

ГІДРОГЕОЛОГІЯ, ІНЖЕНЕРНА ТА ЕКОЛОГІЧНА ГЕОЛОГІЯ

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INTEGRATION OF GEOCHEMICAL DATA FOR DETECTING GROUNDWATER RESPONSES TO GEODYNAMIC PROCESSES: A CASE STUDY FROM AZERBAIJAN

(Представлено членом редакційної колегії д-ром геол. наук, доц. С.Є. Шнюковим)

Background. Hydrogeochemical changes in groundwater are increasingly recognized as potential indicators of stress accumulation preceding earthquakes. However, reliable identification of short-term precursors requires long-term, instrument-based observations and integration of multiple datasets adapted to local geological and hydrogeological conditions. The Shamakhi–Ismayilli seismogenic zone in Azerbaijan, situated at the convergence of the Eurasian and Arabian plates, offers an excellent natural laboratory for studying hydrogeochemical manifestations of geodynamic activity. This research aims to identify groundwater anomalies that precede seismic events, quantify their temporal relationships to earthquake occurrence, and evaluate the effectiveness of integrated geochemical monitoring for early warning applications in the Caucasus region.

Methods. A multi-parameter observation network of seven self-flowing wells and springs was established across contrasting litho-hydrogeological environments. Systematic, time-stamped measurements were performed for pH, Eh, CO_3^{2-} , HCO_3^- , $\Sigma(\text{Cl}, \text{Br}, \text{I})^-$, SO_4^{2-} , total hardness, Ca^{2+} , Mg^{2+} , $\Sigma(\text{Na}, \text{K})^+$, total mineralization, and $\Sigma(\text{Fe}^{2+}, \text{Fe}^{3+})$. Hydrogeodynamic parameters such as water level, temperature, discharge, and color were continuously recorded. Gas-geochemical monitoring focused on dissolved helium, while radiogeochemical control involved α -field measurements at reference sites. An anomaly index ($A_{\text{an}} = K \times X \times \Sigma$) was applied to identify significant deviations from seasonal background levels, enabling automated recognition of abnormal trends.

Results. Prior to the 18 January 2023 Shamakhi earthquake ($M_{\text{pv}} 3.0$; $h=18$ km), synchronous short-lived hydrogeochemical anomalies were observed. Sulfate concentrations (SO_4^{2-}) increased from 440–480 to 640 mg/L, $\Sigma(\text{Na}, \text{K})^+$ decreased from 700–750 to 450 mg/L, and $\Sigma(\text{Cl}, \text{Br}, \text{I})^-$ dropped sharply from 630–660 to 60 mg/L. Total iron ($\Sigma(\text{Fe}^{2+}, \text{Fe}^{3+})$) rose from 6–15 to 48 mg/L, while carbonate (CO_3^{2-}) levels in the Chukhuryurd-49 well increased from 0 to 220 mg/L. Helium concentrations near the epicentral zone rose by almost an order of magnitude, later spreading throughout the network. In the Shamakhi-8 well, water level rose eight days before the shock and sharply declined three days prior, coinciding with darkening of the water.

Conclusions. The results confirm that site-specific, multi-parameter hydrogeochemical monitoring significantly improves the detection and interpretation of earthquake precursors. The nature and amplitude of anomalies are governed by structural position, hydrogeological regime, and focal depth. Integration of hydrogeochemical, hydrogeodynamic, gas, and radiogeochemical data with geodetic and microseismic observations enhances precursor reliability and reduces false-alarm rates. Such interdisciplinary monitoring frameworks can strengthen regional seismic hazard assessment and contribute to the development of an operational early-warning system for the broader Caucasus region.

Keywords: Azerbaijan; earthquake precursors; geodynamic processes; groundwater; helium; hydrogeochemical monitoring; sulfate.

