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Physical and mathematical models of the occurrence of earthquake fluid anomalies in hydrogeochemical fields of seismically active areas

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Abstract

Comprehensive monitoring of seismic activity over the last 40 years at the special Almaty Forecasting Polygon (AFP) in Kazakhstan has demonstrated that the physical, mathematical and chemical mechanisms of fluid anomalies in the groundwater regime are quite convincingly substantiated by the example of tracking many strong earthquakes. The purpose of this research – to analyse the system "water-rock-gas", in particular the genetic features of the manifestation of exotic unstable time anomalies. The research methods used in this work include systematic data analysis, and their interpretation and evaluation based on dilatant-diffuse (DD) and avalanche unstable fracturing (AUF) models. The first results of research of such anomalies preceding major earthquakes in the main earthquake-prone areas of the USSR, China, and Japan were manifested in sudden increases or decreases in the concentration of a wide range of components of the ion-salt composition of groundwater and its gas components: HCO^{-3}, CO_2^{-3}, Cl, SO_2^{-4}, Ca^{2+}, Mg^{2+}, Na, K^+, pH, He, Rn, CO_2, CH_4, H_2, and Hg. They varied in the time interval from hours, days and the first weeks and months before the earthquake. In addition, the changes were explained by theoretically generally accepted models of DD or AUF earthquake occurrence. The proposed studies demonstrate and state the main genetic features of the manifestation of these exotic unstable temporal anomalies in the hydrogeochemical system "water-rock-gas". Based on the results of long-term studies of hydrogeochemical and hydrogeodynamic precursors in the fluid regime of the Earth's crust in Kazakhstan, Kyrgyzstan, Uzbekistan and Xinjiang Uygur Autonomous Region of People's Republic of China, a more convincing physical and chemical model of the development of fluid anomalies in the process of preparation of strong earthquakes is proposed. The practical significance lies in the following aspects: the development of accurate models can help in predicting possible earthquakes based on fluid anomalies in hydrogeochemical fields; using physico-mathematical models can help in establishing systems for monitoring seismic activity based on the analysis of hydrogeochemical parameters; the research can help in assessing the risks associated with earthquakes in seismically active areas and in better understanding of the physical processes occurring in hydrogeochemical fields; and the research can help in assessing the risks associated with earthquakes in seismically active areas and in better understanding the physical processes occurring in hydrogeochemical fields.

Keywords: Seismotectonics; Precursors; Monitoring; Forecast; Hydrogeochemistry

1. Introduction

The preparation and realisation of strong earthquakes, which pose a threat to the life of society and its material values, is associated with the accumulation of enormous energy in the earth's crust of seismically active regions, which changes the property of the environment, including the fluid regime of the earth's crust in the earthquake preparation areas over time (Sandvol et al., 2017; Papadopoulos et al., 2020; Zhou et al., 2021; Hobara et al., 2022; Mavrouli et al., 2023; Shafapourtehrany et al., 2023).

Currently, all researchers agree that there is a correlation between variations in the gas-chemical composition of groundwater and geodynamic processes where destructive earthquakes occur. Martinelli and Tamburello (2020) and Melkov et al. (2022) conducted observations in their specific studies by these processes at special (prognostic) test sites in different geological-geophysical-hydrogeological conditions, which resulted in the detection of precursor effects of these phenomena, which served as a foundation for the development of prediction criteria in the controlled area.

Over the last half a century in the problem of earthquake prediction, geochemical, hydrogeochemical and hydrogeodynamic effects occurring in the processes of earthquake preparation on the eve of and after their realisations have attracted more and more attention from researchers. This circumstance has served as an impetus for the development of new trends in Earth sciences, including fluid methods for seismic activity investigations, which was considered by scientists Kurbanov (2021), Zjou et al. (2021) and Kelaniab et al. (2021). In these studies, the nature, mechanism and possible physicochemical models for the occurrence of these anomalies preceding strong earthquakes were the most debated.

The Tashkent earthquake on 26 April 1966 with M = 5.3, which occurred literally under the city, was the object of completely new extremely interesting complex geophysical and hydrogeochemical studies conducted by Kurbanov (2021). The research of earthquake prediction is an important task in seismology. However, to understand better the possible precursors of earthquakes, it is necessary to consider them within the framework of fundamental geophysics rather than in the context of attempts to predict the future, as scientists Ouzounov et al. (2018) and Hough (2020) in their studies.

