

Geodynamic hazards and risk assessment at the Karachaganak oil, gas, and condensate field

A. Abetov, S. Kudaibergenova*

Satbayev University, Almaty, Kazakhstan



ARTICLE INFO

Article history:

Received 24 March 2022

Received in revised form

17 July 2022

Accepted 15 August 2022

Available online 14 September 2022

Keywords:

Geodynamic monitoring

High precision gravimetric

GPS measurements

Repeat accurate leveling

Seismological observation

ABSTRACT

The geodynamic hazards and risk assessment at the Karachaganak oil, gas, and condensate field (KOGCF) were explored on the northern board of the Pre-Caspian Basin to predict the consequences of the long-term exploitation of this field. We integrate multiple measurements, including repeated accurate leveling, Global Positioning System (GPS) measurements, and high precision gravimetric and seismological monitoring at the KOGCF. The results of geodynamic monitoring at the KOGCF for the first time made it possible to prove noticeable seismic deformation processes in the sedimentary cover under the influence of hydrocarbon production. The vertical displacements and horizontal movement along faults, changes in local gravity anomalies, and earthquake sources at depths comparable to hydrocarbon production intervals at the KOGCF have been identified. The maximum amplitudes of modern vertical movement of the earth's surface and the minimum values of the differently oriented horizontal movement were revealed within the projection on the ground surface of the crest of the carbonate massif (Upper Devonian-Lower Permian age). The results suggest the expansion of uneven compression in the crest of the KOGCF while tension processes occur on its periphery. There is a decrease in gravity variations in relation to the slopes of this massif in areas with active hydrocarbon production. An extended zone of high-gradient steps of ΔG_a anomalies, spatially coinciding with the position of fault zones, is mapped along the periphery of the contour of production wells. In the northeastern part of the KOGCF, seismic events were registered practically in the depth intervals of the productive horizons from which hydrocarbons are produced. A spatial relationship between the seismic events and the anomalous deformation activity in the northeast KOGCF has been revealed. Consequently, the field development has provoked both intense deformation of the earth's surface and weak local seismicity.

© 2022 Editorial office of Geodesy and Geodynamics. Publishing services by Elsevier B.V. on behalf of KeAi Communications Co. Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

1. Introduction

The structure of the KOGCF is a carbonate massif with $30 \times 15 \text{ km}^2$, formed from the late Devonian to the Artinian age of the Lower Permian [1–4].

Genetically, this massif is associated with forming a heterogeneous reef and carbonate platform in the inner part of the northern

board of the Pre-Caspian depression, characterized by a thick sedimentary cover and display of salt tectonics (halokinesis) [5–7].

The complex geological evolution of the KOGCF was reflected in the change in the depths and morphology of the main rock assemblage (e.g., their stratigraphic completeness, lithological composition, and variable thicknesses) [8–11].

In the KOGCF, at a depth of 6–7 km, a complex basement high, with a distance of about 400 m from uplifts to troughs, is bounded from the north by an arcuate trough based on seismic data (Fig. 1).

The Upper Paleozoic structure is divided into three sub-levels: Upper Devonian-Tournian, Visean-Bashkirian, and Early Permian (Fig. 1).

The faults originate in the crystalline basement and are traced up to the Filippovsky Horizon of the Lower Permian. These faults led to weakened and fragmented zones, along which halokinetic dislocations subsequently occurred.

* Corresponding author.

E-mail address: sabina_kudaybergenova@inbox.ru (S. Kudaibergenova).

Peer review under responsibility of Institute of Seismology, China Earthquake Administration.



Production and Hosting by Elsevier on behalf of KeAi

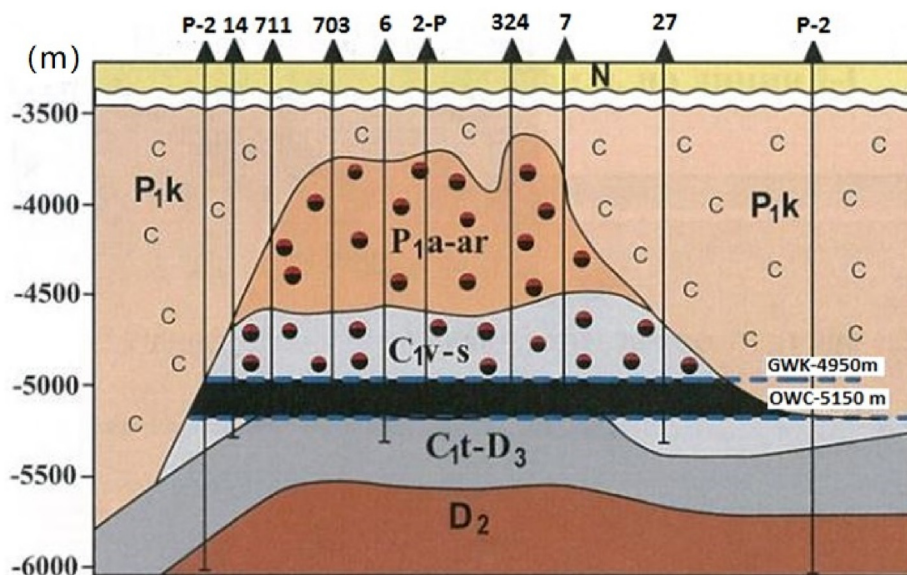


Fig. 1. Typical geological section at the KOGCF.

The main oil and gas condensate reservoir under development is associated with carbonate Upper Devonian (Famennian), Carboniferous, and Lower Permian (up to and including the Artinian stage) sediments, devoid of terrigenous admixture.

A wide range of rocks in the pre-Upper Permian deposits at the KOGCF (e.g., mudstones, organogenic limestones, siltstones, dolomites, carbonate rocks, anhydrites, rock salt, clays, sandstones) created the conditions for the formation of an uneven stress–strain state of the geological environment, which must be taken into account when assessing the geodynamic hazards and risks (anomalous vertical movement along faults, large subsidence of the earth's surface, horizontal movement in rock masses, natural and induced earthquakes) [2,4,12–14].

Under such geodynamic situations, significant subsidence of the earth's surface causes horizontal movement of rock masses toward the subsidence trough. In this case, tensile stresses arise in the crest of the KOGCF, which can be realized in the form of local seismicity along the planes of active faults [15–17]. At the KOGCF, geodynamic monitoring began in 2002 with the initiation of a local seismological monitoring program, which continued until the end of 2007 [14].

In 2008, a comprehensive geodynamic monitoring program evolved, involving class II leveling of increased accuracy, gravimetric and GPS surveys, and seismological monitoring.

