outer flank from the saddle deep downwards consisted of talus slopes of initially decimetre-sized rocks and then gravel. Numerous lithodid crabs were observed with more than 10 crabs in the field of view. Between 620 m and 750 m depth the gravelly sediment with occasional larger blocks was colonised by large isidid octocorals with more than 50 individuals in the field of view, as well as with primnoid octocorals and brisingid starfish.

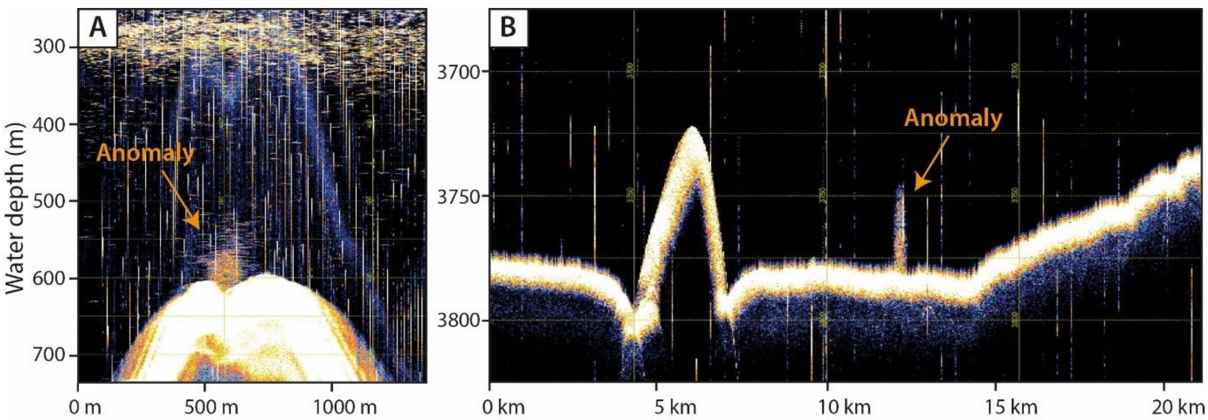

Figure 4. Hydroacoustic anomalies at Protector Seamounts and the Forearc. A) Plume-like, ~ 100 m high, anomaly observed by hydroacoustics in thesaddle of the unnamed volcano during PS81/270-1; B) Hydroacoustic anomaly reaching about 35 m from the seafloor off Saunders Island at position of dive PS81/274-3.

3.1.4. Forearc – off Saunders Island I

The Forearc area off Saunders Island was investigated based on high seafloor backscatter in the HAWAII sidescan sonar map (Vanneste and Larter, 2002) during dive PS81-270-1 (Figure 5A). The northern part of the high-backscatter patch in about 3,660 m depth consisted of a relatively flat seafloor covered by coarser, gravelly sediment showing traces of Lebensspuren, biologically formed structures in sediments, as well as ophiuroids, holothurians and occasional white anemones (Figure 5B). Patches of greenish colour indicated sunken phytodetritus serving as food source for epi- and infaunal taxa. Occasional escarpments, or glassy looking and brecciated volcanic rock occurrences were seen (Figure 5C). One scarp was a few meters high and at the bottom a very dense and localised patch of white anemones was observed (Figure 5D). Beyond this area, gravelly sediment with occasional white anemones, ophiuroids and holothurians continued.

