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GEOPHYSICAL MODELS OF DRAKE PASSAGE AND BRANSFIELD STRAIT CRUSTAL STRUCTURE

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Abstract. The 2004 (9th) and 2006 (11th) Ukrainian Antarctic expeditions acquired new geoelectrical data ('short-impulse electromagnetic field formation' – FSPEF, and 'vertical electric-resonance sounding' – VERS) along profiles across Drake Passage and along Bransfield Strait, Antarctic Peninsula, with the aim of studying the crustal structure of these features down to depths of >30 km.
The electromagnetic experiments yielded new data set with unique information about the inner structure of Drake Passage and West Antarctica crust. New values of Moho discontinuity for these structures were obtained. Results of geophysical researches allow investigating the deep structure of the earth's crust in the region where mantle diapirs have introduced to the ancient continental complexes of Bransfield Strait.
Beneath the Drake Passage, Moho is interpreted at extremely shallow depths of 8–12 km; the origin of a deeper anomalous layer at 14–20 km is unknown at this stage. Both Moho and the deeper layer show strong relief in the vicinity of the Shackleton Fracture Zone. Moho in the Bransfield Strait profile is interpreted at depths of 12–28 km, while the lower crustal layers and crust–mantle transition zone show radical variations in depth and thickness. Geoelectrical data confirm possible crustal extension and existence of mantle material at depth of 12-16 km.
Similar results obtained by three different methods (gravity and magnetic surveys, vertical electric-resonance sounding) during Ukrainian Antarctic expeditions in 2004-2006 years assure the notable magmatic dynamism of Bransfield Trough that forms in the conditions of structural transformations and rifting processes migrating NE-SW along Bransfield Strait.
Key words: geophysical data, crustal inhomogeneities, West Antarctica structures

Геофизические модели структуры земной коры пролива Дрейка и пролива Брансфилда.
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Реферат. Проведен комплексный анализ данных геофизических исследований (сейсмических, вертикального электрорезонансного зондирования и магнитного поля) земной коры проливов Дрейка и Брансфилда в Западной Антарктике. По данным магнитных, грави- и электромагнитных исследований были закартированы геофизические неоднородности, выделены зоны дробления и тектонических нарушений в глубинных горизонтах земной коры, построены разрезы и комплексные геофизические модели глубинного строения основных структур дна континентальной окраины Антарктики. При детализации в разрезах выделяются горизонты, которые могут быть связаны с наличием локальных зон промежуточной кристаллизации и прогрева. В проливе Дрейка раздел Мохо выделен на глубинах 8–12 км. Выделение горизонта на глубинах 14–20 км требует дополнительных исследований, т.к. природа его существования остается неизвестной. Раздел Мохо в проливе Брансфилда находится на глубинах 12–28 км, а значения мощности переходного слоя кора–мантия существенно варьируют вдоль геофизических профилей. Сходные результаты, полученные по трем разным методикам, свидетельствуют о значительной тектонической активности и магматической насыщенности трога Брансфилд, который формируется в условиях структурных преобразований, мигрирующих вдоль пролива Брансфилда с северо-востока на юго-запад. Исследования не дают однозначного подтверждения развития активного спрединга и наличия коры океанического типа в этой части пролива.

Геофізичні моделі структури земної кори протоки Дрейка і протоки Брансфілда.
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Реферат. Проведено комплексний аналіз матеріалів геофізичних досліджень (сейсмічних, вертикального електрорезонансного зондування і магнітного поля) земної кори протоки Дрейка і протоки Брансфілда в Західній Антарктиці. За даними досліджень були закартовані геофізичні неоднорідності, виділені зони дроблення і тектонічних порушень у глибинних горизонтах земної кори, побудовані розрізи і комплексні геофізичні моделі глибинної будови структур дна Західної Антарктики. При деталізації в розрізах виділяються горизонти, які можуть бути пов'язані з наявністю локальних зон проміжної кристалізації і прогрівання. У протоці Дрейка розділ Мохо знаходиться на глибинах 8–12 км. Природа глибинного розділу (14–20 км) не з'ясована. У протоці Брансфілда розділ Мохо знаходиться на глибинах 12–28 км, а товщина проміжного шару кора–мантія значно змінюється вздовж профілів дослідження. Результати свідчать про значну тектонічну активність і магматичну насиченість трога Брансфілд, який формується в умовах структурних перетворень, мігруючих з північного сходу на південний захід. Отримані розрізи не дають однозначного підтвердження розвитку активного спредінгу та наявності кори океанічного типу в цій частині протоки Брансфілда.

