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ENVIRONMENTAL SAFETY ISSUES AND CHALLENGES AND GEODYNAMIC MONITORING AT THE KARACHAGANAK OIL AND GAS CONDENSATE FIELD

Purpose. Environmental safety evaluation and geodynamic monitoring of the Karachaganak oil and gas condensate field (KOGCF) explored on the north board of the Pre-Caspian depression in order to predict the consequences of long-term operation of this field.

Methodology. Synthesis and system analysis of the articles and archival literature on environmental hazards and geodynamic monitoring of the complex methods, repeated levelling process, GPS-measurements, high-precision gravimetry and seismological monitoring.

Findings. At a qualitative and quantitative level, the activation of vertical and horizontal movements of rock masses, changes in the field of local gravity anomalies, more frequent earthquakes whose hypocentres are located at depths comparable to the intervals of field development are substantiated. Trends and tendencies in the study on the relationship between the continuously changing geodynamic state of the subsoil and field-geological processes are outlined. All these manifestations in one way or another find manifestations in the environmental risks of the area of the exploited deposit. In the conclusions, it is recommended to carry out a set of measures to reduce environmental risks.

Originality. The results of geodynamic monitoring at the KOGCF for the northern board of the Pre-Caspian depression for the first time made it possible to obtain convincing evidence in favour of noticeable seismic-deformation processes in the upper part of the earth's crust under the influence of hydrocarbon production processes.

Practical value. The conclusions obtained in the work confirm the necessity and binding of geodynamic monitoring in order to study and assess the possibility of different scenarios of geodynamic situations related to the development of hydrocarbon fields, are recommended for levelling factors of potential geodynamic risk at the KOGCF.

Keywords: *oil and gas condensate field, geodynamic monitoring, high-precision gravimetric and GPS-measurements, levelling, seismology*

Abstract. This article discusses the aims and objectives, status, problems and methods of geodynamic monitoring at the Karachaganak oil and gas condensate field (KOGCF), explored on the northern board of the Pre-Caspian Basin.

The article is based on the results of the author's detailed analysis of archive materials and published literature.

Geodynamic monitoring on the KOGCF was conducted by a complex of methods: repeated accurate levelling, high-precision gravimetric monitoring, GPS-measurements, seismological monitoring for the period of 2009–2012. At qualitative and quantitative level, synthesis and system analysis of the results of the complex GDM (Geodynamical Monitoring) were carried out.

The areal distribution of local intense anomalies of vertical movements, based on the data of repeated accurate levelling, overwhelmingly showed their coincidence in location with faults along the surface of the C9 reflector (Visean stage of the Lower Carboniferous), identified by seismic data CDP-2D and CDP-3D.

According to the results of complex GDM, it was identified that the maximum amplitudes of modern vertical movements of the earth surface are established within the projection of the arch of a sublatitudinally oriented carbonate massif at the KOGCF. Subsequent levelling showed a change in the sign of the direction of movements of the earth's surface, elevations were replaced by depressions.

Against this background, the minimum values of differently oriented horizontal movements in the anticlinal fold of the KOGCF were identified. Its southern and northern peripheries are characterized by increased amplitudes of horizontal movements, which is associated with active faults revealed here.

The orientation of the horizontal motion vectors and their amplitudes give reason to believe that there is uneven compression propagation in the fold of the developed KOGCF, whereas tensile deformation processes are taking place on its periphery.

In the north-eastern part of this compression zone, earthquake focus has been recorded located practically in the intervals of field horizons, from which hydrocarbons (HC) are extracted.

Apparently, there is a spatial relationship between the concentration of earthquake epicentres in the north-eastern part of the KOGCF and the anomalous deformation activity in this part of the field.

Consequently, field development has provoked both intense deformation and weak local seismicity. Thus, it is possible to speak about natural-technogenic genesis of seismicity in the carbonate massif fold at the KOGCF. Peripheral parts of the KOGCF are distinguished by practically aseismic regime.

The results of the analysis of repeated high accuracy gravimetric measurements testify to the fact, that in contour of the developed field, 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 areas of active hydrocarbon production. Its formation is influenced, on the one hand, by mass transfer processes, occurring during field operation, and, on the other hand, by variability of reservoir properties of rocks of operating objects.

Along the periphery of the production wells contour an extended zone of high-gradient stages of Δg_a anomalies coinciding with the position of fault zones has been mapped.

In conclusion of the article the necessity of organization of information support of geodynamic monitoring is substantiated and measures with the purpose of levelling of potential geodynamic risk factors at the KOGCF are recommended.

Introduction. ***A brief geological and tectonic description of the KOGCF.*** The geological and tectonic characteristics of the Karachaganak Oil and Gas Condensate Field (KOGCF) play an important role in understanding the relationship between geodynamic processes and field development.

The structure of the KOGCF is a 30 × 15 km carbonate massif which was formed from the Late Devonian to the Artinian age of the Lower Permian.

