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The structure of sedimentary basins of Antarctica and a new three-layer sediment model

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ABSTRACT

We use geophysical data together with a recent subglacial bedrock map (BEDMACHINE model) to obtain and investigate a new three-layer sediment model for Antarctica that locally improves the global sediment model. We provide a combined, continuous, sediment model for Antarctica and surrounding oceans by joining such improved continental sedimentary model with an existing global one (GlobSed). Our results reveal large differences between sedimentary basins for Antarctica due to their age and origin. The maximum thickness of sediments is reached under Filchner-Ronne Ice Shelf and off the Weddell Sea coast (10–12 km); further offshore, towards the ocean, the thickness of sediments drops to 4–5 km. We divide the sediment cover into three layers to distinguish material with different velocities. The lower sediment layer (deeper than 7 km) with high P-wave velocities (4.0–4.9 km/s) is found only for Lambert Rift and Filchner-Ronne basin. The middle layer (2–7 km) has large variations for different sedimentary basins: 3.5–3.7 km/s for Lambert Basin; 4.0–4.3 km/s for Ross, Byrd and Bentley basins; 3.3–4.0 km/s for Filchner-Ronne Basin. The upper sediment layer (0–2 km) has large velocity variations, from 2.0 km/s for Ross and Lambert basins (young sediments) to 4.7 km/s for Dronning Maud Land basins. We suggest that P-wave velocities larger than 4 km/s represent old, compacted sediments which belong to the Beacon Supergroup; about 3 km/s refer to Mesozoic (rifted?) sediments; and less than 3 km/s relate to young Cenozoic sediments. According to this criterion, Dronning Maud Land, Bentley and Byrd basins belong to the Beacon Supergroup, while more complex and thicker Ross, Lambert and Filchner-Ronne basins contain sediments from Beacon Supergroup in the middle or lower layer, respectively. Other sedimentary basins with more moderate velocities possibly belong to the East Antarctic Rift System which formed later during Gondwana breakup.

1. Introduction

Sediments form a very heterogeneous, and highly varying in thickness, layer of the Earth, that could mask the signature of deeper structure in potential fields, making it more difficult to retrieve. Globally, the thickness of the sediments varies from 0 to more than 20 km (Laske and Masters, 1997). The properties of sediments vary greatly depending on their history and type of sedimentation. In addition, the study of sedimentation provides insight into the past evolution of a region and its climate as well, and provides clues for understanding the origin and geological histories of the region. Continental sediments are especially heterogeneous as a result of the erosion of various continental rocks. After formation, sediments can be tectonically deformed, redeposited or even subducted and therefore enter the deep Earth cycle (Sobolev et al., 2007; Trubitsyn et al., 2007; Bobrov and Baranov, 2018).

West Antarctica is characterized by weak, stretched lithosphere and hot upper mantle with mantle upwelling flows (Danesi and Morelli, 2001; Morelli and Danesi, 2004; Lucas et al., 2020). Stretching began in the Mesozoic (and even earlier) and continues now in some parts of West Antarctica, for example, Terror Rift (Behrendt, 1999; Davey et al., 2006). In West Antarctica, the bottom of the ice sheet in Bentley, Byrd and Ronne depressions (BST, BB, Fig. 1) reaches −2000 m and more below sea level (Morlighem et al., 2020). West Antarctica is characterized by large sedimentary basins. The Ross Ice Shelf (Fig. 1) is a broad region characterized by low subglacial topography. It is a part of the West Antarctic Rift System, formed by stretched continental crust (Ji et al., 2018). The Byrd and Bentley (BB, BST, Fig. 1) subglacial basins are a continuation of the Ross Ice Shelf along the Transantarctic Mountains, with very low subglacial topography. Another large sedimentary basin of West Antarctica is Filchner-Ronne Ice Shelf. It has been suggested that

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Filchner-Ronne Ice Shelf is a failed Jurasic rift (Jokat and Herter, 2016). Now it is a passive continental margin unlike the West Antarctic Rift System.

East Antarctica, in contrast, is characterized by rather strong and thick lithosphere with mantle downwelling flows under it (Danesi and Morelli, 2001; Morelli and Danesi, 2004; Chuvaev et al., 2020). In the past, however, East Antarctica has also experienced extension during the breakup of Gondwana, suggesting that there are extensive sedimentary basins for East Antarctica as well. Some of the sedimentary basins are isolated inside the continent, while others have access to the shelf and continental sediments, thus being carried out into the surrounding seas. In East Antarctica, the deepest onshore depression, the Denman depression, was recently discovered, with bottom reaching 3500 m below sea level (Morlighem et al., 2020). Other deep depressions have also been found, mainly in the Australo-Antarctica block of East Antarctica. Their relief resembles the East African Rift System; the

