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THE VISUALIZATION OF GEOPHYSICAL AND GEOMORPHOLOGIC DATA FROM THE AREA OF WEDDELL SEA BY THE GENERIC MAPPING TOOLS

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Abstract:

The paper concerns GMT application for studies of the geophysical and geomorphological settings of the Weddell Sea. Its western part is occupied by the back-arc basin developed during geologic evolution of the Antarctic. The mapping presents geophysical settings reflecting tectonic formation of the region, glaciomarine sediment distribution and the bathymetry. The GlobSed grid highlighted the abnormally large thickness of sedimentary strata resulted from the long lasting sedimentation and great subsidence ratio. The sediment thickness indicated significant influx (>13,000m) in the southern segment. Values of 6,000–7,000 m along the peninsula indicate stability of the sediments influx. The northern end of the Filchner Trough shows increased sediment supply. The topography shows variability -7,160–4,763 m. The ridges in the northern segment and gravity anomalies (>75 mGal) show parallel lines stretching NW-SE (10°–45°W, 60°–67°S) which points at the effects of regional topography. The basin is dominated by the slightly negative gravity >-30 mGal. The geoid model shows a SW-NE trend with the lowest values <18 m in the south, the highest values >20m in the NE and along the Coats Land. The ripples in the north follow the geometry of the submarine ridges and channels proving correlation with topography and gravitational equipotential surface.

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Key words: Weddell Sea, Antarctic, GMT, Cartography, Geophysics

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INTRODUCTION

The Weddell Sea region is one of the least studied segments of the Antarctic with many undefined and poorly explained correlations between its geophysical, glaciological and topographic settings, geologic evolution (Stolldorf *et al*., 2012). The alteration of the topography of the Weddell Sea seafloor is a consequence of the divergence kinematics of the South American and Antarctic plates, long lasting sedimentation resulted in the accumulated abnormally large thickness of sediment layer, and a great subsidence ratio in the adjacent Antarctic Peninsula, developed during particular stages of the geologic formation of the region. The analysis of the fracture zones and magnetic isochrons in the Weddell Sea enabled to perform modelling of the South American and Antarctic plate divergence, which pointed at changed direction, initially in NW, and rotated into a NS in the period 65–50 Ma. While The mid-ocean ridge in the northern Weddell Sea moved further in a NW direction due to the South American and Antarctic plate divergence (Eagles and Jokat, 2014), the NS directed diverging of the tectonic plates eventually resulted in the formation of the Weddell and Scotia seas, as detailed in the reference studies (Cunningham *et al*., 1995; Barker *et al.,* 1991; Nankivell, 1997). As a result of the plate kinematics, shared subduction boundary of the two plates exist in the NW of the Weddell Sea.

This paper presents a synthesis of the new geological and geophysical data related to the Weddell Sea, the southernmost segment of the Atlantic Ocean and a marginal sea of the Antarctic (Fig. 1). It summarises and reviews recent findings in its geologic evolution and compiles the marine and terrestrial high-resolution datasets on topography, bathymetry, and sedimentation. Using the compilation of these datasets it highlights the correlation between these geospatial phenomena visualized on the grids, presenting a technical application of the GMT scripting toolset. The methodology presents an alternative tool for cartographic data processing to the traditional GIS. Moreover, the paper discusses the geological setting of the evolution of the Weddell Sea, its regional structures and unique hydrological regime affecting global oceanic circulation. The objec-

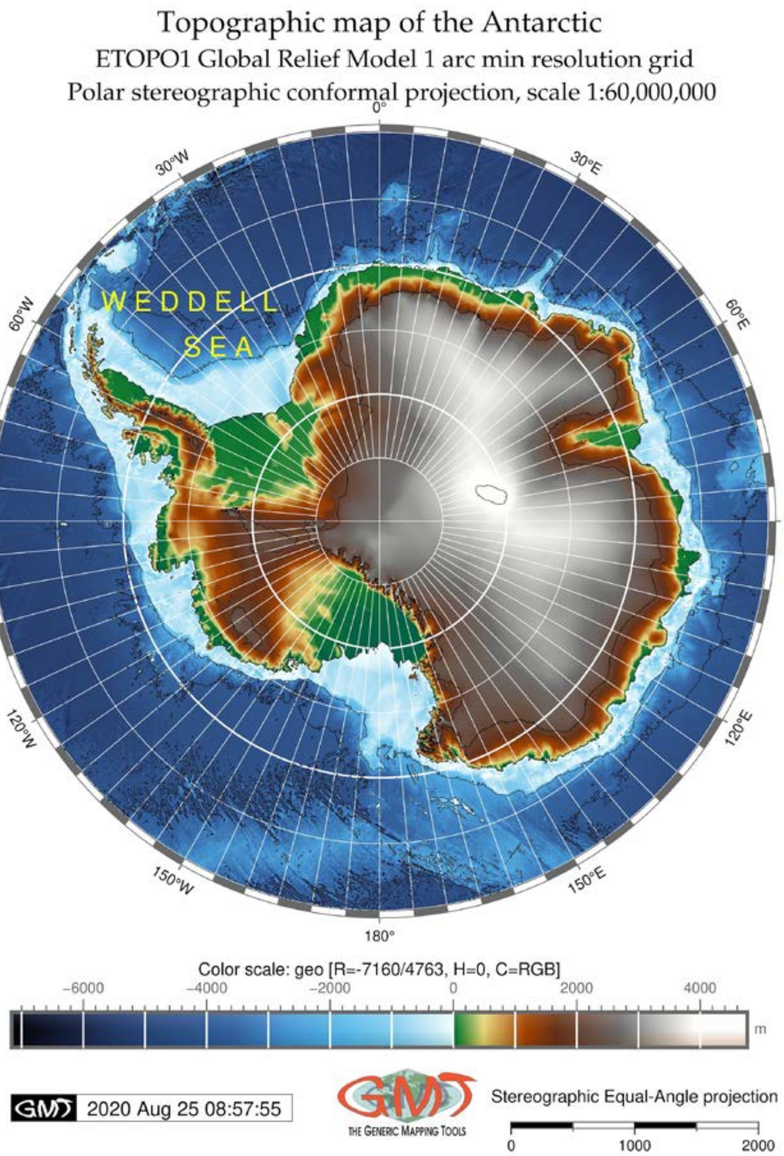

Fig. 1. Topographic map of the Antarctic. Source: author

tive of the present work is a visualization of the geophysical settings and detailed topography of the Weddell Sea using high-resolution datasets supported by the literature review on its evolution since Quaternary.

Using high-resolution datasets and GMT scripting, this study presents an alternative, data-driven method of the cartographic interpretation for topographic-geophysical analysis of the Weddell Sea. The comparative analysis of the thematic datasets aims at highlighting correlation between the topographic and geological variables visualized on the maps. Integration of various high-resolution grids undertaken in this study aimed to analyse geological, geophysical and topographic settings of the Weddell Sea region for proper understanding of the seafloor formation in the polar regions. The objectives of this study include modelling of the geophysical, geological and topographic data for analysis of the correlation between these processes, reflected in the submarine geomorphology through the detailed visualization of the multi-source datasets. The presented methodological principles, described data and visualized grids can be reused for other sectors of the Antarctic and utilised in further research.

