ISSN 2518-170X (Online)
ISSN 2224-5278 (Print)

«ҚАЗАҚСТАН РЕСПУБЛИКАСЫ
ҰЛТТЫҚ ҒЫЛЫМ
АКАДЕМИЯСЫ» РҚБ

«ҚАЗАҚСТАН РЕСПУБЛИКАСЫ
ҰЛТТЫҚ ҒЫЛЫМ АКАДЕМИЯСЫ» РҚБ

Х А Б А Р Л А Р Ы

ИЗВЕСТИЯ

РОО «НАЦИОНАЛЬНОЙ АКАДЕМИИ НАУК РЕСПУБЛИКИ КАЗАХСТАН»

N E W S

OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC OF KAZAKHSTAN

SERIES

OF GEOLOGY AND TECHNICAL SCIENCES

3 (471)

MAY – JUNE 2025

THE JOURNAL WAS FOUNDED IN 1940

PUBLISHED 6 TIMES A YEAR

ALMATY, NAS RK

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News of the National Academy of Sciences of the Republic of Kazakhstan. Series of geology and technology sciences.
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)
Owner: RPA «National Academy of Sciences of the Republic of Kazakhstan» (Almaty).
The certificate of registration of a periodical printed publication in the Committee of information of the Ministry of Information and Social Development of the Republic of Kazakhstan **No. KZ39VPY00025420,** issued 29.07.2020.
Thematic scope: *geology, hydrogeology, geography, mining and chemical technologies of oil, gas and metals*
Periodicity: 6 times a year.
http://www.geolog-technical.kz/index.php/en/

«ҚР ҰҒА» РҚБ Хабарлары. Геология және техникалық ғылымдар сериясы».
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)

Меншіктеуші: «Қазақстан Республикасының Ұлттық ғылым академиясы» РҚБ (Алматы қ.).

Қазақстан Республикасының Ақпарат және қоғамдық даму министрлігінің Ақпарат комитетінде 29.07.2020 ж. берілген **№ KZ39VPY00025420** мерзімдік басылым тіркеуіне қойылу туралы куәлік.

Тақырыптық бағыты: *Геология, гидрогеология, география, тау-кен ісі, мұнай, газ және металдардың химиялық технологиялары*

Мерзімділігі: жылына 6 рет.

http://www.geolog-technical.kz/index.php/en/

«Известия РОО «НАН РК». Серия геологии и технических наук».
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)

Собственник: Республиканское общественное объединение «Национальная академия наук Республики Казахстан» (г. Алматы).

Свидетельство о постановке на учет периодического печатного издания в Комитете информации Министерства информации и общественного развития Республики Казахстан **№ KZ39VPY00025420,** выданное 29.07.2020 г.

Тематическая направленность: *геология, гидрогеология, география, горное дело и химические технологии нефти, газа и металлов*

Периодичность: 6 раз в год.

http://www.geolog-technical.kz/index.php/en/

CONTENTS

Geology

NEWS of the National Academy of Sciences of the Republic of Kazakhstan
SERIES OF GEOLOGY AND TECHNICAL SCIENCES
ISSN 2224–5278
Volume 3. Number 471 (2025), 9–26

https://doi.org/10.32014/2025.2518-170X.507

УДК: 550.8, 551.435.83.
UDC: 550.8, 551.435.83.

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INTEGRATED GEODYNAMIC MONITORING AND RISK ASSESSMENT OF DEFORMATION PROCESSES AT THE BOZASHY NORTH OIL AND GAS FIELD

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Abstract. This article presents the results of a comprehensive study on modern geodynamic monitoring methods used to assess surface deformation at the Bozashy North oil and gas field. The field features a block-faulted structure and shallow productive horizons, making it highly sensitive to anthropogenic impacts. The study focuses on analyzing the causes and dynamics of surface subsidence and uplift driven by hydrocarbon extraction, fluid injection, and natural tectonic factors. An integrated monitoring approach was applied, combining high-precision geometric leveling, GNSS observations, gravimetry, and satellite radar interferometry (InSAR). This integration improved the reliability and spatial resolution of deformation measurements. Stable deformation patterns were identified: subsidence in the central uplifted zone and uplift along the periphery, correlating with reservoir pressure variations and operational activity. A comparative analysis with international cases enabled classification of the observed deformation behavior as typical for geodynamically unstable fields under intensive development. *Scientific novelty* includes the development of an integrated geodynamic monitoring methodology that merges ground-based and remote sensing techniques, surface deformation modeling that accounts for geological, physical, and operational factors, and a risk classification system for induced seismicity based on field data and global analogs. *Practical significance* lies in the applicability of the methods and findings for georisk assessment, prediction of surface behavior, optimization of production and injection strategies, and ensuring safe, sustainable development of oil and gas fields with similar geological and tectonic settings.

Key words: integrated geodynamic monitoring, geo-hazard, repeatable accurate levelling, high-precision GPS measurements, GNSS measurements, high-precision gravimetric measurements, radar interferometry

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СОЛТҮСТІК БОЗАШЫ МҰНАЙ-ГАЗ КЕНОРНЫН ИГЕРУГЕ БАЙЛАНЫСТЫ ДЕФОРМАЦИЯЛЫҚ ПРОЦЕСТЕРДІҢ ПАЙДА БОЛУ ТӘУЕКЕЛІН ГЕОДИНАМИКАЛЫҚ МОНИТОРИНГТЕУ ЖӘНЕ БАҒАЛАУ

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Аннотация. Бұл мақалада Бозашы Солтүстік мұнай-газ кен орнындағы жер қыртысы бетінің деформациялық үдерістерін зерттеу мақсатында заманауи геодинамикалық мониторинг әдістерін кешенді түрде қолдану нәтижелері ұсынылады. Зерттеу нысаны блоктық-жарылымдық құрылымымен және өнімді қабаттардың таяз тереңдікте орналасуымен ерекшеленеді, бұл оны техногендік әсерлерге – әсіресе көмірсутектерді қарқынды өндіру, су айдау және басқа да өндірістік операциялар – жоғары сезімтал етеді. Зерттеу барысында жер бетінің шөгуі мен көтерілуінің себептері, олардың кеңістіктік-уақыттық динамикасы мен өндірістік факторлармен байланысы анықталды. Жоғары дәлдіктегі геометриялық нивелирлеу, GNSS-бақылаулар, гравиметриялық түсірілімдер және спутниктік радарлық интерферометрия (InSAR) әдістерін интеграциялау мониторингтің сенімділігін арттырып, деформациялық үдерістерді жоғары кеңістіктік және уақыттық дәлдікпен бақылауға мүмкіндік берді. Орталық күмбез аймағында жер бетінің шөгуі, ал шеткі бөліктерде көтерілуі тіркелді, бұл пласт қысымының өзгеруіне және техногендік жүктеменің аумақтық таралуына байланысты екендігі көрсетілді.

