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ORIGINAL RESEARCH PAPER

A geomorphological seabed classification for the Weddell Sea, Antarctica

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Abstract Sea floor morphology plays an important role in many scientific disciplines such as ecology, hydrology and sedimentology since geomorphic features can act as physical controls for e.g. species distribution, oceanographically flow-path estimations or sedimentation processes. In this study, we provide a terrain analysis of the Weddell Sea based on the 500 m × 500 m resolution bathymetry data provided by the mapping project IBCSO. Seventeen seabed classes are recognized at the sea floor based on a fine and broad scale Benthic Positioning Index calculation highlighting the diversity of the glacially carved shelf. Beside the morphology, slope, aspect, terrain rugosity and hillshade were calculated and supplied to the data archive PANGAEA. Applying zonal statistics to the geomorphic features identified unambiguously the shelf edge of the Weddell Sea with a width of 45–70 km and a mean depth of about 1200 m ranging from 270 m to 4300 m. A complex morphology of troughs, flat ridges, pinnacles, steep slopes, seamounts, outcrops, and narrow ridges, structures with approx. 5–7 km width, build an approx. 40–70 km long swath along the shelf edge. The study shows where scarps and depressions control the connection between shelf and abyssal and where high and low declination within the scarps e.g. occur. For evaluation purpose, 428 grain size samples were added to the seabed class map. The mean values of mud, sand and gravel of those samples falling into a single seabed class was calculated, respectively, and assigned to a sediment texture class according to a common sediment classification scheme.

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Keywords Weddell Sea · Geomorphic seabed classes · Benthic Positioning Index · Shelf edge · Sediment type assignment

Introduction

High resolution bathymetry, morphology and substrate distribution have proven their value for studies on benthic communities and habitats, biomass, feeding areas for marine mammals and geochemical ocean–atmosphere coupling. While the distribution of benthic fauna may be controlled by a combination of environmental and biological factors (Kostylev et al. 2001, 2003; Parnum et al. 2004; Post et al. 2010), it is generally recognized that many animals show a particular affinity for certain types of terrain (e.g., Dzeroski and Drumm 2003; Wilbur 2000), which provide the physical habitat or structure that is directly or indirectly suited to their mode of living. Characterization of the seabed in terms of terrain parameters such as slope, aspect, or curvature with dependencies as well to sediment distribution may therefore offer a valuable tool for delineating regions of the continental slope that are likely to support particular fauna and thereby provide a distinct habitat. Recent work in shallower water has indicated the potential for these types of techniques (Bekkby et al. 2002; Dartnell and Gardner 2004; Lundblad et al. 2006), but there has been little work in deeper waters beyond the continental shelf (Wilson et al. 2007). The morphology also plays a major role in the rather new scientific discipline of seascape ecology which tries to assess the relationship between ecology and spatial patterns such as patches, eco- or biotopes, habitats or whole landscapes (Boström et al. 2011; Pittman et al. 2011; Wedding et al. 2011).

In seascape ecology, physical characteristics of marine environments are treated as fundamental, landscape-like

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patterns that can be correlated with ecology, life-history, and biodiversity of species of the entire ecosystem. Only then, connectivity or habitat preferences can be analyzed. This approach is especially useful for hardly explored areas like the Weddell Sea.

Based on the data of the International Bathymetric Chart of the Southern Ocean, (IBCSO) (Arndt et al. 2013) we perform, for the first time, a geomorphological classification for the entire Weddell Sea and combine the results with historical sediment data and improved, morphology-related, surface sediment distribution maps.

Study area

The Weddell Sea is a key area for deep water formation and pathways (Huhn et al. 2008) (Fig. 1). Water depths in the Weddell Sea range from about 100 m at some parts of the edge of the ice shelf to 800–4000 m on the continental shelf and slope and to about 5300 m in the Weddell Sea abyssal plain. The Weddell Sea shelf is comparatively deep with a mean depth of 500 m (Haid 2013), and thus the shelf break is located approx. 2–4 times deeper than the 200 m water depth (wd) seen in other oceans (Knox 2007). This is caused by the isostatic response of the shelf to the ice sheet burdening the continent and depressing the earth's crust. For the Weddell Sea shelf, the vertical displacement amounts to 100–400 m (increasing toward the continent) (Huybrechts 2002). However, the area underlies a constant deglacial process that causes an uplift rate of several mm year^{-1} (Whitehouse et al. 2012a, b). In the south, two large ice shelves adjoin the continental shelf, the Ronne Ice Shelf and the Filchner Ice Shelf. They are often collectively called Filchner-Ronne Ice Shelf (or Ronne-Filchner Ice Shelf) since they are divided at their seaward front by Berkner Island, but connected at their

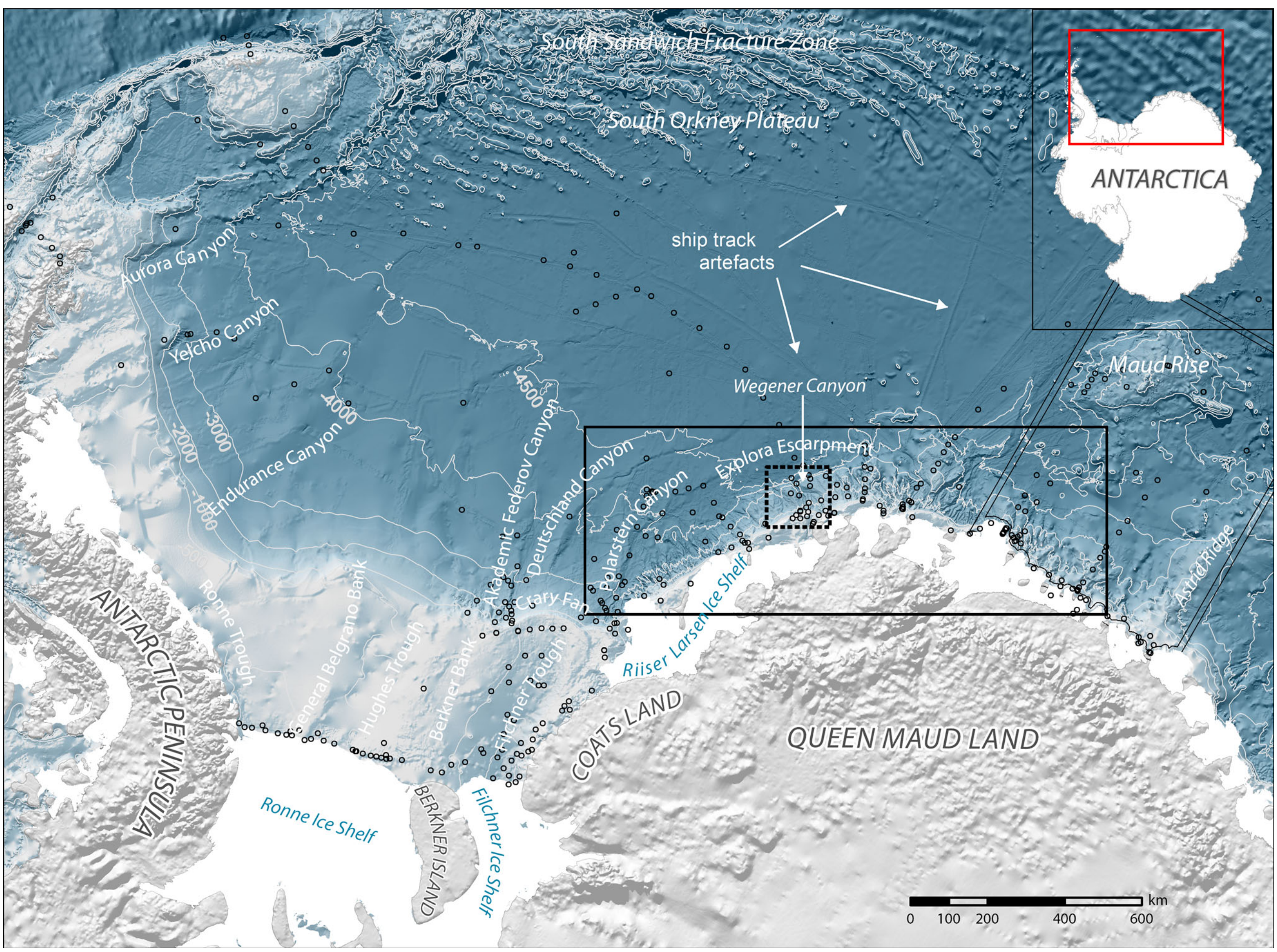


Fig. 1 Bathymetry of the Weddell Sea (IBCSO according to Arndt et al. 2013). The *red rectangle* in the overview map defines the research area. The area in the *black rectangle* is used for a single-feature analysis (section 2.1.3), the *black-dotted box* exemplifies the area for the method explanation given in Fig. 2, the *dots* represent the sediment grain size samples used in this study for the evaluation and the *double lined-box* shows exemplarily the Maud Rise area for the analysis of the association between surficial sediment distribution and geomorphology (section 3.3)