Background

Hydrogeochemical variations – such as changes in water level, temperature, electrical conductivity, ion composition, redox potential (Eh), and dissolved gases – are widely reported in tectonically active regions and are valuable indicators for short- to medium-term earthquake forecasting. Since single-parameter observations rarely yield decisive results, the integration of hydrogeochemical, hydrogeodynamic, gas-geochemical, and radiogeochemical data is required to enhance the reliability of precursor identification under complex geological conditions.

The Shamakhi–Ismayilli seismogenic zone of Azerbaijan, characterized by a centuries-long history of earthquakes and mud-volcano eruptions, provides a natural testing ground for assessing integrated precursor frameworks.

Objectives. (i) To identify and characterize short-term groundwater anomalies in the Shamakhi–Ismayilli seismogenic zone; (ii) To correlate seismic activity with variations in major ions, Eh, helium, and total mineralization; (iii) To propose an operational, multi-parameter monitoring framework for seismic hazard mitigation in Azerbaijan.

Methods

Study area and geological setting. The Shamakhi–Ismayilli seismogenic zone is located on the southern slope of the Greater Caucasus meganticlinorium and is characterized by a complex geological, tectonic, hydrogeological, and hydrogeochemical structure, combined with high seismic

activity. The zone is controlled by major deep-seated faults, including the Vandam and Adzhichay–Agrichay–Alat fault systems, which extend from western Azerbaijan toward the Caspian shelf. Within this tectonically active setting, two principal groundwater groups are distinguished: (i) fissure and fissure-vein waters hosted in fractured and faulted rocks of the Greater Caucasus mountain-fold system, where groundwater circulates through interconnected fractures and mineralized veins formed by intense deformation; and (ii) pore waters occurring in the sedimentary sequences of the Shamakhi–Gobustan basin. The dominance of fissure-vein waters in the mountain-fold zone reflects the strong structural control of deep faults and fracture networks, making these aquifers particularly sensitive to geodynamic processes and related hydrogeochemical anomalies.

Quaternary aquifers, recharged mainly by river underflows (Pirsaat, Gozluchay, Chigilchay, Zogalovaychay), contain predominantly fresh Ca-Na-HCO_3 or mixed sulfate-chloride-bicarbonate waters (0.5–1.0 g/L). Slightly brackish chloride-sulfate-sodium waters (1.3–1.4 g/L) occur along valley margins. This structural and hydrogeological heterogeneity largely governs the detectability and magnitude of pre-seismic hydrogeochemical anomalies.

Monitoring network and measurements. Observation sites were selected based on fault proximity, hydrogeological contrast, and accessibility. Wells and springs were equipped for continuous or semi-continuous

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data collection, with centralized time-stamped archiving to ensure temporal precision.

Groundwater from seven observation wells displayed distinct hydrochemical types (Table 2).

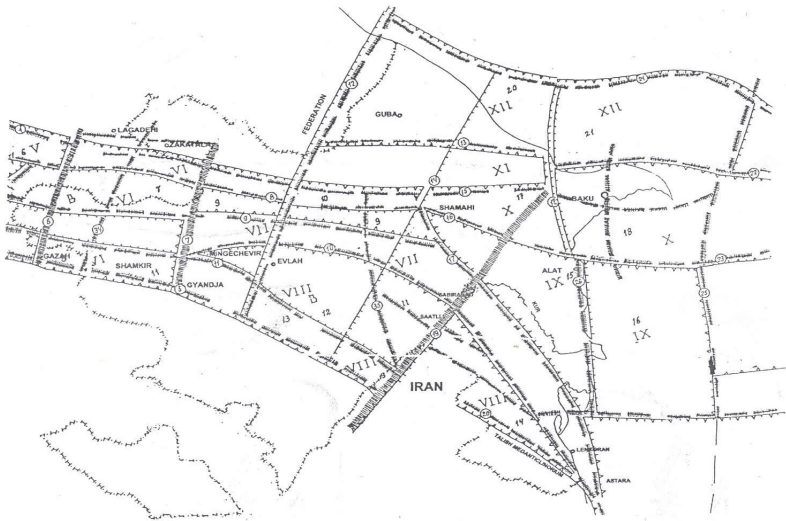


Fig. 1. Tectonic map of deep faults in Azerbaijan (after Shikhalibeyli, 1996)

