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Preliminary results of seismic reflection investigations and associated geophysical studies in the area of the Antarctic Peninsula

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Abstract: A geophysical data set including some 1400 km of reflection seismic profiles and 17000 km of gravity lines was recorded in the waters north-west of the Antarctic Peninsula during the austral spring cruise of *RV Polarstern* (October to December 1987). These data form a contribution to the earlier and continuing studies dealing with the tectonics of Bransfield Strait, the structure of the South Shetland Trench, and the segmentation of the adjacent oceanic crust. The seismic profiles and gravity data illustrate among other features the differential extension of Bransfield Strait and the structure and morphology of the former converging plate boundary, which vary corresponding to the time of the last ridge trench collision. Observations have been made about the active character of several oceanic fracture zones in time which meet the former plate boundary.

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Introduction

The Antarctic Peninsula stretches far across the Antarctic Circle towards South America. Its curved shape and its magmatic history, bearing similarities with those of the southern part of South America, have long been taken as evidence of a former continuity, interrupted by the opening of Drake Passage during the process of break-up of Pangea (Elliot 1985, Gonzáles-Ferrán 1985). The Cenozoic tectonic development of the area north-west of the Antarctic Peninsula (AP) however is rather complicated and deviates considerably from that west of the South American margin (Storey *et al*., 1987).

The main structural elements immediately north-west of the northern part of the AP are:

1. Bransfield Strait: an extensional basin with back arc development, bordered by the South Shetland Islands (SSI) (British Antarctic Survey 1985).
2. The South Shetland Trench (SST), north-west of the SSI, where oceanic plate segments of different ages have been subducted (Herron & Tucholke 1976).
3. The oceanic crust north-west of the SST, characterized by a number of fracture zones (FZ).

The location of these structural entities in the study area and the position of the reflection lines are shown on Fig. 1.

Understanding the structure and tectonic development of this area was a main objective of the studies of the Geophysical Research Group for the Antarctic Peninsula (GRAPE) during cruise ANT-VI/2 of *RV Polarstern* (Alfred-Wegener-Institute, Bremerhaven). From 15 October to 20 December 1987, a geophysical data set was acquired, including some 1400 km of seismic reflection profiles, more than 17000 km of gravity lines, some refraction experiments (combined on- and offshore), magnetic profiles, continuous 3.5 kHz echo soundings and SEABEAM mapping. The seismic source was an airgun array with four to six guns of 9 litres each. The reflection data were acquired with a 24 channel streamer which has an active section of 600 m, and were recorded with an EG & G Geometrics recording system, operated by members of the University of Ghent, Belgium. Gravity recording was made with two "Askania" sea gravimeters (GSS 3.1 and GSS 3.55) loaned by the German Hydrographic Institute in Hamburg.

Processing of the seismic reflection data was performed in Bremerhaven and Kiel and included stacking and filtering. The stacked sections displayed in this paper were generated on the Micro-VAX SSL System of Kiel University. In the process of geometrical corrections every two consecutive

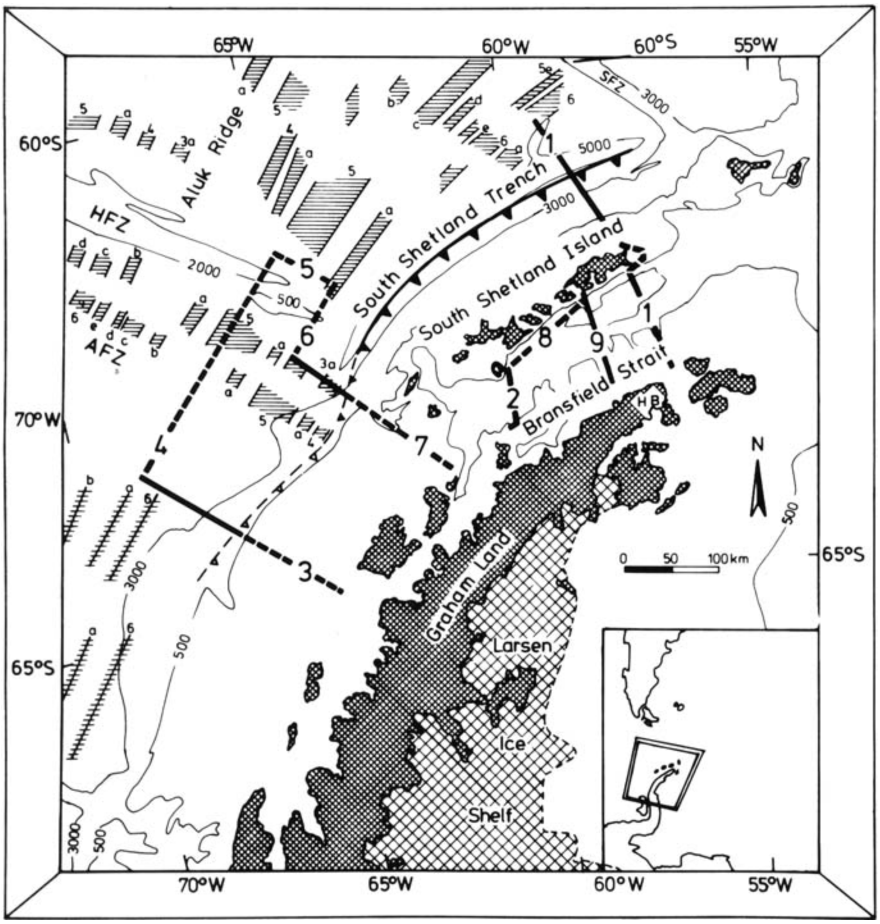


Fig. 1. Location map of the survey area showing seismic reflection lines (thick lines 1–9) and marine magnetic anomalies after Barker & Dalziel, 1983.
HB: Hope Bay,
SFZ: Shackleton fracture zone,
HFZ: Hero fracture zone,
AFZ: Anvers fracture zone.

CDP gathers were stacked in order to achieve a 12-fold coverage. Deconvolution and migration have up to now only been applied on part of the data.

An example of a 12-fold, 24 channel stack and of the corresponding single channel display is shown in Fig. 2. Whereas details in the upper sedimentary sequence are better resolved in the single channel display, the deeper part of the sediments and the response of the oceanic basement are better defined in the stacked section. The improvement of the definition of deeper structures by stacking is especially obvious in trench areas, as will be shown in later examples.

The final processing of the data has not been completed yet. The gravity values used are those read from the continuous records of the GSS 3.55 gravimeter. The gravity curves displayed as relative values in this paper have been properly corrected (Lattitude and Eötvös). Free air and Bouguer anomaly maps including the new data are in preparation.

Bransfield Strait

Previous geophysical observations, mainly carried out with refraction seismic and gravity methods (Ashcroft 1972, Guterch *et al.* 1985, Blankenship & Bentley 1987), and geochemical and tectonic studies (Doake 1987, Garrett & Storey 1987) have shown that Bransfield Strait is an area of very recent extension and possible spreading, at least in its north-eastern part (Fig. 1).

Three seismic reflection profiles were shot across Bransfield Strait: profile 2 in the south-west, profile 9 in the central part and profile 1 in the north-east. Fig. 3a shows a line drawing of these three lines, whereas Figs. 3b, 3c & 3d display the corresponding stacked sections and free air gravity anomaly.

