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ABSTRACT

As part of an expedition aboard the Nathaniel B. Palmer RVIB, hundreds of still images were captured of the Ross Sea continental shelf seafloor. Using a crowd-sourced group of experts, we identified the fauna captured in these images, identifying over 1000 organisms to 15 major taxonomic groups (viz., anemones, bivalves, brittle stars, cephalopods, corals, crinoids, crustaceans, fishes, holothurians, isopods, pycnogonids, sea urchins, sea stars, sponges, tunicates). On the basis of the organisms we could identify to genus or species, we compiled a checklist of the fauna from this poorly-known area. The images from this yo-yo camera survey show a diverse community of life that was largely unknown for this sector and may reveal expanded ranges for some species and potentially new ecological information.

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INTRODUCTION

The Ross Sea is a large embayment in the southwest Pacific sector of Antarctica that lies north of the world's largest body of floating ice, the Ross Ice Shelf (Smith et al., 2007). The ice shelf covers an area of 292,900 km^2 (182,000 mi^2) and receives ice drained from large areas of East and West Antarctica (Fig. 1, 2) (Anderson et al., 2014). The fauna of the Ross Sea remains relatively underexplored despite attempts to understand it dating back to the time of James Clark Ross in the mid-1800s and in spite of 60 years of modern-collections efforts (DeWitt and Tyler, 1960; Eastman and Hubold, 1999; Smith et al., 2007). The fauna beneath the Ross Sea is less explored even compared to other Antarctic regions (e.g., Weddell Sea), perhaps due to its vastness and inaccessibility (Brasier et al., 2018; Pineda-Metz et al., 2020). Here we group, organize, and identify the organisms captured in photographic images from a recent expedition in order to compile a novel checklist of this fauna based on "yo-yo" camera observations and to better understand the distribution of the identified species within the Ross Sea (Fig. 1). (The camera systems used are called "yo-yo" because they are continuously raised and lowered as the ship makes a survey traverse.)

The Antarctic continental shelf has an average depth of 500 meters and is fore-deepened, i.e., deepens towards the continental interior (Holtedahl, 1929; Shepard, 1931). The great depth and landward dip of the continental shelf is due to ice sheet erosion and isostatic adjustments to the weight of the ice sheets (Zhivago and Lisitsin, 1957; ten Brink and Cooper, 1992). The bathymetry of the continental shelf is characterized by large-scale trough and bank topography (Shipp et al., 1999; Bart et al., 2011, 2017). The troughs were eroded by fast-flowing ice streams during waxing and waning of the Antarctic Ice Sheets (Alley et al., 1989). The continental shelf morphology influences Antarctic ice sheet response to climatic forcing (Bart et al., 2016; Colleoni et al., 2018). Grounded ice had last advanced to the outer continental shelf during

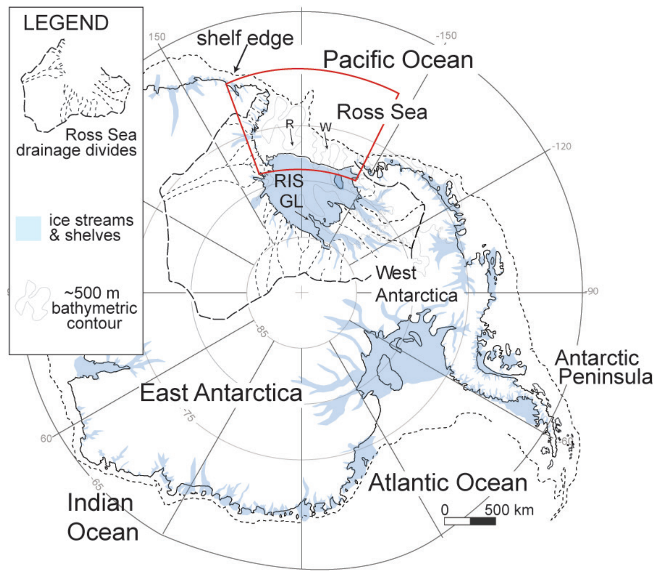


Figure 1: Image of the Antarctic: Red region in the figure to the left is expanded in Figure 2. (RIS=Ross Ice Shelf; GL=grounding line; R=Ross Bank; W=Whales Deep)

