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SEISMOPROGNOSIS OBSERVATIONS IN THE TERRITORY OF AZERBAIJAN

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MACHINE LEARNING FOR INTELLIGENT PATTERN RECOGNITION METHODS FOR SEISMIC SAFETY
(using earthquake swarms as an example)

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ABSTRACT

The paper presents one of the modern and relevant approaches to using Artificial Intelligence in machine learning, namely, the pattern recognition method. It is one of the powerful tools for intelligent analysis of large volumes of data. Today, there are a huge number of recognition algorithms and technologies for their implementation, including in the processing of seismic data, the use of clustering methods and event recognition in seismology. Such events include weak seismicity (earthquake swarms) in any seismically active region. This approach carries a promising method for representing seismic events in real time, and their visualization occurs directly during the continuous flow of seismic events.

To ensure seismic safety of the region in a timely manner, it is necessary to use modernized methods and means of processing large volumes of data. Including the method of cluster analysis of events in the form of pattern recognition, swarms of weak earthquakes.

Keywords: *Machine learning, Artificial Intelligence (AI), intelligent methods, pattern recognition, seismicity, earthquakes, earthquake swarm, seismic safety*

SEYSMİK TƏHLÜKƏSİZLİYİNİN TƏMİN OLUNMASI ÜÇÜN MAŞIN ÖYRƏNMƏSİNƏ ƏSASLANAN İNTELEKTUAL ÖYRƏNMƏ ÜSULLARI (ZƏLZƏLƏ KLASTERLƏRİNİN NÜMUNƏSİNDƏ)

Abdullayev A. U., Lyutikova V.S., Litovçenko I.N.

XÜLASƏ

Məqalədə süni intellektin maşında öyrənməsində istifadəsinə müasir və müvafiq yanaşmalardan biri, məhz nümunələrin tanınması metodu təqdim olunur. Bu, böyük həcmli məlumatların intellektual təhlili üçün güclü vasitələrdən biridir. Bu gün seysmik məlumatların emalı, klasterləşdirmə metodlarından istifadə və seysmologiyada hadisələrin tanınması da daxil olmaqla, onların həyata keçirilməsi üçün çoxlu sayda tanınma alqoritmləri və texnologiyaları mövcuddur. Belə hadisələrə istənilən seysmik aktiv regionda zəif seysmiklik (zəlzələ sürüləri) daxildir. Bu yanaşma seysmik hadisələrin real vaxt rejimində təqdim edilməsi üçün perspektivli metod təklif edir və onların vizuallaşdırılması birbaşa seysmik hadisələrin davamlı axını zamanı baş verir.

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Regionun seysmik təhlükəsizliyini vaxtında təmin etmək üçün böyük həcmli məlumatların emalının modernləşdirilmiş üsul və vasitələrindən istifadə etmək lazımdır. Nümunələrin tanınması, zəif zəlzələlərin sürüləri şəklində hadisələrin klaster analizi metodu da bura daxildir.

Açar sözlər: *Maşın öyrənməsi, Süni intellekt (AI), ağıllı üsullar, nümunənin tanınması, seysmiklik, zəlzələlər, zəlzələ sürüləri, seysmik təhlükəsizlik*

МАШИННОЕ ОБУЧЕНИЕ ИНТЕЛЛЕКТУАЛЬНЫМ МЕТОДАМ РАСПОЗНАВАНИЯ ОБРАЗОВ ДЛЯ ОБЕСПЕЧЕНИЯ СЕЙСМИЧЕСКОЙ БЕЗОПАСНОСТИ (НА ПРИМЕРЕ РОЕВ ЗЕМЛЕТРЯСЕНИЙ)

Абдуллаев А. У, Лютикова В.С., Литовченко И.Н.

АННОТАЦИЯ

В работе представлен один из современных и актуальных подходов использования Искусственного Интеллекта в машинном обучении, а именно, метод распознавания образов. Он является одним из мощных средств интеллектуального анализа больших объемов данных. На сегодняшний день существует огромное количество алгоритмов распознавания и технологий их реализации, в том числе при обработке сейсмических данных, использования методов кластеризации и распознавания событий в сейсмологии. К таким событиям можно отнести слабую сейсмичность (рой землетрясений) в любом сейсмоактивном регионе. Такой подход несет в себе перспективный метод представления сейсмических событий в реальном времени, а их визуализация происходит непосредственно в ходе непрерывного потока сейсмических событий.

Для своевременного обеспечения сейсмической безопасности региона, необходимо использовать модернизированные методы и средства обработки больших объемов данных. В том числе метод кластерного анализа событий в виде распознавания образов, роев слабых землетрясений.

Ключевые слова: *Машинное обучение, Искусственный Интеллект (ИИ), интеллектуальные методы, распознавания образов, сейсмичность, землетрясения, рой землетрясений, сейсмическая безопасность*

INTRODUCTION

At the present stage of development of artificial intelligence (AI) methods, the pattern recognition algorithm is being developed and improved as one of the AI methods. There are various methods used for pattern recognition [1, 2, 3, 4 , 5-8]. Modern recognition methods include the pattern recognition algorithm based on graphical clustering of data (using the example of earthquake swarm's recognition), since the seismicity of the study region acts as data for their clustering. In recent years, pattern recognition has become one of the relevant areas related to the automation of information processing and use. In this direction, certain successes have been achieved in solving theoretical and practical problems [1-23]. Pattern recognition technology remains relevant today [8]. The paper presents the main theoretical and practical issues of applying the pattern recognition algorithm based on the graphical clustering method (GCM) of data - using earthquake swarms as an example, and an attempt is made to assess the prospects for its development and application in machine learning [13-15].

Research methodology

As is known, pattern recognition (objects, signals, situations, phenomena or processes) is the task of identifying an object or determining any of its properties based on its image or other characteristics. In this case, the data in the computer is a set of objects, which is represented by a set of unique elements of the same type. An image is a classification grouping that unites (highlights) a certain group of objects based on a certain feature. Images have characteristic properties. The method of assigning an element to a certain image is called a decision rule. A metric is a way of determining the distance between elements of a universal set. The smaller this distance, the more similar are the objects that we recognize [8]. According to the materials of the Internet "Wikipedia", the concept of a metric is understood as: A metric on a set X is a mapping d: $X \times X \to \mathbb{R}$ that assigns to each pair $(x,y) \in X \times X$ a real number $d(x,y)$ that satisfies the following conditions: 1) non-negativity: $d(x,y) \geq 0$ for any (x,y). 2) $d(x,y) = 0$ if and only if $x = y$. 3) symmetry: $d(x,y) = d(y,x)$. 4) triangle inequality: $d(x,y) \leq d(x,z) + d(z,y)$ for any $x,y,z \in X$. X The set together with the mapping d is called *a metric space*, and is denoted by (X,d). The metric is a generalization of the concept of *distance* to arbitrary spaces. Any space can be provided with a metric.

Setting and solution method

One of the areas of application of AI methods in seismic research is the pattern recognition method. This method uses procedures of intelligent analysis and graphical clustering of events. Based on the formal features of certain seismic events, a seismologist can formulate the stages of recognition of these events and provide AI with a means of a formal procedure for identifying the object that should be recognized in a large flow of seismic events. Machine learning is based on the description of the procedure for recognizing specific seismic objects according to their criteria. Step-by-step machine learning is built from several stages of intelligent data processing.

The following approach is used in the seismic data stream recorded continuously during seismicity monitoring of the study region.

The recognition procedure can be described as follows:

1. From a continuous stream of seismic events, a portion of events (data) is loaded.
2. In this portion of data, the clustering (sampling) procedure is considered.
3. If clustering is successful, then seismic events selected according to specific criteria are allocated to a specific catalog of recognized earthquake swarms.
4. Recognition criteria describe the relationship between seismic events by distance, time between events, and the number of events within a certain radius.
5. Based on the generated catalog of recognized seismic events, a graphical visualization of the swarm activity of the study region is constructed.

That is, machine learning is reduced to specific recognition and visualization of swarm activity in a region and the identification of promising areas of seismic activation in real time. Computer modeling in this case complements the seismicity monitoring maps of the region as a whole, with specific zones of swarm clusters and can be used as interactive zones for observation and monitoring of the pattern of seismicity activation in the region [9-14, 16-23] .

Such maps contain information about the current seismic state of a seismically active region and can be used in further research to ensure seismic safety of the region.

The cluster analysis method has been tested and is used in the laboratory of physics of geodynamic and seismic processes. The author of the earthquake swarm recognition algorithm has a master's degree in engineering and technology, so he can safely call himself an expert in this field . More information about the swarm recognition method can be found in publications [16-20]. Machine learning implementation requires highly qualified specialists in programming and modern software. The machine learning complex should include high-speed Internet for uninterrupted receipt of seismic

data from Internet sources. The Intelligent Shell should include easily configurable and understandable software packages for various procedures. Namely, a complex for monitoring the current seismicity of the region, according to reliable seismic catalogs. Visualization of such seismic events can serve as an initial data set for clustering. The graphical clustering method is the main method in the procedure for recognizing earthquake swarms. The graphical data clustering method for pattern recognition (using earthquake swarms recognition as an example) is universal in various applied recognition problems. The paper considers issues of recognizing earthquake swarms based on graphical data clustering in any seismically active region. The results of applying the specified recognition algorithm showed that graphical clustering of data is most convenient for recognizing swarm patterns in the seismicity of a region [15], and numerical characteristics of swarms were also obtained.

Formal description of machine learning

Thus, the basis of the machine learning algorithm and the method for identifying swarm sequences of events is such a theoretical approach.

Let's a (1,1), a (1,2), ..., a (N N) occurs in a limited area during time t_i. Each of these events is characterized by a set of parameters, some of which may be repeated (coordinates, magnitude, etc.), while others never repeat.

It is always possible to construct a matrix R of states (1), symmetric with a zero diagonal (keeping in mind that in the general case the matrix R can be multidimensional) [14].

$$R = \begin{bmatrix} a_{11} a_{12} .. a_{1N} \\ a_{21} a_{22} .. a_{2N} \\ ..... \\ a_{N1} a_{N2} .. a_{NN} \end{bmatrix} \quad (1)$$

According to generally accepted methods of cluster analysis, we must analyze the correspondence of the elements of the rows in (1) to the given rules.

We believe that if there is a spatial relationship and interdependence of events, then it should be expressed through "distances" (Euclidean or other) between events in n -dimensional space.

If the geographic coordinates of an event are known, then we select the geometric distance between the epicenters of earthquakes as a measure of the relationship.

Considering that the most interconnected events are those for which the inter-epicentral distances are minimal.

After determining the compliance of the matrix elements (1) with a given rule in a given parameter space (for example, the distance between events), we plot them on a graph and connect them with lines in the sequence following from (1).

If there is a relationship and interdependence of events in the matrix (1), related tree-like structures are formed on the graph.

The nodes of each of these trees form clusters similar to those calculated by other cluster analysis methods. MGC does not require additional mathematical operations for clustering, and therefore is performed significantly faster than other cluster analysis methods.

The calculation time for the MGC is proportional to the number of events in the sample that forms the matrix (1).

The advantage of the MGC is that intersecting subsets are allowed in the analyzed state space.

Such situations may arise when analyzing time sequences of events, when there are clusters whose lifetime is less than the interval of the entire sample.

Features of the recognition algorithm. First, we defined the numerical characteristics of "swarms" as earthquake sequences suitable for their description and recognition of swarms in the catalog. This seems important because objective criteria for recognizing and identifying "swarms"

were not known. In general, the process of "swarm" formation can be identified with the procedure of spatial grouping of seismic events. For a more detailed qualitative analysis of swarms, see [14,1 6-20].

Results

The presented method of graphical clustering of data is proposed to carry out recognition of earthquake swarms in the seismically active study region.

Theoretical justifications are proposed and a method for recognizing “earthquake swarms” is described, as well as a step-by-step practical algorithm for their recognition is described.

An important result for machine learning is the Earthquake Swarm Recognition Criteria:

– the number of earthquakes in the “swarm” $N \geq 3$;

– spatial distance between adjacent events forming a “swarm” $L \leq 10'$ in angular measure;

– time between events in the "swarm" $0 < Tm \leq 15\text{-}26$ days.

Using these numerical constraints, machine learning and MHC calculations are performed.

A catalogue of swarms is then compiled for the selected area.

Conclusion

The introduction of machine learning into the process of studying the seismicity of any region will allow obtaining interactive catalogs of swarm events. Mapping of earthquake swarms will be done online, which will allow timely monitoring of seismic safety of areas ready for the occurrence of strong earthquakes.

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VARIATIONAL CHARACTERISTICS OF THE SEISMOMAGNETIC EFFECT (SME) DURING THE SAATLY-SABIRABAD BOUNDARY EARTHQUAKE THAT OCCURRED IN THE MIDDLE KURA DEPRESSION

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ABSTRACT

The article studies data on anomalous changes in the geomagnetic field stress near the earthquake source. The nature of the seismomagnetic effect is determined by the geomagnetic regime in the source. The spatio-temporal distribution of the geomagnetic field stress gradient reflects the geodynamic regime in the Middle Kura depression.

Key words: *SME-seismomagnetic effect, nTl-nanotesla, earthquake source mechanism, geomagnetic regime, geomagnetic field stress, ml-magnet.*

ВАРИАЦИОННЫЕ ХАРАКТЕРИСТИКИ СЕЙСМОМАГНИТНОГО ЭФФЕКТА (СМЕ) ПРИ СААТЛИНСКО-САБИРАБАДСКОМ ПОГРАНИЧНОМ ЗЕМЛЕТРЯСЕНИИ, ПРОИЗОШЕДШЕМ В СРЕДНЕ-КУРИНСКОЙ ВПАДИНЕ

А.Г.Рзаев, М.К.Маммадова

АННОТАЦИЯ

В статье изучены сведения об аномальных изменениях напряжения геомагнитного поля вблизи очага землетрясения. Характер сейсмомагнитного эффекта определяется геомагнитным режимом в очаге. Пространственно-временное распределение градиента напряжения геомагнитного поля отражает геодинамический режим во впадине Средней Куры.

Ключевые слова: *SME-сейсмомагнитный эффект, nTl-нанотесла, механизм очага землетрясения, геомагнитный режим, напряжение геомагнитного поля, ml-магнит.*

ORTA KÜR ÇÖKƏKLİYİNDƏ BAŞ VERMİŞ SAATLI-SABİRABAD SƏRHƏDDİ ZƏLZƏLƏSİNDƏ SEYSMOMAQNİT EFFEKTİN (SME) DƏYİŞMƏ XÜSUSİYYƏTLƏRİ

A.G.Rzayev, M.K.Məmmədova

ANNOTASİYA

Məqalədə zəlzələ ocağının yaxınlığında geomaqnit sahə gərginliyinin anomal dəyişmələri haqqında məlumatlar öyrənilir. Seysmo maqnit effektin yaranma xarakteri ocaqda gedən geomaqnit

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rejimlə təyin olunur.Geomaqnit sahəsinin gərginlik qradientinin məkan-zamana görə paylanması Orta Kür çökəkliyində gedən geodinamik rejimini əks etdirir.

Açar sözlər: *SME- seysmomaqnit effekt, nTl-nanotesla, zəlzələ ocağının mexanizmi, geomaqnit rejim, geomaqnit sahə gərginliyi, ml-maqnituda*

The Republican Center of Seismological Service has been studying temporal variations of seismomagnetic impact in individual local areas for over 35 years. From time to time, anomalous changes caused by strong earthquakes occurring in areas with high seismic risk and geodynamic activity are observed. The accumulation of stress-strain energy at different depths of the Earth is associated with internal and cosmogenic factors. Mechanical, physicochemical and other properties of the environment change with characteristic indicators in the Middle and Lower Kura depressions, the north-south foothills of the Greater Caucasus and the Azerbaijani sector of the Caspian Sea, where anomalous stress-strain energy accumulates. The influence of such active processes on the earth's surface is studied in seismically active regions of the world as anomalous changes in geophysical fields: gravitational, electrical, magnetic and geochemical, earthquake warning factors. Below is a map of epicenters that occurred in the Sredne-Kura Depression and adjacent areas in 2004-2024 (Fig. 1).

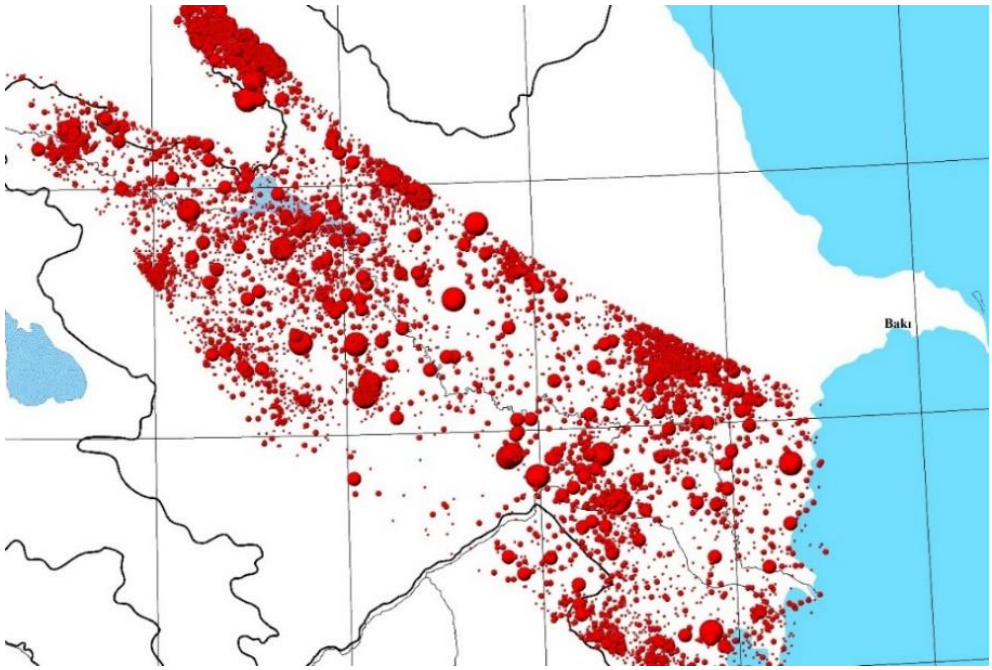


Figure 1. Map of earthquake epicenters that occurred in the Middle Kura Depression and nearby areas in 2004-2024. (Kazimova S.E.)

In the quarters of the Middle Kura basin, seismicity was above the background level. The epicenters of the border Saatly-Sabirabad earthquake and its aftershocks are located in the pan-Caucasian Kura and common Gabala-Chakhirly intersection zones.

In these parts of the Middle Kura Depression, the foci of the Sabirabad earthquakes are known. In 2024, the geodynamic activity of the Sabirabad zone was higher than in other regions.

