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New geological interpretation of multi-channel seismic profiles from the Pacific Margin of the Antarctic Peninsula

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Abstract: The Polish Geophysical Expedition to West Antarctica in 1979–1980 was carried out by the Institute of Geophysics, Polish Academy of Sciences. Beside deep seismic soundings, 12 multi-channel seismic profiles, with a total length of *ca* 1000 km have been recorded north and east of the South Shetland Islands and in the Bransfield Strait, but they have never before been completely interpreted and published. All profiles have been processed with modern processing flow including time migration. Profiles crossing the South Shetland Trench revealed distinct reflector inside continental slope, which has been interpreted as border between buried accretionary prism and overlying slope sediments of glacial-marine origin. Profiles in the Bransfield Strait show traces of the Last Glacial Maximum (LGM) in the form of glacial foreground valleys, with some of them used as weak spots for young age volcanic intrusions. This paper is the first comprehensive geological interpretation of collected dataset and differences between results from other expeditions are discussed.

Key words: Antarctica, Bransfield Strait, South Shetland Trench, marine seismic, subduction zone, glacier valleys, volcanic structure.

Introduction

Extensive geophysical crustal studies in West Antarctica were made by the Polish Geophysical Expedition in the austral summer of 1979–1980. The expedition was organized by the Institute of Geophysics, Polish Academy of Sciences. The experiment consisted of both deep seismic soundings (DSS) and acquisition of multi-channel seismic profiles (MCS) around the South Shetland Islands (SSI) and in the Bransfield Strait (Fig. 1). Deep soundings results from this and three following expeditions (1984–1985, 1987–1988, 1990–1991) have been interpreted

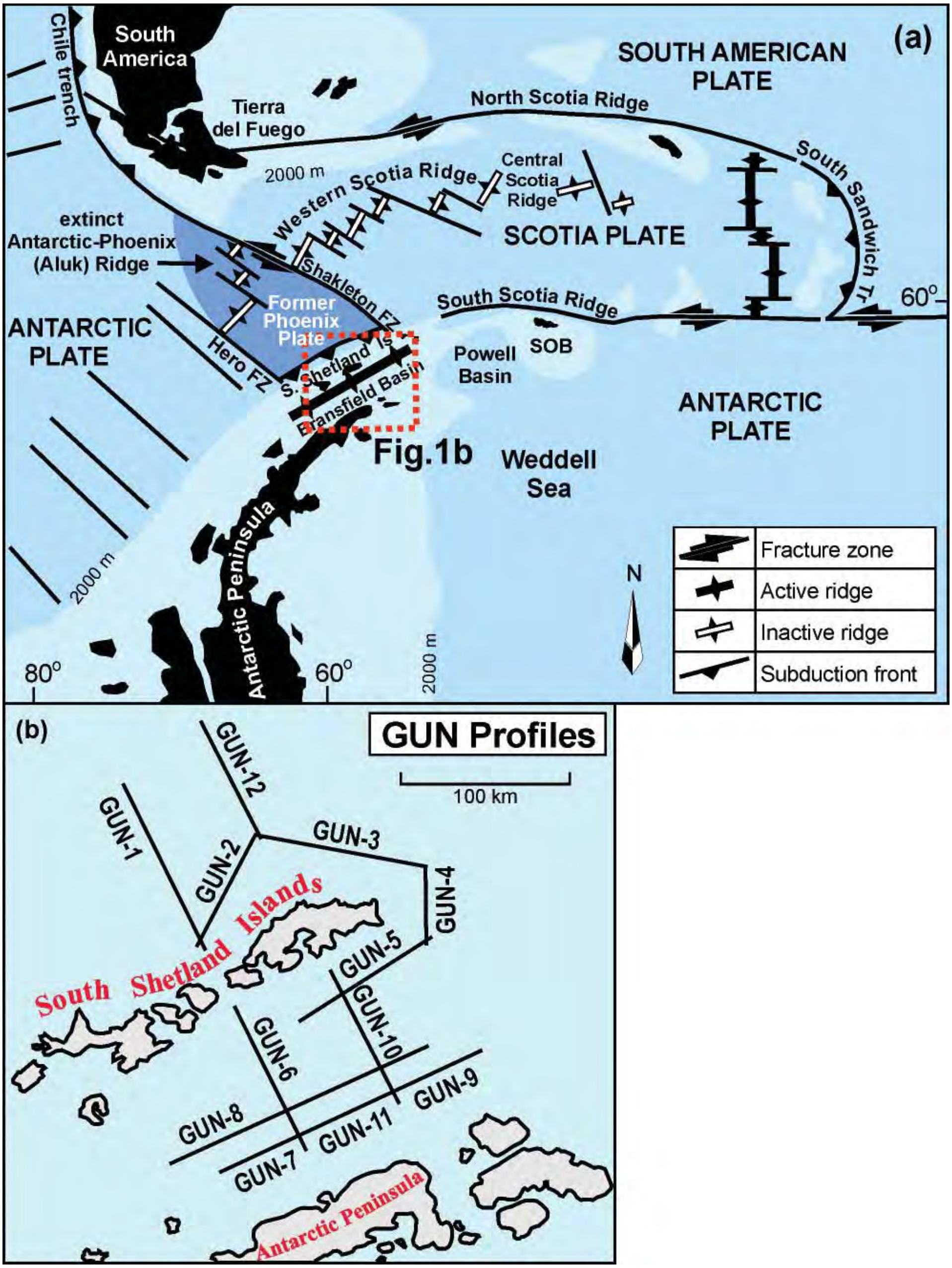

Fig. 1. **a.** Main tectonic units of Antarctic Peninsula and Scotia Sea (Larter and Barker 1991). Dashed line rectangular indicates the area under investigation. Light blue color shows sea-water area shallower than 2000 m., **b.** Map of multi-channel seismic profiles conducted by Polish Academy of Sciences during the Polish Geophysical Expedition in 1979–1980.

and published numerous times, *e.g*. Guterch *et al*. (1985); Grad *et al*. (1992, 1997); Janik (1997a, b); Janik *et al*. (2006, 2014); Środa *et al*. (2002), while the MCS data were never interpreted and they were only published as preliminary results in form of raw single channel sections in after-expedition reports (*e.g*. Guterch *et al*. 1985, 1990) and in summary in the form of part of Antarctic Peninsula – South Shetland Islands seismic transect (Birkenmajer *et al*. 1990). Despite passing years only small numbers of seismic expeditions were carried out in the area of South Shetland Islands from the South Pacific side. East of King George Island (KGI) lays profile 1b of *Antarktis V/2* Expedition (Henriet *et al*. 1992), and in the surroundings there are also profiles from Spanish (Gambôa and Maldonado 1990) and British expeditions (Larter and Barker 1991). In contrast to the outer SSI's side, the inner side (the Bransfield Strait) was covered by a dense net of MCS profiles carried out by several international expeditions (*e.g*. Cunningham *et al*. 1995). Seismic sections from most expeditions are available in a common data base of the Antarctic Offshore Acoustic Stratigraphy Project ANTOSTRAT (*e.g*. Behrendt 1990).

Only few shallow wells have been drilled around SSI. The deepest borehole was the 108.2 m deep SHALDRIL core (Simms *et al*. 2011) located in the middle of the main entrance to the Maxwell Bay from Bransfield Strait, which gives information only for very shallow water sediments (mostly glacial-marine). Ocean Drilling Program made some drills near the Antarctic Peninsula (Barker *et al*. 1999), however, they are few hundred kilometers away from the South Shetland Islands, south to the Hero Fracture Zone, where no traces of subduction zone are visible. Long distance between mentioned drills and experiment area together with different tectonic framework reduced utility of those drills in interpreting of sediments in South Shetland Islands foreground.

Our work is the first attempt at processing and performing full geological interpretation of this dataset in an area largely unexplored seismically.

Tectonic framework

South Shetland Islands lay at the edge of the Antarctic Plate. Shakleton Fracture Zone and South Scotia Ridge to the north-east make a border between the Antarctic and the Scotia plates. However, South Shetland Islands have been also on border between the Antarctic and former Phoenix Plate to the north-west.

The Phoenix Plate was an ancient tectonic plate located to the NW of the Antarctic Peninsula. It started to subduct under Antarctic Plate around 15 Ma (Barker 1982) and this process occurred until about 5.5–3.3 million years ago, when the last ridge segment of the Phoenix Plate reached the south margin of the Hero Fracture Zone (HFZ). The HFZ is a strike-slip fault and north-east from HFZ there is still last remnant of Phoenix Plate preserved up to present times (now considered as a part of the Antarctic Plate), while main subduction stopped around 3.3 Ma ago. South Shetland Trench is remaining part of subduction zone, although oceanic plate is no longer subducting below the Antarctic Plate.

On the other side of South Shetland Islands subduction processes led to the creation of Bransfield Strait. The Bransfield Through is believed to be a young rift system, dated about 3.3 Ma (*e.g.* Galindo-Zaldívar *et al.* 2004). This assumption is confirmed by a High Velocity Body (HVB, with P-wave velocity >7 km/s) discovered by deep seismic expeditions (Ashcroft 1972; Guterch *et al.* 1985; Grad *et al.* 1992, 1997; Janik 1997a, b; Barker *et al.* 2003; Christeson *et al.* 2003; Janik *et al.* 2006) below the Bransfield Thorough. The HVB is believed to be a cause of the rifting process, with melted material originating from the oceanic Phoenix Plate (Janik *et al.* 2014).

Before creation of Bransfield Strait, South Shetland Islands were part of Antarctic Peninsula. Bransfield Rift divided that structure and created South Shetland Block, which started to be pushed in NW direction. This led to the second phase of tectonic activity in SST (*e.g.* Galindo–Zalivar *et al.* 2004) in effect causing distant overlap of accretionary prism on sediments filling SST, with almost horizontal tectonic border of those units. An analogical tectonic structuring can be seen on images from profile ANT 92-17 (NE from KGI see Aldaya and Maldonado (1996) and *e.g.* Maldonado *et al.* (1994); Kim *et al.* (1995) for profiles nearby Anvers Island and between KGI and Elephant Island (Jabaloy *et al.* 2003)).