The evolved program aimed to obtain information about the events of natural and technogenic genesis at the KOGCF to determine their level, scale, and speed of distribution over the area.

Under the evolved work program for 2009–2012, a set of preliminary works was completed at the KOGCF, which included field reconnaissance of the location of the designed monitoring points, the manufacture and laying of these points on the field territory, and one cycle of monitoring on it [14].

The basic set of geodynamic monitoring methods included 1) repeated accurate leveling at 135 points; 2) repeated high precision GPS satellite measurements at 41 points; 3) repeat high precision gravimetric measurements at 135 sites; 4) seismological monitoring at 7 points.

Surveys were carried out to determine:

- 1) modern fault activity, which the development processes may significantly activate at the KOGCF;

- 2) the amplitude of modern vertical surface movement, including its subsidence, associated with hydrocarbon production, reservoir pressure drop, uneven areal distribution of lithology and reservoir properties, etc.;
- 3) the horizontal movement of rock masses due to intensive subsidence of the earth's surface. The values of shifts can increase due to the influence of local heterogeneities in salt-bearing deposits, which play the role of "lubrication" in case of horizontal displacements;
- 4) local deformation processes in pay horizons (compaction of reservoir rocks), which increase subsidence of the ground surface;
- 5) the appearance of local technogenic and induced seismicity.

Comprehensive monitoring was conducted twice a year (the number of cycles depends on the intensity and change of deformation parameters over time).

From 2009 to 2012, 7 monitoring cycles were performed at the KOGCF [17–19].

2. Potential geodynamic hazards and risks at the KOGCF

The Lower Permian–Upper Devonian carbonate sediments with a thickness of more than 1600 m promote the deformation processes since it has a rigid structure and hardness; moreover, its ability to crush increased under the combined influence of external tangential geodynamic stress and the selection of hydrocarbon extraction.

The large size of the carbonate massif ($28 \times 17 \text{ km}^2$) and the large area of active technogenic impact (about 280 km^2), as well as the area uneven distribution of high flow rate production wells and uneven spatial and temporal changes in reservoir pressure, can contribute to significant deformation (compression, stretching) of reservoir rocks during the development of the KOGCF.

Paleotectonic processes that influenced the formation of rock stress anomalies in the geological section, as well as the deformation processes as a result of field development, are considered the main factor in the display of seismicity along faults.

All these natural and technogenic factors contribute to their uneven areal compressibility and, accordingly, to pulsating subsidence of the earth's surface, leading to vertical and horizontal displacements of rock masses at the KOGCF.

In this study, we assess the geodynamic hazards and risk of deformations on the ground surface.

3. Research results

3.1. Repeat accurate leveling

In 2008, Geomar company conducted the first work on the geodynamic monitoring points to study deformation processes in the field [14].

In 2009, the first cycle of high precision class II leveling at the KOGCF was carried out along four profiles, one online and three crossline, which form a free (unclosed) system of profiles.

The first cycles of repeated precise leveling made it possible to identify local high-intensity anomalies in modern vertical movement of the ground surface along all lines of repeated leveling. The existence of such local anomalous areas is also confirmed by repeated high precision GPS measurements.

The width of the anomalous areas was about 1–2 km, while the amplitude of the vertical displacements of the points reached 6–7 cm for half a year intervals, which are quite large (Fig. 2).

The identified local high-intensity anomalies can be associated with various factors, mainly residual surface deformations (subsidence of points after they were laid in the ground), which appeared when comparing subsequent leveling cycles with the first leveling cycle.

According to the results of the combined hydrodynamic model, carried out in 2012, the active rise of the earth's surface occurred mainly before 2011, which led to a restructuring of the structural plan of this surface and is displayed along the profile 1-1, built based on the data of repeated high precision leveling (Fig. 2).

Subsequent repeated leveling revealed a change in the sign of the movement direction of the earth's surface; uplifts were replaced by subsidence along profile 1-1. At the same time, the maximum amplitudes of modern vertical movement of the earth's surface were established in the crest of the KOGCF (Figs. 2 and 3).

Thus, the maximum amplitudes of modern vertical movement of a ground surface have been identified in the crest of the KOGCF (Figs. 2 and 3).

3.2. Repeated high precision GPS acquisition

Repeated high-precision GPS measurements were carried out with the aim of long-term monitoring of modern deformation processes in the KOGCF and nearby zones to determine the geodynamic hazards and risks.

GPS measurement points at the KOGCF are located according to the areal system [14]. One part was tapped into the salt domes distribution zone, the other within the inter-dome trough and the third outside the influence zone of the field development processes.

The maximum values of the modern rise of the earth's surface were revealed in the arch of the KOGCF (GPS-point 40) +111 mm for 2010–2011 (cycles 2–4). At the same time, the average value of this indicator for the same time for the entire field was +15.8 mm.

The zones of modern uplift of the earth's surface have a sub-latitudinal strike, which conforms to the orientation of the carbonate massif at the KOGCF.

An areal distribution analysis of horizontal motion vectors of GPS points over three years made it possible to identify the following features:

Small values of differently oriented horizontal movement (from 1.5 mm to 12.0 mm) are recorded in the crest of KOGCF (GPS points No. 12, 13, 17, 40, 41). At the periphery of the crest, GPS points show increasing values of horizontal movement up to 21–31 mm and more (Fig. 3);

The southern periphery of the KOGCF is mainly characterized by the northwest trending of horizontal movement of GPS points with the horizontal movement amplitude within the wide range of 11.2 mm (GPS-11) up to 40.1 mm (GPS-6);

On the northern periphery of the KOGCF, smaller values of vectors, a predominantly southerly movement direction, and