01/19/2024 Lat =39.76 Lon= 46.68 H= 45 ML= 5.1 (Saatly-Sabirabad)

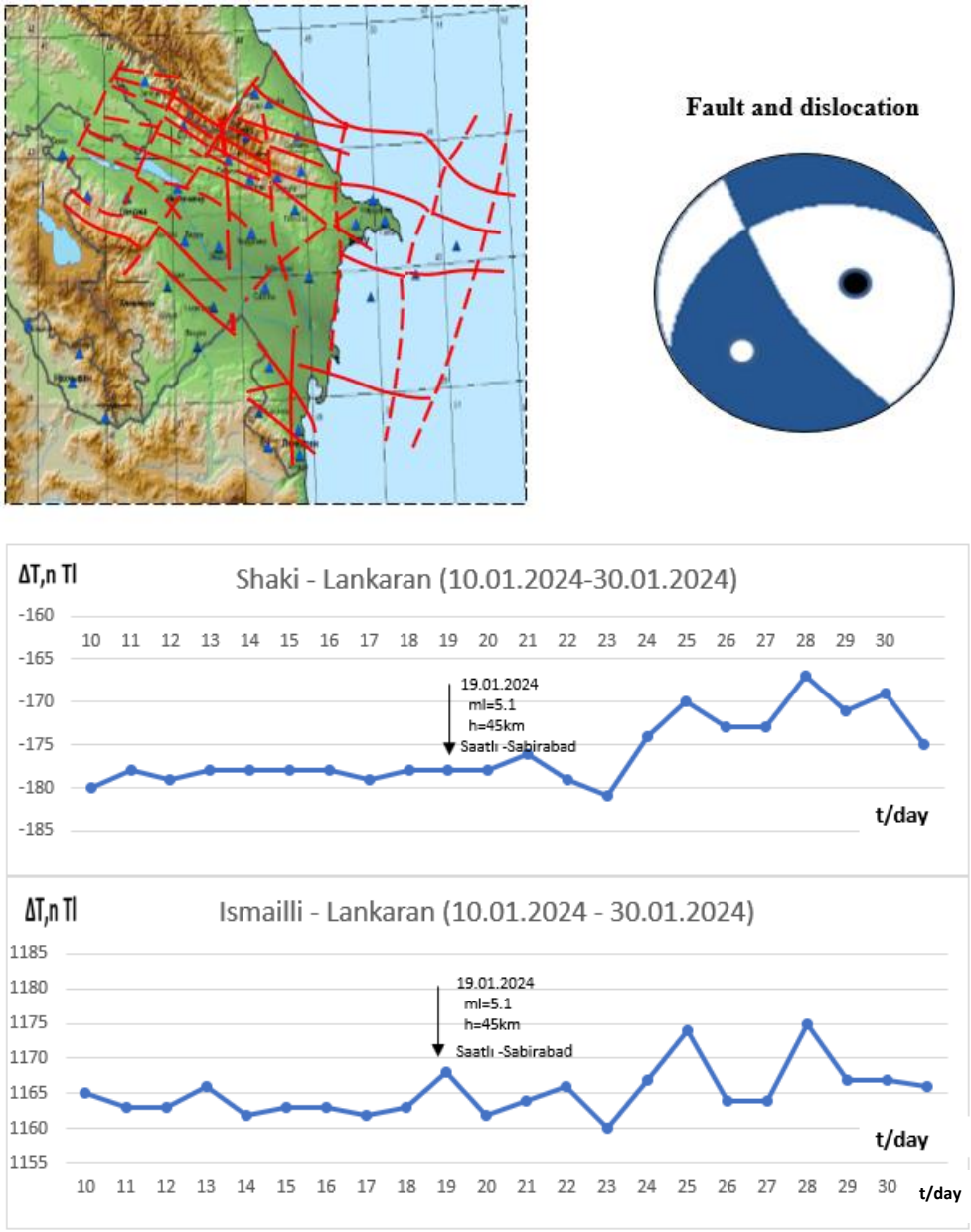


Figure 2. Seismomagnetic effect felt at Ismailly and Sheki stations during the Saatly-Sabirabad border earthquake.

Monitoring of geophysical fields allows us to record complex transformation processes in the earth's crust and draw conclusions about the accumulation and spread of excess stresses in earthquake preparation zones. The geomagnetic field has the ability to record all geological processes occurring in the earth's crust. Seismomagnetic prognostic studies conducted in geodynamic ranges show that the manifestation of the nature of the seismomagnetic effect and magnetometric data are of great importance in developing methods for short-term earthquake forecasting.

On January 19, 2024 (ML=5.1, H=45km) a strong earthquake occurred in the Saatly-Sabirabad border region. It is assumed that the earthquake influenced the activation of deep faults in the oil and gas fields of the Middle and Lower Kura depressions (Muradkhanly, Jafarly, Garaly, Kalmas Garadag, Musovdag, etc.). At this time, after the end of the stress deformation, the stress gradient of the geomagnetic field increased over time towards a positive value. The mechanism of the earthquake source is fault-thrust (fault), shear-extended (according to the RSSC ANAS). The seismomagnetic

effect was observed on the curves constructed from the readings of magnetometers operating at the Ismailly and Sheki stations (Fig. 2).

The increasing gradient of the geomagnetic field stress, detected as a result of discrete geomagnetic observations, carries information about the tense situation in the seismogenic zones at the polygons.

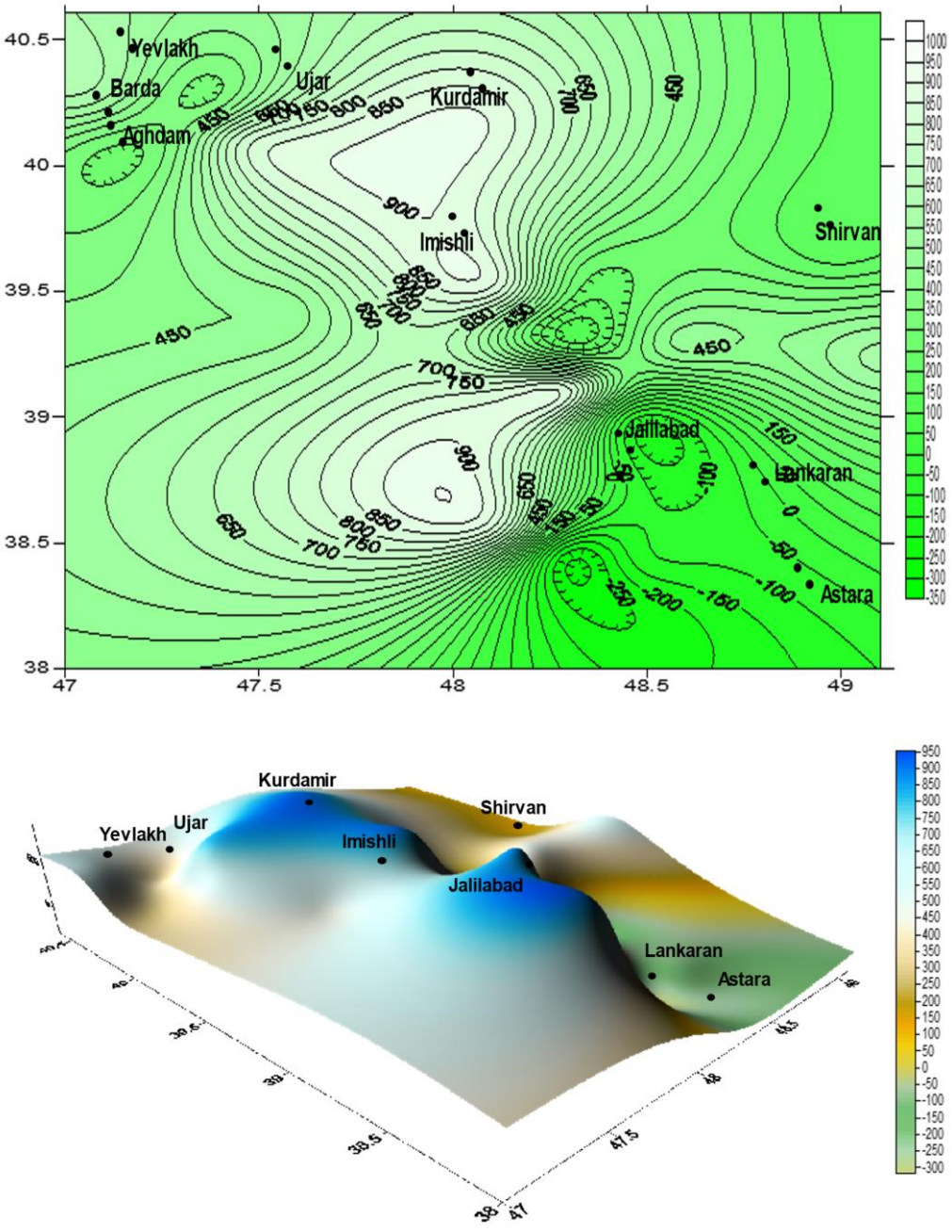


Figure 3. Stress-strain state of the geological environment according to magnetic data at the Kura-Talysh test site (in 2D, 3D format).

Analysis of stress changes and increasing gradients of the geomagnetic field made it possible to identify stress-strain zones in the Middle-Kura Depression and nearby areas. These are the Saatly, Barda, Agdam, Ujar, Zardab zones of long-term stress-strain. Strong earthquakes do not always occur in these areas, but they are considered seismic risk zones and seismomagnetic impact is observed with anomalous changes.

If we look at the 2D and 3D map showing the stress-strain state of the geological environment based on magnetic data in the Kura-Talysh geodynamic range in 2024, then in the regional plan, magnetic maxima are noted in the Jalilabad-Imishli-Kurdamir zone (Figure 3). It is noted that the geodynamic regime of the Middle Kura Depression is mainly associated with the movement of the Kura Depression blocks under the structures of the Greater Caucasus. The formation of a positive seismomagnetic effect in the source of the earthquake that occurred on the Saatly-Sabirabad border once again confirms the above facts.

Conclusion

The geodynamic regime of the territory of Azerbaijan reflects the spatial and temporal change in the gradient of the geomagnetic field stress. The article studies and analyzes in detail the anomalous changes in the geomagnetic field in earthquake foci and nearby areas.

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DEVELOPMENT OF RESEARCH ON FORECASTING STRONG EARTHQUAKES IN THE NORTHERN TIEN SHAN

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ANNOTATION

The Tien Shan Mountain system is one of the most earthquake-prone areas in the Central Asian region, where the maximum strength of earthquakes reaches 10-11 points. Within its boundaries, several zones of possible occurrence of earthquake sources with a magnitude of 7-8.5 are identified. The main seismogenic structures are the North Tien Shan, Gissar-Kakshaal (Southern Tien Shan) and Central Tien Shan seismically active zones. The article discusses the main stages in the development of prognostic research in the Northern Tien Shan. The local telemetry network KNET, installed here in 1991, allows you to register earthquakes in digital form, collect and process seismic information in real time. Note that KNET has no analogues in the Central Asian region. At the same time, geophysical, geodynamic, hydrogeochemical, hydrodynamic and other types of monitoring observations are carried out in order to identify precursor anomalies of expected strong earthquakes.

Key words: *telemetry network KNET, earthquake, seismicity, the Tien Shan Mountain system, epicenter map*

ŞİMAL TYAN-ŞANDA GÜCLÜ ZƏLZƏLƏLƏRİN PROQNOZLAŞDIRILMASI ÜZRƏ TƏDQİQATLARIN İNKİŞAFI

K.E.Abdrahmatov, A.U.Abdullaev, A.M.Muraliev

XÜLASƏ

Tyan-Şan dağ sistemi Mərkəzi Asiya regionunda seysmik cəhətdən ən təhlükəli ərazilərdən biridir, burada zəlzələlərin maksimal gücü 10-11 bala çatır. Onun hüdudları daxilində 7-8,5 bal gücündə zəlzələlərin baş verə biləcəyi bir neçə zona var. Əsas seysmogen strukturlar Şimali Tyan-Şan, Hisar-Kakşaal (Cənubi Tyan-Şan) və Mərkəzi Tyan-Şan seysmik aktiv zonalarıdır.

Məqalədə Şimali Tyan-Şanda proqnostik tədqiqatların inkişafının əsas mərhələləri araşdırılır. 1991-ci ildə burada quraşdırılmış yerli telemetrik şəbəkə KNET zəlzələlərin rəqəmsal formada qeydə alınmasına, real vaxt rejimində seysmik məlumatların toplanmasına və emalına imkan verir. Qeyd edək ki, KNET-in Mərkəzi Asiya regionunda analoqu yoxdur. Eyni zamanda gözlənilən güclü zəlzələlərin xəbərverici anomaliyalarını müəyyən etmək məqsədilə

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Geofiziki, geodinamik, hidrogeokimyəvi, hidrodinamik və digər növ monitorinq müşahidələri aparılır.

Açar sözlər: *KNET telemetriya şəbəkəsi, zəlzələ, seysmiklik, Tyan-Şan dağ sistemi, episentr xəritəsi*

КОМПЛЕКСНЫЕ ПОЛЕВЫЕ СЕЙСМОЛОГИЧЕСКИЕ ИССЛЕДОВАНИЯ И ПЕРСПЕКТИВЫ РАСШИРЕНИЯ СЕЙСМОЛОГИЧЕСКОЙ СЕТИ В РЕСПУБЛИКЕ КАЗАХСТАН

К. Э. Абдрахматов, А. У. Абдуллаев, А. М. Муралиев

АННОТАЦИЯ

Тянь-Шаньская горная система является одной из наиболее сейсмоопасных областей в Центрально-Азиатском регионе, где максимальная сила землетрясений достигает 10-11 баллов. В ее пределах выделяется несколько зон возможного возникновения очагов землетрясений с магнитудой 7-8,5. Главными сейсмогенными структурами являются Северо-Тянь-Шаньская, Гиссаро-Какшаальская (Южно Тянь - Шаньская) и Центрально-Тянь-Шаньская сейсмоактивные зоны.

В статье рассматриваются основные этапы развития прогностических исследований в Северном Тянь-Шане. Локальная телеметрическая сеть KNET установленная здесь в 1991 году позволяет регистрировать землетрясений в цифровом виде, собрать и обрабатывать сейсмической информации в оперативном реальном масштабе времени. Отметим, что KNET не имеет аналогов в Центрально-Азиатском регионе. Одновременно проводятся геофизические, геодинамические, гидрогеохимические, гидродинамические и другие виды мониторинговых наблюдений с целью выявления предвестниковых аномалий ожидаемых сильных землетрясений.

Ключевые слова: *телеметрическая сеть KNET, землетрясение, сейсмичность, система гор Тянь-Шаня, карта эпицентров*

Introduction

The sources of the 10-11 points Kemin in 1911 are confined to the North Tien Shan seismically active zone. (M=8.2±0.3), 10 points Chiliksky in 1889 (M=8.3±0.5), 9-10 points Belovodsky in 1885 (M=6.9±0.0.5), 9-10 points Vernensky in 1887 (M=7.3±0.5), 8-9 points Merkensky in 1865 (M=6.4±0.7), 8-9 points Kemin-Chuysky in 1938 (M=6.9±0.5) and other less weak earthquakes. Their hypocenters lie within the earth's crust and are distributed extremely unevenly vertically. The most widespread are sources with depths of 10-15 km, smaller ones - 16-20 km, and even smaller ones - more than 25 km (Fig. 1).

The Kemin catastrophic earthquake occurred in 1911 on January 3 in the North Tien Shan seismically active zone. It was recorded by a global network of seismic stations, its magnitude was estimated at 8.2, the depth of the hypocenter was 25 km. The maximum force of the shaking at the epicenter reached 10-11 points on the MSK-64 scale, 450 people died [New catalogue..., 1977]. Before the Kemin earthquake, the 10 points Chilik earthquake of 1889 was noted (M=8.3) in the eastern part of the North Tien Shan seismically active zone. The active period of occurrence between these two catastrophic events is 22 years, which determines the high seismicity of this zone during this period. These catastrophic and other strong earthquakes caused significant destruction over a

large area, loss of life and enormous economic damage. To prevent such disasters today is almost impossible, but it is possible to reduce the degree of socio-economic damage and protect people to the maximum extent.

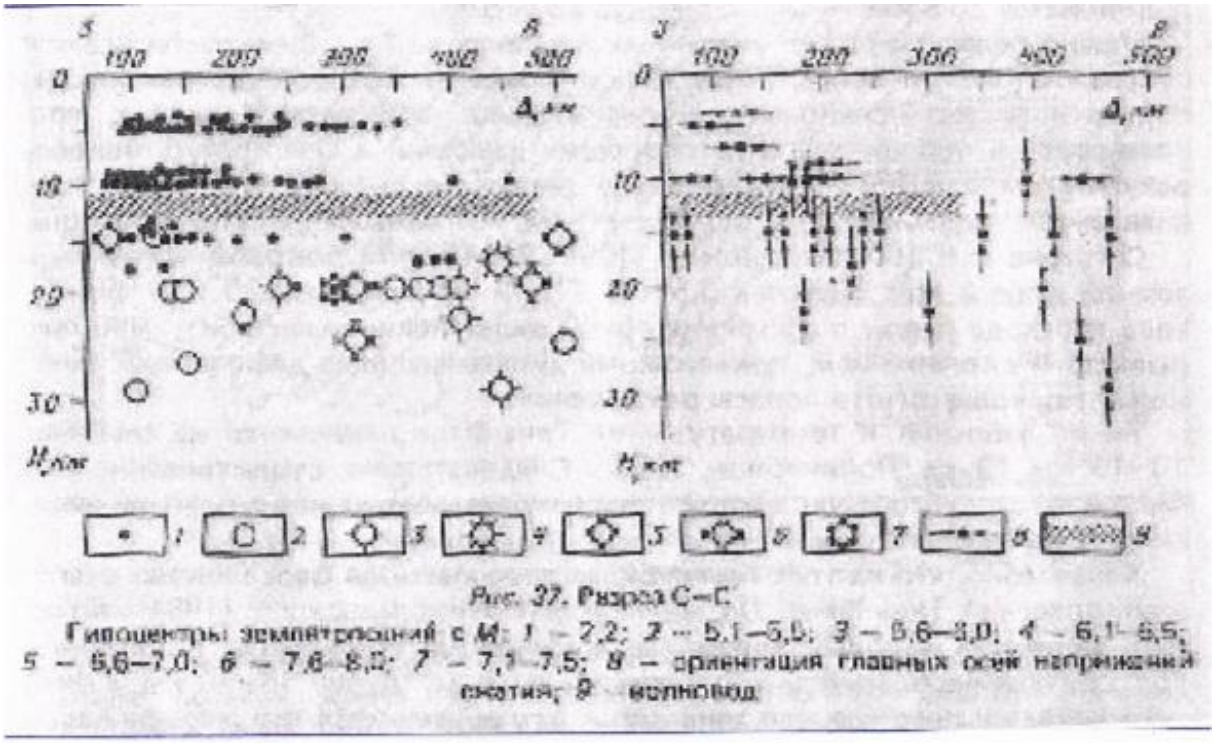


Figure 1 – Location of earthquake hypocenters and mechanisms for their implementation in Northern Tien Shan

In this regard, forecasting strong earthquakes and assessing seismic risk is the most pressing and sought-after problem in modern seismology. The solution to this problem involves predicting the location, strength and time of expected strong earthquakes. The problem of predicting the location and strength of expected events is solved by seismic zoning methods. At the same time, the problem of assessing the maximum possible earthquake in seismically active zones, as well as the parameters of ground vibrations during earthquakes, occupies a major place in complex studies on seismic zoning and ensuring the seismic resistance of structures. Forecasting the timing of expected strong earthquakes of varying urgency requires an integrated approach.

