

Anomalies in groundwater composition caused by earthquakes: examples and modeling issues

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Abstract. The examples of modeling hydrogeochemical anomalies recorded in the observation wells and sources of Kamchatka caused by the preparation of strong local earthquakes and the impact of seismic waves are considered. As a working hypothesis explaining the formation of such anomalies, assumptions about the change of conditions (1) of mixing of two waters, contrasting in chemical composition and (2) interaction in the «water – rock» system are used.

1 Introduction

The Kamchatka branch of Geophysical Survey RAS (KB GS RAS) carries out long-term observations on chemical composition of groundwater in seven deep self-flowing wells and three sources in vicinity of the city Petropavlovsk-Kamchatsky, East Kamchatka (Fig. 1) for the purpose of searching of hydrogeochemical precursors of earthquakes [1, 2, 3].

The anomalies in the composition of groundwater were discovered before the local strong earthquakes 1987-1997, with $M \geq 6.6$ for weeks-months before the occurrence of earthquakes (Fig. 1, Table 1) as well as post-seismic changes owing to shaking at passing of seismic waves. Examples of anomalies, including the hydrogeochemical precursors before the earthquakes and the subsequent post-seismic changes are shown in Figures 2 and 3. In most cases, the anomalies were monotonic and persist for up to one or several months.

Table 1. Data on strong earthquakes with magnitudes $M > 6.5$ in the CMT catalog (<http://www.globalcmt.org/>).

№	Date, yyymmdd	Time, hh:mm	Lat, °N	Lon, °E	Depth, km	M_w	Distance, D, km	
							S1	M-1
1	19871006	20:11	52.78	160.38	47	6.5	143	139
2	19920302	12:29	52.85	160.36	50	6.8	138	135
3	19930608	13:03	51.36	158.75	46	7.5	213	202
4	19931113	01:18	52	159.27	54	7.0	153	142
5	19971205	11:27	54.31	161.91	34	7.8	256	261

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The study of such anomalies using physical-chemical modeling helps to understand of their formation processes and will promote to the optimal organization of specialized observations at the flowing wells and sources. In addition, the study of hydrogeochemical anomalies in water of observational wells and sources on the basis of fundamental laws on the formation of groundwater composition in the «water – rock» systems allows their meaningful explanation not only for purpose of seismic forecast, and also for an assessment of seismic impact on the formation of chemical composition of groundwater in seismically active regions. Some issues of modeling such recorded anomalies were previously discussed in [1, 4, 5, 6].

