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MODERN CRUSTAL MOVEMENTS OF THE ARMENIAN HIGHLAND BASED ON HYDROGEOCHEMICAL MONITORING RESULTS

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Abstract

The paper presents the results of hydrogeochemical monitoring of modern geodynamic processes in the Earth's crust of the Armenian Highland preceding earthquakes and other tectonic processes within the Earth's crust. The application of the hydrogeochemical monitoring method for seismotectonic processes includes continuous collection of information on changes in the chemical composition of waters to identify and study effects genetically associated with the processes of preparation and occurrence of strong tectonic earthquakes, primarily precursor effects. Among the broad range of methods currently used for studying precursors of seismotectonic movements (seismological, hydrogeodynamic, deformation, and others), the role of geochemical methods appears to be the most effective at the stage of short-term and operational forecasting. It has been revealed that changes in hydrogeochemical indicators considered as predictive signs should exhibit an “anomalous” character, i.e., significantly differ from background variations. The paper examines seismicity data (earthquake catalog for 2019–2023), constructs a seismicity map, and determines the spatial-temporal characteristics of seismicity distribution within the territory of Armenia. The seismicity of the region is formed

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by geodynamic processes occurring in the northern, central, and southern regions. An earthquake recurrence graph has been constructed, and the representative part of the graph includes events with M>3. The distribution of the specified parameters was calculated for layers from 0 to 10 km, where the majority of earthquakes are localized. The number of earthquakes recorded in northern Armenia significantly exceeds the number of earthquakes in the central part. The results of comparing the analysis of the chemical composition of mineral waters with the seismicity of the region during the study period are presented.

Keywords: Earth's crust, geodynamics, monitoring, hydrogeochemistry, mineral water, seismicity, fault, tectonic block

Introduction and Problem Statement

The Armenian Highland is located in a seismically active zone where strong catastrophic earthquakes have occurred during both historical and instrumental periods. Some of the strongest seismic events of the 20th century include: the Leninakan earthquake of October 22, 1926 (8–9 intensity), the Zangezur earthquake of April 27, 1931 (9 intensity), the Zangezur earthquake of June 9, 1968 (7–8 intensity), and the Spitak earthquake of December 7, 1988 (9–10 intensity) [Grigoryan et al., 2015]

The folded-block geological structure of the Armenian Highland within the Alpine tectonic complex [Abikh, 1989] is subdivided into marginal folded complexes: South Caucasian, East Pontic, and Taurus complexes, as well as the Central microplate. Through the Khoy-Merend and Erzurum-Yerzndjin nodes of converging folded complexes, the mentioned plate transitions into similar structures, forming the Anatolian-Iranian microplate [Aslanyan, 1983] or subcontinent [Gabrielyan, 1989]. The Yerevan seismotectonic region covers the interfluve of the Araks–Hrazdan–Arpi rivers and is distinguished by complex combinations of linear and arcuate structures as well as high seismic activity. Arc-shaped structures were studied and the seismotectonic features of the Yerevan region were identified. The development of modern tectonic movements is outlined by the distribution of epicenters of strong earthquakes along the Hrazdan–Parakar, Yerevan, and Azat faults, by the 8–9 intensity isoseismal zone covering the middle and lower basins of the Dzhverzh, Azat, and Vedi rivers, by the development of modern thrust-strike-slip displacements along the Garni fault, and by the directions of tectonic movements along faults [Tumanyan, Akhverdyan, 2004]. Thus, modern tectonic movements are actively developing within the Yerevan seismotectonic region.

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This article examines the modern geodynamics of the Earth's crust in the Yerevan seismotectonic region of the Armenian Highland, which includes deformation and seismic processes, as well as associated variations in hydrogeochemical fields. Seismicity is one of the components of the geodynamic process, while deformation processes in the Earth's crust reflect slow modern geodynamic processes. Stresses and deformations represent the force and kinematic forms of the process of movement [Kuzmin, 2014]. The objective of this study is to investigate, using the hydrogeochemical monitoring method, modern movements occurring in the Earth's crust of the Yerevan seismotectonic region. The method contributes to identifying relationships between seismic activity and hydrogeochemical parameters of mineral waters during observations conducted in 2019–2024, with the aim of detecting hydrogeochemical effects preceding earthquakes within the territory of Armenia.

2. Factual Material and Research Methodology

The network of hydrogeochemical observation stations of the Institute of Geophysics and Engineering Seismology of the National Academy of Sciences of the Republic of Armenia includes mineral water sources at Arzni, Bjni, Vedi, and Surenavan and covers the central part of the territory of Armenia (Fig. 1).

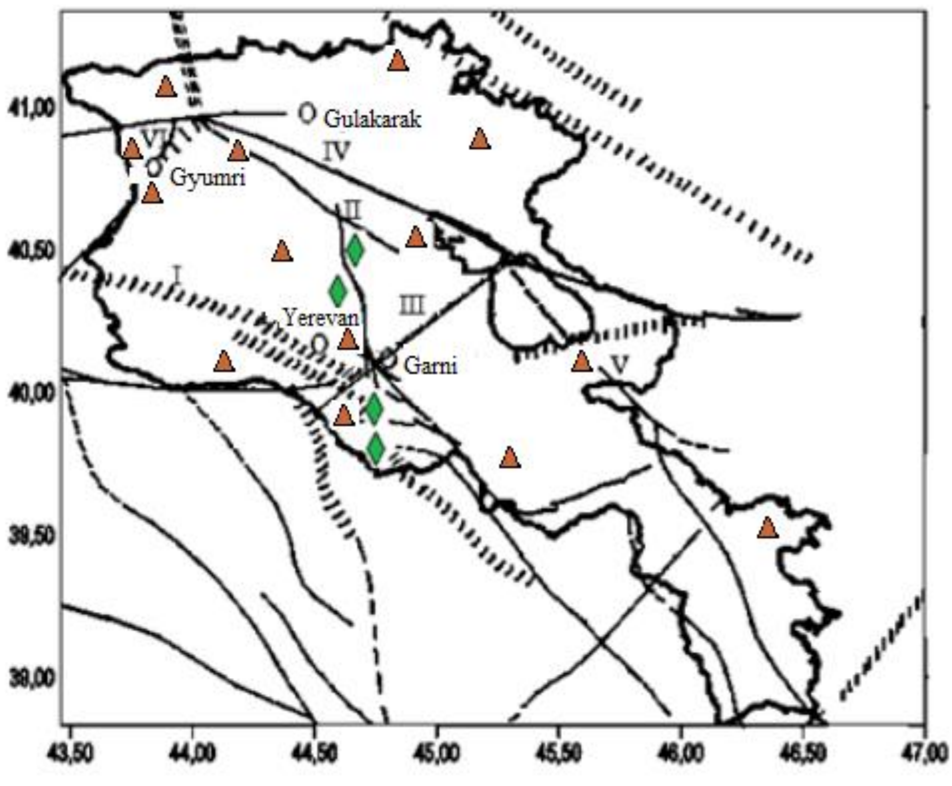

Fig. 1. Map of fault tectonics of the territory of Armenia.