Profile 2 (Fig. 3b, 3a bottom) in the south-western part of Bransfield Strait shows a purely continental structure with an extensional horst-graben character. Most reflections in the uppermost 1 s TWT (about 1 km) below the sea floor seem to come from relatively older sediments, building up the continental margin in this area. Reflections at later times are overprinted by the first sea bottom multiple. The central part of the profile shows a rift basin (I on Fig. 3a bottom), about 5 km wide, with a sediment infill of about 700 m (0.7 s TWT). There are no clear signs of spreading (or oceanization). The reflection pattern in the southern part of the profile (towards the Peninsula) looks less disturbed than the section closer to Deception Island, where the crustal structure may be influenced by the magmatic activity around the island. The free air anomaly (FAA), plotted on top of the

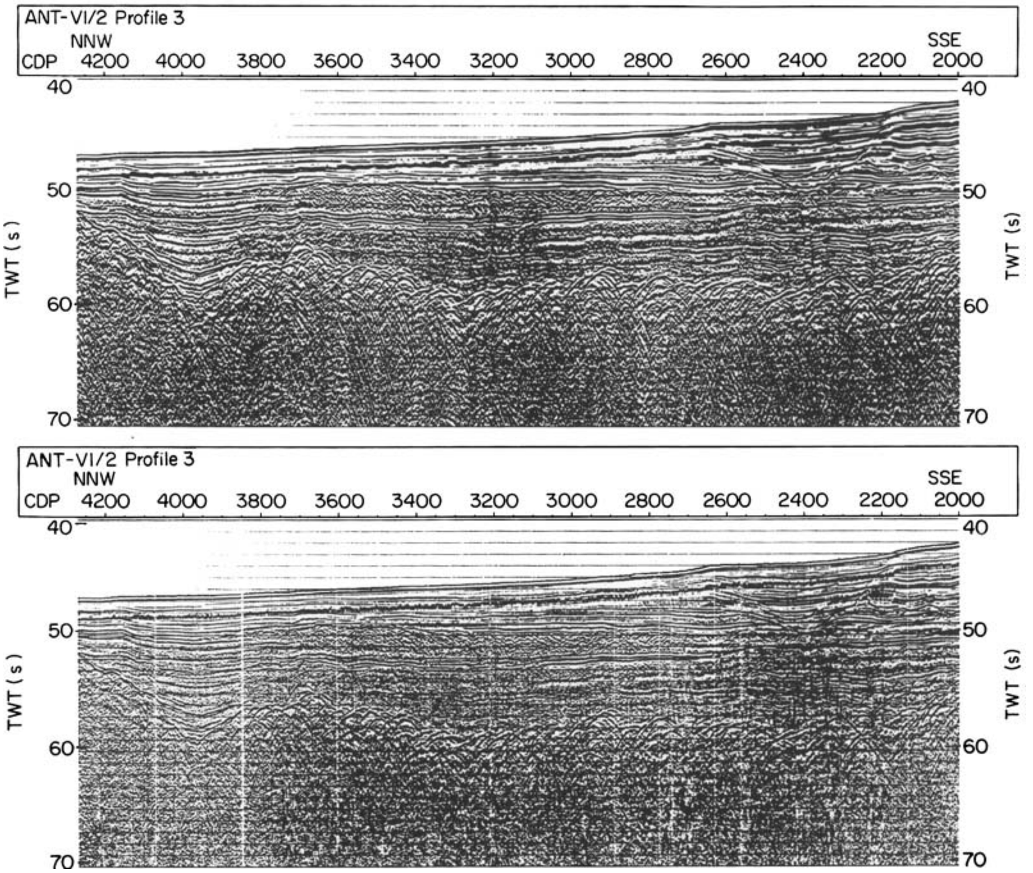


Fig. 2. Example of the processing of single channel (lower half) and a 24 channel stacked section along profile 3. (upper part). Note the excellent resolution of the single channel display and the better penetration of the stacked section.

stacked section, shows a rather smooth shape with a regional (long wavelength) rise on both sides of the profile.

The axial zone of Bransfield Strait as shown on profile 9 (Fig. 3c, 3a middle) has a totally different character to that on profile 2. The central part of the profile, in water depths of about 1500 m (2 s TWT), displays a well-pronounced trough (I & III on Fig. 3a middle), partly filled with some 800–1000 m of highly reflecting, young sediments. The underlying basement has an oceanic character, with dense diffraction patterns (II on Fig. 3a middle). A striking feature is the disturbed character of the northern part of the sediment infill (III on Fig. 3a middle), with numerous diffraction hyperbolae, possibly arguing for the presence of magmatic intrusions. The boundary between the disturbed sediments and the undisturbed strata is almost centrally located in the trough. The relatively young, undisturbed sediments in the southern half (I on Fig. 3a middle) of the basin display a diverging reflection pattern, dipping towards the axis of the rift structure. This might indicate a gentle, rotational subsidence process, generally observed during spreading (Meissner 1981). The subsided area is also associated with a broad minimum in the FAA profile. The northern part of profile 9 shows a 25 km wide mound or ridge-like structure (IV on Fig. 3a middle), rising some 900 m above the basin floor. It is separated from the southern tip of King George Island by a small depression. There is no evidence of reflections below the ridge structure.

Profile 1 (Fig. 3a top), shot in the north-eastern part of Bransfield Strait, also shows an axial sedimentary basin (1 on Fig. 3a top) which is, however, narrower than on profile 9. The sea floor is also deeper (2000 m) and the sediment thickness in the axial basin is less than on profile 9 (some 300–400 m). Again this basin is bordered to the north by an asymmetric ridge-like structure (III on Fig. 3a top), rising some 450 m above the sea floor. Diffraction events (II on Fig. 3a top) are particularly pronounced on this profile and might extend well below the sediments prograding from the slope, in the southern part of the profile. The dip of the sediments in this slope wedge reflects continuing subsidence.

South Shetland Trench

According to the magnetic anomaly pattern, which can be detected discontinuously below the young sedimentary cover, the oceanic crust between the Tula FZ (in the far south-west, not shown on Fig. 1) and the Shackleton FZ is characterized by many parallel fracture zones (Herron & Tucholke, 1976, Groushinsky *et al.* 1982, British Antarctic Survey 1985).

Successive collisions of segments of the Aluk spreading ridge and the continental margin occurred south of the Hero FZ from 5.0 to 5.5 m.y. ago (Barker 1982). After the last ridge-trench collision, apparently no further convergence

