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Research Article

FEATURES OF ENGINEERING-GEOLOGICAL CONDITIONS ON THE EXPOSED BOTTOM OF THE ARAL SEA

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ABSTRACT
Industrial development of the exposed bed of the Aral Sea and the adjacent territories of the Southern Aral Sea region is accompanied by increasing anthropogenic impacts on the geological environment. Deep drilling and gas-production infrastructure within the Muynak–Surgil area are being developed under conditions of a thick sedimentary cover, heterogeneous marine, alluvial–proluvial and aeolian deposits, a variable hydrogeological regime, and the fault-block structure of the Turan Plate. The objective of this study is to assess the engineering-geological and geodynamic prerequisites for potential induced seismicity during the development of gas reservoirs on the exposed bed of the Aral Sea and in adjacent parts of the Southern Aral Sea region.
The study synthesizes published geological, geophysical, seismological and remote-sensing materials, data on the geological and lithological structure of the Muynak District, results of engineering-geological investigations conducted in 2023–2025, and information on regional and international cases of seismicity spatially and temporally associated with hydrocarbon extraction and fluid injection. The mechanisms considered include reservoir-pressure depletion, reservoir compaction, changes in effective stress, and possible reactivation of pre-existing faults. The 1976 and 1984 Gazli strong-earthquake sequence and a local series of events in Bukhara Region in May 2026 are analysed as regional examples requiring differentiation among natural, triggered and induced factors.
Desiccation of the Aral Sea and the associated reduction in surface-water loading are treated as an additional regional geodynamic background that should be considered when interpreting present-day vertical movements, but not as a direct mechanism of potential induced seismicity. The available open data do not confirm a direct causal relationship between gas extraction and seismic events in the Muynak–Surgil area. The need for an integrated monitoring system is substantiated, combining local seismological observations, GNSS, satellite InSAR, monitoring of reservoir and bottom-hole pressures, production and fluid-injection volumes, and geomechanical modelling. The proposed approach can be used to assess geodynamic stability and improve the safety of industrial development on the exposed bed of the Aral Sea.

Keywords: *Exposed Bed of The Aral Sea; Southern Aral Sea Region; Muynak; Surgil; Gas Extraction; Engineering-Geological Conditions; Induced Seismicity; Triggered Seismicity; Reservoir Pressure; Insar; Geomechanical Monitoring*.

INTRODUCTION
Oil and gas field development is among the most extensive forms of anthropogenic impact on the upper crust. Hydrocarbon and formation-water extraction, pressure maintenance by fluid injection, construction of deep wells, and long-term production from reservoir horizons can alter pore pressure and the stress–strain state of the rock mass. Under certain geological and tectonic conditions, these changes are accompanied by reservoir compaction, land subsidence, fault reactivation, and seismic events [1–4].
Contemporary literature distinguishes natural, triggered and induced seismicity. Natural earthquakes are caused by regional tectonic processes. Triggered events are those in which accumulated natural tectonic

energy is released earlier because of a relatively small external perturbation. Induced events result from stress and pore-pressure changes caused by human activity. Differentiating these types of seismicity requires an integrated assessment of temporal association with industrial operations, distance from the source of perturbation, focal depth, fault geometry, focal mechanism, and calculated Coulomb-stress changes [3, 5].

Gas extraction affects the geological environment mainly through reservoir-pressure depletion. As fluid pressure decreases, effective stress in the rock skeleton increases and may cause reservoir compaction. Deformation of the productive interval is transferred to the overburden and may in some cases appear as regional or local land subsidence. At the same time, the balance between normal and shear stresses on existing faults changes. If a fault is close to failure, an additional stress perturbation may promote slip [1, 4, 6].

Not all hydrocarbon production causes seismicity. Most producing fields are not accompanied by felt earthquakes. A seismic response depends on a combination of factors: the volume and rate of fluid extraction or injection, reservoir-pressure changes, mechanical properties of reservoirs and seals, the presence of critically stressed faults, hydraulic communication between formations, and the natural tectonic background. Therefore, spatial coincidence between a gas field and earthquake epicentres does not by itself prove an anthropogenic origin [2, 5, 6].

One of the best-known examples of seismicity associated with gas-field development is Groningen in the Netherlands, where prolonged reservoir-pressure decline was accompanied by reservoir compaction, surface subsidence, and an increase in seismic events. This case demonstrated the need for joint analysis of production parameters, geomechanical models, and seismic catalogues. Other widely discussed cases include the Lacq field in France, Ekofisk in the North Sea, and several sites in the United States where industrial extraction or fluid injection was accompanied by changes in the seismic regime [7–9].

Of particular interest for Central Asia is the Gazli sequence of strong earthquakes in 1976 and 1984. Three events with magnitudes of approximately 7 occurred within the Turan Platform, which had previously been regarded as relatively weakly seismic. The scientific literature discusses both a natural tectonic origin and a possible influence of long-term production from the Gazli gas field. Competing interpretations prevent Gazli from being regarded as an unequivocally proven example of induced seismicity. Nevertheless, the area is an important regional analogue demonstrating the need to consider interactions between natural tectonic stress and anthropogenic changes in the geological environment [10–14].

The Muynak–Surgil area is located in north-western Uzbekistan, within the Southern Aral Sea region and the Ustyurt petroleum province. Geological exploration, deep drilling, and gas-field development are expanding in this area. The Muynak structure was prepared for deep drilling using modern three-dimensional seismic surveys. These activities confirm the continued industrial development of deep hydrocarbon-bearing complexes and the relevance of assessing their impact on the geological environment [15, 16].

Open-source materials do not provide sufficient information on long-term reservoir-pressure dynamics, volumes of gas and formation-water withdrawal, fluid-injection operations, surface deformation, or local microseismicity in the Muynak–Surgil area. Consequently, a direct causal relationship between gas extraction and individual seismic events cannot currently be established. The scientifically justified task is not to assert the existence of induced seismicity, but to identify potential prerequisites, assess data gaps, and develop an instrumental framework for testing the hypothesis.