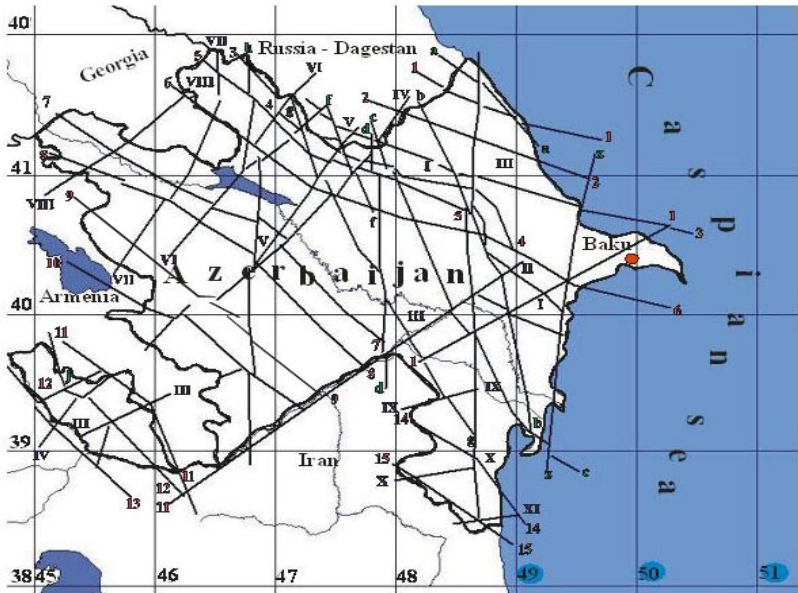


Fig. 2. Deep faults of the pre-Alpine basement in Azerbaijan (after Kangarli, 2005)

Table 1

Instrumentation of the Shamakhi geochemical station						
Geochemical station	Hydrogeochemistry		Gasgeochemistry		Radiogeochemistry	
	Equipment type	Parameters	Equipment type	Parameters	Equipment type	Parameters
Geochem/ station "Shamakh"	Ionomer EB-74	pH, Eh, macronutrients: (ions: pH; Eh; CO ₃ ; HCO ₃ ; SO ₄ ; Σ(Cl,Br,I)); general hardness;Ca; Mg, Σ(Na,K); Mineralization.	Ingem-1	Helium	1) BDZA 2-01	alpha (α) field
	Photocolorimeter	Microelements: sum of iron ions Σ(Fe ²⁺ ,Fe ³⁺)				

Data processing and anomaly detection. Data analysis comprised four stages: (i) compilation of earlier observations and geological maps; (ii) calibrated field measurements; (iii) selection of analytical approaches (hydrogeodynamic, hydrogeochemical, gas-geochemical, and GIS-assisted); and (iv) statistical evaluation of time series relative to seasonal background levels.

An anomaly index was computed as $A_{an} = K \times X \times \Sigma$, where K denotes the stress-strain coefficient, X the seasonal background of the parameter, and Σ the amplitude of fluctuations (max-min). This enabled automated identification of positive and negative anomalies (Table 3).