Ғылыми жаңалығы – Қазақстанда алғаш рет жерүсті және ғарыштық зондтау деректерін біріктіретін интеграцияланған геодинамикалық мониторинг әдістемесі әзірленіп, нақты кен орнына бейімделіп енгізілді. Геофизикалық және техногендік факторларды ескере отырып, жер қыртысының деформациясын модельдеу жүзеге асырылды. Сонымен қатар, индуцирленген сейсмикалық қауіптерді жүйелеу мен жіктеудің жаңа тәсілдері ұсынылды. *Практикалық маңыздылығы* – алынған нәтижелер мұнай-газ кен орындарын қауіпсіз және тиімді игеруді ғылыми негізде жоспарлауға, деформациялық қатерлерді алдын ала болжауға, техногендік әсерлерді азайтуға және жер қыртысының тұрақтылығын бақылауға мүмкіндік береді. Ұсынылған тәсілдер еліміздегі ұқсас геологиялық-геодинамикалық жағдайлардағы жобалар үшін үлгі ретінде пайдаланылуы мүмкін.

Түйін сөздер: интеграцияланған динамикалық бақылау, геоқауіпсіздік, қайталанатын дәл нивелирлеу, жоғары дәлдіктегі GPS өлшемдері, GNSS өлшемдері, жоғары дәлдіктегі гравиметриялық өлшемдер, радиолокациялық интерферометрия

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ГЕОДИНАМИЧЕСКИЙ МОНИТОРИНГ И ОЦЕНКА РИСКОВ ВОЗНИКНОВЕНИЯ ДЕФОРМАЦИОННЫХ ПРОЦЕССОВ, СВЯЗАННЫХ С ОСВОЕНИЕМ ГАЗОНЕФТЯНОГО МЕСТОРОЖДЕНИЯ БОЗАШЫ СЕВЕРНЫЙ

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Аннотация. В статье представлены результаты комплексного исследования современных методов геодинамического мониторинга, применённых для оценки процессов деформации земной поверхности на нефтегазовом месторождении Бозашы Северное. Объект исследования характеризуется блоковой разломной структурой и малой глубиной залегания продуктивных горизонтов, что делает его чувствительным к техногенному воздействию. Основное внимание уделено анализу причин и динамики процессов проседания и поднятия поверхности, вызванных добычей углеводородов, закачкой флюидов для поддержания пластового давления и действием природных тектонических факторов. В рамках работы реализован интегрированный подход, сочетающий данные высокоточного нивелирования, GNSS-наблюдений, гравиметрии и спутниковой радарной интерферометрии (InSAR), что позволило повысить надёжность и разрешающую способность мониторинга. Установлены закономерности пространственного распределения деформаций: проседание в центральной сводовой части и поднятие по периферии, что коррелирует с изменениями пластового давления и операционной активностью. Проведён сравнительный анализ с зарубежными аналогами, позволивший отнести выявленные процессы к типовым проявлениям геодинамической нестабильности в условиях интенсивного освоения. *Научная новизна* заключается в разработке методики интегрированного геодинамического мониторинга, объединяющей наземные и дистанционные методы, моделировании деформаций с учётом геолого-физических и техногенных факторов, а также в классификации рисков индуцированной сейсмичности на основе сравнительного анализа с международными аналогами и полевыми данными. *Практическая* ***ценность*** результатов состоит в возможности их широкого применения для оценки геодинамических рисков, прогнозирования поведения земной поверхности, оптимизации параметров добычи и закачки, а также обеспечения устойчивого и безопасного освоения нефтегазовых месторождений с аналогичным геологическим строением и тектоническими условиями.

Ключевые слова: комплексный геодинамический мониторинг, геоопасность, повторяемое точное нивелирование, высокоточные GPS-измерения, GNSS-измерения, высокоточные гравиметрические измерения, радиолокационная интерферометрия

Introduction. In today's interconnected world, the oil industry holds a central and indispensable role in maintaining global economic stability and growth. Despite the recent surge in the development of renewable "green" energy sources, the vigor of oil and gas field exploitation remains undiminished. Unsustainable production of liquid and gaseous hydrocarbons causes significant changes in the structure of the pore space of reservoir rocks, which can subsequently lead to the emergence of seismic deformation processes.

These deformations, in turn, pose a tangible seismic hazard that can have far-reaching implications for a multitude of construction projects (Kenesbayeva, et al, 2020; Nurpeisova, et al, 2021), pipelines (McCabe, 1986), and other critical infrastructure (Nicholson, et al, 1990; Yerkes, et al, 1969). To maintain reservoir pressure and support production rates, some oil and gas fields implement a practice of injecting a certain volume of fluids, primarily water, into the reservoir to offset the extracted hydrocarbon volume. However, the responses of the reservoir to injection and extraction are not always symmetrical, rendering the resultant ground deformation patterns somewhat unpredictable. Therefore, monitoring these intricate processes is a pivotal endeavor, effectively executed in select oil fields through the use of Radar Interferometry

(InSAR technologies) and GPS measurements, high-precision gravimetry, seismicity monitoring, the results of which are presented in publications.

