

# Magnetic Structure of the Earth's Crust in the White Sea Region

Lyubov Bakunovich, Mikhail Nilov, Nikolay Sharov, Boris Belashev

FGBUN FIC, Karelian Research Center of RAS, Institute of Geology, Petrozavodsk, Russia

Email: sharov@krc.karelia.ru

**How to cite this paper:** Bakunovich, L., Nilov, M., Sharov, N. and Belashev, B. (2021) Magnetic Structure of the Earth's Crust in the White Sea Region. *International Journal of Geosciences*, 12, 1007-1020.  
<https://doi.org/10.4236/ijg.2021.1211053>

**Received:** September 7, 2021

**Accepted:** November 9, 2021

**Published:** November 12, 2021

Copyright © 2021 by author(s) and Scientific Research Publishing Inc. This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).

<http://creativecommons.org/licenses/by/4.0/>



Open Access

## Abstract

The geological structure of the White Sea area and the surrounding land areas has been well studied in the framework of individual case studies. There are a number of local models of the deep structure of the Earth's crust available. We propose a uniform assessment of deep crustal bodies responsible for long-period (regional) magnetic anomalies and consider their correlation with surface structures. The aim of the study is to build a three-dimensional magnetic model of the Earth's crust in the White Sea region using aeromagnetic data and modeling technologies of the Integro software package. The model is formed on the basis of a digital map of the anomalous magnetic field reduced to the pole. The sources of magnetic anomalies are considered to be located in the Earth's crust. The 3D distribution of the relative magnetic susceptibility of rocks was obtained by solving the inverse problem of the magnetic survey. To separate the magnetic sources by frequency and depth, it was necessary to continue the magnetic field of the model upward and to calculate the TDR derivatives, which determine the lateral boundaries of the sources of positive magnetic field anomalies. 2D distributions of magnetic sources of the model for vertical and horizontal sections with depths of 10, 15 and 20 km are analyzed. The correlation between the surface and deep structures of magnetic sources of the Earth's crust in the region is shown.

## Keywords

White Sea, Earth's Crust, Anomalous Magnetic Field, Effective Magnetic Susceptibility, 3D Model

## 1. Introduction

The practical study of an anomalous magnetic field has shown that it contains a regional constituent, which can be used for the study of the deep structure of the

earth's crust. Methods for identifying mathematically interpreting regional magnetic anomalies (RMA) and understanding the genesis of their sources have been described by many authors [1] [2]. Anomalous magnetic field gradients contain evidence for the positions of magnetic sources. Vertical gradients are sensitive to the depth of occurrence of sources [3]. Obtaining anomalous magnetic field gradients from the sources located in the lower horizons of the earth's crust, remains a complex problem, which has not been completely resolved [4]. Therefore, mathematical modelling remains an efficient and relatively cheap method for the structural study of the earth's crust.

Magnetic models of the earth's crust, based on the results of the areal aeromagnetic survey, establish a relationship between an anomalous magnetic field and rock magnetization. The scope of information obtained using such models is believed to be controlled by igneous rocks' property to preserve information on the Earth's magnetic field in magnetized state upon rock crystallization. Linking geomagnetic field states to time helps reconstruct the past states of the geomagnetic field, lithosphere and climate [5]. Such models are usually constructed for geodynamically active regions [6] [7] [8].

The White Sea basin and adjacent areas are at the conjugation zone of the uplifting Fennoscandian Shield and the Russian Plate is overlain by sedimentary strata. Interest in the region's deep structure and geodynamics is due to its mineralogenic kimberlite magmatism, various useful mineral deposits and oil and gas prospecting [9].

The deep structure of some portions of the Fennoscandian Shield has been repeatedly studied [10] [11] [12] under national and international research projects [13].

The earth's crust of the east-facing slope of the Fennoscandian Shield and the White Sea basin, Russia's inland sea) has mainly been studied by Soviet and Russian scientists [14] [15] [16] [17] [18].

The formation of our knowledge of the deep crustal structure of the White Sea using aeromagnetic data has been described in [19], where an evolutionary model of the white Sea rift system, connecting the structural levels of a magnetically active layer with stages in the region's tectonic activation from the Middle to the Late Riphean to the events that took place during the last glaciations in the Quaternary period.

Our knowledge of the division of the earth's crust in the White Sea region into three basic arbitrary variably deep layers—"sedimentary", granitic-metamorphic" and "granulitic-basic"—differing in density [14] [20], obtained by generalizing seismic data, can be used to estimate the depth of occurrence of the upper and lower margins of RMA sources. Scientists who study RMAs on the Fennoscandian and Ukrainian shields [21] think that the arbitrary "granitic" layer could be connected with local magnetic anomalies.

The construction of magnetic models is contributed to by computer technologies operating with large amounts of data, solving problems under uncertain conditions and presenting the results of studies in various ways [22].

A modern tool for mathematical modelling is provided by the Integro GIS Complex designed to approach various problems in earth sciences [23]. The complex solves direct and inverse geophysical problems automatically, provides the possibility to construct and analyze complex models, to take into account a priori information and to do complexing of methods.

