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Polish Geodynamic Expeditions – seismic structure of West Antarctica

ABSTRACT: During the Polish Antarctic Geodynamic Expeditions, 1979–91, a wide geophysical and geological programme was performed in the transition zone between the Drake and South Shetland microplates and the Antarctic Plate, in West Antarctica. In the Bransfield Strait area, and along passive continental margin of the Antarctic Peninsula, 20 deep seismic sounding profiles were made. The interpretation yielded two – dimensional models of the crust and lithosphere down to 80 km depth. In the coastal area between the Palmer Archipelago and the Adelaide Island, the Earth's crust has a typical continental structure. Its thickness varies from 36 to 42 km in the coastal area, decreasing to about 25–28 km toward Pacific Ocean. In the surrounding of Bransfield Strait, the Moho boundary depth ranges from 10 km beneath the South Shetland Trench to 40 km beneath Antarctic Peninsula. The crustal structure beneath the Bransfield Strait trough is highly anomalous. Presence of a high-velocity body, with longitudinal seismic wave velocities $V_p > 7.0$ km/s, was detected there in the 6–32 km depth range. This inhomogeneity was interpreted as an intrusion, coinciding with the Deception-Bridgeman volcanic line. In the transition zone from the Drake Passage to the South Shetland Islands, a seismic boundary in the lower lithosphere occurs at a depth ranging from 35 to 80 km. The dip of both the Moho and this boundary is approximately 25° towards the southeast, indicating the direction of subduction of the Drake Plate lithosphere under the Antarctic Plate. Basing on the results of four Polish Geodynamic Expeditions, the map of crustal thickness in West Antarctica is presented.

Key words: West Antarctica, Antarctic Peninsula, Bransfield Strait, deep seismic sounding, crustal thickness, lithospheric structure, subduction zone.

Introduction

Four Polish Geodynamic Expeditions to West Antarctica were organized in 1979–1980, 1984–85, 1987–1988 and 1990–1991 by the Institute of Geophysics of the Polish Academy of Sciences. The expeditions carried out seismic studies of the Earth's crust and lower lithosphere structure together with geological, sedimentological and palaeontological investigations, within the general programme of geodynamic studies in West Antarctica. These studies were carried out along the Antarctic Peninsula from the Elephant Island to the Marguerite Bay including: the South Shetland Islands, The Bransfield Strait, subduction zone in the Drake Passage, the Deception Island, the Palmer Archipelago and the Adelaide Island. Special attention was paid to tectonically active zones and the contact zones between the blocks of the Earth's crust and the litospheric plates.

Seismic refraction and wide angle reflection measurements were done using explosions in the sea along profiles of total length about 4500 km. Shots of between 25 and 120 kg of TNT were electrically detonated in the sea from the ship at depths 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. During last expedition the shots along profiles in the Bransfield Strait were recorded by Ocean Bottom Seismographs in cooperation with the Hokkaido University in Sapporo. Additionally 1200 km shallow reflection profiles were made by the Polish Geodynamic Expeditions in the Bransfield Strait and Drake Passage.

The present paper summarizes results of seismic profiling obtained during Polish Geodynamic Expeditions to West Antarctica, which were published in a number of papers (Guterch *et al.* 1985, 1990, 1991; Grad *et al.* 1992, 1993a, b, 1997a, b; Janik 1997a, b; Środa *et al.* 1997).

Outline of geological history and structure

The Antarctic Peninsula and the South Shetland Islands had a similar geological history up to the Jurassic. These regions were morphologically contiguous with the Southern Andes in the Mesozoic (Arctowski 1895, De Witt 1977), and were separated during opening of the Scotia Sea in the Tertiary (Dalziel and Elliot 1973). The opening of Drake Passage and Western Scotia Sea took place between 28 and 6 Ma, when the North and South Scotia ridges separated from the southernmost South America (Acosta *et al.* 1992).