In this context, we direct our focus to the North Bozashi hydrocarbon field, situated in southwestern Kazakhstan, adjacent to the Caspian Sea coast. Presently, this field is in a phase of active exploitation, witnessing the production of 23,518 thousand tons of heavy oil and 1,210.8 million cubic meters of gas from production wells. This field is distinctive for its relatively shallow oil and gas plays, positioned at depths ranging from 300 to 550 meters. Consequently, the migration of fluids within the reservoir due to oil and gas extraction, coupled with water injection, is anticipated to exert a discernible influence on surface deformations, particularly when contrasted with deposits situated at far greater depths.

The Bozashi North deposit is located in a region with an elevated seismicity level, experiencing earthquakes with a amplitudes of up to 4.0-4.5 and higher. This necessitates specific operational requirements for the development of this deposit.

In this research, we scrutinize ground deformations above the Bozashi North reservoir using GPS and leveling data. Additionally, we analyze variations in the gravity field, which yield supplementary insights into the reservoir's dynamics such as reservoir pressure depletion, reduction of production rates and increase of water cut. Ultimately, we endeavor to provide a qualitative explanation for the observed deformation patterns. This study contributes to our comprehension of fluid dynamics within the intricate realm of oil and gas deposits.

Study Area and Geologic Settings. The North Bozashi field lies in Kazakhstan's Mangistau region, between the Caspian Sea and Mangyshlak Mountains. Discovered in 1975, it holds 84 million tons of recoverable hydrocarbons, with peak output in 2012.

Drilling has reached 3,500 m at the field, revealing Devonian to Quaternary deposits. Triassic formations, up to 2,686 m thick in some wells, consist of argillites and sandstones and show strong deformation. The field structure is an asymmetric NE-trending anticline, disrupted by faults within the Bozashy arch (Fig. 1).

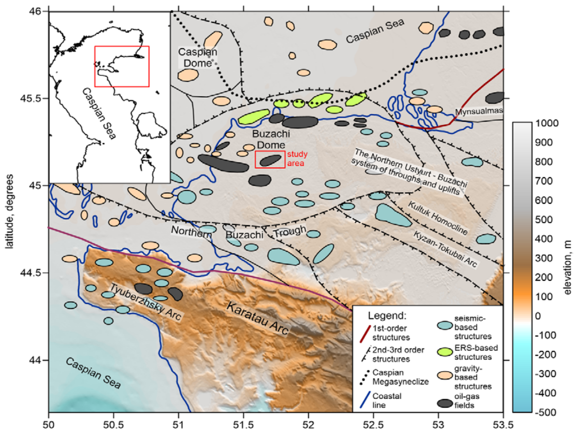

Fig. 1 – Location of the study area and the main tectonic structures. Background is relief from GMRT (Shi, et al, 2019).

Meso-Cenozoic strata include Triassic to Quaternary deposits. Middle Jurassic clastic sediments (J-I and J-II horizons) and Lower Cretaceous formations (A–D horizons) form the main reservoirs. These feature interbedded sands, siltstones, and clays of varying thickness and depositional environments (lacustrine, deltaic, marine).

The region is tectonically active, with the Bozashi North fault displacing blocks by up to 100 m. Secondary fault systems indicate changes in stress regimes between the Jurassic and Cretaceous periods (Figs. 2, 3). The structure is divided into ~14 blocks, with productive zones controlled by both structural features and reservoir facies.

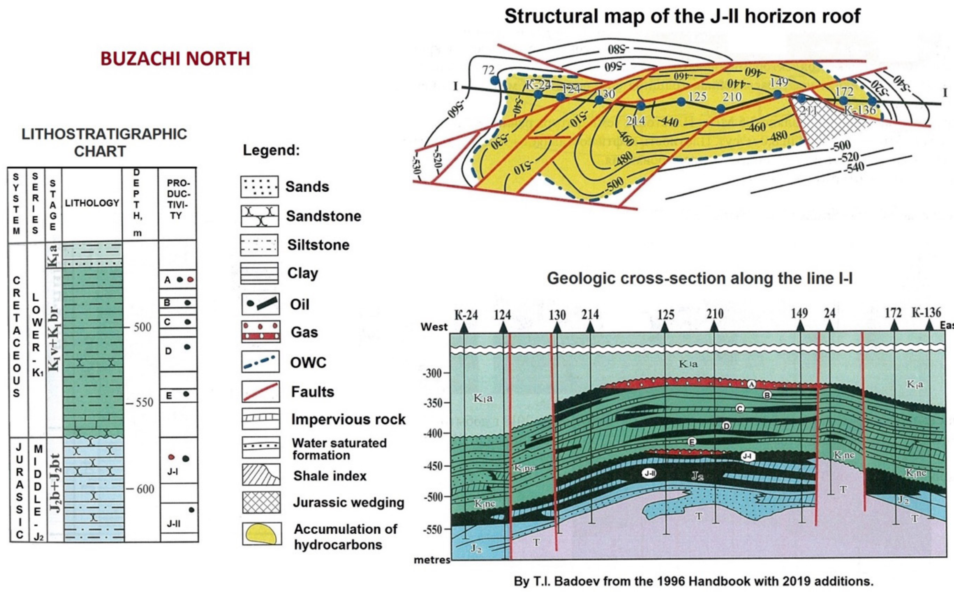

Fig. 2 – North Bozashi field integrated geologic model: a) general lithology-stratigraphic section; b) J-II horizon top structure map; c) geologic section along the line I-II (Turkov, et al, 2020).