The Hero Fracture Zone is border between passive and active margins of Antarctic Peninsula. The tectonic map of Barker *et al.* (1999) does not show any old spreading zone on the oceanic plate south-west of HFZ, which is explained to be a result of Ridge-Trench collision south of HFZ that stopped the subduction. Traces of subduction zone shows up to 50 km south as derived from seismic reflection and bathymetry profiles (Larter and Barker 1991; Tomlinson *et al.* 1992; Maldonado *et al.* 1994; Jabaloy *et al.* 2003). Deep seismic investigations (Janik *et al.* 2006) confirmed the results of previous magnetic investigations by Herron and Tucholke (1976), which claimed that the landward projection of HFZ separates the South Shetland Islands and the Bransfield Strait from a continental, passive zone further to the south-west.

North of HFZ main subduction process is ceased, but numerous authors also suggest crustal roll-back under South Shetland Trench (Barker 1982; Larter and Barker 1991; Maldonado *et al.* 1994). In addition there are observations of seismic activity in subduction zone resulting in deep seismic events from subducting plate (Robertson Maurice *et al.* 2003), volcanic activity on South Shetland Islands and earthquakes generating in areas of Shackleton and Hero Fracture zones, as well as around extinct Phoenix Plate Ridges and South Shetland Trench (Kanao 2015). All these activities make South Shetland Islands a highly seismic area.

South of the HFZ early ceasing of subduction (around 3.3 Ma, see Eagles 2003) – changed the basic sedimentation regime on the continental slope and at its base. In the interpretation by Henriet *et al.* (1992), uniform sediment cover of the continental slope and oceanic plate started to grow in the middle Miocene to Pliocene and the process of its growth showed strong dynamics. At the base of the slope, the authors interpret the presence of huge marine landslides (probably oligostrome, as in Jabaloy *et al*. 2003) and debris flows. On border between the Miocene and Pliocene (Rebesco *et al*. 2008) show distinct erosive unconformity, connected to change in the Antarctic ice sheet. Younger sediments however lie in without any unconformity. Map estimating age of the sediments was drawn by those authors for different regions of Antarctica, however without the area of South Shetland Islands.

Data acquisition

The MCS data were acquired using multichannel seismic system DFS-IV and bolt air-guns operated from ORP *Kopernik*. The streamer used in the experiment was 1150 m long with 24 channels (50 m group length). The shot interval varied between 25 m and (in most profiles) 50 m. This gives nominal CDP bin of 25 m and fold of 24 or 12, which by present standards is extremely low. The data were recorded along almost linear profiles (Table 1). The air gun array used was of *ca* 34 litres capacity, 120 bar pressure and towed at 11 meters depth. Data were originally recorded on magnetic tapes, which were read and written as standard SEG-Y files in 1999 by the *Geofizyka Toruń* Company.

Table 1

Shot points (SP) coordinates of MCS profiles
from the Polish Geophysical Expedition 1979–1980.

Name of the profile	Length [km]	No. of shots	First SP coordinate		Last SP coordinate	
			Latitude W	Longitude S	Latitude W	Longitude S
GUN-1	106	2121	61°19’59.66”	60°26’59.27”	62°11’04.39”	59°33’04.58”
GUN-2	69.3	2791	62°10’30.17”	59°39’58.45”	61°41’42.66”	58°48’45.46”
GUN-3	95.1	3860	61°42’59.78”	58°54’58.82”	61°43’08.82”	57°06’10.93”
GUN-4	51.3	1851	61°41’01.37”	57°07’01.11”	62°08’34.50”	57°06’59.69”
GUN-5	104	2046	62°05’59.90”	57°05’00.20”	62°37’09.42”	58°44’31.71”
GUN-6	91.1	1835	62°29’08.27”	59°12’50.88”	63°13’02.21”	58°24’56.17”
GUN-7	43.2	1960	63°07’31.73”	58°29’58.72”	63°18’01.60”	59°23’08.15”
GUN-8	145	5861	63°16’00.03”	59°55’59.17”	62°43’14.12”	57°20’05.25”
GUN-9	74.6	2972	62°41’59.76”	56°31’00.39”	62°59’03.43”	57°50’15.37”
GUN-10	83.2	1637	62°19’00.04”	58°14’59.75”	62°58’59.50”	57°32’00.88”
GUN-11	43.6	1735	62°59’16.04”	57°48’53.93”	63°09’06.94”	58°35’33.11”
GUN-12	102	1599	61°44’42.07”	58°04’48.61”	61°05’53.42”	59°25’40.80”

Data processing

The main goal of this project was to get as much geological information as possible from archival dataset using modern processing techniques. Unfortunately, various problems were encountered, which seriously hampered processing of seismic data:

- Short streamer – the maximum recorded offset was 1258 m, while the seafloor was as deep as 4.8 km in the middle of the subduction zone. Basically all data below the continental slope are too deep to allow any velocity analysis; CDP gathers are almost flat even without NMO corrections.
- 50 m receiver spacing – in addition to low fold, such a big spacing (100 m spacing in CDP domain) is a cause to spatial aliasing clearly seen in the F-K domain. Spatial aliasing is a serious problem in many processing procedures.
- Source signature was not recorded during acquisition – which reduced effectiveness of deconvolution attempts.

The final processing flow consisted of water noise filtering (F-K and bandpass filters), gain, predictive deconvolution, velocity analysis, NMO correction and post- or pre-stack time migration (very minor difference in final stack). Data were processed using GLOBE Claritas software suite. Major improvement was obtained by predictive deconvolution, because the original data were highly reverberated. No depth conversion was made due to insufficient velocity analysis' precision – both seismic and geological sections are in two-way travel time rather than depth.

Dominant frequency varied between profiles as the depth of the streamer changed – this was the main technical cause of difference in quality between profiles. Better recordings were made with streamer towed at around 24 meters depth (profiles GUN-8 and GUN-10), while deeper streamer depth of 28 meters resulted in profiles of considerable worse. This is explained by the change in "ghost notch" – frequencies attenuated by the "ghost" wave (wave reflected from sea surface), which for streamer of 24 m depth would attenuate frequencies around 30 Hz, while for streamer depth of 28 m the notch is around 26 Hz. Unfortunately nothing can be done to overcome this problem, especially since the source signature was not recorded. In modern seismic surveys much smaller streamer depths are used (usually less than 10 meters) which preserves the useful frequency ranges by placing ghost notches at higher frequencies (>75 Hz). The GUN-12 profile, which was carried out at the end of the experiment, was conducted with streamer depth of only 13 meters, which improved the quality of the sedimentary reflections considerably compared to the parallel GUN-1 profile (Fig. 2).

Various attempts on multiple removal were made, including radon analysis and Surface Related Multiple Elimination (SRME, see Verschuur *et al*. 1992), yet no significant results were obtained due to outdated acquisition schemes (mostly due to low fold and a lack of far offsets) and difficult geological

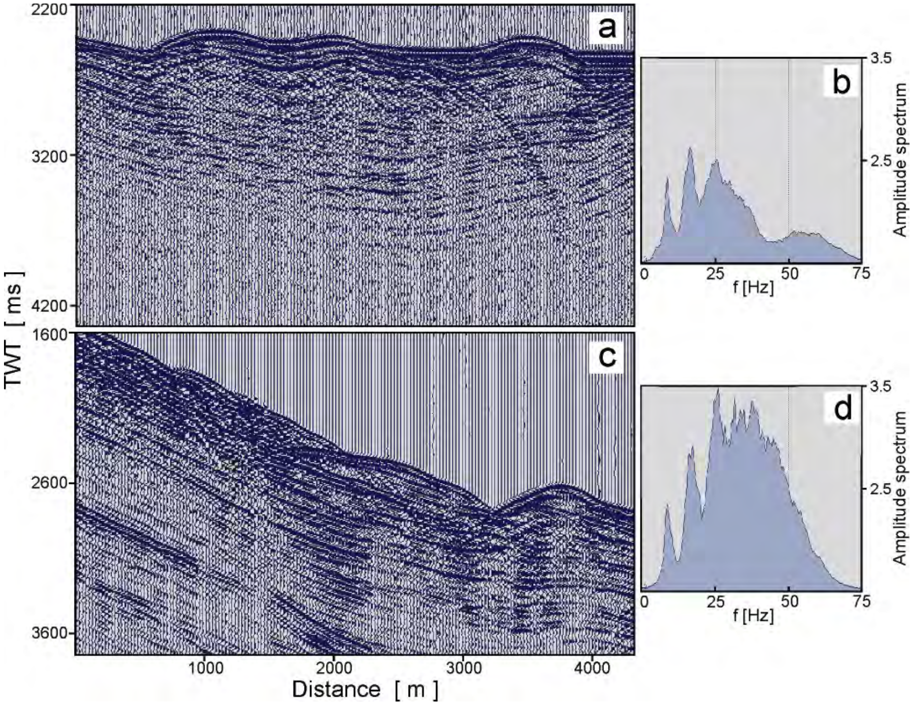

Fig. 2. **a.** Fragment of GUN-1 profile, notice low dominant frequency of registration around 20 HZ, visible also on frequency spectrum **b**, **c**. Fragment of GUN-12 profile with significantly higher dominant frequency around 30 HZ and significantly stronger resolution (40–50 HZ) component, visible also on frequency spectrum **d**.

setting (very compacted seafloor built from glacial sediments). The data were tail-muted if multiples were very visible to make final section more clear, but some multiples are still present on final sections. Most of the data do not provide reliable RMS velocities, so interval velocities could not be derived. Most of the interpretation takes account of only the shape and strength of reflections rather than velocity (similar to single channel data analysis). Even with no detailed velocity information, the data were stacked, which improved S/N ratio considerably compared to previous publications of only near-trace sections. An example of the processing results for GUN-12 profile can be seen in Fig. 3.