Research results

Below we will consider some results and the phased development of research on the forecast of strong earthquakes in Kyrgyzstan. The main studies are carried out within the North Tien Shan seismically active zone, where the Bishkek forecasting site is located, which includes the territories of the Chui and Issyk-Kul intermountain depressions and their mountain frames, as well as the southern part of the Ili depression (Fig. 2). The manifestation of high seismicity here is associated with ancient faults, rejuvenated in modern times, stretching in the sublatitudinal direction from the western part of the Kyrgyz ridge to the eastern border of the republic. The Northern Tien Shan is experiencing the youngest stage of deformation in the modern era and is therefore characterized by large earthquakes and low seismic activity due to weak earthquakes.

The development of prognostic research in the Bishkek and Almaty test sites is aimed, first of all, at the development of comprehensive seismic monitoring, the study of the main patterns of spatio-temporal distribution of sources of historical strong earthquakes and the features of the time course of seismic regime parameters.

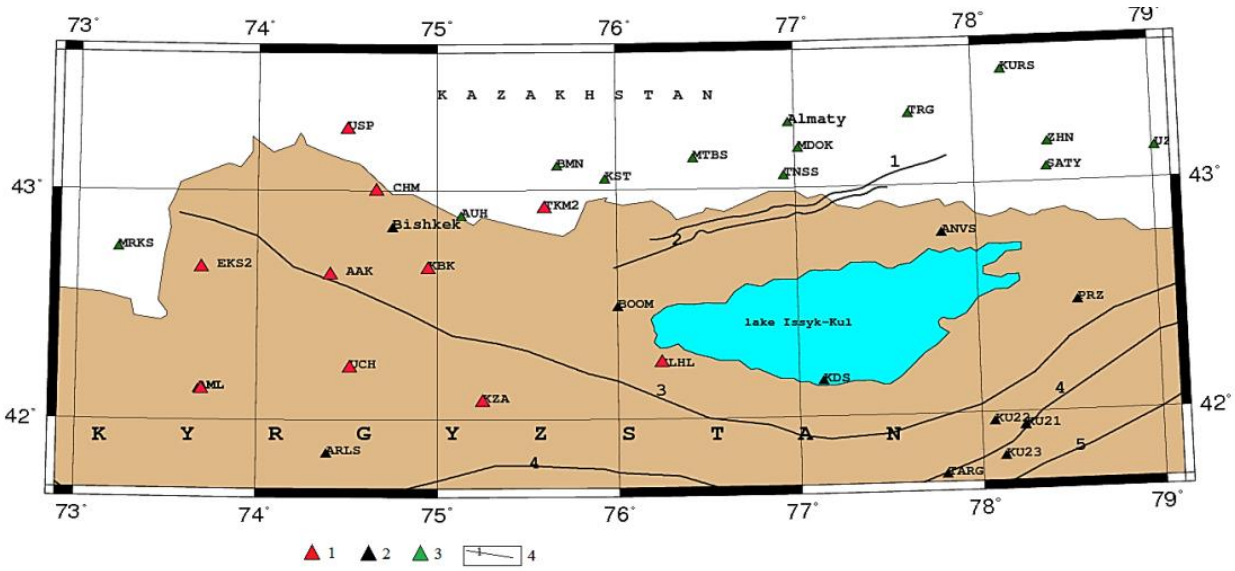


Figure 2 - Territory of the Bishkek forecasting site: (1) KNET station, (2) stationary seismic stations of Kyrgyzstan and (3) Kazakhstan; 4 - faults.

On the territory of the test site, control of the seismic situation at the initial stage was carried out using 15 highly sensitive analog seismic, 7 magnetometric, 5 electrometric, 7 hydrogeochemical, 6 hydrogeodynamic, 2 autonomous seismic stations, as well as the Ala-Archa seismic geophysical observatory, class 1 leveling. In addition, several electrometric, magnetometric and light ranging stations of the NS RAS are located in the Chuisky section of the test site; regime electrometric studies are also carried out here using signals from a powerful MHD generator [Abdullaev et al., 1994]. Currently, some types of observations are temporarily suspended due to lack of funds. The main results of research on the search for earthquake precursors in the Northern Tien Shan are presented in many well-known works [4,7,8,11,12].

In 1990, specialist scientists from the Institutes of Seismology of the National Academy of Sciences of the Kyrgyz Republic and the Ministry of Education and Science of the Republic of Kazakhstan developed a new concept for the development of complex seismological observations. In the future, it is planned to operate four forecasting sites: Bishkek, Osh, Issyk-Kul and Naryn. In order to implement the stated concept, in 1991, an American-made local radio telemetry network KNET was launched at the Bishkek and Almaty forecasting sites [8,9].

The KNET local network, consisting of 10 observation points, plays a significant role in the development of seismological research, especially in the processes of collecting, processing and interpreting seismic data in real time.

Over the past 35 years, unique digital seismic data have been collected, which are successfully used to most accurately determine the focal parameters of earthquakes. Note that KNET has no analogues in the Central Asian region. In addition, geophysical, geodynamic, hydrogeochemical, hydrodynamic and other regime observations were carried out at all test sites in order to identify precursor anomalies before strong earthquakes [2, 3, 5, 10].

It has been established that in the North Tien Shan seismogenic zone the spatio-temporal pattern of seismicity is cyclical, manifested in the alternation of periods of activation with a period of relative seismic quiescence. The duration of these periods is 19-22±6 years [4,7]. The occurrence of sources of strong earthquakes along the North Tien Shan seismogenic zone is of a migratory nature. The direction of migration coincides with the strike of geological structures (edge faults) and seismogenic zones [4,7].

So, in 1865, in the western part of the test site, the Merken earthquake with M = 6.6 occurred, and 20 years later in 1885, at a distance of 80 km to the east in the village of Belovodsk, an earthquake with M = 6.9 occurred. It was followed, after a relatively short period of time, by the Vernensk earthquake with M=7.3 in 1887 (200 km east of the village of Belovodsk) and then even further east by the Chilik earthquake of 1889 with M=8.3. Thus, after the Merken earthquake, the epicenters moved from west to east at a speed of 19 km/year. After a period of revival of seismic activity due to strong earthquakes (M≥6.3), a 22-year period of calm followed until 1911. Kemin earthquake with M=8.2. 27 years later, to the west of the epicenter of the Kemin earthquake, in the area of the western immersion of Kungei Ala-Too, the Kemin-Chuya earthquake of 1938 occurred again. Average activity level A10=0.15. Several strong earthquakes occurred here in the past at short intervals: Merken 1865. with M=6.3, Belovodsk 1885. with M=6.9, Vernensk 1887. with M=7.3, Chilik 1889. with M=8.3, Keminsk 1911. with M=8.2, Kemin-Chuysk 1938. with M=6.9. In addition, numerous earthquakes with M≤4.6 have been recorded. Thus, the epicenters of strong earthquakes in the North Tien Shan seismogenic zone migrate in the sublatitudinal direction (Fig. 3).

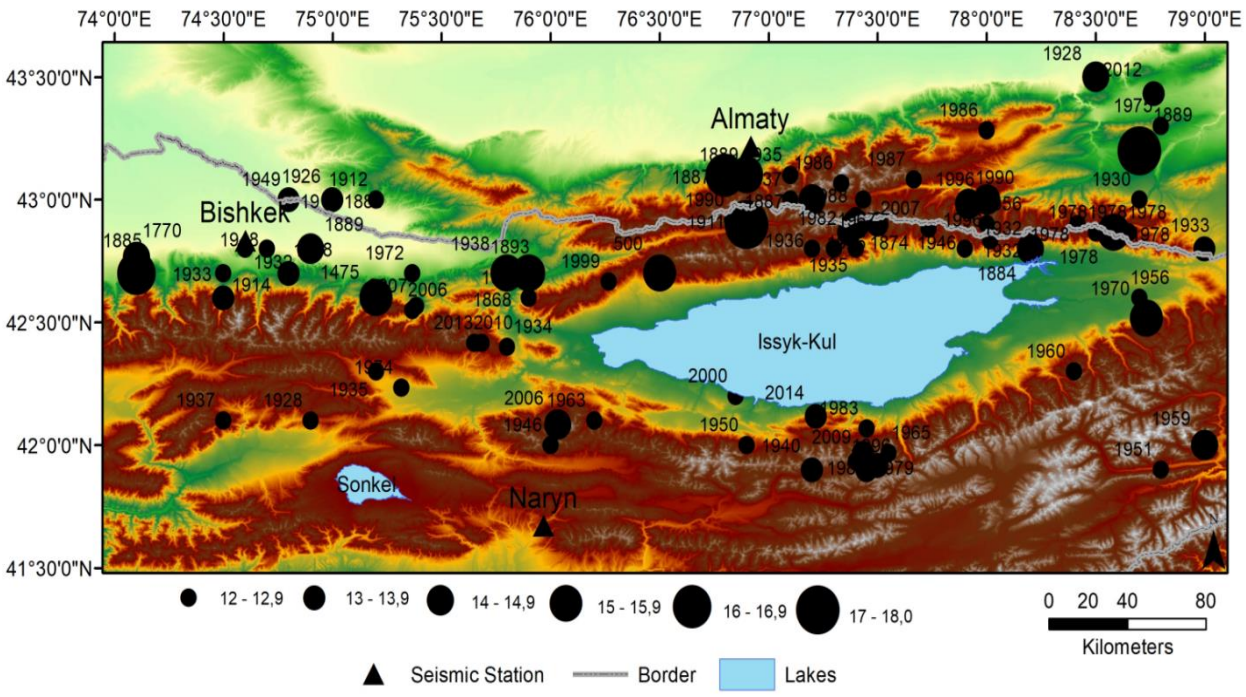


Figure 3 - Distribution of epicenters of strong earthquakes at the test site. The size of the circle corresponds to the energy class K=12 - 18.

The South Issyk-Kul zone stretches along the northern Teskey Ala-Too to the southern slope of the eastern part of the Kyrgyz ridge. It coincides with the Karakol and Pre-Teskey faults, as well

as with the Central Teskey fault zone, which is associated with seismically active feather faults of northwestern strike.

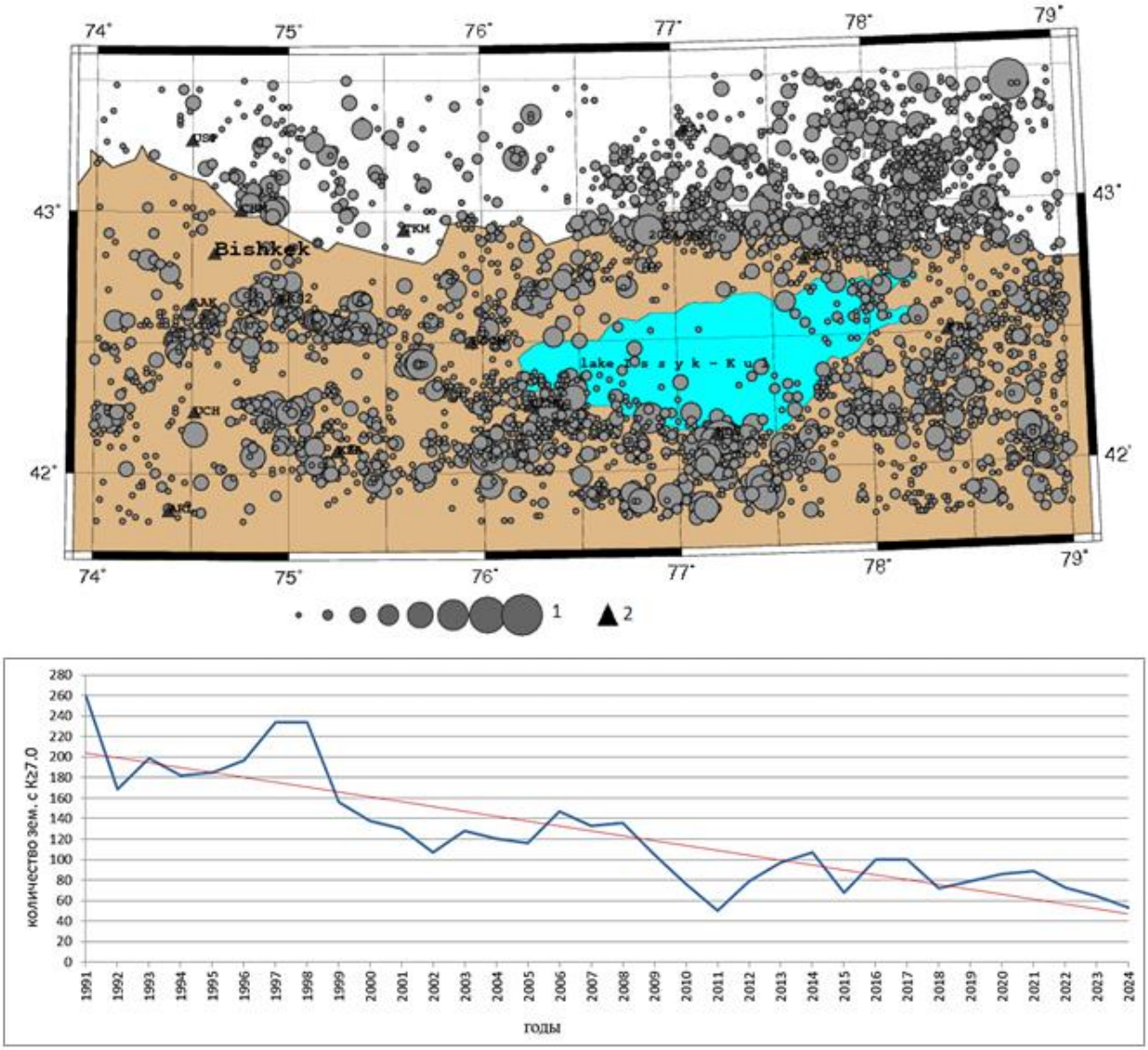


Figure 4 - Distribution of epicenters of earthquakes with energy class K=7-14 across the territory of the Bishkek prognostic testing ground for the period 1991-2024 (upper); change in the number of seismic events by year (lower), the red line shows the direction of the trend.

The South Issyk-Kul zone is also characterized by fairly high activity. The strength of observed earthquakes in this zone increases from west to east. The strongest of them is Sarykamysh 1970. with M=6.6 are confined to the eastern seismically active node (Fig. 2).

The following complex parameters of the seismic regime are studied on the territory of the test site: spatio-temporal distribution of historically strong earthquakes and the time course of the seismic process: migration of epicenters of strong earthquakes, seismic gaps, variations in seismic activity, slope of earthquake recurrence graph, changes in seismic wave velocity over time, as well as a set of geophysical (magnetometric, etc.), GPS and deformation processes, a full list of geochemical, hydrogeochemical and hydrogeodynamic observations.

Figure 4 shows the distribution of epicenters of weak and perceptible earthquakes with energy class K=8-14 on the territory of the Bishkek prognostic testing ground for the period from 1990 to

2024. The location of earthquake epicenters on the territory of the testing ground shows the existence of relatively narrow zones tracing in the sublatitudinal direction. The concentration of weak earthquake epicenters is observed within the North Tien Shan and South Issyk-Kul seismically active zones. The greatest concentration of weak earthquake epicenters is observed in the area of the epicenters of the Kemin 1911 and Chilik 1889 earthquakes, as well as in the south of Bishkek and the South Issyk-Kul seismically active zone (Fig. 3). The change in the number of weak earthquakes at the test site for the period from 1991 to 2024 is shown in the lower figure 3. We observe a trend (red line) showing a decrease in the number of weak earthquakes over time at the Bishkek prognostic test site over the past 33 years. If in 1991 the number of seismic events reached 260, then in 2024 there were 50. This may be due to a change in the stress-strain state of the earth's crust of the test site or the preparation of a strong earthquake.

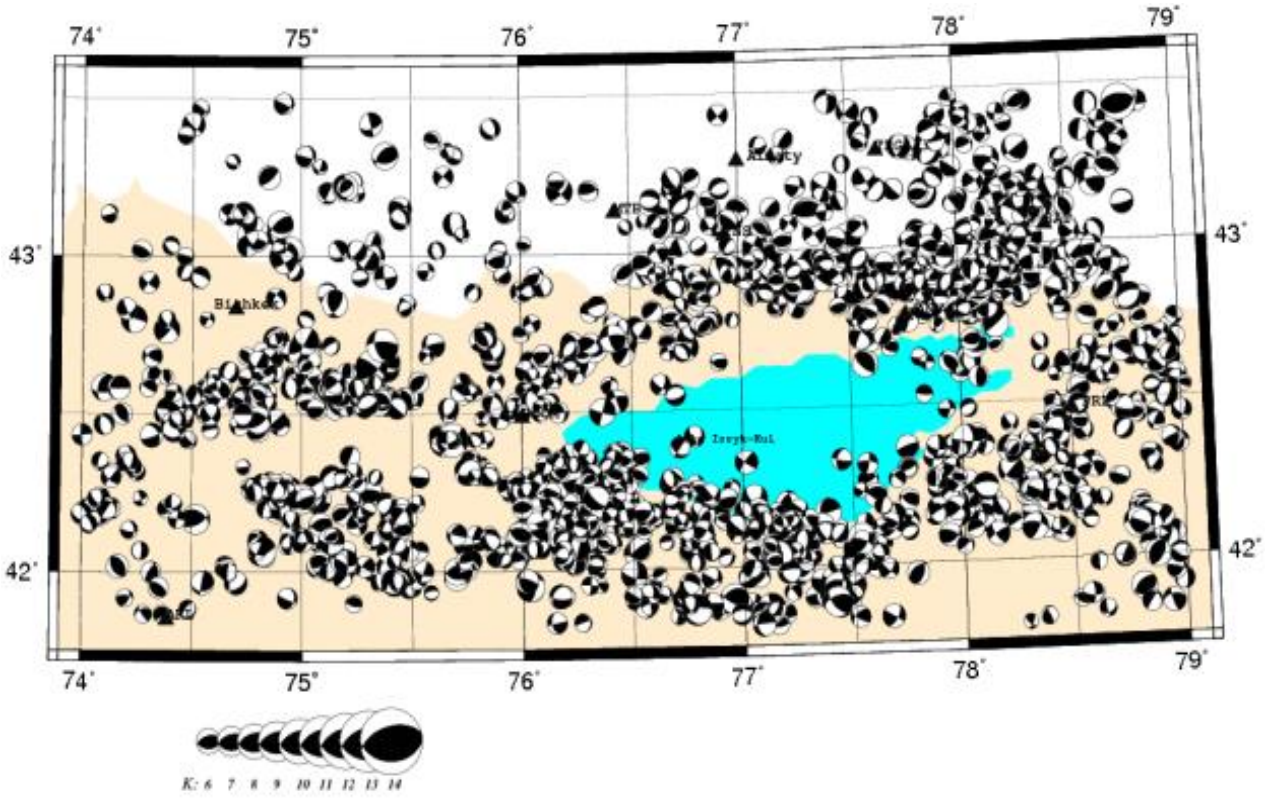


Figure 5 - Focal mechanisms of earthquakes in the polygon. Diagram of focal mechanisms of earthquakes with K=7-14 for the period from 1991 to 2024

To obtain a general idea of the modern tectonic stress field, we present some results of the study of the focal mechanisms of earthquakes at the test site. Figure 5 shows the distribution of focal mechanisms for 1736 earthquakes that occurred at the test site during the period 1991-2024. In the foci of the studied earthquakes, reverse and strike-slip types of movements predominate. The position of the nodal planes, in general, coincides with the position of geological faults, tracing mainly from west to east. The axes of the main compression and extension stresses in the earthquake foci of the polygon show different orientations.

