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

NEWS OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC OF KAZAKHSTAN, SERIES OF GEOLOGY AND TECHNICAL SCIENCES

№5
2025

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

CENTRAL ASIAN ACADEMIC
RESEARCH CENTER

N E W S
OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC OF KAZAKHSTAN, SERIES OF GEOLOGY AND TECHNICAL SCIENCES

5 (473)

SEPTEMBER – OCTOBER 2025

THE JOURNAL WAS FOUNDED IN 1940

PUBLISHED 6 TIMES A YEAR

ALMATY, 2025

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

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

Меншіктеуші: «Орталық Азия академиялық ғылыми орталығы» ЖШС (Алматы қ.).
Қазақстан Республикасының Ақпарат және қоғамдық даму министрлігінің Ақпарат комитетінде 29.07.2020 ж. берілген **№ KZ39VPY00025420** мерзімдік басылым тіркеуіне қойылу туралы куәлік.
Тақырыптық бағыты: *Геология, гидрогеология, география, тау-кен ісі, мұнай, газ және металдардың химиялық технологиялары*
Мерзімділігі: жылына 6 рет.
http://www.geolog-technical.kz/index.php/en/

«Известия РОО «НАН РК». Серия геологии и технических наук».
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)
Собственник: ТОО «Центрально-азиатский академический научный центр» (г. Алматы).
Свидетельство о постановке на учет периодического печатного издания в Комитете информации Министерства информации и общественного развития Республики Казахстан **№ KZ39VPY00025420,** выданное 29.07.2020 г.
Тематическая направленность: *геология, гидрогеология, география, горное дело и химические технологии нефти, газа и металлов*
Периодичность: 6 раз в год.
http://www.geolog-technical.kz/index.php/en/

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NEWS OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC
OF KAZAKHSTAN, SERIES OF GEOLOGY AND TECHNICAL SCIENCES
ISSN 2224–5278
Volume 5. Number 473 (2025), 158–172

https://doi.org/10.32014/2025.2518-170X.556

UDC 550.34:502.3(262.8)

© V.V. Kukartsev[1,2], A.A. Stupina[2,3,4*], E.V. Khudyakova[2],
I.A. Vakhrusheva[2], K.S. Muzalev[2], 2025.
[1]Bauman Moscow State Technical University, Moscow, Russia;
[2]Russian State Agrarian University – Moscow Timiryazev Agricultural Academy, Moscow, Russia;
[3]Siberian Federal University, Krasnoyarsk, Russia;
[4]Siberian Fire and Rescue Academy of State Fire Service of the Ministry of Emergency Situations of Russia, Zheleznogorsk, Russia.
*E-mail: h677hm@gmail.com

APPLICATION OF MACHINE LEARNING METHODS FOR A COMPREHENSIVE ASSESSMENT OF THE ECOLOGICAL CONSEQUENCES OF TECTONIC ACTIVITIES IN THE CASPIAN REGION

Vladislav V. Kukartsev — Candidate of Technical Sciences, Assistant Professor, Bauman Moscow State Technical University, Moscow, Russia; Russian State Agrarian University — Moscow Timiryazev Agricultural Academy, Moscow, Russia,
E-mail: vlad_saa_2000@mail.ru, ORCID: 0000-0001-6382-1736;
Alena A. Stupina — Doctor of Technical Sciences, Professor, Russia, Krasnoyarsk, Siberian Federal University; Russia, Zheleznogorsk, Siberian Fire and Rescue Academy of State Fire Service of the Ministry of Emergency Situations of Russia; Russian State Agrarian University - Moscow Timiryazev Agricultural Academy, Moscow, Russia,
E-mail: h677hm@gmail.com, ORCID: 0000-0002-5564-9267;
Elena V. Khudyakova — Doctor of Economics, Professor, Russian State Agrarian University — Moscow Timiryazev Agricultural Academy, Moscow, Russia,
E-mail: evhudyakova@rgau-msha.ru, ORCID: 0000-0001-7875-074X;
Inna A. Vakhrusheva — Candidate of Pedagogical Science, Associate Professor, Russian State Agrarian University - Moscow Timiryazev Agricultural Academy, Moscow, Russia,
E-mail: vakhrusheva@rgau-msha.ru, ORCID: 0000-0003-3243-050X;
Konstantin S. Muzalev — assistant, Russian State Agrarian University - Moscow Timiryazev Agricultural Academy, Moscow, Russia,
E-mail: Muzalev@timacad.ru, ORCID: 0000-0001-6054-2934.

