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NEW INSIGHT INTO THE DEEP STRUCTURE OF ANTARCTIC PENINSULA CONTINENTAL MARGIN BY METHODS OF 2D GRAVITY/MAGNETIC MODELLING AND 3D SEISMIC TOMOGRAPHY

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Abstract. The Antarctic Peninsula, one of several terrains of Western Antarctica, is a Mesozoic magmatic arc at the southeastern Pacific margin. In order to investigate the structure of the crust and uppermost mantle of Antarctic Peninsula continental margin we have developed joint geophysical models by 2D gravity and magnetic modelling along two most representative and lengthy seismic refraction lines, acquired by Polish Academy of Sciences in 1980-1990th. Resulting model along line I-I (along the DSS line 12), crosssing the Antarctic Peninsula margin near the Anvers Island, shows the features of passive continental margin of convergent type. The joint model on line II-II, passing from the Drake Passage through the South-Shetland Trench/Islands system and Bransfield Strait to Antarctic Peninsula, indicates continental margin structure of active style, caused by recent subduction and on-going continental rifting in the Bransfield Strait. This subduction activity is responsible to the stripes of gravity and magnetic anomalies along the Antarctic Peninsula shelf, caused by many batholits and plutons of mafic rocks (gabbro and diorites), intruded into the crust due to partial melting of the upper mantle caused by south-eastward progradation of subduction front. On-going tectonic processes within the South-Shetland Islands – Bransfield Strait block relate to mobilization of the upper mantle substance characterized by the lowest density (3.18 g/cm^3) against the uppermost mantle densities of 3.21 and 3.30 g/cm^3 revealed beneath the oceanic crust and Antarctic Peninsula continental crust respectively.

To study the lithosphere structure of the region of Antarctic Peninsula and adjoining sea-water areas we implemented the seismic tomography method which is based on Backhus-Gilbert approximation and uses the data on earthquake foci and time arrival of P-waves recorded by network of seismic stations. On the first stage only 27 events from the International Seismology Center (ISC) for the period 1992-2005, recorded by five permanent seismic stations, were used. Preliminary computation of P-wave velocity field results in construction of a velocity section at the depth of 100 km. It shows a low-velocity zone, which covers the major part of the Drake Passage, South-Shetland Islands and western part of the Scotia Sea.

Key words: the Antarctic Peninsula, 2D gravity and magnetic modeling, continental margin, Drake Passage, tectonic, Bransfield Strait, seismic tomography.

Introduction

The Antarctic Peninsula is the largest terrain of Western Antarctica. In contrast to Eastern Antarctica, the main part of which belongs to Precambrian craton, Western Antarctica represents a complex geological structure of mainly Phanerozoic age (Grikurov, 1973; Dalziel and Elliot, 1982). Before the Gondvana break-up, the Antarctic Peninsula terrain, together with the archipelagoes of the South-Shetland Islands and the South Orkney Islands, also with the South Georgia Island, was a continuation of the South American Cordilleras. Formation of the Scotia Arc at the end of Oligocene – beginning of Pliocene led to their separation. At present the Antarctic Peninsula represents Mesozoic-Cenozoic magmatic arc at the south-east Pacific margin, formed by southeastward subduction of proto-Pacific lithosphere below the Antarctic Plate. The only remnant surviving of this subduction system, which existed in the Mesozoic along the whole Antarctic Peninsula margin, is the South-Shetland Trench located between the south-eastern terminations of Shackleton and Hero fault systems (Fig. 1). The subduction in the South-Shetland Trench is assumed to be recent (stopped nearly 4 Ma ago), either slow ongoing, or there is a possibility for a back-off of the subducted plate towards the ocean (in connection with the subduction cessation nearly 3.3 Mä) (Robertson et al., 2003; Gracia et al., 1996; Galindo-Zaldivar et al., 1996, 2004). These processes led to the formation of a back-arc basin in the Bransfield Strait.

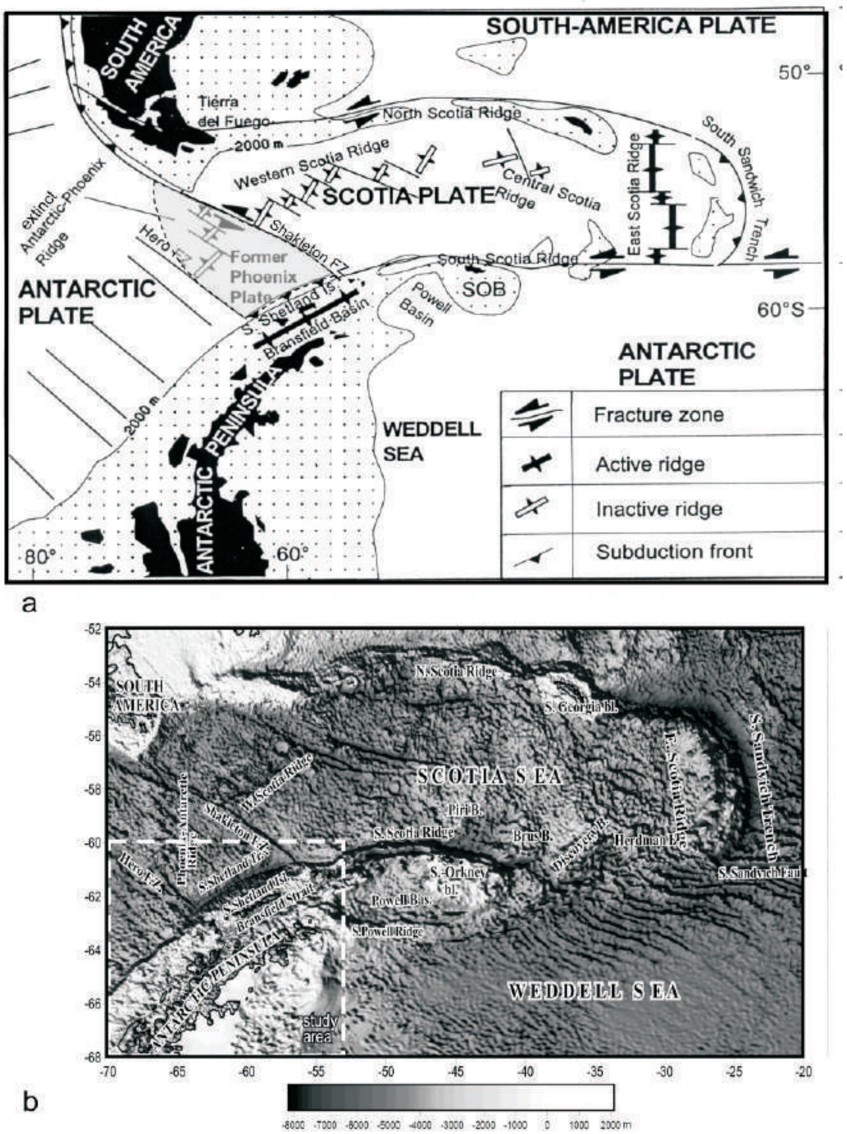

Fig. 1. Main tectonic units of Antarctic Peninsula and Scotia Sea seen in the tectonic map of Larter and Barker (1991) (a) and in the topography/bathymetry map (b).

Dotted line rectangular in (b) indicates area under investigation.

The Bransfield rift is a Late Cenozoic tensional structure, about 40 km wide near King George Island, reaching 100 km width in some places. The central part of the rift graben, only 15-20 km wide, contains several subaerial and submarine volcanoes on a line between the Deception and Bridgeman Islands. The last eruptions of 1967, 1969 and 1970 at Deception Island (Baker, Davis änd Roobol, 1969; Birkenmajer, 1987; Smellie, 1988, 1989), as well as permanent seismic activity (Pelayo änd Wiens, 1989), prove that the tectono-volcanic activity along the Bransfield Strait is still under way.

The present-day geodynamics and seismicity of the region of Antarctic Peninsula and Scotia Plate are determined by the dynamics and kinematics of the Antarctic Plate (AN), Scotia Plate (SC) and South-American Plate (SA). Predicted velocities of westward motion of SA (2.2 cm/y) and SC (1.4 cm/y) relatively to S-SW slow motion of AN (0.5 cm/y) leads to a situation when the North Scotia Ridge shows left-lateral strike-slip motion with a component of convergence, and the South-Scotia ridge shows left-lateral motion with a component of extension (Pelayo and Wiens, 1989), Convergence between the SC and AN in Drake Passage region appears to be taken through diffuse compressional deformation as well as strike-slip faulting along the Shackleton Fracture Zone (Fig. 1a; Pelayo and Wiens, 1989).

