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TECTONOSPHERE OF THE KERGUELEN PLATEAU ON GEOPHYSICAL DATA

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Complex history of the Kerguelen Plateau formation accompanied by intensive magmatic and tectonic activity, determined various structure of the crust and the tectonosphere of its singular blocks. The data on potential fields, seismic tomography data and other geological and geophysical information allow us to identify plateau's singular blocks and define their structure and the tectonosphere's evolution.

Keywords: potential fields, seismic tomography, crust, tectonosphere, Indian Ocean.

INTRODUCTION

The Kerguelen Plateau is situated in the southern part of the Indian Ocean's central segment between 46°-64°S. It is located within the active South-West-Indian and South-East Indian spreading ridges and the Antarctic continent. The plateau is separated from the Antarctic by a deep (> 3,500 m) strait that is associated with the Princess Elizabeth Trough in the Davis Sea, and is bordered in the northeast by the Australian-Antarctic Basin, in the northwest by the Crozet Basin, and in the southwest by the Enderby Basin (fig. 1*a*). The plateau extends ~2300 km in a northwest direction with an average ~500 km width and an average 3 km height above sea level. It is divided into the Southern, Central and Northern Provinces. There are the Elan and Skiff

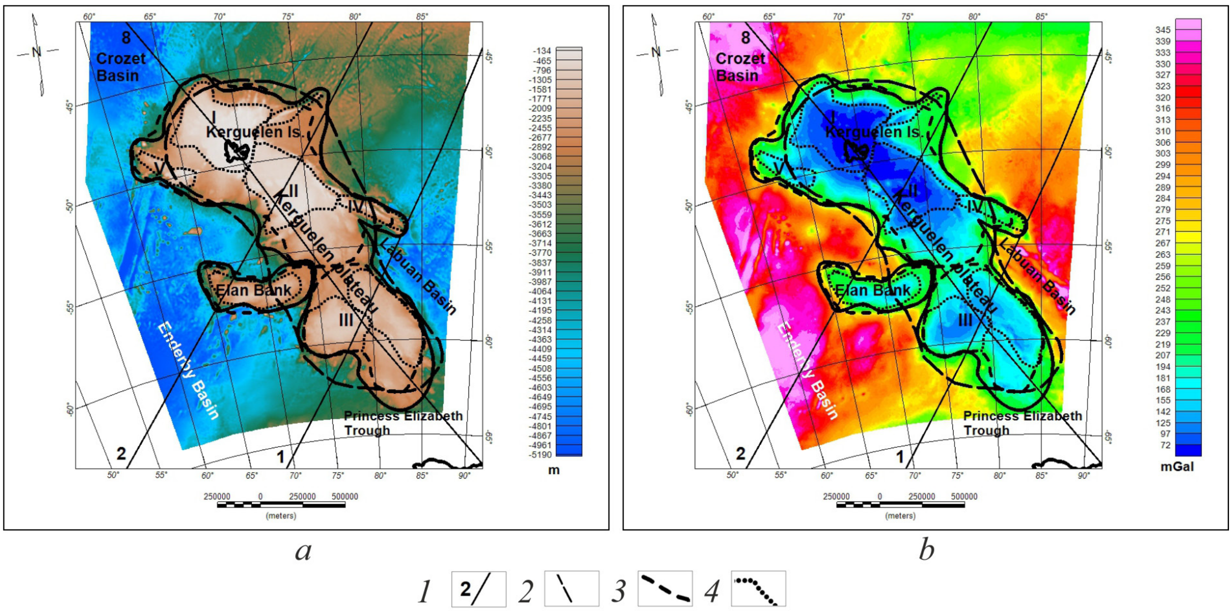

Fig. 1. Maps of the seafloor topography (*a*) and gravitational field anomalies in Bouguer reduction (*b*) of the Kerguelen Plateau. Kerguelen Plateau provinces: I – Northern Province; II – Central Province; III – Southern Province; IV – William's Ridge; V – Skiff Bank: *1* – interpretation profiles; areas of reduced values of gravitational field: *2* – low frequency, *3* – medium frequency, *4* – high-frequency component.