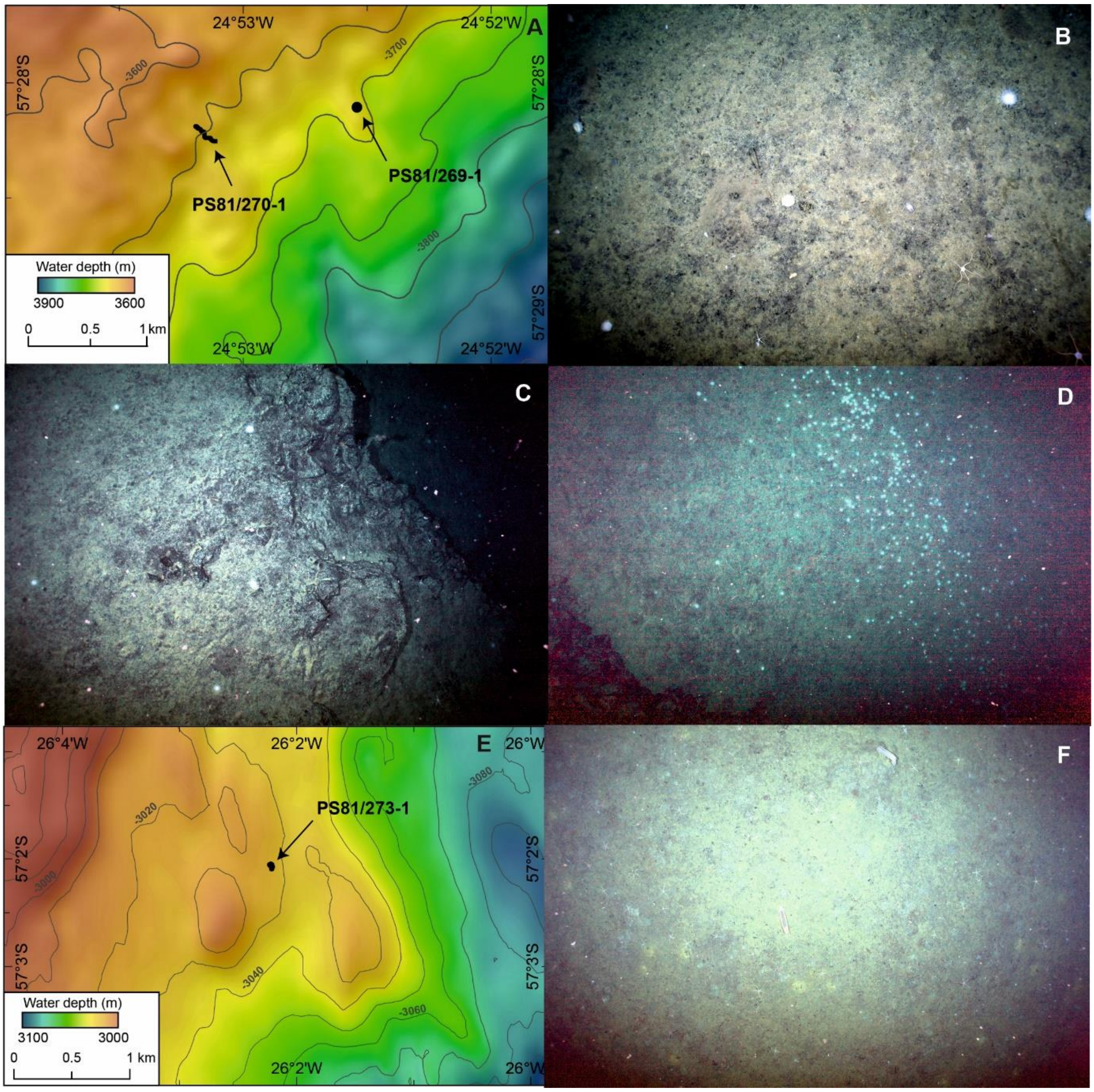

Figure 5. Potential seep areas based on sidescan backscatter anomalies in Forearc. A) Map of PS81/269-1 and PS81/270-1 tracks off Saunders Island; B) Gravelly sediment with large blocks showing Lebensspuren and inhabited by white anemones, ophiuroids and red shrimps; C) Escarpment of glassy looking volcanic rocks; D) Large numbers of white anemones below escarpment; E) Map of PS81/273-1 track off Candlemas Island; F) Gravelly sediment with large blocks showing Lebensspuren and inhabited by white anemones, ophiuroids and red shrimps.

3.1.5. Forearc – off Saunders Island II

On the forearc slope off Candlemas Island (57°19 S 25°29 W, 3723 m) a hydroacoustic flare-like anomaly reaching about 35 m into the water column was detected, and the area was investigated during OFOS dive PS81/274-3 (Figure 4B). The area was characterised by relatively flat, gravel and finer sediment covered seafloor and elevated areas with large volcanic blocks, some of which appeared to have fractured edges. The gravelly sediment areas had abundant Lebensspuren, ophiuroids, holothurians and occasional macrourid fish.

3.1.6. Forearc – off Candlemas Island

The forearc area off Candlemas Island was investigated based on high seafloor backscatter in the HAWAII sidescan sonar map (Vanneste and Larter, 2002) during dive PS81-273-1 (Figure 5E). No temperature anomalies were observed (Table 2). The seafloor was relatively flat, sediment with occasional gravel and covered in a fine greenish layer of phytodetritus (Figure 5F). Large numbers of epi- and infauna were visible, including several species of ophiuroids and at least three different species of large holothurians: *Bathyplotes* indet., a pale elasipodid and a purple elasipodid. The frame’s bow wave occasionally pushed the phytodetritus and top sediment layer off, revealing numerous tubes, probably of polychaete origin.