The main tectonic units of the region of Antarctic Peninsula and Scotia Sea are seen in the sea floor bathymetry (ín Fig. 1b) showing the uplifted block of the Antarctic Peninsula, which extends eastwards along the South-Scotia Ridge up to the South-Orkney block. It has a clear continental margin along the 2000 km with the Pacific Ocean. Ocean spreading ridges, deep trenches and transform faults can also be seen here. We focus our study in the area of the South-Shetland Islands and Bransfield Strait (rectangular polygon in Fig. 1b) – the most interesting region of Antarctic Peninsula to study the deep structure and recent tectonic processes which occurred along the south-east Pacific continental margin. The peculiarities of the crustal structure and tectonic processes are manifested in the patterns of geophysical fields. The continental margin here is marked by stripes of strong gravity and magnetic anomalies caused by a magmatic arc system which consists of a series of plutons and batholiths of different composition and age (Renner et al., 1985; Garrett and Storey, 1987; Garrett, 1990). The Antarctic Peninsula shelf is the most studied area in Antarctica by seismic refraction study. During last thírty years the Polish Academy of Sciences carried out a refraction seismic study on a network of DSS (deep seismic refraction study) profiles across and along the Antarctic Peninsula shelf (Sroda et al., 1997; Guterch et al., 1998; Grad et al., 2002; Janik et al., 2006).

Despite great progress being achieved in studying the deep structure of the Antarctic Peninsula continental margin by different geophysical methods, it is evident that there is a necessity for carrying out a joint geophysical interpretation of these data. Thus the main objective of our study is to develop joint geophysical models along the acquired DSS profiles.

1. Gravity field

The data of the gravity surveys, carried out in the Antarctic Peninsula by the British Antarctic Survey, were used to construct the regional Bouguer anomaly map of the Antarctic Peninsula (Renner et al., 1985) shown in Fig. 2. It shows three main domains. The first domain includes the South Shetland Islands (anomalies up to 120 mGal), the Bransfiled Strait (80 mGal) and the northern termination of the Antarctic Peninsula. The second area characterizes Graham Land – part of the Antarctic Peninsula and its shelf which extends between Anvers Island on the north and Adelaide Island on the south. Here Bouguer anomalies of the Antarctic Peninsula (20 mGal) are surrounded from both side by stripes of highs reaching 80 mGal and 60 mGal on the west and east correspondingly. The third domain includes Palmer Land and Alexander Island with negative Bouguer anomalies (Fig. 2).

A specific feature of the satellite-derived Free-Air anomalies (Sandwell and Smith, 1997) of the north-western part of the Antarctic Peninsula shelf are high-amplitude striped anomalies which

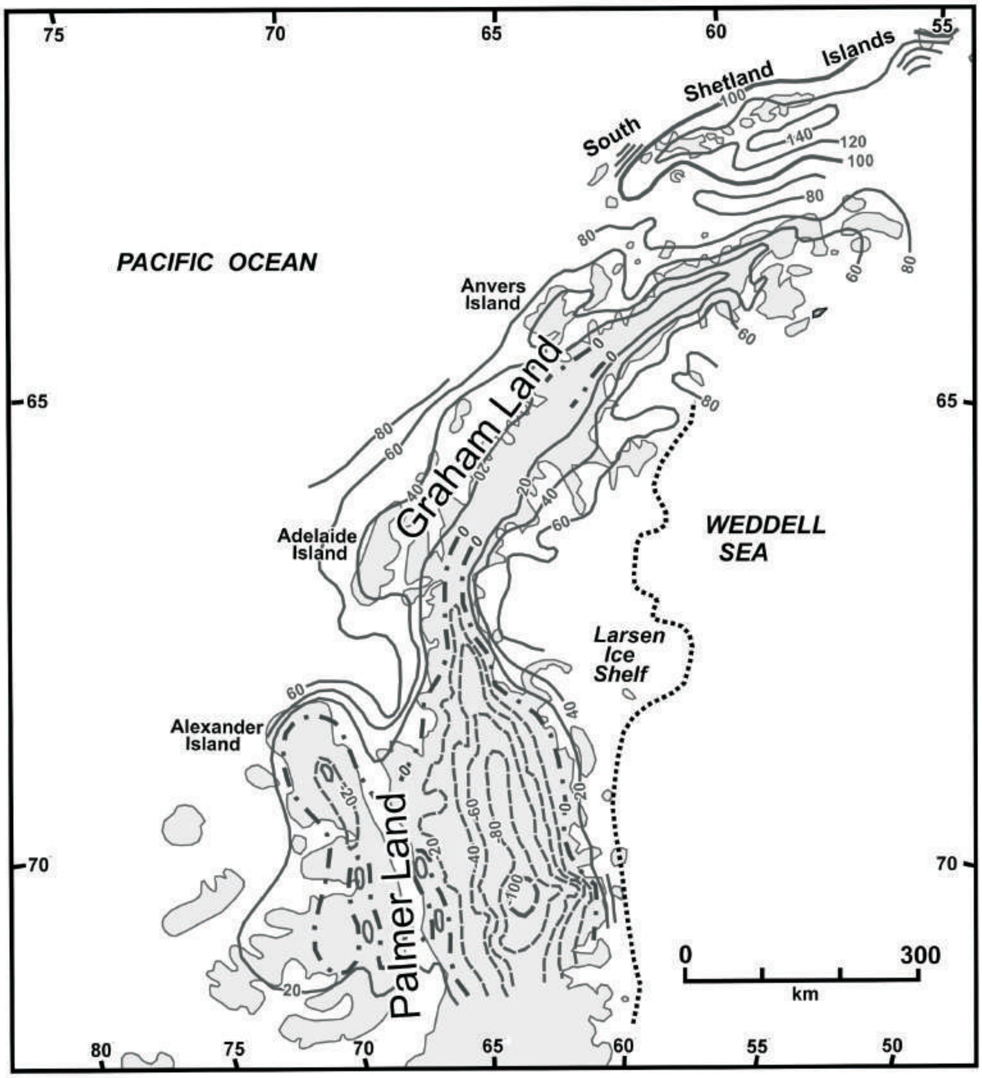

Fig. 2. Map of Bouguer gravity anomalies of Antarctic Peninsula (Renner et al., 1985).

include chains of highs and lows (Fig. 3a). The lows correspond to deep-water trench system along the Pacific margin of the Antarctic Peninsula with the minimal values of Free-Air anomalies (-100 mGal) above the South-Shetland trench. South-eastwards and in parallel to the gravity low a stripe of highs of the Antarctic Peninsula shelf, reaching > 100 mGal above the South-Shetland Islands, can be distinguished. These are caused by high-density bodies of large plutons which constitute the magmatic arc of the Pacific continental margin (Renner, 1980, Renner et al., 1985; Garrett and Story, 1987). The density of these bodies, deepening down to the depth of 10-20 km, was estimated by Garrett (1990) in the range 2.8-3.0 g/cm^3 that corresponds to intrusive rocks of gabbro-anorthositic formation.

2. Magnetic field

The continental margin of Antarctic Peninsula is marked also by wide (nearly 120 km in width) belt of strong magnetic anomalies seen in Fig. 3b showing the anomalies of the total vector of the magnetic field (Golynsky et al., 2002). This is the so-called Pacific Margin Anomaly (PMA, Maslyaniy et al., 1991) or West Coast Magnetic Anomaly (WCMA, Renner et al., 1982) – a vast arcuate belt of anomalies that extended 3800 km from the South-Orkney Island to Terston Island. The magnitude of the PMA reaches 700 nT in the region of the South-Shetland Islands. A specific feature of the PMA is its splitting occurred along the Bransfield Rift into two parts – the western and eastern branches with higher magnitude of the former (Fig. 3b).

The PMA is assumed to be caused by strong magnetization of a chain of batholiths which were formed in the subduction environment at the shelf zone of the Mesozoic-Cenozoic magmatic arc of the Antarctic Peninsula (Renner et al., 1985; Garrett, 1990). Magnetite-bearing gabbro and diorites are the main rock types composing the batholiths (Johnson, 1996; Johnson and Swain, 1995). Johnson (1999) has shown that the PMA is explained by bodies with a magnetic susceptibility of 0.055-0.075 SI and lower bounds at the depth of nearly 20 km, the estimated depth of the Curie isotherm. Depth to the upper bounds varies from zero to 6 km. Magnetic modelling performed by Garrett (1990) indicates the PMA to be caused by the effect of bodies in the upper-middle crust of about 2 A/m magnetization; the highest magnetization (2.6 A/m) was determined for the South-Shetland Islands and Drake Passage section.

A marine magnetic survey, carried out in the Bransfield Strait, revealed positive anomalies varying from 200 nT to 2000 nT and interpreted as coming from intrusions of basalt dikes along a ridge axis (Kim et al., 1992). Gracia et al. (1996) correlate positive magnetic anomalies (300-400 nT) to large volcanoes.

3. Seismic refraction study, velocity models and Moho map

In the transition zone between the Drake and South Shetland microplates and the Antarctic Plate, 20 deep seismic sounding profiles were acquired during the Polish Geodynamic Expeditions, 1979-91 (Sroda et al., 1997; Guterch et al., 1998; Grad et al., 2002; Janik et al., 2006). The scheme of DSS profiles is shown in Fig.4. The interpretation yielded two-dimensional models of the crust and lithosphere down to 80 km depth. Seismic refraction and wide angle reflection measurements were done using explosions in the sea along profiles of a total length of about 4500 km. Shots of between 25 and 120 kg of TNT were electrically detonated in the sea from the ship at a depth of 70-80 m. The distances between shots were 1-5 km. All shots were recorded by three and five channel seismic stations located on land. The shots along profile 20 in the Bransfield Strait were recorded by OBSs (Grad et al., 1997). Below we describe briefly the seismic models along the DSS profiles 12, 17 and 20 that were used for constructing the joint geophysical models.

