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Results of long-term tectonomagnetic research in the Akademik Vernadsky station region, the West Coast of the Antarctic Peninsula

Abstract. The study aims to analyze the results of long-term tectonomagnetic observations on the Antarctic tectonomagnetic polygon in the region of the Akademik Vernadsky station to investigate the current geodynamics at the West Coast of the Antarctic Peninsula. The data (1998—2020) were collected as regular discrete geomagnetic measurements. They were used to study the temporal changes of the local magnetic field between the observation epochs and tectonomagnetic anomalies. We create a temporal series of the changes in the local magnetic field for every point of the observation network on the polygon and provide the map of tectonomagnetic anomalies over different observation periods. The tectonomagnetic anomalies of 2.0—2.8 nT · year^{-1} were found in the Argentine Islands region. The anomalies' spatial structure agrees with elements of the tectonic structure of the Earth crust. We studied the spatial-temporal connection of the tectonomagnetic anomalies with the region seismicity and estimated the values of tectonic stresses in the lithosphere within the piezomagnetic mechanism. The spatial-temporal structure of tectonomagnetic anomalies in the region shows the response of the geological environment to the change in the tectonic stresses in the local crust. Based on the theoretical calculations and other geological and geophysical data, we conclude that a piezomagnetic effect causes the anomalies under the action of stretching tectonic stresses (~1 bar · year^{-1}) in the sub-latitudinal direction. Given the urgency of discovering the seismotectonic processes and current regional dynamics, the tectonomagnetic observations on the polygon should be continued as a yearly monitoring program, including other methods of geophysics and geodesy.

Keywords: monitoring, seismic activity, tectonic stress, tectonomagnetic anomalies

1 Introduction

Geophysical methods are widely applied to reveal the deep structure of the Earth crust and its current dynamics, meaning the deep physical-chemical processes of different sizes and periodicity from seconds to decades. These processes are Earth crust movements, earthquakes, and karst phenomena and cause the temporal shifts in geophysical fields, parameters, etc. (Maksymchuk et al., 2001; Tretyak et al., 2015).

An important branch of geodynamic research is studying seismoactive areas and faults as potentially dangerous objects for the densely-populated and industrially developed territories. The urgency of these studies of the tectonically active areas in the Antarctic region is linked to the large oil and gas fields and other mineral resources being found in the region of such geological structures. It has vast implications for the future exploitation of the Antarctic mineral resources.

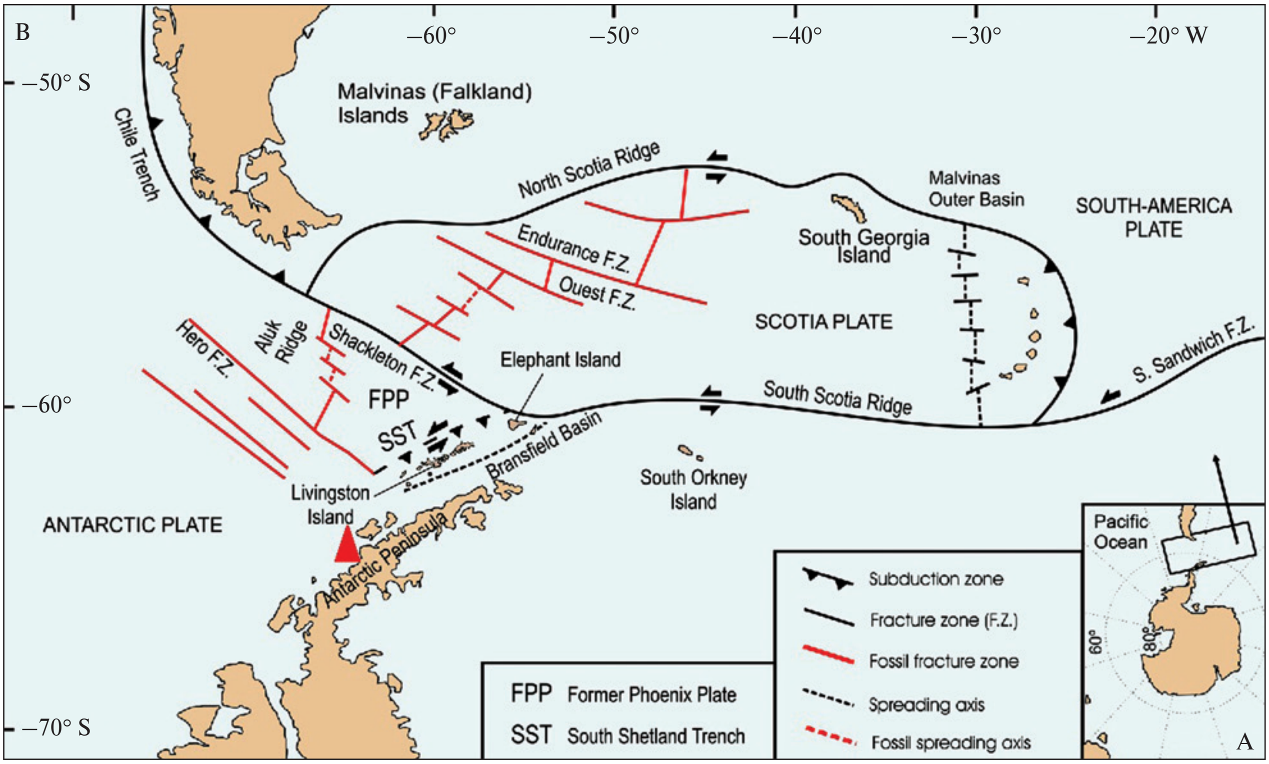

Figure 1. Location of the Vernadsky station (red triangle) on the tectonic map. The figure is modified after Alfaro et al. (2010)

Ukrainian scientists have been focusing on the current geodynamics of the Antarctic Peninsula since the Faraday Base was transferred to Ukraine and renamed as the Akademik Vernadsky station. The relevance of studying the modern geodynamics of the station region is due to its location in the zone of the Bransfield Rift geodynamic influence, where strong earthquakes of M = 6÷8 occur. Near the station, the deep fault lines of sub-latitudinal and sub-meridional directionality are located, where active seismotectonic processes take place that are quite significant for deep crust modeling.

The Ukrainian Antarctic Akademik Vernadsky station (hereinafter — Vernadsky station) is located on the West Coast of the Antarctic Peninsula and exhibits low seismic activity (Bakhmutov et al., 2017). Meanwhile, from the global tectonic point of view, the Vernadsky station is located on the Antarctic plate at one of the most globally active seismic zones at the border of the Scotia Plate and the Phoenix Plate (Fig. 1).

According to the USCS Catalogue (The Earthquake Hazards, 2022), from January 2000 to November 2021, 6724 earthquakes of $M \geq 4$ with hypocentral depths of 1.2—272.4 km and 1289 earthquakes of $M \geq 5$ (hypocentral depths of 6.3—170.8 km) were registered (Fig. 2). Most earthquakes were registered NE of the Vernadsky station in the South Sandwich Islands region, about two thousand kilometers away. Many of them took place in the Bransfield Strait within the Bransfield Rift subduction zone and the Shackleton and Hero Fracture Zones. The earthquakes of $M \geq 4$ registered closest to the Vernadsky station occurred at the westernmost tip of the Bransfield Rift at the epicentral distance of 200 km. Although the Bransfield Rift zone does not include the Argentine Islands, where the Vernadsky station is situated, the Vernadsky station area is located at the continuation of the southern tip of the Bransfield Rift zone (Bakhmutov et al., 2017).