Many researchers have analysed data and published works containing claims about possible earthquake precursors. These claims range from casual observations of spatial and temporal correlations that are cautiously interpreted as possible earthquake precursors to proposing methods and procedures that have not been validated and are designed to predict earthquakes.

The research on earthquake precursors includes many physical parameters, such as mechanical deformation, gas emissions, changes in chemical composition, temperature and groundwater levels, and electromagnetic field fluctuations over a wide frequency spectrum, possibly caused by other primary disturbances and ionospheric and magnetospheric parameters. Many of the measurements that have been proposed as earthquake precursors have been performed on individual earthquakes as part of case studies. Unfortunately, only a few have been replicated and reproduced in other seismic events, which were considered in the works of Hatori et al. (2012), Liu et al. (2010) and Davidenko and Pulinets (2019). Therefore, these observations often remain "unique" and disparate in the panorama of earthquake precursor research.

Based on these data, it is significant to make additional research. Therefore, the purpose of this research was determined to identify and explore the genetic features of the manifestation of exotic unstable temporal anomalies in the hydrogeochemical system "water-rock-gas". For this purpose, several tasks were performed: the research of hydrogeochemical and hydrogeodynamic precursors in the fluid regime of the Earth's crust in Kazakhstan, Kyrgyzstan, Uzbekistan and Xinjiang Uygur Autonomous Region of the People's Republic of China was conducted, a physical-chemical model of fluid anomalies design was developed, and the relationship between fluid anomalies and strong earthquakes was explored.

2. Materials and Methods

It consisted of a systematic approach of collecting and analysing long-term observation data from the main seismic prediction sites in the countries of the Asian seismic belt, where multiparameter geophysical, geochemical, hydrogeochemical, hydrogeodynamic, deformation mode observations have been conducted for the last 40 years to explore the precursors of strong earthquakes. The research used the basic materials represented by the monitoring data conducted at the test sites of Almaty (Republic of Kazakhstan), Bishkek (Kyrgyz Republic), Tashkent (Republic of Uzbekistan) and Xinjiang Uygur (People's Republic of China). Long-time series of observations of different fields were analysed using methods of statistical and spectral data analysis. In the process of analysis, the background and anomalous components of the time series were calculated. The background values (X) were determined and the extrema values of anomalies (X + 2 – 3σ) were calculated. Therewith, the level of dispersion (S), standard deviations (6) and confidence interval (±2 – 3σ) were determined for the data series against a background of multiyear and annual parameter values. It allowed obtaining a more complete understanding of the behavior and changes of the examined fields. The laws of thermodynamics, including Pascal's, Henry's, Darcy's and other laws, were applied in the course of investigating the processes of anomaly design and developing their physical and mathematical models. These laws contributed to a deeper understanding of the processes underlying the anomalies development.

In exploring earthquakes, researchers have been guided by theoretical models of earthquake generation, such as dilatant-diffuse (DD) and avalanche unstable fracturing (AUF) models (Abdullaev, 2022). These models have helped to develop a more accurate representation of the processes involved in earthquakes and have facilitated more in-depth analyses of the data. In determining the possibility of propagation of precursor anomalies in the physical and hydrogeochemical fields, the calculated rates of propagation of anomalous effects were used depending on the energy of future realised events, i.e. a regular relationship between the range of manifestation of anomalies (distance R) and the magnitude of a given earthquake in the ratio: R = 100.43M; where R – the radius of the zone of manifestation of precursors in km and M – the magnitude of the earthquake that occurred. The possible time of occurrence of anomalies (T) was determined according to the Rikitaka model (Hobara et al., 2022), according to the following Eq. (1):

$$\lg T = 0.66M - 1.57, \tag{1}$$

where T – time in days, M – magnitude of this event.

The experiment demonstrated that anomalies can occur when the ratio of earthquake magnitude (M) to the logarithm of the distance (lgR) to the epicentre exceeds the value of 2.5. This observation is in excellent agreement with theoretical calculations and supports the hypothesis of a connection between earthquake parameters and the occurrence of anomalies. Anomalies occurring at the specified ratio $M/\lg R > 2.5$ may indicate special conditions under which earthquakes occur. Such conditions may be related to geological features of the region, such as the presence of active seismic zones, tectonic fractures, or changes in the geological structure. Such experimental results shed light on the physical processes that occur on the earth during earthquakes. It can help scientists better understand the mechanisms of earthquake origin and development and provide tools for predicting and warning about these phenomena.

When exploring the main mechanism of hydrogeochemical anomalies generation, the laws of action of thermodynamics of locally equilibrium open hydrogeochemical systems (Pascal, Henry, Darcy, etc.) and the triggering mechanisms of internal phase change processes (Duriez et al., 2023) were used.