3a. Seismic profile DSS 12

Seismic profile DSS 12 was one of seven profiles acquired during 1984-1985 (Sroda et al., 1997) within the passive margin of the Antarctic Peninsula between the Palmer Archipelago and Adelaide Island. The profile of 160 km length crosses the Antarctic Peninsula shelf from Anvers Island to the edge of the continental margin (Fig. 4). The final velocity model along the profile DSS12 is shown in Fig. 5. In the area adjacent to the Antarctic Peninsula, a thin sedimentary cover of 0.2 to 1.5 km thickness was found, while in the western part of the study area sedimentary basin with a thickness up to 3 km is observed. P-wave velocities of 4.4-5.2 km/s were assumed for sediments. The crystalline crust consists of three parts, with velocities of 6.3-6.4, 6.6-6.8 and 7.1-7.2 km/s (Fig. 5). The thickness of the crust varies from 36 km to 42 km, and maximum thickness is observed below Anvers Island. A Moho shallowing up to about 22 km is observed towards the Pacific Ocean (Sroda et al., 1997).

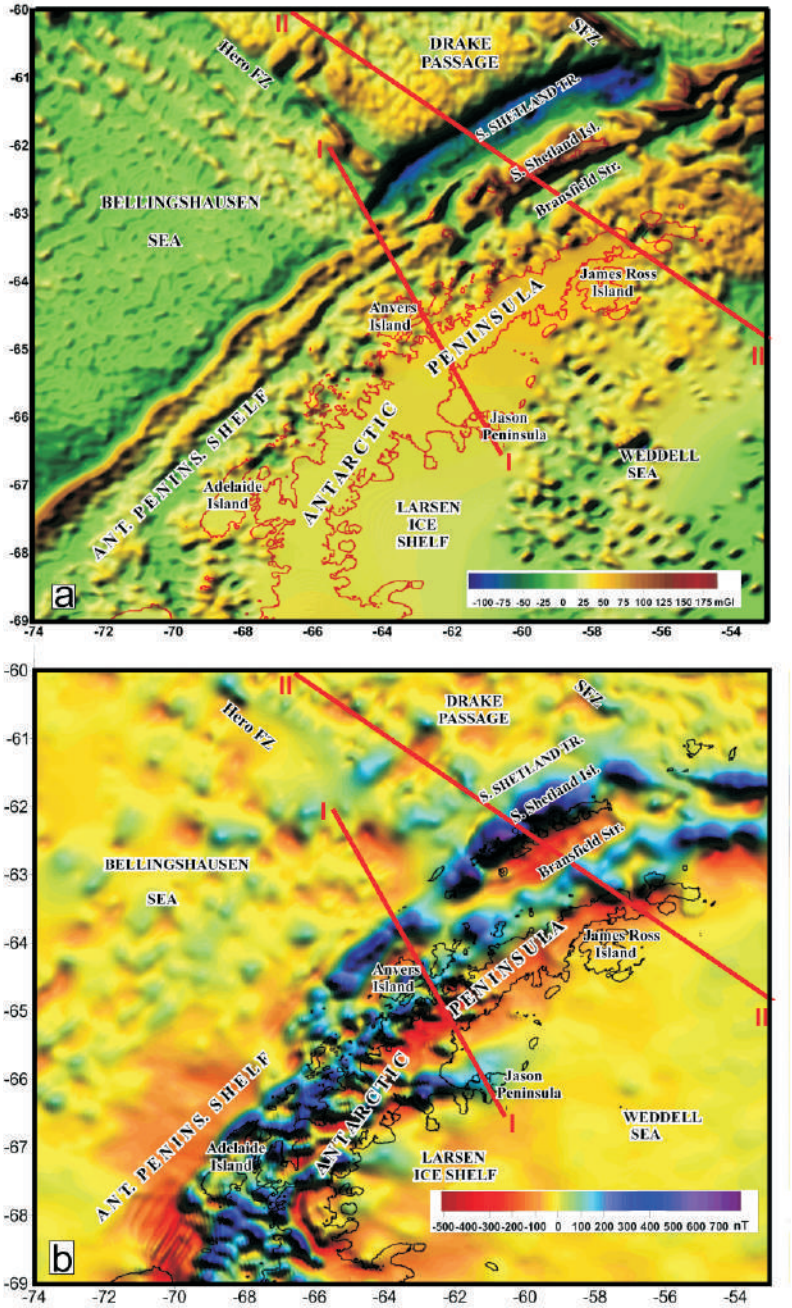

Fig. 3. Maps of potential field anomalies of the study region (dotted line in Fig. 1b) used for present joint geophysical study along the interpretation lines (shown by red solid lines) I-I and II-II: satellite-derived Free-Air gravity anomalies (a) from (Sandwell and Smith, 1997) and anomalies of the total vector of the magnetic field (Golynsky et al., 2002).

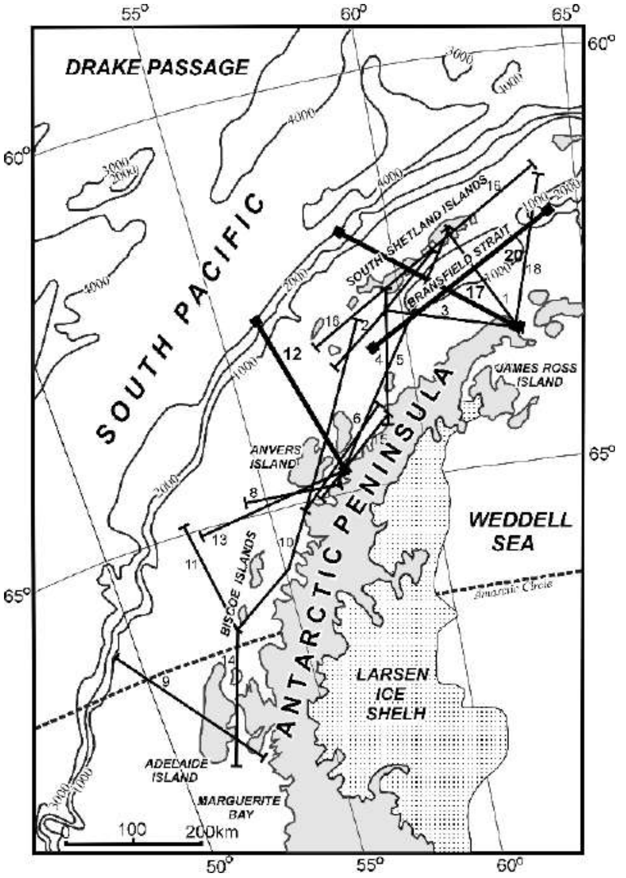

Fig. 4. Location of deep seismic sounding (DSS) profiles in Antarctic Peninsula Shelf (Guterch et al., 1998). Thick lines indicate the DSS profiles 12, 17 and 20 (their velocity models are shown in Figs. 5 and 6) used for 2D gravity and magnetic modelling.

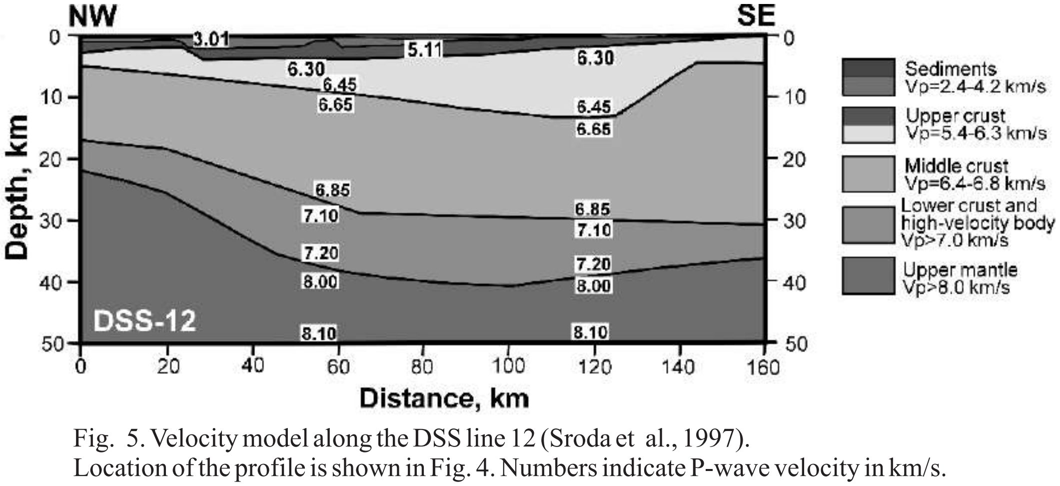

Fig. 5. Velocity model along the DSS line 12 (Sroda et al., 1997).
Location of the profile is shown in Fig. 4. Numbers indicate P-wave velocity in km/s.

