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SPATIAL ANALYSIS OF LINEAMENT STRUCTURES AND VEGETATION CHANGES IN THE SHURTAN GAS FIELD

ABSTRACT

The Shurtan Mining Complex, located within the Beshkent Depression in southern Uzbekistan, is one of the largest natural gas production centers in the country. The geological activity of the region, combined with intensive exploitation of the field, necessitates comprehensive monitoring to assess geodynamic processes and associated environmental risks. The objective of this study was to identify spatiotemporal patterns of structural activity and vegetation cover using satellite methods. The analysis was performed based on Landsat-8 multispectral images (L2 processing level) for 2022, 2023 and 2024. Lineament analysis and normalized vegetation index (NDVI) calculation methods were applied. The results showed an increase in the density of linear structures in 2023, followed by localization of lineament anomalies in 2024. The predominance of the north-eastern orientation of lineaments was established, reflecting the regional stress field, and west-east elements potentially associated with hydrocarbon traps were identified. The NDVI analysis revealed vegetation degradation in lineament intersection zones and near active production areas. Comparison with the operational pressure map showed spatial coincidence of NDVI reduction areas, high lineament density, and anthropogenic load. These results confirm that satellite monitoring can serve as an effective tool for assessing geodynamic instability and diagnosing environmental impacts of field development. The proposed approach can be useful for drilling planning, improving infrastructure safety, and reducing risks in gas producing areas.

KEYWORDS: lineament analysis, normalized difference vegetation index, global navigation satellite system, gas leaks, technogenic impacts

INTRODUCTION

The development of satellite technologies has opened up new prospects for studying the geodynamics of mining areas in order to prevent emergencies and ensure the safe operation of infrastructure facilities [*Lord*, 2017; *Murodch* et al., 2020; *Wang* et al., 2022; *Abetov* et al., 2023; *Saha*, 2025]. One of the key methods for monitoring geodynamic processes is remote sensing, in particular, lineament analysis, which effectively solves two important problems in the field of hydrocarbon exploration:

- predicting possible migration routes of hydrocarbons in the earth's crust and identifying potential zones of their accumulation;
- tectonic zoning within the framework of geological exploration [*Kats* et al., 1986].

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Lineament analysis based on satellite imagery and geospatial data allows the identification of linear features — faults, cracks and other structural forms associated with active tectonic processes or subsurface movements [*Raj* et al., 2017; *Sichugova*, *Fazilova*, 2020; *Sichugova*, *Fazilova*, 2022; *Demircioğlu*, 2024; *El-Omairi* et al., 2024]. One of its main advantages is the ability to cover large areas without the need for expensive ground-based infrastructure, which makes this method particularly valuable for revealing regional patterns of geodynamic activity and monitoring their changes over time.

Integrating lineament analysis with the calculation of the normalized vegetation index (NDVI) allows for expanded analytical capabilities in the study of gas fields. Lineaments indicate structural features, and NDVI can indicate potential gas leakage zones through anomalies in the vegetation cover [*Haereuddin*, *Irawan*, 2019]. The integrated application of these methods provides a deeper understanding of the spatial structure of gas-saturated zones and improves the efficiency of risk assessment during field exploitation.

The Shurtan Mining Complex is one of the leading centers of natural gas production in Uzbekistan and is part of the richest hydrocarbon deposits of the Amu Darya basin. The Shurtan field contains various types of deposits: gas, gas condensate and oil. For several decades, deep drilling and geophysical studies have been carried out here to study underground structures and identify promising areas of hydrocarbon accumulation.

Successful exploitation of such resources requires an understanding of the complex interactions between geodynamic conditions and mining activities. Until now, monitoring of geodynamic processes in the area has been largely limited to traditional geodetic methods such as leveling. However, there are no publications using modern satellite methods to analyze actual crustal movements.

This paper proposes a complex approach to monitoring the geodynamic state of the Shurtan gas field. The study includes: lineament analysis based on Landsat-8 images, NDVI calculation to assess the possible impact of gas leaks on vegetation, and comparison with previously obtained ground pressure monitoring data [*Fazilova* et al., 2025]. This approach will allow identifying potential hydrocarbon migration zones, tracing their spatial relationship with the lineament system, and assessing the environmental impact of gas production on vegetation cover.

RESEARCH MATERIALS AND METHODS

Study area

The Shurtan Mining and Processing Complex, located in the southern part of the Republic of Uzbekistan, is one of the key centers for natural gas production and is part of the hydrocarbon fields of the Amu Darya Basin (ADB). The ADB, a prominent petroleum province in the former Soviet Union, ranks as the second richest in natural gas reserves and production after West Siberia. The total resources of the basin were estimated at 40.3 billion barrels of oil equivalent, primarily in the form of natural gas [*Ulmishek*, 2004]. Territorially, the basin covers Uzbekistan and Turkmenistan, with minor outlets in Afghanistan and northeastern Iran [*Hosseinyar* et al., 2019] (Fig. 1, bottom).

The Shurtan field is situated in the Beshkent Depression, a geologically active zone with high potential for new discoveries. The depression is characterized by a wide distribution of reef and complex traps, which are of significant interest for further exploration of hydrocarbons [*Yixin* et al., 2015; *Hosseinyar* et al., 2019]. The main productive horizons of the Shurtan field include Upper Jurassic carbonate rocks and Lower Cretaceous terrigenous rocks, which dominate the Beshkent depression. Reef and complex traps, containing a significant portion of unexplored resources, are located in the carbonate formations at depths of approximately 3.5 km [*Yixin* et al., 2015].