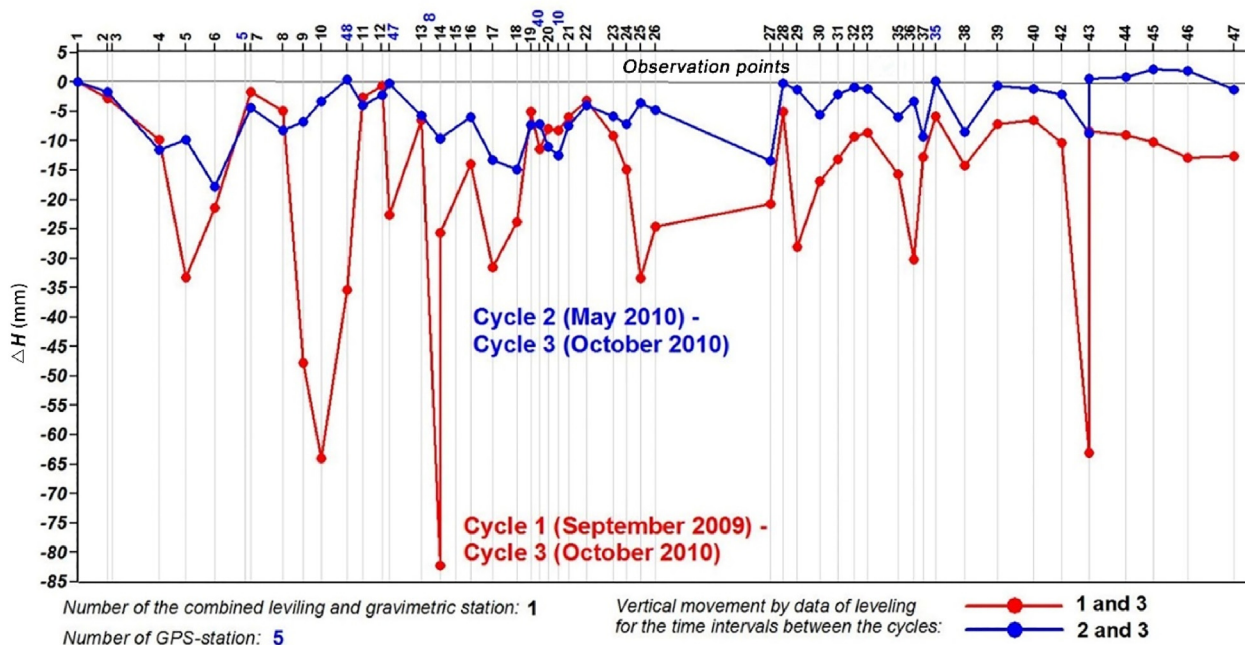


Fig. 2. Modern vertical movements of the earth's surface along profile 1-1 for various periods.

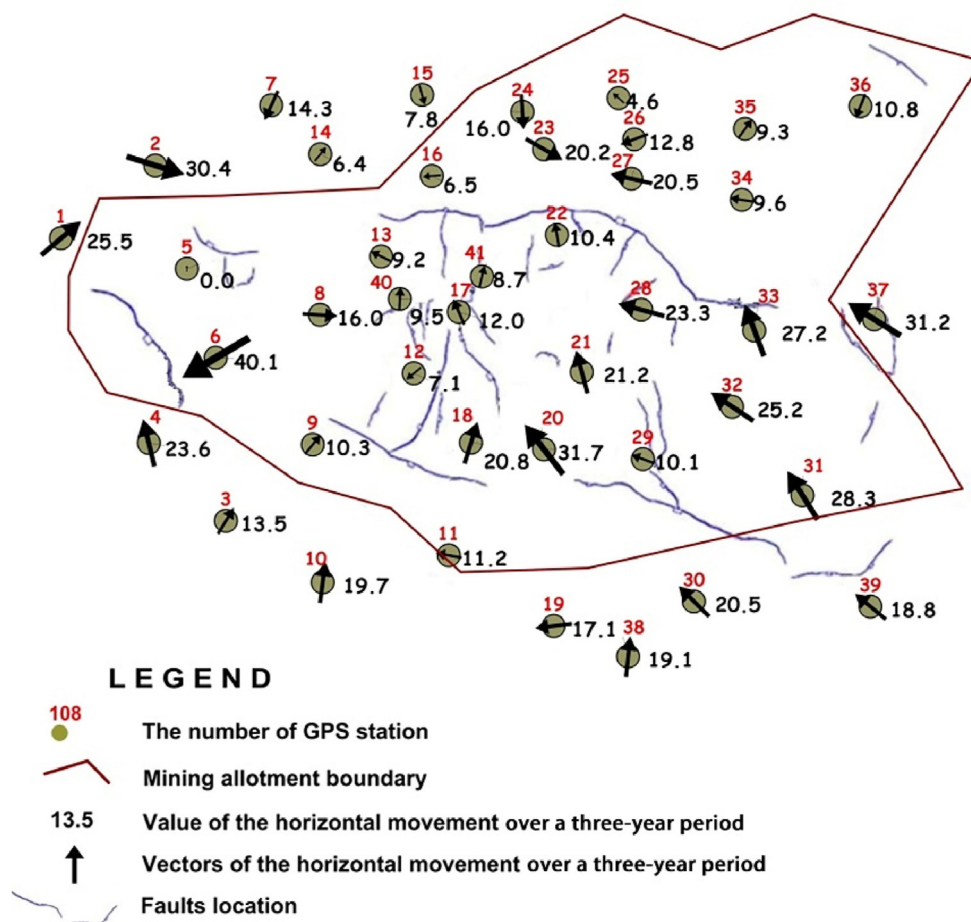


Fig. 3. The spatial distribution of the horizontal movement at the KOGCF based on high-precision repeat GPS measurements over three years.

amplitudes varying from 6.4 mm (GPS-14) to 30.4 (GPS-2, Fig. 3) were revealed;

About-face change in the orientations of the horizontal movement vectors falls on the fault that separates the northern periphery of the KOGCF from its crest.

The results of the horizontal movement of GPS points for 2009–2012 led to two conclusions:

Significant deformation processes with amplitudes of horizontal movement up to +20–35 mm have been established, characterizing the current geodynamic state of the KOGCF subsoil;

The orientation of horizontal movement vectors and their amplitudes suggest the development of irregular compression in the arc of the developed KOGCF, whereas tensile deformation processes occur at its periphery (Fig. 3).

The conclusions are clearly illustrated in Fig. 4, which shows the compression and extension zones.

Differently oriented local anomalies No.1–4, characterizing the zones of extension (dilatation), form a closed ring along the periphery of the projection of the crest of the Upper Paleozoic carbonate massif at the KOGCF on the ground surface (Fig. 4). The sizes of these local anomalies are $4 \times (7-8) \text{ km}^2$ (anomaly 1 - GPS points 5-8-9, anomaly 2 - GPS points 19-20-29, anomaly 3 - GPS points 28-32-33, anomaly 4 - GPS points 25-26-35). The magnitude of dilatation, i.e., areal stretching, varies in the range of $(0.5-1.5) \times 10^{-5}$.

A large arc-shaped compression anomaly (No.5) with its convex part facing southwest has been detected at the arc of the Upper Paleozoic carbonate massif projection on the ground surface (Fig. 4).

A large anomaly of compression of an arcuate shape (No.5), facing the convex part in a southwestern direction, was revealed in the crest of the projection of the Upper Paleozoic carbonate massif on the ground surface (Fig. 4).