An additional regional feature is large-scale surface unloading caused by desiccation of the Aral Sea. Satellite radar interferometry and geodynamic modelling have shown that the loss of a substantial water mass was accompanied by broad regional uplift and a viscoelastic response of the lithosphere and asthenosphere [17]. This process is not considered here as a direct cause of anthropogenic seismicity. However, it may act as a background factor modifying the regional stress field and should therefore be considered when interpreting present-day vertical movements.

Thus, the relevance of the study lies in the need to move from qualitative assumptions to an integrated assessment of the geodynamic state of gas-producing territories in the Southern Aral Sea region. Such an assessment should integrate geological structure, tectonic faults, production parameters, local seismicity, surface deformation, and hydrogeological changes. This approach is required to improve industrial and seismic safety, support sustainable field development, and provide a sound basis for geological-risk management.

The aim of this study is to assess the engineering-geological and geodynamic prerequisites for potential induced seismicity in the Muynak–Surgil gas-producing area through joint analysis of the geological environment and regional and international analogues, and to substantiate the required instrumental monitoring system. The scientific novelty lies in considering gas production and regional unloading caused by desiccation of the Aral Sea as processes operating at different scales whose contributions must be separated when interpreting present-day deformation.

ENGINEERING-GEOLOGICAL CONDITIONS OF THE STUDY AREA. The study area includes the Muynak District, adjacent parts of the exposed bed of the Aral Sea, and gas-bearing structures of the southern Aral Sea region. Regionally, it lies within the Turan Plate, which is characterized by a thick sedimentary cover overlying a folded Paleozoic basement. The present-day structure is defined by platform depressions, local anticlinal uplifts, and faults of different orders, some of which may retain geodynamic activity under the current stress field [18].

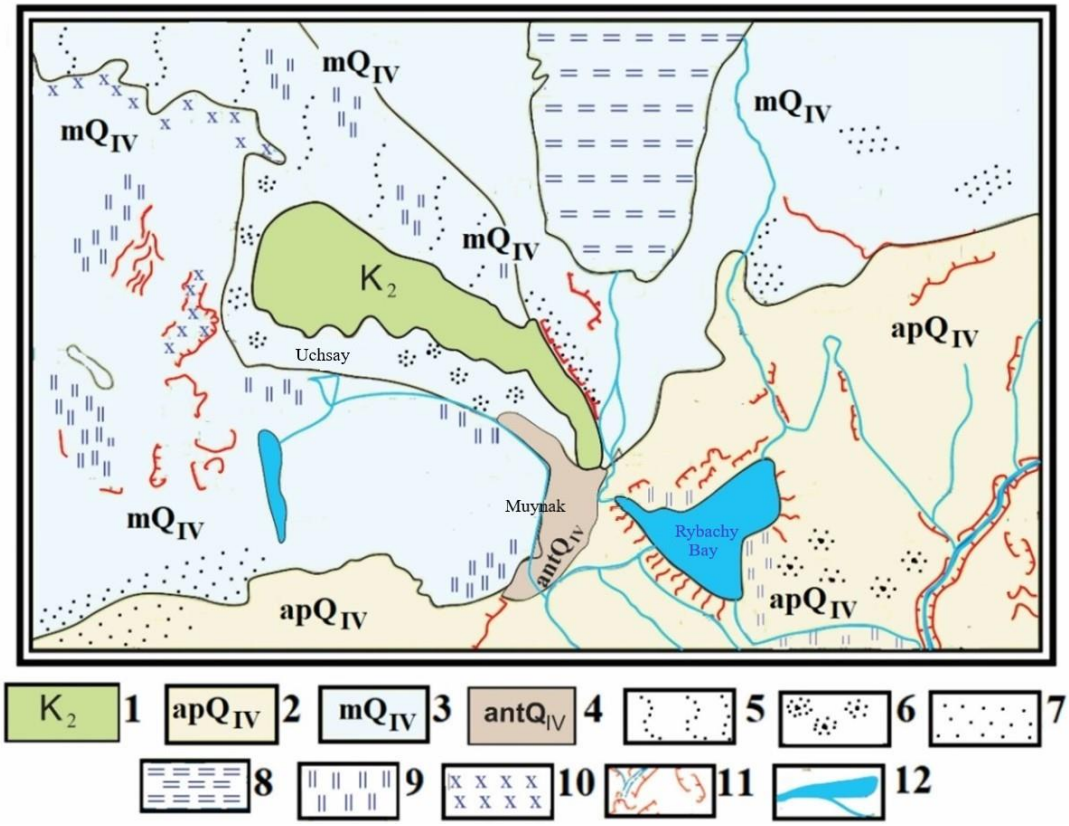


Fig. 1. Schematic geological–lithological map of the Muynak District (based on the authors' field investigations; scale 1:100,000; 2026): *1 – Upper Cretaceous deposits; 2 – alluvial–proluvial deposits; 3 – modern marine deposits; 4 – anthropogenic and fill ground; 5–7 – sands of different morphology and genesis;*
8 – waterlogged areas; 9 – solonchaks; 10 – chemogenic deposits; 11 – erosional landforms and dry channels; 12 – water bodies.

The Muynak District occupies a transitional position between the Southern Aral depression, the Ustyurt Plateau, and the Amu Darya delta plain. This setting has produced a complex combination of structural-denudational, accumulative, alluvial-deltaic, marine, and aeolian landforms. A local structural-denudational upland with elevations mainly between 74 and 85 m is distinguished within the Muynak Peninsula. Its slopes and exposures contain Upper Cretaceous ferruginous and gypsiferous sandstones, chalk-like marls, and grey to greenish-grey clays. An ancient abrasion escarpment is traced in the eastern part of the peninsula, separating bedrock continental formations from young marine sediments of the former Aral Sea water area (Fig. 1) [19–21].

Quaternary formations of different genesis are widespread in the upper part of the section. Marine deposits of the exposed seabed consist of silts, sandy loams, loams, and fine-grained sands characterized by elevated contents of readily soluble salts, heterogeneous composition, and high susceptibility to deflation. Alluvial–proluvial deposits of the Amu Darya delta consist of alternating sandy loams, loams, and sands whose thickness and grain-size composition vary with position relative to palaeochannels, floodplain areas, and deltaic depressions.

