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Deep crustal structure in the region of the Antarctic Peninsula from seismic refraction modelling (next step of data discussion)

ABSTRACT: Three Polish Antarctic Geodynamical Expeditions in 1979/80, 1984/85 and 1987/88 undertook seismic investigations in West Antarctica. Seismic measurements, including multichannel seismic reflection and deep seismic soundings, were carried out in the region of the west coast of the Antarctic Peninsula, between Antarctic Sound and Adelaide Island, Bransfield Strait, South Shetland Islands and South Shetland Trench along several lines with a total length of about 5000 km. Selected crustal sections and one and two-dimensional models of the crust for this area are discussed in detail. The thickness of the crust ranges from 30—33 km in the South Shetland Islands to 38—45 km near the coast of the Antarctic Peninsula. The crustal structure beneath the through of Bransfield Strait is highly anomalous; a seismic discontinuity with velocities of 7.0—7.2 km/s was found at a depth of 10 to 15 km, and a second discontinuity with velocities of about 7.6 km/s was found at a depth of 20—25 km. A seismic inhomogeneity along the Deception-Penguin-Bridgeman volcanic line has also been found. A scheme for the geotectonic division and a geodynamical model of the area are discussed. On the base of all experimental seismic data, it will be possible to construct a continuous geotraverse from Elephant Island, across Bransfield Strait, up to Adelaide Island with a total length of about 1100 km. Crustal section and seismic models along the northern segment of the geotraverse from the King George Island to the Palmer Archipelago are discussed in detail here.

Key words: Antarctica, Bransfield Trough, deep crustal structure, geotraverse.

Introduction

During the Polish Antarctic Geodynamical Expeditions in 1979/80, 1984/85 and 1987/88, seismic multi-channel reflection and deep seismic refraction measurements were made by the Institute of Geophysics of the Polish Academy

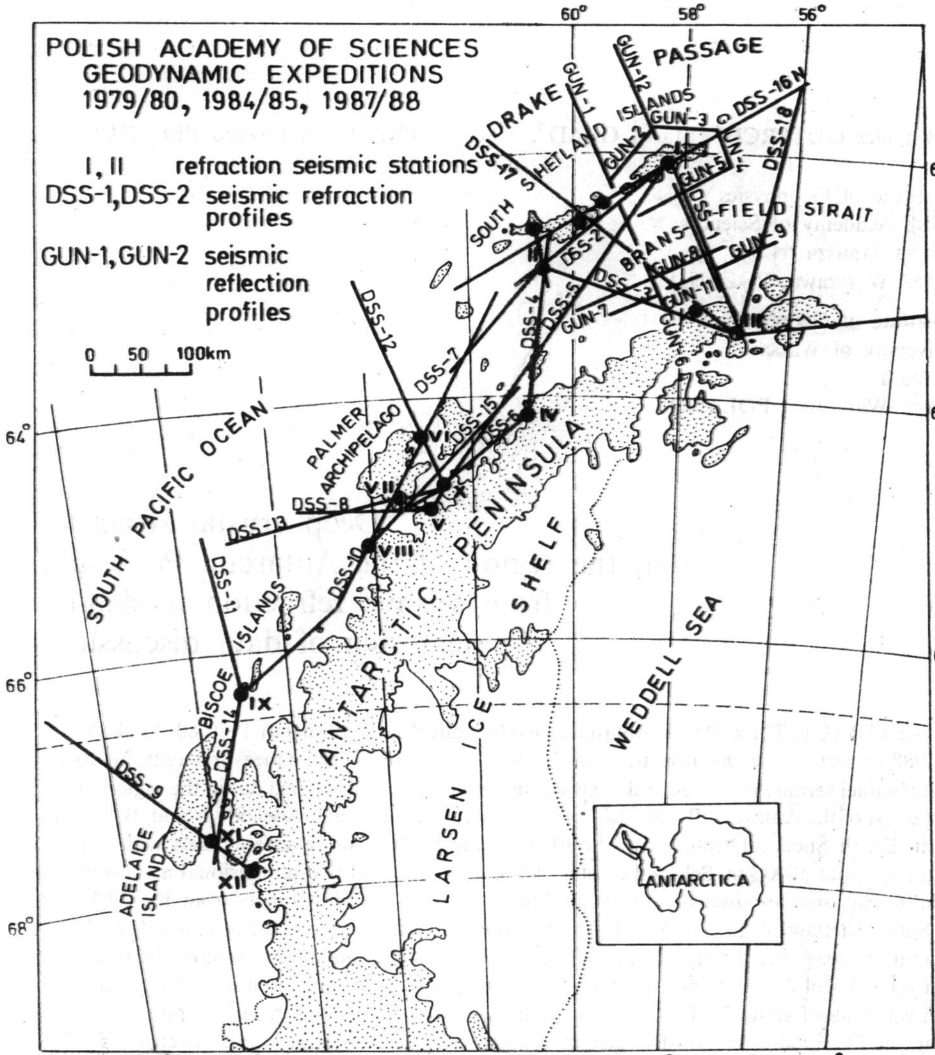

Fig. 1. Locations of seismic refraction and reflection profiles. I, II... = refraction seismic stations; DSS-1, DSS-2... = deep seismic sounding profiles; GUN-1, GUN-2... = seismic reflection profiles

of Sciences. Seismic measurements were carried out in West Antarctica approximately between 61°—68°S and 56°—72° W. The studies covered the western margin of the Antarctic Peninsula, from the Antarctic Sound to Marguerite Bay, and the surrounding archipelagoes and islands: South Shetland Islands, Palmer Archipelago, Biscoe Islands and Adelaide Island. Seismic measurements were also carried out in Bransfield Strait, in Gerlache Strait, on the shelf of the Bellinghausen Sea, and on the western shelf of the refraction branch was located on the eastern shelf of the Antarctic Peninsula.

Special attention was paid to tectonically active zones and to the contact zones between the crustal blocks and the lithospheric plates.

The network of profiles along which refraction and reflection soundings were carried out is shown (Fig. 1). Deep seismic refraction measurements were carried out along profiles of a total length more than 4000 km. Shots were fired in the sea at depths of 70—80 m, using dynamite charges of between 20 nad 120 kg. The distance between shot points was about 5 km on average. Three and five channel refraction stations on land recorded all the shots made along different profile lines. Altogether about 1500 seismic records of high quality were obtained at distances from a few to about 200 km from shot points. The largest distance at which good records could be obtained was 350 km. Seismic reflection measurements, using a multichannel system DFS-IV with Bolt airguns, were carried out along profiles with a total length of about 1100 km.

First results of the studies have been published by Guterch *et al.* (1985, 1987, 1990) and Birkenmajer *et al.* (1989). Next step of interpretation of the seismic refraction data is presented in this paper.

Interpretation

The results of the crustal studies presented in this paper are basad on the interpretation of travel times of refracted as well as reflected waves. The correlation of wave groups was based on their kinematic and dynamic properties, using composite records and seismic record sections. Examples of seismic refraction record sections are shown (Figs. 2, 3a, b, 4 and 5a, b). Each

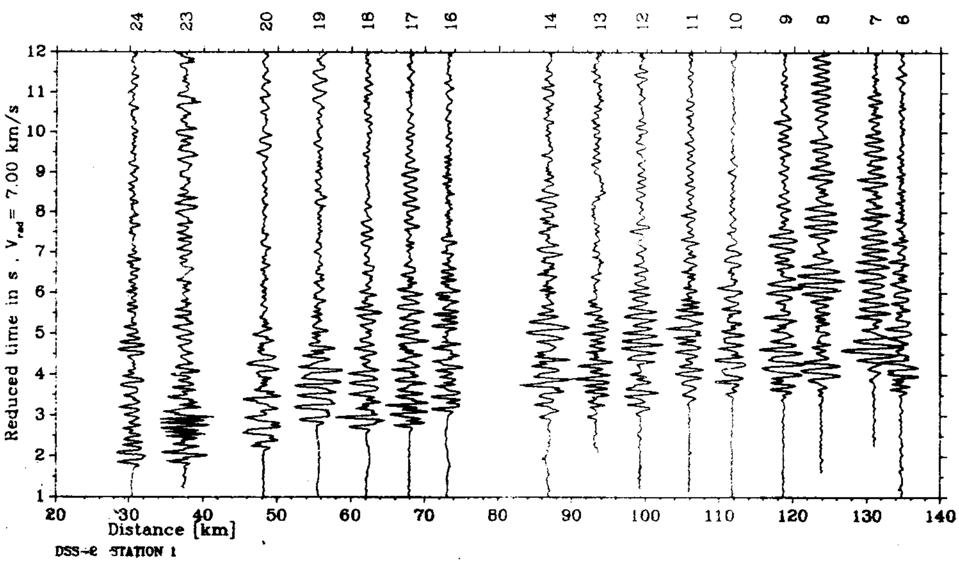

Fig. 2. Example of seismic refraction record section. DSS-2, station I

record on the sections corresponds to a 3-channel or 5-channel seismic record. Multichannel refraction records, with 200 m distances between them, made it easier to correlate waves. In particular, it is very important for correlation of reflected waves and for interpretation of fracture zones and tectonic disturbances.

Initial interpretation were achieved using simple methods of effective and apparent velocities. For the particular branches of the travel times of reflected waves, the effective velocities were calculated and, by considering the relations between effective and mean velocities, the depths of the reflection boundaries were determined (Grad 1983). Depths of refraction boundaries were determined by assigning mean velocities to refracted waves. By testing one-dimensional (1-D) models of the crust, it is possible to evaluate the validity of correlations and also to determine the mean velocities and depths of the boundaries. Theoretical travel times were calculated within the individual crustal blocks using the ray method for multilayer models (Alekseev and Gelchinsky 1959, Fuchs and Müller 1971). The 1-D models were then used to develop two-dimensional (2-D) models with curvillinear boundaries and complex velocity distribution v(x,z) (Červený and Pšenčík 1983). As a result of a multistage process of interpretation, good agreement between theoretical and experimental travel times, and also qualitative agreement among the amplitudes of main wave types, were obtained.

Examples of seismic reflection record sections are shown (Figs. 6 and 7). The multichannel reflection data have been processed by Geophysical Enterprise Toruń in Poland, using standard processing procedures.