In this compression zone, the horizontal movement vectors of GPS points Nos. 23, 24, 25, 26, and 27 naturally directed toward each other (Figs. 4 and 5).

Significant sizes of the compression zone (anomaly No.5 in Fig. 4) framed by extension areas may indicate the existence of active faults along the periphery of the crest of the Upper Paleozoic carbonate massif at the KOGCF.

At the sites of GPS points 26 and 27, the maximum subsidence of the earth's surface for the KOGCF takes place (up to –80 mm over three years) based on repeated accurate leveling, bounded by zones of high gradients of vertical movement (Fig. 5). This zone is characterized by the development of maximum compressive stresses.

Such a geodynamic situation could provoke the occurrence of earthquakes. Indeed, there is a correlation between earthquake epicenters and the location of compression anomaly (No.5).

3.3. Earthquake monitoring system

A network of seismic stations has been created at the KOGCF for seismological monitoring, which is optimal both in terms of aperture (a geometric shape) and in relation to the infrastructure systems of the field and its main geological features.

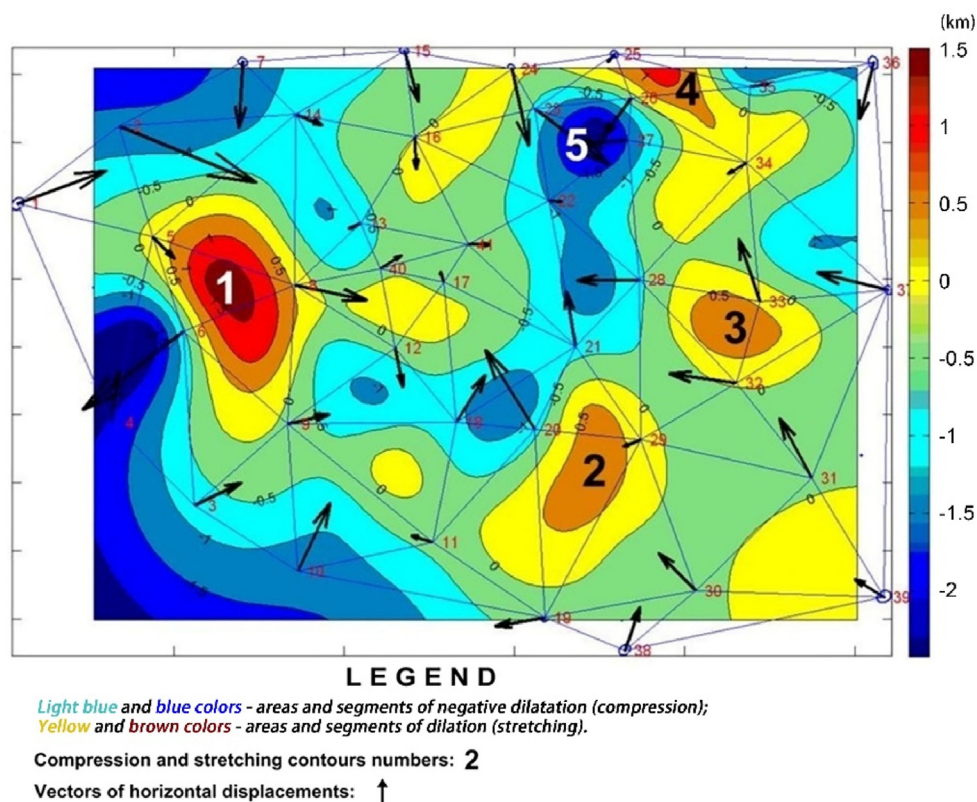


Fig. 4. Stretch and compression zones at the KOGCF.

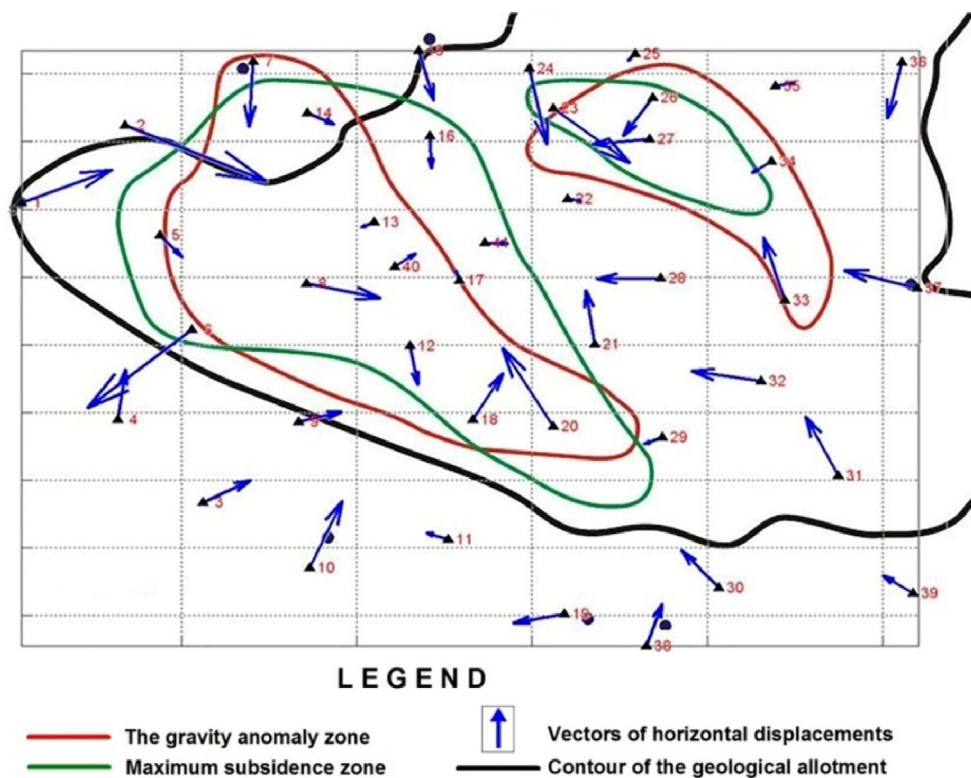


Fig. 5. Distribution of the local gravity anomalies and zones of the maximum subsidence.

The number and location of the earthquake monitoring system stations were determined based on the minimum energy class of expected earthquakes.

As a result of seismological monitoring, it was found that: a) KOGCF is currently characterized by a weak level of seismicity; b) almost all earthquake epicenters are grouped along the periphery of the carbonate massif (Fig. 6).

