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THE FALKLAND BASINS: NEW STRUCTURAL MODEL AND HYDROCARBON BEARING PROSPECTS (BY REMOTE SENSING AND GEOELECTRIC DATA)

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New results of geoelectric measurements were obtained during the season works of 17 Ukrainian Antarctic Expedition (XVII UAE, 2012). New data on the deep structure of the tectonic zone between the Falkland Islands and the South Shetland Islands make it possible to estimate the probable nature of geodynamic processes in this region. Deep geoelectric boundaries position and nature of their contacts near the South Shetland Islands and the Falkland Islands show a fundamentally different distribution of crustal and mantle layers in the Strait structures with continental and oceanic rock complexes.
Some anomalous zones of “hydrocarbon deposit” type were detected in the South Falkland Basin shelf by the special technology of satellite data processing and interpretation using. The "deposit" type anomalies were mapped by FSPEF survey and anomalous polarized layers of "hydrocarbon deposit" type were studied by VERS sounding in the South Falkland Basin. These results are new and additional to oil and gas potential data for the South Falkland Basin shelf zone.
Keywords: South Falkland Basin region, remote data processing, geoelectric survey, deep structure, hydrocarbons

Фолклендські котловини: нова структурна модель і перспективи нафтогазоносності (за результатами дистанційних і геоелектричних досліджень)
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Реферат. За матеріалами геоелектричних вимірювань під час сезонних робіт 17 Української антарктичної експедиції (УАЕ) в 2012 р. було отримано нові дані про глибинну будову структур тектонічної зони між Фолклендськими островами на півночі та Південно-Шетландськими островами на півдні. Вони дають можливість оцінити ймовірнісний характер геодинамічних процесів формування та еволюції, що відбувалися в межах цього регіону. Положення основних глибинних геоелектричних розділів і характер їх контактів поблизу Південних Шетландських і Фолклендських островів свідчить про принципову різницю в розподілі корових горизонтів і мантійних неоднорідностей, що формують комплекси порід континентальної та океанічної кори.
Під час проведення сезонних робіт на акваторії Південно-Фолклендського басейну методом ВЕРЗ було закартовано АТП типу «поклад вуглеводнів» та визначено їх параметри для низки ділянок. Ці результати доповнюють дані про можливу нафтогазоносність структур Південно-Фолклендського басейну.

Фолклендские котловины: новая структурная модель и перспективы нефтегазоносности (по результатам дистанционных и геоэлектрических исследований)
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Реферат. По материалам геоэлектрических измерений во время сезонных работ 17 Украинской антарктической экспедиции (XVII УАЭ, 2012 г.) были получены новые данные о глубинном строении тектонической зоны между Фолклендскими островами на севере и Южно-Шетландскими островами

на юге, дающие возможность оценить вероятностный характер геодинамических процессов формирования и эволюции, происходивших в пределах этого обширного региона. Положение основных глубинных геоэлектрических границ и характер их контактов вблизи Южных Шетландских и Фолклендских островов свидетельствует о принципиально различном распределении в структурах пролива коровых слоёв и мантийных неоднородностей, формирующих комплексы пород континентальной и океанической коры. Во время проведения сезонных работ на акватории Южно-Фолклендского бассейна методом ВЭРЗ были закартированы и определены параметры АТЗ типа «залежь углеводородов» для ряда участков шельфовой зоны. Эти результаты дополняют данные о нефтегазоносности структур дна Южно-Фолклендского бассейна.

1. Introduction

Formation and evolution of a broad tectonic zone with the Falkland Basin, Drake Passage and the Scotia Sea (Scotia Plate) bottom structures was a subject of geological and geophysical investigations for a long time because this structural unit is one of the most interesting features in this part of the Southern Atlantic Ocean [1, 2, 9, 10, 13, 17].

New geoelectric measurements results, during the season works of the 17th Ukrainian Antarctic Expedition (XVII UAE, 2012) obtained, can help to study the probable nature of some geodynamic processes in this region (Fig. 1). (Fig. 1-9 see the color paste 1.)