In general, the Pacific margin of the Antarctic Peninsula is characterized by a very complex subduction history (see *e.g.* Barker 1982, Barker and Dalziel 1983). The 1500-km-long Antarctic Peninsula separates the southeast Pacific Ocean from the Weddell Sea. The tectonic evolution of the Antarctic Peninsula was controlled by subduction of the Pacific Plate under the Antarctic Peninsula from the Triassic up to recent times. The continental crust of the Antarctic Peninsula was thickened by magmatic and accretionary processes during the Mesozoic and Cenozoic (Garrett and Storey 1987). The recent history of subduction and associated events can be traced from the Pacific seafloor magnetic anomalies pattern. The subduction of Pacific seafloor segments had ceased progressively from SW to NE, following ridge-trench collisions. Ridge segment boundaries are located along the major fracture zones. The subduction in the last segment, south of the Hero Fracture Zone, stopped 6.5 to 4 Ma ago (Barker 1982). Since the last ridge-trench collision, the Antarctic Peninsula margin has become tectonically passive.

The Bransfield Rift, together with the Bransfield Platform, represent a back-arc basin with respect to the Late Mesozoic–Cenozoic South Shetland Islands volcanic arc. The initiation of the Bransfield rift dates back to the Late Oligocene–Early Miocene times, as evidenced by a system of rift-parallel antithetic faults along the outer margin of the rift (Birkenmajer *et al.* 1990, Birkenmajer 1992). The Bransfield rift is a Late Cenozoic tensional structure, about 40 km wide near King George Island which separates the Bransfield Platform from the South Shetland Islands Microplate (González-Ferrán 1985). 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.

More information on geology and tectonics data of the Antarctic Peninsula may be found in papers by Barker (1982), Barker and Dalziel (1983), Birkenmajer *et al.* (1990), Henriet *et al.* (1992), Acosta *et al.* (1992), Birkenmajer (1994), Lawver *et al.* (1995).

Seismic data and interpretation

As a part of the geodynamic programme, seismic refraction and reflection soundings in West Antarctica were made during four Polish Geodynamic Expeditions in the years 1979–1991. An extensive project of seismic refraction studies into the deep structure of the crust and lower lithosphere with explosion seismology methods were made in the area of the Bransfield Strait and passive continental margin of the Antarctic Peninsula shelf. Deep seismic sounding measurements were made along 20 profiles (Fig. 1). Examples of seismic record sections from the study area are presented in Fig. 2.

The complicated pattern of the seismic wave field of the study area is indicative of the complex structure of the crust and lower lithosphere. Bearing in mind the large variations in the bottom depth, velocity differences in the medium, intrusions and dipping boundaries, a one-dimensional modelling is of a very limited validity. In the so complicated structures, with large vertical and horizontal inhomogeneities, a two-dimensional modelling is necessary. In the present work, we used the method of seismic ray tracing in two-dimensional models with curvilinear boundaries and complex velocity distribution (Červený and Pšenčík 1981, 1983; Komminaho 1993; Thybo and Luetgert 1990). An example of two-dimensional modelling of the crustal structure is presented in Fig. 3.