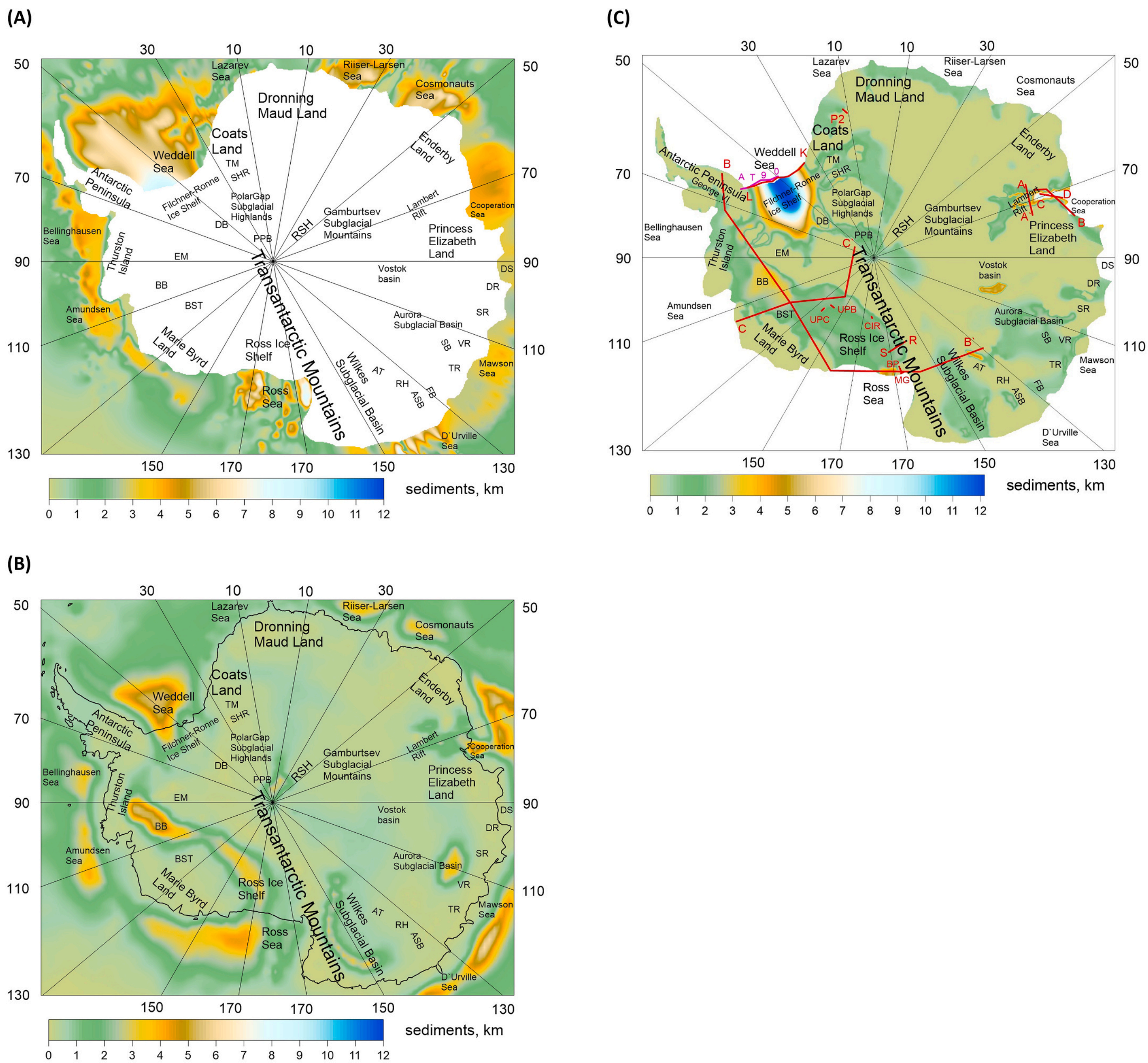

Fig. 1. a. Map of the sediment thickness from GlobSed (Straume et al., 2019) in the azimuthal equidistant projection. Used abbreviations: PPB - Pensacola-Pole Basin, EM - Ellsworth Mountains, BB – Byrd Basin, BST – Bentley Subglacial Trench, SHR- Shackleton Range, TM - Theron Mountains, SR - Scott rift, DR - Denman rift, VR - Vanderford rift, TR - Totten rift, AT - Adventure Trench, ASB - Astrolabe Subglacial Basin, RH - Resolution Highlands, DB - Dufek Block, RSH - Recovery Subglacial Highlands, FB – Frost Subglacial Basin, SB – Sabrina Subglacial Basin, DS – Davis Sea.
b. Map of the sediment thickness from CRUST 1.0 model (Laske et al., 2013). The same abbreviations as in Fig. 1a are used.
c. Map of the sediment thickness from our new ANTASed-II sediment model (this study). The same abbreviations as in Fig. 1a are used. Seismic profiles containing information about sediment velocities are shown as red lines: BB`, CC` (Bentley, 1973); LK (Leitchenkov and Kudryavtzev, 1997); P2 (Hungeling and Tyssen, 1991); AB, CD, AA` (Kolmakov et al., 1975; Fedorov et al., 1982); MG (McGinnis et al., 1985); BP profile (Beaudoin et al., 1992); SR (ten Brink et al., 1993); CIR, UPB (Rooney et al., 1987); UPC (Munson and Bentley, 1992); ANT II/4, 90,200, 92,010 profiles (Hübscher et al., 1996) are shown by magenta lines (symbols A, T, 9, 0). The interpretation of the profiles is also given in Table 1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Vostok, Astrolabe and Adventure depressions are similar to the structures of lakes Tanganyika, Nyasa, and the Baikal Lake in Siberia. Obviously, such deep depressions are a trap for sediments, if they formed before glaciation of the continent.

Recently, several regional and global models of sediments have been built. Global compilations of sediment thickness have been published by Laske and Masters (1997); Divins (2003); Laske et al. (2013); Straume et al. (2019), and others. Regional sediment models in the Antarctic region have been compiled by Whittaker et al. (2013) for the Australo-Antarctic region; Huang et al. (2014) for Weddell Sea; Wobbe et al. (2014) and Lindeque et al. (2016) for the West Antarctic margin; Straume et al. (2019) - sediment thickness in the world's oceans (include previous sediment models); Baranov et al. (2021a, 2021b) for the whole Antarctic continent.

Thus, for the South region there are two recent sediment models: GlobSed for South Ocean (Straume et al., 2019) and ANTASed for the Antarctic continent (Baranov et al., 2021a, 2021b). Each of these models is obtained independently from a large amount of geophysical data. It appears necessary then to combine these two models into a single sediment model for the whole Southern region.

The depth to the basement is among the parameters most reliably determined by seismic data. However, geophysical data can also provide information about structure and other properties of sediments, giving hints about their origin. Except for the studies by Bassin et al. (2000); Laske et al. (2013) and Baranov et al. (2018a), no models have been focused on investigating the inner sedimentary structure for the Antarctic region. However, global models CRUST2.0 (Bassin et al., 2000) and CRUST1.0 (Laske et al., 2013) have poor accuracy in Antarctica and do not provide information about data coverage. It is thus unknown where these models are based on real data and what geophysical datasets have been used. Moreover, geophysical data obtained after 2013 have not been incorporated in the compilation of CRUST1.0. We argue that some old seismic profiles have not been included in CRUST1.0 too. The regional sediment model from Baranov et al. (2018a) used seismic data, but not, e.g., the old seismic profiles from Beaudoin et al., 1992, Bentley (1973), McGinnis et al. (1985), ten Brink et al. (1993) and others, and did not use other geophysical data (magnetic, radar and new BEDMACHINE subglacial relief). In addition, it does not include part of the sedimentary basins mainly from the Australo-Antarctica block.

Large differences in the thickness and properties of the Antarctic crust between the CRUST1.0 model (Laske et al., 2013) and the improved ANTMoho model (Baranov et al., 2021a, 2021b) suggest the need to revise the properties of the sedimentary model of Antarctica. In this study, we first update a previous model (ANTASed, Baranov et al., 2021a, 2021b) on the basis of geophysical data (magnetic, radar and BEDMACHINE subglacial relief), not considered before, related to sedimentary basin structure; and then we combine the sediment grid of the new Antarctic continental model (ANTASed-II), together with information about the South Ocean (GlobSed, Straume et al., 2019) into a continuous 5-arc-minute sediment thickness grid. The differences between total thickness of sediments in CRUST1.0 and our combined model are also presented. In CRUST1.0, sediments are divided into upper, middle and lower layers. We use the same structure for consistency with global CRUST1.0 model. Main parameters of sediment layers are depth, thickness, and P wave velocities. We therefore use seismic data to construct the new three-layer sediment model. The average P-wave velocity diagrams for sedimentary basins in Antarctica is presented too. The new model is then analyzed and compared to CRUST1.0 sediment model.

2. Methods and data

2.1. Combining ANTASed and GlobSed into a single model

GlobSed (Straume et al., 2019) and ANTASed (Baranov et al., 2021a, 2021b) are natively represented with different projections, that need to be homogenized. GlobSed is presented as a Cartesian 5-arc-minute sediment thickness grid whereas ANTASed is presented as a pole-equidistant grid created with an azimuthal equidistant projection centered at the South Pole. The relationship between the coordinates (θ, ρ) of the point on the globe in the azimuthal equidistant projection with the center in the South Pole, and its latitude and longitude coordinates (φ, λ) are given by the equations (Snyder and Voxland, 1989):

$$\rho = (\pi/2 + \lambda) \times cos(\varphi) \quad (1)$$

$$\theta = (\pi/2 + \lambda) \times sin(\varphi) \quad (2)$$

At first, we chose to convert the GlobSed dat file to an azimuthal equidistant projection with center in the South Pole— that we deem more appropriate for the high-latitude geographical region.

Then we build a 5-arc-minute grid using a kriging technique for interpolation (linear variogram; SURFER, Golden Software package). This method has been described in detail and used for Moho constructing in different regions (Baranov, 2010; Baranov and Morelli, 2013; Baranov et al., 2018a; Baranov et al., 2018b). We then blank out the resulting grid by the continental shelf border (Fig. 1a) and convert the blanked grid to a data file. We thus obtain the thickness of sediments, in an appropriate polar projection, for the South Ocean surrounding continental Antarctica. Similarly, to the GloblSed model, we convert the sediment thickness data from the CRUST 1.0 model to azimuthal equidistant projection for further comparison with our combined sediment model and build the 5-arc-minute grid using the same a kriging technique (Fig. 1b).

Further we significantly improve the continental model for some important regions. To construct the new ANTASed-II model, we add fresh information from newly accessed data to previously published model ANTASed (Baranov et al., 2021a, 2021b). Specific references for different regions are mentioned in the following. We start from the contour levels in ANTASed by comparing their values to 2D seismic profile data, and manually update the thickness values preserving the shapes of contours. This is quite a labour-intensive endeavour, but it is necessary to prevent unrealistic features correlated to data distribution along linear profiles. During this procedure, we consider other information — such as the BEDMACHINE bedrock model — as prior geological information. Finally, the model consisting of (updated) contour levels is interpolated to values on regularly-spaced grid points using kriging.