Deep geoelectric boundaries position and their contacts near the South Shetland Islands and the Falkland Islands show different distribution of crustal and mantle heterogeneities in the bottom structures of the Scotia Plate. Studying their spatial and depth distribution and the possible nature of these inhomogeneities is the aim of our research.

2. Deep geophysical heterogeneities and the geodynamics features of the Antarctic Peninsula – Falkland Islands tectonic zone

Traditionally, the geological history, tectonic transformations and evolution stages of this broad area have been considered as a result of the fragmentation of the continental connection between South America and the Antarctic Peninsula. It is a tectonic belt with complex crustal structure separating the Mesozoic/Cenozoic magmatic arcs of these continents [2, 9, 10, 13].

The modern history of tectonic development in this part of Scotia Plate began within the past 30 million years (Middle Oligocene). Most of new oceanic crust in the Western part of Scotia plate has been formed in Cenozoic by sea-floor spreading processes, which are marked by the oldest linear magnetic anomalies of the Scotia Sea [2, 9, 13].

This complex of the Drake Passage, Scotia Sea and adjacent basins heterogeneous structures can also be viewed as a single tectonic zone where continental bridge between South America and the Antarctic Peninsula has experienced in the past. In deep structure of this zone structural features of the Southern Patagonia paleo-Earth are preserved too. The dynamics of its development was determined by possible hot mantle uplift and lithosphere heating in conditions of local spreading processes between South America and Antarctica [17]. During evolution stages of this shear zone some additional deep structures with anomalous distribution of geophysical inhomogeneities at various levels were formed.

Geoelectric measurements during seasonal Antarctic expeditions showed the principal possibility of this method using for the crustal section construction and deep inhomogeneities mapping to a depth of 24-32 km [1, 10, 16].

Over the last 5-10 years our complex of new geophysical technologies was successfully used in applied geophysics too, in oil and gas searching especially. It includes modern geoelectric methods of forming a short-pulsed electromagnetic field (FSPEF), vertical electric-resonance sounding (VERS) and new technology - frequency resonance processing and interpretation of the Earth multispectral remote sensing (RS-) data [1, 10-12, 16, 18].

The FSPEF and VERS technologies are based on medium geoelectric parameters in pulsed transient fields. The spectral features of the Earths' quasi-stationary electric field over hydrocarbon (HC) accumulation are studying too because there is a direct relationship between the resonating frequencies of waves and the depths to the various geologic boundaries. **The VERS technology** is based on processes which polarize naturally-occurring electric fields at the surface of Earth. The polarised fields are analysed for their spectral characteristics [10-12, 18].

This complex allows not only to detect the existence of hydrocarbons in the investigated area, but also to determine the deep section basic parameters (location and capacity of the anomalous formations), as well as to evaluate the distribution of reservoir pressure within the studied areas and possible risks of their operation.

Express-technology of HC accumulations "direct" prospecting with geoelectric methods (FSPEF-VERS) was developed by experiments on many known oil and gas fields within the largest gas-and-condensate fields [11,12,16,18].

RS-technology is based on the satellite special data processing and interpretation with resonance frequencies of the electromagnetic field data for each type of hydrocarbons' compounds using. Special processing and analysis of space data obtained from remote sensing satellites (Landsat-7, etc.) within the study area can allocate the local sites for detailed works by FSPEF and VERS (or other geophysical) field methods. Experiments show that there is a real opportunity map the "hydrocarbon deposit" anomalies. Obtained data may be used to locate the most promising areas.

This original satellite data processing technology may be integrated with the traditionally used methods of HC accumulations and gas hydrates prospecting too. Thus, there are new possibilities of detection and mapping (in a first approximation) of the of the "hydrocarbon accumulation" type anomalous zones for large and medium hydrocarbon deposits.