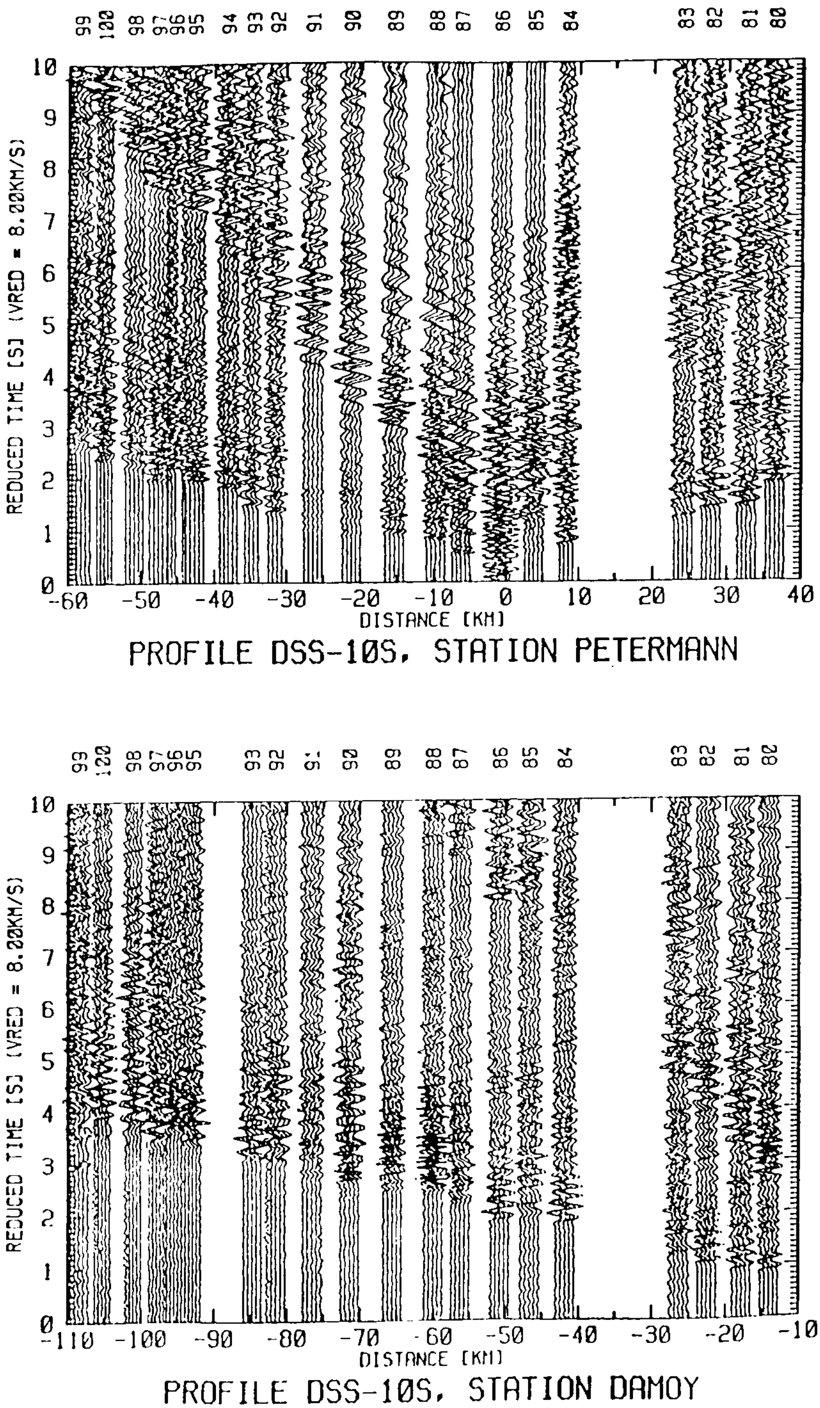

Fig. 2. Seismic record sections for profile DSS-10S, stations Petermann and Damoy.