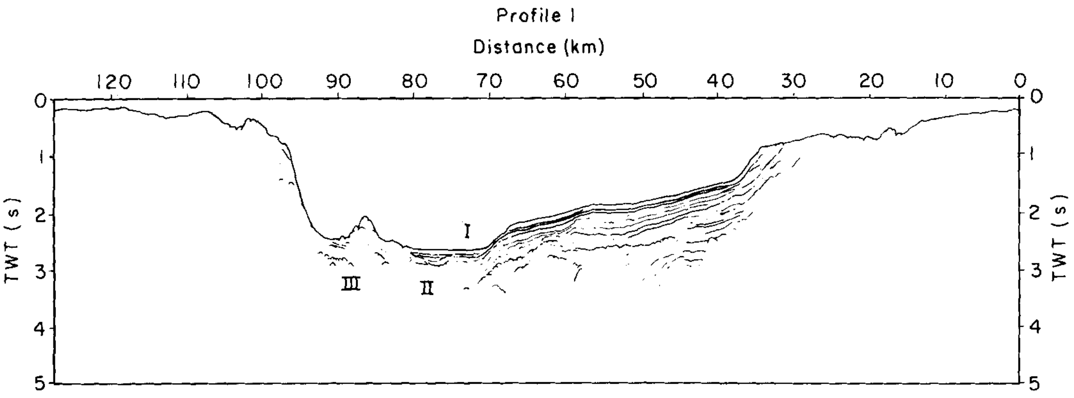
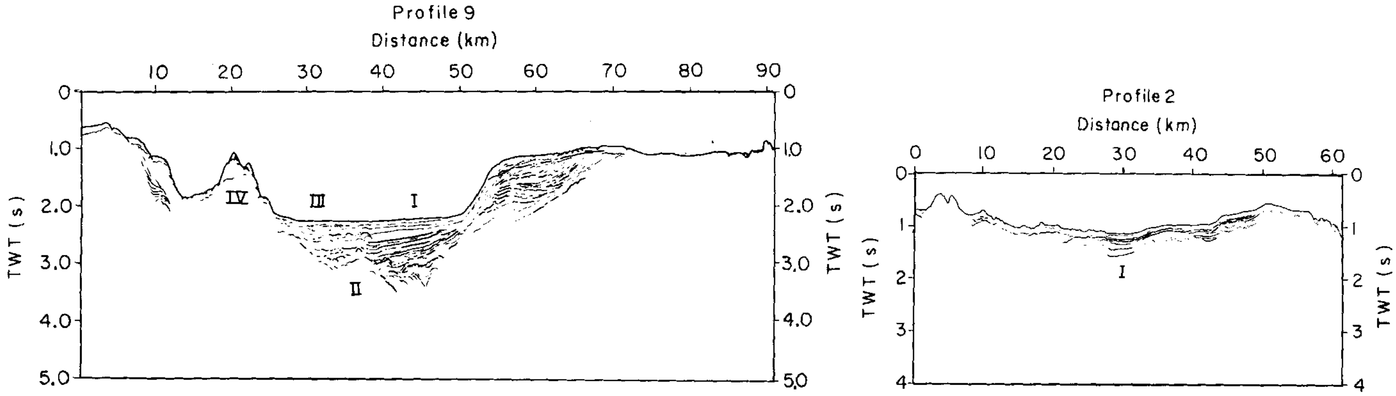


Fig. 3a. Line drawings of the three reflection lines 1, 2, and 9 crossing the Bransfield Strait (with the Free Air Anomalies (FAA).)
top: I undisturbed sediments, II diffraction events, III rift-like structure;
bottom left: I undisturbed sediments, II diffraction events, III magmatic influenced



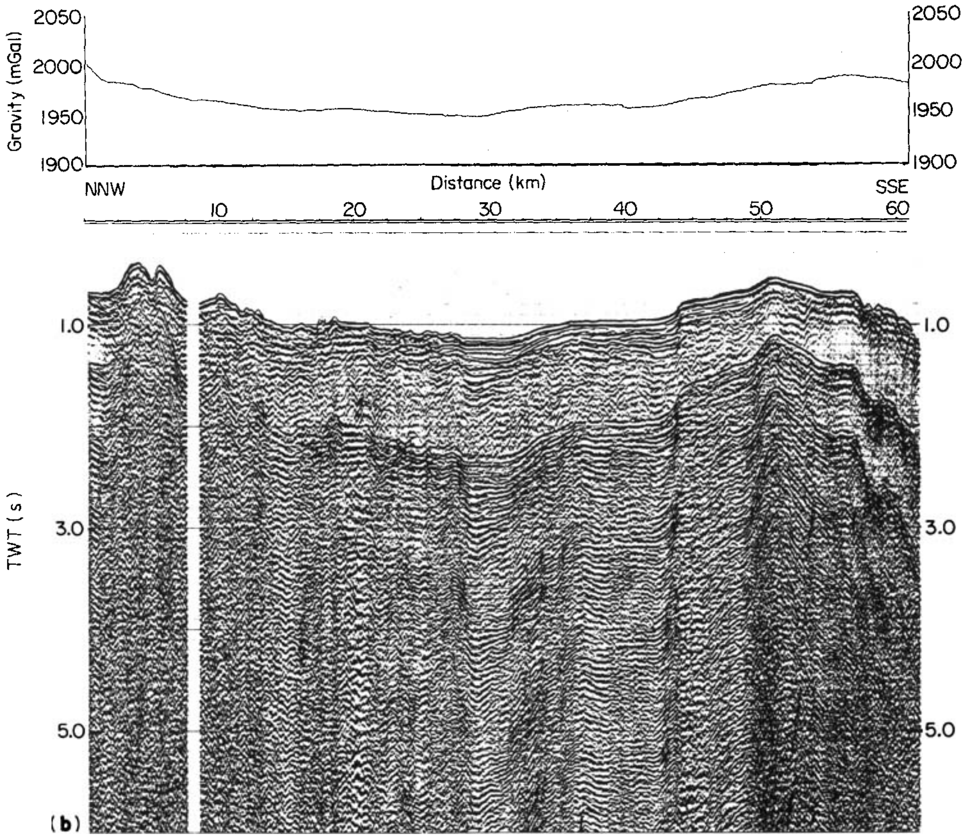


Fig. 3b. Profile 2; stacked section and the Free Air Anomaly (FAA) on top.

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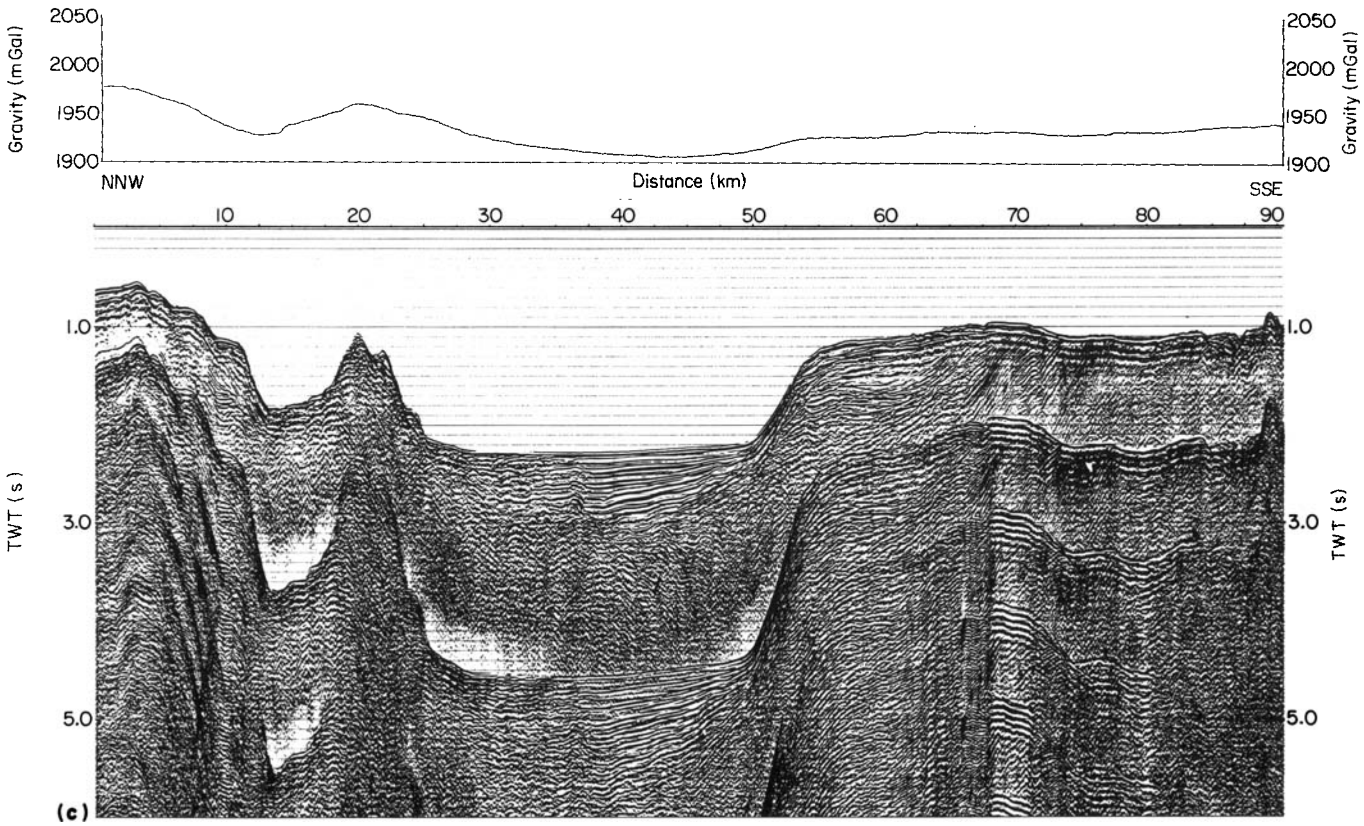