3.1.7. Forearc - Peridotite Location, off Zavodovski Island

Intensely serpentinized peridotites were dredged during a previous British expedition in the fore-arc area off Zavodovski Island (Pearce et al., 2000). This area was selected as a site for investigation because abiogenic methane production is a known product of the serpentinisation process and could be seeping from the seafloor here. During PS81 and PS119, hydroacoustic anomalies were detected at a ridge structure in this location. In 2019 (PS119), a camera dive was conducted across an arc-parallel ridge around the most prominent hydroacoustic water column anomaly (Figure 6A). The seafloor was characterised by volcanic rock outcrops and escarpments, often without sediment cover, and flatter, gravelly sedimented areas. The hard-rock outcrops at bathyal depths of over 2300 m in southern-eastern part of the investigated area were densely colonized by a rich epifaunal suspension feeder assemblage, including comatulid and stalked crinoids, isidid and primnoid octocorals, as well as motile asteroids, ophiuroids and gastropods (Figure 6C-E). Multiple macrouroid fish were in single fields of view (Figure 6C). At the bottom of one escarpment, close to the approximate center of the hydroacoustic water column anomaly, a dense biogenic substrate was seen, which potentially could be bivalves or cnidarians, and might indicate active fluid flow in the sediments (Figure 6E). On the flat, gravelly bottom seafloor areas, partially buried ophiuruids were seen, together with rare occurences of a decapod lobsterette (Figure 6F). MAPR data recorded during the entire deployment did not reveal any anomaly indicating active fluid flow, i.e. temperature, ORP signal, nephelometer.