3. Results

The occurrence of hydrogeochemical precursors of anomalies in the chemical composition of groundwater from the position of modern earthquake preparation models (DD or AUF) is associated with the second and third stages of preparation, i.e., inelastic increase in rock volume and diffusion of water into the dilatant zone, which, subsequently, develops into a trunk rupture – to the earthquake (Hobara et al., 2022; Mavrouli et al., 2023; Wu et al., 2023). Both of these models provide a physical basis for the occurrence of hydrogeochemical anomalies, i.e., changes in the concentrations of individual components in groundwater in focal zones with at minimum up to three times the variation of background values of these parameters. It is important to note that during the analysis of the hydrogeochemical anomalies, the possibility of errors or variations in conditions was considered. Variations in the local environment, such as changes in temperature, atmospheric pressure, and water composition over time, were carefully monitored. While these conditions could potentially affect the accuracy of the results, the data collection methods and statistical analysis were designed to minimize such impacts. For instance, confidence intervals for the anomalies were calculated, and standard deviations were used to assess the potential variability in the results. In addition, the background concentrations were derived from long-term data to account for seasonal fluctuations and other environmental factors.

To explain this phenomenon, it was assumed that a relatively short time before the earthquake, the water of a different chemical composition enters the active water-supply system and is delivered to the surface without special displacement with the waters of the given horizon. These waters of a different composition are designed in the earthquake preparation zone, where fracturing develops, due to three causes: displacement of waters, isolated aquifers, influx of deep fluids, and influx of pore solutions and vapors of gas mixtures squeezed from rocks into the aquifer (Martinelli and Tamburello, 2020; Kurbanov, 2021; Melkov et al., 2022; Jiang et al., 2023). The above-mentioned idea about the mechanism of hydrogeochemical anomalies development imposes special requirements for stationary monitoring of indicator parameters of the controlled areas.

When exploring the mechanism of occurrence of gas geochemical anomalies, the most important property of these anomalies has been established, i.e. their long-range effect, which manifests itself tens and hundreds of kilometres away from the earthquake origin. This fact contradicts the above-mentioned notion.

Notably, hydrogeochemical anomalies and hydrogeodynamic anomalies precursor effects of strong earthquakes are spatial and temporal unstable masses in the form of bays, humps, shelves, surges, and pulses. To explore these anomalies, a wide range of components of the gas-chemical composition of groundwater in all earthquake-prone areas of the USSR were explored (Abdullaev et al., 2022; Abdullaev, 2022; Wu et al., 2023). They included physicochemical parameters (temperature, salt composition, pH, Eh, concentration of Na, K^+, Ca^{2+}, Mg^{2+}, Cl, HCO^{-3}, $CO_2{}^{-3}$, $SO_2{}^{-4}$, H_4SiO_4, H_2S ions) and other gases (CO_2, CH_4 and Hg), and micro components F, B, mercury, uranium and Rn, and isotopic ratio of deep gases (He, Ar, D/H, C_{13}, H_2). For this purpose, the ion-selective technique of expressing chemical and chromatographic analysis was improved (Kelaniab et al., 2021).

For continuous monitoring of the fluid regime, statistical methods were used to process daily or hourly data, where variations in background concentrations of components were calculated using the Eq. (2):

$$V = Sb/Xb \,.\, 100\%, \tag{2}$$

where Xb – average value of background concentrations (calculated from multiyear data) and Sb – standard deviations. Abnormal kit concentrations (c) were calculated using the Eq.: c $> Xb + 3Sb$ and c $< Xb - 3Sb$ for the observation period.

Initially, on the recommendation of the Institute of Geochemistry and Analytical Chemistry (Russia), the sum of maximum amplitudes of longitudinal and transverse seismic waves was taken as a quantitative parameter for comparing hydrogeochemical anomalies with seismic events: the Ap + As value. Knowing the energy class of the earthquake (C) and the distance from the epicentre to the observation point (R) for hydrogeochemical anomalies, the magnitude of Ap + As can be considered (Kelaniab et al., 2021). A correlation is then made between the seismic regime and hydrogeochemical anomalies. Recently, this correlation has been refined using a Eq. (3) that considers the energy class (C) at the observation site, i.e., the reduced class:

$$C = C_0 - 1.1 lnR, \tag{3}$$

where C_0 – energy class of the earthquake, R – distance to the observation point.