The massif is complicated by domes: northern, central two-folded, southern and western. Genetically, this massif is

associated with the formation of a heterogeneous reef and platform carbonate rock assemblage.

Tectonically, the KOGCF is located in the inner part of the northern near-edge zone of the Pre-Caspian Basin, characterized by a thick sedimentary cover and the occurrence of salt tectonics (halokinesis).

The complex history of the geologic development of the KOGCF has displayed itself in contrasting changes in the morphology of the occurrence of major lithological-stratigraphic rock assemblage and their thickness.

In the area of the field, according to seismic data, at a depth of 6–7 km, a basement high with a complex structure is distinguished, with an amplitude of uplifts and troughs of about 400 m, bounded from the north by an arcuate trough [1] (Fig. 1).

To the south, the basement high is flanked by two branches of the sublatitudinal strike-slip (with amplitude up to 1,200 m) along which the basement surface dips stepwise from north to south.

The Upper Paleozoic structural level is divided into three sub-levels: Upper Devonian-Tournean, Visean-Bashkirian, and Early Permian, each characterized by a bit different structural plan (Fig. 1).

The faults originate in the crystalline basement and can be traced all the way back to the Philippian horizon of the Lower Permian. These faults caused the generation of weakened zones through which salt was subsequently introduced and salt domes formed.

Carboniferous reservoirs are divided into a layered series of the upper inner platform (shallow zone), lower and upper biohermal series.

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.

The upper part of the reservoir is represented by Early Permian reefs, which were formed over the pre-existing Carboniferous platform.

In the composition of the carbonate massif, the most widespread rocks are of biohermal (43 %) and biomorphic-detrital (38 %) types, there are also organogenic-clastic (3 %) and biochemogenic varieties of limestone (2 %).

Recrystallized carbonate rocks account for 14 %. The central part of the massif is dominated by limestones (70–80 %), dolomites and dolomitized rocks (30–20 %). On the slopes of the massif, the proportion of limestones (up to 30 per cent) and dolomites (20 %) sharply decreases, whereas the proportion of transitional rocks increases (50 %).

At the bottom of the Lower Permian sediments and in the lower part of the Viseian Stage, the strata of shaly limestone with interlayers of mudstones are unstable in thickness and strike-slip.

At the base of the Lower Permian deposits and at the bottom of the Visean stage, layers of argillaceous limestones with interlayers of mudstones are traced, which are not consistent in thickness and bearing.

As a whole, the presence of a wide set of rocks in the Upper Permian deposits of the KOGCF: argillites, organogenic limestones, siltstones, dolomites, carbonate rocks, anhydrites, rock salt, clays, sandstones created conditions for formation of uneven stress-strain state of geological environment, which is necessary to consider at estimations of possibility of occurrence of various scenarios of geodynamic situations (anomalous vertical movements on faults, large subsidence of a terrestrial surface, from tens centimetres to meters, horizontal movements in masses of rocks, natural and technogenic earthquakes) [2].

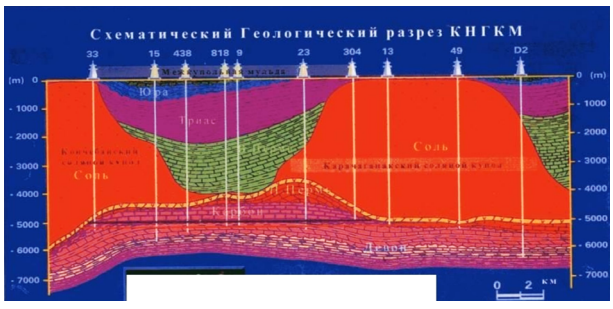

Fig. 1. Typical schematic geological cross-section of the KOGCF

At such scenarios of geodynamic situations, significant sag of earth surface causes horizontal movements of rock massifs in the direction of subsidence trough. In this case on periphery of deposit tensile stresses arise, which can be realized in the form of local seismicity on planes of active faults [2, 3].

Potential geodynamic risk factors in the KOGCF area.

1. The predominant distribution of Lower Permian-Upper Devonian carbonate deposits, more than 1,600 m thick, creates a unique opportunity for the generation of deformation processes, because this type of rocks has a rigid internal structure, increased hardness, brittleness and the ability to fracture under the combined influence of external tangential geodynamic stress and hydrocarbon extraction.

2. Possibility of generation of deformation processes is increased by big sizes of carbonate massif (28 × 17 km) and a large area of active technogenic influence (about 280 km^2), area irregularity of distribution of producing wells with high production rates and lateral spatial and temporal changes in reservoir pressure.

The development in all productive horizons of area heterogeneity of reservoir rocks their increased filtration-capacitive properties of rocks contributes to their uneven area compressibility and accordingly to the uneven subsidence of the earth surface and, consequently, horizontal shifts of rock massifs at the KOGCF.

