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Seismic characteristic of the crust in the transition zone from the Pacific Ocean to the northern Antarctic Peninsula, West Antarctica

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Abstract Between 1979 and 1991, the Polish Academy of Sciences Institute of Geophysics conducted an extensive programme of wide-angle refraction experiments to investigate deep crustal structure in the northern Antarctic Peninsula region. In the course of these investigations, 20 wide-angle seismic refraction profiles (totalling c. 4500 line-km) were obtained across the Antarctic Peninsula continental shelf off Graham Land, Bransfield Strait, and the continental margin northeast of the South Shetland Islands. In this paper, we use results of these studies to describe crustal structure in the northern Antarctic Peninsula region. Crustal velocity models extending across the Antarctic continental shelf between Adelaide Island and Bransfield Strait show typical continental crustal structure, with crustal thicknesses of 36–42 km near the coast, decreasing to 25–28 km beneath the outer continental shelf. Farther north in the Bransfield Strait region, the models describe a crustal structure, with the Moho dipping southeastward from a depth of 10 km beneath the South Shetland Trench to 40 km under the northern tip of the Antarctic Peninsula. Beneath the trough of Bransfield Strait the presence of a high-velocity body, with compressional-wave velocities exceeding 7.0 km/s, was detected at a depth range of 6–32 km.

Keywords Antarctic Peninsula; Bransfield Strait; West Antarctica; crustal structure; Moho depth; subduction zone

INTRODUCTION

The Antarctic Peninsula (Fig.1, inset) extends northward from Ellsworth Land over 1500 km between the southeast Pacific Ocean and the Weddell Sea, and is one of the discrete crustal blocks of West Antarctica (Dalziel & Elliot 1973, 1982). Previous studies (e.g., Pankhurst 1982; Thomson et al. 1983) show that the peninsula is a Mesozoic–Cenozoic magmatic arc, which was formed in response to the subduction of proto-Pacific Ocean lithosphere at a trench formerly located along its western margin. Marine magnetic anomalies identified on the continental rise to the northeast (Herron & Tucholke 1976; Barker 1982; Larter & Barker 1991) record the southeastward migration of the Antarctic-Phoenix ridge toward the trench during the Tertiary. These data show that subduction stopped along most of the Antarctic Peninsula as ridge-crest segments migrated into the margin, first in the southwest, and progressively later to the northeast. During the Mesozoic, the Antarctic Peninsula formed part of the now-fragmented western margin of Gondwana, and was morphologically contiguous with the Andes Mountains in southernmost South America (Arctowski 1895; De Witt 1977). However, this continental connection was later disrupted with the opening of Drake Passage and the western Scotia Sea during the mid–late Cenozoic (between 29 and 6 Ma; Barker & Burrell 1977).

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. Birkenmajer (1989) and Birkenmajer et al. (1990) suggested that the initial formation of the Bransfield Basin dates back to Late Oligocene–Early Miocene times, on the basis of a system of rift-parallel antithetic faults identified along the outer margin of the rift. The rift in Bransfield Strait is a late Cenozoic tensional structure, c. 40 km wide near King George Island, which separates the Bransfield Platform from the South Shetland Islands microplate. 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 (Jeffers & Anderson 1990; González-Ferrán 1991).

Seismic refraction data

Between 1979 and 1991, the Polish Academy of Sciences Institute of Geophysics conducted four geophysical expeditions in the northern Antarctic Peninsula region (Guterch et al. 1985, 1990, 1991; Grad et al. 1992, 1993a,b, 1997a,b; Janik 1997a,b; Środa et al. 1997). These investigations were carried out to determine the structure of the Earth's crust and lower lithosphere by geophysical means, and were conducted as part of a wider programme of geodynamic studies of West Antarctica. A series of seismic refraction profiles were obtained using explosion seismology methods in the Bransfield Strait region, and across the Antarctic Peninsula shelf off Graham Land. In total, c. 4500 line-km of data were obtained in the form of 20 deep seismic sounding (DSS) profiles between Marguerite Bay and Elephant Island (Fig. 1). Seismic refraction records obtained in this area show a complicated seismic wavefield, resulting from large variations in seafloor depth, large subsurface velocity structures in the sedimentary cover, and the presence of intrusions and steeply dipping seismic (geological) boundaries. As a consequence, the data were analysed using the method of seismic ray tracing in 2D models with curvilinear boundaries and a complex velocity distribution (Červený & Pšenčík 1981, 1983; Hirata & Shinjo 1986; Thybo & Luetgert 1990; Komminaho 1993).