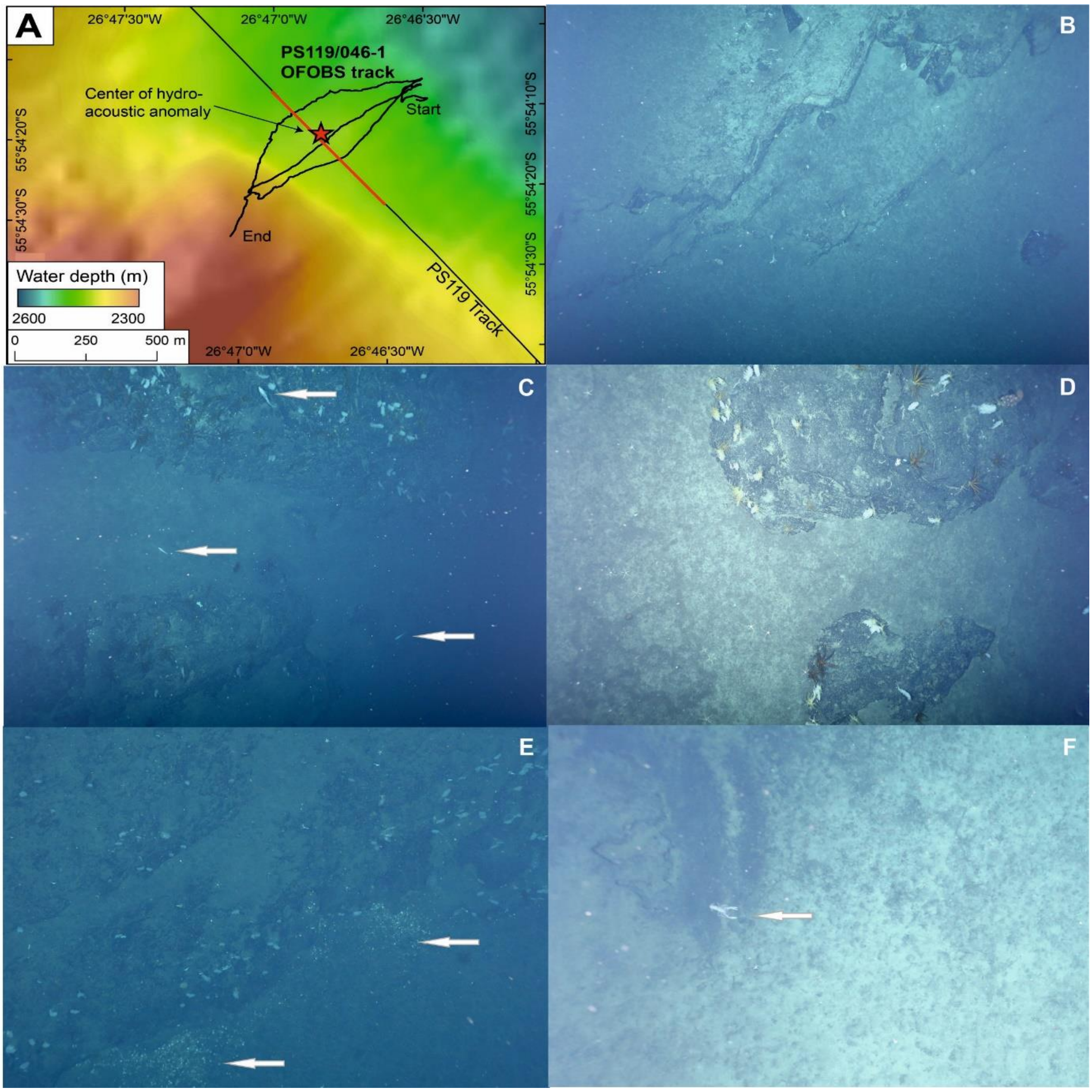

Figure 6. Potential seep area at Peridotite Location. A) Map showing the transect of PS119/046-1; B) Arc-parallel scarp with thin sediment layer; C) Densely colonised scarp with suspension feeder assemblage including comatulid and stalked crinoids, isidid and primnoid octocorals, motile asteroids, ophiuroids and gastropods, in the soft sediment pennatulid *Umbellula* indet., asteroids and ophiuroids, and macrourid fish (arrows) present; D) Volcanic outcrop with suspension feeder assemblage; E) Escarpment with dense biogenic substrate (arrows), potentially bivalves or cnidarians, on the bottom; F) Gravelly sediment in flat areas with adundant, slightly buried ophiroids and a decapod lobsterette (arrow).

3.1.8. East Scotia Ridge - Segment E5

Based on previously detected water column anomalies indicating hydrothermal activity (German et al., 2000), the axial rift site at E5 (57°22S 30°07 W, ~3800m) was investigated with MAPRs and relatively weak anomalies suggested a source of hydrothermal fluids in the area. The MAPR deployment during PS81/032-1 localised two sites of temperatures anomalies during the micro-bathymetry survey, but the imaging survey missed these sites (Figure 7A, D, E). The area of the imagery survey showed heavily sedimented pillow lava and escarpments (Figure 7B, C). The sediments between the pillow lavas were sparsely inhabited by different species of holothurians, stalked crinoids, ophiuroids and enteropneusts (Figure 7B, C), while few sponges, hydrocorals, ophiuroids and a very large anemone were seen on the lavas.