Paleotectonic processes that have influenced the formation of rock stress anomalies in the geological section and the development of deformation processes as a result of field development may have led to an increase in seismicity along faults.

History of geodynamic monitoring at the KOGCF. At the KOGCF, monitoring of geodynamic processes began in 2002 with the initiation of a local seismological monitoring programme, which continued until the end of 2007 [4].

In 2008, a comprehensive geodynamic monitoring programme was developed, involving the use of Class II levelling of increased accuracy, gravimetric and GPS surveys, and seismological monitoring.

The purpose of the developed program is to obtain information on the development of events of natural-technogenic genesis at the KOGCF, to determine their level, scale and speed of areal spreading.

In accordance with the developed program of works for 2009–2012 a set of preliminary works was performed on the KOGCF, which included field reconnaissance of the location of the projected points of geodynamic monitoring, manufacturing and laying of the points on the territory of the field and implementation of one cycle of monitoring [4].

The basic set of geodynamic monitoring methods included:

- repeated accurate levelling at 135 points;
- repeated high-precision GPS satellite measurements at 41 points;
- repeated high-precision gravimetric measurements at 135 sites;
- seismological monitoring at 7 points.

Surveys were carried out to determine:

- modern fault activity which may be significantly activated by the development processes at the KOGCF;
- amplitude of present-day vertical surface movements, including subsidence of the latter, connected with hydrocarbon extraction, fall of reservoir pressure, irregular area distribution of physical properties of reservoir rocks, and others;

- horizontal movements of rock massifs as a result of intensive subsidence of the earth surface, which may be intensified by local inhomogeneities in plastic rocks (salt-bearing sediments) playing the role of a "grease" in the process of horizontal displacements;

- local deformation processes in productive intervals of the section (consolidation of reservoir rocks), which intensify surface subsidence;

- development 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). In total, from 2009 to 2012, 7 monitoring cycles were performed at the KOGCF [5].

Research results. ***Repeat accurate levelling.*** The first works on laying of geodynamic monitoring points for studying deformation processes in the field were carried out by Geomar company in 2008 [4].

In 2009, the first cycle of high-precision class II levelling 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 accurate levelling revealed a set of local high-intensity anomalies of modern vertical movements of the ground surface along almost all of the repeated levelling lines. The existence of such local anomalous areas is also confirmed by the results of repeated high-precision GPS measurements.

The width of the identified anomalies was about 1–2 km according to the results of repeated levelling and GPS measurements. Amplitude of vertical displacements of points reached 6–7 cm in semi-annual intervals, which are sufficiently large values (Fig. 2).

It seems that identified local high-intensity anomalies may be due to various factors, including residual surface deformations (subsidence of points after their embedding in the ground) and were manifested when comparing subsequent cycles of levelling with the first cycle of levelling.

According to the results of a complex GDM, carried out in 2012, it is noted that active surface elevation occurred mainly until 2011, which led to the reconstruction of the structural plan of the surface and is clearly shown in the profile 1-1, constructed by the results of levelling (Fig. 2).

Subsequent levelling revealed a change in the sign of the direction of movements of the earth surface, elevations were replaced by subsidence on all profiles of levelling. Thus, the maximum amplitudes of modern vertical movements of a terrestrial surface are established in the fold of the KOGCF (Figs. 2 and 5).

Repeated high-precision satellite (GPS) measurements. Repeated high-precision GPS satellite measurements were carried out for the purpose of long-term monitoring of current deformation processes at the KOGCF and nearby areas to determine the current and assess the future geodynamic state of the geological environment [6].

GPS-points at the KOGCF were placed according to the areal system [7]. One part of them was placed directly in the zone of salt domes, another part was placed within the interdome trough and the third one was placed outside the influence zone of field development processes.

The maximum values of the modern ground surface elevation were revealed in the fold 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 period of time for the entire field was +15.8 mm.

The contours of the zone of modern uplift of the earth surface have a sublatitudinal strike, which generally corresponds to the orientation of the carbonate massif at the KOGCF.

The analysis of schemes of area distribution of vectors of horizontal movements GPS-points for the three-years period, allowed revealing several main features:

1. Small values of differently oriented horizontal movements (from 1.5 to 12.0 mm) are recorded in the fold of KOGCF (GPS-points Nos. 12, 13, 17, 40, 41). At the periphery of the arch GPS-points show increasing values of horizontal movements up to 21–31 mm and more (Fig. 3).

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

3. The northern periphery of KOGCF is characterized by the smaller values of vectors and predominantly southern direction of movements with the amplitudes of horizontal movements varying from 6.4 mm (GPS-14) to 30.4 mm (GPS-2, Fig. 3).

4. The reversion of the abrupt change in the vectors of horizontal movement falls on a fault that delimits the northern part of the KOGCF from its arch.

