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Lithospheric transect Antarctic Peninsula — South Shetland Islands, West Antarctica

ABSTRACT: The lithospheric transect South Shetland Islands (SSI) — Antarctic Peninsula (AP) includes: the Shetland Trench (subductional) and the adjacent portion of the SE Pacific oceanic crust; the South Shetland Microplate (younger magmatic arc superimposed on continental crust); the Bransfield Rift and Platform (younger back-arc basin); the Trinity Horst (older magmatic arc superimposed on continental crust); the Gustav Rift (Late Cenozoic) and James Ross Platform (older back-arc basin). Deep seismic sounding allowed to trace the Moho discontinuity at about 30 km under South Shetlands and at 38—42 km in the northern part of Antarctic Peninsula (Trinity Horst), under typical continental crust. Modified crust was recognized under Bransfield Strait. Geological interpretation based on deep seismic refraction and multichannel reflection soundings, and surface geological data, is presented.

Key words: West Antarctica, Antarctic Peninsula, South Shetland Islands, lithosphere structure, deep seismic soundings, plate tectonic elements, geology.

Introduction

The lithospheric transect here discussed is constructed along a NW-SE-oriented corridor between King George Island, South Shetland Islands (SSI), and Hope Bay, Antarctic Peninsula (AP), across Bransfield Strait. It continues due north-west to include the South Shetland Trench and the adjacent portion of the SE Pacific oceanic floor, and due south-east within the James Ross Platform and the adjacent portion of the Weddell Sea shelf which are separated from Antarctic Peninsula by the Gustav Rift.

The base for constructing the deep crustal section of the transect derives from explosion refraction soundings (DSS) and multichannel reflection soundings (GUN) by three successive Polish Geodynamic Expeditions of 1979/80, 1984/85 and 1987/88 (Guterch *et al.* 1985, 1987, 1990a, 1990b). The base for geological interpretation is derived from a variety of published sources, the most detailed ones pertaining to King George Island (among others, Barton 1956; Birkenmajer 1980, 1981, 1982a—c, 1983, 1984, 1987a, 1988a, 1989a; Birkenmajer and Gaździcki 1986; Birkenmajer *et al.* 1981, 1983a, b, 1985a, b, 1986a, b; Smellie *et al.* 1984; Fensterseifer *et al.* 1988; Fig. 1, Table 1). The geological structure of the Trinity Peninsula sector of Antarctic Peninsula, and

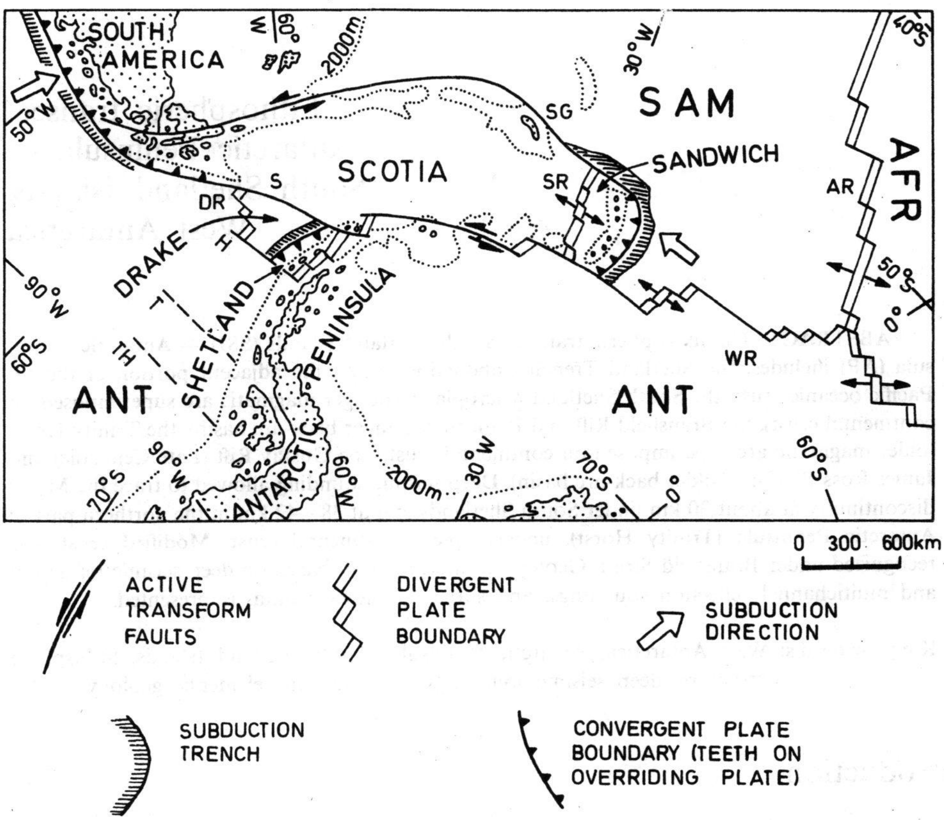
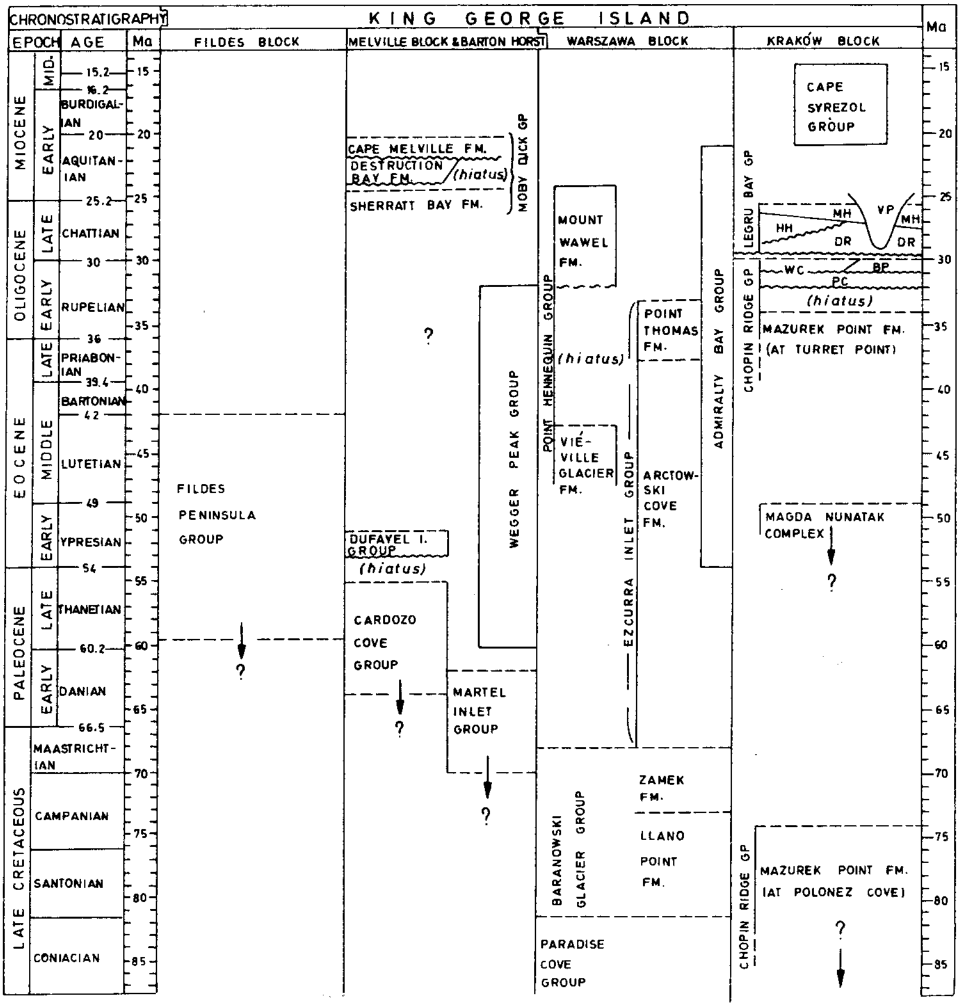