the last glacial maximum, i.e., about 18,000 years before present (Anderson et al., 2014). Since the end of the last glacial maximum, grounded and floating ice has retreated to the inner continental shelves (Domack et al., 1999). In the Ross Sea sector, the West Antarctic Ice Sheet has retreated more than 1000 km from the continental shelf edge (Shipp et al., 1999; Anderson et al., 2014). Marine geological and geophysical data demonstrate that five major ice streams (zones of fast flowing ice), drained into the Ross Sea (Mosola and Anderson, 2006). The ice streams occupied trough basins that are as much as 100 km wide; one of these basins, "Whales Deep" was a focus of a recent geological investigation in the Ross Sea by the last author (PJB in McGlannan et al., 2017) that took the images investigated in this study.

The first attempts at video observations from beneath the Ross Shelf observed a limited number of fishes (one identified as a *Trematomus:* Nototheniidae) and invertebrates (mostly amphipods) (Clough and Hansen, 1979; Bruchhausen et al., 1979). These early images were taken at a time that few observations of life in the Antarctic were known. Although faunal studies of the Antarctic continue to increase (Brasier et al.,

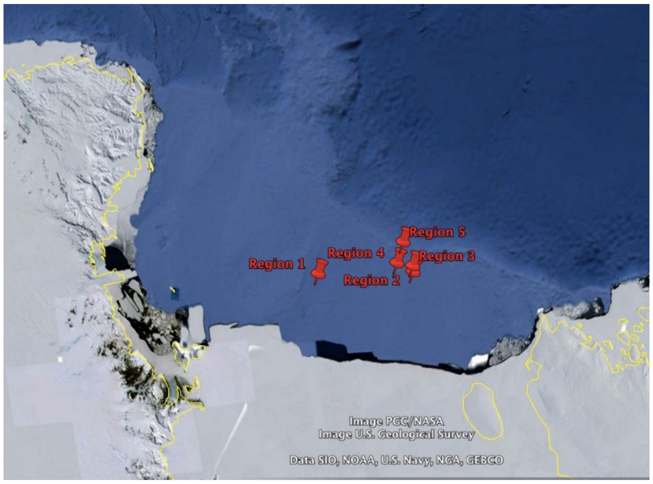


Figure 2: Regions sampled and imaged from the Ross Ice Sea Shelf. Descriptions in Table 1.

2018; Pineda-Metz, 2020), surveys to date have been far from exhaustive.

"Gyre-like" undershelf circulation, extreme seasonality and the geographic diversity described above may lead to higher species diversity than a more uniform homogeneous setting (Smith et al., 2007). Because the habitat of the Ross Sea is not uniform, we hypothesize that the benthic marine community of this region will be similarly varied.

MATERIALS AND METHODS

All images in this study were taken aboard the Nathaniel B. Palmer RVIB from January 27 to February 17, 2015. Depth and tow duration are provided in Table 1. The focus of that expedition was geological and not biological (McGlannan et al., 2017). Images were taken in short transects at sites where geological coring of sediments were collected to reconstruct the deglacial history and to assess the degree to which benthic organisms may have disturbed the sediment-water interface and near-seafloor marine sediments (McGlannan et al., 2017). The last author (PJB) and a team of researchers deployed a yo-yo camera along five geographic locations that correspond to sediment coring stations (Fig. 2) and used the ship's GPS to estimate the geographic location of the images.

The sea floor images were taken with a vertically-oriented "yo-yo" camera system that was continuously raised and lowered as the ship traveled at approximately 1 knot. A weight suspended approximately 2.5 meters below the camera's housing triggered a bottom contact switch on the camera. The field of view on the images is approximately 3 m^2. Two parallel laser beams were set 10 cm apart for scaling.