Based on the analysis of the results of the study on the horizontal component of GPS-point movements over the period 2009–2012, two conclusions are drawn:

1. Noticeable deformation processes with amplitudes of horizontal movements up to +20–35 mm, characterizing modern geodynamic state of KOGCF subsurface, are established.

2. The orientation of horizontal movement vectors and their amplitudes suggest the development of irregular com-

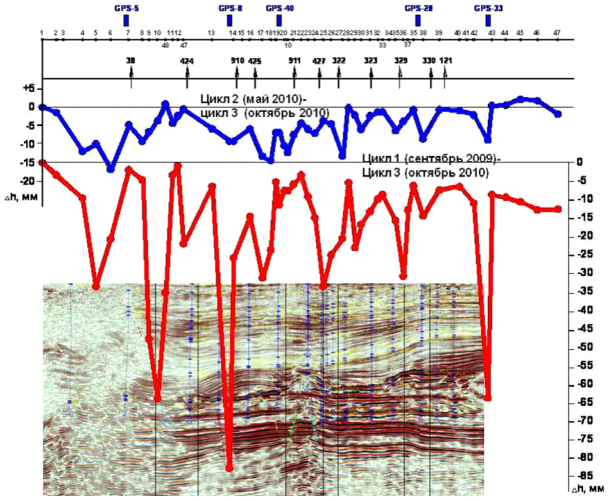

Fig. 2. Modern vertical movements of the earth's surface along Profile 1-1 at different time intervals compared with the depth section

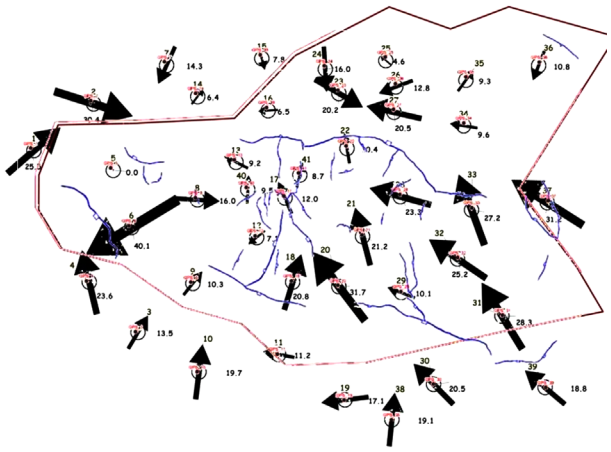

Fig. 3. Schematic comparison of the spatial distribution of the horizontal component of ground motions of the KOGCF from repeated high-precision GPS measurements over a three-year interval with the faulting pattern of the C9 surface seismic survey data

pression in the arc of the developed KOGCF, whereas tensile deformation processes take place at its periphery (Fig. 3).

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

Differentially oriented local anomalies Nos. 1–4, characterizing the stretching zones, form an almost closed ring around the periphery of the projection of the Upper Paleozoic carbonate massif of the KOGCF fold on the ground surface (Fig. 4). The sizes of these local anomalies (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) are 4 × 7–8 km. The magnitude of the positive dilatation, i.e. area stretching, varies in the range of 0.5–1.5 × 10–5.

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

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

The significant value of the compression area in anomaly No. 5 (Fig. 4) framing the extension areas may indicate the existence of active fracture zones along the periphery of the Upper Paleozoic carbonate massif fold at the KOGCF.

In the area of GPS-points 26 and 27 the maximum ground surface subsidence for this field (up to –80 mm during three years) by the data of repeated precision levelling is observed; it is limited by the zones of high gradients of vertical movements (Fig. 5). This zone is characterized by the development of maximum compression stresses.

This geodynamic situation could not but provoke the occurrence of earthquakes. Indeed, there is a correlation between earthquake epicentres and local compression anomaly contours No 5.

Seismological monitoring. To conduct seismological monitoring at the KOGCF a network of seismic stations was created which is optimal both in terms of aperture (geometric shape) and in relation to the systems of oil and gas production facilities and main structural and geological features of the field.

The number and location of stations in the local observation network was determined on the basis of the minimum energy class of expected earthquakes.

As a result of seismological observation, it was established that: a) the territory of the KOGCF is currently characterized by weak seismicity; b) practically all epicentres of earthquakes are clustered along the periphery of carbonate massif (Fig. 6).