Introduction

New geological and geophysical data that have been obtained during last years for bottom structures of West Antarctica are of particular importance for evolution and geodynamics processes of this region understanding. Obtained crustal inhomogeneities could be connected with some evolution stages of Antarctic Plate, Drake Passage and magmatic processes of Bransfield Strait. Figure 1 shows the principal tectonic elements of study area [1].

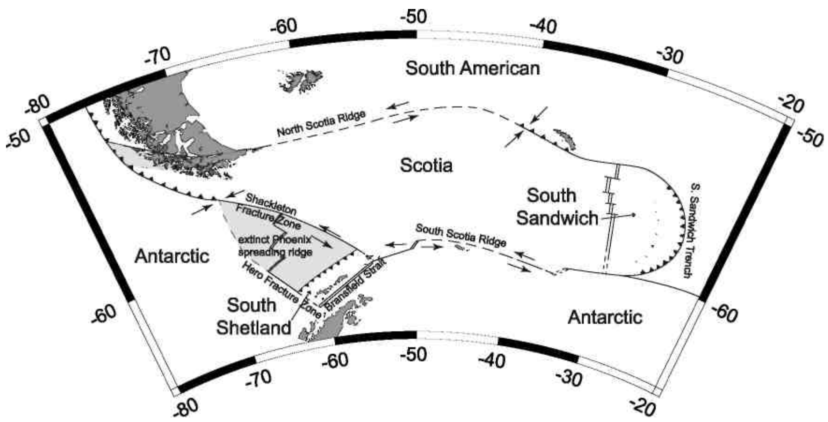

Figure 1. Tectonic map of the Antarctic Peninsula and Scotia Sea region.

Drake Passage – Antarctic Peninsula region is a complex geodynamic system with rapid changes in motions of different parts of tectonic plates. There are some tectonic models that have been proposed to explain the origin and geodynamic evolution of the study area. Geophysical surveys near Antarctic Peninsula enabled to specify the inner structure of some blocks of Drake Passage, Bransfield Strait and continental margin [2–10].

The field methods employed in this study were based: (i) on the use of applied electromagnetic fields which were pulsed, (i.e. non-stationary); and (ii) on measurements of naturally-occurring "quasi-stationary" Earth electric fields; and the spectral characteristics of the latter in the vicinity of investigated objects. More specifically, the field procedures of this study combined the methods of "short-impulse electromagnetic field formation" (FSPEF) and "vertical electric-resonance sounding" (VERS).

The FSPEF method is based on the use of small ferrite dipole antennas to transmit and receive short-impulse electromagnetic fields. This method uses short but high-power electric pulses. Compared with earlier techniques, this method has the benefits of increased field efficiency and productivity. The VERS method is based on processes which polarize naturally-occurring electric fields at the surface of Earth. The polarised fields are analysed for their spectral characteristics. The method makes possible the efficient and accurate determination of a stratigraphic model beneath a sounding site.

These techniques were applied during the 2004 (9th) and 2006 (11th) Ukrainian Antarctic expeditions. Marine observations were carried out from the vessels Ushuaya (2004) and Humboldt (2006) using compact, computerized equipment. The portable measuring equipment "GEMA" (Geo-Electromagnetic Application) was an important element of this technology. GEMA was connected with a GPS-receiver and a laptop computer using special program interfaces.

This equipment allows investigations to be carried out over large areas in short time-frames and at minimal expense [2, 3].

During expeditions more than 200 soundings were done. The main purpose of these works was to investigate the deep structure of the Earth's crust along some profiles through Drake Passage and Bransfield.

Strait area. Profiles were acquired in the Drake Passage between southernmost South America and the northern tip of the Antarctic Peninsula (Fig. 2a) and in the Bransfield Strait in the vicinity of the Ukrainian Antarctic Station Academician Vernadsky (Fig. 2b).

The results are displayed here in the form of interpreted profiles on which the VERS soundings and FSPEF profiles are overlaid. Study area has been the subject of our marine geophysical investigations during 1997-2006 years [2,3]. The geodynamic setting of the crustal structures of this area have been reconstructed from the marine magnetic anomalies, modelling of the gravity anomalies, seismic reflection and refraction results and geoelectrical studies.