The images of the seafloor cover five locations (Table 1, 2; Fig. 2), and were used to describe the existing seafloor conditions at those core stations as well as to understand the degree to which the seafloor may have experienced post-depositional disturbances including bioturbation that might affect the interpretability of near-surface sedimentologic changes (see below). These five core stations were surveyed at two general locations that were of interest to the geological objectives. One station, box core 1 (Region 1: BC1), was surveyed at the crest of Ross Bank (Fig. 1,2); core samples were acquired from four other stations (Regions 2-5: KC3, KC4, KC6 and KC12) surveyed in the Whales Deep Basin (Fig.1,2).

Time-stamped images from this expedition (Fig. 3) were made available via the web (https://rossiceshelf.shutterfly.com/) to six taxonomic experts (including authors of this paper and those in the acknowledgments) in different zoological fields from January 2018-March 2021 (the site is now open for public viewing and comment). The organisms in the images were grouped and organized based on morphology and geographic location (we divided the sampling sites into five regions; see Table 1). We categorized the faunal images into 15 broad taxonomic groups: brittle stars, sea stars, fishes, crinoids, cephalopods, urchins, sponges, corals, crustaceans, holothurians, anemones, pycnogonids, isopods, bivalves and tunicates. These 15 groups were examined to better describe their distribution and abundance in the Ross Sea. The organisms were then identified to the most specific level of classification possible (the consensus identifications are reported here if multiple identifications were initially provided). When we report a count of an "individual" that

Table 1: Descriptions of each region with the dates the images were taken and GPS coordinates for each site. The depth of each region as well as the length of the transect the ship traveled are in the last column.

Region #: Official Name Date Images Taken	GPS COORDINATES	Depth/Transect Length
Region 1: Ross Bank BC1 January 27, 2015	Lat.: 76°42.414 S; Long: 179°6.051W	174 m/1 km
Region 2: Whales Deep KC3 February 3, 2015A	Lat.: 76°46.134 S; Long: 170°31.341 W	512 m/6 km
Region 3: Whales Deep KC4 February 3, 2015B	Lat.: 76°38.730 S; Long: 170°34.149 W	576 m/5 km
Region 4: Whales Deep KC6 February 10, 2015	Lat.:76°35.154 S; Long: 168°80.099 W	584 m/8 km
Region 5: Whales Deep KC12 February 17, 2015	Lat.: 76°09.099 S; Long: 168°79.976 W	596 m/.5 km

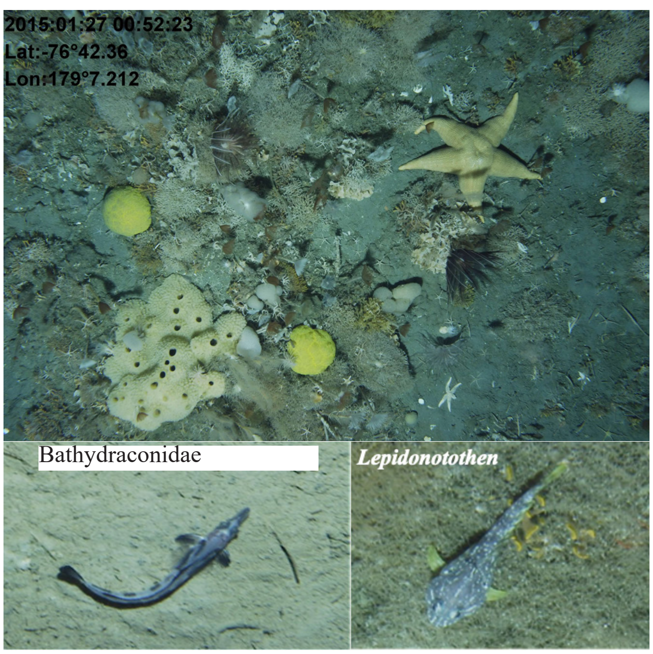


Figure 3: Example whole image taken from the yo-yo camera survey in the Ross Sea as well as selected individual fish taken from part of other images (Bathydraconidae left; *Lepidonotothen* right).

observation reflects a single observation of one "organism" or "cluster of organisms" in the case of colonial animals, such as corals.

RESULTS AND DISCUSSION

We compiled the following checklist based on the lowest taxonomic level to which we were able to make identifications. The organisms were all captured in images from our yo-yo camera surveys. Table 2 shows the observed abundance information for the organisms that we could identify to each of the 15 major taxonomic groups. The checklist below includes all the taxa we were able to identify to the family level or lower. Unfortunately, of those 15 major taxonomic groups we were only able to identify organisms to genus or species for the fishes, cephalopods, sea urchins, sponges, sea stars, and holothurians.