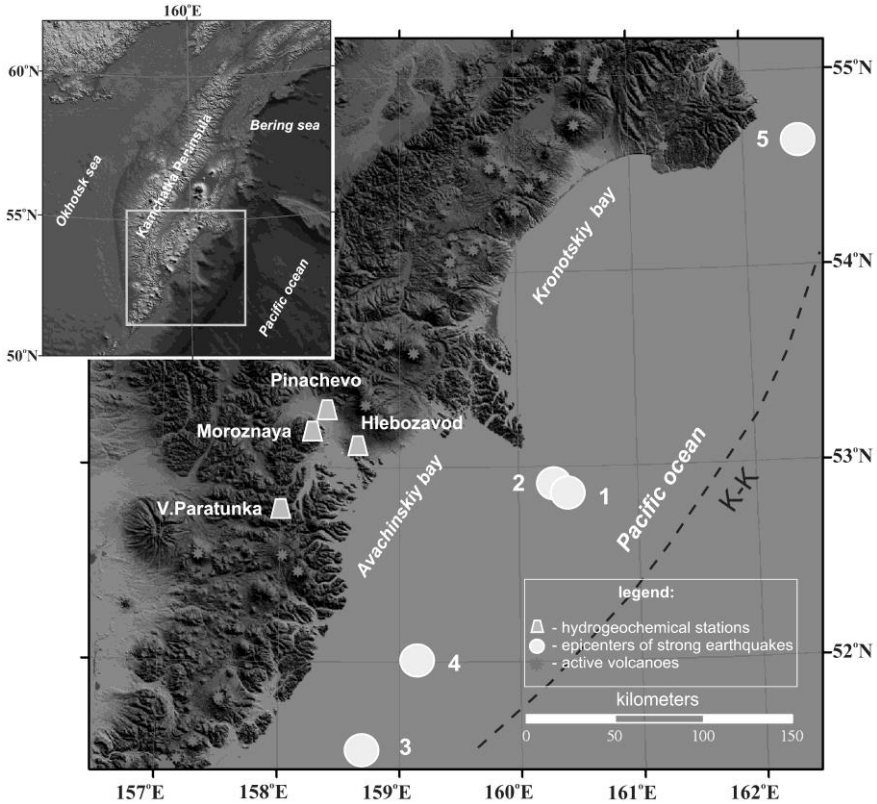


Fig. 1. The scheme showing an arrangement of hydrogeochemical stations and epicenters of strong earthquakes 1987-1997 (Table 1), accompanied by manifestations of hydrogeochemical precursors and post-seismic changes in the chemical composition of underground water. Data about the M-1 well, Moroznaya station, and source 1, Pinachevo station presented in Table 2. K-K – the Kuril-Kamchatka trench.

When modeling of hydrogeochemical anomalies developing in real time it is necessary to consider local geological and hydrogeological conditions and technical features of observations. For each observational well is necessary to estimate the volume of water in the wellbore (V, m^3) and discharge time as a result of its self-flowing ($T = 0.001V/Q, c$, here Q – flow rate, dm^3/s). The characteristic volumes of water in the wellbore are composed from units to tens m^3 , flow rate – from $n \times 0.01 dm^3/s$ to $n \times 0.1 - n dm^3/s$, here $n = 1, 2 \dots 9$. Thus, discharge time T can range from several hours to first years. The value T needs to be considered at assessment of duration of hydrogeochemical anomaly in water-bearing rocks connected with observational well, because such duration is equal or exceeds value T .

Table 2. Data about the objects of observations.

	Water-bearing rocks: composition, age	Flow-rate, l/s	Mineralization, g/l	Water chemistry	T, °C
Source 1, Pinachevo station (S1)	Andesite, volcanogenic-sedimentary rocks, Q	0.3	0.3	(Cl-HCO ₃)/Na	6.5
M-1 well, Moroznaya station (M-1)	Tuff, N ₂	1.5	0.2	(SO ₄ -HCO ₃)/(Ca-Na)	16

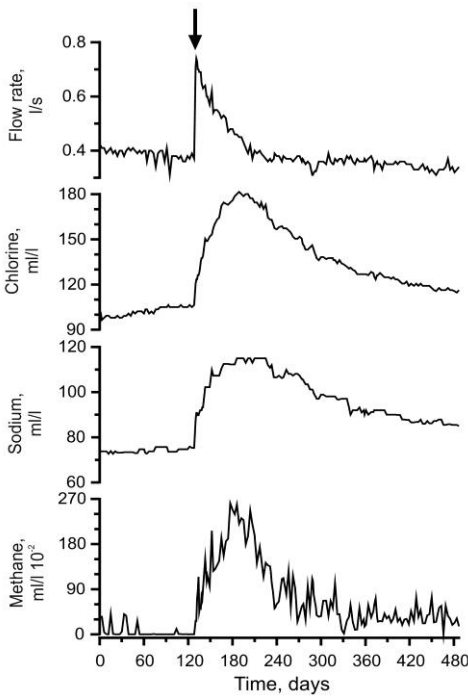


Fig. 2. Changes in the flow rate and concentrations of the components of the chemical composition of the water in source 1, Pinachevo station, caused by the earthquake on October 6, 1987, M=6.5, D=143 km (shown by the arrow). Observation time from June 1, 1987 to September 29, 1988 [5].

The time interval of sampling (Δt) and sensitivity of chemical analysis of individual components of water composition (accuracy, relative error Δ_i) also need to be considered when creating models of the registered hydrogeochemical anomalies.

When modeling hydrogeochemical anomalies it is necessary to have ideas concerning a structure of the water-bearing rocks and hydrodynamic and hydrogeochemical processes in water-bearing rocks due to preparation of earthquakes and seismic shaking. Character of the post-seismic anomalies (Fig. 2) demonstrates an increase of fluid pressure by the dynamic impact of seismic waves on the water-bearing rocks, connected with well or source, because flow rate always increases after earthquakes. The increase or decrease of the concentrations of chemical components in water is caused generally of change in the quantitative ratio of waters with different concentrations owing to their mixing. Therefore in water-bearing rocks feeding the source or the well there have to be waters with various chemical composition [6].