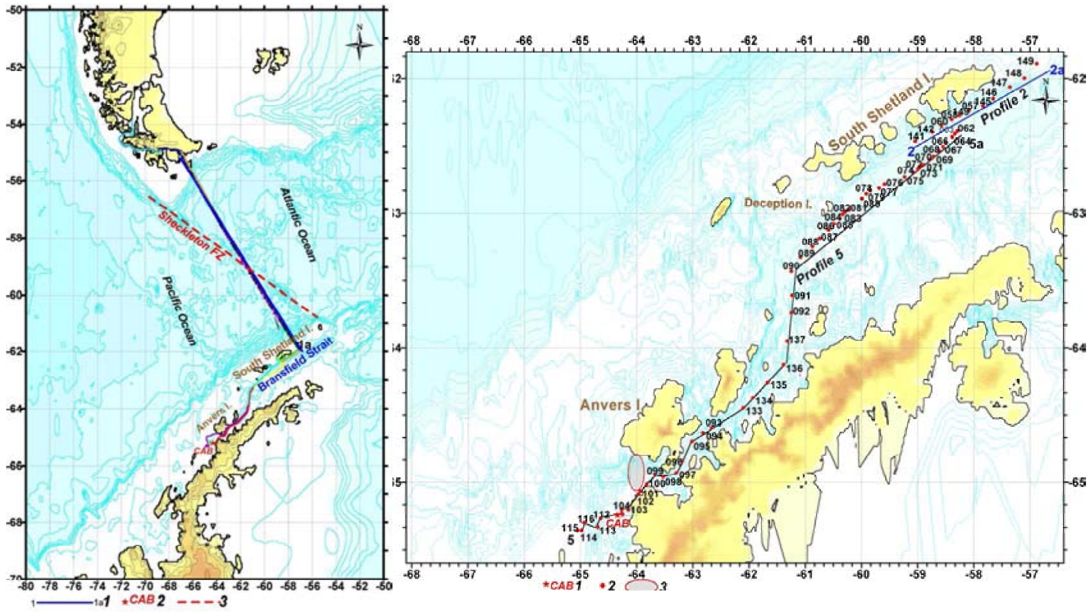

Figure 2a. Location of VERS and FSPEF profile through Drake Passage. Legend: 1 – location of sounding profile; 2 – UAS "Academician Vernadskiy" (Galindez Island); 3 – Shackleton Fracture Zone.
Figure 2b. Location of the VERS and FSPEF profiles on the northern margin of the Antarctic Peninsula (Bransfield Strait). Legend: 1 – UAS "Academician Vernadskiy" (Galindez Is.); 2 – VERS sounding points; 3 – area of “deposit” type geoelectric anomaly.

Investigation results

The results of geoelectrical modeling along these profiles through tectonically active zones of Drake Passage, Bransfield Strait and South Shetland Trench are discussed.

The interpreted geoelectrical cross-section along the profile through Drake Passage shown in Figure 3 was acquired in 2004 down to a depth of approximately 7 km. In 2006, the application of the VERS technique was modified to allow the acquisition of data down to a depth of >30 km (Fig. 3). from north to south (left to right) the profiles show the continental crust of the South American continental margin, oceanic crust of the Scotia and Pacific Plates, separated by the Shackleton Fracture Zone, southwards subduction of the Pacific Plate at the South Shetlands Trench, and the continental crust of the Antarctic Peninsula.

The areas of raised polarization and geoelectrical resistance (dike zones), as well as area of the lowered geoelectrical resistance (zones of the crushing) stand out on sounding diagram in the crystalline basement rocks. Dike series are clearly distinguished in local fragmenting and heating zones on this part of the lithosphere of the Drake microplate In the crystalline basement rocks, zones of increased polarization and resistance are interpreted as intrusive igneous rocks, while areas of the decreased resistance are interpreted as due to the crushing of rocks at major basement fractures.

The analysis of the magnetic anomaly patterns in Drake Passage has allowed the reconstruction of the geological events since Late Oligocene [4–6]. The existent negative and positive magnetic anomaly distribution associated with different time of the formation of the oceanic floor areas corresponds with the dated linear anomalies of the Lamont paleomagnetic scale whose age is 7.07–8.28 m.y. Paleoreconstructions based on the magnetic anomalies analysis yielded detailed data on Drake Passage opening history and recovered the geodynamic events that took place in West Antarctica as a region of the interaction and the evolution of large structures of SW Pacific and Antarctic Peninsula unified in Early Mesozoic by a single active volcanic arch that formed the western marginal Gondvana zone.