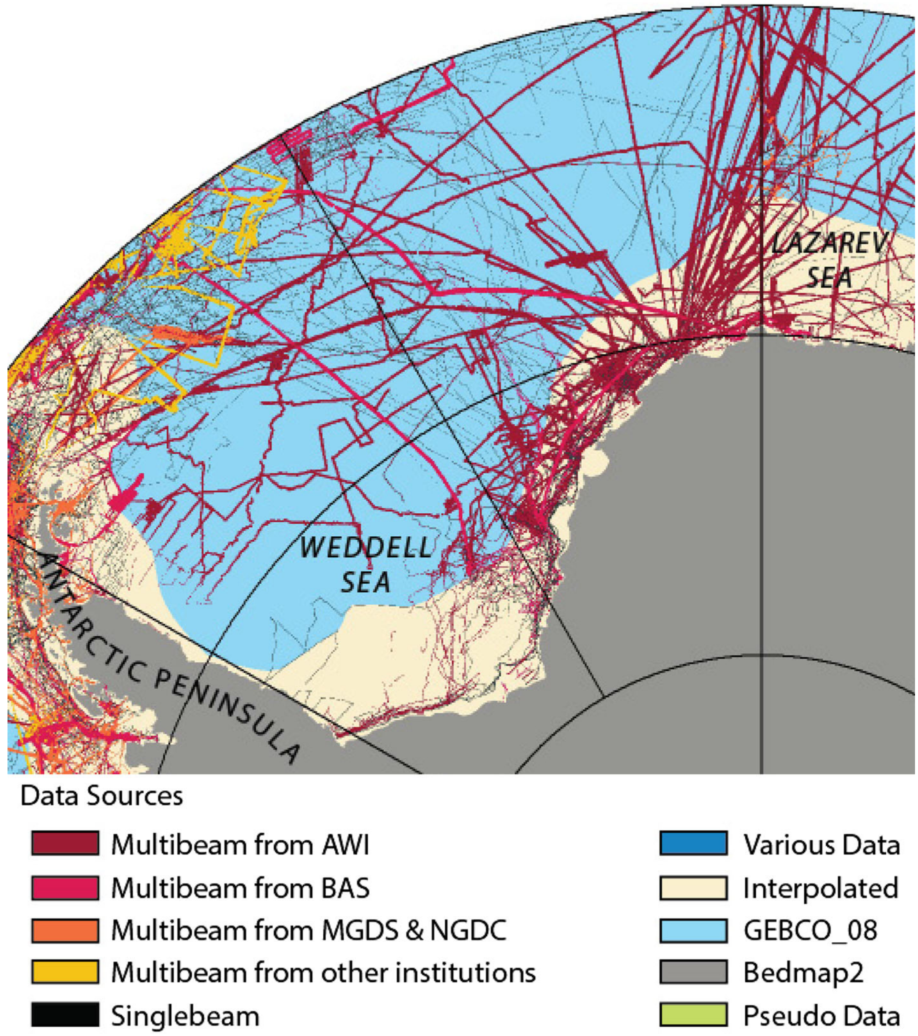


Fig. 2 Data sources for IBCSO DBM (modified from Arndt et al. 2013)

grounding zones where they are fed by various ice streams draining the West (WAIS) and East Antarctic Ice Sheets (EAIS). Prominent geomorphic features of the Weddell Sea are the relative narrow, complex structured shelf and steep continental slope in the eastern Weddell Sea and the broad shelf in the southern Weddell Sea that extends up to 500 km seaward from the coast. The deeper Filchner Trough (Fig. 1) in the southeast Weddell is a cross-shelf trough oceanographically connecting the Filchner Ice Shelf with the continental slope and the abyssal plain. The Weddell Sea abyssal plain is up to 5300 m deep. It is part of the exclusive deep connection between the great ocean basins. Only here, a latitudinal circum-navigation of the globe is possible and the west wind belt, which also is unobstructed by continents, gives rise to the world's strongest current system, the Antarctic Circumpolar Current (Haid 2013).

During former glaciations, ice sheets in the Weddell Sea extended across the shelf to the shelf break (Hillenbrand et al. 2014). They shaped the seabed and created typical glacigenic morphological features like mega scale glacial lineation (MSGLs) or grounding zone wedges (GZWs) on the shelf (Larter et al. 2012; Stolldorf et al. 2012). Since the last ice sheet retreat, icebergs continuously scour the shallower, outer parts of the shelf. This part of the shelf is structured in gullies and shows submarine landslides (Gales et al. 2014). Channel–levee systems are found at the continental slope reaching out to the Weddell Sea abyssal plain (Kuhn and Weber 1993; Michels et al. 2001, 2002). At least in the deep parts of southeast Weddell Sea, these channel-levee systems guide Weddell Sea Bottom Water (WSBW) into north-easterly direction (Haid 2013). Seismic data from the basin-floor show a deep, broad, and elongate erosional channel filled by thick chaotic-facies deposits, basin-floor fans, and channel-levee deposits. It has been formed by large-volume mass wasting sourced from poorly sorted glacial sediments from Crary Fan and Queen Maud Land slopes (Bart et al. 1999).

Bathymetry data of the southern ocean is provided by the mapping project IBCSO (Arndt et al. 2013). Thus, added values can be created by classifying and interpreting the bathymetric data. Terrain indices derived from bathymetry such as slope, orientation, curvature, terrain variability and morphology are relevant for benthic habitats, species and sediment distribution, oceanographically flow-path estimations and cold, dense shelf water pathways (Hellmer et al. 2011, 2012). They bridge the data gap between sparser biological and sedimentological sampling and the requirement for full coverage habitat maps.

Bathymetry can be a surrogate for temperature, salinity, light etc. and is often the dominant variable in habitat modelling studies (Dolan et al. 2009). Slope is relevant for the stability of the sediments, gravity driven processes and, therefore, relevant for a species having the ability to life in or on the sediment. The exposure to regional or local bottom currents from a particular direction is important for food supply, larval dispersion but also for erosion and transport of sediment particles and the creation of bed forms. Curvature and terrain variability influence the food supply and channeling of sediments and currents. Thus, the derived variables assist describing, interpreting and classifying marine geomorphology (Dolan et al. 2012); and the structural diversity of the seabed can be associated to biodiversity, flow-path estimations and surficial sediment distribution due to its reflection of dominant geomorphological processes in the Southern Ocean.

Materials and methods

In the following, the different topographical variables needed to classify the geomorphology of the Weddell Sea are described. The key data source is the IBCSO bathymetrical raster map (Arndt et al. 2013) which is the basis for terrain parameters such as inclination or slope and benthic terrain index that are required for a calculated identification of seabed classes as well as for aspect and rugosity. Furthermore, sediment grain size samples are used to evaluate these seabed classes.