The specific structure and current geodynamics of the Antarctic Peninsula western shelf are not yet well

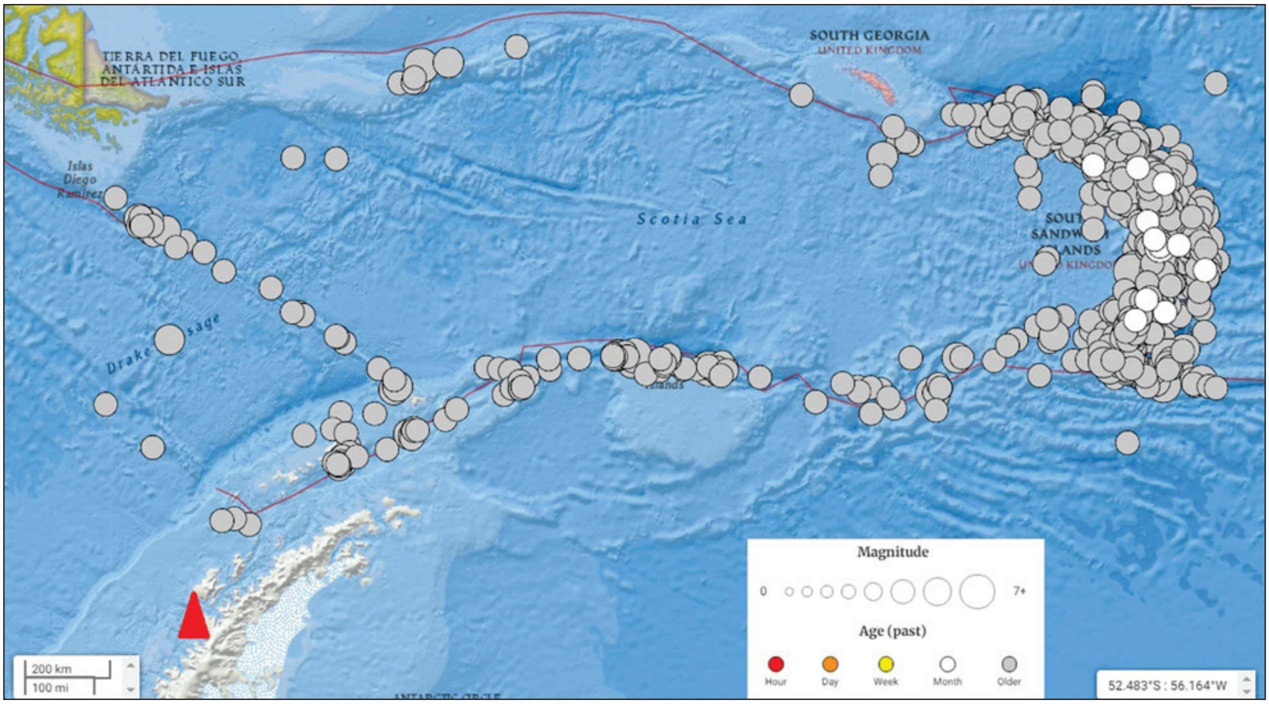

Figure 2. Epicenters of earthquakes with magnitude M > 5 for the interval 01.01.2000—01.11.2021 in the area of contact of the bevel plate with the surrounding tectonic structures. Red triangle — location of the Vernadsky station. The map is modified from the Earthquake Hazards Program of the United States Geological Survey (USGS) (retrieved February 28, 2022, from https://www.usgs.gov/programs/earthquake-hazards)

known. Until the time when the Faraday Base was transferred to Ukraine in 1996, this kind of study was not done in the region.

The tectonomagnetic studies at the Vernadsky station region started in 1998 as part of the State Special-Purpose Research Program in Antarctica for 2011—2023 to investigate the current geodynamics of the West Coast of the Antarctic Peninsula. To do this study, a complex tectonomagnetic polygon was established. The first step was to trace the tectonomagnetic profile (Fig. 3) from The Barchans to Rasmussen Island, 11 km long, with seven stationary observation points, and to conduct the first cycle of tectonomagnetic measurements. The polygon network increased to 28 observation points in 2020 (Fig. 3). Nowadays, it ranges 20 km from West to East: from the Roca Islands to Moot Point, and 46 km from North to South: Pleneau Island — Beascochea Bay.

Due to the regional specifics, most polygon points are located in the Argentine Islands area. There have been made thirteen observation cycles there. The research program more or less increased into a tectonomagnetic monitoring service for the geodynamic processes in the Vernadsky station region.

This paper aims to analyze the long-term tectonomagnetic observations on the Antarctic tectonomagnetic polygon established in the region and to study the geodynamics of the Antarctic Peninsula West Coast near the Vernadsky station.

2 Materials and methods

The current dynamics of the Earth crust are mostly studied by geodesic, seismic and geophysical methods on specially established tectonomagnetic polygons. Among most geophysical methods, the tectonomagnetic one has shown excellent results. Tectonic magnetism is the phenomenon of local magnetic field changes induced by the tectonic processes in the crust. As the reason for the magnetic field local changes, i.e., tectono-

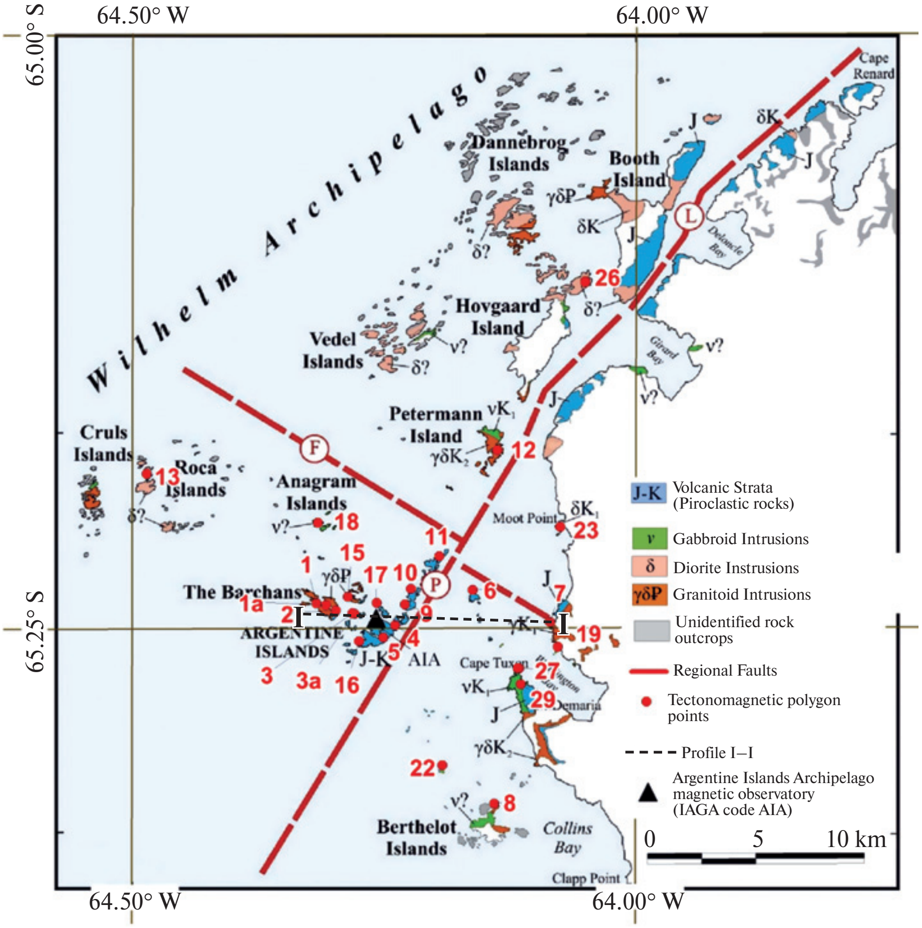

Figure 3. The layout of the tectonomagnetic observation points on the geological map of the Argentine Islands. The figure is modified after Mytrokhyn & Bakhmutov (2021)