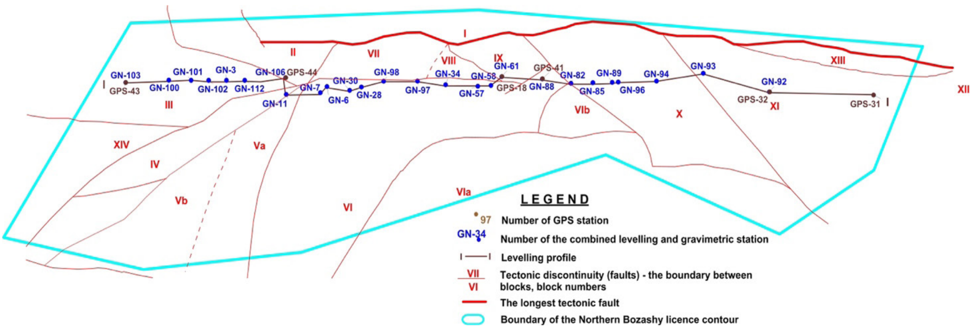

Fig. 3 – Geodynamic polygon at the North Bozashi field. The term «geodynamic polygon» (abbreviated as GDP) refers to a purposefully selected area where a complex of regular geodetic and gravimetric observations is conducted, aimed at quantitatively determining the deformations of the Earth's surface and changes in the local gravitational field.

Materials and methods. In 2007, a geodynamic monitoring polygon was established at the Bozashi North oil and gas field to study natural and anthropogenic deformation processes and their links to field development (Fig. 3). The monitoring program employed a suite of complementary geodetic and geophysical methods, enabling cross-validation and reliable identification of deformation anomalies.

The monitoring aimed to assess:

• Activity of fault systems potentially affected by field operations (Abetov, et al, 2021; Abetov, et al, 2019);

• Amplitudes of vertical and horizontal displacements due to subsurface processes such as pressure decline, reservoir compaction, and heterogeneous rock properties (Hubbert, et al, 1959; Kashnikov, et al, 2007; Nesterenko, et al, 2017; Kazhgeldin, et al, 1996; Sonich, et al, 1997).

The primary methods included:

• Repeated high-accuracy leveling (Class II);
• High-precision GPS measurements;
• Gravimetric observations;
• Radar Interferometry (InSAR).

From 2007 to 2014, 13 full monitoring cycles were conducted, with biannual observations. Between 2013 and 2016, a GNSS network was deployed to support continuous coordinate tracking at reference stations.

High-Precision Leveling. Leveling was conducted along the 24.2 km profile 1-1, covering 32 stations using LEICA DNA 03 digital level. RMS error was within ±0.8–1.0 mm/km, ensuring high consistency between cycles.

*GPS Measurements***.** A network of six GNSS stations was installed to monitor deformation across zones with different production intensities. Equipment included multi-frequency receivers (Trimble R7, R5) and GNSS Choke Ring antennas. Field data were processed in Trimble Business Center for QC and Topcon Tools for final analysis. Typical RMS errors were ±0.9 mm horizontally and ±1.0 mm vertically.

Gravimetric Measurements. Gravimetric stations (104 total) were co-located with leveling sites and measured using SCINTREX CG-5 “AUTOGRAV” gravimeters. Sessions involved simultaneous readings at two instruments, with multiple 40-second measurements per site. Gravity differences within sets did not exceed 0.005 milligal. Processing accounted for microseismic noise and tidal effects, and included control measurements for quality assurance (Eppelbaum , 2015; Gadirov, et al, 2012; Veselov, 1986).

Satellite Radar Interferometry. Since 2014, COSMO-SkyMed satellite data (e-GEOS, Italy) have been used for InSAR monitoring. Processing used the SARscape software (Exelis VIS, USA) and the Small Baseline Subset (SBaS) technique to track surface deformation trends in near-real time (Karegar, et al, 2015; Umirova, et al, 2015).

Results. *Terrain deformations based on repeated high-precision leveling***.** Repeated leveling along the I-I profile, which spans ~20 km west to east across the Bozashi North field, revealed a pronounced central subsidence zone. This segment coincides with the main cluster of production wells and shows a maximum surface drop of 81.5 mm over 10 years (Fig. 5).

At the profile's flanks, particularly near injection wells (e.g., NB753, NB14), stations recorded uplift up to 40.5 mm—attributed to reservoir pressure support via water injection. The average subsidence rate along the profile is 7.9 mm/year, with rates increasing proportionally to cumulative production volumes. This indicates non-linear and spatially variable deformation, driven by uneven hydrocarbon withdrawal.

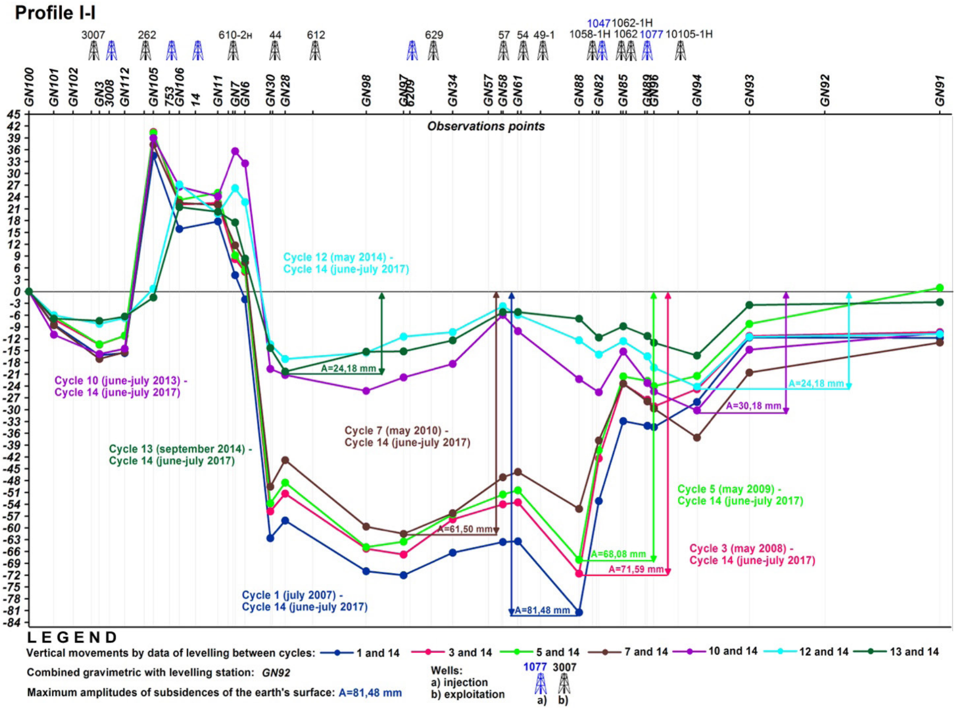

Fig. 5 - Plot of modern vertical movements of the earth's surface along line I-I for time intervals between cycles 1 and 14, 3 and 14, 5 and 14, 7 and 14, 10 and 14, 12 and 14, 13 and 14.