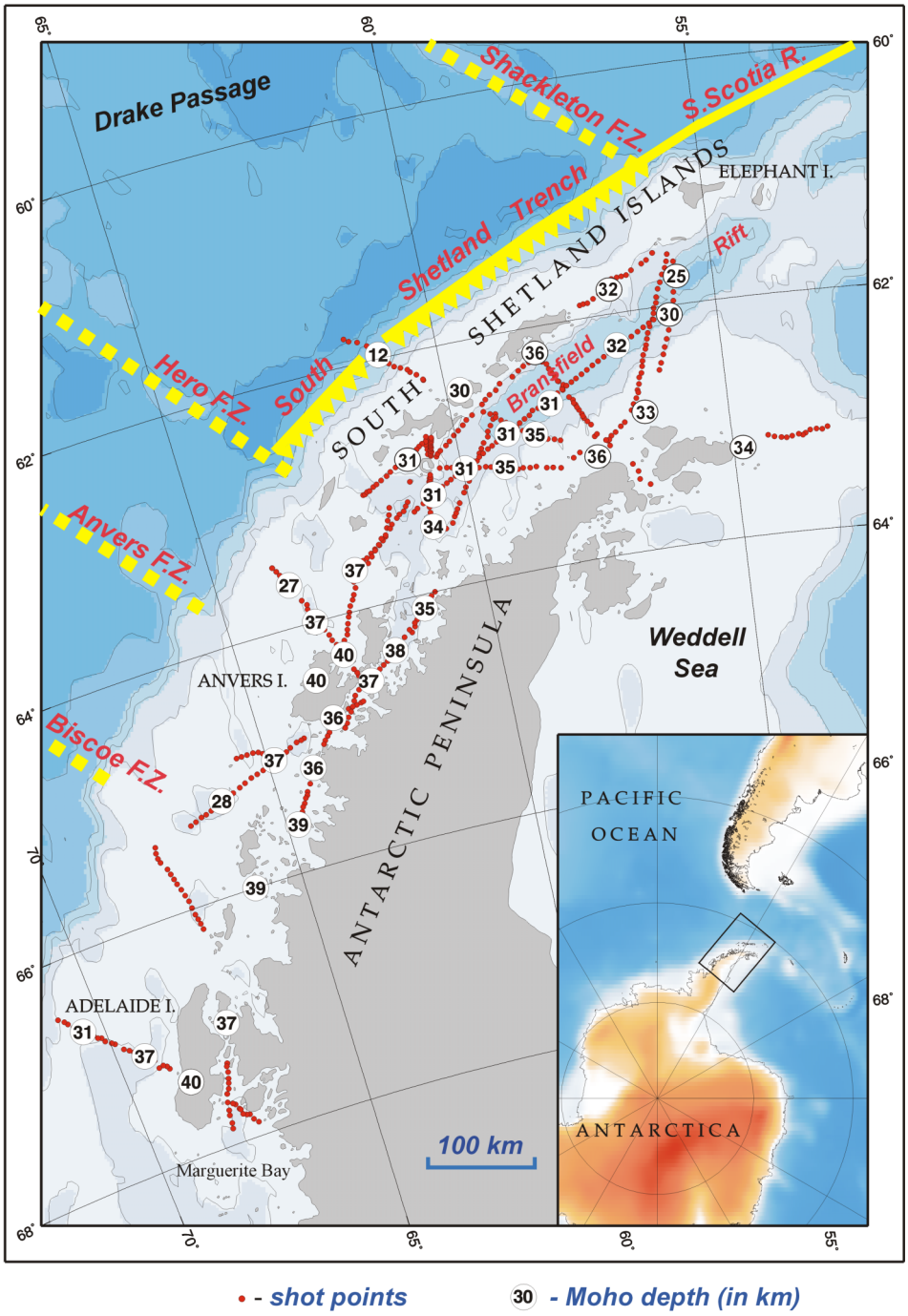

Fig. 1 Crustal thickness in the northern Antarctic Peninsula region based on the results of deep seismic soundings. Bathymetry contours are plotted at 500 m intervals (Wessel & Smith 1995). The positions of fracture zones (F.Z.), the South Shetland Trench, and the South Scotia Ridge (S.Scotia R.) are taken from Garrett & Storey (1987) and Gambôa & Maldonado (1990).