Apparently, the process of occurrence of strong earthquakes according to the analysis of earthquake foci mechanisms occurs in various types of seismotectonic deformations and stresses of the earth's crust. This is the subject of further research.

According to the new catalogue, 95 strongest and catastrophic earthquakes with energy class K=12-18 have occurred at the testing ground, starting from the historical period to the present day (Fig. 6). The analysis showed that in certain places (areas) strong earthquakes have not been observed for a long time. In other words, seismic gaps of the 1st kind are revealed on the territory of the testing ground (Mogi, 1988). In the North Tien Shan seismically active zone, 5 seismic gaps are noted, three of them are located in the south of Bishkek, two in the epicenter area of the Kemin 1911 and Chilik 1889 catastrophic earthquakes. The remaining seismic gaps, numbers 6, 7, 8, are in the South Issyk-Kul seismically active zone. Thus, 8 areas of expected strong earthquakes have been identified at the Bishkek prognostic testing ground. For example, it can be said that only in the Bishkek sector of the Northern Tien Shan, according to our analytical materials, it is possible to indicate the presence of 5 seismic windows (gaps), which is shown in Fig. 6.

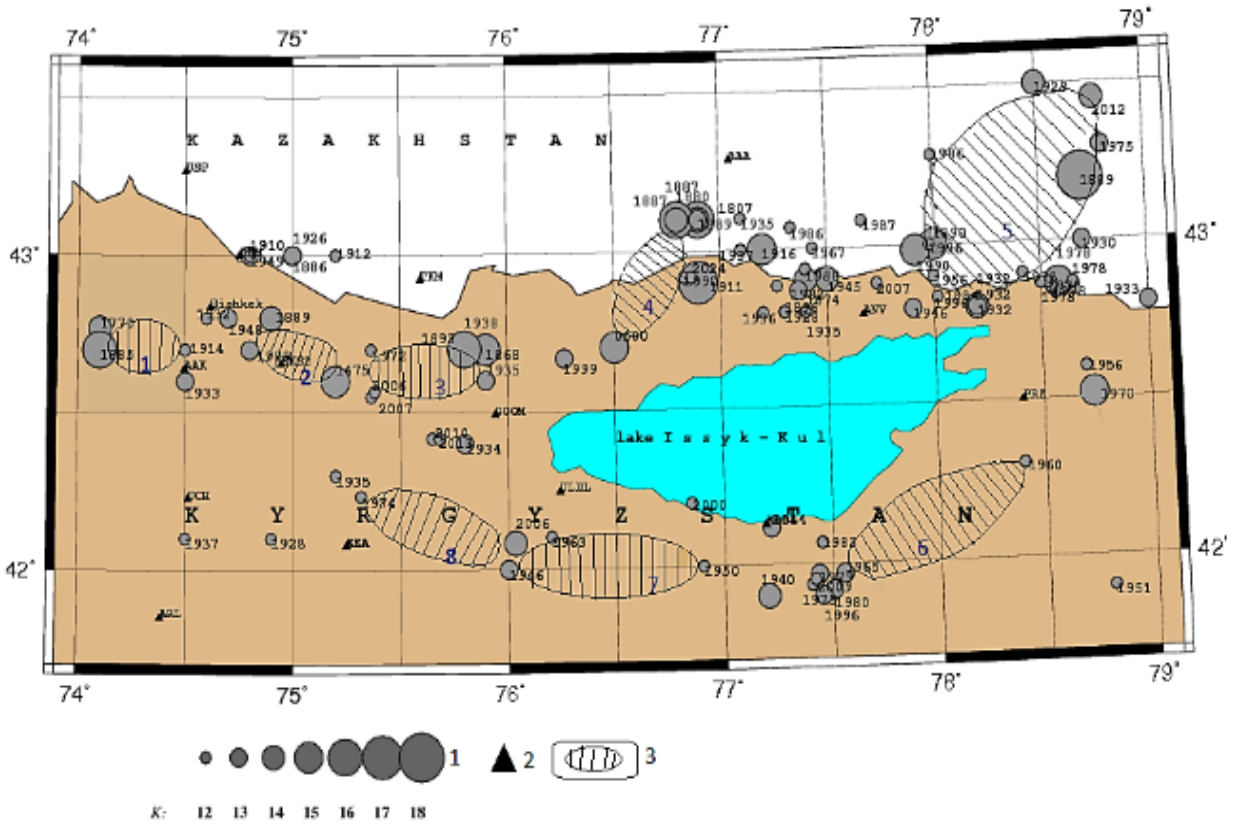


Figure 6 - Map-scheme of areas of expected strong earthquakes of the polygon based on the distribution of epicenters of 95 strong earthquakes.
1 - earthquake epicenters (K=12 - 18), 2 - seismic station,
3 - area of expected earthquakes.

Hydrogeochemical (HGH) studies in Kyrgyzstan have been conducted since 1978 on the basis of oil circulations of thermal waters Alamedin, Issyk-Ata, Jety-Oguz, Karaoi in zones of active faults. At HGH stations, continuous observations are carried out on wide complexes of parameters of self-flowing thermal waters: Rn, He, CO2, H2, Hg, F and others with an interval of measurements from continuous to once a day. At the observation stations of the test site, GGH precursor anomalies of more than ten strong earthquakes (K=13-17) were recorded, the period from the first days to months before the earthquakes at a distance of 30 to 350 km from the epicenter. Geochemical precursor

effects are usually expressed in the form of bay- and peak-shaped and pulsed concentration bursts of components (15-100%) against the background of their stable time course with rapid attenuation of anomalies after the events. The prospects of the GGH method of searching for precursors, especially at the stage of short-term forecasting, require improvement of the methods for identifying precursor signals against the background of station regime observations of measured parameters.

Research into the fluid regime of groundwater with the aim of searching for hydrogeochemical (HGC) and hydrogeodynamic (HGD) precursors of strong earthquakes in Kazakhstan and Kyrgyzstan allows us to conclude that these indicators (flow rate, or pressure of self-flowing water and level in wells) are quite informative as precursors of earthquakes [3].

Conclusion

At present, the ideology of forecast observations should be based on tracking the dynamics of the development of major earthquake foci at complex forecasting sites. The experience of recent years has shown the need for centralization of observations and operational data processing in the center of expert assessment, taking into account the influence of external fields and the development of cyclic processes.

In this regard, in the future, forecast work should be based on the processing of a large array of data, taking into account the seismic patterns of the controlled territories.

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INTERCONNECTION OF GEODYNAMIC PROCESSES IN THE CAUCASUS AND ADJACENT REGIONS (TURKEY, IRAN)

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ABSTRACT

This article is dedicated to the study of the tectonic evolution of the Caucasus within the context of the central segment of the Alpine-Himalayan orogenic belt, including the adjacent territories of Turkey and Iran. Based on paleotectonic and geophysical data, including the research of A.A.Belov (1986), R.Kolman (1974), N.Kelder (1975), N.Falcon (1977), V.E.Khain (1990), F.Ahmedbeyli (2010), Cowgil (2016), Forte (2015), T.Kengerli (2018) and others, the stages of regional formation from the Mesozoic to the present are analyzed. It is established that the Caucasus, Turkey, and Iran initially constituted a single tectonic block associated with Gondwana, the collapse of which during the Jurassic period and the subsequent formation of the Red Sea Rift led to their tectonic differentiation. Special attention is given to the role of Arabian Plate movement, the influence of compression, and autonomous geodynamic processes in the development of structures such as the Greater and Lesser Caucasus, Pontides, Taurides, Elburz, and Zagros, as well as differences in geological structure, volcanic activity, and rock distribution. An analysis of GPS data (2018–2024) and Lode-Nadai coefficient maps (2019–2024) reveals a shift in dominant stresses in the region—from extension in 2019–2022 to compression in 2023–2024 linked to tectonic activity and earthquakes. Linear seismic zones reflecting the region's high seismicity are identified, including events such as the Shamakhi (1902), Spitak (1988), and Racha (1991) earthquakes. In conclusion, it is emphasized that the tectonic evolution of the region is driven by both horizontal and vertical movements, and the Caucasus, Turkey, and Iran remain interconnected without breaking into separate plates. This study is significant for assessing seismic hazards and predicting geodynamic processes.

Keywords: *Caucasus, Turkey, Iran, Alpine-Himalayan belt, tectonics, geodynamics, Gondwana, Red Sea Rift, seismicity, GPS, Lode-Nadai coefficient.*

ВЗАИМОСВЯЗЬ ГЕОДИНАМИЧЕСКИХ ПРОЦЕССОВ КАВКАЗА И СОСЕДНИХ РЕГИОНОВ (ТУРЦИЯ, ИРАН)

Казымов И.Э., Казымова С.Э.

АННОТАЦИЯ

Статья посвящена исследованию тектонической эволюции Кавказа в контексте центрального сегмента Альпийско-Гималайского горно-складчатого пояса, включая прилегающие территории Турции и Ирана. На основе палеотектонических и геофизических данных, включая исследования А.А.Белова (1986), Р.Колмана (1974), Н.Кельдера (1975), Н.Фолкона (1977), В.Е.Хаина (1990), Ф.Ахмедбейли (2010), Ковгила (2016) [3], Форте (2015), Т.Кенгерли (2018) и др., анализируются этапы формирования региона с мезозоя до настоящего времени. Устанавливается, что Кавказ, Турция и Иран изначально составляли единый тектонический

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блок, связанный с Гондваной, распад которой в юрском периоде и последующее формирование Красноморского рифта обусловили их тектоническую дифференциацию. Особое внимание уделено роли движения Аравийской плиты, влиянию сжатия и автономных геодинамических процессов на развитие структур (Большой и Малый Кавказ, Понтиды, Тавриды, Эльбурс, Загросс), а также различиям в геологическом строении, вулканической активности и распределении пород. Анализ данных GPS (2018–2024) и карт коэффициента Lode-Nadai (2019–2024) демонстрирует смену доминирующих напряжений в регионе – от растяжения в 2019–2022 годах к сжатию в 2023–2024 годах, что связано с тектонической активностью и землетрясениями. Выделяются линейные сейсмические зоны, отражающие высокую сейсмичность региона, включая такие события, как Шемахинское (1902), Спитакское (1988) и Рачинское (1991) землетрясения. В заключение подчеркивается, что тектоническая эволюция региона определяется как горизонтальными, так и вертикальными движениями, а Кавказ, Турция и Иран сохраняют взаимосвязь, не разделяясь на отдельные плиты. Работа имеет значение для оценки сейсмических рисков и прогноза геодинамических процессов.

Ключевые слова: Кавказ, Турция, Иран, Альпийско-Гималайский пояс, тектоника, геодинамика, Гондвана, Красноморский рифт, сейсмичность, GPS, коэфициент Лоде-Надаи.

QAFQAZ VƏ QONŞU REGIONLARIN (TÜRKIYƏ, İRAN) GEODINAMIK PROSESLƏRININ QARŞILIQLI ƏLAQƏSİ

Kazımov İ.E., Kazımova S.E.

XÜLASƏ

Məqalə Türkiyə və İranın qonşu əraziləri də daxil olmaqla, Alp-Himalay dağ qırışığı qurşağının mərkəzi seqmenti kontekstində Qafqazın tektonik təkamülünün öyrənilməsinə həsr edilmişdir. Paleotektonik və geofiziki məlumatlara, o cümlədən A.A. Belov (1986), R. Koulman (1974), N. Kelder (1975), N. Falkon (1977), V.E. Xain (1990), F. Əhmədbəyli (2010), Kovgil (2016), Forte (2015), T. Kəngərli(2018) və başqaları bölgənin mezozoydan bu günə qədər formalaşma mərhələləri təhlil edilmişdir. Müəyyən olunmuşdur ki, Qafqaz, Türkiyə və İran ilkin olaraq Qondvana ilə əlaqəli vahid tektonik bloku təşkil edirdi. Yura dövründə Qondvananın parçalanması və sonrasında Qırmızı dəniz riftinin formalaşması bu regionların tektonik diferensiasiyasına səbəb olmuşdur. Xüsusi diqqət, Ərəbistan plitəsinin hərəkətinə, sıxılma proseslərinin təsirinə və avtonom geodinamik proseslərin Böyük və Kiçik Qafqaz, Pontidlər, Tavridlər, Elburs, Zaqros və digər struktur vahidlərinin inkişafına təsirinə yönəldilmişdir. Eyni zamanda, geoloji quruluş, vulkanik aktivlik və süxur paylanmasındakı fərqlər də araşdırılmışdır. 2018–2024-cü illər üzrə GPS məlumatlarının və 2019–2024-cü illər üzrə Lode-Nadai əmsal xəritələrinin təhlili göstərir ki, regionda 2019–2022-ci illərdə dominant gərginlik rejimi dartılma (ekstensiya) olub, 2023–2024-cü illərdə isə sıxılma (kompressiya) üstünlük təşkil edib. Bu dəyişikliklər tektonik aktivlik və zəlzələlərlə bağlıdır. Yüksək seysmikliyə malik xətlər boyunca yerləşən seysmik zonalar müəyyən edilmişdir, o cümlədən 1902-ci il Şamaxı, 1988-ci il Spitak və 1991-ci il Raça zəlzələləri kimi hadisələrə diqqət yetirilmişdir. Nəticə etibarilə vurğulanır ki, regionun tektonik təkamülü həm üfüqi, həm də şaquli hərəkətlərlə müəyyən olunur və Qafqaz, Türkiyə və İran vahid tektonik əlaqəsini qoruyaraq ayrı-ayrı plitələrə parçalanmır. Bu araşdırma seysmik risklərin qiymətləndirilməsi və geodinamik proseslərin proqnozlaşdırılması baxımından əhəmiyyətlidir.

Açar sözlər: *Qafqaz, Türkiyə, İran, Alp-Himalay qurşağı, tektonika, geodinamika, Qondvana, Qırmızı dəniz rift sistemi, seysmiklik, GPS, Lode-Nadai əmsalı.*

Introduction

The Caucasus, along with key tectonic elements of Turkey, Iran, Russia, as well as the Black Sea and Caspian basins, forms part of the central segment of the Alpine-Himalayan orogenic belt. This belt has undergone a long and multi-stage process of geotectonic and geodynamic development. According to paleotectonic studies conducted by A.A.Belov in 1986, during the early stages of Alpine orogenesis, the present-day outlines of the belt were not yet clearly defined. At that time, vast territories were occupied by the Meso-Tethys Ocean, as well as large fragments of Gondwana and young epigeric platforms [6, 15].

An analysis of available data indicates that by the mid-Mesozoic period, around the beginning of the Early Cretaceous, the contours of the Alpine belt started to become more distinct, although major sections, such as the Arabian and Punjab segments, were not yet fully formed. Different regions of the Alpine fold belt exhibit variations in the intensity and frequency of tectonic movements, levels of volcanic activity, differences in the structure of Mesozoic-Cenozoic deposits at various depths, the development of deep fault networks, as well as lateral propagation of folding deformations and other processes [4, 15].

In the geophysical fields of the fold-block structure of the Greater Caucasus, a negative gravity field is observed, with an intensity of up to -50 mGal on the outer periphery of the structure and up to -130 mGal in areas associated with Neogene-Quaternary volcanic activity. The magnetic field varies from -0.5 to +1.0 nT, while in certain areas it can reach -15.6 nT to +3–5 nT, reflecting the geological characteristics of the pre-Jurassic basement [26].

The primary first-order Alpine structure within the fold-block system of the Greater Caucasus is the fold-block uplift of the Main Ridge and the North Caucasian marginal massif. The structural framework of the Main Ridge uplift is inherited from the Hercynian basement structure, and its precise delineation is complicated by modern erosion of the sedimentary cover.

The Caucasus within the Alpine-Himalayan Belt

The Caucasus, in combination with adjacent countries such as Turkey and Iran, represents a significant geological entity with a highly complex tectonic organization. Following the collapse of the Gondwana supercontinent, this territory fragmented into separate large blocks (microplates or microcontinents), each possessing unique characteristics in terms of internal structure, geotectonic evolution, fold structures, magmatism, and other features. By the beginning of the neotectonic stage (approximately in the Oligocene), the main structural elements of the region – the Caucasus, Pontides, Taurides, Elburz, Zagros, as well as the Black Sea and Caspian basins – had acquired outlines close to their present-day configuration (Fig.1). These structures are bounded to the north by the Scythian Plate, to the south by the Arabian Plate, to the east by the Lut Block (Central Iran), and to the west by the Rhodope Massif (eastern part) [4, 10].

After the collapse of Gondwana in the Jurassic period, this vast area separated from the Afro-Arabian block, maintaining its integrity until the mid-neotectonic stage. During this period, the formation of the Red Sea Rift began, leading to the north-eastward movement of the Arabian Plate. As noted by R.Coleman [21] in 1974, the rift formed in post-Miocene time, at the late stage of neotectonic development, and, according to GPS data, its expansion process continues to this day.

Before their division into separate microplates, the Caucasus, Turkey and Iran developed within a single geodynamic regime, experiencing horizontal compression between the Arabian Plate and the East European Platform. According to N.Kelder (1975) [20], the Iranian segment also took an active part in this process from the beginning of the Miocene (about 17 million years ago). However, each of these regions continued to evolve autonomously, especially at the stage of neotectonic development, when the final tectonic differentiation of such structures as the Greater

and Lesser Caucasus, the Kura-Rion Depression, the Anatolides, the Taurides, the Elburz and the Zagross occurred. Each of these large structures is distinguished by the types of folding, their morphology (linear, arc, etc.), the time of formation, the relationship with volcanic complexes and magmatic formations, as well as the degree of complexity of rupture deformations and the location of faults [16].