GPS-Based Terrain Deformations. GPS monitoring from 2007 to 2017 (cycles 1–14) shows clear subsidence in the field's center and uplift along its structural wings (Fig. 6).

Key findings:

1. Vertical displacements ranged from +115.5 mm to −58 mm.
2. Maximum subsidence overlaps with high-density production zones.
3. Surface movements exhibit a block-like distribution, aligned with structural elements.
4. Horizontal movements showed a steady trend, averaging 139 mm over 10 years, with a maximum of 35.1 mm at GPS19.

These patterns suggest surface deformation is largely driven by technogenic effects, particularly intensive production activity.

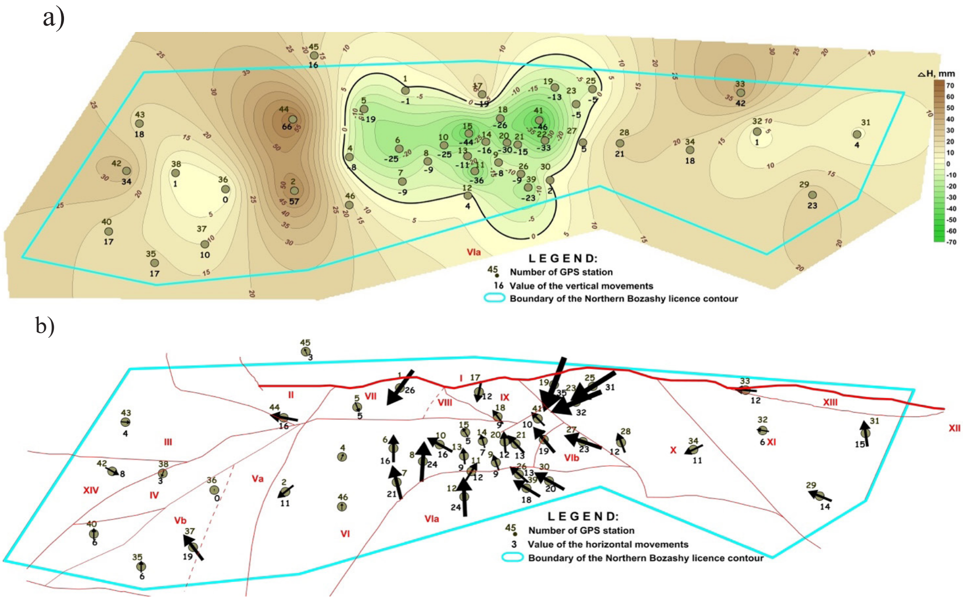

Fig.6 – Map of the areal distribution of the vertical (a) and horizontal (b) components of modern movements of GPS stations for the time period between cycle 1 (July 2007) and cycle 14 (July 2017).

Across the 10-year observation period, accumulated horizontal displacements maintain relatively modest rates, averaging at 139 mm. The maximum horizontal displacement value recorded from July 2007 to July 2017 is 35.1 mm (as observed at GPS19).

It is interesting that the maximum amplitudes of surface subsidence at the Bozashi North field, according to GNSS monitoring data, occur in the area with the highest concentration of wells with the most accumulated oil and gas production. Consequently, the observed area of relative subsidence of the terrain may be associated with the influence of technogenic processes.

*Terrain deformations from Space Radar Monitoring***.** Geodynamic studies at the Bozashi North oil and gas field included methods of remote sensing of the Earth. Throughout the monitoring period, a total of twenty-three satellite images were collected. Specifically, space radar imagery was procured for this field and its adjacent regions from the COSMO-SkyMed satellite, covering the span between September 17, 2013, and November 10, 2014.

The employment of interferometric processing of radar satellite images made it possible to identify displacements and deformations of the surface at the Bozashi North field, and to obtain an idea of the dynamics of movements of this surface over a certain period of time.

During the data processing and interpretation of radar satellite images along profile line I-I, two distinct graphs outlining vertical surface displacements were constructed (as depicted in Figure 7):

1) One graph was established based on the radar survey data acquired from Cosmo SkyMed within the timeframe of October 2013 to May 2014.

2) The other graph was derived from leveling data collected during the period spanning from September 17, 2013, to May 30, 2014.

Comparison of ground-based instrumental and remote sensing observations along line I-I revealed a high degree of convergence (Fig. 7).

The maximum discrepancy in the amplitudes of vertical movements over the observation period (9 months) was recorded at the line ends at the stations GN103 (9.9 mm) and GN91 (3.7 mm). Thus, according to the results of InSAR, the instability of the initial levelling station along the profile I-I is detected. This circumstance needs additional study.

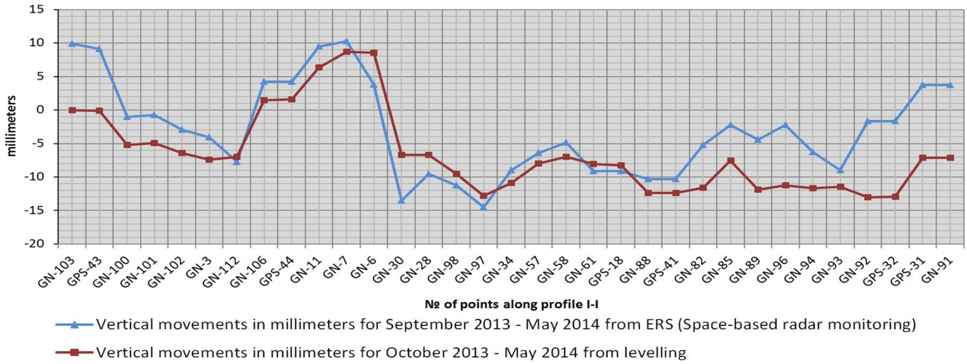

Fig.7 – Plots of vertical displacements along the line I-I at the North Bozashi field based on radar surveys and high-precision leveling.