Banks, Williams Ridge and the Labuan Basin within the plateau (Leichenkov et al., 2018; Borissova et al., 2002). The northern province of the plateau within which, the Kerguelen Archipelago is located, could be found at shallower depths (<1000 m) than the Central and Southern ones. It seems that it is resulted from a large-scale generation of magma associated with the hot spot or the Kerguelen mantle plume activity. The central part of the plateau, located at depths close to the southern part (from 1000 to 2000 m), includes volcanically active Heard and McDonald islands. It is obvious that in order to explain the southern part of the ridge formation we cannot deny the hypothesis of its continental structure (Leichenkov et al., 2018; Benard et al., 2009).

The aim of the paper is the investigation of the Kerguelen Plateau tectonosphere's dense structure based on analysis of the free-air gravity anomalies maps (Sandwell et al., 2005), the Bouguer gravity anomalies calculated using the author's program, with regards to the spherical Earth ($\sigma_{сл} = 2.67$ g / cm^3) with two angular minutes discreteness.

We also used the EMAG 2 anomalous magnetic field model (Maus et al., 2009), the LLNL-G3Dv3 seismotomography model (Simmons et al., 2012), the GEMMA model of the crust (Reguzzoni et al., 2014), the data on sediment thickness (Whittaker , 2013) and the geoid excess over the reference ellipsoid (Barthelmes, 2013) (Shaykhullina et al, 2017a, 2017b).

THE KERGUELEN PLATEAU TECTONIC HISTORY

Although most researchers suppose that the plateau's age is 120-110 million years, the age of the plateau formation is still the topic to discuss. It could be supposed that the plateau's age is even smaller (Coffin et al., 2002).

Geological and geophysical data evidence that the Kerguelen Plateau has complex structure. We can assume blocks with thick ocean crust, resulted from plume activity and underplating (the Northern Province), and blocks with thin continental crust resulted from rifting (the Southern and probably Central Provinces, and also the Elan Bank (Leichenkov et al., 2018; Benard et al., 2009; Borissova et al., 2002). The data from deep sea drilling and dredging, as well as seismic researches, have shown that the Kerguelen Plateau singular provinces comprise relicts of blocks composed of continental crust. Drilling of the central part of the Elan Bank (borehole 1137) revealed volcanoclastic conglomerates containing the Late Proterozoic fragments of garnet-biotite gneisses beneath the 150-meter layer of 110 million years old basalts (Borissova et al., 2002; Coffin et al., 2002). This fact exactly states that the crustal composition of the Elan Bank is parentally continental.

The continental type of the crust is assumed within the Southern Province of the Kerguelen Plateau (58°S) beneath the 5.5 km thick volcanic rock mass. Seismic data, obtained using the methods of refraction and reflected waves in the layer between basalts and the Moho boundary, indicated relatively small P-wave velocity (6600-6900 m/s) (Operto, Charvis, 1996). Large amount of ancient metamorphic and igneous rocks' fragments, dredged from one of the rises of the plateau's eastern base also evidence for continental nature of the north part of the Southern Province (Montigni et al., 1993).

The Earth's crust structure in the Central and Northern Provinces significantly differ from the Southern Province and the Elan Bank. The main difference is in higher velocities in the lower part of the crust (up to 2100 m/s), which are typical for oceanic cross-section. Volcanic rocks geochemical characteristics also evidence this. The Earth's crust thickness within the Kerguelen Plateau comprise 18-23 km (Charvis et al., 1995; Gladzhenko, Coffin, 2001; Gohl et al., 2008; Operto, Charvis, 1996).

Extended rift system between the Antarctic, Australia and India with the triple junction, the Naturaliste Plateau, in the area of the Bruce Bank was formed in Middle Jurassic (Lawver et al., 1992; Leitchenkov et al., 2008). In Early Cretaceous (~130-120 million years) the process of rifting ended and the ocean's opening, accompanied by the Kerguelen plume magmatic activity, occurred. The Kerguelen hot spot's magmatic peak was revealed for the period 120-110 million years ago and was fixed in formation of the Kerguelen Plateau Southern Province (Leuchenkov et al., 2018; Coffin et al., 2002). The Elan Bank's Central Province was formed from 110 to 100 million years (Coffin et al., 2002), after the Enderby Basin spreading ridge jumped towards the young Indian plate's margin and isolated the Elan Bank's micro-continent. About 83 million years ago the plume activity decreased, and the north-west to the south-east oriented spreading processes reached their maximum. The ocean opening between Australia and the Antarctic occurred in the east (Benard et al., 2009). The Southeast Indian Ridge began its activity, moving both eastwards and westwards. 43-42 million years ago, it crossed the Kerguelen Plateau and divided it into two large structures: the Broken Ridge and the modern Kerguelen Plateau. Complicated history of the Kerguelen Plateau and the adjacent basins formation, accompanied by intensive magmatic and tectonic activity, formed special heterogenic type of the tectonosphere crust.