We delineate the contours of the Antarctic Peninsula and Alexander I Island more clearly, obtaining a new sedimentary basin under the George VI Ice Shelf between them. This is confirmed by the BEDMACHINE model and different geophysical data (Bell and King, 1998; Crabtree et al., 1985; Maslanyj, 1988). In the central part of Ross Ice Shelf sediment thickness is rather moderate (1–2 km) as confirmed by seismic profiles UPC, SERIS, CIR and UPB (Rooney et al., 1987; Munson and Bentley, 1992; ten Brink et al., 1993). In the Byrd and Bentley basins sediments are about 2–4 km thick, according to seismic profiles BB`, CC` (Bentley, 1973), and in the area around McMurdo Sound sediments reach up to 4 km and more (Beaudoin et al., 1992; ten Brink et al., 1993).

For East Antarctica we add new Frost and Sabrina subglacial basins in the Australo-Antarctica block. These basins are added according to a more thorough analysis of various geophysical data: magnetic data from Aitken et al. (2014); subglacial relief from BEDMACHINE model (Morlighem et al., 2020); paleotopography reconstructions (Wilson and Luyendyk, 2009); and gravity anomalies (Scheinert et al., 2016). We also use these data to more accurately map existing sedimentary basins: Wilkes, Aurora, Astrolabe, Adventure, and others. We also use old seismic data for improving Lambert basin borders (Fedorov et al., 1982; Kurinin and Grikurov, 1982). Two seismic profiles cross Lambert graben. The first profile AB, lying approximately at 70^0 S, provides 6–9 km of multilayer sediments under Amery Ice Shelf between Prince Charles Mountains and Larsemann Hills as a single sedimentary basin. At the same time, the lower layer with 1–2 km thickness consists of high-velocity Permian sediments, and Cenozoic sediments lie on the top. For this profile, the northern extension of the Mawson Escarpment does not come to the surface and is covered with sediments having a thickness of 1–2 km but is clearly visible below. To the south, on the second profile AA` (Prince Charlez Mountains, Lambert Rift, Grove Mountains), a single basin is divided into two branches, define two sediment basins, which are separated by the Mawson Escarpment in the middle. At the same time, the thickness of sediments in the eastern branch between the Mawson Escarpment and the Grove Mountains is even higher (up to 6 km) than in the western branch between the Prince Charlez Mountains and the Mawson Escarpment. However, the eastern part in the surface subglacial relief is weakly expressed in contrast to the western part. In the eastern branch of the Lambert Basin, there is another escarp of basement rocks that does not outcrop.

After adding new geophysical data, we rebuild the improved ANTASed model to 5-arc-minute grid in spherical azimuthal equidistant projection for compatibility with CRUST1.0 and GlobSed grids, blank the ANTASed-IIgrid by the continent margin (Fig. 1c) and convert the blanked grid to a data file. Next, we merge together the revised ANTASed, and the GlobSed data files. Using the kriging interpolation method with linear variogram (Golden Software package) we finally interpolate the resulting data array onto a geographical grid created with an azimuthal equidistant projection centered at the South Pole. The kriging parameters were chosen as follows: the interpolation area was from the South Pole to 60°S, the 5-arc-minute grid step on a geographical latitude-longitude grid with no anisotropy, and the scale was set one. This technique can be used to combine heterogeneous data files into a single one.

To find the difference between the new ANTASed-II model and the previous ANTASed sediment model, and between the new combined sediment model for Antarctica and surroundings and the CRUST1.0 sediment model, we subtract the 5-arc-minute ANTASed sediment grid (CRUST1.0 sediment grid) in spherical azimuthal equidistant projection from the new received model grids (ANTASed-II and combined) in the same projection respectively using grid manipulation modules of the Generic Mapping Tools (Wessel et al., 2019).

2.2. Three-layer sediment model

The depth to the basement is among the parameters most reliably determined from seismic data, and is the main parameter represented by the two input models. Additionally, we also compile elastic properties (P-wave velocity and density). Since these parameters usually increase rapidly with depth, it is necessary to divide the sediment layer into a number, most often three, layers. We hence provide three layers of sediments to ensure consistency with CRUST1.0 (Laske et al., 2013). The first (upper) layer includes sediments with thickness less than 2 km. The middle layer describes sediments below 2 km, whereas the lower layer of sediments lies below 7 km. Using this arrangement, we divide the sediment thickness into 3 layers using the merged model for Antarctica

Table 1
Seismic profiles and origin of sedimentary basins.

Source	Type	Sediment properties	Region	Additionally,
Bentley, 1973	Long seismic refraction profiles	Ross Ice Shelf: 2.4 km/s for upper sediments, 4.2 km/s for middle sediments (BB' profile); Byrd and Bentley sedimentary basins: 4.1 and 4.3 km/s for upper sediments (BB' profile); Bentley basin: 4.3 km/s for upper sediments (CC' profile)	BB' profile: Antarctic Peninsula – Victoria Land; CC' profile: Marie Byrd Land– Transantarctic Mountains	These profiles provide information for sediments and upper crust
Hungeling and Tyssen, 1991	Refraction profile	4.7 km/s for upper layer of sediments	P2 profile: Western Dronning Maud Land near the coast	This profile provides information for sediments and crust
Fedorov et al., 1982; Kurinin and Grikurov, 1982; Kolmakov et al., 1975	Three DSS profiles	Upper layer of sediments 2.0–3.0 km/s; middle layer 3.5–3.7 km/s; lower layer 4.0–4.5 km/s	AB profile: Prince Charles Mountains, Lambert Rift, Princess Elizabeth Land; AA` profile: Prince Charles Mountains, Lambert Rift, Mawson Escarpment, Lambert Rift, Grove Mountains; CD profile: Lambert Rift	These profiles provide information for sediments and crust
McGinnis et al., 1985	Refraction profile	2.5 km/s s for upper sediments	MG profile: Near Ross Island	This profile provides information for sediments and crust
Rooney et al., 1987	CIR and UPB refraction profiles	CIR profile: 4.0 km/s for upper sediments; UPB profile: 2.0 km/s for upper sediments	CIR profile is located in Ross Ice Shelf near Shackleton Glacier; UPB profile is located near the Siple Coast, West Antarctica	Only sediments and upper crust
Munson and Bentley, 1992	Refraction, wide-angle reflection UPC profile	2.0 km/s for upper sediments	UPC profile: West Antarctica between Bentley Subglacial Trench and Siple Coast	Only sediments and upper crust
ten Brink et al., 1993	Refraction, wide-angle reflection SERIS profile	2.2–2.6 km/s for upper sediments	SR profile: border between Ross Ice shelf and Transantarctic Mountains (near Nimrode Glacier)	This profile provides information for sediments and crust
Beaudoin et al., 1992	Refraction and reflection profiles	2.7 km/s for upper sediments; 4.2 km/s for lower sediments	BP profile: near Ross Island, the profiles are aligned approximately perpendicular to the Cenozoic alkaline volcanics of the Ross Archipelago	Only sediments and upper crust
Hübscher et al., 1996	Two refraction and one reflection profiles	Upper layer of sediments (with ice and water) 2.2 km/s; middle layer 3.5–3.7 km/s; lower layer 4.1–4.8 km/s	ANT II/4, 90,200, 92,010 profiles: Ronne Ice Shelf along the border between Antarctic Peninsula and Berkner Island	These profiles provide information for sediments and crust
Leitchenkov and Kudryavtzev, 1997	DSS profile	Upper layer of sediments 2.6–3.0 km/s; middle layer 3.3–4.0 km/s; lower layer 4.6–4.9 km/s	LK profile: Filchner- Ronne Ice Shelf along the border between Antarctic Peninsula and East Antarctica	Long profile across the main tectonic structures of the Weddell Sea border. This profile provides information for sediments and crust

region (GlobSed + ANTASed-II database) as a basis. We create separate grids for the upper, middle and lower sedimentary layers using a standard kriging technique with a linear variogram (SURFER, Golden Software package). The kriging parameters are chosen as follows: the interpolation area was from the South Pole to 60°S (on an azimuthal equidistant projection), the 5-arc-minute grid on a geographical latitude-longitude grid with no anisotropy.