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- deep faults, ♦ - mineral springs, ▲-hydrogeodynamic wells, ○-cities. Faults: I- Yerevan, II-Garni, III-Ararat-Sevan, IV-Pambak-Sevan, V-Pambak-Sevan-Syunik, VI-Akhuryan.

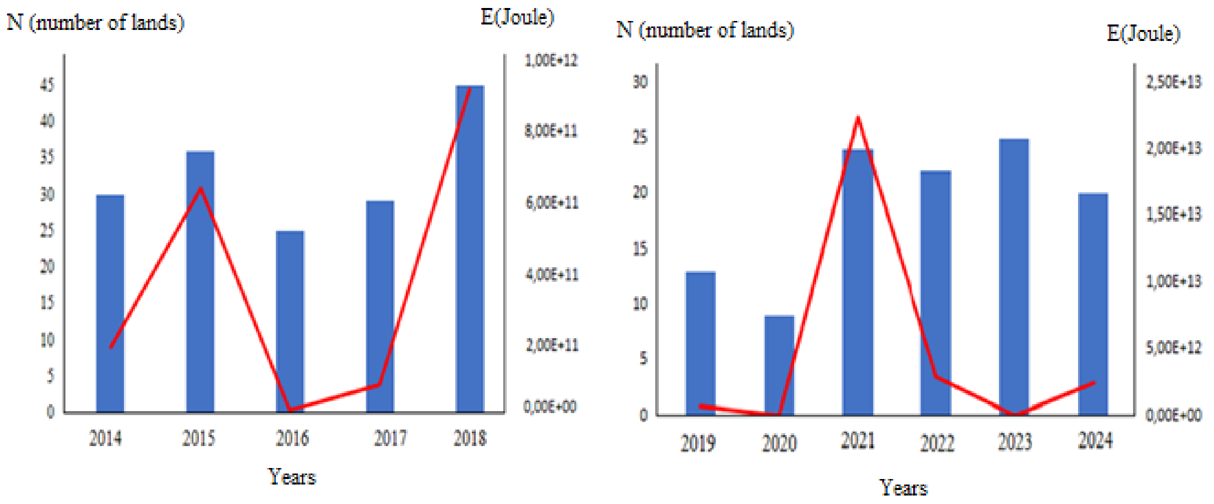
Mineral water deposits are confined to tectonic zones of active deep faults [Grigoryan, 2015]. Hydrogeochemical observation stations cover the central part of the Republic's territory. The geological structure of the area includes sedimentary, volcanogenic-sedimentary, magmatic, and metamorphic formations. Among geological formations of the Quaternary age, lava covers and flows occupy a special place [Geology of the Armenian SSR, 1969]. Regional tectonic disturbances are represented by the Garni and Yerevan faults (Regional Faults of Armenia According to Geophysical Data and Seismicity, 2015).

The groundwater of the study area belongs to the intermountain Ararat Basin. The Ararat Basin is an area of groundwater flow accumulation and the formation of unconfined and confined aquifers, and it includes large reserves of mineral waters characterized by bicarbonate-calcium composition [Hydrogeology of the USSR, 1968]. Carbon dioxide is the dominant gas component, accounting for 97–99% of the total water composition. According to gas composition, Armenian mineral waters are divided into carbonated and mixed groups. The main components of carbonated mineral waters are bicarbonates, chlorine, sulfate, sodium, calcium, magnesium, and iron. According to chemical composition, the waters of the mineral sources Surenavan, Vedi, Arzni, and Bjni are classified as bicarbonate, bicarbonate-chloride, sodium, and chloride-sodium waters. The total mineralization of the waters ranges from 3.6 g/L to 7.8 g/L [Pashayan, 2008].

Research on the search for geochemical precursors of earthquakes in Armenia has been conducted since 1979 by the National Survey for Seismic Protection (NSSP). Correlations were established between the observed parameters (macrocomponents, pH, Eh, and dissolved helium were studied) over a six-year period preceding the 1988 Spitak earthquake [Igumnov et al., 1992]. As an example, changes in helium content in the Ararat borehole were considered, where helium concentrations were measured automatically. The six-month interval preceding the earthquake showed a characteristic decrease in helium concentration and an increase after the earthquake. A similar variation was also observed prior to the 1983 Erzurum earthquake (M = 6.9) [Igumnov, 1992].

Seismic Regime of the Territory of Armenia for 2019–2024

The earthquake catalog was provided by the Territorial Seismic Protection Service of the Ministry of Internal Affairs of the Republic of Armenia (TSPS MIA RA). Based on the catalog data for 2019–2024, graphs of the distribution of the number of earthquakes by year and seismic energy release were constructed (Fig. 2a, b).



a) b)

Fig. 2 a, b. Graph of distribution of earthquakes and seismic energy, a) for 2014-2018, b) for 2019-2024.

The largest number of earthquakes and the highest seismic energy release were recorded in 2021 and 2024. When compared with the graph of the previous five years (Fig. 2b), it can be noted that the number of earthquakes during 2014–2018 was greater than during the subsequent period of 2019–2024, while the magnitude of seismic energy release was an order of magnitude lower. This indicates that during the study years, a greater number of seismic events with M≥3.5 occurred.

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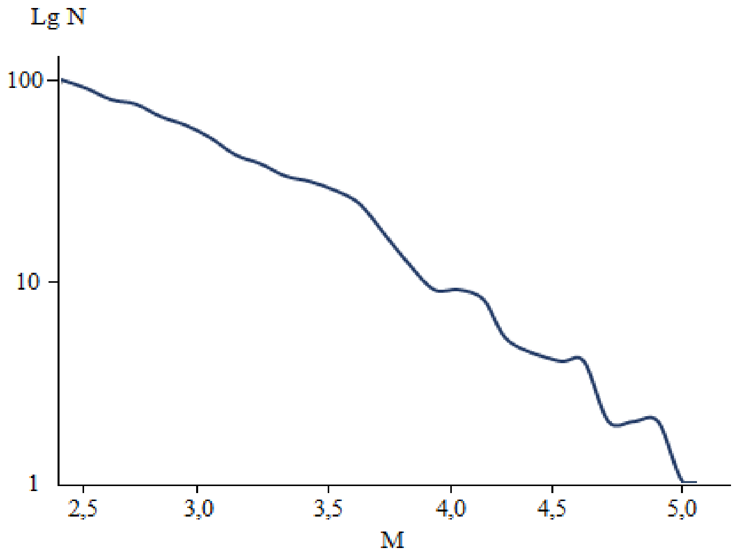

Fig. 3. Graph of earthquake recurrence in the territory of Armenia for 2019-2024.

An earthquake recurrence graph was constructed (Fig. 3), showing on a logarithmic scale the distribution of the number of earthquakes (N) during 2019–2024 according to their magnitude M following the law Lg=a−bM, where *a* is seismicity, *b* is the slope angle of the graph relative to the x-axis, and *M* is magnitude [Gutenberg et al., 1956]. The recurrence parameters were determined as: a=3.8, b=0.7. The slope parameter relative to the x-axis for this period equals b=0.7, which is higher than the average value of b=0.5 for the territory of Armenia. The recurrence graph suggests that the earthquake sample used is representative for earthquakes with M≥2.5. The linear section of the graph corresponds to earthquakes with 2.5<M≥3.5. The shown section of the recurrence graph for earthquakes with M>3.5 indicates a stepwise decrease in the number of earthquakes as magnitude increases.