Upper Cretaceous clays form relatively persistent horizons in the lower part of the engineering-geological section. They are predominantly water-saturated and occur in a semi-solid or stiff-plastic state. Bulk density ranges from 1.97 to 2.02 t/m³, dry density from 1.53 to 1.61 t/m³, porosity reaches 41.4–44.2%, and the degree of saturation approaches unity. These properties indicate potential deformation sensitivity of the clays to changes in hydrogeological conditions and the stress state of the rock mass [22, 23].

Aeolian sands are widespread on the marine accumulative plain and are represented mainly by fine-grained and silty varieties. Their natural density is 1.78–1.87 t/m³, porosity is approximately 39–41%, and the degree of saturation ranges from 0.51 to 0.67. The prevalence of fine and silty fractions accounts for the high mobility of these deposits and their low resistance to wind action. Anthropogenic and fill ground, generally 1–3 m thick, also occurs within settlements, industrial sites, roads, and pipeline corridors.

The hydrogeological conditions are formed within the Southern Aral artesian basin. The section contains Upper Pliocene–Quaternary, Jurassic–Paleogene, and Paleozoic aquifer systems. During field observations in 2023–2025, groundwater was encountered mainly at depths of 3.8–4.7 m. Allowing for seasonal fluctuations, the calculated highest groundwater level may reach 2.8–3.7 m below the ground surface. Groundwater mineralization is approximately 1.9 g/L, with sulfate ions predominating.

Changes in the hydrogeological regime can affect the upper part of the section. Groundwater decline may be accompanied by desiccation and additional compaction of certain soils, whereas local groundwater rise and saturation reduce strength and increase deformability. At gas-production infrastructure sites, these processes should be considered together with pressure changes in deep productive horizons [24].

According to the general seismic zoning of Uzbekistan, the study area lies predominantly within a zone of intensity 7. Present-day seismic activity in the Republic of Karakalpakstan is generally lower than in the active mountainous regions of eastern and south-eastern Uzbekistan. Nevertheless, the platform setting does not exclude deep faults and local zones of elevated tectonic stress.

The Gazli sequence of strong earthquakes in 1976 and 1984, which occurred in the central part of the Turan Plate, is of fundamental importance for regional assessment. It showed that strong events may also occur within platform areas previously considered relatively weakly seismic. The causes of the Gazli earthquakes remain debated: in addition to natural tectonic factors, a possible influence of long-term gas-field development and associated stress changes in the geological environment has been proposed.

Gas-bearing complexes of the Southern Aral Sea region are mainly associated with Mesozoic, including Jurassic, deposits. The great depth of the productive horizons, multilayered sedimentary cover, thick clay seals, and possible faults create a complex pathway for transmitting deformation from the reservoir to the overburden and ground surface. During prolonged gas withdrawal, reservoir-pressure depletion may increase effective stress, compact reservoir rocks, and redistribute stress in the surrounding rock mass. Where hydraulic or mechanical connections with faults exist, these changes may extend beyond the reservoir boundary.

Thus, the geological environment of the Southern Aral Sea region combines a thick sedimentary cover, local platform structures, heterogeneous Quaternary deposits, variable hydrogeological conditions, and increasing anthropogenic loading. These features provide the basis for an integrated analysis of the present geodynamic state and the possible influence of gas extraction on the stress–strain state of the rock mass (Table 1).

Table 1: Generalized engineering-geological characteristics of the main ground types

Parameter	Upper Cretaceous clays	Aeolian sands	Engineering-geological significance
Bulk density, t/m³	1.97–2.02	1.78–1.87	Characterizes density state and potential compressibility
Porosity, %	41.4–44.2	39–41	Elevated deformation sensitivity
Degree of saturation	0.98–1.00	0.51–0.67	Influence of the hydrogeological regime on strength and deformability
Predominant state	Semi-solid to stiff-plastic	Fine-grained and silty	Clays are sensitive to saturation changes; sands to deflation and differential settlement

Note. Generalized from engineering-geological investigations in the Muynak District conducted in 2023–2025.

MATERIALS AND METHODS

The study is based on a synthesis of geological, engineering-geological, hydrogeological, geophysical, and seismological materials for the Southern Aral Sea region. The source base included published geological and tectonic maps, general seismic-zoning materials for Uzbekistan, results of engineering-geological investigations in the Muynak District, remote-sensing data, and scientific publications on induced and triggered seismicity associated with oil and gas field development [3, 8, 18, 24].

Particular attention was paid to comparing natural and anthropogenic factors capable of influencing the present stress–strain state of the geological environment. The analysis covered the regional tectonic setting, thickness and structure of the sedimentary cover, depth of productive horizons, physical and mechanical properties of the principal ground types, aquifer-system positions, and features of the current hydrogeological regime.

The upper part of the section was characterized using laboratory measurements of density, porosity, moisture content, degree of saturation, and plasticity of Cretaceous clays, as well as density, grain-size distribution, and saturation of aeolian sands. These data were used to assess the deformation sensitivity of the ground and the possible transmission of deep deformation to the ground surface.

The seismological component included analysis of published information on seismic events in western Uzbekistan and adjacent territories. Interpretation considered magnitude, focal depth, epicentral position relative to gas-production facilities and known tectonic structures, and temporal association with stages of industrial development. The strong Gazli earthquake sequence was treated as a regional analogue, but not as unequivocal proof of an anthropogenic origin of seismicity [3, 5]. A separate dataset included six events recorded in the Karakul and Jondor districts of Bukhara Region on 20–22 May 2026; their time, magnitude, focal depth, and macroseismic intensity were compared using reports of the Republican Center for Seismic Prog-nostic Monitoring of the Ministry of Emergency Situations of the Republic of Uzbekistan [20].

A set of diagnostic criteria was applied to evaluate the plausibility of an anthropogenic origin, including spatial proximity to extraction or injection facilities, temporal association with operational changes, correspondence of focal depth to productive horizons or connected faults, changes in background seismicity, surface deformation, and the availability of an alternative natural tectonic explanation. No single criterion was regarded as sufficient on its own [7–14].

Published data from Gazli, Kumdag, Groningen, Lacq, Ekofisk, and other sites where seismicity was spatially or temporally associated with hydrocarbon production or fluid injection were analysed as comparative analogues. Comparisons considered productive-horizon depth, reservoir-pressure changes, injection operations, surface-deformation magnitude, focal depth, and the level of evidence for an induced origin [21].