Fig. 1. Plate-tectonic elements around Scotia Sea (adapted from Tectonic Map of the Scotia Arc, 1985; Craddock *et al.* 1983; Barker 1982). **Plates**: AFR — Africa; ANT — Antarctica; SAM — South America. **Microplates**: Drake; Sandwich; Shetland. **Spreading centres** (ridges): A — Atlantic; DR — Drake; SR — Sandwich; WR — Weddell. **Transform faults**: H — Hero; S — Shackleton; T — Tula; Th — Tharp; SG — South Georgia

Table 1

Lithostratigraphy and age of Late Cretaceous through Tertiary rock complexes on King George Island (based mainly on Birkenmajer 1988a, 1989a, 1989b)



the adjacent shelf platforms of Bransfield Strait and Weddell Sea, were interpreted from geological map 1 : 500,000 of Northern Graham Land and South Shetland Islands (Fleming and Thomson 1979) and other published sources (among others: Elliot 1965, 1967; Halpern 1965; Bibby 1966; Dalziel and Elliot 1973; Thomson 1975), moreover from new data obtained during the Polish Geodynamic Expeditions (Birkenmajer 1987b, 1988b).

The geological structure of the shelf area adjoining the Shetland Trench north of King George Island, and of the Bransfield shelf platform adjoining the

Antarctic Peninsula from the north, are very poorly known. Some information is available from interpretation of reflection sounding profiles (*e.g.*, Figs. 5, 6), and aeromagnetic profiling of the area (Parra *et al.* 1984), however both sources of information, while being very valuable from structural viewpoint, supply no data as to the age of rocks.

A preliminary version of our SSI-AP lithospheric transect has been presented for discussion at the meetings of the SCAR Group of Specialists on Antarctic Lithosphere in 1988 (XX SCAR Meeting, Hobart) and 1989 (Workshop on Antarctic Geochronology, Munich; 28th International Geological Congress, Washington D.C. —*see* Birkenmajer *et al.* 1989) as part of the Group's work. The version presented now (Table 2) is an updated modification of the former one. Though by no means a final one, it nevertheless is the only one available for the SSI-AP sector for which crustal structure has been recognized based on extensive deep seismic sounding.