Bathymetric data

An extracted area from 60°S to the coast and from 65°W to 20°E of the IBCSO map published by Arndt et al. (2013) was used to calculate slope, aspect, curvature, terrain variability, hillshade and geomorphology. The digital bathymetric model of IBCSO Version 1.0 has a horizontal resolution of 500 m × 500 m and a vertical resolution of 1 m based on a Polar Stereographic projection with true scale at 65°S and covers the area south of 60°S. IBCSO Version 1.0 DBM (Arndt et al. 2013) was compiled from available bathymetric data collectively gathered by more than 30 institutions from 15 countries. These data include multibeam and single beam echo soundings, digitized depths from nautical charts, regional bathymetric gridded compilations, and predicted bathymetry (Fig. 2) (Arndt et al. 2013).

Ship track artefacts in the bathymetric raster (Fig. 1) are integration artifacts from multibeam data and satellite derived data (Fig. 2). Consequent artifacts in the classification data were manually removed from the classification result. In the area of the abyssal plain all pairs of two isolated pixels belonging to other seabed classes were assigned to the seabed class abyssal plain. Furthermore, all features intersecting the track lines or were completely within the track lines were also assigned to the abyssal plain class. Additionally, features of one pixel size were merged to the neighbor feature they share the longest border with (Eliminate Tool, ArcGIS). Remaining unambiguous artefacts were removed manually similar to Harris et al. (2014).

Terrain variables derived from bathymetric data

The *slope* of the seabed (here the inclination of the seabed expressed in degree; as opposed to the continental slope) is a key variable in a wide selection of seabed analysis. It affects the speed of water currents and consequent erosion, slumping potential, and distribution of benthic fauna (Kostylev et al. 2003). Slope and aspect are both calculated from the directional East–West and North–South gradient (Jenness 2013). Various methods for estimating these directional gradients from a 3 × 3 set of elevation grid cells or points exist, but in general slope is defined as the seabed gradient in the direction of maximum inclination, and aspect is defined as the direction of maximum inclination. For more information on the calculation, please refer to Lundblad et al. (2006), Wilson et al. (2007), Zevenbergen and Thorne (1987) or Jenness (2004). Aspect is an important contributor to marine habitat types, as current-facing slopes often have very different conditions and nutrient supply than current-opposite slopes. It provides information on the exposure of any given area to such water movements, which may be important in shaping habitat and colonization. Also, the variability or *complexity of the terrain* has been linked to the distribution of fauna by several researchers (Beck 2000; Kostylev et al. 2005; Lundblad et al. 2006). The terrain variability can be expressed as several indices: Terrain Ruggedness Index is a measure of the local variation in seabed terrain about a central pixel (Bekkby et al. 2005; Riley et al. 1999; Wood 1996). Roughness, according to Dartnell and Gardner (2004), provides the difference between maximum and minimum bathymetry value within a user defined n × n rectangular neighborhood. Rugosity, gives the ratio of the surface area to the planar area across the neighborhood of the central pixel (Jenness 2004). Flat areas will have a rugosity value near to 1, while high relief areas will exhibit higher values.

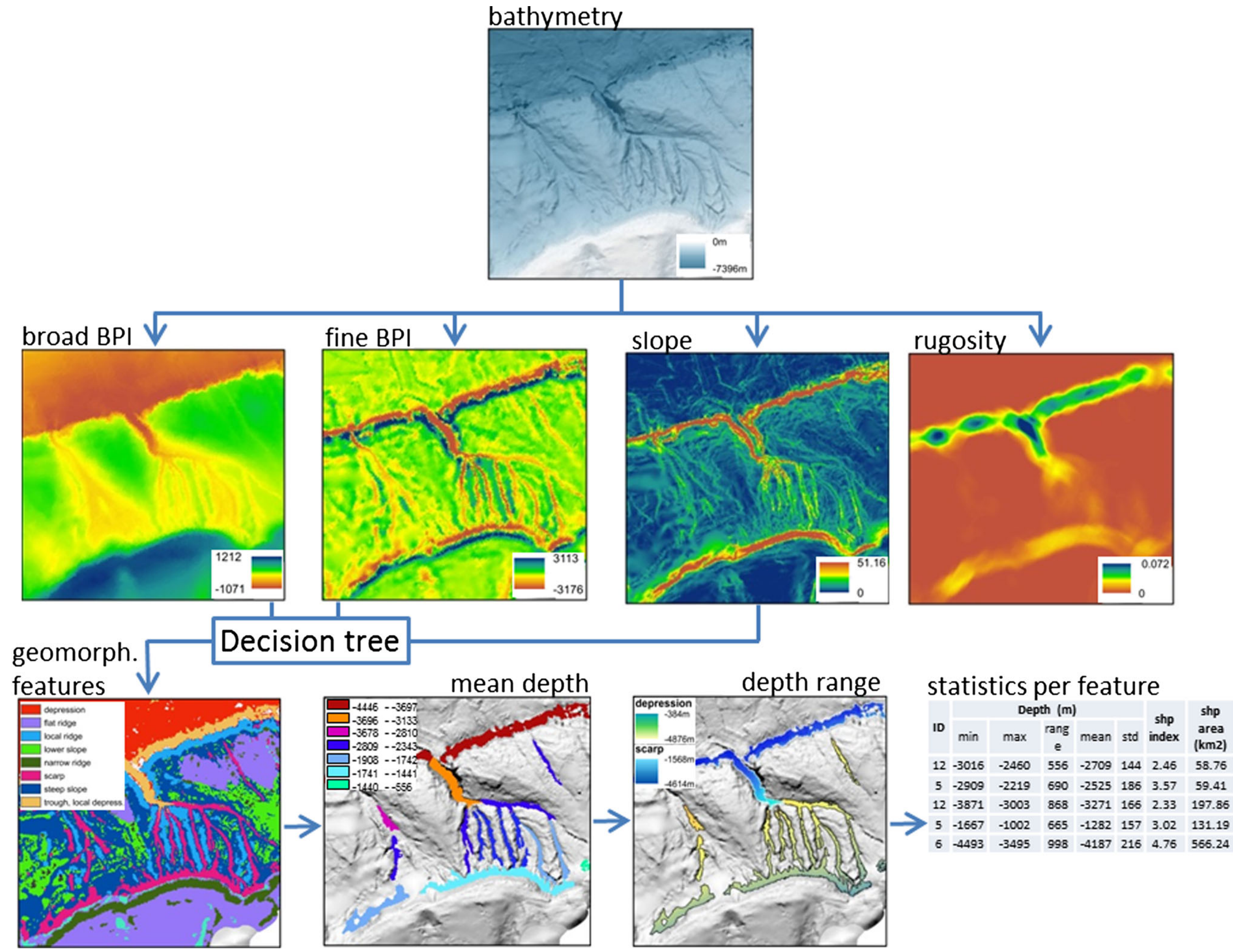


Fig. 3 Flow chart of morphology classification scheme for the Weddell Sea shown exemplarily at the Explora Escarpement, Wegener Canyon (Fütterer et al. 1990) (for geographical position please refer to Fig. 1). The final products (last image row) represent the topographical characteristics based on bathymetry and derived products (BPI and rugosity)

In this study, the vector Ruggedness Measure (VRM) (Hobson 1972) was used to measure the dispersion of vectors normal (orthogonal) to grid cells within the specified neighborhood. This method appears to decouple terrain ruggedness from slope better than other indices and effectively captures variability in slope and aspect into a single measure (Sappington et al. 2007). Ruggedness values in the output raster can range from 0 (no terrain variation) to 1 (complete terrain variation). Typical values for natural terrains range between 0 and about 0.4.

Classification of the geomorphology

The classification of the geomorphology is based on the bathymetry, the broad and fine scale Benthic Positioning Indexes (BPI), the slope, and a decision table containing definitions and thresholds appropriate to the data input (Fig. 3).