3b. Seismic profiles DSS 17 and 20

The 310-km long profile DSS 17 carried out in 1987 runs from the South Shetland Trench through the South Shetland Islands and Bransfield Strait to terminate at the Antarctic Peninsula (Trinity Peninsula) (Fig. 4, Grad et al., 1993a, b). 30 shots were fired in the sea. Seismic waves from explosions were recorded by analogue seismic instruments on four land stations in the South Shetland Islands (AP – the Arturo Prat station at Greenwich Island, HM – a station at Half Moon Island) and the Antarctic Peninsula (HB – at the Hope Bay, OH – station O'Higgins).

The complicated pattern of the seismic wave field on profile DSS 17 is indicative of the complicated structure of the crust and lower lithosphere. According to the velocity model of Grad et al. (1993 a, b) in Fig. 6a, the Moho boundary (with the velocities underneath 8.2-8.3 km/s) depths range from 10 km for the oceanic crust below the Drake Passage and the South Shetland Trench area to 40 km under the Antarctic Peninsula. The velocity structure reveals several individual blocks in the crust. In the oceanic domain a sequence of strata with velocities ranging from 2.0 to 5.6 km/s overlies the 5.5 km-thick layer of crystalline crust with approximately 7.2 km/s velocity. In the South-Shetland Islands block the low-velocity sedimentary complex (2.0-4.0 km/s) covers the three crystalline crust complexes with Vp of 5.6-6.1 km/s, 6.4-6.8 km/s and about 7.2 km/s. The crustal structure beneath the Bransfield Strait is highly anomalous. Its specific feature is a high-velocity body with P-wave velocities > 7.0 km/s, detected in the depth range 6-30 km. Later interpretation of the DSS profile 17 data, done by Janik (1997) for the area of Bransfield Strait, reveals more complicated structure of the mid-lower crust interval in regard the configuration of the high-velocity crustal body (Fig. 6b).

The seismic study of the Bransfield Strait was continued in 1990-1991, when the first detailed seismic refraction study using five OBS (spaced at 50-70 km interval) was acquired along a 310-km long seismic profile DSS 20 (Grad et al., 1997) running along the Bransfield Rift axis (Fig. 4) from southwest (in the vicinity of Deception Island) to northeast (in the vicinity of Bridgeman Island). 51 shots were fired in the sea with the distance of approximately 6 km. The crustal velocity section on this profile (Fig. 6c) shows three crustal blocks – western, central and eastern subbasins (Grad et al., 1997). The seismic section along the profile 20 have permitted to study the configuration and structure of the high-velocity crustal structure with Vp=7.4=7.7 km/s along the Bransfield Rift axis. The high-velocity body beneath the central sub-basin in the Bransfield Strait is interpreted as magmatic material underplated to the crust during rifting.

Davey (1972) and other authors have suggested the existence of a semi-oceanic crust beneath the Bransfield Strait. Seismic experiments on profile DSS 20 have shown an absence of oceanic crust here. Later wide-angle seismic surveys, consisting of a grid of eight dip profiles, conducted in Bransfield Strait in 2000, were published by Barker et al. (2003) and by Christeson et al. (2003). They revealed a similar pattern along the profiles 17 and 20, and high P-wave velocities (>7.25 km/s) at a depth of 10-15 km below the central part of Bransfield Strait, which they interpreted as the Moho boundary. In Fig. 6 (Sections 17 and 20) it corresponds to the top of high-velocity body.

3c. Moho map of Antarctic Peninsula shelf

Results of these deep seismic sounding were synthesized to produce a map of Moho depth beneath the NW coast of the Antarctic Peninsula (Fig. 7) (Guterch et al., 1998; Janik et al., 2006). The map shows that the maximum crustal thickness, 38-42 km, occurs along the Antarctic Peninsula shelf between Adelaide Island and the Palmer Archipelago. Towards the Pacific Ocean, the Moho depth decreases and reaches 30-32 km at the edge of study area. The dipping Moho boundary indicates the occurrence of a transition zone between the oceanic Pacific crust and the continental crust of the Antarctic Peninsula. In the area of South-Shetland Trench, the depth of the Moho discontinuity increases from about 12 km for the oceanic crust of the Phoenix Plate to about 25 km for the South Shetland Islands shelf, and 30-33 km for the South Shetland Islands crustal block. By contrast, the Antarctic Peninsula and its adjacent shelf have a typical continental crustal thickness of 36-45 km. The Moho depth beneath the Bransfield trough is about 30-32 km.

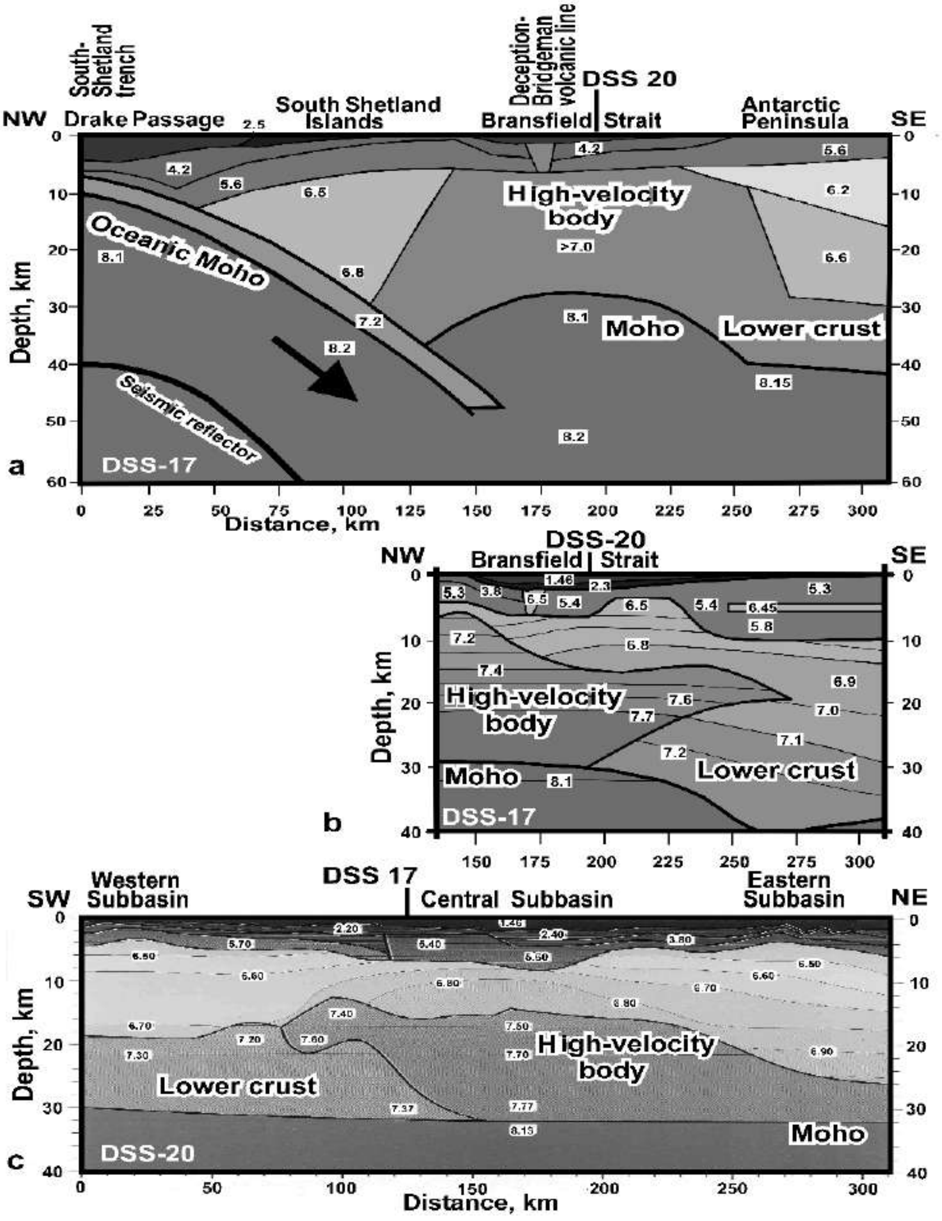

Fig. 6. Velocity models along the DSS line 17, (a) interpreted by Grad et al. (1993a, b) and (b) – by Janik (1997), and 20 (Grad et al., 1997).

Location of the profile is shown in Fig. 4. Numbers indicate P-wave velocity in km/s.