In addition to the above noted long-range property, the following phenomenal properties of hydrogeochemical precursor anomalies, generalised and defined by the authors, should be mentioned. They are as follows:

- unstable, mosaic (flickering) character of their manifestation in time (hours, days, weeks, months, years).
- diverse ("non-standard") forms of their manifestation both in the focal area of strong earthquakes and far beyond it.

It has been established that there are no universal anomalies or sets of precursor parameters for most of the earthquakes that have occurred. To explain such diverse exotic properties of hydrogeochemical and hydrogeodynamic anomalies of earthquakes various mechanisms of their generation have been suggested.

In general, it was found that hydrogeochemical and hydrogeodynamic anomalies of strong earthquakes are mainly associated with the fields of development of deformation processes that establish extreme stresses in the structure of their location (Gapeev and Marapulets, 2023; Martinelli and Tamburello, 2020; Kurbanov, 2021; Wu et al., 2023). Meanwhile, as the analysis of experimental data and observed anomalies, their morphological features are difficult to fit into the framework of a purely "dry" deformation model.

As is known, conventional straight measurements of deformation precursors are $\varepsilon = 10^6$, and most often $\varepsilon = 10^7 - 10^8$ (Hobara et al., 2022). If this fact is taken as a starting point, then, obviously, the order of the expected value of ε in the changes of hydrogeodynamic parameters of groundwater at a particular point Δh or $Q_{borehole}$ (flow rate) will be the same as Eq. (4):

$$\varepsilon = \frac{\Delta h}{H}, \tag{4}$$

where ε – volume deformation, H – groundwater level, Δh– level increment (change) at ε.

Thus, for an aquifer of thickness m = 100 m, the change in groundwater level at $\varepsilon = 10^6$ will be of the order of 0.1 mm, and at $\varepsilon = 10^7$ only 0.01 mm. If assuming that strong deformation of the order $\varepsilon = 10^{-5}$ occurred in the area of earthquake preparation, ε may be only 1 mm. Such a value is completely inconsistent with the observed magnitudes of groundwater level change before strong earthquakes, which are typically from a few millimetres to several centimetres, or up to the first few metres (Papadopoulos et al., 2020; Kelaniab et al., 2021; Baptie et al., 2022).

Calculation of the volume deformation ε in a well opening an aquifer under the condition of ignoring the flow of water in the layer over time Δt and the change in water pressure $\Delta\rho$ in it as a function of the volume deformation ε will be expressed by the following Eq. (5):

$$\Delta P = -(2G\beta/3)[1 + V/1 - 2V]\Delta \mathcal{E}, \tag{5}$$

where G – shear modulus of the rock in the layer, V – Poisson's ratio, β – Kempton's coefficient.

It follows that the variation of water pressure (Δρ) in the considered well directly determines the variation of groundwater level (Δh). Sign "–" compression of the formation.

According to Eq. (3), the magnitude of water level change Δh at volume deformation $\varepsilon = 10^{-8}$ can be estimated. If $G = 3 * 10^5$ kg/cm^2, β = 0.8, and ν = 0.3, the expected change in groundwater level is 0.5 cm.

It is known that groundwater level in the well responds to changes in barometric pressure Δb. Then for an isolated aquifer this reaction is expressed by the Eq. (6):

$$\Delta h = -(1/pg)[(1 - \beta/3)(1 + V)]\Delta\beta. \tag{6}$$

The strain-inducing additional stresses (G) in the rock massif are not uniform in various parts of the massif in the earthquake preparation region. Associated with this is a change in fluid pressure gradients and hence a change in the gas-chemical composition of groundwater (ΔC) (Zhou et al., 2022). During the earthquake preparation period, the pore-fracture water pressure (ΔP) changes by a certain amount, which can be up to 10 atmospheres or higher. If the water in the weakly permeable part of the massif differs significantly from the permeable aquifers with the concentration of chemical composition C. Then in the water coming from wells, there is an increase of this concentration by the value of ΔC which can be defined by the Eq. (7) (Kelaniab et al., 2021):

$$\Delta C = \frac{0{,}3 * \Delta PC\sqrt{\frac{t}{x}}}{\mu m h}. \tag{7}$$

I.e. the value of ΔC depends completely on the filtration properties of the massif. Thus, if assuming a fractured layer or zone with porosity m = 0.1; kh/μ = 10^4 cm^3/atm., s.; h = 1 m.; C = 5 g/l, x = 10^5 cm^2/s; ΔP = 10^{-2} atm, it will be obtained that changes of additional concentration ΔC can make up 2% against the background value. From here this dependence can be written as Eq. (8):

$$\frac{\Delta\rho}{\rho} = \frac{\Delta c}{c};\ \Delta c = \frac{c * \Delta\rho}{\rho}. \tag{8}$$

Hence, it can be seen that hydrogeochemical anomalies developed during earthquake preparation depend directly functionally on the applied additional mechanical stress in the form of ΔP on the aquifer or horizon. It provokes various physicochemical processes in the local-equilibrium hydrogeochemical system: dissolution, precipitation, adsorption-desorption, and ion exchange between the rock-solid skeleton and its liquid phase (Ahmad, 2021).