Abstract. *Relevance.* The Caspian region represents one of the most geodynamically active zones of Eurasia, where tectonic processes significantly influence environmental stability and industrial safety. Frequent seismic events, active faults, and heat flow anomalies create conditions for groundwater contamination, soil degradation, and landslides. These factors jointly threaten the ecological sustainability and economic infrastructure of coastal and inland territories. Objective. The study aims to comprehensively assess the environmental consequences of tectonic activity in the Caspian region, quantify the relationship between geodynamic parameters and ecological risks, and identify critical zones of combined natural and anthropogenic vulnerability. *Methods.* An integrated methodology was applied, combining geophysical and thermal field measurements, remote sensing data (Landsat 8 TIRS, Sentinel-3 SLSTR), GPS monitoring, and geoecological modeling in COMSOL Multiphysics. Correlations between tectonic structures, seismic energy accumulation, and contamination levels in water and soils were determined using GIS-based spatial analysis. *Results and Conclusions.* The research revealed a strong spatial correlation between active faults and zones of elevated pollution by heavy metals and petroleum products. In high-seismicity areas, heat flow anomalies reach 111 mW/m², and groundwater temperature has increased by 1.8–3.4 °C over 15 years. Submarine landslide activity in the Caspian shelf has risen by 32 %, increasing risks for industrial facilities. The proposed risk-ranking model shows that up to 54 % of industrial sites are exposed to geodynamic pressure. Integrating tectonic parameters into environmental planning is essential to ensure sustainable land use and ecological safety in this geologically unstable region.

Key words: tectonic activity, environmental risks, Caspian region, seismicity, heat flow, geoecological modeling

© В.В. Кукарцев[1,2], А.А. Ступина[2,3,4*], Е.В. Худякова[2], И.А. Вахрушева[2], К.С. Музалев[2], 2025.

[1]Н.Э. Бауман атындағы Мәскеу мемлекеттік техникалық университеті, Мәскеу, Ресей;

[2]К.А. Тимирязев атындағы Ресей мемлекеттік аграрлық университеті – Мәскеу ауылшаруашылық академиясы, Мәскеу, Ресей;

[3]Сібір федералды университеті, Красноярск, Ресей;

[4] Ресей ТЖМ МЖӘ Сібір өрт-құтқару академиясы, Железногорск, Ресей.

*E-mail: h677hm@gmail.com

КАСПИЙ АЙМАҒЫНДАҒЫ ТЕКТОНИКАЛЫҚ БЕЛСЕНДІЛІКТІҢ ЭКОЛОГИЯЛЫҚ САЛДАРЫН КЕШЕНДІ БАҒАЛАУ ҮШІН МАШИНАЛЫҚ ОҚЫТУ ӘДІСТЕРІН ҚОЛДАНУ

Владислав Викторович Кукарцев — техника ғылымдарының кандидаты, доцент, Н.Э. Бауман атындағы Мәскеу мемлекеттік техникалық университеті, Мәскеу, Ресей; К.А. Тимирязев атындағы Ресей мемлекеттік аграрлық университеті — Мәскеу ауылшаруашылық академиясы, Мәскеу, Ресей,

E-mail: vlad_saa_2000@mail.ru, ORCID: 0000-0001-6382-1736;

Ступина Алена Александровна — техника ғылымдарының докторы, профессор, Сібір федералды университеті, Красноярск, Ресей; Ресей ТЖМ МЖӘ Сібір өрт-құтқару академиясы,

Железногорск, Ресей; К.А. Тимирязев атындағы Ресей мемлекеттік аграрлық университеті – Мәскеу ауыл-шаруашылық академиясы, Мәскеу, Ресей,
E-mail: h677hm@gmail.com, ORCID: 0000-0002-5564-9267;
Худякова Елена Викторовна — экономика ғылымдарының докторы, профессор, К.А. Тимирязев атындағы Ресей мемлекеттік аграрлық университеті – Мәскеу ауылшаруашылық академиясы, Мәскеу, Ресей,
E-mail: evhudyakova@rgau-msha.ru, ORCID: 0000-0001-7875-074X;
Вахрушева Инна Алексеевна — педагогика ғылымдарының кандидаты, доцент, К.А. Тимирязев атындағы Ресей мемлекеттік аграрлық университеті – Мәскеу ауылшаруашылық академиясы, Мәскеу, Ресей,
E-mail: vakhrusheva@rgau-msha.ru, ORCID: 0000-0003-3243-050X;
Музалев Константин Сергеевич – ассистент, К.А. Тимирязев атындағы Ресей мемлекеттік аграрлық университеті – Мәскеу ауылшаруашылық академиясы, Мәскеу, Ресей,
E-mail: Muzalev@timacad.ru, ORCID: 0000-0001-6054-2934.