2.3. Sediment velocity model

Seismic velocity information for sedimentary basins can be provided by different types of seismic data, notably seismic profiles (Deep Seismic Sounding, wide-angle reflection, and refraction profiles). The seismic data used for the analysis of sediment structure are summarized in Table 1. Here we use only intracontinental seismic profiles containing information about inner sediment structure. For the surrounding seas there are also many seismic profiles, but we neglect them as they do not reach on the continent, that is our interest. Obviously, the reliability of this information decreases with increasing distance away from seismic profiles. However, many sedimentary basins are not large, so one profile alone — combined with information about the shape of the basin — carries significant information. We must also acknowledge that, for a part of sedimentary basins — mainly from the Australo-Antarctica block — there are no any seismic data at all.

For Dronning Maud Land, seismic profile P2 from Hungeling and Tyssen (1991) provides P-wave velocity of about 4.7 km/s for sediments. Seismic data for Lambert Rift provide P-wave velocity in three-layer sediments: upper layer of sediments (2.0–3.0 km/s); middle layer (3.5–3.7 km/s); lower layer (4.0–4.5 km/s) (Fedorov et al., 1982; Kurinin and Grikurov, 1982; Kolmakov et al., 1975). The seismic profile for the Vostok Basin only provides thickness of sediments (Isanina et al., 2009). Similarly, the receiver functions data show the presence of sediments for the Wilkes Basin (Agostinetti et al., 2005). Unfortunately, there are no seismic data on their internal structure for the remaining sedimentary basins of East Antarctica.

Some P-wave velocity models from seismic profiles (McGinnis et al., 1985; Rooney et al., 1987; Beaudoin et al., 1992; Munson and Bentley, 1992; ten Brink et al., 1993) provide information about sediment properties for the Ross Ice Shelf. For this region, the P-wave velocity varies from 2.0 to 4.2 km/s. Several refraction profiles near Ross Island provide information about crustal and sedimentary properties (McGinnis et al., 1985). Here the P-wave velocity in the sedimentary layer is about 2.5 km/s. Refraction profile CIR reveals one sediment layer with P-wave velocity of about 2.4 km/s for the Ross Ice Shelf near Transantarctic Mountains (Shackleton Glacier). Another refraction profile (UPB) reveals one sediment layer (4.0 km/s) near the Siple Coast (Rooney et al., 1987). The refraction and wide-angle reflection profile UPC between Bentley Subglacial Trench and Siple Coast provide P-wave velocity of about 2.0 km/s for upper sediments (Munson and Bentley, 1992). Refraction and reflection profiles lying perpendicular to the Cenozoic alkaline volcanics of the Ross Iceland reveal a P-wave velocity in sediments of about 2.7 km/s and 4.2 km/s for upper and middle sedimentary layer respectively (Beaudoin et al., 1992). At the border between Transantarctic Mountains and Ross Ice Shelf, near the Nimrode Glacier area, seismic profile SERIS reveals P-wave velocity in sediments of about 2.2–2.6 km/s (ten Brink et al., 1993).

Under the Filchner-Ronne Ice Shelf, a large subglacial basin lies between the Antarctic Peninsula and East Antarctica. This basin is characterized by low bedrock topography. A 800 km-long DSS profile has been carried out across the Filchner- Ronne Ice Shelf (Leitchenkov and Kudryavtzev, 1997). This profile reveals a complex multilayer sedimentary basin and provides quite detailed data about sediment structure of this region. Sedimentary properties change along the DSS profile near the coastline. The following structure of sediments has been identified: upper layer of sediments with P velocity of about 2.6–3.0 km/s; middle layer (3.3–4.0 km/s) and lower layer (4.6–4.9 km/s). Two refraction profiles between the Antarctic Peninsula and Berkner Island also reveal a complex structure of sediments: an upper layer with P velocity about 2.2 km/s; a middle layer (3.5–3.7 km/s); and a lower layer (4.1–4.8 km/s) (Hübscher et al., 1996). However, it should be noted that in this study, water and ice have been included in the upper layer of sediments - hence such low velocities in the upper layer. Long seismic profiles AA', BB' and CC' (Bentley, 1973) also provide information about the subglacial structure of Antarctica. Profile AA' does not show a significant amount of sediments. Profile BB' provides velocity for the Byrd and Bentley sedimentary basins (4.1–4.3 km/s) and the Ross Ice Shelf (two layers with 2.4 and 4.2 km/s respectively). The third seismic profile CC' provides 4.3 km/s for the Bentley sedimentary basin.

It is indeed quite difficult to estimate uncertainties of a three-layer model that has been obtained by merging different types of data with large empty gaps. Unfortunately, for many areas we had only one data source, so we had no possibility to evaluate uncertainties. The accuracy of the seismic profiles seems however to be quite high. The best resolution for seismic boundaries in crust and sediments is often obtained using reflection profiles. Intermediate resolution can be obtained using refracted and wide-angle reflected waves. The accuracy for these methods is of the order of 1–2 km (Kanao et al., 2011). However, due to the vastness of sedimentary basins, the parameters of sediments far from the profiles can differ significantly.

3. Results

3.1. Combined sediment model

The combined sediment thickness for Antarctica and surroundings, derived from merging our improved continental sedimentary model ANTASed-II with the Southern Ocean model GlobSed from Straume et al. (2019), is shown in Fig. 2a.

The marginal seas of Antarctica contain a significant amount of sediments (with 2–6 km thickness). The thickest sedimentary basin is located under the Filchner Ronne Ice Shelf (up to 12 km, with multilayer sediments). At the same time, towards the Weddell Sea, the thickness of sediments decreases to 6–8 km. Another large sedimentary basin lies under the Ross Ice Shelf and Ross Sea (1–6 km) with a continuation to Byrd and Bentley basins. In the southern part of the Ross Sea, the sedimentary basins of Victoria Land, the Central and Eastern sedimentary basins (between which lie the Coulman High and Central High seamounts) are distinguished. Bentley and Byrd basins have 2–3 km of sediments. New revealed George VI basin has 1–2 km of sediments.

Sedimentary basins of East Antarctica are less extensive but also diverse. Pensacola-Pole and South Pole basins have about 1–2 km of sediments. The narrow and deep Coats Land depressions are extensions of the Filchner-Ronne basin (1–3 km of sediments). In the western part of Dronning Maud Land near the coast we find sedimentary basins 1–2 km thick, and the deep sediment-filled JutulStraumen Rift between the western and eastern parts of Dronning Maud Land. In the eastern part of Dronning Maud Land, near the coast, there are sedimentary basins 1–2 km deep. Between Enderby Land and Princess Elizabeth Land, the deep Lambert Rift lies with continuation to the Cooperation Sea. It is characterized by multilayer sediments with thickness up to 8 km or more, formed during the breakup of Gondwana and possibly earlier (Boger and Wilson, 2003; Lisker et al., 2003; Whitehead et al., 2006).

East of the coast, two narrower and deep rifts begin: Scott and Denman. There are no seismic data for them. Geophysical data and analogy with other Antarctic rifts indicate sediments with thickness about 1–2 km. The vast inland Vostok sedimentary basin lies to the southeast. Here seismic data show multilayer sediments with thickness of up to 5 km. The elongated Aurora basin, lying in the intercontinental realm of the Australo-Antarctica block, has 1–3 km of sediments. The recently discovered Vanderford and Totten rifts are characterized by sediments with thickness up to 2 km. Newly revealed Frost and Sabrina sedimentary basins have 1–2 km of sediments. Two other