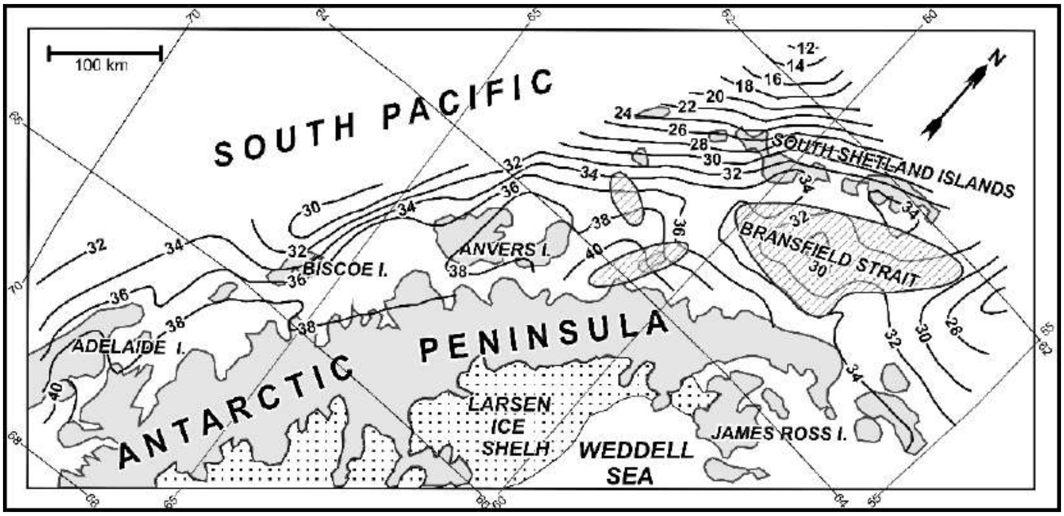

Fig. 7. Map of the depth to the Moho boundary along the Antarctic Peninsula, based on data from ray-tracing models of the crustal structure (Janik et al., 2006).

Areas filled with gray lines in the central part of the Bransfield Strait mark the extent of the high velocity anomaly, where at a depth of 13-18 km P-wave velocities reach 7.2 km/s, as well as the extent of two other areas of anomalously high velocity.

4. Results of 2D modelling of potential fields

Interpretation lines, along which we performed 2D gravity and magnetic modelling, were set along the longest DSS profiles. Velocity models on these seismic lines were used to constrain the structure of initial crustal model. The interpretation lines were extended considerably on both sides from the seismic line in order to construct the model from oceanic to continental domain.

4a. Density model of the crust and uppermost mantle along the line I-I Bellingshausen Sea – Antarctic Peninsula

The interpretation line I-I of length 520 km, crossing the continental margin in the area of Anvers Island, runs along the DSS 12 profile (Fig. 5), which constitutes the central (one third) part of line I-I. The line I-I crosses the ocean domain (120 km segment) of the Bellingshausen Sea, Antarctic Peninsula Shelf, Antarctic Peninsula mainland of 60-km length and Larsen Ice Shelf to terminate in the vicinity of the Jason Peninsula (Fig. 8). This line crosses a strong (100 mGal) Free-Air gravity anomaly at the edge of the continental slope and the magnetic anomaly PMA consisting of two branches – western and eastern – of 300 and 250 nT in amplitude respectively (Figs. 3 and 8). For 2D modelling we used satellite-derived Free-Air gravity anomalies (Sandwell and Smith, 1997) and aeromagnetic anomalies (Golynsky et al., 2002) shown in Fig. 3. Density parameterization of the initial model was made by conversion of P-wave velocities of the seismic model (Fig. 5) into densities using the conventional conversion function.

The final density model along the line I-I (Fig. 8) shows two crustal blocks – oceanic and continental. The continental block of the Antarctic Peninsula shelf and the Peninsula mainland has a 40 km thick crust with a rather thick (to 20 km) middle crust of 2.87 g/cm^3 average density. Densities of 3.0 g/cm^3 were obtained in the lower crust layer as thick as 10 km. The upper crystalline crust of 10 km thickness is characterized by densities in the range of 2.74 to 2.78 g/cm^3. The basement of the Antarctic Peninsula shelf is distinguished with Vp=5.11 km/s änd ≥=2.50 g/cm^3.

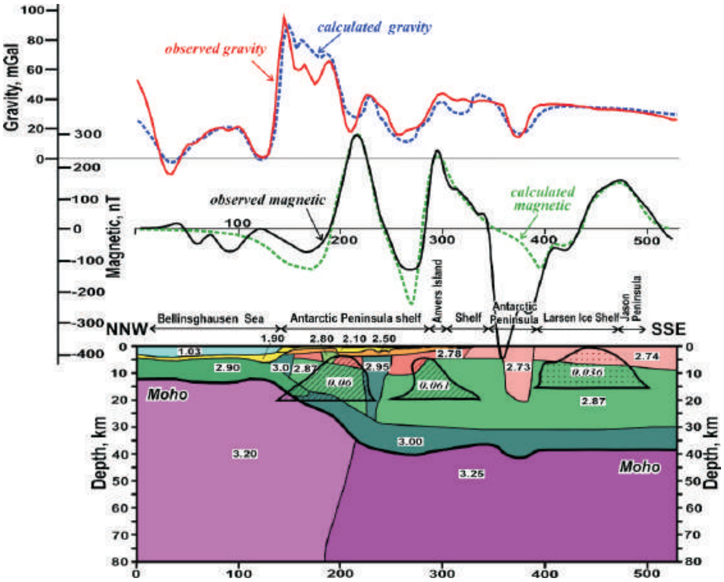

Fig. 8. Density and magnetic model on line I-I crossing the continental margin near the Anvers Island (along the DSS line 12), location of which is shown in Fig. 3. Curves of potential fields (observed and calculated) are shown in the upper part of the figure. Numbers on the cross-section indicate density values in g/cm^3. Domains with hatching above the 20-km depth level shows magnetic bodies with calculated susceptibility (numbers in italic, SI units).

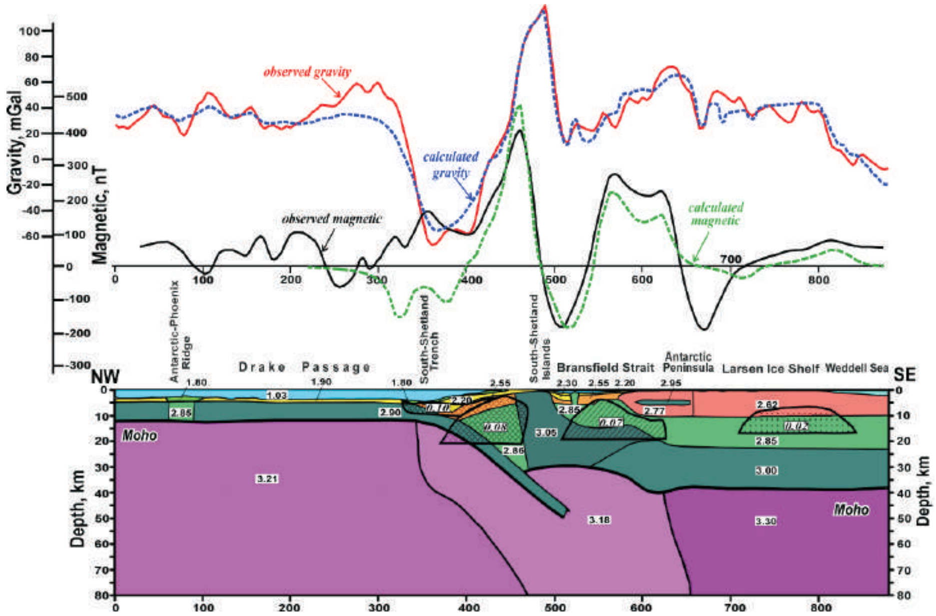

Fig. 9. Density and magnetic model on line II-II (along the DSS line 17), location of which is shown in Fig. 3, crossing the study area from Drake Passage through the Bransfield Rift to the Weddell Sea. For explanation see captions to Fig.8.

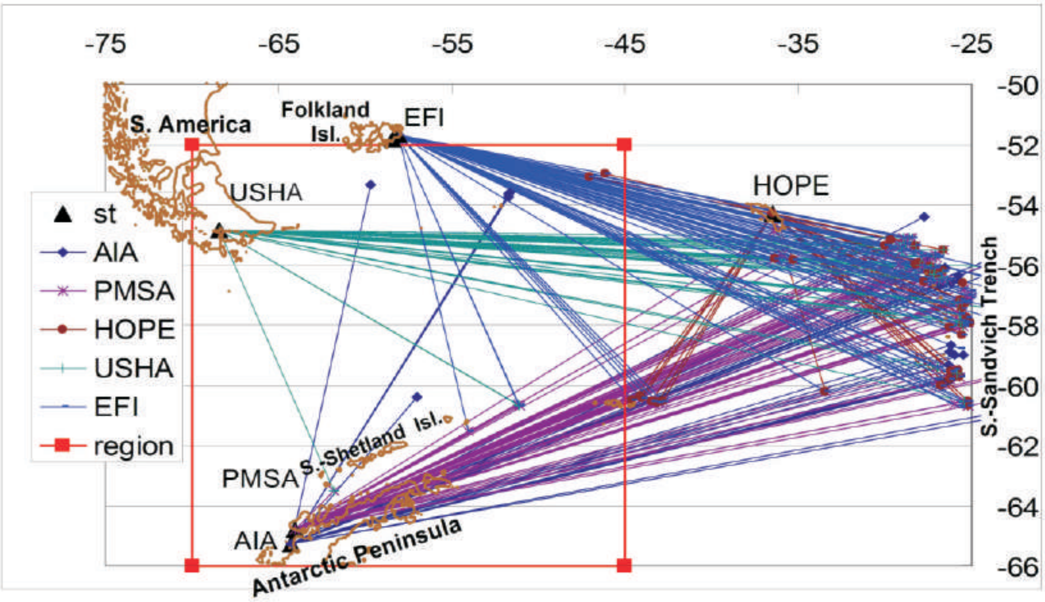

Fig. 10. Location of permanent seismic stations (triangles) and traces of seismic waves from the earthquakes foci (rhombs) in the study region.