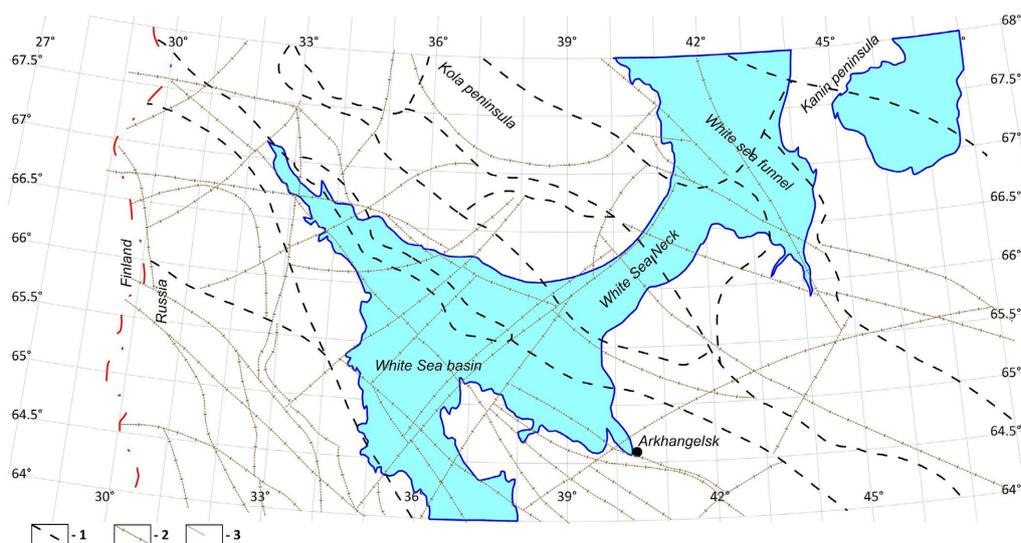
The purpose of the present study is to construct a generalized 3D magnetic model of the earth's crust of the White Sea and adjacent areas using the Integro Complex.

## 2. Data and Methods

### 2.1. Initial Data and Provisions 3D Magnetic Model Was Constructed Using

- A scheme showing the region's block structure;
- 1:1,000,000 scale digital maps of an anomalous magnetic field ( $\Delta T$ ) [24] [25];
- A 3D density model of the region's earth crust and a scheme of the depth of occurrence of M-discontinuity [26];
- A 1:1,000,000 scale state geological map of Russia and explanatory notes to sheets Q-35, 36, 37 and 38 [27];
- 1:1,000,000 scale petrophysical and metromagnetic maps of the eastern Fennoscandian Shield [28];
- A scheme of temperature distribution in the crustal sequence [29];
- Tectonic maps of the White Sea and adjacent areas [17] [30].

**Figure 1** shows the geographical position of the region, the main elements of its structure and the location of the main tectonic lineaments of the earth's crust the positions of the main regional faults of the Earth's crust.



**Figure 1.** Scheme of the white sea and adjacent territories with the location of the main tectonic lineaments of the earth's crust: 1—Tectonic boundaries of blocks, 2—Intrablock tectonic faults, 3—State border, A—Omega-Kandalaksha graben, B—Keretsky graben, C—Mezensky graben.

Figure 2 shows a diagram of the block structure of the region. The block designations are given in Table 1.

The basic aeromagnetic data for the White Sea region, obtained by 1:1,000,000 to 1:200,000 scale survey in 1958-1989, were transformed into a digital matrix with a 500 × 500 m cell of the eastern portion of sheet Q-35 and sheets Q-36 - Q-38 in full format.

The total magnetic intensity matrix was reduced to the pole. The map compiled (Figure 3) is a superposition of the contributions of variably deep anomalies sources. Regional magnetic field anomalies are believed to control deep

Table 1. Main Geoblocks of the white sea region.

Label	Terrain	Age (under discussion)
CKa	Central Karelian terrain	Late Archaean
NKa	North Karelian terrain	Late Archaean
WS	White Sea terrain	Archaean
Kol	Kolvitskiy terrain	Archaean
SoK	South Kola terrain	Archaean
TeZ	Tersko-Zolotitskiy terrain	Archaean
ImV	Imandra-Varzugskiy terrain	Archaean
CKo	Central Kola terrain	Early Archaean
EKo	East Kola terrain	Early Archaean
Mur	Murmansk terrain	Early Archaean
WMe	West Mezen' terrain	Palaeozoic
EMe	East Mezen' terrain	Palaeozoic
TiK	Timano-Kaninskiy terrain	Palaeozoic

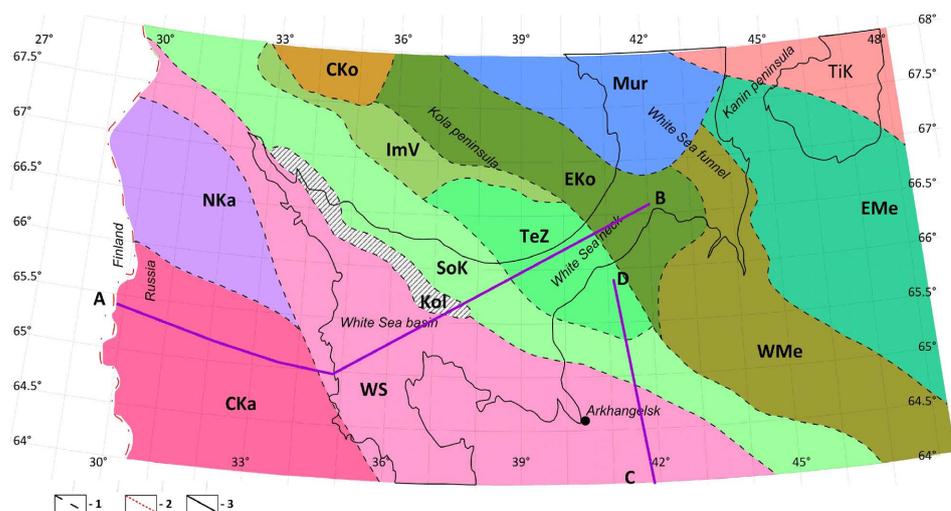
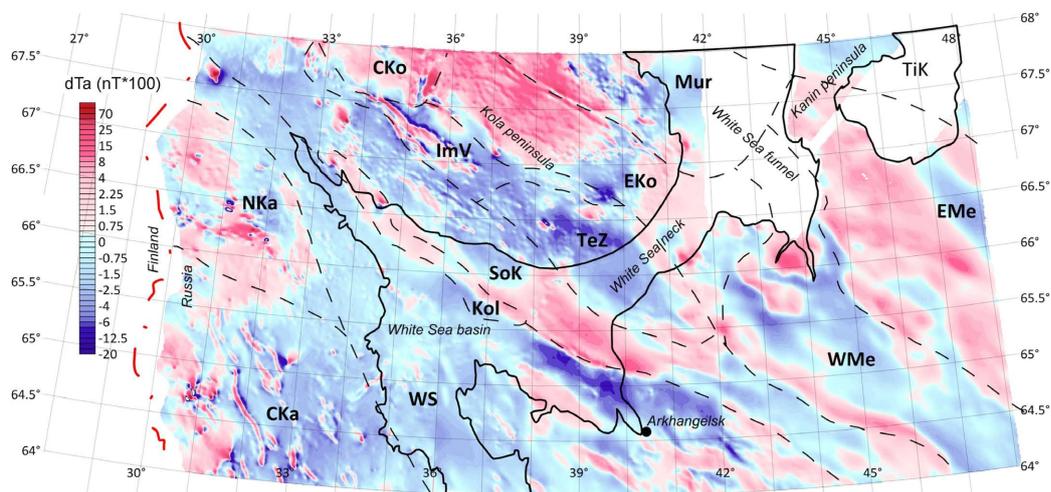