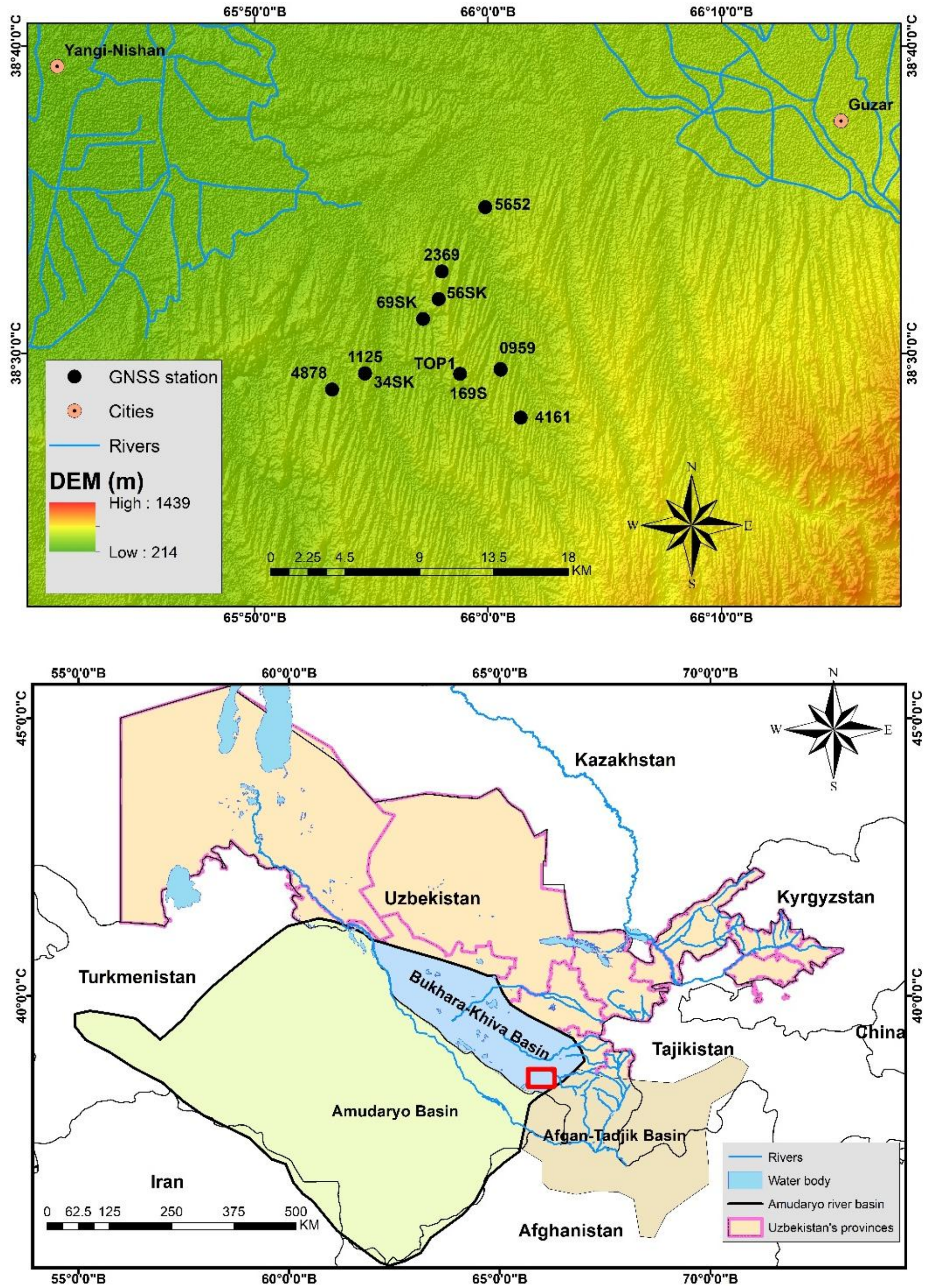


Fig. 1. Study area (Digital Elevation Model, SRTM) and GNSS network (top) and geographic location of the study area (bottom)

Since the 1950s, intensive deep drilling and geophysical surveys have been carried out to study subsurface rock formations and explore potential oil and gas reserves. These studies have made it possible to clarify the structure of the field and the patterns of placement of productive objects. Gas reservoirs in the region are usually formed under the influence of tectonic processes — folding and fracturing of rocks [*Sivyakova*, 2019].

In one of the previous studies [*Fazilova* et al., 2025] an assessment of the technogenic impact on the geodynamic state of the Shurtan field area was carried out based on GNSS data. The location of the GNSS points is shown in Fig. 1, top. At that time, about 200 wells had been drilled in the area, and gas exploitation volumes were recorded at each of them on a regular basis. To quantitatively assess the technogenic load near GNSS observation points, the average volume of gas production from wells located within a radius of 1 km from each station was calculated. The number of wells taken into account varied from 2 to 11 (Fig. 2). The results showed a strong correlation between production intensity and vertical ground displacements: areas with the highest operational load exhibited subsidence rates ranging from −0.5 to −3.4 mm/year (Table 1) [*Fazilova* et al., 2025].