CRUSTAL STRUCTURE

Figure 1 is a summary map showing shot point locations and crustal thickness. Figure 2 shows the crustal structure beneath the Antarctic Peninsula shelf and Bransfield Strait along a 1000 km SW–NE transect corridor between Marguerite Bay and Elephant Island. This crustal velocity model is derived from profiles DSS-14, DSS-10 (southern, central, and northern parts), DSS-20, and DSS-18 (Grad et al. 1997a,b; Środa et al. 1997). Figure 3 shows examples of crustal velocity models crossing the Antarctic Peninsula continental shelf off Graham Land (profiles DSS-9 and DSS-13) and the tectonically active Bransfield Strait region (profile DSS-17: Grad et al. 1993a,b; Środa et al. 1997; Janik 1997a,b; Środa this volume).

Antarctic Peninsula continental shelf

Seismic refraction profiles were obtained across the Antarctic Peninsula continental shelf between the projected south-eastward positions of the Tula and Hero Fracture Zones. Near the coast of the Antarctic Peninsula, crustal velocity models reveal sediments with a thickness of 0.2–1.5 km. Farther northwest, sediments with a thickness of up to 5 km are observed beneath the mid–outer continental shelf (e.g., on the northwestern part of profile DSS-9; Fig. 3). The crustal velocity models also describe high velocities of 6.3–6.4 km/s at depths <1 km in a wide belt beneath the Antarctic Peninsula continental shelf, increasing to 6.6 km/s at depths of 5–15 km. Near the Graham Land coast, the Antarctic Peninsula has a typical continental structure, and has been