This study continues the research on the analysis of the geological setting and oceanological regime of the Weddell Sea (Crawford *et al.*, 1996; Elverhøi, 1981; Elverhøi and Roaldset, 1983) and aims to present a data-driven analysis of the topographic variability in the context of the geological settings in this area. Specifically, the cartographic processing and aimed at the retrieval of the information from the visualized thematic raster grids to highlight the coherency between the geological, topographic and geophysical grids. Because of the multi-source character of the original datasets and variations in their content and consistency, the data processing aimed at the analysis of the metadata, spatial extent and format: projections, datum, extent, range, resolution. The visualized datasets correlations between the relief of the Weddell Sea and the accumulated glaciomarine sediments, which also have been reflected in the existing studies (Bradley *et al.*, 2015; Anderson *et al.*, 1991). Other considered studied concerned the development of the coastal polynyas of the Weddell Sea, fluctuations of the sea ice extent and volume in context of the oceanographic and meteorological parameters explaining the circulation relevant to its origin and stability (Haid and Timmermann, 2013; Carsey, 1980; Bart *et al.*, 1999). These studies described the variability in the composition and distribution of the sediments over the basin of the Weddell Sea. Previous considered studies present the application of the geophysical data for the geodynamic modelling of the Weddell Sea embayment (Jokat *et al.*, 1997; Maldonado *et al.*, 2006), oceanographic modelling (Kjellsson *et al.*, 2015), or rise practical questions of high-resolution bathymetric mapping (e.g. Gauger *et al.*, 2007; Fretwell *et al.*, 2013; Lemenkova, 2020a, b, c; Suetova *et al.*, 2005).

REGIONAL SETTING

The study area extends over a longitude of 70°W to 0°W and a latitude of -80°S to -60°S, generally constraining the WE land boundaries of the Weddell Sea between the coasts of Coats Land and the Antarctic Peninsula (Fig. 2). It presents the largest marginal depression of the basement surface of the Precambrian structures on the Antarctic shelf. The geomorphology includes landforms varying in the morphology, such as submarine gullies, system of channels, terminal moraine and scalloped embayments, submarine slides, iceberg scours, sediment depositions and a mouth fan offshore from the Filchner Trough (Anderson, 1972a). The morphologic variations are affected by the extent of the past ice-sheet grounding near to the shelf edge during the Late Quaternary (Gales *et al.*, 2014) and variability in Cenozoic sedimentation and depths related to the glacial conditions of Antarctica. The Precambrian

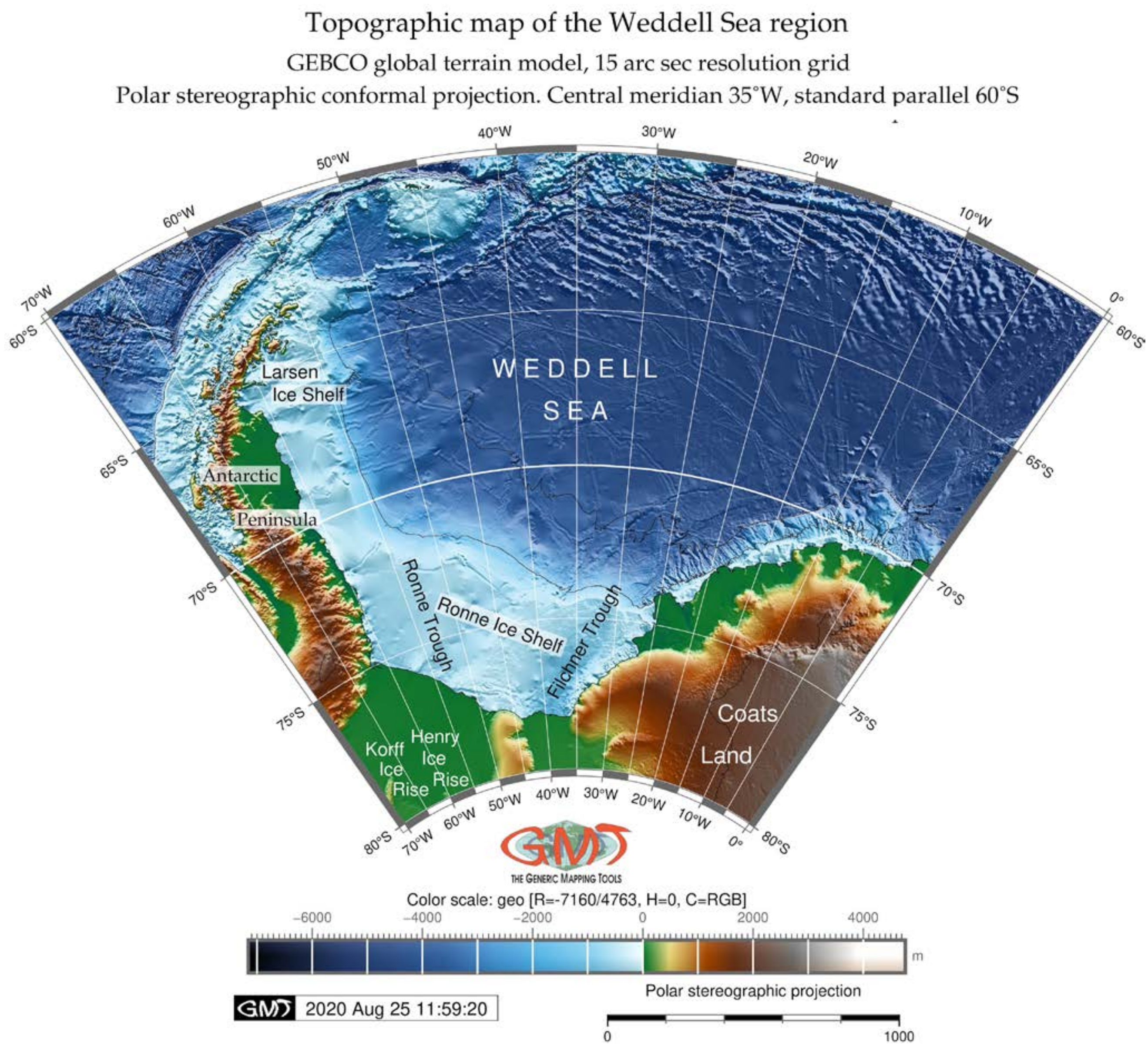

Fig. 2. Topographic map of the Weddell Sea region. Source: author

basement of normal continental crust is typical beneath the eastern Filchner Ice Shelf (Tingey, 1991).

The slope geomorphology in the Weddell Sea has a relatively simple geometric profile with concave form. Its foot is located at the depths 3,100–4,000 m, where it smoothly continues by an accumulative plume plain (Fig. 1). The seafloor is presented by numerous landforms of block dissection. For instance, the SW-NE oriented sediment ridges up to 300 m high with channels located on a terrace of the continental slope in water depths of 2,000–3,300 m were traced in the eastern part of the Weddell Sea by Kuhn and Weber (1993) and further described by Weber *et al.* (1994). An illustration to the interaction between the seafloor geomorphology and bottom currents which flows clockwise following the Weddell Gyre is shown by Maldonado *et al.* (2005, 2006) who observed a variety of contourite deposits in the northern part of the Weddell Sea, which is also proved by Michels *et al.* (2001). Although there is lack of information about crystalline basement of southern segment of the Weddell Sea, but its northern margin is well visible in the gravity anomaly maps showing a narrow belt of positive anomalies in its southern margin, which may reflect a local anomaly of thickness due to glacial sedimentation or young magmatic rocks in the rift zone.