Checklist of the Undersea Fauna of the Ross Sea Continental Shelf - # of individuals identified in parentheses, followed by region(s) observed.

Fishes (Chordata: Vertebrata)

Notothenioidei
 Bathydraconidae
  Bathydraco sp. (1) Region 4
 Channichthyidae
  Champsocephalus sp. (1) Region 4
 Harpagiferidae
  Harpagifer sp. (21) Region 1, 3
 Nototheniidae
  Lepidonotothen sp. (1) Region 1
  Trematomus sp. (1) Region 1

Note: An individual of the Notothenioidei (not identified to family) was observed in Region 2, and members of the Bathydraconidae (9 individuals) were observed in Regions 3 and 4 and Channichthyidae (4 individuals) in Regions 1 and 5 were also identified. These could not be identified below the level of family. All fishes identified belong to the suborder Notothenioidei.

Cephalopods (Mollusca: Cephalopoda)

Octopoda
 Megaleledonidae
  Pareledone albimaculata (1) Region 1
  Pareledone pan chroma (1) Region 5
  Pareledone turqueti (1) Region 2
 Octopodidae
  Graneledone antarctica (1) Region 1

Sea Urchins (Echinodermata: Echinoidea)

Ctenocidaridae
  Ctenocidaris sp. (28) Region 1, 5
Echinidae
  Sterechinus sp. (11) Region 5

Note: Eight members of the Cidariidae were observed in Regions 1 and 5. These could not be identified below the level of family.

Sponges (Porifera)

Haplosclerida
 Callyspongiidae
  Callyspongia sp. (1) Region 1
 Chalinidae
  Haliclona sp. (5) Region 1, 4
  Haliclona tenella (1) Region 1
Lyssacinosida
 Euplectellidae
  Holascus tenuis (1) Region 2
 Rossellidae
  Rossella sp. (1) Region 1
Poecilosclerida
 Acarnidae
  Iophon unicorne (1)
 Coelosphaeridae
  Lissodendoryx sp. (1) Region 1
 Desmacididae
  Desmacidon fruticosum (1) Region 1
 Hymedesmiidae
  Phorbas areolatus (1) Region 1
 Isodictyidae
  Isodictya sp. (1) Region 1
 Microcionidae
  Clathria sp.(27) Region 1
 Latrunculiidae
  Latrunculia sp. (1) Region 1
 Mycalidae
  Mycale (*Oxymycale*) *acerata* (8) Region 4
  Mycale sp. (29) Region 1
Suberitida
 Stylocordylidae
  Stylocordyla borealis (1) Region 1
 Suberitidae
  Suberites caminatus (1) Region 1
  Suberites topsenti (2) Region 1, 5
Tetractinellida
 Tetillidae
  Antarctotetilla leptoderma (2) In Region 1, 2
  Antarctotetilla sp.(13) Region 1, 2
  Cinachyra barbata (1) Region 1
  Cinachyra sp.(1) Region 2

Note: Eight members of the Calcarea were observed in Region 3, and 14 members of the Tetillidae were observed in Region 2. These could not be identified below the level of family.

Sea stars (Echinodermata: Asteroidea)

Forcipulatida
 Asteriidae

Diplasterias brucei (3) Region 1
Notasterias armata (4) Region 1, 4
Paxillosida
Astropectinidae
Macroptychaster accrescens (17) Region 1, 3
Psilaster charcoti (3) In Region 1, 4
Notomyotida
Benthopectinidae
Cheiraster (Luidiaster) gerlachei (1) Region 5
Spinulosida
Echinasteridae
Henricia sp. (2) Region 2
Valvatida
Ganeriidae
Perknaster sp. (1) Region 1
Odontasteridae
Acodontaster conspicuus (4) Region 1, 4
Acodontaster hodgsoni (1) Region 2
Acodontaster sp. (4) Region 1, 2
Odontaster validus (11) In Region 1
Poraniidae
Glabraster antarctica (1) Region 4
Solasteridae
Lophaster gaini (1) Region 1
Paralophaster antarcticus (3) In Region 1
Velatida
Pterasteridae
Pteraster sp.(2) Region 4, 5
Korethrasteridae
Peribolaster macleani (2) Region 5

Note: Three members of the Odontasteridae were observed in Region 5, and five members of the Asteriidae were observed in Region 1, these could not be identified below the level of family.