The conducted experiments showed that revealed RS-data of the "hydrocarbon accumulations" type confidently correlated with the geoelectric FSPEF-VERS - anomalous zones. We showed that these new geophysical methods based on the principles of "substantial" paradigm of objects study.

The obtained results of geoelectric (FSPEF-VERS) and RS-technologies in seasonal works (2012), in our opinion support the possibility of its using for the local and deep crustal inhomogeneities study and also for local and regional detection and mapping of the "hydrocarbon accumulation" type anomalies in this region.

New materials showed the sediments distribution in the Falklands basin, determined the position of the tectonics elements and deep crustal horizons that formed the modern border zone between the structures of the South America and Scotia Plate [1,2,10,13,16,].

3. Deep structure of the Falkland basin by geological and geophysical data (brief review)

Deep structure of the Falkland Plateau and the Falkland Islands offshore (Fig. 2) has been studied during several past decades. First geophysical data, including DSS-data for this area were published in 1964 [14,15]. Complex deep geophysical models were published only some years ago [2, 9]. New geophysical data have revealed the internal structure of sedimentary basin (Fig. 3) and indicate the presence of a sedimentary section ranging from 2 to 10 km in thickness [9].

The South Falkland Basin and Burdwood Bank lie south from the islands (Fig. 2). Thicknesses increase towards an area of southward-dipping extensional fault blocks within the South Falkland Basin (Fig. 3).

VERS – profile 4-4a crossed the Drake Passage, the Scotia Sea, the South Falkland Basin (Burdwood Bank, Falkland trough, South Falkland Shelf) bottom structures which we combined in the South Falkland basin title (Fig. 2). Below we produce some geological and geophysical data on the morphology and the deep structure of tectonic elements.

The Falkland Island with surrounding structures is located within a vast shelf area continue, extended to the east from the Patagonian. The islands are surrounded on all sides by Meso-Cenozoic sedimentary basins: North Falkland (in the North); Falkland Plateau (in the East), South

Falkland (in the South) and Malvinas (in the W) basin (Fig. 2). Each of them exhibits its own unique structural style [9, 13-15]

There are Late Precambrian granitic gneisses and Paleozoic metamorphic basement that exposed on the islands with Early Paleozoic-Devonian and Upper Paleozoic sediment cover. Also the Early and Middle Jurassic rift volcanic and clastic continental complex, post rift marine sediments of the Upper Jurassic, Cretaceous and Cenozoic were found here. Their formation was associated with rift system destruction during the initial processes of Gondwana separation [7].

The South Falkland Basin is bordered by the Malvinas basin (in the West) and Falkland Plateau Basin (in the East). Basin lies beneath 500 m to 2500 m of water to the immediate south of the Falkland Island. It is bounded by the Scotia/South American plate boundary to the south. In the western part of the basin the sedimentary cover (outside the trough) is represented by Phanerozoic sediments with capacity from 0.5 km to 1-2 km. The South Falkland Basin is classified as "passive margin" that developed in a fully marine setting. The structural style here is similar to the southern part of the Malvinas Basin [7, 9, 14, 15]. It is assumed that the main geological characteristics can be estimated from the wells drilling results in the adjacent Malvinas Basin, as well as from existing deep drilling (DSDP 330 and 511) materials on the Falkland Plateau [7].

The Falkland trough is a fault trough, with depths from 900 m near the Falkland Islands to 3700 m at the Falklands Plateau (48°W) (Fig. 3). It is a deep structure with depth comparable to other oceanic trenches. The Falkland trough may be a tectonic expression of the convergence in a zone of two lithospheres' plates separating [9, 13-15]. The southern slope section of the trough is represented by metamorphic and consolidated sedimentary rocks of the Late Paleozoic and Tertiary age. These rocks are similar with the rocks of the Andean folded structures [8, 9]. The ancient granites and gneisses on the northern slope of the trough form the Falkland Plateau basement that is overlap by sedimentary and metamorphic rocks of the Paleozoic-Mesozoic age [17]. The presence of large negative gravity anomaly over the Falkland trough may be connected with the influence of sediments (Fig. 3) with total thickness about 7 km [14, 17].