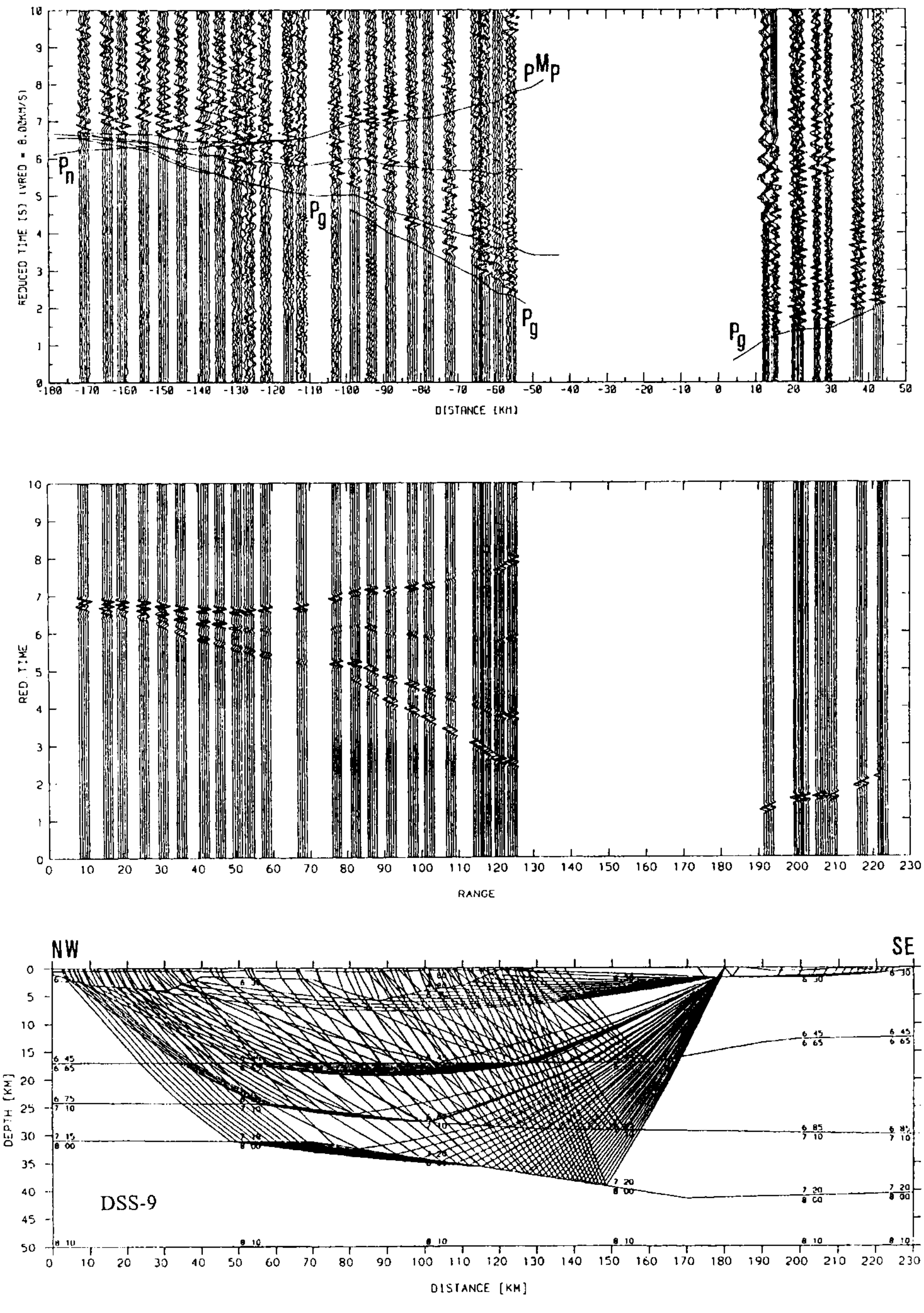

Fig. 3. An example of the results of crustal structure modelling along profile DSS-9. Seismic record section with theoretical travel times (upper diagram), synthetic seismograms (middle) and model of the structure with seismic rays (bottom) for station Rothera. Reduction velocity is 8.0 km/s.

Structure of the crust and lower lithosphere

Passive continental margin of Antarctic Peninsula

During the second Polish Geodynamic Expedition, Austral summer 1984–85, seismic measurements were made along 7 deep seismic profiles (Fig. 1). The study area was located on the Antarctic Peninsula shelf between extensions of the Tula Fracture Zone and the Hero Fracture Zone. The models of the crustal structure for profiles DSS-9, DSS-11, DSS-12 and DSS-13 are shown in Fig. 4 (Środa *et al.* 1997).

In the area adjacent to the Antarctic Peninsula, a sedimentary cover, 0.2 to 1.5 km thick was recognized, while in the western part of the study area, basins with sediment cover up to 5 km thick were observed. The P-wave velocities of 4.4–5.2 km/s were assumed for the sediments. The deep structure has some common features in all models applied. Particularly worth mentioning are the relatively high P-wave velocities of 6.3–6.4 km/s found at a shallow depth (less than 1 km) in a wide belt along the Antarctic Peninsula. The P-wave velocities of 6.6 km/s were found below 5–15 km depth. These high velocities confirm the existence of a large linear body with intermediate to basic composition which was intruded during the Mesozoic–Cenozoic subduction, as modelled by Garrett (1990) from aeromagnetic anomalies data.

The Earth's crust in the coastal area has a typical continental structure. The crystalline complex of the crust consists of three parts, with velocities of 6.3–6.4, 6.6–6.8 and 7.1–7.2 km/s. The thickness of the crust varies from 36 to 42 km, and maximum thicknesses are observed below Adelaide Island, Biscoe Islands and Anvers Island. A decrease of crustal thickness to about 25–28 km is observed toward the Pacific Ocean (Fig. 4).

