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Seismohydrogeological Phenomena as a Earthquakes' Trigger Impact on Groundwater (by the Example of the Wells of the Petropavlovsk-Kamchatsky Test Site, Kamchatka Peninsula)

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Abstract—Based on the long-term observations of the wells on the Petropavlovsk-Kamchatsky Test Site, the Kamchatka Peninsula, the paper analyzes manifestations of three main types of seismohydrogeological effects—hydrogeological precursors, coseismic pressure jumps and postseismic effects of the vibrational impact of seismic waves in measurements of the pressure and chemical composition of groundwater, depending on the earthquake parameters (magnitude, epicentre distance, intensity of seismic impact in the observation areas). The paper presents data on the earthquakes that were preceded by hydrogeological precursors in several (n = 2–4) wells. It is discussed whether it is possible to use hydrogeological precursors to predict strong earthquakes in Kamchatka. The authors also discuss the results of their experimental use in a real-time environment with weekly reports on the current observational data for the Kamchatka Branch of the Russian Expert Council. By the example of water level observations in YUZ-5 Well, the authors analyzed coseismic jumps in the groundwater pressure due to rupture formation in the sources of local $M_w > 6.0$ earthquakes and four types of effects of the vibrational impact of seismic waves during local and distant $M_w = 6.8–9.3$ earthquakes at epicentral distances from 80 to 14600 km; the study demonstrates that such effects depend on the earthquake parameters and the intensity of seismic impact in the well area.

Keywords: well, earthquake, water level, chemical composition of groundwater, hydrogeological precursor, seismic prediction

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INTRODUCTION

For decades, scientists studying the Earth have been discussing the impact of earthquakes on groundwater based on well and spring observations in order to estimate the variability of pressure, discharge, temperature and hydrogeochemical regimes of groundwater depending on parameters of seismic events (Wakita, 1995; Reddy et al., 2011; Yusupov et al., 2014; Skelton et al., 2014; 2019; Barberio et al., 2017; Boschetti et al., 2019; Chiodini et al., 2020; Martinelli et al., 2020; Tsunogai, Zhou et al., 2020; Kopylova and Boldina, 2020; 2021; Kopylova et al., 2020; 2022). The findings of such studies permit to explore into the space-time scales of the manifestation of seismohydrogeological effects, depending on parameters of seismic events, which facilitates effective management of water resources and environmental control in seismically active regions. Besides, the development of adequate models of the response of groundwater to seismic impacts helps to improve the methods for search and practical use of hydrogeodynamic and hydrogeochemical precursors in earthquake prediction research and the analysis of seismic effects in geophysical and geochemical fields during variations in the water content and permeability of rocks.

Seismohydrogeological effects that occur before, during and after earthquake moments are considered with regard to three factors of the earthquake impact on groundwater (1–3).

(1) Pre-earthquake processes in the fluid-saturated geological environment that become manifest in hydrogeological (hydrogeodynamic and hydrogeochemical) precursors (Wang and Manga, 2010; 2021; Kopylova and Boldina, 2020). Formation of fissure dilatancy in water-bearing rocks, changes in filtration properties and the hydraulic relationship between different elements of hydrogeological systems, controlled by wells (Skelton et al., 2014; 2019; Kopylova and Boldina, 2021 et al.), or a quasi-elastic deformation of water-bearing rocks caused by pre-earthquake aseismic motions in the source area (Kopylova and Boldina, 2012) are analyzed as hypothetical mechanisms

of variations in the pressure, temperature, ionic-salt and gas composition of groundwater in wells before earthquakes.

(2) Rupturing at earthquake sources is accompanied by variations in the static stress state of water-bearing rocks and an abrupt coseismic increase or decrease in the groundwater pressure in piezometric wells (Wakita, 1975; Kopylova et al., 2010).

(3) Propagation of seismic waves from the source of an earthquake is accompanied by dynamic deformation of water-bearing rocks and various co- and post-seismic variations in the pressure, temperature and chemical composition of groundwater and gases (Wang et al., 2001; Kitagawa et al., 2006; Kopylova and Voropaev, 2006; Shi et al., 2013; 2015; Sun et al., 2015; Boschetti et al., 2019; Kopylova and Boldina, 2020; Chiodini et al., 2020; Martinelli et al., 2020, etc.).

These factors of the seismic impact account for the time sequence of pre-, co- and post-seismic variations in groundwater in relation to the instrumental earthquake time but cannot explain a wide variety of the observed responses of the groundwater parameters even in nearby wells. The variety of the responses of the pressure and other physical and chemical parameters of groundwater to the seismic impact is explained by using data on the peculiarities of the local geological and hydrogeological conditions, such as filtration and elastic properties of water-bearing rocks, the unique hydrogeodynamic and gas-hydrogeochemical characteristics of groundwater in individual observation wells (Kopylova and Boldina, 2006; 2020; Boldina and Kopylova, 2013), the degree of correlation between the groundwater regime and seismogenic structures and the variability of stress fields and deformations with time (Shi et al., 2013; 2015; Sun et al., 2015). Yet, despite many years of research in this field, there is no sufficient explanation of the variety, mechanisms, and processes of the generation of seismohydrogeological effects recorded in the variations in the levels, discharges, temperature, gas- and hydrogeochemistry of groundwater in seismically active regions before, during and after earthquakes (Wang and Manga, 2010; 2021).

Among the most underexplored seismohydrogeological effects are hydrogeological precursors, which manifest themselves at earthquake preparation stages and which can be potentially used through well observations for predicting the time of large seismic events. Relatively few solid data on such precursors have been collected globally, which explains the pessimism of a certain part of the scientific community about whether they really exist. Another reason why the phenomenon of hydrogeological precursors remains underexplored is that such precursors become manifest in relatively small territories in the areas of the sources of future large earthquakes, including their near and intermediate field zones (Kopylova and Boldina, 2020; Kopylova et al., 2022), but large earthquakes quite rarely occur in the same location.

More solid documentary evidence of seismohydrogeological effects recorded in various seismically active regions is about variations in the levels, pressure, temperature, and ionic-salt and gas composition of groundwater at the moment and after earthquakes (referred to below as co- and post-seismic effects). Adequate models have been suggested for such effects to describe their manifestation in individual observation wells and springs (Wang et al., 2001; Kitagawa et al., 2006; Shi et al., 2013; 2015; Sun et al., 2015; Boldina and Kopylova, 2017; Kopylova and Boldina, 2021; etc.).

The description of hydrogeological precursors, their correlation with parameters of subsequent earthquakes and processes of their generation in individual observation wells on the basis of conceptual models considering peculiarities of the manifestation of hydrogeological precursors and a combination of the local natural and technical conditions (Kopylova and Boldina, 2021; Kopylova et al., 2022) helps to understand the significance of the hydrogeological method in earthquake prediction. Studies of the co- and post-seismic effects in groundwater help to gain a deeper insight into hydrogeodynamic and hydrogeochemical processes in the water-saturated environment of seismically active and aseismic regions of the Earth.

It is evident that studying hydrogeological precursors and other seismohydrogeological effects in the near and intermediate field zones of earthquake sources requires detailed and long-term observations over the regime of wells and springs. This paper discusses the findings of the studies of the seismohydrogeological effects on the Petropavlovsk-Kamchatsky Test Site on the Kamchatka Peninsula (PKTS), obtained by the Kamchatka Branch of the Geophysical Survey of the Russian Academy of Sciences (KB GS RAS) during long-term (1977–present) observations in five deep wells (Table 1).

The Kamchatka Peninsula is situated at the junction of the Pacific Oceanic Plate with the continental Eurasian and North American plates and is one of the most seismically active regions of the Earth, where the occurrence frequency of major earthquakes with a magnitude of about 8–9 does not exceed the first hundreds of years, and large perceptible earthquakes that in continental areas produce shakes with an intensity of 5–6 and more points according to the 12-point *MSK-64* scale (Medvedev et al., 1965) occur at intervals in the first years (Chebrov et al., 2011).