Burdwood Bank is an extended (more than 900 km) bottom structure (Fig. 3) which located between the border structures of the South Falkland trough (in the North) and the North Scotia Ridge (in the South). Minimum bottom depth here does not reach 50 m. In the eastern part of this structure average depth is less than 400-450 m. The deep section of the Bank is represented by Paleozoic, Upper Cretaceous and Tertiary rocks of the Andean Patagonian branch. The total crustal thickness increases (Fig. 3) from 20 – 28 km (Burdwood Bank) to 30 – 33 km beneath the Falkland Islands [9].

Below we introduce the deep sounding (VERS) results along the meridian profile with total length of more than 1150 km from the South Shetland Islands to the Falkland Islands obtained. Deep geoelectric boundaries position and their contacts variability show different distribution of crustal and mantle heterogeneities in deep continental and oceanic crust sections for bottom structures of this part of the Scotia Plate (Fig. 3).

On this profile some horizon segments (with total thickness of 1 – 3 km) are located at different depths (12 – 23 km). In the western part of the Scotia Sea there are two breaks of this horizon which extending up to 50 – 70 km (Fig. 2). We suppose that these places can be possible channels of the upper mantle hot rocks. Deep rocks below the geoelectric section M2 were probably formed via these channels distribution. This cut indicates the tectonic mobility of the earth's crust, the separate layers uneven distribution and geophysical heterogeneity of lithospheres' plate in this region. All selected heterogeneities may be results of large-scale nonlinear geodynamic processes during new oceanic structures formation [8].

4. About oil and gas bearing prospects of the Falkland Islands offshore structures

4.1. The North Falkland Basin

Published data shows that the North Falkland Basin was a lake throughout much of its geological history [7, 13, 15]. First oil reserves in areas to the north of the Falkland Islands were discovered in

1993 [7, 14]. The total area of promising reservoirs in this North Falkland sedimentary basin of Mesozoic-Cenozoic age exceeds 400 000 km^2. The basin lies beneath 150 m to 2000 m of water. Central structure of the North Falkland basin is North Falkland Graben (rift zone). It consists of two depocentres (Western and Eastern) which are separated by a faulted ridge (Intra-Graben High).

Six wells (Fig. 4) were drilled in the central part of the North Falkland Graben area in 1998 [7, 8] and three wells were drilled in the Eastern Depocentre, two on the intra-Graben High, and one in the Western Depocentre.

The producing horizons are located at depths of 1600 to 2800 m in drilled wells which characterized the hydrocarbon potential of the basin only partially. Five from the six wells drilled having oil shows, mostly in post-rift sandstones. One well recovered live oil to surface from Lower Cretaceous sediments, and gas was also recovered from the same horizon. There was an opinion that "one of the richest source rock intervals anywhere in the world has been encountered in the North Falkland Basin" [7, 8].

According to new seismic data and drilling results interpretation, in the structures of the North Falkland Basin all necessary elements of the petroleum geology and hydrocarbon generation have been founded that allowing hope to achieve successful business results in future oil exploration of this petroleum province [7]. This basin contains the sediments of considerable thickness with rich hydrocarbon source potential. It may have expelled up to 60 billion barrels of oil if mature interval will be about 400 m thick [7]. Structures in the central part of the basin are of particular interest because there is fractures system which may be the lead vertical channels for deep oil. Stratigraphic traps may occur at regional unconformities and within submarine fan deposits, whereas potential structural traps include Mesozoic fault blocks and thrust and sub-thrust structures generated by more recent compression [7].

This supposes are confirmed our RS-results (2012) for the northern part of the Falkland Shelf. According to these data, there are some hydrocarbon perspective areas which located near the drilled wells. One separate area is located outside the known potential sites (Fig. 4).