Two major factors causing the filling a sedimentary basin include tectonic subsidence and high sedimentary rate which largely contributes to the sediment accumulation. Research over the last decades reveals an impact of the ice advancing on both sediment thickness in the Weddell Sea through the contribution of the materials, and seafloor geomorphology (e.g. levee channels and ridges). Therefore, the submarine geomorphic forms are shaped under the influence of a variety f factors including tectonic historical evolution that involves plate movements and associated complex processes, geologic structure and glacial regime, mirrored in the sediment thickness of the shelf bottom and bathymetry (Lemenkova, 2018). Therefore, geographically distinct segments of the basin may either vary or resemble following local setting. Thus, the three segments of the Weddell Sea, the western, the southern and the northwestern show similar contour currents off the Larsen Ice Shelf that have been present since the late Miocene. The lithological column of the Weddell Sea bottom rocks starts in many places at least from the Late Cretaceous sediments and the Palaeogene clastic rocks.

The submarine topography reacts to climate change since Late Quaternary. Thus, the periods of ice advancing resulted in high sediment input from the shelves which developed a network of levee channels and ridges dominated over the transport of sediments (Michels *et al.*, 2001). The predominant sediments of the submarine ridges in the Weddell Sea include coarse-grained levee types affected by the erosional processes and deposited mostly on the NW flanks. The sediments of the Ronne Ice Shelf vary from the very well sorted pure sands in its SE part, soft pebble-sized sediments of muddy to sandy muds in the middle part, and heavily glacially influenced, pebbly muds in the west, near the foot of the Antarctic Peninsula. The sub-seabed structure beneath the Ronne Ice Shelf shown that the ice shelf has a 350 m thickness and the seabed undulates gently between 650 and 675 m below sea level (King and Bell, 1996). In the eastern part, a set of open folds were observed with width of 200–300 m and a NNE-SSW strike direction. The diversity of sediment types (marine to glacial) show that both the marine and glacial depositional processes control their accumulation (Haase, 1986).

The Late Quaternary sediment sequence of the continental margin in the eastern Weddell Sea studied in palaeoenvironmental reconstructions (Grobe *et al.*, 1993) indicated that the Antarctic ice sheet extended to the shelf edge during the Last Glacial Maximum (LGM), while ice streams thinned due to ocean warming and sea-level rise since the LGM (Hein *et al.*, 2011). For example, the extent of ice surface elevations in the Filchner Trough and Ronne ice shelves during the LGM were a few hundred metres higher (Larter *et al.*, 2012). Recent studies on the Antarctic ice dynamics (Hein *et al.*, 2016; Hegland *et al.*, 2012; Siegert *et al.*, 2013; Johnson *et al.*, 2019) also confirmed a complicated pulsation of rapid thinning and ice retreat since Quaternary glaciation.

The complexity of these processes is also reflected in the distribution of sediments on the continental margin of the SE margins of the Weddell Sea Embayment (Weber *et al.,* 1994; Lindeque *et al.*, 2013) where a submarine fan complex has been developed during Tertiary (Haugland *et al.,* 1982, 1985). The glacial-influenced sedimentation processes along the continental margin of the southeastern Weddell Sea originated from the Middle Miocene are constrained by a series of sedimentary features. Other studies on glacial geologic data (Bentley *et al.*, 2010) demonstrate that the southwestern Weddell Sea embayment of the West Antarctic Ice Sheet was thinner in the ice sheet by 230–480 m since ca. 15,000 years ago. Nowadays, the prominent ice shelf can be seen as the Ronne Ice shelf (Fig. 2).

The embayment of the Weddell Sea experienced at least two glaciations (Bentley *et al.*, 2017): an old and warm-based and a recent cold-based one with ice thickened by at least 450 m in the southern part of the sea (around 84°S) during the last glaciation. Changes in the ice extension is impacted by the oceanological and climate factors, such as the magnitude and the duration of the sea-level depression during a glacial period resulted by a global climate evolution (Kuhn *et al.*, 2006). More detailed discussions on the glacial history of the Weddell Sea embayment and the maximum LGM surface reached by the West Antarctic Ice Sheet in the Weddell Sea drainage are given in comments of Clark (2011), Bentley and Anderson (1998), Bentley *et al.* (2012).

In general, the seafloor of the Weddell Sea shelf has depths at -200–300 m with dominating hilly relief. Its southern part includes the sequences of the subglacially deposited tills and compacted sediments (Hillenbrand *et al.*, 2012). The shelf gradually becomes shallower and narrower in eastward direction (Fig. 2). In some places, the mouths of the transverse troughs continue from beneath the glaciers with depths over -400 m (Anderson, 1972b). The bathymetry of the outer edge of the shelf in the Weddell Sea shows depths at about 300–350 m and asymmetry for the western and eastern parts, comparing to the other seas of the Southern Ocean (Fig. 1). This may reflect the particular stages of geologic formation of the Antarctic Peninsula that influenced the formation of the western part of the Weddell Sea which was occupied by the back-arc basin. There are two distinct transverse troughs – the Ronne Trough (shallower, depths of 500–600) and the Filchner Trough (depths -1400 to -1600 m) in the SW and SE segments of the shelf extending beneath the ice shelf (Fig. 2). The troughs present the two deep palaeo-ice streams eroded into the southern Weddell Sea shelf, fed by glaciers and ice streams (Hillenbrand *et al*., 2012).

The Weddell Sea is notable for a unique glacial-hydrological regime: it is a place for the main deep water mass formation in Antarctic through the thermohaline circulation and circulation affected by the opposite hydrological forces (Fahrbach *et al*., 1995; Mueller and Timmermann, 2017). The coldest Antarctic Bottom Water moves to the north through the system of passages, troughs and basins. At the same time, the Circumpolar Deep Water brings warmer waters south cooled in the Weddell Gyre by heat loss, interaction with sea ice and cold water. The mixing of these water masses is strongly affected by the wind forcing. Being an outlet for about 20% of Antarctica's continental ice volume (Hillenbrand *et al*., 2014) the Weddell Sea makes a significant contribution to the global oceanological circulation system by recirculation of icebergs which trajectories are influenced by currents, sea ice distribution, bathymetry and winds (Collares *et al*., 2018). The hydrographic variability of the Weddell Sea deep-layer bottom water controls changes in global ocean circulation and climate change (Kerr *et al*., 2018). The transformation of the bottom waters in the Weddell Sea from the original off-shelf waters is triggered by the continental shelf processes (Nicholls *et al.,* 2009), which demonstrate the connectivity of the glacial and geological factors.

MATERIAL AND METHODS

Advanced methods of data analysis for studying such an unreachable region of the Earth include effective cartographic solutions for data visualization in geoscience. Therefore, prior to mapping workflow, it is important to choose a suitable GIS software, select datasets with suitable resolution, precision and accuracy, as well as apply relevant approaches and algorithms of data processing (Smith, 1993; Schenke and Lemenkova, 2008). Although many studies have been realised on mapping in geosciences using ArcGIS (Lemenkova, 2011; Klaučo *et al*., 2013, 2014, 2017; Lemenkova *et al*., 2012), the advantages of the scripting languages in cartographic visualization and modelling are evident and have been discussed previously (e.g. Lemenkova, 2019a, c, 2020d).