Fig. 3c. Profile 9; stacked section and the FAA on top.

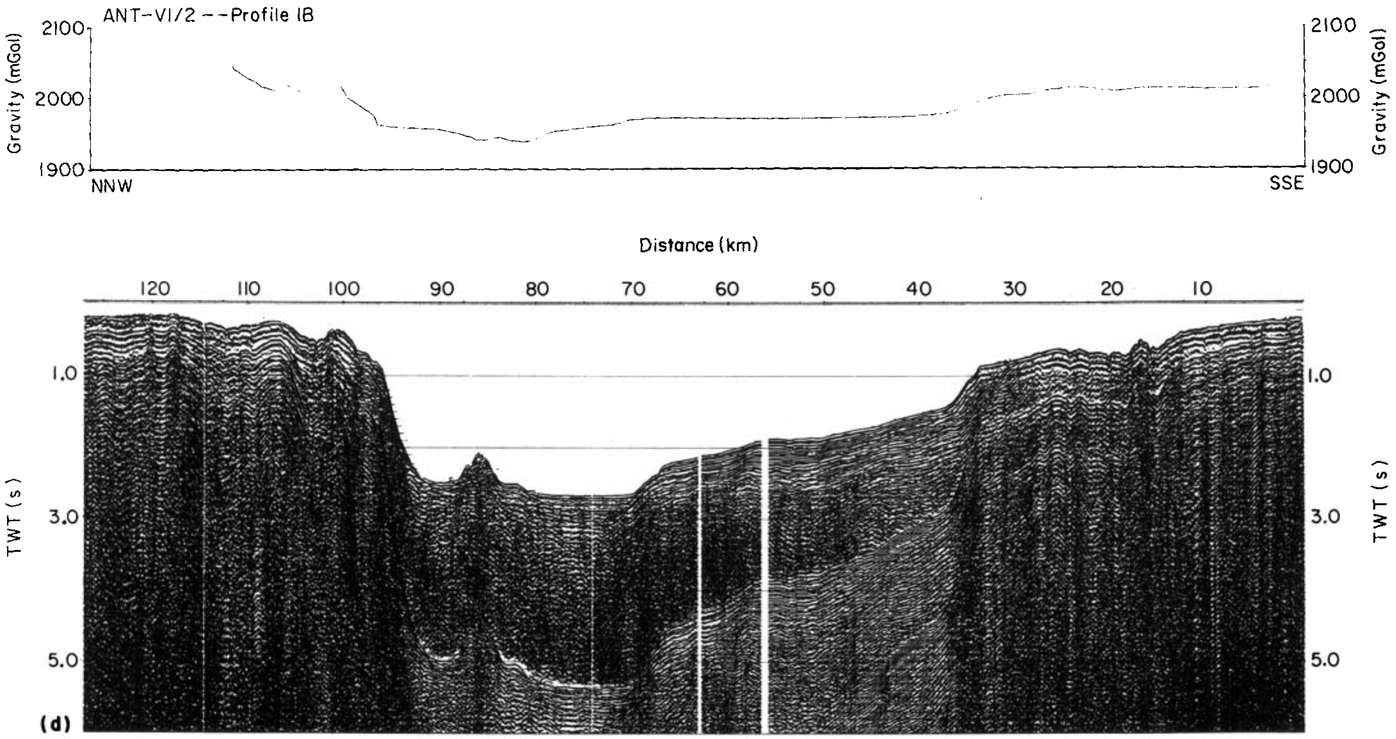

Fig. 3d. Profile 1; stacked section and FAA on top.

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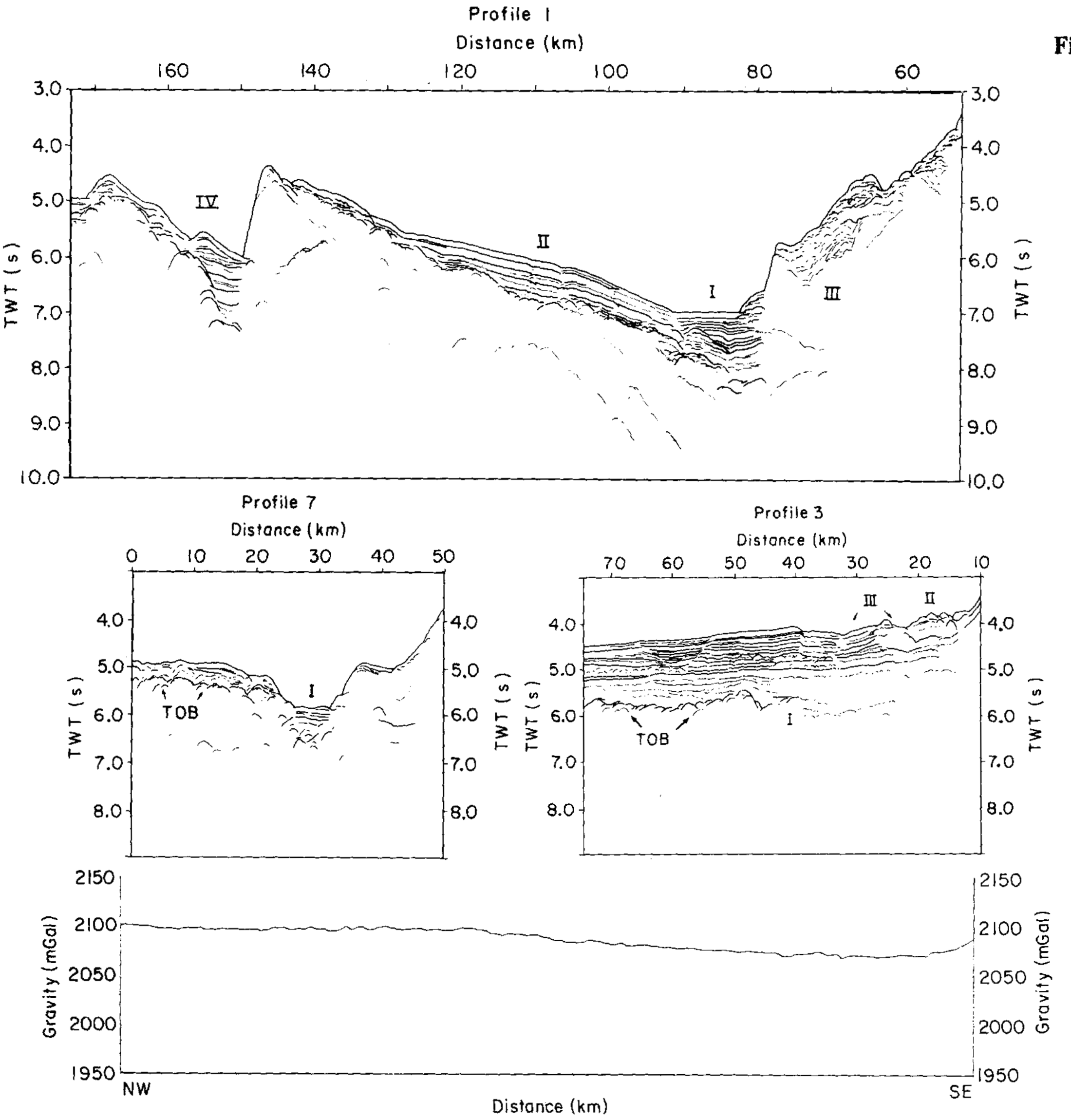