Figure 2. Block structure diagram of the region: 1—Block boundaries, 2—Profile lines of complex depth studies, 3—State border [31]. The figure is made using interpolated data, in the areas uncovered by aeromagnetic survey on the Figure 3.



**Figure 3.** Digital map of anomalous magnetic fields reduced to pole.

crustal structures, while local anomalies are ascribed to sources in its upper stores.

When constructing magnetic models of the earth's crust, selecting magnetic susceptibility values for rocks becomes a problem. In some models, workers use the table magnetic susceptibility values of known rocks or calculate them from rock density using regression equations. Equation coefficients are calculated for certain lithologic rock groups [32]. This method is used for relatively small compositionally homogeneous areas and drill hole records.

When solving an inverse magnetic prospecting problem for the White Sea region, which displays a mosaic structure, we oriented ourselves at relative magnetic susceptibility, an arbitrary value used in the model models of the Integro package, rather than the absolute magnetic susceptibility values of rocks [23].

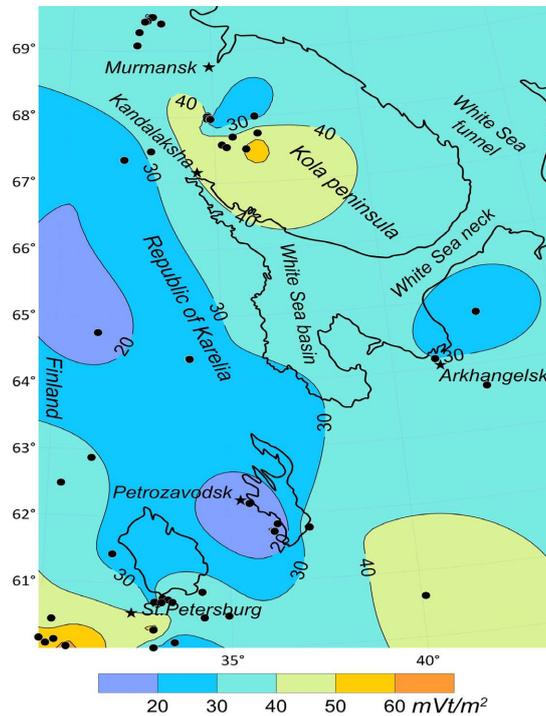
The depth range of magnetic anomaly sources in the model was chosen using Curie's isotherm depth estimate [6] [33] [34]. According to [29] [35] [36] the heat flow values 10 - 50 mWt/m<sup>2</sup> in the region are consistent with a cold lithosphere (Figure 4).

In accordance with known petromagnetic models of the earth's crust [6] [34] [37] [38], we will consider the region's mantle to be nonmagnetic and arrange magnetic anomaly sources in the earth's crust, assuming M-discontinuity as the boundary of their lower margins.

A 3D density model was used to show heterogeneities in the region's earth crust and to compare them with the structures of magnetic anomaly sources [26]. The model shows the boundaries of the density layers of the earth's crust of the sedimentary, granitic-metamorphic, granulite-basic M-discontinuity (M-boundary or M-surface).

## 2.2. Data Processing and Modelling Technologies

Stages in the construction and analysis of the 3D model using the Integro



**Figure 4.** Heat flux of the Barents region [31].

complex comprised preparing a digital map of the region's anomalous magnetic field, its reduction to the pole, solving an inverse magnetic prospecting problem, obtaining the vertical and horizontal sections of the model, recalculating a model anomalous magnetic field upwards, calculating recalculated field derivatives and laterally delineating the sources of positive anomalies in the horizontal sections of the model.

Inverse problems in the Integro package were solved on a 3D net using a regularization method [39] [40] and updated spectral algorithms based on Fourier's rapid transformation [40] [41]. The net step of the model along the axes was 1 km. The algorithms used function rapidly and remove marginal effects arising because of lateral limits and lack of data periodicity.

The standard geophysical procedures of the Integro package were performed by reducing the anomalous magnetic field to the pole, recalculating the field up and down and calculating its derivatives [40]. The reduction of the magnetic field to the pole yields the magnetic field of the substance of the same magnetization directed vertically upwards, topography and the various directions of the orientation of rock magnetization. The upward extension of the magnetic field uses a different field variation rate from variably deep sources, yields the distribution patterns of sources differing in spatial frequencies and identifies a field constituent from the sources of horizontal layers with preset depths.

A combination of the derivatives of the model magnetic field recalculated upwards was used as a detector of the lateral boundaries of the sources. The role of a spatial filter was played by a vertical to horizontal field derivative ratio expressed as the arc tangent of an angle denoted as a TDR derivative or a TDR an-

gle [42]. The TDR derivative is positive above the magnetic source, is close to zero near its boundaries and is negative where no source exists [8]. Similarly [8], the lateral boundaries of positive magnetic anomalies were obtained by placing the transparent windows of the positive TDR derivative on the horizontal sections of the 3D magnetic model.