More complex processes in water-bearing rocks can develop at stages of earthquakes preparation causing sometimes the change of hydrogeochemical type of underground water. For example, an increase of mineralization to 25% and a change the hydrogeochemical type of water as a result of the relative increase of sulphate ion concentration and decreasing the concentration of hydrocarbonate ion was observed in the M-1 well before the March 2, 1992 earthquake (Table 1) (Fig. 3) [4]. It demonstrates not only changing the conditions of mixing of waters contrasting on a mineralization, but also indicates changes of conditions of water-rock interaction in water-bearing system of the well.

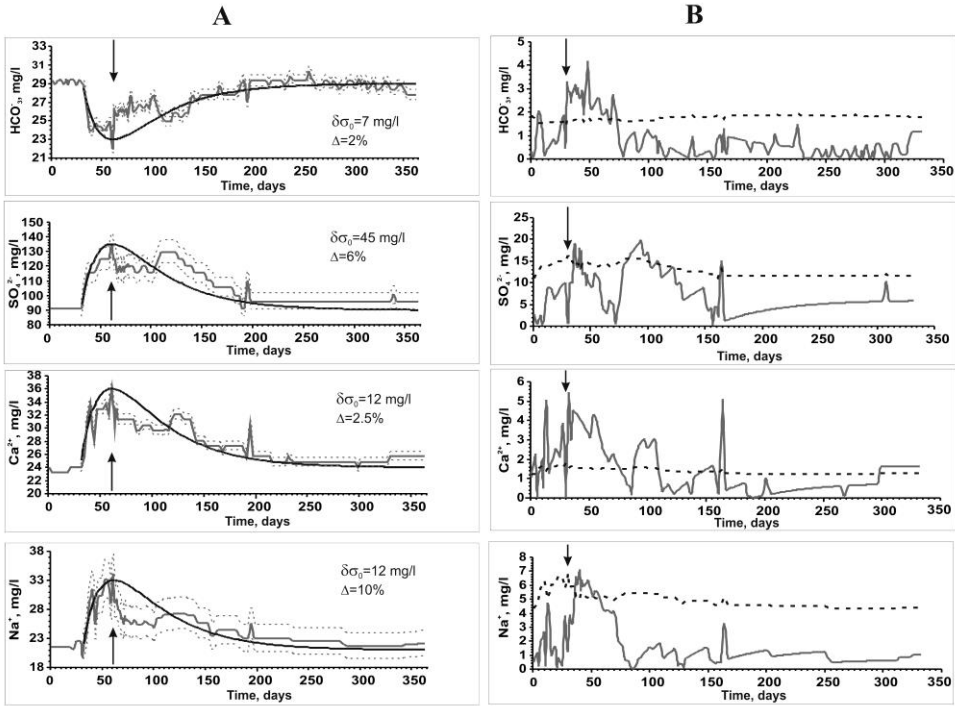


Fig. 3. Manifestations of the precursor and post-seismic effect of the earthquake on March 2, 1992, $M=6.8$ (the moment of earthquake is shown by an arrow), in changes in the concentrations of macro components of chemical composition of water in the M-1 well and the results of modeling by (1). A – The changes of concentrations and the fit by simulation for (1) by the $t_0=20$ days and $\tau_0=50$ days. Gray lines – observation data; dotted lines show the concentrations intervals taking into account the relative errors of chemical analysis Δ ; black lines – the calculated changes of concentrations according to (1); $\delta\sigma_0$ – the amplitude of changing concentration due to earthquake. B – The changes of the absolute values of differences between the measured concentrations and their calculated values on (1) (solid lines) in comparison with a double relative errors of chemical analysis for each value of the concentration (dotted line). The increase in the absolute values of the differences during the first tens of days after the earthquake shows the superposition of the post-seismic effect on the precursor anomaly [4].

2 Models of hydrogeochemical anomalies

On example of the source 1, Pinachevo station (S1) and the M-1 well, Moroznaya station (M-1) are considered models of hydrogeochemical anomalies caused by earthquakes. The schematization of hydrogeological conditions in area of the Pinachevsky sources is presented in Fig. 4A [5]. The scheme of forming chemical composition of water in the M-1 well is shown in Fig. 4B [4].