In brief, the machine learning approaches in cartographic routine result in the increased speed, accuracy and precision of the data processing and mapping. The automatization of plotting results in fine graphical output. Besides, comparing to the handmade mapping routing by the traditional GIS, scripting enables a high degree of repeatability of techniques, since scripts can be applied for similar research. Therefore, this study was made using the Generic Mapping Tools (GMT) scripting toolset developed by P. Wessel and W.H.F. Smith, (Wessel and Smith, 1991, 1995; Wessel *et al*., 2013). The scripting for data visualization in GMT were applied from the existing developed methodology (Lemenkova, 2019d, e). The descriptive and qualitative analysis of the geological evolution in the region of Weddell Sea was based on the available literature and published research.

The effective data visualization in cartography also depends on the correct choice of map projections, because the distortions vary spatially along with map extent. Therefore, the visualization part of this research included comparison of map projections and assessment of their applicability for polar regions (Snyder, 1993). Most of the maps were plotted in Polar Stereographic conformal projection (Snyder, 1987). The bathymetric and topographic data were based on the General Bathymetric Chart of the Oceans (GEBCO) grid with extra fine 15 arc-seconds resolution (GEBCO Compilation Group, 2020). Visualization of the sediment thickness was based on the GlobSed 5-arc-minute grid of the total sediment thickness in the oceans (Straume *et al*., 2019).

Technically, the combination of the GMT modules was used for scripting. These include, among the most important ones, the 'grdimage' (for visualization of the grids), 'psbasemap' (for plotting the cartographic grid, title, projection annotation), 'grdcontour' (for plotting the isolines by tracing each contour through the grid and annotating intervals), 'pstext' (for text annotations), 'psconvert' (for converting the ps file by GhostScript). More detailed explanation of the workflow with fragments of scripts and code snippets is presented in the existing works (Lemenkova, 2019b, 2019f).

Fig. 1 (Topographic map of the Antarctic) was visualized using a clipped area of Antarctica which was subset using the following code: 'gmt grdcut ETOPO1_Ice_g_gmt4.grd -R-180/180/-90/-60 -Ga_relief.nc'. Here the '-R-180/180/-90/-60' defines the region in West-East-South-North convention, and '-Ga_relief.nc' command defines the output file in netCDF format (a_relief.nc). The clipped grid was then projected using the code 'gmt pscoast -R-180/180/-90/-60 -Js0/-90/-71/1:60000000 -Di -W0.25p -K > $ps'.

Fig. 2. (Topographic map of the Weddell Sea region) was visualized using the 'grdimage' module of GMT using the following code: 'gmt grdimage ws_relief.nc -Cmyocean.cpt -R290/360/-80/-60 -Js325/-90/5.5i/-60 -I+a15+ne0.75 -Xc -K > $ps'. Here the '-Js325/-90/5.5i/-60' command defines the Stereographic Equal-Angle projection with longitude and latitude of the projection centre and plotting size of the map (5.5.inches) and 35°W as a central meridian (defined in GMT as 360°-325°).

Fig. 3 (Sediment thickness of the Weddell Sea basin) is plotted in the same projection as Fig. 2. The grid used for mapping was visualized by the 'grdimage' module as described above (similar for Fig. 2). The color palette was defined using the 'makecpt' module of GMT by the following code: 'gmt makecpt -Cturbo.cpt -V -T0/14000/200 > colors.

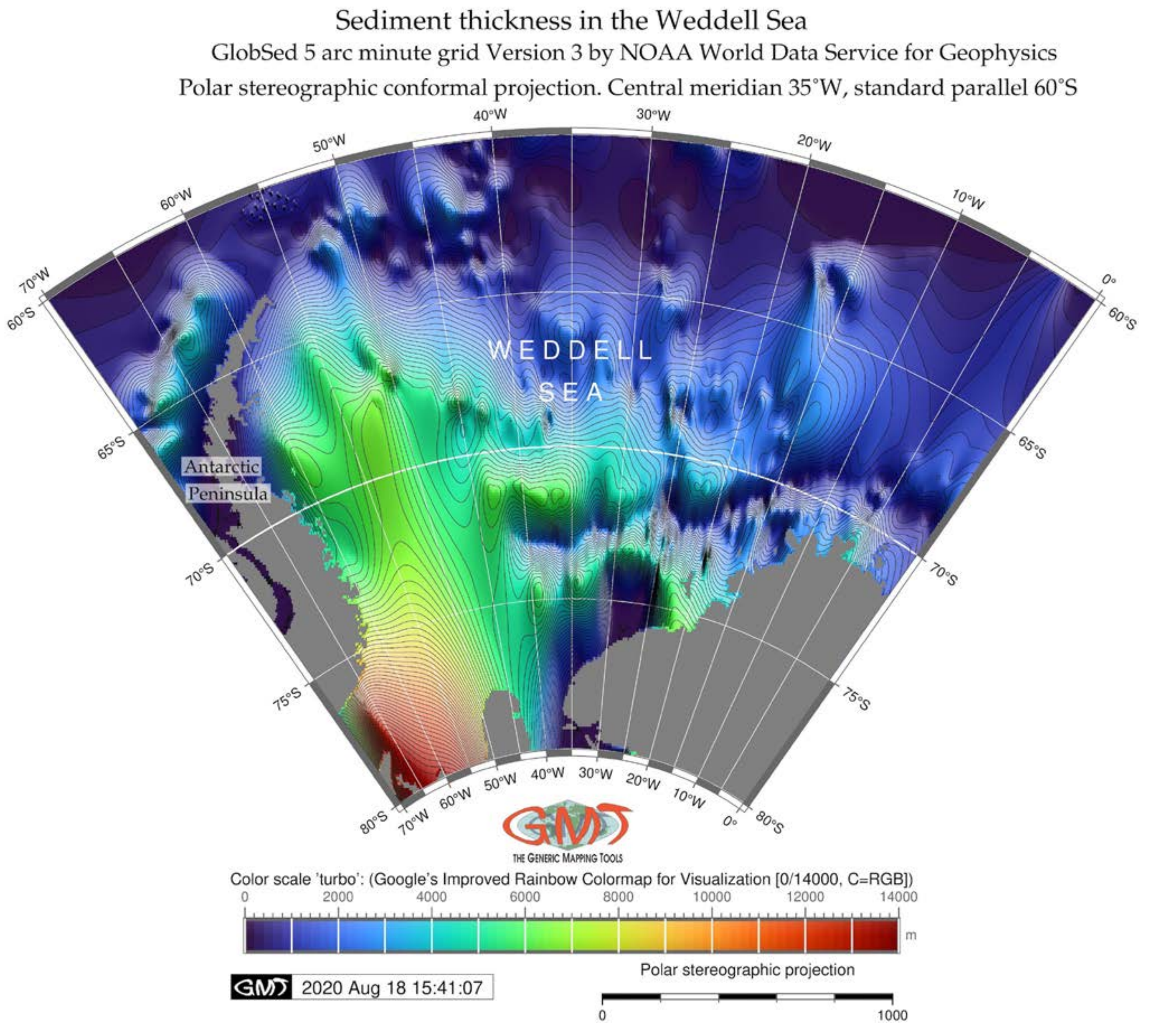

Fig. 3. Sediment thickness of the Weddell Sea basin. Source: author

cpt'. Here the '-T0/14000/200' command defines the extent of the data range (from 0 to 14000 m and a step of 200 m between the colour gradations).

