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Satellite Gravimetry as a Tool for Forecasting Oil and Gas Potential

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Abstract: This study explores the use of satellite gravity data and derived crustal models for predicting oil and gas potential in the east of the Russian platform. The research utilizes structural data (including GOCE satellite gravity-derived Moho depth), thermal data, and hydrocarbon potential data. The methodology involves three steps: 1) statistical analysis using Student's t-test to identify significant parameters distinguishing areas with and without hydrocarbon fields; 2) classification of the study area into three zones based on their hydrocarbon potential; and 3) application of a logistic regression machine learning model to forecast hydrocarbon potential in uncertain areas. The results show that most analyzed parameters have statistically significant differences between areas with and without hydrocarbon fields. The logistic regression model achieves 83% accuracy in predicting hydrocarbon potential. The study concludes that satellite gravity data and derived crustal models can be effectively used to forecast oil and gas potential in sedimentary basins, with the Precaspian basin, Cis-Ural trough, parts of the Central-Russia and Mezen rift systems, and the Timan-Pechora basin identified as the most promising areas in the east of the Russian platform.

Keywords: satellite gravimetry, oil and gas content, hydrocarbon deposits, gravity field, hydrocarbon exploration, heat flow, machine learning, logistic regression.

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Research Article

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1. Introduction

Gravity measurements have long been used for hydrocarbon (HC) exploration and historically it was one of the initial geophysical techniques aimed at locating oil and gas fields [*Constantino et al.*, 2017; *Nabighian et al.*, 2005]. Nevertheless, exploring for HCs in remote and expansive territories often requires extensive land, marine, or airborne gravity surveys, yet combining these different ground-based measurements over large areas remains challenging [*Förste et al.*, 2016]. The solution is to measure the gravity field components from space using satellites. Modern satellite gravity missions have reached unprecedented spatial resolution of ∼80 km which was achieved by Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) satellite [*Bouman et al.*, 2013; *Zheng et al.*, 2014].

The resolution of GOCE gravity data and its particular sensitivity to the Moho boundary has made it essential in the regional and global scale solid Earth research [*Bouman et al.*, 2015]. Therefore, a large number of crustal models was built based on the GOCE gravity field using inverse and forward gravity modelling techniques, e.g. [*Haas et al.*, 2020; *Ognev et al.*, 2022a; *Sobh et al.*, 2019]. Considering a direct link between the crustal and geothermal structure of any geological province [*Fowler*, 2004], such crustal models gain utmost importance for studying the geothermal heat flow and temperature distribution within the crust. Given that the thermal maturity of HC-generating source rocks is closely tied to sediment temperatures, these models are becoming valuable tools for predicting geothermal properties and assessing oil and gas potential [*Beardsmore et al.*, 2001].

In our study we show how satellite gravity data and its derivatives can be used for forecasting oil and gas potential in the east of the Russian platform.

2. Data and methods

The dataset used in the present study can be subdivided into three categories: structural data, thermal data, and the data on HC-bearing potential. The data are summarized in Table 1.

As the structural data, the depth of lithosphere-asthenosphere boundary (LAB) from the thermal isostasy model of Europe [*Artemieva*, 2019], sedimentary cover thickness from EUNAseis model [*Artemieva et al.*, 2013], and the Moho depth of Volgo-Uralian subcraton derived from the inversion of GOCE gravity data and subsequent forward gravity modelling [*Ognev et al.*, 2022a] were used. The thermal data included the surface heat flux (HF) distribution obtained from the Thermoglobe database [*Jennings et al.*, 2021], the maps of lateral distribution of crustal thermal conductivity and radiogenic heat production (RHP), upper mantle thermal conductivity, and mantle HF derived from [*Ognev et al.*, 2022b]. Assessment of HC-bearing potential was based on polygons of the oil and gas fields [*Paraskun et al.*, 2011] and the zones of HC prospectivity from [*Avrov et al.*, 1969].

The workflow of the study consisted of the following 3 steps. Firstly, it was necessary to consider whether the areas with existing HC fields differ statistically from the areas without HC fields in terms of crustal and geothermal structure. We addressed this problem using the Student's *t*-test to assess the significance of the difference in means for the available thermal and structural parameters. Here, we considered only the Volgo-Ural HC province since it is the most studied province and it lies fully within the study area. The analyzed parameters were subdivided into two sampling groups based on the spatial location: (1) areas with HC fields, (2) areas without HC fields (Figure 1a). The *t*-test analysis allowed us to see which parameters have significant differences in means between these zones and thus can be used in the further analysis.

Table 1. Dataset used in the study.