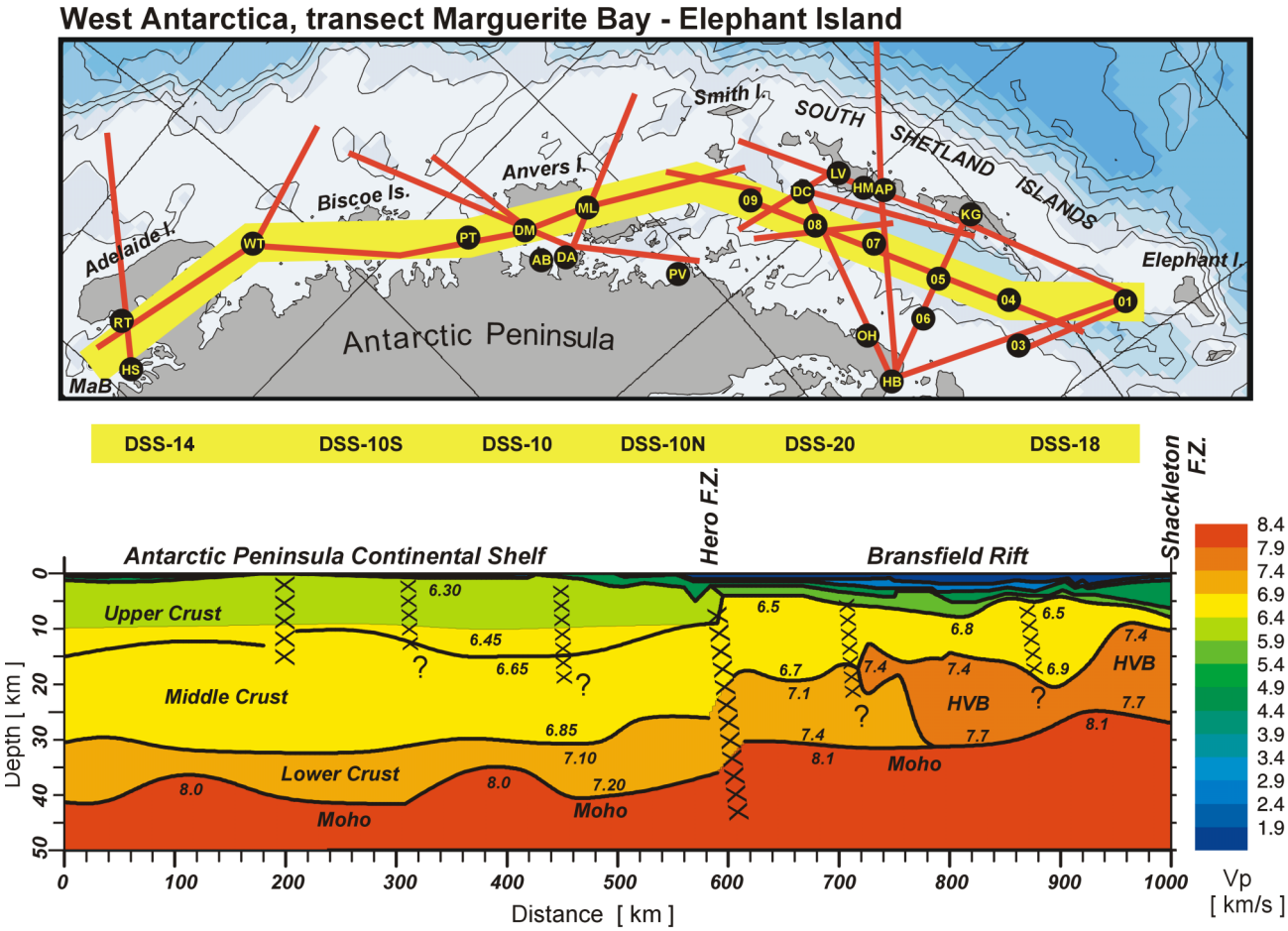

Fig. 2 Location of a 1000 km seismic refraction transect (wide stripe) across the continental shelf of the Antarctic Peninsula and Bransfield Strait in West Antarctica between Marguerite Bay (MaB) and Elephant Island, and the accompanying crustal model. The beginning of the transect has co-ordinates 68.12W, 67.68S (0 km) and the end of the transect 55.50W, 61.44S (1000 km). Intermediate points have co-ordinates: station WT 67.15W, 66.40S (182.4 km); station PT 64.16W, 65.17S (375.9 km); crossing point of profiles DSS-10 and DSS-20 62.31W, 63.68S (565.3 km). 01–09 – ocean bottom seismographs OBS 04 56.85W, 62.17S (883.6 km). Seismic stations: AB, Almirante Brown; AP, Arturo Prat; DA, Danco; DC, at Deception Island; DM, Damoy; HB, Hope Bay; HM, at Half Moon Island; HS, Horseshoe; KG, at King George Island; LV, at Livingston Island; ML, Melchior; OH, O'Higgins; PT, Petermann; PV, Primavera; RT, Rothera; WT, Watkins. Thin lines locate deep seismic profiles. Crosses show crustal discontinuities, corresponding in some cases to fracture zones. Numbers – *Vp* velocities in km/s. HVB – high-velocity body beneath Bransfield Strait.

modelled with three layers with velocities of 6.3–6.4, 6.6–6.8, and 7.1–7.2 km/s. The total thickness of the crust varies from 36 to 42 km, and maximum crustal thicknesses are observed beneath Adelaide Island, the Biscoe Islands, and Anvers Island. The models also show that the Antarctic Peninsula crust thins oceanward to a thickness of 25–30 km beneath the mid–outer shelf.

Bransfield Strait

Velocity models (Fig. 2, 3) show crustal thicknesses of 28–32 km beneath Bransfield Strait, and compressional-wave velocities of 8.1–8.2 km/s beneath the Moho. Beneath the neighbouring Antarctic Peninsula and South Shetland Islands, the Moho lies at depths of 40–45 and 30–35 km, respectively. During the Antarctic summer of 1990/91, a detailed deep seismic refraction survey was undertaken in Bransfield Strait using sensitive ocean bottom seismographs along profile DSS-20 (a distance range of 600–900 km; Fig. 2) in co-operation with the Hokkaido University in Sapporo (Grad et al. 1997a,b). The experiment focused on the deep crustal structure beneath the axial part of the Bransfield Trough, which is suspected to be a young rift system. Velocity models derived from these data show a sedimentary(?) cover (Vp = 2.0–5.5 km/s) extending to 8 km depth. At greater depth, the models show velocities of 6.4–6.8 km/s. The data also demonstrate the existance of a high-velocity body (Vp > 7.0 km/s) at depth of 6–12 km, extending to depths 22–32 km. These inhomogeneities are 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 depths of 30–32 km.