Table 1. Vertical (V_h) velocities and their standard deviations (SDv_h) of each GNSS site

Station	Longitude (°)	Latitude (°)	V_h (mm/yr)	SDv_h (mm/yr)
4161	66.023	38.465	−2.4	0.3
0959	66.009	38.491	−2.6	0.2
5652	65.998	38.579	−1.0	0.3
TOP1	65.979	38.489	−3.4	0.4
2369	65.967	38.544	−2.9	0.3
56SK	65.965	38.529	−3.9	0.8
69SK	65.954	38.519	−3.0	0.5
1125	65.912	38.489	−0.5	0.9
4878	65.888	38.480	−1.8	0.3

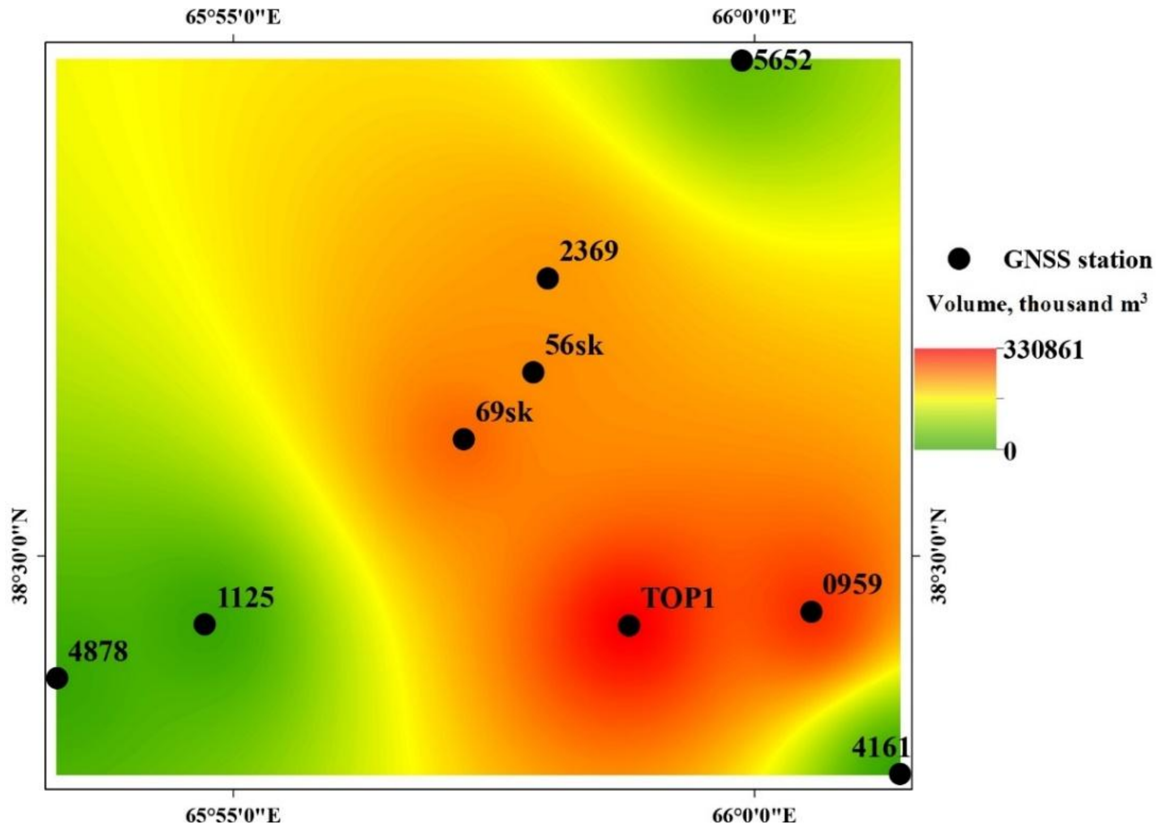


Fig. 2. Average volume of produced gas [*Fazilova* et al., 2025]

Lineament analysis

In this study, lineament analysis was used to identify areas with a potentially increased risk of earth surface deformation, implemented in the pyLefa program version 0.61a[1] [*Shevyrev*, *Carranza*, 2020; *Shevyrev* et al., 2023]. The algorithm includes several stages: pre-processing of satellite images, edge detection, extraction of linear structures and calculation of lineament density. Compared to previous versions presented in [*Shevyrev*, 2018], this technique is based on improved pre-processing algorithms and more accurate methods of extracting lineaments, which ensures higher accuracy and reliability of the obtained results.

The analysis was performed using Landsat-8 OLI multispectral images (L2 processing level) covering the periods of May 2022, March 2023, and April 2024. These time slices were selected taking into account that GNSS observations were carried out during the same periods, which ensured consistency in the interpretation of deformation processes. The images were previously geometrically and radiometrically corrected, and converted to UTM projection, zone 42N (WGS-84). These images were downloaded from the Earth Explorer website of the United States Geological Survey (USGS)[2]. The Landsat-8 images have a resolution of 30 m, which is appropriate for studying surface deformations on a regional scale. The key characteristics of lineaments were calculated for each period: total number, length, average length and density. Then, these parameters were used for spatial analysis of possible tectonic fault activity and assessment of their changes over time.

Canny edge detection algorithm with the parameter $\sigma = 0.1$ was used to detect contours, providing high-precision binarization of edge features and minimization of artifacts. Lineament extraction was performed using the Hough transform, the parameters of which were set as follows:

- threshold value of peak intensity in Hough space is 5;
- minimum line length is 10 pixels;
- the maximum allowable gap between segments is 1 pixel.