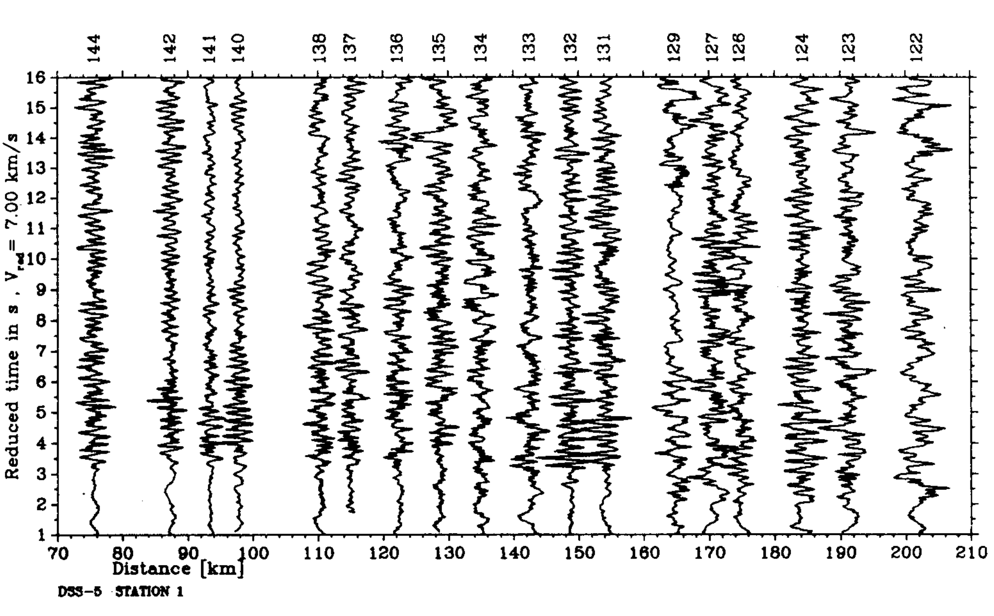

Fig. 3a. Example of seismic refraction record section. DSS-5, station I

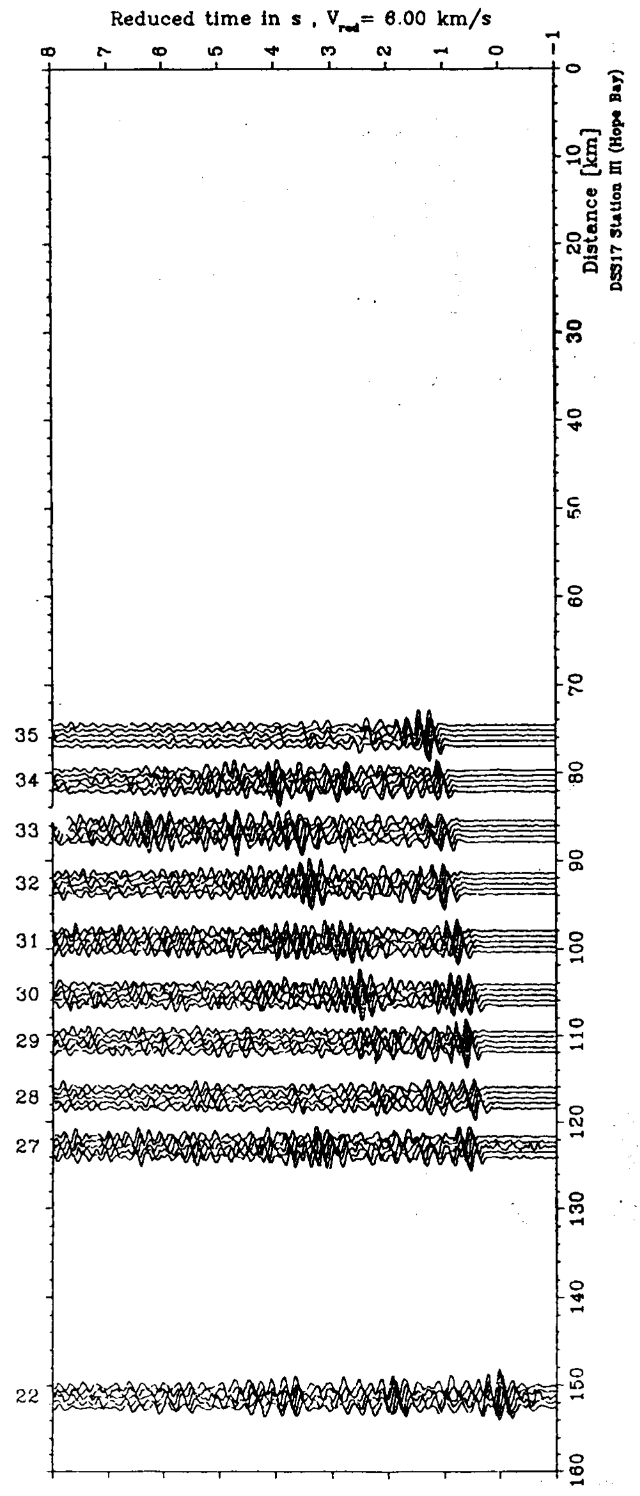

Fig. 3b. Example of seismic refraction record section. DSS-17, station III

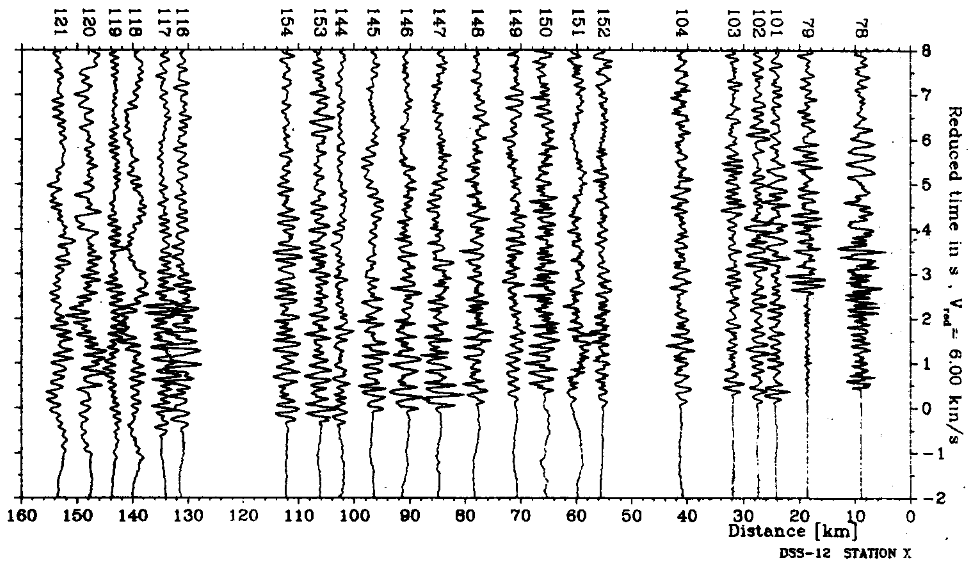

Fig. 4. Example of seismic refraction record section. DSS-12, station X

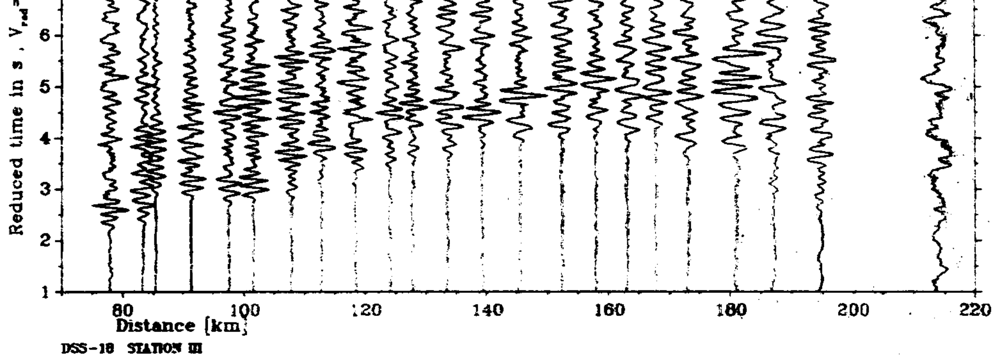

Fig. 5a. Example od seismic refraction record section. DSS-18, station III

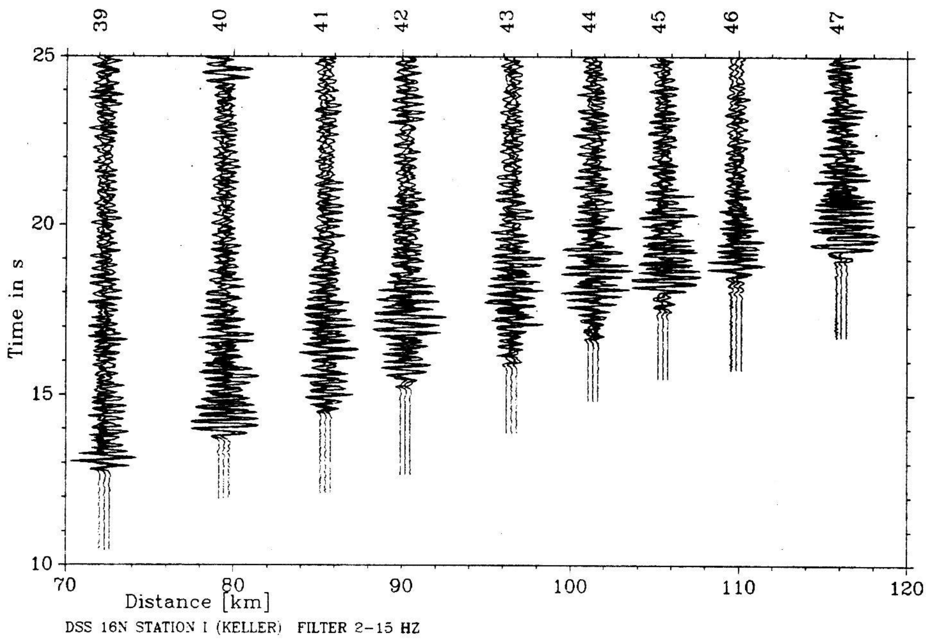

Fig. 5b. Example of seismic refraction record station (part of profile). DSS-16N, station I