Holothurians (Echinodermata: Holothuroidea)
Elasipodida
Elpidiidae
Peniagone sp. (10) Region 4
Protelpidia murrayi (9) Region 3, 4
Holothuriida
Holothuriidae
Psolus sp. (198) Region 4
Synallactida
Synallactidae
Bathyplotes moseleyi (23) Region 5

Anemones sensu lato (Cnidaria: Hexacorallia)

Note: None of the five anemones observed (all in Region 4) could be identified below the family level and were determined to likely be members of the orders Actiniaria or Ceriantharia (see Rodríguez et al. 2013)

Despite more than 60 years of study, the aquatic environment of the Ross Sea continental shelf is one of the least studied habitats on Earth (DeWitt and Tyler, 1960). Our survey revealed several habitat types and less homogeneous habitat than expected (Eastman and Hubold, 1999). The common macrofauna included fishes (62 individuals), brittle stars (188), cephalopods (8), urchins (93), sponges (131), sea stars (184), tunicates (96), crustaceans (18), holothurians (235), pycnogonids (17), corals (86), crinoids (18), anemones (5), isopods (7) and bivalves (48).

Our understanding of life in this extreme environment has improved with recent advances in imaging technology permitting us to view the areas that are sea-ice covered most of the year. With the help of a global network of researchers, we identified a significant number of organisms (1216) living on or near the seafloor of the Ross Sea. Unfortunately, identifications were made only from images as voucher specimens were not collected for this geological survey. For that reason, there were several taxa that were identified only to order or family. In these cases, we sided with caution rather than positing an identification that is tenuous. We expect these identifications to be dynamic as other researchers may now go to these images on the web (https://rossiceshelf.shutterfly.com/) and add their own comments and potentially new identifications. However, this paper reflects the best attempt by taxonomic experts to identify the fauna captured in these images.

Ross Bank (the site of Region 1) is one of the

Table 2: Breakdown of the number of individual observations by group and region. See also Figure 4.

	Region 1	Region 2	Region 3	Region 4	Region 5
Fishes	26	15	14	5	2
Brittle Stars	8	90	26	12	52
Cephalopods	5	1	1	0	1
Urchins	20	1	14	28	30
Sponges	83	19	0	21	8
Sea stars	100	49	7	8	20
Tunicates	50	0	0	11	35
Crustaceans	0	5	1	12	0
Holothurians	2	0	93	124	36
Pycnogonids	0	0	10	7	0
Corals	0	0	3	52	31
Crinoids	0	0	0	18	0
Anemones	0	0	0	5	0
Isopods	0	0	0	0	7
Bivalves	0	0	0	0	48