Red line rectangular indicates an area of preliminary seismic tomography model, shown in Fig. 12.

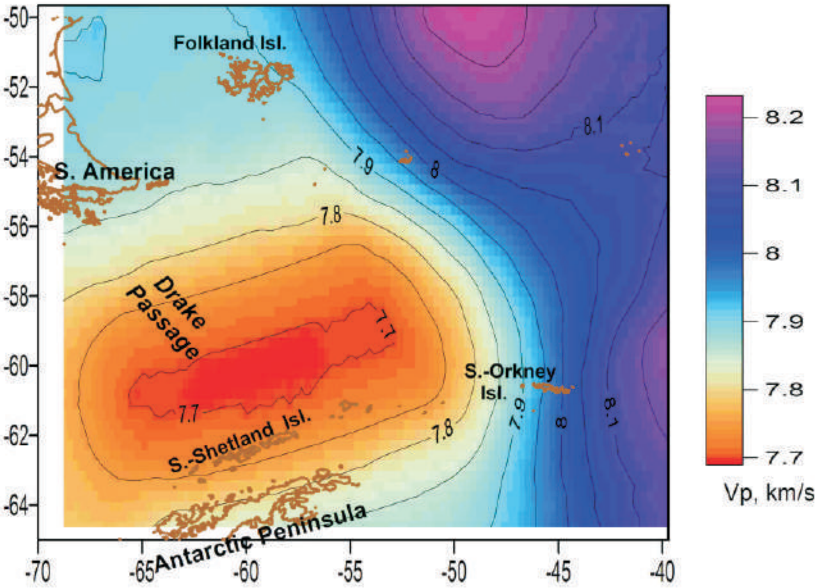

Fig. 12. Distribution of P-wave velocities on the depth of 100 km.

The oceanic domain shows a 7-8 km thick crystalline layer of 2.9 g/cm^3 density overlain by thin (≥1 km) oceanic sediments of 1.9 g/cm^3 density under the 3.5-4 km sea-water column. The thickness of sediments in the Bellingshausen Sea was taken from the estimates derived from the seismic reflection study (Scheuer et al., 2006).

The transition (from oceanic to continental) block demonstrates dramatic changes in the crustal structure, where within the 100-km distance the crust thickens from 10 to 25 km. Morphologically this block represents uplift of the basement and crustal block of 2.87 g/cm^3 density, which correspond to the striped gravity high (Fig. 8). Westwards from this high a gravity low is caused by a 3 km thick sediments of former accretional wedge. Coincidence of the uplifted dense crustal block with the magnetic body of 0.06 SI susceptibility causing the western anomaly of the PMA (Fig. 8) is indicative of their common sources. Another magnetic body of the same susceptibility, determined in the area of Anvers Island, explains the eastern anomaly of the PMA. Derived values of the magnetic susceptibility and density point out at mafic rocks (diorite, gabbro, gabbro-diorite) composition of the magnetic bodies.

4b. Density model along the line II-II (Drake Passage-Bransfield Strait-Antarctic Peninsula)

A second interpretation line (II-II) of 860 km total length was set along the seismic profile DSS 17 (Fig. 6, Grad et al., 1993a,b) crossing the South-Shetland Trench and Islands and Bransfield Strait (Fig. 4). Thus, the central part of the line II-II, which is one third of the whole line length, is elucidated by seismic data from DSS lines 17 and 20, while the crust structure on both sides of it was constructed by 2D gravity and magnetic modeling.

The final density model on line II-II (Fig. 9) consists of three main domains – the continental crust of the Antarctic Peninsula and Larsen Ice Shelf (km 630-860 km), the oceanic block of Drake Passage (km 0-340 km) and, located in between a transition block of a very complicated crust structure between the South-Shetland Islands and Bransfield Strait.

The thick continental crust of the Antarctic Peninsula and Larsen Ice Shelf consists of three layers. The upper crust reaching 10 km in thickness has an average density of 2.77 and 2.62 g/cm^3 for the Antarctic Peninsula and Larsen Ice Shelf correspondingly. The middle crust as thick as 12-14 km is characterized by a density of 2.85 g/cm^3 and the 15 km thick lower crust has the highest values of velocity and density (>7.0 km/s and 3.0 g/cm^3). The Moho is a flat boundary lying at a depth of 38-40 km with a velocity and density underneath the boundary of 8.10 km/s and 3.30 g/cm^3 respectively.

The crust of the Drake Passage has typical values for the oceanic domains – a thin (6-7 km) crystalline crust of high velocity (7.2 km/s) and density (2.9 g/cm^3) overlain by a thin layer of light (1.9 g/cm^3) oceanic sediments under the 3-3.5 km thick sea-water layer. Below the Moho, occurring at a depth of 12 km, velocity and density were estimated as 8.1 km/s and 3.21 g/cm^3 respectively.

A very complicated crust structure is seen in the transition block (km 340-630 km) which includes the area between the South-Shetland Trench and the Bransfield Strait. One can distinguish here two sub-blocks separated by the South-Shetland Islands block that is marked by a strong gravity high reaching 110 mGal along the profile (Fig. 9). Performed gravity modelling indicates this high as caused by a large crustal diapir (batholith) of 40 km width near the surface with density of 3.05 g/cm^3 (velocities > 7.2 km/s), which is indicative of its ultramafic composition. In the middle and lower crust this high-velocity/density body thickens eastwards forming at the depth of 14-29 km a kind of pillow below the Bransfield Rift (Fig. 9). To the west from the South-Shetland batholith right up to the South-Shetland Trench there is an uplifted crustal wedge of 2.86 g/cm^3 density, the formation of which occurred in a subduction environment (slow ongoing subduction of a remnant of Phoenix Plate under the South-Shetland Islands). This uplifted crustal wedge, which is very similar to that found along the line I-I (Fig. 8), is indicated also by a strong magnetic lineation of more than 400 nT, which corresponds to western branch of the PMA. This anomaly is caused by a magnetic body of 80 km width occurring at 3-20 km depth. The rather high magnetic susceptibility (0.08 SI) and density (2.86 g/cm^3) values (Fig. 9) indicate that this body is composed of mafic rocks of intrusive complex (gabbro-diorites, gabbro, gabbro-norites).

The gravity low (-60 mGal) of the South-Shetland Trench is caused by sediments consisting of a thin (1 km) sequence of light oceanic sediments (≥ =1.8 g/cm^3, Vp=2.5 km/s) and sediments of accretionary wedge complex (≥=2.2 g/cm^3 and Vp=4.2 km/s). The latter became as thick as 8 km at 25-30 km to the southeast from the trench axis. In addition, a definite contribution to this gravity low is made by the sequence of meta-sedimentary rocks of the basement and intercalated volcanics (2.55 g/cm^3). The occurrence of volcanic rocks here corresponds to very high values of magnetic susceptibility (0.10 SI) derived below the South-Shetland Trench at the depth of 1-8 km (Fig. 9).

The same rock complexes of the basement are present at a depth of 2-5 km below the Bransfield Strait, where they are overlain by thin sediments of density 2.20-2.30 g/cm^3. The latter, as it follows from the seismic model in Fig. 6,a-b, are cut by a small, high-velocity body (Vp=6.5 km/s, ≥=2.85 g/cm^3) in the form of a volcanic edifice, which is indicated also by the local gravity anomaly of 15 mGal (Fig. 7) and the local magnetic anomaly (Kim et al., 1992). These gravity and magnetic anomalies mark the presence of a chain of subaerial and submarine volcanoes along the Bransfield rift axis developed from the Deception volcano on the south to Bridgeman Island on the north (Gracia et al., 1996).

In general, the crystalline crust below the Bransfield rift is highly anomalous and is featured by Moho shallowing up to the depth of 29 km. The upper crust of 2.85 g/cm^3 density contains a magnetic body of 0.07 SI susceptibility (Fig. 9) causing the 250-300 nT magnetic anomaly of the eastern branch of the PMA. The lower crust beneath the Bransfield Strait is featured by the presence of high-velocity and density body (Vp=7.4-7.7 km/s, ≥=3.05 g/cm^3).

The transition from the anomalous crust of the Bransfield Strait to the Antarctic Peninsula crust (km 580-640) is distinguished by an upper crustal domain of increased to 2.77 g/cm^3 density with high-velocity/density (Vp=6.45 km/s, ≥=2.95 g/cm^3) layered inclusion at the depth of 5 km. The latter can be a small layered intrusion (apophys) of the parent high-velocity lower crust body below the Bransfield Rift.

The three main crustal blocks on the line II-II are underlain by an uppermost mantle of different density. The highest density (3.30 g/cm^3) was derived for the lithospheric mantle below the continental crust of the Antarctic Peninsula, while the oceanic upper mantle has decreased to 3.21 g/cm^3 density. Minimal density values (3.18 g/cm^3) were estimated below the block between South-Shetland Trench - Bransfield Strait indicating a very complicated structure.