Within the period of seismological observations in 2009–2012, 16 local seismic events with magnitudes up to 2 and 1 event located outside the field were registered here. Focal depths of earthquakes range from 5 to 6.5 km, i.e. practically within the interval of productive of the KOGCF. It is obvious,

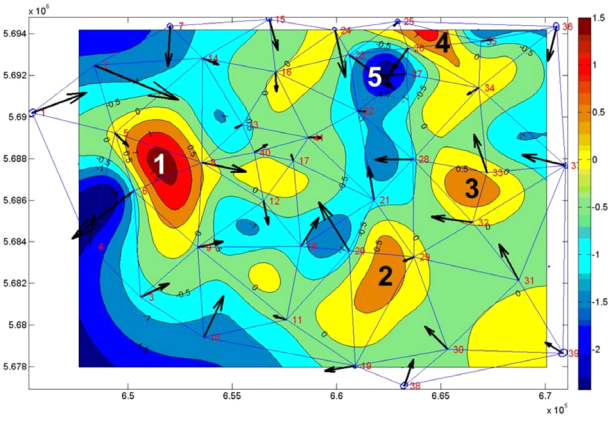

Fig. 4. Schematic of the change in the area of the KOGCF territory compared to the vectors of planned offsets of the GPS-points

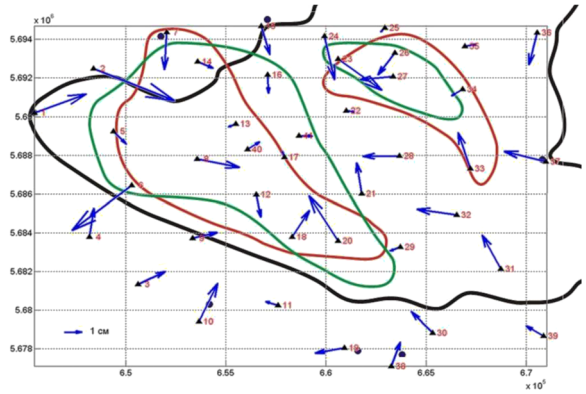

Fig. 5. Schematic of the spatial distribution of horizontal motion vectors of GPS-points in comparison with the zones of land surface subsidence according to repeated accurate levelling and increase in gravity in the territory of KOGCF over a three-year interval:

1 – contour of the zone of relative increase in gravity; 2 – contour of the zone of maximum subsidence of the ground surface

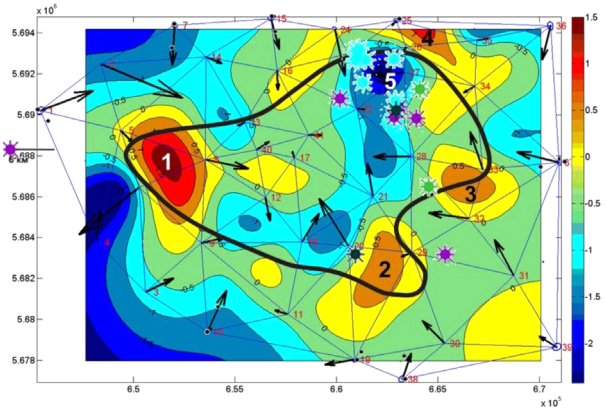

Fig. 6. Scheme of dilatation (area change) of the KOGCF area against the vectors of planned GPS-point displacements against the contour of production well clusters from all development facilities for the time interval between Cycle 1 and Cycle 7, as well as against the epicentres of earthquakes for the period 2009–2012

that there is a spatial relationship between the concentration of seismic events in the north-east of the KOGCF and anomalous deformation activity of this part of the field. The storages of this activity are the faults identified on the surface of C9 horizon.

Significant area irregularity in the position of seismic events' epicentres was detected. Of the total number of events, about 80 % are concentrated within the local compression anomaly No. 5 (Fig. 6).

Of undoubted interest is the fact that the identified seismic and deformation anomalies are located on the territory of the KOGCF under development in the contour of the wells that produced hydrocarbons from all development facilities for the period 2009–2012.

In this regard, it can be assumed that a certain role in the formation of the local compression anomalous zone No. 5 and the occurrence of earthquakes may belong to a technogenic factor, i.e. the process of field development.

In other words, there was a natural anomalous tension in the subsurface in the area of anomaly No. 5. However, the identified deformation and seismic anomalies could not have occurred if there had been no field development.

Field development provoked both intense deformation and weak local seismicity.

The results of seismological monitoring lead to the following conclusions:

1. The spatial confinedness of the earthquake concentration zone to the zone with maximum values of negative dilatation, i.e. anomalous compression, characterized by relative uplift of the ground surface, has been revealed.

2. Peripheral parts of the KOGCF are distinguished by relative lowering of the earth's surface. Seismic sources here are exception rather than a rule.

3. Seismic events are located in the zone of anomalous deformation processes and high gradient changes in the current formation pressure on different development objects.

4. Causes of ground surface movements in the field are caused by natural-technogenic factors. It can be assumed that for the KOGCF, the development of active faults of the identified level and weak seismicity may be a favourable circumstance and a factor that relieves the accumulated stresses due to the production of the field.

Repeated high-precision gravimetric measurements. Repeated high-precision gravity measurements at the KOGCF were made at long-term gravimetric points and aligned with the levelling points. Gravity measurements were made relative to a central gravimetric reference point, which is permanent in all monitoring cycles [8].