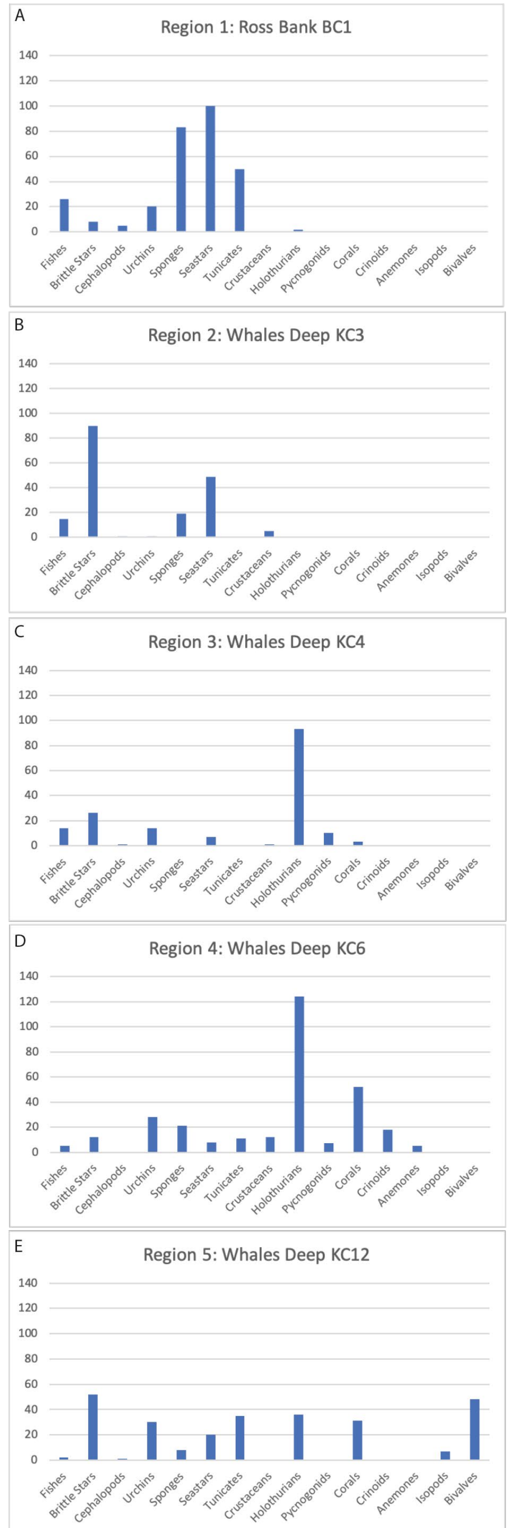
the shallowest areas in the Ross Sea, and the shallowest region sampled here (<200 versus 500-600 meters for Regions 2-5); it also is notable for having only a thin and patchy layer of fine-grained glacial marine sediment covering lithified rock. The crest of the bank was covered by grounded ice during the last glacial maximum (Shipp et al., 1999). Geophysical data suggests that the floating Ross Ice Shelf was pinned to the crest of the bank during most of the deglacial retreat after the last glacial maximum. These data indicate that Region 1 was probably the last place in the Ross Sea that benthic organisms could have recolonized after the last glacial maximum. Region 1 had the highest number of sea stars (100 versus <50 elsewhere). It is also notable that brittle stars were more often observed where sea stars were relatively limited in number and vice versa (with the qualifier that brittle stars can be very small and may have eluded detection in some images): there were only eight brittle stars in Region 1, while in Region 2 and 5 which had brittle stars in high numbers (>50) there were fewer sea stars (<50). Region 1 also had the highest abundance of sponges (83 individuals, all others had <22), fishes (26 individuals versus <16 in all other areas), cephalopods (5 versus 1 or fewer elsewhere) and tunicates (50 versus <36 elsewhere). Region 1 lacked crustaceans, pycnogonids, corals, crinoids, anemones, isopods and bivalves that and had few holothurians (2) relative to deeper sites where these organisms were much more abundant. We can only postulate that the relative shallow depths and thin layer of sediment of this site explain those higher counts.

In contrast to Region 1, radiocarbon dates of in situ benthic foraminifera from subsurface sediments cored at the outer continental shelf of the Whales Deep Basin (the core sites of Regions 2, 3 and 4) was free of grounded ice by ~14,700 years before present (Bart et al., 2018). Those benthic foraminifera lived below a small ice shelf that formed as grounded ice (ice in contact with the seafloor) retreated. Thick ice shelf cover existed until ~12,300 years before present and during that time, approximately three meters of sediment accumulated in the sub-ice-shelf environment; Regions 2-4 have a thicker layer of fine-grained sediment with scattered clasts. These outer continental shelf sites were thus transformed into open-marine sites after approximately 12,300 years ago and since that time, approximately 20 cm of diatom ooze has accumulated (Bart et al., 2018). Grounded ice then retreated ~200 km from the middle continental shelf 11,500 years ago (Bart et al., 2018) before eventually retreating to its current location sometime around 3,200 years ago (Conway et al., 1999). This geological history's link to the biological diversity is unclear, but we do note that Regions 2-4 are notable in having high abundance of brittle stars (68% of total individuals), crustaceans (absent elsewhere), holothurians (85% of total individuals), pycnogonids (only in regions 3 and 4), crinoids and anemones (both only in Region 4).