5. Interpretation and discussion of the results of 2D gravity and magnetic modelling

Ongoing tectonic processes operate within the northern sector of the Antarctic Peninsula continental margin – in the area of South-Shetland Trench – Bransfield Strait (profile II-II, Fig. 9). The presence of an active continental margin here is highlighted by stripes of strong gravity and magnetic anomalies reflecting a very complicated crust structure caused by subduction and recent continental rifting processes. Subduction is shown in Fig. 9 by the underthrusting of the oceanic plate of Drake Passage (Phoenix Plate in Fig. 1a) with a density of 2.9 g/cm^3 and a velocity of 7.2 km/s under the South-Shetland Islands. At present the subduction is assumed to be shallow at low rates or it could even have stopped (Galindo-Zaldivar et al., 2000; Maldonado et al., 2000). That could happen after the almost total consumption in Pliocene (nearly 6-3 Mä) of the Phoenix Plate in the subduction zone and the extinction of Antarctic-Phoenix Ridge (Fig. 1a). This could result in a return process of subduction (back-off) in the region of the South-Shetland Islands that may cause opening of the back-arc basin of the Bransfield Strait (Gracia et al., 1996; Galindo-Zaldivar et al., 1996, 2004; Robertson et al., 2003).

The South-Shetland Trench is an accretional trough filled with 5 km-thick sediments of 2.2 g/cm^3 density (velocity 4.2 km/s), overlain by thin oceanic sediments (density 1.8 g/cm^3), which cause the strong gravity low of the South-Shetland Trench. Southeastward progradation of the subduction front have led to the formation in its frontal zone of an uplifted crustal wedge of 2.87 g/cm^3 density and high magnetic susceptibility (0.08 SI) causing strong gravity and magnetic anomalies.

The archipelago of the South-Shetland Islands, marked by a stripe of strong gravity anomalies, is caused, most probably, by the large crustal batholith of ultrabasic rocks (peridotites) of 3.05 g/cm^3 density (Fig. 9), which in a subduction related environment intruded into the crust from the upper mantle. Exposures of ultramafic rocks (ultrabasites, periddotites) were found on Gibbs Island, which is included in the group of northern islands of the archipelago of the South-Shetland Islands (Sílänt'ev et äl., 1997).

The Bransfield Trough has typical features of a rift zone. It is an asymmetrical graben with a steep north-western flank, from the side of South-Shetland Islands, and a wide, gently sloping south-eastern flank, formed by the Antarctic Peninsula shelf. Sedimentary fill of the Bransfield Trough consists of thin successions with density 2.2-2.3 g/cm^3, which cover meta-sedimentary rocks of basement and intercalated volcanics (Vp=5.3 km/s; ≥=2.55 g/cm^3). These volcanic rocks occur in volcanic edifices and sea mountains, which constitute a chain of neotectonic volcanoes along the Bransfield rift axis. The crystalline crust of the Bransfield rift is highly anomalous because of the occurrence of high density and velocity heterogeneities. The density increase in the upper crust to 2.85 g/cm^3 (Vp=6.5-6.8 km/s) is assumed to be caused by intrusions and sills of mafic rocks coming from the lower crust. Extremely high densities and velocities (≥=3.05 g/cm^3, Vp=7.4-7.7 km/s) found below the depth of 15 km are indicative of the presence of a so-called "high-velocity" body in the lower crust, which is considered to be a spectacular feature of many rifts, recent and old, attributed to "rift pillow" or mantle underplating. Very high densities and velocities are indicative of high progradation of this process that can led also to substantial Moho uplift below the central part of the rift (up 30 km depth), that is 10 km higher than the Moho position on the neighboring Antarctic Peninsula shelf.

Fig. 8 shows the crust structure, which is typical for a passive continental margin of convergent type, where thin oceanic crust of the Bellingshausen Sea meets thick continental crust of the Antarctic Peninsula with origin in the transition zone of an uplifted crustal block (wedge) intruded by batholits and diapirs of basic composition (bodies of high density and susceptibility in Fig. 8). The Moho relief and structure of the lower crust is a consequence of recent tectonic processes of underthrusting of the oceanic plate of the Bellingshausen Sea under the continental crust of the Antarctic Peninsula. Tectonic activity terminated here in Late Miocene-Early Pliocene (6-3 Ma) because of the extinction of the Antarctic-Phoenix Ridge after the consuming of the Phoenix Plate in subduction zone (Galindo-Zaldivar et al., 2000; Maldonado et al., 2000).

A boundary between active (line II-II) and passive (line I-I) continental margin styles of the Antarctic Peninsula should occurr in the area of the Hero fault zone (Fig. 1a). Though no direct indication of recent tectonic activity (recorded earthquakes, strike-slip tectonics and so on) are observed here, the Hero fracture zone is considered to be a distinct structure discontinuity distinguished well throughout the whole crust. Above all, the Hero fracture zone is clearly distinguished in the gravity field by the stripe Free-Air anomaly highs of 100-150 mGal amplitude accompanied by gravity lows (Fig. 3a). In addition, the Hero zone represents a step-like fault on the sea floor, which separates the plate of Drake Passage with the sea-floor depths at 3500-3700 m from the deeper part (4100-4300 m) of the Bellingshausen Sea (Fig. 1b). Multichannel seismic studies conducted in the area of SW end of South Shetland Trench and the resulting evolutionary model shows existence in the area of the Hero fault zone of transition from an active to a passive margin style (Jabaloy et al., 2003). A 1000 km long combined seismic section, constructed by Grad et al. (2002) along the Antarctic Peninsula margin between Marguerite Bay and Elephant Island, shows a major crustal boundary, which corresponds to the southeastward projection of the Hero fracture zone. This discontinuity separates a thick (~ 40 km) three-layer continental crust of the Antarctic Peninsula to the southwest from a thinner two-layer crust with high-velocity intrusions extending beneath the Brandsfield Strait to the northeast.

The obtained distribution of physical parameters (density, magnetic susceptibility and P-wave seismic velocity) permits a conclusion to be drawn on the composition of the main blocks and layers of the crust of the study region. The crust of the block of Antarctic Peninsula shelf, the Peninsula itself and Larsen Ice Shelf belongs to the thick three-layer continental crust. The 10-km thick upper crust with Vp=6.2-6.45 km/s, ≥=2.62-2.77 g/cm^3 is assumed to be composed of granites, granodiorites, diorites and biotite (tonalite) gneisses. The middle crust of Vp=6.6-6.9 km/s, ≥=2.85-2.87 g/cm^3 occurring down to a depth of 23-29 km, is represented mostly by enderbites and, to a lesser extent, by amphibolites and mafic granulites. Mafic granulites prevail in the lower crust (Vp=7.0-7.2 km/s, ≥=3.0 g/cm^3) of 10-15 km thickness, substitited at the lowermost crust (above the Moho) by garnet mafic granulites. This type of the crust links the Antarctic Peninsula crust to continental arcs crust rather than to shields and platforms (Christensen and Mooney, 1995).

The crust of the Bransfield Strait is defined by much higher velocities and densities than that determined by Christensen and Mooney (1995) for the average section of rifts and also by higher Moho uplift. High-velocity units start to develop here at 10 km. Deeper 15 km, as it was discussed above, there is distinguished a high-velocity and density lower crust body due to mantle underplating.

The accomplished gravity modelling indicates density variation in the uppermost mantle of the study region. The continental crust of Antarctic Peninsula is underlain by upper mantle of 3.30-3.25 g/cm^3 density, which is considered to be typical ("normal") for Precambrian and Phanerozoic platforms. The young oceanic crust of the Bellingshausen Sea and Drake Passage relates with lower densities (3.20 g/cm^3) of the upper mantle below the Moho. These distinctions are explained by the difference in age and composition of oceanic and continental lithosphere.

The anomalous upper mantle of 3.18 g/cm^3 density below the Bransfield Strait and South-Shetland Islands is indicative, first of all, of temperature mobilization of the upper mantle below the rift zone. We relate it to the high-density crystalline crust below the Bransfield Rift, which is explained by many intrusions of mafic and ultramafic magmas due to the partial melting in the upper mantle-lower crust. These ongoing tectonic processes in the upper mantle of the Bransfield Strait, which led to the occurrence of soft mantle, are confirmed by very high heat flow density (150-250 mW/m^2) in the Bransfield Strait (Lawrer and Nagihara, 1991; Lawrer et al., 1995). Strong hydrothermal activity, found the Bransfield Strait in general (Suess et al., 1987; Schloesser et al., 1988; Klinkhammer et al., 2001) and, in particular, in the Deception Island area (Somoza et al., 2004), confirms the presence of marine volcanic activity. The axial zone of the central part of the Bransfield Strait is marked by a chain of neovolcanic crests and cones (Gracia et al., 1996; Lawrer et al., 1996). The largest of them are the active volcano of Deception Island at the western termination of the strait and the submarine volcanos Orka and Three Sisters. They represent the only visible part of a large submarine ridge, about 300 km long, that runs between the Deception and Bridgeman Islands formed after the Pleistocene due to opening of the Bransfield Strait (Weaver et al., 1982; Gonzälez-Ferrän, 1985). The chemistry of basalts dredged from the volcanoes of the Bransfield rift shows transition between magmas of a standard Pacific back-arc basin and depleted upper mantle mid-ocean ridge basalts (Keller et al., 2002). In the latter case melting of basalt magmas occurred at shallow depths due to the rising of asthenospheric diapir (Süshchevskäyä et äl., 2002). Surface wave seismic tomography perfomed for the area of Bransfield Strait by joint inversion of Rayleigh and Love dispersion curves from 15 s to 50 s reveals that low upper mantle velocities (soft lid) extend down to depth exceeding 70 km (Vuan et al., 2005). This low velocity upper mantle below the Bransfield Strait is explained by the authors as a consequence of elevated temperatures and may be indicative of the presence of a mantle plume or asthenospheric diapir.