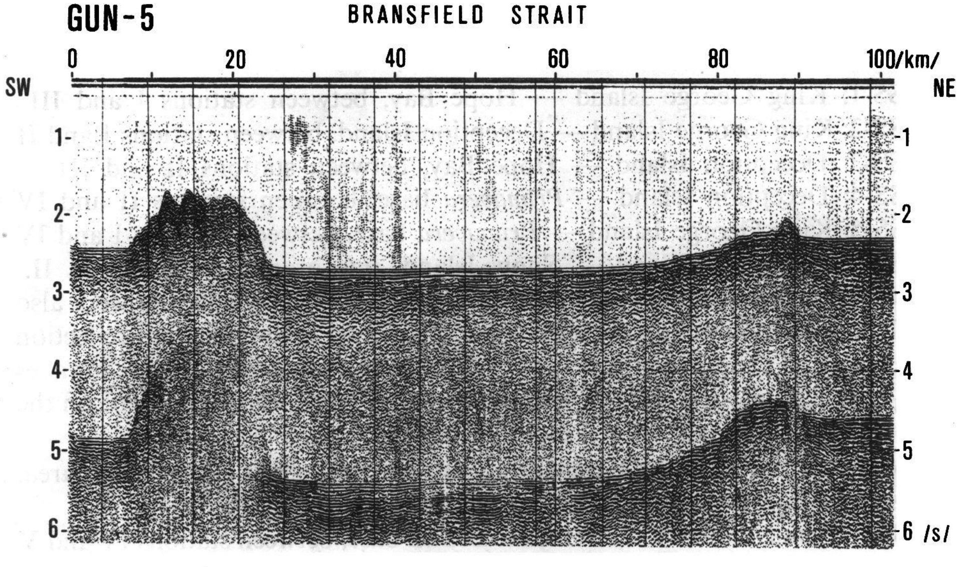

Fig. 6. Example of seismic reflection sections. GUN-5

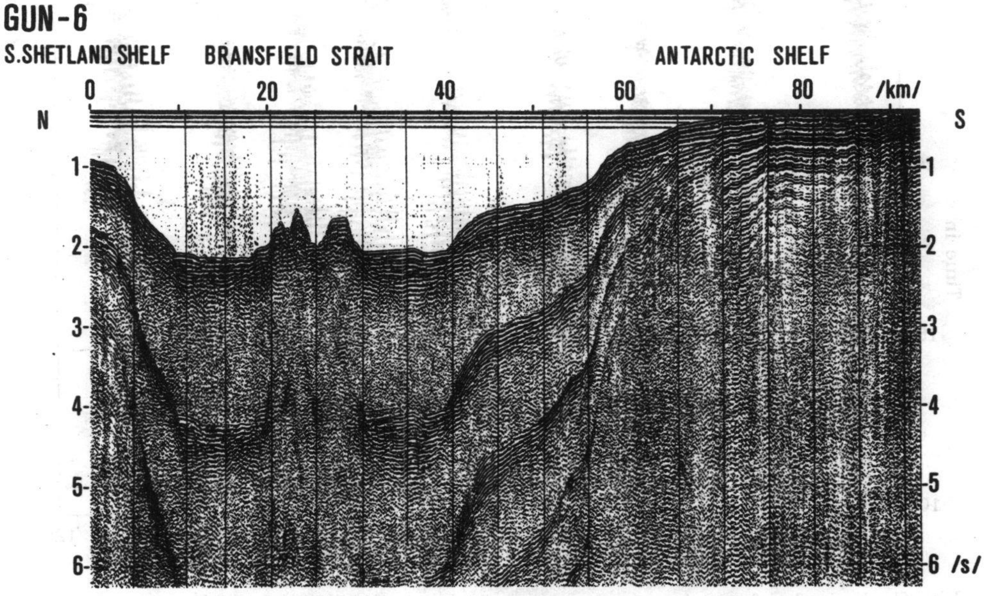

Fig. 7. Example of seismic reflection sections. GUN-6

Some results

The deep crustal structure over the area from the western margin of the Antarctic Peninsula, across Bransfield Trough in Bransfield Strait, to the South Shetland Islands and the South Shetland Trench along the DSS-1, DSS-2, DSS-3, DSS-4, DSS-5 and DSS-7 profiles (*see* Fig. 1) is discussed here. These are:

DSS-1: King George Island — Hope Bay, between stations I and III
DSS-2: King George Island — Deception Island, between stations I and II
DSS-3: Deception Island — Hope Bay, between stations II and III
DSS-4: Deception Island — *Primavera* base, between stations II and IV
DSS-5: King George Island — *Primavera* base, between stations I and IV
DSS-7: Deception Island — Snow Island, one branch from station II.

Moreover, records made at station I from shots in profile DSS-4 were also used. The crustal refraction data were complemented with data from reflection profiles (Fig. 1). The travel times of correlated refracted and reflected waves with 1-D crustal models are presented (Figs. 8, 9, 10, 11, 12). Each point on the travel time corresponds to a 3-channel seismic record.

The travel times and 1-D crustal models for the Palmer Archipelago area, discussed in this paper are presented (Figs 13, 14, 15). These are:

DSS-6: Primavera base — Almirante Brown base, between stations IV and V
DSS-5: records of shots by the station V (*Almirante Brown*) from DSS-5 and from DSS-7
DSS-8: records of shots by the station IV (*Primavera* base) and by the station V (*Almirante Brown* base).

The crustal modelling for the remainder of the profiles has not been finished yet.

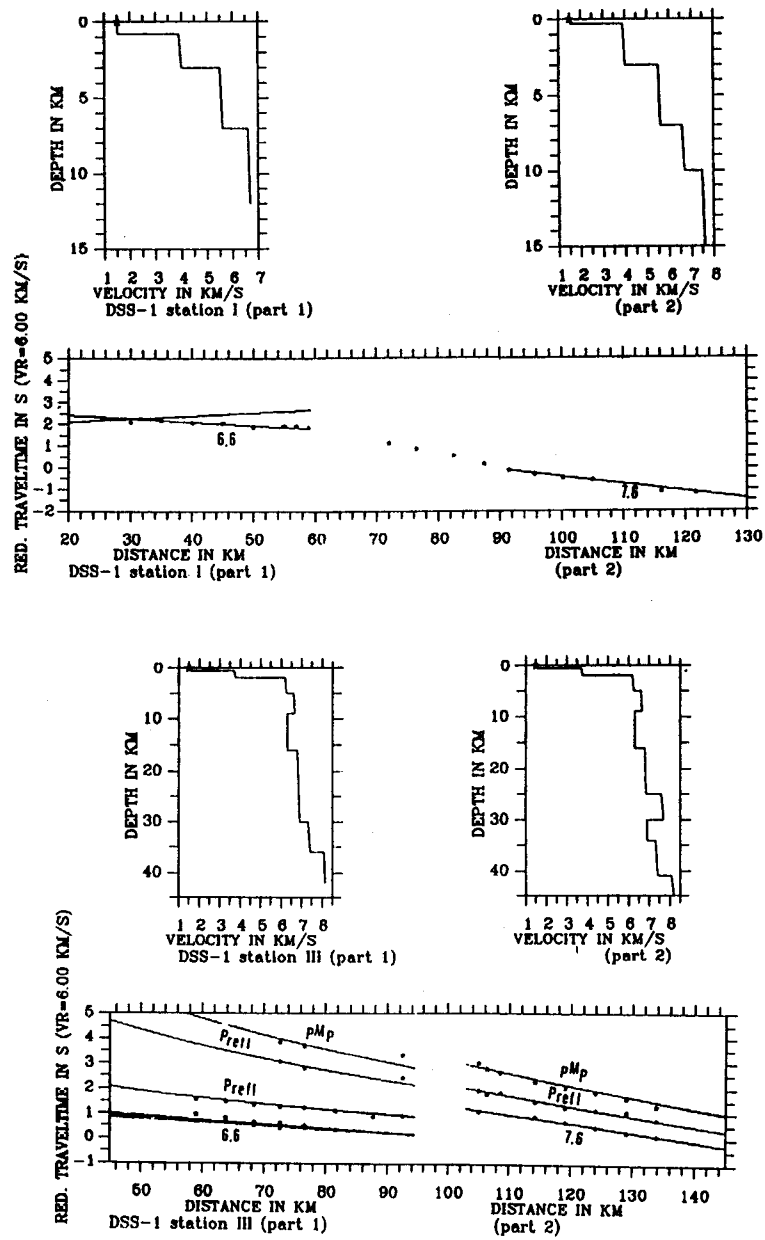

Fig. 8. Travel times and crustal models for DSS-1 profile, stations I and III, between the Antarctic Peninsula and South Shetland Islands. Experimental data are indicated by the dots. Each point on the travel times corresponds to a 3- or 5-channel seismic record, with 200 m distance between them. Theoretical travel times for the corresponding models indicated by the solid curve. 6.6, 7.6... = apparent velocities of refracted waves in km/s; P_{refl} = reflected waves; PMP = waves reflected from the Moho discontinuity