TECTONOSPHERE STRUCTURE ON GEOPHYSICAL DATA

The use of large variety of geological and geophysical parameters allow significant improvement of the Kerguelen Plateau's blocks configuration, deep structure and nature. The analysis of intensity of the Kerguelen Plateau's Bouguer gravity anomalies confirms the need to define the Northern, Central and Southern Provinces within the plateau (fig. 1*b*). In general, the northern part of the Kerguelen plateau has the lowest value gravity (~90 mGal). The increased to ~160 mGal gravity values in the southern sector of the plateau evidence for its heterogeneous structure (table). To divide the fields into components associated with the main anomalies formation layers of the tectonosphere, we use such methods of field transformation as the method of gravitational field recalculation into the upper various heights half-space, and the method of calculation of the vertical gradient of the Bouguer gravity anomalies field. The gravitational field low-frequency component is represented by the Bouguer gravity anomalies field recalculated to the 200 km height (fig. 2*a*); the mid-frequency component is represented by the field of differential anomalies recalculated to the 75 and 150 km heights (fig. 2*b*); the high-frequency component is represented by the vertical gradient of the Bouguer gravity anomalies field at a level of 0 km (fig. 2*c*). The gravitational field's low-frequency component of the Kerguelen Plateau (fig. 2*a*) is represented by the lower values zone (~200 mGal). In the mid-frequency component's field (fig. 2b) we can distinguish large zone of minimum values in the area of the plateau: ~(-35) mGal above the northwestern part, ~(-25) mGal above the central part, ~(-14) mGal above the southeast part and ~(-9) mGal above the Elan Bank. The Enderby and Labuan Basins, adjoined to the plateau, are represented by zones with the increased values: ~300 mGal — in the low-frequency component's field and ~15 mGal in the mid-frequency component's field.

Intensive local negative anomalies of the Kerguelen Plateau more evident in the high-frequency component's field (fig. 2*c*). The northern, central