### 3. Results

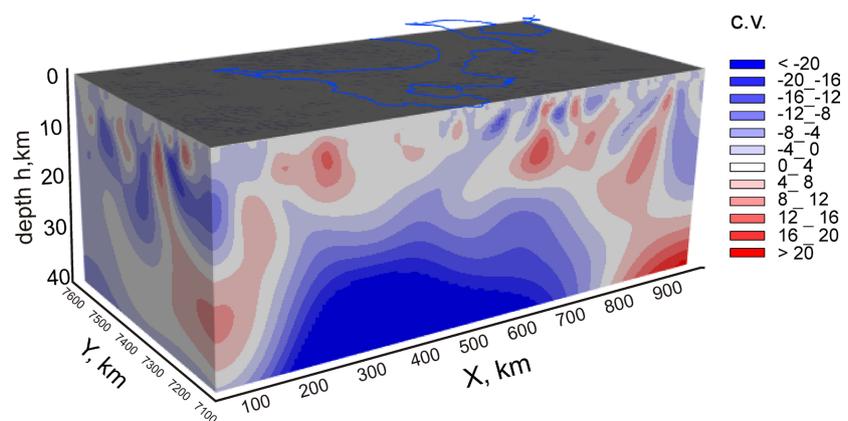
**Figure 5** demonstrates the volume distribution of the relative magnetic susceptibility in the Earth's crust of the White Sea region obtained by solving the inverse problem of magnetic survey.

In **Figure 6**, this distribution is represented by a set of vertical sections of the 3D magnetic model (a) and images of individual sections (b)-(i).

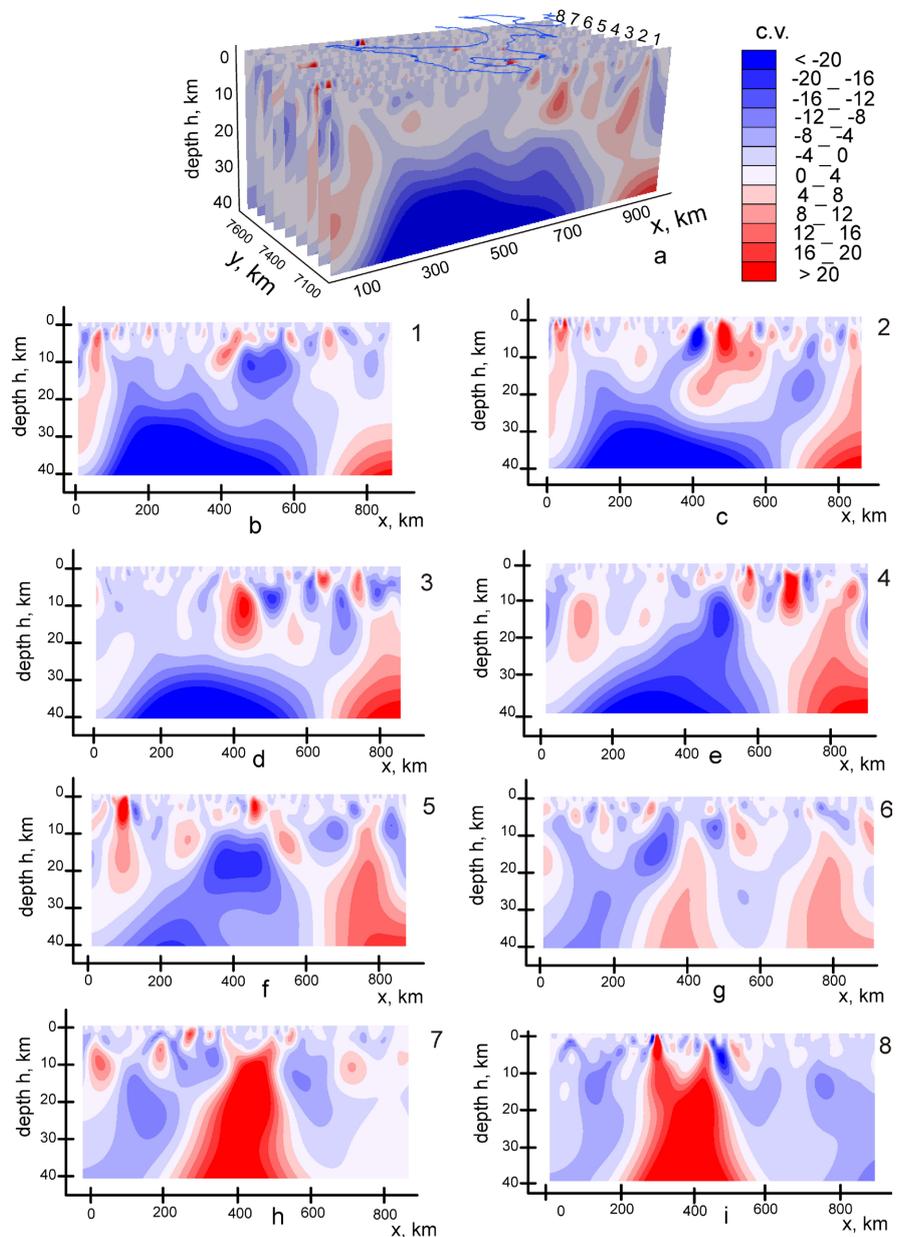
**Figure 5** and **Figure 6** show that large magnetic sources are present at depths from 30 to 40 km, and in the northwest of the region at depths from 10 to 40 km. The regions of magnetization from sources in the southeast and northeast of the region rise upward, branch out in the northwest and northeast directions, disintegrating into smaller bodies. Small bodies are concentrated in the upper layer of the Earth's crust with depths from 0 to 10 km. The northwestern source of high magnetization, located under the Murmansk block (see **Figure 2** and **Figure 3**), forms two branches at a depth of about 10 km, one of which almost reaches the Earth's surface beneath the Khibiny massif.