Considering the above features of hydrogeochemical and hydrogeodynamic anomalies, it can be argued that their development before the earthquake is caused by changes in the stress-strain state of the medium, the development of cracks, faults, and caused by them the emission of elastic high-frequency waves at the stage of geodynamic instability and its transition to the main rupture, i.e. the development of the earthquake origin (Melkov et al., 2022; Jiang et al., 2023; Chersky et al., 1997).

Many authors believe that deformation processes and the high-frequency ultrasonic or acoustic waves caused by them are the most general universal factor acting both in the source zone and at significant distances from it. For the development of fluid anomalies, the main condition is the occurrence of inhomogeneities in the pore-crack space of the rock massif filled with fluids (Yerlan et al., 2021; Markhaba et al., 2024). As a model of such heterogeneity, a multiphase system with double porosity, which consists of weakly permeable blocks with more permeable channels (for example, a rock broken by a network of permeable fractures or interlacing of weakly and highly permeable granular rocks) is taken. These differences in the structure of the pore-fracture space determine both the number of fluids confined in different blocks of the Earth's crust and the conditions of mass transfer between the fluids and the host rock in direct dependence on the intensity of the stress-strain state of the Earth's crust during earthquake preparation, i.e., on the volumetric deformation in the region of the developing origin.

Evidently, inside and outside the drainage zone, the reaction of water-saturated rocks to the change of stress-strain state (Δσ) will be different. Inside the zone, when pressure (+ΔP) increases on the system, water displacement from both media and its removal through the well begins. If ΔP≈0 after some time (t), water displacement stops. Thus, the presence of groundwater draining well establishes conditions for the most intensive migration of water between the media and the associated development of hydrogeochemical anomalies (ΔC) against the background of their usual chemical composition and concentration (C).

A natural classical model of such a process can be considered as earth tides, which form daily and semi-daily waves in groundwater levels, well flow rates, and with the same periodicity concentration waves in the gas-chemical composition of groundwater. It is necessary to emphasise that this planetary mechanism and its influence on pore-crack pressure differ from the mechanism of earthquake preparation: if, in the first case, these pressure changes will represent harmonic oscillations, in the second case the pressure increase (Δρ) will cause a jump process. Thus, as a result of anomalous stresses (volumetric deformations) in the rock massif, variations of external pressure (ΔP) arise, which lead to changes in the water flow rate (Q) in the well and its gas-chemical composition for some time Δt.

Experimental data obtained by specialists from the Institute of Geochemistry and Analytical Chemistry (Russia) in the Belarusian Polesie have unambiguously demonstrated the influence of seismic vibration processes and acoustic waves on the physical and chemical state of rocks and the water-bearing environment (Jiang et al., 2023; Chersky et al., 1997), it can be stated that ultrasonic and acoustic waves occurring in the area of focal zone development are powerful stimulators of jump changes in groundwater levels, well flow rates and chemical composition of groundwater.

It has been established that ultrasonic waves can destroy the film of bound water protected by a double electric layer, which leads to a sharp increase (tens of times) in pore permeability and further to a significant increase in filtration coefficients. The effects of increasing aquifer permeability in the acoustic field lead, first of all, to a decrease in groundwater level and, therewith, to an increase in the flow rate of self-pouring wells according to Darcy's law due to an increase in the filtration rate (Hobara et al., 2022; Zhou et al., 2021; Kelaniab et al., 2021).

Consequently, well-isolated pressure, aquifers or fracture-vein hydrogeological massifs in block tectonic structures represent an ideal elastic body. Then the steady-state groundwater level (H) or flow rate (Q) in these wells can be considered a sensitive volumetric deformograph. When there is no external influence, the background geodynamic state of the system "aquifer-well" is maintained in conditions of hydrogeological equilibrium:

$$\left(1+\frac{\Delta V}{V}\right)\left(1+\frac{\Delta n}{n}\right)*\left(1+\frac{\mathrm{P}}{\Delta \mathrm{P}}\right)=1, \quad (9)$$

where n and Δn – aquifer porosity and its increment; V and ΔV means aquifer volume and its increment; P and $\Delta\mathrm{P}$ – aquifer water density and its increment.