Geological interpretation

South Shetland Trench – Profiles GUN-1 and GUN-12. — Both profiles run from the termination of the oceanic plate through the South Shetland Trench, ending up high over the continental slope in the surroundings of South Shetland

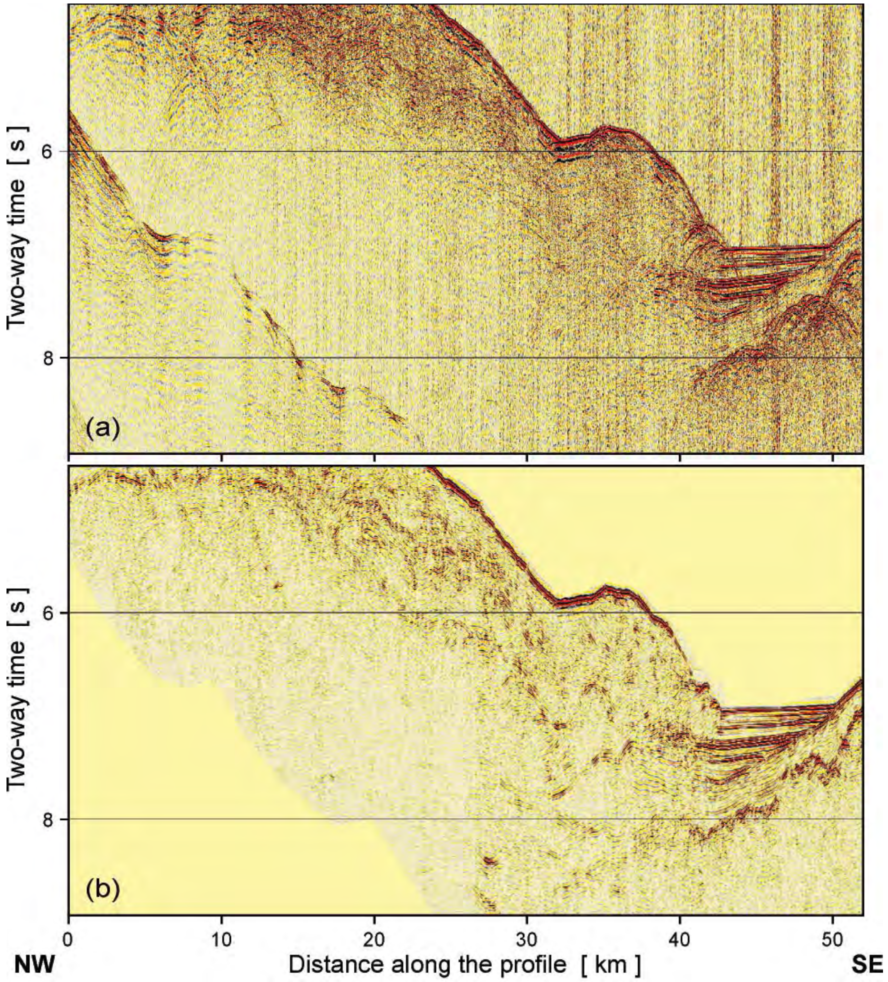

Fig. 3. Fragment of seismic section from GUN-12 profile, **a.** before and **b.** after processing.

Islands (Fig. 4). Our data corroborate well with the results of Spanish ANT-92 (Gambôa and Maldonado 1990) and English BAS-845 (Larter and Barker 1991) expeditions (Fig. 4). Presented profiles document huge marine landslides on the upper part of the profile, the continental slope in the middle and plate subduction in the trench area (Figs 5–6).

Profiles start at the edge of the trench sediment formations where the ocean plate has already subducted below continental plate. Oceanic sediments (purple layer on Figs 5–6) is clearly distinguishing itself from trench sediments due to lack of strong inner reflections. This layer is built from pelagic or semi-pelagic sediments, since all heavier materials from South Shetland Islands would be surely deposited in trench (Kim *et al*. 1995). Oceanic bedrock (gray layer on

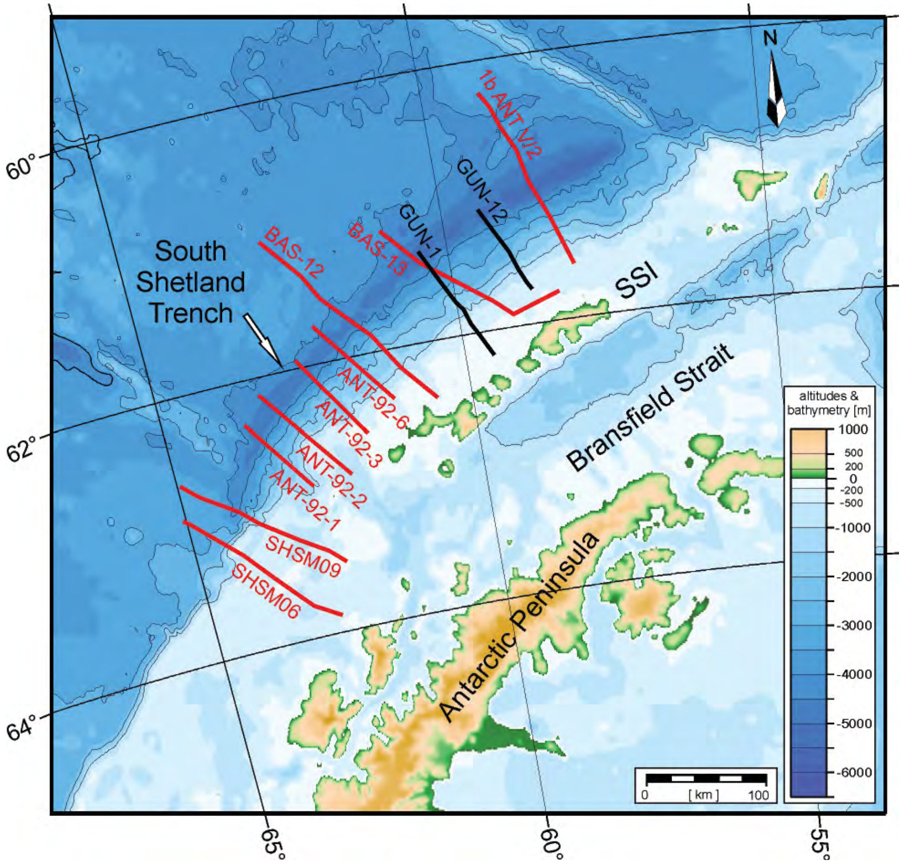

Fig. 4. Map of seismic profiles from later expeditions (red color) used for interpretation of South Shetland Trench profiles. Bathymetry (legend on figure) from ETOPO1 (Amante and Eakins 2009). Profiles SHSM06 and SHSM09 from Jabaloy *et al.* 2003, BAS-12 and BAS-13 from Kim *et al.* 1995, 1b ANT V/2 from Henriet *et al.* 1992, ANT92 from Maldonado *et al.* 1994, GUN-1 profile can be seen on Fig. 5, and GUN-12 on Fig. 6.

Figs 5–6) was recognized due to very strong and continuous reflection, as well as strong migration parabolas prior to seismic migration. There are some minor faults visible on bedrock surface, which is understandable in surroundings of subduction zone.

Trench sediments are clearly divided into two main layers. The first one (marked red on Figs 5–6) has some significant interior reflections, probably because it is built from relatively recent, unconsolidated sediments. Maldonado *et al.* (1994) suggested that trench sediments of this thickness may be only few hundred thousand years old. Deeper layer (marked pink in Figs 5–6) do not generate any significant internal reflections and thus is more similar to oceanic sediments, yet strong reflection on border between deeper trench sediments and oceanic sedi-

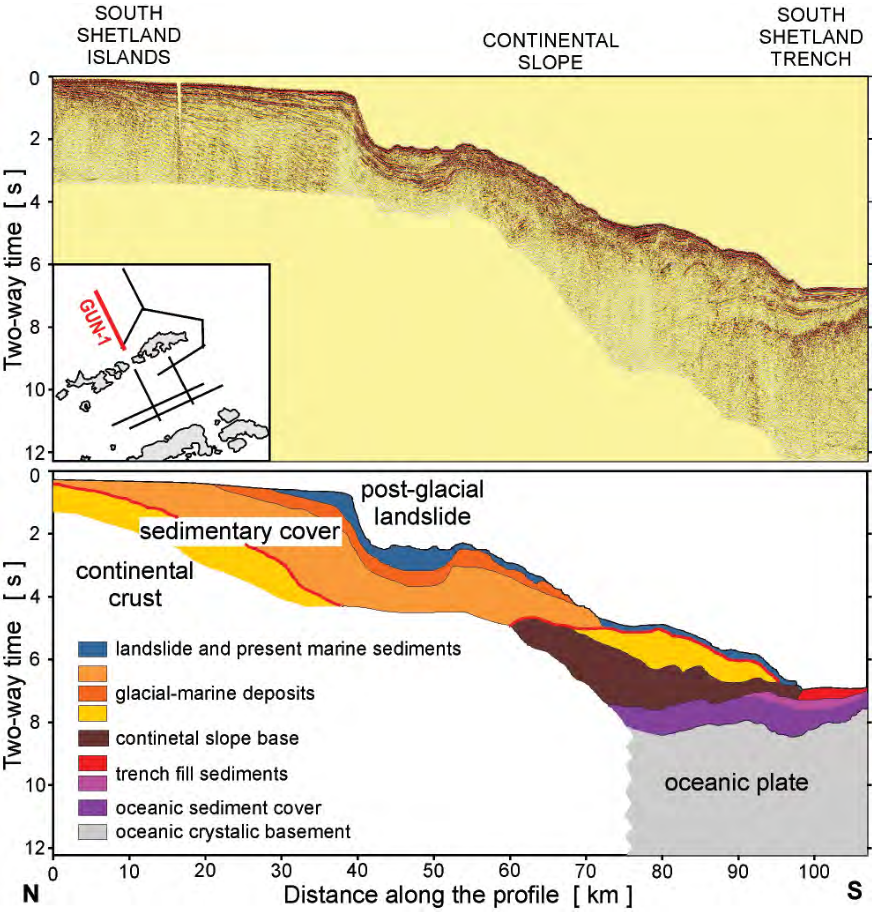

Fig. 5. Seismic section and geological scheme of profile GUN-1. Colors represent different layers as described on figure's legend.

ments clearly indicate significant contrast in acoustic impedance (and probably in density). Kim *et al*. (1995) stated that trench fill sediments are probably high resolution record of few glacial-interglacial cycles. Distinctive border between two subunits of trench sediments indicate major change in sedimentation regime. Unfortunately due to lack of drills in trench sediments, there is no possible sediments dating available, however older sediments (violet in Figs 5–6) would be associated with the period before the creation of the series of glacial-marine strata (marked gold), and before the beginning of the South Shetland Block movement caused by the creation of the Bransfield Through. Quaternary sediments (marked red in Figs 5–6), as generated in deep sea conditions, should be clay deposits, with possible interbeds created by density currents, marine landslides, and dropstones as well as bigger ice-rafted blocks (Gilbert 1990; Michalchuk 2009).