The *BPI* was adapted from a method first proposed by Weiss (2001). The Benthic Terrain Modeler (BTM) Version 3.0 extension for ArcGIS^{TM} (Wright et al. 2005), calculates at user-defined scales standardized (to avoid spatial auto-correlation) BPIs comparing the elevation of each cell to the mean elevation of the defined number of neighborhood cells. The BTM (Wright et al. 2005) comprises a set of algorithms designed for seabed classifications solely on the basis of bathymetric data. In the BTM, from the bathymetry raster the slope raster (1st derivative of the bathymetry) and the BPI grids were computed. To avoid the influence of spatial auto-correlation in the broad and fine scale BPIs, the BPIs were standardized to 1 standard deviation. Furthermore, the aspect, hillshade and rugosity were calculated using ArcGIS and BTM, respectively (*PANGAEA doi will be added during the review process*). Thus, the BPI is a measure of relative elevation in the overall "seascape". The classification table required for the identification of seabed classes in the

Table 1 Decision table summarizing the factors used for the definition of seabed classes in the Weddell Sea based on IBCSO data set (Arndt et al. 2013)

ID	Seabed Classification	Broad Scale BPI		Fine Scale BPI		Slope		Depth	
		Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper
1	Local ridge, pinnacle on slope deeper than 1000 m	100		−100	100	0.4			−1000
2	Plain deeper than 1000 m	−100	100	−100	100		0.4		−1000
3	Gentle slope deeper than 1000 m	−100	100	−100	100	0.4	1.2		−1000
4	Steep slope deeper than 1000 m	−100	100	−100	100	1.2			−1000
5	Depression	−100	100		−100				
6	Scarp		−100	−100	100	0.4			
7	Local depression on flat ridge		−100	100					
8	Flat ridge	−100	100	100					
9	Narrow ridge, rock, outcrop, seamount	100		100					
10	Local ridge, pinnacle in depression	100			−100				
11	Trough, local depression		−100		−100				
12	Local flat ridge top	100		−100	100		0.4		
13	Local depression		−100	−100	100				
14	Plain shallower than 1000 m	−100	100	−100	100		0.15	−1000	
15	Gentle slope shallower than 1000 m	−100	100	−100	100	0.15	1.2	−1000	
16	Steep slope shallower than 1000 m	−100	100	−100	100	1.2		−1000	
17	Local ridge pinnacle on slope shallower than 1000 m	100		−100	100	0.15		−1000	

Weddell Sea is given in Table 1. It is based on and adapted from former decision tables of Erdey-Heydorn (2008) and Wienberg et al. (2013).

They were modified to fulfill the requirements of the Weddell Sea morphology by using a fine scale radius of 0–5 km and a broad scale radius of 0–125 km. For the morphological seabed classification, quantiles (Evans et al. 2000) of the slope distinguished the thresholds for plain areas (<0.4°), gentle slopes (0.4°–1.2°) and steep slopes (>1.2°) on the continental slope and in the abyssal areas; while for shelf areas (<1000 m) the following quantile values were used: plain (<0.15°), gentle slopes (0.15°–1.2°) and steep slopes (>1.2°). The 1000 m isobaths were chosen to distinguish between similar seabed classes on the continental shelf and classes on the slope or in the abyssal area.

Seabed classes were identified by combining the four terrain variable grids (bathymetry, slope, BPIs at a fine and broad scale) according to a decision table defining the geomorphic properties (convex or concave shapes) (Fig. 3). The outcome of the BTM describes statistically derived, generic seabed classes. It does not consider geological or biological processes. The interpretation of these generic features in relation to the geological and biological setting is done in the discussion.

Topographical characterization of the seabed classes

The seabed classes were converted from raster cells into polygons and zonal statistics (maximum, minimum, range, mean, standard deviation, and sum) were calculated based on values from the bathymetry raster by using the ArcGIS 10.2.2 Spatial Analyst. Furthermore, the shape index (SI) was calculated. The SI characterized the deviation of a surface from its optimal enclosing circle. The smaller the SI of a shape the more compact is the shape. SI values can range between 1 for a maximally compact shape (circle) and >1 to infinity for structure-richer forms (Forman and Godron 1986).

In selected areas with high multibeam data coverage and complex morphology (Fig. 1, black rectangle), single-feature analyses were accomplished for the following seabed classes: trough or local depression (ID 5), scarp (ID 6), flat ridge (ID 8), and narrow ridge, rock outcrop or seamount (ID 9).

Sedimentological characterisation of seabed classes using historical grain size samples

The grain size data (n = 428) (Fig. 1) was standardized from absolute content values of gravel, sand, silt and clay to percentages (*PANGAEA doi will be added during the review process*). In order to correlate seabed classes with surface sediment composition, the mean fraction values (e.g. from sand) of all samples falling into one seabed class was calculated and assigned to a sediment texture class according to Folk (1954). The resulting sediment classes were then applied to the appropriate classes in the classification raster.

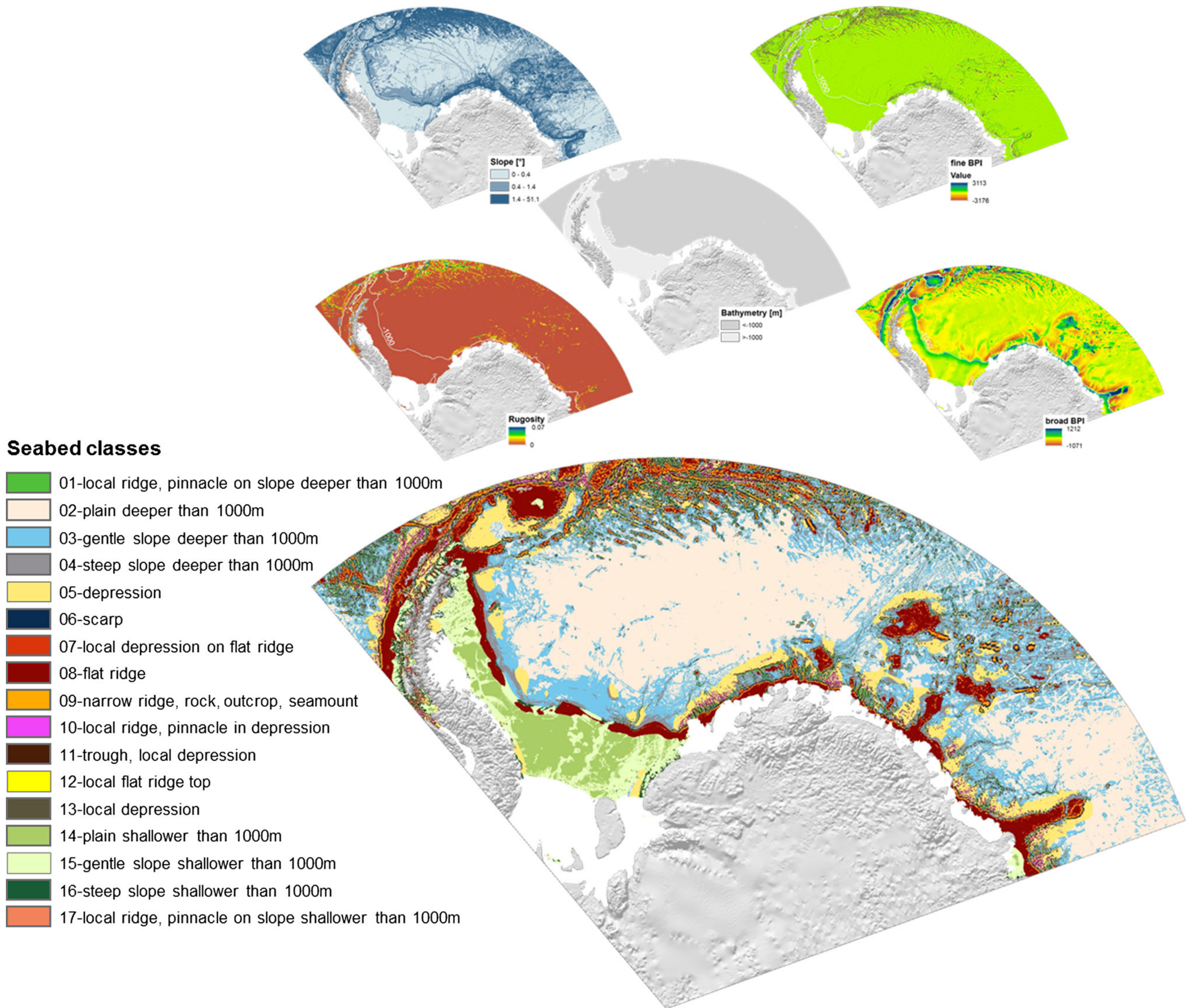


Fig. 4 The following parameters were derived from the IBCSO 2013 (Arndt et al. 2013): hillshade (ArcGIS 10.2.2 Spatial Analyst tools, ESRI), aspect and slope (DEM surface tools, Jenness 2013), VRM, broad and fine scale BPI (B-BPI, F-BPI) as well as the seabed classes derived from bathymetry, slope B-BPI and F-BPI (BTM, Wright et al. 2005). Note that areas appearing as *lines* are artefacts from ship tracks. The datasets are available at *PANGAEA doi* (*will be added during the review process*)