Within the period of seismological monitoring (2009–2012), 16 local seismic events with magnitudes up to 2 and 1 event located outside the field were registered. Focal depths of earthquakes range from 5 km to 6.5 km, i.e., practically within the production at the KOGCF. Obviously, there is a spatial relationship between the concentration of seismic events in the northeast of the KOGCF and anomalous deformation activity of this part of the field.

The carriers of this activity are the faults identified on the surface of the Carboniferous 9 reflecting horizon.

A significant areal non-uniformity in the position of the epicenters of seismic events was revealed. Of the total number of events, about 80% are concentrated within compression anomaly (No.5) (Fig. 6).

Of undoubted interest is that the identified seismic events and deformation anomalies are located on the operated KOGCF, in the contour of wells that produced hydrocarbons from all objects during the period 2009–2012.

Therefore, it can be assumed that in the formation of the local anomalous compression zone (No.5) and the generation of seismic events, a large role belongs to the technogenic factor, i.e., the field development process.

In other words, there was a natural tension of the bowels in the area of anomaly (No.5). However, the identified deformation movement and seismic events could not have occurred if there had been no development of the KOGCF.

Field development provoked both intense deformation and weak local seismicity.

The results of seismological monitoring lead to the following conclusions:

1. The spatial confinement of the area of concentration of earthquake sources to the zone of anomalous compression, characterized by relative subsidence of the ground surface, identified from the data of the areal distribution of the horizontal movement vectors of GPS points, repeated high precision leveling and an increase in gravity at the KOGCF over a three-years (Fig. 5).
2. The flanks of the KOGCF are separated by the relative subsidence of the earth's surface. Seismic sources are the exception rather than the rule.
3. Seismic events were identified in the zone of anomalous deformation processes and high-gradient changes in the current reservoir pressure at various development targets at the KOGCF;
4. The earth's surface movement at the field are caused by natural-technogenic factors. It can be assumed that for the KOGCF, fault movement and weak seismicity can be considered factors that relieve accumulated stresses due to field development.

3.4. Repeated high precision gravimetric measurements

Repeated high-precision gravity measurements at the KOGCF were made at long-term gravimetric points and aligned with the leveling points. Gravity measurements were made relative to a central gravimetric reference point, which is permanent in all monitoring cycles [20–23].

In 2009, a network of long-term gravimetric points combined with leveling points was located at the KOGCF. In 2011, high-

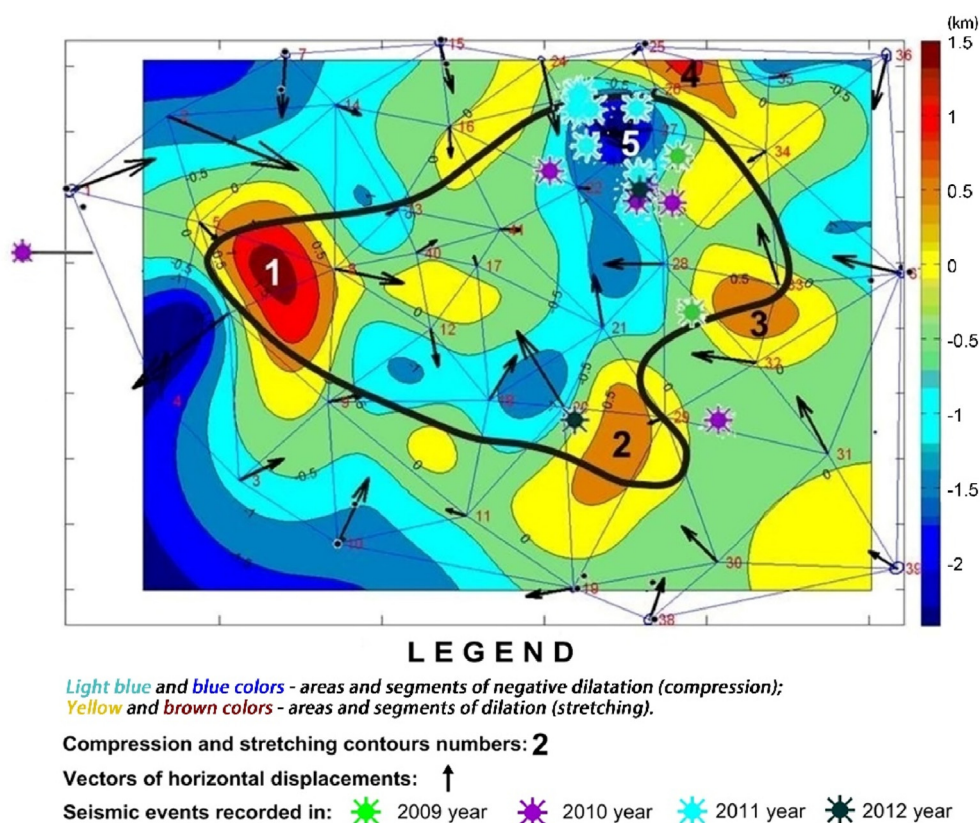


Fig. 6. Stretch and compression zones at the KOGCF, including seismic data for 2009–2012.

precision gravimetric measurements were performed at 118 gravimetric points located along four re-leveling lines [14].

The main factors to be assessed in the study of gravity variations between 2009 and 2012 at the KOGCF field were vertical displacements of gravimetric points over time, hydrocarbon production and deformation processes.

However, two possible cases are distinguished:

- 1) Change in the heights of points at a constant mass of underlying rocks;
- 2) Change in heights with a simultaneous change (increase or decrease) in bedrock mass, which occurs with changes in points elevation, hydrocarbon production, injection of chemicals and water to maintain recoverable product volume and compaction of reservoir rocks.

Time-varying hydrocarbon production and significant lateral variability of the properties of reservoir rocks due to the display of their compaction processes led to a complex spatial–temporal changes in gravity changes.

The multifactorial nature of gravity variations is confirmed by the graphs of the ratios of this parameter and the relative heights of gravimetric points.

The results of repeated high-precision gravimetric measurements at the KOGCF allow us to draw the following conclusions:

1. Significant changes in gravity variations over time, reaching 20–30 microGal per year, have been detected;
2. There is a relative increase in total gravity background;
3. In the arch of the carbonate massif, there is a relative decrease in gravity variations in relation to the slopes of this massif (Fig. 7).

The zone of relative reduction of gravity variations has a northwest-southeast extension with a characteristic decrease in gravity variations toward adjacent areas (section 1 in Fig. 7).

Of note is the very high block differentiation of gravity variations in the north-east of the KOGCF (section 2, Fig. 7), which appears as a combination of a block of increased gravity variations (to +30 microGal) and a block of decreased gravity variations (to +10 microGal).