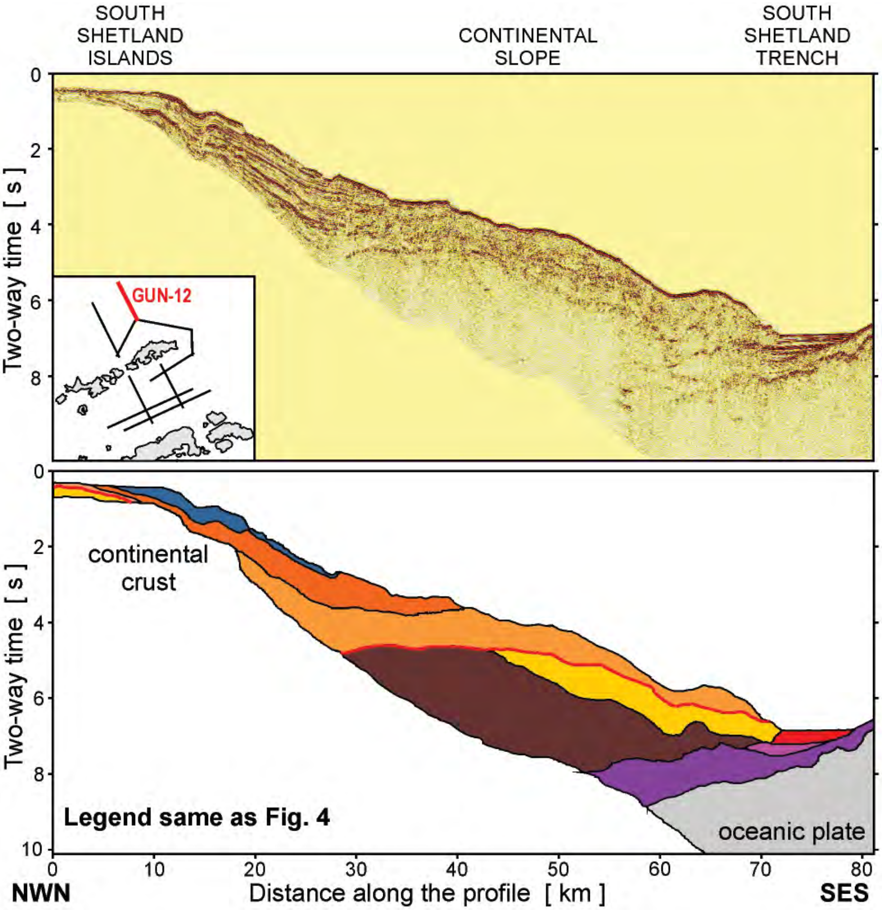

Fig. 6. Seismic section and geological of profile GUN-12. Same colors as in Fig. 5.

Analysis of continental slope's image recorded on our section give new insight in internal structure of continental slope base. Maldonado *et al*. (1994) interpret accretionary prism outcropping on seafloor in lower part of profiles, and suggest that overlying layers are part of "Hesperides fore-arc basin" sediments. Moreover, they saw distinctive reflection inside accretionary prism yet they interpreted it as internal boundary. On our profile this reflection is clearly a border between two distinct layers: upper is much less compacted, with numerous internal reflectors, while lower is more compacted, and no further reflection can be see under this layer boundary. It led us to conclusion that previous interpretation of Maldonado *et al*. (1994) overestimated accretionary prism, which on our profiles should be restricted only to area below the last visible reflection (brown layer on Figs 5–6) while overlaying layers are continental slope sediments. Our profiles clearly show the upper boundary of the accretionary prism, which was not visible on the BAS profile and was marked on the ANT-92 profiles as a layer boundary inside the accretionary prism (boundary above brown layer on Figs 5–6). On our data this boundary is clearly visible probably due to our air-guns having 34 liters volume, compared to 8.5 liters only for BAS-845 and 16 liters for ANT-92.

Continuous boundary and strong reflection visible far below the continental slope sediments is indicating high acoustic contrast between layers which made us into assumption that continental slope base is built from higher density material, accretionary prism or metamorphic basement (Birkenmajer 1990), significantly denser than overlaying continental slope sediments.

Continental slope is overlapped almost horizontally over trench sediments. Golden layer is overlapping on purple sediments, while brown layer is overlapping on oceanic sediments subducted under the trench. This displacement is caused by roll back of South Shetland Block over the trench caused by opening of Bransfield Rift. In our image of the profile no decollement can be found. If oceanic sediments are stripped from the bedrock, and thus creating accretionary prism, it is happening somewhere deeper and further landward.

Above the continental slope base we can distinguish up to three layers of glacial-marine sedimentation on the continental slope, plus recent marine deposits on the top of older layers. This whole complex can be equivalent of “Hesperides fore-arc basin” sediments after Maldonado *et al*. (1994). The deepest of these layers (golden color on geological schemes on Figs 5–6) is clearly distinguished on the section, even though no interpretations of this layer’s bottom boundary have been provided by previous expeditions. In our opinion this layer is built from the oldest glacial-marine sediments (probably Miocene: see Davies 2012). This layer is limited by an erosion surface (Rebesco and Camerlenghi 2008), marked by red line on our sections (Figs 5–6), with Pliocene-Holocene layers of the glacial deposits (Davies *et al*. 2012) lying above. Increased thickness of glacial-marine sediments on profile GUN-1 (compared to other profiles) can be caused by lying on the extension of the Nelson Strait (between Roberts and Nelson islands), which would be major route of transporting melted material from glaciers (Davies 2012).

The conditions of sedimentation also varied during the mapped timeframe. During older glaciations, before creation of the Bransfield Strait (*ca* 3 Mya, Galindo-Zalivar *et al*. 2004), the ice cover of the Antarctic Peninsula was a single entity with a continental dome, which provided similar conditions for development of the edge of ice shelf and connected sedimentation. During the Pleistocene glaciations, mainly the Last Glacial Maximum (LGM), part of the ice cover reaching the area of SSI was an ice tongue connected at the base with the continental ice cap, yet separated in the eastern part by the ice gulf of Weddell Sea (Davies *et al*. 2012).

The reach of the marine-glacial slope sedimentation seems to be smaller near KGI than nearby Anvers Island, which creates difficulties when using the sedimentation scheme described by Camerlenghi *et al*. (2002), as it was constructed for area south of HFZ, not the foreland of South Shetland Island. The reach of the Antarctic ice sheet during LGM (max 15.000 ya) did not change during a long period of time, from 20 to 10 thousands of years (Michalchuk *et al*. 2009), in NE direction (Elephant Island), reaching 50 km from KGI. The primer line was around present isobath of 400 m. The deep part of the Bransfield Through was at that time free from ice (Simms *et al*. 2011; Davies *et al*. 2012). This extent of the LGM ice sheet let us assume that younger marine-glacial sediments on the continental slope of KGI are related to this phase of glaciations. All earlier glaciations had “easier task” as the Bransfield Strait did not exist, so there was shorter distance to the edge of continental shelf. The lack of deep boreholes around the South Shetland Islands archipelago restricts further interpretation of glacial deposits.

Due to the limited resolution of our seismic data there is a possibility that some thin layers of the recent sediments, not marked on the figures, are in fact present in upper part of glacial sediments. The layer marked on all figures with blue color indicates that there is a significant, well visible layer of recent, unconsolidated sediments overlaying deeper rocks. Analogically to bedrock layers which were marked in areas of good signal-to-noise ratio – they probably reach outside the colored area, yet our data are not conclusive. Both of these comments apply to all profiles discussed in the following.

Profiles around South Shetland Islands GUN-2, GUN-3 and GUN-4. — Most of the profiles around KGI were conducted in shallow water where the acquisition design was not optimum (low dominant frequency and large receiver spacing). Profile 2 (location marked on Fig. 1) shows a layer built from high density glacial-marine sediments dipping NNW, similar to the continental slope (Larter and Barker 1989). The same layer can also be seen on the crossing profile GUN-1. The rest of GUN-2 and GUN-3 are of very poor quality, and therefore not included in this paper. The first arrival refraction shows high sea-floor velocities of around 3000 m/s, which indicates highly compacted glacial sediments. No deeper reflections can be seen because very strong multiple reflections cover all recordings. At the GUN-4 profile one can see the edge of the South Shetland Islands passing into the Bransfield Strait (Fig. 7). Some deeper reflections were also recorded, although they are highly discontinuous, probably because of tectonically deformed bedrock.