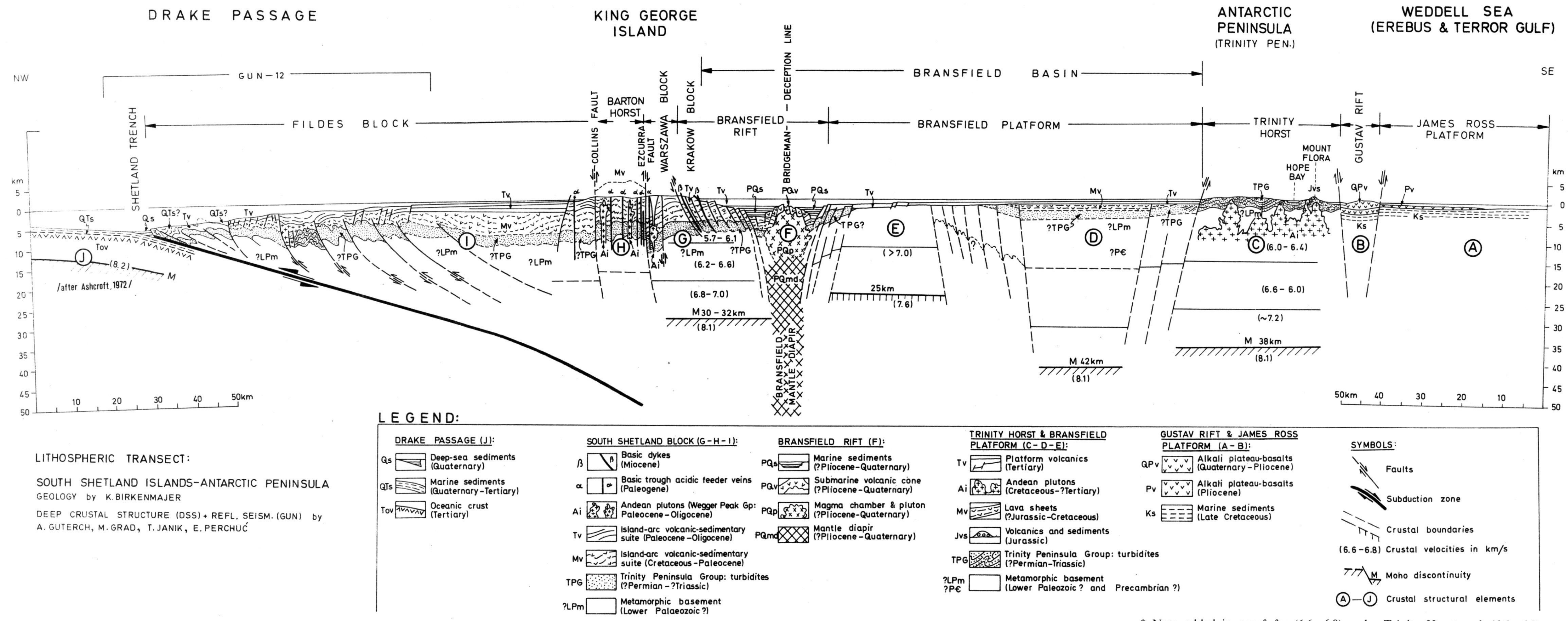
Seismic data

Seismic measurements, including multichannel seismic reflection and deep refraction seismic soundings of the crust, were carried out along numerous profiles with a total length of about 5000 km (Fig. 2). When all of the seismic lines shown in Fig. 2 have been fully processed, it will be possible to construct a continuous transect corridor from the South Shetland Trench in Drake Passage across King George Island, Bransfield Strait, Antarctic Peninsula (Hope Bay), and western part of the Weddell Sea shelf, with a total length of about 500 km. The following profiles lie near to the location of the transect corridor: DSS-17, DSS-1, DSS-2, DSS-3, GUN-1, GUN-6, and GUN-12, but data from other profiles in the area will also be used. Crustal refraction studies discussed in this paper (Fig. 3) are based on the interpretation of travel times of refracted waves as well as reflected waves from discontinuities in the middle and lower part of the crust on DSS-1 and DSS-3 profiles. The seismic wave field, crustal modelling and crustal sections in the area between the Antarctic Peninsula and the South Shetland Islands were analyzed in detail by Guterch *et al.* (1985, 1990a, 1990b).

The thickness of the crust in the area of the transect corridor varies from about 30 km in the South Shetland Islands to 38—43 km in the coastal zone of the Antarctic Peninsula. The main seismic discontinuities in the crust of the Antarctic Peninsula, with velocities 6.2, 6.8 and about 7.2 km/s, occur at the depths of 1—2, 15—18 and about 30 km, respectively. These seismic discontinuities determine boundaries of the upper, middle and lower layers of the crystalline crust. The crust of the South Shetland Islands is characterized by weak seismic stratification of its crystalline complex.

Table 2

Lithospheric transect South Shetland Islands (King George Island) — Bransfield Strait — Antarctic Peninsula (Hope Bay)



* Note added in proof: for (6.6—6.0) under Trinity Horst, red: (6.6—6.8)

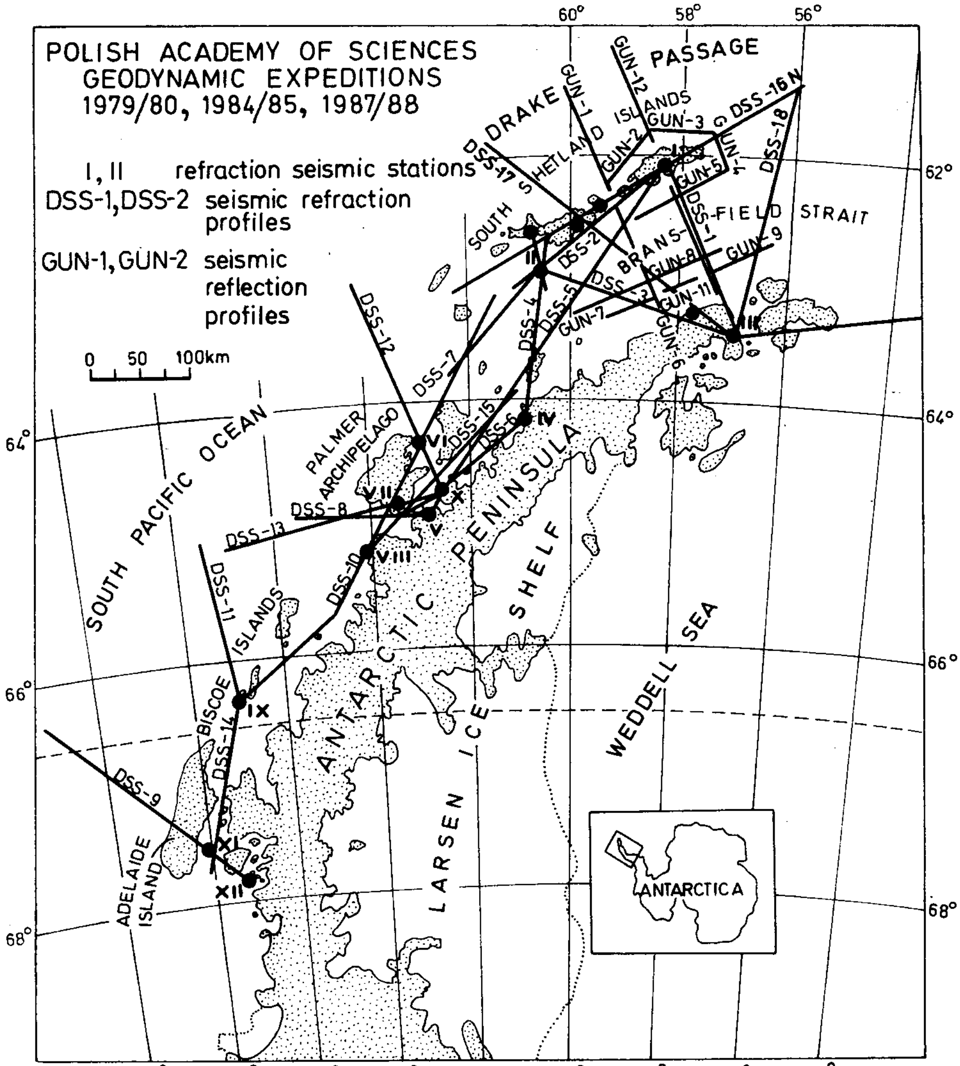


Fig. 2. Location of deep seismic refraction (DSS) and reflection (GUN) profiles by the Polish Geodynamic Expeditions of 1979—1988, in the Antarctic Peninsula sector