Results

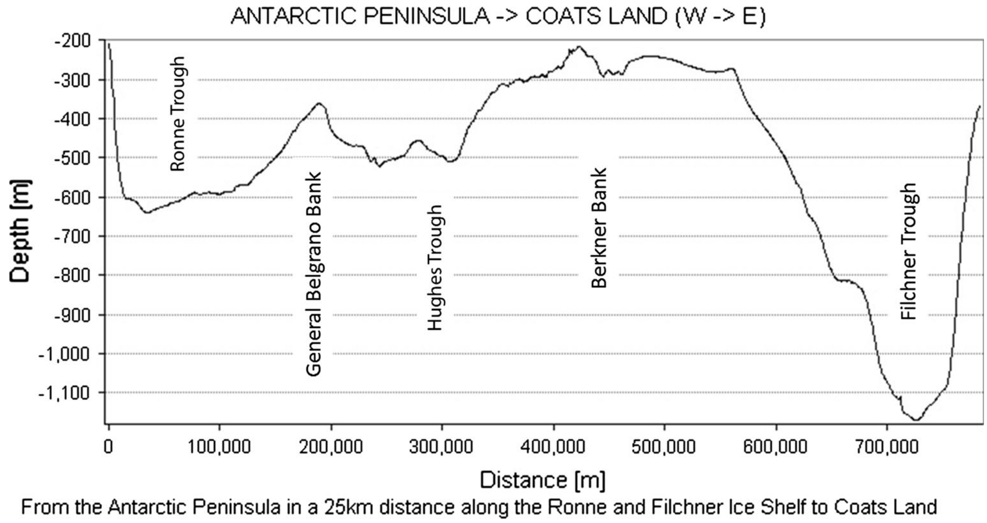
Distribution of the seabed classes

In the Weddell Sea, 17 seabed classes are recognized by the BTM. Figure 4 furthermore presents the bathymetry and its derivatives (slope, fine-scale BPI, broad-scale BPI, rugosity and the classification raster) for the Weddell Sea. Bathymetry and slope display classified rasters according to the classification table (Table 1). Rugosity only reveals increased values at the continental slope, Maud Rise area and the South Sandwich Fracture Zone. Based on these data sets, three main areas were defined: (1) the continental shelf and its shelf edge, (2) the continental slope and (3) the abyssal plain.

The continental shelf is characterized by alternating convex or concave areas and plain zones identified as gentle slopes (ID 15) and plain areas (ID 14) between depressions (ID 5) in the East and in the West (Fig. 4). In the south Weddell Sea, they indicate the Berkner Bank (approx. 160 km wide), the central Hughes Trough and the General Belgrano Bank (approx. 120 km wide and open to the Eastern plain areas) between the Filchner Trough in the East, and the low-gradient Ronne Trough in the West (see also Fig. 5). The broad-scale BPI clearly highlights these structures and incorporates them into the classification raster.

The shelf edge, the seaward determination of the shelf, is unambiguously identified by the seabed class ‘narrow ridge’ (ID 9). According to this classification, the shelf

Fig. 5 Elevation profile from the Antarctic Peninsula in a 25 km distance along the Ronne and Filchner Ice Shelf to Coats Land



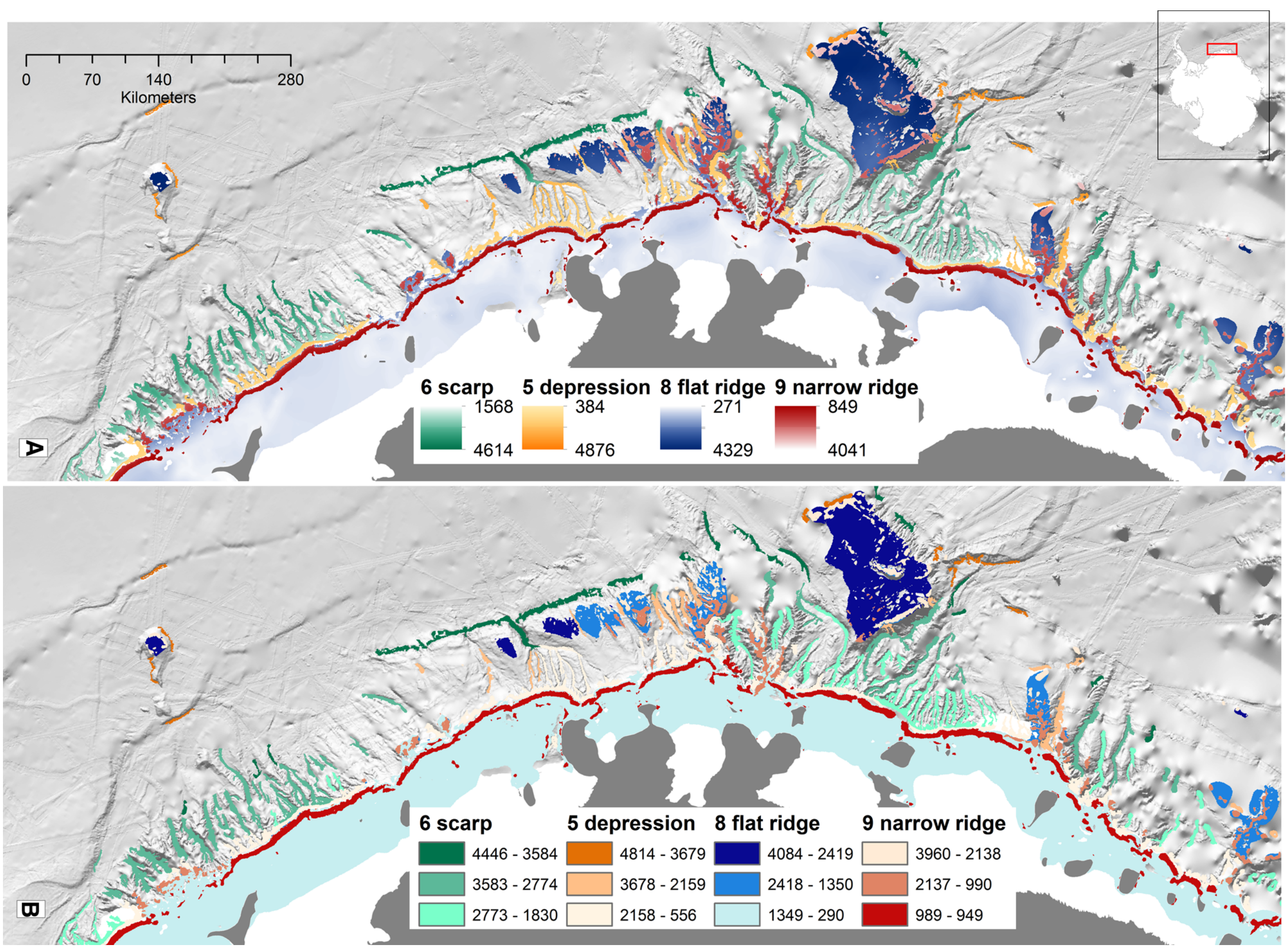


Fig. 6 Single-feature analyses for the following seabed classes: scarp (ID 5), trough or local depression (ID 6), flat ridge (ID 8), and narrow ridge, rock outcrop or seamount (ID 9). **a** shows the continuous depth range of these features and **b** their mean depth

edge is mainly 5 km wide and in some areas interrupted by continuous flat ridge areas (ID 8). This slightly convex flat ridge surrounding the shelf edge includes parts of Astrid Ridge (Fig. 1) and Gunnerus Ridge further in the East and has a width of 45–70 km and a depth-ranges from 290 to 1350 m (1200 m wd mean depth) (Fig. 6).