The paper focuses on the manifestations of hydrogeological precursors in several ($n \geq 2$) PKTS wells, depending on the ratio of magnitudes and epicentre distances of earthquakes as well as the intensity of their impact in the observation areas. The earthquake intensity according to *MSK-64*, the density of seismic energy (Wang, 2007), and amplitude-frequency char-

Table 1. Characteristics of the observation wells on the Petropavlovsk-Kamchatsky Test Site, Kamchatka Peninsula

Well	Coordinates	Depth, m Open interval, m	Water-bearing rocks: age, composition	Flow, q, L/s Water level, h, m	Water temperature, °C	Water mineralization, g/L	Water type	Gas composition	Observations: period, frequency of measurement
GK-1	53.28° N 158.40° E	1261 400–1261	Q, N, K_2, tuff, siltstone, shale	Flowing well $q = 0.1$	16	10	Cl–Na–Ca	Free gas, $CH_4–N_2$	1986–1998, 3 days
M-1	53.18° N 158.28° E	600 310–313 407–410 553–556	N, tuff	Flowing well $q = 1.5$	16	0.25	SO_4–Ca–Na	Dissolved gas, N_2	
G-1	53.05° N 158.66° E	2500 1710–1719 1750–1754 1790–1799 2415–2424	Q, K_2, diorite, shale	Flowing well $q < 0.001$	10	12	Cl–Na	Free gas, $CH_4–N_2$	
E-1	53.26° N 158.48° E	665 625–645	N, tuff	Piezometric well, $h = 28$	10	1.5	Cl–HCO_3–Na	Free gas, $N_2–CH_4$	1987–2016: January 3, 1987–July 8, 1994, 1 day; January 29, 1996–2016, 5–10 minutes
YUZ-5	53.17° N 158.41° E	800 310–800	K_2, mudstone, shale	Piezometric well, $h = 1.5$	14	0.45	HCO_3–SO_4–Na–Ca	Dissolved gas, N_2	September 9, 1997–2016, 5–10 minutes

acteristics of seismic waves according to the earthquake data recorded at the Petropavlovsk seismic stations that is the closest to the observation sites (Kopylova and Boldina, 2020) were used as the parameters of the intensity of the seismic impact.

All in all, seven earthquakes occurred during the observation time in 1977–2021 (Table 2) which were preceded by the manifestations of hydrogeological precursors in several wells operating in natural conditions without any man-made impact. All the seven earthquakes are classified as the largest (M_w = 6.5–7.8) seismic events in the region of the Kamchatka Peninsula, which occurred at a depth of up to 200 km. This demonstrates that the complex occurrence of hydrogeological precursors as a natural phenomenon observed in a seismically active region at large earthquake preparation stages is relatively rare and unique.

INPUT DATA

The authors were directly involved in the observations at the PKTS wells, in the development and improvement of a groundwater parameter observation system (Kopylova et al., 2016; Kopylova and Boldina, 2019; Boldina et al., 2022), and in the development of methods and software tools for processing observational data (Kopylova et al., 2003; 2009). Descriptions of the wells, observational techniques and data processing methods for the detection of seismohydrogeological effects can be found in (Kopylova et al., 1994; 2016; Khatkevich and Ryabinin, 2004; Kopylova and Boldina, 2019; Boldina et al., 2022).

All PKTS observation wells, in which precursors were recorded, are deep, water-bearing rocks wells, characterized by a variety of hydrogeological and hydrogeochemical parameters (Table 1). The intervals of the intake portion of the wells are 310–2423 m at a depth of 600–2500 m. The structure of the wells is described in detail in (Kopylova et al., 2016; Kopylova and Boldina, 2021; 2022).

The 2018–2022 studies (Kopylova et al., 2018; 2020; 2022; Kopylova and Boldina, 2019; 2020a; 2020b; 2021) present generalized data on the seismohydrogeological effects recorded in the wells on the Kamchatka Peninsula due to the local and teleseismic earthquakes. In particular, coseismic pressure jumps during local earthquakes and four types of effects of the vibrational impact of seismic waves (I–IV) were detected in the water level variations in YUZ-5 Well, and dependencies on earthquake parameters were determined for them. This paper uses previously published as well as updated and recent data on such effects. Earlier publications of the authors on the topic are listed in the references to the 2018–2022 studies mentioned above. All those findings are the backbone of the data on the seismohydrogeological effects in the PKTS wells, presented in this paper.

Hydrogeological Precursors

A criterion for the detection of hydrogeological precursors (HP) in the variations in the level, ionic and gas composition of groundwater is an anomalous behaviour of individual parameters against the background long-term annual average values in several ($n \geq 2$) wells before the earthquakes.

Figure 1 shows examples of hydrogeodynamic precursors in the water level variations in YUZ-5 and E-1 Wells during the M_w = 7.2 Zhupanovsky earthquake of January 30, 2016 (Table 2, No. 7).

In E-1 Well (Table 1), earlier a signal was detected in the form of a decrease in the water level at a higher average daily rate of ≤–0.06 cm/day before $M \geq 5.0$ earthquakes at epicentral distances $d_e \leq 350$ km during weeks—the first months (Kopylova, 2001; Kopylova and Boldina, 2012a). This signal of the water level decrease with a threshold value of –0.06 cm/day (a hydrogeodynamic precursor) was observed in 100% of cases before $M_w \geq 6.5$ earthquakes and approximately in 50% of cases before M = 5.0–6.4 earthquakes (Kopylova and Boldina, 2020). Since 2002 the authors have been monitoring this hydrogeodynamic precursor in real-time mode, with weekly reports on its presence/absence, for the Kamchatka Branch of the Russian Expert Council for Earthquake Forecasting (KB REC) (Chebrov et al., 2011). An example of this hydrogeodynamic precursor before the Zhupanovsky earthquake, detected in real time, is shown in Fig. 1b.

In YUZ-5 Well, two cases of anomalous variations in the water level were recorded: the variations manifested in a significant disruption of its long-term annual average seasonal trend: before the M_w = 7.8 Kronotsky earthquake of December 5, 1997 (Table 2) during three weeks (Kopylova, 2006; Kopylova and Boldina, 2012), and before the Zhupanovsky earthquake (see Fig. 1a) during three months (Boldina and Kopylova, 2017). Before the Kronotsky earthquake, the water level was decreasing with an amplitude of 11 cm. Before the Zhupanovsky earthquake, the water level was increasing with an amplitude of about 30 cm against the long-term annual average seasonal trend (see Fig. 1a C).

Hydrogeochemical precursors and postseismic effects in the variations of the ionic-salt and gas composition of water from GK-1, M-1 and G-1 Wells due to the 1987–1997 earthquakes are shown in Fig. 2 (Kopylova and Boldina, 2021). In GK-1 Well, the chloride ion concentration was observed to be decreasing during one-nine months before seven earthquakes (Table 2, Fig. 2a, the left diagram). Before the earthquakes of January 1, 1996, December 5, 1997 and January 30, 2016, the decrease in the chloride ion concentration alternated with a sharp increase lasting for 4–5 months (Ryabinin and Poletaev, 2021). The augmented dispersion and changes in the average concentrations of free gases were observed during two

Table 2. Earthquakes (https://earthquake.usgs.gov/earthquakes/, http://sdis.emsd.ru/info/earthquakes/catalogue.php) preceded by hydrogeological precursors in two–four observation wells