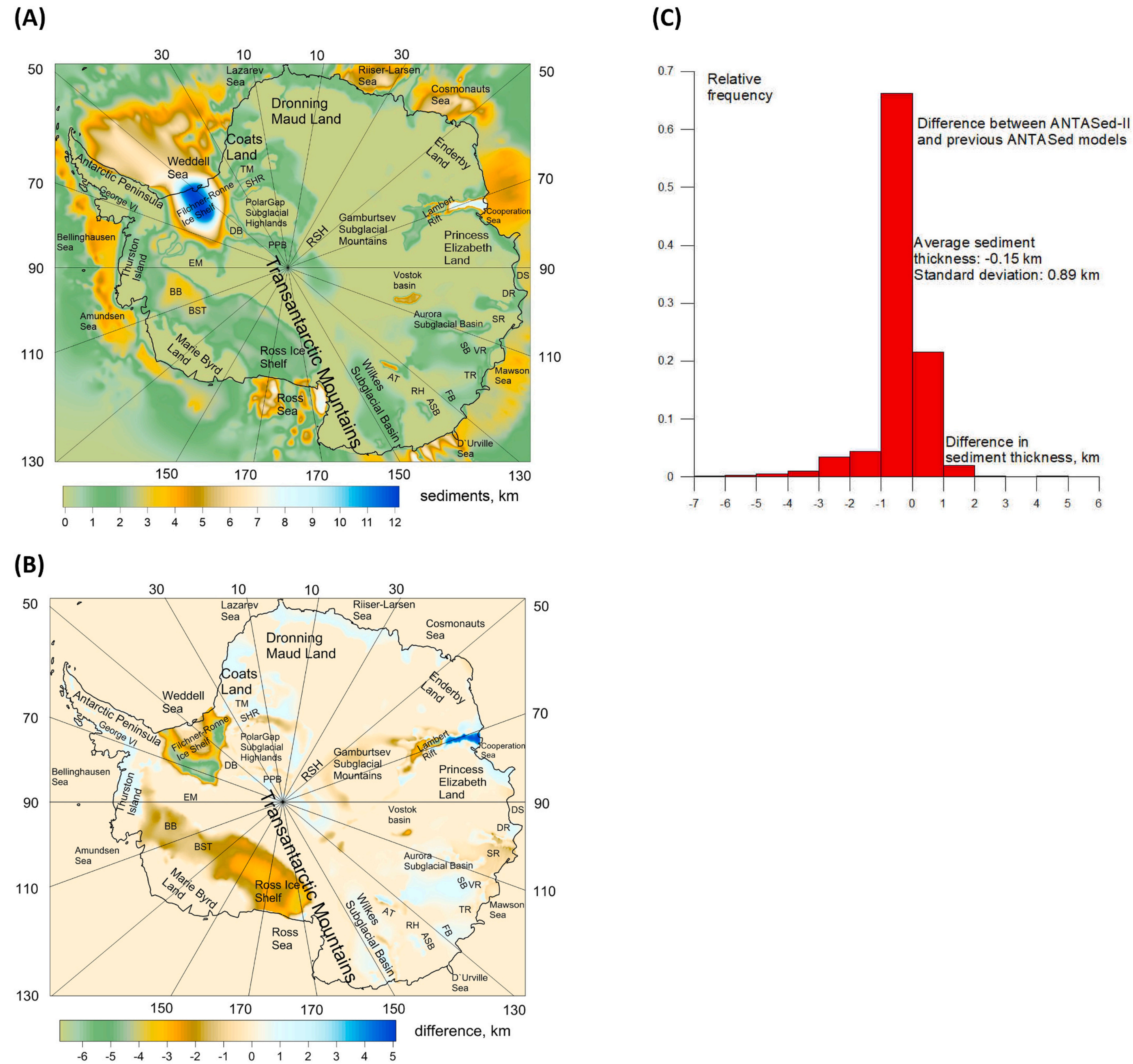

Fig. 2. a. Combined map of a sediment thickness for Antarctica (improved ANTASed-II modelBaranov et al., 2021a, 2021b) and surroundings (GlobalSed model, Straume et al., 2019). It is used the same abbreviations as in Fig. 1a.
b. Difference between new ANTASed-II sediment model (this study) and the previous ANTASed model (Baranov et al., 2021a, 2021b). It is used the same abbreviations as in Fig. 1.
c. Histogram of the difference between new ANTASed-II sediment model (this study) and the previous ANTASed model.
d. Difference between merged sediment model (GlobSed and ANTASed-II) and the CRUST1.0 model. It is used the same abbreviations as in Fig. 1.
e. Histogram of the difference between new merged sediment model (GlobSed and ANTASed-II) and the CRUST1.0 model.

intracontinental basins in the Australo-Antarctica block (Adventure and Astrolabe) have 2–4 km of sediments. In these basins, seismic data are absent. Finally, the Wilkes basin has sediments about 1–3 km thick.

The difference between our new ANTASed-II sediment model (this study) and and the previous ANTASed model (Baranov et al., 2021a, 2021b) is −6/+5 km (mean − 0.15 km, standard deviation 0.89 km, see Fig. 2b, c). There are significant differences in regions such as under the Filchner-Ronne Ice Shelf (−6 km), basins of Coats Land (−1 km), coastal basins of Dronning Maud Land (about 1 km), Lambert Rift and surroundings (−5 / +5 km), Denman, Scott, Vanderford and Totten rifts (−2 / +1 km), Vostok Basin (−2 km), Aurora Basin (−3/+1 km), Sabrina Basin (+1 km), Frost Basin (+1 km), Adventure Basin (1–2 km), Astrolabe Basin (about 1 km), Wilkes Basin (−1/+1 km), Ross Ice Shelf (−3 km), Bentley and Byrd basins (−2 km), South Pole Basin (about 1 km), Thurston Island (about 1 km), Antarctic Peninsula (about 1 km).

The difference between our combined sediment model (this study) and CRUST 1.0 (Laske et al., 2013) is −3/+11 km (mean 0.52 km, standard deviation 1.56 km, see Fig. 2d, e). There are significant differences in regions such as under the Filchner-Ronne Ice Shelf (+11 km), Weddell Sea (+5 km), basins of Coats Land (−2/+3 km), coastal basins

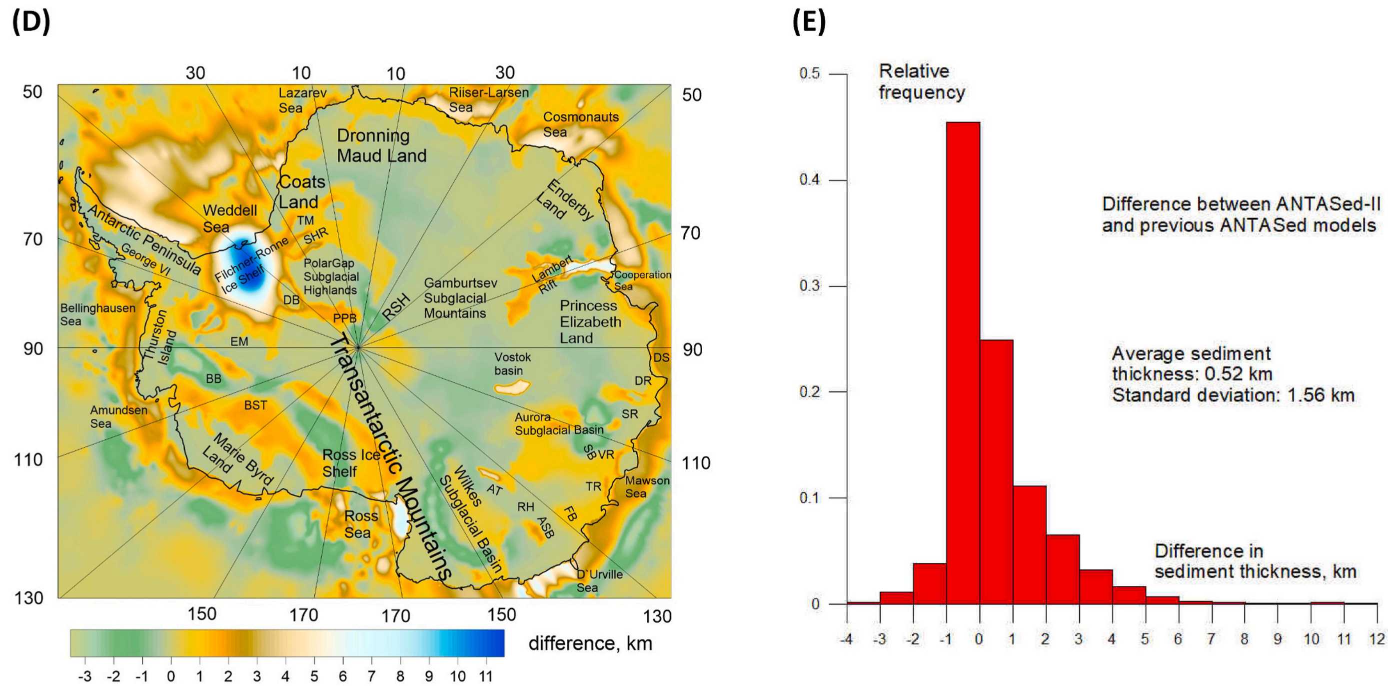

Fig. 2. (*continued*).