The thickness of the crust in the area of the transect corridor is greater than estimated by Ashcroft (1972). Travel times 40—100 km long presented by Ashcroft allowed him to determine mainly the structure of the upper crust. Our travel times much longer, 130—220 km, give us data to determine the structure of the lower crust.

The crustal structure beneath Bransfield Strait is highly anomalous; a seismic discontinuity with velocities of 7.0—7.2 km/s was found at a depth of

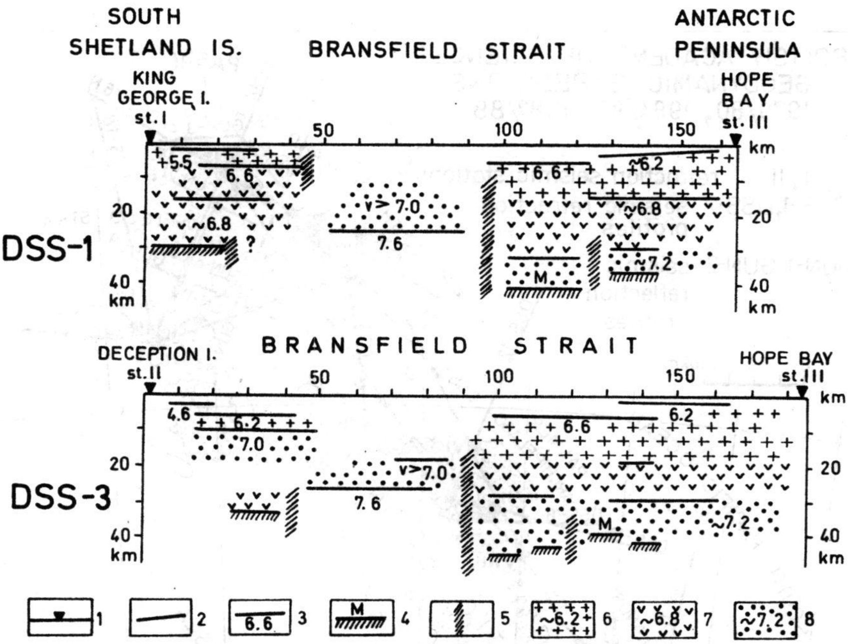
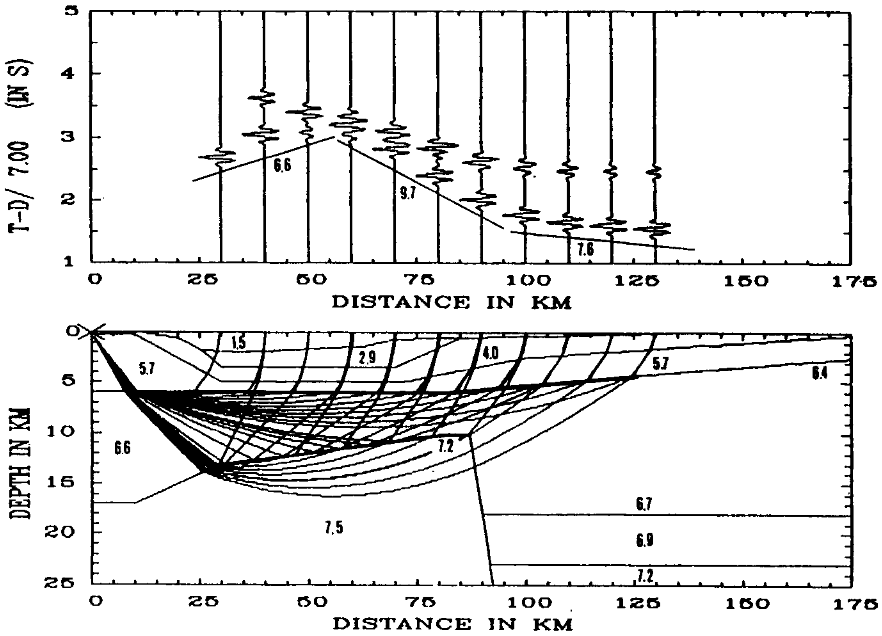