Summarizing the above mentioned, the results of processing the 30-pass radar survey carried out on the Bozashi North field between 17.09.2013 and 30.05.2014 are in fairly reliable agreement with the results of repeated satellite observations performed in 11 (October 2013) and 12 (May 2014) cycles of geodynamic monitoring.

Consequently, the convergence of the results of daily surface displacements over the same period obtained by two independent methods has been revealed. The difference in values is within the limits of permissible errors of measurements and observations, and can be explained by different dates of obtaining information at one point or another.

For this reason, radar surveys can gradually become a key source of obtaining reliable information on vertical displacements of the earth's surface and, if not completely replace levelling, then reduce the volume of the labor-intensive terrestrial method (Aimaiti, et al, 2016; Hu, et al, 2020).

At the same time, the use of geodetic observations along the line I-I to control the unfavorable events of geodynamic processes on the surface not always advisable due to their high cost, significant time duration, and the large area of the Bozashi North oil and gas field (Nusipov, et al, 2004; Zemtsova, et al, 2012).

In this case, it is logically justified to control the dynamics displacement of the earth's surface by satellite observations - determination of the position of stations of the global navigation satellite network, differential interferometry technology, etc. (Shi, et al, 2019; Staniewicz, et al, 2020).

*Terrain deformations through high-precision gravimetric measurements***.** Over 14 cycles (2007–2017), 104 gravity stations revealed substantial variation in the gravity field (Fig. 8):

• Positive anomalies dominated the western and central parts of the field (up to +68.2 μGal, max at GN39), linked to rock compaction and fluid injection.

• Negative anomalies appeared in eastern and northern zones, potentially due to excessive extraction and insufficient injection.

• Gravity changes range from −20.3 μGal to +68.2 μGal and align with zones of vertical displacement, reflecting structural segmentation.

The gravitational field, known for its exceptional sensitivity to environmental changes, displays a notable response with an increase in values at monitoring stations due to the technogenic effects on the geological formation. An additional contributor to this increase in gravity values may stem from the influence of injected fluids to maintain reservoir pressure

Since fluid injection into productive formations is not uniform across the field, it is plausible that the negative impact of hydrocarbon production may overshadow the effects of reservoir rock compaction in the spatial distribution of gravity variation anomalies.

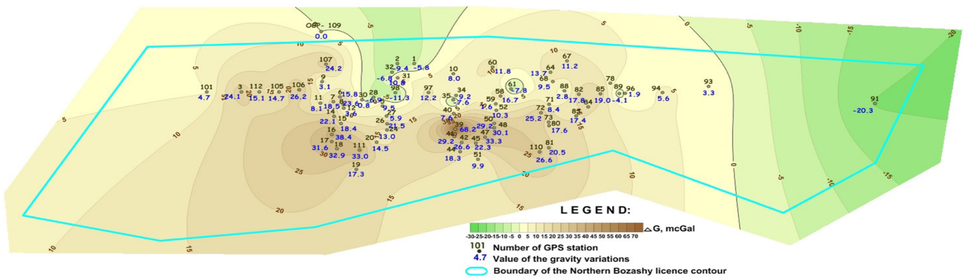

Fig.8 – Map of gravity variations in the territory of the North Bozashi field based on results of gravimetric measurements for 10 years.

Thus, assessing the results over a long-time interval (cycles 1-14), it can be assumed that hydrocarbon production is accompanied by subsequent deformation (compaction) of reservoir rocks, which is expressed in increased gravity values. Additionally, the injection of fluids into these formations may contribute to this phenomenon, given that water has a higher density compared to oil.

An analysis of the spatiotemporal changes in gravity variations from 2007 to 2017 yields the following conclusions:

1) The Bozashi North field predominantly exhibits a positive background of gravity variations. This background undergoes non-linear changes over time, with a

prevailing inclination towards increasing gravity values. Over the 1-14 observation period, accumulated gravity values escalated to 68.2 μGal.

2) The distribution of gravity variations across the field follows a distinct block pattern, marked by high-gradient shifts at block boundaries, mirroring the zones of pronounced changes in contemporary vertical movements of the Earth's surface.

3) Evidently, the principal cause behind the gravity variations at the Bozashi North field is linked to hydrocarbon production, the injection of reagents into development horizons, and the complex structural and tectonic makeup, all of which contribute to the block distribution of gravity variation anomalies.

*Modeling surface deformation based on high-precision gravimetric and geodetic data***.** Combining leveling, GPS, gravity, and production data, surface deformation modeling along profile I-I reveals:

• Maximum subsidence at GN88 (−81.5 mm) corresponds closely with GPS41 (−46 mm).

• Consistent reduction in subsidence towards the eastern edge of the profile correlates with rising reservoir pressures from active injection (Fig. 9).

Gravity anomalies also track production intensity. For instance, Δga increases up to +36.3 μGal near GN58 (compaction + injection), then declines to −27.1 μGal near GN91 (high production, low injection).

Such correlations confirm that surface deformation is tightly coupled to field development parameters, especially in heavy-oil, shallow, terrigenous, and faulted reservoirs.

