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Upper crustal structure of Deception Island area, Bransfield Strait, West Antarctica

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Abstract: This paper describes the results of seismic refraction investigations of the upper crustal structure in the area of Deception Island, West Antarctica, which were made during the Polish Antarctic Geodynamical Expeditions in 1979–80 and 1987–88. In the caldera and immediate vicinity of Deception Island a layer of unconsolidated and poorly consolidated young sediments of 1.9–2.2 km s^{-1} P-wave velocity was found. Velocities of 4.1–4.3 km s^{-1} were found in the depth interval from 0.6–1.3 to about 3 km. Lateral differences in upper crustal structure between the south-eastern and western sectors were identified. In the region between Deception and Livingston islands an inclined boundary with a velocity of about 6.1 km s^{-1} occurs. A deep fault zone dividing crustal blocks beneath Deception Island is associated with a prominent volcanic line within Bransfield Strait extending between Deception and Bridgeman islands.

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Introduction

Four Polish Geodynamical Expeditions to West Antarctica were organized in years 1979–1991 by the Institute of Geophysics of the Polish Academy of Sciences. The main purpose of the expeditions was to carry out structural studies of the Earth's crust and lower lithosphere by using different geophysical methods, within the general programme of geodynamic studies of West Antarctica. Special attention was paid to tectonically active zones and to the contact zones between the blocks of the Earth's crust and the lithospheric plates. As a part of the programme, seismic refraction measurements were made in the area of Deception Island during expeditions in 1979–80 and 1987–88. In the caldera and close vicinity of Deception Island three profiles each about 10 km long were made using a Bolt airgun system as a source. The results of the upper crustal studies, based on data from refraction profiles up to 80 km long, are also presented in this paper. Shots of between 25 and 120 kg of TNT were electrically detonated from the ship at depths of 70–80 m. The distance between shots was 1–5 km. A three-channel seismic station located on Deception Island recorded shots made along different profiles. The shots along one profile (DSS-19) were recorded by five-channel seismic stations located on Deception Island and Livingston Island.

Geology and tectonics of the region

Deception Island lies on a volcanic line in the Bransfield Rift zone between the South Shetland continental microplate and the Antarctic Peninsula. The neighbouring Drake microplate (also referred to in the literature as the "Phoenix" or "Aluk" plate) became part of the Antarctic plate when seafloor spreading stopped in Drake Passage 4 Ma ago (Barker 1982). A simplified tectonic scheme for this region is shown in Fig. 1. The depth of the Moho discontinuity increases from about 10 km for the oceanic crust of the Drake plate to about 25 km for the South Shetland Islands shelf, and 30–33 km for the South Shetland Islands crustal block. By contrast, the Antarctic Peninsula and its adjacent shelf has a typical continental crustal thickness of 40–45 km. The Moho depth beneath Bransfield Trough is still unknown. High velocities of P-waves of 7.2–7.6 km s^{-1} were found in the depth interval 10–25 km (Guterch *et al.* 1985, 1990, 1991).

The rift in Bransfield Strait is a late Cenozoic tensional structure about 40 km wide near King George Island, separating the Bransfield platform from the South Shetland Islands microplate (González-Ferrán 1985). The central part of the rift graben, only 15–20 km wide, contains several subaerial and submarine volcanoes on a line between Deception and Bridgeman islands. The Deception Island volcano is still active (Baker *et al.* 1975). A subparallel "volcanic line" links the Penguin Island and Melville Peak volcanoes, on the southern margin of the South Shetland Island crustal block. The central, submarine trough, 1000–2000 m deep, is filled with horizontal strata of considerable thickness, probably mainly tephra and young glacio-marine sediment. The Quaternary volcanoes consist of three compositionally distinct volcanic suites: alkaline and calc-alkaline lavas occur in the Penguin, Deception, Bridgeman and Melville Peak volcanoes, whereas the seamounts are composed of tholeiites (González-Ferrán & Katsui 1970, Weaver *et al.* 1979, Pankhurst 1982, Birkenmajer & Keller 1990, Birkenmajer *et al.* 1990, Jeffers *et al.* 1991, Fisk 1991). This difference may reflect not only the youth