The graph of earthquake distribution by magnitude and depth showed that the largest number of earthquakes with M = 2.5–5.0 corresponded to depths of 2–10 km (Fig. 4).

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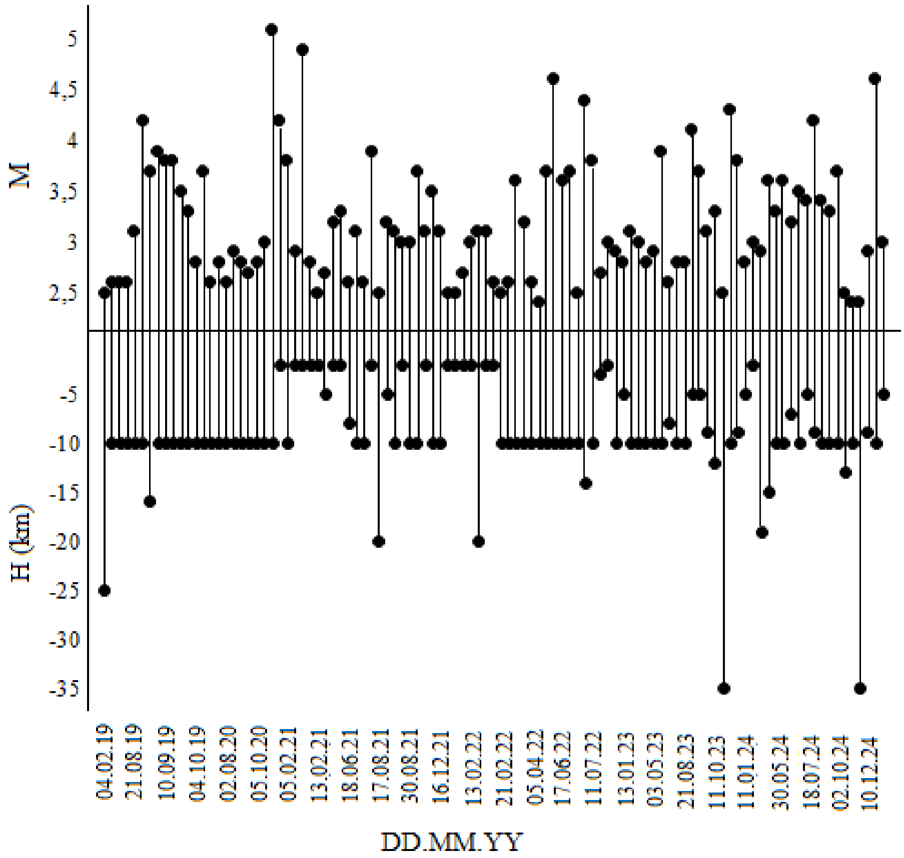

Fig. 4. Graph of distribution of earthquakes that occurred in Armenia in 2019-2024, by magnitude and depth

The focal depths of the earthquakes ranged within H=5–20 km, with a dominant focal depth of 10 km. Out of the total number of earthquakes, only a few seismic events had focal depths greater than 10 km. Thus, the thickness of the seismically active layer of the Earth's crust during the study period may range from 3–10 km [Sargsyan et al., 2021].

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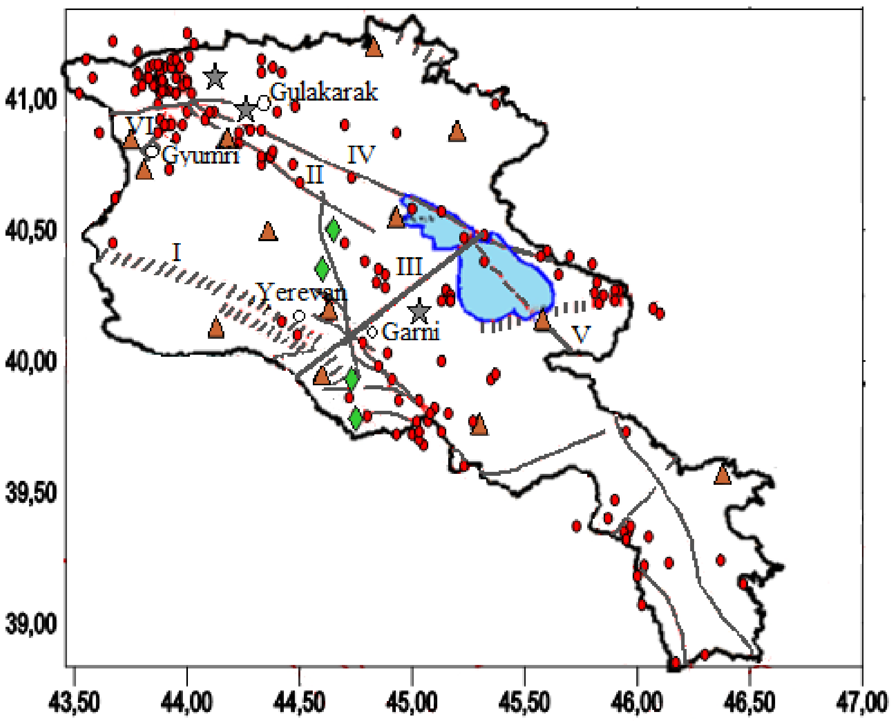

Fig. 5. Map of spatial distribution of epicenters of earthquakes that occurred in Armenia in 2019-2024

- deep faults, ♦ - mineral springs, ▲-hydrogeodynamic wells, ○-cities,

earthquakes: ●- M=2.5 4.0, ✯-M=4.0. Faults: I- Yerevan, II-Garni, III-Ararat-Sevan, IV-Pambak-Sevan, V-Pambak-Sevan-Syunik, VI-Akhuryan.

To study the spatial distribution of seismicity across Armenia, a map of earthquake epicenters was constructed (Fig. 5). A dense concentration of earthquake epicenters was observed in the northern part of the region (Javakheti Highland), along the border with Georgia, and around the eastern shore of Lake Sevan. An absence of earthquake epicenters was observed in the northeastern, northwestern, and southern parts of Armenia. The seismicity map of the Armenian Highland reflects the confinement of earthquake epicenters to deep faults: in the north—at the intersection of the Akhuryan fault and one branch of the Pambak-Sevan fault system; in the east—at the junction of the Ararat-Sevan and Pambak-Sevan faults; and in the central part—along the Yerevan fault.