Fig. 4a. Line drawings of the three reflection lines 1, 3, and 7 crossing the South Shetland Trench.
top: I sediment infill of trench, II oceanic sediments, III accretionary wedge, IV trench-like structure;
bottom left: I sediment infill of trench, TOB top of basement;
bottom right: 1 basement step, 11 turbitides, 111 normal faults.

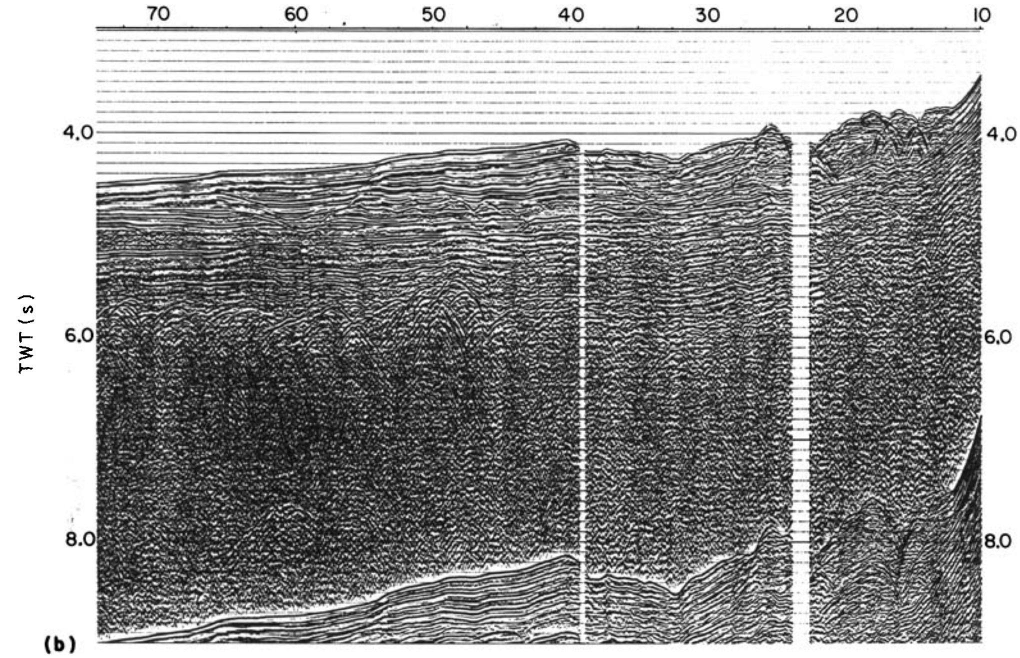

Fig. 4b. Profile 3; stacked section and FAA.

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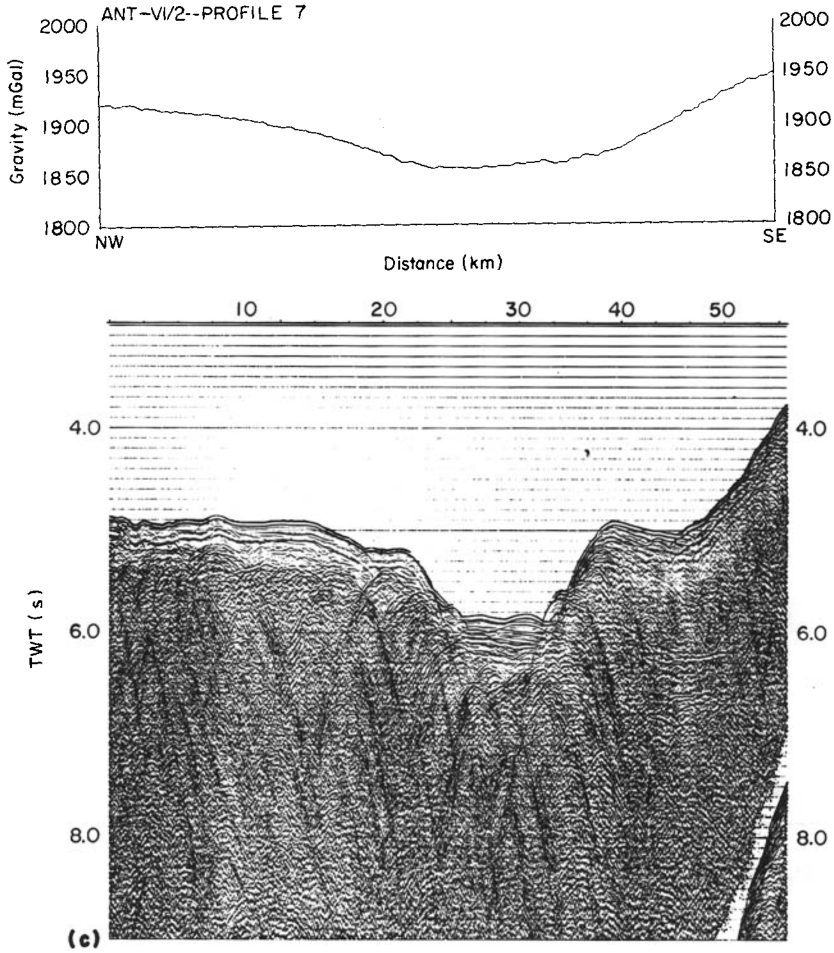

Fig. 4c. Profile 7; stacked section and FAA.