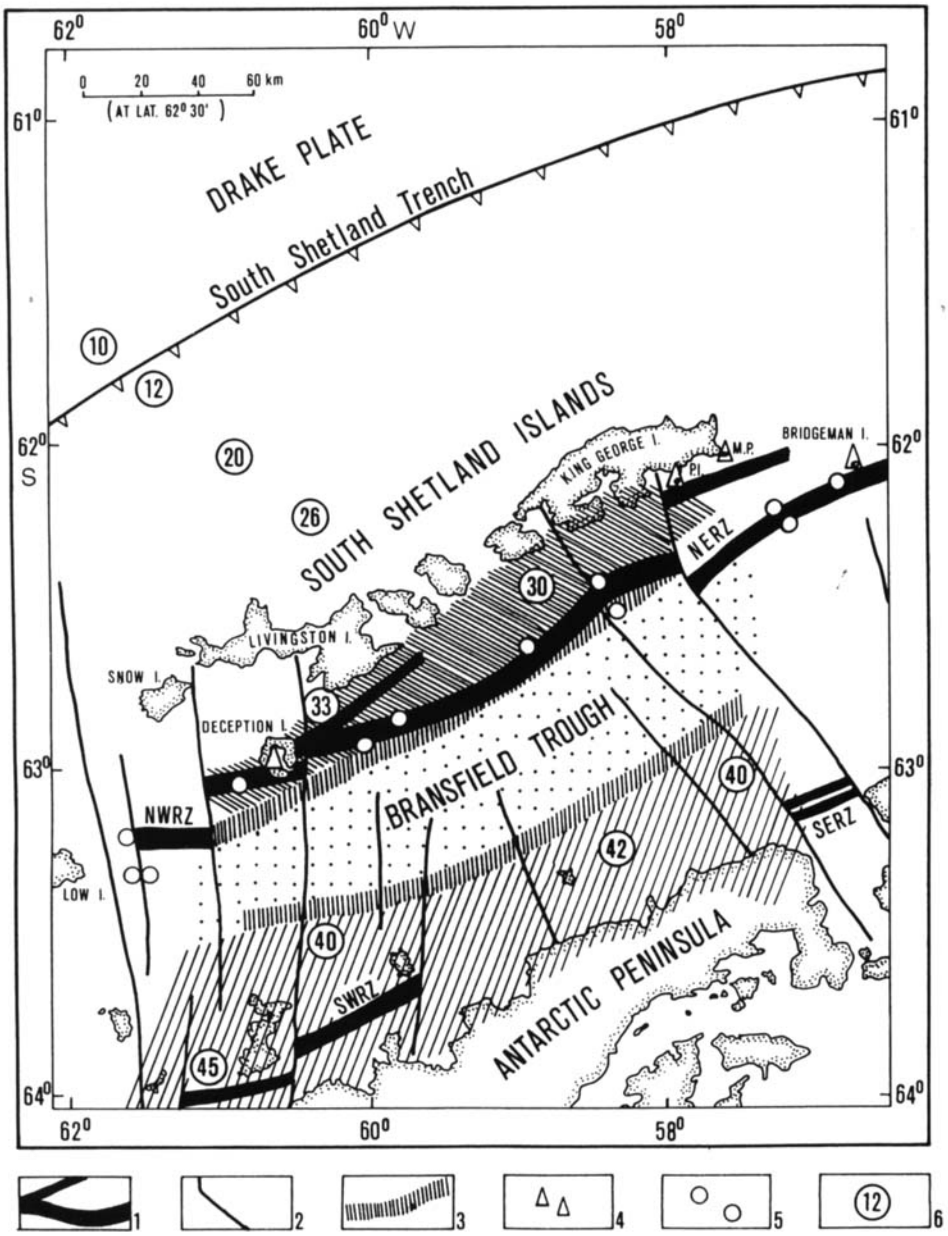

Fig. 1. Simplified tectonic map of the northern Antarctic Peninsula region, Antarctica: 1 = rift zones, 2 = faults, 3 = fault zones bounding Bransfield Trough, 4 = subaerial volcanoes, 5 = submarine volcanic seamounts 6 = depth (in km) to the Moho discontinuity. Dashed area = Antarctic Peninsula crustal block, densely dashed = South Shetland crustal block. P.I.= Penguin Island; M.P.= Melville Peak; NWRZ, SWRZ, SERZ= north-west, south-west and south-east rift zone, respectively. Compiled from Guterch *et al.* (1985, 1991), Birkenmajer & Keller (1990), González-Ferrán (1991).

of the basin, but also the crustal structure below the volcanoes. Normal continental crust, about 30 km thick, occurs below the Melville Peak and Penguin Island volcanoes situated on, or near to King George Island, whereas highly anomalous crust has been recognized below the Bransfield Trough (Ashcroft 1972, Guterch *et al.* 1985, Birkenmajer & Keller 1990). Teleseismic observations of earthquakes in Bransfield Strait, close to Deception Island, show NW–SE tension in agreement with geological evidence indicating rifting and extension (Pelayo & Wiens 1989).