We used a mathematical model of mixing [5, 6]:

$$\delta\sigma(t) = \pm\delta\sigma_0 \frac{e^{-t/h_0} - e^{-t/\tau_0}}{(1 - \tau_0/t_0)(\tau_0/t_0)^{t_0/(t_0 - \tau_0)}} + const, \quad (1)$$

where $\delta\sigma(t)$ – changing the component concentration (mg/l) in time t ; $\delta\sigma_0$ – the amplitude of change the component concentration in mg/l. The values t_0 – the relaxation time of pressure pulse in the aquifer in days and τ_0 – the traveling time of mixed water flow in

days, characterize the perturbed hydrodynamic state of the aquifer. The sign in front of the right part of the expression (1) is determined by the nature of the change in the concentration of the water composition component: with increasing concentration – «plus», with decreasing concentration – «minus».

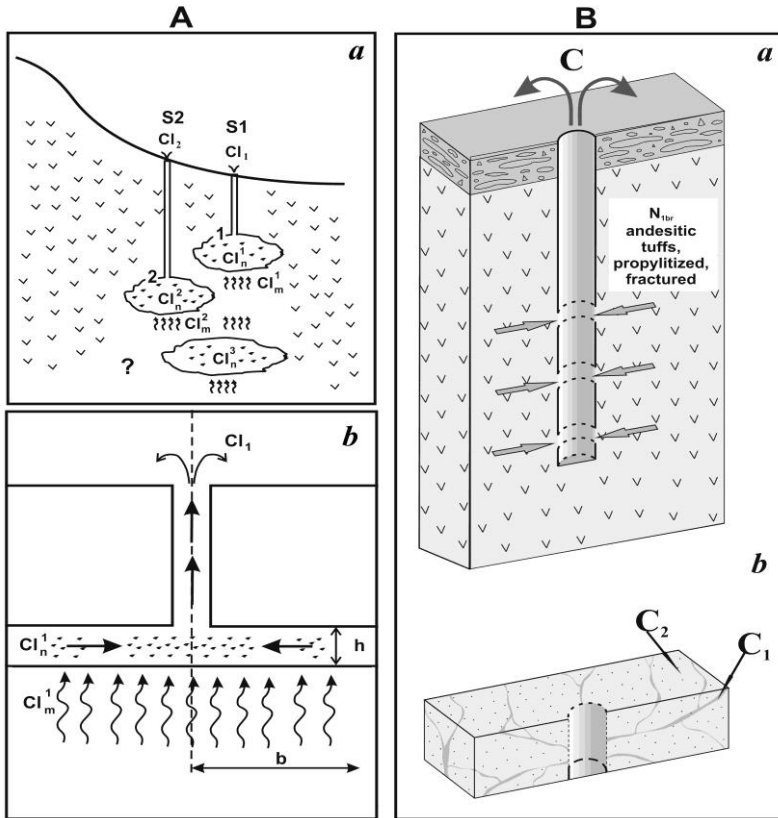


Fig. 4. Schemes of formation of underground water chemical composition: **A** – Sources, Pinachevo station: *a* – scheme of aquifer system: S1 – source 1, S2 – source 2; **1** and **2** – zones of increased transmissibility (mixing zones); Cl_n^1, Cl_n^2 – the concentrations of chlorine ion in the flow of waters in zones **1** and **2** ($Cl_n^1 < Cl_n^2$); Cl_m^1, Cl_m^2 – the concentrations of chlorine ion in the mineralized water entering in the mixing zones **1** and **2** by microfractures ($Cl_m^1 < Cl_m^2$); Cl_1, Cl_2 – the concentrations of chlorine ion in waters of sources 1 and 2 ($Cl_1 < Cl_2$); *b* – scheme of mixing two contrasting waters in an area of increased transmissibility (for example, source 1): *h* – effective thickness of the fracture zone and *b* – characteristic radius of the mixing area (zone of increased transmissibility) [5]. **B** – The M-1 well: *a* – the structure of the wells and aquifer: the dotted lines show the portions of wellbore perforations, horizontal arrows – inflow the mixed water into the wellbore, C – the concentration of macrocomponent in mixed water flowing from the well; *b* – water-saturated medium with double porosity; C₁ – the concentration of macrocomponent in the water from the «fracture», C₂ – the concentration of macrocomponent in the water from the «blocks» [4].