magnetic anomalies (effects), they can arise from the magnetic properties shift of the rocks under varying tectonic stresses (piezomagnetic effect, electrokinetic phenomena in rock fissures, etc.). The tectonomagnetic method is used to study and to map tectonically active fissures, research seismotectonic processes and earthquake predictors, tectonic zonation, and search for hydrocarbon deposits. According to tectonomagnetic research in different world regions (Nishida et al., 2004; Waghmare et al., 2009; Dyadkov et al., 2018), in the current tectonic active zones, the tectonomagnetic anomalies ranging from one to dozens of nT, lasting from minutes to dozens of years, spreading over dozens and hundreds of miles were studied (Abdullabekov & Maksudov, 1975; Maksymchuk et al., 2001).

The methodology of tectonomagnetic research used on the Antarctic tectonomagnetic polygon is widely applied to predict seismic activity. It was described in detail (Maksymchuk et al., 2008; 2009; 2018).

The tectonomagnetic method studies temporal changes of the local geomagnetic field (the so-called tectonomagnetic variations) over a network of stationary observation points by regular discrete or continuous measurements. The module of the total magnetic induction vector B is the value of interest.

The base (main) station of the polygon is the Argentine Islands Archipelago magnetic observatory (IAGA code AIA). The total geomagnetic vector B module is continuously measured in the pavilion every ten seconds using the proton magnetometer POS-1 with 0.1 nT sensitivity.

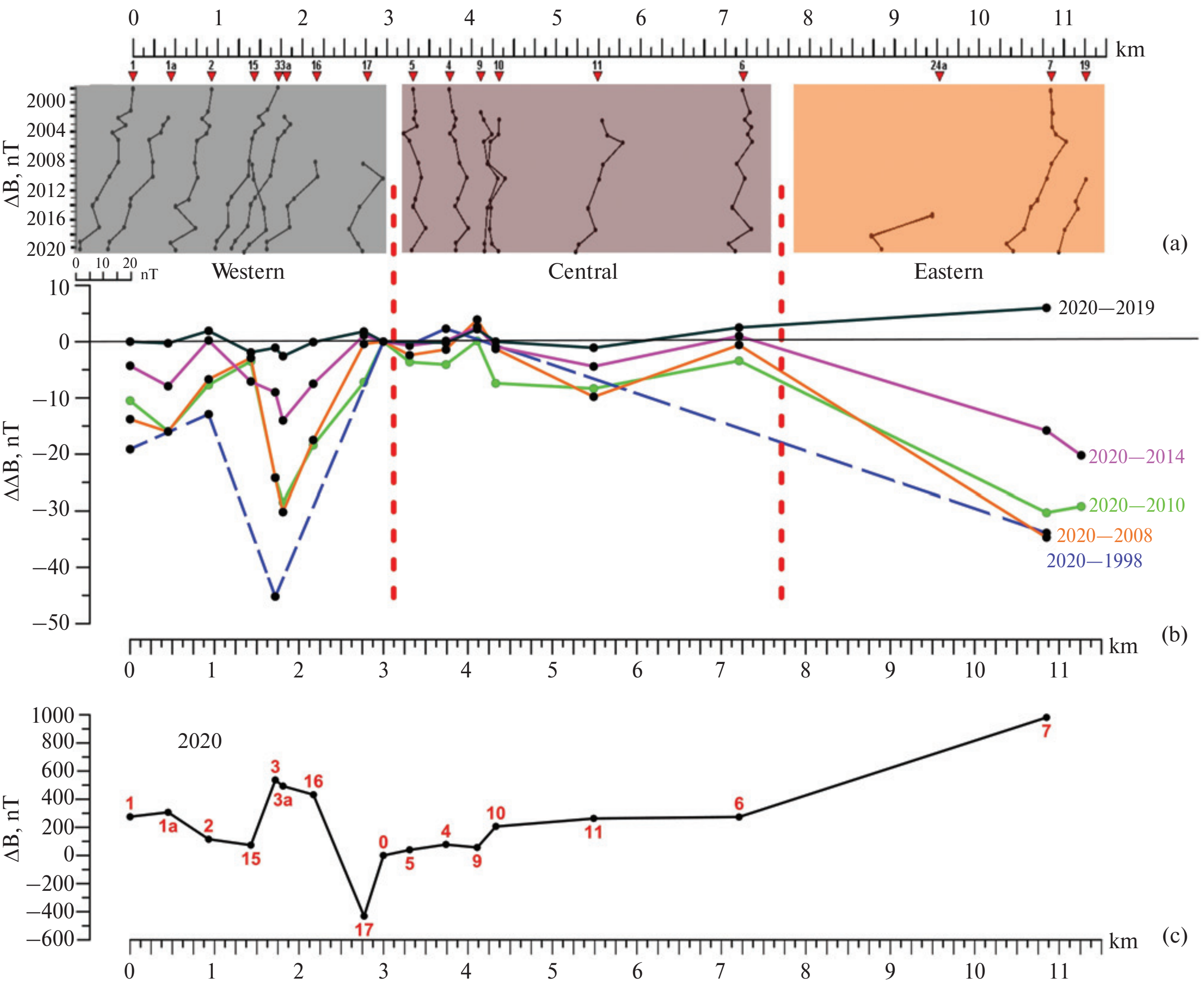

Figure 4. The local magnetic field ΔB changes in time in the 2020—1998 period at the points of the tectonomagnetic landfill (a), along The Barchans—Rasmussen profile (b), and the ΔB field observed in 2020 along the profile (c)

On other (ordinary) observation points of the polygon, the field vector B is measured mostly using proton magnetometers MMP-203 with 1.0 nT sensitivity. Since 2019, these measurements have been provided with the proton magnetometer PMP-8. At these points, the observation cycle lasts over half an hour with the frequency of 1 measurement per 20 seconds. The differential value of the field B is the main parameter for study:

$$\Delta B = B_p - B_b, \tag{1}$$

where B_p and B_b are the values of B at the base and the ordinary observation point.

The tectonomagnetic parameter ΔΔB of the temporal change of the differential magnetic field is determined as the increment of the ΔB values between observation cycles:

$$\Delta\Delta B = \Delta B_2 - \Delta B_1, \tag{2}$$

where ΔB_1 and ΔB_2 are the ΔB values between observation cycles (here, between cycle 1 and cycle 2).