Deception Island is an almost circular volcanic island lying in south-west Bransfield Strait (Fig. 2). The island is bounded on all sides by vertical cliffs of rock and ice, and a narrow channel in the south- east gives access to the interior basin of Port Foster, water depths are *c.* 180 m in the centre and less than 50 m at Neptunes Bellows. The island has been built by successive volcanic eruptions from a variety of vents in Quaternary to Recent times. Eruptions occured in 1842 (south-west side of island), *c.* 1912–1917 (south of Fumarole Bay), in 1967 and 1970 (Telefon Bay), and in 1969 (Pendulum Cove). Each event was associated with the emplacement of a reservoir of magma at shallow depths, each in a slightly different state of chemical evolution; precursory seismicity was also sometimes observed (Baker *et al.* 1975, Lorca 1976, Roobol 1979, Newhall & Dzurisin 1988). The caldera of Deception Island was formed by the subsidence of a group of overlapping volcanoes along arcuate and radial faults (Hawkes 1961, Smellie 1988, 1989). The greater part of the caldera floor is submerged beneath Port Foster. The caldera wall is well defined along the western side of the island, where it typically forms a prominent fault scarp. The continuity of the caldera rim is broken in a number of places by radial faults

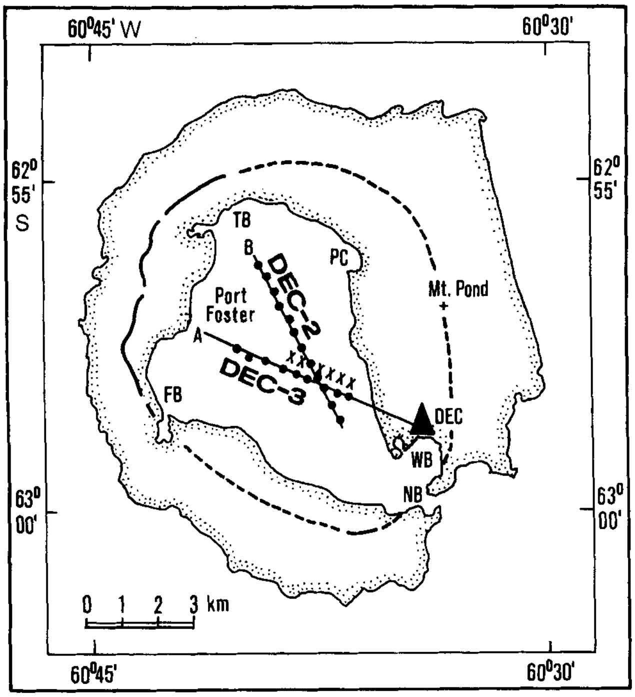

Fig. 2. Location of seismic profiles DEC-2 and DEC-3 within the Deception Island caldera. • = airgun shots; ▲ = location of seismic station; xxx = possible location of the fault determined from DEC-2 data. Solid and broken lines indicate the position of the caldera rim (Hawkes 1961). TB = Telefon Bay; PC = Pendulum Cove, NB = Neptunes Bellows, WB = Whalers Bay, FB = Fumarole Bay.

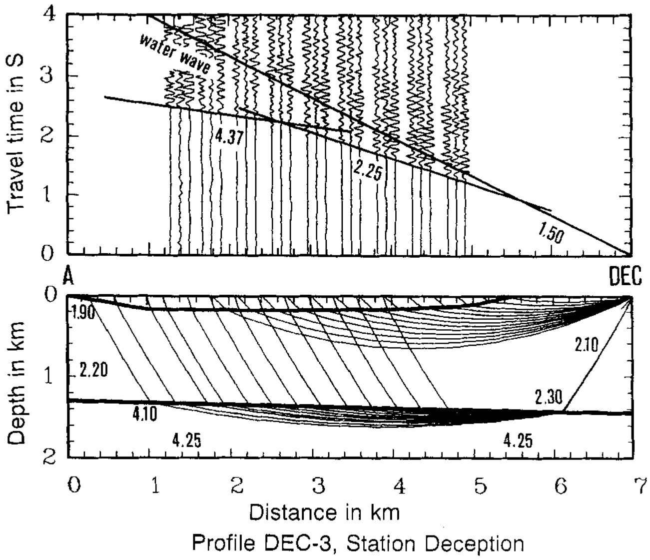

Fig. 3. Seismic record section with theoretical travel times and ray diagram for profile DEC-3; velocity in km s^{-1}.