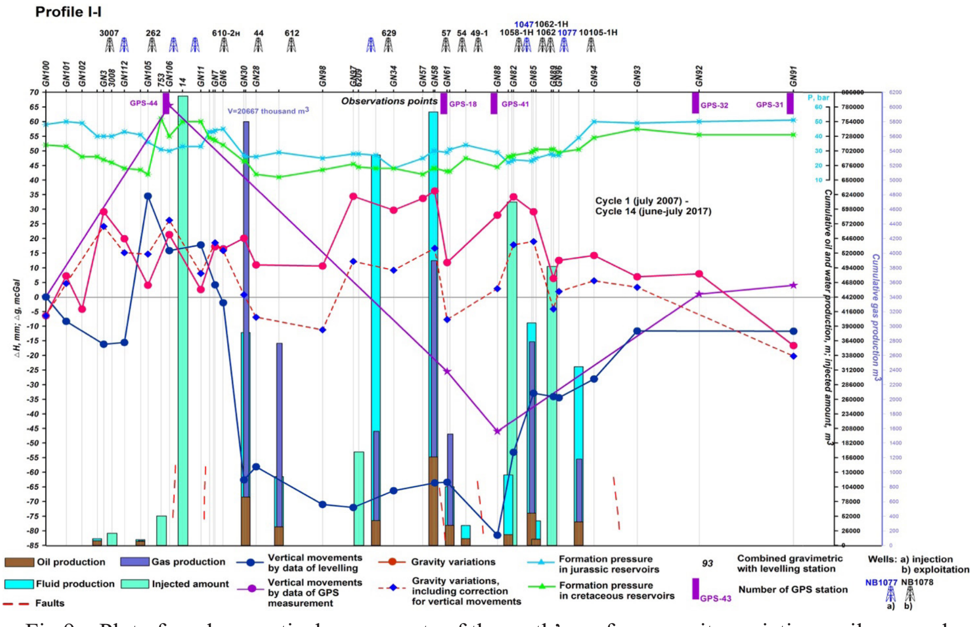

Fig.9 – Plot of modern vertical movements of the earth's surface, gravity variations, oil, gas and liquid production volumes, fluid injection and current reservoir pressures along the line I-I for the time interval between cycle 1 (2007) and cycle 14 (2017).

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Between 2011 and 2017, wells within the subsidence zone showed:

• −28% in oil production

• −61.2% in gas production

• +17.6% in water cut

• +128% in fluid injection, which failed to fully offset production-related compaction.

Average oil and gas output per well declined by 46.2% and 48.7%, respectively.

The integration of leveling, GNSS, gravimetry, and satellite data provides a comprehensive understanding of surface deformation at the Bozashi North field. These deformations are clearly linked to production and pressure support operations, underscoring the need for continuous geodynamic monitoring in managing reservoir integrity and long-term productivity.

Discussion. To better understand surface deformation at the Bozashi North field, a comparative analysis was conducted involving 17 foreign hydrocarbon fields known for subsidence. These analogs helped validate the mechanisms of deformation observed in Bozashi.

Surface subsidence is common during prolonged field development, typically ranging between 1–2 cm/year, with cumulative subsidence usually within tens of centimeters. More severe cases can reach several meters, causing damage to infrastructure and triggering seismic activity.

Notable international examples:

• Wilmington (USA): Up to 8.7 m of subsidence over 40 years, attributed to reservoir compaction due to pressure loss.

• Ekofisk (Norway): Subsea floor subsided by up to 4.4 m over several decades; caused by increased effective stress in overlying rocks.

• Inglewood (USA): Subsidence up to 1.7 m over 50 years; deformation correlated with extraction volumes.

These cases reveal a consistent pattern: subsidence is most pronounced in structurally elevated zones with intensive production. At Bozashi North, similar deformation was observed—maximum subsidence in the structural crest, diminishing toward the flanks, with some uplift in injection zones.

Across the reviewed fields, reservoir rocks typically consist of unconsolidated or weakly consolidated sands, gravels, and siltstones with high porosity (20–35%) and permeability (up to 2000 mD). Bozashi North is comparable, with porosity up to 34% and permeability between 0.106–0.365 µm².

Most foreign analogs feature structural traps and complex fault systems, leading to block segmentation and variable reservoir behavior. Bozashi North mirrors this, being divided into 14 fault-bounded blocks.

Depths of productive intervals across fields vary widely:

• Bozashi North: 320–522 m

• Ekofisk: up to 3000 m

• Wilmington, Surakhani, Shebelinskoye: 180–1900+ m Yet in all cases, subsidence tends to affect shallow, productive intervals first.

Subsidence rates also vary:

• Wilmington, Ekofisk: ~0.2 m/year

• Inglewood, Surakhani: 0.03–0.05 m/year

• Bozashi North: up to 0.08 m/year over 10 years

At Inglewood and Ekofisk, central compression and peripheral tension were observed—patterns mirrored at Bozashi, where subsidence affects the crest and uplifts occur on the flanks.

This comparative analysis confirms that Bozashi's subsidence arises from both natural and technogenic factors. Key contributors include:

• Shallow, high-porosity reservoirs with significant lateral heterogeneity;

• Extensive production concentrated in structural highs;

• Uneven fluid injection and varying reservoir pressures;

• Fault segmentation and block movement potential.

These combined effects heighten the risk of induced tectonic responses—such as reactivated faults, surface ruptures, or localized seismicity—underscoring the importance of continuous monitoring and adaptive reservoir management.

Geodynamic Risk Factors at the Bozashi North Field. Several inherent geological features contribute to elevated geodynamic risks:

• Large field size (20 × 6 km): Increases the number of tectonic blocks and faults, raising the potential for seismic deformation.

• Block structure and fault density: The field is segmented into 14 tectonic blocks by a dense fault network, leading to localized stress variations.

• Shallow reservoirs: Productive Jurassic and Cretaceous intervals occur at shallow depths (340–470 m), accelerating surface deformation.

• Thick pay zones: Combined thickness of productive layers exceeds 100 m (e.g., A–D, J-I, J-II), amplifying compaction risks.

• Seismic context: Located in a seismically active area (up to M5.6 nearby), though in-field seismological monitoring is lacking.

• Weakly consolidated rocks: Sands and siltstones in pay zones are prone to compaction, subsidence, and displacement.

• Heterogeneous lithology: Variations in physical and mechanical properties across the field lead to uneven compaction and surface deformation.

• Good reservoir quality: High porosity and permeability facilitate fluid flow but also increase susceptibility to compaction.

Trigger mechanisms:

• Stress accumulation at block boundaries due to contrasts in rock properties.

• Field development releases built-up stress, especially near active faults.