Recently two systems of oceanic anomalies are usually distinguished here. One of them was formed at different stages of the existence and the evolution of the migrating Aluc (Phoenix) ridge spreading center and the other is associated with spreading center of the Nasca Ridge situated south-west of the South America coast [6]. The complicated tectonic interaction of several large and small plates (North American, Antarctic, Scotia, Aluc (Phoenix), Shetland) was at some evolution stages discontinuous and was alternatively dominated by phases of regional and local influence. It was accompanied by processes of accretion, spreading and subduction expressed in dated linear magnetic anomalies and fixing of the dynamics of the behavior of the spreading rates for the last 35my [5–6].

Figure 3 indicates that sedimentary rocks are largely absent on the South American margin, whereas they are relatively thick on the Antarctic margin, and particularly in the South Shetlands Trench. The sedimentary cover thins towards the West Scotia Ridge in the central part of Drake Passage, and the ridge crest is generally sediment-free.

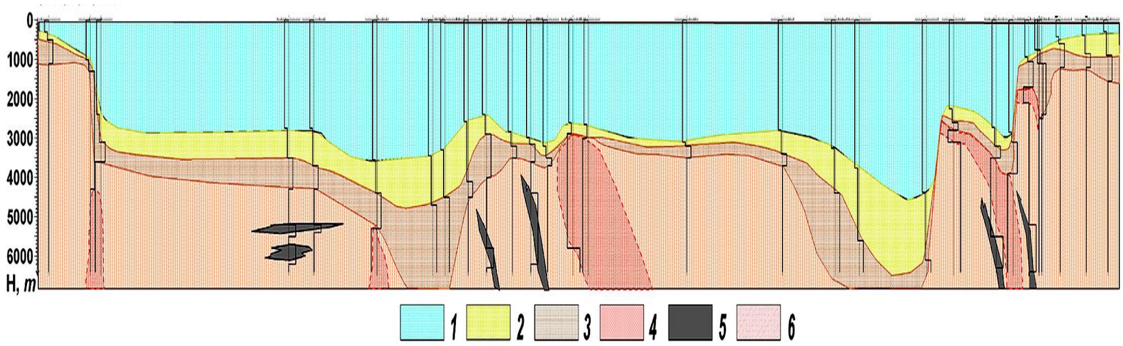

Figure 3. Interpreted geoelectrical cross-section of the upper part of the crust along the profile through Drake Passage and the South Shetland Trench. Location of profile shown in Figure 1(a). Legend: 1 – water; 2 – sedimentary layer of low geoelectric resistance (silts, clay and sandy sediment); 3 – layer of high geoelectric resistance (detrital rocks; muddy sediment; shallow, hydrothermally altered basement rocks); 4 – unaltered basement rocks; 5 – zones of high polarization and resistance in basement rocks, interpreted as volcanic intrusions); 6 – zones of low resistance in basement rocks (interpreted as fracture zones)

The South Shetland Trench is a long segment of a subduction zone that once extended all along the western margin of the Antarctic Peninsula but there is no sign of active subduction at depths to 6 km (figure3). Possibly, this distribution of the geophysical inhomogeneities of the upper part of the lithosphere near the Antarctic Peninsula may be local and notably differ from those at other Drake Passage areas. It's known, that seismological evidence of subduction and the possible presence of downgoing lithosphere beneath the South Shetland Islands is limited. But recent seismic data are consistent with GPS measurements that suggest a subduction rate of less than 1 cm/yr. Absence of intermediate depth earthquakes is consistent with thermal assimilation of the slab at shallow depths [7]

Variant of schematic electromagnetic crustal model of Drake Passage is rather complicated (fig.3, 4). It was the first experience of deep modification (up to 32 km) of VERS method using.

Obtained VERS-data have been used to compare Drake Passage crustal sections at opposite sides of transect and seismic data for deep structure of continental margin at the South Shetland Islands and South America. There were many points where transition layer "crust – mantle" was obtained. An additional deep horizon was detected on this profile at depth about 15-20 km (fig.4). Now it is rather difficult to identify its nature.

Application of deep VERS profiling has also provided new data about the deep crustal structure of Bransfield Strait.