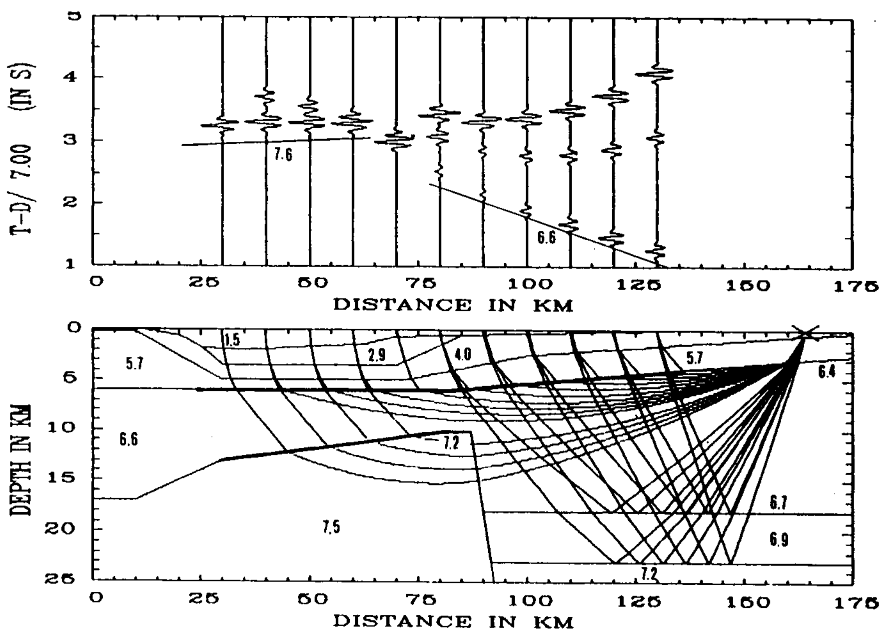
Fig. 3. Crustal model sections of the transition between the Antarctic Peninsula and South Shetland Islands along DSS-1 and DSS-3 profiles (*see* Fig. 2)
1 = position of refraction stations; 2 = reflection discontinuities; 3 = refraction discontinuities and boundary velocities in km/s; 4 = Moho discontinuity; 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

about 10—12 km. Two-dimensional model of this discontinuity is shown (Fig. 4). At depths greater than 10—12 km, an increase of the velocity was observed. Moreover, in the northern and deepest part of the Bransfield Strait (Bransfield Trough), the 7.6 km/s velocity was found at a depth of about 25 km. This boundary becomes distinctly shallower in the area of Deception Island. The P-wave velocity close to 7.6 km/s may be interpreted as corresponding to the top of an anomalous upper mantle below the Bransfield Trough and Platform.

The contact zones between crustal blocks, marked in the transect (Table 2), which may correspond to zones of deep fractures, were determined on the basis of very specific properties of seismic wave fields, strong attenuation of seismic waves, and discordances between depths of recognized seismic boundaries. The crustal structure of the South Shetland Islands is, in general, distinctly different from that of the Antarctic Peninsula. There are changes both in the thickness of the crust and the physical properties of the crustal layers. The seismic wave field in the AP crust is characterized by the presence of numerous strong reflected P and S waves. On the contrary, the seismic wave field in the SSI area is rather poor, without S waves.



West Antarctica DSS-1 ST.I (King George I.)



West Antarctica DSS-1 ST.III (Hope Bay)

Fig. 4. Two-dimensional model of the 7.2 km/s discontinuity in the Bransfield Trough along DSS-1 profile (*see* Fig. 2)

Geological interpretation

Nine major structural elements (A—J) have been distinguished along the SSI-AP transect (Birkenmajer *et al.* 1989; Table 2).

(A) James Ross Platform

The James Ross Platform consists of Late Miocene to Pliocene alkali plateau basalts which cap Early Tertiary and Late Mesozoic predominantly marine strata of the Larsen-Marambio-James Ross basins (*see* Bibby 1966; Fleming and Thomson 1979; also unpublished seismic refraction data from the Marambio-Larsen Basin, by M. A. Keller). Our interpretation is temporarily restricted to the upper part of the crustal section only (Table 2), as geophysical modelling of the structure of the earth crust under James Ross Platform, based on our deep seismic soundings, has not yet been finished.

(B) Gustav Rift

This is a Late Cenozoic rift structure filled with Quaternary to Pliocene alkaline basaltic volcanics (Fleming and Thomson 1979; González-Ferrán 1983, 1985, Parra *et al.* 1984) which probably overlie Neogene volcanics and Mesozoic sediments of the same type as those in the James Ross Platform (A). The Gustav Rift, itself a downthrown inner part of the James Ross Platform, is juxtaposed against the Trinity Horst; Jurassic sediments and associated volcanics trace the northern margin of the graben.

(C) Trinity Horst

The Trinity Horst exposes mainly folded clastic marine turbidites of the Trinity Peninsula Group (?Carboniferous through Triassic), at least 1—2 km thick (TPG — Table 2). Unconformably upon TPG come terrestrial plant-bearing clastics (Mid- through ?Upper Jurassic). Both units are crossed by uncommon acidic dykes and sills, apparently feeder veins for the capping acidic lavas, agglomerates and ignimbrites (?Lower Cretaceous) belonging to the basal part of the Antarctic Peninsula Volcanic Group (APVG). All the units, but principally the TPG sediments, are intruded by moderate- to large-scale gabbroic through granitoid plutons of the Andean intrusive suite (AIS) and associated basic dykes, being the evidence for an older, Late Mesozoic (Jurassic — Cretaceous) magmatic arc. Radiometric dating indicates a northward migration of plutonic centres which are Mid-Jurassic to Early Cretaceous in age in the southern, and Late Jurassic to Late Cretaceous in age in the northern part of Trinity Peninsula (*see e.g.*, Elliot 1965, 1967; Dalziel and

Elliot 1973; Fleming and Thomson 1979; Pankhurst and Smellie 1983; Birkenmajer 1988b).

Taking into account that the Trinity Peninsula Group represents either an Early Mesozoic (Triassic) or Late Palaeozoic-Early Mesozoic (?Permo-Triassic) sediment, and that the continental crust under the Trinity Horst is some 38 km thick (Table 2), we may expect an Early Palaeozoic to Precambrian basement to be present below the TPG. There is no geophysical evidence for the presence of any basic oceanic-crust type basement below the TPG. In view of that, the substratum of the TPG from 1—2 to 15 km below the surface, has been interpreted as metamorphic rocks (Lower Palaeozoic and ?Late Precambrian) considerably granitized and intruded by discordant Andean plutons AIS (Table 2).

(D—E) Bransfield Platform

This unit includes two structurally different blocks situated between the Trinity Horst and the Bransfield Rift which have a common cover of platform-type volcanics and sediments of Tertiary age, probably less than 1 km thick. The Tertiary volcanics crop out at Tower Island (Paleocene and Eocene radiometric dates, 64—55 Ma — Fleming and Thomson 1979), Astrolabe Island, Montravel Rock and Gourdon Islands in shelf area north of Trinity Peninsula; horizontally stratified, probably Tertiary (and Quaternary) rocks are recognizable on seismic reflection profiles.