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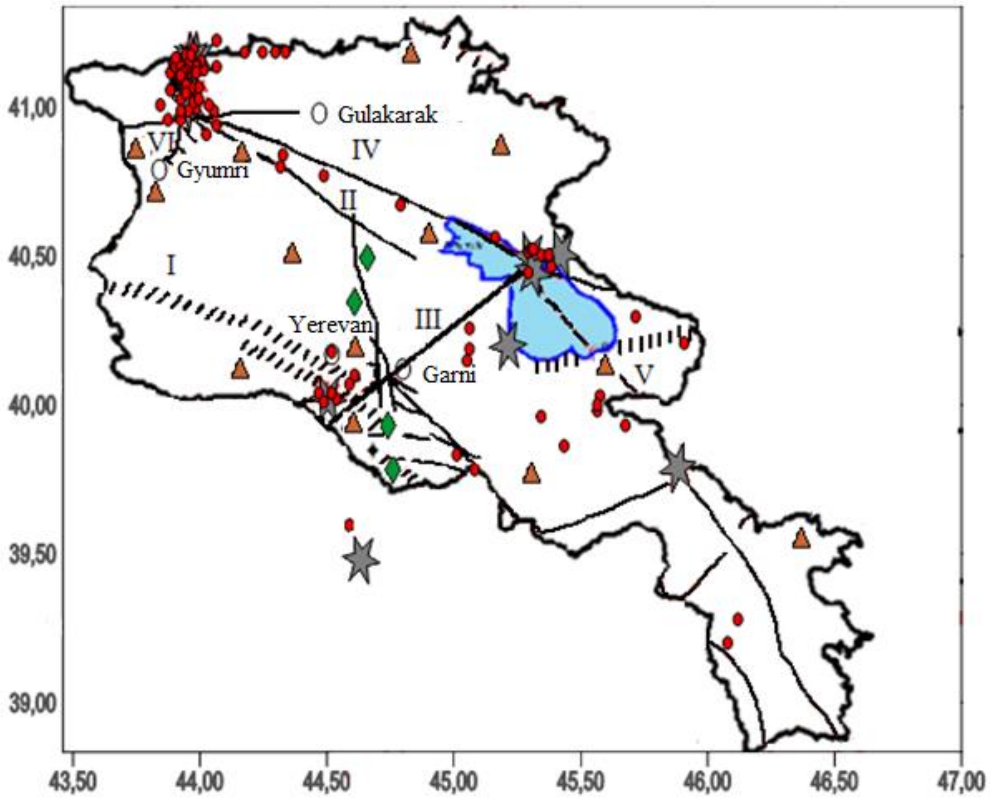

Fig. 6. Map of the spatial distribution of epicenters of earthquakes that occurred in Armenia in 2019-2024.

- deep faults, ♦ - mineral springs, ▲-hydrogeodynamic wells, ○-cities,

earthquakes: ●- M=2.5 4.0, ★-M=4.0. Faults: I- Yerevan, II-Garni, III-Ararat-Sevan, IV-Pambak-Sevan, V-Pambak-Sevan-Syunik, VI-Akhuryan.

To compare the seismic regime of recent years with previous periods, maps in Figures 5 and 6 were compared. The seismicity map of recent years differs by the localization of earthquake epicenters along deep faults: in the north along the Akhuryan fault, along the Pambak-Sevan fault and Lake Sevan, and in the southwestern part of the Yerevan fault zone. Based on the distribution of earthquake epicenters, it is possible to characterize deep faults. According to the study results, the Bazum-Sevan fault is seismogenic in its northern and eastern parts, where displacements along the fault direction are observed. The southern part of the Yerevan fault may also be seismogenic. Along the Garni fault, seismically active sections are observed in both its southern and northern parts. In the northern part of the Garni fault, an earthquake occurred on March 8, 2025 (M=5.2). Based on this, it can be assumed that the seismic-geodynamic activity of the Garni fault zone has increased in recent years (2019–2024).

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Hydrogeochemical monitoring studies have been conducted at the Institute since 1998. Processing of data on the mineral water regime in central Armenia for the period 1989–1992 made it possible to identify hydrogeochemical effects preceding strong earthquakes in Armenia. The hydrogeochemical monitoring method contributes to identifying medium-term and short-term precursors through anomalous changes in mineralization and other components of the chemical composition of waters that precede earthquakes (Kissin, 2015). A correlation relationship was established between hydrogeochemical and spatial-temporal parameters of earthquake characteristics. This was demonstrated using changes in chloride ion concentrations in the mineral waters of Surenavan and Vedi (Ryabinin et al., 2017).

Using the hydrogeochemical monitoring method, which continues to be applied to the present day, studies of water chemical composition and the response of cationic and ionic composition to earthquakes occurring during 2019–2024 were continued. For this purpose, water samples are regularly collected from the mineral water sources of Bjni, Arzni, Vedi, and Surenavan, followed by laboratory chemical analysis of water composition and dissolved carbon dioxide content. The results of chemical analyses and statistical processing of time series of ionic composition (Cl^-, SO_4^{2-}, HCO_3^-), cationic composition (Mg^{2+}, Ca^{2+}, total mineralization), and gaseous composition (CO_2) were then compared with regional seismic events to identify precursor effects preceding earthquakes.

To improve the correlation of the obtained data with seismicity, the study considered a methodology for selecting seismic events from the catalog for different observation points, taking into account deformation in the vicinity of the epicenter of a developing earthquake. Components of the chemical composition of mineral waters were compared with seismic events whose parameters (epicentral distance and deformation) were determined according to the formula .

$$\varepsilon = \left(\frac{d}{10^{0.413\mathrm{M}-2.66}} - \right)^{-3},$$

where ε is deformation, *d* is epicentral distance, and *M* is earthquake magnitude.

The majority of expected hydrogeochemical precursors are recorded within the zone corresponding to the deformation propagation area. The radius of the precursor manifestation zone was determined using the formula:

$$R=10^{-0.43M}$$

It was assumed that earthquake preparation processes could reveal effects only if the calculated deformation reached a value of 10^{-8}, exceeding the magnitude of Earth-tide deformation. In some cases, the potentially high strain sensitivity of observation points should be considered, in which case deformations on the order of 10^{-9} and higher should be taken into account. Statistical processing of chemical component time series included determination of the mean background concentration values and the standard deviation from the background value.

At present, for studying precursors of seismogeodynamic movements, geochemical methods appear to be most effective at the stage of short-term and operational forecasting. The relationship between changes in chemical components of mineral waters and seismic events was investigated, which made it possible to determine that variations in gas composition (CO_2) have a short-term character, whereas changes in total mineralization content demonstrate long-term effects.

Research Results

The hydrogeochemical method applied in this study includes monitoring observations and statistical processing of time series aimed at identifying anomalous changes in the values of water chemical composition parameters associated with earthquakes and other geodynamic processes occurring in the Earth's crust of the region.