The standard deviation of the ΔB determination for the different years of observations on the polygon

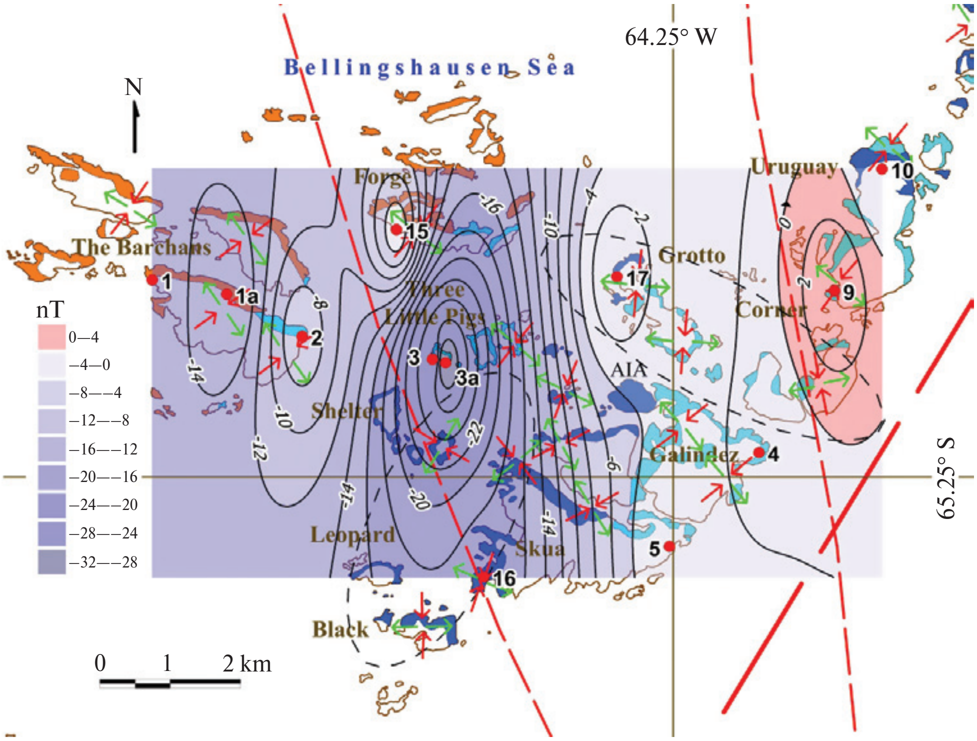

Figure 5. Tectonomagnetic anomalies ΔΔB for 2008—2020 on the geological map of the Argentine Islands (Mytrokhyn & Bakhmutov, 2021) (for the legend, see Fig. 3), red dashed lines are the predicted tectonic faults (Bakhmutov et al., 2017), red arrows — compression axes, green arrows — the axes of stretching (Murovskaya & Bakhmutov, 2015). The figure is modified after Mytrokhyn & Bakhmutov (2021)

fluctuates between 0.7 and 1.2 nT. Therefore, the long-term over a yearlong change in the local field ΔB can be studied at the polygon. Over the whole period of the polygon functioning (1998—2020), the thirteen cycles of tectonomagnetic observation time series of field ΔB over 22 years have been provided. All polygon points were marked with brass marks to position the recorder of the magnetometer with the precision of several millimeters during the repeated measurements.

3 Results

The long-term tectonomagnetic observations (1998—2020) are presented as the time series of the local magnetic field ΔB for every polygon point (Fig. 4). The map of tectonomagnetic anomalies ΔΔB over different time ranges shows the revealed anomaly temporal and spatial changes (Fig. 5).

The most detailed study of the local magnetic field ΔB was done along the I—I profile (The Barchans—Rasmussen), where most of the observation points are concentrated (Fig. 3). Most cycles of magnetic field ΔB measurements were obtained at this profile. The 11 km long I—I profile crosses the main tectonic structures and rock formation complexes of the shoreline shelf from The Barchans to Cape Rasmussen at the Antarctic Peninsula.

The temporal change of the local ΔB field variations has a complex nature with the trend and the local components (Fig. 4). The character of temporal changes of the ΔB field over 1998—2020 and their intensity and morphology over different sections of the I—I profile are notably different (Fig. 4). The most intense ΔB changes were seen in the western part of the profile (points 1, 1a, 2, 3, and 3a, 1a, 2, 3, 3a) and at point 3 (Three Little Pigs Islands). Over the 1998–2020 period, they reached −44 nT, which is −2.0 nT · year^{-1} on average.

According to the tectonomagnetic observations on the Antarctic tectonomagnetic polygon, we drew maps of tectonomagnetic anomalies over different time intervals (Fig. 5). The construction was somewhat complicated by the very uneven spacing of the observation points. Because of this, ΔΔB maps were drawn only for the central part of the polygon limited by the Skua Island, The Barchans, the Forge, Grotto, and Uruguay Islands. However, even within this scope, the spatial structure of ΔΔB anomalies is a general outline. Figure 5 presents the map of anomalies ΔΔB for the 2008—2020 period. In the structure of ΔΔB, the two intense negative ΔΔB maximums on The Barchans (point 1, –15.9 nT), the Three Little Pigs Islands (point 3, –22.4 nT), and a maximum on the Uruguay Island (point 10, +8.3 nT) are seen in Figure 5.

The similar structure of the ΔΔB field has remained more or less stable practically over the whole study period, with changes in the intensity and direction of the anomalies with insignificant fluctuations in their placement. To correctly describe the nature of tectonomagnetic anomalies on the Antarctic polygon, it is important to reveal their spatial-temporal connection with other geological-geophysical data, especially seismicity and the current motions of the Earth crust.

For further analysis of the spatial-temporal structure of the tectonomagnetic anomalies, we focus on the results for the I—I profile (The Barchans — Cape Rasmussen). It is mostly within a fairly narrow band 1 km wide along the I—I line, where most of the tectonomagnetic observation points are located and have the longest data series. The time series of the tectonomagnetic observations for the points along the I—I profile are shown in Figure 4. In general, three groups of points: Western, Central, and Eastern, are seen in Figure 4.

The Western group (The Barchans, the Three Little Pigs Islands, Forge Islands, Skua Island, and Grotto Island (points 1, 1a, 2, 15, 3, 3a, 16, and 17)) is characterized by a clear negative linear trend. The most intense changes in ΔB were seen for the Three Little Pigs Islands, where at point 3, changes in ΔB reached –44 nT over 2020—1998.The Central group of islands (Galindez, Skua, Yalour, Uruguay, Irizar; points 5, 4, 9, 10, 11, 12 (Fig. 4)) has small changes in the ΔB field, fluctuating around the null horizontal trend almost within the error (±1.5—2 nT). Between 2020 and 2019, the field increased by 2.84 nT for point 6. The Eastern group (points 24, 7, and 19) has a distinct morphology: ΔB field almost without anomalies in 1998—2003, then a sharp negative trend after 2004, declining by 40 nT over 2020—1998 (point 7).

In the case of ΔB (t) graphs, some regularities in the distribution of the tectonomagnetic field ΔΔB along the I—I profile are seen. The ΔΔB distribution along the I—I profile over different time intervals is fairly stable and generally reflected by the summary ΔΔB profile for 2020—1998, which can be seen in the Western, Central, and Eastern sections with different anomalies amplitude for ΔΔB: the Western points 1, 1a, 2, 3, and 3a with strongly anomalous negative values from –15 nT to –44.0 nT at point 3; the Central (points 4, 5, 9, 10, and 11) where the ΔΔB field does not exceed ±2.0 nT; and the Eastern (points 7, 24, and 19) with the negative ΔΔB field at the level of –6 nT.