Bransfield Strait, marginal basin located between the South Shetland archipelgo and the Antarctic Peninsula, usually has been considered as a back – arc basin developed in relationship with the subduction of the former Phoenix plate under the Antarctic plate. In other models its formation may be related mainly with the geodynamical interactions between the Antarctic and the Scotia plates[8]

Crustal thickness estimates for Bransfield Strait have been inconsistent. Seismic and active seismicity data confirm that Bransfield Basin is undergoing extension but new oceanic crust is not forming. Extension is focused in the side of the strait adjacent to the South Shetland Islands.

The 5 to 15 km estimate of extension is consisstent with the amount of intrusive material observed from seismic data. The basin crust is too thick to be normal oceanic crust.Magnetic anomaly data across Bransfield Strait produce a strong positive magnetic anomaly over the linear extrusive features due the volcanic extrusions of basalts. This anomaly along the axis of the basin coincides with neovolcanic ridge. Free air gravity values for Bransfield basin are relatively uniform and correlate with water depth, with the exception of the major volcanic features- locations of recent extension and volcanism [8–10].

This could be caused either by rift propagation toward the southwest into continental crust which has undergone less extension [4], or by the rift opening about a near pole located to the southwest of Bransfield Strait [5]. These conclusions agree with bathymetric evidence that shows shallower depths and no clear rifting zones south of Deception Island [6, 7].

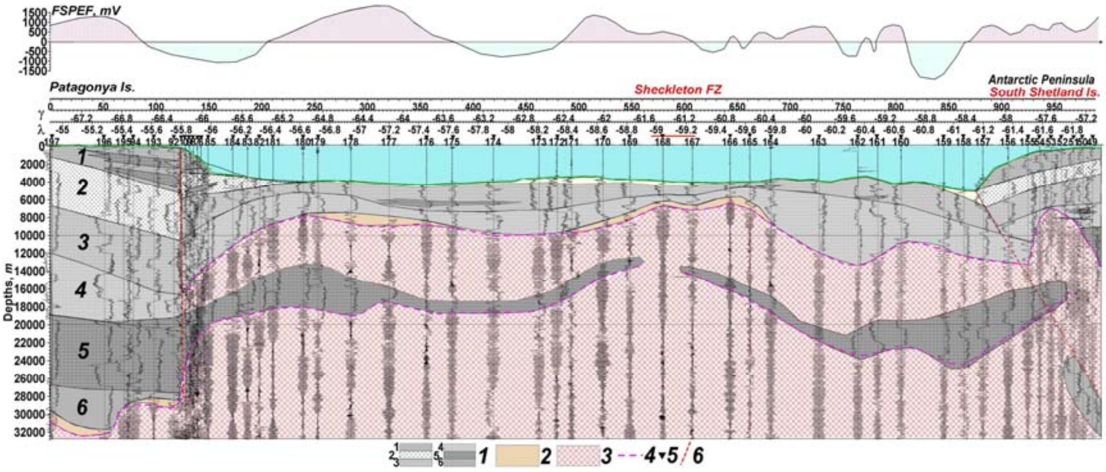

Figure 4. Schematic model of the deep crustal structure along profile 4 in Bransfield Strait. Location of the profile shown in Figure 1(b). 1 – complex of volcanic and crystalline rocks; 2 – rocks of crust–mantle transition; 3 – rocks of the upper mantle; 4 – Moho boundary; 5 – VERS points; 6 – tectonic fractures.

Polish Antarctic expeditions have obtained new data on the crustal structure of this region. They have shown different types of continental crust in separate blocks of the Antarctic Peninsula and provided new information about anomalous crust in Bransfield Strait at depths of 14–30 km. The crustal thickness varies from 36–42 km (Adelaide, Anvers Islands) to 25–28 km towards the Pacific Ocean [9,10]. The geoelectrical interpretation presented here confirms possible crustal extension and the existence of mantle material at depth of 12–16 km (Fig. 5).That is why new geophysical data about deep structure of study area are crucial for tectonic models that propose the different mechanism of the rifting processes in Bransfield Strait

The primary observations in the interpretation of this along-strike profile can be summarized as follows:

a) upper and middle basement layers, down to depths of about 14 km, are of generally uniform thickness;
b) deep basement is restricted to the southern end of the profile, where it is found at depths of 14–24 km;
c) crust–mantle transition rocks of highly variable thickness are interpreted along much of the line; and
d) Moho depths are highly variable along the profile.