New wells on the Sea Lion site (Fig. 5) were successfully drilling in 2011, and oil flowed from a depth of 2400-2700 m. The exploration well 14/10-3 encountered good quality reservoir from 2,425 to 2,535meters in a sequence of four main sandstone intervals.One of drilled wells (14/10-5) reached a total depth of 2,726 meters proving a very thick, high-quality reservoir package and a substantial oil column. The oil production from this field is planning to start in 2017 [3-7]. Total oil reserves in offshore structures according to various estimates range from 8.3 to 60 billion barrels. It should be noted that some experts do not share the views on a very large offshore hydrocarbon reserves of the Falkland Islands [7, 8]. The analysis of the previous seismic surveys and drilling results in areas of the North Falkland Basin has given reason to believe that promising oil deposits in some sections may lie at depths of more than 3000 m. Shallower hydrocarbon depths may be caused by processes of vertical, not only horizontal migration. Therefore, subsequent wells planned to drill to a depth of 5,000 m or more [7].

4.2. The South and East Falkland Basins

New results of large-scale geophysical surveys near the Falkland Islands have opened up new development prospects for this oil and gas province, covering different parts of the Falkland Islands shelf. New materials, including drilling data, have provided a basic understanding the sedimentary cover distribution in the Falkland basins, help to determine the tectonic elements and deep horizons of the crust position [5-9, 13-15].

In recent years significant amount of high seismic studies (including 3-D seismic) has made within the South Falklands Basin. The resulting materials have allowed to allocating extended structural belt of Mesozoic rocks in which some series of anticlines were identified.

Within the South Falkland Shelf areas five oil wells (Toroa, Darwin, Stebbing, Loligo and Scotia) were drilled in 2012 (Fig. 5). All wells have been drilled in the South Falkland Basin's regions where drilling operations are not carried out earlier.

The production well on Darwin East area was drilled (Apr. 2012) to a depth of 4876 m. The main hydrocarbon bearing reservoir interval (about 70 m thickness) was represented by the Lower Cretaceous shallow-water sandstones and by Lower Cretaceous shales overlain. The recoverable volume of condensate may be about 200 million barrels [3-7].

Stebbing well was drilled in summer of 2012 to a total depth 3060 m where anomalous pressure conditions prevented the further drilling to the deeper zones [3-7].

Loligo well (Fig. 5) was drilled in summer of 2012 to a total depth 4043 m. The gas-bearing strata containing two productive reservoir capacity of 46 m and 59 m at depths of 3462 – 3558 m and 3608 – 3705 m respectively was found. The Loligo well demonstrated a working oil and gas system in the East Falkland basin but real prospects of this oil-bearing area remain unclear.

At the end of 2012, **Scotia well** (Fig. 5) reached the Middle Cretaceous rocks at a depth of 5555 m. Hydrocarbons were encountered in two zones of low-quality fine-grained sandstones and mudstones (4719 m – 4769 m and 4900 m – 5164 m) with poor and uncommercial reservoir quality [4-9].

Analysis of obtained drilling data showed necessity of additional three-dimensional seismic survey (about 1000 km^2) in the southern part of the licensed areas within the Cretaceous alluvial fan complexes Diomedia, as well as to the west and northwest from the Darwin condensate field at a distance of 3-10 km from the Darwin well [3-7].

Below there are some results of applying the remote sensing (RS) - data interpretation to anomalies of "oil and gas reservoirs" type [10-12, 18] at the local areas where an official data on drilled wells and their productivity are known.

We used for interpretation the available RS-data on the 1:500000 scale, and open data on the Darwin, Stebbing and Toroa wells site position [3-7].