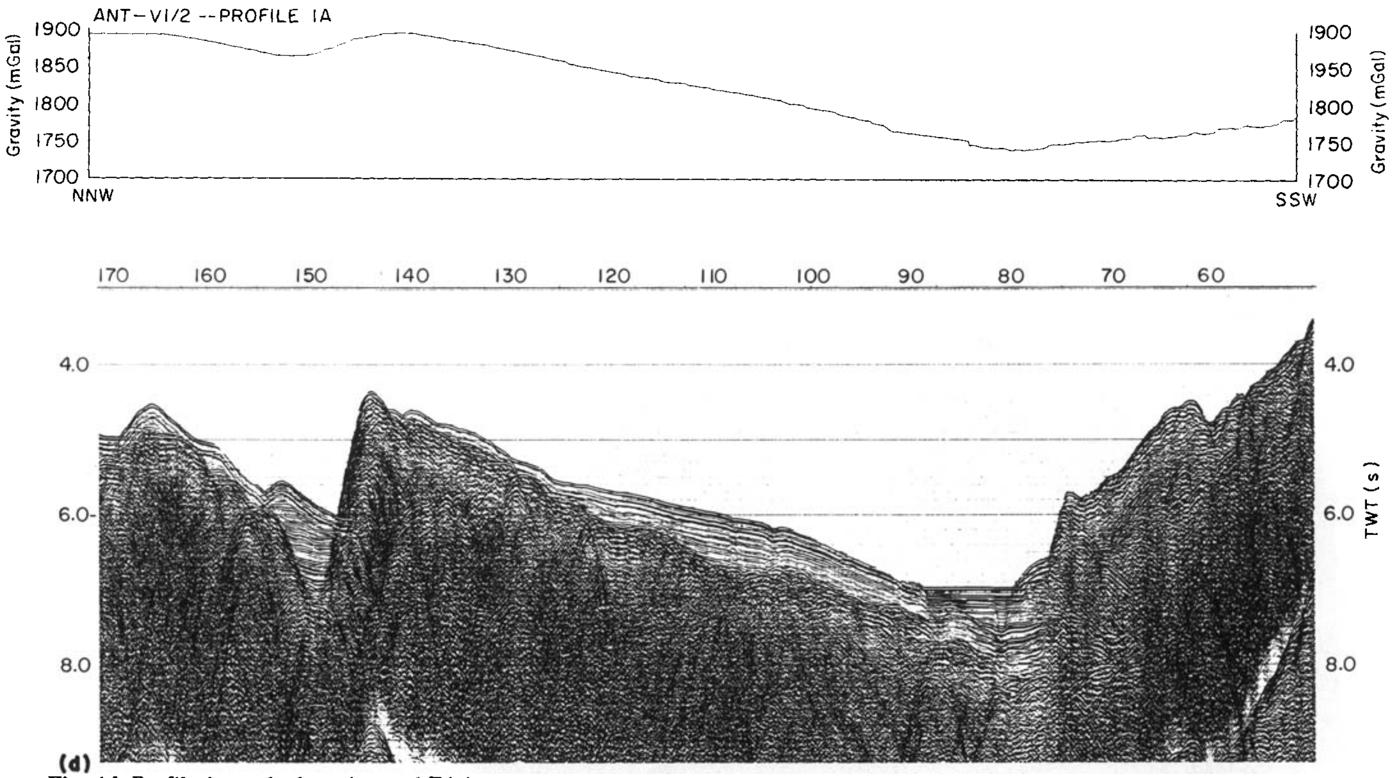

Fig. 4d. Profile 1; stacked section and FAA.

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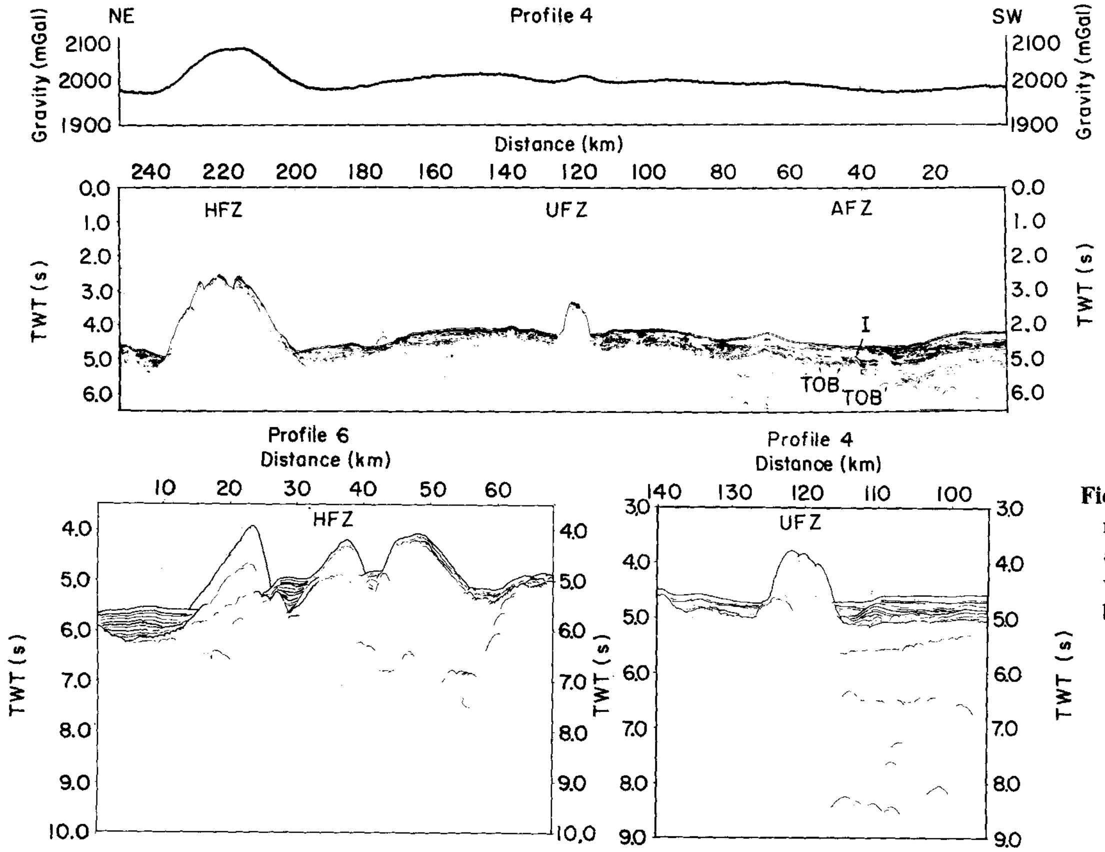

Fig. 5a. Line drawings of reflection lines 4 and 6 across fracture zones: I volcanic dome; TOB top of basement.

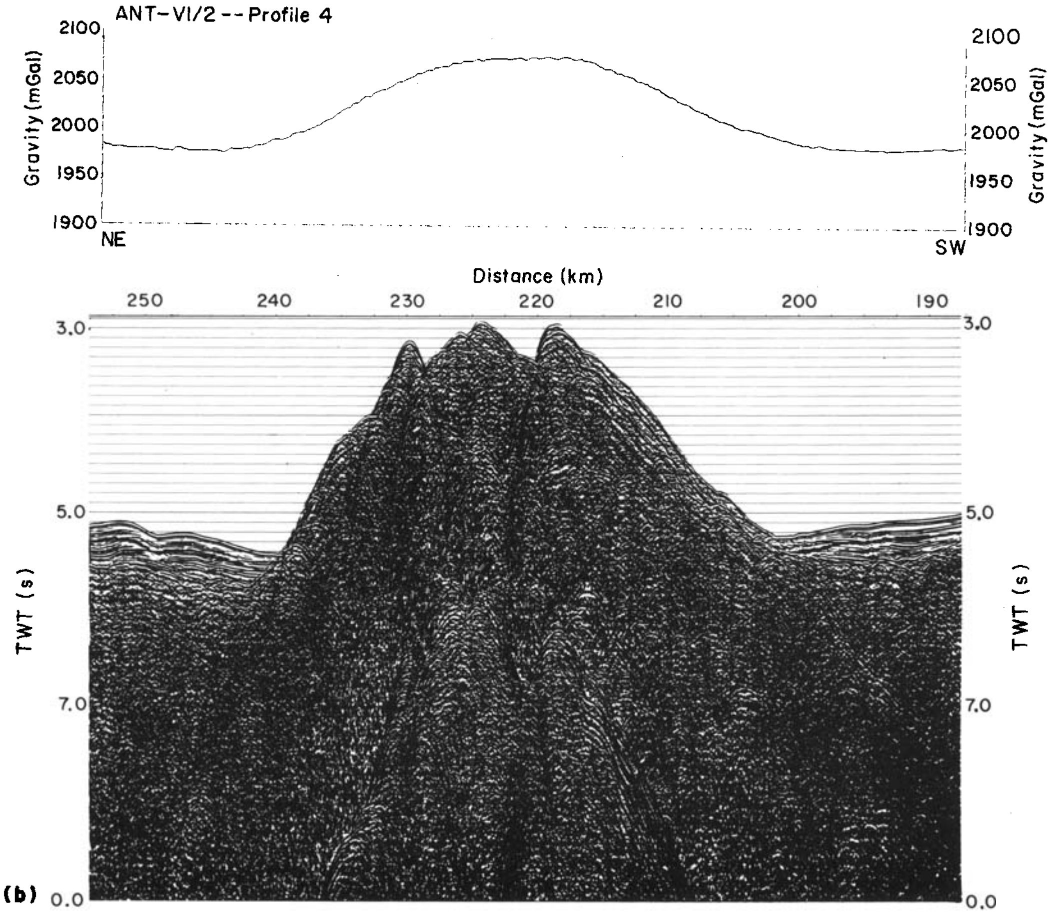

Fig. 5b. Profile 4; Hero FZ.