No.	Date, dd.mm.yyyy	Earthquake epicentre coordinates	Depth H, km	Magnitude M_w	Earthquake source length$^{(1)}$ L, km	Epicentre distance to the well d_e, km	d_e/L	Specific seismic energy density e, J/m^3	Seismic intensity I according to *MSK*-64$^{(2)}$	Wells (precursor duration T_1/precursor lead time, $T_2$$^{(5)}$, weeks)
1	06.10.1987	52.86° N 160.23° E	33	6.5	37	130–134	3.5–3.7	0.1	5	GK-1 (30/30), M-1 (4/4), E-1$^{(3)}$(5/5)
2	02.03.1992	52.76° N 160.20° E	20	6.9	56	133–136	2.4	0.2	5–6	GK-1 (39/39), M-1 (4/4), E-1$^{(3)}$(9.5/9.5)
3	08.06.1993	51.20° N 157.80° E	40	7.5	103	220–233	2.1–2.3	0.3	5	GK-1 (4/4), M-1 (4/21.5), E-1$^{(3)}$(36/36)
4	13.11.1993	51.79° N 158.83° E	40	7.0	62	157–167	2.5–2.7	0.1–0.2	5–6	GK -1 (4/4), M-1 (4/17), E-1$^{(3)}$(12/12)
5	01.01.1996	53.88° N 159.44° E	0	6.6	41	95–108	2.3–2.6	0.1–0.2	4–5	GK-1 (30/30), M-1 (4/13), G-1 (21.5/21.5)
6	05.12.1997	54.64° N 162.55° E	10	7.8	139	305–314	2.2–2.3	0.3–0.4	5–6	GK-1 (21.5/21.5), G-1 (13/13), E-1$^{(3)}$(3/3), YUZ-5$^{(4)}$(3/3)
7	30.01.2016	53.86° N 158.73° E	168	7.2	76	70–80	0.9–1.1	2.7–4.1	4	E-1 (3/3), YUZ-5 (15/15) GK-1(24/24)

(1) the maximum linear size of the earthquake source according to (Riznichenko, 1976).

(2) the Medvedev–Sponheuer–Karnic scale, also known as the 12-point *MSK-64* scale, is a macroseismic intensity scale used to evaluate the severity of ground shaking on the basis of observed effects in an area where an earthquake transpires; points are given for Petropavlovsk-Kamchatsky city.

(3) a decrease in the water level with an amplitude of >3 cm at an increased rate (see Table 3 in (Kopylova, 2001));

(4) precursors in the water level variations during three weeks were first described in (Kopylova, 2006);

(5) precursor duration T_1—duration of the anomalous variation in the hydrogeological parameters in the well, precursor lead time T_2—the time from the onset of the anomalous variation in the hydrogeological parameters in the well to the earthquake.

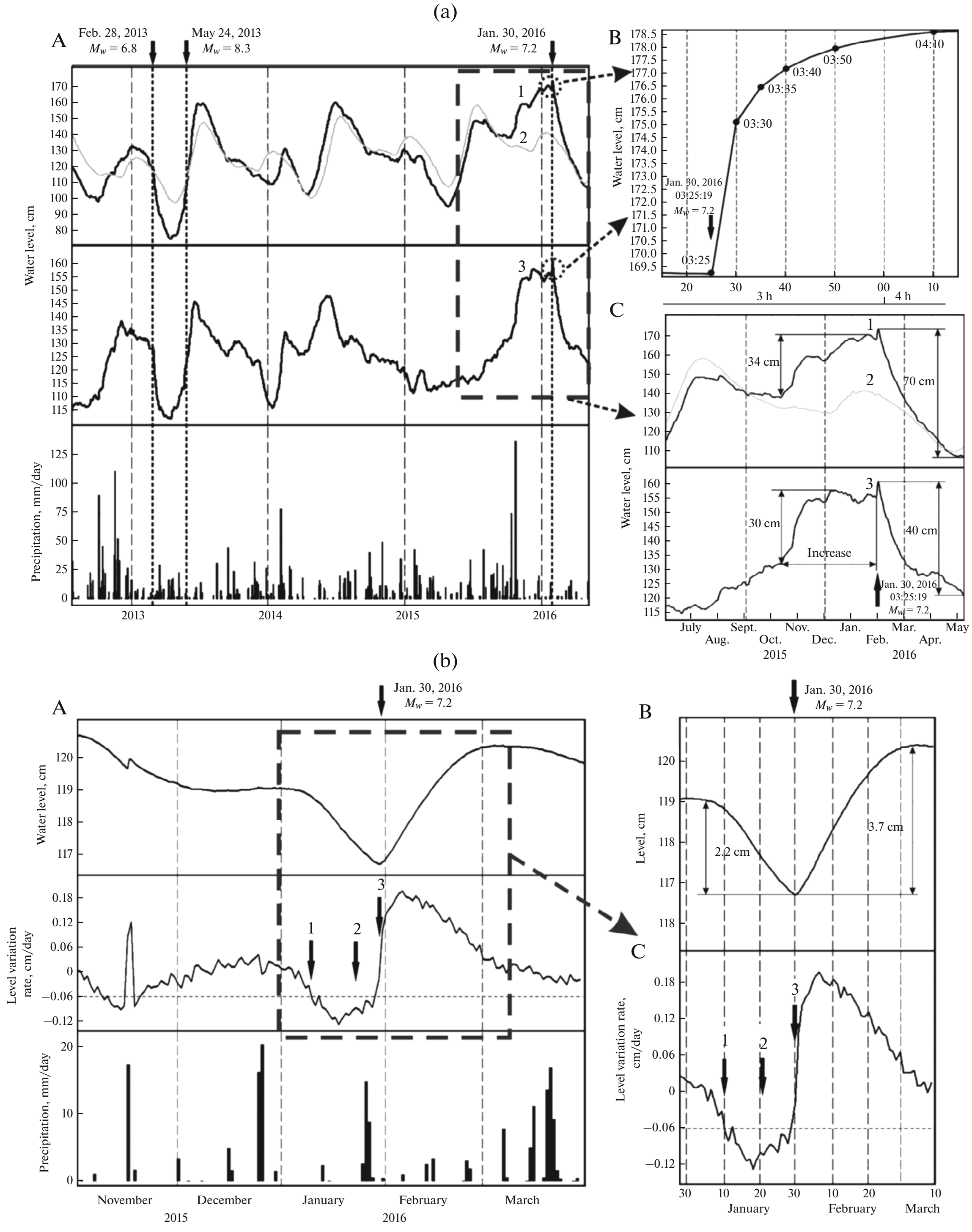

Fig. 1. Variations in the water level in YUZ-5 (a) and E-1 (b) Wells due to the $M_w = 7.2$ Zhupanovsky earthquake (below—ZhE) of January 30, 2016 (Table 2). Variations in the water level in YUZ-5 Well: A—water level variations in July 2012—May 2016, against precipitation and $M_w \geq 6.5$ earthquakes (indicated with arrows): 1—hourly average observational data with compensated barometric variations; 2—seasonal water level variations; 3—residuals in the water level variations after compensation of the annual seasonality and trend: the bold dashed line indicates the fragment of graphs during ZhE, see Fig. C); B—a coseismic increase in the water level after the onset of seismic waves (03:25); C—precursor and postseismic water level variations. Variations in the water level and its daily average rate in E-1 Well: A—from November 2015 to March 2016, against precipitation; ZhE is indicated with an arrow. In the graph of the daily average rate of water level variations, numbers show: January 1—10—the onset of the hydrogeodynamic precursor, January 2—21—the date of submission of a forecast report on a potential strong earthquake to KB REC, January 3—30—ZhE; the dashed line indicates the threshold water level decrease rate –0.06 cm/day; the bold dashed line outlines the fragment of water level variations, shown in the figures: B—water level variations from December 30, 2015 to March 10, 2016, including a hydrogeodynamic precursor and a postseismic increase; C—change in the daily average water level variations rate against its threshold –0.06 cm/day (according to (Boldina and Kopylova, 2017)).

months before the earthquake of March 2, 1992 (Fig. 2a, the right diagram) (Kopylova et al., 1994).

In M-1 Well, the concentration of bicarbonate ion decreased before five earthquakes (Table 2, Fig. 2b). In four cases, a simultaneous increase in the concentration of sulfate ion, calcium and sodium was observed. A month before the earthquake of March 2, 1992, the water mineralization increased by 25% and the hydrogeochemical type of water changed due to the increase in the concentration of sulfate ion and the decrease in the concentration of bicarbonate ion (Kopylova et al., 1994; 2022).