**Figure 7** shows the results of TDR filtering in horizontal sections of the model with depths of 10, 15 and 20 km.

Most of the positive sources of the section 10 km deep, extended in the northwest direction, trace the Onega-Kandalaksha, Keretsky and Mezensky grabens of the White Sea rift system (**Figure 7(a)**). The structures of the sources in the southwestern and central parts of the region are characterized by a northeastern run. As the sections become deeper, the structures of the sources become simpler; their bodies increase in size, and disintegrate. In the section 15 km deep, the Onega and Kandalaksha rifts are presented separately (**Figure 7(b)**). The



**Figure 5.** Distribution of relative magnetic susceptibility in the volume of the Earth's crust of the Belomorsk region.

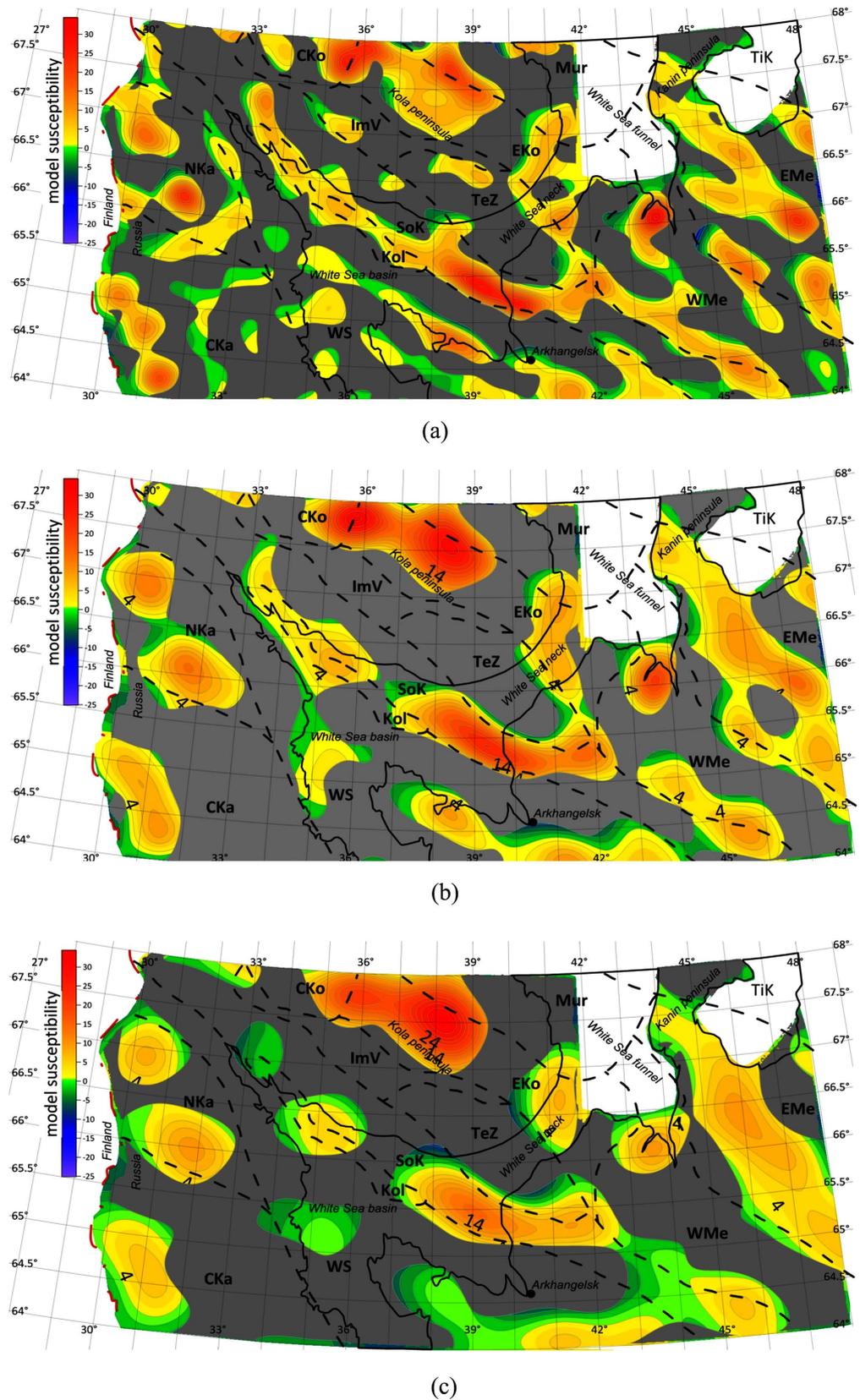


**Figure 6.** The distribution of the relative magnetic susceptibility in the 3D magnetic model volume is represented by a set of vertical Sections 1 - 8 (a) shown in images ((b)-(i)), respectively.

Keretsk rift looks like a coherent structure, but it also disintegrates in a section 20 km deep (**Figure 7(c)**).

In the White Sea Throat, on the Zimniberezhny Uplift, and on the Onega Peninsula, the closures of magnetic sources form ring structures. With an increase in the depth of the section, the rings of the structures expand, and the closures are precluded.

Overlay of horizontal sections with transparent windows of positive TDR filters indicates the proximity of the lateral projections of the corresponding sources at different depths (**Figure 7**).



**Figure 7.** Distribution patterns of positive anomaly sources in 3D model sections of depth of 10 km (a), 15 km (b) and 20 km (c) in transparent window of TDR filter.

## 4. Discussion

Comparison of the block diagram of the region (see **Figure 2**) and the map of the anomalous magnetic field (see **Figure 3**) shows that the boundaries of positive and negative magnetic field anomalies trace the boundaries of lithospheric blocks.