This parameterization allowed us to reliably identify structurally significant linear objects while maintaining a low level of false positives.

After extracting the lineaments, their geometric characteristics were analyzed, including length, orientation, and spatial density. To further minimize misclassification, all extracted lineaments were cross-checked against vector road datasets (OpenStreetMap) and topographic maps. Linear features corresponding to roads or infrastructure were excluded from further analysis. To construct lineament density maps, an averaging filter with a 300 m window was used, corresponding to the scale of the detected geodynamic processes and the resolution of the satellite data. The selection of such a window ensured a balance between smoothing small-scale noise and preserving informative structural anomalies reflecting both natural (tectonic) and technogenic processes, including deformations caused by the exploitation of gas fields.

Thus, the conducted lineament analysis made it possible to localize areas with signs of increased tectonic activity and identify the directions of possible hydrocarbon migration, which is of significant interest for the tasks of geodynamic monitoring and planning of further geological exploration activities.

[1] PyLEFA (Pythonic Lineament Extraction and Fracture Analysis). Web resource: http://lefa.geologov.net (accessed 02.02.2025)

[2] The United States Geological Survey (USGS). Web resource: https://earthexplorer.usgs.gov/ (accessed 02.02.2025)

Analysis of the vegetation index (NDVI)

To assess the state of the vegetation cover, the Normalized Difference Vegetation Index (NDVI) was used, which is an indicator of the photosynthetic activity of plants. The NDVI index was calculated using the standard formula (1):

$$NDVI = \frac{NIR - RED}{NIR + RED} \quad (1),$$

where NIR — the reflectivity in the near infrared range,
RED — in the red part of the spectrum.

NDVI values range from −1 to +1. In this case:

- values of −1 to 0 correspond to water surfaces;
- values of 0 and 0.015 indicate barren lands;
- values of 0.015–0.3 are typical for sparse vegetation;
- values of 0.3 and 1 indicate dense vegetation.

In this study, the NDVI analysis was performed using the same Landsat-8 satellite data for the relevant months and time periods. Data processing was carried out in the ArcGIS 10.8.2 program using the module "Spatial Analyst Tools" and "Raster Calculator". Based on the obtained raster data, color maps were constructed, which made it possible to assess the interannual dynamics of the vegetation cover and identify possible changes caused by technogenic factors, including gas leaks.

RESEARCH RESULTS AND DISCUSSION

Based on Landsat-8 satellite images from May 2022, March 2023, and April 2024, a series of maps were constructed to visualize the spatial distribution of lineament density (Fig. 3).

In 2022, the density of lineaments is local: areas with moderate and high values (from 210 to 1 080 relative units) are mainly concentrated in the southeast of the study area. The main part of the area demonstrates low density values, which may indicate a relatively stable geodynamic environment during this period.

In 2023 observed a significant increase in the total number of lineaments and their density. Areas with an increased concentration of linear structures are noticeably expanding and cover almost the entire central part of the territory. This growth can be interpreted as an increase in tectonic activity or as a result of the activation of existing faults under the influence of both natural and technogenic factors.

In 2024, high density values are maintained, but become more localized. In the center and southern part of the territory, areas with extremely high density (from 420 to 1 080 relative units) are formed, which may indicate the concentration of deformation processes along individual active structures.

Thus, the lineament analysis conducted allowed us to record an increase in the activity of linear structures in 2023, followed by their concentration in certain zones in 2024. These results indicate an increase in geodynamic activity against the background of possible technogenic impacts.

Comparison of the lineament density maps with the results of the pressure distribution analysis (gas extraction volumes) from the previous study shows a significant coincidence of the most active areas. The zones with the highest lineament density in 2023–2024 spatially coincide with the areas of maximum operational loads, in particular, near the TOP1, 69sk, 56sk and 0959 wells, where the total volume of extracted gas reaches hundreds of thousands of m^3. On the given map (Fig. 2), these areas are picked out with red and orange spots, corresponding to peak pressure values.