In G-1 Well, anomalous variations in the concentrations of chloride ion, sulfate ion, hydrocarbonate ion, sodium and calcium were observed before the earthquakes of January 1, 1996 and December 5, 1997 (Fig. 2c) (Khatkevich and Ryabinin, 2004; Ryabinin and Khatkevich, 2009).

Figure 3 shows the relationship between manifestations of HP in several wells and the parameters of subsequent earthquakes—their magnitudes M_w and epicentral distances d_e (km) with regard to the calculated specific density of seismic energy e, J/m^3 in the observation area (Wang, 2007; Wang and Manga, 2010; 2021; Kopylova and Boldina, 2020a; 2020b, 2021; Kopylova et al., 2022). Table 2 also shows the shaking intensity according to the 12-point *MSK-64* scale in the area of Petropavlovsk-Kamchatsky during all the seven earthquakes in question.

Figure 3 demonstrates that hydrogeological precursors were observed in several wells before the M_w = 6.5–7.8 earthquakes at epicentre distances d_e = 80–300 km. Those earthquakes were followed by the ground shaking with $I_{MSK\text{-}64}$ = 4–6 points. The density of seismic energy e during those events in the area of the wells was from 0.1 to 4.5 J/m^3. Hydrogeological precursors were observed in the near and intermediate field zones of the earthquake sources, for which the epicentre distance d_e (km) to the maximum earthquake source linear size L (km) ratio was d_e/L = 0.9–3.7.

Duration and lead time of hydrogeological precursors before the earthquakes in specific wells (T_1 and T_2) are shown in Table 2. They varied from 1 to 9 months (Fig. 4). It should be noted that there is no relation between the precursor duration T_1 and the magnitudes of the subsequent earthquakes (Fig. 4a). At the same time, for M-1 Well the following trend can be seen: the hydrogeochemical anomaly lead time T_2 increases within 1–5 months with the increase in the magnitude of the subsequent earthquake (Fig. 4b).

The hypothetical mechanisms of hydrogeodynamic and hydrogeochemical precursors in the observation wells on the Kamchatka Peninsula were analyzed in (Kopylova and Boldina, 2012; 2020a; 2020b; 2021; Kopylova et al., 2022). For example, in order to explain anomalous variations in the water level in YUZ-5 Well before the Kronotsky and Zhupanovsky earthquakes, the authors used the mechanism of quasi-elastic deformation of water-bearing rocks caused by pre-earthquake aseismic motions in the source areas. The tidal sensitivity of the water level in relation to the theoretical volume deformation at the depth of 500 m (the mid-point of the open section of the wellbore) A_v = 0.161 cm/10^{-9} (Kopylova et al., 2010) was used to estimate the amplitudes of deformation of the volume expansion of water-bearing rocks upon the decrease in the water level before the Kronotsky earthquake at -0.7×10^{-7} (-11 cm/0.161 cm/10^{-9}) and the volume compression at 1.9×10^{-7} (30 cm/0.161 cm/10^{-9}) before the Zhupanovsky earthquake.

The concept of the quasi-elastic deformation of water-bearing rocks cannot explain the uniform manifestation of the hydrogeodynamic precursor in the form of a decrease in the water level in E-1 Well at an increased rate. For this well, more plausible appears to be the mechanism of the formation of fissure dilatancy at earthquake preparation stages, associated with an increase in the capacity of water-bearing rocks and a decrease in the hydrostatic pressure head. Given the presence of a methane-nitrogen gas in groundwater (Table 1), it can also be assumed that phase changes in the state of gas at earthquake preparation stages have their effect by decreasing the volume of free gas coming to the wellbore, increasing the groundwater density and downgrade the water column height. Furthermore, it can be assumed that as a result of seismic shakes the volume of free gas in the wellbore grows and the water column height increases (see Fig. 1b—the increase in the water level with an amplitude of 3.7 cm during approximately 30 days after the Zhupanovsky earthquake).

The mechanism of the occurrence of hydrogeochemical precursors in flowing wells is analyzed in (Kopylova and Boldina, 2021; 2022). By the example of the earthquake of March 2, 1992 (No. 2 in Table 2 and in Fig. 2a, Fig. 2b) it is demonstrated that the anomaly precursors in GK-1 and M-1 Wells resulted from the change in hydrodynamic conditions of mixing of waters with different chemical compositions, which are found in the aquifer systems of both wells. Most probably, this process was triggered by an unbalanced formation of fissure dilatancy in water-bearing rocks with different permeability, disturbance of the hydrodynamic water exchange conditions, and changes in the chemical composition of water flowing out of the wells. The main parameters of this process that define the form and the duration of hydrogeochemical anomalies are the time of relaxation of the groundwater pressure impulses upon initiation of the dilatancy process in water-bearing rocks and the time of movement of mixed water of an anomalous composition in the aquifer system and in the wellbore.

The results of the analysis of the manifestation of hydrogeological precursors in five PKTS wells also

