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Hydrogeological Earthquake Precursors: A Case Study From the Kamchatka Peninsula

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The relevance of hydrogeological precursors (HGPs) study is justified by the need to obtain reliable information about the spatio-temporal manifestations and the relationships of HGPs with the parameters of subsequent earthquakes for seismic forecasting. In the review the data on repeated manifestations of HGPs before strong earthquakes obtained from long-term observations in five deep wells on the Kamchatka Peninsula (Far East of Russia) are presented. The analysis of the correlation of HGPs occurring in several wells is carried out in comparison with earthquake parameters characterizing both earthquake sources (magnitude, linear size of the source) and the impact of earthquakes in the area of wells (specific energy density in wave, intensity of shaking). It is shown that the manifestation of HGPs in several wells is observed before earthquakes with M_w = 6.6–7.8 at epicentral distances up to the first hundreds of km to observation wells in the near and intermediate zones of the sources with the ratio of the epicentral distances and the source sizes no more than 1–5. A feature of our study was the use of certain types of HGPs in water-level changes for predictive assessments of the strong earthquakes in the Kamchatka Peninsula. The review presents precursors in water-level changes detected in real time and the corresponding earthquake forecasts, which were recognized as successful according to the conclusions of the expert council on earthquake prediction.

Keywords: precursor, earthquake, seismic forecast, observational well, water-level, Kamchatka Peninsula, groundwater chemical composition

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INTRODUCTION

Studies of hydrogeological precursors of earthquakes, manifested in changes in physical and chemical parameters of groundwater HGPs have been carried for decades (Roeloffs, 1988; Thomas, 1988; Wang and Manga, 2010; King, 2018; King and Manga, 2018; Skelton et al., 2019). The relevance of studying such phenomena is justified by the need to obtain reliable information about the spatio-temporal manifestations and the relationships of HGPs with the parameters of subsequent earthquakes for seismic forecasting. The basis for studying the HGPs for predicting earthquakes is the systematization of their recurring manifestations according to the data of long-term observations in individual wells. Unfortunately, there are few such reliable data on HGPs. In the above-mentioned works, it is reported mainly about "supposed" precursors in the parameters of groundwater. The lack of a sufficient number of such "supposed" precursors does not