Bransfield Strait Profiles (GUN-5 to GUN-11). — GUN-5 profile (Fig. 8) is a continuation of profile GUN-4 along the South Shetland Islands, on the side of the Bransfield Strait Trough. Two examples of uplifted bedrock material

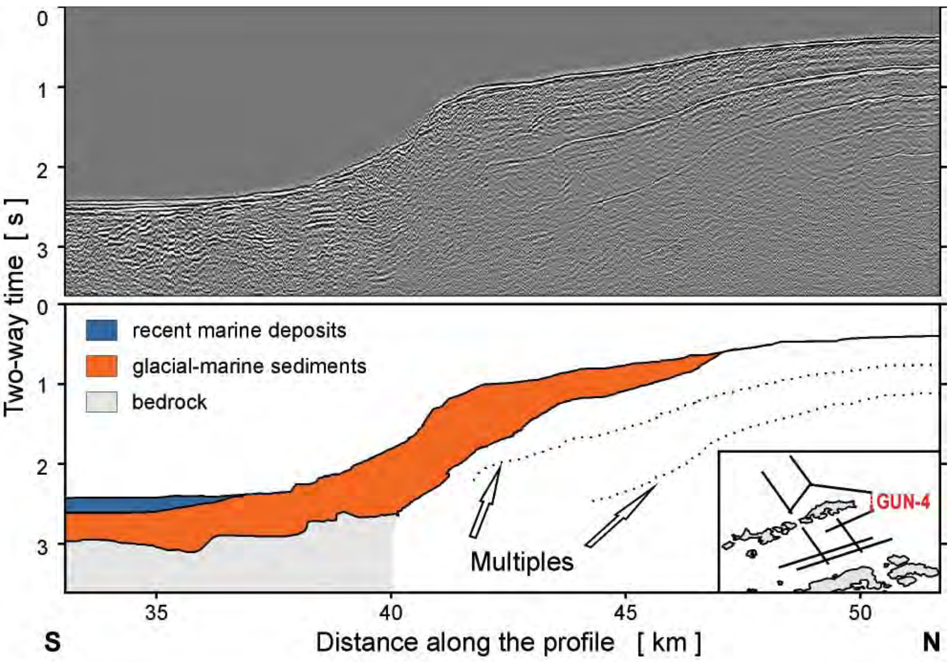

Fig. 7. Slope on the edge of Bransfield Strait – part of GUN-4 profile.

on the seafloor are clearly visible. The northern one looks relatively young – glacial-marine sediments are still covering the uplift, although highly deformed. Some weak, internal reflections were recorded in the sediments and one stronger reflection was observed on top of the bedrock beneath. The bathymetry shows that this structure is part of a nearby seamount. A smaller, shallow block to the south looks like a small dyke which has reached the seafloor. This sea-floor uplift can be of volcanic origin, since the volcanic belt in Bransfield Strait lies parallel to the South Shetland Islands and this profile (Grácia *et al*. 1996).

Profile GUN-6 crosses the Bransfield Strait (Fig. 9) – starting between Robert and Nelson islands toward the Antarctic Peninsula. The profile presents (Fig. 9 going from left to right) the slope of the South Shetland Islands, a seamount (of volcanic origin) bounded by two sedimentary basins, and the gently inclined slope of the Antarctic Peninsula. Judging from reflection's energy and velocity analysis the sea-floor sediments are of low density and compaction and they are probably of very young age (LGM or younger). Beneath the first layer there are sediments with higher velocities, which coupled with relatively strong reflection would indicate higher density – probably of glacial origin. Volcanic

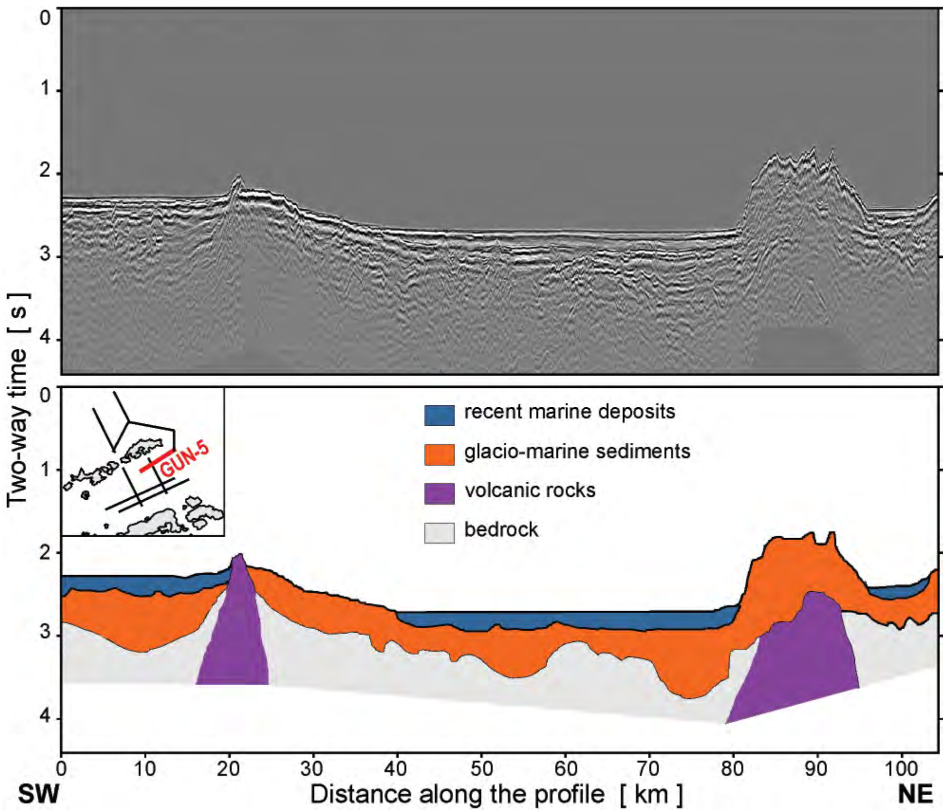

Fig. 8. GUN-5 – continuation of GUN-4 profile alongside the South Shetland Islands.

products seem to be flowing over older parts of the sediments. A possible fault location from Gràcia *et al*. (1996) was marked in Fig. 9, yet no faulting could be clearly seen on our profile which extends about 15 km further to SW. The overall penetration range through the profile is very low, no deeper reflections are visible. The volcanic edifice clearly visible in the middle of the profile is part of the rift volcanic belt going from the Deception Island to Bridgeman Island (Birkenmajer 1995).

Profile GUN-10 (Fig. 10) is the second profile which crosses the Bransfield Strait. This profile had a different streamer depth, which changed the frequency spectrum of the records. After deconvolution this gave us a seismic section with much better seismic resolution. A complex system of glacier sediments was revealed on the western flank of the profile, with at least 3 distinct boundaries which could be connected to different glacial periods. The thickness of sediments might be explained by the high capacity for material transport by melt waters outflow from glaciers above the Antarctic Sound. The Antarctic Peninsula's

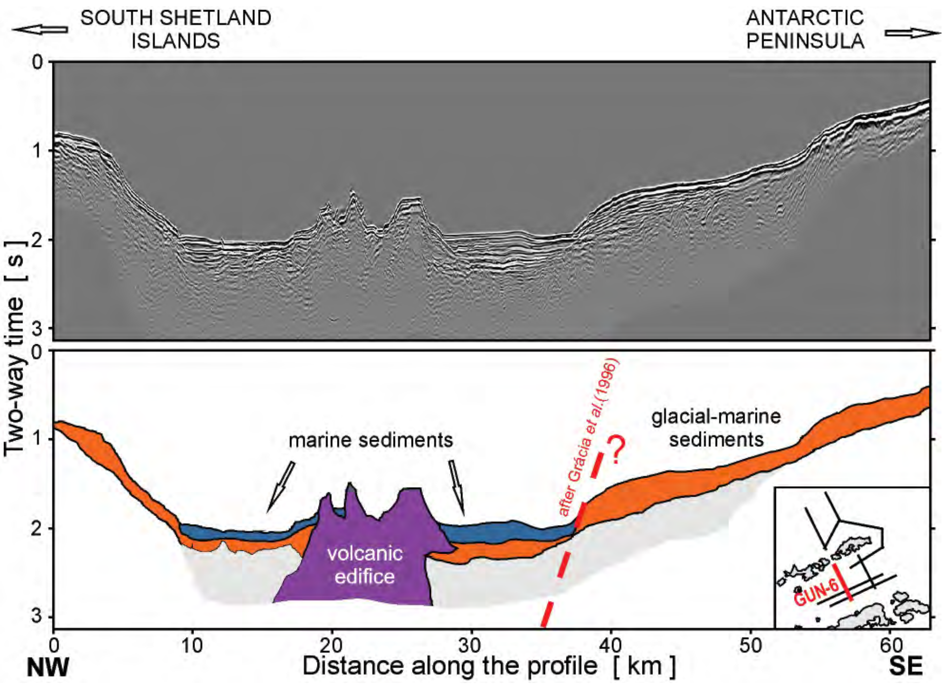

Fig. 9. Profile GUN-6 going across the Bransfield Strait.

flank has significant traces of sequential glacial periods, which are reflected in distinctive layers inside the continental slope. Similar features are visible at GUN-6 profile's slope, although with much less details. The velocity analysis shows velocities of around 3000 m/s, which indicates highly compacted glacial sediments. This appears as typical sedimentation of subsequent glaciations and deglaciations periods.

Profile GUN-8 and profiles GUN-7, GUN-9 and GUN-11 form two long seismic sections located on the shelf parallel to the Antarctic Peninsula. They cross a system of glacier valleys in the southern Bransfield Strait, as shown on Fig. 11. Most of the profiles from the Bransfield Strait are partly very shallow and are highly contaminated with multiple reflections created by hard rock seafloor. Similar to GUN-4 profile, most of the seafloor is covered with highly compacted glacial sediments with Vp velocity around 3 km/s. Sparse shot and receiver spacing and unknown wavelet limit our possibilities of removing multiples, which in shallow areas completely cover any following arrivals.