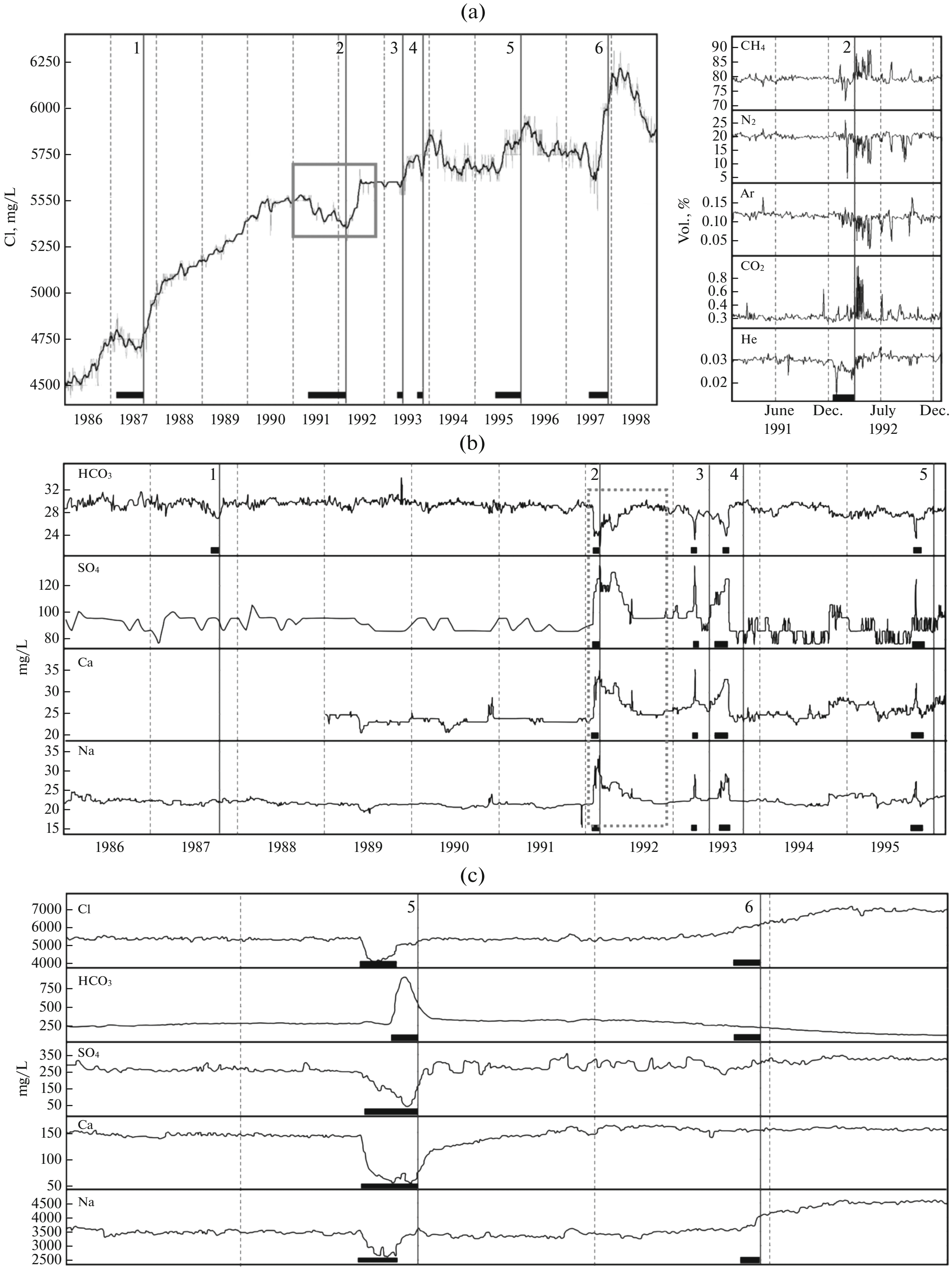

Fig. 2. Pre-earthquake anomalous variations (bold horizontal lines) in the parameters of the ionic and gas composition of groundwater from the wells: (a) GK-1, (b) M-1, (c) G-1. Vertical lines show the 1987–1997 earthquakes, earthquake numbers correspond to Table 2. The grey rectangle highlights variations in the concentration of Cl^- in the water from GK-1 Well, the grey dashed rectangle highlights variations in HCO_3^-, SO_4^{2-}, Ca^{2+} and the concentration of Na^+ in the water from M-1 Well due to the March 2, 1992 earthquake (Table 2) (according to (Kopylova and Boldina, 2020; 2021; Kopylova et al., 2022)).

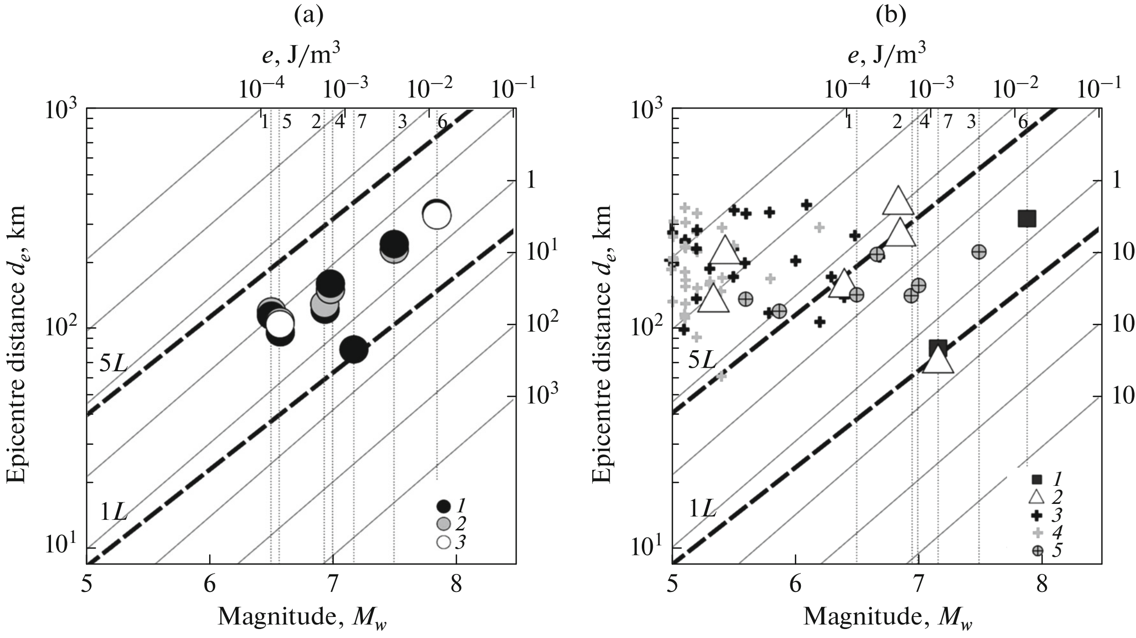

Fig. 3. Distribution of hydrogeological precursors in the observation wells, depending on the magnitude M_w, the epicentre distance d_e of the earthquakes, and the specific density of seismic energy e: (a) hydrogeochemical precursors in the variations in the ionic-salt and gas composition of groundwater from the flowing wells: *1*—GK-1; *2*—M-1; *3*—G-1; (b) hydrogeodynamic precursors in the water level variations in the piezometric wells: *1*—YUZ-5; *2*–*5*—E-1: *2*—precursors are revealed in real time, with a report on a potential earthquake for KB REC, *3*—precursors before $M \geq 5$, $d_e \leq 350$ km earthquakes are revealed retrospectively, *4*—no precursors manifested before $M \geq 5$, $d_e \leq 350$ km earthquakes, *5*—precursors before the 1987–1996 earthquakes are revealed retrospectively (Kopylova, 2011). Thin vertical dashed lines indicate earthquakes 1–7 (Table 2). Lines 1*L*, 5*L* show along the vertical axis one and five maximum linear sizes of the earthquake source according to (Riznichenko, 1976), depending on the magnitude.

demonstrate that all the observation wells under study provide insights for the detection of precursors before large local earthquakes if the wells run in natural conditions without any man-made impact. It appears that the increased sensitivity of the pressure of groundwater in E-1 well to the earthquake preparation processes (Fig. 3b), revealed on the basis of precise water lever observations, is due to the local hydrogeological conditions, specifically, the low porosity (5%) and water inflow (0.004 m^2/day water transmissivity) of water-bearing rocks, and the presence of a methane-nitrogen gas in groundwater (Kopylova et al., 2012).

The analysis of the manifestations of hydrogeological precursors on the PKTS shows that runtime diagnostics of anomalous variations in the parameters of groundwater in the studied observation wells on the basis of routine observations permits us to use them, along with other earthquake prediction data, in the mid- and short-term forecasting of the strongest earthquakes in Kamchatka first months—days in advance.

Since 2022, in cooperation with the Kamchatka Branch of the Russian Expert Council for Earthquake Forecasting (KB REC), the authors have been carrying out an experiment by using hydrogeodynamic precursors in the variations of the water levels in E-1 and YUZ-5 Wells for the real-time prediction of earthquakes, with weekly reports on the presence/absence of hydrogeodynamic precursors according to routine observations (Chebrov et al., 2011). In 2002–2016, the reports of KB REC helped to predict, on the basis of water-level data, the location, the magnitude and the time of six $M = 5.3–7.2$ earthquakes: four of them had a magnitude of 6.4–7.2 (Fig. 3b). Before the $M_w = 6.6$, $d_e = 350$ km earthquake of March 16, 2021, a hydrogeodynamic precursor was also detected in real time in the variations of the water pressure in E-1 Well (Boldina et al., 2022).

Co- and Post-Seismic Effects

Effects of coseismic deformation of water-bearing rocks. Abrupt increases or decreases in the groundwater pressure upon changes in the static stress state of water-bearing rocks due to rupturing at earthquake sources were recorded at various times in YUZ-5 Well. 14 cases of their manifestation, with amplitudes of 0.2 to 12.0 cm of water column, recorded during 5–12 min after the instrumental time of the earthquake at the origin, are described in (Kopylova et al., 2010; Boldina and Kopylova, 2016, 2017; Kopylova and Boldina, 2019).