Compiling the spatial structure of tectonomagnetic anomalies with the geologic-tectonic data for the region shows that the most intense anomalies tend to the areas of vulcanite and intrusions of The Barchans, Forge, Three Little Pigs Islands region, and the tectonic fault running from NW to SE. In this fault (contact) area, there is a local intense magnetic anomaly of ~600 nT on the Three Little Pigs Islands and an anomaly of +430 nT west of Skua Island (Fig. 4).

A position of the tectonomagnetic maps with the geologic-tectonic and geodesic data shows that the apparent sections (areas) are limited by lines of tectonic disruptions seen from the geologic-tectonic and geodesic data (Tretyak et al., 2016; 2018). Naturally, the ΔΔB anomaly extremums change their module or direction over different time intervals and “migrate” within every section. The section structure of the region by tectonomagnetic monitoring coincides with the geologic-tectonic data, which exhibits the Penola tectonic fissure running alongside the Penola Strait and playing an important role in the local tectonics (Fig. 5). The horizontal and vertical tectonic motions of various modules and signs can be seen in each tectonic zone. For example, in the Eastern area (inland part of the tectonomagnetic polygon: point 7 (Cape Rasmussen), point 19 (Rasmussen Island)), the vertical motions of lowering and horizontal shifts to SE predominate. In the Western tectonic area, the uplifting and horizontal motions to NW predominate (Savchyn et al., 2021a; 2021b).

Comparison of these tectonomagnetic anomalies over different time intervals with the geological structure and with the tensions of the compression-stretching axes demonstrates that the most intense dynamic changes in the field ΔΔB tend to the tectonic block bearing the Three Little Pigs Islands. Along the eastern shoreline of The Barchans and Forge Islands, the mapped narrow band of older volcanic rocks (the metamorphized lithoclastic lapile tuffs) is shown (Fig. 5). They are quite different from the volcanites foliating off in the east on the Shelter, Three Little Pigs, and Grotto Islands. The main difference is the intense milonitization and schistosity of volcanites on the eastern shores of The Barchans and Forge Islands. The volcanites are crisscrossed with numerous mafic dykes of various ages. The youngest rocks are the volcanites, dykes and granitoids of The Barchans—Forge. The intrusive contact of granitoids with volcanic rocks was seen and studied on The Barchans (Barchans-I and Barchans-II) and the Forge Islands. Near the contact, granitoids and volcanites alternate (Mytrokhyn & Bakhmutov, 2019; 2020).

Such a complex geologic structure, intense formation of cracks, schistosity, and metamorphization of rocks where the volcanites meet The Barchans—Forge intrusive massive are evidence of a tectonic fault solidly supported by tectonomagnetic data. In particular, for this contact zone up to one kilometer wide, a local ΔB anomaly of around 600 nT on the Three Little Pigs Islands is found. This contact area is also characterized by intense minimums of the tectonomagnetic anomalies of ΔΔB in the area of the Three Little Pigs and Shelter Islands (Fig. 5). Although the extremum of the dynamic anomaly of ΔΔB is also one kilometer off to SE from the contact line on the day surface, the "roots" of the granitoid intrusion are much deeper. The abnormal character of the magnetic field of ΔΔB of the block is also coordinated with the fields of tension. In Figure 5, the predominating stretching direction is NW — SE, and the compression direction is SW — NE. The orientation of the stretching axis perpendicular to the main riftogenic structures of the region allows linking their formation with the stretching regime (Murovskaya & Bakhmutov, 2015). In the fault areas oriented from SW to NE, there act the stresses of stretching, and the faults such as the Penola Fault occur. Along the line from NW to SE, landslides both to the left and to the right occurred. On the map (Fig. 5), two areas are shown by the dashed ovals where the tension field has an anomalous orientation. For the Argentine Islands group, the anomalous zones cross the Grotto and Corner Islands along the Meek Channel and along the zone including the Shelter and Indicator islands. Obviously, these anomalies are connected with sliding faults where the corresponding cracks return to the horizontal plane together with the respective tension tensor. Note that the southern dashed oval in Figure 5 with the anomalous orientation in comparison to the predominant general direction of the stretching and compression axes is located to the south of the Three Little Pigs Islands area.This area has the "anomalous" dynamic changes (see points 3 and 3a in Figure 4) of the field ΔΔB over all reviewed time intervals.

4 Discussion

The possible connection of the tectonomagnetic anomalies with the changes in tectonic stresses is supported by the correlation of the magnetic field changes and the surface concentration of radon in the Vernadsky station region (Rusov et al., 2014).To discover the nature of the tectonomagnetic anomalies on the Antarctic polygon, we shall analyze the possible contribution of the secular variation of the magnetic field and their connection with the region's seismicity. Knowledge of the spatial structure of the secular trend in the region of the tectonomagnetic polygon is very important since the variations can contribute to the tectonomagnetic anomalies. There are two possible mechanisms: one based on the gradient of secular variation between the polygon points and the base point at the AIA, and the other based on the magnetization of rock massif under the action of secular variation.

The spatial structure of the secular trend of the geomagnetic field B in Antarctica in the time intervals of

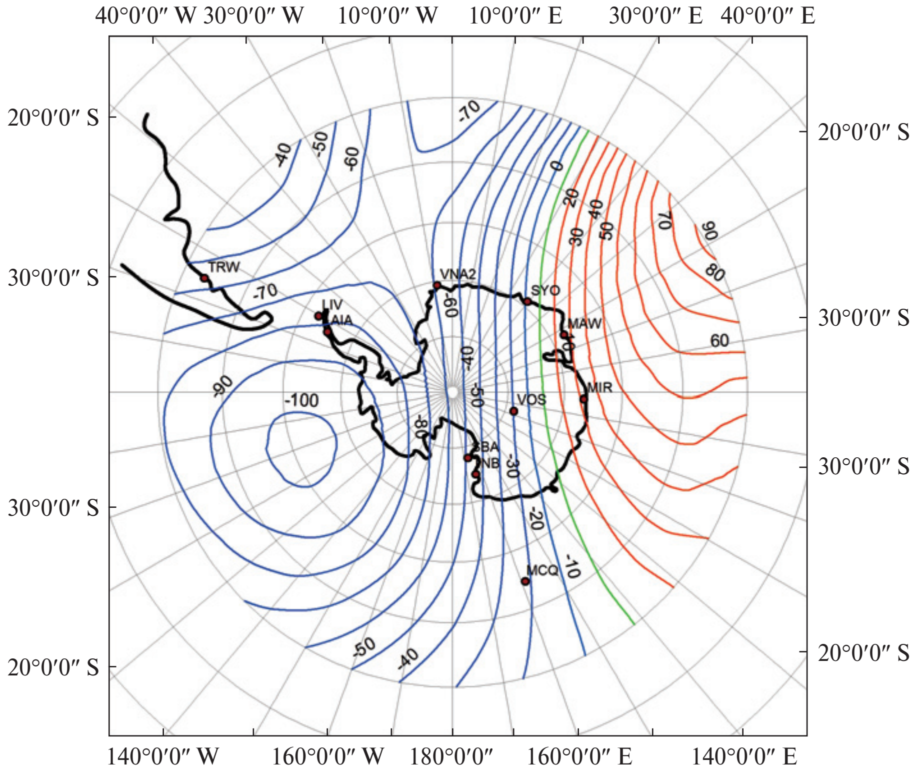

Figure 6. Secular variation of the geomagnetic field ΔB (nT · year^{-1}) according to the IGRF-20 model for the 2015—2020 period