The southern of the two blocks (D) has a considerable thickness of the crust: the Moho discontinuity drops there down to 42 km. This represents a 4 km downthrow with respect to the Trinity Horst (with Moho at 38 km — *see* Table 2). The (D) block is likewise a graben with respect to both the Trinity Horst (C) and the (E) block. It may have a sedimentary cover of TPG overlain by Mesozoic (probably mainly Cretaceous) volcanics (APVG), altogether 3—3.5 km thick.

Our interpretation (Table 2) suggests that the graben structure pre-dates the Tertiary platform-type volcanics; it could date back to a mid-Cretaceous deformation phase as recognized in the Danco Coast — Gerlache Strait area further south-west (Birkenmajer 1987b, 1988b).

The northern block (E) is a geological puzzle. It consists of a modified crust in which two crustal layers are distinguishable, at about 12 km and 25 km, corresponding to the velocities of 7.0 and 7.6 km/s respectively. The Moho discontinuity (with velocities of 8.1 km/s) has not been recognized there. Compared with crustal layers of the Trinity Horst, it seems that only lower and middle layers are here present, while the upper one (granitic, with maximum velocities of 6.0—6.4 km/s) is missing. In our transect the discussed block is shown as a horst with respect to the southern one (D), its basic crustal layer being elevated almost to the surface and covered directly by Tertiary platform volcanics (Table 2: Tv).

There seems to be a coincidence between seismic refraction data which show anomalous basic crust in shallow depth within the discussed (E) block (Fig. 3; Table 2), and linear magnetic high anomaly recorded from the outer marginal zone of the Bransfield Platform, and attributed by Parra *et al.* (1984) to the effect of basic intrusive rocks.

Our interpretation of the transect suggests that the (D) and (E) blocks were faulted together before the onset of Early Tertiary volcanism, probably during either mid-Cretaceous or Late Cretaceous deformation phases. The northern flank of the Bransfield Platform is involved in a series of step faults generally downthrowing to the north, towards the Bransfield Rift; such faults are recognizable on reflection seismic profiles (particularly those presented at the Group of Specialists' meetings by Brazilian geologists L. F. Gamboa and R. Trouw) in Tertiary cover of (E) block.

(F) Bransfield Rift

This is a Late Cenozoic tensional structure about 40 km wide near King George Island (Table 2) which separates the Bransfield Platform from the South Shetland Microplate. The central part of the rift graben, only 15—20 km wide, coincides with a line of mildly alkaline to calc-alkaline subaerial and submarine volcanoes (Deception — Bridgeman Line), of which the Deception Island caldera is still active. A subparallel volcanic line links Penguin Island (dormant volcano) and Melville Peak (extinct) situated on the southern margin of the South Shetland crustal block (on King George Island — Fig. 5). Submarine trough 1000—2000 m deep is filled with horizontal strata of considerable thickness, probably mainly tephra and glacio-marine sediment, ?Pliocene and Quaternary in age, which bifurcate to form symmetrically arranged basins along sides of submarine volcanoes (Table 2).

The Quaternary volcanoes produce three distinct volcanic suites: alkaline and calc-alkaline suites occur on the volcanic islands of Penguin, Deception and Bridgeman, and on Melville Peak, while the seamounts are composed of tholeiites (González-Ferrán and Katsui 1970; Weaver *et al.* 1979; Fisk *in press;* Birkenmajer and Keller *in press*).

The Bransfield Rift (F) together with the Bransfield Platform (D—E) represent a back-arc basin with respect to Cenozoic SSI volcanic arc. Its initiation dates back to Late Oligocene-Early Miocene times, as evidenced by a system of rift-parallel antithetic faults along the outer margin of the rift. These faults displace Late Oligocene and older rocks of King George Island, and had been used by basaltic dykes K-Ar-dated at 21—20 Ma (Birkenmajer *et al.* 1985a, 1986a; Birkenmajer 1989a,b).

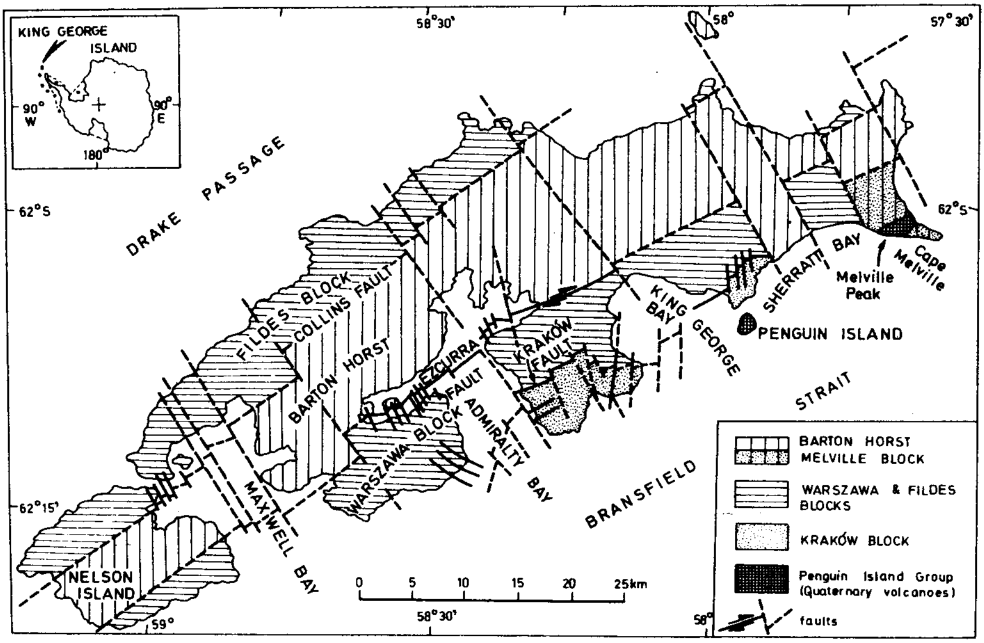


Fig. 5. Tectonic structure of King George Island, South Shetland Islands (*after* Birkenmajer 1983)

(G—I) South Shetland Platform

The South Shetland Platform or microplate represents a crustal wedge (overriding plate) bounded on the south by the Bransfield Rift (F) and on the north by the Shetland Trench (J). The structure of the platform is known in considerable detail only in its southern part (Table 2: G—H), represented in our transect corridor by several tectonic blocks exposed on King George Island (Birkenmajer 1983, 1989a). The structure of the northern part of the crustal wedge is very poorly known, mainly from seismic reflections studies (*cf.* Fig. 6).