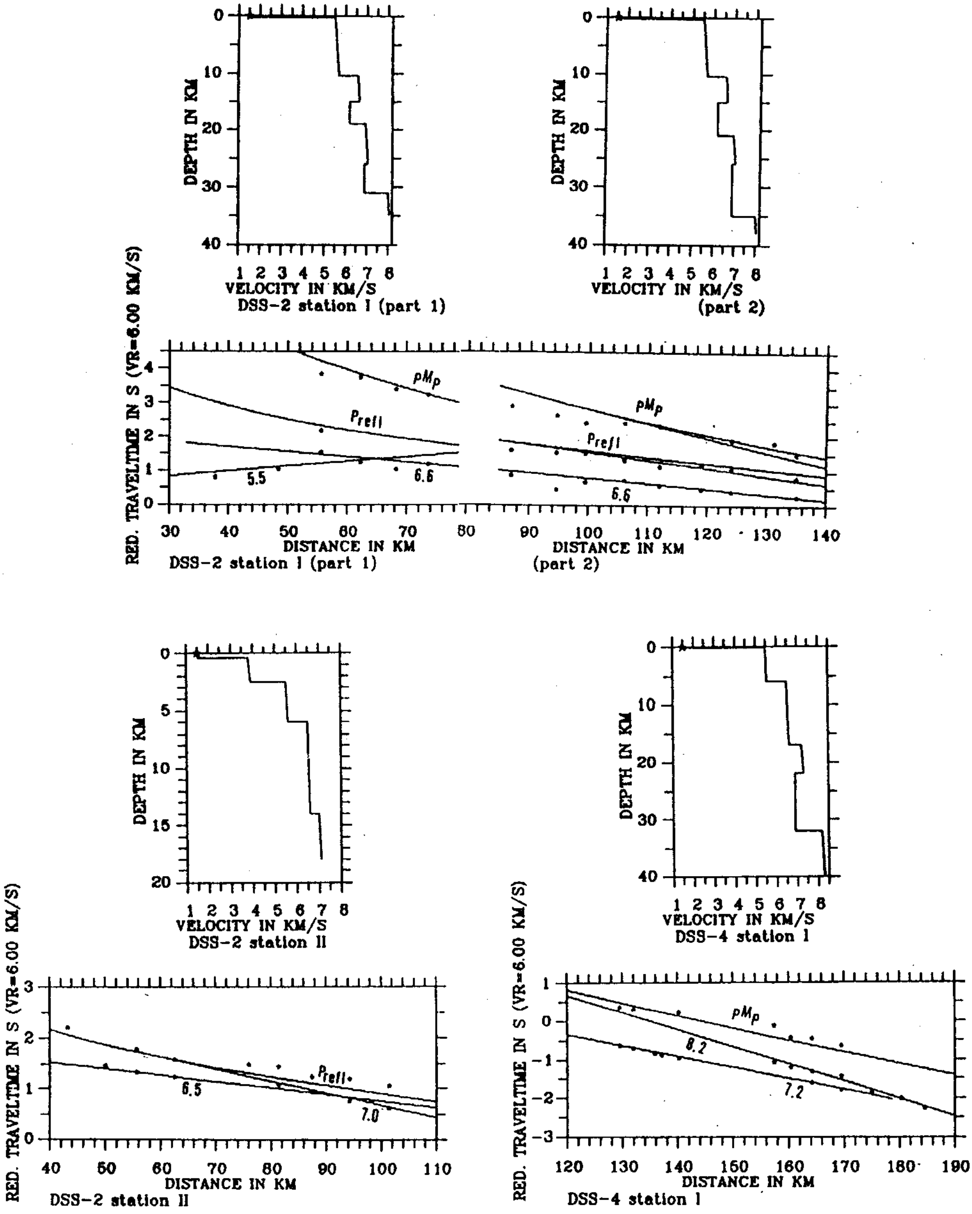

Fig. 9. Travel times and crustal models for DSS-2 profile, stations I and II and for DSS-4 profile, station I. Explanation *see* Fig. 8

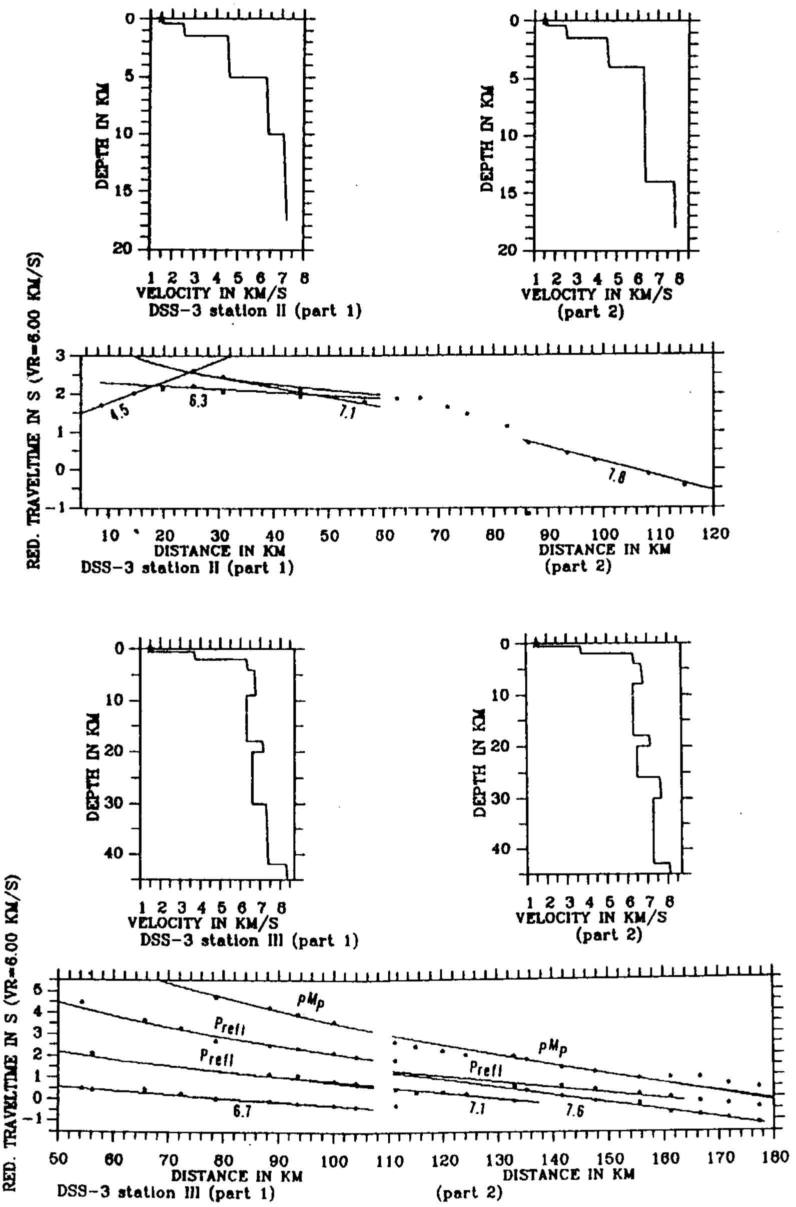

Fig. 10. Travel times and crustal models for DSS-3 profile, station II and III. Explanation *see* Fig. 8

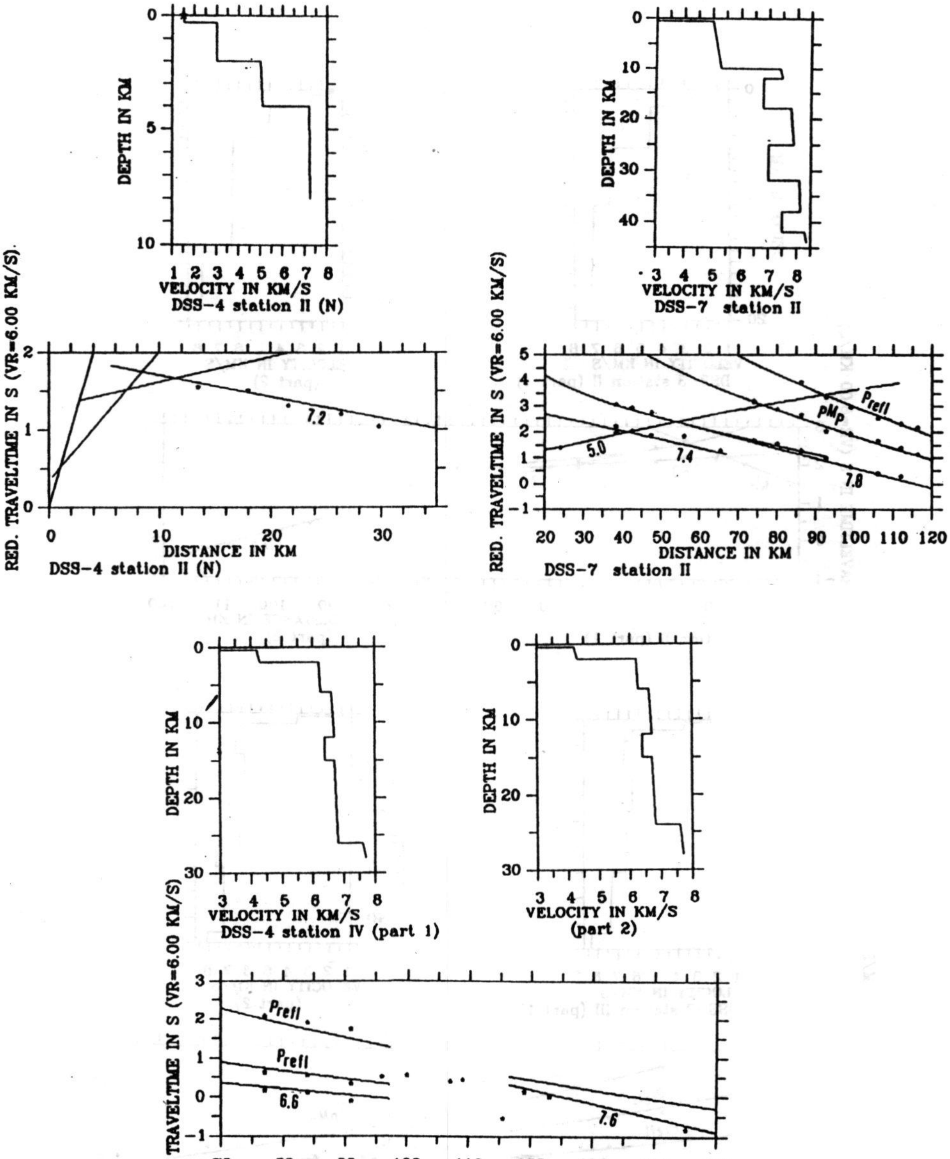

Fig. 11. Travel times and crustal models for DSS-4 profile, station II and IV and for DSS-7 profile, station II. Explanation *see* Fig. 8