2010—2015 and 2015—2020 is shown in Figures 6 and 7. In the 2010—2020 period in the Antarctic Peninsula region, the so-called intense focus of secular variation of the module of the full vector B with the amplitude of 100 nT · year^{-1} in the epicenter existed. The epicenter of the focus is displaced westwards relative to the Antarctic Peninsula. At the Antarctic tectonomagnetic polygon, the secular trend of B under the model of IGPF-20 reached around 90 nT · year^{-1}. According to the observation data at the AIA, in 2010—2015, the secular trend B was 90.2 nT · year^{-1} as well (Fig. 7).

The spatial gradient of the B-field secular trend should be evaluated by comparing the secular variation of B with the tectonomagnetic effects on the polygon. In Figures 6 and 7 the maximum secular trend gradient is seen from NE to SW (c. 0.1 nT · km^{-1} · year^{-1}) in the region of the Vernadsky station. In this case, at the most distant points N and S from the Vernadsky station, the contribution of the secular trend at distances of up to 20 km would be +0.2 nT · year^{-1} for the northernmost point (Petermann) and –0.2 nT · year^{-1} for the southernmost point (Berthelot). Considering the linear secular trend at the Vernadsky station area over the last 20 years for these observation points, its maximum contribution over the whole observation period would not exceed ±4 nT.

In the NW — SE direction, the secular trend gradient of the B field in the area of the Vernadsky station is close to zero (Fig. 6, 7). It is important for interpretation of the discovered tectonomagnetic effects along The Barchans—Rasmussen profile, which goes through the Vernadsky station area from NW to SE, where most of the observation points and interpretation models are situated (Maksymchuk et al., 2008; 2021). The contribution of the secular trend to the tectonomagnetic anomalies on The Barchans—Rasmussen profile is close to zero.

To discuss the possible magnetizing effect of the secular variation on the tectonomagnetic anomalies, we should consider the magnetic field B secular trend specifically at the AIA.

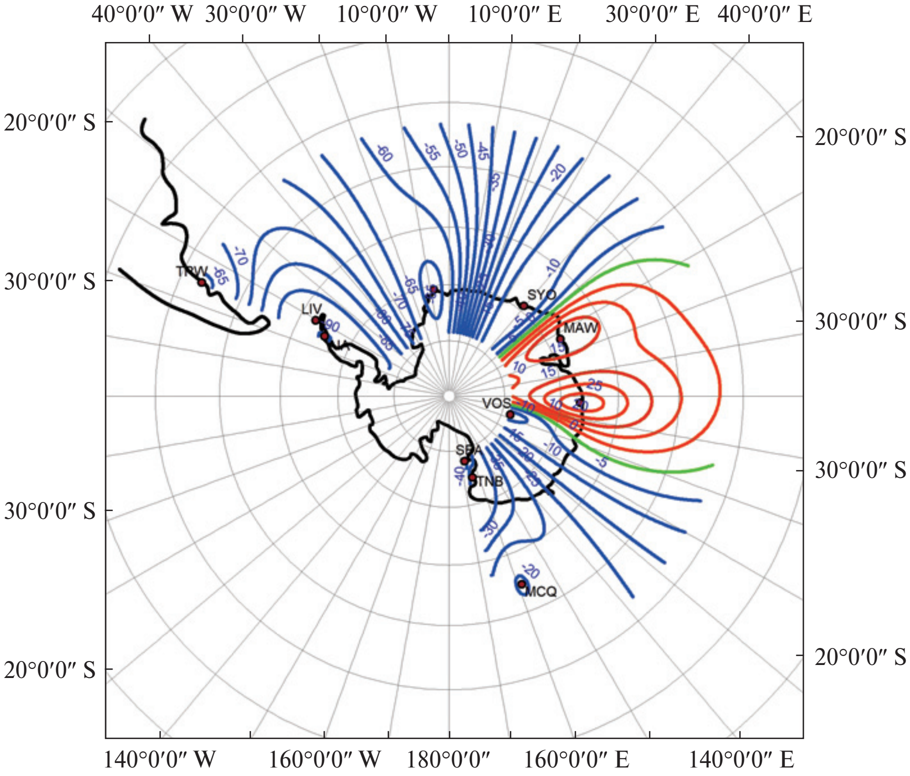

Figure 7. Secular variation of the geomagnetic field ΔB (nT · year^{-1}) according to observations at geomagnetic stations for the 2010—2015 interval

According to the measurements at the AIA observatory (Fig. 8a), a clear linear trend of field B is seen reaching around 90 nT · year^{-1}. A comparison of the ΔB field trend at point 3 with the B field at the AIA shows their similar behavior, so their interrelation can be assumed. The possible contribution of the magnetized effect of the secular variation has been evaluated by Maksymchuk et al. (2009), analyzing the time series for 1998—2005. However, from Figure 8c, the behavior of ΔB at point 3 changed significantly in 2007—2020, while the change of the B field at the AIA shows its character to remain linear.

Notably, the similarity of the secular trend of the B field at the AIA with ΔB at point 7 in the eastern part of the polygon (Fig. 8e) is not observed, where the value of the anomalous field ΔB is close to the ΔB at point 3. Therefore, there is no contribution of the secular trend of field B to the tectonomagnetic anomalies.

Besides the long-term component, we observe local effects in the ΔB behavior at point 3 in 2008—2010 at the level of 5—10 nT relative to the trend component. The ΔB field returned to the trend level only in 2013. A similar character of change of the ΔB field is also seen at the point 3a. Note that the points 3 and 3a are located on the Three Little Pigs Islands within 500 m from each other in the area of intense local magnetic ΔB anomaly, which is in the same geological and tectonic conditions.

The possible connection of the tectonomagnetic effects with geodynamic processes can be supported by their similar spatial-temporal behavior with seismicity. The ΔB graph for point 3 and the graphs of the earthquake numbers (Fig. 8f) in the Bransfield Rift region have a similar behavior. The section of anomalous ΔΔB data at point 3 in 2008—2012 may coincide, or possibly precedes the 2011—2013 period of the seismic activation in the Bransfield Rift with M > 5.

A similar structure was seen in 2017—2020. In the ΔB graph for point 3 in 2017, a local ΔB anomaly of 5 nT is seen, preceding a series of earthquakes in the

Bransfield Rift in 2020—2021 (Fig. 8). However, this local anomaly in ΔB changes was not clearly isolated due to the lack of magnetic field records in 2015—2016. Evidently, to study the spatial-temporal connections of the tectonomagnetic effects with seismicity, we should consider the epicentral distance, magnitude, and depth of the hypocenter parameters.

