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DEEP STRUCTURE OF THE ANTARCTIC PLATE'S BOUNDARY ZONE ALONG MID-OCEAN RIDGES ON THE CROSS-SECTIONS AND LATERAL SLICES

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Abstract. 3D vertical structure of the Antarctic Plate's boundary along longitudinal cross-sections and lateral slices at different depths is displayed through a distribution of density anomalies using the harmonic coefficients of the EGM96 geoid model. Features of interaction between the Antarctic Plate and other plates are shown with our gravimetric tomography data over more than 40,000 km along the palte boundary. Two bodies (plumes) dominate in the mantle. Less dense masses ascend from depth of 2800 km and then split up at the depth of 200 km as three branches to the Australian-Antarctic Discordance (AAD), the Ross Sea and the Nazca plate. Dense masses descend from a surface as subducted slabs and collect at depths of 60 km and 280 km. It was discovered in the AAD area and the Nazca Ridge that thinning hot masses penetrate into the colder crust and lithosphere.
Key words: density anomalies, plumes, subducted slabs, lithosphere.

Резюме. В работе рассматриваются вертикальный разрез строения Земли вдоль границы Антарктической плиты, а также карты латеральных сечений распределения плотностных неоднородностей на различных глубинах. Аномалии плотности рассчитаны с использованием гармонических коэффициентов гравитационной модели геоида EGM96. Особенности взаимодействия между Антарктической плитой и другими литосферными плитами на протяжении более чем 40 000 км показаны на ортогональных по отношению к границе разрезах. Два тела (плюмы) доминируют в мантии Антарктического региона. Менее плотные массы поднимаются с глубины 2800 км и затем на глубине 200 км разделяются на три отдельных ветви в районах Австралийско-Антарктического Несогласия (ААН), моря Росса и плиты Наска. Плотные массы погружаются от поверхности подобно субдукционным слэбам и концентрируются на глубинах 60 км и 280 км. Обнаружено, что разуплотнённые разогретые массы проникают в более холодную океаническую кору и литосферу в области ААН и хребта Наска.
Ключевые слова: аномалии плотности, плюмы, субдукционные плиты, литосфера.

Introduction

The Antarctic Plate Boundary (APB) zone was studied using data from the PB2002 digital model (Bird, 2003). Vertical cross-sections and lateral slices were calculated using the gravimetric tomography method (Greku et al., 2006). The extent of the boundary is 40,311 km taking into account many of offsets and discontinuities of ridges. The APB is a contact zone with segments of five other large plates (Africa, Australia, Nazca, Pacific, South America) and five small plates (Shetland, Scotia, Sandwich, Somalia, Juan Fernandez). The historical origin and tectonics of these plates are different for the lithosphere and mantle layers. The spreading system of the APB influences the oceanic lithosphere of the Antarctic Plate. At the same time the Antarctic continent shows extensional features in spite of low seismicity (Reading, 2006; Dietrich et al., 2001). It requires combined consideration for both Antarctic Plate internal and interplate processes. Our contribution to the study of the APB are the tomographic images of dense structures at different depths. The limited paper size does not allow us to substantiate the methodology of the gravimetric tomography technique including the algorithm for a decision on the inverse problem from the work of Moritz (1990). Nevertheless, the appropriateness of this method was determined by comparison with seismic tomography data for different regions of the Earth. Therefore, we present the structure and geodynamic analysis of this key Antarctic area. This paper uses the works on separate segments of APB including the Scotia Sea region (Bird, 2003), AAD (Gurnis et al, 1998; Ritzwoller et al., 2001), the Pacific-Antarctic segment of the East Pacific Rise (Lonsdale, 1994) and the Bouvet Triple Junction (Bulychev et al., 2000).

Gravimetric tomography method and initial data

The gravimetric tomography technique is based on the theoretical approach of Prof. H. Moritz (Moritz, 1990) that the Earth's equipotential surfaces coincide with surfaces of the constant density and on the usage of his algorithm for determination of the harmonic dense anomalies through the spherical harmonics of the gravity potential. The method included implementation of the following steps:

1. Determination of a relationship between the harmonic degree of the geoid topography and depth of the corresponding disturbing mass.
2. Determination of the density of anomalous disturbing mass.
3. Visualization of tomographic models of density inhomogeneities.