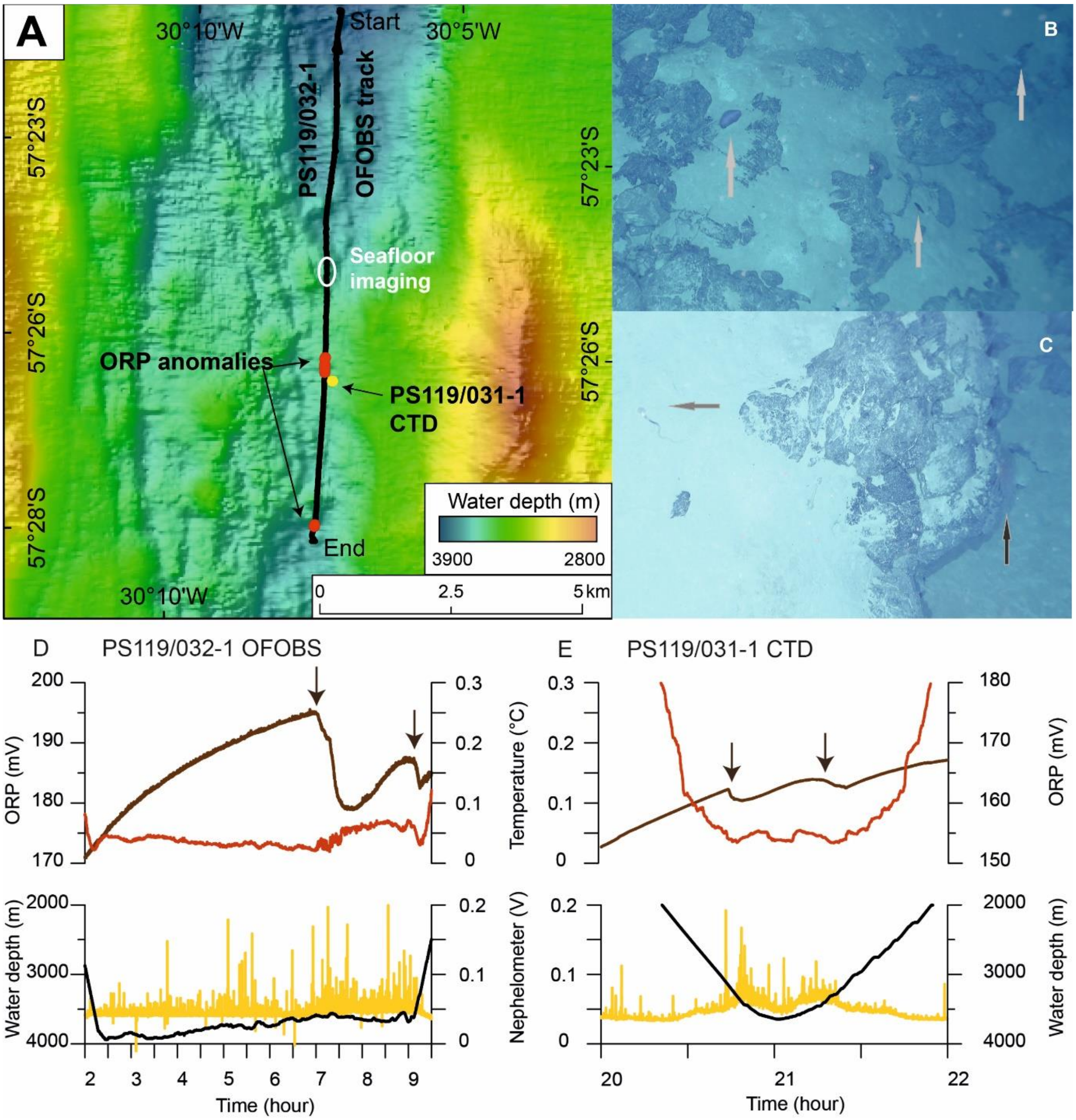

Figure 7. Site of water column anomaly at ESR segment E5. A) Map showing the transect of PS119/032-1; B) Three different species of holothurians (light grey arrows) on the soft sediment; C) Sedimented area and pillow lava inhabited by an enteropneust (mid grey arrow) and a very large anemone (black arrow); D) MAPR detected redox potential, temperature and turbidity anomalies during OFOBS PS119/032-1; E) MAPR detected redox potential, temperature and turbidity anomalies during CTD PS119/031-1. OFOBS/CTD profile – black line, redox potential - brown line, temperature - red line, turbidity yellow line.

3.2. Megabenthos habitat comparisons between sites

For the comparison of megabenthos habitats between sites, the relative percentage abiotic and biotic substrate cover was assessed based on in-situ images taken from less than 10 m distance (Table 3). The investigated sites and depths varied in their abiotic substrate and megabenthic faunal traits (deposit or suspension feeder). The relative biotic substrate cover was low with <0.1% - 4.1%, apart from the area at the top of the Quest Caldera, where 20.1% of the substrate cover was suspension feeders, indicating a rich food supply.

Table 3. Relative abiotic and biotic substrate cover at the investigated sites

Area	**Protector Seamounts**				**Forearc**			**East Scotia Ridge**
Location	Quest Caldera	Quest Caldera	Quest Caldera	Quest Caldera	off Saunders Island I	off Candlemas Island	Peridotite Location	Segment E5
Station	PS81/268-1&2	PS81/268-2	PS81/268-2	PS81/268-2	PS81/270-1	PS81/273-1	PS119/046-1	PS119/032-1
Depth range	716-744 m / top	outer rim	inner rim	shute	3659-3681 m	3025-3026 m	2500-2313 m	3649-3886 m
No of images	80	77	65	33	46	14	68*	29
Mud	6.9%	43.8%	64.3%	50.3%	49.5%	90.4%	46.8%	52.2%
Sand	-	-	-	-	-	-	-	-
Gravel	-	-	6.8%	8.8%	-	-	13.2%	-
Pebbles	2.2%	26.5%	14.9%	21.9%	24.8%	9.6%	-	-
Cobbles	9.2%	5.6%	3.9%	11.6%	-	-	0.1%	-
Boulders	35.1%	18.0%	3.2%	4.1%	-	-	0.6%	-
Bedrock	-	-	2.4%	-	-	-	31.1%	-
Basalt/pillow lava	-	-	-	-	18.3%	-	-	40.0%
out of sight	25.5%	1.9%	4.1%	1.8%	8.8%	-	5.3%	7.8%
Deposit feeder	0.1%	0.3%	0.2%	0.4%	<0.1%	<0.1%	0.8%	<0.1%
Suspension feeder	20.1%	4.1%	0.4%	1.3%	0.9%	-	2.1%	<0.1%