Along the extended zones of high-gradient steps, spatially coinciding with the position of the fault zones, there is a transition from low to high values of gravity variations (Fig. 7).

In addition, the confinement of low values zone of gravity anomaly to areas with active production was established for 2009–2012. 4865300 tons of hydrocarbons were extracted.

4. Gravity variations along the profiles have a block character, which is probably determined by their multifactorial nature, including deformation processes in the pay horizons, the influence of the hydrocarbon extraction, and the fluid injection into productive formations to maintain reservoir pressure and enhance oil recovery [24–28].

Thus, the analysis of the ratios of gravity variations values and the relative heights of gravimetric points indicates a decrease in the anomalies ΔG_a in time directly above the developed part of the field. On the one hand, this is due to mass transfer processes at the hydrocarbons production (rates of extraction of non-free condensate, oil and gas, gas re-injection into productive formations to maintain the reservoir pressure and increase oil recovery, oil-water contact movement), on the other hand, with the variability of the reservoir properties of rocks in pay zones at the KOGCF. Together, these factors lead to deformation processes in these zones.

4. Discussion

The article reflects the results of studies to find common features of the display of geodynamic parameters between measurement cycles, which show, with a certain degree of probability, some relatively stable display of these parameters for 2009–2012.

In total, geodynamic monitoring included four methods, the results of which, to one degree or another, proved themselves during the development of the KOGCF.

4.1. Repeat accurate leveling

The maximum amplitudes of modern vertical movement of the earth's surface are established within the crest of the KOGCF. It is noted that the active uplift of the earth's surface mainly occurred until 2011, which led to the reconstruction of the structural plan of this crest.

Subsequent high precision repeated leveling showed a change in the sign of movement direction of the earth's surface; uplifts were replaced by subsidence of this surface everywhere.

4.2. Repeated high precision satellite (GPS) measurements

The contours of the zone of modern uplift of the earth's surface have a sublatitudinal strike, which generally to the strike of the projection of the carbonate massif on the ground surface at the KOGCF. At the same time, the maximum values of the modern rise of the earth's surface were revealed above the crest of the KOGCF (up to +111 mm).

Area distribution of horizontal movement vectors allowed to reveal the following features:

- (a) Small values of differently oriented horizontal movement (with amplitude from 1.5 mm to 12.0 mm) were recorded in the crest of the KOGCF. At the periphery of the crest, an increase in the values of horizontal movement up to 21–31 mm and more was observed. In the north-eastern part of the crest projection, the Upper Paleozoic carbonate massif on the ground surface revealed a large arc-shaped compression anomaly (No. 5), in which the horizontal vectors of movement are directed toward each other.
- (b) A wide range of variations characterizes horizontal movement amplitudes for the southern and northern periphery of the KOGCF, with bigger variations for the southern part (from 11.2 mm to 40.1 mm) and smaller variations for the northern part (from 6.4 mm to 30.4 mm);
- (c) The existence of active faulting along the periphery of the Upper Paleozoic carbonate massif fold at the KOGCF is assumed.

The orientation of horizontal movement vectors and their amplitudes suggest the development of irregular compression in the crest of the developed KOGCF, while tensile deformation processes take place at its slopes.

4.3. Seismological monitoring

The spatial confinement of the concentration zone of earthquake epicenters to the zone of anomalous compression, characterized by the relative elevation of the ground surface, is revealed. Of the total number of earthquakes, about 80% of them are concentrated within the local compression anomaly No.5, identified in the northeastern part of the carbonate massif and confined to wells actively producing hydrocarbons from all development