Bransfield Rift and surrounding

The results of modelling the crustal structure in the Bransfiel Strait along profiles DSS-17 and DSS-20 are shown in Figs 5 and 6 (Grad *et al.* 1993a, b, 1997a, b). The main element of both models is a high velocity body ($v_P > 7.0$ km/s) at depths of 6–12 km. The crustal thickness in Bransfield Strait is about 28–32 km, and the velocity underneath the Moho ranges from 8.1 to 8.2 km/s. The Moho depths in the neighbouring blocks of the Antarctic Peninsula and the South Shetland Islands are 40–45 and 30–35 km, respectively.

Along profile DSS-17, we also observe differentiation in the velocity distributions within individual blocks of the crust (Fig. 5). In the oceanic crust, a sequence of layers with velocities from 2.0 to 5.6 km/s overlies the 4–5 km thick main layer of approximately 6.9 km/s velocities. In the South Shetland Islands block, under the low-velocity complex (2.0–4.0 km/s), there are three crystalline crust complexes with velocities of 5.6–6.1 km/s, 6.4–6.8 km/s and about 7.2

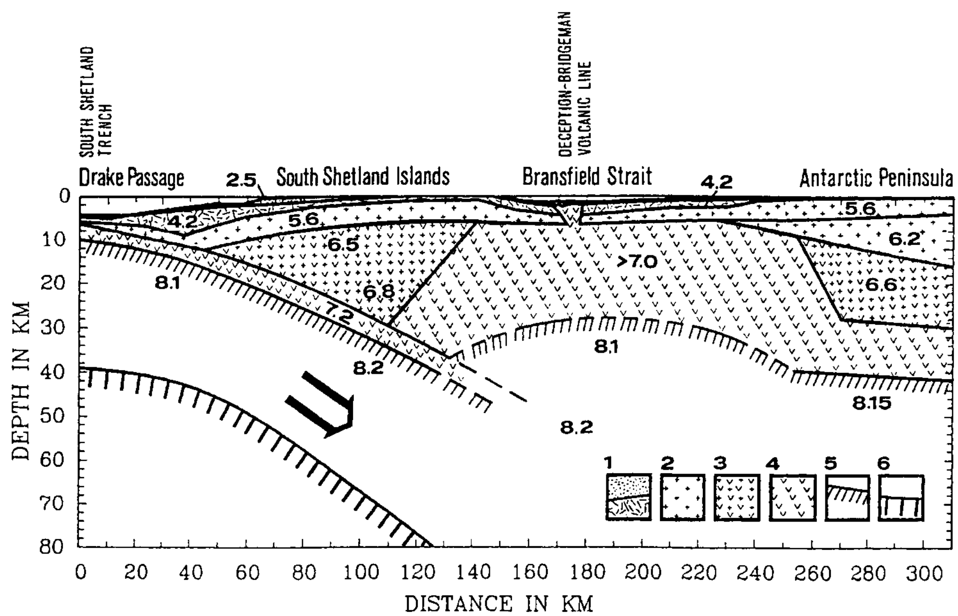

Fig. 5. Seismic model of the lithosphere along profile DSS-17 between the Drake Passage and Antarctic Peninsula. 1 – sediments, v_P = 2.5–4.2 km/s; 2 – upper crust, v_P = 5.4–6.3 km/s; 3 – middle crust, v_P = 6.4–6.8 km/s; 4 – the lower crust and high velocity body in the Bransfield Strait, v_P > 7.0 km/s; 5 – the Moho boundary, v_P > 8.0 km/s; 6 – the reflection boundary in the lower lithosphere.

km/s. In the Bransfield Strait, the main element of the crust is the high velocity body of v_P > 7.0 km/s. In the Antarctic Peninsula crust, we can detect a relatively thin sedimentary cover, and consecutive layers of about 5.6, 6.6, and 7.2 km/s velocities.