• Maximum surface subsidence is expected along tectonic block boundaries.

Technogenic Factors or Anthropogenic activities further intensify geodynamic risks:

• Intensive long-term production: Nearly 70 million tons of oil extracted by 2014 has significantly disturbed local stress fields.

• Uneven production: Irregular hydrocarbon withdrawal disrupts the geomechanical balance and induces differential subsidence.

• Fluid injection: Over 52 million m³ of water injected for pressure maintenance introduces additional stress, especially if fluids enter fault zones, potentially reducing friction and triggering fault movement.

• Induced seismicity: Active production and injection near fault zones in a naturally seismic area increase the risk of anthropogenic seismic events.

Technogenic Triggers of Geodynamic Risks and Induced Seismicity. The interaction between technogenic activities and the geological environment at the Bozashi North field contributes to stress field redistribution, leading to surface deformation—subsidence in the structural crest and uplift at the flanks.

Subsidence is frequently accompanied by induced seismicity—microseismic events or tremors triggered by human activity, such as hydrocarbon extraction or fluid injection. These events reflect the release of stored tectonic stress, possibly accelerated by field development, though the precise cause-effect relationship remains under study.

Observed patterns of induced seismicity include:

• Most induced earthquakes are moderate (M 3.5–4.5), with stronger events (M > 4.5) typically occurring below or adjacent to hydrocarbon fields.

• Epicenters often align with pre-existing faults in accordance with the regional stress field and are triggered by anthropogenic changes such as pressure drops or fluid migration.

Five Models of Induced Seismicity Formation:

1. Fluid Injection: Documented in the USA and Canada, high-pressure water injection near fault zones can exceed rock strength and initiate seismicity.

2. Subsidence-Driven Fault Slip: Large-scale subsidence (e.g., Wilmington, USA) induces horizontal fault movement, generating M 3.5–4.5 quakes.

3. Caprock Deformation: Severe pressure depletion beneath a rigid caprock can lead to brittle failure and seismicity within the caprock ($M \leq 4$).

4. Stress Rebalancing from Extraction:

o *Oil fields:* Extraction without pressure support (e.g., Coalinga, USA) reduces load on deeper formations, causing M ≥ 5 events.

o *Gas fields:* Replacing gas with denser brine increases loading on already stressed rocks, as seen in Gazli (Uzbekistan), where M > 6 quakes occurred.

5. Hydrogeological Effects: Fluid migration along permeable faults reduces friction and triggers earthquakes in overstressed zones.

Timing: Seismicity can occur from 2 to 87 years after production begins (e.g., Strachan gas field in 2 years; Coalinga oil field after 87).

Seismicity by Depth and Location:

A. Caprock Interval: Example is Lacq (France), where pressure reduction deformed the caprock overlying the gas reservoir, triggering seismicity.

B. Productive Reservoir Interval examples:

• *Extraction-induced:* Fashing and Imogene (USA) gas fields.

• *Injection-induced:* Rangely (USA), where water injection increased pore pressure >170 bar above original, and Cogdell (USA), where seismicity followed fluid pressure exceeding hydrostatic gradients.

In both cases, imbalance between fluid extracted and injected, or excessive injection pressures, led to seismic events.

C. Beneath Reservoirs examples:

• *Gazli (Uzbekistan):* Injection of 600 million m^3 water led to deep, destructive earthquakes.

• *Strachan (Canada):* Pressure depletion in the gas reservoir caused fault reactivation in the Precambrian basement.

Induced seismicity at hydrocarbon fields, including Bozashi North, arises from both extraction and injection operations. When pore pressure increases or rock stress balance is disrupted—especially near faults—seismicity can be triggered. Monitoring, modeling, and controlled reservoir management are key to mitigating these risks.

Conclusions. This study presents the results of a decade-long geodynamic monitoring program at the Bozashi North field, aimed at identifying and analyzing the emergence of seismic-deformation processes of both natural and anthropogenic origin.

Extensive data from Kazakhstan and international analogs were analyzed to assess:

• Activation potential of fault systems during hydrocarbon development;

• Modern vertical and horizontal surface movements linked to production, reservoir pressure decline, and heterogeneous reservoir properties;

• Localized rock compaction processes within productive horizons contributing to broader deformation.

Key findings at Bozashi North include:

• Persistent subsidence in the field's crest, confirmed by GPS and leveling data, corresponds to high production zones and declining reservoir pressure.

• Uplift at the field's periphery is linked to water injection and pressure increases in sparsely drilled zones.

• Gravity anomalies correlate with hydrocarbon extraction and fluid injection volumes, revealing the impact of reservoir dynamics on the gravitational field.

• Strong agreement between instrumental and satellite-based monitoring confirms the reliability of results, with discrepancies attributed to permissible measurement errors and observation timing.

The robustness of the findings was reinforced through integrated interpretation and modeling of geological, geophysical, and production data, taking into account measurement frequency, duration, and spatial coverage.

This research highlights the importance of systematic, long-term geodynamic monitoring in detecting early signs of surface deformation. In contrast, short-term or irregular observations limit the ability to assess and forecast such changes.

Although most geodynamic indicators at Bozashi North are of moderate intensity, certain zones show elevated risk levels. These are driven by the combined effects of natural block structure and technogenic activities, such as uneven production and fluid injection.

In conclusion, hydrocarbon extraction and water injection are the primary drivers of subsidence and uplift. The observed block-structured distribution of vertical and horizontal movements is shaped by both reservoir compaction and tectonic segmentation, confirming the multifactorial nature of geodynamic risks at the field.

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ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)

Директор отдела издания научных журналов НАН РК *А. Ботанқызы*
Редакторы: *Д.С. Аленов, Ж.Ш.Әден*
Верстка на компьютере *Г.Д.Жадыранова*

Подписано в печать 15.06.2025.
Формат 70x90 1/16. Бумага офсетная. Печать – ризограф.
14,5 п.л. Заказ 3.

РОО «Национальная академия наук РК»
050010, Алматы, ул. Шевченко, 28, т. 272-13-19