Table 2 Depth-related description and shape index of the seabed classes

ID	Seabed class	Depth				Shape index		
		Min	Max	Range	Mean	Min	Max	Mean
1	Local ridge, pinnacle on slope deeper 1000 m	−5533	−1000	−4533	−3623	1.13	8.52	1.66
2	Plain deeper than 1000 m	−5586	−1000	−4586	−4646	1.13	28.84	1.52
3	Gentle slope deeper than 1000 m	−5624	−1000	−4624	−4249	1.13	48.59	1.65
4	Steep slope deeper than 1000 m	−5606	−1000	−4606	−3933	1.12	29.24	1.64
5	Depression	−6845	0	−6845	−3159	1.11	25.64	1.59
6	Scarp	−5629	0	−5629	−3512	1.13	11.17	1.68
7	Local depression on flat ridge	−4899	−10	−4889	−2064	1.13	6.22	1.64
8	Flat ridge	−4931	0	−4931	−1223	1.13	17.92	1.62
9	Narrow ridge, rock, outcrop, seamount	−5218	0	−5218	−2329	1.13	8.93	1.75
10	Local ridge, pinnacle in depression	−6773	0	−6773	−3247	1.13	5.23	1.62
11	Trough, local depression	−7396	0	−7396	−3408	1.13	15.47	1.79
12	Local flat ridge top	−5368	0	−5368	−3245	1.13	2.53	1.33
13	Local depression	−5531	0	−5531	−3622	1.13	3.87	1.36
14	Plain shallower than 1000 m	−1000	0	−1000	−465	1.13	19.08	1.49
15	Gentle slope shallower than 1000 m	−1012	0	−1000	−496	1.13	46.02	1.48
16	Steep slope shallower than 1000 m	−1000	0	−1000	−487	1.13	9.75	1.71
17	Local ridge pinnacle on slope shallower 1000 m	−999	0	−999	−319	1.13	5.13	1.64

Beyond the shelf edge followed the continental slope. In the western and the central part of the Weddell Sea, slopes of steep (around 3°) and gentle values (1°), respectively, and adjacent canyons in perpendicular positions to the slope classified as depressions (ID 5) in the map. At the coast of Queen Maud Land, from Astrid Ridge to Coats Land, the shelf edge (ID 9) features inclination values around 15° and margins distinctly and visibly the continental shelf from the complex continental slope pattern of troughs, flat ridges, pinnacles, steep slopes, seamounts, outcrops, and narrow ridges. The congeries builds a swath of complex geomorphology of approx. 5–7 km width and approx. 40–70 length. The extensive morphology here is dominated by scarps (ID 6), troughs or local depressions (ID 5), flat ridges (ID 8), and narrow ridges (ID 9) (Fig. 6). Table 2 also provides shape indices for the seabed classes and its means indicate the scarps (ID 6) and the depressions (ID 5) as structure-richer forms compared to plain areas (ID 14) or flat ridge tops (ID 12). The slope, the fine-scale BPI as well as the broad-scale BPI are responsible for these structures in the classification raster (Fig. 4).

The abyssal plain is an extensive flat area (ID 2) of about 2 Mio $km^{2.}$ in the central and north Weddell Sea In this area, the seabed inclination is <0.4° and the mean depth is 4600 m wd. In the Southeast, South and Southwest, the abyssal plain is bordered by continental slopes. In the North, the South Sandwich Fracture Zone defines the northern extend. All result maps are available on Pangaea *doi* (*will be added during the review process*).

Association of seabed classes and surface sediment composition

For the entire Weddell Sea, the existing sediment data were used to calculate the mean surface sediment composition. The resulting compositions were correlated with the seabed classes. Table 3 summarizes the area in km^2 belonging to a seabed class, the sample density, the fraction mean values and standard deviations (gravel, sand, silt and clay) per seabed class as well as the appropriate Folk (1954) classification.

Note that the seabed classes were not evenly covered with sediment samples due to the limited number of sediment samples. Two classes were not sampled (ID 12 and ID 13). Consequently, the correlation values display high standard deviations. However, the analysis shows that grain sizes are related to the identified seabed classes and their geomorphic properties. 21.49 % of the samples fall into the right sediment class after the adaption to the classification raster (true label in Fig. 7). 53.03 % meet the dominating sediment fraction (good label) and 25.46 % fail to hit the right class. In more detail, the Maude Rise area shows exemplarily that coarser grain sizes appear on more exposed geomorphic features like flat ridges (ID 08) and narrow ridges, outcrops and seamounts (ID 09) (Fig. 8).

Table 3 Grain size distribution (mean in %) and standard deviation (σ) per seabed classes

ID	Seabed class	No. of samples	Area (km^2)	Sample density (100 km^{-2})	Gravel		Sand		Mud		Folk (1954) classification
					Mean %	σ	Mean %	σ	Mean %	σ	
1	01-Local ridge, pinnacle on slope deeper than 1000 m	18	1666.37	0.01080	6.73	10.35	24.75	20.83	68.53	22.61	Gravelly mud
2	02-Plain deeper than 1000 m	55	24833.67	0.00221	4.86	8.55	6.95	10.67	88.19	15.74	Slightly gravelly mud
3	03-Gentle slope deeper than 1000 m	37	11700.86	0.00316	4.84	6.32	10.80	15.77	84.37	16.65	Slightly gravelly sandy mud
4	04-Steep slope deeper than 1000 m	34	7219.43	0.00471	7.08	9.16	35.60	28.24	57.32	31.71	Gravelly mud
5	05-Depression	46	6451.96	0.00713	6.87	9.70	15.25	18.44	77.88	21.86	Gravelly mud
6	06-Scarp	20	2137.40	0.00936	5.09	11.07	49.41	30.85	45.50	30.82	Gravelly muddy sand
7	07-Local depression on flat ridge	13	467.88	0.02778	4.79	11.80	59.99	23.05	35.22	25.05	Slightly gravelly muddy sand
8	08-Flat ridge	79	5837.96	0.01353	6.14	8.98	55.28	25.77	38.58	27.26	Gravelly muddy sand
9	09-Narrow ridge, rock, outcrop, seamount	39	1820.95	0.02142	11.08	10.16	58.71	23.71	30.20	25.70	Gravelly muddy sand
10	10-Local ridge, pinnacle in depression	3	527.00	0.00569	2.31	2.42	34.77	42.40	62.92	44.80	Slightly gravelly sandy mud
11	11-Trough, local depression	9	2018.35	0.00446	1.86	2.93	27.51	30.88	70.63	32.40	Slightly gravelly sandy mud
12	12-Local flat ridge top	0	30.08		0.00	0.00	0.00	0.00	0.00	0.00	
13	13-Local depression	0	73.01		0.00	0.00	0.00	0.00	0.00	0.00	
14	14-Plain shallower than 1000 m	12	3867.37	0.00310	0.60	1.50	50.89	36.38	48.51	36.45	Slightly gravelly muddy sand
15	15-Gentle slope shallower than 1000 m	55	5549.48	0.00991	3.22	8.52	51.05	31.14	45.73	32.11	Slightly gravelly muddy sand
16	16-Steep slope shallower than 1000 m	6	939.77	0.00638	1.44	3.19	59.26	31.80	39.30	32.67	Slightly gravelly muddy sand
17	17-Local ridge, pinnacle on slope shallower than 1000 m	2	229.19	0.00873	7.00	9.90	41.58	0.60	51.42	10.49	Gravelly mud

Discussion

The 17 seabed classes occurring in the Weddell Sea seabed highlight the diversity of 'landscape' in the study area. It includes glacially carved shelf, intensely structured continental slope and the abyssal plain (Fig. 4). The detected small scale geomorphic features (Fig. 6) are of particular importance for ecosystem studies since the small-scale morphology of the seabed affect the distribution of benthic communities by influencing environmental factors like substratum, erosion or deposition of sediment, currents and nutrients. Prominent examples are depressions on the continental shelf eroded during glacial maxima with low currents today forming sediment traps for fine sediments. They provide appropriate habitats for mobile deposit feeder and infaunal communities (Gutt 2007; Post et al. 2011). Furthermore, the steepness of slope provides hints for the occurrence of hard rock surfaces which also influences the benthic community structure (Fig. 6).