A network of long-term gravimetric points, combined with levelling points, was established at the KOGCF in 2009. In 2011 high precision gravimetric measurements were carried out at 118 gravimetric points, which were located along four re-levelling lines [4].

The main factors to be assessed in the study on gravity variations between 2009 and 2012 at the KOGCF field were:

- vertical movements of gravimetric points over time;
- hydrocarbon production;
- deformation processes (compaction of reservoir rocks).

In practice, however, two possible cases are distinguished [9, 10]:

1. Changes in point heights with a constant bedrock mass.

2. Changes in elevation with a simultaneous change (increase or decrease) in bedding rock, which occurs with changes in elevation, hydrocarbon production, injection of chemicals and water to maintain the volume of recoverable product, and compaction of reservoir rocks.

Time-varying hydrocarbon production and substantial lateral variability in reservoir rock properties due to the development of compaction processes have resulted in a complex process of spatial and temporal variations in gravity field.

The multifactorial nature of gravity variations is confirmed by graphs of relations between gravity variation values and relative heights of gravimetric points.

The results of the analysis of repeated high-precision gravity measurements allow the following conclusions to be drawn for the KOGCF:

1. Significant changes in gravity variations over time, reaching 20–30 mGal per year, have been detected.

2. There is a relative increase in total gravity background.

3. In the fold of carbonate massif, i.e., within the field contour, there is relative decrease in gravity variations with respect to slopes of this massif (Fig. 7).

The zone of relative reduction of gravity variations has northwest – southeast extension with characteristic reduction of gravity variations in relation to adjacent areas (section 1 in Fig. 7).

Within this zone, gravity variations are less than 5 mGal, while in adjacent areas these values are increased to +28 + + 30 mGal in the north, +16 mGal in the west, +15 + 24 mGal in the south and +25 + 30 mGal in the east of the KOGCF.

The transition from lowered to higher values of gravity variations occurs through extended zones of high-gradient steps, which spatially coincide with the position of fault zones (Fig. 3).

In addition, a zone of reduced values of gravity anomalies is confined to areas with active hydrocarbon production,

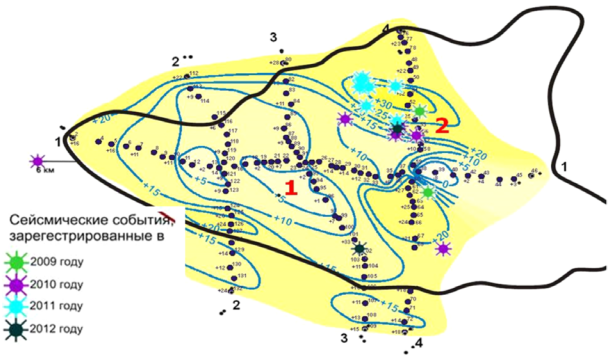

Fig. 7. Schematic of gravity variations from repeated high-precision gravity measurements over a three-year interval in the KOGCF area

where 4865.3 thousand tons were extracted in the period 2009–2012.

4. Gravity variations along the profiles have a block character, which is probably determined by their multifactorial nature – deformation processes in pay zone, influence of hydrocarbon production and fluid injection into productive formations to maintain reservoir pressure and increase oil recovery [11, 12].

Thus, the analysis of dependency network of gravity variations and relative heights of gravimetric points indicates that gravity decreases in time directly above the developed part of the field and is associated, on the one hand, with mass-exchange processes (the rate of withdrawal of non-free condensate and oil, as well as gas, gas re-injection into productive formations to maintain reservoir pressure and enhance oil recovery, advance of the oil-water contact), i.e. with operations on hydrocarbon production, on the other hand, with variation of hydrocarbons in the formation. In combination, these factors lead to deformational processes in pay zone.

Conclusions. In this article, the available material was analysed in advance to find some common features of the occurrence of geodynamic parameters between methods. As a result, the most optimal intervals between measurement cycles were selected, which reflect, with a certain probability, some relatively stable features of evidence of geodynamic parameters for the period of 2009–2012.

In total, four main forms of manifestation of geodynamic events associated with the development of the KOGCF were identified.

Repeated accurate levelling. According to the results of the complex geodynamic monitoring, it was defined that the maximum amplitudes of modern vertical movements of the earth's surface were established within the fold of the KOGCF. It is noted that active surface elevation occurred predominantly before 2011, which led to the reconstruction of the structural plan of this surface.

Subsequent levelling showed a change in the sign of the direction of movements of the earth surface, elevations were replaced by depressions of this surface on all levelling profiles.

Repeated high-precision satellite (GPS) measurements. The contours of the zone of modern surface uplift have a sub-latitudinal strike, which generally corresponds to the orientation of the projection of the carbonate massif on the ground surface at the KOGCF. At the same time, the maximum values of modern surface uplift have been detected above the fold of the KOGCF (up to +111 mm).