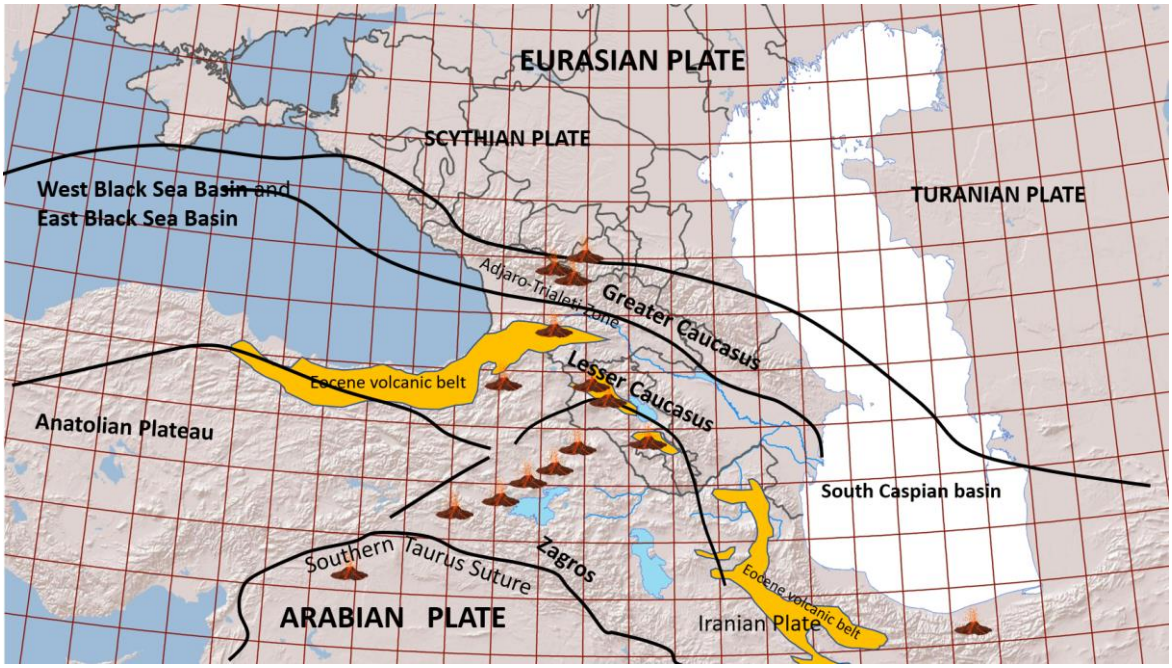


Figure1. Mesozoic-Cenozoic tectonic zones of the Black Sea-Crimean-Caucasian-Caspian region in their modern boundaries [15, 23,24]

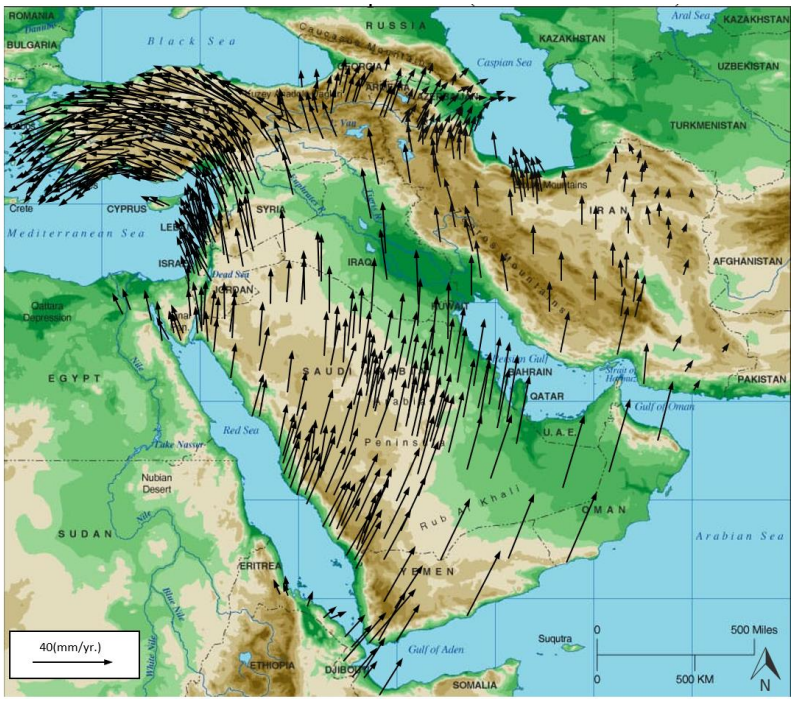


Figure 2. Horizontal movement directions among GPS stations installed in Turkey, Arabia, Iran, and Azerbaijan (2018-2023) [1, 2, 8, 9]

Geodynamic features of the region.

Within each region, zones with different characteristics, mentioned above, are distinguished. In the South Caucasus, such zones include the southern slope of the Greater Caucasus, its southeastern plunge, the northeastern, central, and southwestern parts of the Lesser Caucasus, and the Talysh folded zone. In Iran, according to the classification of N. Falcon (1977) [25], three main zones are distinguished: a region of complex structure with metamorphic rocks, a zone of imbricated thrusts, and a zone of simple folds of the foothills. These zones are parts of the large megastructure of Zagross and adjacent territories. For Turkey, E.Ilkhan (1977) [19] described zones such as the Pontides, Taurides, areas of marginal folds and depressions, including regions of Neogene and modern volcanism, distributed over these four zones. The structural zone of the Pontides is elongated in the latitudinal direction, while in the Taurides, arcuate folding forms are sometimes found. In this aspect, some similarities are observed between the Caucasus and Turkey. The orientation of the structures of the Greater Caucasus and the Pontides is very similar, while in the Lesser Caucasus and southwestern Turkey, arcuate structures predominate. The general sizes of these regions are also similar: the length of the Caucasus is about 1125 km, Turkey - 1300 km, and their transverse sizes vary from 300-500 km for the Caucasus to 380-700 km for Turkey. Something in common can be noted in geological characteristics, such as the distribution of sedimentary, volcanic and metamorphic rocks and fault deformations. As can be seen, the fragments of Gondwana - the Caucasus, Turkey, and Iran - developed under the influence of both regional compression and partially autonomous geodynamic processes. This was reflected in differences in the deep structure and surface structure, heterogeneity of the thickness of the sedimentary layer and the earth's crust, and variations in the distribution of rocks on the surface. For example, in Turkey, sedimentary rocks make up about 40%, volcanic rocks - 25%, metamorphic rocks - 10%, and ultramafic rocks - 25%, intrusions are rare. In Iran, according to J. Stecklin (1979) [28], sedimentary rocks occupy 50%, metamorphic rocks - 45%, and intrusive rocks - 5%. In the South Caucasus, approximately: sedimentary rocks - 50%, volcanic rocks - up to 30%, metamorphic rocks - 15%, intrusions - 5%.

GPS studies of the Caucasus, Turkey, and Iran

These differences indicate that deep processes in the lithosphere of these geostructures developed under partially independent geodynamic regimes that varied in time and space. The direction of compression associated with the movement of the Arabian Plate plays an important role here (Fig. 2).

According to GPS measurements, the vectors of horizontal compression movements in Iran and the Caucasus are predominantly oriented to the north, with minor deviations to the northeast.

In the east of Turkey, the direction of modern movements gradually changes to the northwest, then in the central part, to the latitudinal, and in the west of regions, to the southwest. The boundary of these changes coincides with a significant tectonic element - the Transcaucasian submerged uplift (north-south), which crosses the entire Caucasus and extends to the border zones of Turkey and Iran.

The general picture of horizontal movements indicates a translational-rotational movement of the Arabian Plate, probably caused by the uneven expansion of the Red Sea rift. Its modern transverse dimensions are 175 km in the northern part, 265 km in the central part and 375 km in the south. Thus, the speed of movement of the Arabian Plate is significantly higher on its southern edge, and the direction of movement is northeast. The northern part of the plate acts as a kind of support, where the speed of horizontal movements is lower.

As already mentioned, the separation of the Arabian Plate from Africa began in the Miocene, at the late neotectonic stage. The researchers suggest that GPS data on modern velocities and directions of horizontal movements can be extrapolated to the entire late orogenic stage, although taking into account periodic changes in these parameters. The presented maps (Fig.3) show the

distribution of the Lode-Nadai coefficient in the Middle East, Caucasus, and Turkey region for two time periods: the left map is data for 2019–2022; the right map is data for 2023–2024 yy. The maps demonstrate how the tectonic state of the region changes over time, which is important for assessing seismic risks and forecasting geodynamic processes.

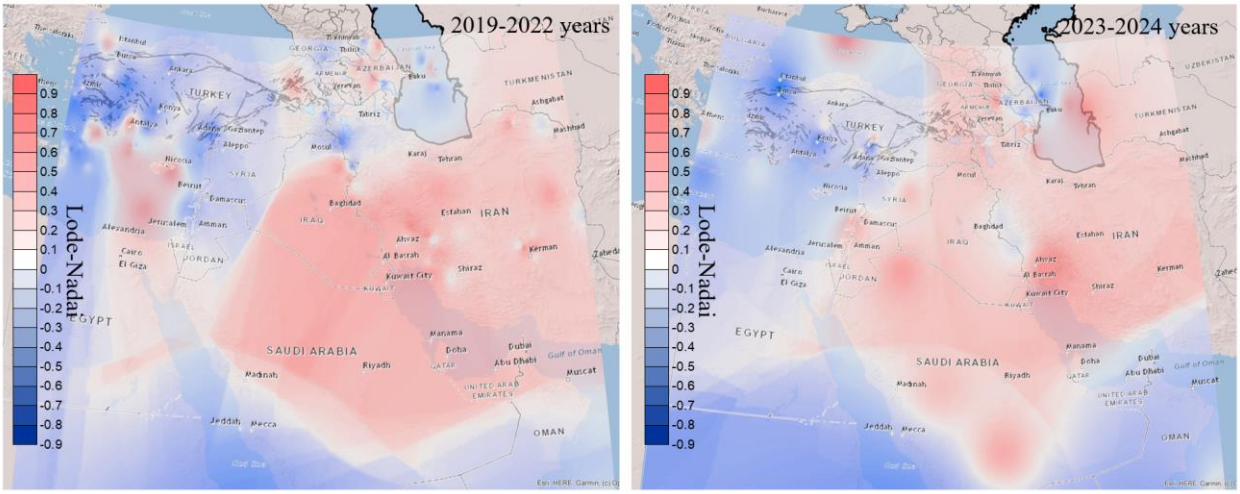


Figure 3. Distribution map of the Lode-Nadai stress coefficient for earthquakes that occurred in 2019-2022 and 2023-2024

The color scale to the right of the maps reflects the values of the Lode-Nadai coefficient, which characterizes the type of stress state in the earth's crust: red shades (positive values, up to 0.9, $\sigma1 > \sigma2 > \sigma3$) indicate dominant extension (rock separation), which is typical for areas where normal faults occur; blue shades (negative values, up to -0.9, $\sigma1 < \sigma2 < \sigma3$) – indicate the predominance of compression, which is typical for areas where reverse faults or thrusts are formed; neutral (white) areas are zones where the stress state is balanced [8, 12, 13]. During the period 2019–2022yy, extensional stresses (red areas) prevailed, especially in: Iran – a wide extension zone in the central and southern parts of the country (Tehran, Isfahan, Kerman); Saudi Arabia – a significant area of positive values, indicating tectonic extension; Northwestern Turkey – areas of positive values are also noticeable, which may be associated with the activity of the North Anatolian Fault. Compressional areas (blue shades) were comparatively less pronounced, but small areas of negative values were present in eastern Turkey and western Iran. There are also signs of compressive stresses in the eastern Mediterranean and the Caucasus regions. In 2023–2024, compared to the previous period, there was a noticeable redistribution of stresses: an increase in compression (blue areas).

In the Caucasus region, especially in Azerbaijan and Georgia, a significant increase in negative values of the Lode-Nadai coefficient is observed. This may be due to regional tectonic activity and stress redistribution. In northern Turkey, compression areas have also increased, consistent with the North Anatolian Fault activity. Pronounced compressive stresses have also appeared in Egypt and the eastern Mediterranean. A decrease in extension is observed in several regions. In Iran and Saudi Arabia, a weakening of extension is observed compared to the previous period. In Turkey, the areas of positive values have decreased, which may indicate a redistribution of stresses after earthquakes. In general, during the period under review, there was a change in the dominant stress mechanism. If 2019–2022yy, extension stresses prevailed (especially in Iran and Saudi Arabia in 2023–2024yy, an increase in compression is observed, especially in the Caucasus, northern Turkey, and the eastern Mediterranean. Such changes may be associated with regional geodynamic processes, including:

displacement and activation of fault zones, consequences of recent earthquakes, deep processes in the lithosphere, reflecting the redistribution of stresses.

Tectonic-geomorphological structure of the region

In the areas of the Greater and Lesser Caucasus, Pontides, Taurides, Elbrus, and Zagros, sedimentary strata of varying thickness accumulated, represented by terrigenous, carbonate, and, in places, flysch deposits. In the orogenic zones, Mesozoic-Paleogene deposits formed regional thrusts large layers to the south, sometimes creating overturned folds [16]. In these tectonic zones, volcanic activity manifested with varying intensity, sometimes covering significant areas. An extensive strip of ophiolitic tectonomagmatic complex is associated with the orogenic structures of Elbrus, Lesser Caucasus, and Pontides. In the Paleocene-Eocene period, differentiated uplifts created a pronounced relief contrast (Fig. 4).

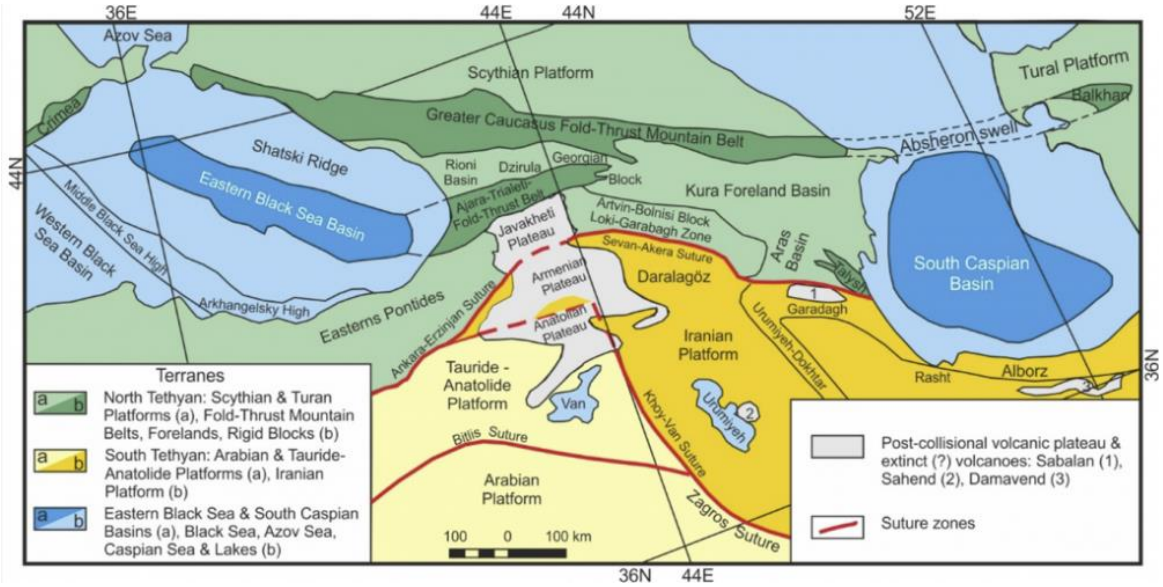


Figure 4. Correlation map of the central tectonic units of the Caucasus and adjacent areas [6]

Analysis of available data shows that at the beginning of the Mesozoic, the Caucasus and adjacent regions of Turkey and Iran represented a single tectonic block associated with Gondwana, whose disintegration, according to scientists, occurred in the Late Cretaceous. The African continent, including the Arabian platform, remained intact until the formation of the Red Sea rift.

After tectonics, and the development of the Caucasus, Turkey, and Iran was analyzed from the standpoint of this theory. Such elements as the Rio-Shirvan, Middle Kura, Transcaucasian, Turkish, and Lut plates, the Jeyranbatan-South Kura microplate, and the Iranian microcontinent were identified. Their boundaries were determined by the linear concentrations of earthquake epicenters, similar to the boundaries of global lithospheric plates. As noted by B.Isaacs, J.Oliver and L.Sykes in 1974 [14], "many of the key data obtained by seismology are so obvious that they are often accepted without in-depth analysis of their nature; they are in good agreement with the concept of a new global tectonics, including a system of seismically active zones dividing the earth's surface into stable blocks."

Seismostatistical data show the presence of linear seismically active zones in the Caucasus, Turkey, and Iran. Examples include the strip of the southern slope of the Greater Caucasus, Pontides, Zagros (all sublatitudinal), as well as the East Azerbaijan (meridional) and Central Caucasian zones (along the Transcaucasian uplift). Clusters of epicenters often form narrow but relatively short strips. Many authors who distinguished these plates, microplates, and microcontinents sometimes did not

take into account the depth and types of seismic sources, the frequency of strong earthquakes, their intensity, the connection with different depth levels, or lateral displacements of the plates. Also, insufficient attention was paid to the transregional geodynamic regime. Today, it is known that the seismic activity of the lithosphere has changed over time, which leads to more frequent strong earthquakes in Turkey and Iran to those in the Caucasus (according to statistics). The features of the geomorphology of the orogenic structures that form the extended mountain ranges in the region are also important. The ranges of Elbrus, Talysh, Lesser Caucasus, and Pontides stretch for almost 2300 km, in places forming arcs with bulges to the south (Elbrus, Eastern Pontides) or the north (Lesser Caucasus, Western Pontides). The Greater Caucasus is a linear megastructure 1250–1300 km long. The Tauride Mountains and the Zagros Range form a single strip about 3,000 km long, starting in southwestern Turkey and extending to the Persian Gulf coast in a gently curved arc to the north.

There is no convincing evidence for stable plate or microplate boundaries in the modern tectonic structure of the South Caucasus, Turkey, and Iran. Some scientists' attempts to interpret suture zones such as the Anatolian-Middle Kura as plate boundaries are not supported by specific data. Modern geophysical studies show that the Middle Kura zone is only a deep regional fault that does not penetrate below the lower crustal boundary.

According to the authors presented in [16], the folded mountain systems of the region cannot be explained solely by the collision of plates or microplates, although this process is important. An essential role in the formation of orogens was played by vertical tectonic movements, which, in combination with horizontal movements, determined the main features of modern geology. Another feature of the tectonic-geomorphological structure of the region is the relationship of the main tectonic elements of the Caucasus, Turkey, and Iran. Geological and tectonic maps show that key folded and orogenic structures smoothly pass from one region to another without abrupt changes. An example is the Elborz-Talysh-Lesser Caucasus-Pontides and Zagross-Taurides chains.