Modern capabilities of satellite radar interferometry were considered in assessing possible surface deformation. Sentinel-1 data and InSAR time-series methods can be used to identify subsidence or uplift zones within gas-production areas. Interpretation requires separating local field-related effects, seasonal moisture changes, settlement of anthropogenic ground, hydrogeological fluctuations, and regional uplift associated with reduced water loading from the Aral Sea.

The geomechanical interpretation was based on the effective-stress concept. Reservoir-pressure decline during gas withdrawal was treated as a factor increasing effective load on the rock skeleton, compacting the reservoir, and redistributing stress in the surrounding rock mass. If a fault is close to limiting equilibrium, such redistribution may affect its stability. Where fluid injection occurs, an additional mechanism is increased pore pressure and reduced effective normal stress on the fault plane [17].

Desiccation of the Aral Sea and the associated reduction in surface loading were considered an additional regional geodynamic factor. This process was not equated with a direct source of induced seismicity, but was taken into account when interpreting present-day vertical movements and possible changes in the regional stress field.

Because open information on reservoir-pressure dynamics, gas withdrawal, formation-water production, injection regimes, and local microseismicity in the Muynak–Surgil area is limited, the study is analytical in nature. Its purpose is to identify potential engineering-geological and geodynamic prerequisites and to define the data required for subsequent instrumental testing of the hypothesis that gas production may influence the seismic regime of the Southern Aral Sea region.

RESULTS AND DISCUSSION

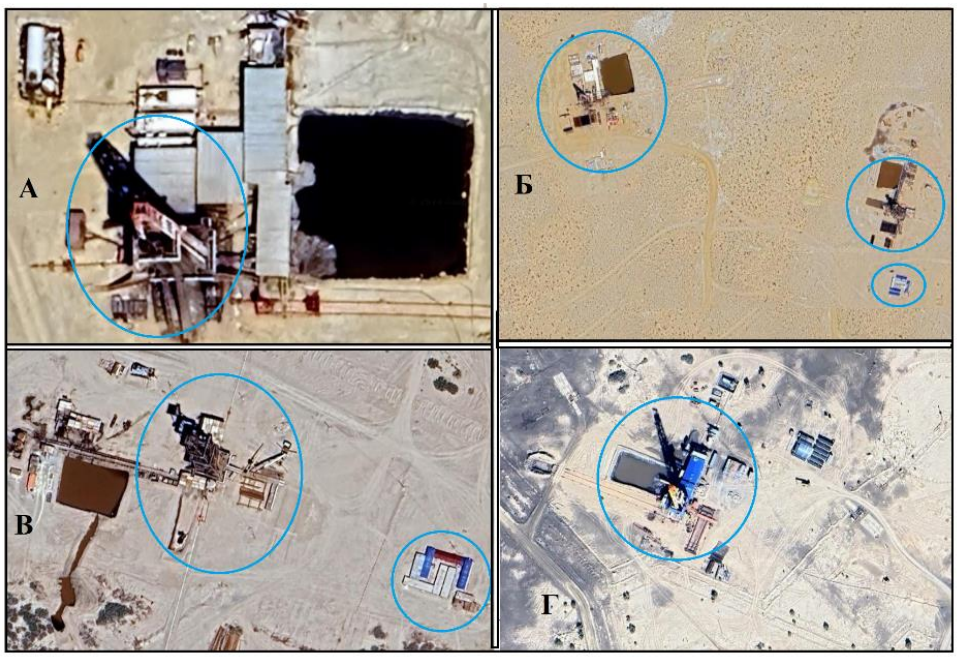


Fig. 2. Gas-production and industrial facilities in the Muynak–Surgil area: a, b – facilities near Karavulbazar; c, d – facilities on the exposed bed of the Aral Sea (Camp Surgil site). Satellite basemap source: *Google Earth [19].*

Anthropogenic loading of the geological environment in the Muynak–Surgil gas-producing area. The analysis shows that present-day development of gas resources in the Southern Aral Sea region is taking place under a complex combination of platform tectonics, a thick sedimentary cover, deeply buried productive horizons, and an intensely transformed natural environment. Gas-production facilities in the Muynak–Surgil area create local zones of anthropogenic impact associated with deep-well drilling, extraction of gas and formation fluids, and construction of production sites, pipelines, and auxiliary infrastructure (Fig. 2) [15, 16, 19].

Unlike near-surface disturbances caused by construction, the principal geodynamic impact of gas-reservoir development is associated with pressure changes in the productive formation. Gas withdrawal reduces pore and reservoir pressures, thereby increasing the effective load carried by the reservoir-rock skeleton. If the reservoir is sufficiently compressible, pore-space compaction and thinning of the productive interval occur. Reservoir deformation is transmitted to the overburden and may appear as surface subsidence or as a more complex combination of vertical and horizontal displacements.

The magnitude and spatial pattern of deformation depend on reservoir depth and thickness, mechanical properties of the reservoir and seal, pressure-decline rate, productive-layer geometry, and the presence of faults. Even relatively small absolute deformation may be important for faults already close to failure. In that case, field operations do not supply the total energy of the seismic event but modify the stability conditions of an existing fault zone.

For the Muynak–Surgil area, the principal limitation is the lack of publicly available detailed time series of reservoir pressure, gas and formation-water production, and possible fluid-injection operations. Quantitative assessment of anthropogenic stress changes is therefore not currently possible. Nevertheless, deep drilling, long-term gas production, and the complex structure of the sedimentary basin make geomechanical monitoring a necessary component of industrial safety.