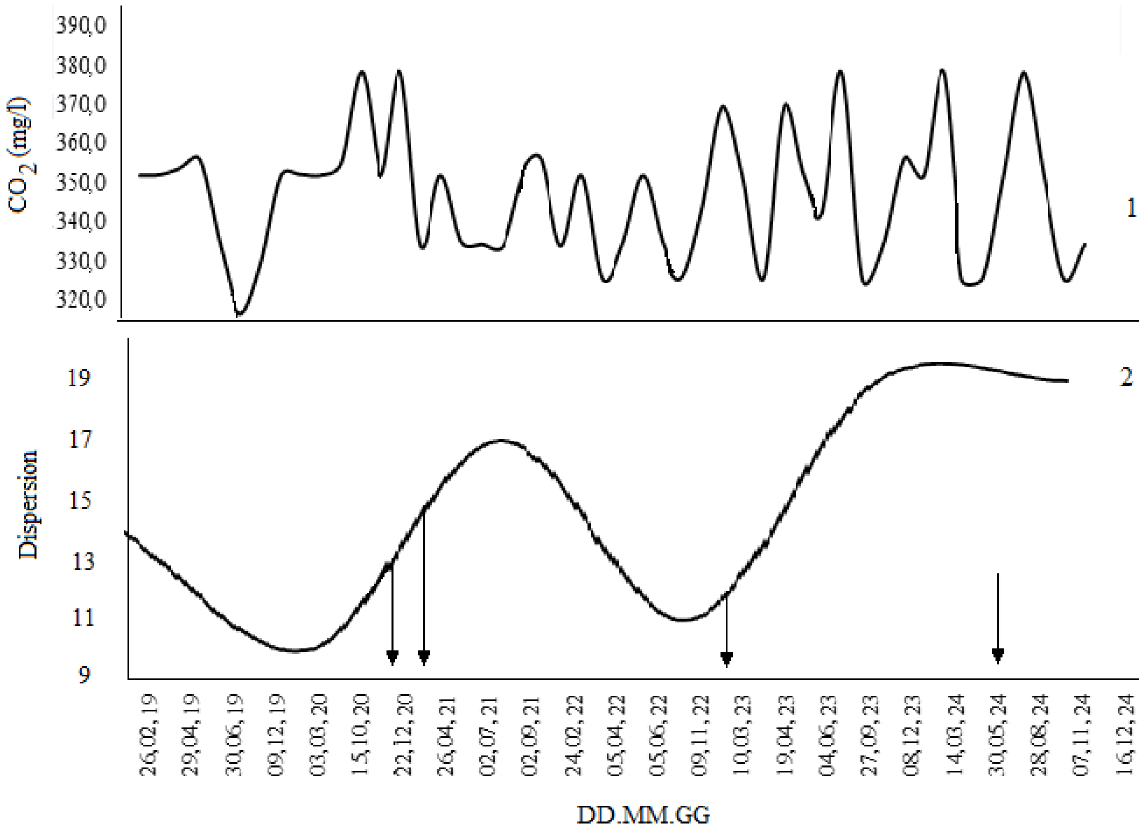

Fig. 7. Graph of variation of time series of CO2 values in water of mineral spring Surenavan. 1-variations of CO2 values, 2-variations of dispersion values of CO2

Parameters of earthquakes indicated on the graph of dispersion change (Fig. 7).

Table 1

Observation post	Data dd.mm.gg	φ, ºN	λ, ºN	M	R, km	Volumetric deformation
Surenavan	30,08,2020	39,83	45,00	3,0	28	1,36E-09
Surenavan	13,02,2021	40,02	44,49	4,9	39	2,04E-07
Surenavan	06,02,2023	37,08	37,17	7,8	893	6,64E-08
Surenavan	30,05,2024	40,04	44,51	3,6	39	4,99E-09

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The mineral sources of central Armenia differ in chemical composition and mineralization and are confined to active deep faults: the Yerevan fault (Surenavan, Vedi) and the Garni fault (Arzni, Bjni) (Fig. 7). During the observation period, graphs of variations in water chemical composition components (Mg, Cl), dissolved carbon dioxide, and total mineralization preceding earthquakes were constructed.

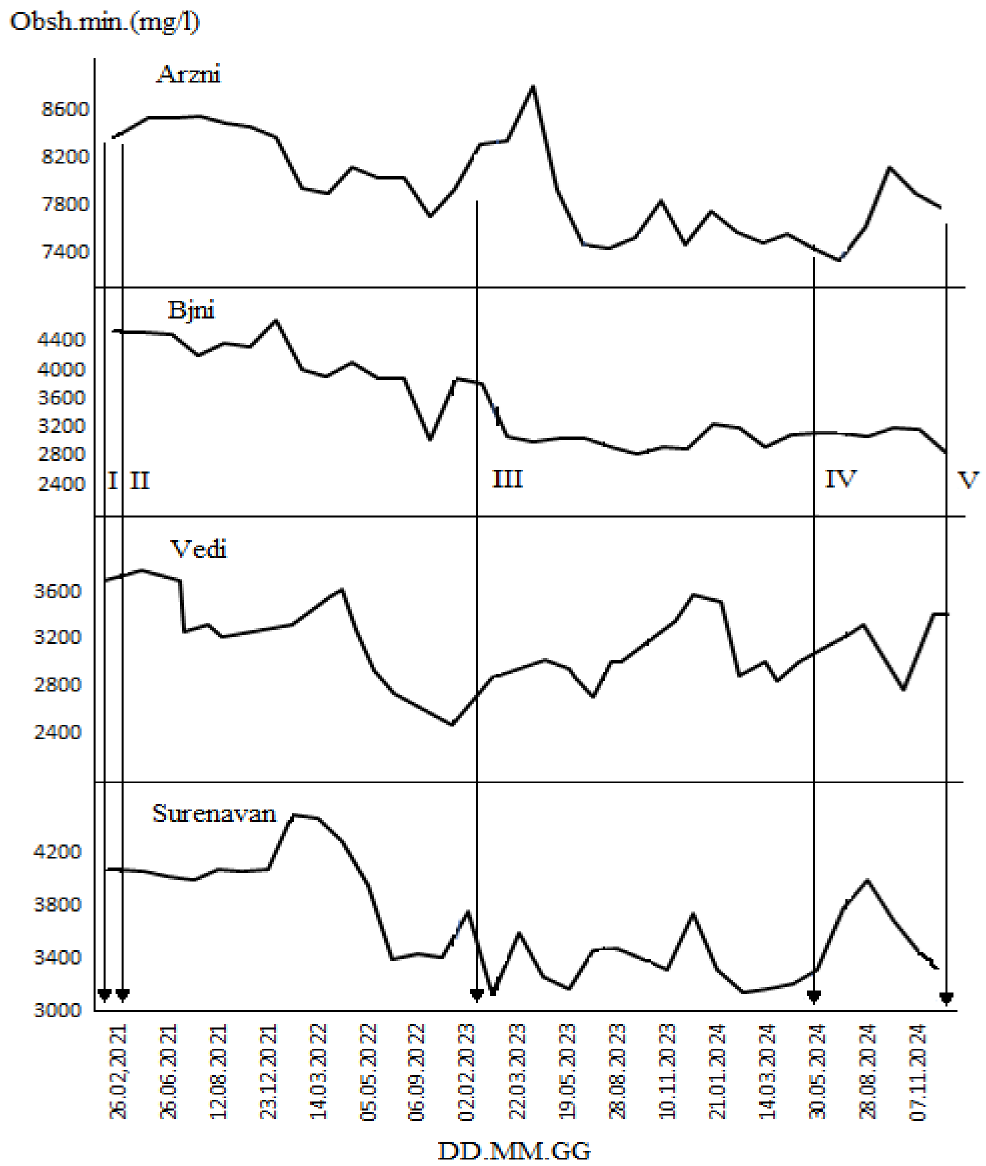

Fig. 8. Graph of variations in the values of total mineralization of waters of mineral springs: Arzni, Bjni, Vedi and Surenavan for 2019-2024. Earthquakes are indicated by arrows (Table 2).