The distribution of magnetic anomaly sources in the volume of the Earth's crust, shown in **Figure 5** and **Figure 6**, confirms that relatively small sources determining local magnetic field anomalies should be assigned to the upper levels of the Earth's crust, and larger sources of regional anomalies, to its middle and lower levels. The magnetization pattern of the Earth's crust is not chaotic. The model identified the regions of large sources magnetization in the lower crust: they extend upward, forming branched structures that permeate the entire Earth's crust. In the upper crust, the branches of magnetization flatten out and finally acquire a northwestern and northeastern run in accordance with the inclination of the Earth's crust set by the M-surface [26].

The fact that the sources located in a layer of the Earth's crust which is 10 - 20 km deep are associated with vertical structures is confirmed by the proximity of their lateral projection centers of the horizontal sections of the model (see **Figure 6**).

The distribution of magnetic sources in depth is consistent with the concept of the evolution of the White Sea paleorift system during the tectonic activation of the region. This process is associated with Riphean-Vendian basic volcanism and Middle Paleozoic (Late Devonian) alkaline-ultrabasic magmatism [19]. Subvertical crustal magnetization structures indicate the activity of the White Sea suture zone, which is a magma and fluid supply channel with the mantle. The intense regions of magnetization of such structures at medium depths indicate the staging of magmatism.

The structures of magnetic sources of the northwestern run of the upper and middle crust trace the main riftogenic grabens of the White Sea. By overlaying the sources of structures of northeasterly striking, they cause closure of magnetic bodies and form rings (see **Figure 5**). The occurrence of rings is expected in tectonic nodes and in places where the directions of the main faults change. The crust of ring structures is the most disturbed and most permeable. The upper levels of the rings in the region are associated with manifestations of kimberlite magmatism and with the fields of chimney deposits.

At the point where the White Sea Throat enters the funnel three riftogenic structures of the region are linked. A feature of the ring structure revealed herein by the 3D magnetic and density models [26] is the depression of the M-boundary surrounded by local uplifts.

This topology is considered a criterion for diamond potential [43]. The Zimniberezhny ring structure is located on an ancient ledge of the crystalline basement. The diamondiferous kimberlite field is located in the Riphean aulacogen of northwestern run in the conjugation zone of the Kola craton and the Mezen

syncline. The promising Nenoksa field of the development of olivine melilitites chimney deposits is associated with the Onega Peninsula ring structure [19].

As for the nature of the sources of intense high-frequency magnetic anomalies in the uppermost parts of the Earth's crust, it should be noted that these sources could be intrusions of the basic composition, fluvioglacial deposits of the Late Pleistocene-Holocene—moraines. In the middle and lower levels of the Earth's crust, weakly magnetic rocks predominate. Rocks of high magnetic susceptibility are attributed to the areas of ferruginous fluids intrusion, concentration of ferruginous volcanics, intrusive differentiates and products of their processing. Such areas are associated with the cores of the most ancient consolidation of the crust, processed cores, suture zones, charnockite-granulite belts [44]. The main carrier of the magnetization of rocks is magnetite.

## 5. Conclusions

A 3D magnetic model of the White Sea crust and adjacent territories was developed on the basis of aeromagnetic survey data, geological and geophysical maps, diagrams and materials, a seismic density model of the White Sea crust. The model was built using the technologies of the *Integro* software package.

The model contrastively represents the block structure of the region and magnetic bodies in the volume of the Earth's crust. It allows assessing the positions, sizes, magnetization of these bodies and assigns the sources of local and regional anomalies to the upper, middle and lower levels of the Earth's crust. The localization and visualization of magnetic bodies and structures are facilitated by the sections of the 3D magnetic model.

The model clearly demonstrates the relationship between the surface and deep structures of the region's crust. Subvertical magnetization structures start from large sources in the lower crust and transform as they rise by branching in the northwestern and northeastern directions and disintegrating into separate bodies in the upper crust.

Corresponding to different spatial frequencies, the distribution patterns of sources of horizontal sections of the 3D magnetic model with depths of 10, 15 and 20 km reveal extended structures of magnetic sources of northwestern run that trace riftogenic grabens of the White Sea.

The ring structures of magnetic sources could represent territories promising for mineral exploration.

## Acknowledgements

The research is performed within the framework of the research project AAAA-A18-118020290086-1 with the financial support of the Russian Foundation for Basic Research in the framework of scientific projects No. 21-05-00481 "Structure and Dynamics of the Lithosphere of the White Sea Region" and No. 20-35-90034 "Integration of Geophysical Methods for 2D and 3D Modeling of the Earth's Crust of the White Sea and Adjacent Territories".

## Conflicts of Interest

The authors declare no conflict of interest.