6. P-wave seismic tomography study

Among geophysical methods the seismic tomography is assumed to be the most comprehensive method to study the 3D inner Earth's structure of vast regions. Application of seismic tomography method to kinematic data of seismic waves, generated by the earthquakes occurred the region of Antarctic Peninsula and adjoining Pacific Ocean, will allow us to get more information of the structure of lithosphere and operated tectonic processes. For that we applied 3D local seismic tomography (Gobarenko et al., 1987) based on Backhus-Gilbert approximation using the data on earthquake foci and time arrival of P-waves recorded by available in the region network of seismic stations. The method allows getting smoothed estimates of velocity parameters consistent with resolution of initial data, even in the case of data shortage.

The main sources of seismology information in the study region are catalogues of International Seismology Center (ISC), of IRIS Corporation (Incorporated Research Institutions for Seismology), data of Geological Survey of USA (USGS) and that of AIA seismic station deployed on the Ukrainian Antarctic station “Akademik Vernadsky”. Fig. 10 shows the scheme of location of seismic stations, earthquakes with magnitude M ≥ 5, occurred in the region during the period 1992-2005, and traces of seismic waves, for which data on P-wave time arrival are available. Fig. 10 shows that main seismic activity is concentrated within the South-Sandwich Arc, South and North Scotia Ridges and Shackleton fracture zone.

On the first stage of seismic tomography study we choose a region between Antarctic Peninsula, South-Orkney Islands, Falkland Islands and southern termination of Southern America (red rectangular in Fig. 10). Since the study region is characterized by small number of earthquakes, for computation of velocity field we used only 27 events from the ISC catalogues, which were recorded by five seismic stations located inside the region. They include the stations placed on the southern end of South America (USHA station), Falkland Islands (stations EFI), South Georgia Islands (station HOPE) and Antarctic Peninsula (stations PMSA and AIA). In addition to the network of permanent stations, a temporary network of seismic observations was deployed in 1998-2001 during the Seismic Experiment in Patagonia and Antarctica (SEPA, Fig. 11, Robertson et al., 2003). Further inclusion of SEPA data would permit to organize more representative data set and to get more detailed and reliable results.

These seismology data with small number of traces were used for appraisal of method and program of local seismic tomography for computation of P-wave velocity field of Antarctic Peninsula and adjoining sea-water areas. Jeffris model was used as a referent velocity model since main seismology data are taken from the ISC catalogues. Interval of seismic ray penetration into the upper mantle is estimated as 60-160 km, maximal ray density falls on the depth range of 100-130 km. Thís permítted to mäke seísmíc tomogräphy cälcülätíons resülted ín constrüctíon of ä mäp of P-wäve velocítíes ín the depth of 100 km (Fig. 12) It clearly distinguishes vast low-velocity zone in the central and south-western parts of the study region including the major part of Drake Passage, South-Shetland Islands and western part of the Scotia Sea. Unfortunately, we have not enough data now to judge of the origin of this anomaly zone. Nevertheless, in this regard it should be noted that accomplished surface wave seismic tomography study (Vuan et al., 2005) has revealed here an area of substantial decrease of Love and Rayleigh wave group velocities for 15-50 s time periods, which Vuan et al. (2005) relate to temperature increase in the upper mantle. Thus, in the course of applying of local seismic tomography method for the region of Antarctic Peninsula first consistent results were obtained. We plan to continue the seismic tomography study by inclusion more data from permanent seismic stations and temporary

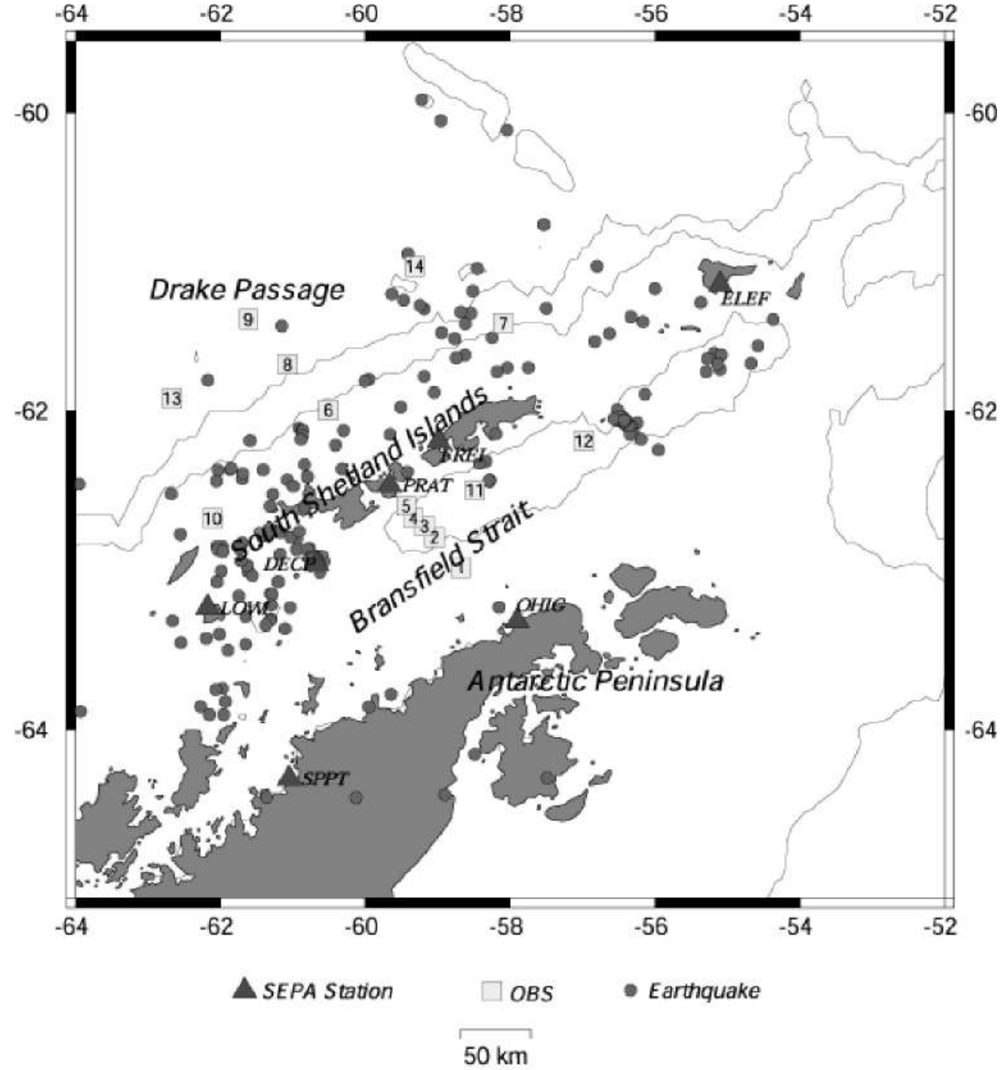

Fig. 11. Location of seismic stations of Seismic Experiment in Patagonia and Antarctica (SEPA), 1998-2001.

seismic network of SEPA experiment.

Conclusion

The paper represents new results in studying the lithosphere structure in the region of Antarctic Peninsula. The results, obtained in two directions, could be briefly concluded as following.

(1) Two joint geophysical models have been set up for the lithosphere structure of Antarctic Peninsula margin using the 2D gravity and magnetic modeling along the deep seismic refraction lines. Lithosphere structure along the first line (I-I), crossing the margin in the vicinity of Anvers Island, indicates the continental margin of passive style of convergent type. Joint model along the second line

(II-II), crossing the study region from the Drake Passage to Antarctic Peninsula, shows all features of Pacific continental margin of active style with active subduction related processes and on-going continental rifting in the Bransfield Strait. Setting up of joint geophysical models for Antarctic Peninsula continental margin will be continued by inclusion of more seismic lines.

(2) First consistent results of body wave seismic tomography study for the lithosphere of Antarctic Peninsula region and adjoining sea-water areas of Drake Passage and Scotia Sea are shown on the horizontal P-wave velocity section constructed for the depth of 100 km. It shows high efficiency of the seismic tomography method in the study region. This research will be continued by completing the seismological data set by inclusion of more events and seismic stations from permanent and temporary networks.

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