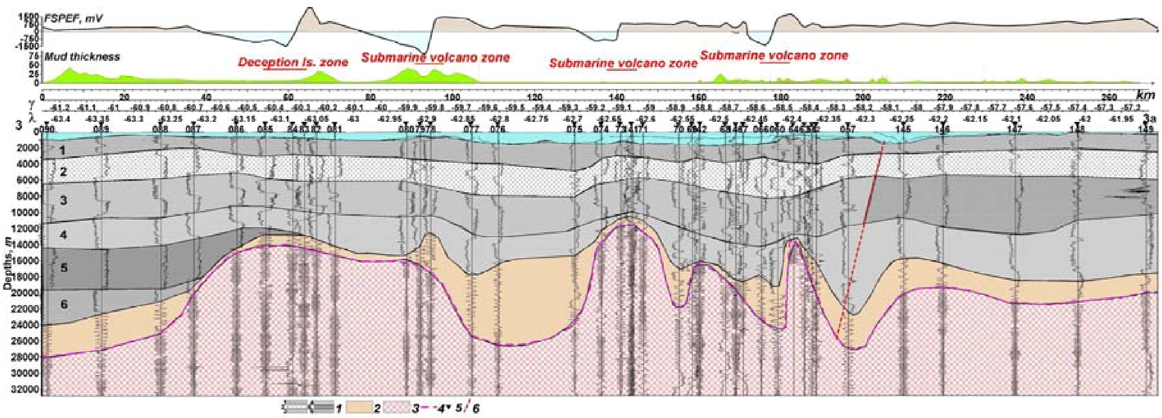

Figure 5. Schematic model of the deep crustal structure along profile 4 in Bransfield Strait. Location of the profile shown in Figure 1(b). 1 – complex of volcanic and crystalline rocks; 2 – rocks of crust–mantle transition; 3 – rocks of the upper mantle; 4 – Moho boundary; 5 – VERS points; 6 – tectonic fractures.

Position of mantle diapir or high velocity block in lower part of the earth's crust of Bransfield Strait is enough confidently determined by seismic data. Its role in formation history of this rifting region is rather unknown. It is possible to assume that introduction of mantle diapir in the Earth's crust of axial zone of Bransfeild Strait has happened during early stages of its forming. Series of plateau upwelling in SW part of the Antarctic Peninsula shelf area in Pliocene – Pleistocene happened as a result of such introduction. Process of the equalized plateau surface lowering was beginning with cooling of hot masses in the north-eastern part of Bransfield Strait. Deep diapir formation that accompanied by rift introduction to the continental Paleozoic – Mesozoic massive had important value for geodynamic processes in this region.

We also observe that the location of submarine volcanic structures in Bransfield Strait appears to be given by high gradient zones in the FSPEF data where its sign changes. The geophysical data interpretation suggests a local character of the present submarine volcanic activity in the SE part of Deception Island. The magma source has deep roots and is associated with a local tectonic disturbance. Its top has been estimated to be at 1.5–1.8km depth.

Active rift of the Bransfield Strait is the component part of the regional rift zone that is stretched out from the Deception Island on the West to the South-Sandwich Island arc on the East. At the modern stage of its development it is possible to suppose further rifting processes advancement in SW direction.

Conclusions

The electromagnetic experiments conducted by the Ukrainian Antarctic expeditions in 2004 and 2006 yielded a new dataset containing potentially valuable information about the internal crustal structure of Drake Passage and Bransfield Strait. New estimates of the depth of the Moho discontinuity in these areas were obtained.

The new geophysical data allow investigation of the deep crustal structure in a region where possible mantle diapirs have been emplaced into the pre-rift continental complexes of Bransfield Strait Therefore this region is interesting not only from the viewpoint of studying processes of multiphase expansion in Mesozoic, but also as an area of young tectono-geodynamic processes (2.5–4.0 Ma) accompanied by the formation of multiple volcanic uplifts and ridges composed of different basalts. We also observe that the location of submarine volcanic structures in Bransfield Strait appears to be given by high gradient zones in the FSPEF data where its sign changes. Geoelectrical data reflect complicated structural and tectonic geology, resulting from marked changes in the physical properties of the Earth's. Newly interpreted values of the depth to Moho confirm the tectonic view of Bransfield Strait as a modern rift basin with anomalous crust. Modelling experience of deep crust structure by geophysical data with VERS method shows that there is a possibility to investigate the fluid regime, tectonic disturbances and crush zones in basement and local places of submarine volcanic activity too.

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