As noted by McGlannan et al. (2017), Region 5 is closest to the continental shelf edge and the deepest water depth site sampled; it is dominated by coarser sediments in the sand and pebble size range. The coarse sediments at that site indicate that the region is actively affected by bottom currents. The other sites (from Regions 2, 3 and 4) are further from the continental shelf edge and finer-grained open-marine sediments are observed to be at the seafloor in all three of those areas (McGlannan et al., 2017). The fauna in Region 5 included the only observations of bivalves (48 versus 0 elsewhere) and isopods (7 versus 0) and had the highest abundance of urchins (30 versus fewer than <29 elsewhere).

It is hard to draw broad conclusions from the faunal distribution but it has been argued that the distribution of suspension feeders with low potential for dispersal may be linked to areas where ice has been free the longest, although this point is a subject of varying opinions and lines of evidence (Filliger et al., 2013; Pasotti et al., 2015; Barnes et al., 2016). We refrain from drawing a strong conclusion here based on our ambiguous results as different kinds of filter feeders were found in areas that were ice free for different periods of time.

Radiocarbon ages indicate that the current



Figures 4. Breakdown of major groups by abundance of individuals in Region 1: Ross Bank BC1; Region 2: Whales Deep KC3; Region 3: Whales Deep KC4; Region 4: Whales Deep KC6; Region 5: Whales Deep KC12.

open-water conditions on the outer continental shelf existed up to 12,300 years ago. The diatom, foraminifera and macroscopic fossil assemblages in open-marine sediments indicating that the Ross Sea continental shelf is currently most biologically productive in the austral summers as sea-ice melts (Domack et al., 1999; Majewski et al., 2018, 2019). Seasonality likely plays a strong role in the faunal diversity of this region (see Smith et al., 2007).

The geological and geophysical data explain that the five regions investigated here were covered by grounded and then floating ice several thousands of years ago (Conway et al., 1999; Anderson et al., 2014; Bart et al., 2018). The current open-marine conditions, with its assemblage of epibenthic and benthic life, we show here, were established sometime after grounded and floating ice retreated. Where surveyed, benthic assemblages on Antarctic shelves are often dominated by sessile suspension-feeders but the sampling to date remains highly patchy (Clarke and Johnston, 2003). Post et al. (2011) used video to analyze benthic communities at 22 sites across the George V shelf of East Antarctica from sites that ranged in depth from 177 to 1175 meters. A high cover, diverse benthos that included bryozoan, demosponges, colonial tunicates, holothurians, crinoids, brittle stars and soft corals was reported. Seabed imagery showed sessile suspension feeders transitioned to grazing organisms with increasing distance from open water below the Amery Ice Shelf of East Antarctica (Post et al., 2014). These findings are consistent with the hypothesis that a food web develops below a floating ice shelf in close proximity to grounded ice where light is absent and food is scarce (Bart et al., 2016; Kingslake et al., 2018; Majewski et al., 2018, 2019). Indeed, video and photographic images collected in 2015 from below the Ross Ice Shelf as part of the Whillans Ice Stream Subglacial Access Research Drilling (WISSARD) project observed fish (what appeared to be nototheniid fish, possibly *Pleuragramma*) to be found near the West Antarctic Ice Sheet grounding zone, which in this sector is several hundreds of kilometers from open-water (Fox, 2015).

Threats to the Antarctic fauna include diminished ice cover from a warming climate (Aronson et al., 2009), overexploitation (Hibberd, 2016), and even SARS-CoV-2 which could affect organisms at higher trophic levels before indirectly impacting those below the ice (Barbosa et al., 2021). These unique ecosystems will likely experience changes as calving fronts and ground lines oscillate in response to climatic warming. The documentation of the current state of the habitat beneath the Ross Sea is important because it allows subsequent changes to be measured. Although this study is a preliminary one incidentally born out of a geological exploration, it may help explain this unique community as it exists today further permitting it to be recorded for posterity in the face of an uncertain future.

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