Data	Reference
Structural data	
LAB depth	[*Artemieva*, 2019]
Moho depth derived from satellite gravity data	[*Ognev et al.*, 2022a]
Sedimentary cover thickness	[*Artemieva et al.*, 2013]
Thermal data	
Surface HF	[*Jennings et al.*, 2021]
Crustal thermal conductivity and RHP	[*Ognev et al.*, 2022b]
Upper mantle thermal conductivity and HF	[*Ognev et al.*, 2022b]
HC-bearing potential data	
Polygons of the oil and gas fields	[*Paraskun et al.*, 2011]
Zones of HC prospectivity	[*Avrov et al.*, 1969]

Secondly, the study area was subdivided into three zones in terms of its HC potential: (1) no HC-bearing potential, (2) high HC-bearing potential, (3) uncertain HC-bearing potential. The subdivision was done based on the map of HC prospectivity zones of the USSR [*Avrov et al.*, 1969]. Here in the zone 1 we incorporated only the regions which objectively hold minimal potential for HC exploration due to either thin or absent sedimentary cover (Voronezh massif, Fennoscandia, part of Ukrainian shield) or due to orogens with low preservation potential for oil or gas (Ural mountains). The rest of the territory was subdivided into zones 2 and 3 by the relative area of the grid pixel that was covered by HC fields. If more than 1% of the pixel was covered by HC fields, it was considered as zone 2 with existing HC fields. If less than 1% of a pixel's area was covered, it was considered as zone 3 with uncertain HC-bearing potential (Figure 1b). The size of the pixel is ~ 50 km × 50 km.

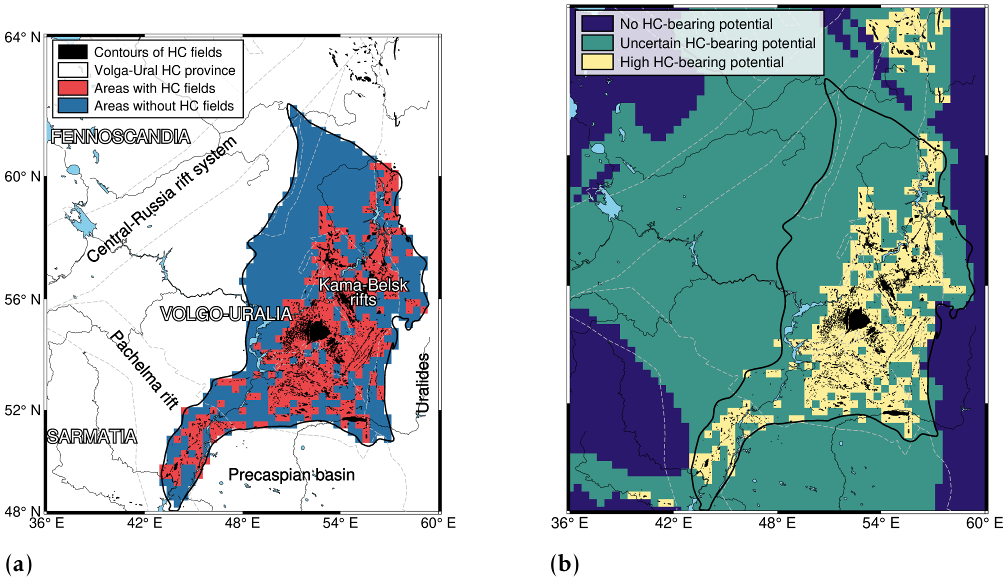


Figure 1. Study area classification for the Student's t-test (a) and for the logistic regression ML algorithm (b).

Thirdly, the selected parameters from step 1 were used to train the machine learning (ML) model based on logistic regression scheme. Here the 1st and 2nd zones from the step 2 were taken to train the model, and zone 3 was used to forecast the HC potential. Before the training was commenced, the values of input parameters were standardized to have 0 mean and standard deviation of 1.

