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Evaluation of Hydrocarbon Potential at a Regional Scale Using Morphometric and Lineament Analysis of DEMs

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Abstract: This study presents the results of morphometric and lineament analysis conducted on a DEM of a study area in the southwestern Siberian Platform, encompassing several petroleum provinces. The research highlights the informative value of the difference between 6th and 7th order base surfaces, revealing that known deposits are predominantly located in areas with low amplitudes of neotectonic movements. This correlation was used as a prospectivity indicator. Additionally, the relationship between macrofracturing in the sedimentary cover, expressed through lineament density, and the location of known deposits was examined. Known petroleum deposits are mainly situated in areas with low to medium macrofracturing, suggesting this characteristic can be considered a factor in petroleum trap integrity. A comprehensive prospectivity map was generated based on these two exploration criteria, and its reliability was validated. The study demonstrates the effectiveness of using geographic information systems in petroleum exploration.

Keywords: petroleum exploration, neotectonics, morphometric analysis, lineament density, geographic information system, Siberian Platform.

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1. Introduction

Modern hydrocarbon exploration approaches emphasize the crucial role of geodynamic processes in the formation and reformation of petroleum deposits. This approach, first proposed by geomorphologists, neotectonics specialists, and petroleum geologists as far back as 50 years ago [*Lastochkin*, 1974], implies that petroleum deposits are relatively young, with their age comparable to the formation time of the modern-day landscape in petroleum provinces [*Nurgaliev et al.*, 2009].

Neotectonic activity affects the integrity of hydrocarbon deposits in various ways. Generally, higher activity increases the likelihood of discovering hydrocarbon accumulations, but excessively high tectonic activity can lead to deposit destruction [*Chernova et al.*, 2021; *Lastochkin*, 1974]. Therefore, petroleum forecasting should analyze two interrelated processes: deposit formation under neotectonic influences (particularly the intensity of vertical movements) and their degradation due to geodynamic factors (specifically, the macroscopic fracturing of the sedimentary cover).

The task of determining quantitative characteristics of neotectonic processes (direction and amplitude of vertical movements, fracture density) in the areas with hydrocarbon deposits or accumulations can be effectively accomplished through morphometric and lineament analysis of a DEM. It can be performed automatically using GIS tools [*Chernova et al.*, 2021] along with ranking the territories based on said characteristics.

This study aims to discuss the informative value and effectiveness of the proposed method for assessing hydrocarbon potential, focusing on regional-scale petroleum exploration in an area that is promising for new petroleum discoveries, but poorly explored.

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2. Study area

The study area covers 270,969 km^2 in the southern part of Eastern Siberia, extending from 94°30′ to 102°40′ E and from 56°0′ to 61°30′ N (Figure 1a). The topography is characterized by a substantial elevation gradient, ranging from 80 to 980 meters, with a mean elevation between 300 and 400 meters. This type of terrain is conducive to effective morphometric analysis [*Filosofov*, 1975; *Lastochkin*, 1974].

The sedimentary cover of the Siberian Platform underwent multiple restructurings throughout the Phanerozoic [*Seregin et al.*, 1985; *Sokolov et al.*, 1985; *Varlamov*, 1985], leading to repeated re-formations of large dome-shaped deposits. Recent tectonic activity amplified the structural expression of pre-existing anticlines while promoting their fragmentation into discrete blocks [*Sokolov et al.*, 1985]. Late Cenozoic tectogenesis is considered a factor controlling the degree of preservation or destruction of petroleum deposits [*Seregin et al.*, 1985; *Varlamov*, 1985], underscoring the value of neotectonic analysis in petroleum exploration strategies.

3. Methodology and input data

The DEM was generated using 1:100000 scale topographic maps (339 map sheets in .gdb format, from which terrain and hydrography were extracted). Data processing and visualization were performed using ESRI's ArcGIS Pro 3.0 and WinLessa, a specialized lineament analysis software [*Zlatopolsky*, 1992; 2024].

3.1. Morphometric Analysis

The analysis was based on V. P. Filosofov's concepts [*Filosofov*, 1975] with modifications through the application of ArcGIS hydrological modeling tools [*Chernova et al.*, 2021]. The analysis focused on base surfaces (surfaces that connect local erosion base levels) and differences between them, as these can be generated almost entirely automatically. The hydrological modeling resulted in a stream order map, with the lower reaches of the Angara and Podkamennaya Tunguska rivers attaining 9th to 10th order status (Figure 1b).