Area distribution of horizontal movements vectors allowed revealing the following features:

1. Small values of differently oriented horizontal movements (with amplitude from 1.5 to 12.0 mm) were recorded in the fold of the KOGCF. At the periphery of the arch, an increase in the values of horizontal movements up to 21–31 mm and more was observed. In the north-eastern part of the fold

projection Upper Paleozoic carbonate massif on the ground surface revealed a large arc-shaped compression anomaly (No. 5), in which the horizontal vectors of movements are directed towards each other.

2. Horizontal movement amplitudes for the southern and northern periphery of the KOGCF are characterized by a wide range of variations, with larger variations for the southern part (from 11.2 to 40.1 mm) and smaller variations for the northern part (from 6.4 to 30.4 mm).

3. The existence of active faulting along the periphery of the Upper Paleozoic carbonate massif fold at the KOGCF is assumed.

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

Seismological monitoring. The spatial confinedness of the zone of earthquake epicentres concentration to the zone with anomalous compression, characterized by relative uplift of the day surface, is revealed. Of the total number of events (about 80 %) are concentrated within the local compression anomaly No. 5 identified in the north-eastern part of the carbonate massif and are confined to wells actively producing hydrocarbons from all development facilities, where anomalous deformation processes and high-gradient changes in the current reservoir pressure are manifested.

Consequently, the development of the field provoked the occurrence of both intense deformation and weak local seismicity. Thus, it is possible to speak about natural-technogenic genesis of seismicity in the fold of the carbonate massif at the KOGCF.

Peripheral parts of the KOGCF are distinguished by practically aseismic regime.

Repeated high-precision gravimetric measurements. The results of the analysis of repeated high-precision gravity measurements indicate that there is a zone in the fold of the carbonate massif, i. e., within the field contour, where there is a relative decrease in gravity variations relative to the slopes of the massif. Spatially, this zone coincides with areas with active hydrocarbon production,

Direct influence on the formation of the zone had, on the one hand, mass-exchange processes (non-free condensate and oil, as well as gas production rate, gas reinjection into productive layer to maintain reservoir pressure and increase oil recovery, advance of VPC), i. e. hydrocarbon production operations, on the other hand, variability of reservoir rock properties at the KOGCF. In sum, these factors led to deformation processes in pay zone.

Thus, the results of geodynamic monitoring at the KOGCF, for the first time for the Pre-Caspian Basin, provided convincing evidence of notable seismo-deformation processes in the subsurface associated with hydrocarbon production.

Use of geophysical and geodesic methods, in a complex has given the chance to fix natural-technogenic events in the form of earthquakes, activization of breaks, deformations of a ground surface under the influence of vertical and horizontal movements of rocks masses.

In turn, the obtained conclusions confirm the necessity and binding of geodynamic monitoring in order to study and assess the possibility of various scenarios of geodynamic situations associated with the development of hydrocarbon field.

In this regard, this article attempts to outline trends and tendencies so that the next stage of monitoring could be more reasonably investigated the relationships between the continuously changing in time geodynamic state of the bowel and field geological processes.

In order to mitigate potential geodynamic risk factors at the KOGCF, there is an urgent need to implement the following:

1. Geodynamic zoning of the KOGCF area taking into account the available geological and geophysical and field data and identifying potential areas of high geodynamic risk, including:

- areas of anomalous deformation of the geoenvironment into the fault zones;
- areas of abnormal subsidence of the ground surface in zones of high hydrocarbon production;
- areas of abnormal horizontal displacement of rock mass;
- areas of potential manifestation of seismic events, especially where there is a change in the vectors of horizontal movements and dilation processes for compression.

2. Calculation and subsequent analysis of components of stationary stress field anomalies – potential zones of induced earthquakes, zoning of the KOGCF territory on this basis.

3. Study on possible mechanisms of interconnection of deformation, seismic and geodynamic processes of natural and anthropogenic origin in conditions of long-term operation of the field with explanation of spatial and temporal changes in monitoring data.

4. Modelling of complex manifestation of effects from the volume of hydrocarbon production and deformation of reservoir rocks using the data on variations of gravity field and ground surface subsidence.

The combination of methods for studying the above-mentioned factors of potential geodynamic risk at the KOGCF will undoubtedly provide sufficient information to explain the causes of seismic deformation processes in this field. This will not only make it possible to assess the seismic deformation status of the hydrocarbon fields under development, but will also provide a basis for prediction the consequences of long-term exploitation of the field.

References.

1. Mashkova, E. A., & Muratov, A. T. (2021). Geological structure and formation conditions of oil-bearing subsalt complex of Karachaganak field. *Bulatov readings,* 64-66. ISSN: 2587-8913.

2. Nesterenko, M. Y., & Tsvyak, A. V. (2017). Technogenic geodynamic processes at hydrocarbon fields under development. *Bulletin of the Orenburg Scientific Centre of the Ural RAS Department*, 4-8.