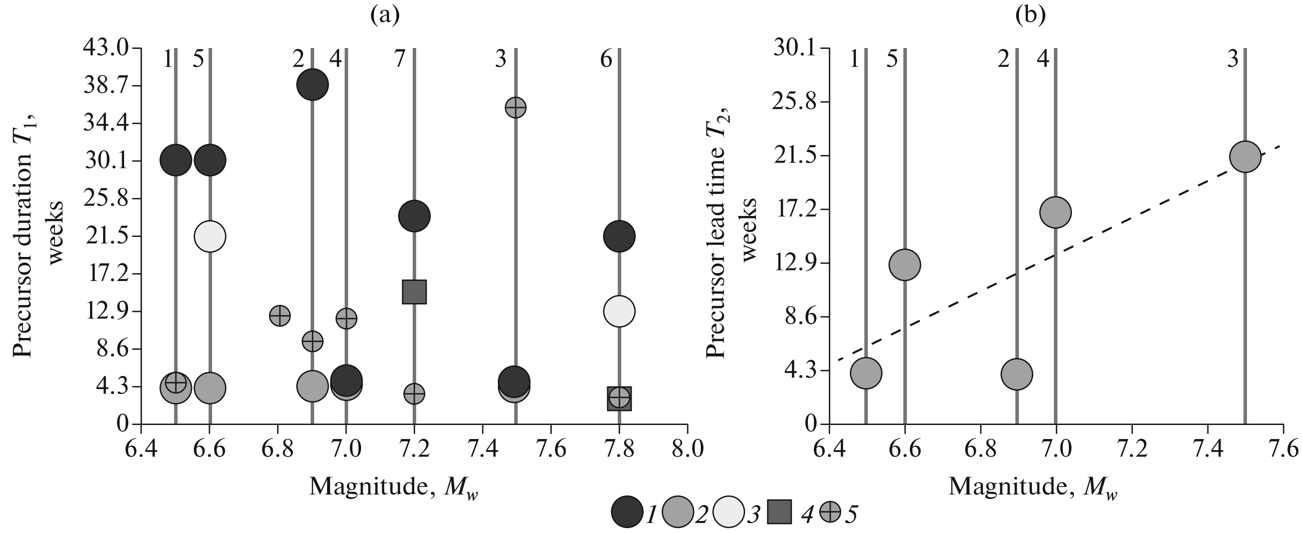

Fig. 4. (a) Distribution of the precursor duration T_1 in the observation wells: *1*—GK-1, *2*—M-1, *3*—G-1, *4*—YUZ-5, *5*—E-1, depending on the magnitude M_w of earthquakes No. 1–7 in Table 2; the earthquakes are shown with grey vertical lines. (b) Distribution of the lead time T_2 of the hydrogeochemical precursor in M-1 Well (Fig. 2b), depending on the magnitude M_w of earthquakes No. 1–5 (linear correlation coefficient 0.74).

Table 3 presents data on the earthquakes, during which such coseismic abrupt increases or decreases in the pressure were recorded in YUZ-5 Well. Figure 5 shows the distribution of coseismic pressure jumps, depending on the earthquake parameters—ratios of their magnitudes M_w to epicentre distances d_e in km. At a first approximation, manifestation of coseismic pressure jumps is described by the dependence $M_w \geq 0.003d_e + 6.0$ (boundaries of the area of the earthquakes followed by coseismic jumps in the water level in Fig. 5).

Coseismic jumps in the groundwater pressure can yield point estimates of the type and the amount of the volume coseismic deformation of water-bearing rocks with amplitudes ≥unit × 10^{-9} (Kopylova et al., 2010). The amount and the type of the volume coseismic deformation (compression or extension), estimated at the mid-depth of the penetrated water-bearing strata of 500 m by the amplitudes of pressure jumps and their direction, generally correspond to a volume coseismic deformation within one order according to the dislocation source model (Okada, 1985) if the parameters of mechanisms of sources of respective earthquakes are used (Table 3).

Effects of the vibrational impact of seismic waves. The results of the studies of the co- and post-seismic responses of the water pressure in YUZ-5 Well to the passage of seismic waves from 19 M_w = 6.8–9.1 earthquakes at epicentre distances d_e = 80–14600 km are presented in (Kopylova and Boldina, 2020). Based on the morphological features and duration of the variations in the water level, the authors distinguished four type of such effects: oscillations (type *I*), short (up to tens of hours) water level rises superimposed on oscillations (type *II*), short water level rises (type *III*), and long (1.5–3 months) drawdowns (type *IV*).

The maximum amplitude of the water level oscillations (types *I* and *II*) is determined by the pressure variations in the well—water-bearing rock system, which occur due to the passage of surface seismic waves with periods corresponding to the resonant frequency of the well (Kopylova and Boldina, 2007). The rise in the water level for tens of minutes-hours (types *II* and *III*) after the onset of seismic waves can be due to the increase in pressure upon disturbance of the steady water flow conditions near the wellbore. Strong local earthquakes with the intensity $I_{MSK\text{-}64} \geq 5$ points were accompanied by sustained water drawdowns in the well with the amplitudes of 0.3–1 m (type *IV*) due to the increase in permeability of water-bearing rocks during seismic shakes and a drop in pressure.

Figure 6 shows the dependences of the occurrence of the distinguished types of vibrational effects of seismic waves *I–IV* on the earthquake parameters (Fig. 6a) and the amplitude-frequency content of the maximum seismic wave velocity phases at the nearest Petropavlovsk seismic station (PET) (Fig. 6b).

Hence, various types of the vibrational effects of seismic waves in water level variations reflect cumulative changes in the groundwater pressure upon dynamic deformation of water-bearing rocks and associated filtration processes, caused by changes in the properties of water-bearing rocks, mainly, their permeability (Kopylova and Boldina, 2007; Wang and Manga, 2010). Formation of fissure dilatancy in water-bearing rocks, groundwater degassing, unclogging of the fracture-pore space, effects of the cumulative accumulation of interblock deformations, and

Table 3. Data on the local earthquakes (https://earthquake.usgs.gov/earthquakes/, http://sdis.emsd.ru/info/earthquakes/catalogue.php) followed by coseismic water level jumps in YUZ-5 Well

No.	Hypocentre					M_w	Epicentre distance, d_e, km/seismic intensity according to *MSK-64*	Coseismic water level/pressure jump amplitude***, Δh, cm	Volume coseismic deformation in the area of YUZ-5 Well, 10^{-9}		
	date dd.mm.yyyy	time hh:mm	coordinates, degrees		H, km				by coseismic level jumps, D_1****	according to the dislocation source model (Okada, 1985), D_2	reference
			N	E							
1	05.12.1997*	11:27	54.0**	162.3**	25	7.8	200**/5–6	–12.0	75	40	(Kopylova et al., 2010 (updated))
2	01.06.1998	05:34	52.81	160.37	31	6.9	136/3–4	–1.0	6.3	1.0	
3	08.03.1999	12:26	51.93	159.72	7	7.0	162/5	–1.7	10.6	16.4	
4	20.12.2000	09:20	53.31	160.06	65	6.2	110/4	0.6	–3.8	–1.4	
5	16.06.2003	22:08	55.30	160.34	190	6.9	266/2–3	–0.3	1.9	0.6	
6	20.03.2004	08:53	53.74	160.76	31	6.2	167/4–5	0.25	–1.6	–0.5	
7	05.07.2008	02:12	53.82	153.53	610	7.7	253/3–4	0.3	–1.9	–3.4	*****
8	24.11.2008	09:02	53.77	154.69	564	7.3	328/3	0.2	–1.2	–3.7	*****
9	28.02.2013	14:06	50.67	157.77	61	6.8	260/4–5	0.6	–3.7	–1.5	(Boldina and Kopylova, 2016)
10	24.05.2013	05:45	54.76	153.79	630	8.3	348/4	6.0	–37.3	–62.0	
11	30.01.2016*	03:25	53.85	159.04	180	7.2	80/5	7.3	–45	–46.0	(Boldina and Kopylova, 2017)
12	17.07.2017	23:34	54.35	168.90	7	7.8	700/2–3	2.0	–12.4	–10	*****
13	20.12.2018	17:02	54.95	164.85	17	7.3	260/3–4	≈3.2	≈–19.9	–1.8	*****
14	25.03.2020	02:49	49.09	157.85	53	7.5	451/4–5	0.65	–4.0	–2.6	*****

* Earthquakes preceded by revealed anomalous water level variations; ** coordinates of the centre of the source area based on the aftershocks of the first twenty-four hours, and the corresponding distance to the well; *** "+"—an increase in the level, "–"—a decrease in the level;**** $D_1 = -\Delta h/A_v$, where A_v—the tidal water level sensitivity 0.161 cm/10^{-9} (Kopylova et al., 2010); ***** the authors' data on file. *MSK-64*—the Medvedev-Sponheuer-Karnic 12-point macroseismic intensity scale (Medvedev et al., 1965).