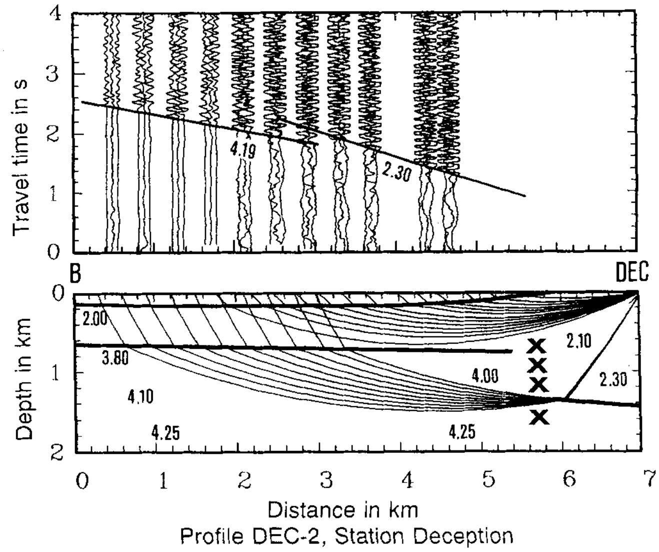

Fig. 4. Seismic record section with theoretical travel times and ray diagram for non-longitudinal profile DEC-2. Part of the model in the distance interval 5.5–7 km confirms results from profile DEC-3 (the layer 4.25 km s^{-1} at the depth 1.4 km). Model for the distance 0–5.5 km corresponds to the northern part of the caldera. Crosses show the possible location of the fault also shown in Fig. 2; velocity in km s^{-1}.

and is breached at Neptunes Bellows (Hawkes 1961, Baker *et al.* 1969, 1975, Birkenmajer 1987, Smellie 1988, 1989). The results of the detailed seismo-acoustic reflection profiling also show significant inhomogeneities in the uppermost 100 m of the sediments on the floor of Port Foster. The pre-caldera and post-caldera formations are cut by numerous faults, vents and of intrusions (Kowalewski *et al.* 1990).

Shallow structure within the Deception Island caldera

During the Polish Antarctic Geodynamical Expedition in 1979–80 three refraction profiles, each about 10 km long, were shot in the area of Deception Island using an airgun array with a total capacity about 30 l as a source. Two of them, profiles DEC-2 and DEC-3, were shot across Port Foster to investigate the structure of the caldera (Fig. 2). Seismic record sections are shown in Figs 3 & 4. In the distance range 2–7 km waves with apparent velocities of about 2.2–2.3 and 4.2–4.4 km s^{-1} were recorded. For profile DEC-3, a very clear water wave with velocity 1.5 km s^{-1} is observed. For profile DEC-2, some records are saturated, so only correlation of first arrivals was possible. At a distance of 4 km from the station a travel time discontinuity is observed. Such a configuration of travel time branches can be explained by the existence of a fault displacing the top of the 4.2 km s^{-1} layer. Two-dimensional models with ray diagrams for both profiles are shown in Figs 3 & 4. Beneath water with 1.5 km s^{-1} velocity, an uppermost layer is characterized by increasing velocities from 1.9 km s^{-1} near the surface to 2.3 km s^{-1} at a depth of 1.5 km. Along profile