According to the results of the study [16], it was established that after the separation of the Arabian Plate from Africa in the Miocene, associated with the expansion of the Red Sea rift, a vast territory including the Caucasus, Turkey and Iran was not divided into separate plates, microplates or microcontinents, as some researchers assumed without sufficient grounds. Proponents of the "plate" interpretation have often revised their conclusions based on plate tectonics, but the area remained unified even after the breakup of Gondwana, when large plates such as Africa, Australia, India, and Antarctica separated.

Seismicity

The Caucasus region, being part of the ongoing continental collision between the Arabian and Eurasian plates, is characterized by moderate to high seismicity. Destructive earthquakes in this area have repeatedly caused significant loss of life and property, including the Shamakhi earthquake (Azerbaijan, 1902), the Spitak earthquake (Armenia, 1988), and the Racha earthquake (Georgia, 1991). The eastern part of the North Caucasus (Dagestan, Chechnya, Ingushetia, North Ossetia) is also subject to powerful seismic events, including earthquakes in Dagestan (1830, 1970), Chechnya (1976), and Karachay-Cherkessia (Teberda, 1905).

Figure 5 presents a map of earthquake epicenters in the Caucasus and neighboring regions with a magnitude of 4.5 and above. Earthquake data were taken from the catalogues of the Republican Seismological Service Centre, as well as from the EMSC website. Below is a brief overview of seismic activity within the Earth's crust in this area. Earthquake focal points are typically associated with tectonic faults of various orientations. However, of the East Anatolian and North Anatolian Faults, as well as the Greater Caucasus Thrust Zone, there are no clearly defined linear chains of seismic events on the map. Overall, earthquake epicenters are unevenly distributed. The western part of the Caucasus Mountain belt is characterized by relatively low seismic activity.

However, significant historical earthquakes have occurred near Novorossiysk, including the Lower Kuban events in 150 BCE (Ms=6.1) and 1879 (Ms=6.0). East of this region, there is a noticeable decrease in the number of significant earthquakes. However, further east, seismic activity increases again, with events of magnitude 6–7 concentrated along the southern slope and foothills of the Greater Caucasus Thrust.

The number of large earthquakes rises in the central part of the Greater Caucasus Thrust, near the active Kazbek volcano. These events are distributed along the range's southern and northern slopes. In the northeastern foothills, the epicenters of the strongest earthquakes are located closer to the foreland zone. The eastern part of the Caucasus range exhibits the highest seismic activity. This region has recorded the strongest earthquakes in the Caucasus, from 742 CE to 2012, with magnitudes ranging from 5.7 to 7.8. The Shamakhi region stands out in particular, having experienced dozens of powerful earthquakes. This area's most recent strong event occurred in February 2019, with Mw=5.5.

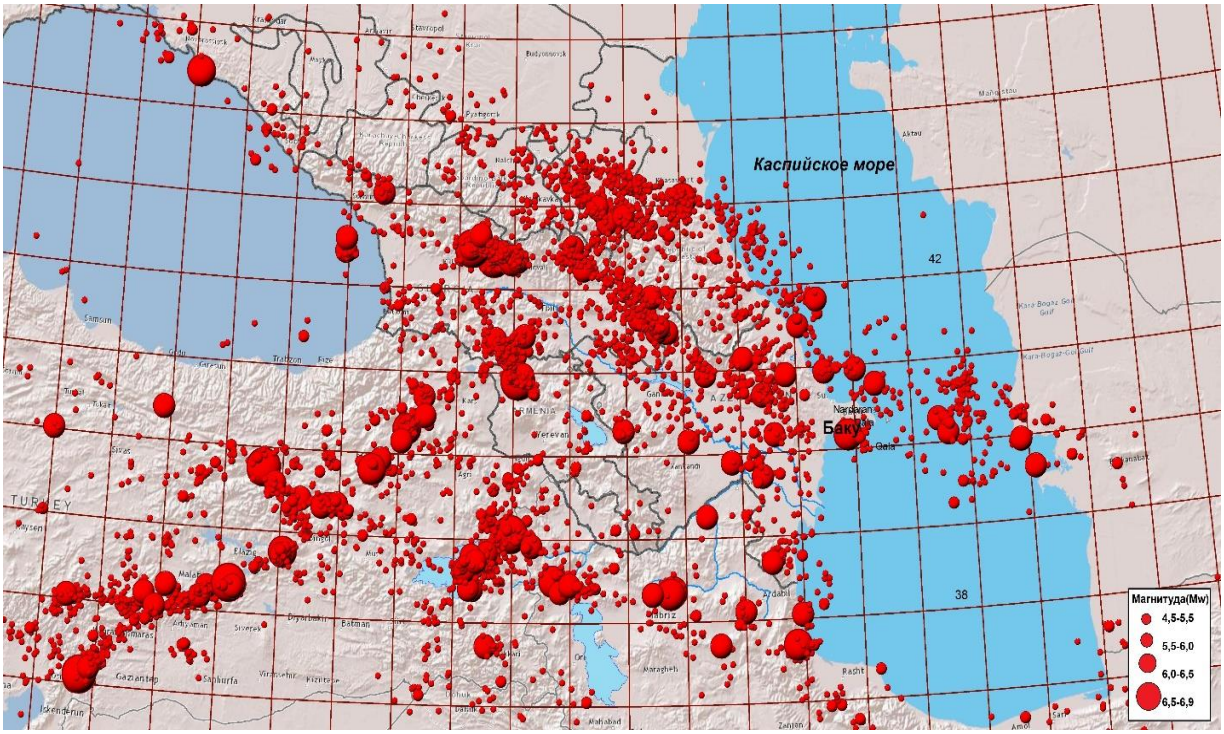


Figure 5. Map of earthquake epicenters in the Caucasus and adjacent territories with a magnitude of 4.5 or more for 1990–2024

High seismic activity is also observed along the southern boundary of the Scythian Plate, in the Terek-Caspian Depression and Dagestan. In these areas, earthquakes with magnitudes of 5.7–6.8 have been recorded between 650 and 1976 CE. Approximately 95% of all earthquakes in the Greater Caucasus Thrust Zone and 85% within the Scythian Plate occur within the upper 20 km of the Earth's crust. Most events are concentrated at depths of 5 and 10 km, while in the Scythian Plate, earthquakes also occur at depths of 15–25 km. In the Greater Caucasus Thrust, about 4% of earthquakes occur at depths of 21–40 km, while 1% occur within the 41–80 km range. In the Scythian Plate, 12% of events have been recorded at depths of 21–45 km, and 3% at depths exceeding 46 km, reaching as deep as 150 km.

Data analysis indicates that earthquakes with magnitudes below five predominantly occur in sedimentary deposits, whereas events with $M \geq 5$ are associated with granitic rocks.

According to Akhmedbeyli [16], in the pre-neotectonic period, the Caucasus, Turkey, and Iran constituted a single large tectonic block or terrane, which is confirmed by the following facts. The

central segment of the Alpine-Himalayan belt is characterized by high seismic activity. According to B. Isaacs et al. (1974) [14], most earthquake epicenters are concentrated along linear zones that form a trapezoidal configuration. The diagrams of V.E.Khain and L.I.Lobkovsky (1990) [26] demonstrate not only crust-mantle, but also mantle earthquakes, with linear seismic zones 1,750 km (southwestern boundary), 800 km (northwestern), 1,300 km (northeastern), and 1,400 km (eastern) long. The territory's total area is 1,677,500 km², and the width of the linear seismic zones does not exceed 80–110 km, indicating a high concentration of epicenters.

These linear zones are reflected on the Earth's surface and in the deep layers of the lithosphere as transregional deep faults penetrating the crust and upper mantle. Seismic activity of linear seismic zones is associated with foci at different depths, but is manifested unevenly: earthquakes occur fragmentarily, and the velocities and directions of horizontal movements measured by GPS differ significantly. The modern tectonic structure and seismicity of linear seismic zones are heterogeneous. For example, the zone passing near the eastern part of the Black Sea Basin coincides with the convergence of Alpine and Cimmerian structures, where many epicenters are concentrated. Here, the distances between the latitudinal Phanerozoic faults coming from the Black Sea Basin also decrease, and the contours of the granite-free crust narrow, as shown by N.A.Belyaevsky and A.E.Mikhailov (1980) [17]. Another linear seismic zone runs through Iran from northeast to southwest to the Persian Gulf, crossing the eastern part of the Elburz belt, the area of its junction with the Kopetdag, the southeastern part of the Zagros, and intermediate structures. According to J.Stecklin [28, 29] and N. Falcon (1977) [25], these structures are complex, with high tectonic activity in the Cenozoic. Orogenic processes in the Elburz were accompanied by increased compression, which reduced the transverse dimensions of the belt by about half. Most of the foci of crust-mantle earthquakes are concentrated along this seismic zone, while mantle earthquakes are rare, except the area near the coast of the Persian Gulf. Another linear seismic zone is characterized by seismically active structures such as the "Dagestan wedge" and the Makhachkala-Krasnovodsk fault, associated with earthquakes of 7-8 points, as well as the boundary between the Middle and South Caspian basins. Of particular interest are seismic zones with of mantle foci, which coincide with the folded structure of Zagros (e.g., Eppelbaum and Katz, 2017), then passes through the eastern part of the Tauride Mountains and stretches along the Pontides. These linear seismic zones are explained as the boundaries of the Caucasus-Turkey megablock, which underwent significant changes in the neotectonic period. Their destruction did not begin immediately: at the end of the Mesozoic, after the breakup of Gondwana, the African-Arabian continent, as a single plate, began to move to the north-northeast. According to the paleotectonic reconstructions of M.I.Rustamova (2001) [22], the Caucasus-Turkey-Iranian single microplate was located between the northern and southern branches of the Mesotethys, which closed before the beginning of the neotectonic stage. The geodynamic regime in this microplate was repeatedly activated or weakened unevenly in time and space, which is confirmed by changes in the intensity of tectonic movements, volcanism, metamorphism, geomorphological relief, large, folded structures, depressions, ophiolite belts, and other features.

Conclusions

The Caucasus occupies an important place in the Alpine-Himalayan belt; its tectonic evolution is associated with the breakup of Gondwana, the movement of the Arabian Plate, and complex geodynamic processes that formed the modern structure of the region under conditions of compression and autonomous development. By the middle of the Mesozoic period (Early Cretaceous), the outlines of the Alpine belt began to appear, although large segments such as the Arabian and Punjab had not yet fully formed. Different parts of the belt differ in the intensity of

tectonic movements, volcanic activity, sediment structure, fault development and the nature of folded deformations.

The Caucasus, Turkey, and Iran form a complex geological object. After the breakup of Gondwana in the Jurassic period, the region was divided into large blocks (microplates), each with unique structure, folding, and magmatism characteristics. By the beginning of the neotectonic stage (Oligocene), the main structures had formed: the Caucasus, Pontides, Taurides, Elborz, Zagross and adjacent basins, bounded by the Scythian Plate in the north and the Arabian Plate in the south. The formation of the Red Sea rift in the post-Miocene period caused the Arabian Plate to move to the northeast, affecting the region's geodynamics.

In the orogenic zones (Caucasus, Pontides, Elborz, Zagros), sedimentary strata accumulated, thrusts and overturned folds formed. Volcanic activity was significant, with ophiolite complexes in the Elborz, Lesser Caucasus, and Pontides. At the beginning of the Mesozoic, the Caucasus, Türkiye, and Iran formed a single block associated with Gondwana, the breakup of which occurred in the Late Cretaceous. Before the division into microplates, the Caucasus, Turkey, and Iran developed in a single compression regime between the Arabian Plate and the East European Platform. At the stage of neotectonic development, differentiation of structures (Greater and Lesser Caucasus, Anatolides, Elborz, Zagros) occurred, differing in folding types, volcanism, and faults. Zones with different characteristics are distinguished in the region: in the Caucasus - the southern slope of the Greater Caucasus, Lesser Caucasus, Talysh zone; in Iran - zones of metamorphic rocks, thrusts and folds; in Turkey - the Pontides, Taurides and volcanic areas. The Greater Caucasus and Pontides (Turkey) have a latitudinal orientation, while the Lesser Caucasus and southwest Turkey are arc structures. The length of the Caucasus is about 1,125 km, Turkey – 1,300 km; transverse dimensions: 300-500 km (Caucasus) and 380-700 km (Türkiye). The distribution of rocks varies: Turkey has more volcanic (25%) and ultramafic (25%) rocks, Iran has more metamorphic (45%) rocks, and the Caucasus has more sedimentary (50%) and volcanic (30%) rocks. Deep processes in the region developed partially autonomously, which is reflected in the differences in structure and rocks. GPS data show compression to the north in Iran and the Caucasus, and from the northwest to the southwest in Turkey, associated with the Transcaucasian uplift. The movement of the Arabian Plate is due to the expansion of the Red Sea rift (175–375 km in diameter), which is confirmed by GPS data.

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COMPREHENSIVE FIELD SEISMOLOGICAL RESEARCH AND PROSPECTS FOR EXPANSION OF THE SEISMOLOGICAL NETWORK IN THE REPUBLIC OF KAZAKHSTAN

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ABSTRACT

C A final review of complex field seismological studies and development of a network of seismological stations is conducted. The prospects for the development of complex seismological networks for the implementation of strong earthquake forecasting in the Republic of Kazakhstan on a probabilistic basis are described.

A final review of integrated field seismological research and the seismological research development network was carried out. The prospects for the development of complex seismological networks for the implementation of the forecast of strong earthquakes on the territory of the Republic of Kazakhstan on a probabilistic basis are described.

Key words: *seismological research, seismological monitoring, network of seismological stations, tectonic processes, earthquake forecast.*

QAZAXSTAN RESPUBLİKASINDA KOMPLEKS SEYSMOLOJİ ÇÖL TƏDQİQATLARI VƏ SEYSMOLOJİ ŞƏBƏKƏNİN GENİŞLƏNDİRİLMƏSİ PERSPEKTİVLƏRİ

A. Abdullayev, R. Həşimov, E. Yesenjigitova

XÜLASƏ

Kompleks çöl seysmoloji tədqiqatlarının və seysmoloji stansiyalar şəbəkəsinin inkişafının yekun icmalı aparılmışdır. Ehtimal əsasında Qazaxıstan Respublikası ərazisində güclü zəlzələlərin proqnozunun məqsədilə kompleks seysmoloji şəbəkələrin inkişaf perspektivləri təsvir edilmişdir.

Açar sözlər: *seysmoloji tədqiqatlar, seysmoloji monitorinq, seysmoloji stansiyalar şəbəkəsi, tektonik proseslər, zəlzələ proqnozu.*

КОМПЛЕКСНЫЕ ПОЛЕВЫЕ СЕЙСМОЛОГИЧЕСКИЕ ИССЛЕДОВАНИЯ И ПЕРСПЕКТИВЫ РАСШИРЕНИЯ СЕЙСМОЛОГИЧЕСКОЙ СЕТИ В РЕСПУБЛИКЕ КАЗАХСТАН

А. Абдуллаев, Р. Гашимов, Э. Есенжигитова

АННОТАЦИЯ

Проведен итоговый обзор комплексных полевых сейсмологических исследований и развития сети сейсмологических станций. Описаны перспективы развития комплексных

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сейсмологических сетей для реализации прогноза сильных землетрясений на территории Республики Казахстан на вероятностной основе.

Ключевые слова: *сейсмологические исследования, сейсмологический мониторинг, сеть сейсмологических станций, тектонические процессы, прогноз землетрясений.*

Kazakhstan is one of the most seismically active regions of the Asian continent, where large seismic disasters have repeatedly occurred in the recent past (Fig. 1). Since 1976, active research work on the seismic regime, seismic hazard assessment, as well as the creation of networks of seismological stations and earthquake forecasting have begun in Kazakhstan.



Figure 1 – Consequences of earthquakes in different years

In order to reduce the consequences of strong earthquakes occurring here with the development of forecasting methods for possible destructive earthquakes, a comprehensive multi-parameter seismological monitoring has been created in the territory of the Republic of Kazakhstan since 1976, which includes, in addition to various seismological methods, also comprehensive field seismological studies. The most important task of seismological monitoring is the rapid determination of the parameters of the largest earthquakes that pose a potential danger to the population and economy of the country. The results of such monitoring, obtained almost in real time, are used to forecast strong earthquakes. Another very important task is the most complete study of the seismic regime by recording all earthquakes, including the weakest ones. This is necessary for a detailed study of the tectonic activity of the earth's crust in the territory of the Republic of Kazakhstan and the development of probabilistic models of seismic hazard. Based on the results of seismological monitoring, maps of

seismic zoning and zoning of various levels are constructed and special norms and rules for earthquake-resistant construction are developed.

In the most general terms, the most important content of seismological monitoring is determining the location, strength and frequency of earthquakes, where "location" in this case means not only the local epicentral zone, but also the regional seismogenic structure. The problem of predicting the time and place of occurrence of strong earthquakes (SE) is a rather complex task and its solution is possible in two directions. The first is an instrumental study of regional seismicity using complex field studies. However, its capabilities are limited, on the one hand, by the difficulties of creating a sufficiently dense network of recording equipment, and on the other, by the duration of observations for accumulating statistically reliable information on extreme events. The second direction is seismotectonic. It is intended that the shortcomings of the first can be compensated for by historical-tectonic and geological analysis of the studied territory. In the optimal variant, these two directions complement each other. Determining the place of possible occurrence of earthquakes depending on the task and the degree of study of the territory can be considered in a sequential analysis of global, regional and local patterns.

Special attention should be paid to comprehensive field seismological studies in various fields: geophysical, geochemical, hydrogeochemical, hydrogeodynamic, deformation and the influence of external factors, which play a major role in collecting and analyzing comprehensive monitoring seismological data used in making strong earthquake forecasts, constructing seismic zoning maps and developing earthquake-resistant construction standards and rules (Fig. 2).