Anomaly effects on the resonant frequencies of gas, gas condensate and oil were appeared in processing of these data. As an interpretation result, the three anomalous zones were identified, two of which coincided with the position of wells. The third anomaly in the western part of this area (Fig. 6) was not delineated. According to our data, the value of the maximum reservoir pressure within the drilled wells does not exceed 21 MPa. Anomaly effects of gas resonant frequencies did not appear at the higher pressure. It means that strong oil flow from a depth of 4633 – 4681 m cannot be obtained because of the large depth of productive horizon. Based on drilling results descriptions, this horizon in all wells is represented by the interbedded sandstones, shales and clays with poor quality and porosity. The relatively low reservoir pressure values from the processing of RS-data obtained in the areas Darwin and Stebbing (Fig. 6) may be probably associated with these factors.

Results of RS-data data processing show that anomalous zones such as "gas accumulation" type with relatively low reservoir pressure values also may be used for the detection and mapping of "Sweet Spots" sites during the prospecting and exploration of shale gas accumulations.

Some VERS-anomalies of "hydrocarbon deposit" type have been mapped and parameters of anomalous bodies in section (position, thickness) were defined during the seasonal works in the South Falkland Basin (Fig. 7, 8, 9).

Extended anomaly zones of "oil deposit" type are connected with the polarized layers that lie at depth 1200 m to 2800 m (Fig. 10, 11). These zones have a variable thickness in the first tens (up to hundreds) of meters and are confined to the bottom depth of 650 – 800 m.

The obtained values of reservoir pressure for these anomalies are about 23-30 MPa, which may indicate the possibility of oil flow in these promising areas

These obtained results can be used to estimate oil and gas bearing prospects for some new areas of the South Falkland basin.

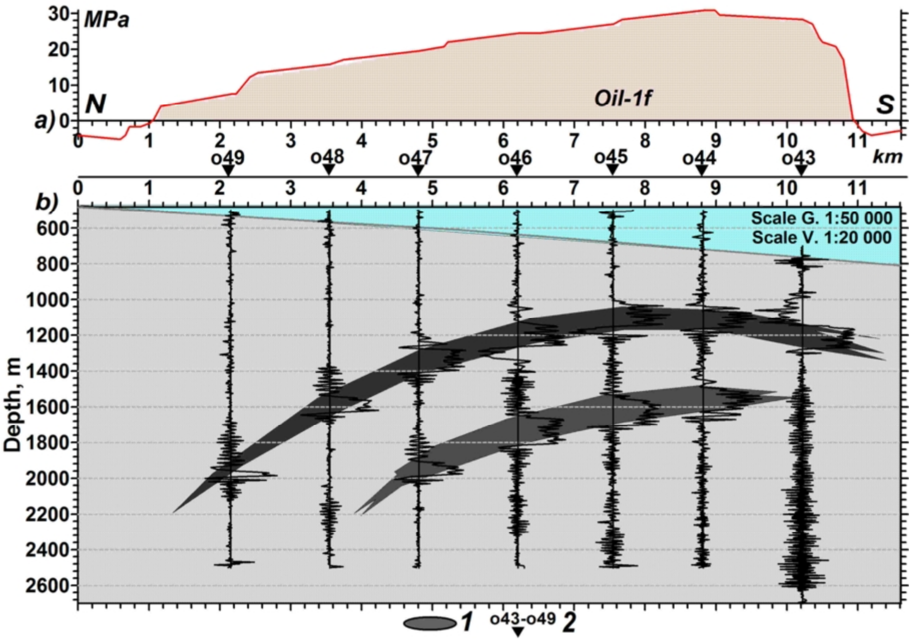

Fig. 10. Vertical cross-section along the geoelectric anomalous zones of the "oil deposit" type (Oil-1f) on the southern shelf of the Falkland Islands (XVII UAE, 2012). a) values' graph of the reservoir pressure in collectors; b) a vertical geoelectric cross-section. 1 – zones of anomalous polarized layers of the "oil deposit" type; 2 – VERS points.