The southern Kraków and Warszawa blocks (G) expose gently folded subduction-related calc-alkaline, mainly terrestrial volcanic-sedimentary complex about 3 km thick, of Late Cretaceous (> 77 Ma) through Late Oligocene — Early Miocene ages, with subordinate marine and continental tillite horizons of Eocene, Oligocene and Lower Miocene ages (Table 1). The substratum of the volcanics is unknown; it may be represented by the TPG clastics which are known to occur on Livingston Island west of King George Island (*e.g.*, Dalziel 1972; Fleming and Thomson 1979). Three crustal layers have been distinguished based on deep refraction seismic studies (Fig. 3;

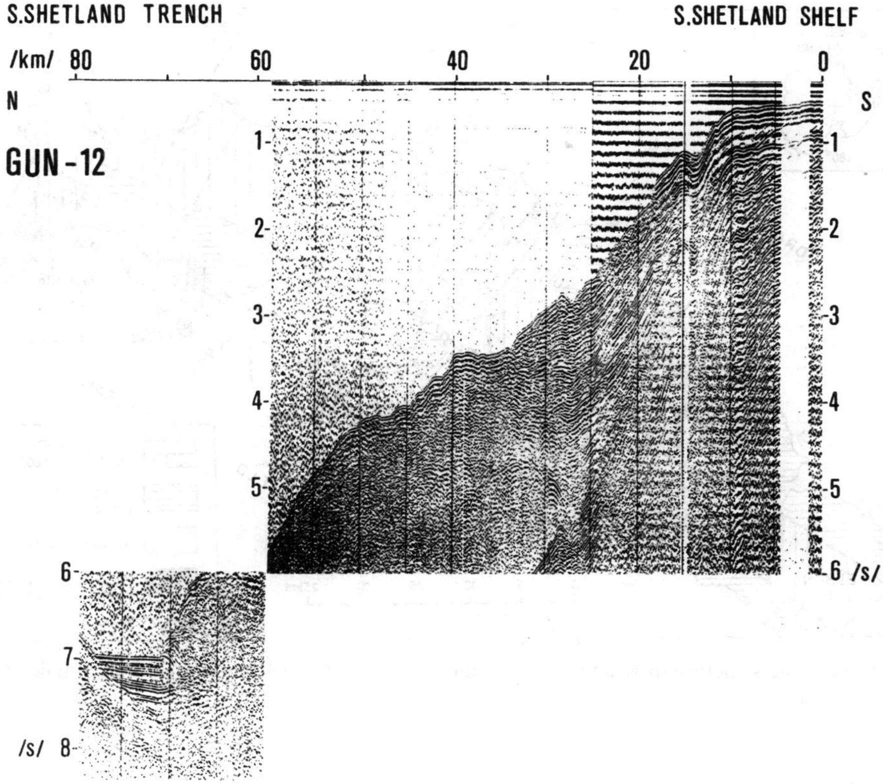


Fig. 6. Seismic reflection profile across South Shetland Trench/Drake Passage (GUN-12 — *see* Fig. 2)

Table 2), with velocities 5.7—6.1, 6.2—6.6. and 6.8—7.1 km/s. The Moho discontinuity with velocity 8.1 km/s occurs at the depth of 30—32 km.

The Kraków Block is involved in extensional antithetic fault system of the Bransfield Rift and is separated by a normal fault from the upthrown Warszawa Block in the north. Both blocks are downthrown with respect to the axial Barton Horst which is bounded from the south against Warszawa Block, and from the north against Fildes Block, by strike-slip faults older than the Bransfield Rift (Birkenmajer 1983, 1989a; *see* Fig. 5).

The Barton Horst exposes folded and altered calc-alkaline subductional volcanic-sedimentary complex, the Martel Inlet (terrestrial) and Cardozo Cove (terrestrial and shallow-marine) groups, for a long time considered to represent a pre-Tertiary rock succession (*e.g.*, Barton 1965; Birkenmajer 1982b; Birkenmajer *et al.* 1985b). K-Ar dating of its lavas proved to be inconclusive, with the oldest dates apparently indicating a lower part of Palaeogene or Palaeogene—Cretaceous boundary for the Martel Inlet Group. The Rb-Sr dating indicates a Paleocene age for the Cardozo Group (Birkenmajer *et al.* 1983a, 1986b; Soliani and Kawashita 1986; Kawashita and Soliani 1988; Birkenmajer 1989b; Table 1).

The Martel Inlet and Cardozo Cove groups are intruded by moderate-size gabbroic to granitic plutons of the Wegger Peak Group (Table 2: Ai) which range in K-Ar ages from Paleocene through Early Oligocene. They are equivalent to, but generally younger than, the Andean Intrusive Suite (AIS) of the Trinity Peninsula Horst, the latter representing a Jurassic-Cretaceous stage of arc magmatism.

The youngest element in the Barton Horst is represented by the Moby Dick Group volcanics and marine and glacio-marine sediments of Lower Miocene age (Birkenmajer 1984, 1987a). They are crossed by hypabyssal andesite and basalt dykes K-Ar-dated at 20 Ma (Birkenmajer *et al.* 1985a). The base of the Martel Inlet and Cardozo Cove groups is unknown: it probably consists of folded and considerably granitized TPG clastics.