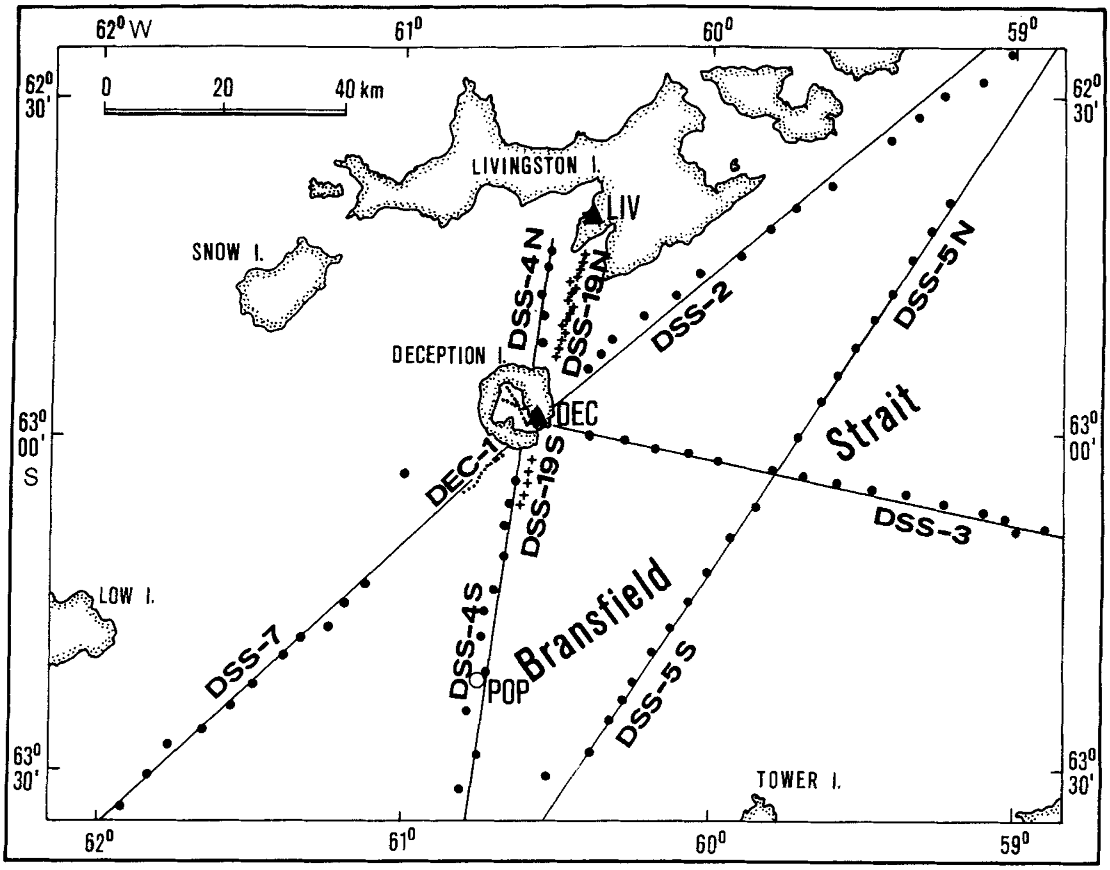

Fig. 5. Location of seismic profiles in the vicinity of Deception Island made during Polish Antarctic Geodynamical Expeditions 1979–80 and 1987–88. • • • = large size shot points (50–120 kg TNT) along deep seismic sounding (DSS) profiles; +++ = shot points (24 kg TNT) along profile DSS-19; ···· = airgun shots along profile DEC-1 and profiles inside the caldera of Deception Island (see Fig. 2); ▲ = location of seismic stations on Deception Island (DEC) and Livingston Island (LIV); POP is the beginning of the two-dimensional profile.

DEC-3 the depth to the 4.2 km s^{-1} boundary is 1.4 km. In the northern part of the caldera, the depth to this same boundary is 0.6 km in profile DEC-2. The possible location of the fault is shown in Fig. 2. The continuation of this fault coincides with a normal fault in the south-west part of island (Smellie 1989).

The differences in travel times and models along profiles DEC-2 and DEC-3 (Figs 3 & 4) show that the structure of the caldera is not entirely what was suggested by Ashcroft (1972) on the base of data from his profile 30NW/SE. However, our results confirm his values of velocities. Velocities of 1.9–2.3 km s^{-1} suggest a layer of ash and other variably compacted volcanic debris. The velocity of the 4.1–4.3 km s^{-1} layer (cf. 3.96 km s^{-1} in Ashcroft (1972)) is typical of more consolidated volcanic rocks forming the bedrock.

Upper crustal structure from one- and two-dimensional modelling

The results of the upper crustal studies presented in this paper are based on the interpretation of travel times of refracted waves. Correlation of wave groups was based on their kinematic properties, using seismic record sections and seismograms. Altogether about 100 three- and five-channel seismograms recorded in the vicinity of Deception Island were used. The locations of seismic profiles made during Polish Antarctic Expeditions 1979–80 and 1987–88 in the vicinity of Deception Island are shown in Fig. 5. Seismic record sections from profile DSS-19, recorded at stations on Deception and Livingston islands, are presented in Fig. 6. The apparent velocities of first arrivals measured from shots in the *c.* 15 km long interval between Deception Island and Livingston Island are 7.2 and 5.0 km s^{-1} for stations Deception and Livingston, respectively. This is a clear indication of a strong inclination of the seismic boundary, for which the real velocity of P-waves is of the order 6.0–6.2 km s^{-1}. Some of the data from other profiles in this area were published in earlier papers (Guterch *et al.* 1985, 1990, 1991).

The station on Deception Island was used as the receiver point for several profiles. Only profile DSS-19 was reversed by setting up another receiving station on Livingston Island. Thus, for the other profiles shown in Fig. 5, it was possible