When modeling of hydrogeochemical anomalies for each component of water composition the values $\delta\sigma_0$ were estimated from observed data. The values of t_0 and τ_0 determined by the choice with the minimum discrepancy between the model and the observed data at all major macrocomponents of water composition. The necessary conditions for modeling also are accounting errors in determining each component of water composition Δ_i and electrical neutrality of groundwater.

Under the proposed models describes the post-seismic hydrogeochemical anomalies in the source 1, Pinachevo station (Fig. 5) and in the M-1 well (Fig. 3) [4, 5]. Using the model of aquifer system as a medium with double porosity for the M-1 well (Fig. 4B) the chemical compositions of the mixed waters were estimated (Fig. 3). It was discovered that during the preparation of earthquakes there was an increase of water flow with raised concentrations of sulfate ion, calcium, and sodium from low permeable blocks to the fractures system [4].

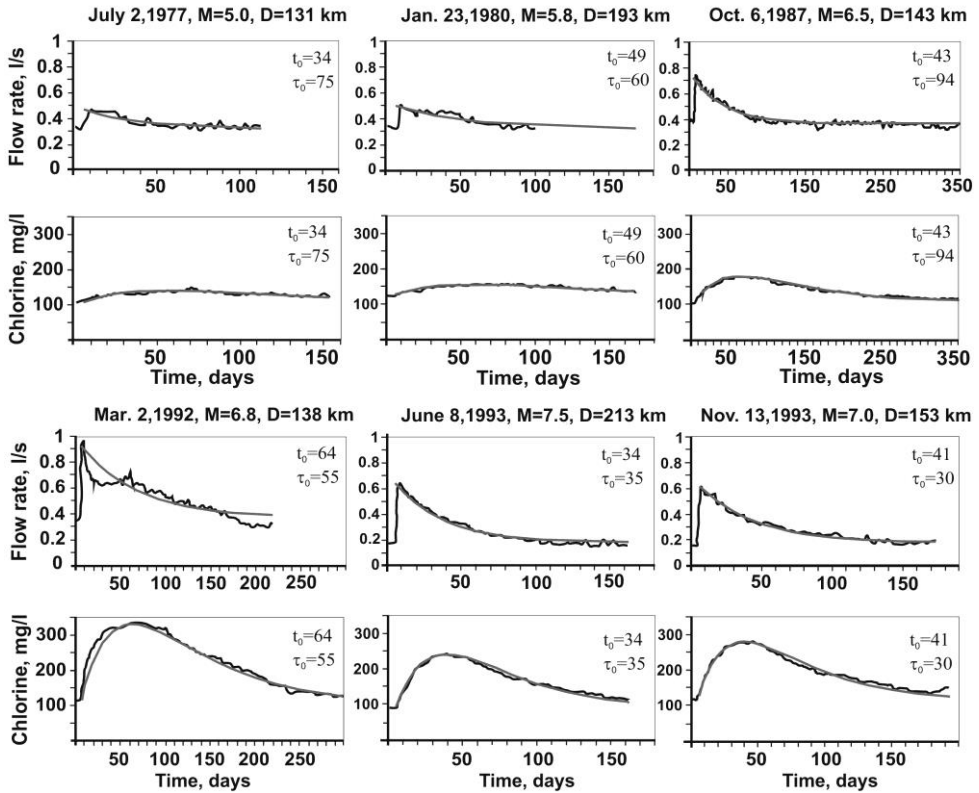


Fig. 5. Post-seismic changes in the flow rate and chlorine ion concentration in the water of the source 1, Pinachevo station, due to earthquakes in 1977-1993. Black color shows the observational data, the gray color shows the approximation by (1) [5].

In the second model of hydrogeochemical anomalies registered in the changes composition of groundwater from the M-1 well during the preparation and implementation of the earthquake March 2, 1992, $M = 6.8$, were used methods of equilibrium thermodynamics and analysis of elementary chemical reactions taking place in the «water – rock» system [7]. It was assumed that the initial products of these reactions are the rock-forming minerals and water, the final products - secondary minerals, as well as the ions and neutral molecules entering in the groundwater.