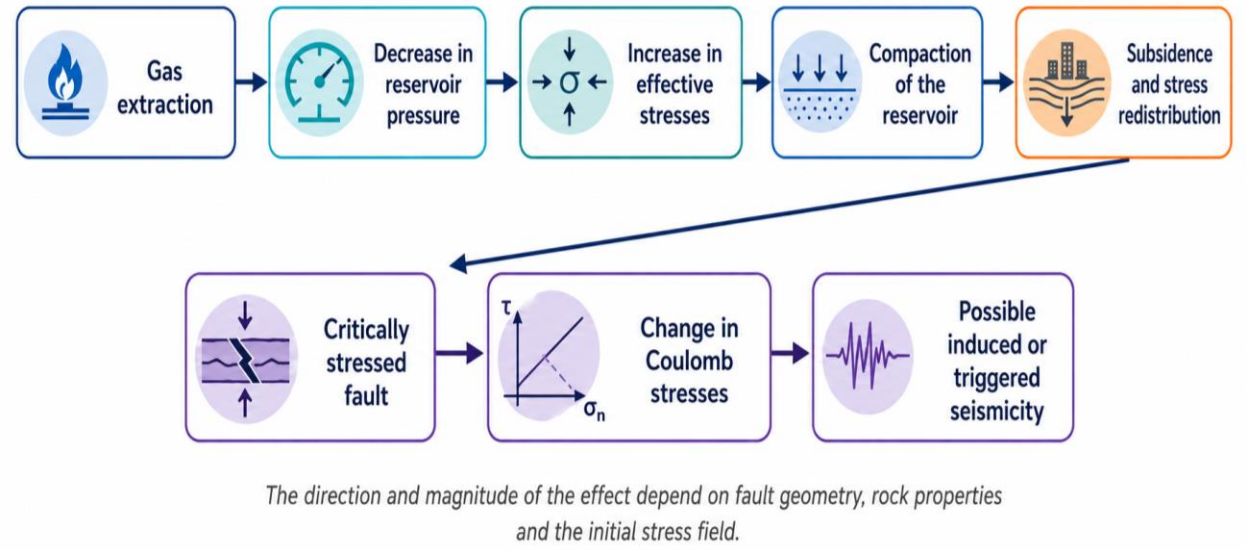


Fig. 3. Conceptual model of changes in the stress–strain state of the geological environment during gas-reservoir development (compiled by the authors after [1, 4, 6]).

Geomechanical prerequisites for potential induced seismicity. The main mechanism of a possible seismic response to gas-reservoir depletion is redistribution of effective stress. As reservoir pressure declines, the stress carried by the mineral skeleton increases. This promotes reservoir compaction and alters the stress state both within the reservoir and in the surrounding rock mass. Additional stress concentrations may develop at reservoir boundaries and near structural heterogeneities [1, 4, 6].

The effect on a fault depends on its orientation relative to the regional stress field. In some settings, pressure decline may increase fault stability by increasing normal compression, whereas in other geometries redistribution of shear and normal stresses may bring the fault closer to slip. Reservoir-pressure decline therefore does not inevitably increase seismicity; the decisive factors are fault geometry, the initial stress state, and the hydromechanical properties of the rocks [1, 4, 6].

Where water or other fluids are injected, the mechanism differs. Increased pore pressure reduces effective normal stress on the fault plane and lowers shear resistance. Pressure may propagate through permeable formations and fault zones to considerable distances from the injection well. Therefore, spatial separation between an epicentre and an industrial facility does not exclude a possible connection if a hydraulically transmissive structure links them (Fig. 3) [4, 5, 25].

The marked vertical and lateral heterogeneity of the sedimentary cover must also be considered in the Southern Aral Sea region. Alternation of reservoir units and low-permeability clay strata may both restrict pore-pressure propagation and localize stress. Thick clay seals reduce the probability of direct hydraulic communication with shallow horizons but do not preclude mechanical transmission of deformation.

Water-saturated Cretaceous clays and weakly consolidated Quaternary deposits in the upper section are not direct sources of deep seismicity, but they may amplify the engineering consequences of surface deformation. Their high porosity, saturation, and deformation sensitivity promote differential settlement, particularly at industrial sites, pipelines, and fill foundations. Geodynamic-risk assessment should therefore include not only seismic events but also slow deformation processes.

Natural, triggered, and induced components of seismicity. The results show that potential seismicity in a gas-producing area cannot be explained by a single factor. The Turan Plate is traditionally regarded as a relatively stable platform region, but its sedimentary cover and basement are dissected by faults, and the present stress field is governed by interacting regional tectonic processes [3, 26, 27].

Under these conditions, three fundamentally different situations are possible. First, a seismic event may be natural and unrelated to industrial activity. Second, an anthropogenic pressure or stress change may accelerate an event that would otherwise have occurred naturally at a later time; this is triggered seismicity. Third, industrial activity may create a critical stress change without which the event would not have occurred during the period considered; this is induced seismicity.

Table 2: Diagnostic criteria for natural, triggered, and induced seismicity

Criterion	Natural	Triggered	Induced
Temporal relationship with operations	Absent	A delay after an operational change is possible	Pronounced relationship with production/injection
Spatial relationship	Controlled by tectonic zones	The fault may extend beyond the facility boundary	Clustering near the facility or a hydraulically connected fault
Focal depth	Corresponds to the regional seismogenic layer	May be deeper than the productive formation	Often close to the formation or a connected fault
Energy source	Tectonic	Predominantly tectonic; an anthropogenic factor triggers the event	Pressure and stress changes are essential to event occurrence
Required data	Regional catalogue and tectonics	Catalogue, focal mechanisms, production time series	Production data, pressure, InSAR/GNSS, local network

Note. Classification should be based on a combination of independent criteria [3, 5, 6].

Distinguishing among these cases requires more data than simple coincidence of epicentres and gas fields. Required information includes the pre-development seismic background, timing of operational changes, reservoir-pressure dynamics, hypocentral depths, focal mechanisms, fault geometry, and surface deformation. The absence of these data prevents confident classification of individual events and simultaneously demonstrates the need for targeted monitoring (Table 2).

The Gazli sequence as a regional analogue. The Gazli earthquakes of 1976 and 1984 are of particular interest for assessing potential seismicity in the Southern Aral Sea region. Three strong events with magnitudes of approximately 7 occurred within a relatively short period in the central Turan Plate. Their occurrence in an area not previously characterized by a persistent concentration of strong seismicity substantially changed perceptions of the geodynamic potential of platform territories in western Uzbekistan [10–14, 26–28].

Some publications relate the Gazli sequence to intensive development of a major gas field. Proposed mechanisms include reservoir-pressure depletion, deformation of productive horizons, and stress redistribution in deep faults. Other studies, however, attribute the earthquakes mainly to natural tectonic activation of deep crustal structures [10–14, 26–28].