## References

- [1] Blakely, R.J. (1995) Potential Theory in Gravity and Magnetic Applications. Cambridge University Press, Cambridge.  
<https://doi.org/10.1017/CBO9780511549816>
- [2] Lyngsie, S.B., Thybo, H. and Rasmussen, T.M. (2006) Regional Geological and Tectonic Structures of the North Sea Area from Potential Field Modeling. *Tectonophysics*, **413**, 147-170. <https://doi.org/10.1016/j.tecto.2005.10.045>
- [3] Hood, P.J. and Teskey, D.J. (1989) Aeromagnetic Gradiometer Program of the Geological Survey of Canada. *Geophysics*, **54**, 1012-1022.  
<https://doi.org/10.5636/jgg.44.367>
- [4] Nelson, J.B., Marcotte, D.V. and Hardwick, C.D. (1992) Comments on “Magnetic field Gradients and Their Uses in the Study of the Earth’s Magnetic Field” of by Harrison and Southam. *Journal of Geomagnetism and Geoelectricity*, **44**, 367-370.  
<https://doi.org/10.5636/jgg.44.367>
- [5] Lorenzen, B. (2019) Earth’s Magnetic Field—The Key to Global Warming. *Journal of Geoscience and Environment Protection*, **7**, 25-38.  
<https://doi.org/10.4236/gep.2019.77003>
- [6] Kimbell, G.S. and Stone, P. (1995) Crustal Magnetization Variations across the Iapetus Suture Zone. *Geological Magazine*, **132**, 599-609.  
<https://doi.org/10.1017/S0016756800021257>
- [7] Fedi, M., Florio, G. and Cascone, L. (2012) Multiscale Analysis of Potential Fields by a Ridge Consistency Criterion: The Reconstruction of the Bishop Basement. *Geophysical Journal International*, **188**, 103-114.  
<https://doi.org/10.1111/j.1365-246X.2011.05259.x>
- [8] Beamish, D., Kimbell, G. and Pharaoh, T. (2016) The Deep Crustal Magnetic Structure of Britain. *Proceedings of the Geologists’ Association*, **127**, 647-663.  
<https://doi.org/10.1016/j.pgeola.2016.10.007>
- [9] Kazanin, G. (Ed.) (2020) Shelf Sedimentary Basins of the Russian Arctic: Geology, Geo-Ecology, Mineral Resources Potential. ISC MAGE-Murmansk, Saint Petersburg.
- [10] Kempton, P.D., Downes, H. and Neymark, L.A. (2001) Garnet Granulite Xenoliths from Northern Baltic Shield—The Underplated Lower Crust of a Paleoproterozoic Large Igneous Province. *Journal of Petrology*, **42**, 731-763.  
<https://doi.org/10.1093/petrology/42.4.731>
- [11] Kontinen, A., Paavola, J. and Lukkarinen, H. (1992). K-Ar Ages of Hornblende and Biotite from Late Archaean Rock of Eastern Finland—Interpretation and Discussion of Tectonic Implication. *Bulletin of Geological Survey of Finland*, **365**.
- [12] Korja, A., Korja, T., Luosta, U. and Heikkinen, P. (1993) Seismic and Geoelectric evidence for Collisional and Extensional Events in Fennoscandian Shield—Implications for Precambrian Crustal Evolution. *Tectonophysics*, **219**, 129-152.  
[https://doi.org/10.1016/0040-1951\(93\)90292-R](https://doi.org/10.1016/0040-1951(93)90292-R)
- [13] Pajunen, M. and Poutanen, M. (1999) Palaeoproterozoic Prograde Metasomatic-Metamorphic Overprint Zones in Archean Tonalitic Gneisses, Eastern Finland. *Bulletin of the Geological Society of Finland*, **71**, 73-132.  
<https://doi.org/10.17741/bgsf/71.1.005>

- [14] Mitrofanov, F.P., Sharov, N.V., Zagorodny, V.G., Glaznev, V.N. and Korja, A.-K. (1998) Crustal Structure of the Baltic Shield along the Pechenga-Kostomuksha-Lovisa Geotraverse. *International Geology Review*, **40**, 990-997. <https://doi.org/10.1080/00206819809465250>
- [15] Bibikova, E., Skiold, T., Bogdanova, S., Gorbachev, R. and Slabunov, A. (2001) Titanite-Rutile Thermochronometry across the Boundary Zone between the Archaean Craton in Karelia and the Belomorian Mobile Belt, Eastern Baltic Shield. *Precambrian Research*, **105**, 315-330. [https://doi.org/10.1016/S0301-9268\(00\)00117-0](https://doi.org/10.1016/S0301-9268(00)00117-0)
- [16] Starostenko, V.I., Shuman, V.N., Ivashenko, I.N., Legostaeva, O.V., Savchenko, A.S. and Skrinik, O.Ya. (2009) Magnetic Fields of 3-D Anisotropic Bodies: Theory and Practice of Calculations. *Izvestiya, Physics of the Solid Earth*, **45**, 640-655. <https://doi.org/10.1134/S1069351309080047>
- [17] Baluev, A.S., Zhuravlev, V.A., Terekhov, A.N. and Przhiyalgovsky, E.S. (2012). Tectonics of the White Sea and Adjacent Areas (Explanatory Note to a 1:500 000 Scale Tectonic Map of the White Sea and Adjacent Areas). GEOS, Moscow.
- [18] Glaznev, V.N., Mints, M.V., Muravina, O.M., Raevsky, A.B. and Osipenko, L.G. (2015) Complex Geological—Geophysical 3D Model of the Crust in the Southeastern Fennoscandian Shield: Nature of Density Layering of the Crust and the Crust—Mantle Boundary. *Geodynamics & Tectonophysics*, **6**, 133-170. <https://doi.org/10.5800/GT-2015-6-2-0176>
- [19] Baluev, A.S., Brusilovsky, Y.B. and Ivanenko, A.N. (2018) Crustal Structure of the Onega-Kandalaksha Paleorift Based on Combined Analysis of the White Sea's Anomalous Magnetic Field. *Geodynamics & Tectonophysics*, **9**, 1293-1312. (In Russian) <https://doi.org/10.5800/GT-2018-9-4-0396>
- [20] Pavlenkova, N.I. (2006) Three-Dimensional Model of the Earth's Crust of the Baltic Shield Based on Deep Seismic Data. *Izv. Academy of Sciences of the USSR. Physics of the Earth*, **12**, 43-54. (In Russian)
- [21] Pashkevich, I.K., Sharov, N.V., Savchenko, A.S. and Starostenko, V.I. (2014) 3D Geologo-Geophysical Lithospheric Model of the Central Karelian Craton. *Geofizicheskiy Zhurnal*, **36**, 58-78. (In Russian) <https://doi.org/10.24028/gzh.0203-3100.v36i6.2014.111024>
- [22] Cooper, G.R.J. (1997) Forward Modelling of Magnetic Data. *Computers & Geosciences*, **23**, 1125-1129. [https://doi.org/10.1016/S0098-3004\(97\)00099-X](https://doi.org/10.1016/S0098-3004(97)00099-X)
- [23] Cheremisina, E.N., Finkelstein, M.Ya. and Lyubimova, A.V. (2018) GIS INTEGRO—Import Substitution Software for Geological and Geophysical Tasks. *Geoinformatika*, **3**, 8-17. (In Russian)
- [24] Aslamov, Y.V. (Ed.) (1999) Anomalous Magnetic Field Map. Scale: 1:1 000 000 Q-35, 36. WIRG-Rudgeophysics, St. Petersburg. (In Russian)
- [25] Aslamov, Y.V. (Ed.) (2000) Anomalous Magnetic Field Map. Scale: 1:1 000 000 Q-37, 38. WIRG-Rudgeophysics, St. Petersburg. (In Russian)
- [26] Belashev, B., Bakunovich, L., Sharov, N. and Nilov, M. (2020) Seismic Density Model of the White Sea's Crust. *Geosciences*, **10**, Article No. 492. <https://doi.org/10.3390/geosciences10120492>
- [27] (2009) State Geological Map of the Russian Federation. Scale 1:1,000,000. VSEGEI. (In Russian).
- [28] Dortman, N.B. (Ed.) (1980) Petrophysical Maps of Geological Forms of the Eastern Part of the Baltic Shield (Petro Density and Petro Magnetic). 1:1,000,000: Oblivious Note to Maps/Scientific. Leningrad, Moscow.
- [29] Tsybulya, L.A. and Levashkevich, V.G. (1992) Thermal Field of the Barents Sea Region. KSC, RAS, Apatity. (In Russian)