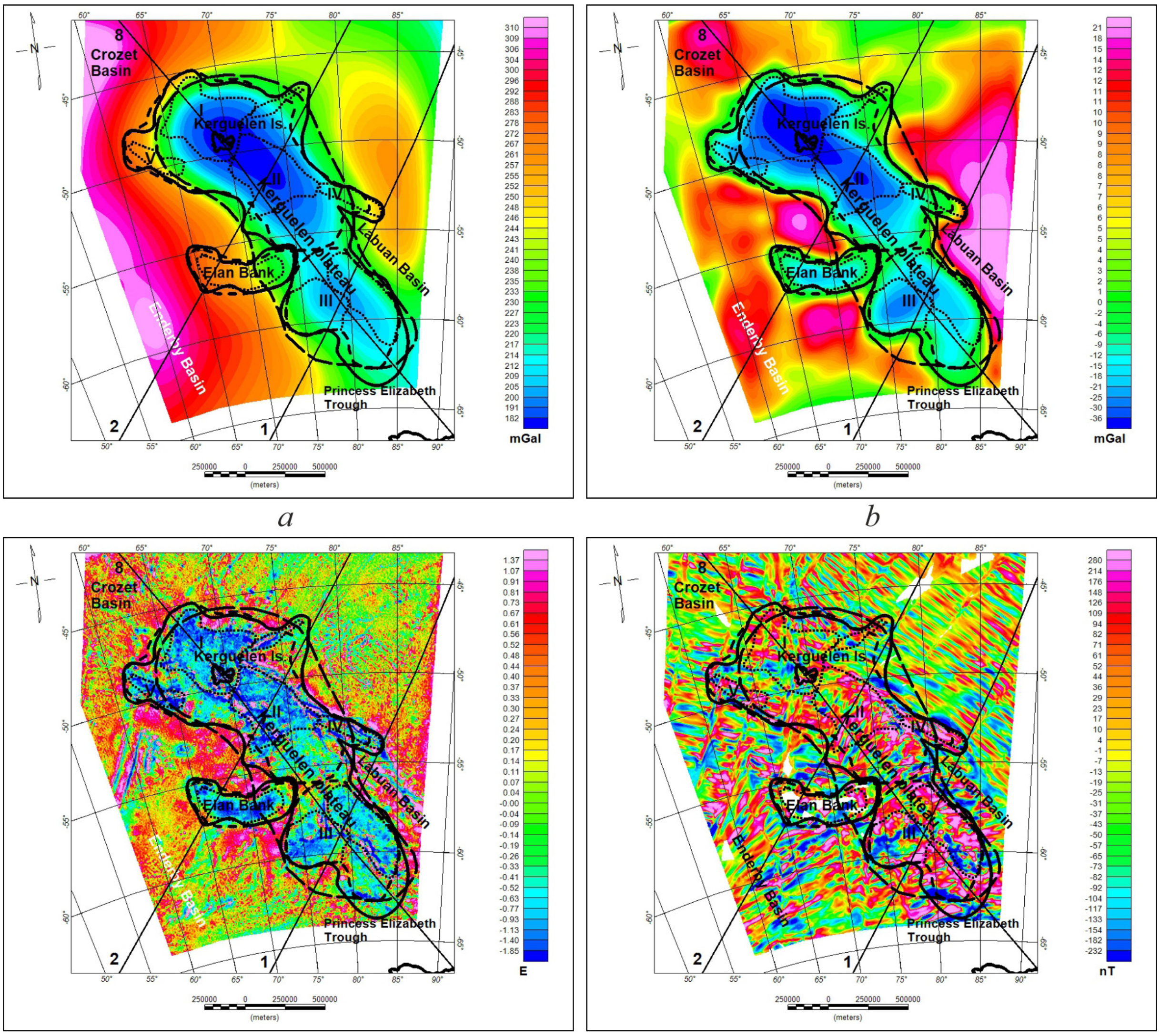

Fig. 2. Components of Bouguer anomalies and anomalies of magnetic field ΔTa. Low frequency component (*a*), medium frequency component (*b*), vertical gradient (*c*), ΔTa (*d*). Conventions see fig. 1.

and southern sectors are areas of intensive negative anomalies. The crust's continental nature influence on more intensive local negative anomalies of Williams Ridge and the Elan and Skiff Banks.

The magnetic field anomalies ΔTa map (fig. 2*d*) shows northwest directed linear anomalies with alternating signs in the northern part of the Kerguelen Plateau, which may indicate the oceanic type of this block's crust. The Central and Southern Provinces of Williams Ridge and the Elan and Skiff Banks on this map are shown as chaotic distribution of anomalies with alternating signs without any evident trend. We also analyzed seismic tomographic data (Simmons et al., 2012) and the data on the geoid excess over the reference ellipsoid (Barthelmes, 2013).

The seismotomography model estimations reveal that the earth's crust of the Kerguelen Plateau's northern and central sectors are zones of the increased, relative to the southern sector and the Elan Bank, P-wave velocities, resulted from different genesis of these structures.

The Moho boundary's at 5-20 km depth of the Kerguelen Plateau's northern part is characterized by the decreased velocities and the central sector of the plateau is characterized by the increased towards the Labuan Basin gradient zone,velocities. The same picture of velocity distribution is revealed at the depths of 80 and 150 km.

The geoid excess over the reference ellipsoid reaching 40 m in the northern part of the Kerguelen Plateau and decreasing to 15 m towards the southern part, could be explained by the tectonosphere density properties. This also evidence for the Kerguelen Plateau blocks' different genesis.

TWO-DIMENSIONAL DENSITY MODELING

The data on the depth of the main tectonosphere layers boundaries and their density characteristics allow us to develop two-dimensional density model on profiles crossing the main morphostructures of the Indian Ocean's southern region (Bulychev et al., 2015). Some of these cross-sections demonstrating density structure of the Kerguelen Plateau tectonosphere's different blocks are shown in Figures 3*a-c*.