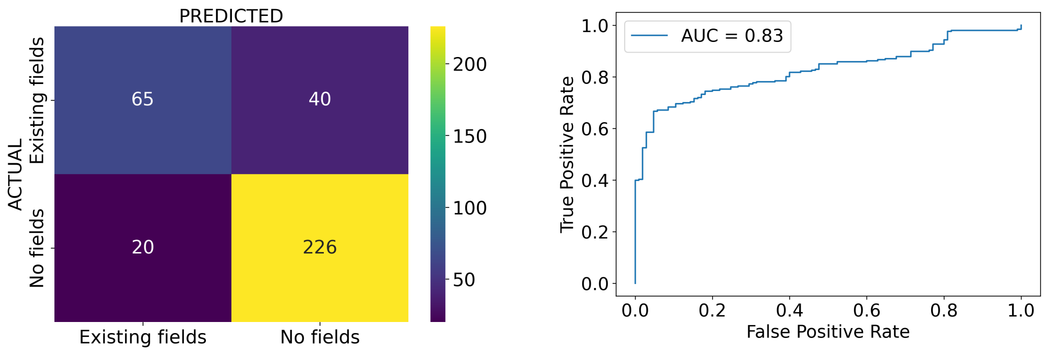
3. Results and discussion

Student's t-test was performed with a threshold p-value of 0.001 for the available parameters (Table 2). It can be seen that only the upper mantle thermal conductivity has a p-value > 0.001. The rest of the analyzed parameters can be considered to have statistically significant difference in means, so they can be used further in logistic regression model.

Table 2. Student's t-test results.

Parameter	Mean value in areas without HC fields	Mean value in areas with HC fields	P-value of Student's t-test
Sedimentary cover thickness (km)	4.33	5.68	2.53×10^{-10}
Moho depth (km)	43.33	41.54	6.77×10^{-22}
Lithosphere-asthenosphere boundary depth (km)	190.8	179.29	2.54×10^{-15}
Crustal thermal conductivity (W m^{-1} K^{-1})	2.06	2.12	5.77×10^{-4}
Upper mantle thermal conductivity (W m^{-1} K^{-1})	3.73	3.76	4.01×10^{-3}
Crustal radiogenic heat production (μW m^{-3})	0.56	0.62	1.22×10^{-5}
Surface HF (mW m^{-2})	43.03	46.18	6.79×10^{-8}
Mantle HF (mW m^{-2})	19.04	20.42	2.37×10^{-16}

The results of logistic regression performance are shown on Figure 2. The accuracy of the model was calculated to be 83%. Here 62% of territories with existing HC fields and 92% of barren territories were predicted correctly (Figure 2a). Receiver operating characteristics (ROC) curve shows high value of area under the curve (AUC) of 0.83 (Figure 2b).



(**a**) (**b**)

Figure 2. Confusion matrix (a) and ROC curve (b) of the trained logistic regression model.

To forecast the HC potential in the east of the Russian platform predicted probability of HC fields' occurrence from the logistic regression model was visualized (Figure 3). As it can be seen, Precaspian basin, Cis-Ural trough, some parts of Central-Russia Rift System, Mezen rifts, and Timan-Pechora basin are the areas with the highest predicted probability of HC occurrence. These areas coincide with the thickest sedimentary column and higher values of geothermal parameters. The lowest predicted probability corresponds to the central-western part of Volgo-Uralia, which has the thickest crust, the deepest LAB, and the lowest HF.

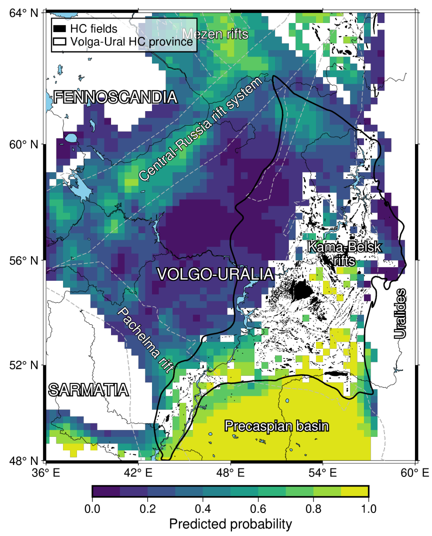


Figure 3. Predicted probability of HC fields' occurrence in the east of the Russian platform.

The performed analysis in case of the east of the Russian platform has its own limitations. As it is seen on Figure 2a, the model performs moderately better for defining barren territories rather than spotting the existing fields. Therefore, extra caution must be taken with the decision-making process for new areas of oil exploration and the areas with the highest probability must be evaluated first. To improve the presented model, several strategies might be undertaken: (1) use data with a finer spatial resolution, (2) incorporate spatial data sets with source-rocks' characteristics to account for the petroleum charge, (3) utilize other ML algorithms.

4. Conclusion

The described approach uses a satellite-gravity-derived structural model of the Earth's crust along with thermal parameters to forecast the oil and gas potential of sedimentary basins using a logistic regression ML algorithm. It has been shown in the case of the east of the Russian platform that the most perspective territories are located in the Precaspian depression, Cis-Ural trough, parts of the Central-Russia and Mezen rift systems, and Timan-Pechora basin. The presented logistic regression approach demonstrated a considerable accuracy with 62% of true positive and 92% of true negative predictions. Nevertheless, other ML methods, additional source-rocks' related data and overall finer spatial resolution must be examined to improve the predictability of the forecast.

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