The Fildes Block (I), downthrown with respect to the Barton Horst, consists again of subduction-related terrestrial complex of Paleocene-Eocene volcanics and sediments (Smellie *et al.* 1984; Fensterseifer *et al.* 1988; Soliani *et al.* 1988), equivalent to the Palaeogene part of the Warszawa Block suite (Table 1). The substratum of the Fildes Peninsula Group is unknown. It could still be represented by the TPG rocks, however the appearance of a magnetic high anomaly which parallels the South Shetland Islands along their northern shelf margin (Parra *et al.* 1984) may suggest that basic basement rocks corresponding to intermediate crustal layer raise here considerably close to the surface.

Small Tertiary hypabyssal dykes, plugs, sometimes also sills cut through the Fildes as well as Barton and Warszawa blocks. Many of these intrusions have been recognized as feeder veins for the Tertiary lava complex.

The structure of the northern part of the Fildes Block is almost unknown. There are no rock exposures above sea level in a 100-km wide shelf platform between King George Island and Shetland Trench, the refraction seismic studies did not as yet supply suitable information, and only the reflection seismic profiles give some insight into the structure of the shelf and its outer margin (Fig. 6). It seems that the upper portion of the shelf platform is here formed of Tertiary platform-type volcanics (Table 2: Tv) and sediments which, together with their substratum (Mv), are involved in tensional-type normal faulting. Late Tertiary to Quaternary sediments (QTs) are folded and thrust on approaching subductional Shetland Trench (Fig. 6; Table 2).

It was not possible at this stage of investigations to determine to what extent the normal continental-type substratum of the Tertiary to Late Mesozoic volcanics (Tv and Mv), underlain by the TPG clastic wedge and matamorphic-granitic basement, continues above subduction zone toward the trench, and to what extent oceanic crust is involved in accretion thrust folds (Table 2). In our present interpretation, we decided to give more credit to a concept of strongly attenuated continental crust wedge rather than to speculate on the structure of leading edge of the overriding continental plate involving oceanic crust.

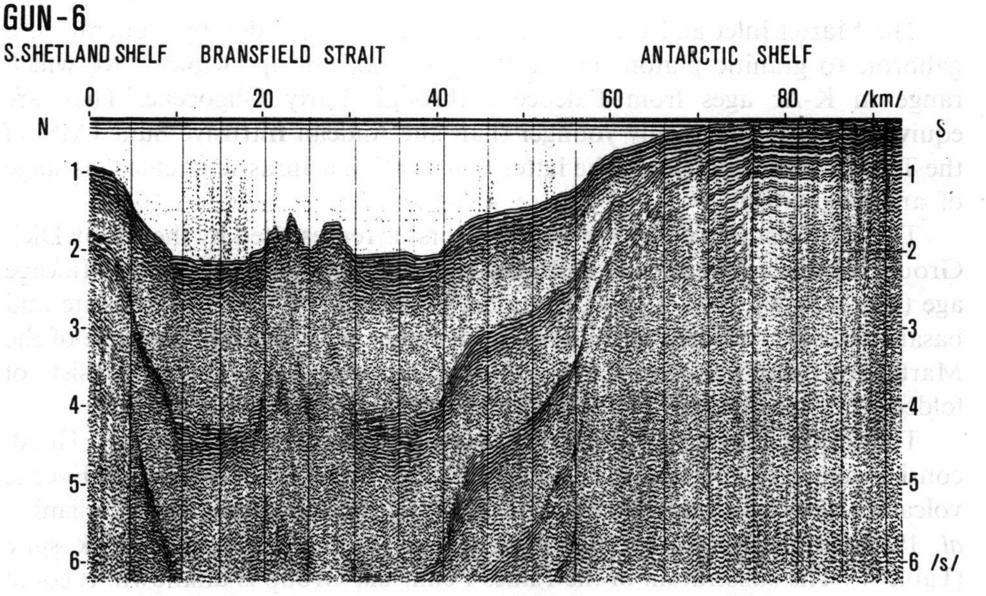


Fig. 7. Seismic reflection profile across South Shetland Trench/Drake Passage (GUN-12 — *see* Fig. 2)

(J) South Shetland Trench

The South Shetland Trench, some 5 km deep, is filled with undisturbed Late Cenozoic (Quaternary and ?Pliocene) sediments plunging down under the leading edge of the SSI crustal wedge. This is well seen on reflection seismic profiles (Fig. 6). The subduction surface dips gently at about 25—30 degrees under the South Shetland Microplate. The Pacific oceanic crust and its late Cenozoic sedimentary cover are well recognizable at outer margin of the trench.

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Streszczenie

Transekt litosferyczny dyskutowany w tej pracy jest zlokalizowany w Antarktyce Zachodniej, w przybliżeniu wzdłuż „korytarza", od rowu oceanicznego Szetlandów Południowych, przez Wyspę Króla Jerzego w Archipelagu Szetlandów Południowych, Cieśninę Bransfielda, Półwysep Antarktyczny w rejonie Zatoki Nadziei z zakończeniem na zachodnim Szelfie Morza Weddella (fig. 1). Podstawą konstrukcji transektu są wyniki refrakcyjnych sondowań sejsmicznych skorupy ziemskiej wzdłuż profili przedstawionych na fig. 2. Wyniki modelowania sejsmicznego głębokiej struktury skorupy dla dyskutowanego transektu litosferycznego zostały przedstawione na fig. 3—4. Uzupełniają je dane z sejsmicznego profilowania refleksyjnego przedstawione przykładowo (fig. 6).

Interpretację geologiczną transektu oparto na wynikach badań prezentowanych w cytowanych publikacjach, ze szczególnym uwzględnieniem danych dotyczących Wyspy Króla Jerzego (tab. 1 i fig. 5). Kompleksowa interpretacja wszystkich danych geofizycznych i geologicznych, dotąd opracowanych i publikowanych, pozwoliła na konstrukcję głównej części transektu, którego całkowita długość wynosi ponad 500 km (tab. 2). Dalsze prace zmierzające do pełnego przedstawienia przekroju litosferycznego w tej części Antarktyki Zachodniej są kontynuowane.