The first detailed deep seismic refraction study in the Bransfield Strait, using sensitive OBSs (ocean bottom seismographs), was carried out successfully during the Antarctic summer of 1990/1991 along profile DSS-20 (Grad *et al.* 1997a, b). The experiment focused on the deep crustal structure beneath the axial part of the Bransfield Rift. Seismic profile DSS-20 was located exactly in the Bransfield Trough, which is suspected to be a young rift system. The uppermost (sedimentary?) cover, with velocities of 2.0–5.5 km/s, reaches a depth down to 8 km. Below this, a complex with velocities of 6.4–6.8 km/s is observed. The presence of a high velocity body, with v_P = 7.3–7.4 km/s, was detected in the 14–32 km depth range in the central part of profile (Fig. 6). These inhomogeneities can be interpreted as a result of back-arc spreading and stretching of the continental crust, coinciding with the Deception – Bridgeman volcanic line. Velocities of 8.1 km/s, characteristic of the Moho, are observed along the profile at a depth of 30–32 km.

The modelling of the lower lithosphere was made only along profile DSS-17. The Moho boundary depth ranges on this 310-km long profile in a very broad interval: from 10 km for the oceanic crust in Drake Passage, to 40 km under the Antarctic Peninsula. In the transition zone from the South Shetland Trench to the South Shetland Islands, another boundary occurs under the Moho, at a depth growing from 35 to 80 km. The dip of the Moho, and also of the reflecting boundary in the lower lithosphere, is about 25° towards the southeast. The lithosphere structure model is shown in Fig. 5.

Summary and discussion

The results obtained in the passive continental margin of the Antarctic Peninsula can be compared with other results in this part of Antarctica. The location of sedimentary basins on profiles DSS-9, DSS-12 and DSS-13 coincide with locations indicated by reflection profiling (Anderson *et al.* 1990; Henriet *et al.* 1992). Relatively high velocities (6.3–6.4 km/s) observed at shallow depths, suggest mafic composition of a wide belt along the Antarctic Peninsula, as was expected from the aeromagnetic anomalies pattern (Garrett 1990). The depth of the Moho boundary in the coastal area varies from 36 to 42 km which is much more than the previously assumed range of 30–35 km based on gravity and aeromagnetic data (Garrett 1990). 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 Bransfield Strait area, the depth of the Moho discontinuity increases from about 10 km for the oceanic crust of the Drake Plate (also referred to in the literature as the "Phoenix" and "Aluk" 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 28–32 km. High velocities of P-waves of 7.2–7.6 km/s were found in the depth interval 10–25 km (Guterch *et al.* 1985, 1990, 1991; Birkenmajer *et al.* 1990; Grad *et al.* 1992, 1993a, b, 1997a, b; Janik 1997a, b).

The results relating to the shallow structure are consistent with those obtained using the reflection profiling method by various expeditions in the area of Bransfield Strait (e.g., Meissner *et al.* 1988; Henriet *et al.* 1989, 1992; Jeffers and Anderson 1990; Gambôa and Maldonado 1990; Jeffers *et al.* 1991). This is especially true for Bransfield Strait (structure of the central sub-basin axial ridge) and Drake Passage (axial part ofthe South Shetland Trench). We also observe a close similarity to Ashcroft's models of the upper crust, at depths of 10–15 km (Ashcroft 1972), but discrepancies occurr with respect to the Moho boundary. Depths of 15–20 km for the South Shetland Islands and Bransfield Strait were obtained by