The relationship between the magnitude M and the radius of the earthquake preparation zone R is described by the expression $LgR = 0.35M + 0.04$ (Skovorodkin, 1985). Therefore, the tectonomagnetic effect for an earthquake $M = 6$ can be expected at a distance of up to 130 km, at $M = 7$ — at a distance of up to 300 km. An important parameter for this is the time of preparation of the earthquake. According to (Skovorodkin, 1985), the duration of preparation of an earthquake $Lgt = 0.73M - 1.57$ with a magnitude of $M = 7$ is nine years.

The local tectonomagnetic anomalies of ΔB in 2008—2012 possibly connected with a powerful earthquake of $M = 5.7$ on July 16, 2013, at the epicentral distance of ~200 km from the Vernadsky station. According to the empirical dependencies between M and R, the radius of the earthquake preparation area can reach ~100 km, and the preparation time of about a year. In the following period of the seismic activation of the Bransfield Rift, the epicenters of earthquakes with $M = 5.6$—5.9 and $M = 6.9$ on January 24, 2021 were much further from the Vernadsky station at 600—700 km away. Therefore, it is clear why the local tectonomagnetic effect in 2018 lasted for a shorter time and had a lesser amplitude than the previous. This is possible evidence of the influence of seismotectonic processes in the western part of the Bransfield Rift on the geodynamic situation and the changes of the tectonic stresses in the crust in the Vernadsky station region.

Obviously, a direct effect of the earthquakes on the change in tectonic tensions in the crust in the Vernadsky station area should not be expected given the described relationship of M and R. However, we think that regionally, the seismic activity of the Bransfield area reflects the complex nature of changes in tectonic stresses in the crust. In this case, the magnetic inhomogeneities in the Vernadsky station region can react

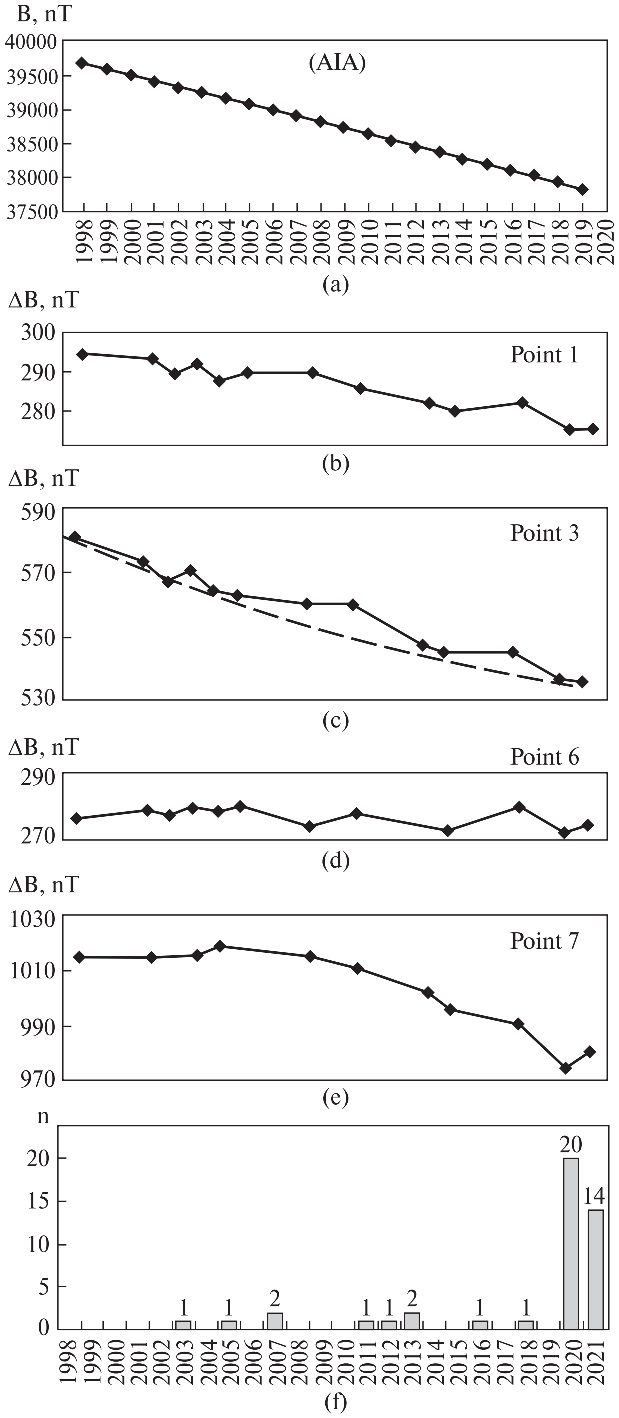

Figure 8. Time changes of the geomagnetic field B (nT) on the AIA observatory (a), local field ΔB (nT) at tectonomagnetic points № 1 (b), 3 (dashed line — the trend) (c), 6 (d), 7 (e), and histogram of the number of earthquakes with M > 5 in the Bransfield Strait region (f)

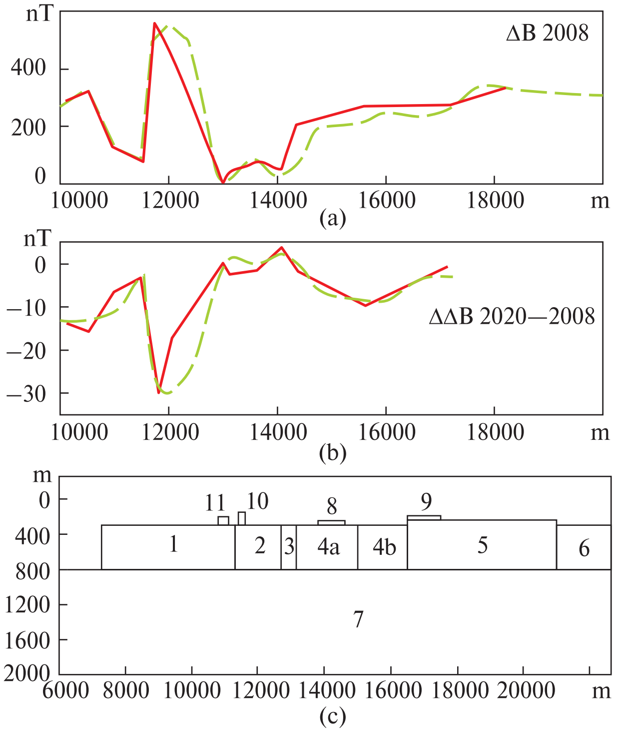

Figure 9. The tectonomagnetic model along The Barchans-Rasmussen profile: (a) field distribution ΔB for 2008, (b) distribution of time field changes ΔΔB in the 2020—2008 period (solid line — observed field, dashed line — calculated field), (c) the model of the ΔB anomaly sources as the set of vertically magnetized sub-meridional oriented parallelepipeds (blocks)

Table. The calculated changes in tectonic stresses ΔP in blocks of the Earth crust along The Barchans-Rasmussen profile at the different periods

N block	ΔP (Bar · year^{-1})			
	2017—2008	2019—2008	2020—2008	2020—2019
1	1.7	3.8	3.0	−0.7
2	4.9	6.1	5.7	−0.4
3	0.6	0.0	0.0	−0.1
4a	−0.2	−0.3	−0.3	0.0
4b	−0.6	−0.2	−0.2	0.0
5	−2.2	−1.0	−1.1	−0.1
6	−1.3	0.0	−0.1	0.0
7	−0.3	−6.8	−8.3	−1.5
8	−3.2	−7.0	−9.6	−2.6
9	−2.5	−4.1	−1.9	2.2
10	−1.4	−13.4	−11.7	1.7
11	−7.8	−5.1	−4.1	1.0

to changes in tectonic tensions caused by the preparation of powerful earthquakes over long distances.