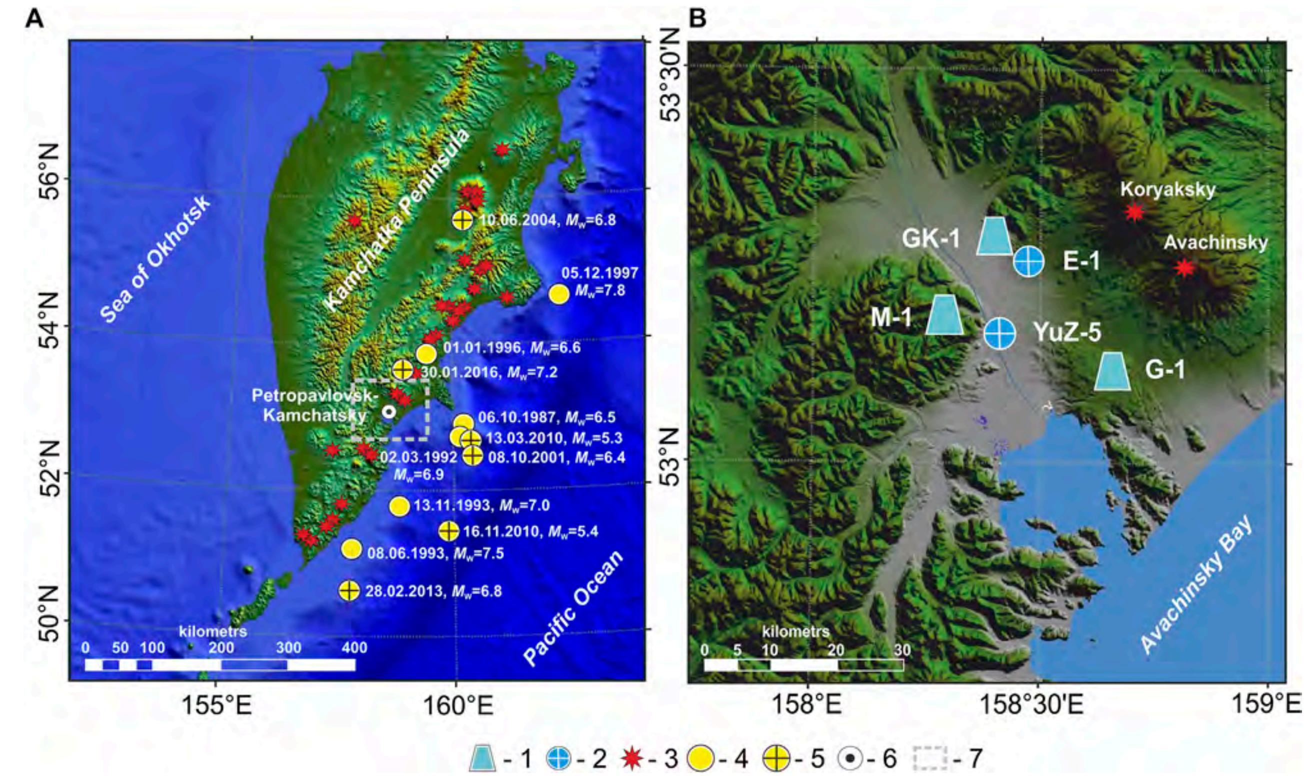

FIGURE 1 | The layout of the observation wells and earthquake epicenters in the Kamchatka Peninsula: **(A)** earthquakes preceded by hydrogeological precursors; **(B)** observation wells at the Petropavlovsk-Kamchatsky test site. Designations: 1, flowing wells; 2, piezometric wells; 3, active volcanoes; 4, 5, earthquake epicenters: 4, hydrogeological precursors revealed retrospectively; 5, hydrogeological precursors detected in water-level changes in the E-1 well in real time; 6, Petropavlovsk-Kamchatsky city; 7, Petropavlovsk-Kamchatsky test site in **Figure 1A**.

allow them to be used for seismic forecasting and obtaining of such new data is the primary task of further research.

The review presents data on HGPs obtained from long-term hydrogeochemical and level observations in five wells on the Kamchatka Peninsula. These data are poorly known, because most of the previous publications about HGPs in wells of Kamchatka were in Russian. Brief information on hydrogeochemical observations in the Kamchatka Peninsula is given in (Wang and Manga, 2010). In Biagi et al. (2000a) and Biagi et al. (2000b) some anomalies in the chemical composition of groundwater and gas before the Kamchatka earthquakes of the 1990s were described.

Our review is aimed to a description at both of data on HGPs in the Kamchatka wells, and an experiment for predicting earthquakes in real time using some types of HGPs. The data on HGPs in previously works of authors and other researchers along with the graphical presentation of the HGPs (see **Supplementary Materials S1**) provide detailed information on the observation wells, methods of observations and the features of HGPs manifestations in the individual wells. These materials form the basis of generalization about the relationship of the considered HGPs with parameters of the subsequent earthquakes.

An important feature of our long-term study of HGPs in water-level changes is the combination of observations in wells with an experiment on the use of certain types of HGPs for predictive assessments of the strong earthquakes in the Kamchatka Peninsula. This review presents examples of the precursors in water-level changes detected in real time, and forecasts of strong earthquakes recognized as successful according to conclusions of the expert council on earthquake prediction working in the Kamchatka Krai.

OBSERVATIONAL DATA, PRECURSORS, COOPERATION WITH THE EXPERT COUNCIL

The Kamchatka Peninsula (**Figure 1A**) is part of the Kamchatka Krai in the Russian Far East. It is located at the junction of the Pacific oceanic plate with the Eurasian and North American continental plates. This region is prone to frequent strong earthquakes which cause damaging ground motion and devastating tsunami. The strategies for reducing negative impacts from the earthquakes include, inter alia, the monitoring studies aimed at establishing the precursors and forecasting the time of the strong earthquakes.