*in-situ images of bedrock areas with dense suspension fauna were taken from >10 m distance

4. Discussion

The RV Polarstern expeditions PS81 and PS119 carried out the first visual investigations of potential hydrothermally active sites on the Sandwich Plate that had been indicated during previous explorations as hydroacoustic, light scattering, or sidescan anomalies. Our results were able to confirm anomalies at the Protector Seamounts and the ESR segment E5 and to present geomorphology and megafauna information of all investigated sites.

4.1. Geomorphology and hydrothermal activity

The Protector Seamounts form the northernmost part of the South Sandwich Islands volcanic island arc and the last explosive eruption on the site was noticed in 1962 (Gass et al., 1963, Holdgate, 1963; Leat et al., 2016). Previous expeditions studied the seafloor bathymetry by single beam and multi-beam mapping, and dredged samples revealed a dominance of silicic magmatic rocks (Leat et al 2013). At the southernmost part of the volcanic arc, in the Kemp Caldera, the vents sites are basalt- to basalt andesite hosted vent chimneys (Cole et al. 2014; Linse et al. 2019; Pape et al., this issue). The in-situ imagery from the PS81 expedition to the Protector Seamounts revealed pillow lavas, as well as small chimney structures on the top of the Quest Caldera, but as no physical samples were collected, no analyses could be done to determine the mineralogy and geochemistry of these chimneys. In the inner slope of the Adventure Crater, again at the southernmost part of the arc, thin, needle-like chimneys were seen by towed imagery survey, but no samples were collected (Tyler, 2011). The near-bottom temperature anomalies of 0.2°C to 1.5° above ambient at Quest Caldera, Protector Shoal and the unnamed volcano, clearly demonstrate that hydrothermal activity is present in the Protector Seamounts area. The highest anomalies (2.2°C above ambient) were discovered in the depression on top of the Quest Caldera, where chimney structures were also observed. Temperature anomalies with similar ranges were discovered at the ESR segments E2 and E9, and the southernmost arc Kemp Caldera at sites where active vent fields with hydrothermal venting of 212°C to 383°C where later confirmed (Rogers et al., 2012; Hawkes et al. 2013; Linse et al. 2019). Apart from the chimney structures at Quest Caldera, the Protector Seamounts vent sites have not been localised and no hydrothermal fluid samples have been collected. Therefore, no vent fluid analysis has been done to assess the chemical composition of the end members, especially for iron, (Hawkes et al 2013), which is likely to influence the overlying water column geochemistry and phytoplankton population (Ardyna et al. 2019; Shine et al. 2021).

The four sites in the Sandwich Plate forearc can be separated by the background of their previous investigations, based on dredged peridotites off Zavodovski Island (Barker, 1995) and also sidescan anomalies off Candlemas and Saunders islands (Vanneste and Larter, 2002), which could indicate the presence of mud volcanoes. The northern study site off Zavodoski Island, at the Peridotite Location, was based on the record of dredged peridotites (Barker, 1995), which were interpreted as ocean lithosphere modified by metasomatic processes associated with the subduction of the South Sandwich Trench (Pearce et al., 2000; Leat et al., 2016). Research on the mid-Atlantic Ridge Lost City vent field and other locations had created interest in the role of serpentinization of peridotite in generating hydrogen- and methane-rich fluids and supporting chemosynthetic ecosystems (e.g., Charlou et al 1998, 2002; Kelley et al., 2001, 2005; Schmidt et al. 2007). Active serpentinization has been studied at the western Pacific Mariana Trench region and revealed a serpentinite-hosted ecosystem (e.g., Ohara et al., 2012; Fryer et al., 2020). The serpentinite mud volcanoes in the Mariana Trench region, Conical and South Chamorro Seamounts, are known to host chemosynthetic bathymodiolin mussels, vesicomyid clams, galatheid crabs, actinarians and zoanthid corals (Ohara et al. 2012). These taxa are absent at Lost City, which is known for macrofauna and *Desmophyllum* sp. octocorals (Kelley et al. 2005), but bathymodiolin mussels, vesicomyid clams and gastropods have been found in a 100 kyr serpentinization-related Ghost City site on the mid-Atlantic Ridge, near the Rainbow vent site (Lartaud et al., 2011). During dive PS119/046-1 no hydrothermal activity, mud volcanoes or chimney structures were discovered, but dense assemblages of alcyonarian corals, crinoids and other suspension feeders were observed at 2330 m to 2500 m depth. This suggests frequent, if not year-round food supply, which in an aphotic zone could be of hydrothermal origin or comevia pelagic-benthic coupling from area of high epipelagic primary production. The three study sites off Candlemas and Saunders islands did not reveal hydrothermal mud volcano activity. During dive PS81/270-1 a dense assemblage of white anemones was observed in 3660 m off Saunders Island, with patches of sunken phytodetritus observed nearby.