Focal depths and rupture dimensions indicate that the energy of the strong Gazli earthquakes was tectonic in origin. Even if anthropogenic influence was present, gas extraction could not have been the direct source of all released energy. A more defensible model is that industrial activity acted as an additional trigger in an already stressed tectonic system [10–14, 26–28].

Gazli should therefore be regarded not as an unequivocally proven induced-earthquake case, but as a regional example of possible interaction between anthropogenic and natural factors. For the Muynak–Surgil area, its main significance is that it demonstrates the limitations of the traditional assumption of complete geodynamic stability of the Turan Plate.

The local earthquake sequence recorded in western Bukhara Region on 20–22 May 2026 is also of interest. The first and strongest event occurred at 01:40 on 20 May in Karakul District. It had a magnitude of 5.3 and a focal depth of 10 km; shaking of intensity 3–4 was felt in Bukhara Region and intensity 2–3 in Navoi Region [20].

During the following two days, five additional weak-to-moderate events were recorded in Jondor District: M 3.4 at 12:29 and M 3.8 at 15:47 on 21 May; and M 4.0 at 01:32, M 3.8 at 10:15, and M 4.0 at 10:44 on 22 May. Focal depths were mainly 10–15 km [20] (Table 3).

The tremors were felt in the city of Gazli and in the Peshku, Karakul, and Jondor districts. For the event at 01:32 on 22 May, intensity reached 3 in Gazli, 2–3 in Peshku District, and approximately 2 in Karakul and Jondor districts. The epicentre was in Jondor District, approximately 28 km from Gazli [20].

Table 3: Local earthquake sequence in Bukhara Region, 20–22 May 2026 [20]

Date and time	Epicentral area	Magnitude	Depth, km	Felt intensity
20 May 2026, 01:40	Karakul District	5.3	10	Bukhara Region: 3–4; Navoi Region: 2–3
21 May 2026, 12:29	Jondor District	3.4	10	Locally up to 2
21 May 2026, 15:47	Jondor District	3.8	10	Gazli: 2–3; Peshku District: 2
22 May 2026, 01:32	Jondor District	4.0	10	Gazli: 3; Peshku District: 2–3; Karakul and Jondor districts: 2
22 May 2026, 10:15	Jondor District	3.8	15	Gazli: 2–3; Peshku and Karakul districts: 2
22 May 2026, 10:44	Jondor District	4.0	10	Gazli: 2–3; Peshku, Karakul, and Jondor districts: 2

The short-term spatiotemporal concentration of six events with magnitudes 3.4–5.3 indicates local activation of the seismic process in western Bukhara Region. However, proximity of the epicentres to the Gazli gas-producing area does not itself prove an anthropogenic origin. Establishing or excluding such a link requires comparison of the earthquake catalogue with reservoir- and bottom-hole-pressure dynamics, production and injection volumes, deep-fault locations, focal mechanisms, and geodetic-monitoring results.

The 2026 activity supplements historical data on seismicity in the Gazli region and confirms that the platform territories of western Uzbekistan cannot be considered entirely aseismic. However, differences in magnitude, focal depth, and released-energy scale do not permit direct equivalence between the 2026 events and the strong Gazli earthquakes of 1976 and 1984. They should be treated as a separate local sequence requiring further instrumental observation and geodynamic interpretation.

Comparison with international gas-producing areas. The best-documented example of seismicity associated with gas-reservoir depletion is Groningen in the Netherlands. Long-term gas extraction caused substantial reservoir-pressure decline, reservoir compaction, land subsidence, and an increase in local seismic events. A dense monitoring network made it possible to establish spatiotemporal relationships among reservoir development, deformation, and seismicity [7–9].

The Groningen experience shows that seismicity may lag behind the start of production. Initially, deformation accumulates mainly aseismically; a seismic response appears later when individual faults reach a critical state. The absence of recorded seismicity during early production is therefore not sufficient evidence of the absence of long-term risk [7–9].

Pressure-depletion-related deformation has also been observed at the Lacq and Ekofisk fields. The seismic response differed, confirming its dependence on local geological and mechanical conditions. In some cases, surface subsidence was the main manifestation; in others, local microseismicity or fault reactivation occurred [4, 5, 25].

Table 4: Comparison of selected seismicity cases at gas-production and gas-technology facilities

Site	Operation type	Main mechanism	Maximum magnitude	Assessment of relationship	Sources
Muynak–Surgil	Gas extraction; deep drilling	Potential pressure depletion and stress redistribution	No confirmed sequence	Hypothesis requires monitoring	[14, 22, 23]
Gazli	Long-term gas extraction	Possible triggering against a background of tectonic stress	M 7.3	Debated	[9–13, 19–21]
Groningen	Gas-reservoir depletion	Reservoir compaction and fault reactivation	M 3.6	Well documented	[16–18]
Lacq	Gas extraction	Pressure depletion and fault reactivation	Approximately M 4	Probable	[1, 19]
Castor	Gas injection	Pore-pressure increase and fault reactivation	M 4.2	Probable	[1, 4]
Central United States	Deep wastewater injection	Pore-pressure diffusion	M 5.8	Well documented	[4–6]

Fluid-injection cases demonstrate a different mechanism. In the central United States, the sharp increase in earthquake occurrence was associated mainly with deep disposal of large volumes of formation and wastewater rather than directly with hydraulic fracturing. These examples show that seismic-risk assessment must distinguish the effects of gas withdrawal from those of injection operations.

Comparison of international examples with the Muynak–Surgil area identifies several common risk factors: large and sustained reservoir-pressure changes, critically stressed faults, high rates of fluid extraction or injection, mechanical compressibility of the reservoir, and insufficient seismological-station density. Quantitative relationships cannot be transferred directly from one field to another because reservoir architecture, stress state, and operating regimes differ (Table 4).

Regional unloading caused by desiccation of the Aral Sea. The reduction in surface loading caused by the loss of water mass from the Aral Sea deserves separate consideration. Recent satellite studies have identified broad regional uplift interpreted as a delayed viscoelastic response of the lithosphere and asthenosphere to unloading [17].