Depth resolution between earth layers is defined by an interval between depths which correspond to fixed harmonic degrees. These intervals vary for different ranges of harmonics. Practically, we used the following intervals to construct vertical slices: 0.5 km for depths of 1-20 km (360-50 degrees) and 1.0 km for depths of 20-30 km (50-39 degrees). The values within the depth range of 30-5300 km are calculated for each degree from 39 up to 3. The spatial-scale of harmonics (half-wavelength) or lateral resolutions is 0.5°. Computing was carried out with an interval of 0.5°...0.25°. Linean meanings of the resolution (km) at different depths depend on the corresponding radius of the sphere inside the Earth. The spherical coefficients of the EGM96 global geopotential geoid model were used as initial data. Data of the bottom topography (ETOPO5, NOAA-NGDC), free-air gravity anomalies KMS2002 (Andersen et al., 2002), and depths of Moho from the crustal model Crust 2.0 (Bassin et al., 2000) support our tomographic models.

Intraplate structure within the APB at the depth of 82 km

The APB (red line in Figure 1) includes the following spreading ridges and adjacent plates: Pacific Antarctic Ridge (PAR), Pacific and Antarctic Plates; East Pacific Ridge (EPR); Chile (or Nazca) Ridge (CR), Nazca Plate and Antarctic Plates; South Scotia Ridge (SSR), Scotia and Antarctic Plates; Sandwich Ridge (SR), Sandwich and Antarctic Plate; American Antarctic Ridge (AAR), South America and Antarctic Plates; western Southwest Indian Ridge (wSWIR), Africa and Antarctic Plates; eastern Southwest Indian Ridge (eSWIR), Somalia and Antarctic Plates; Southeast Indian Ridge (SEIR), Australia and Antarctic Plates; Australia-Antarctic Ridge (AuAR). Short lines which intersect APB in Figure 1 are geographic positions of start-end points between the ridges.

Background data of the map in Figure 1 displays a distribution of structures, which are the harmonic density anomalies at a depth of 82 km that corresponds to the harmonic of the 21st order. Blue color indicates regions of less dense structures and yellow color indicates more dense structures. Density differentiation in the region corresponds to locations of well known geographic structures in the lithosphere. The East Antarctic craton is marked by higher density. But, the thinning masses from the Ross Sea area penetrate under the Transantarctic Mountains to the Wilkes area. Most of the APB ridges are located in brighter areas, i.e. the roots of the ridges achieve depths of 82 km. Similar lateral slices are built for different characteristic layers of the Antarctic region. The shown anomalies are isostatic uncomprensated.

Vertical cross-section along APB

Deep structure of APB is shown in the vertical cross-section from the sea-bed up to a depth of 5300 km (Figure 2). Profiles of the bottom topography, the free-air gravity anomalies from KMS2002 and a curve of spreading rates along APB from (Bird, 2003) are shown in Figure 2a. APB against (white line) a background of the bottom topography and continents are shown in Figure 2b. Density inhomogeneities are displayed in Figure 2c.

The spatial resolution is 60 km along the APB to simplify the image, although the EGM96 geoid data allows to compute with the resolution of 30 km. The vertical exaggerations in Figure 2c are different for distinct layers (divided by horizontal lines), aimed to show important features within their boundaries. Therefore, the color scales are maintained within distinct layers only. The whole range of density anomalies values is between -0.0983 g/cm^3 and 0.0491 g/cm^3. The thick isoline marks the value of 0.0 g/cm^3. These are the following depth ranges of the layers: solid sea-bed surface-20 km, 20-100 km, 100-750 km, 750-5300 km.

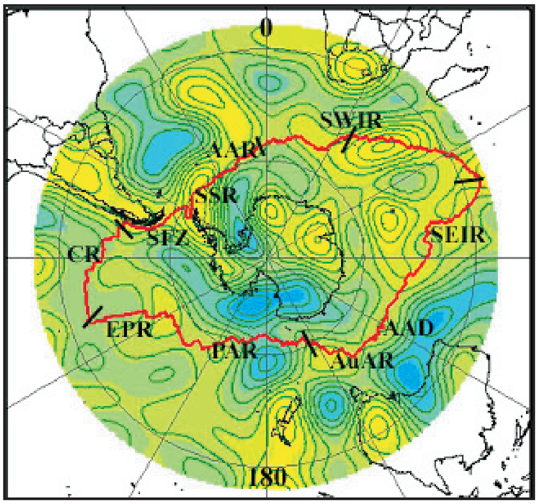

Figure 1. Distribution of density heterogeneities at depth of 82 km. Blue color indicates regions of less dense structures and yellow color indicates more dense structures. Red line is APB. SFZ – Shackleton Fracture Zone. Other abbreviations are in the text above. Short lines intersecting APB are frontiers between ridges.