Table 2

Ionic-salt composition of groundwater at Shamakhi wells	
Object	Kurlovs formula
well. "Shamakha 8"	$pH = 7.6; Eh = +110; M = 0.6; SO_4 46; HCO_3 35; \Sigma Cl; \Sigma(Na, K) 82; Mg 10$
well. "Shamakha 9"	$pH = 8.4; Eh = +45; M = 1.5; HCO_3 28; \Sigma(Na, K) 91$
well. "Shamakha 10"	$pH = 8.7; Eh = +90; M = 1.2; HCO_3 40; \Sigma Cl 36; SO_4 24; \Sigma(Na, K) 93$
well. "Shamakha 11"	$pH = 8.0; Eh = +30; M = 1.3; SO_4 48; \Sigma Cl 32; HCO_3 20; \Sigma(Na, K) 81; Mg 12$
well. "Shamakha 1"	$pH = 5.0; Eh = +15; M = 0.8; HCO_3 67; \Sigma Cl 26; \Sigma(Na, K) 43; Mg 34; Ca 23$
well. "Shamakha 2"	$pH = 6.5; Eh = +30; M = 1.2; HCO_3 80; \Sigma Cl 20; \Sigma(Na, K) 47; Ca 37; Mg 17$
well. "Shamakha 12"	$pH = 5.3; Eh = +45; M = 0.6; HCO_3 74; \Sigma Cl 26; Ca 53; Mg 22$

Table 3

Conditional calculation and detection of anomalous parameters for December 2024 (2σ threshold).
(Provide editable text; highlight positive and negative deviations accordingly.)

Sampling date month day		Name of parameters													
		background boundaries min+max													
		pH	Eh	HCO ₃ ⁻	CO ₃ ²⁻	ΣCl	SO ₄ ²⁻	general hardness	Ca ²⁺	Mg ²⁺	Σ(Na,K) ⁺	Mineralization (TDS)	ΣFe	He	α-field
		7,0	80	300	0	700	450	1,0	20	10	900	2400	0,036	0	0,2
		÷	÷	÷	÷	÷	÷	÷	÷	÷	÷	÷	÷	÷	÷
		8,0	120	400	20	800	500	0,5	30	10	100	2600	0,045	0,001	0,6
1		2	3	4	5	6	7	8	9	10	11	12	13	14	15
12	01	8,4	75	256	156	715	355	0,65	16	6	820	2324	0,086	0	0,2
12	02	7,8	95	567	0	609	725	1,8	18	33	873	2826	0,066	0	0,4
12	03	8,5	80	305	120	727	346	0,6	16	5	817	2335	0,15	0	0,4
12	04	8	90	525	0	702	355	0,65	16	6	793	2397	0,15	0	0,4
12	05	6,3	10	488	0	517	336	0,6	18	4	653	2015	0,15	0	0
12	07	7,8	45	848	0	507	691	1,4	32	15	915	3008	0,061	0	0
12	10	7,7	90	817	0	504	672	1	24	10	911	2938	0,066	0	0,6
12	11	8	40	714	0	568	173	1	26	9	674	2163	0,15	0	0,6
12	12	7,9	20	610	0	721	638	1,55	14	29	932	2945	0,15	0	0,6
(Background: Sept 23 – Dec 21, 2024) Program for conditional calculation and detection of anomalous parameters for December 2024															
Calculation legend:															
for all parameters, An = 2.0σ;															
1.		positive anomaly							2.		negative anomaly				

Results

Short-term anomalies before the 18 January 2023 event. Prior to the Shamakhi event (Mpv=3.0; depth=18 km), a series of short-lived hydrogeochemical anomalies were detected across several monitoring stations. Sulfate (SO₄²⁻) concentrations increased from 440–480 mg/L to 640 mg/L, while total iron (Σ(Fe²⁺, Fe³⁺)) rose from 6–15 mg/L to 48 mg/L. In contrast, Σ(Na, K)⁺ decreased from 700–750 mg/L to 450 mg/L, and Σ(Cl, Br, I)⁻ fell sharply from 630–660 mg/L to 60 mg/L. Carbonate (CO₃²⁻) concentrations in the Chukhuryurd-49 well increased from 0 to 220 mg/L. Dissolved helium in the vicinity of the epicentral area rose by nearly one order of magnitude and subsequently propagated across the monitoring network. In the Shamakhi-8 well, the groundwater level rose eight days before the main shock and dropped sharply three days prior, accompanied by visible darkening of the water.