At the SW edge of the GUN-8 profile one can see a valley with continuous sediments (Fig. 12) and sediment uplift in the middle of the valley. The parallel profile GUN-7 (Fig. 13) suggests that the uplift represents an about 400 m high,

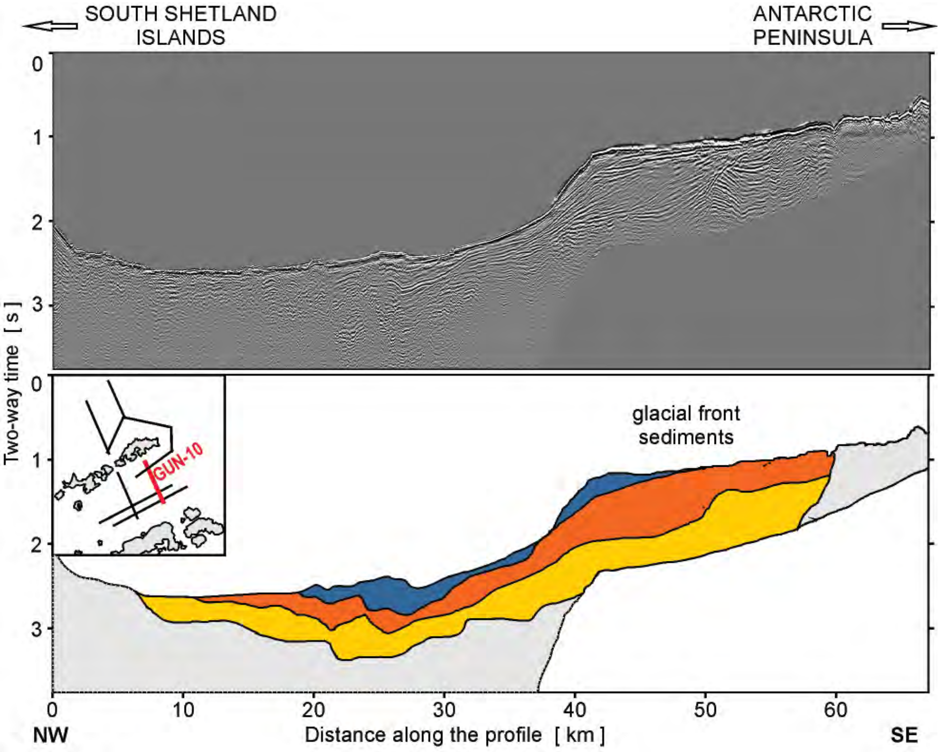

Fig. 10. Seismic section and geological scheme of profile GUN-10. Subsequent glacial deposits marked with blue, yellow and orange color while bedrock was marked with gray color.

probably volcanic intrusion, which has not reached the seafloor on profile GUN-8. We thus interpret this as a glacier valley with a volcanic intrusion, which agrees with previous publications about a shallow batholith with high density and high Vp velocity below the Antarctic Peninsula margin (*see* Garret (1990); Yegorova *et al*. (2011). There, a huge, high-density body is located right next to the AP margin, while Janik (1997b) interpreted the high velocity layer at 2 km depth (visible at ~220 km of DSS-17 profile). It is highly probable that this intrusion has its roots in the above-mentioned batholith.

Prolongation of the GUN-8 profile (Fig. 14) shows few details due to very strong multiple reflections. The profile reveals two glacier valleys, which have been cut through heavily compacted sediments. Some of the interfaces below the seafloor are continuous and rather flat between valleys, which proves erosion, not tectonic formation of those valleys. Based on their shape, both on our profiles and the bathymetric image, we assume they are glacier foreground valleys.

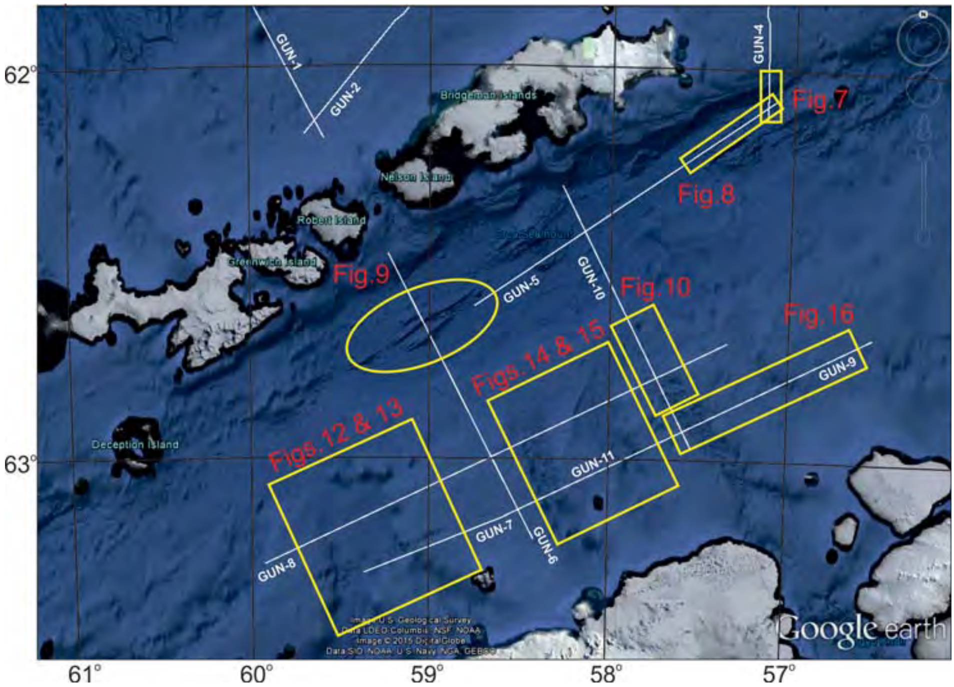

Fig. 11. Bransfield Strait's profiles on the background of Google Earth seafloor image. Yellow geometrical figures point the seafloor areas with characteristic forms on seismic sections corresponding to: Figs 7 and 8 show Bransfield Strait's edge and nearby seamount; Fig. 9 shows volcanic edifice in the middle of spreading zone; Fig. 10 shows edge of Bransfield Strait on the Antarctic Peninsula side; Figs 12–16 show glacier valleys in the southern Bransfield Strait, in shelf of the Antarctic Peninsula.

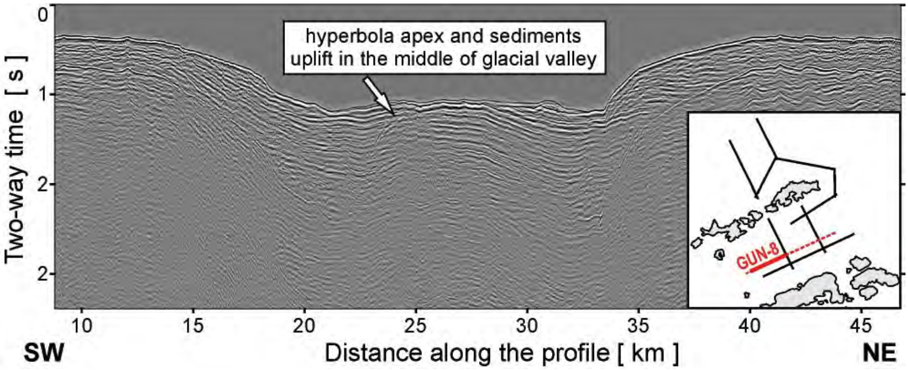

Fig. 12. Western part of GUN-8 profile – Seafloor valley with easily spotted sediment uplift in the middle.

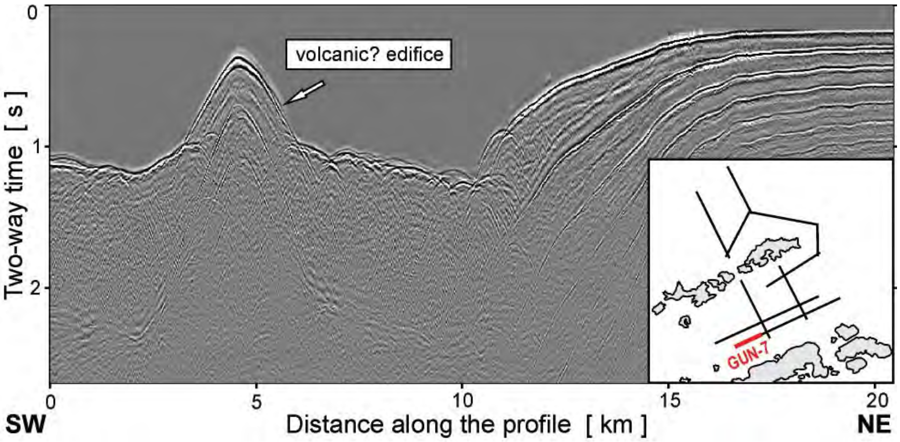

Fig. 13. GUN-7 profile parallel to profile GUN-8. Same glacial valley yet with big, probably volcanic intrusion.

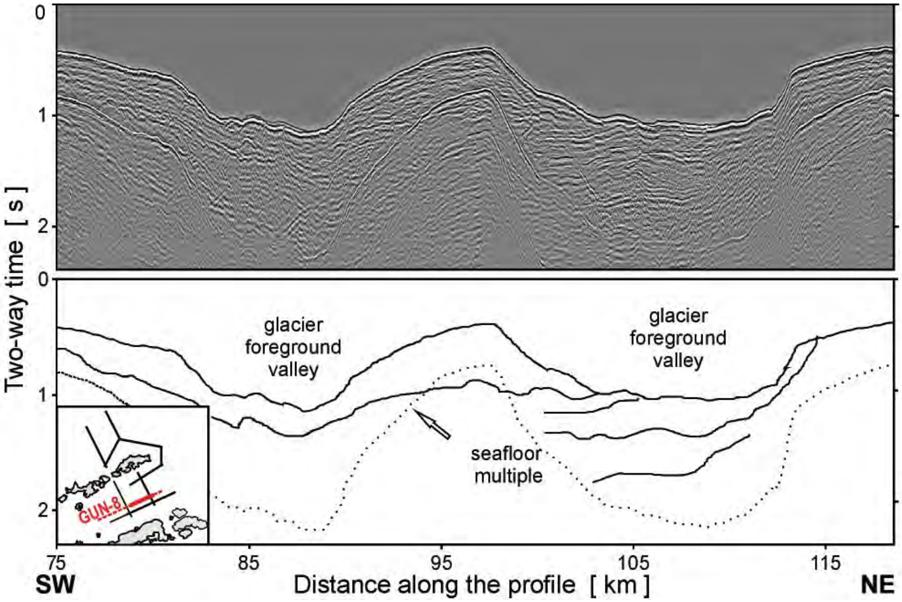

Fig. 14. Eastern part of GUN-8 profile. Valleys with continuous sediment layers below reveal compaction and erosion genesis rather than tectonic origin.