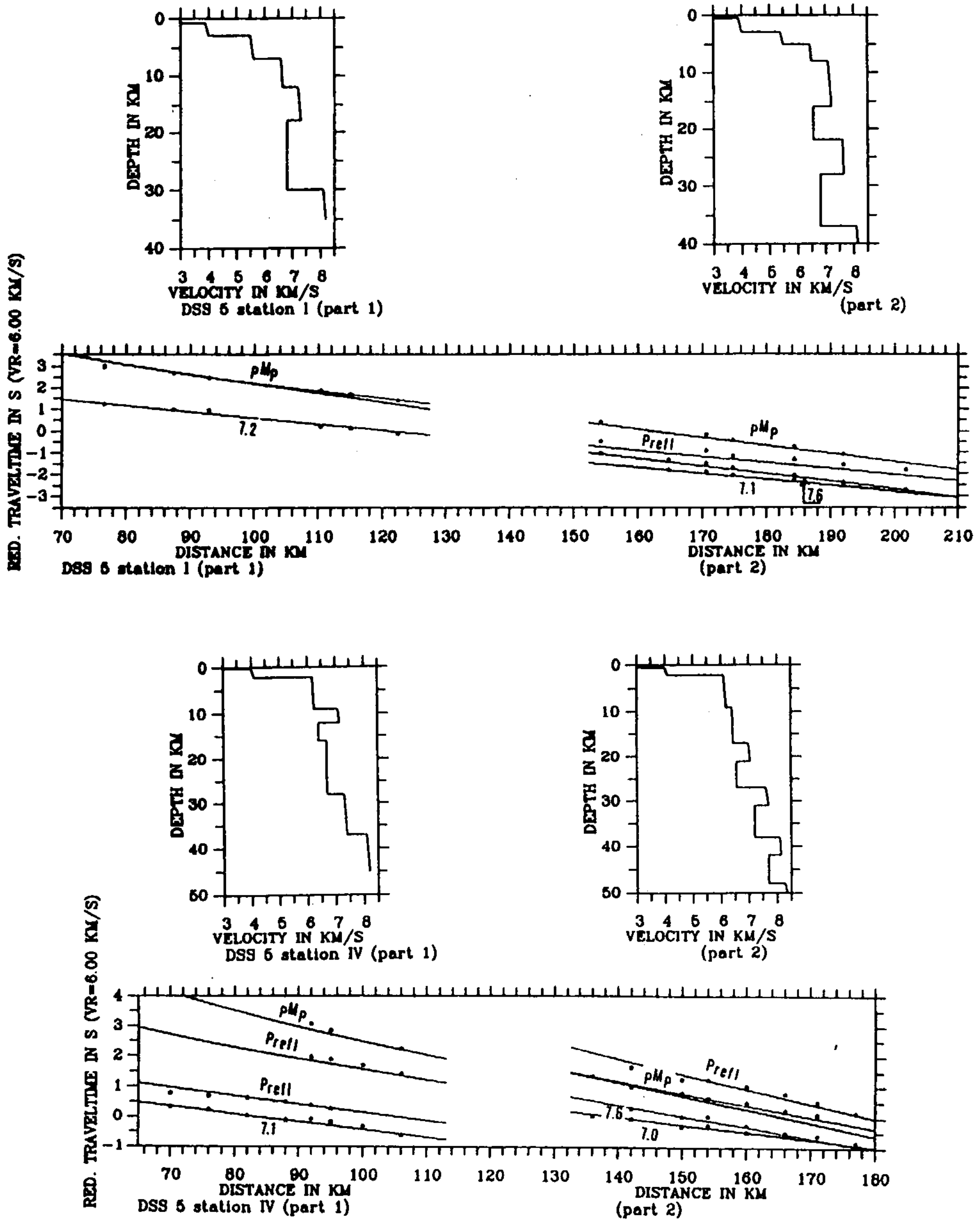

Fig. 12. Travel times and crustal models for DSS-5 profile, station I and IV. Explanation *see* Fig. 8

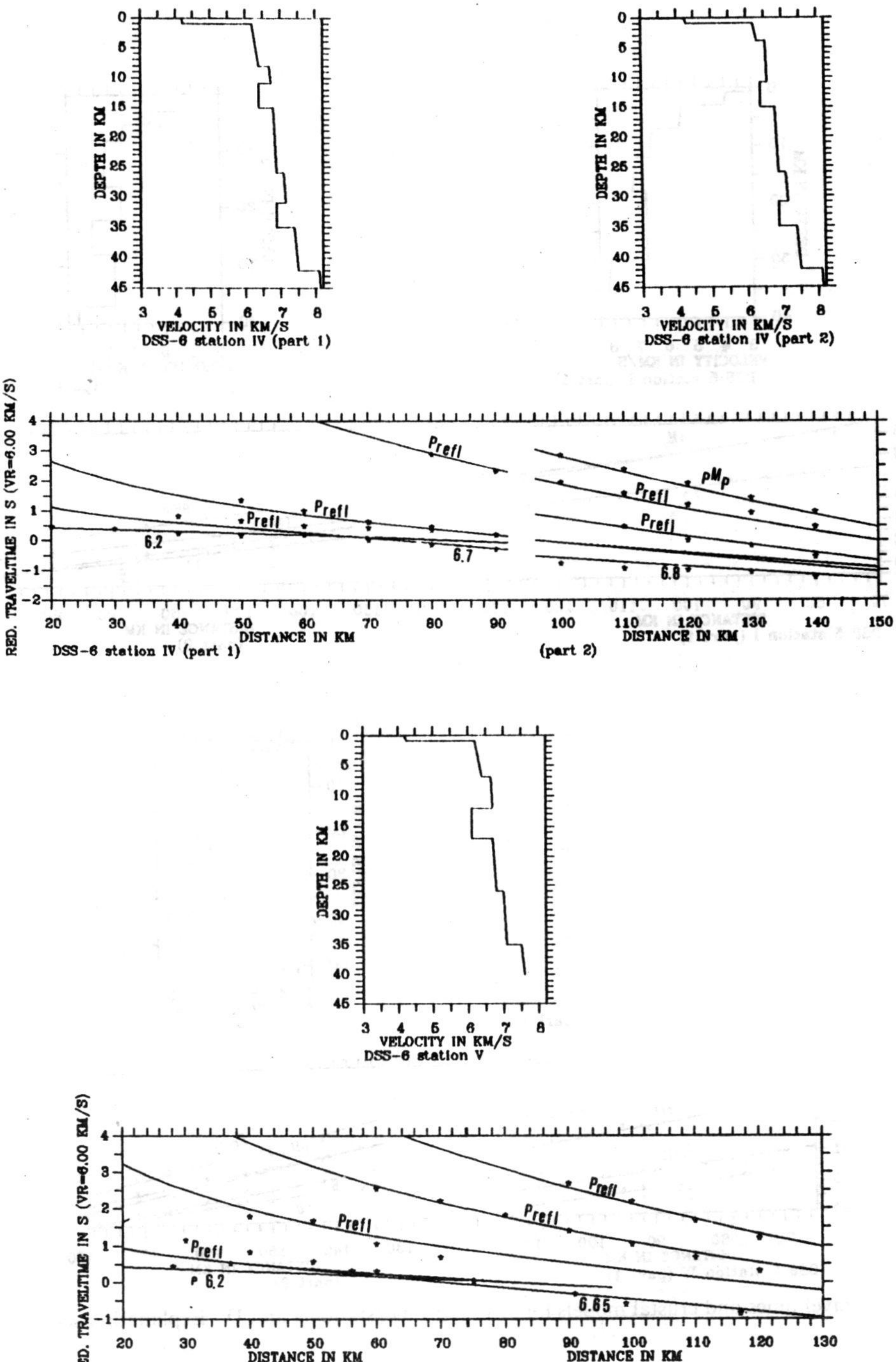

Fig. 13. Travel times and crustal models for DSS-6 profile, station IV and V. Explanation *see* Fig. 8

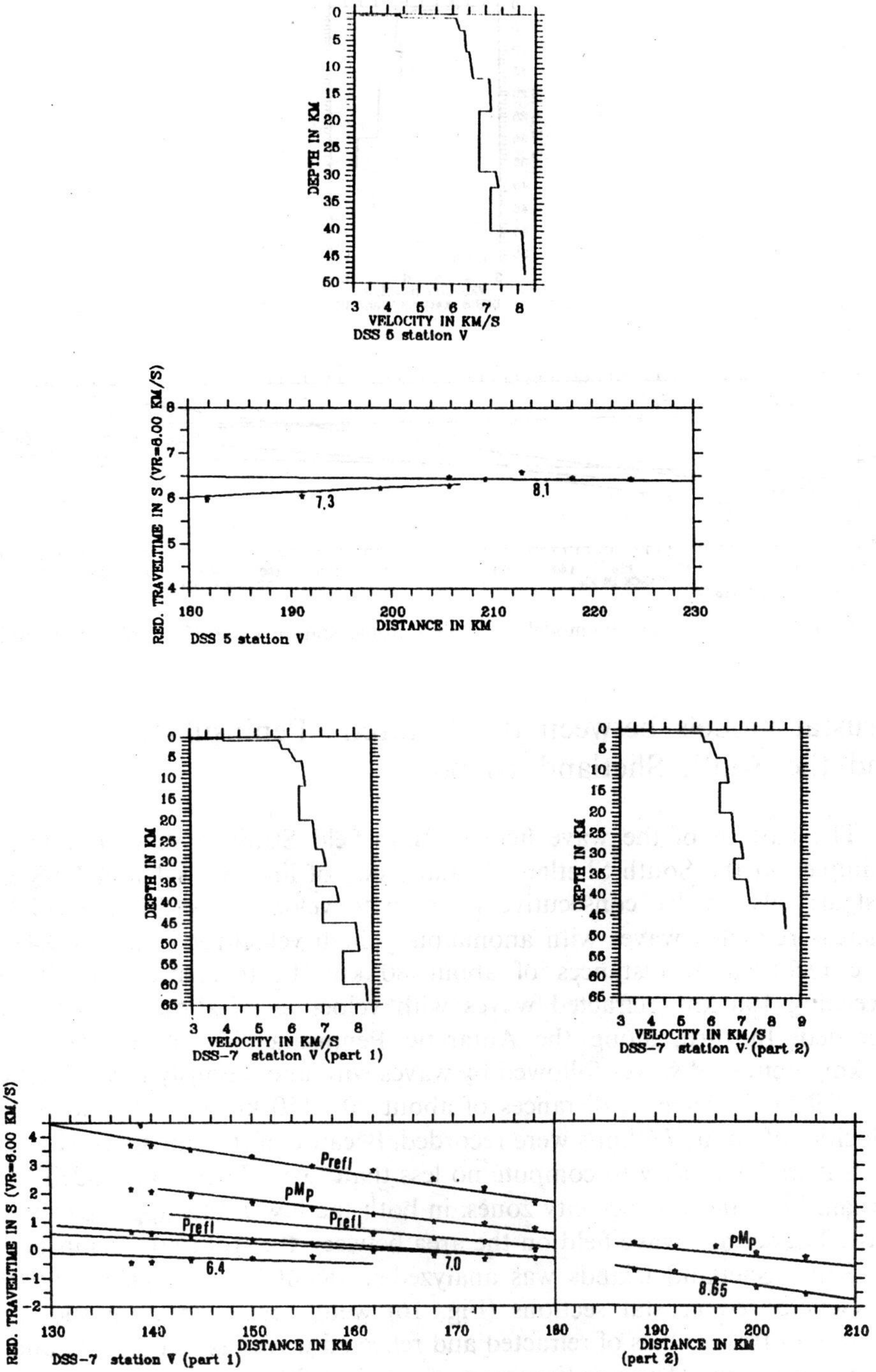

Fig. 14. Travel times and crustal models for DSS-5 profile, station V and DSS-7 profile, station V. Explanation *see* Fig. 8