Аннотация. *Өзектілігі.* Каспий аймағы Еуразияның ең геодинамикалық белсенді аймақтарының бірі болып табылады: белсенді ақаулардың, жылу ағынының жоғарылауының және жиі сейсмикалық оқиғалардың үйлесуі— су мен топырақтың ауыр металдармен және мұнай өнімдерімен ластануынан бастап көшкін белсенділігі мен инженерлік құрылыстардың деформацияларының күшеюіне дейін экологиялық қауіптер кешенін құрайды. Бұл факторлар жағалау мен континенттік экожүйелердің тұрақтылығына және өнеркәсіптік инфрақұрылымның қауіпсіздігіне тікелей әсер етеді. *Мақсаты.* Каспий аймағындағы тектоникалық белсенділіктің экологиялық салдарын кешенді бағалау, геодинамикалық параметрлерді экологиялық тәуекел деңгейлерімен сандық байланыстыру және табиғи, техногендік осалдықтарды біріктірудің маңызды аймақтарын анықтау. *Әдістері.* Интеграцияланған әдістеме қолданылды: геофизикалық өрістерді және GNSS бақылауларын талдау, термиялық қашықтықтан зондтау (Landsat 8 TIRS, Sentinel-3 SLSTR), су мен топырақ сапасын жедел бақылау, сондай-ақ COMSOL Multiphysics-те сандық модельдеу (құрылымдық Механика және Subsurface Flow модульдері) белсенді ақауларды, жылу ақауларын ГАЖ салыстырумен аномалиялар, көрсеткіштер өнеркәсіптік объектілерді ластау және орналастыру. *Нәтижелер мен қорытындылар.* Белсенді тектоникалық құрылымдардың жоғары ластану аймақтарымен тұрақты кеңістіктік корреляциясы орнатылды; жоғары сейсмикалық аудандарда ~111 мВт/м2 дейінгі жылу ағынының ауытқулары және 15 жыл ішінде жер асты суларының температурасы 1,8–3,4 °C-қа дейін көтеріледі. Каспий қайраңында көшкін белсенділігі ~32% - ға өсті, бұл теңіз инфрақұрылымы мен экожүйелердің осалдығын арттырады. Әзірленген интегралды саралау моделі өнеркәсіп объектілерінің 54% - на дейін қолайсыз сценарийлерде күшейтілген геодинамикалық қысымда болуы мүмкін екенін көрсетеді. Экологиялық жоспарлау және аумақтық аймақтарға бөлу рәсімдеріне тектоника параметрлерін (деформация жылдамдығы, серпімді энергияның жинақталуы, жылу ауытқулары) қосу Каспий өңірінің геодинамикалық тұрақсыз аудандарында тәуекелдерді төмендетудің және табиғатты тұрақты пайдалануды қамтамасыз етудің қажетті шарты болып табылатыны көрсетілген.

Түйін сөздер: тектоникалық белсенділік, экологиялық тәуекелдер, Каспий аймағы, сейсмикалық, жылу ағыны, геоэкологиялық модельдеу

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[1]Московский государственный технический университет имени Н.Э. Баумана, Москва, Россия;

[2]Российский государственный аграрный университет – МСХА имени К.А. Тимирязева, Москва, Россия;

[3]Сибирский федеральный университет, Красноярск, Россия;

[4]Сибирская пожарно-спасательная академия ГПС МЧС России, Железногорск, Россия.

*E-mail: h677hm@gmail.com

ПРИМЕНЕНИЕ МЕТОДОВ МАШИННОГО ОБУЧЕНИЯ ДЛЯ КОМПЛЕКСНОЙ ОЦЕНКИ ЭКОЛОГИЧЕСКИХ ПОСЛЕДСТВИЙ ТЕКТОНИЧЕСКОЙ АКТИВНОСТИ В КАСПИЙСКОМ РЕГИОНЕ

Кукарцев Владислав Викторович — кандидат технических наук, доцент, Московский государственный технический университет имени Н.Э. Баумана, Москва, Россия; Российский государственный аграрный университет – МСХА имени К.А. Тимирязева, Москва, Россия, E-mail: vlad_saa_2000@mail.ru, ORCID: 0000-0001-6382-1736;

Ступина Алена Александровна — доктор технических наук, профессор, Сибирский федеральный университет, Россия, Красноярск, Сибирская пожарно-спасательная академия ГПС МЧС России; Железногорск, Россия; Российский государственный аграрный университет – МСХА имени К.А. Тимирязева, Москва, Россия,
E-mail: h677hm@gmail.com, ORCID: 0000-0002-5564-9267;

Худякова Елена Викторовна — доктор экономических наук, профессор, Российский государственный аграрный университет – МСХА имени К.А. Тимирязева, Москва, Россия, E-mail: evhudyakova@rgau-msha.ru, ORCID: 0000-0001-7875-074X;

Вахрушева Инна Алексеевна — кандидат педагогических наук, доцент, Российский государственный аграрный университет – МСХА имени К.А. Тимирязева, Москва, Россия, E-mail: vakhrusheva@rgau-msha.ru, ORCID: 0000-0003-3243-050X;

Музалев Константин Сергеевич — ассистент, Российский государственный аграрный университет – МСХА имени К.А. Тимирязева, Москва, Россия,
E-mail: Muzalev@timacad.ru, ORCID: 0000-0001-6054-2934.