Two bodies (plumes) with maximum depths of near 2800 km on the core-mantle boundary dominate in the mantle. Less dense hot masses (blue tint) ascend upright and become as three branches from the depth of 200 km. One of them is directed towards AAD (124°E), another one - northward the Ross Sea (175°E) and third one to the boundary of the Nazca plate (250-280°E). Near 175°E, the asthenosphere and lithosphere are transparent for penetration of thinning mantle masses up to depth of 7.0 km. An active penetration of the masses in the form of impulse drops is visible up to the surface in area of lengthening transform fault zone of the Chile Ridge. It apparently causes an accelerated spreading process (Lonsdale, 1994). Dense masses (yellow tint in area of 50°E) are apparently cold relict plume (Conrad-Del Cano), which was shaped under Gondwanaland and then was involved in the process of separation of the Antarctic block from other continents (Storey, 1995). The Figure 2 shows the depths that are maximal for roots of different ridges, where an accumulation of a subduction material occurs and where it drops to deeper layers. Regional features of triple-junctions were also considered. So, the thickness crust of 36 km in Figure 2 (longitude of 359°) corresponds to the results of detailed modeling of the lithosphere with the altimeter data at the Bouvet area (Bulychev et al., 2000). A rise of the upper mantle hot matter at the north-east end of AAR is also confirmed (longitude 350°) (Jonson et al., 1973, cited from Bulychev et al., 2000). The contours and distribution of the anomalous bodies in Figure 2 can be used to draw the internal boundaries of the Earth (Moho, D”, CMB and others).