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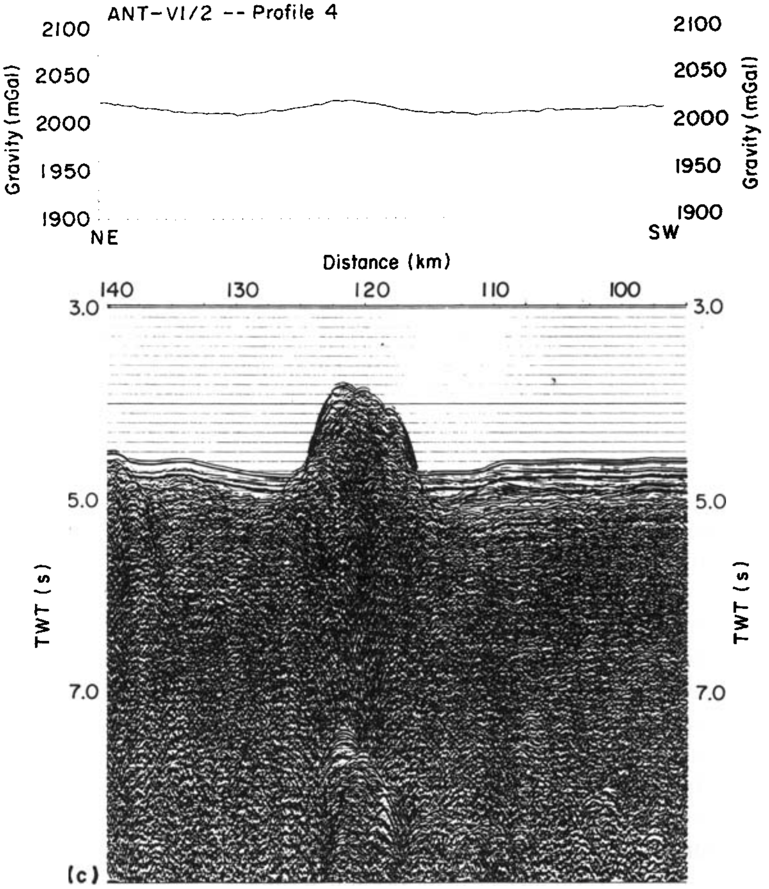

Fig. 5c. Profile 4; unnamed FZ with seamount.

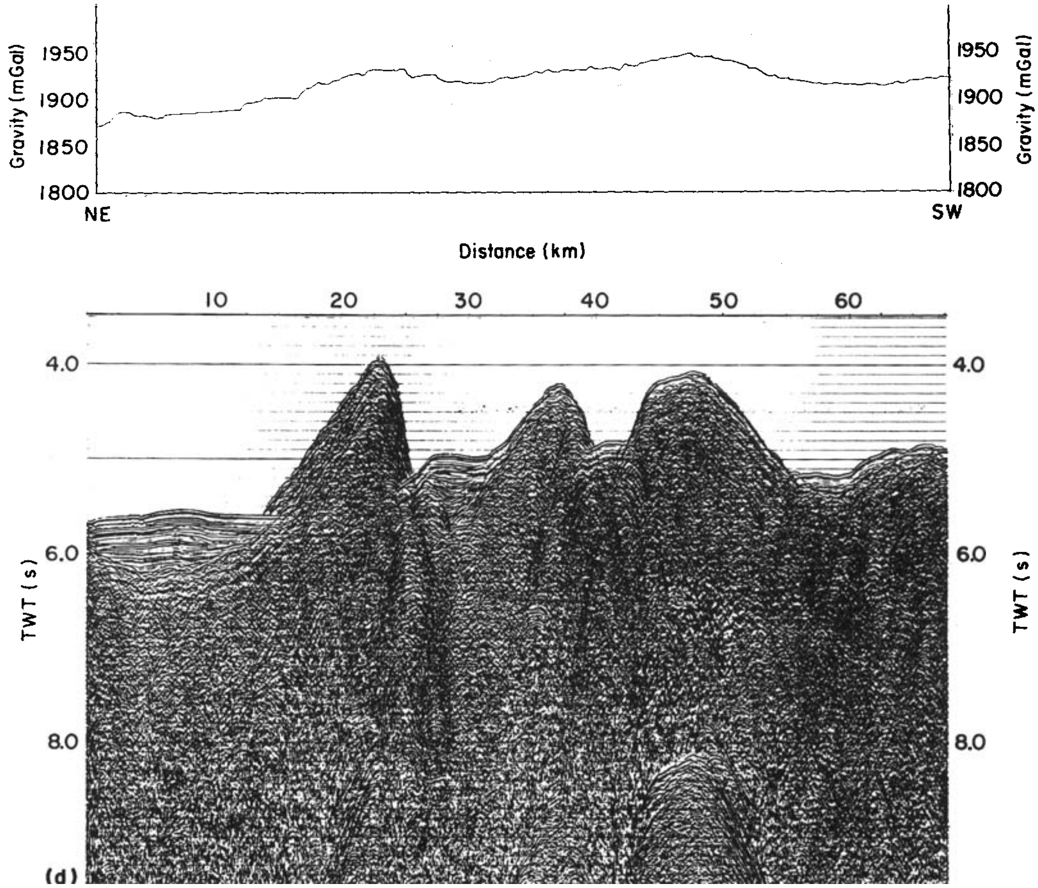

Fig. 5d. Profile 6; Hero FZ.

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took place. The cessation of the convergence is supported by the magnetic pattern along the Aluk ridge and by the undisturbed character of the young trench-fill sediments north of Hero FZ (Fig. 4b). It should be noted here that the relict oceanic plate segment between Hero FZ and Shackleton FZ belongs to what has been called the Aluk plate by some authors (Herron & Tucholke 1976) and the Drake plate by others (Tucholke *et al.* 1976, British Antarctic Survey 1985, Doake 1987).

The South Shetland Trench (SST) and its possible southern extinct continuation was investigated along seismic profiles 1, 7 and 3 (Fig. 1). The line drawings of profiles 1, 7 and 3 (Fig. 4a) illustrate the morphological and structural expression of the transition from a palaeotrench environment (ridge trench collision site, profile 3) to a recently deactivated trench (profile 1).