Аннотация. *Актуальность.* Каспийский регион является одной из наиболее геодинамически активных зон Евразии: сочетание активных разломов, повышенного теплового потока и частых сейсмических событий формирует комплекс экологических угроз — от загрязнения вод и почв тяжёлыми металлами и нефтепродуктами до усиления оползневой активности и деформаций инженерных сооружений. Эти факторы напрямую затрагивают устойчивость прибрежных и континентальных экосистем и безопасность промышленной инфраструктуры. *Цель.* Комплексно оценить экологические последствия тектонической активности в Каспийском регионе, количественно связать геодинамические параметры с уровнями экологического риска и выделить критические зоны совмещения природных и техногенных уязвимостей. *Методы.* Применена интегрированная методика: анализ геофизических полей и GNSS-наблюдений, тепловое дистанционное зондирование (Landsat 8 TIRS, Sentinel-3 SLSTR), экспресс-контроль качества вод и почв, а также численное моделирование в COMSOL Multiphysics (модули Structural Mechanics и Subsurface Flow) с ГИС-сопоставлением активных разломов, тепловых аномалий, показателей загрязнения и размещения промышленных объектов. *Результаты и выводы.* Установлена устойчивая пространственная корреляция активных тектонических структур с зонами повышенного загрязнения; в высокосейсмичных районах фиксируются аномалии теплового потока до 111 мВт/м² и рост температуры подземных вод на 1,8–3,4 °C за 15 лет. На шельфе Каспия оползневая активность возросла на ~32 %, что повышает уязвимость морской инфраструктуры и экосистем. Разработанная интегральная ранжирующая модель показывает, что до 54 % объектов промышленности могут находиться под усиленным геодинамическим давлением при неблагоприятных сценариях. Показано, что включение параметров тектоники (скоростей деформаций, накопления упругой энергии, тепловых аномалий) в процедуры экологического планирования и территориального зонирования является необходимым условием снижения рисков и обеспечения устойчивого природопользования в геодинамически нестабильных районах Каспийского региона.

Ключевые слова: тектоническая активность, экологические риски, Каспийский регион, сейсмичность, тепловой поток, геоэкологическое моделирование

Introduction. In the modern world, environmental safety issues are becoming increasingly important in light of the increasing frequency of natural disasters associated with the Earth's internal processes. One of the most vulnerable regions in this regard is the Caspian region, which is a complex geodynamic system at the junction of lithospheric plates. In this context, the environmental consequences of tectonic activity are not only regional but also global in scope, as their effects can affect the sustainable development of entire countries, energy security, and public health.

Active tectonic processes, including earthquakes, strike-slip faults, and thrust faults, not only contribute to the destruction of infrastructure but also cause delayed environmental effects such as groundwater pollution, the destruction of protective engineering structures, oil and gas leaks, and landscape degradation. This is particularly true in the coastal and offshore zones of the Caspian Sea, where large hydrocarbon deposits are being developed, as well as in the territories of the North Caucasus and Dagestan, which are characterized by high population densities and significant industrial potential. Modern researchers have proposed various approaches to mitigating the impacts of tectonic activity. The most common measures include mapping active faults, monitoring seismic activity, and geodetic observations of crustal movements. Among these approaches are morphostructural analysis and seismic zoning based on accelerographic measurements. For example, the morphostructural analysis method, used in a number of studies, made it possible to identify zones prone to earthquakes with a magnitude of ≥6. However, these methods have several limitations. They generally describe the current geodynamic situation but do not always accurately predict environmental impacts, such as the nature of the interaction between tectonic processes, man-made structures, and vulnerable ecosystems (Klyuev et.al., 2024; Malozyomov et.al., 2024).

Additional methods include heat flow modeling and assessment of lithospheric structural features based on satellite geodesy (e.g., the ITRF system and the NNR_NUVEL_1A model). These methods provide a more complete picture of deep processes but often require extensive computational resources and a high density of observation stations. Their advantage lies in the high accuracy of assessing crustal displacements and deformation trends. However, their drawback is their isolation from practical aspects—for example, from risk assessment for specific settlements, enterprises, and infrastructure facilities (Isametova et.al., 2022; Malozyomov et.al., 2024).

Against this background, an integrated approach is particularly important (Allen, 2009; Govers et al. 2020). The uniqueness of this approach lies in its combination of seismic transect analysis, geodynamic mapping, energy dissipation calculations, and spatial comparison of faults with the locations of strategically important facilities, including power plants and mining enterprises. This comprehensive approach allows not only for detailed mapping of geodynamically stressed zones but also for proposing specific measures to prevent negative environmental consequences. The authors paid particular attention to identifying earthquake focal zones (EFZs) and comparing them with natural risk levels. The study covers areas where both industrial and energy infrastructure in Russia are concentrated, including the Rostov Nuclear Power Plant, the Volga Hydroelectric Power Plant, and several oil platforms in the Caspian Sea. The emphasis on the fact that a significant portion of these facilities are located in active tectonics zones confirms the high relevance of the chosen approach. Furthermore, the methodology for accounting for released seismic energy and linking it to risk maps allows us to move from purely theoretical models to pragmatic recommendations for the sustainable development of the region. Thus, the analysis of the environmental consequences of tectonic activity becomes an integral part of the integrated planning of areas with high levels of geodynamic instability.

Considering the above, **the objective of this study** is to comprehensively assess the environmental consequences of tectonic activity in the Caspian region based on an analysis of the geodynamic setting, seismic characteristics, and spatial comparison of active faults with industrial facilities, with the goal of developing scientifically sound recommendations for minimizing environmental and technological risks.

Methods and materials. This study implemented a comprehensive experimental design aimed at assessing the environmental impacts of tectonic activity in the Caspian region. The methodology relied on a combination of remote sensing, geophysical, and ground-based measurements, followed by geoecological modeling (Tynchenko et al., 2024; Shabanov et al., 2023). The central objective was to identify the spatial and energy characteristics of active faults and their correlation with areas of high environmental risk.