According to the results of chemical analysis of water composition estimated the degree of groundwater saturation relative to secondary minerals with using the saturation index SI in [1]: $SI = \lg(Q/K_p)$, where Q – quotient reactions or ratio the actual product of the reaction products activities to the actual product of the activity initial materials, K_p – reaction constant. Positive SI values show that the water is saturated with secondary minerals and the value of SI increases as the water is being saturated with secondary minerals.

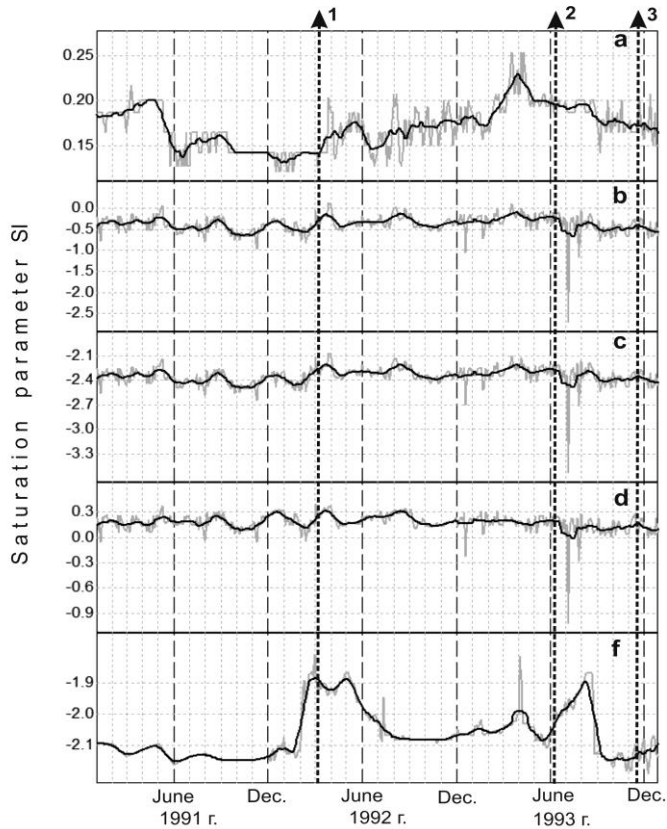


Fig. 6. The 1991-1993 variation in the saturation of groundwater from the M-1 well with respect to kaolinite (a), Ca-montmorillonite (b), Na-montmorillonite (c), calcite (d), and anhydrite (f). Heavy lines show averaged theoretical saturation indices in a moving time window of 30 days at a step of 3 days. The vertical arrows mark the times of earthquakes: **1** – March 2, 1992, $M=6.8$; **2** – June 8, 1993, $M=7.5$; **3** – November 13, 1993, $M=7.0$ (Table 1) [1].

Using observed data on chemical composition of water in wells and sources were calculated time-dependent changes of SI parameters with respect to secondary aluminosilicate minerals, calcite, anhydrite, etc. in relation to earthquakes that were accompanied by shakings of intensity 5-6 points on the MSK-64 scale in areas of the observing stations.

The results processing of observational data show the changes of interaction in the «water – rock» system caused by the 5-6- points shakes (on the MSK-64 scale), especially evident in the case of the March 2, 1992 earthquake. Before this earthquake was discovered a new type of hydrogeochemical precursor in the form of increasing saturation of the groundwater from the M-1 well by anhydrite [1] (Fig. 6).

3 Conclusions

1. Model of mixing two contrasting waters in a zone of raised transmissibility explains much of the post-seismic anomalies in the regime of wells and sources, in which were registered hydrogeochemical anomalies due to earthquakes, in particular, in the regime of source 1, Pinachevo station. For this source were detected changes of mixing conditions in the aquifer in time. This is indicated by the distinction of obtained values t_0 – time of head

relaxation and, especially, τ_0 – a parameter characterizing the time of flow through the mixing zone for different earthquake (Fig. 5). Under the constant conditions in time the state and geometric dimensions of the aquifer (Fig. 4A) should be expected the constancy these parameters for different earthquakes.

2. The results of regime observations data processing at wells and sources show changes of interaction in «water – rock» system caused by the impact of earthquake of 5-6 point intensity (according to the MSK-64 scale) (post-seismic effect). Before the Kamchatka earthquake on March 2, 1992, a new type of hydrogeochemical precursor was discovered in the form of increase in saturation of anhydrite of groundwater from the M-1 well [1].

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