3. Zemtsova, A. V., & Baygurin, Z. D. (2012). On development of geodetic works on geodynamic forecasting polygons in the Republic of Kazakhstan. *Proceedings. Plenary meeting. Interexpo GEO-Siberia*, *243*.

4. Shevelyova, A. (2010). Integrated geodynamic monitoring and risk assessment of occurrence of seismic deformation processes related to development of raw hydrocarbon deposits. *SPE Caspian carbonates technology conference,* 1-8. https://doi.org/10.2118/139949-MS.

5. Abetov, A. E., & Kudaibergenova, S. S. (2021). Integrated research of suffosion and karst processes in the oil-gas-condensate field Karachaganak by geological and geophysical and geodesic methods. *Proceedings of the National Academy of Sciences of the Republic of Kazakhstan. Series of Geology and Technical Sciences*, *5*(449), 14-22. https://doi.org/10.32014/2021.2518-170X.93.

6. Zemtsova, A. V., & Zhantasova, S. (2012). Monitoring using GPS at the geodynamic site of an oil and gas field. Int. conf. *Innovative technologies of geospatial data collection and processing for natural resources management*, 112-118.

7. Abetov, A. E., & Kudaibergenova, S. S. (2021). Creation of geodynamic polygons and technologies of geodynamic monitoring in hydrocarbon fields. *Vestnik KAZNRTU, 143*(2), 3-13.

8. Nazirova, A. B. (2018). Methods for assessing gravity anomalies in oil and gas fields using information technologies. *Bulletin of KBTU. Physical, mathematical and technical sciences, 3*, 118-128. Retrieved from https://kbtu.edu.kz/images/vetnikn-2018-3.

9. Lee, L. V., & Sidorov, V. A. (2019). Aspects of geodynamic safety in the development of oil and gas fields. *Exploration of shallow oil and gas strata in Kazakhstan Proceedings of KONG based on the reports of the V-International Geological Conference "AtyrauGeo-2019", 7*, 185-202. 86. ISBN 978-601-7837-07-5.

10. Koshim, A. G., & Akhmedenov, K. M. (2015). Technogenic relief formation in the area of Karachaganak field. *Oil and Gas*, *1*(85), 79.

11. Akhmedenov, K. M., Iskaliev, D. Zh., & Petrishev, V. P. (2014). Karst and Pseudokarst of the West Kazakhstan (Republic of Kazakhstan). *International Journal of Geosciences, 5*, 131-136.

12. Lee, L. V., & Kudaibergenova, S. S. (2018). Study of Suffosion and Karst phenomena by complex geophysical methods. *Proceedings of the 14th EAGE scientific and practical conference*, *2018*, 1-11. Retrieved from https://www.earthdoc.org/content/papers/10.3997/2214-4609.201800565.

Проблеми й завдання екологічної безпеки та геодинамічний моніторинг на Карачаганакському нафтогазоконденсатному родовищі

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Мета. Оцінка екологічної безпеки й геодинамічний моніторинг на Карачаганакському нафтогазоконденсатному родовищі (КНГКР), розвіданому на північному борту Прикаспійської западини з метою прогнозування наслідків довгострокової експлуатації цього родовища.

Методика. Синтез і системний аналіз літературних і фондових матеріалів досліджень з екологічних ризиків та геодинамічного моніторингу, комплекс методів, що охоплює повторне точне нівелювання, GPS-вимірювання, високоточний гравіметричний і сейсмологічний моніторинг.

Результати. На якісному й кількісному рівні обґрунтована активізація вертикальних і горизонтальних рухів масивів гірських порід, зміни в полі локальних гравітаційних аномалій, почастішання землетрусу, гіпоцентри яких перебувають на глибинах, що можна порівняти з інтервалами розробки родовищ. Намічені тренди й тенденції дослідження співвідношення між геодинамічним станом надр, що безперервно змінюються в часі, і промислово-геологічними процесами. Усі ці прояви так чи інакше знаходять прояви в екологічних ризиках району родовища, що експлуатується. У висновках рекомендується проведення комплексу заходів щодо зниження екологічних ризиків.

Наукова новизна. Результати геодинамічного моніторингу на КНГКР для північного борту Прикаспійської западини вперше дозволили отримати переконливі свідчення на користь помітних сейсмодеформаційних процесів у верхній частині земної кори під впливом процесів видобутку вуглеводнів.

Практична значимість. Отримані у роботі висновки підтверджують необхідність і обов'язковість проведення геодинамічного моніторингу з метою вивчення та оцінки можливостей виникнення різних сценаріїв геодинамічних ситуацій, пов'язаних із розробкою родовищ вуглеводнів, також рекомендовані заходи з метою нівелювання факторів потенційного геодинамічного ризику на території КНГКР.

Ключові слова: *нафтогазоконденсатне родовище, геодинамічний моніторинг, високоточні гравіметричні та GPS-виміри, нівелювання, сейсмологія*

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