The first indications of hydrothermal activity at the ESR segment E5 were based on water column and sidescan anomalies (German et al., 2000; Livermore et al., 2003, 2006). In 2012, persistent water column anomalies at the site described in German at al. (2000) were confirmed by temperature (0.2°C above ambient) and redox potential anomalies (Tyler, 2013). Equivalent temperature anomalies at the ESR segments E2 and E9 led to the discovery of the active hydrothermal vent fields there (Rogers et al., 2012; Hawkes at al. 2013). During PS119, temperature and redox potential anomalies were confirmed at E5 by MAPRs on OFOBS and CTD deployments, with temperature anomalies of 0.2°C above ambient close to the OFOBS track. Comparing these anomalies with those at E2 and E9, we suggest there is a site of high temperature venting at E5 close to the position investigated during dive PS119/032-1. We recommend that this position should be examined in the future by ROV. The positions of the temperature anomalies were missed by the visual imagery during dive PS119/032-1. The in-situ imagery survey revealed heavily sedimented pillow lavas and basalt rocks, similar to the non-active areas close to the hydrothermal vent fields at E2 and E9 (Linse, Bohrmann, Little and

Römer; personal observations during ChEsSO and PS119 expeditions). The basalts analysed previously from E5 were like mid-ocean ridge basalts (MORB), while lavas recovered from E2 and E9 were enriched in Rb, Ba and light rare earth elements compared to MORB (Fretzdorff et al., 2002). The uppermost sections of high-temperature fluid venting chimneys from E2 and E9 were described by James et al. (2014) for their mineralisation and were found to be similar to those found at sediment starved mid-ocean ridge hydrothermal sites.

4.2. Megabenthic Epifauna

Megabenthic epifauna was observed at all the eight investigated sites, from the shallow, 60 m deep top of Protector Shoal to the abyssal, over 3600 m deep ESR segment E5. Additionally, broad, single-bladed macroalgae were observed as a dense cover at the top of Protector Shoal, down to 66 m. Common, large, and single-bladed macroalgae in the Southern Ocean are the brown algae *Himantothallus grandifolius* (A. Gepp & E.S. Gepp) Zinova and the red algae *Sacropeltis antarctica* Hommersand, Hughey, Leister, & P.W. Gabrielson, which are commonly known as dominant benthos cover from 10 m to 40 m, and deeper (Wiencke et al., 2014; Hughey et al., 2020). The megabenthic epifauna observed in the in-situ imagery resembled faunal elements described either from the upper slope of the South Sandwich Islands (Arntz and Brey, 2003; Downie et al, 2021; Hogg et al., 2021), from the Southern Ocean in general (Gutt et al. 2013 and references therein), and from Southern Ocean seamounts (Bowden et al., 2011; Clark and Bowden, 2015). Despite finding evidence for nearby hydrothermal activity (e.g., as temperature anomalies), no recognisable megabenthic Southern Ocean hydrothermal vent taxa were seen, such like yeti crabs, *Sericosura* spp. pycnogonids, peltospirid gastropods, seven-armed star fish, and vesicomyid clams (Marsh et al., 2012; Arango and Linse, 2015; Chen et al., 2015; Mah et al., 2015; Thatje et al., 2015; Linse et al., 2019, 2020). The megafaunal elements recognised on the in-situ imagery included a long-tentacled anemone and decapod spider crabs and lobsterettes.