Applying the BTM approach to the newly available IBCSO data (Arndt et al. 2013), generates a detailed seabed classification for the Weddell Sea. The identified seabed features (troughs and ridges) indicate a very diverse environment. This is important, because the Weddell Sea, is a key area for deep water formation and pathways, and this study produces valuable base maps, such as slope or morphology, for one of the least explored area of the world due to ice cover and difficult access and are made available now for the public (*PANGAEA doi* (*will be added during the review process*). Furthermore, certain benthic species have restricted depth ranges (e.g. Brandt et al. 2009; Douglass et al. 2014; Duhamel and Hautecoeur 2009; Held and Wägele 2005; Hunter and Halanych 2008), therefore, depth and depth-related factors can be strong barriers to

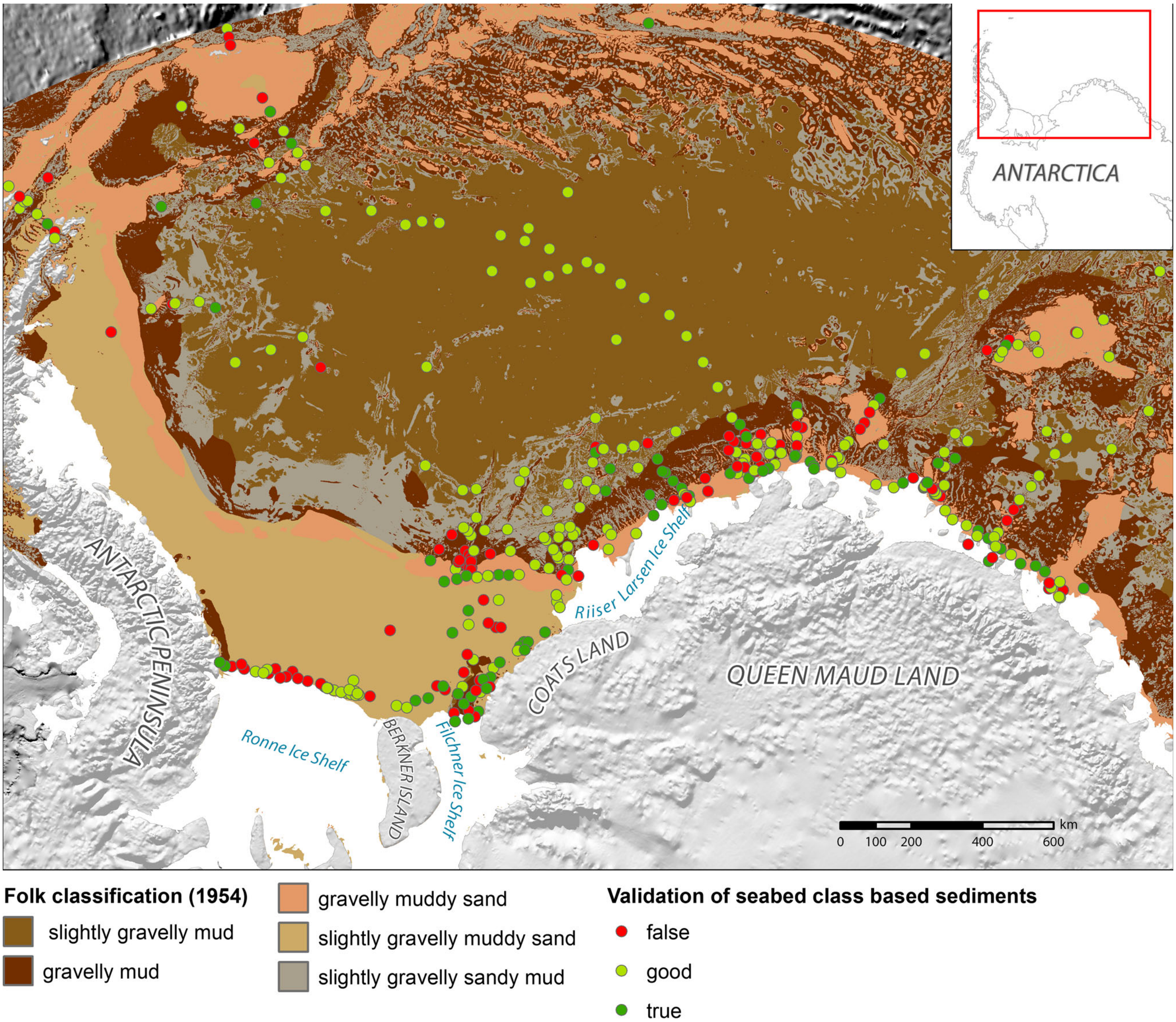


Fig. 7 Potential surface sediment distribution in the Weddell Sea. The mean fraction value of all samples falling into one seabed class was calculated, assigned to a sediment texture class according to Folk (1954) and then applied to the classification raster map. Five sediment type classes result from this procedure

dispersal of benthic species. However, the Weddell Sea contains a smaller proportion of depth-restricted species than other oceans (Brey et al. 1996, Thatje et al. 2005), since the continental shelf of the Weddell Sea provides a comparable environment as the abyssal plain due its intermittent glaciations of the shelf reducing the light availability. The ranges of depth portioning assemblage structures can be characterized as bathomes (Douglass et al. 2014).

Seascape ecology is the study of structure, function, and change in a heterogeneous seabed area which contains interacting ecosystems (Forman and Godron 1986). In this study, indications of such connections and interactions between shelf and deep sea across the continental slope are analyzed in more detail for the area near Queen Maud Land by adducing the shape and the geographic properties of selected geomorphic features. These geomorphic features are of ecological and sedimentological interest as they can act as physical controls for e.g. species distribution or bottom currents and sedimentation processes (Post et al. 2010). Figure 6 shows unambiguously where scarps and depressions control the connection between shelf and abyssal and where e.g. high and low declination within the scarps occur.

The distribution of samples in comparison to the seabed classification patterns (Fig. 7; Table 3), allow for more detailed sediment distribution models for the Weddell Sea. Refining of sediment distribution patterns by considering