Figure 3 presents so-called *identification graphs*, illustrating an example of a geochemical "portrait" of a specific stress-strain zone formed during seismic activation within the Shamakhi seismogenic zone. The ordinate axis represents the anomalous geochemical parameter and the phase of its variation. The "maximum–minimum" indication along the Y-axis reflects whether a positive or negative phase anomaly of a given geochemical component is observed; this anomaly is graphically represented by a parabolic curve. The abscissa axis corresponds to the time remaining before the occurrence of a specific seismic event. This temporal interval was determined empirically and ranges from 1 to 16 days, indicating that geochemical anomalies manifest as transient variations exclusively within this pre-seismic time window.

Figure 4 illustrates short-period geochemical anomalies corresponding to the final stage of earthquake preparation within the given focal zone. The variations of the most informative parameters – chloride (Cl⁻) and sulfide (S²⁻)—in the monitored groundwater systems are clearly distinguishable in the figure.

The observed hydrogeochemical variations demonstrate a clear temporal association with the seismic event, as the most pronounced anomalies in major ions, redox conditions (Eh), and dissolved gases occurred within a limited pre-seismic interval and decayed after the main shock. The synchronous increase in SO₄²⁻, CO₃²⁻, ΣFe, and helium, combined with a sharp decrease in Σ(Cl, Br, I)⁻ and Σ(Na, K)⁺, indicates a coupled response of the groundwater system to stress accumulation and fluid redistribution in the seismogenic zone. These correlations confirm that variations in groundwater chemistry are directly linked to seismic activation rather than random hydrogeochemical fluctuations.

Discussion and conclusions

The integration of geochemical data enabled a comprehensive assessment of groundwater responses to geodynamic processes preceding seismic events, rather than merely describing isolated chemical variations. The results demonstrate that the recorded hydrogeochemical anomalies represent a systematic response of groundwater systems to stress accumulation, fault activation, and deep fluid migration within the geological environment, and are closely related to lithological composition, tectonic disturbance, and deep fluid-dynamic conditions.

A combined analysis of macro- and microelement composition, ionic ratios, and geochemical indicators confirmed the high sensitivity of groundwater to variations in the physicochemical conditions of its formation environment.

Variations in the concentrations of major ions (SO_4^{2-} , CO_3^{2-} , Cl^- , Ca^{2+} , Mg^{2+} , Na^+), as well as a number of trace elements and gaseous components, were shown to reflect processes of water–rock interaction, redox reactions, ion exchange, and the influx of deep-seated fluids.

The integration of heterogeneous datasets made it possible to differentiate the contributions of surface and

deep factors to the formation of groundwater chemical composition and identify zones of active geochemical transformation. It was established that groundwater can be regarded as an informative indicator of contemporary geochemical and tectonic processes, including the activation of fault zones.