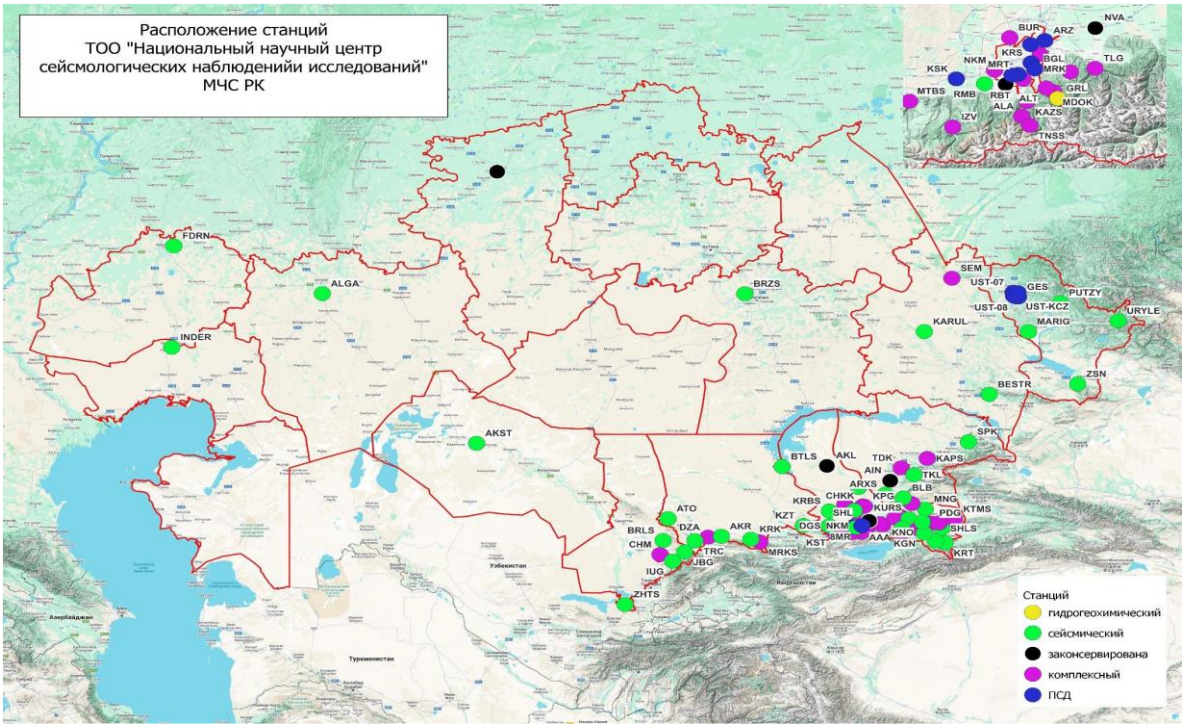


Figure 2 – Layout of seismological stations

Complex field seismological studies are systematic, continuous observations of the parameters of natural fields of the earth's crust, conducted with the purpose of recording its vibrations and searching for precursor effects of strong earthquakes in various fields. These observations include high-precision measurements of seismic data, geophysical fields, geochemical -hydrogeological parameters, as well as monitoring modern movements of the earth's crust and the behavior of some biological species in areas of increased tectonic activity.



Figure 3 – Complex seismological stations "Kurty" and "Saty"

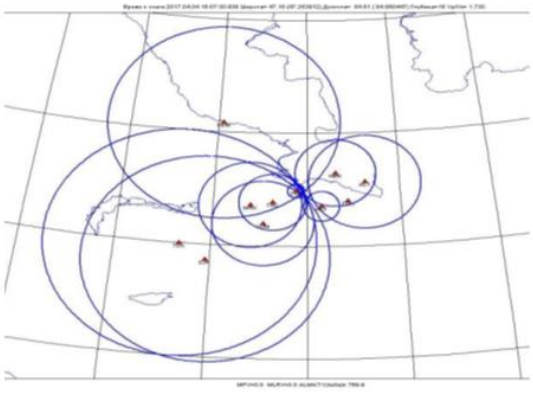
Over a 40-year period, predictive complex field seismic studies are carried out through a network of seismological, geophysical, and hydrogeological stations using continuous measurement of predictor parameters using various methods and observations depending on the geological conditions of the area where the seismological and other stations are located (the presence of tectonic faults, the outcrop of bedrock on the earth's surface, the possibility of laying self-flowing aquifers, the absence of factors that have a negative impact on the quality of seismological data).

At present, in order to implement comprehensive field seismological research at the network of seismological stations of the National Center for Seismic Research (NCSNI) on the territory of the Republic of Kazakhstan, the following methods of comprehensive seismological monitoring are being implemented:

1) Seismic monitoring. It is carried out by digital recording of seismic vibrations and seismic elastic waves generated in rocks by earthquakes with a wide dynamic range, necessary for recording both weak and strong earthquakes of various distances. Short-period equipment (periods from 0.02 to 10 sec.) with high sensitivity records earthquakes in the near zone. Long-period equipment (periods from 10 to 360 sec.) allows recording earthquakes both in the near zone and strong earthquakes at a distance of thousands of kilometers (Fig. 3);



Isoseist map South Saur earthquake 04.04.2017

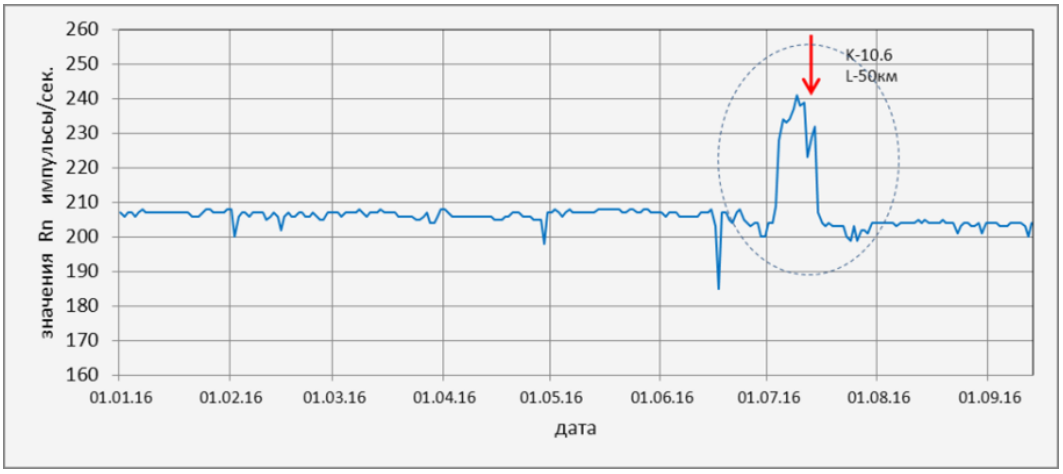


Definition scheme epicenter

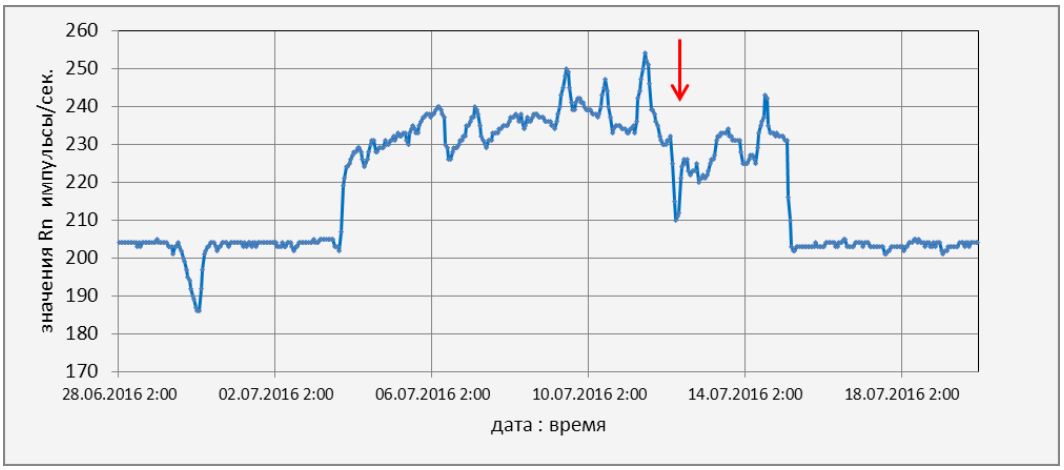
Figure 4 - Map of isoseismals of the South Saur earthquake of 04.04.2017. Earthquake Epicenter Determination Scheme

2) Geophysical monitoring. It is carried out by means of round-the-clock recording of parameters of geomagnetic and geoelectric fields using various geophysical methods (magnetometry, analysis of pulse flow of geoelectric fields). The main task of geophysical monitoring is to obtain long-term series of observations of variations in geophysical fields to provide observation materials for work on searching for precursors of strong earthquakes.

3) Hydrogeochemical and hydrogeodynamic monitoring is carried out by means of hydrogeological observations of variations in hydrogeodynamic, hydro- and gas-chemical parameters of groundwater and the formation of a hydrogeological data bank in order to search for precursor effects of strong earthquakes within the study area. Hydrogeological monitoring includes the analysis of chemical and physical parameters of groundwater, carried out in accordance with the technological scheme for the production of regime hydrogeological observations (Fig. 5);



*Graph of relative variations of **average daily** values of radon Rn at the Alma- Arasan station*



*Graph of relative variations of **hourly** radon Rn values at the Alma- Arasan station*

Figure 5 - Graphs of relative variations in average daily and hourly values radon Rn at the Alma- Arasan station

4) Deformation monitoring. It is based on measurements of the network of the radio channel, local installation (IVT, RAS, CAIAG, NNCSNI, etc.). Studies of deformation using quartz flat strainmeters in adits.

The Medeu, Kurty and Talgar reference stations are equipped with quartz strain gauges. The strain gauges are designed to record horizontal movements of two pedestals relative to each other.

The strain gauge rods are 30 m long. Movements are recorded in the range of periods from tens of minutes to several years.

The strain gauge rods at the Medeu and Kurty stations are oriented north-south and west-east. To improve the reliability of operation and to perform internal control of observation results, the strain gauges at these stations have two independent devices in each direction. Information is recorded digitally on the recording unit with subsequent transmission to the PC. At the Talgar station, the strain gauge has one rod (north-south), which is equipped with a digital recording system.

5) Seismobiological monitoring is carried out through regular observations of certain animal species under conditions of limited freedom of movement, which makes it possible to identify and record changes in behavior for use as a predictive indicator used in earthquake forecasting. The following are used: visual observations of animals, automatic recording of animal activity, and instrumental measurements.

Experience shows that good results are achieved by combining field studies and analyzing multiparameter data to identify the precursor effects of strong earthquakes. Many modern seismological publications on predicting expected seismic events are based on the elastic recoil hypothesis. The meaning of this hypothesis is as follows: "It is impossible for a rock to fail without first being subjected to elastic stresses greater than it can withstand. The only conceivable ways of rapidly applying these stresses are by explosion or by rapidly removing or adding a load under some part of the crust. We conclude that the crust in many parts of the Earth moves slowly, and the differences in displacements in adjacent areas create elastic strains greater than the rock can withstand, which eventually leads to a rupture, and the deformed rocks experience a recoil under their own elastic stresses until these strains are almost completely removed...".

Most scientific works on the subject of early forecasting and studying the processes involved in the preparation of earthquakes have been poorly studied to date and represent only hypotheses that require more research, more extensive collection and study of seismological, geophysical, hydrogeological and geochemical data, and training of a larger number of qualified specialists in the field of seismological, geophysical and hydrogeological studies of processes occurring in the depths of the Earth. The development of seismology as an applied science will make it possible to exert a great influence on the formation of a knowledge base in the field of early earthquake forecasting, to obtain a clearer idea of the geological processes occurring during the preparation of expected earthquakes, and will also make it possible to more thoroughly study anomalous and precursor phenomena indicating a direct genetic connection with the preparation of destructive earthquakes.

Today, one of the most important problems of complex field seismological research in the Republic of Kazakhstan is an insufficiently wide network of seismological stations. In the countries of the far and near abroad (USA, South Korea, Japan, China, etc.), the number of points of the seismological activity registration network reaches, according to various sources, from 1,500 to 6,000 units, which significantly exceeds the number of seismological stations in the territory of the Republic of Kazakhstan, which, of course, negatively affects the completeness of seismological data. Undoubtedly, the expansion of the network of complex field seismological stations is a rather complex process and labor-intensive in terms of organizing preparatory and research, construction and installation work and operation of seismological observation facilities. All these works require the involvement of qualified specialists in the field of seismology, which is currently in dire shortage. Not to mention other geophysical, hydrogeological and other field observations, as well as huge financial investments. But at the same time, there is no doubt that the expansion of the network of stations for complex seismological research will have an extremely positive effect on the quality and efficiency of collecting and analyzing seismological data. At the same time, there is no doubt that a

radical reorganization and expansion of the network will in turn affect early earthquake forecasting and the possibility of a more detailed study of geological and geophysical processes indicating the occurrence of earthquakes.

Prospects for the development of a seismological observation network and research in Kazakhstan

As of 29.01.2025, the network consists of 98 seismological stations, 71 stations for monitoring and 27 stations under program-targeted financing (PTF) located in 12 regions of Kazakhstan: Almaty; Zhetysu; East Kazakhstan; Abay; Zhambyl; Karaganda; Kostanay, Kyzylorda, Aktobe, Atyrau, West Kazakhstan and Turkestan, as well as in the megacities of Almaty and Shymkent. The stations conduct comprehensive studies on seismic, geophysical, hydrogeological, deformation, seismobiological and other types of observations - a total of 162 parameters.

In 2025-2026, it is planned to open new seismic stations in the Republic of Kazakhstan: including within the framework of program-targeted financing (PTF) for 2024-2026 (Agreement No. 382 / PTSF24-26 dated October 1, 2024 with the KN MNVO RK) in the spring (April-May) of 2025, installation of 10 strong movement points in the territory of the city of Taraz, and in the summer (August-September) it is planned to install 8 broadband seismometers in the territories of the Turkestan region. In the spring of 2026 (April-May), it is planned to install 7 broadband seismometers in the territories of the Mangistau region.

Pursuant to the instruction of the Government of the Republic of Kazakhstan dated October 1, 2024 No. 16-01/04-656//24-01-12.1, information is provided on paragraph 1.11 "Take measures to study China's experience in the practical application of scientific developments in production and various sectors of the economy." At the initiative of the Institute of Geophysics and the Earthquake Administration of China, the issue of creating a China-Kazakhstan seismic network and a Global Navigation Satellite System is being worked out together with the National Scientific Center for Seismic Research. Financing of this network in the Republic of Kazakhstan is planned by the China Earthquake Administration within the framework of the Belt and Road Initiative (BRI) project.

In pursuance of paragraph 1.11 of the instruction of the Government of the Republic of Kazakhstan, 5 stations will be installed in 2025.

Thus, by the end of 2026, it is planned that the total number of seismic stations will be 198, including both existing and new facilities under construction.

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INFLUENCE OF NATURAL ATMOSPHERIC FACTORS ON RADON EMISSION

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Abstract: In recent decades, the problem of exceeding the critical level of radon gas concentration has become very urgent. According to some estimates, radon (^{222}Rn) and its decay products can make up 50-70% of the radiation dose received by the population from all natural sources of radiation. One of the factors that makes radon gas dangerous is that it leaks through cracks and crevices in foundations, accumulates in living spaces, and enters the human body through inhalation. It is believed that 10-14% of all lung cancer cases are due to elevated radon concentrations in the air of residential buildings (Kiselev S.M., 2016). Radon emission is more pronounced in mountainous and seismically active regions of the planet, and due to this property, it is used as a criterion for warning about earthquakes in many seismically active countries of the world. The article presents a project for a radioecological station that measures radon levels in an automated mode. In addition, abnormal changes in the concentration of Rn gas in underground waters (in the "Surakhany" and "Shikhov-2" wells) were observed on the eve of earthquakes.

Key words: *radiation, radon emanation, earthquake, radon concentration.*

Introduction

Radon is a decay product of radioactive uranium-238 and its amount in the Earth's crust reaches at least 4.5%. This gas, which easily enters the human body through air, water, and dust particles and can cause serious problems in the body, is colourless and odorless. It is easily soluble in water and in the human body, especially in fatty tissues. Radon is present in almost all rocks, and the decrease in its concentration due to both decay and migration into the air is compensated by the continuous formation of this gas again as a radioactive decay product. Therefore, radon is always present in the soil and its concentration can decrease or increase from season to season, year to year. The most likely sources of radon gas formation in the atmosphere include soil, plants, groundwater, volcanic eruptions, natural gas and coal combustion, and mining and processing of minerals. The reason for the release of radon into the atmosphere is the migration process in the soil as a result of diffusion and advection processes. The concentration of radon in the atmosphere at ground level can vary significantly depending on the time of day (due to solar radiation during the day; temperature inversion at night and in the morning) and the time of year (due to changes in humidity) (Sakharov, 2006). Humidity also has a significant effect on the emanation process. Since radon is highly soluble in water, as a rule, the absorption of radon atoms by water leads to a decrease in this coefficient, and therefore in coastal areas it may also depend on the direction and strength of the wind. The rate of radon emission varies depending on the composition, moisture, porosity and permeability of the soil (Sapozhnikov, Aliev, Kalmykov, 2006).

The highest concentration of radon is observed in soil and groundwater sources. The highest level of radioactivity is observed in groundwater in contact with radioactive crystalline fractured rocks - granites, gneisses, schists, diorites, clays.

Unlike many elements, the history of radon gas began long before its discovery. Thus, the harmful effects of Rn gas on the human body were known long after silver mining began in

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Schneeberg, Germany, around 1470. In Schneeberg, silver was mined from great depths (some mines reached a depth of even 400 m), and at that time the conditions of workers working in the mines of the Schneeberg region differed significantly from other mining regions in Europe. Already at the beginning of the 16th century, an unusually high mortality rate from lung diseases was noted among local mine workers, especially among young workers. The incidence of miners in Schneeberg was compared with data from similar mines in Sweden, Hungary, Tyrol and Joachimstal. It turned out that the health of workers working in these mines is much better than in Schneeberg, and the incidence of lung cancer is much lower. It took researchers about five centuries to conclude that not only "ore dust containing various metals", as Paracelsus wrote, but also the invisible gas radon, an intermediate link in the decay chain of radioactive uranium and thorium, can affect the development of lung diseases (Kiselev S.M., 2016). This fact proves that underground workplaces (mines, tunnels, basements) often increase the effect of radon gas due to geological conditions or limited ventilation.

Exposure of the population to natural sources is one of the main factors of the radioactive impact of the environment on humans. Radon and its decay products account for about half of the total radiation dose of the population. According to the World Health Organization, radon is one of the most toxic and radioactive gases (Radon and health…, 2014). An analysis of the health risk assessment of exposure to radon radiation by UNSCEAR showed that 10-14% of lung cancer cases are associated with exposure to radon decay products in homes. After smoking, radon radiation is the next leading cause of this serious disease (Kiselev S.M. 2016).

The negative impact of radon on human health has been studied since the early 1980s. According to the International Organization for Radiation Protection, radon and its decay products account for 40-75% of the total radiation dose of the population from natural sources. In 1987, radon and its decay products were included in the group of carcinogenic elements for the human body by experts of the International Agency for the Study of Malignant Formations (Aliyev, Mahmudova, 2018). Radonometry studies are actively conducted in many countries of the world (Belgium, Great Britain, Germany, Italy, Russia, USA, Czech Republic, Sweden, etc.). In world practice, radon risk or radon potential mapping of the territory is used to control the danger of radon gas.