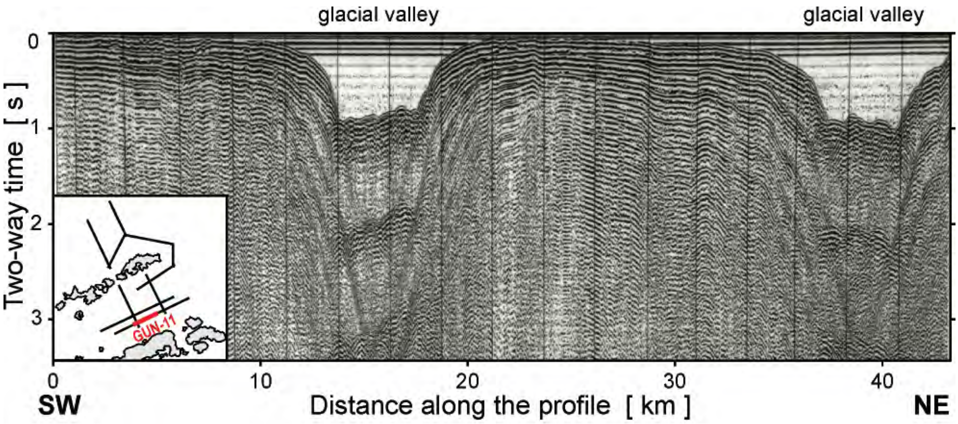

Fig. 15. Profile GUN-11 scanned from on the board single channel printer with no processing.

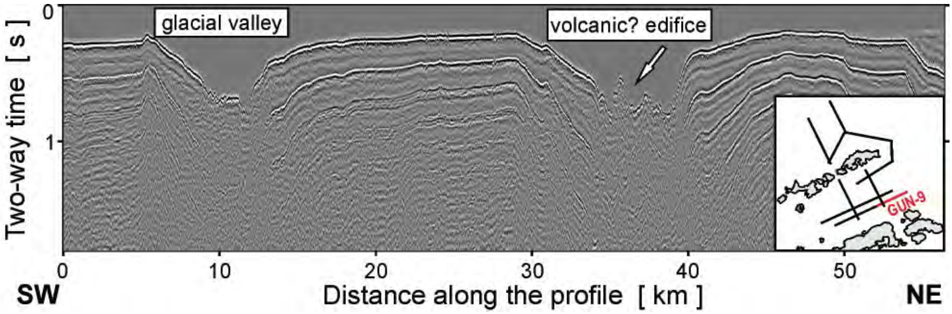

Fig. 16. GUN-9 profile in southern Bransfield Strait.

The tapes for profile GUN-11 was partly corrupted, creating multiple gaps in shots. The profile was only available in form of a print from the on-board single channel camera as profile preview (Fig. 15). The output is highly reverberated and is a good example of typical raw data from this expedition. Two glacier valleys are easily recognizable on the sea floor, but nothing below can be seen due to signal reverberations, strongly attenuated on other profiles by deconvolution.

Profile GUN-9 (Fig. 16) is the easternmost of the glacial valley subset. The profile shows two valleys; unfortunately, due to poor quality, small water depth resulting in strong multiples and no parallel profile it can only give some information about sea-floor morphology. The floor of the valley on the right part of the profile appears like a volcanic intrusion.

Discussion

Our dataset, despite being old, reveals new geological information – especially in the area of the South Shetland Trench and its accretionary prism. In all of the profiles from the SST area (both presented in this paper and in the previous works of Maldonado *et al*. 1994 and Kim *et al*. 1995) oceanic sediments are subducting mostly undisturbed under the continental plate and decollement of oceanic sediments from the oceanic bedrock is not visible at any profile. Maldonado *et al*. (1994) interpreted significant accretionary prism inside the lower part of the continental slope with thickness of about 5 km (at least, since we do not know exact depth of the accretionary prism roots) starting at the trench and reaching far up the slope. On our profiles, we distinguished reflector which divides the continental slope and could be interpreted as accretionary prism buried under slope sediments. In our interpretation, the bottom layer has a thickness of about 2 km, much less than the accretionary prism in the interpretation of Maldonado *et al*. (1994).

In addition, we believe that presence of 5 km thick accretionary prism is not possible due to the subduction parameters, such us convergence rate and thickness of sedimentary cover. Subduction started around 50 Ma and ended with ridge collision 3.3 Ma (see Eagles 2003) with convergence rate about 30 mm/y. Thickness of sediments on the oceanic plate is relatively low (maximum 300 meters), and trench sediments thickness is less than 1 km, (which would indicate very small sedimentation from the continent side). Clift and Vanucci (2004) showed that subduction zone with around 30 mm/y convergence rate could accrete about 25% of sediments, and the rest is subducted together with the oceanic plate further into the mantle.

If we calculate this for a 2D model (assuming that character of the subduction zone do not vary alongside the trench) this together would give us: average convergence rate of 30 mm/y multiplied with ~47 Ma of subduction would give us about 1400 km of subducted oceanic plate. If average thickness of sediments on oceanic plate would be 250 meters, which multiplied by 1400 km of subducted plate, gives us estimated area of subducted sediments on geological cross-section of ~350 km^2. Since only 25% would be accreted on the prism, area of accretionary prism on geological cross section should be around 85 km^2.

On the other hand, forearc slope (measured as distance between trench and shelf) has 62 kilometers. Maldonado *et al*. (1994) interpreted accretionary prism of 5 km thickness visible as bottom layer of the continental slope. Area of that accretionary prism would have to be around at least 150 km^2 on the geological cross-sections. This gives us accretionary prism almost 75% bigger than estimated accreted sediments area (150 km^2 *vs* 85 km^2), without any compaction, and assuming that decollement acting as roots of the accretionary prism is relatively shallow (around the depth of penetration of our profiles). Adding compaction or placing roots of accretionary prism deeper would further increase that disproportion.

We believe that accretionary prism thickness has been previously interpreted too generously, and should be constrained to the lower boundary as shows Figs 5–6 (brown layer). This statement is by no means ultimate, since there is scarce information about bottom layers of the continental slope. All scientific expeditions (that authors are familiar with) did not reach to decollement of sedimentary cover, and did not localize roots of accretionary prism. Furthermore accretionary prism boundary shows no tectonic faults which would be expected. According to Clift and Vanucci (2004), forearc slope angle of accretionary subduction zone should be less than 3°, while SSI's slope is almost 10° steep. Restraining accretionary prism to the lower boundary would also help us meet the slope condition as well.

Maintaining steeper slope requires hardrock (volcanic or metamorphic) bedrock, yet we have no evidence of it at all. This would point out to erosion subduction zone, where the bottom layer of continental slope is not an accretionary prism, but already metamorphic rocks of the South Shetland Islands' crust.

Conclusions

Despite following years, the dataset of multi-channel seismic profiles (MCS) collected during the Polish Geophysical Expedition in 1979–1980 retained some valuable geological information, and gives us some new insight into the deep structure of the South Shetland Islands that was not delivered by any other scientific expedition up to date.

The Bransfield Strait's profiles confirm Last Glacial Maximum (LGM) glacier's traces (in the form of glacier foreground erosion valleys) near the middle of Bransfield Strait (as seen on profiles GUN-8 and GUN-11), which provides some hints about the extent of the LGM. Profiles GUN-7 and GUN-8 probably show a volcanic intrusion into a glacial valley in the south Bransfield Strait, with uplift of sediments visible up to a few kilometers away from the intrusion. This might be the location of an intrusion originating from a batholith interpreted by previous seismic and gravity researches.

Most focus of this paper was in the area of South Shetland Trench (SST), where the profiles are of highest quality and revealed some new and interesting information about the deep structure:

- Our profiles revealed distinct horizons below the continental slope of the South Shetland Islands, as well as a subducting, undisrupted ocean plate. An analysis of our image shows that almost the entire continental slope is covered by marine-glacial sediments (which could be considered as a part of

"Hesperides Forearc Basin"); while in our interpretation accretionary prism is restricted to an area below boundary visible inside continental slope.

– All of the profiles from SST do not show location of oceanic sediments decollement from oceanic bedrock under continental crust, therefore we are unable to point out location of root of the accretionary prism.
– The South Shetland Trench sediments are clearly divided in two different units. Older (probably glacial-marine) sediments, partially overlapped by the accretionary prism, had been created most likely before the beginning of the South Shetland Block movement caused by the opening of the Bransfield Through.
– We are uncertain if South Shetland Trench was typical accretionary subduction zone. Seismic data, both reflection and refraction, are not conclusive.
– It seems to be very useful to consider common reinterpretation of existing profiles from other investigations, aiming to confirm (or deny) suggestion of buried accretionary prism.

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References

ALDAYA F. and MALDONADO A. 1996. Tectonics of the triple junction at the southern end of the Shackleton Fracture Zone (Antarctic Peninsula). *Geo-Marine Letters* 16: 297–286.

AMANTE C. and EAKINS B.W. 2009. ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis. NOAA Technical Memorandum NESDIS NGDC-24. *National Geophysical Data Center, NOAA*.

ASHCROFT W.A. 1972, Crustal structure of the South Shetland Islands and Bransfield Strait, *British Antarctic Survey Scientific Report* 66, 43 pp.

BARKER P.F., CAMERLENGHI A., ACTON G.D. and RAMSAY A.T.S. (eds) 1999. Leg 178 summary, *Proceedings of the Ocean Drilling Program, Initial Reports* 178: 1–60.

BARKER P.F., CAMERLENGHI A., ACTON G.D. and RAMSAY A.T.S. (eds) 2002. *Proceedings of the Ocean Drilling Program, Scientific Results* 178: 1–40.

BEHRENDT J.B. 1990. Multichannel seismic reflection surveys over the Antarctic continental margin relevant to petroleum resource studies. *In*: B. St John (ed.) *Antarctica as an Exploration Frontier – Hydrocarbon Potential, Geology, and Hazards*. American Association of Petroleum Geologists, Tulsa. *Studies in Geology* 31: 69–75.