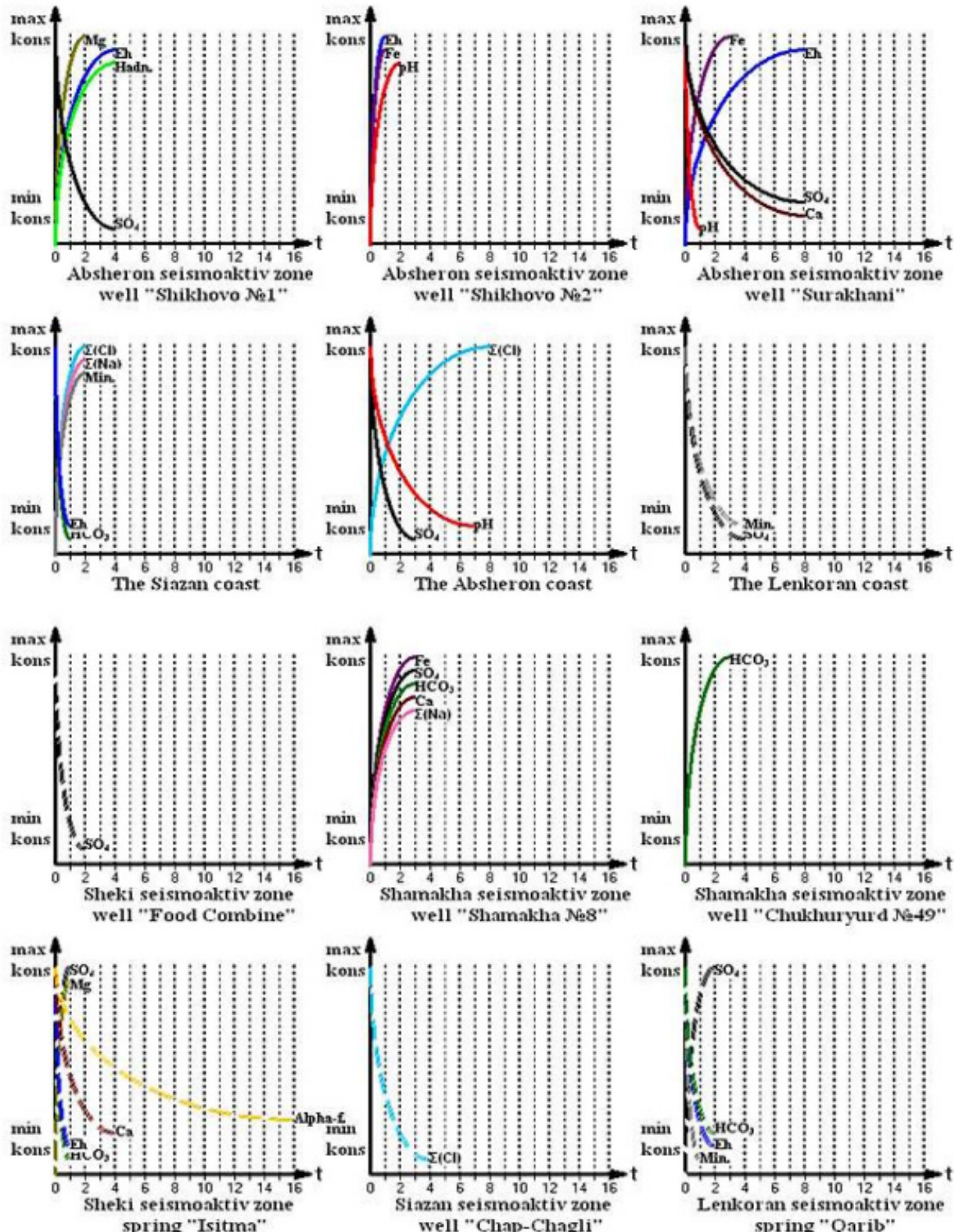


Fig. 3. Identification of stress–strain zones during seismic activation using geochemical fluid anomalies