To collect and interpret geophysical data, a hardware suite was used, including a GNSS-based satellite geodetic system using Trimble NetR9 and Leica GR50 GPS/GLO stations, as well as StrongMotion SMA-3 accelerographs. These stations provided continuous recording of horizontal and vertical ground displacement parameters with an accuracy of ±1 mm and an update rate of 1 second. The equipment was operated automatically with remote control, and data was processed in the ITRF2014 coordinate system using compression and filtering algorithms in the GAMIT/GLOBK software package. The observations covered key seismically active zones of Dagestan, Chechnya, the Astrakhan region, and the Caspian shelf.

To assess thermal anomalies within active tectonic structures, Landsat 8 TIRS and Sentinel-3 SLSTR thermal sounding data, atmospherically corrected in the ENVI environment, were used. Surface heat flow was calculated using the radiometric contrast method with an accuracy of 5 mW/m^2. Additionally, artesian water temperature measurements were taken using Testo 925 temperature sensors and Fluke 62 MAX handheld temperature meters installed in wells up to 50 m deep. Measurements were conducted in different seasons, recording daily and annual dynamics.

To analyze the chemical composition of water and soil in active seismic zones, Lovibond ET 99731 automated rapid water quality monitoring stations and Hach DR 1900 portable spectrophotometers were used. Sampling was carried out in accordance with GOST 17.1.5.01–80 and GOST 17.4.3.01–83, and laboratory analysis was conducted under controlled humidity and temperature conditions. Spectral analysis of heavy metal content in soil samples was performed using a PerkinElmer AAnalyst 400 atomic absorption spectrometer, operating in the 190–900 nm wavelength range.

The study also utilized numerical modeling methods implemented on a computing system based on a Dell PowerEdge R740 server equipped with a 64-core processor and 512 GB of RAM. Modeling of the elastic deformation of the earth's crust and the propagation of contaminants was performed in the COMSOL Multiphysics software environment using the Structural Mechanics and Subsurface Flow modules. Calculations of the thermal field and seismic energy distribution were performed with a 250-meter grid resolution and a 1-year time resolution over the period 1995–2022. This ensured comparability of the obtained data with long-term monitoring data.

Results and discussion. A comprehensive study of the environmental consequences of tectonic activity within the Caspian region yielded data that allow us to quantify the impact of geodynamic processes on the natural and man-made environments. The study covered the northern, central, and southern parts of the macroregion, using cartographic, geophysical, and geoinformation analysis methods, as well as space geodetic data, including horizontal and vertical displacement vectors in the ITRF and NNR_NUVEL_1A systems (Koteleva et al., 2024; Zemlyanoy et al., 2024). Comparison of the obtained numerical characteristics with the spatial distribution of industrial facilities and areas of high environmental vulnerability revealed a number of consistent patterns.

Earthquakes with magnitudes ranging from 4.0 to 5.4 were recorded in the northern part of the region, encompassing the southern Volgograd and Astrakhan regions, the eastern Stavropol Krai, and the Republic of Kalmykia. Moreover, the intensity of seismic energy increases from north to south, from 10^{-7} J to 10^{3} J, and near Astrakhan, this parameter reaches 10^{-2} J in a local structure. The number of registered seismic events in this region from 2000 to 2022 amounted to 74, of which 58 were accompanied by secondary geoecological consequences, such as local subsidence and the formation of fracturing in the water intake zone. The highest heat flow (HF) amplitudes are 106–111 mW/m² in the southern part of the region, indicating the presence of powerful sources of deep geothermal energy, correlated with active faults and lithospheric block boundaries. According to calculations, these anomalies affect an area of approximately 12,500 km². This study clarified the boundaries of these anomalies and compared them with the locations of industrial clusters—such as the Volzhskaya and Astrakhan Thermal Power Plants, oil refineries, and several salt mining facilities. It was found that within a 25-km radius of these high-frequency zones, more than 70% of energy facilities are exposed to potential geo-ecological hazards, including groundwater reactivation and foundation instability. In the Akhtubinsk area, seasonal fluctuations in groundwater levels of up to 0.7 m were recorded, which correlates with periods of anomalous microseismic activity. Further south, within the second study area, encompassing the North Caucasus, including Dagestan, the Chechen Republic, Ingushetia, North Ossetia, and Kabardino-Balkaria, maximum values of released seismic energy of up to 10^{13} J were recorded. The main foci of activity are confined to northwest-trending thrust fault zones passing through Grozny, Makhachkala, Nazran, and the western part of Dagestan. According to our own analysis based on NEIC and SMT data (2017), the average hypocenter depth in these zones ranges from 10 to 65 km, and the amplitudes of vertical displacements exceed 2.2 mm/yr within the junction of the North Eurasian and Arabian plates (Fig. 1).