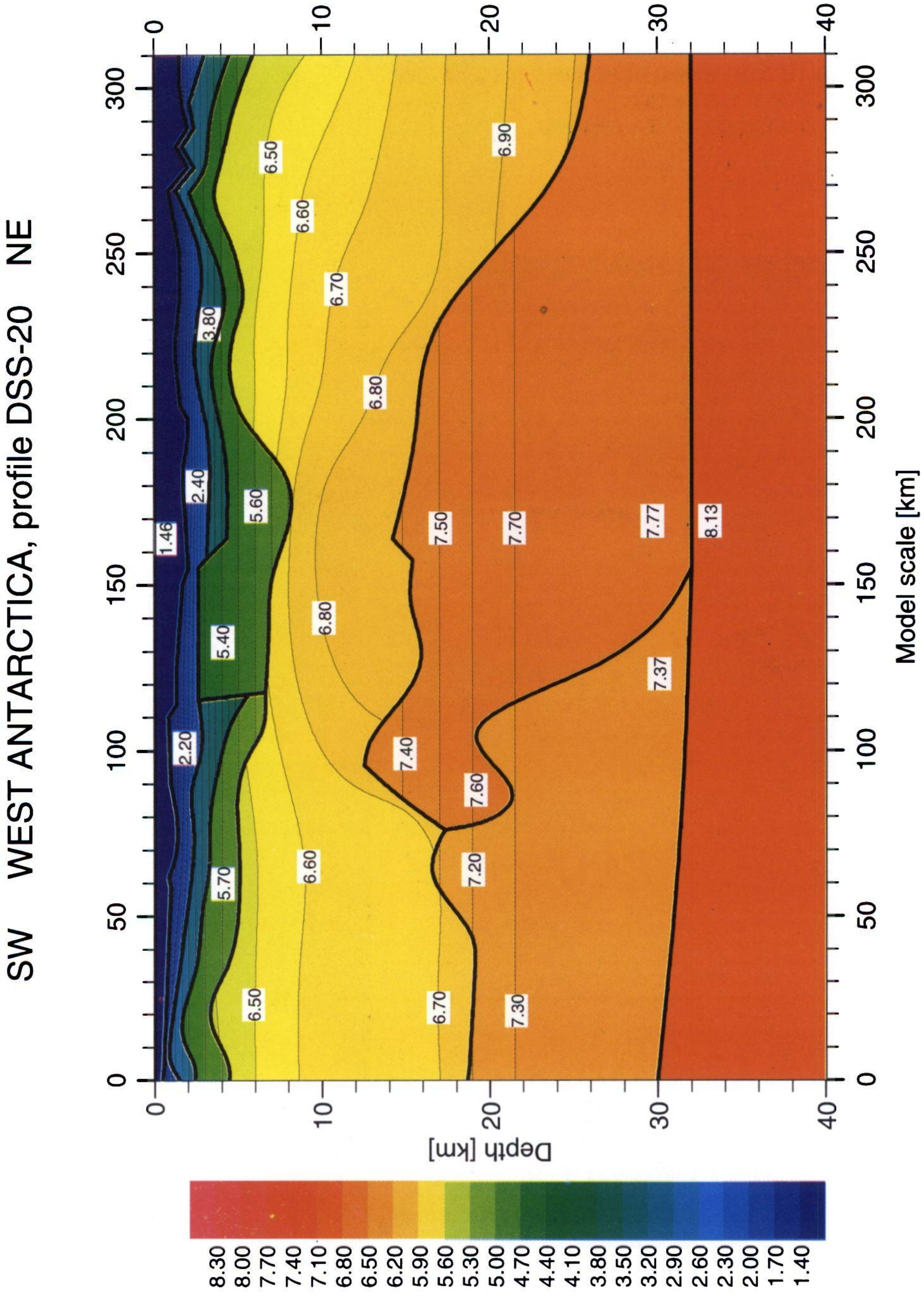

Fig. 6. Seismic model of the crust along the Bransfield Strait for profile DSS-20.