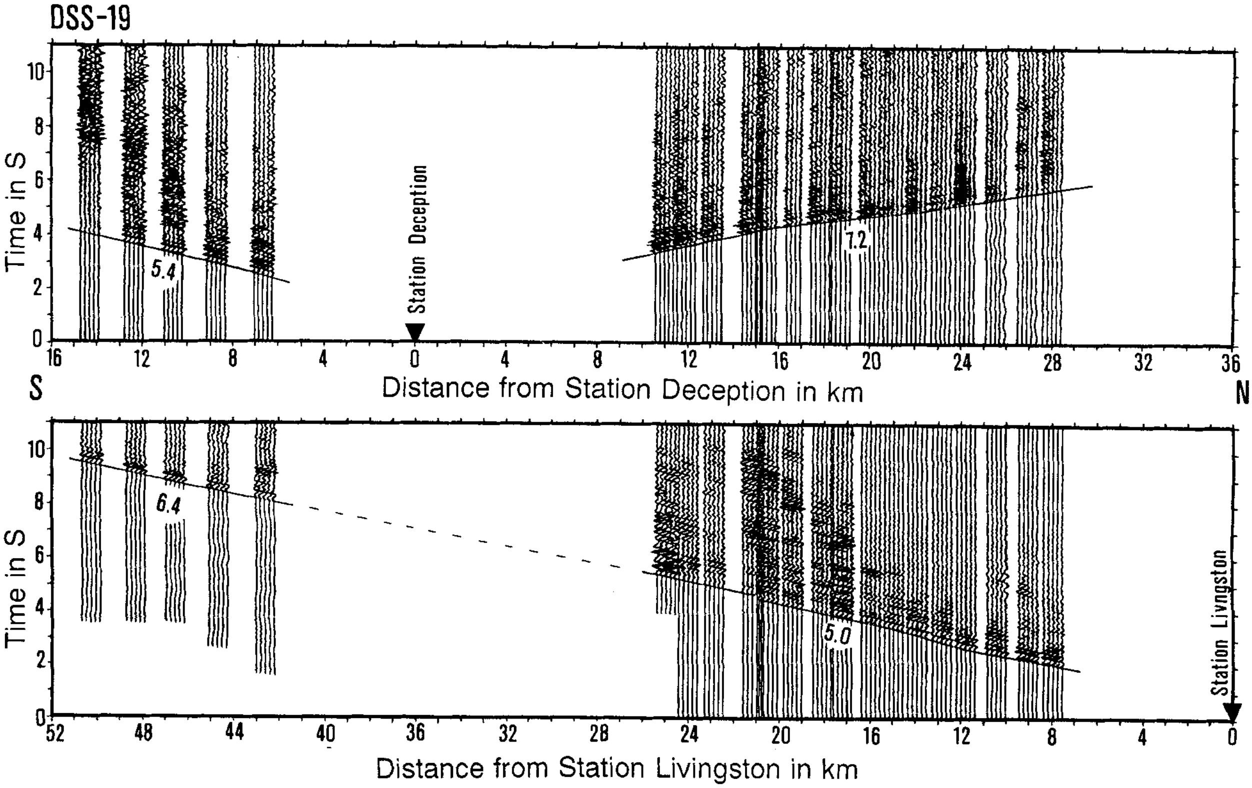

Fig. 6. Seismic sections from profile DSS-19 recorded on Deception Island and Livingston Island; apparent velocities of first arrivals in km s^{-1}.

to determine only one-dimensional models of the structure. The theoretical travel times for profiles DSS-7, DSS-4, DSS-5, DSS-3 and DSS-2 were fitted by trial and error to an accuracy of ± 0.1 s. The results of modelling, one-dimensional models of the upper crust in the vicinity of Deception Island, are presented in Fig. 7. The models for the sector from north-east to south (between profiles DSS-2 and DSS-4S, respectively) have some similarities. The uppermost sediments have mean P-wave velocities of 3.0–4.0 km s^{-1}. This layer covers a bedrock with velocities of 5.5–5.7 km s^{-1} and 6.4–6.7 km s^{-1}. The corresponding depths of these boundaries are 2–4 km and 5–7 km respectively, having their maximum in the area east of Deception Island (profiles DSS-3 and DSS-5N). However, models for profiles DSS-7 & DEC-1 and DSS-19N & DSS-4N differ from the others. The high apparent velocity layer in model DSS-19N & DSS-4N results from strong inclination of the boundary at the top of a 6.0–6.2 km s^{-1} layer, whereas the high velocity in model DSS-7 & DEC-1 corresponds with a zone of anomalous seismic structure in the central part of the Bransfield Trough (Guterch *et al.* 1985, 1991). Two-dimensional modelling of the upper crustal structure was possible along a profile in