The very large and long-tentacled anemone seen at the ESR segment E5 resembles a member of the deep-sea actinarian family Relicanthidae (Rodriguez et al., 2014). The species *Relicanthus daphneae* (Daly, 2006) has been reported as associated with hydrothermal sites from the Northeast Pacific to the Southern Ocean, including records at the hydrothermal vent sites of the ESR segments E2 and E9 (Rogers et al. 2012; Rodriguez et al. 2014).

Lithodid crabs, including *Paralomis* indet., were present, sometimes in some density, at all sites on the Protector Seamounts. Records for the South Sandwich Islands list *Paralomis formosa* Henderson, 1888, while further *Paralomis* species, *P. anamerae* Macpherson, 1988 and *P. spinosissima* Birstein & Vinogradov, 1972, occur at similar depths at South Georgia (Griffiths et al., 2013).

The presence of a decapod lobsterette species and observations of five individuals at 2313-2500 m depth on the Peridotite Location in the South Sandwich Islands northern forearc is a new record of this rarely encountered taxon for the region. The deep-sea Nilenta lobsterette *Thymopsis nilenta* Holthuis, 1974 is known from the south-east of the Falkland Islands and south of South Georgia at 1976-3040 m depth (Holthuis, 1974). The depth (2313-2500 m) reported for the lobsterettes from the Peridotite Location is within the known depth range of *T. nilenta* and if this identificaiton could be confirmed the range of *T. nilenta* would be extended 10 degrees longitude to the east of the current known range. Two other lobsterettes are reported from South Georgia. The Patagonian lobsterette *Thymops birsteini* (Zarenkov & Semenov, 1972) and the species *Thymops takedei* Ahyong, Webber & TY Chan, 2012 are known from Southern South America, the Falkland Islands and South Georgia with shallower depth distributions of 122 m to 1400 m and 265 m to 1739 m, respectively (Wahle, 2011; Griffiths et al., 2013). However, without collected specimens the identification of the Peridotite Location lobsterette species is currently unknown.

In Antarctic and sub-Antarctic benthic habitats, a common opinion is that suspension feeders dominate in shallower waters while deposit feeders are more abundant at greater depths (Orejas et al., 2000; Gutt et al., 2013; Downie et al. 2021). Suspension feeder assemblages on the high Antarctic continental shelf and at seamounts north of the Ross Sea in 580 m to 600 m depth have been characterised as archaic assemblages based on the dominance of passive, sessile suspension feeders like primnoid and isidid octocorals, sponges, and stalked crinoids (Gili et al., 2006; Bowden et al., 2011). Our study found sessile and mobile suspension feeders to be dominant elements of the epibenthic fauna of the investigated bathyal Sandwich Plate sites, although assemblage composition varied widely between sites and depth. The surveyed abyssal sites in the forearc and ESR in general were inhabited by mobile deposit feeders, like holothurians and burrowing brittle stars. We discovered dense suspension feeder assemblages on the top of the Quest Caldera in ~700 m to 750 m depth and at Peridotite Location in 2300 m to 2500 m depth, with suspension feeders also being present on the slopes of the Protector Shoal volcanoes. These deep dense suspension feeder assemblages occurred in areas with either confirmed (Quest Caldera) or possible (Peridotite Location) hydrothermal activity. We hypothesize that those dense megafaunal assemblages are supported by emissions of hydrothermal fluids in a similar way that Arctic cold seeps support megafauna outside the seeping pockmarks (Åström et al., 2018, 2020).

Our investigation of eight sites on the Sandwich Plate has shown that sites with hydrothermal activities are not uncommon, from relatively shallow to abyssal depth. The Sandwich Plate hosts a variety of marine habitats, including seamounts, submarine volcanoes and hydrothermal vents, and the biodiversity assessment of the marine flora and fauna is still incomplete. The geomorphology and localised extents of these habitats will require remotely operated vehicle deployments to collect physicals samples for the identification of biological, geological, and chemical origins. Future studies should aim to address the role the hydrothermal habitats play against sunken epipelagic primary production in shaping the regions benthic communities.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Katrin Linse: Conzeptualization, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing review & editing, Visualiziation. **Miriam Römer**: Methodology, Investigation, Data curation, Writing review & editing. **Crispin T.S. Little**: Investigation, Writing review & editing. **Yann Marcon**: Methodology, Software, Writing review & editing. **Gerhard Bohrmann**: Writing review & editing, Project administration, Funding acquisition.

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Data management

PS81 and PS119 data, including images, videos and hydroacoustic recordings are stored in the World Data Center PANGAEA Data Publisher for Earth & Environmental Science (www.pangaea.de) with a secured access.

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