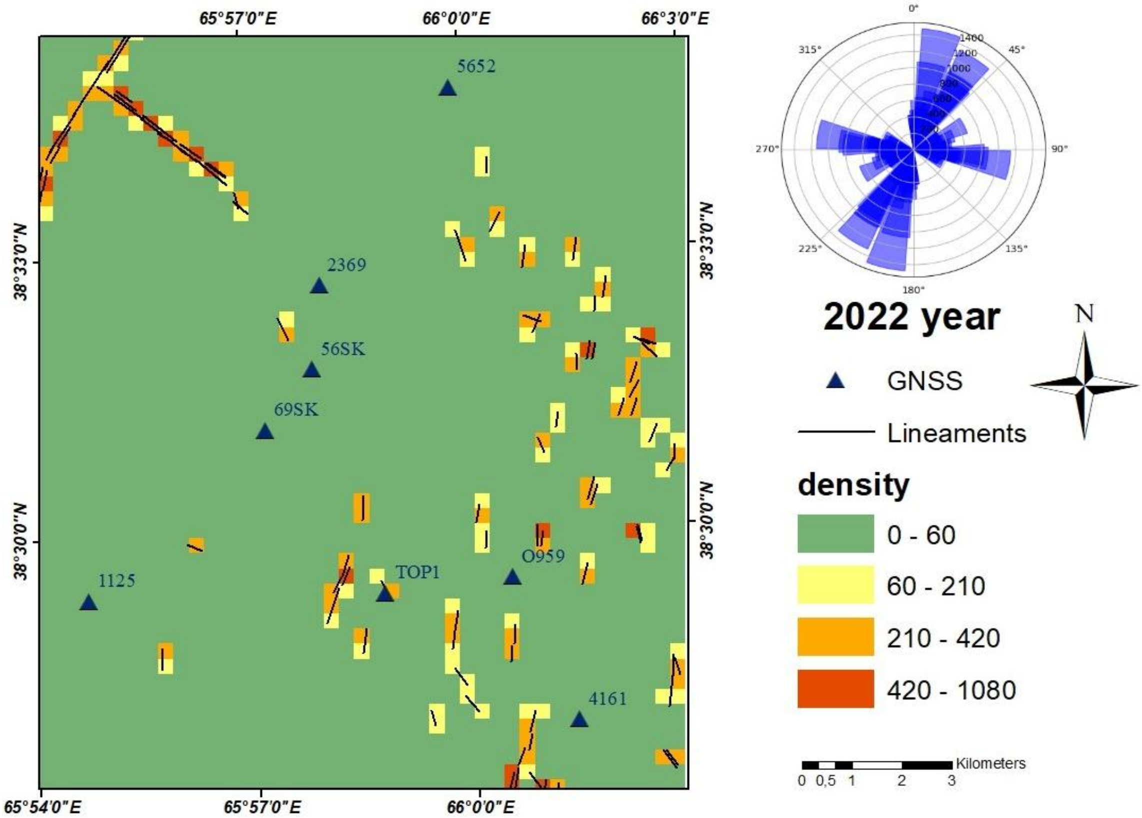


Fig. 3. Density map and rose diagrams of lineaments (May 2022)

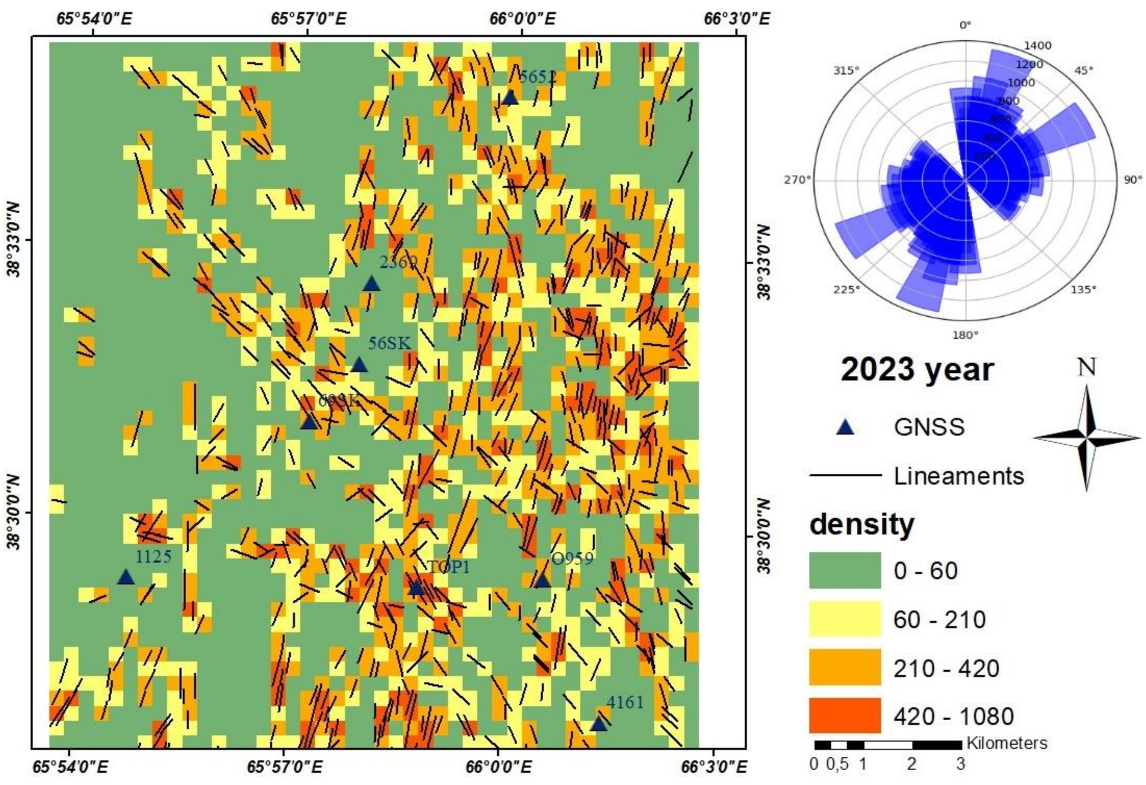


Fig. 4. Density map and lineament rose diagrams (March 2023)