The Eq. (10) of the physical state of the aquifer then has the form:

$$\Delta V = V[n\beta + (1 * n)a]\Delta\sigma z, \quad (10)$$

where, a – coefficient of vertical compression of aquifer; $\Delta\sigma z$ – variable of vertical stress, β – coefficient of volumetric compression of water inside the aquifer.

In this case, the Eq. (11) of state of water can be written in principle in this form:

$$\Delta\mathrm{P}/\mathrm{P} = \Delta n/n = \beta\Delta\mathrm{P}, \quad (11)$$

where $\Delta\mathrm{P}$ – change of head.

Since the value of β can be practically neglected, it can be assumed that $\Delta\mathrm{C}$ and $\Delta\mathrm{H}$ or $\Delta\mathrm{Q}$ are practically a function of the effects of external pressure P and acoustic high-frequency oscillations of the medium, i.e.:

$$\Delta\mathrm{H}(\Delta\mathrm{C}) = f(P) + \varepsilon, \quad (12)$$

where, ε – intensity of high-frequency oscillations in the area of development of anomalous deformation processes.

The connection of these quantities leading to a change in groundwater level or $\mathrm{Q}_{\mathrm{sqv}}$ can be expressed by the Eq. (13):

$$\Delta H(\Delta Q) = \Delta P/g\rho, \quad (13)$$

where g – acceleration of gravity. This correlation demonstrates that tidal forces are important in the development of hydrogeochemical and hydrogeodynamic anomalies.

In the chemical aspect, the development of hydrogeochemical anomalies is connected with the transfer of easily soluble salts from rocks to the aquifer or the departure of hard-soluble salts into sediments or the mixing of waters of different compositions in mountain massifs. The developed hydrogeochemical ($\Delta\mathrm{C}$) salts are carried to the surface of the ground by the flow of the carrier-self-discharge from wells. In this case, the growth of additional concentration ($\Delta\mathrm{C}$) will fully depend on the filtration parameters of the rock massif and the time of action of anomalous stresses. Consequently, this process can be represented in the form of the following Eq. (14):

$$(\Delta\mathrm{C}) = \Delta\mathrm{P} * \frac{\mathrm{C}}{\mu},\ nh * \varepsilon\Delta t, \quad (14)$$

where $\Delta\mathrm{P}$ – variations of external pressure created by deformation processes, C – background concentration of chemical components of water in a given well, μ - viscosity of water, n – porosity of water-permeable layer,

h – thickness of this horizon, e – intensity of high-frequency oscillations in the area of the observed array, Δt – time of exposure to anomalous stresses.

Then the connection between change of groundwater level in wells and change of stress s in aquifers will have the following form:

$$-\Delta \mathrm{H} = n\beta + (1+n)\alpha/\beta \mathrm{P} g, \tag{15}$$

where the "–" sign indicates aquifer compression.

In this equation, the vertical compression coefficient a can be replaced by the inverse of Young's modulus, i.e. $\mathrm{E} = 1/\alpha$. Then Eq. (8) will have the following form:

$$\Delta\sigma = -\frac{\beta \mathrm{P} g}{n\beta} + \frac{1-n}{\mathrm{E}} * \Delta \mathrm{H}(\Delta Q). \tag{16}$$

Neglecting very small values of β, simplifying Eq. (14, 15), it can be written as follows:

$$\Delta \mathrm{H}(\Delta Q) = K_w * \Delta\sigma, \tag{17}$$

where K_w – well proportionality factor, numerically characterising each individual water point with its barometric efficiency; $\Delta\sigma$ – variable voltage value.

The analysis confirms a strong correlation between hydrogeochemical anomalies and the preparatory phases of earthquakes. These phases are characterised by changes in groundwater chemical composition, gas emissions and hydrostatic pressure fluctuations. The data underscore the significant role of deep aquifer interactions, fluid migration processes and localized stress-strain states in triggering these anomalies. These findings validate the applicability of the DD and AUF models for understanding earthquake-related fluid dynamics. The results also highlight the unique properties of hydrogeochemical anomalies, including their temporal and spatial instability, non-standard forms of manifestation, and correlation with seismic activity in diverse geophysical settings. Such insights contribute to refining predictive models for seismic monitoring and improving earthquake preparedness strategies.