In the modeling process, we used seismic velocity alteration fields, obtained using seismotomography data (Mégnin et al., 2000), which also reflects the difference in the structure of blocks of the Kerguelen Plateau. This can be seen particularly well on profile 8 (fig. 3*c*). The velocity anomalies values decrease from the southeastern section of the plateau to the northwestern. The tectonosphere's cross-section in different provinces of the plateau has its own characteristic features. Thus, the maximum depth crust is observed under the northern sector of the plateau (up to 30 km), and the lowest under the southern (~25 km) (Bulychev et al., 2015). The lowest density of the crust is noted under the northern province of the plateau, which may be explained by the loose material presence, which is formed due to the Kerguelen hot spot. The subcrustal lithosphere layer varies slightly in thickness and density, which slightly decrease in the direction from the southern plateau to the north. The modeling also confirmed the continental nature of the Elan Bank's crust (fig. 3*b*) (Bulychev et al., 2015). The area dividing the Southern and the Central Provinces, is characterized by relatively increased values of the Bouguer gravity anomalies (up to 200 mGal) and their low and mid-frequency transformants (fig. 2*a*, 2*b*) evidencing on deeper subcrustal density inhomogeneities in this area. The nature of the field of the vertical gradient of the Bouguer gravity anomalies and the anomalous magnetic field (fig. 2*d*) also significantly changes in this area. The Earth's crust in this area is thin (~15 km) due to rifting processes at the early stage of the Kerguelen Plateau formation (Leichenkov et al., 2018). Such geophysical anomalies even more evident in the area of the Princess Elizabeth Trough, dividing the Southern Province of the Kerguelen Plateau from the Antarctic continent (fig. 1, 2, 3*c*). Here, the depth of the bottom increases to 3.7 km, the Bouguer gravity anomalies increase to 300 mGal, the crust thickness decreases to 10 km, and the linear magnetic anomalies (M12 to M10 series (Gaina et al., 2007)) evidence on the continental crust and the initial stage of spreading, which could separate the Southern Province of the Kerguelen Plateau's micro-continental block from Antarctica (Leichenkov et al., 2018).

CONCLUSIONS

As the Earth's crust average thickness for all blocks is 20-25 km, the plateau is represented either by blocks with thick oceanic crust, or by thin continental crust, overlaid by powerful basalt flows.

For comparison, the table shows the parameters of rise with the established type of the crust. The Batavia Rise, characterized by the average (230 mGal) values of the Bouguer gravity anomalies and the relatively large (540-530 million years) age is the structure with thin continental crust. We compared the Bouguer gravity anomalies values of the Batavia Rise with the values of the Kerguelen Plateau's blocks and noted that these values were similar to those of the Elan Bank and Williams Ridge. We should note that these structures have continental nature of the earth's crust.

Broken Ridge, characterized by the average (160 mGal) values of the Bouguer gravity anomalies and the relatively small (94-95 million years) age is the structure with a thick ocean crust. The Bouguer gravity anomalies values of Broken Ridge (~160 mGal) didn't agree with the values of the central and northern sectors of the Kerguelen Plateau's blocks (90-100 mGal).