In Azerbaijan, in 2010, the Institute of Geology and Geophysics of ANAS, with the support of the Swiss Science Foundation, began implementing a grant project entitled "Creation of a radon cadastre and radon distribution map in Azerbaijan using Swiss methodology and experience". As a result of the research work carried out, a radon cadastre was created for the first time for the territory of Azerbaijan, a map of the distribution of radon volume activity was compiled, and regions where anomalous radon concentrations were observed were identified (Aliyev, Feyzullayev, Baghirli, Mahmudova, 2017). In addition, indicators of radon volume activity in Azerbaijan were included in the European radon map. According to existing regulatory documents, the permissible limit of radon volume activity in enclosed spaces is 200 Bk/m³ for old buildings and 100 Bk/m³ for new buildings (Mahmudova, 2018).

According to the authors, the concentration of radon is higher in the Shamakhi-Ismayilli, Guba, Zagatala-Balakan and Sheki regions, which are active seismic zones and radon gas also comes to the surface from faults. At the same time, there are some places in the Gazakh-Tovuz, Ganja, and Talysh Mountains zones where the concentration of radon gas is high and should be under control.

High radon concentrations can also occur in factories, shops, schools, museums and in most common workplaces such as offices, due to the fact that the building's foundation is above ground, poor ventilation systems or activities related to the processing of raw materials. In addition, people can be exposed to radon gas in houses and sanatoriums that use natural groundwater with high radon levels in geological areas rich in granite rocks.

According to the state program of the Republic of Azerbaijan, after its liberation from the Armenian occupation, industrial zones began to be created in the western regions. Since the creation and development of industrial facilities is directly related to the increase in industrial waste, including

radioactive waste, and at the same time, these regions are seismically active, radon gas exhalation in these areas must be constantly monitored.

An automated radioecological station has been established in the western zone of Azerbaijan to study the problems of industrial waste in seismically active areas and to measure radon exhalation from the soil (Bayramov A.A. 2025). The conventional layout of the station is shown in the diagram below (Figure 1).

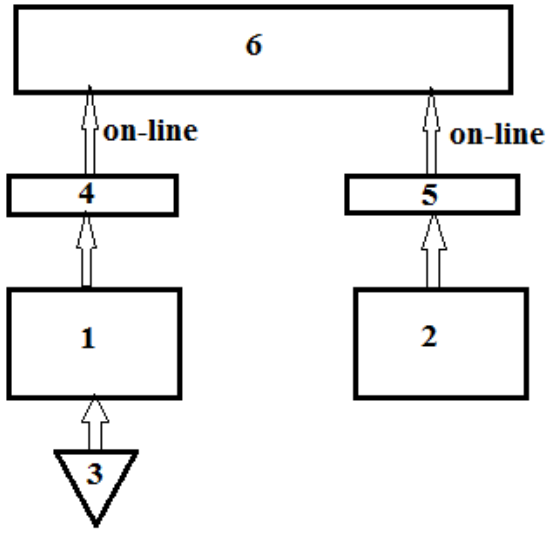


Figure 1. Scheme of measuring radon emission in soil and surface

1,3 - Radon radiometer measuring radon emission in soil
2 - Radon radiometer measuring radon on the soil surface
4,5 - Interface blocks for online transmission of measurement data
6 - Computer for receiving and processing data

As a result of studies conducted in seismically active regions of various countries, it has been found that radon, a radioactive gas that is released from geological rock layers and penetrates the air, is also considered one of the informative seismic forecast parameters as an indicator of rock changes during tectonic earthquakes. Due to its radioactive properties, radon is the most suitable for this type of research, since its volume activity level (Q) is quite easily determined in the environment. The migration of radon in mountainous areas and its separation from the soil surface is determined by the macroscopic diffusion coefficient, which largely depends on the porosity, permeability and fracturing of the massif. The permeability of the massif, the presence of associated pores and cracks in it, significantly depends on the stress-strain state of the massif. It is obvious that when the massif is compressed, its permeability decreases, and during tension, it increases, and the diffusion coefficient changes accordingly. Consequently, changes in radon concentration in the soil layer near the earth's surface can significantly reflect dynamic changes in the stress-strain state of the mountain range (Utkin, 2000).

Data were also obtained by recording the dynamic changes in the concentration of radon dissolved in groundwater as a short-term precursor of seismic events. The solubility of radon gas in water at room temperature is 460 ml/l, which is higher than the solubility of lighter inert gases. Self-flowing wells are usually used for these purposes. The processes associated with the preparatory period of an earthquake (deformation, changes in various geophysical fields, etc.) affect the rocks, disrupting the balance of the rock-water system, thereby creating conditions for radon to enter the water from the rocks. The time of manifestation of radon anomalies detected during earthquakes in

seismically active regions is closely related to the energy and epicentral distance of the earthquakes. These factors were the basis for the study of radon gas as a short-term precursor of seismic events. The goal was achieved by solving the following problems: organization of detailed regime observations of radon gas in the groundwater of the Absheron Peninsula; analysis of radon variations in the taken water sample; justification of the selection of the most significant earthquakes for 2023 (analysis of the spatial position of the seismic source relative to the sampled objects and the magnitude of the earthquake); determination of the emanation responses of the radon field to earthquakes.

Radon (Rn) gas analysis was conducted in the groundwater of the Absheron seismic zone (Shikhov-2, Surakhani facilities) at the Bibi-Heybat gk/st. Water samples were taken once a day, 5 days a week. The measuring equipment used is the "Alpharad Plus" radiometer, included in the list of devices in the state register (database 49013-12). The radiometer is characterized by a relative error limit of ±30%.

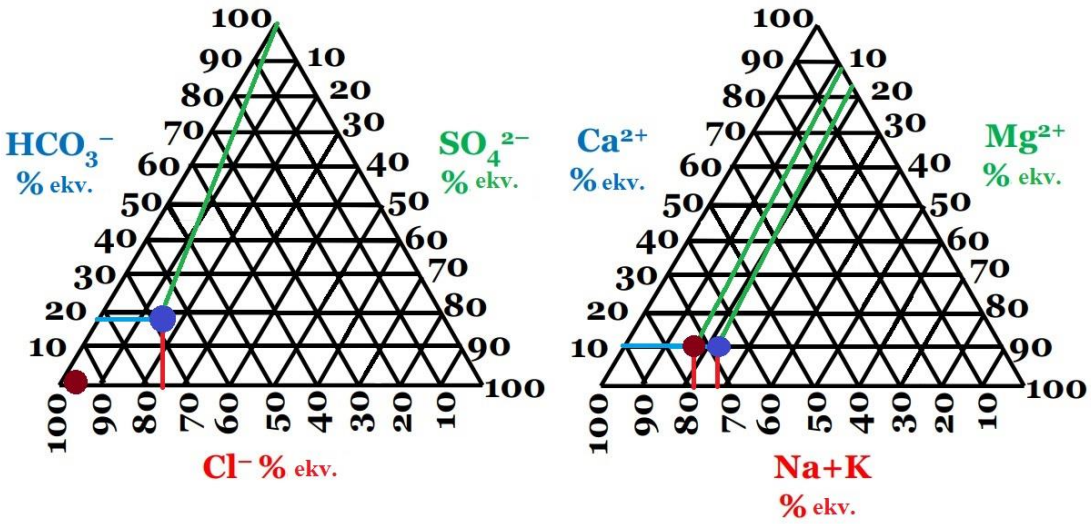


Figure 2. Chemical composition of "Shikhov-2" and "Surakhani" well water
Symbols:
- "Shikhov-2" well water
- "Surakhani" well water

The subthermal (T°C =18÷24) waters of the Shikhov-2 and Surakhani wells are located outside the oil fields. However, they differ significantly in all hydrogeochemical parameters (migration conditions, genesis, mineralization, ion-salt and gas composition).

In particular, the well water "Shikhov-2" is highly mineralized saline (M=260÷280 g/l), has a neutral (pH=7.1÷7.2) alkaline-acid reaction of the migration medium, has a sodium-magnesium chloride composition, belongs to the nitrogenous waters of the fracture-vein type. Despite the significant depth of the well h≥800 m, the water migrating to the surface comes into contact with the sea water of the Caspian Sea. This is due to the oxidizing properties of the water indicates high price (Eh=+140÷+170) and proximity to the seashore (Δ=100÷140 m).

The formation of the "Surakhani" water well occurs in a sharply reducing environment (Eh=-300÷-270). According to the migration conditions, the layer belongs to the subartesian type and is the water behind the contour of the oil field (h=24÷60 m). This water has a chloride-bicarbonate, sodium-magnesium-calcium ion-salt composition and belongs to slightly acidic (pH=6.6÷6.7), moderately mineralized (M=5÷6 g/l) waters. The gas composition is hydrosulfide-hydrogen sulfide-methane-radon (Керамова, 2003).

The composition of both waters is shown below with the Fere graph.

Both waters contain dissolved Rn gas, albeit in small amounts. Graphs of changes in the volume activity of radon for 2023 have been constructed (Figures 4,5). Measurements began at the end of February. Initially, it should be noted that during 2023, the volume activity of radon varied between 10 - 30 Bk/m^3 (depending on the season, there may be a 5-10% change). As can be seen from the variation, the radon concentration in the Shikhov-2 well water has the highest concentration during the year (the radon concentration increased approximately 6 times). It was observed on 01.03.2024 that three days after this event, on 04.03.2023 local time, an earthquake was recorded in Hajigabul, which repeated 5 times (ml=3.1-3.7). (Figure 3)



Figure 3. Changes in the concentration of Rn gas in water before the Hajigabul earthquakes of 03.04.23

An increase in the gas concentration was also observed in the “Surakhani” water 6 days before the seismic event, and the gas concentration was 0 the day before the event.

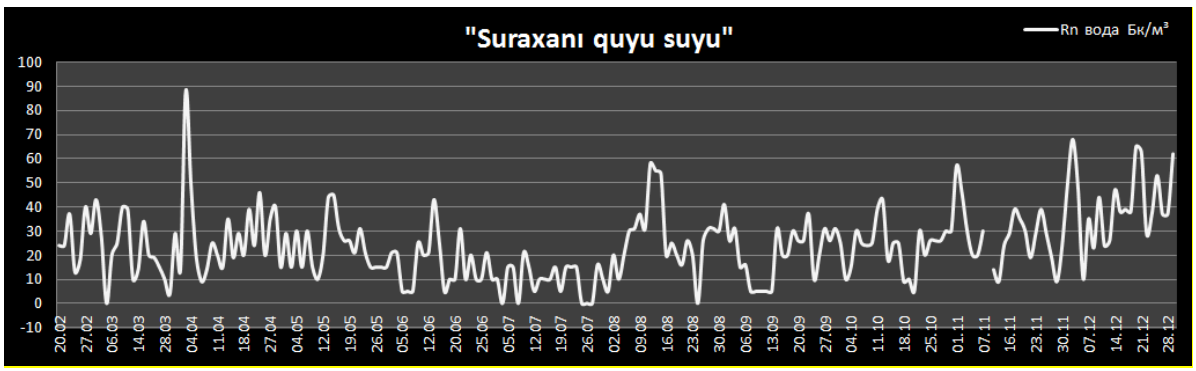


Figure 4. Rn gas concentration in “Surakhani” well water

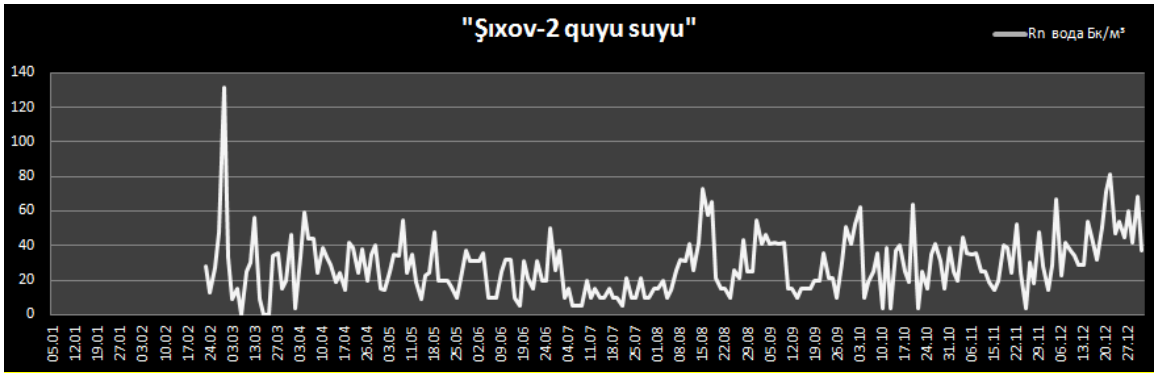


Figure 5. Rn gas concentration in "Shikhov-2" well water

A noticeable change in the Rn gas concentration began in early August and continued almost until the end of October. During this time, due to the high seismicity in the territory of the republic, it was not possible to say whether the change in gas concentration was related to a specific earthquake (Table 1, Figure 6).



Figure 6. Changes observed in the concentration of Rn gas during the earthquakes that occurred between 08.08.23 and 22.10.23

In general, since the number of earthquakes above ml=3.5 was high in March and April, more mobility was observed in the graph in these months. In May and June, since seismic events were at the background level, there was relative stability in the concentration of Rn. If we look at the variation, we can see that at the end of June, an increase in the concentration of Rn gas was observed again. As we know, on 03.07.2023, an earthquake with a magnitude of ml=5.6 occurred in the Middle Caspian, which was felt in a number of regions of Azerbaijan, including Baku. In general, with the exception of the earthquakes that occurred in the Middle Caspian on July 3 with a magnitude of ml=5.6 and in Lankaran on July 26, 2023 with a magnitude of ml=4.8, there was also relative calm in the hydrogeochemical fields, mainly due to seismic calm (Figure 4-5).

If we look at the subsequent change in the concentration of Rn, mobility is observed in October and the first half of November, during which several earthquakes occurred in the Caspian and the Southern region.

Two days before the earthquake (ml=5.6) in the Caspian Sea on 07.12.2023, an increase in the concentration of Rn was observed in both waters (Fig. 7).

Table 1.

Date	***ml***	***h, km***	***Source location***
08.08	3.2	62	South Caspian
09.08	3.9	53	Saatly district
13.08	3.1	47	Guba district
22.08	4.9	35	Masally district
31.08	3.0	26	Sheki district
03.09	5.2	52	Kurdemir district
03.09	3.2	53	Kurdemir district
03.09	3.0	52	Kurdemir district
16.09	3.2	42	Guba district
16.09	4.6	62	South Caspian
19.09	3.8	62	Middle Caspian
19.09	3.5	52	South Caspian
12.10	3.2	9	Lenkeran district
15.10	3.6	19	Lerik district
16.10	3.1	3	Gobustan district
19.10	4.4	44	Middle Caspian
21.10	3.5	18	Masally district
22.10	3.3	62	South Caspian

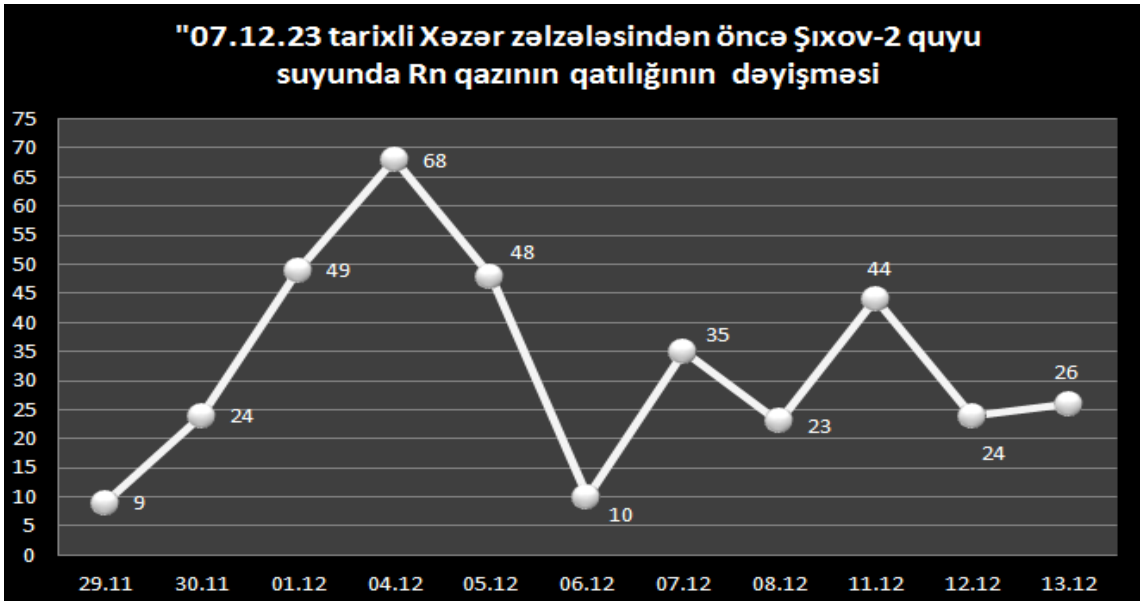


Figure 7. Changes in the concentration of Rn gas in the water of the Shikhov-2 well before the Caspian earthquake of 07.12.23

In general, several factors should be taken into account to determine the warning effect of radon emission before strong earthquakes in the region: the magnitude of the earthquake, the depth of the focus, and the distance between the object and the seismic focus.

Conclusion

The conducted pilot studies allow to obtain results such as preparation of mobile stations for measuring radon concentration; development of a software-hardware complex for conducting analysis at a central point; creation of a database for monitoring radon emission based on a number of geodynamic factors; preparation of a digital map of radon distribution in selected areas; assessment of the seismic risk of selected areas.

Some regions of the territory of the Republic of Azerbaijan are famous for their world-famous mineral water sources due to the peculiarities of geological and geochemical conditions. Conducting seismohydrogeochemical monitoring can be important not only from a seismic point of view, but also from a human safety point of view. Because we know that groundwater (artesian, subartesian, self-flowing springs, etc.) is also used in everyday life.

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CONTENTS

Abdullaev A.U., Lyutikova V.S., Litovchenko I.N.: Machine learning for intelligent pattern recognition methods for seismic safety (using earthquake swarms as an example) 3

Rzayev A.G., Mammadova M.K.: Variational characteristics of the seismomagnetic effect (sme) during the saatly-sabirabad boundary earthquake that occurred in the middle Kura depression 10

K.E.Abdrakhmatov, A.U.Abdullaev, A.M.Muraliev: Development of research on forecasting strong earthquakes in the northern Tien Shan 15

Kazimov I. E., Kazimova S.E.: Interconnection of geodynamic processes in the Caucasus and adjacent regions (Turkey, Iran) 25

Abdullaev A., Gashimov R, Yesenzhigitova E.: Comprehensıve fıeld seısmologıcal research and prospects for expansıon of the seısmologıcal network ın the republıc of Kazakhstan 38

Bayramov A.A. , Karamova A.A., Tagiyeva M.R, Ismayilzadeh X.H, Mammadzadeh S.A: Influence of natural atmospheric factors on radon emission 46

SEISMOPROGNOSIS OBSERVATIONS IN THE TERRITORY OF AZERBAIJAN

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