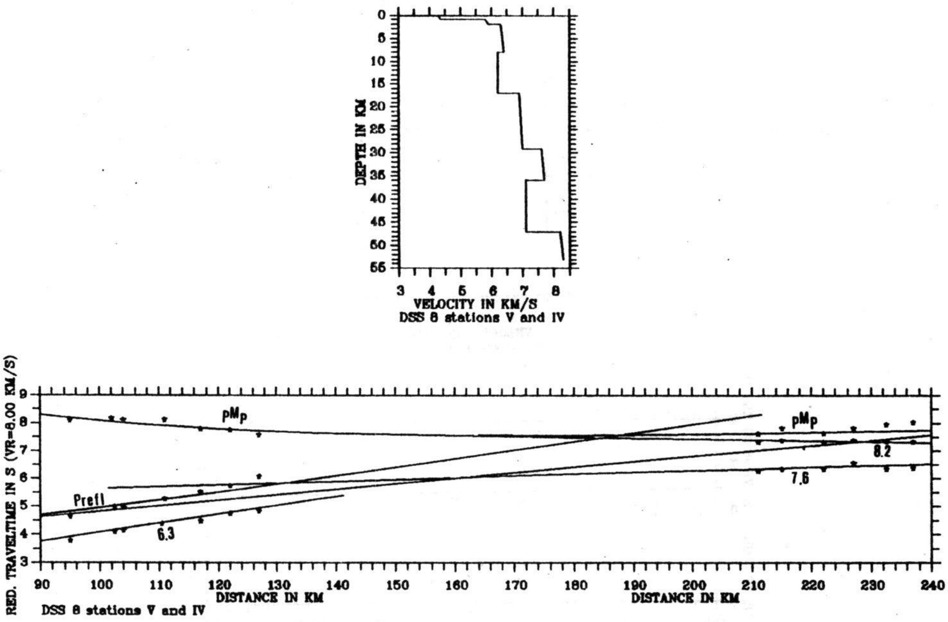

Fig. 15. Travel times and crustal models for DSS-8 profile, station V and IV. Explanation *see* Fig. 8

Crustal models between the Antarctic Peninsula and the South Shetland Islands

The pattern of the wave field in Bransfield Strait is very complex. For example, on the South Shetland Islands, side of lines DSS-1 and DSS-3, the first arrivals involve consecutive waves with velocities of 5.7 and 6.5 km/s, whereas refracted waves with anomalously high velocities, of about 9.4 km/s were recorded at distances of about 80 km. Farther away, at distances exceeding 100 km, refracted waves with velocities of about 7.6 km/s were recorded. In turn, along the Antarctic Peninsula side of the same lines, 6.6 km/s refracted waves followed by waves with anomalously low velocities of 5.7—5.9 km/s. Then at distances of about 90—150 km refracted waves with velocities of about 7.6 km/s were recorded. Because of this, for successive travel times it was necessary to compute no less than two 1-D crustal models. These contain high and low velocity zones, in both the lower and upper parts of the crust. The seismic wave field on the area between the Antarctic Peninsula and the South Shetland Islands was analyzed in detail by Guterch *et al.* (1985).

Generalized crustal sections (Fig. 16) were developed from the interpretation of travel times of refracted and reflected waves as well as 1-D and 2-D crustal modelling. The northern part of profile DSS-1 was complemented with data from profile DSS-2 (Guterch *et al.* 1985). The boundary velocities measured, or the probable layer velocities estimated from 1-D modelling, are

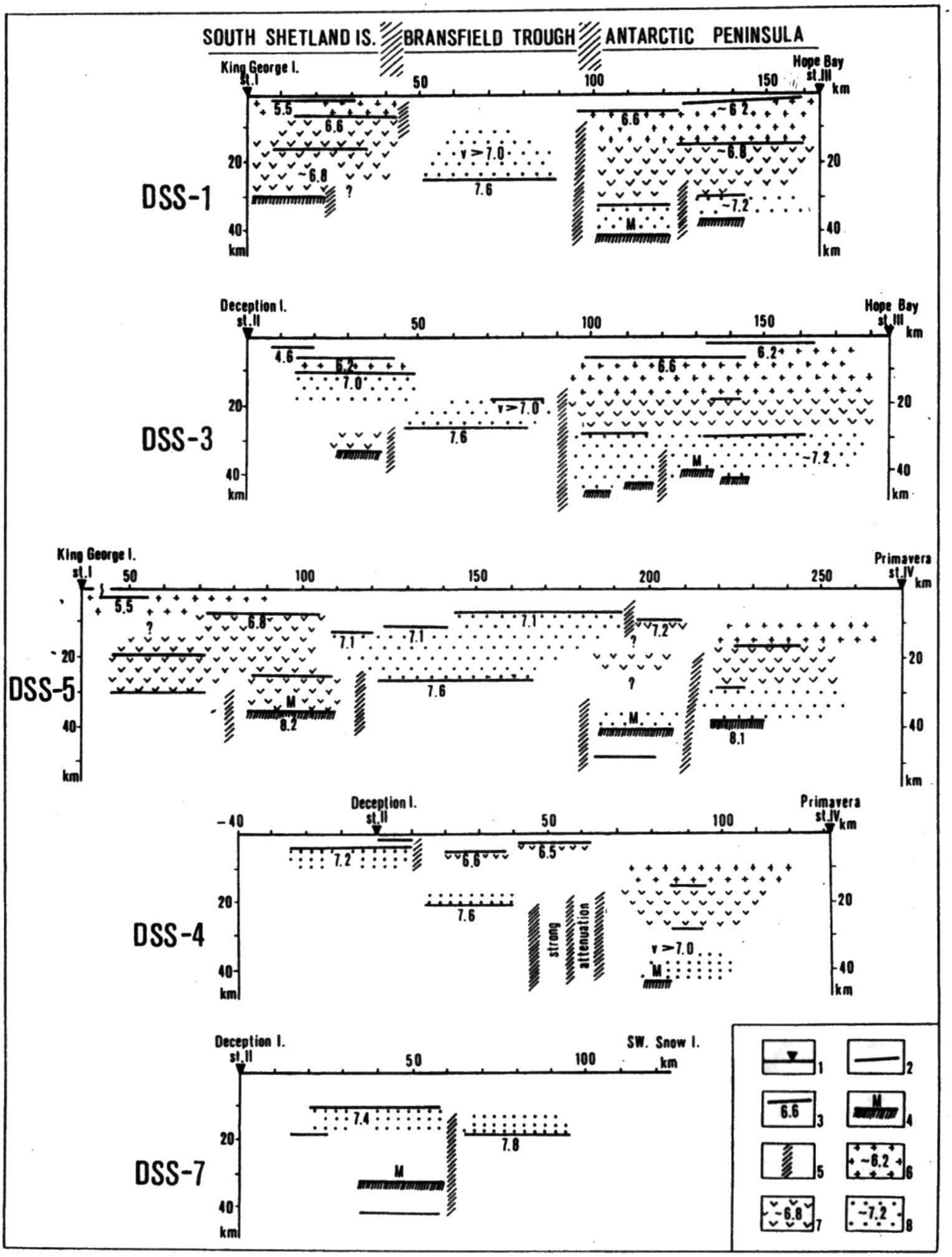

Fig. 16. Generalized crustal sections of the transition between the Antarctic Peninsula and the South Shetland Islands. 1 = position of refraction stations; 2 = reflection discontinuities; 3 = refraction discontinuities and boundary velocities in km/s; 4 = Moho discontinuity; 5 = contact zones of the crustal blocks (deep fractures?) and zones of strong attenuation of seismic waves; 6 = upper part of the crust and approximate layer velocities; 7 = lower part of the crust and approximate layer velocities; 8 = high velocity crustal layer

marked on the sections. The zones of the contact between crustal blocks marked on these sections, which may be zones of deep fractures, were determined on the basis of distinct variations in seismic wave fields, the strong attenuation of seismic waves and discordances between the depth of the determined seismic boundaries. The zones of contact between crustal blocks occur mainly in the lower part of the crust.

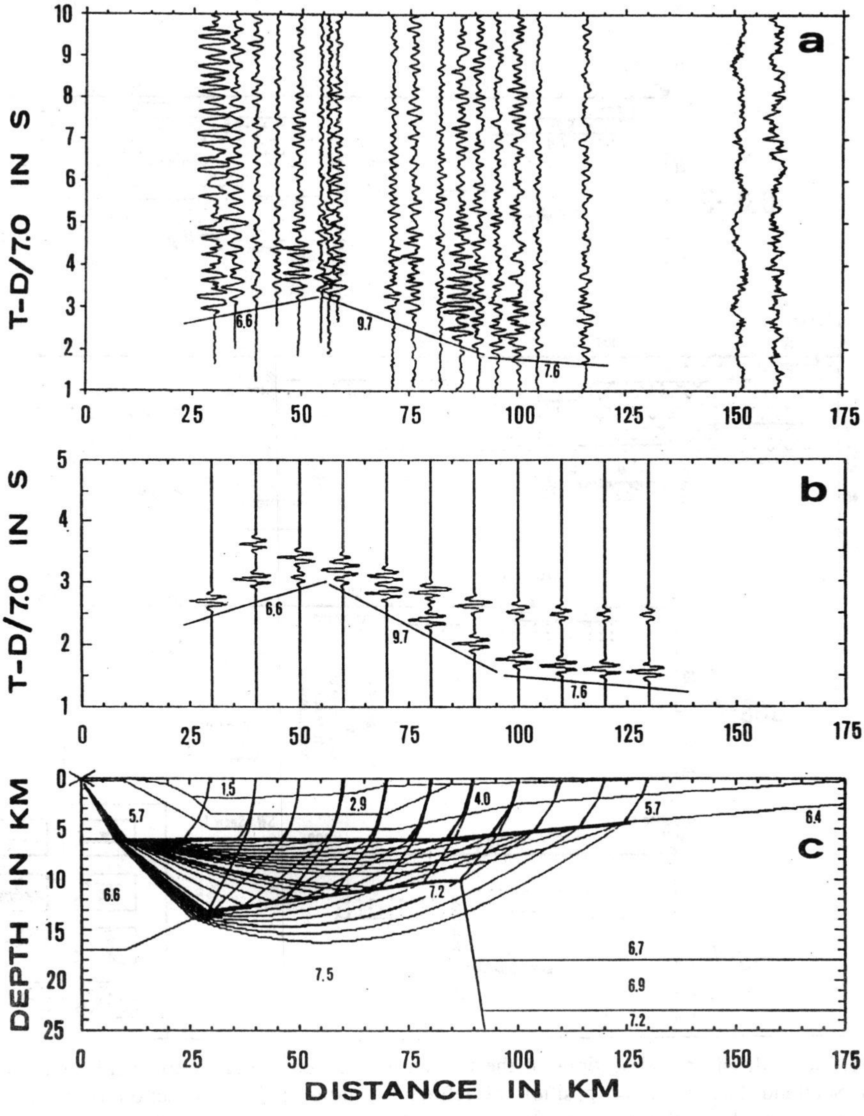

Fig. 17. Record section (a), synthetic record section (b) and two-dimensional crustal model (c) for DSS-1 profile. Velocity of seismic waves in km/s