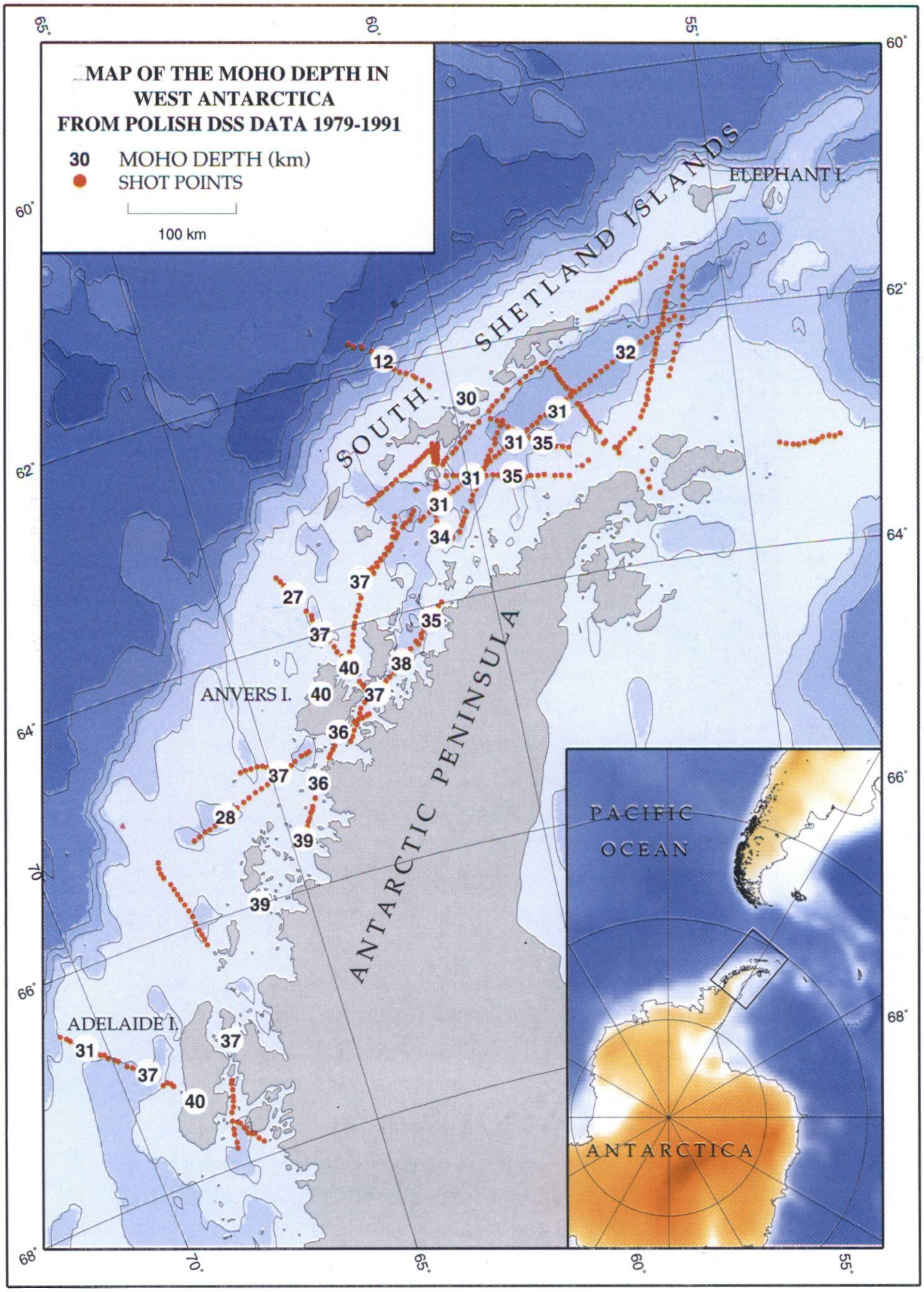

Fig. 7. Crustal thickness of the West Antarctica based on the results of deep seismic soundings performed during Polish Geodynamical Expeditions in 1979–1991.

Ashcroft on the basis of relatively short travel time branches – up to 80–100 km. The results from profiles DSS-17, DSS-1, DSS-5 and DSS-20 show that the Moho boundary is situated much deeper (in Bransfield Strait at a depth of 28–32 km), and the observed high values of apparent velocities result from inhomogeneity and inclination of the boundaries within the crust.

In the presented lithosphere model, in the contact zone of the Drake Plate and South Shetland Microplate, the dip of the subducting plate is about 25° towards the southeast. Similar figures were also obtained with the deep seismic sounding method in other regions of the circum-Pacific zone: about 10° in Southern Alaska (Fuis *et al.* 1991), 8–17° in Vancouver Island (Hyndman *et al.* 1990, Green *et al.* 1990, Morgan and Warner 1990), 8–15° in New Zealand (Davey and Smith 1983), 7° in Kuril Trench and 11° in Ryukyu Trench (Iwasaki *et al.* 1989).

Basing on the results of four Polish Geodynamical Expeditions to West Antarctica we present crustal thickness map of that area (Fig. 7).

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