of Dronning Maud Land (about 1 km), Lazarev Sea (+1/+2 km), Riiser-Larsen Sea (1–2 km), Cosmonauts Sea (−1/+4 km), Lambert Rift and surroundings (−2 / +7 km), Cooperation Sea (−1/+4 km), Denman, Scott, Vanderford and Totten rifts (1–2 km), Vostok Basin (3–5 km), Davis Sea (1–2 km), Aurora Basin (−3/+1 km), Sabrina Basin (+1 km), Frost Basin (+1 km), Mawson Sea (−3/+2 km), Adventure Basin (2–3 km), Astrolabe Basin (1–2 km), Wilkes Basin (−3/+1 km), D'Urville Sea (−2/+5 km), Ross Ice Shelf (−2/+5 km), Ross Sea (−3/+7 km), Bentley and Byrd basins (−3/+2 km), Amundsen Sea (−2/+2 km), Pensacola-Pole Basin (1–2 km), South Pole Basin (−2/+1 km), Thurston Island (1–2 km), Bellingshausen Sea (−1/+3 km), Antarctic Peninsula (1–2 km).

3.2. Three-layer sediment structure

We have identified 3 layers in sedimentary basins as described in the Methods section. Upper, middle and lower sediment layers are shown in Fig. 3.

Fig. 3a shows the top layer of sediments (thickness up to 2 km). All sedimentary basins have this layer. West Antarctica is actually a single sedimentary basin and consists of two blocks: the vast Filchner-Ronne Ice Shelf Basin with continuation to Weddell Sea, South Pole area and Coats Land; and the vast Ross Ice Shelf Basin, with continuation to Ross Sea, Bentley trench and Byrd Basin. These two large sedimentary blocks are connected by a deep depression between the Antarctic Peninsula and Ellsworth-Whitmore Mountains and are separated from the marine sedimentary basins on the Pacific Ocean side by the uplifted area of Marie Byrd Land. The sedimentary basins of East Antarctica are less extensive and are not interconnected as in West Antarctica.

There are sedimentary basins in Eastern Antarctica extending into the ocean such as: Dronning Maud Land basins and JutulStraumen Rift with continuation to Lasarev Sea; Lambert Rift with continuation to Cooperation Sea; Scott and Denman rifts with continuation to Davis Sea; Vanderford and Totten rifts with continuation to Mawson Sea; Wilkes basin with continuation to D'Urville Sea. South Pole and Pensacola Pole sedimentary basins have continuation to Filchner-Ronne basin in West Antarctica. Aurora and Sabrina sedimentary basins have continuation to Vanderford and Totten rifts whereas Frost Basin continues to D'Urville Sea. The rest of the East Antarctica sedimentary basins are isolated areas within the Australo-Antarctica block of East Antarctica: Vostok, Adventure and Astrolabe sedimentary basins.

As seen in Fig. 3b, a middle layer of sediments (from 2 to 7 km) is present in many basins in Antarctica. In West Antarctica these are Filchner-Ronne Basin (0–5 km), Bentley and Byrd basins (0–2 km), and parts of Ross Ice Shelf Basin (up to 3 km). In East Antarctica the Dronning Maud Land, JutulStraumen, Scott, Denman, Vanderford, Totten, Frost, Sabrina, South-Pole and Pensacola-Pole sedimentary basins do not have a middle layer of sediments. For other sedimentary basins of East Antarctica this layer is present: Coats Land basins (0–1 km), Lambert Rift (0–5 km), Wilkes basin (0–1 km); Vostok basin (2–4 km); Aurora basin (0–1 km); Adventure and Astrolabe basins (0–2 km).

Significant differences are already visible for this sediment layer in the seas surrounding Antarctica. The most powerful is the continuation of the vast Filchner-Ronne Basin into Weddell Sea (1–5 km). This layer is present for Ross Sea (0–5 km), Riiser-Larsen Sea (0–5 km), Cosmonauts Sea (0–5 km) and D` Urville Sea (0–5 km) as a fragmentally separate deep basins. For other marginal seas middle layer has more moderate thickness.

According to available geophysical data the lower layer of sediments (below 7 km) is present only in the central part of Filchner-Ronne Ice Shelf and Lambert Rift (Fig. 3c). The thickness of the lower layer of sediments changes from 0 km near the borders to 5 km in the center of the Filchner-Ronne Basin, with moderate continuation into Southern Weddell Sea. In Lambert Rift, 1–2 km of lower sediments lie from Prydz Bay to Mawson Escarpment. In Ross Sea, this layer is mainly present in the Victoria Land Basin along the Transantarctic Mountains (~1 km). For other marginal seas this sedimentary layer is not found.

3.3. Sediment velocity model

In CRUST1.0, the P-wave velocity in the upper sediments is 3.2 km/s for all Antarctica, except under Ross and Filchner-Ronne Ice Shelves where it is from 1.8 to 2 km/s. Compared to CRUST1.0, our new ANTASed-II model reveals more detail in the pattern of seismic velocity for the upper sedimentary layer. The P-wave velocity diagrams for the sediments in our model is shown in Fig. 4. The upper sedimentary layer