BIRKENMAJER K. 1994. Evolution of the Pacific margin of the northern Antarctic Peninsula: an overview. *Geologische Rundschau* 83: 309–321.

BIRKENMAJER K. 1995. Volcano-structural Evolution of the Deception Island Volcano, West Antarctica. *Terra Antarctica* 2(1): 33–40.

Birkenmajer K., Guterch A., Grad M., Janik T. and Perchuć E. 1990. Litospheric transect Antarctic Peninsula – South Shetland Islands, West Antarctica. *Polish Polar Research* 11: 241–258.

Camerlenghi A., Rebesco M., Santis De L., Volpi V. and Rossi De A. 2002. The Antarctic Peninsula Pacific margin: modelling flexure and decompaction with constrains from ODP Leg 178 initial results. *Royal Society of New Zealand Bulletin* 35: 261–267.

Christeson G.L., Barker D.H.N., Austin J.A. and Dalziel I.W.D. 2003. Deep crustal structure of Bransfield Strait: initiation of a back arc basin by rift reactivation and propagation. *Journal of Geophysical Research* 108 (B10): 2492, 21pp.

Clift P. and Vannucchi P. 2004. Controls on tectonic accretion versus erosion in subduction zones: Implication for the origin and recycling of the continental crust. *Reviews of Geophysics* 42, RG2001, 31 pp.

Cunningham A.P., Vanneste L.E. and Antostrat Antarctic Peninsula regional Working Group 1995. The ANTOSTRAT Antarctic Peninsula regional Working Group digital navigation compilation. *Geology and Seismic Stratigraphy of the Antarctic Margin, Research Series* 68: A297–301.

Davies B.J., Hambrey M.J., Smellie J.L., Carrivick J.L. and Glasser N.F. 2012. Antarctic Peninsula Ice Sheet evolution during the Cenozoic Era. *Quaternary Science Reviews* 31: 30–66.

Eagle G. 2003. Tectonic evolution of the Antarctic-Phoenix plate system since 15 Ma. *Earth and Planetary Science Letters* 217: 97–109

Galindo-Zaldivar J., Gamboa L., Maldonado A., Nakao S. and Bochu Y. 2004. Tectonic development of the Bransfield Basin and its prolongation to the South Scotia Ridge, northern Antarctic Peninsula. *Marine Geology* 206: 267–282.

Gambôa L.A.P. and Maldonado P.R. 1990. Geophysical Investigations in the Bransfield Strait and in the Bellingshausen Sea – Antarctica; *In*: B. St John (ed.) *Antarctica as an Exploration Frontier – Hydrocarbon Potential, Geology, and Hazards*. American Association of Petroleum Geologists, Tulsa. *Studies in Geology* 31: 127–142.

Gambôa L., Cunningham A.P., Bochu Y., Camerlenghi A., Nakao S. and Rudowski S. 1994. Origin and Evolution of the Bransfield Basin Based on Integrated MCS Data. *Terra Antarctica* 2(2): 293–294.

Garret S.W. 1990. Interpretation of reconnaissance gravity and aeromagnetic surveys of the Antarctic Peninsula. *Journal of Geophysical Research* 95 (B5): 6759–6777.

Gilbert R. 1990. Rafting in glacimarine environments. *Glacimarine Environments: Processes and Sediments*. *Geological Society Special Publication* 53: 105–120.

Gràcia E., Canals M., Farràn M.L., Prieto M.J., Serribas J. and GEBRA TEAM 1996. Morphostructure and Evolution of the Central and Eastern Bransfield Basin (NW Antarctic Peninsula). *Marine Geophysics Research* 18: 429–448.

Grad M., Guterch A. and Janik T. 1993. Seismic structure of the lithosphere across the zone of subducted Drake plate under the Antarctic plate, West Antarctica. *Geophysical Journal International* 115: 586–600.

Grad M., Shiobara H., Janik T., Guterch A. and Shimamura H. 1997. Crustal model of the Bransfield Rift, West Antarctica, from detailed OBS refraction experiments. *Geophysical Journal International* 130: 506–518.

Guterch A., Grad M., Janik T. and Perchuć E. 1990. Deep crustal structure in the region of the Antarctic Peninsula from seismic refraction modeling (next step of data discussion). *Polish Polar Research* 11: 215–239.

Guterch A., Grad M., Janik T., Perchuć E. and Pajchel J. 1985. Seismic studies of the crustal structure in West Antarctica 1979–1980 – Preliminary Results. *Tectonophysics* 114: 411–429.

HENRIET J.P., MER R., MILLER H. and the GRAPE TEAM 1992. Active margin along the Antarctic Peninsula. *Tectonophysics* 201: 229–253.

HERRON E.M. and TUCHOLKE B.E. 1976. Sea-floor magnetic patterns and basement structure in the souteastern Pacific. *In:* C.D. Hollister, C. Craddock *et al*. (eds) *Initial Reports of the Deep Sea Drilling Project*. U.S. Government Printing Office, Washington DC: 263–278.

JABALOY A., BALANYÁ J.-C., BARNOLAS A., GALINDO-ZALDÍVAR J., HERNÁNDEZ J., MALDONADO A., MARTÍNEZ-MARTÍNEZ J.-M., RODRÍGUEZ-FERNÁNEZ J., DE GALDEANO C.S., SOMOZA L., SURIÑACH E. and VÁSQUEZ J.T. 2003. The transition from an active to a passive margin (SW and of the South Shetland Trench, Antarctic Peninsula). *Tectonophysics* 366: 55–81.

JANIK T. 1997a. Seismic crustal structure in the transition zone between Antarctic Peninsula and South Shetland Islands. *In*: C.A. Ricci (ed.), *The Antarctic Region: Geological Evolution and Processes*. *Terra Antarctica Publication*, Siena: 679–684.

JANIK T. 1997b. Seismic crustal structure of the Bransfield Strait, West Antarctica. *Polish Polar Research* 18, 3–4: 171–225.

JANIK T., GRAD M., GUTERCH A. and ŚRODA P. 2014. The deep seismic structure of the Earth›s crust along the Antarctic Peninsula – A summary of the results from Polish geodynamical expeditions. *Global Planetary Change* 123: 213–222.

JANIK T., ŚRODA P., GRAD M. and GUTERCH A. 2006. Moho depth along the Antarctic Peninsula and crustal structure across the landward projection of the Hero Fracture Zone. *In*: D.K. Fütterer, D. Damaske, G. Kleinschmidt, H. Miller, F. Tessensohn (eds), *Antarctica: Contributions to global earth sciences*, Springer-Verlag, Berlin Heidelberg New York: 229–236.

KANAO M. 2015, Seismicity in the Antarctic continent and surrounding ocean. *Open Journal of Earthquake Research* 3: 5–14.

KIM Y., KIM H.S., LARTER R.D., CAMERLENGHI A., GAMBÔA A.P. and RUDOWSKI S. 1995. Tectonic deformation in the upper crust and sediments at the South Shetland Trench. *Antarctic Research Series* 68: 157–166.

LARTER R.D. and BARKER P.F. 1989. Seismic stratigraphy of the Antarctic Peninsula Pacific margin: A record of Pliocene-Pleistocene ice volume and paleoclimate. *Geology* 17: 731–734.

LARTER R.D. and BARKER P.F. 1991. Effects of ridge crest-trench interaction on Antarctic-Phoenix spreading: Forces on a young subducting plate. *Journal Geophysical Research* 96: 19583––19607.

MALDONADO A., LARTER L.D. and ALDAYA F. 1994. Forearc tectonic evolution of the South Shetland Margin. *Tectonics* 13: 6.

MICHALCHUK B.R., ANDERSON J.B., WELLNER J.S., MANLEY P.L., MAJEWSKI W. and BOHATY S. 2009. Holocene climate and glacial history of northeastern Antarctic Peninsula: the marine sedimentary record from a long SHALDRIL core. *Quaternary Science Reviews* 28: 3049–3065.

REBESCO M. and CAMERLENGHI A. 2008. Late Pliocene margin development and mega debris flow deposits on the Antarctic continental margins: Evidence of the onset of the modern Antarctic Ice Sheet? *Palaeogeography, Palaeoclimatology, Palaeoecology* 260: 149–167.

ROBERTSON MAURICE S. D., WIENS D. A., SHORE P. J., VERA E. and DORMAN L.M. 2003. Seismicity and tectonics of the South Shetland Islands and Bransfield Strait from a regional broadband seismograph deployment. *Journal of Geophysical Research* 108 (B10), 2461.

SIMMS A.R., MILLIKEN K.T., ANDERSON J.B. and WELLNER J. 2011. The marine record of deglatiation of the South Shetlands Islands, Antarctica since the Last Glacial Maximum. *Quaternary Science Review* 30: 1583–1601.

ŚRODA P. 2002. Three-dimensional seismic modeling of the crustal structure between the South Pacific and the Antarctic Peninsula. *In*: J.A. Gamble, D.N.B. Skinner and S. Henrys (eds)

Antarctica at the Close of a Millennium. *Royal Society of New Zealand Bulletin*, Wellington, 35: 555–561.

TOMLINSON J.S., PUDSEY C.J., LIVERMORE R.A., LARTER R.D. and BARKER P.F. 1992. Long-range side scan sonar (GLORIA) survey of the Pacific margin of the Antarctic Peninsula. *In*: Y. Yoshida *et al*. (eds) *Recent progress in Antarctic earth science*. *Terra Scientific Publishing*, Tokyo: 423–429.

VERSCHUUR D.J., BERKHOUT A.J. and WAPENAAR C.P.A. 1992. Adaptive surface-related multiple elimination. *Geophysics* 57: 1166–1177.

YEGOROVA T., BAKHMUTOV V., JANIK T. and GRAD M. 2011. Joint geophysical and petrological models for the lithosphere structure of Antarctic Peninsula continental margin. *Geophysical Journal International* 184: 90–110.

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