This process differs substantially in spatial and temporal scale from local deformation associated with gas-field operation. Uplift caused by sea desiccation is long-wavelength and regional, whereas deformation caused by reservoir compaction is generally localized within the reservoir and its immediate surroundings (Fig. 5) [17].

Nevertheless, lithospheric unloading may modify the regional component of the stress state. In theory, even small stress changes can affect faults near a critical state. Available data, however, do not yet establish a relationship between the observed uplift and specific seismic events in the Southern Aral Sea region [17].

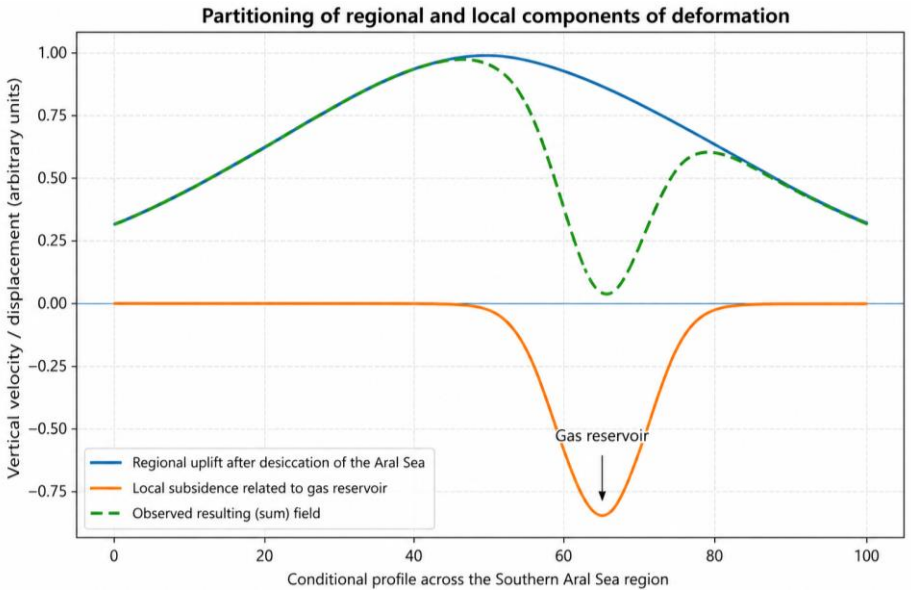


Fig. 5. Conceptual separation of the regional long-wavelength uplift component associated with unloading of the Aral Sea and local production-related subsidence [17].

In this study, desiccation of the Aral Sea is treated as an additional background geodynamic factor. Its inclusion is required primarily for correct interpretation of satellite measurements. Without removal of the regional long-wavelength component, local production-related subsidence may be underestimated or misinterpreted.

Assessment of the available evidence. The analysis did not identify a sufficient body of data to demonstrate proven induced seismicity in the Muynak–Surgil area. Open sources lack consistent time series of production, reservoir pressure, ground-surface deformation, and local microseismicity. A detailed three-dimensional fault model required for quantitative stress-change assessment has also not been published.

At the same time, a potential influence of gas production on the geodynamic regime cannot be reasonably excluded. The combination of deep productive horizons, prolonged anthropogenic impact, fault-block structure of the Turan Plate, and regional vertical movements provides sufficient grounds for dedicated monitoring.

The most scientifically appropriate formulation is therefore an assessment of potential induced or triggered seismicity. This recognizes a plausible mechanism while emphasizing that the data remain insufficient to establish a direct causal relationship.

Principles of integrated monitoring. The results show that a reliable assessment of possible anthropogenic influence must be based on joint analysis of several independent data groups. Seismological observations should record weak local events, determine their hypocentres, and derive focal mechanisms. A local station network is required because the regional network may not provide sufficient accuracy for low-magnitude events [6, 8, 9].

Production data should include gas and formation-water withdrawal, reservoir and bottom-hole pressures, periods of operational change, and fluid-injection information. Only comparison of these parameters with the seismic catalogue can reveal a possible temporal relationship.

InSAR is required to construct spatiotemporal deformation time series. Its application must separate regional uplift caused by unloading of the Aral Sea from local subsidence related to reservoir depletion, groundwater changes, or deformation of anthropogenic ground. Ground-based GNSS observations should independently validate the satellite results [21].

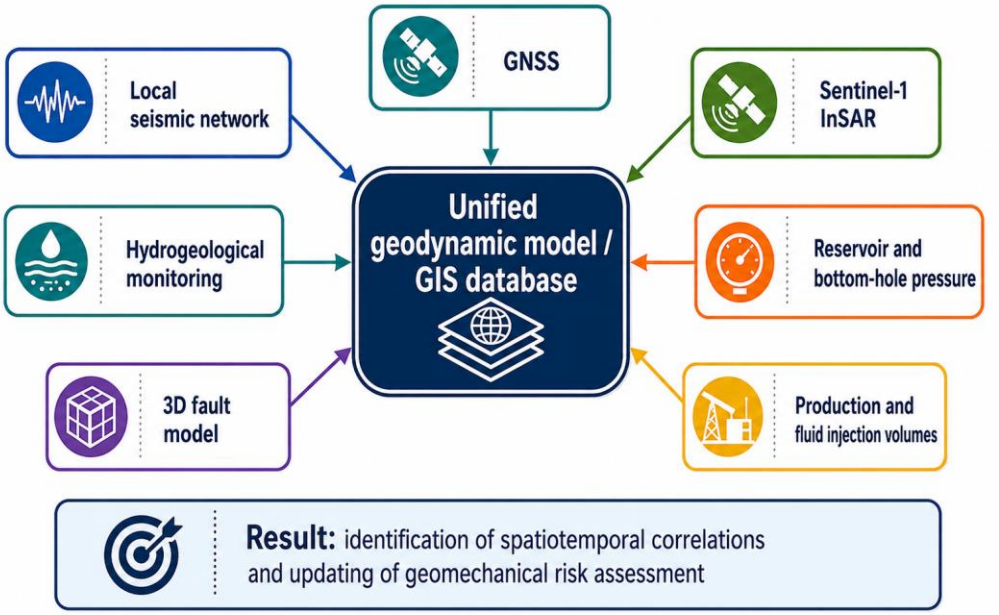


Fig. 6. Structure of integrated monitoring for potential induced seismicity in a gas-producing area (compiled by the authors after [6, 8, 9, 21]).