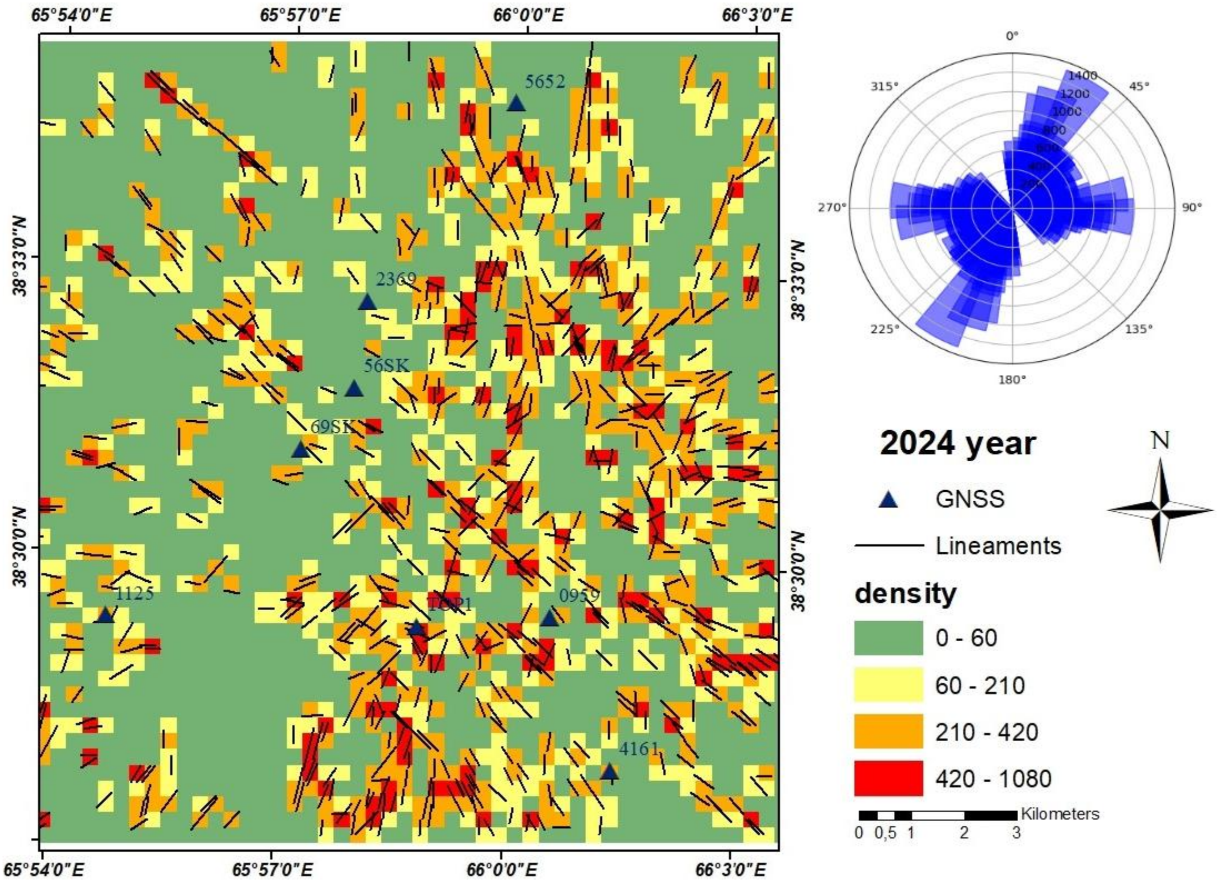


Fig. 5. Density map and rose diagrams of lineaments (April 2024)

This spatial coincidence supports the hypothesis that gas production influences the activation of linear structures and points to possible induced stress in the crust. The obtained data allow us to talk about a potential relationship between production volumes and structural changes in the subsurface zone, which emphasizes the need for regular monitoring based on GNSS and satellite methods.

A characteristic feature of the identified lineament systems is the dominance of the north-eastern orientation, clearly traced in all rose diagrams for the analyzed periods. This direction probably reflects the influence of a stable regional stress field formed under the influence of long-acting tectonic forces. According to studies [*Tsay*, 2006], for gas and gas condensate fields, the predominance of north-eastern and submeridional lineaments is considered a positive structural factor that promotes gas accumulation. In contrast, for oil fields the situation is the opposite: an increase in the density of northwestern and latitudinal lineaments favors the formation of oil traps, while northeastern structures are considered less promising in the context of oil accumulation. Thus, the identified northeastern trends in the structure of lineaments in the study area confirm the gas-bearing specificity of the studied field and are consistent with theoretical models of stress distribution and fluid migration in carbonate formations.