DISCUSSION AND SUMMARY

Velocity models described in this study can be compared with results of previous studies describing the tectonic and sedimentary architecture of the Antarctic Peninsula shelf. The sedimentary basins resolved on profiles DSS-9, DSS-12,

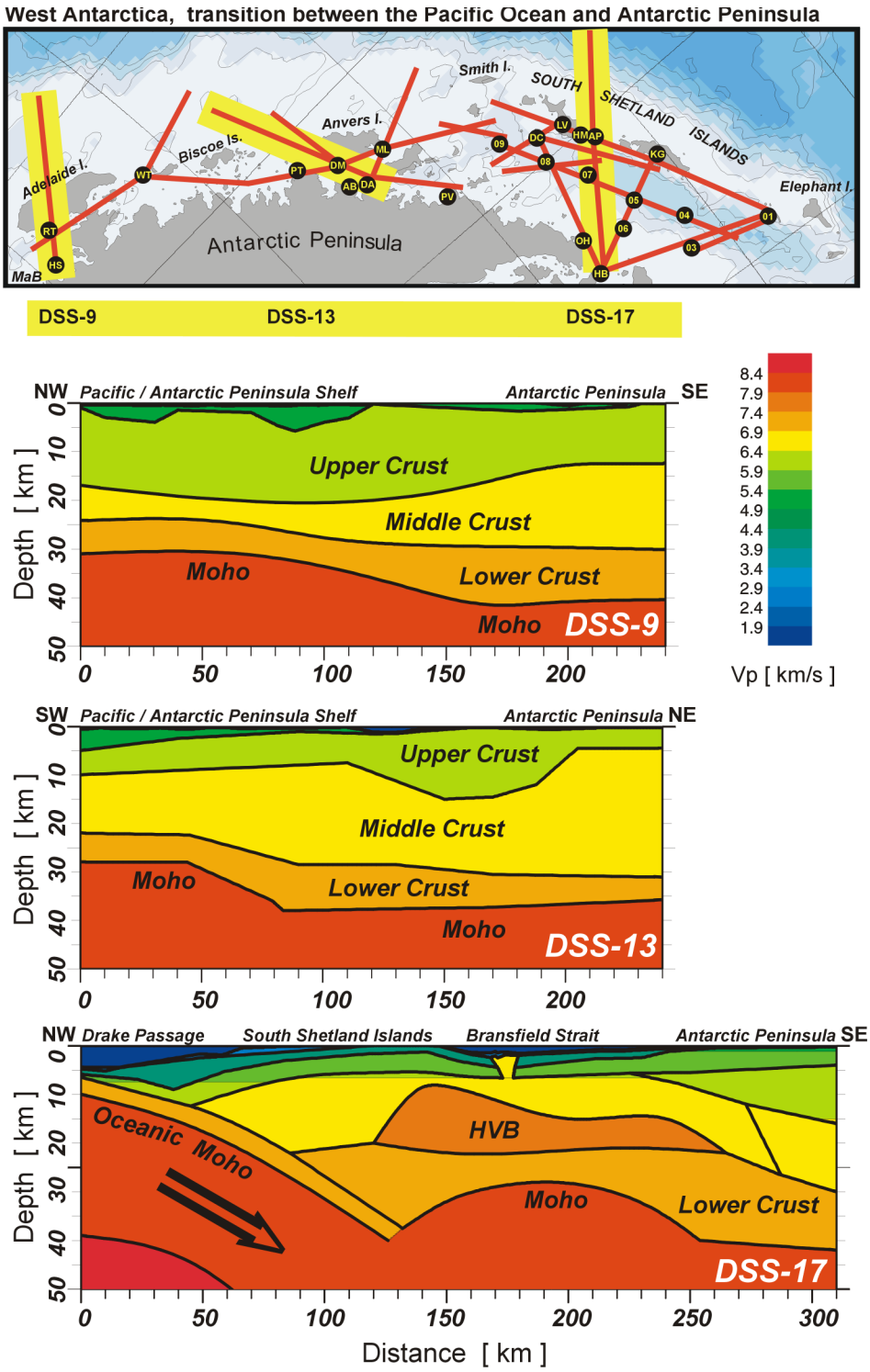

Fig. 3 Location map and crustal velocity models across the passive continental shelf of the Antarctic Peninsula along profiles DSS-9 and DSS-13 (Środa et al. 1997) and across the active marginal zone in the area of Bransfield Strait along profile DSS-17 (Grad et al. 1993a,b; with modification by Janik 1997a,b). Explanations as in Fig. 2.

and DSS-13 coincide with basins identified by reflection profiling (Henriet et al. 1989; Anderson et al. 1990). High compressional-wave velocities in the upper (6.3–6.4 km/s) and middle crust (6.6–6.8 km/s) beneath the inner shelf correspond to the mafic–intermediate Antarctic Peninsula batholith complex, which was intruded in response to Mesozoic–Cenozoic subduction described previously from aeromagnetic data (Garrett 1990). Near the coast of the Antarctic Peninsula, velocity models show the Moho at depths of 36–42 km. These Moho depths are significantly greater than depths estimated previously on the basis of gravity and aeromagnetic data (30–35 km; Garrett 1990). The dipping Moho describes the transition between the oceanic crust of the southern Pacific and the continental crust of the Antarctic Peninsula. The Earth's crust in the coastal area has a typical continental structure, and maximum thicknesses are observed below Adelaide Island, the Biscoe Islands, and Anvers Island (Fig. 2). Changes in the crustal structure along the Marguerite Bay–Elephant Island transect (Fig. 2) suggest the presence of structural discontinuities in

the crust at 200, 310, and 450 km, corresponding perhaps to the southeastward projections of the Biscoe and Anvers Fracture Zones.

In the Bransfield Strait area, the depth of the Moho increases from c. 10 km beneath the South Shetland Trench, to c. 25 km beneath the South Shetland Islands shelf, and then to 30–33 km beneath the South Shetland Islands crustal block. In 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 c. 28–32 km. We interpret the high-velocity body as an intrusion extending beneath much of Bransfield Strait.