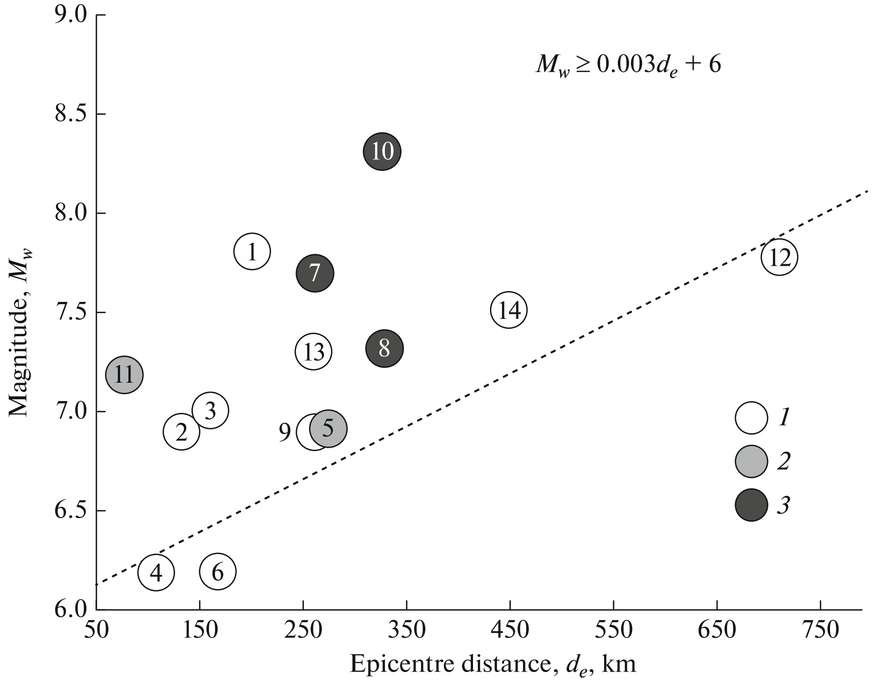

Fig. 5. Distribution of coseismic water level (pressure) jumps in YUZ-5 Well in 1997–2020, depending on the earthquake parameters—the magnitude M_w to the epicentre distance d_e ratios. *1–3*—the earthquake hypocentre depth: *1*—H = 1–70 km; *2*—H = 70–300 km; *3*—H = 500–600 km. Figures are numbers of the earthquakes from Table 3.

other factors were earlier considered as hypothetical mechanisms of changes in permeability during the passage of seismic waves. By the example of YUZ-5 Well, it was found that, depending on the intensity of the seismic impact and the amplitude-frequency content of seismic waves, various types of water level variations caused by the occurrence and development of specific hydrogeodynamic processes in the well—water-bearing rock system can initiate and occur according to a set pattern. Among such processes are harmonic variations in the groundwater pressure at frequencies of tens of Hz during the passage of surface waves and their intensification at the resonant frequency of the well, impulses of the local increase in the pressure head in water-bearing rocks near the wellbore, increase in the permeability of water-bearing rocks during seismic shaking followed by a decrease in the groundwater pressure.

RELATIONSHIP BETWEEN VARIOUS TYPES OF SEISMOHYDROGEOLOGICAL EFFECTS AND EARTHQUAKE PARAMETERS

The paper analyzes three types of seismohydrogeological effects in changes in the regime of the PKTS observation wells: (1) hydrogeodynamic and hydrogeochemical precursors of individual earthquakes, which manifest in several ($n \geq 2$) wells; (2)—coseismic pressure jumps recorded during 14 local earthquakes, and (3)—four types of vibrational effects of seismic waves in water level variations during earthquakes within a wide range of magnitudes and epicentre distances. Figure 7 shows the diagram of the distribution of such types of seismohydrogeological effects, depending on the earthquake parameters and the intensity of the seismic impact in the observation areas.

In Kamchatka, hydrogeological precursors were observed in three flowing and two piezometric wells during a period from one to nine months before seven M_w = 6.5–7.8 earthquakes at epicentre distances d_e = 80–300 km (Fig. 3, Fig. 7, Table 2). Those earthquakes were the largest seismic events during the period of observations and were followed by shakes with an intensity of four to six points according to *MSK-64*. The density of seismic energy during those events in the area of the wells was e = 0.1–0.4 J/m. Hydrogeological precursors were revealed in the conditions of undisturbed (natural) operation of the observation wells and were highly anomalous. In relation to the instrumental epicentre of the earthquakes, hydrogeological precursors were observed in the near and medium (intermediate) field zones of the earthquake sources (d_e/L = 1–3.7) (Table 2, Fig. 7).

Runtime diagnostics of hydrogeological anomalies on the basis of routine observations permits us to use them, along with other earthquake prediction data, in the mid- and short-term forecasting of strong earthquakes in the Kamchatka Krai (Kopylova and Boldina, 2020).

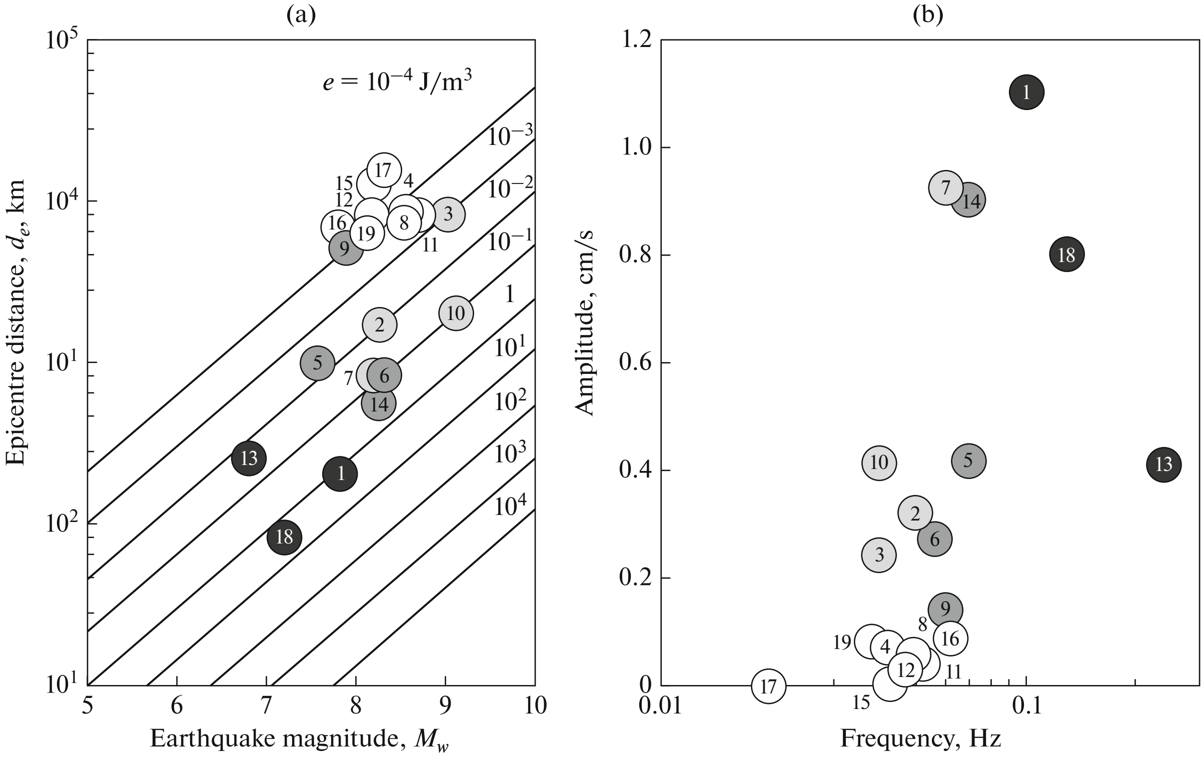

Fig. 6. Distribution of the four types of the effects of the vibrational impact of seismic waves in the water level variations in YUZ-5 Well (type *I*—white circles, type *II*—grey circles, type *III*—dark grey circles type *IV*—black circles), depending on: (a) the earthquake parameters M_w and d_e, the density of seismic energy *e* in the wave and (b) the amplitude-frequency content of the maximum phases of seismic wave velocity in BHZ channel, PET seismic station. Figures are numbers of the earthquakes from Table 1, 2 in (Kopylova and Boldina, 2020).