Base surfaces and the differences between them illuminate long-term terrain evolution patterns. Like watercourses, base surfaces are classified by order [*Filosofov*, 1975]. Differences between base surfaces reveal the magnitudes of vertical crustal movements during specific time frames. For instance, the differences between first and second-order surfaces, as well as between second and third-order surfaces, correspond to the most recent periods of neotectonic activity. Meanwhile, the differences between fifth and sixth-order surfaces, sixth and seventh-order surfaces, and those of even higher orders represent earlier stages of neotectonic activity.

Neotectonic activity is believed to influence hydrocarbon deposit distribution, but the specific stages causing large-scale hydrocarbon migration are unknown. To investigate this, spatial correlations between neotectonic movement amplitudes and known deposit locations were analyzed by overlaying deposit outlines onto calculated differences between base surfaces of consecutive orders.

The most revealing result came from the difference between 6th and 7th order base surfaces, showing that known deposits are predominantly located in regions of neotectonic quiescence (Figure 1d).

3.2. Lineament Analysis

The WinLESSA software [*Zlatopolsky*, 2024] was employed to generate a map of lineament traces — linear elements identified in the DEM. A macro-fracturing raster was then created by calculating the density of lineament traces (using Zlatopolsky's method [*Zlatopolsky*, 1992]). Each cell in this raster represents the ratio of the total length of all lineament traces to the area of a defined neighborhood around that cell (Figure 1c). The values are expressed in arbitrary units on an 8-bit scale (0–255). Known hydrocarbon deposits are predominantly located in areas with low macro-fracturing (Figure 1c), suggesting that structural integrity plays a significant role in deposit preservation.