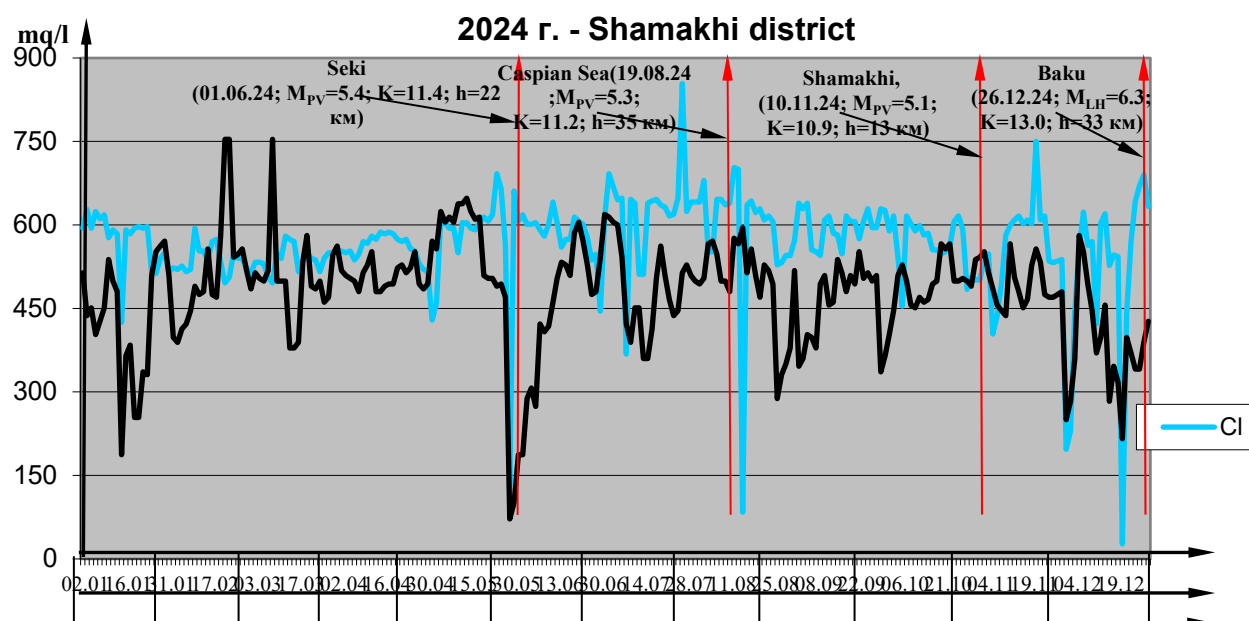


Fig. 4. Geochemical anomalies of groundwater during earthquakes. Spatial-temporal variations of the geochemical field prior to seismic events (using Cl^- and S^{2-} ions as examples)

The obtained results emphasize the effectiveness of an integrated geochemical approach for the study of natural mineral waters, monitoring of the geodynamic environment, and forecasting changes in hydrogeochemical conditions. Thus, geochemical data integration represents a reliable scientific basis for further regional investigations.

Importantly, the combined use of hydrochemical parameters, redox indicators, gas-geochemical data (helium), radiogeochemical measurements, and automated anomaly detection provides the basis for an operational multi-parameter monitoring framework. This framework allows the identification of short-term, pre-seismic hydrogeochemical signals and their discrimination from seasonal or hydrometeorological effects, thereby offering practical applicability for seismic hazard monitoring in tectonically active regions of Azerbaijan.

Key Findings. The following key findings summarize the results of the study in direct relation to the stated objectives of identifying groundwater anomalies, correlating them with seismic activity, and developing an operational monitoring approach.

1. The influence of the stress-strain field on the year-round geochemical monitoring regime of fluids during periods of seismic activation in Azerbaijan was investigated.

2. Characteristic patterns in the temporal dynamics of fluid geochemical fields during seismic activation in the Shamakhi seismogenic zone were identified.

3. Rapid methods for identifying different seismic sources were developed based on data from continuous geochemical monitoring of fluids.

4. Anomalies in fluid geochemical fields were shown to occur predominantly during the final stage of earthquake preparation, with a characteristic lead time predominantly ranging from 1 to 16 days.

5. Hydrogeochemical maps and temporal variation graphs were compiled for monitoring sites within the year-round geochemical observation network.

6. Fluid geochemical monitoring data were correlated with seismological parameters for all recorded earthquakes within the Shamakhi seismogenic zone.

7. Short-period geochemical anomalies exceeding background levels by 50–100 % were identified during continuous fluid monitoring. These anomalies are independent of seasonal and hydrometeorological influences and occur only during periods of increased seismicity and mud volcanic activity.

8. A method was developed to differentiate the azimuthal orientation of the stress-hydrodeformation field in the mountainous Shamakhi-Ismayilli zone based on geochemical fluid monitoring data.