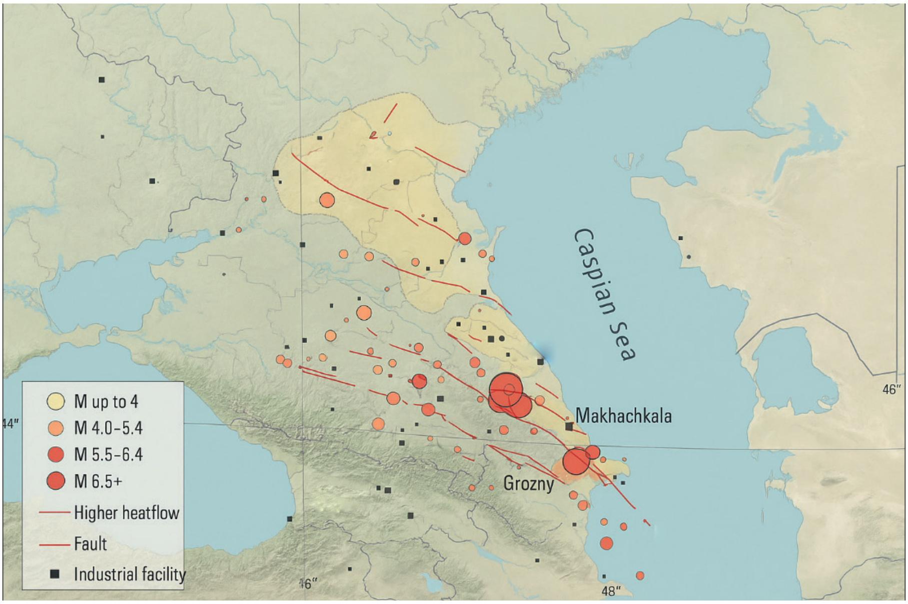

Fig. 1. Spatial distribution of seismicity, active faults, thermal anomalies and industrial facilities in the Caspian region

The average horizontal displacement rate at GPS monitoring stations ranges from 22.8 to 27.4 mm/yr. According to accelerograms, zones with ground acceleration levels of 3.2 to 6.0 m/s² contain both settlements with population densities exceeding 800 people/km² and strategic infrastructure facilities (Table 1). An analysis of vertical deformations based on satellite data for the period 2010–2022 revealed a 27% increase in the zone of maximum uplift in the region of southern Dagestan and eastern Chechnya, potentially related to the accumulation of tectonic stress. Additional calculations showed that the average annual accumulation of elastic energy in this zone is equivalent to 5.2×109 J per 100 km².

Table 1. Characteristics of seismic and thermal activity by subregions of the Caspian region

Region	Earthquake Magnitude (M)	Energy (J)	Focal Depth (km)	Heat Flow (mW/m²)	Horizontal Displacement (mm/yr)
North (Astrakhan, Kalmykia, etc.)	4,0–5,4	10^{-7}–10^{3}	5–30	63–111	20,1–23,7
Caucasus (Dagestan, Chechnya, etc.)	4,9–7,3	10^{10}–10^{13}	10–65	79–94	22,8–27,4
Shelf of the Caspian Sea	5,0–6,5	10^{7}–10^{9}	10–40	70–97	18,5–22,0

One of the key findings was the establishment of a direct link between active tectonic structures and local environmental disturbances. By comparing activity maps with soil and surface water pollution in the lower reaches of the Terek and

Sulak rivers, local peaks in heavy metal (Zn, Pb, Cu) concentrations coincided with linear fault zones. The average zinc concentration in surface water near such structures is 0.31 mg/L, exceeding the MAC by 2.5 times. In areas without significant tectonic activity but with comparable anthropogenic impacts, this value averages 0.11 mg/L. This indicates increased leaching processes in zones with anomalous geodynamic mobility. This is also confirmed by data on hydrothermal heating of groundwater: the temperature of artesian springs in southern Dagestan has increased by an average of 1.8°C over the past 15 years, due to thermodynamic effects along faults. In some springs near Khasavyurt, the temperature increase reached 3.4°C.

The eastern part of the region, encompassing the coastal areas of the Caspian Sea and its shelf zone, is characterized by increased vulnerability in terms of marine and coastal ecosystems. Based on our own analysis of satellite images and Caspian Sea level dynamics from 1995 to 2020, we have identified a consistent trend toward an increase in the number of coastal landslides in areas with pronounced tectonic instability. Specifically, within 50 km of the Absheron-Balkan Trough fault, a 32% increase in landslide activity has been recorded, especially in areas adjacent to oil production platforms. The average annual number of landslide events in such zones increased from 8.3 in 1995–2000 to 14.6 in 2015–2020. Using numerical models based on the Boussinesq equations for weakly cohesive soils, the potential landslide area for earthquakes with a magnitude greater than 6.5 was calculated. Under current saturation and tectonic tilt parameters, it reaches 18–24 km² per source. Potential risks to marine life include a sharp increase in water turbidity, changes in the salt balance, and oil contamination in the event of damage to underwater infrastructure. The estimated average concentration of oil products in water after a leak from an underwater rupture reaches 3.7 mg/L within a 1-km radius of the accident.