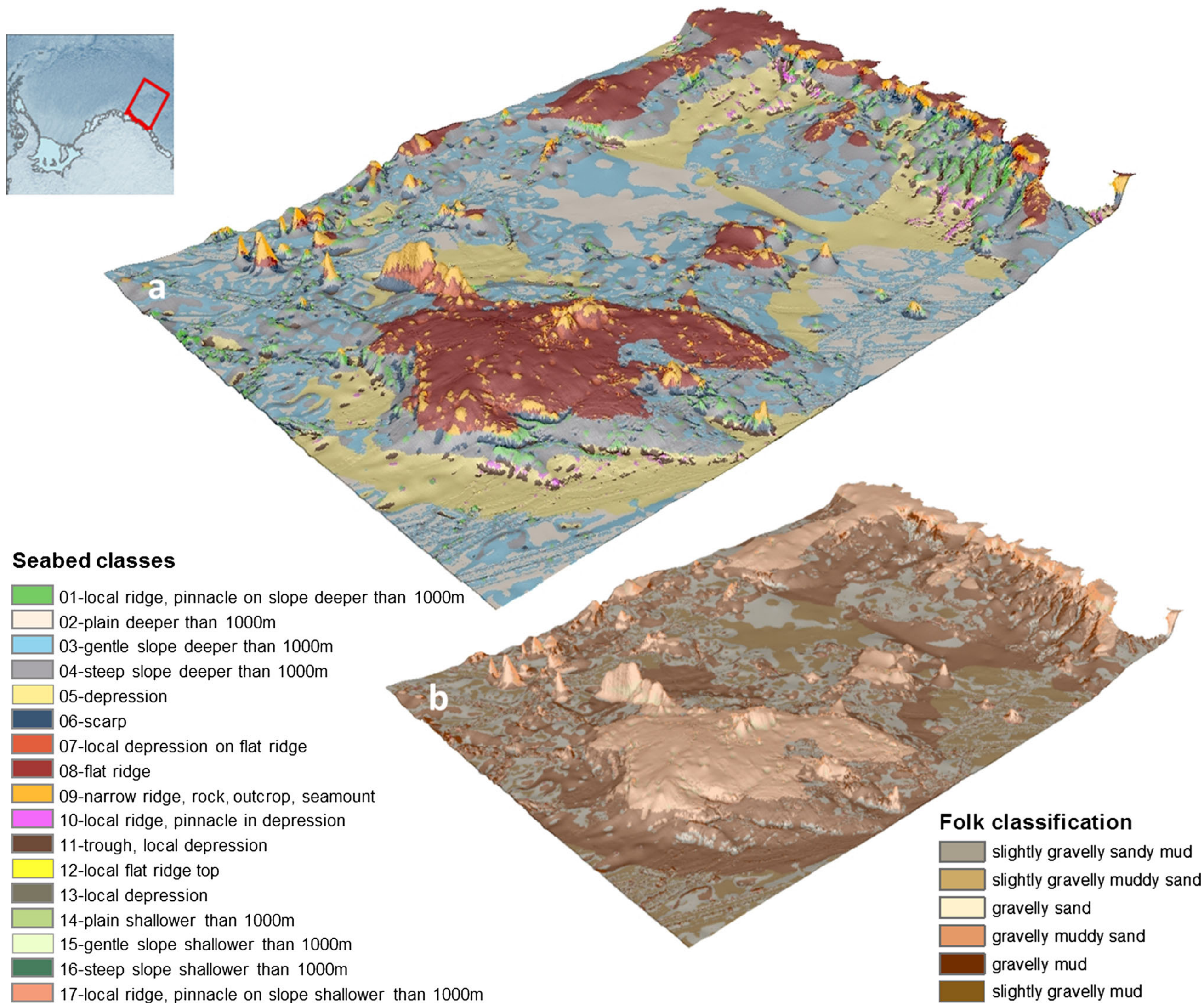


Fig. 8 Display of the Folk (1954) classified mean grain sizes adapted to the seabed classes of Maud Rise area

the geomorphology of the Weddell Sea allows for a better understanding of the sedimentological processes in the Weddell Sea.

This study presents the first statistical analysis of the association between seabed morphology and surface sediment distribution for the Weddell Sea. Figure 7 shows that this approach meets the expectations in homogeneous areas such as the plain deep areas (ID 2) and the flat ridge area (ID 8). The incorrect predictions of the sediments samples fall into heterogeneous seabed morphologies mainly occurring at the continental slope (seabed classes IDs 5, 6, 8 and 9). These areas need a high positioning quality and higher sample density for a better understanding of the surface sediment association. In front of the Ronne Ice Shelf the relatively low success rate of the approach can be presumably explained by the recent sedimentation processes of the shelf ice. Here, the geomorphology of the seabed is certainly not the dominating factor for the sediment distribution.

Previously, Diekmann and Kuhn (1999) gave a comprehensive overview on general grain-size distribution, mineral composition and sediment provenance in the whole Weddell Sea area. The main sediment transport processes by current and ice rafting were discriminated. On the shelves and upper slopes, strong currents let to a general removal of mud (silt and clay fraction). Also on the slopes, rises and abyssal plains muds are removed mainly in the channels. One problem—like with most seabed sampling investigations—is the fact that the samples were taken very selective, mostly in areas selected with sub-bottom echo sounders where sediment coring was easily possible. Therefore, areas with sorted sands (turbidities) like south of Maud Rise, and in the eastern Weddell Sea abyssal plain (Diekmann and Kuhn 1997) are underrepresented with samples and not well mapped (Wright and Anderson 1982; Anderson 1971).

Anderson et al. (1986) e.g. mapped the whole area in the eastern Weddell Sea as the "Weddell Fan". The whole area east of the elongation of the western levee of Polarstern Canyon is characterized as a prolongation of the Filchner Trough Mouth Fan with minor sediment supply from the East. Coarse grain sizes (sands) are found in front of the recent calving line in the southern Weddell Sea off Berkner Island (Fig. 1). Here the ice thickness nearly reaches the total water depth and tidal currents flowing out and in the ice cavity lead to well sorted sands on the seabed (Melles et al. 1995). High bottom current velocities associated with sandy sediments as well characterize the overflow of ISW on the shelf break off Crary Fan and to the west on the eastern side of the downslope ridge and upper part of the Akademic Federov Canyon (Melles and Kuhn 1993; Melles et al. 1995).

The continental slope of the +southeast Weddell Sea is heavily structures into ridges and canyons depressions perpendicular to the slope (Figs. 4, 6, 8). The upper and lower water depth limits of these structures reaching from the shelf break to the continental rise are between 380 and 4600 m (Fig. 6). The Wegener Canyon in the NE of this slope sector is the most pronounced one (Fütterer et al. 1990). The structures are assumed to be old post Cretaceous to pre Miocene erosional features formed by a fluviatile drainage system before glaciation of East Antarctica reached the coast of this area (Lindeque et al. 2013).

Cold and dense Ice Shelf Water (ISW) is formed on the broad shelf in the southern Weddell Sea (Haid 2013). This ISW flows off the shelf into the deep sea guided by ridges and canyons (see Figs. 1, 4) the Akademic Federov, Deutschland and Polarstern Canyons (Fig. 1) perpendicular to the general slope (Melles and Kuhn 1993; Kuhn and Weber 1993; Michels et al. 2001, 2002). Although these ridges were formed mainly by gravity flows on a trough mouth fan and showed their highest activity mainly during glacial times (Kuvaas and Kristoffersen 1991; Moons et al. 1992; Weber et al. 2011) they are preferred pathways for dense bottom water during the recent interglacial.

Haid (2013) indicated that the outflow of Weddell Sea- and Antarctic Bottom Water into the other world's ocean basins is strongly stirred by deep cross shelf valleys in the NW Weddell Sea (Fig. 3). Here the outflowing Antarctic Bottom Water shapes the seabed with outwash at the foot of steeper slopes of the continental rise and contouritic depositions further to the east (Fütterer et al. 1988).

The depth of the shelf edge could act as a barrier for, but as well could redirect warmer deep water upwelling onto the shelf, filling depression in front of and cavities below large ice shelves and thawing these from below as postulated and modeled for the Filcher Ice Shelf by Hellmer et al. (2012).

Conclusions

A spatial seabed class map of the Weddell Sea derived from the IBCSO DEM (Arndt et al. 2013) and historical surface sediment samples were used to analyze the relation between the geomorphological seabed classes and sediment distribution. The new seabed classification allows for a detailed analysis of indications of connections and interactions between shelf and deep sea across the continental slope. Depressions in the shelf morphology highlight potential pathways of water masses across the shelf while ridges and elevation identify sills and obstacles. The small scale geomorphic features allow further ecosystem studies on the effect of geomorphology and the distribution of benthic communities related to other environmental factors such as erosion or deposition of sediment, currents and nutrients. On the continental slope, the classification captures the brought- and fine-scale complexity of the geomorphology. It has been demonstrated that the seabed classes identified in this study can be to some extend be used to predict surface sediment types geomorphological areas of the Weddell Sea. The correlation is best in flat Weddell Sea Abyssal Plain. In areas with complex sedimentary setting, however, the correlation between surface sample composition and seabed morphology is not as clear. In front of shelf ice edges, for example, seabed classes only poorly correlate with the surface sediment compositions and thus, there the seabed classification need to be refined to better represent surface sediment compositions. This indicates that in these areas, the surface sediment compositions are not primarily controlled by the seabed morphology.

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