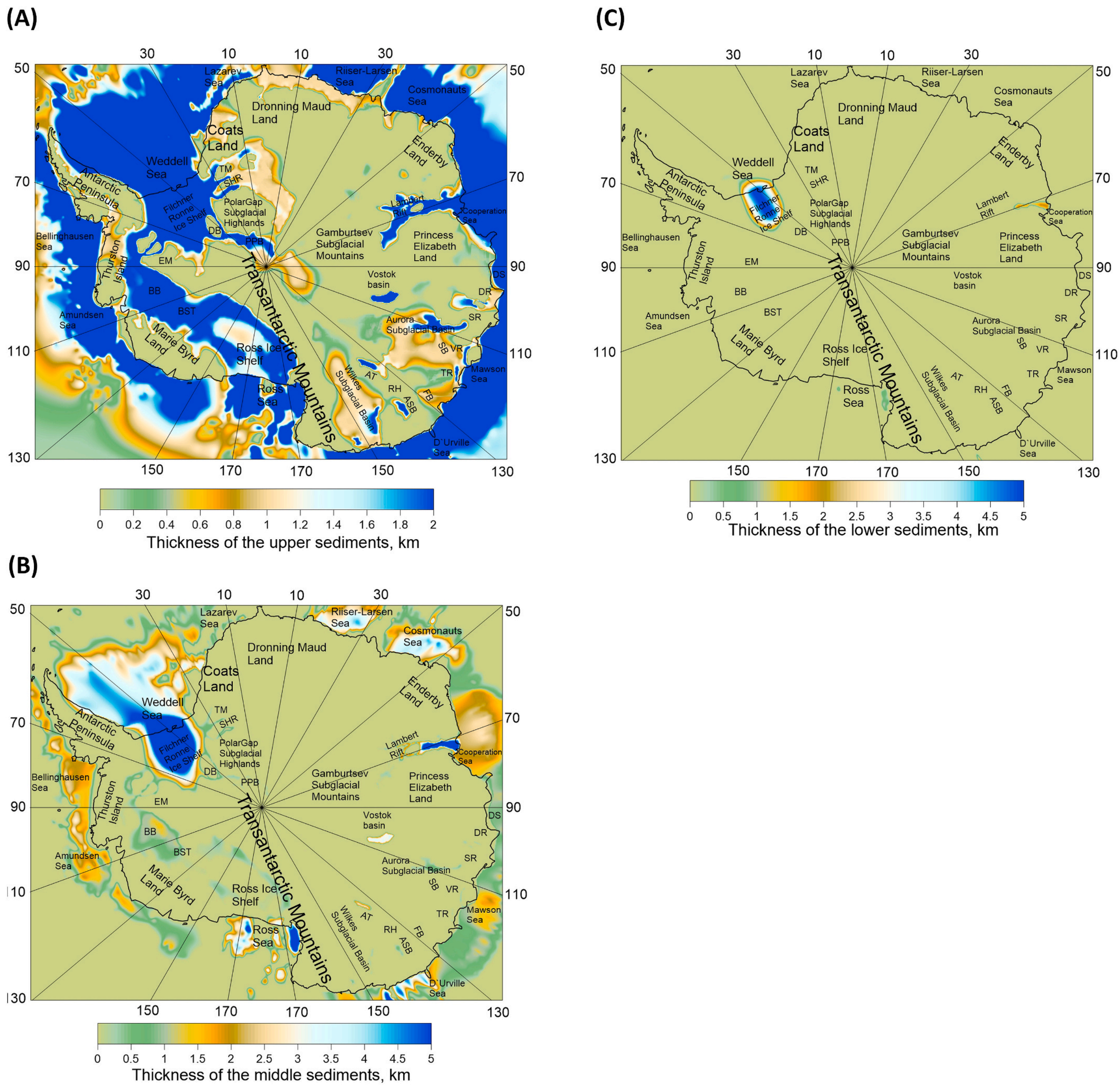

Fig. 3. a. Thickness of an upper layer of sediments. It is used the same abbreviations as in Fig. 1a.
b. Thickness of a middle layer of sediments. It is used the same abbreviations as in Fig. 1a.
c. Thickness of a lower layer of sediments. It is used the same abbreviations as in Fig. 1a.

has large velocity variations from 2.0 to 3.0 km/s for young sediments (Ross Basin) to 4.1–4.7 km/s for parts of Beacon Supergroup (Dronning Maud Land, Byrd and Bentley basins).

In the middle sedimentary layer of CRUST1.0, P-wave velocity has large variations: from 3.3 km/s for Ronne, Ross and Lambert basins, to 4.6 km/s for the area between Marie Byrd Land and Transantarctic Mountains and for Wilkes Basin. In the Pole area and Aurora Basin it is about 4.0 km/s. In our model P-wave velocity in the middle sedimentary layer also has significant variations: from 3.3 to 4.0 km/s in Filchner-Ronne Basin to 4.0–4.2 km/s in Ross Basin (Fig. 4). Lambert Rift has intermediate velocity in the middle sedimentary layer of about 3.5–3.7 km/s. In our model, the sediment thickness for the Pole basin does not exceed 2 km and therefore the middle sedimentary layer here is absent.

In the lower sedimentary layer of CRUST1.0, P-wave velocity is about 5 km/s in the area between Marie Byrd Land and Transantarctic Mountains, although — according to the thickness of sediments in CRUST1.0 being less than 7 km — there is no lower layer in this area. In our model the lower sedimentary layer is present only in the Filchner Ronne Ice Shelf and Lambert Rift with P-wave velocity of (4.1–4.9 km/s) and (4.0–4.5) respectively (Fig. 4).

3.4. *Sediment density model*

We found density in sedimentary layers using an empirical relation between the P-wave velocity and density from Brocher (2005):

$\rho(g/cm^3) = 1.6612Vp - 0.4721V^2p + 0.0671\ V^3p - 0.0043\ V^4p +$

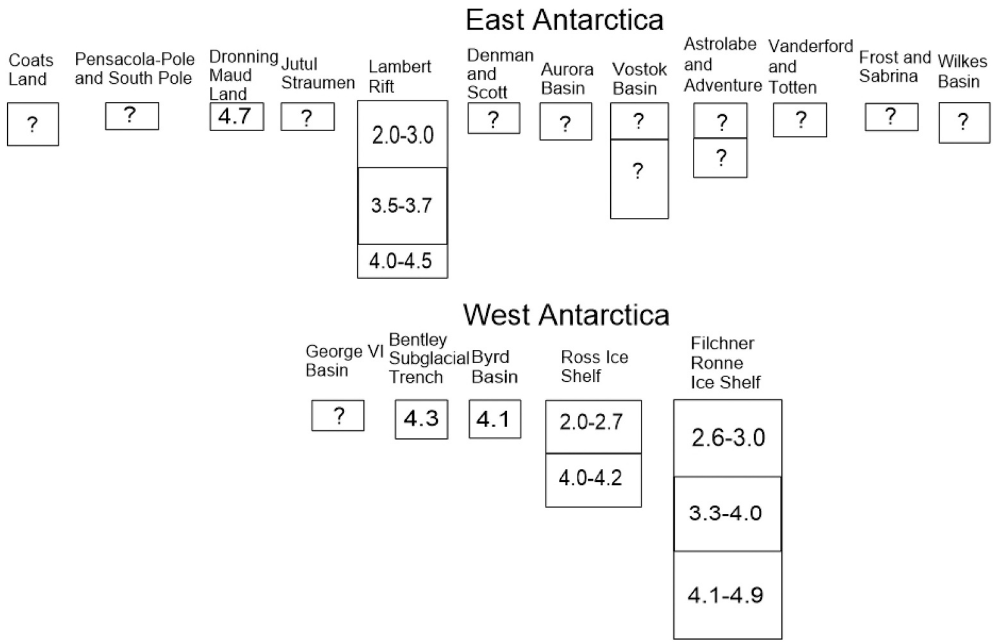

Fig. 4. The average P-wave velocity diagrams for sedimentary basins in Antarctica.

Table 2
Thickness, density and origin of sedimentary basins.

Sedimentary basin	Total thickness, km	Upper layer, km	Middle layer, km	Lower layer, km	Upper layer, density (kg/m^3)	Middle layr, density (kg/m^3)	Lower layer, density (kg/m^3)	Origin
Coats Land	1–3	1–2	0–1	–	?	?	–	Rifted sediments in deep trenches
Western Dronning Maud Land	1–2	1–2	–	–	2490	–	–	Beacon Supergroup
Jutulstraumen Rift	1	1	–	–	?	–	–	Rifted sediments?
Lambert Rift	2–9	2	0–7	02	2300–2320	2320–2350	2400–2470	From Devon to Cenozoic rifted sediments
Scott and Denman rifts	1–2	1–2	0	–	?	–	–	Rifted sediments
Vostok Basin	2–6	2	2–4	–	?	?	–	Rifted sediments
Aurora Basin	1–3	1–2	0–1	–	?	?	–	Rifted sediments?
Adventure Trench	2–4	2	0–2	–	?	?	–	Rifted sediments?
Astrolabe Subglacial Basin	2–4	2	0–2	–	?	?	–	Rifted sediments?
Frost Subglacial Basin	1–2	1–2	0	–	?	–	–	Rifted sediments?
Vanderford and Totten rifts	1–2	1–2	0	–	?	–	–	Rifted sediments?
Sabrina Subglacial Basin	1–2	1–2	0	–	?	–	–	Rifted sediments?
Wilkes Subglacial Basin	1–3	1–2	0–1	–	?	?	–	Beacon Supergroup, Cenozoic marine sediments?
Ross Ice Shelf	2–6	2	0–4	–	1860–2060	2420	–	Part of West Antarctic Rift System, Mesozoic- Cenozoic sediments in the upper layer, Beacon Supergroup in the lower layer
Byrd and Bentley Subglacial basins	2–4	2	0–2	–	2410	2420–2430	–	Part of West Antarctic Rift System, Beacon Supergroup
Filchner-Ronne Basin	2–12	2	0–5	0–7	2120–2220	2280–2390	2480–2520	Sediments of terrigenous, marine and glacial marine origin in the upper and middle layer, Beacon Supergroup in the lower layer
Pensacola-Pole Subglacial Basin	1–2	1–2	–	–	?	–	–	Beacon Supergroup?
South-Pole Subglacial Basin	1–2	1–2	–	–	?	–	–	Beacon Supergroup?
George VI Basin	1–2	1–2	–	–	?	–	–	Cenozoic rifting, Fossil Bluff Group, sediments of glacial marine origin

0.000106 V^5p. (3).

Eq. (3) is the Nafe–Drake curve. It was previously published only graphically (Ludwig et al., 1970) and has been converted to a formula by Brocher (2005).

According to this formula the sediment density in Antarctica varies in a wide range, from 1860 kg/m^3 for young Cenozoic sediments in the Ross basin, to 2490 kg/m^3 for old and dense Paleozoic sediments belonging to Beacon Supergroup. The thickness and density of consolidated crustal layers are summarized in Table 2.