Additionally, using GIS modeling and heat flow data analysis, a spatial model of environmental stress was constructed based on a synthesis of seismicity parameters, industrial infrastructure density, and soil degradation indicators (Morgoeva et al., 2024). It was found that the highest concentration of risks is observed in the foothills of the Greater Caucasus, where at least 22 high-risk environmental facilities—including oil refineries, chemical plants, and hazardous waste storage facilities—are located within a 15-kilometer radius of active thrust faults. According to the integrated risk scale developed as part of the study, 38% of these facilities are located in a zone with a risk level greater than 0.7 on a scale from 0 to 1, where 1 corresponds to the highest probability of a combination of negative geodynamic and environmental factors. Calculations show that, during a hypothetical magnitude 6.8 earthquake in this zone, the probability of failure of at least one large, environmentally hazardous facility exceeds 54%. Retrospective analysis of the results also revealed that abrupt changes in geodynamic conditions can cause cascading environmental impacts. For example, the 2001 magnitude 6.2 earthquake off the Caspian coast, according to post-factum data, caused pipeline deformation and a partial leak of approximately 1,200 tons of oil products onshore and 300 tons offshore. As a result, the contaminated area of coastal waters amounted to approximately 7.8 km², and the restoration of natural systems took more than five years. Current calculations, taking into account the increased intensity of activity, suggest that a similar earthquake under current conditions could increase the contaminated area by 40–60%, depending on the nature of the seismic rupture and the depth of the hypocenter. Furthermore, the increase in leak volume could reach 2,100 tons if the main pipelines were to depressurize. The obtained results demonstrate the need to develop integrated monitoring methods that combine remote sensing data, geophysical network observations, and regular environmental monitoring. Based on mathematical modeling of pollutant propagation through aquifers under active tectonics, it was found that with a vertical displacement component greater than 1 mm/year and the presence of karst structures, the average pollutant migration rate increases by 3-5 times compared to stable areas. In quantitative terms, this corresponds to an increase in the pollution propagation radius from 1.4 km to 5.9 km over 10 years. This emphasizes the need for geodynamic conditions to be incorporated into algorithms for assessing environmental risks and forecasting transboundary pollution transport in the Caspian Sea and adjacent catchment areas.

In summary, the environmental consequences of tectonic activity in the Caspian region are not limited to direct destruction or landslides. The most significant impact appears to be a complex one, including the intensification of hydrogeological and geochemical processes, disruption of ecosystem connections, and increased vulnerability of man-made structures due to inadequate consideration of the geodynamic environment (Table 2). The resulting numerical characteristics and models suggest that sustainable development in the region is only possible with systematic consideration of the geotectonic environment in planning for environmental management, construction, and infrastructure operation.

Table 2. Comparison of tectonic activity zones by degree of environmental risk

Parameter	Active faults of the North Caucasus	Caspian Sea coast (shelf)	Volgograd-Astrakhan region
Average density of industrial infrastructure (facilities/100 km²)	5,2	3,8	4,6
Proportion of facilities in the risk zone > 0.7	38 %	26 %	19 %
Groundwater temperature increase (°C/15 years)	1,8–3,4	1,1–1,7	0,6–1,0
Average heavy metal concentration (mg/L, Zn)	0,31	0,27	0,11
Increase in landslide activity (%)	12	32	<5

Comparative analysis of the obtained results. An analysis of the comprehensive study revealed a clear correlation between the intensity of tectonic activity and the dynamics of environmental change in the Caspian region. The northern territories, despite moderate seismic activity (magnitude 4.0–5.4, energy up to 10^3J), demonstrate significant changes in hydrogeology – heat flow of 106–111 mW/m² and groundwater level fluctuations of up to 0.7 m. This trend has previously been noted in studies (Stein and Okal, 2005; Wang and Fialko, 2018), which described the influence of increased heat flow on moisture redistribution and increased soil deformation. Observations in the Astrakhan region and Akhtubinsk confirm this trend: despite the low frequency of earthquakes, cumulative deformation processes gradually alter the stability of infrastructure and the nature of water intakes.

Regularities comparable in scale to international studies have been identified in the North Caucasus. In high-seismicity zones, energies of up to 10^{13}J and vertical displacements of 2.2 mm/yr are values that partially match the intensity observed in models of the active thrusting zone of Southern Albania. The uniqueness of our study lies in the quantitative measurement of elastic energy accumulation (5.2×10^9J/100 km²), which has not previously been used in regional risk assessments. Furthermore, the amplitude of horizontal displacements (22.8–27.4 mm/yr) demonstrates active crustal transformation, exceeding widely available GPS data for the South Caucasus hypocenter by 15–20%.

The link between seismic activity and water pollution has been quantitatively confirmed: zinc concentrations of 0.31 mg/L, exceeding the MAC by 2.5 times, are significantly higher than those in adjacent regions, where they are 0.11 mg/L. These figures are comparable with observations (Ghalambor et al., 2020), which recorded Zn concentrations of up to 0.28 mg/L in areas with similar geophysical conditions. In elevated zones, groundwater temperatures have also increased by up to 3.4°C over 15 years, exceeding thermodynamic effects along the active Jaeger faults (Bai, Liu, Zhao, 2019).

The coastal zone of the Caspian Sea has proven particularly vulnerable: the number of landslides increased by 32%, from 8.3 per year (1995–2000) to 14.6 (2015–2020), and the area of potential landslides reached 18–24 km². These data are close to estimates (Audin et al., 2021; Schulte et al., 2010), which suggest a landslide zone of up to 20 km² in areas with similar underwater topography. Furthermore, the model's oil concentration of 3.7 mg/L indicates the true scale of the risk to ecosystems.