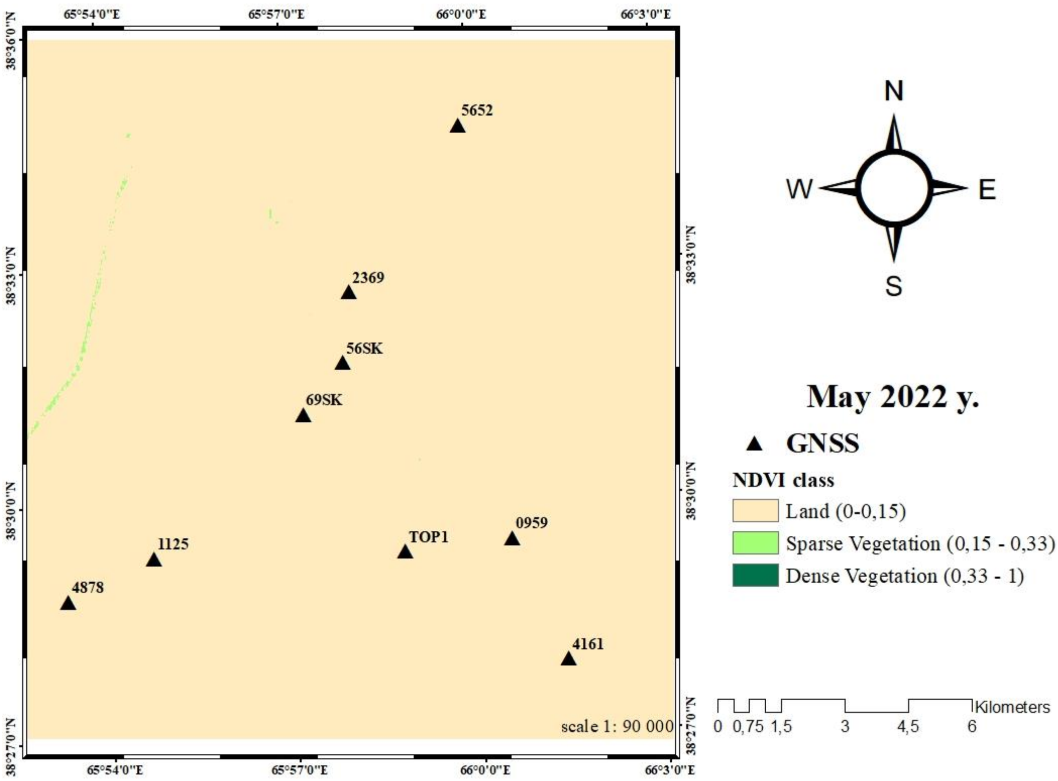
In accordance with the provisions of lineament tectonics [*Kats* et al., 1986; *Sichugova*, *Fazilova*, 2020; 2022], special attention in structural-geological analysis should be paid to the areas of intersection of lineaments with arched uplifts. As a rule, hydrocarbon deposits are confined to zones of convergence and intersection of lineaments, or are located near the axial lines of anticlines. This is explained by the fact that in the process of block movements of the earth's crust, elongated weakened zones are formed in the sedimentary cover, facilitating the migration of oil and gas [*Haereuddin*, *Irawan*, 2019]. Such zones serve as natural channels for the movement of fluids and create favorable conditions for the formation of hydrocarbon traps.

To test this hypothesis, a vegetation map was constructed based on the calculation of the normalized vegetation index (NDVI) for May 2022, March 2023, and April 2024 (Fig. 4). NDVI is a reliable indicator of biomass and vegetation productivity, and its decrease may indicate degradation processes, including anthropogenic impact and geodynamic instability.

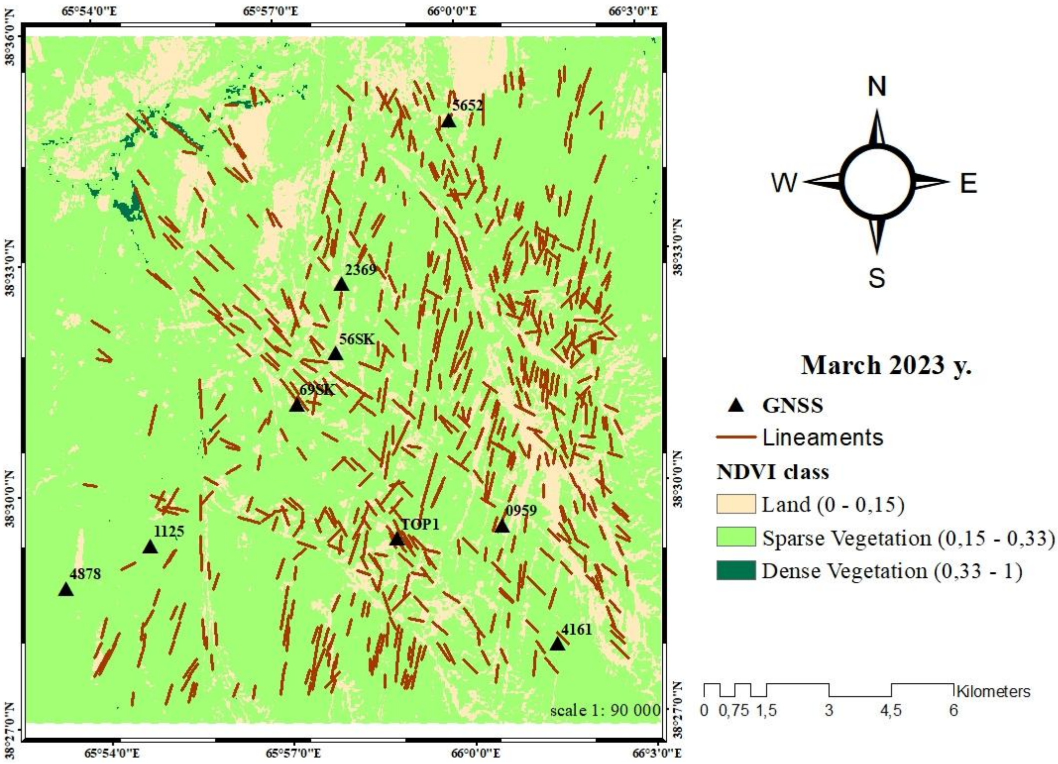
In 2022 (Fig. 6a), almost the entire territory is characterized by low NDVI values (0–0.15), indicating poorly developed or degraded vegetation cover. The exception is certain areas in the northwest, where fragments of sparse vegetation were observed. This period corresponds to a relatively low density of lineaments and the absence of significant geodynamic changes recorded by other sources.

In 2023 (Fig. 6b), a significant improvement in the state of vegetation was observed: in most of the territory, the NDVI exceeds 0.3, which reflects the formation of a dense and active green cover. This year also coincides with the peak of lineament activity: the map clearly shows an increase in the number and length of linear structures. This may indicate the influence of tectonic disturbances on local moisture circulation and microclimatic conditions conducive to vegetation development.