Figure 8 presents a graph showing temporal changes in water mineralization for the four mineral sources with earthquakes indicated on the graph (Table 2).

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Parameters of earthquakes indicated in Fig. 8, 9, which occurred in 2019-2024.

Table 2

Date of earthquakes dd.mm.yyyy	Earthquake parameters				Epicenter distance km	Deformation ε
	Coordinates of the land		Magnitude M	Depth H (м)		
	φ, °	λ, °				
Arzni	40,35	44,6				
13.02.2021	40,02	44,49	4,9	2	38	2,14E-07
03.05.2023	40,18	44,51	3,0	10	21	5,61E-09
30.05.2024	40,04	44,51	3.6	15	11	2.03E-07
18.07.2024	40,04	44,46	3.4	5	38	1.17E-09
12.03.2025	40,13	44,59	4,0	10	24	6,48E-08
Bjni	40,5	44,65				
13,02,2021	40,02	44,49	4,9	2	57	6,96E-08
06.02.2023	37,08	37,17	7,8	20	912	6,35E-08
03.05.2023	40,18	44,59	3,0	10	39	1,16E-09
30.05.2024	40,4	44,51	3.6	15	19	4.34E-09
12.03.2025	40,18	44,59	4,0	10	19	1,40E-07
Vedi	39,93	44,73				
13.02.2021	40,02	44,49	4,9	2	28	5,36E-07
06.02.2023	37,08	37,17	7,8	20	896	6,70E-08
26.08.2021	40,12	45,03	3.1	10	39	1.19E-09
13.11.2023	39.,48	44,62	4.3	10	51	1.64E-08
12.03.2025	40,18	44,59	4.0	10	32	2,94E-08
Surenavan	39,78	44,75				
13.02.2021	40,02	44,49	4.9	2	39	2.04E-07
06.02.2023	37,08	37,17	7,8	20	893	6,78E-08
13.11.2023	39.48	44.62	4.3	10	36	4.66E-08
12.03.2025	40,18	44,59	4.0	10	48	8,65E-09

Before the Turkish earthquake (06/02/2023, M=7.8), the graph (Fig. 8) shows an almost synchronous decrease in water mineralization values at the Vedi, Surenavan, Bjni, and Arzni sources. The mineralization level in the Arzni source water decreased by 255 mg/L. The decrease in mineralization values for the water sources was observed beginning at the end of 2021. This indicates that changes in mineralization content at the source exhibit characteristics of a long-term precursor effect associated with the distant Turkish earthquake. Changes in water mineralization following the earthquake (13/02/2021, M=4.9) occurred against a background trend of decreasing values, indicating a possible long-term precursor of tectonic movements in the Earth's crust of the central Armenian region. During the study period, variations in the chemical components of the Arzni mineral water were observed (Fig. 9), while the volumetric deformation of the earth's crust in this area was approximately 10^{-7}.

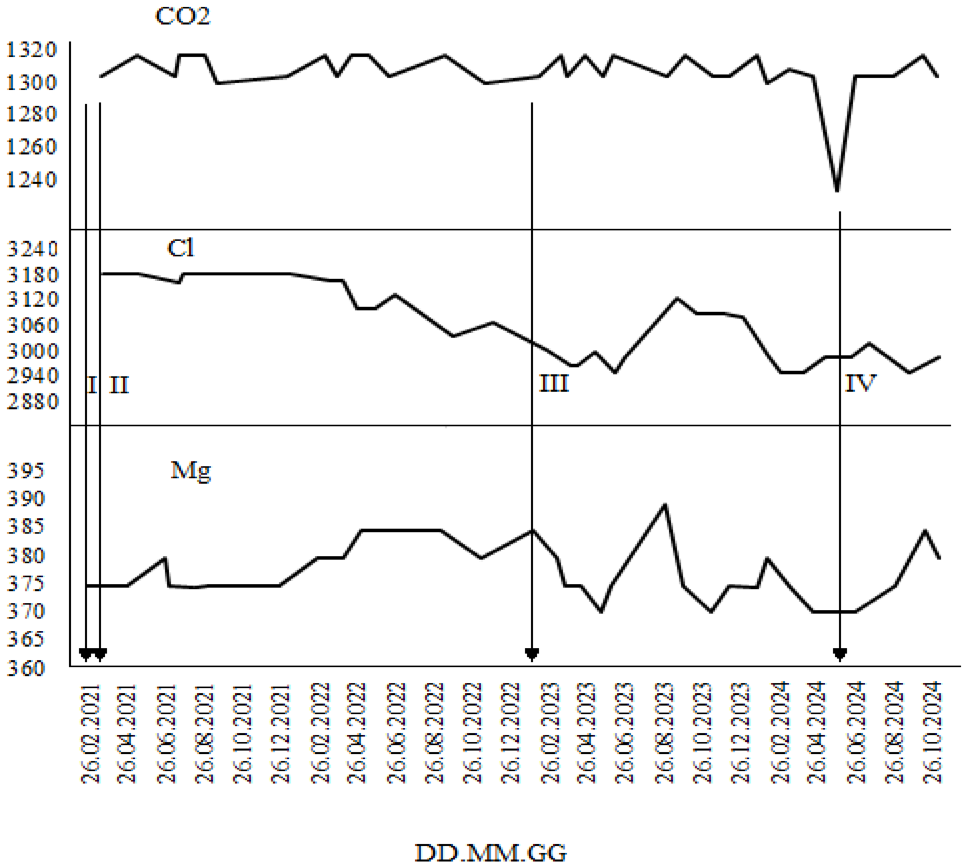

Fig. 9. Graph of changes in the values of chemical components: CO2, Cl, Mg in the mineral water of the Arzni spring for 2019-2024. Earthquakes are indicated by arrows (Table 3).

Variations in the chemical components CO_2, Mg, and Cl in the Arzni mineral source waters revealed precursor effects preceding earthquakes occurring during this period. Based on statistical processing of time series of mineralization changes and chemical components of source waters, hydrogeochemical effects preceding earthquakes were calculated (Table 3).