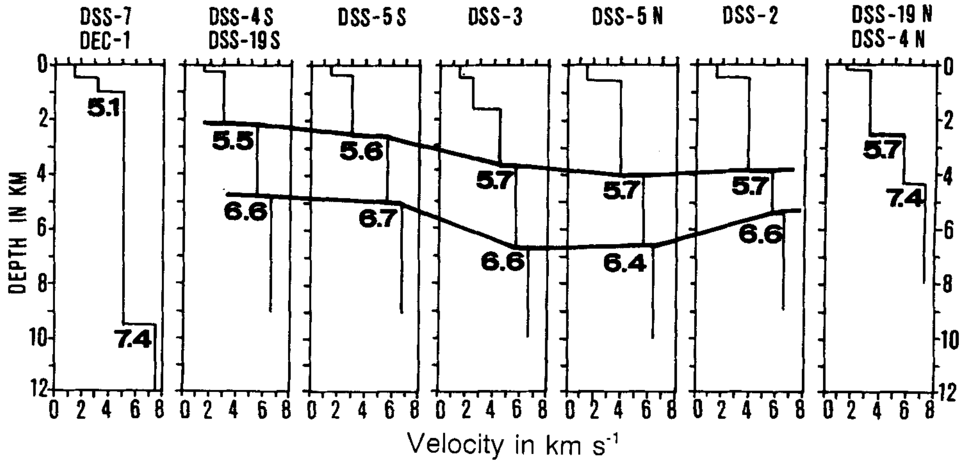

Fig. 7. One-dimensional model representations of the upper crustal structure along seismic profiles in the vicinity of Deception Island. For location of profiles see Fig. 5.

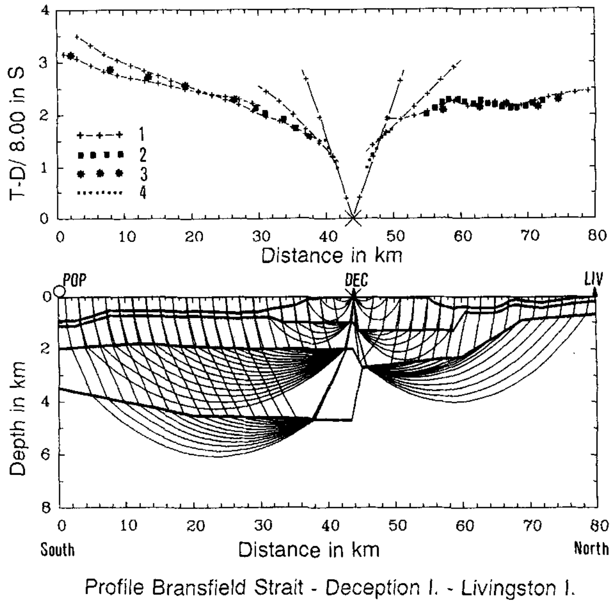

Fig. 8. Comparison of theoretical and observed travel times (above) and ray diagram (below) for profile Bransfield Strait–Deception Island–Livingston Island, measured at station Deception; 1 = theoretical travel time, 2,3,4 = observed travel times from profiles DSS-19, DSS-4 and DEC-3, respectively.

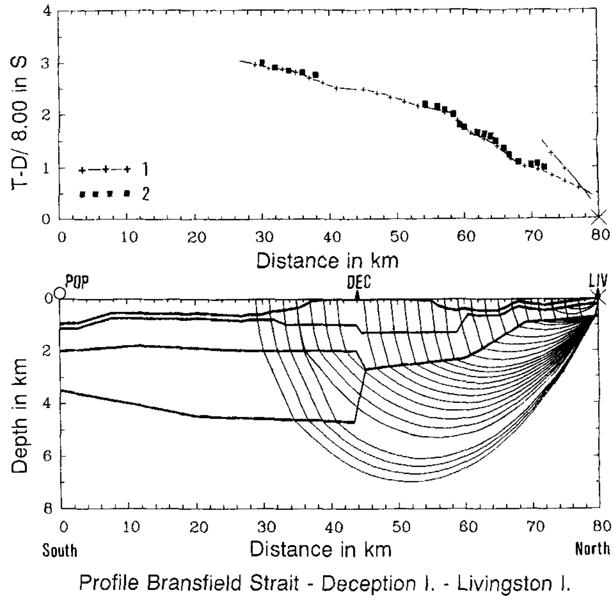

Fig. 9. Comparison of theoretical and observed travel times (above) and ray diagram (below) for profile Bransfield Strait–Deception Island–Livingston Island, measured at station Livingston; 1 = theoretical travel time, 2 = observed travel time from profile DSS-19.