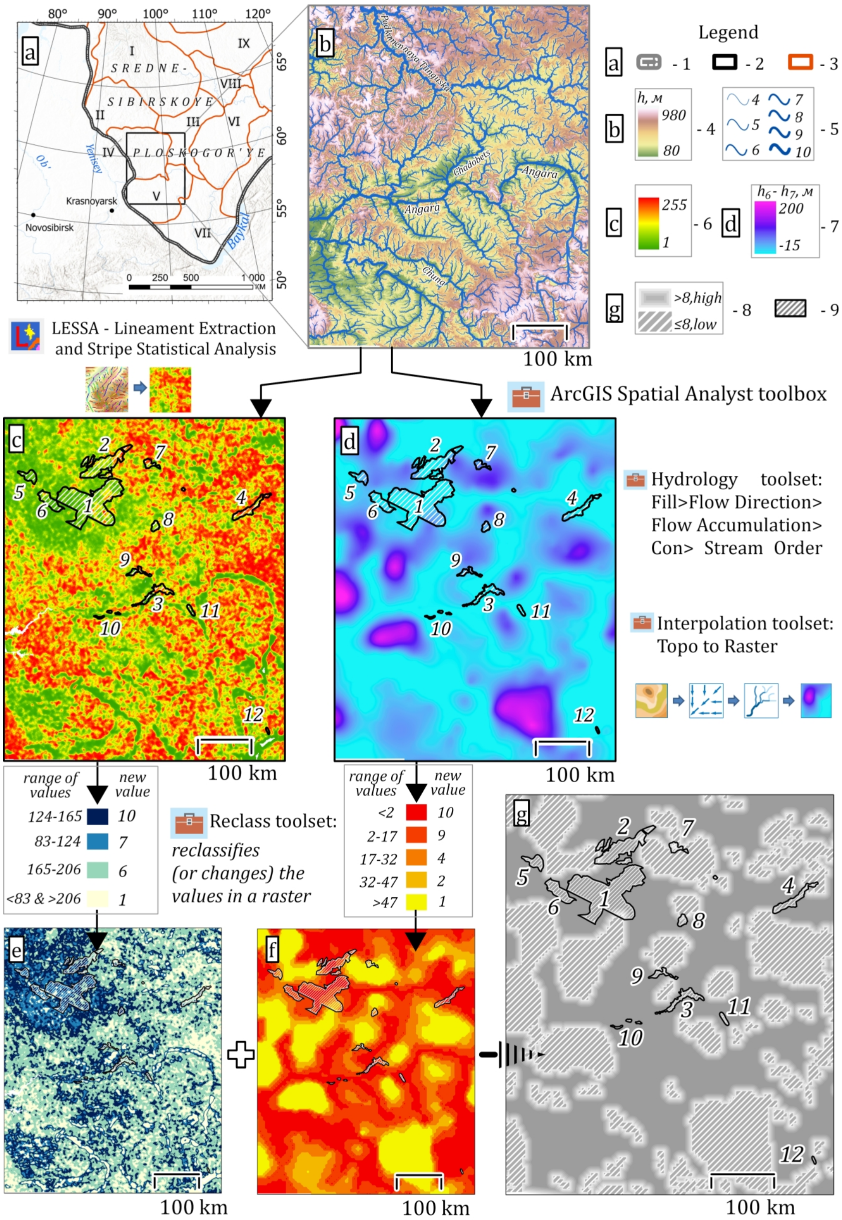

Figure 1. Creation of a prospectivity map using GIS tools: a) overview map; b) DEM of the study area and the stream order map created from it; c) macrofracturing of the sedimentary cover; d) difference between the base surfaces of the 6th and 7th orders; e) reclassification of the macrofracturing raster; f) reclassification of displacement amplitudes; g) comprehensive solution based on two factors.
Legend:
a: 1 — Siberian Platform; 2 — study area; 3 — petroleum province (I — North-Tungusskaya, II — South-Tungusskaya, III — Katangskaya, IV — Baikitskaya, V — Prisayano-Eniseiskaya, VI — Nepsko-Botuobinskaya, VII — Angaro-Lenskaya, VIII — Syugdzherskaya, IX — Anabarskaya);
b: 4 — DEM, scale 1:100 000; 5 — stream order map (the map does not show streams of less than 4th order because of their large number);
c: 6 — macrofracturing (standard units);
d: 7 — difference between the base surfaces of 6th and 7th orders (m);
g: 8 — likelihood of petroleum occurrence (high, low); 9 — hydrocarbon fields (1 — Yurubcheno-Tohomskoye, 2 — Kuyumbinskoye, 3 — Agaleyevskoye, 4 — Sobinskoye, 5 — Borshchevskoye, 6 — Omorinskoye, 7 — Shushukskoye, 8 — Ischuhskoye, 9 — Ilbokichskoye, 10 — Imbinskoye, 11 — Beryambinskoye, 12 — Bratskoye).

3.3. Creating a Prospectivity Map

ArcGIS geoprocessing tools were used to determine specific ranges of neotectonic indicators for a more precise and quantitative description of observed spatial correlations. First, all cells within the boundaries of known deposits were extracted from the macro-fracturing raster (Figure 1c) and the base surface difference raster (Figure 1d). Frequency distribution diagrams were then constructed for extracted cell values representing macro-fracturing intensity and neotectonic movement amplitudes.

The frequency distribution of macro-fracturing values approximates a normal distribution, with most deposits falling within a range of 124 to 165. In terms of deposit preservation potential, this range offers optimal conditions for undiscovered deposits. While visual analysis suggested deposits were mainly in low macro-fracturing areas, statistical analysis showed correlation with both low and moderate macro-fracturing. For neotectonic movement amplitudes, the distribution exhibits a positive skew, with peak frequencies occurring at low amplitude values. Most petroleum fields are associated with neotectonic movement amplitudes falling within two distinct ranges: −15 to 2 meters and 2 to 17 meters. These intervals are likely most favorable for new petroleum discoveries when considering neotectonic activity intensity.

The next step in creating a prospectivity map involves reclassifying the rasters of base surface differences and macro-fracturing using a unified scale (from 1 to 10), where 1 indicates areas least likely to contain deposits, and 10 represents the most promising locations. The final prospectivity map was generated through arithmetic addition of the two reclassified rasters (Figure 1f, e), producing a comprehensive solution ranking the study area according to its potential for new discoveries (Figure 1g).

4. Discussion

The prospectivity map illustrates areas of high potential, indicating locations with the most favorable conditions based on neotectonic movement intensity and sedimentary cover macrofracturing. The validity of this map is reinforced by the close alignment between known deposit boundaries and high-ranking areas in the proposed classification scheme.

In assessing the accuracy of the prediction, it's important to note that results were most significantly influenced by the cluster of deposits in the Yurubcheno-Tokhomskaya petroleum province, particularly the Yurubcheno-Tokhomskoye and Kuyumbinskoye petroleum fields. These large fields are predominantly situated in zones of low neotectonic activity and minimal macrofracturing. Smaller fields with different characteristics received lower weights in the reclassification process.

The Shushukskoye field appears to be in the least favorable position, situated in a region characterized by high-amplitude neotectonic movements and extensive macrofracturing. It is highly probable that this field is currently experiencing rapid deterioration.

The neotectonic phase in the Siberian Platform's evolution is critical for understanding the distribution of modern deposits, as the platform's structural layout reached its final form during the Late Cenozoic. Some active structures in the region may still be in the process of formation.

Conclusion

The proposed method is recommended for regional and preliminary exploration in poorly studied platform areas due to its high efficiency and cost-effectiveness. This method:

- requires no field;
- identifies important stages in the neotectonic history that critically influenced hydrocarbon deposits formation and destruction in the study area;
- enhances the reliability and value of DEM data interpretation by automating all stages of data processing, thus reducing time to results.

However, the significance of the macrofracturing factor is still poorly understood and requires additional studies.

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