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Table of calculated values of hydrogeochemical effects - earthquake precursors, for 2019-2024

Table 3

Earthquake parameters				GGH									
Data	φ, ºN	λ, ºN	M	D	Mg			Cl			Obsh.min.		
					$\overline{K}$	δ	A	$\overline{K}$	δ	A	$\overline{K}$	δ	A
Arzni 40,35 44,6													
13.02.2021	40,02	44,49	4,9	38	374			3169	4	2δ	8420	52	2δ
03.05.2023	40,18	44,51	3,0	21	370	6	2δ	2995	29	5δ	7360	345	19δ
30.05.2024	40,04	44,51	3.6	11	370	7	3δ	2979	18	4δ	7220	388	19δ
18.07.2024	40,04	44,46	3.4	38	375	2		3014	53	7δ	8000	392	20δ
12.03.2025	40,13	44,59	4,0	24	379	13	4δ	2979	35	6δ	7940	8	2δ
Bjni 40,5 44,65													
13,02,2021	40,02	44,49	4,9	57	82			434	4	2δ	4500	77	9δ
03.05.2023	40,18	44,59	3,0	39	82			408	7	3δ	3050	47	7δ
30.05.2024	40,4	44,51	3.6	19	96	8	3δ	401	17	4δ	3130	138	12δ
12.03.2025	40,18	44,59	4,0	19	92			429			3610	142	12δ
Vedi 39,93 44,73													
13.02.2021	40,02	44,49	4,9	28	101	11	3δ	131	5	2δ	3700	14	4δ
26.08.2021	40.12	45.03	3.1	39	110			145	8	2δ	3220	253	16δ
13.11.2023	39.48	44.62	4.3	51	148	5	2δ	166	16	4δ	3520	424	21δ
12.03.2025	40,18	44,59	4.0	32	192	16	4δ	166	15	4δ	3230	158	12δ
Surenavan 39,78 44,75													
13.02.2021	40,02	44,49	4.9	39	345	7	3δ	540			4060	4	14δ
26.08.2021	40.12	45.03	3.1	49	350	3	2δ	527	13	4δ	4060	48	7δ
13.11.2023	39.48	44.62	4.3	36	379			582	44	7δ	3320	100	10δ

$\overline{K}$ *-фоновое значение минерализации, δ-дисперсия, *A* – величина гидрогеохимического эффекта.

The magnitude of the hydrogeochemical effect A=nσ is equal to the standard deviation of mineralization from the background value (σ) multiplied by *n*, where *n* is the factor indicating how many times the variance of a chemical element increases before an earthquake (Grigoryan et al., 2014).

Statistical analysis of the collected material showed that the most informative characteristic for obtaining short-term earthquake prediction criteria is the variance of carbon dioxide content in water over a specific time interval. The considered prediction method is based on a statistical assessment of the variability of carbon dioxide variance over time intervals. Processing of the time series of carbon dioxide concentration changes is presented for water from the Surenavan mineral source (Fig. 7). Seismic events occurring at different distances from the mineral source are plotted on the graph; earthquakes occurred during periods of declining variance after previous increases and displayed a bay-shaped pattern.

Studies of the spatial distribution of earthquake epicenters that occurred during the observation period (Fig. 6), which caused crustal deformation around each observation point, enabled investigation of the deformation-stress state of the Earth's crust in the region. Deformation processes in the geological environment caused by tectonic processes within the Earth's crust of Armenia are reflected in the chemical indicators of mineral waters and water dynamics in hydrogeodynamic boreholes (results concerning changes in borehole water dynamics are not presented in this study but are used for constructing a hydrogeodeformation field map of the Earth's crust). To monitor deformation processes, measurements of groundwater levels and changes in the concentrations of chemical components in mineral waters were used and compared with regional seismicity. Based on these observational parameters, a hydrogeodeformation field was constructed (Fig. 10), making it possible to monitor the buildup or decline of stress within the Earth's crust of the region.

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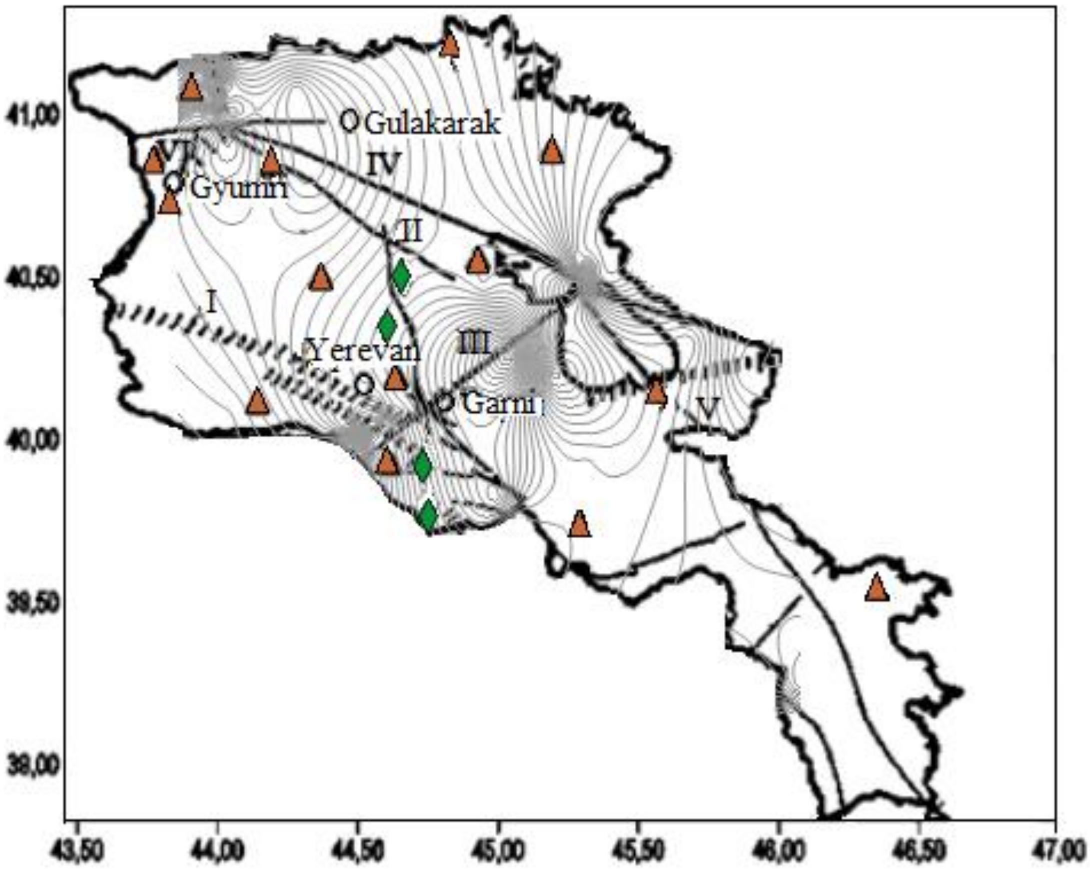

Fig.10. Map of the hydrogeodeformation field of the earth's crust of the territory of Armenia for 2019-2024.

- deep faults, - deformation contours, ♦ - mineral springs, ▲- hydrogeodynamic wells, ○-cities. Faults: I- Yerevan, II-Garni, III-Ararat-Sevan, IV-Pambak-Sevan, V-Pambak-Sevan-Syunik, VI-Akhuryan.