Between Drake Passage and the South Shetland Islands, crustal velocity models resolve a seismic boundary in the lower lithosphere at a depth of 35–80 km (profile DSS-17; Fig. 3). The velocity below the reflector in the lower lithosphere was not determined because no waves were recorded coming through this medium. So, in particular, we are not able to answer if it is "asthenosphere" or not. This boundary and the overlying Moho have a dip of c. 25°, and together describe the trend of the subducting lithosphere of the Phoenix plate. The shallow structure on profile DSS-17 (Fig. 3) crossing Bransfield Strait is also consistent with results of previous studies based on reflection profiling (e.g., Meissner et al. 1988; Henriet et al. 1989, 1992; Jeffers & Anderson 1990; Gambôa & Maldonado 1990; Jeffers et al. 1991). In particular, we resolve the structure of the axial ridge in the central sub-basin of Bransfield Strait and the structure of the South Shetland Trench. Our results are also similar to Ashcroft's models of the upper crust at depths of 10–15 km (Ashcroft 1972), although discrepancies occur with the Moho boundary identification.

The crustal structure of Bransfield Strait between the Shackleton and Hero Fracture Zones differs from that of the Antarctic Peninsula shelf to the southwest due to the presence of the high-velocity body with the crust. Crustal discontinuities (fracture zones?) at 710 and 880 km could be related to the subdivision of the Bransfield Basin into western, central, and eastern sub-basins.

Finally, our data describe a major crustal boundary at 600 km (Fig. 2), which corresponds to the southeastward projection of the Hero Fracture Zone. This discontinuity separates the three-layer continental crust of the Antarctic Peninsula to the southwest from the two-layer crust and high-velocity intrusions extended beneath Bransfield Strait to the northeast.

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