Fig. 4 (Free-air gravity anomaly in the Antarctic up to 80° basin) was visualized using the code 'gmt img2grd grav_27.1.img -R-180/180/-80/-60 -Ggrav.grd -T1 -I1 -E -S0.1 -V' which extracts the subset of img file in Mercator or Geographic format. This file was then processed and visualized as in previous maps using combinations of the following modules: 'grdimage' for grid visualization, 'psbasemap' for adding graticule and title on the map, 'pstext' for adding annotations and 'psscale' for adding colour legend.

Fig. 5 (Free-air gravity anomaly in the Weddell Sea) visualizes the clipped region of the free-air gravity as in Fig. 4 but subset for the region of the Weddell Sea: 'img2grd grav_27.1.img -R290/360/-80/-40 -Ggrav.grd -T1 -I1 -E -S0.1 -V'. It has been plotted using the Stereographic Equal-Angle projection, similar to the maps in Figs 2 and 3. Both Figs 4 and 5 apply 'haxby' colour palette developed by W. F. Haxby for visualization of the gravity and geoid fields of the World's oceans in 1985.

The raw binary data for the geoid EGM-2008 were first converted to the GMT grid using code 'grdconvert s90w45/ EGM2008ws1.grd' and 'grdconvert s90w90/ EGM2008ws2.grd', for the two tiles covering the study area. The grid (Fig. 6) was generated by a sequence of GMT code: 'ps=Geoid_WS.ps', which generated the file, following by the raster grids visualization: 'gmt grdimage EGM2008ws1.grd -Ccolors.cpt -R290/360/-80/-60 -JM5.5i -P -I+a15+ne0.75 -Xc -K > $ps' and for the second: 'gmt grdimage EGM2008ws2.grd -Ccolors.cpt -R290/360/-80/-60 -JM5.5i -P -I+a15+ne0.75 -Xc -O -K >> $ps'. Due to the data compilation from the two different grids, the map of geoid (Fig. 6) has been plotted in Mercator projection to avoid the mesh breaks.

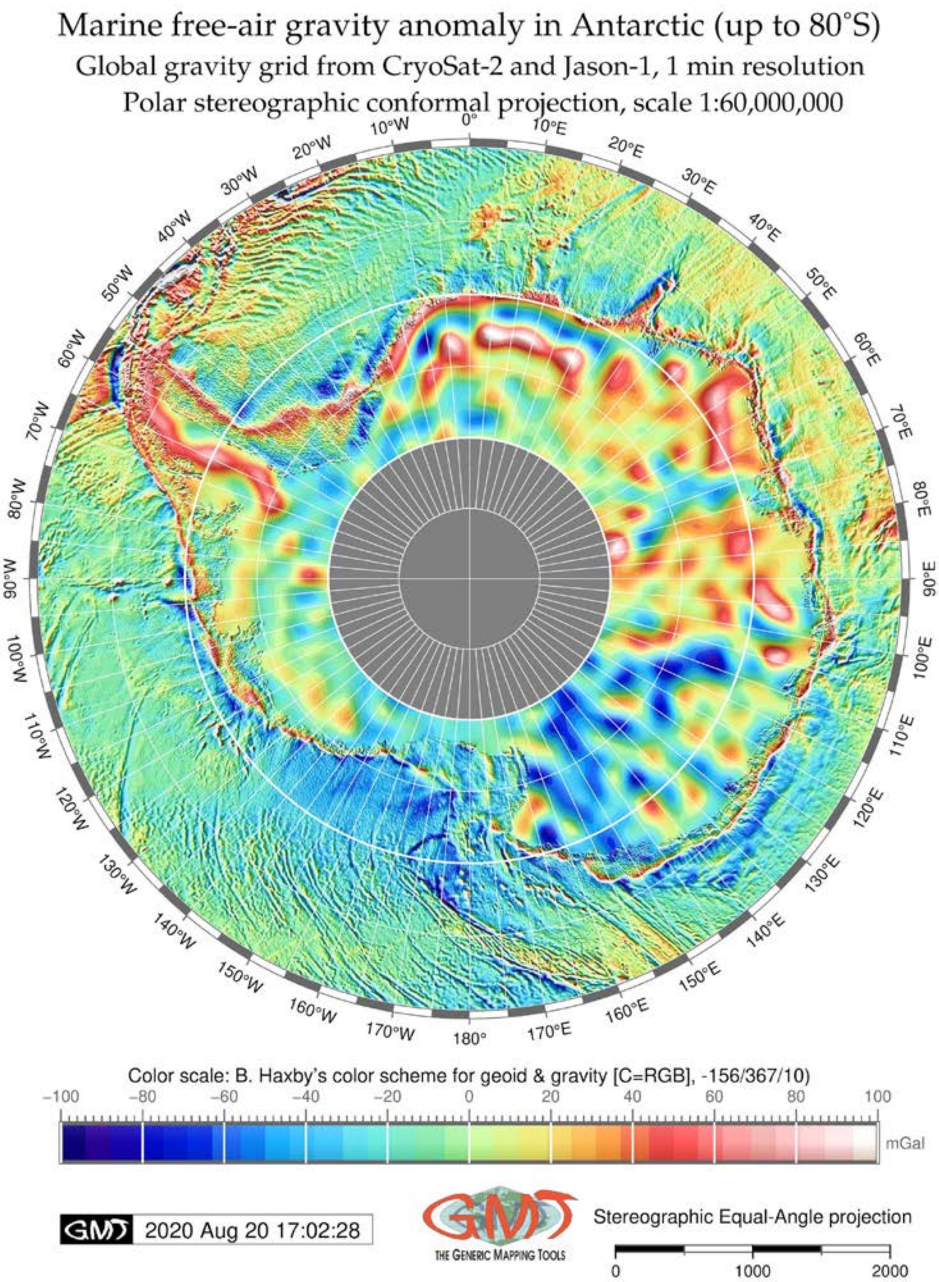

Fig. 4. Free-air gravity anomaly in the Antarctic up to 80° basin. Source: author

The shorelines and continent contours were plotted by the GMT-embedded vectors from the Global Self-consistent, Hierarchical, High-resolution Shoreline Database (GSHHSD) (Wessel and Smith, 1996). The geoid geopotential visualization was plotted using Earth Gravitational Model 2008 (EGM2008), a dataset published with described technical characteristics by Pavlis *et al.* (2012), which presents an improved and upgraded version of the previous issue of EGM96 (Lemoine *et al.*, 1998). Due to the data availability (Sandwell *et al.*, 2014), the free-air gravity anomalies were plotted until the 80°S. The metadata of the grids were processed by GDAL (GDAL/OGR contributors, 2020).

RESULTS

The results obtained from the present research on geophysical, geological and topographic analysis on the Weddell Sea can be summarised in a following list.