The final monitoring component is geomechanical modelling. It should incorporate the geometry of productive layers and faults, elastic and strength properties of rocks, the initial stress field, pressure

dynamics, and deformation observations. Calculation of Coulomb-stress changes will identify faults that may be approaching slip conditions.

The monitoring system should therefore be regarded not as a set of separate observations but as a single integrated model of the geological environment. Only the combination of seismological, geodetic, production, and geomechanical data can distinguish the natural seismic background from a possible anthropogenic response (Fig. 6).

Practical significance of the results. The practical significance of this analysis lies in substantiating a transition from general regional seismicity assessment to site-oriented monitoring of gas-producing areas. General seismic-zoning intensity characterizes the expected effects of natural earthquakes but does not reflect local changes associated with operation of a specific field.

For facilities in the Southern Aral Sea region, early detection of slow deformation and weak microseismicity is particularly important. These indicators do not necessarily signify preparation of a strong earthquake but may reflect changes in the stress state of the rock mass. Timely detection allows operational regimes to be adjusted, fault-stability models to be refined, and risks to wells, pipelines, and industrial structures to be reduced.

The results confirm that potential induced seismicity in the Muynak–Surgil area should be treated as an interdisciplinary problem involving engineering geology, geomechanics, seismology, and satellite geodesy. A central requirement for a scientifically sound assessment is to avoid a predetermined conclusion of anthropogenic origin and instead test alternative hypotheses consistently.

CONCLUSIONS

The analysis showed that gas-producing territories of the Southern Aral Sea region, including industrial-development sites on the exposed bed of the Aral Sea, are characterized by a complex combination of platform tectonics, a thick and heterogeneous sedimentary cover, deeply buried productive complexes, fault-block structure, and increasing anthropogenic loading. These features preclude treating the geological environment of the Muynak–Surgil area as completely inert under long-term industrial influence.

The principal potential mechanism of gas-production impact is reservoir-pressure depletion, accompanied by increased effective stress, compaction of reservoir rocks, and stress redistribution in the surrounding rock mass. Where pre-existing faults are close to limiting equilibrium, such redistribution may theoretically alter their stability and create conditions for induced or triggered seismic events. The direction and magnitude of the effect, however, depend on fault geometry, orientation of the regional stress field, rock mechanical properties, pressure-decline rate, and hydraulic communication between productive horizons and fault structures.

Regional and international analogues confirm that the seismic response to oil and gas development is not universal. At some sites, reservoir-pressure decline produces mainly aseismic compaction and surface subsidence, whereas at others local microseismicity or fault reactivation is recorded. Gas production alone is therefore not proof of an anthropogenic earthquake origin.

The strong Gazli earthquake sequence of 1976 and 1984 is particularly important as a regional example of high seismic activity within the Turan Plate. Existing scientific interpretations, however, do not allow these events to be classified unequivocally as induced. Gazli is best regarded as a debated case of interaction between natural tectonic potential and possible anthropogenic influence, in which the main energy source was tectonic and industrial activity may have been one additional factor modifying the stress state. The local sequence of 20–22 May 2026, with magnitudes of 3.4–5.3, confirms continuing seismic activity in western Bukhara Region, but without production, focal-mechanism, and geodetic data it cannot be classified as induced [20].

At present, open data do not establish a direct causal relationship between gas-field operation and seismic events in the Muynak–Surgil area. The main information gaps are the absence of continuous series of reservoir pressure and production volumes, data on formation-fluid withdrawal and injection, a detailed

local microseismic catalogue, focal mechanisms of weak events, a three-dimensional fault model, and long-term surface-deformation records.

Accordingly, the scientifically correct outcome of this study is not a claim of proven induced seismicity, but identification of engineering-geological and geodynamic prerequisites requiring dedicated instrumental verification. These include deeply buried productive complexes, long-term reservoir-pressure changes, possible hydromechanical connections with faults, heterogeneity of the sedimentary cover, and the regional tectonic background of the Turan Plate.

The reduction in water mass of the Aral Sea and the associated broad regional uplift represent an additional geodynamic factor. This process differs from local gas-production effects in scale, mechanism, and duration. It cannot be regarded as direct evidence of induced seismicity, but it should be considered when interpreting present-day vertical movements and separating regional and local components of the deformation field.

An integrated monitoring system is required for objective assessment of the geodynamic state of gas-producing territories in the Southern Aral Sea region, including facilities on the exposed bed of the Aral Sea. It should combine local seismological stations, satellite InSAR, ground-based GNSS observations, monitoring of reservoir and bottom-hole pressures, accounting of production and injection volumes, and geomechanical modelling. Joint analysis of these data will reveal spatiotemporal relationships among industrial operations, surface deformation, and changes in the microseismic regime.

Particular attention should be paid to recording weak events preceding a possible increase in seismic activity. Increases in microearthquake occurrence, hypocentral migration, changes in the frequency–magnitude relationship, persistent deformation anomalies, and accelerated reservoir-pressure decline should not be regarded as independent evidence of preparation of a strong event, but as complementary indicators of changes in the geological environment.

The practical significance of the results is the substantiation of a transition from regional seismic-hazard assessment to site-oriented monitoring of individual gas-producing structures. General seismic-zoning materials characterize natural regional hazard but do not reflect local stress changes developing during field operation.

Thus, potential induced seismicity in the Southern Aral Sea region should be treated as an interdisciplinary problem at the interface of engineering geology, geomechanics, seismology, hydrogeology, and satellite geodesy. Gas-production facilities located on the exposed bed of the Aral Sea require particular attention because industrial development is taking place against a background of substantial transformation of the natural geological environment. Further research should focus on accumulating instrumental data and quantitatively testing the hypothesis that gas production may influence the present geodynamic regime of the Muynak–Surgil area.

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DATA AVAILABILITY

The study used published materials and open-access data. Complete production data on reservoir pressure and fluid production and injection volumes in the Muynak–Surgil area were not available to the authors. Additional field and laboratory materials may be provided upon reasonable request, subject to restrictions on dissemination of the source data.

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