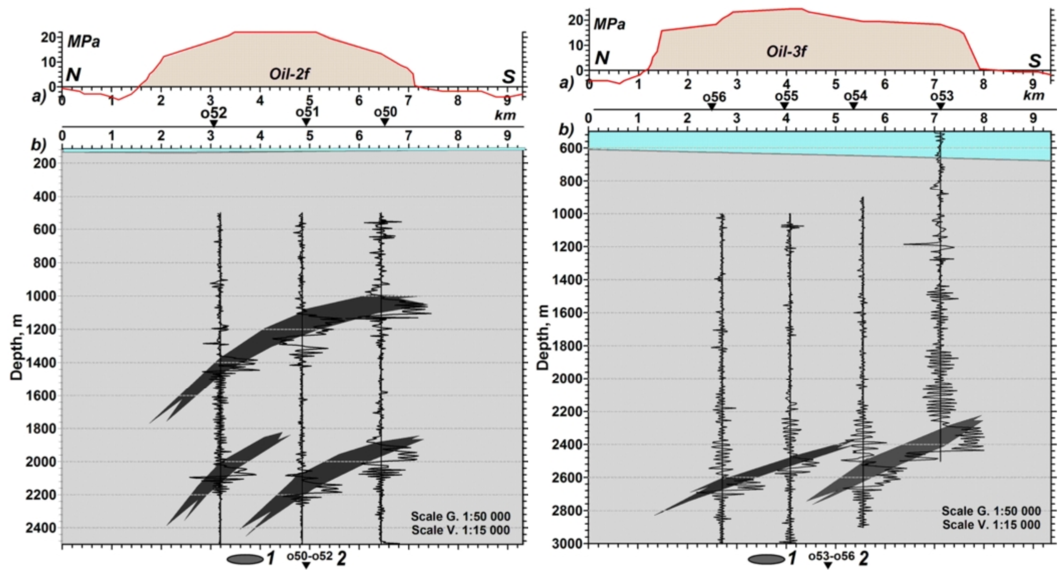

Fig. 11. Vertical cross-section along the geoelectric anomalous zones of the "oil deposit" type (Oil-2f) on the southern shelf of the Falkland Islands (XVII UAE, 2012). a) values' graph of the reservoir pressure in collectors; b) vertical geoelectric cross-section. 1 – zones of anomalous polarized layers of the "oil pool" type; 2 – VERS points.

5. Conclusions

1. New geophysical data, during the seasonal work of the 17 UAE (2012) obtained, show that this region includes a set of morphological structures with different types of crust. Revealed deep geoelectric boundaries distribution and the presence of large mantle heterogeneities in the various segments of the region may be interpreted as a reflection of the scale formation and evolution of the Drake Passage and Scotia Sea basic bottom structures. These data can also be possible linked with deep transformations of ancient crust fragments.

The intensity and duration of these geodynamic processes are highly dependent not only on the characteristics of deep heat admission into the upper geosphere, but also on an uneven cosmic factors impact on the Earth.

2. The results of geoelectric studies show the significant variations in crustal thickness, and possible presence of the upper mantle hot rocks in the crustal sections as result of tectonic structures' geodynamic evolution in this region. Investigation results have demonstrated high efficiency of the VERS-method for the Earth crustal study.

3. Practical experiments in the Antarctic region testify that integration of RS-data processing results and data of geoelectric survey by the FSPEF-VERS methods may be used for the hydrocarbon accumulation prospecting in the difficult of access and remote regions. The obtained results confirm that the technology of RS-data processing allows operatively to detect and map the anomalous zones of "reservoir of oil and (or) gas" type, which in most cases connected with large-scale and medium-scale HC reservoirs. The results of the FSPEF-VERS methods have confirmed their efficiency and mobility for the HC accumulation prospecting.

4. Results of RS-data data processing show that anomalous zones such as "gas accumulation" type with relatively low reservoir pressure values also may be used for the detection and mapping of "Sweet Spots" sites during the prospecting and exploration of shale gas accumulations.

5. The obtained results confirm the high oil and gas potential for new areas of the Falkland Basins region.

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