Profile 3 (Fig. 4c, 4a bottom right) crosses the continental margin where the ridge trench collision took place some 15 m.y. ago. Up to 2000 m of sediments are found at the foot of the continental slope on top of the oceanic basement (TOB in Fig. 4a bottom right), which displays the characteristic pattern of diffraction hyperbolae (at about 5.8 s TWT) and which still shows a small landward dip (I on Fig. 4a bottom right). This depression of the oceanic basement is also detectable in the FAA profile. Diffraction patterns in the sediments close to the slope (II on Fig. 4a bottom right), probably turbidites, might be due to slumping. Local strong variations in a buried erosion surface in the oceanic sediment cover have caused differential compaction and associated normal faulting in the overlying strata (III within km 10-30 on Fig. 4a bottom right).

In the region south of profile 7 (Fig. 4c, 4a bottom left), the Aluk ridge collided with the South Shetland Trench some 4.5 m.y. ago (British Antarctic Survey 1985). Trench-like features show up both in the sea-floor topography and the gravity profile (I on Fig. 4a bottom left). A diffraction pattern at about 5.2 s TWT again marks the oceanic basement (TOB on Fig. 4a), which is here covered by some 200 m of sediments. The oceanic crust dips landwards underneath both the 15 km-wide trench and the adjacent inner-wall structure, as is suggested by the gravity anomaly. The absence of deformation in the trench sediments (I on Fig. 4a bottom left) argues for deposition after the cessation of the convergence or for deposition down the axis of an active trench system (e.g. Fig. 4d and other world trenches).

Profile I (Fig. 4d) crosses the trench (1 on Fig. 4a top) in an area, where subduction seems to have stopped or slowed down some 3 to 4 m.y. ago, as indicated by the ending of the activity of the Aluk ridge, which lies about 250 km seaward of the trench. The trench shows a depression of some 1900 m (2.5 s TWT). The horizontal layering of the youngest trench fill sediments is continuous and undisturbed, arguing for deposition after the cessation of subduction or at least for a lack of compressional forces. The sediments on the dipping oceanic plate (II on Fig. 4a top) onlap oceanic basement in a seaward direction and are cut by normal faults, apparently related to slumping or extensional faulting of the basement. The continental slope is here much steeper than where it faced the palaeotrench near Smith Island (62° 59'S, 62° 30'W; the accretionary wedge (III on Fig. 4a top) itself shows little internal structure and is covered by prograding sediments of probable glacial origin. A remarkable feature is the asymmetric, trench-like structure in the northern profile (IV on Fig. 4a top), about 70 km north of the main trench. The sediments in this trough do not show an undisturbed horizontal layering. Their degree of deformation might suggest recent tectonic stresses. Whether this deformation argues for some form of back-stepping of the subduction process or simply was caused by the possible transpressional activity of the neighbouring Shackleton FZ is a subject of debate.

Fracture zones

Three fracture zones were crossed along profile 4 (Fig. 5a), the most pronounced being Hero FZ (Fig. 5b), also observed on profile 6 (Fig. 5d). The magnetic anomaly (MA) pattern shows left lateral ridge offsets along all these fracture zones, with significant age differences across the various segments (British Antarctic Survey 1985), which means that all fracture zone segments linking the spreading ridges were right-lateral transform faults.

Profile 4 (Fig. 5a) crosses Anvers FZ (AFZ), in the south-western part of the profile, where 20 m.y. old crust (MA 6) south of the fracture zone is in contact with 12.5 m.y. old crust in the north. This is reflected on the seismic record:

1. by the displacement of the oceanic basement (TOB on Fig. 5a); the crustal elevation on either side of the FZ matches the Parson & Sclater (1977) curve,
2. by the difference in sediment thickness on either side of the fracture zone, and
3. by some features (I on Fig. 5a), probably volcanic domes, arguing for the leaky nature of the fracture zone.

Farther to the north-east an unnamed fracture zone (UFZ on Fig. 5a) was crossed, also displaying a change in elevation of the oceanic crust and a thinning of the sediment cover (Fig. 5c). The age difference between the two adjacent plate fragments amounts to about 3 m.y. This fracture zone is marked by a pronounced seamount or ridge.

The third and most impressive fracture zone feature on this profile is Hero FZ, which towers about 1600–1800 m above the sea floor. HFZ is characterized by a FAA of more than 100 mgal, which is embedded in a regional trend showing a general decrease towards the north over the whole length of the profile. The apparent coincidence of the crustal ages across Hero FZ along the track of profile 4 is purely fortuitous, as MA 5 is found landward of the Aluk ridge north and seaward of the collided spreading ridge south of HFZ. We are here crossing the transform fault part of Hero FZ. The depth to the oceanic basement and the thickness of the sediments are about equal on either side, as might be expected. The downward deflection of the oceanic crust on both sides of HFZ might either be a loading effect (if the seamount/ridge observed is of effusive nature) or a thermal bending effect similar to that observed south of Anvers FZ. At HFZ it is possibly associated with the flanks of an intrusion-like body. No decision can been made whether this body is the effusive extrusion of basalts or a diapiric intrusion of serpentinite.

Hero FZ (HFZ on Fig. 5a) was crossed again by profile 6 (Fig. 5d). There the basement depth and the sediment thickness are different across the fracture zone, in accordance with the different ages of the two sides. The FAA values vary less than they do on profile 4, although the general regional trend is present here too. Hero FZ is here about 60 km wide and shows three seamounts about 700 to 800 m high. The outer two are characterized by a strong positive FAA, which may support the assumption of a dense mafic composition.

Discussion and conclusion

The preliminary results of the reflection and gravity studies underline the complexity of the geological structures around the Antarctic Peninsula. Crustal extension which seems to be a major process in Bransfield Strait (Thomson *et al.* 1983, Garrett & Storey 1987), is observed to be stronger in the north-eastern than in the south-western part of Bransfield Strait. The depth of subsidence and the typical oceanic diffraction patterns indicate a young oceanic environment, especially in the north-east along profiles 9 and 1. Continental extension still seems to be the dominant process on profile 2, in the south-western part of Bransfield Strait. It is tempting to compare this kind of development in the Bransfield Strait to the evolution of the Red Sea, where the south-eastern part is purely oceanic, whereas the north-western part in the Gulf of Suez is still in a stage of continental extension (Steckler 1985, Cochran & Martinez, 1988). New studies in the Red Sea (Bonatti, 1987) show that this similarity is even stronger: the transition from continental to oceanic floor is not continuous but stepwise and discontinuous, a pattern which is also followed by the volcanic activity.

In Bransfield Strait and the South Shetland Islands the transition from a calc-alkaline basaltic series to an olivine-alkaline one (Thomson *et al.* 1983, Gonzáles-Ferrán 1985) also suggests a general change from a continental to an oceanic regime during the last few m.y. The young volcanism, such as that of Deception Island (north-western end of profile 2), has a mixed character, transitional between island arc and oceanic ridge basalts with a shallow-level source (Tarney *et al.*, 1981)

A north-westerly movement of the South Shetland Islands, caused by the fan-shaped opening of Bransfield Strait, must have resulted in an additional relative velocity with regard to the subducting oceanic plate, a phenomenon which may have locally increased the period of subduction. This increase may have caused the small secondary trench observed in the northern part of profile 1.

In the area south-west of Hero FZ the termination of subduction was controlled by the ridge-trench collisions of the various oceanic segments. Hero FZ ceased being an active transform fault between Aluk ridge and the SSI about 4.5 m.y. ago, when the Aluk ridge in the north-east also became inactive. Shear movements along the Hero transform fault were about 4.8 $cm a^{-1}$ at 4.5Ma. These shear movements might have caused "leakage", thereby explaining the widespread occurrence of seamounts, as seen on the bathymetric maps (Hydrographic Department 1984).

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