4. Discussion and concluding remarks

In this study we considerably improve the previous ANTASed model in several key regions and delineate new sedimentary basins: George VI in West Antarctica; South Pole, Frost and Sabrina subglacial basins in East Antarctica (Australo-Antarctica block). We also merge the GlobSed and the improved ANTASed-II sediment thickness grids and construct the inner sediment structure for each sedimentary basin.

The combined sediment model that we construct for the continent and the surrounding South Ocean differs significantly (−3 /+11 km) from CRUST1.0 (Fig. 2d, e).

In addition to significant differences within the continent, rather large differences are also revealed for the seas surrounding continental Antarctica. The greatest differences between our sediment model and CRUST1.0 are found for the southern part of the Weddell Sea. Here our new combined model shows large differences in sediment thickness compared to CRUST1.0 (up to 8 km). The rest of the coastal seas are also characterized by significant excess of the sediment thickness in the new model (up to 4 km). At the same time for the part of Ross Sea, the sediment thickness in the new model is less than in the CRUST1.0 model (up to 3 km).

Geophysical data show the presence of sediments related to a wide range of epochs: from Devonian to Cenozoic deposits. There are numerous factors controlling sediment distribution and properties. Part of sedimentary basins in Antarctica belong to the Beacon Supergroup — connected to sedimentation on the Pacific edge of Gondwana — the other part e.g. Lambert Rift includes sedimentary basins of rift origin. These basins began to form during the Gondwana breakup; for part of the West Antarctica, rifting continues to the present.

Some sedimentary basins of Antarctica have extensions in the surrounding seas and receive significant contributions to their sedimentation today. For them, sediments are carried out into the sea and thus they can be studied directly (e.g. Whitehead et al., 2006). Other basins are intracontinental (South Pole, Astrolabe, Adventure, Aurora, Frost, Sabrina and Vostok basins of Australo-Antarctica block).

The distribution of sediments over the basins, as well as their properties, is uneven. There are sedimentary basins with a rather flat relief — Ross, Filchner- Ronne, western and eastern Dronning Maud Land, South Pole and Pensacola-Pole basins. These basins belong to Beacon Supergroup. The rest of the sediments are located in deep depressions of probably rift origin on the continent. Some of them have access to the sea through which the sediments have been carried out to sea before glaciation. Others lie in a landlocked intercontinental realm. However, here it should be taken into account that the paleotopography before and during the glaciation was very different from the modern bedmap relief (e.g. Wilson and Luyendyk, 2009).

We find several intracontinental depressions inside the continent. According to the subglacial relief (BEDMACHINE, Morlighem et al., 2020), Antarctica is the continent with deepest intracontinental depressions on land that are filled by ice. These are the Bentley and Byrd depressions in West Antarctica, reaching depth up to 2000 m below sea level; the Lambert Rift in East Antarctica; the recently discovered narrow Denman depression with a maximum depth of about 3000 m below sea level on the border of Indo-Antarctica; the Australo-Antarctica blocks of East Antarctica; and some others. At the same time, for the Byrd and Bentley depressions, according to seismic profiles, the sediment thickness is about 2–3 km, which is significantly less than for the Lambert Rift and less than the thickness of sediments in the central part of Filchner-Ronne Ice Shelf, despite the fact that Byrd and Bentley depressions are much deeper. The Byrd and Bentley subglacial depressions certainly have a rift origin but contain dense sediments of presumably Paleozoic age from the Beacon Supergroup. The absence of a significant layer of young sediments for the Bentley and Byrd depressions indicates that their formation probably began after the glaciation of this area of Antarctica.

Lambert Rift has a complex structure. The eastern branch is not very pronounced in the subglacial relief and is well compensated by sediments—apparently, rifting has stopped long time ago. The western branch of the Lambert Rift is strongly uncompensated, bedrocks lie up to 2000 m below sea level, which means that rifting continued after the glaciation. The bedrock topography is highly contrasting, from a deep depression to the Prince Charles Mountains on the western edge of the Lambert Rift. The Mawson Escarpment between West and East continues towards Prydz Bay under sedimentary cover.

We believe that a similar situation exists in other deep depressions identified by the BEDMACHINE bedrock model, where seismic data are absent: deep trenches bordering the Filchner Ronne Ice Shelf, in the Coats Land, Denman, Scott, Vanderford and Totten depressions, deep grabens of Wilkes Basin with depth in excess of 2 km below sea level. The origin of such deep, narrow, depressions filled by ice can be explained by the continuing rifting after the glaciation of these areas, when sedimentation had already ceased. In the same time the main sedimentation for the Vostok Basin and Filchner Ronne Ice Shelf appears to have occurred prior to glaciation. This fact can be well explained by the ongoing activity of West Antarctic Rift System after glaciation in the Miocene till the present days. The presence of narrow and deep depressions in East Antarctica (Denman, Scott, Wilkes, Vanderford and Totten, Lambert, Coats) and on the border of the Filchner-Ronne Ice Shelf near Coats Land shows that extension could have continued after the glaciation of these parts of Antarctica. Hence parts of East Antarctic Rift System were active after Miocene too.

We conclude that narrow subglacial depressions in West and East Antarctica continued to form after glaciation and they practically did not fill with sediments since that time. When approaching the coastline from the land side, the relief of deep depressions quickly flattens out. This can be explained by the periodic regression and transgression of the sea. With local warming and melting of ice near the coast, the subglacial depression is flooded by the sea, and sediments quickly deposit in a deep depression. Closer to the center of the continent, ice has been preserved since the moment of glaciation, preventing deep depressions from filling with sediments.

We divided sediments into three layers for compatibility with previous global sediment models CRUST 2.0 and CRUST 1.0. The upper sediment layer is presented in all sedimentary basins with thickness less than 2 km. Below 2 km we use the middle sediment layer to describe sediment deposits down to the depth of 7 km, and an additional lower layer for sedimentary basins where thickness exceeds 7 km. The seismic velocity of sediments also has significant variations. We suggest that velocity larger than 4 km/s marks old Paleozoic sediments from the Beacon Supergroup, while Mesozoic sediments have intermediate velocity (3.4–3.7 km/s), and young Cenozoic sediments have velocity of 2.0–3.0 km/s. West Antarctica contains young, rifted sediments (upper layer of Ross Ice Shelf basin, 2.0–2.7 km/s; upper layer of Filchner Ronne Ice Shelf, 2.6–3.0 km/s; George VI Basin) and more dense sediments (Byrd, Bentley, lower layers of Ross and Filchner-Ronne basins).

The Indo-Antarctica block of East Antarctica has rather high subglacial relief (Morlighem et al., 2020). For this block there are two types of sedimentary basins: deep rifted depressions (JutulStraumen Rift and Lambert Rift, 3.5–3.7 km/s) and more vast basins that belong to Beacon Supergroup having high seismic velocities (Dronning Maud Land basins, 4.7 km/s; Pensacola-Pole Basin, South Pole Basin). The Australo-Antarctica block of East Antarctica is characterized by rather low subglacial relief (Morlighem et al., 2020) and East Antarctic Rift System (Aitken et al., 2014; Frederick et al., 2016; Baranov et al., 2021b). There are rifted depressions filled by sediments with unknown velocities (Scott and Denman rifts; Vostok Basin; Aurora Basin; Adventure Trench; Astrolabe Basin; Frost and Sabrina basins, Vanderford and Totten rifts and Wilkes Basin). These results confirm a significant contrast between the deep structure of West Antarctica, Indo-Antarctica and Australo-Antarctic blocks of East Antarctica.

Despite the extremely small amount of original seismic data, we observe some regional details in P-wave velocities and maps of the sedimentary layers that are absent in CRUST1.0 and CRUST2.0 models (Figs. 3, 4). We find large variations in sediments properties and origin for Antarctica using geophysical data and sufficiently improved three-layer sediment CRUST1.0 model for this region. Nevertheless, new data are still needed particularly for Australo-Antarctica block.

Author contributions

AB designed and performed the model and figures, provided a main framework of the research. AM provided a general leadership and corrected the manuscript.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tecto.2022.229662.

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