The topographic map shows that the GEBCO based data ranges between the -7,160 m to 4,763 m. The map (Fig. 2) clearly shows the asymmetry in the distribution of depths over the Weddell Sea with depths gradually increasing eastwards from -4,800 to -7,160 m, and western part having a larger shelf. The central and northern parts of the sea are occupied by the vast flat abyssal Weddell Plain (65°S, 20°W to ca. 65°S, 50°W) with the relief typical for the underwater

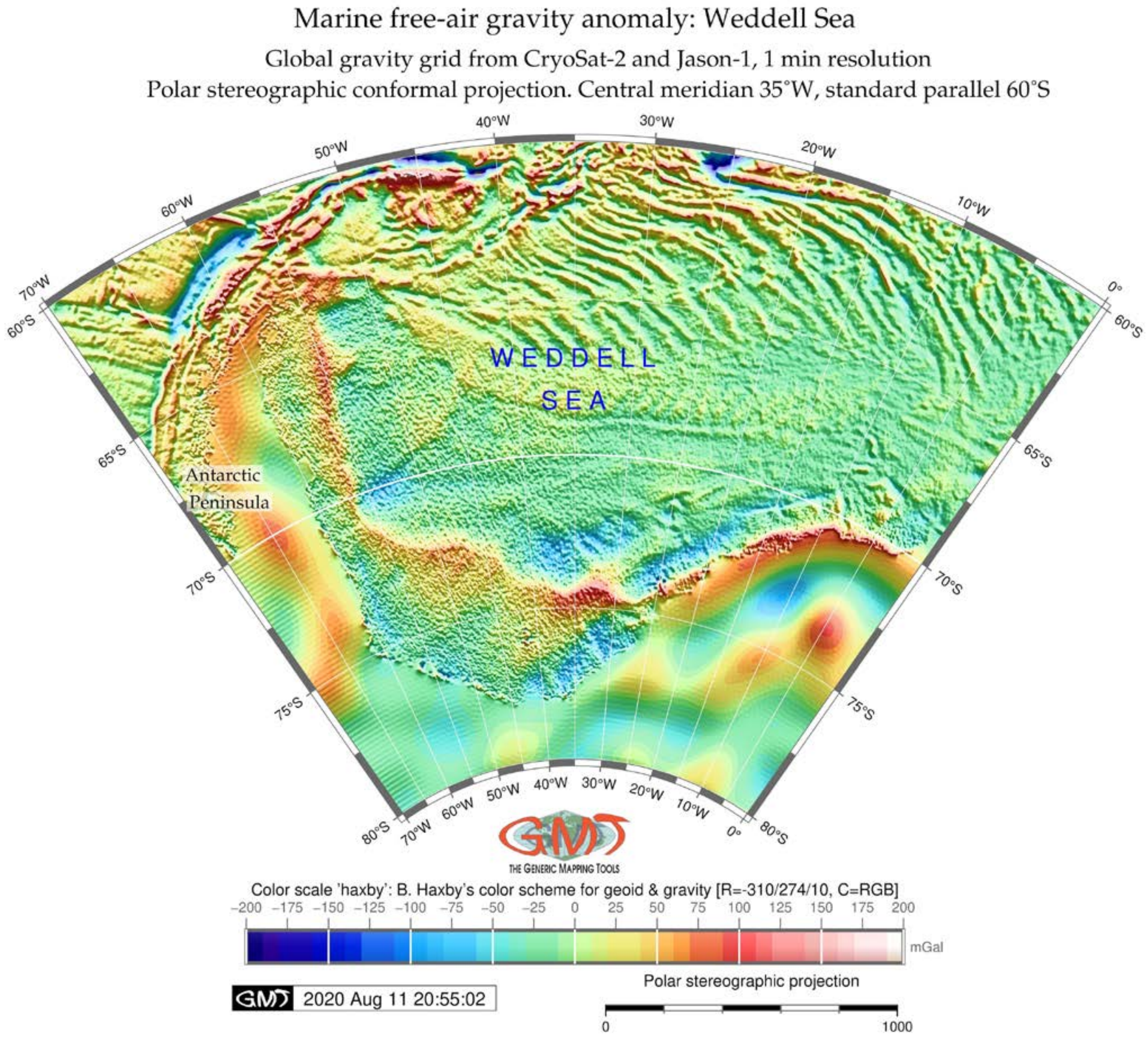

Fig. 5. Free-air gravity anomaly in the Weddell Sea. Source: author

plain on the deep ocean floor (Fig. 2). The northern border of the Weddell Sea follows a line connecting the southern shores of the South Orkney and South Sandwich Islands. In the west and south, the sea is limited by the coast of Antarctica. A distinct ice shelf surface, clearly visible on the map, makes the Weddell Sea only comparable to the Ross sea, among the other seas of the Southern Ocean (Fig. 1).

The distribution of the sediments observed in Fig. 3 reflects variation in sedimentary processes associated with the subsidence, tectonic processes, and ice shelf extent that contributes significantly to the sediment intake. The highest values of sediment thickness above 13,000 m (Fig. 3) are dominating in the southmost segment of the sea with isolines gradually diminishing northwards. A specifically elongated area of sediments with values between the 6,000–7,000 m (Fig. 3) stretches out as an elongated tongue along the Antarctic Peninsula which indicates the stability of the sediments influx in this part of the sea. The increased values of the sediment thickness can also be seen around the mouth of the Filchner Trough (74°–75°S to 36°–25°W), while the channel has sharply low values (dark blue areas in Fig. 3). In contrast, the northern segment of the sea has significantly lower values of the sediment thickness with no more than 3,000 m (dark to middle blue colours in Fig. 3) in all areas north of 66°S. This indicates first, the effects of the bottom currents, second, the increased distance from the main sediment source, the extent of the ice sheet, and the active circulation of the Antarctic bottom waters.

The values of the marine free-air gravity anomalies visualized in Fig. 4 (in regional scale for the Antarctic) and Fig. 5 (in local scale for the Weddell Sea) were obtained from the grid (grav_27.1.img) and can be interpreted