4. Discussion

Based on the above arguments regarding the genesis and mechanisms of development of medium-short-term hydrogeochemical and hydrogeodynamic anomalies and their comparison with actually observed anomalies at different prognostic polygons in Asia (Hobara et al., 2022), the most common features of such anomalies include the following:

1) The times of occurrence are within hours, days to months, which occur in the final stage of earthquake preparation.
2) Anomalies have manifold forms of manifestation in the form of coves, shelves, humps and surges, pulses or ripple changes in the course of the indicators.
3) Spontaneous attenuation of anomalies and their rapid return to the initial value after earthquakes.
4) The long-range impact of manifested anomalies, tens and hundreds of km. from the epicentre of the earthquake.
5) The heterogeneous, unstable, shimmering nature of the anomalies over time and area.

From the standpoint of classical mechanical earthquake models, hydrogeochemical and hydrogeodynamic anomalies are assigned to the final stages of earthquake preparation; however, many of these features are not convincingly explained here. They contradict actual observations. It has been argued that avalanche fracturing involves previously isolated flank deep aquifer structures. The avalanche fracture region receives pore solution waters of different compositions from the surrounding rocks (Mustafayeva and Tagiyev, 2023; Floqi et al., 2019).

If this model is followed, the "introduction of anomalies" and their rapid propagation at very low filtration rates is impossible, and their rapid dissolution (anomalous concentrations of components) after an earthquake is very controversial (Kuzmenko and Chyzhevska, 2024).

In the Institute of Geochemistry and Analytical Chemistry (Russia) in the 80s of the last century a new model of formation of hydrogeochemical anomalies was proposed. It consisted in that the earthquake origin is a generator of oscillations of variable increasing frequency. When the frequency of oscillations reaches a frequency close to the natural frequency, they cause the phenomenon of resonance, which leads to the appearance of an anomaly. In the Caucasus, a sharp increase (4-5 times) in groundwater chloride content and total mineralisation has been observed before many earthquakes that have a deep-seated character (Papadopoulos et al., 2020; Sandvol et al., 2017).

Based on detailed research of the Tashkent earthquake that occurred on 26 April 1966, it was found that during the stage of crustal compression in the focal area, radon is emitted from pores, and its dissolution in the surrounding water is enhanced (Kurbanov, 2021; Rusho et al., 2024). This observation points to the importance of exploring the evolution of specialist scientists' opinions on the nature and possible mechanisms of the development of hydrogeochemical anomalies during different periods of research. Changes in the scientists' understanding of these anomalies were observed during the research process. Initially, researchers focused on the processes of radon released from rocks and dissolved in water around the earthquake. However, with the passage of time and the development of scientific methods, scientists' opinions have expanded to consider other factors and mechanisms that may influence the development of hydrogeochemical anomalies.

Zaier et al. (2021) explored the geodynamic process of pressure rise ($\Delta\rho$) is related to the phenomenon of displacement of waters of different horizons and its consequences, such as the increase of ion concentration in groundwater. In addition, this theory considers the squeezing of pore solutions, which leads to an increase in the solubility of matter in rocks under the action of anomalous stresses. It, in turn, contributes to an increase in the concentration of easily soluble salts such as Na, Cl and others. Significantly, based on the research conducted, it was highlighted that there is a failure of anomalies and different distances of earthquake focal zones. It demonstrates that the increase in the concentration of ions in groundwater will not always equal a single value considering the different characterisation indices, which is not a universal theory.

The development of ultrasonic oscillations in the focal zone of cracking is a complex process involving several physicochemical phenomena, as highlighted by scientists Ki et al. (2021). One of the key components of this process is the processes of sorption and desorption, and radioactive gas emission. According to this theory of the group of scientists, ultrasonic vibrations occurring in the focal zone of strong earthquakes can influence chemical processes in rocks and groundwater. The process of sorption, i.e. attraction and retention of gas molecules or dissolved substances on the rock surface, can lead to changes in the concentration of various anions and cations (Montayev et al., 2024; Pangaliyev et al., 2024). Therewith, the desorption process, i.e. the emission of previously sorbed molecules from the rocks, can be stimulated by ultrasonic vibrations. It can lead to both an increase in the concentration of particular ions and a decrease in groundwater in the focal zone of strong earthquakes.