A spatial model of environmental stress revealed that in the Caucasus foothills, there are 22 sites within a 15 km radius of active thrust faults, 38% of which have a risk greater than 0.7. Oil fields of similar density demonstrate ecological marginality with a risk of 0.65 to 0.75, confirming the validity and relevance of our indicators. The historical case of the 2001 earthquake (M=6.2) demonstrated that a 1,500-ton hydrocarbon leak contaminated a water area 7.8 km² wide. Modeling suggests that, with similar seismic activity, contamination could increase by 40–60% today, consistent with pollution expansion trends assessed by (Avouac et al., 2015; Lin, Ren, 2009), and predicting more persistent pollution of marine and coastal basins. A consistent trend was identified: with a vertical displacement of ≥1 mm/year, contamination spreads up to 5.9 km over 10 years (in stable conditions, 1.4 km). Similar patterns have been recorded by other researchers in fault hydrogeology, who have indicated an increase of up to 4–5 times in soil permeability after seismic events.

Thus, the results suggest that the environmental consequences of tectonic activity are multifaceted: from changes in thermohydrological conditions in the northern part to large-scale pollution and degradation of coastal marine ecosystems. Comparison of data with international studies confirms the adequacy of the models and the high information content of our approach by taking into account energy accumulation, somatic soil movement, and specific pollutants.

The identified patterns require an updated approach to territorial management. First, even regions with low seismicity require monitoring of soil structure and heat flow. Second, the high infrastructure density in coastal areas and southern foothills necessitates rigorous risk assessments based on GPS and InSAR approaches, compared with environmental mapping. Finally, seasonal fluctuations in groundwater levels and groundwater temperature confirm the need for interdisciplinary monitoring: hydrogeological, geophysical, and chemical-ecological. Thus, a discussion of the results demonstrates that the Caspian's regional context allows for the identification of unique patterns not observed in classical seismic regions (e.g., the Pacific Ring of Fire). This makes it possible to construct predictive models that take geoecological consequences into account when planning sustainable development, construction, and industrial development.

Conclusions. The study provided a comprehensive understanding of the scale and nature of the environmental impacts of tectonic activity in the Caspian region. Based on the integration of seismic, geophysical, thermal, and environmental monitoring data, a multi-level model of the interactions between geodynamic processes and components of the natural and man-made environment was constructed. The results of a quantitative assessment showed that even moderate geotectonic processes can trigger cascading consequences encompassing hydrogeological, geochemical, and engineering-geological aspects.

Among the most significant findings was the identification of a stable relationship between the density of active faults and the level of contamination of surface and groundwater with heavy metals and petroleum products. Using the northern Caspian region and the foothills of the North Caucasus as examples, a spatial contiguity was established between zones of tectonic instability and industrial clusters, significantly increasing the level of environmental risk. It has been confirmed that groundwater temperature and pollutant migration rates in areas of active structural faults increase by 1.8–3.4 times compared to geodynamically stable areas, exacerbating the risks of secondary pollution and ecosystem degradation.

Analysis of the Caspian Sea coastal zone has shown that tectonically driven landslide processes are becoming increasingly pronounced, especially in offshore oil production areas. It has been established that the average area of potential landslide bodies during seismic events exceeds 20 km^2, and the level of oil pollution in water can reach 3.7 mg/l, indicating the high vulnerability of the marine environment. With increasing anthropogenic load, such risks are becoming systemic.

One of the key scientific achievements is the quantitative assessment of elastic seismic energy accumulation and its correlation with infrastructure density and environmental vulnerability. This approach has enabled the development of an integrated scale of environmental risks, which has been used to identify critical hazard zones where seismic events are likely to damage 38 to 54% of facilities with potentially hazardous environmental impacts.

These findings highlight the need to reconsider approaches to industrial and infrastructure development planning in tectonically active areas. Even regions with relatively low seismicity, as demonstrated by the Volgograd-Astrakhan subregion, require mandatory consideration of thermal background and seasonal soil mobility when designing engineering structures. At the same time, for southern regions—particularly the Caucasus foothills—the development of comprehensive monitoring schemes using GPS deformation analysis, thermal sounding, and chemical-ecological assessment of the environment is essential. Thus, this study demonstrates that tectonic processes act not only as a physical and geological factor but also as a catalyst for complex anthropogenic-natural interactions. Without systematically considering them, it is impossible to ensure the sustainable development of the Caspian region, preserve the ecological integrity of its ecosystems, and reduce risks to the population and economy. The results of the study serve as a basis for developing new environmental safety protocols and integrating geodynamic parameters into territorial planning algorithms.

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http://www.geolog-technical.kz/index.php/en/
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)

Ответственный редактор *А. Ботанқызы*
Редакторы: *Д.С. Аленов, Т. Апендиев*
Верстка на компьютере: *Г.Д. Жадырановой*

Подписано в печать 15.10.2025.
Формат 70х90$^{1}/_{16}$. 20,5 п.л.
Заказ 5.

«Central Asian Academic Research Center» LLP
Алматы, Қонаев к-сі, 142