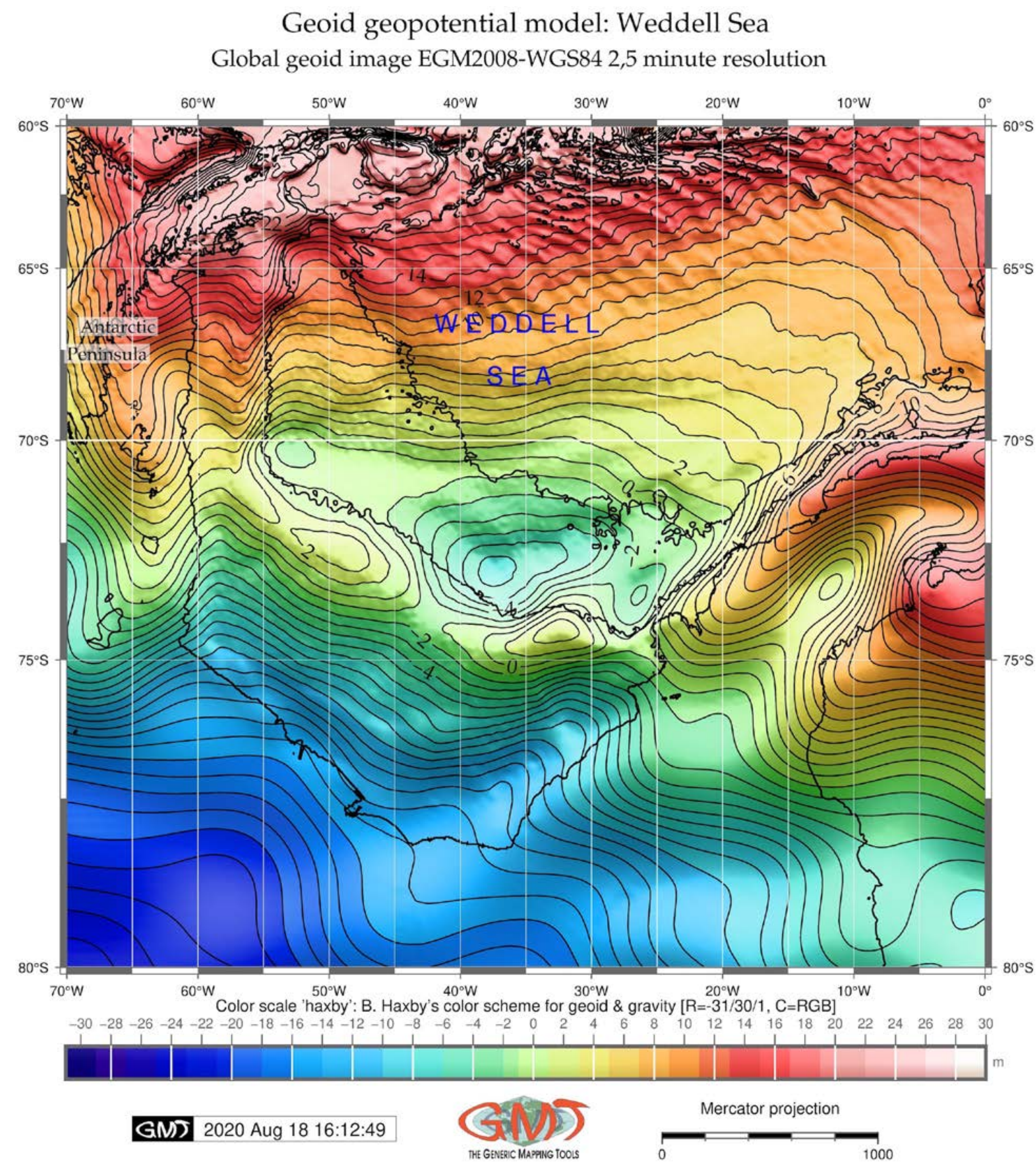

Fig. 6. Geoid model of the Weddell Sea basin. Source: author

as follows. The marine free-air gravity anomalies of the Weddell Sea basin show correlation with the geomorphic structures (comparing Fig. 2 to Fig. 5 and Fig. 1 to Fig. 4). Clearly visible ridges in the northern part of the sea (Fig. 2) as well as gravity approximation anomalies (Fig. 5), show a set of the parallel lines stretching in the NW-SE direction (10°–45°W, 60°–67°S). These can be interpretable in the free-air gravity anomalies affected by the regional submarine topography dissecting submarine ridges (Fig. 2), which supports the previously published studies on gravity in the Weddell Sea and Antarctic (Bell *et al.*, 1990; Aleshkova *et al.*, 1997; Scheinert *et al.*, 2016). Specifically, the higher values generally correspond to the ridges with values over 75 mGal (dark orange to red colours in Fig. 5), while the majority of the basin is dominated by the slightly negative values with values no lower than 30 mGal (light green colours on Fig. 5). Similar situations can be interpreted for the whole Antarctic region (Fig. 4). Moreover, some of the submarine ridges can be seen in the segment of 43°–55°W as a line stretching in SW-NE direction. It clearly corresponds to the moderate elevations in the bathymetry in Fig. 2. The effect of such a correlation between the topography and geophysical setting appears to have a systematic pattern over the basin of the Weddell Sea and well as the Antarctic in general. It demonstrates that the free-air gravity anomalies have lower values in the local geomorphological depressions of the seafloor and conversely for the elevations.

The geopotential model of geoid (Fig. 6) shows the undulations of the Earth Gravitational Model (EGM-2008) consisting of the spherical harmonic coefficients. The dataset ranges to a maximal at 28,752 m. A general trend of the undulations clearly shows a SW-NE orientation where the lowest values below 18 m (dark blue colours in Fig. 6) are located in the continental part of the southern segment of the Weddell Sea, south Antarctic Peninsula. On the contrary, the highest values above the 20 m generally correspond to the northeastern part of the area with elevated values along the Coats Land. Clearly visible ripples on the isoline contours can be seen on the northern part of the basin, which correlates with the extent of the submarine ridges and channels. This demonstrates the correlation of geoid with topographic structure showing gravitational equipotential surface of the Weddell Sea basin and surrounding Antarctic coastal land which coincides with the sea level in the Southern Ocean areas. Abstracted from the bathymetric features of the seafloor and surrounding terrestrial areas, the geoid represents the model of the Weddell Sea basin based on the EGM2008 and WGS-84 system.

The results of the visualization of the sediment thickness are supported by previous studies. For instance, the sediment thicknesses in the southeastern margin of the Weddell Sea Embayment exceed 5 km (Haugland *et al.,* 1985).

DISCUSSION

The paper presented the visualized geophysical and topographic analysis of the Weddell Sea with a focus on sediment distribution over the basin. Weddell Sea serves as a center of ice melting in Antarctic and has a specific pattern of the sedimentation distribution according to its topography, hydrological regime and local glaciological situation. Specific sedimentation pattern of the Weddell Sea is furthermore controlled by a large catchment area and sea level changes. The sediment thickness is also affected by the bottom currents and the dynamics of the ice streams and distribution of the turbidity contourites (Stow *et al.*, 2002). Studies carried out in the area also revealed specific effects of the currents and climatic conditions, which can be revealed by the comparison of the along-slope or down-slope direction types of the sediment transport (Uenzelmann-Neben, 2006). Present studies correlate with the glacial investigations in the Weddell Sea show that the main deposition centre of the full-glacial unit lies in front of the Filchner-Ronne Ice Shelf where the sedimentation rates reach up to 140–200 m/Myr which shows that bottom-water currents strongly impacted the sedimentation (Huang *et al.*, 2014).

In addition to the sediments transported in the water column and as biogenic ones, the significant amounts of the sediments originate from the Antarctic ice, icebergs and sea ice. As discussed previously, the specifics of the transport of icebergs and ice in Antarctic in general and in the Weddell Sea in particular consists in the two systems of transport in the opposite directions that affect the distribution of the sedimentation in the Weddell Sea. The ice changes its direction along the coast of the continent, being initially transported westward, and turns in an opposite direction after the divergence zone. Therefore, ice and icebergs, moving along the coast to the west, are ‘caught’ in the Weddell Sea, where the elongated Antarctic Peninsula and islands presents a kind of bag where the sediments are accumulated. As a result, a significant part of the ice from Antarctica melts in the basin of the Weddell Sea. Consequently, the sedimentation rates of the southern parts of the Weddell Sea embayment are considerably higher than in other seas of the Southern Ocean. In parallel to these processes, the sedimentation uplifts include an enlarged thickness of the sediments, as visualized in Fig. 3. To a lesser extent, such a boundary effect can also be seen in the central and NW segments of the Weddell Sea.