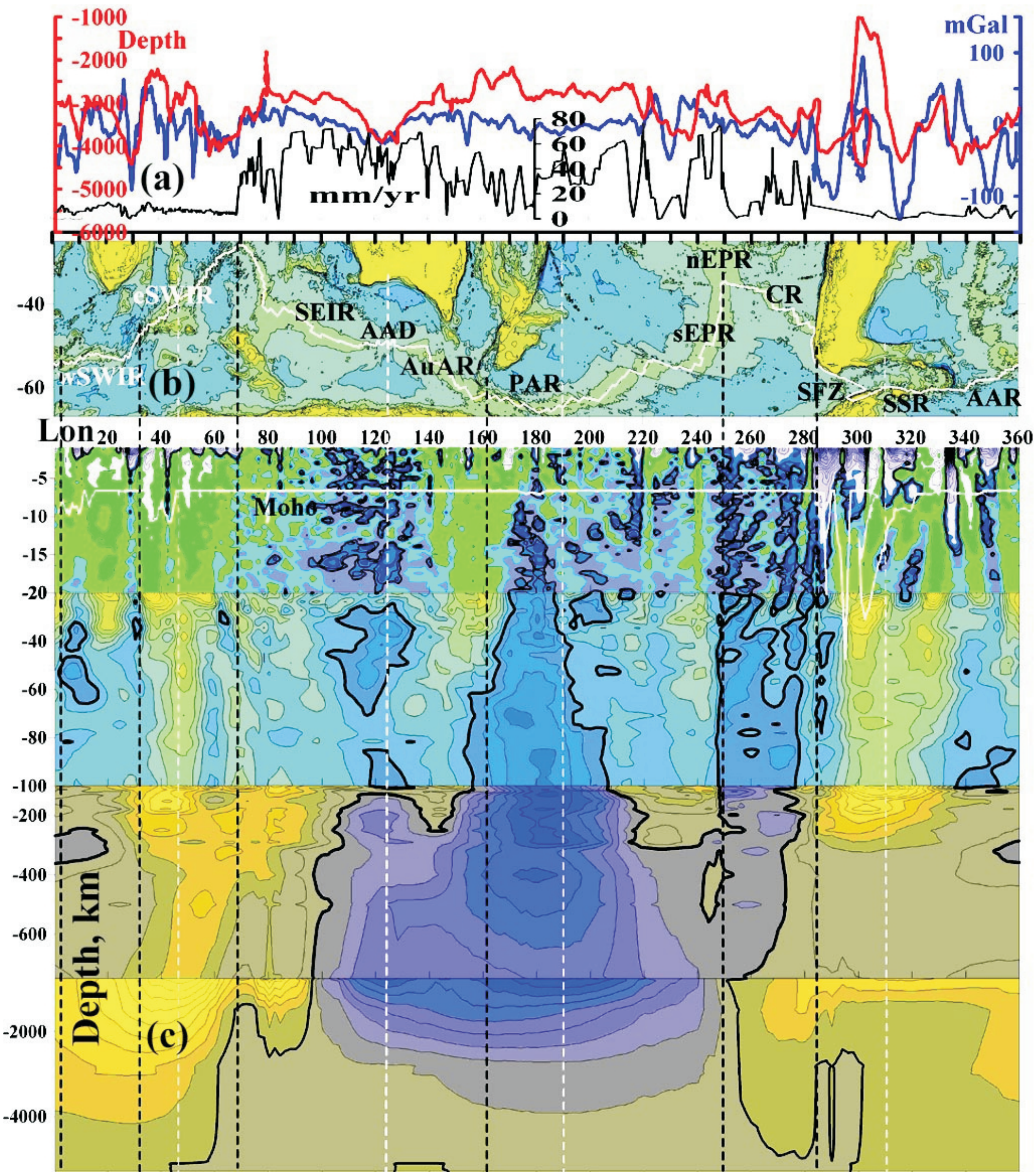

Figure 2. Deep structure of APB. (a) Profiles of the bottom topography (red), free-air gravity anomalies (blue) and spreading rates (black curve, mm yr^{-1}). (b) Ocean floor with APB (white line). (c) The vertical density section along APB. The vertical exaggerations are different for distinct layers. White dotted lines are positions of orthogonal to APB cross-sections and black dotted lines are locations of triple-junction points. White line is the Moho boundary from the Crust 2.0 model.

The AAD anomalous structure's formation

We obtained new information for the AAD area, due to many vertical and lateral slices by the gravimetric tomography, where thinning hot masses penetrate into the colder crust and lithosphere. Our interpretation consists of the following.

The rising of the plume fluids (see Figure 2c) are discovered on the longitude of 124°E from the depth of 150 km. That is a beginning of forming of the AAD anomalous zone of width of 90 km. The ascending masses hinder to join SEIR and AuAR in an interval of 110°E-135°E. Subduction slabs of the root parts of these ridges within intervals of 80°E-120°E and 120°E-150°E accordingly almost join together at the depth of 80 km. On the other hand it is also seen two slabs in Figures 3a where there is a cross-section along the meridian of 124°E. The root parts of SEIR and AuAR are diverged southward and northward accordingly on the lateral maps at depths of 50 km, 30 km and 10 km. It is the result of an infiltration of the plume material into the AAD area from depths of 50-60 km (Figure 3a, b). The area between slabs in Figures 3a and 3b is characterized by an active intrusion of the plume thinning masses (darker tint). A curved form of dense structures at the right south part in Figure 3a supposes an abrupt displacement of the ocean crust up to depths of 5-6 km northward from the Antarctic continent. At the same time, an active displacement southward is obvious at larger depths from 20 km up to 1200 km (Figure 3a). Such scheme of the interplate interaction can be an answer to the question in the ANTEC/SCAR (Lithosphere Structure & Stress) materials (www.antec.scar.org): "How to resolve the geodynamic paradox: Antarctica is surrounded by spreading centres but shows extensional features and low seismicity?"

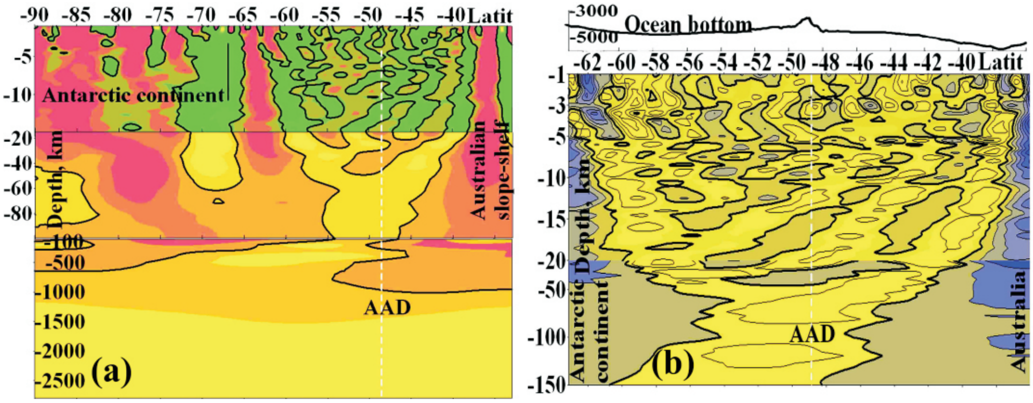

Figure 3. Vertical cross-sections of dense heterogeneities along the meridian of 124°E cross AAD. (a) – Depths are up to 2800 km. (b) – Fragment from (a) between latitudes of 33°S and 63°S up to depth of 150 km.

Summary

The gravimetric tomography data along and across the APB contains new information on structure and interplate processes on both global and regional scales. We compared our gravimetric tomography data with seismic tomography (Ritzwoller et al., 2001). There is a coincidence of the low-velocity anomaly and of our thinning structure within the AAD area in Figure 3b. The same agreement is between the high-velocity "lid" (Ritzwoller et al., 2001) at depths of 70-80 km and our slab's joining area at depths of 80 km and 120°E in Figures 2c and 3b. Something similar to the AAD situation is discovered at the Chile Ridge. There is a possibility to double-enhance the spatial resolution of images for special studies using the EGM96 geoid model and it will be of significantly higher resolution using the EGM08.

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