To determine zones of deformation accumulation or stressed areas in the region, a hydrogeodeformation field was constructed from observational data. This field reflects changes in the Earth's crust deformation across Armenia in the form of compression and extension structures represented by deformation isolines. The hydrogeodeformation field of Armenia's crust was compiled using calculated crustal deformation values formed at observation points depending on earthquake parameters (magnitude and epicentral distance). The hydrogeodeformation field reflects a structure of stress accumulation in the Earth's crust (compressional deformation) in the north (Javakheti Highland), along the Pambak–Sevan fault to the eastern shore of Lake Sevan, and at the intersection of the central part of the Yerevan

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deep fault with the Ararat–Sevan fault. Stress reduction (extensional deformation) occurs in the northeastern and southwestern regions. Weak crustal deformation is observed in southern Armenia due to seismic events with M=2.0 and the near absence of earthquakes in the northwestern region. Modern crustal movements within Armenia occur along the Akhuryan, Pambak–Sevan, Yerevan, and Garni deep faults. The calculated deformation values used for constructing the hydrogeodeformation field reached maximum values of 10^{-6} and 10^{-7}, most frequently in the northern Javakheti Highland region. A possible explanation for this is the complex tectonic structure of the area, saturated with active deep faults; the activity of modern crustal movements; the growth and expansion of uplifts; and the intensification of geodynamic processes within the Gyumri and Javakheti sectors (Boynagaryan, 1992). In the central part of the Yerevan region, in the southwestern part of the Yerevan deep fault zone, and on the eastern shore of Lake Sevan, deformation values were approximately the same.

4. Discussion of Results

The results of long-term monitoring observations of the chemical composition of mineral waters in central Armenia and their systematization increase the reliability of identifying hydrogeochemical effects in water chemistry that precede earthquakes and other tectonic movements of the Earth's crust.

The confinement of mineral sources within the territory of Armenia to deep faults facilitates the monitoring of modern geodynamic processes of the region’s deep faults using the hydrogeochemical monitoring method. In recent years of research, seismically active sections of the Pambak–Sevan and Yerevan faults, as well as the seismogenic northern section of the Garni fault, have been identified.

The further application of an integrated approach to the study of modern crustal movements within fault zones and tectonic blocks of Armenia will lead to a more comprehensive interpretation of the research objectives.

The high seismicity of the region serves as evidence of its significant tectonic activity.

5. Conclusion

The geodynamics of the Earth's crust within the territory of Armenia were investigated in this study using modern hydrogeochemical methods together with an assessment of the stress-strain state of the Earth's crust and current seismicity.

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The hydrogeochemical monitoring method contributes to identifying short-term and medium-term precursors through anomalous phenomena preceding earthquakes, during which changes occur in the chemical and gas composition of mineral waters and in the deformation of the Earth's crust.

Studies of modern geodynamic processes within the Earth's crust across Armenia were carried out within zones of active deep faults, which represent concentrations of modern anomalous stress-strain conditions. The gas composition, specifically carbon dioxide (CO_2), responds first to the stress state of faults, followed by the macrocomponent composition of mineral water.

Since Armenia’s mineral waters are primarily confined to deep faults, changes in the concentration values of chemical elements serve as indicators of the activation of movements along tectonic faults.

Hydrogeochemical indicators serve as markers of deformation processes occurring not only in the near-surface layer but also within deep zones of the Earth's crust.

References

Abich H., 1989. *Geologiya Armyanskogo nagor’ya. Zapadnaya i vostochnaya chasti*. Kavkazskoe otdelenie Geograficheskogo obshchestva, Books XXI–XXII, Tiflis–Pyatigorsk, 68 p.

Aktivnye razlomy i seysmichnost’ Armyanskogo nagor’ya, 1990. Proceedings of the All-Union Conference “Sovremennaya geodinamika, aktivnye razlomy i seysmicheskoe raionirovanie”, Moscow, 12–14.

Aslanyan A.T., 1983. Osnovnye cherty geologicheskogo stroeniya i tektonicheskogo razvitiya Tavro-Kavkazskogo regiona. *Izvestiya Akademii Nauk Armyanskoi SSR. Nauki o Zemle* 3, 23–32.

Boynagryan B.V., 1992. *Noveishaya tektonika i tektonicheskie napryazheniya Severo-Zapadnoi Armenii*. Extended abstract of Candidate of Geological and Mineralogical Sciences dissertation, Moscow State University, Moscow.

Gabrielyan A.A., 1989. Seysmotektonika Armyanskogo nagor'ya. *Izvestiya Akademii Nauk Armyanskoi SSR. Nauki o Zemle* 4, 39–143.

Geologiya Armyanskoi SSR. Tom IX: Mineral'nye vody, 1969. Academy of Sciences of Armenian SSR Publishing House, Yerevan, 523 p.

Gidrogeologiya SSSR. Tom XI: Armyanskaya SSR, 1968. Nedra, Moscow, 351 p.

Grigoryan A.G., Durgaryan R.R., Mirzoyan L.B., Nazaretyan S.N., Shahbekyan T.A., 2015. *Regional'nye razlomy territorii Armenii po geofizicheskim dannym i ikh seysmichnost'*. Gitutyun, Yerevan, 184 p.

Grigoryan S.V., Pashayan R.A., Harutyunyan L.V., 2014. Vzaimosvyaz' gidrogeokhimicheskikh parametrov mineral'nykh vod Tsentral'noi Armenii s seysmichnost'yu. *Doklady National Academy of Sciences of the Republic of Armenia* 114, 44–50.

Gutenberg B., Richter C.F., 1956. Magnitude and energy of earthquakes. *Annali di Geofisica* 9, 1.

Igumnov V.A., Stepanyan Z.G., 1992. Nekotorye gidrogeokhimicheskie aspekty Spitakskogo zemletryaseniya. *Izvestiya Akademii Nauk Armyanskoi SSR. Nauki o Zemle* 3, 24–33.

Kissin I.G., 2015. *Flyuidy v Zemnoi kore: geofizicheskie i tektonicheskie aspekty*. Nauka, Moscow, 328 p.

Kissin I.G., Stklyanin Yu.I., 1985. O formirovanii gidrogeokhimicheskikh predvestnikov zemletryasenii. In: Varshal G.M. (Ed.), *Gidrogeokhimicheskie predvestniki zemletryasenii*. Nauka, Moscow, 286 p.

Kuzmin Yu.O., 2014. Recent geodynamics of fault zones: faulting in real time scale. *Geodynamics & Tectonophysics* 5, 401–443. https://doi.org/10.5800/GT-2014-5-2-0135

Pashayan R.A., 2008. Gidrogeokhimiya Araratskogo geodinamicheskogo seysmopoligona. *Izvestiya National Academy of Sciences of Republic of Armenia. Nauki o Zemle* 61, 32–36.

Rubinin G.V., Pashayan R.A., Harutyunyan L.V., 2017. Changes in the concentrations of chloride ion in the mineral waters of Central Armenia. *Electronic Journal of Natural Sciences of NAS RA* 28, 21–24.

Sargsyan R.S., Kazaryan K.S., Burmin V.Yu., 2021. Seysmotektonika Armenii: osnovnye problemy. *Vestnik Saint Petersburg University. Earth Sciences* 66(3).

Tumanyan G.A., Akhverdyan L.A., 2004. Seysmotektonika Yerevanskogo regiona. In: *Proceedings of the Conference Dedicated to the 60th Anniversary of NAS RA*. Gitutyun, Yerevan, 129–143.