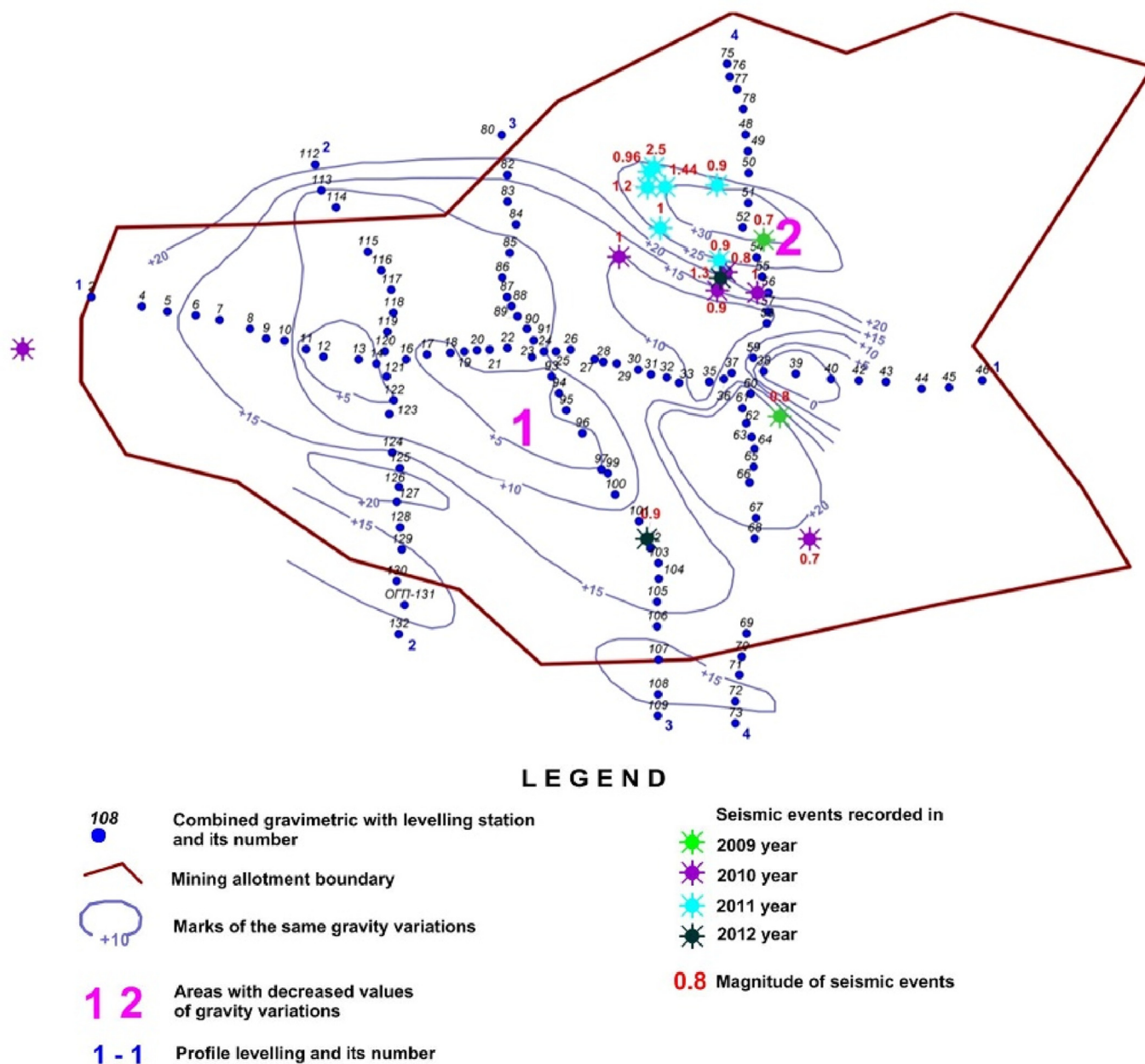


Fig. 7. Gravity variations obtained from the repeated high precision gravimetric measurements over 3 years at the KOGCF.

sites, where anomalous deformation processes and significant changes in the current reservoir pressure appear in the pay zones.

Consequently, the exploitation of the field provoked the occurrence of both intense deformations and weak local seismicity. Thus, we can speak about the natural-technogenic genesis of seismicity in the crest of the carbonate massif at the KOGCF.

The flanks of the KOGCF are separated by an almost aseismic regime.

4.4. Repeated high precision gravimetric measurements

The results of repeated high precision gravimetric measurements indicate that in the crest of the carbonate massif at the KOGCF, a zone is isolated, where there is a relative decrease in gravity variations in relation to the slopes of this massif. Spatially,

this zone coincides with the areas where active hydrocarbon production is carried out.

On the one hand, the formation of this zone was directly affected by the volumes of extraction of non-free condensate and oil, gas, as well as the re-injection of gas into productive formations to maintain reservoir pressure and increase oil recovery, i.e. hydrocarbon production operations, on the other hand, lateral variability of reservoir properties of pay horizons at KOGCF. Together, these factors led to deformation processes in pay zones.

Thus, the results of geodynamic monitoring at the KOGCF for the first time for the Pre-Caspian depression made it possible to obtain convincing evidence of noticeable seismic–deformation processes in the subsoil, displayed on the ground surface and associated with hydrocarbon production.

Combining geophysical and geodetic methods made it possible to study natural and technogenic events in the form of earthquakes, faults activation, and deformation of the earth's surface under the influence of vertical and horizontal movement of rock masses.

In turn, the findings confirm the necessity and obligation of geodynamic monitoring in order to study and assess the geodynamic hazards and risks associated with the development of the KOGCF.

In this regard, in this article, trends and tendencies are highlighted so that the next stage of geodynamic monitoring could purposefully research the relationship between the geodynamic state of the subsoil, which is continuously changing over time, and the field and geological processes.

In order to mitigate the factors of potential geodynamic hazards and risks at the KOGCF, there is an urgent need to perform:

1. Geodynamic zonation at the KOGCF, taking into account the available geological, geophysical and field data, identifying potential areas of geodynamic hazards and increased risks in areas and areas of anomalous deformations of the geological environment in fault zones.

The confinement of three-dimensional deformations to fault zones is substantiated by the following factors that we have identified:

- a) The faults localization is identified by the maximum values of subsidence of the ground surface, reaching the values: –65 mm (GPS-33), –80 mm (GPS-8), –60 mm (GPS-5) according to high precision leveling;
- b) The faults localization occurs by an about-face in the vectors of horizontal movement, during the transition from the crest of the KOGCF to its periclinals, where increased values of displacements are observed (GPS points No. 23, 24, 25, 26, 27, etc.), while in crest they are minimal according to repeated high precision satellite (GPS) measurements;
- c) Faults are localized along linear gradient transition zones from lower to higher values of gravity variations, spatially coinciding with the position of these faults;
- d) Within the zones of anomalous deformation processes associated with faults, seismic events and significant changes in the current reservoir pressure at various development targets were recorded;
- e) The confinement of anomalous subsidence of the earth's surface to areas of high hydrocarbon production.

2. The calculation and subsequent analysis of the components of the anomalies of the stationary stress field – potential zones of occurrence of natural and technogenic earthquakes, zonation of the KOGCF on this basis;
3. The study of correlations of seismicity and deformation processes of natural and technogenic origin in the conditions of long-term operation of this field.
4. Modeling the combined display of the effects of the volume of hydrocarbon production and the deformation of reservoir rocks using data on gravity variations, the magnitude of subsidence of the earth's surface

5. Conclusions

The comprehensive interpretation of the monitoring results allows us to perform:

1. Geodynamic zonation at the KOGCF, taking into account the available geological, geophysical and field data, to identify

potential areas of geodynamic hazards and high risks, which include:

- anomalous deformation areas within fault zones;
 - abnormal subsidence areas within high hydrocarbon production zones;
 - anomalous horizontal displacements areas;
 - potential zones of induced earthquakes and zoning of the KOGCF area;
 - detailed seismic zonation.
2. Possible mechanisms analysis of the interrelation between deformation and natural or anthropogenic origin seismic processes under the long-term operation of the field and interpretation of spatial–temporal changes in geodynamic monitoring data.
 3. Modeling of deformation processes in reservoir rocks in connection with the volumes of recoverable hydrocarbons using gravity variations and subsidence data of the earth's surface. We integrate various geodetic methods to study the properties and causes of seismicity and deformation processes at the KOGCF. This analysis can assess the seismic–deformation status of the petroleum accumulations under development, moreover, provide a basis for predicting the geodynamic hazards and risks of exploitation in this field.

Conflicts of interest

The authors declare that there is no conflicts of interest.