The results of the analysis of the manifestation of HP in five Petropavlovsk-Kamchatsky Test Site wells also demonstrate that all the observation wells provide insights for the detection of precursors before large earthquakes if the wells run in natural conditions without any man-made impact.

Figures 5 and 7 show, with the magnitude M_w—the epicentre distance d_e as coordinates, the distribution of the Kamchatka $M_w \geq 6.2$ earthquakes that were followed by coseismic jumps in the water level (pressure) in YUZ-5 Well (Table 3). The coseismic jumps (Table 3, Fig. 7, white crosses), as well as hydrogeological precursors (Table 2, Fig. 7, grey stars) were observed mainly in the near and medium field zones of the earthquake sources (d_e/L = 1–5).

A characteristic feature of the study region is that strong earthquakes followed by coseismic water level (pressure) jumps occurred for the most part within the Kamchatka seismic focal zone at epicentre distances of up to 450 km from the well (Table 3, Nos. 1–11, 13). The maximum epicentre distance of the earthquake followed by coseismic pressure jump in YUZ-5 Well was recorded for the Near Islands Aleutian earthquake of July 17, 2017 in the Commander segment of the Aleutian Island arc (Chebrov et al., 2019). Its epicentre distance d_e = 700 km (Table 3, No. 12) was 1.5 times and more greater than the distances of other earthquakes followed by coseismic water level jumps in that well.

From Fig. 6 and Fig. 7 it follows that the distribution of the four types of effects of the vibrational impact of seismic waves in the water level variations in YUZ-5 Well depends on the earthquake parameters—the earthquake magnitude M_w to the epicentre distance d_e ratio, the specific density of seismic energy *e,* and the amplitude-frequency characteristics of seismic waves (Fig. 6b). This combination of the quantitative earthquake characteristics can be regarded as a complex indicator of the intensity of the impact of seismic waves radiating from the source on the observation well. For a strong earthquake at a distance of up to thousands of km from the well, we can estimate the behaviour of the water level variations and associated hydrogeodynamic processes in the YUZ-5 Well—water-bearing rocks system, as well as in other comparable wells, by using the values of M_w, d_e, *e,* and other indicators, by extending in this way the potential of the method of water-level observations in the system of geophysical monitoring of seismically active regions.

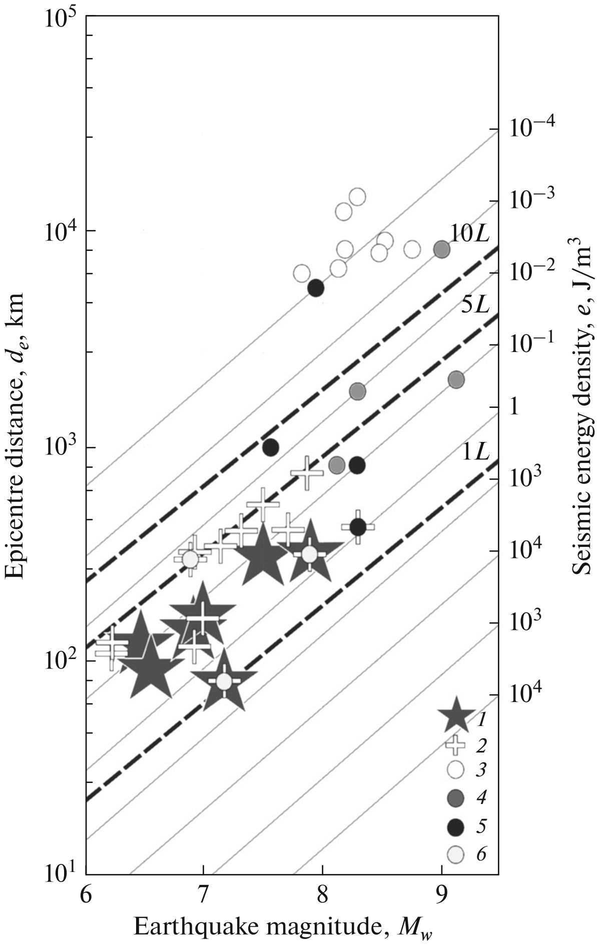

Fig. 7. Distribution of the manifestations of hydrogeological precursors in several (n = 2–4) PKTS wells (*1*), coseismic water pressure jumps (*2*) and various types of the vibrational effects of seismic waves in the water level variations in YUZ-5 Well (*3*–*6*): *3*—type *I*, *4*—type *II*, *5*—type *III*, *6*—type *IV*, depending on the earthquake magnitude M_w to the epicentre distance d_e ratio and the density of seismic energy *e*. 1*L*, 5*L* and 10*L* show one, five and ten maximum linear sizes of the earthquake source (Riznichenko, 1976), depending on the magnitude.

CONCLUSIONS

(1) Earthquake parameters and the intensity of their impact upon occurrence of hydrogeological precursors in several (n = 2–4) wells of the Petropavlovsk-Kamchatsky Test Site were estimated: $M_w = 6.5$–7.8, d_e = 80–300 km, $e \geq 0.1$ J/m^3, $I_{MSK\text{-}64} \geq 4$–6 points.

The time and the lead time of the occurrence of HP before such earthquakes varied from 1 to 9 months.

The wells, in which HP manifested, are in the near and medium (intermediate) field zones of the earthquake sources, for which d_e/L = 1–3.5, where d_e—is the epicentre distance to the well in km and L—is the maximum linear size of the earthquake source in km.

The obtained data on hydrogeological precursors and other types of seismohydrogeological effects in Kamchatka and the established relationship between their manifestations and earthquake parameters (Fig. 7) can be used in studies of the behaviour of natural hydrogeological systems during the preparation and occurrence of earthquakes, as well as of other fields of the Earth relating to variations in the water-saturated environment of seismically active regions.

(2) Since 2022, in cooperation with the Kamchatka Branch of the Russian Expert Council for Earthquake Forecasting (KB REC), the authors have been carrying out an experiment by using hydrogeodynamic precursors in the variations of the water levels in E-1 and YUZ-5 Wells for the real-time prediction of earthquakes, with weekly reports on the presence/absence of HP according to routine observations. In 2002–2016, the reports of KB REC helped to predict, mainly on the basis of water-level observations in E-1 Well, six M = 5.3–7.2 earthquakes, four of which had a magnitude of 6.4–7.2 (Fig. 3b). Before the $M_w = 6.6$, d_e = 350 km earthquake of March 16, 2021, a precursor was also detected in real time in the variations of the water pressure in E-1 Well (Boldina et al., 2022).

The results of observations in E-1 Well show that there is a certain relationships between changes in the hydrogeodynamic state of the well—water-bearing rocks observation system and the processes of the preparation of strong local seismic events and make it possible to use the current observational data in the earthquake prediction system in the Kamchatka Krai. At the same time, the developed concept of the mechanisms of this relationship is largely hypothetical and needs further research.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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