Anomalous effects in geophysical parameters at considerable distances from the epicenters of earthquakes have already been documented (Maksymchuk et al., 2001). We presume that at some observation points located in favorable geotectonic conditions, there can be registered changes in the regional tectonic stresses locally reflected in the geophysical fields.

The Three Little Pigs Islands (points 3 and 3a) is a “special” point where the anomaly of the local magnetic field ΔB manifests intense changes.

Taking into account the time and amplitude of the discovered tectonomagnetic anomalies, their tendency to occur near magnetized geological bodies, and their certain temporal-spatial connection with seismicity, we conclude that the most probable reason for anomalies is the tectonic stress changes. As a mechanism of their generation, we consider the piezomagnetic effect. The effect is due to the change of the value and spatial distribution of the ferromagnetic magnetization vectors under mechanical deformations, which then causes magnetic field variations in the geological medium — the tectonomagnetic anomalies.

To estimate the contribution of the piezomagnetic mechanism to the temporal changes of the local magnetic field, we considered a two-dimensional model of the magnetic inhomogeneity and changes in its magnetization under the effect of tectonic stresses along the profile of The Barchans — Rasmussen Island (Maksymchuk et al., 2008; 2018). The model of the ΔB anomaly source is chosen as a set of vertically magnetized sub-meridional oriented parallelepipeds (blocks) (Fig. 9). The field ΔB calculated from this model agrees with the observed field. By the experimentally established changes in the local magnetic field ΔB, we found the changes in the magnetization ΔJ based on the functional dependence of ΔJ and the change in stresses ΔP (Skovorodkin, 1985):

$$\Delta J = J\,\Delta P\,(2\beta\sin\gamma - \beta\cos\gamma), \qquad (3)$$

where γ is the angle between the magnetizing field direction and the axis of the main residual stress.

According to equation (3), we suggest $\gamma = \pi/2$, which corresponds to horizontal stress. The changes of tensions ΔP calculated over different time intervals according to the model are given in Table.

The average changes in ΔP over a year do not exceed ~1 Bar · year^{-1}. However, we note that for model blocks 1, 2, and 3 (the Western block), there are positive changes in tectonic stresses in the NW direction on all considered time intervals from 2008 to 2020. In the Eastern block (4a, 4b, 5, 6, and 7), we observe the negative values of ΔP, which are the stretching changes of stresses in the SE direction. In the 2019—2020 period the situation with ΔP changed noticeably. All blocks of the model underwent stretching stresses, except for blocks 9, 10, and 11 in the surface part of the section, where ΔP reached positive values at the level of 1—2 Bar · year^{-1}. Given that the changes of ΔP in 2019—2020 do not exceed ~1 Bar · year^{-1}, we can conclude that the geodynamic situation in the region was relatively calm in the considered time interval or the trend of tectonic stresses of 2008—2020 is ongoing. We note that the division of the area into the Western and Eastern blocks with differently directed changes of tectonic stresses agrees with the results of the GPS observation (Bakhmutov et al., 2017). The GPS points in the Western block (Galindez Island, Roca Islands) shifted to the W and NW, and the points in the Eastern block (Yalour Island, Cape Tuxen, Berthelot Islands) shifted to SE, at 5—7 mm · year^{-1}.

The results allow considering the geological inhomogeneity of the Three Little Pigs Islands, where observation points 3 and 3a are situated, as a “special place”. These “special places” are known from seismoprognostic studies in China and Middle Asia (Skovorodkin, 1985), where earthquake predictors were recorded at vast distances from the epicenters.

5 Conclusions

According to the results of long-term tectonomagnetic observations in 1998—2020 on the Antarctic tectonomagnetic polygon in the region of the Vernadsky station, the temporal changes of the local geomagnetic field at the West Coast of the Antarctic Peninsula have been studied. The temporal-spatial structure of tectonomagnetic anomalies agrees with the elements of the geological structure and tectonics of the region. Based on a comprehensive analysis of the tectonomagnetic anomalies with seismicity of the Antarctic Peninsula region, secular variations of the geomagnetic field, and data on the current motions of the crust, their changes over time were caused by tectonic stresses in the lithosphere.

We interpreted the tectonomagnetic anomalies within the piezomagnetic mechanism. The blocks of Earth crust in the region of the Argentine Islands undergo stretching sublatitudinal horizontal deformations of ~1 bar · year^{-1}.

The research demonstrates the efficiency of the tectonomagnetic method in studying the current geodynamics of the West Coast of the Antarctic Peninsula. In the Vernadsky station region, the geological structures were found especially sensitive to the changes in tectonic stresses in the crust at the regional level. Among such objects is the geological structure of the Three Little Pigs Islands, where a unique tectonomagnetic anomaly was registered, with dynamic changes in the field at the level of 2 nT · year^{-1}. Further tectonomagnetic research on the Antarctic tectonomagnetic polygon should be developed to study the seismotectonic processes in the crust in combination with other methods of geophysics and geodesy.

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Результати багаторічних тектономагнітних досліджень в районі антарктичної станції «Академік Вернадський», західне узбережжя Антарктичного півострова

Реферат. Мета роботи – аналіз результатів багаторічних спостережень на Антарктичному тектономагнітному полігоні та дослідження на цій основі сучасної геодинаміки західного узбережжя Антарктичного півострова в районі розташування Української антарктичної станції «Академік Вернадський». Методика тектономагнітних досліджень полягає у проведенні дискретних геомагнітних спостережень (через певні часові інтервали) на мережі пунктів та вивченні часових змін локального магнітного поля між епохами спостережень — тектономагнітних аномалій. Проаналізовано результати багаторічних (1998—2020 рр.) тектономагнітних досліджень, побудовано часові ряди змін локального магнітного поля для кожного пункту полігону, а також карти тектономагнітних аномалій за різні часові інтервали спостережень. В районі Аргентинських островів виявлено інтенсивні тектономагнітні аномалії до 2.0—2.8 нТ · рік$^{-1}$, просторова структура яких узгоджується з елементами тектонічної будови земної кори. Досліджено просторово-часовий зв'язок тектономагнітних аномалій із сейсмічністю регіону. В рамках п'єзомагнітного механізму оцінено величини змін тектонічних напружень у літосфері регіону. Просторово-часова структура тектономагнітних аномалій у районі станції «Академік Вернадський» є відгуком геологічного середовища на зміну тектонічних напружень у земній корі регіону. На основі теоретичних розрахунків з урахуванням інших геолого-геофізичних даних зроблено висновок, що їх природа зумовлена п'єзомагнітним ефектом під дією розтягуючих тектонічних напружень (~1 бар · рік$^{-1}$) субширотного напрямку у земній корі регіону. Враховуючи актуальність вивчення сейсмотектонічних процесів та сучасної динаміки регіону, тектономагнітні спостереження на Антарктичному полігоні варто продовжити у режимі щорічного моніторингу в комплексі з іншими геофізичними та геодезичними методами.

Ключові слова: моніторинг, сейсмічна активність, тектонічні напруження, тектономагнітні аномалії