References

- [1] S. Elliot, H.H. Hsu, T. O'Hearn, I.F. Silvester, R. Vercesi, Karachaganak one of the world's largest gas condensate reservoirs, requires an innovative team approach to maximize field potential, *Oilfield Rev.* (1998) 16–25.
- [2] A.E. Abetov, S.S. Kudaibergenova, V.A. Sidorov, Conceptual approach to monitoring of land surface deformations in hydrocarbon fields, *Proceedings of the 17th EAGE Scientific and Practical Conference: Engineering and Ore Geophysics*, <https://www.earthdoc.org/content/papers/10.3997/2214-4609.202152160>, 2021.
- [3] O.S. Turkov, et al., Atlas of oil and gas fields of the republic of Kazakhstan, *Almaty Social Organization Kazakhstan Society of Uphole Oilman and Geologists 2* (2020) 84–85.
- [4] A.T. Muratov, E.A. Mashkova, Geological Structure and Formation Conditions of Oil-Bearing Subsalt Complex of Karachaganak Field, *Bulatov readings*, 2021, pp. 64–66. <https://www.elibrary.ru/item.asp?id=45942674>.
- [5] Y.A. Volozh, M.P. Antipov, V.A. Bykadorov, et al., *Orenburg Tectonic Junction: Geological Structure and Oil-And-Gas Bearing Capacity*, Moscow Scientific World, 2013, p. 264.
- [6] A.V. Chuvaev, N.V. Danshina, Peculiarities of geological structure of upper devonian-lower carboniferous deposits of the devonian part of the pre-caspian depression of saratov region, *Subsoil of Volga and Pre-Caspian regions* 41 (2005) 34–45.
- [7] S.V. Yatskevich, V.Ya. Vorobyov, Formations of Middle Devonian-Arthynian oil-and-gas-bearing stage of south-eastern Russian plate (Pre-Caspian mega depression and its frame), *Subsoil of Volga region and Pre-Caspian region* 63 (2010) 3–16.
- [8] S.V. Yatskevich, E.V. Postnova, L.N. Umnova, Lithologic-stratigraphic and facies features of sections of pre-salt Paleozoic of Volga-Ural oil and gas bearing province, *Subsoil of Volga and Pre-Caspian* 57 (2009) 3–28.
- [9] M.P. Antipov, V.S. Parasyna, V.A. Bykadorov, et al., Pre-Caspian Basin: tectonic events and sedimentation at the Early-Middle Carboniferous boundary and formation of oil and gas reservoirs, *Geotectonics* (2019).
- [10] F.U. Georgy, *Petroleum Geology and Resource of the North Caspian Basin*, Kazakhstan and Russia, USGS Bull. 2201 B, 2001, pp. 29–40.
- [11] B.M. Kuandykov, Y.A. Volozh, M.P. Antipov, et al., Caspian region: the problem of hydrocarbon prospecting at great depths, possible ways of its solution, *Almaty: ONGC 4* (2014) 20–33.
- [12] A.V. Zemtsova, Z.D. Baygurin, On Development of Geodetic Works on Geodynamic Forecasting Polygons in the Republic of Kazakhstan, *Proceedings: Plenary Meeting, Interexpo GEO-Siberia*, 2012, p. 243.
- [13] A.E. Abetov, S.S. Kudaibergenova, Creation of geodynamic polygons and technologies of geodynamic monitoring in hydrocarbon fields, *Vestnik KAZNRTU* 143 (2) (2021) 3–13. URL: <https://vestnik.satbayev.university/index.php/journal/article/view/60>.
- [14] A. Shevel'yova, Integrated Geodynamic Monitoring and Risk Assessment of Occurrence of Seismic Deformation Processes Related to Development of

- Raw Hydrocarbon Deposits, SPE Caspian Carbonates Technology Conference, 2010.
- [15] A.E. Abetov, S.S. Kudaibergenova, Factors of geodynamic risk by the example of the Buzachinskiy fold hydrocarbon field, Proceedings of the II International Scientific Conference: New Directions of Oil and Gas Geology and Geochemistry, Development of geological prospecting, 2019, pp. 8–17. URL: <https://www.elibrary.ru/item.asp?id=41536217>.
- [16] A.V. Tsvyak, M.Y. Nesterenko, Technogenic Geodynamic Processes at Hydrocarbon Fields under Development, Bulletin of the Orenburg Scientific Centre of the Ural RAS Department, 2017, pp. 4–8.
- [17] A.E. Abetov, S.S. Kudaibergenova, Integrated research of suffosion and karst processes in the oil-gas-condensate field Karachaganak by geological and geophysical and geodesic methods, Proc. Natl. Acad. Sci. Republ. Kazakhstan Ser. Geol. Techn. Sci 5 (449) (2021) 14–22, <https://doi.org/10.32014/2021.2518-170X.93>.
- [18] A.V. Zemtsova, S. Zhantasova, Monitoring using GPS at the geodynamic site of an oil and gas field, Int. Conf. Innovat. Technol. Geospat. Data Collect. Process. Nat. Resourc. Manag. (2012) 112–118.
- [19] A.E. Abetov, S.S. Kudaibergenova, Environmental safety issues and challenges and geodynamic monitoring in the KOGCF, Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu 3 (2022) 118–124, <https://doi.org/10.33271/nvngu/2022-3/118>.
- [20] L.D. Nemtsov, High-accuracy Gravity Prospecting, Nedra, Moscow, 1967.
- [21] K.E. Veselov, Gravimetric Survey, Nedra, Moscow, 1986.
- [22] V.G. Gadirov, L.V. Eppelbaum, Detailed gravity, magnetics successful in exploring Azerbaijan onshore areas, Oil Gas J. 110 (11) (2012) 60–73.
- [23] L.V. Eppelbaum, Interpretation of microgravity and magnetic data for delineation of subsurface salt bodies in unfavourable S/N ratio conditions, Proceedings of the 2015 SAGEEP Conference, Austin, Texas 28 (2015) 686–695.
- [24] A.G. Koshim, K.M. Akhmedenov, Technogenic relief formation in the area of Karachaganak field, Oil Gas 1 (85) (2015) 79.
- [25] K.M. Akhmedenov, D.Zh. Iskaliev, V.P. Petrishev, Karst and pseudokarst of the west Kazakhstan (republic of Kazakhstan), Int. J. Geosci. 5 (2014) 131–136.
- [26] L.V. Lee, V.A. Sidorov, Aspects of geodynamic safety in the development of oil and gas fields. Exploration of Shallow Oil and Gas Strata in Kazakhstan Proceedings of KSPG Based on the Reports of the V-International Geological Conference AtyrauGeo-2019, 2019, pp. 185–202.
- [27] Zh. Jin, J. Wang, Sh. Zhang, et al., Main factors controlling hydrocarbon reservoir and exploration direction in the pre-salt sequence in Pre-Caspian Basin, Petrol. Geol. Experiment 29 (2) (2007) 111–115.
- [28] L. Liu, Y. Guo, Y. Zhu, Reservoir characteristics and oil-bearing characters of the Carbonate reservoirs in the pre-salt sediments of the Pre-Caspian Basin, J. Xi'an Shiyou Univ. Natur. Sci. Edition 22 (1) (2000) 53–58.



Abetov Auez is a Professor at Satbayev University. His research interests include geodynamics, engineering geophysics, tectonophysics, sedimentology, seismostratigraphy, a system approach to the study of oil and gas reservoirs.