The Weddell Sea basin presents the westernmost sea of the Southern Ocean that plays an important role in the glacier regime, ocean circulation, surface ice runoff and sediment accumulation into the stream channels. The topographic map of the basin plotted against the gravity anomalies and geoid model in the present study highlights the correlation of the isolines, clearly seen in a majority of the submarine topographic structures. Similar geometric correlation is found to be existing between the sediment thickness map and the bathymetry of the Weddell Sea under consideration which further indicates the seafloor as having uniform underlying lithology of the flat abyssal Weddell Plain. These outcomes also exemplifies that the distribution of the sediment thickness over the Weddell Sea basin mainly depends on the local glaciological, geophysical and topographic settings.

Recent reconstructions of past morphology of Antarctica show that the bathymetry of the Weddell Sea has not changed substantially since the Eocene (Paxman *et al.*, 2019) and reveal the series of sedimentary features along the continental margin of the SE Weddell Sea which constrain glacial-influenced sedimentation processes from the Middle Miocene to the present (Huang and Jokat, 2016). For instance, they shown a specific correlation of the NE-SW-oriented bathymetric structures, such as over 150 km wide and 700 km long, where a sediment has a thickness up to 2 km. The evolution of sedimentary basins in the Weddell province experienced various stages of the development in its structure. For instance, this includes, strong stretching in Late Palaeozoic to Early Mesozoic time along the trans-crustal detachment faults, which resulted in an uplift of the lower crust into shallow level and can explain the extraordinary crustal section in the Weddell Sea (Grikurov *et al.*, 1991).

Patterns of the sediment thickness demonstrated higher values in the southern parts of the sea, which indicates a clear correlation with the glacial-geomorphological constraints. The ice influx importing sediment material to the basin causes such variations in a character of data distribution. The geomorphological pattern is characterized by an asymmetric relief of the shelf area with clearly visible shallower parts of the western sector of the sea and deeper bathymetry in the east. The mean values for the marine free-air gravity approximation is 1.0156, while actual range of the grid lies between -309.888 and 273.712 mGal. The values common in the central part of the basin where geologic structures causing fewer values are between -50 to 10 mGal (aquamarine to light green colors in Fig. 5). This seems contrasting with the other seas of the Southern Ocean, e.g. Ross Sea, where dominating values are between the -60 to -35 mGal in the centre. In general, the structure of the seafloor relief within the Weddell Sea basin can be seen in the isolines of the gravity signals.

The major geomorphological systems and depressions have impacts on the geoid values, together with the bathymetry where geoid signals correlate with the shelf areas and the coastline of the Weddell Sea (Ronne Ice Shelf, elongation of the two major troughs of the Weddell Sea, the Ronne Trough and the Filchner Trough). The geoid undulations of the Weddell Sea has a gradually increasing pattern of data distribution in a NE direction (reaching from -30.191 m to 28.752), which suggest that the seafloor of this segment of the basin shows gravity anomalies causing differences in the Earth's gravity field. This can be affected by variations in the rock mass distribution over the seafloor, and be in turn reflected as variations in the submarine relief of the Weddell Sea.

CONCLUSIONS

The Antarctic region is playing an increasingly important role in the global climate and ocean circulation system, since the Antarctic ice sheet is considered as a primary contributor for the global mean sea level rise. For instance, Antarctica might contribute towards the one-meter sea-level rise by 2100 as estimated by DeConto and Pollard (2016). Therefore, the actuality of the presented research consists in the contributed studies on the westernmost segment of the Antarctic, notable for its unique hydrological and glaciological regime and extensive magnetic anomalies in its south. The geophysical complexity of the region reflects its long geological evolution which includes the plate motions during common the geological history with South American Patagonia and Andean orogeny since Mesozoic separation of East and West Gondwana resulting in the seafloor spreading in the southern Weddell Sea (Livermore and Hunter, 1996; Storey *et al.*, 1988; Curtis and Storey, 1996; König and Jokat, 2006; Riley *et al.*, 2020). The seafloor spreading in the Weddell Sea initiated during the Jurassic–Cretaceous compression (Storey *et al.*, 1996; Kristoffersen and Hinz, 1991) and experienced changes in its directions during several periods afterwards (Livermore, Woollett, 1993): in the Cretaceous, the Paleocene (~5 Ma) and the mid-Eocene (~50 Ma). The consequences of such an uneven geological development is resulted in the formation of basaltic successions, silicic magmatism, rifting as well as Triassic–Jurassic arc extension, which continued as a formation of the ocean-continent boundary along the northern margin of the Weddell Sea and current morphologic variability of the seafloor of the Weddell Sea, as demonstrated in this work.

Analysing correlations in geophysical, geological and topographic datasets of the Weddell Sea can be made possible through application of the high-resolution datasets by GMT. The geophysical and topographic mapping is largely used both in pure and applied tasks of various geosciences. High-resolution datasets used in this study highlighted correlation between the geographic and geological phenomena based on the cartographic visualization, which aims to advance in understanding of the effects of seafloor geomorphology and sediment thickness. In general, gravimetric terrain mapping accounts for the variations of topographic elevations. Therefore, high-resolution data are of high importance for the correct analysis. The high-resolution GEBCO DEM has an unprecedentedly high resolution of 15-arc seconds. The gravity mapping was performed using the EGM-2008 grid with 2,5 minute resolution which is an updated version of previous EGM96 grid with 15-arc-minute resolution. The ETOPO1 DEMs with lower resolution (1 minute) was applied for plotting regional map of the Antarctic (Fig. 1). The results reveal that the elevated areas of the submarine ridges and mountainous regions of the Antarctic Peninsula and Coats Land particularly correlate with the marine free-air gravity grids in Faye's reduction showing positive anomalies in computations.

The visualization of the geophysical settings of the seafloor in context of its local topographic structure formed in course of the geological evolution is crucial for the reliability of data analysis, assessment of correlation and mapping. In this study, several maps based on high-resolution raster grids (GEBCO, EGM-2008, satellite-derived gravity grid from CryoSat-2 and Jason-1) were established for mapping aimed at the analysis of the Weddell Sea geophysical settings, processes of the glaciomarine sediment formation, closely connected with the sea ice distribution, to present observations on the possible effects of topography and bathymetry on the geophysical settings.

The paper furthermore presented the multi-source topographic, geological and geophysical analysis, and visualized free-air gravity approximation and thematic mapping of the geoid geopotential grids in the Weddell Sea processed by GMT. These data were interpreted and their comparativeness was analysed, combined with published literature, existing studies on the westernmost segment of the Antarctic. The results indicated that the bathymetry of the Weddell Sea well correlates with its geophysical setting and geological evolution reflecting the tectonic movements in the past, properties of the underlying rocks and strong impact of the glacier regime of the Antarctica. The visualization of the sediment deposition along the continental shelves of the Weddell Sea helps to improves the understanding of the variability in its topographic structure related to the past ice sheet dynamics. The research contributed both to the studies of the Antarctic and polar regions and to the development of the cartographic methods applied for geophysical and geological research.

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