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ІНТЕГРАЦІЯ ГЕОХІМІЧНИХ ДАНИХ ДЛЯ ВИЯВЛЕННЯ РЕАКЦІЙ ПІДЗЕМНИХ ВОД НА ГЕОДИНАМІЧНІ ПРОЦЕСИ: ДОСЛІДЖЕННЯ НА ПРИКЛАДІ АЗЕРБАЙДЖАНУ

Вступ. Гідрогеохімічні зміни у підземних водах дедалі частіше розглядаються як потенційні індикатори акумуляції напружень, що передують землетрусам. Проте надійна ідентифікація короточасних попередників можлива лише за умови довготривалих інструментальних спостережень та інтеграції багатьох типів даних, адаптованих до місцевих геологічних і гідрогеологічних умов. Шамахинська Ісмаїлінська сейсмогенна зона в Азербайджані, розташована на межі Євразійської та Аравійської плит, є унікальною природною лабораторією для вивчення гідрогеохімічних проявів геодинамічної активності. Метою дослідження є виявлення підземноводних аномалій, що передують сейсмічним подіям, визначення їх часових закономірностей щодо моменту землетрусу та оцінка ефективності інтегрованого геохімічного моніторингу для систем раннього попередження у Кавказькому регіоні.

Методи. Створено багатопараметричну мережу спостережень із семи самовиливних свердловин і джерел, розташованих у контрастних літолого-гідрогеологічних умовах. Виконувалися систематичні, прив'язані до часу вимірювання показників рН, Eh, CO_3^{2-} , HCO_3^- , $\sum(\text{Cl}, \text{Br}, \text{I})^-$, SO_4^{2-} , загальної твердості, Ca^{2+} , Mg^{2+} , $\sum(\text{Na}, \text{K})^+$, мінералізації та $\sum(\text{Fe}^{2+}, \text{Fe}^{3+})$. Гідрогеодинамічні параметри – рівень, температура, витрата і колір води – фіксувалися безперервно. Газогеохімічний моніторинг охоплював визначення розчиненого гелію, а радіогеохімічний контроль – вимірювання α -поля на реперних ділянках. Для виявлення суттєвих відхилень від сезонних фонів застосовано індекс аномальності ($A_{\text{an}} = K \times X \times \Sigma$), що дозволяє автоматично розпізнавати ненормальні тенденції.

Результати. Перед землетрусом у Шамахі 18 січня 2023 року (M_{рв} 3.0; h = 18 км) було зафіксовано синхронні короточасні гідрогеохімічні аномалії. Концентрація сульфатів (SO_4^{2-}) зросла з 440–480 до 640 мг/л, $\sum(\text{Na}, \text{K})^+$ зменшилися з 700–750 до 450 мг/л, а $\sum(\text{Cl}, \text{Br}, \text{I})^-$ різко знизилася з 630–660 до 60 мг/л. Вміст загального заліза ($\sum(\text{Fe}^{2+}, \text{Fe}^{3+})$) підвищився з 6–15 до 48 мг/л, тоді як концентрація карбонатів (CO_3^{2-}) у свердловині Чухурюрд-49 зросла з 0 до 220 мг/л. Вміст гелію в підземних водах біля епіцентру збільшився майже на порядок, а згодом поширився по всій мережі. У свердловині "Шамахи-8" рівень води піднявся за вісім днів до поштоху, а за три дні до нього різко знизився, супроводжуючись потемнінням води.

Висновки. Отримані результати підтверджують, що локальний багатопараметричний гідрогеохімічний моніторинг істотно підвищує ефективність виявлення та інтерпретації попередників землетрусів. Характер і амплітуда аномалій визначаються структурним положенням, гідрогеологічним режимом та глибиною осередку. Інтеграція гідрогеохімічних, гідрогеодинамічних, газових і радіогеохімічних даних із геодезичними та мікросейсмічними спостереженнями підвищує надійність прогнозу та зменшує кількість хибних спрацювань. Такий міждисциплінарний підхід може зміцнити систему оцінки сейсмічної небезпеки регіону та сприяти створенню оперативної системи раннього попередження для всього Кавказького регіону.

Ключові слова: Азербайджан; попередники землетрусів; геодинамічні процеси; підземні води; гелій; гідрогеохімічний моніторинг; сульфати.

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