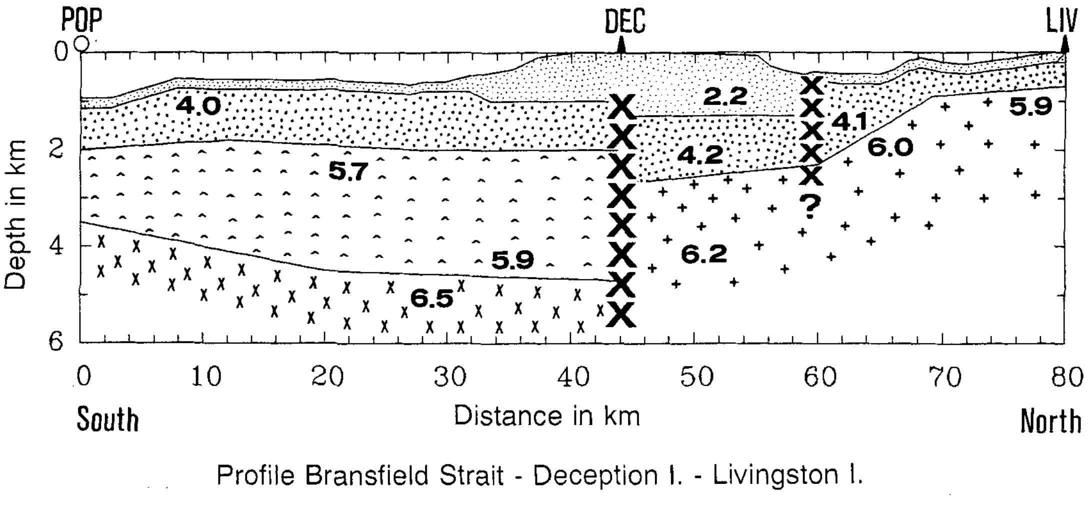

Fig. 10. Seismic model of the upper crust structure along profile Bransfield Strait–Deception Island–Livingston Island. Crosses show locations of inferred faults; velocity in km s^{-1}.

Bransfield Strait, with a reversed system of seismic stations at Deception Island and Livingston Island. Point POP is the beginning ("zero") of the profile and LIV is the receiving station on Livingston Island (end of two-dimensional profile), and are labelled as such in Fig. 5. Geographical coordinates of the profile terminations are POP = 63.361°S, 60.753°W and LIV = 62.663°S, 60.390°W. In modelling along this line, data from profiles DSS-19, DSS-4 and DEC-3 were used. A two-dimensional model was fitted using a ray tracing method (Červený & Pšenčík 1981, 1983). As a result of a multistage process of interpretation , good agreement (of the order ± 0.1 s) between theoretical and observed travel times was obtained (Figs 8 & 9). A more detailed explanation of the modelling is given by Środa (1991). In the model (Fig. 10), two sedimentary layers with velocities 1.9–2.2 km s^{-1} and 4.0–4.2 km s^{-1} were distinguished mainly using data from profile DEC-3 and Ashcroft (1972). The southern and northern parts of the model differ. To the south, two layers with velocities of 5.7–5.9 and about 6.5 km s^{-1} are present, whereas in the north there is an inclined basement boundary, where velocities increase with depth from 5.9–6.2 km s^{-1}. The 5.7 and 6.2 km s^{-1} layers are in faulted contact beneath Deception Island.

Conclusions

Elements of the shallow structure within the Deception Island caldera were determined using two seismic profiles in Port Foster. An upper layer, (0.6–1.4 km thick) with seismic velocities of 1.9–2.2 km s^{-1} corresponds to unconsolidated and poorly consolidated young sediments, probably containing considerable amounts of lava and tuff. The underlying layer, with velocities of 4.1–4.3 km s^{-1}, possibly consists of older and better consolidated sediments and lavas (Ashcroft 1972). It should be noted that, in addition to the fault scarp which forms the almost circular caldera wall, there is evidence of a major fault separating blocks within the caldera. Beneath profiles DEC-2 and DEC-3 the difference in depth to the top of the 4.1–4.3 km s^{-1} layer is about 0.7 km. This fault may be connected with successive episodes of collapse and subsidence of the Port Foster Group volcanoes. More detailed seismic reflection and/or gravimetric investigations are needed to define the caldera structure better.

The results of one- and two-dimensional seismic modelling of the upper crustal structure around Deception Island show that in the sector from north-east to south, two seismic layers with velocities 5.5–5.7 and 6.4–6.7 km s^{-1} occur at depths 2–4 km and 5–7 km, respectively. Observed velocities beneath the sedimentary cover of 5.5–5.7 km s^{-1} are typical for acid crystalline or metamorphic rocks, whereas velocities 6.3–6.7 km s^{-1} are characteristic for basic rocks. In the area between Deception and Livingston islands an inclined boundary with a velocity of about 6.1 km s^{-1} occurs. This velocity is typical for continental crystalline basement. The results presented here allow as to distinguish different geotectonic units on either side of Deception Island. This suggests that the location of Deception Island is controlled by the position of a major volcanic fault zone separating these different crustal blocks.

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