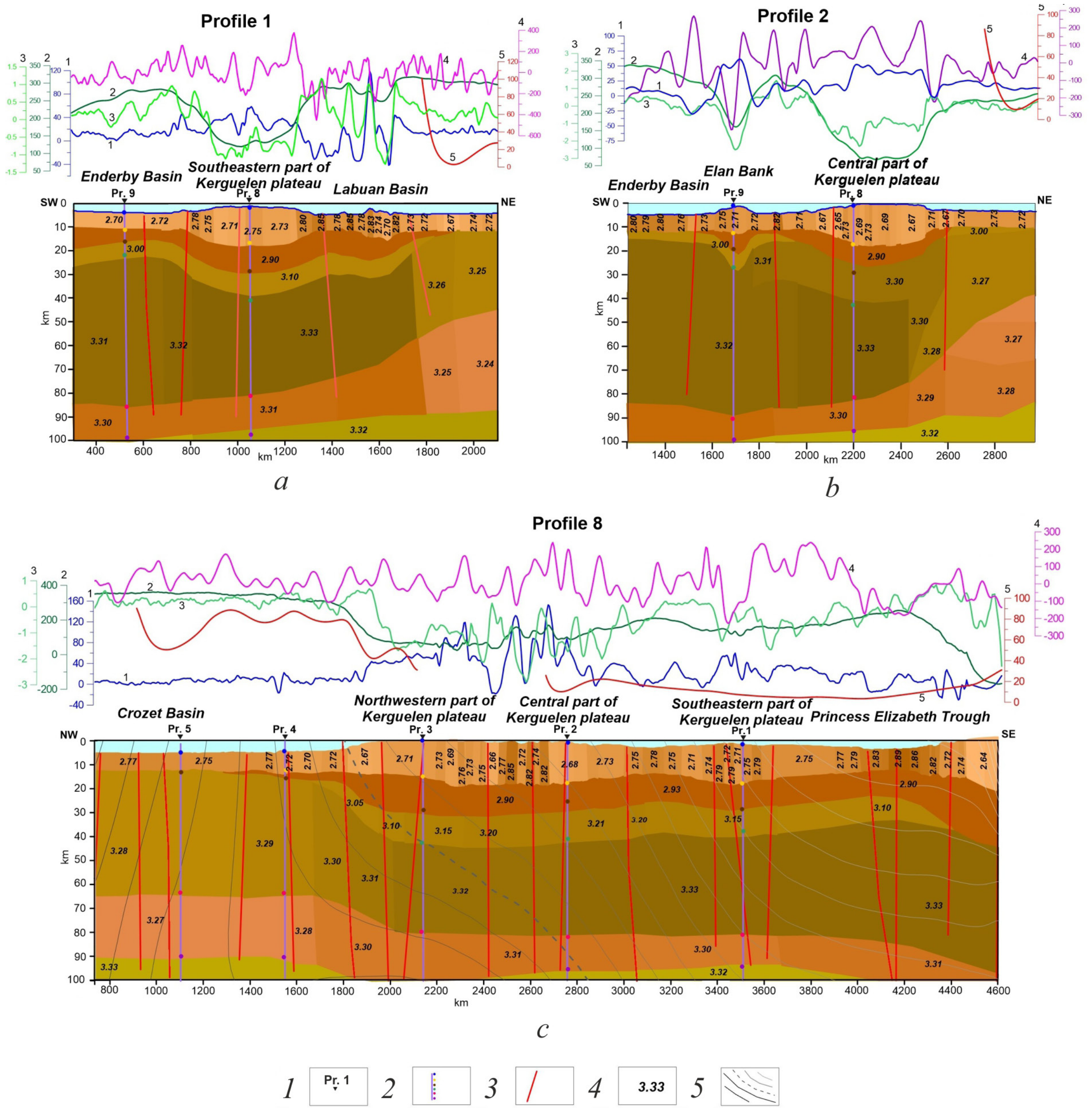

Fig. 3. Structural-density models along profiles 1, 2 and 8 (Bulychev et al, 2015): *1* – the intersection of the profile line with other profiles; 2 – the plane of the crossed profile and the boundary of the layers of the tectonosphere according to its model (circles are the position on the cross-sectional profile of the base of the main layers of the lithosphere); *3* – fracture zones revealed as result of interpretation of gravity and magnetic anomalies; *4* – average value of density in block (g/sm^3); *5* – isolines of seismic velocities by seismotomography data (lighter isolines – higher speed, dotted line is zero). Graphs over models (curve number corresponds to the scale number): *1* – anomalies of gravitational field in free air reduction (mGal); *2* – anomalies of gravitational field in Bouguer reduction (mGal); *3* – vertical gradient of Bouguer anomalies (E); *4* – anomalies of magnetic field (nT); *5* – age of the seafloor (Ma).

This could be explained by different age of the blocks with oceanic crust composing the Kerguelen Plateau.

The correlation of the Bouguer gravity anomalies' values of the reference structures (Broken Ridge, the Batavia Rise) with the values of the other blocks of the Kerguelen Plateau is not evident. At the same time the Bouguer gravity anomalies' values for the northern and central sectors of the Kerguelen Plateau are 90-100 mGal, which may indicate mantle rocks decompression resulted from activity of the Kerguelen hot spot. The Skiff Bank and the southern sector of the Kerguelen Plateau have continental crust. At that the Bouguer gravity anomalies' values above them correspond to ~165 mGal. These values of the Bouguer gravity anomalies could be revealed above Broken Ridge with ocean type of the crust.

Magnetic field anomalies distribution confirms oceanic nature of the northern block, continental nature of the Elan Bank and William Ridge and heterogeneous nature of the central and southern sectors of the Kerguelen Plateau. It is difficult to define the type of the crust for the central and southern sectors only based on the gravitational field analysis. Highly likely these blocks have continental crust covered by volcanic products.

There is a special sector with thin crust and high values of the Bouguer gravity anomalies evidencing on rifting that divided them. Such division of the Southern Province and the Antarctic continent through the Princess Elizabeth Trough even more evident in the crust's surface subsidence, the Bouguer gravity anomalies' values increase and anomalous thinning of the crust till crustal collapse and a small spreading basin formation.

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