Seismic boundaries with anomalous seismic wave velocities were found in Bransfield Trough. Seismic boundaries with velocities of 7.0—7.2 km/s occur as shallow as about 10—15 km, whereas boundaries with velocities of about 7.6 km/s are present at depths of 20—25 km. A special case is near Deception Island, where a seismic boundary was found with velocities of 7.4 km/s at a depth of only 8 km, and of 7.8 km/s at a depth of about 18 km. In general, the Moho discontinuity in the studied area of the South Shetland Islands occurs at depths of 30—33 km, and along the western margin of the Antarctic Peninsula it is present at depths of about 38—45 km. The seismic wave field in the crust of the Antarctic Peninsula is characterized by the presence of numerous strong reflected waves. These waves are mainly related to discontinuities in the lower crust. The most effective seismic reflection boundaries, above the Moho discontinuity, usually occur at depths of 25—35 km. In the area of the Antarctic Peninsula, distinct S-waves (both refracted and reflected) were also

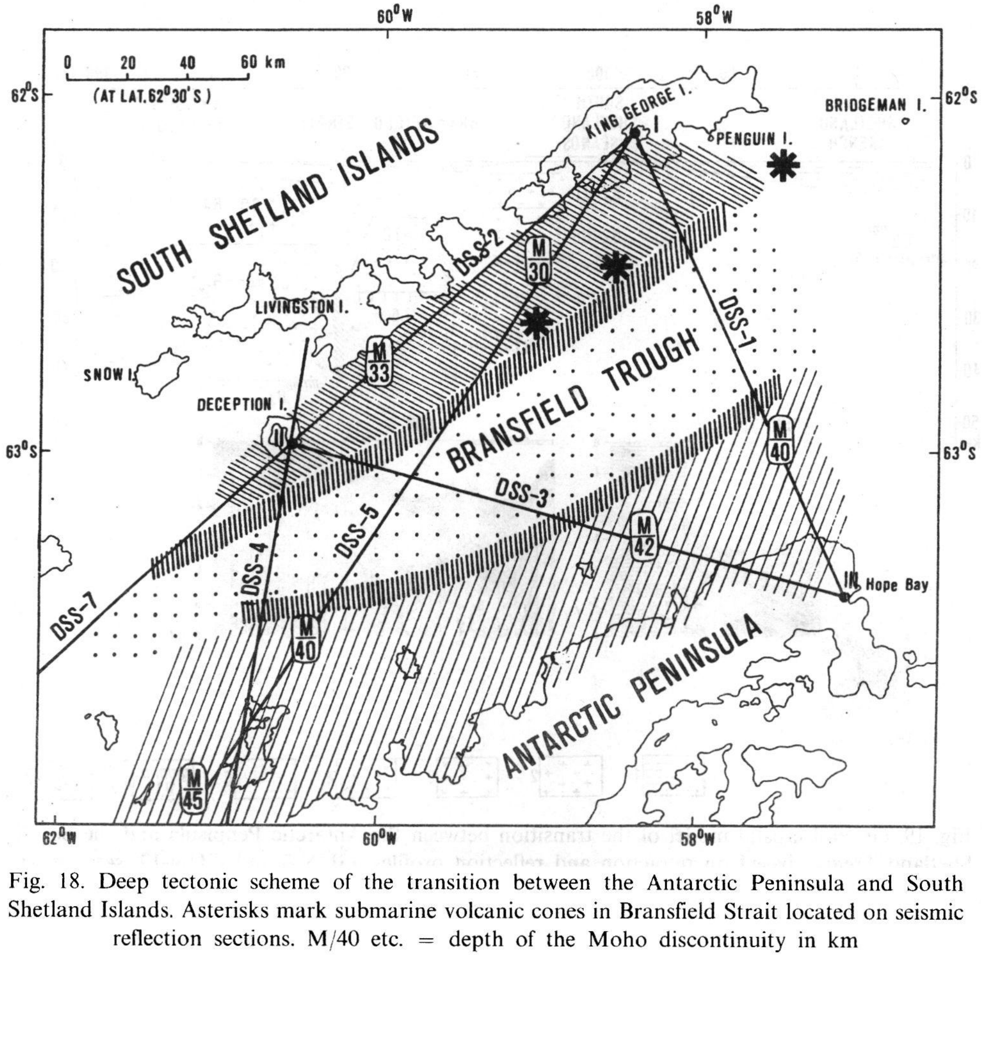

Fig. 18. Deep tectonic scheme of the transition between the Antarctic Peninsula and South Shetland Islands. Asterisks mark submarine volcanic cones in Bransfield Strait located on seismic reflection sections. M/40 etc. = depth of the Moho discontinuity in km

recorded. By contrast the seismic wave field in the area of the South Shetland Islands is poor, with no strong reflected waves and no S-waves. In general the crustal structure of the South Shetland Islands is quite distinct from that of the Antarctic Peninsula.

It is very difficult to carry out 2-D modelling of Bransfield Trough because, with the very complex tectonic structure of this region and the large distances between seismic stations recording explosions (150—180 km), the seismic data obtained are relatively poor. An example of 2-D crustal modelling (Fig. 17) shows a record section for station I on profile DSS-1, synthetic section and crustal model of Bransfield Trough.

Contact zones between crustal blocks (Fig. 16) made it possible to determine the limits of Bransfield Through which separates the Shetland block from that of the Antarctic Peninsula. The position of Bransfield Trough as determined in the lower part of the crust is shifted to the east with respect to that located by bathymetric and seismic reflection measurements (Fig. 18). The

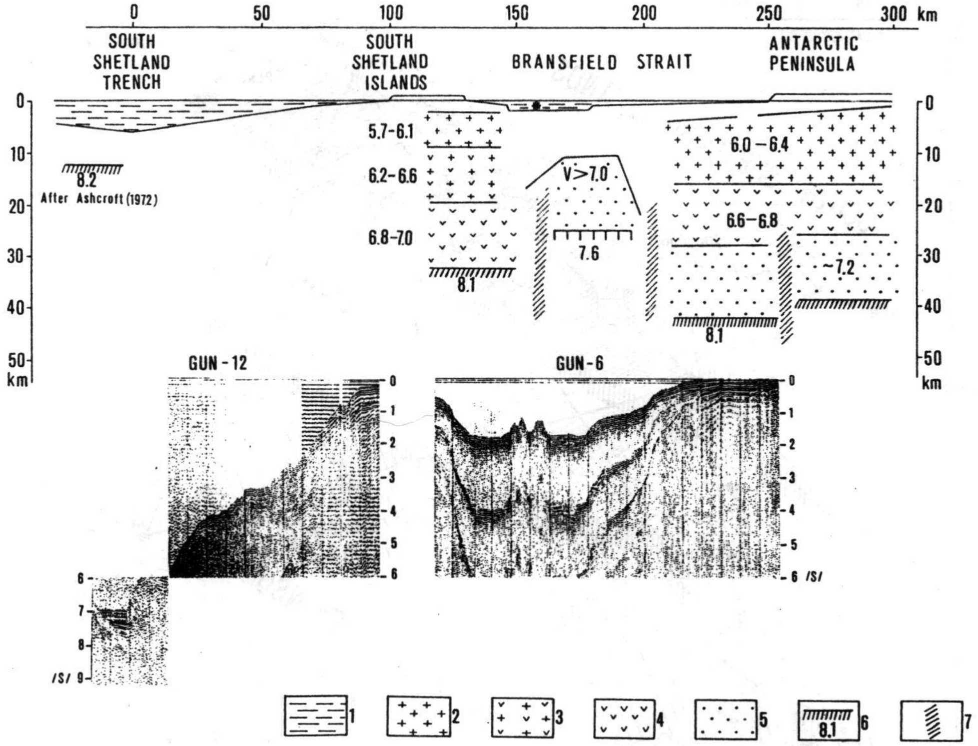

Fig. 19. General crustal model of the transition between the Antarctic Peninsula and the South Shetland Trench, based on refraction and reflection profiles (GUN-6 and GUN-12, *see* Fig. 1). 1 = sea; 2,3,4,= upper, middle, lower part of the crust, and layer velocity in km/s; 5 = high velocity crustal layer; 6 = Moho discontinuity and boundary velocity in km/s; 7 = contact zones of the crustal blocks

position of submarine volcanic cones found on seismic reflection sections in Bransfield Strait are also shown. These cones occur west of the zone of deep contact between crustal blocks in Bransfield Strait, along the line of the volcanoes Deception-Penguin-Bridgeman.

The geotectonic situation described is illustrated by the general transect model (Fig. 19) which was determined approximately for the central part of the transect from the Antarctic Peninsula, across Bransfield Strait, the South Shetland Islands to the South Shetland Trench. For construction this transect the seismic reflection profiles GUN-6 and GUN-12 were taken (Fig. 1). On profile GUN-6, we can see the outline of a volcanic cone in Bransfield Strait (*compare* Guterch *et al.* 1985). The transect clearly shows a shift in the outline of Bransfield Trough marked on seismic reflection profiles and bathymetry with respect to the deep refraction part of the section.