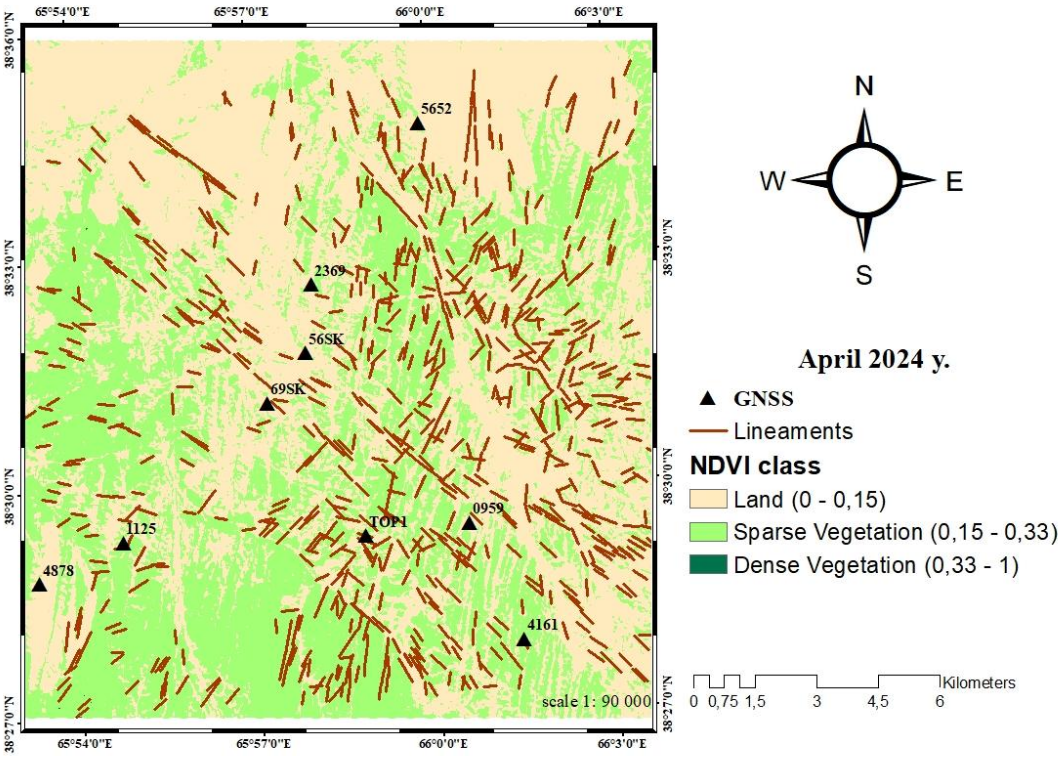
In 2024 (Fig. 6c), on the contrary, degradation of the vegetation cover was recorded: a significant part of the territory returned to an NDVI value below 0.3. A particularly pronounced decrease is observed in the central and north-eastern parts, where a high density of lineaments was previously noted and wells with maximum gas production volumes are located (e. g. TOP1, 0959). The coincidence of degradation zones with areas of active exploitation and localized density of lineaments indicates a possible environmental impact of gas pumping.



a) May 2022



b) March 2023



c) April 2024

Fig. 6. Changes in vegetation cover and lineaments for 2022–2024

Comparison of three-year data on NDVI, lineament activity and pressure maps reveals a stable pattern: in areas where active lineaments intersect with vegetation, degradation of the latter was observed, especially near intensively exploited wells. This may be due to the influence of subsurface processes on the root system of plants, including gas leaks, water imbalance and micro-displacements. Thus, NDVI in this case acts as an indicator of the ecological response of the geosystem to geodynamic and technogenic changes.

CONCLUSIONS

The integration of modern satellite technologies, geodetic observations and geoinformation analysis methods made it possible to obtain a comprehensive picture of the geodynamic and environmental processes occurring in the territory of the Shurtan mining complex. The applied methodology, including lineament analysis, NDVI calculation, as well as accounting for gas production data and GNSS measurements, has proven its effectiveness in identifying potential deformation zones and assessing technogenic impacts on the natural environment.

The results of lineament analysis showed an increase in the number and density of linear structures in 2023, followed by localization of abnormally high density in 2024. A stable north-eastern orientation of lineaments, typical for the active regional stress field, was revealed, as well as local west-east faults, potentially indicating oil structures. The spatial coincidence of high-density lineament zones with areas of intensive gas production confirms the influence of techno-genic load on the geodynamic behavior of the earth's crust.

The NDVI-based vegetation assessment revealed significant degradation of green cover in areas where lineaments intersect and near operating wells. In 2024, NDVI decreased in the central part of the territory, where the highest lineament density and maximum gas pumping volumes were previously observed. This indicates the possible environmental impact of gas leaks, including vegetation suppression and water imbalance.

Comparison with previously obtained data on vertical displacements using GNSS, as well as pressure maps, further confirmed the relationship between hydrocarbon production, structural activity and the ecological state of the territory.

Thus, the proposed integrated approach allowed: to identify zones of potential tectonic instability; to determine channels of possible hydrocarbon migration; to record environmental changes associated with the exploitation of the field. The obtained results can be used for: optimization of well placement, planning geoecological monitoring, minimizing the risks of infrastructure damage, as well as to justify environmental protection measures in areas of active operation.

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