Scientists Gupta et al. (2022) described the increase of elastic stresses and the appearance of acoustic waves in the focal zone of fracture development, which are important processes in the focal zones of strong earthquakes. One of their theories explaining these phenomena is the theory of rock structure failure and the process of desorption of gravitationally bound water. According to this theory, under the influence of increasing elastic stresses, the rock structure is disturbed, leading to mechanical deformations, cracks and destruction of the porous rock structure. As a result of such disturbance, there is a process of desorption of gravity-bound water, i.e. release of previously absorbed aqueous solutions from pores. Within the framework of this theory, it is mentioned that under the influence of increasing elastic stresses desorption and degassing occur, which in turn increases the content of various components in groundwater. The desorption process releases dissolved gases, including ionised components, which can affect the chemical composition of groundwater (Easa et al., 2024; Ongayev et al., 2024). This theory discloses the essence of the development of the dynamics of geological structures.

Geodynamic processes associated with the increase of hydrostatic pressure in fracture zones play a significant role in shaping the hydrogeochemical composition of groundwater, as indicated by Andrén et al. (2016). Within the framework of their theory, it is noted that the increase in hydrostatic pressure contributes to an increase in the solubility of mineral substances and the activation of exchange reactions between rocks and groundwater. Under the influence of increased hydrostatic pressure, there is an increase in the concentration of specific salts in groundwater (O'g'li and Karshiboevna, 2024; Karches, 2023). Particularly the increase in the content of sodium and calcium chloride salts is noted. It is explained by the fact that under increased pressure there is an active dissolution of mineral components containing these ions. Thus, the growth of hydrostatic pressure in fracture zones can lead to the intensification of dissolution processes and the concentration of these salts in groundwater.

Faybishenko and Witherspoon (2004) highlighted that fracture development in source zones is an essential phenomenon associated with the development of earthquake preparation processes. According to this theory, cracks developed in focal zones can serve as a pathway for the transport of matter through the porous structure of rocks. Thus, fracturing can result in the flow of various substances such as water, mineral salts and other chemical constituents into groundwater. In the context of this theory, it is noted that fracturing can lead to an increase in chloride salts in groundwater. It is explained by the fact that fractures can serve as a pathway for the percolation of salts in groundwater. Therewith, the groundwater is enriched with chloride salts, which leads to an increase in their concentration.

Abrupt changes in hydrostatic pressure in the focal zone, leading to fluid heads and alternating phase transitions in local equilibrium open systems, are associated with the violation of equilibrium in the system (rock-soil-chemically active fluid). Within the framework of this theory, it is noted that there is an exchange of phase reactions of different signs and reorganisation of the system "water-rock-gas". As a result, there are concentration anomalies in groundwater in the focal area, which is a sign of preparation for strong earthquakes. This theory can be considered significant because it explains the occurrence of element and salt concentrations changing in the rock of focal areas.

The above-mentioned theories play a significant role in explaining the mechanisms of earthquake-related groundwater anomalies. However, present research based on physical and mathematical models is of particular importance for a complete investigation of this subject. This approach enhances the understanding of the processes related to hydrogeochemical fields and seismic activity and makes an important contribution to unravelling the mechanisms of anomalies in groundwater before seismic events.

5. Conclusions

Anomalous variations in hydrogeochemical fields in earthquake preparation zones reflect the combined effects of seismic, deformation, tectonic processes, and external fields. Long-term monitoring data from Kazakhstan (1990–2022) corroborates this relationship. These anomalies are attributed to contrasting stress-strain changes in earthquake preparation zones. The observed heterogeneity of these anomalies can be attributed to variations in the petro-lithological composition of rock massifs, groundwater types, and the seismotectonic, hydrogeological, and geophysical conditions at observation points. These factors are contingent on the energy parameters and mechanisms of earthquakes occurring in specific seismogenic structures. The proposed physical-chemical and physical-mathematical models provide a universal framework for explaining the processes within local-equilibrium open hydrogeochemical systems during earthquake preparation, independent of the seismic regime in a given area.

Further research in this area may cover the following aspects: establishing more precise links between fluid anomalies in hydrogeochemical fields and preceding accompanying or following earthquakes; more accurate modelling of hydrogeochemical fields and their influence on earthquake occurrence may contribute to a better understanding of the physical processes occurring in the Earth's crust. Multiparametric analysis of continuous monitoring data, both hydrogeochemical, seismic data, and geophysical and cosmophysical parameters, allows more objective development of more accurate physical and mathematical models of the precursor factors of strong earthquakes for the development of methods and prediction, and real integration of various observation sources, including deformation, geodetic measurements, GPS, atmospheric processes, for this purpose.

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