Seismic crustal geotraverse

When all of the seismic lines shown in Fig. 1 have been fully processed, it will be possible to construct a continuous geotraverse 1100 km long, from Elephant Island in the South Shetland Archipelago, through Bransfield Strait, the western margin of the Antarctic Peninsula in the area of Gerlache Strait, the Palmer Archipelago, Biscoe Islands, up to Adelaide Island. The following profiles lie closest to location of the geotraverse: DSS-16N, DSS-5, DSS-6, DSS-15, DSS-10 and DSS-14 (*see* Fig. 1), but data from other profiles in the area will also be used.

This study discusses the northern segment of the geotraverse, from King George Island to the Palmer Archipelago. For this segment, the main profiles are DSS-5 and DSS-6. The crustal data for these profiles were complemented by data obtained from modelling of the travel times of waves recorded by stations IV and V from shot points on profiles DSS-7 and DSS-8. The crustal modelling for the remainder of the geotraverse is not finished yet.

The travel times of refracted and reflected waves recorded on profiles DSS-5 and DSS-6, and at station IV and V from shot points on profiles DSS-7 and DSS-8, are presented in Figs. from 8 to 15 together with one dimensional crustal models. On the basis of interpretation of travel times and crustal modelling, a generalized crustal section is presented (Fig. 20). The contact zones between crustal blocks, which may be zones of deep fracture, occur mainly in the lower part of the crust. Also marked on the section are the measured boundary velocities, or the probable layer velocities estimated from 1-D modelling. The section shows that the crustal structure along the northern segment of geotraverse varies markedly. There are changes both in the thickness of the crust and the physical properties of the crustal layers. The thickness of the crust ranges from 30—33 km in the South Shetland Islands

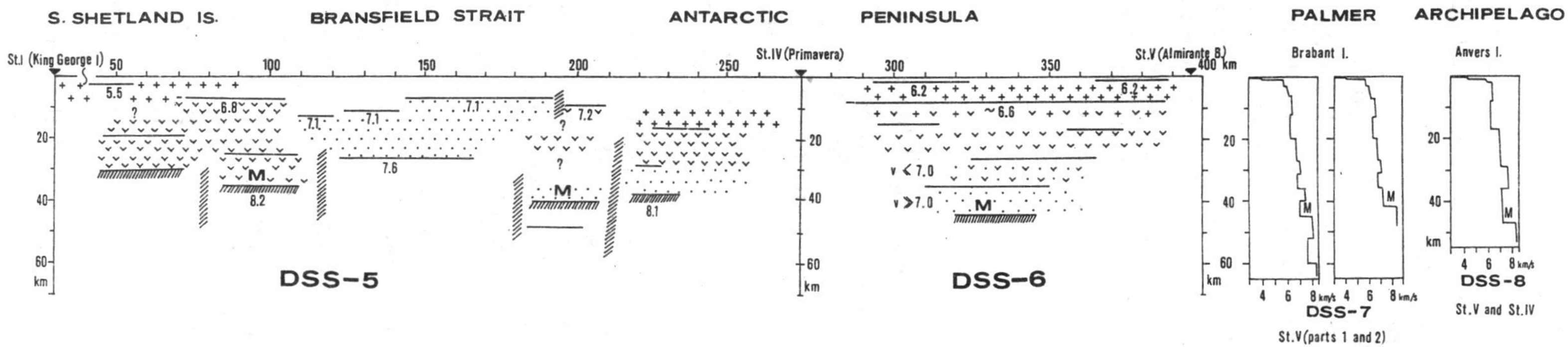

Fig. 20. Crustal section and crustal models along the first part of the proposed geotraverse between King George Island and the Palmer Archipelago The Moho (M) discontinuity is marked by a thick line; the upper middle and lower parts of the crust are marked by crosses, dashes and dots, respectively; the contact zone between crustal blocks is shown by vertical dashed lines; the boundary and layer velocities are given in km/s

area to 40—45 km on the coast of the Antarctic Peninsula, and about 45 km in the region of Anvers Island in the Palmer Archipelago.

The seismic wave field in the crust of the Antarctic Peninsula is characterized by the presence of numerous strong reflected waves. These waves are mainly related to discontinuities in the lower crust. The most effective seismic reflection boundaries usually occur at depths of 25—35 km. In the area of the Antarctic Peninsula, distinct S-waves, (both refracted and reflected) are also recorded. By contrast the seismic wave field in the area of the South Shetland Island is poor, with no strong S-waves.

The crustal structure beneath the tectonic trough of Bransfield Strait is highly anomalous, and a seismic discontinuity with velocities of 7.0—7.2 km/s was found at a depth of about 10 km. Another seismic discontinuity with velocities of about 7.6 km/s was found at a depth of 20—25 km.

In conclusion, it seems that the discussed geotraverse can play the important role of a general crustal profile connecting four transects planned within the framework of the Antarctic Geoscience Transect Project.

Discussion of results

In the light of the data presented, the thickness of the crust in the part of West Antarctica under consideration is calculated to be 30—45 km. These values are considerably higher than those of 25—30 km generally accepted until now (Ashcroft 1972, Dalziel and Elliot 1982, Barker and Dalziel 1983). According to Ashcroft the trough of Bransfield Strait resembles that of an oceanic ridge crest with a 7.6—7.7 km/s boundary at about 13—16 km below sea level. Davey (1972) used marine gravity measurements made in this area to prove the existence of a semi-oceanic crust beneath Bransfield Strait.

Greater thicknesses of the Earth's crust obtained in this experiment are confirmed by interpretation of refracted and reflected waves. Lengths of travel times are 130—220 km. In the Antarctic Peninsula region refracted waves of velocities about 8.0 km/s in first arrivals were not observed up to distances of 180—200 km. Strong waves reflected from the Moho discontinuity were recorded usually started from distance of 80—100 km. In this case seismic modelling of the wave field gives explicitly high thicknesses of the crust (30—45 km). Much shorter travel times presented by Ashcroft (1972), 40—100 km, allowed to determine mainly the structure of the upper crust. Our travel times much longer, 130—220 km, give us data to determine also the structure of the lower crust.

Conclusions

The crustal structure beneath the tectonic trough of Bransfield Strait is highly anomalous. P—wave velocities of 7.0—7.2 km/s were found at depths of 10 to 15 km below Bransfield Trough. At depths greater than 10—15 km an increase in the velocity was observed (*see* 2-D model, Fig. 17). Moreover, in the northern part of Bransfield Strait the 7.6 km/s velocity was found at a depth of about 25 km, whereas in the southern part the same velocity was found at a depth of about 20 km. This boundary becomes distinctly shallower in the area of Deception Island. It seems that the P-wave velocity close to 7.6 km/s can be interpreted as corresponding to the top of anomalous upper mantle below Bransfield Trough. Detailed 1-D modelling of the seismic wave field shows, that in the earth crust in Bransfield Strait occur zones with normal seismic velocities 6.3—6.8 km/s, and zones of high velocities 7.2—7.8 km/s. Thus, only 2-D modelling of the seismic waves field gives correct results.

The position of Bransfield Trough in the lower crust (Fig. 19) is shifted to the east with respect to that located by bathymetric and seismic reflection measurements.

On the base of all experimental seismic data, it will be possible to construct a crustal geotraverse in West Antarctica, from Elephant Island up to Adelaide Island, with a total length of about 1100 km.

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Streszczenie

Trzy Polskie Antarktyczne Ekspedycje Geodynamiczne, zorganizowane przez Instytut Geofizyki PAN, w latach 1979/80, 1984/85 i 1987/88, w ramach programów badań polarnych koordynowanych przez Polską Akademię Nauk, zrealizowały obszerny program prac sejsmicznych w sektorze Antarktyki Zachodniej, między 61° i 68° S oraz 56° i 72° W. Głębokie sondowania sejsmiczne skorupy ziemskiej oraz sejsmiczne sondowania refleksyjne wykonane zostały w rejonie Półwyspu Antarktycznego, między Cieśniną Antarctic na północy i Zatoką Margerity na południu. Pomiarami objęto Półwysep Antarktyczny, Cieśninę Bransfielda, Szetlandy Południowie do rowu oceanicznego w Cieśninie Drake, a także Archipelag Palera, Archipelag Biscoe i Wyspę Adelaidy. Łączna długość wszystkich profili sejsmicznych wynosi ponad 5000 km. Miąższość skorupy ziemskiej na badanym obszarze zmienia się od 30—32 km w rejonie Szetlandów Południowych do 38—45 km w rejonie zachodniego szelfu Półwyspu Antarktycznego oraz na obszarze Archipelagu Palmera. Struktura skorupy ziemskiej w Cieśninie Bransfielda ma cechy wybitnie anomalne. Nieciągłość sejsmiczna 7,2 km/s była zlokalizowana już na głębokości 10—12 km, a druga nieciągłość około 7,5 km/s występuje na głębokości od 20—25 km. Rów tektoniczny zlokalizowany w Cieśninie Bransfiełda o powyższych własnościach sejsmicznych jest młodą strukturą ryftową, której natura jest aktualnie przedmiotem dalszych studiów geologicznych i geofizycznych. Zlokalizowane zostały strefy głębokich rozłamów lub kontaktu bloków skorupy ziemskiej. Na podstawie interpretacji danych refrakcyjnych i reflesyjnych zlokalizowano niejednorodność sejsmiczną wzdłuż strefy występowania wulkanów: Deception-Penguin-Bridgeman. Opracowano schemat podziału geotektonicznego oraz model geodynamiczny dla obszaru między Półwyspem Antarktycznym, Cieśniną Bransfielda a Szetlandami Południowymi. Na podstawie dotychczas wykonanych badań jest przygotowywany ciągły przekrój sejsmiczny skorupy ziemskiej w Antarktyce Zachodniej od Wyspy Elephant w Archipelagu Szetlandów Południowych na północy, przez Cieśninę Bransfielda do Wyspy Adelaidy na południu. Tak skonstruowany geotrawers skorupowy o długości około 1100 km przecina szereg wielkich dyslokacji i struktur bardzo istotnych dla Antarktyki Zachodniej. Północna część geotrawersu o długości ponad 400 km jest dyskutowana w niniejszej pracy. W nawiązaniu do wcześniej wykonanych badań w Antarktyce Zachodniej stwierdzono, że skorupa ziemska w tej części Antarktyki jest skorupą o normalnych miąższościach, a nie anomalnie cienka, jak do tej pory przyjmowano w rozważaniach geodynamicznych.

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