- [30] Sidorenko, A.V. (Ed.) (1978) Map of Faults in the USSR and Adjacent Countries. Scale: 1:2 500 000. VSEGEI, Leningrad. (In Russian)
- [31] Sharov, N.V., Bakunovich, L.I., Belashev, B.Z., Zhuravlev, V.A. and Nilov, M.Yu. (2020) Geological-Geophysical Models of the Crust for the White Sea Region. *Geodynamics & Tectonophysics*, **11**, 566-582. (In Russian)  
<https://doi.org/10.5800/GT-2020-11-3-0491>
- [32] Merkulov, V.P., Orekhov, A.N., Volkova, A. and Korovin, M.O. (2019) Developing a Technology for Prospecting Potentially Productive Units in the Rocks of a Pre-Jurassic Complex, Tomsk Region. 3D Modelling of Gravity and Magnetic Fields. Petroleum Learning Center, Heriot-Watt University, Tomsk Polytechnic University, s.l. (In Russian)  
<https://depnedra.tomsk.gov.ru/uploads/ckfinder/277/userfiles/files/1045.pdf>
- [33] Aboud, E., Salem, A. and Mekkawi, M. (2011) Curie Depth Map for Sinai Peninsula, Egypt Deduced from the Analysis of Magnetic Data. *Tectonophysics*, **506**, 46-54.  
<https://doi.org/10.1016/j.tecto.2011.04.010>
- [34] Wasilewski, P.J., Thomas, H.H. and Mayhew, M.A. (1979) The Moho as a Magnetic Boundary. *Geophysical Research Letters*, **6**, 541-544.  
<https://doi.org/10.1029/GL006i007p00541>
- [35] Kukkonen, I.T., Gosnold, W.D. and Šafanda, J. (1998) Anomalously Low Heat Flow Density in Eastern Karelia, Baltic Shield: A Possible Palaeoclimatic Signature. *Tectonophysics*, **291**, 235-249. [https://doi.org/10.1016/S0040-1951\(98\)00043-2](https://doi.org/10.1016/S0040-1951(98)00043-2)
- [36] Veikkolainen, T., Kukkonen, I.T. and Tiira, T. (2017) Heat Flow, Seismic Cut-Off Depth and Thermal Modeling of the Fennoscandian Shield. *Geophysical Journal International*, **211**, 1414-1427. <https://doi.org/10.1093/gji/ggx373>
- [37] Wasilewski, P.J. and Mayhew, M.A. (1982) Crustal Xenolith Magnetic Properties and Long Wavelength Anomaly Source Requirements. *Geophysical Research Letters*, **9**, 329-332. <https://doi.org/10.1029/GL009i004p00329>
- [38] Wasilewski, P.J. and Mayhew, M.A. (1992) The Moho as a Magnetic Boundary Revisited. *Geophysical Research Letters*, **19**, 2259-2262.  
<https://doi.org/10.1029/92GL01997>
- [39] Paštekaa, R., Karcolb, R., Kušnirák, D. and Mojžeša, A. (2012) REGCONT: A Matlab Based Program for Stable Downward Continuation of Geophysical Potential Fields Using Tikhonov Regularization. *Computers & Geosciences*, **49**, 278-289.  
<https://doi.org/10.1016/j.cageo.2012.06.010>
- [40] Category GIS “Integro” User Guide. <https://integro.ru/dl/ingeo/docs/> (In Russian).
- [41] Priezzhev, I.I. (2005) Constructing the Distribution of the Physical Parameters of the Medium on the Basis of Gravity Prospecting and Magnetometry. *Geofizika*, **3**, 46-51. (In Russian)
- [42] Miller, H.G. and Singh, V. (1994) Potential Field Tilt—A New Concept for Location of Potential Field Sources. *Journal of Applied Geophysics*, **32**, 213-217.  
[https://doi.org/10.1016/0926-9851\(94\)90022-1](https://doi.org/10.1016/0926-9851(94)90022-1)
- [43] Golubev, Yu.K., Vaganov, V.I. and Prusakova, N.A. (2005) Principles of Forecasting Diamond Prospects in the East European Platform. *Rudy i Metally*, 55-70. (In Russian)
- [44] Krutikhovskaya, Z.A. (1986) Deep-Seated Magnetic Heterogeneities: A Myth or Reality? *Geophysical Journal*, **8**, 3-23. (In Russian)