Kamchatka Branch of the Geophysical Survey of the Russian Academy of Sciences (KB GS RAS) conducts long-term groundwater-level and chemical composition monitoring at a network of wells in the Petropavlovsk-Kamchatsky testing site (**Figure 1B**) in order to search for hydrogeological precursors of earthquakes and other effects of seismicity in groundwater parameters (Kopylova and Boldina, 2019). The data on the wells with repeated HGPs occurrences are presented in **Supplementary Materials Table S1 and Figure S1**. In all considered wells, water is not pumped out, as well as other man-made activities do not affect their natural state.

During the visits to the flowing wells GK-1, M-1, and G-1, the employees of the Laboratory of hydroseismology carried out flow rate measurements and water sampling every three days in 1986–1999. Free gas sampling was conducted from the GK-1 well. Water samples were tested for pH as well as for the anion and cation concentrations. The gas content was analyzed chromatographically. Water and gas parameters were determined with an accuracy of 2–10% (Khatkevich and Ryabinin, 2006). After 1999, the system of hydrogeochemical observations had changed due to an increase in the observation interval, a decrease in the set of determined parameters of the groundwater composition and experiments with the installation of equipment into wellbores that violate the natural hydrodynamic and hydrogeochemical regime of wells. Therefore, we consider the hydrogeochemical data only for the period 1986–1998, for which uniform time series were obtained under the conditions of the natural regime of observation wells.

In piezometric wells E-1 and YuZ-5 the instruments installed in 1996 provide highly sensitive water-level and atmospheric pressure recording up to ±0.1 cm and ±0.1 hPa, respectively, with a frequency of 5–10 min (Kopylova et al., 2017). In 1987–1994, water-level measurements in the E-1 well were carried out daily with an accuracy of ±0.5 cm, variations in atmospheric pressure were recorded by a barograph with an accuracy of 1 hPa (Kopylova, 2001). The seismic effects in water-level changes are identified with due regard of the influence of atmospheric pressure, precipitation, Earth's tides, seasonal trend, and other factors (Kopylova et al., 2019).

The primary outcome of long-term observations is that it was revealed hydrogeochemical and hydrogeodynamic phenomena preceding strong local earthquakes (**Figure 1A**). The data on earthquakes preceded by HGPs manifested in two to four observation wells are presented in **Supplementary Materials Table S2**.

In this paper, we consider the following effects as HGPs originally detected retrospectively:

i) visually distinguishable and statistically confirmed anomalies in the ionic and dissolved gas composition of the groundwater in the flowing wells GK-1, M-1 and G-1 (Kopylova et al., 1994; Biagi et al., 2000a; Biagi et al., 2000b; Khatkevich and Ryabinin, 2006; Kopylova and Taranova, 2013);
ii) higher-rate water-level decreases repeatedly manifested before earthquakes with $M \geq 5.0$ in the E-1 well which were identified as the precursors PS1 and PS2 (Kopylova, 2001; Kopylova and Boldina, 2012; Kopylova and Boldina, 2019);
iii) substantial deviation in water-level behavior from seasonal average pattern in the YuZ-5 well (Boldina and Kopylova, 2017; Kopylova and Boldina, 2019; **Supplementary Materials Figure S4**).

Hydrogeological precursors in the groundwater ion and gas composition in three wells are presented in **Supplementary Materials Figure S3**.

In the GK-1 well, a decline in chloride ion concentration was observed within one to nine months before six earthquakes (**Supplementary Materials Table S2 and Figure S3A**, left diagram). In the cases of the earthquakes of January 1, 1996 and December 5, 1997, the decreases in chloride ion concentration were changed into the sharp increases lasting 4–5 months. The increase in the variance and the change in the average concentrations of free gases were observed during 2 months before the earthquake of March 2, 1992 (**Supplementary Materials Figure S3A**, right diagram).

In the M-1 well, the concentration of bicarbonate ion decreased before five earthquakes (**Supplementary Materials Table S2 and Figure S3B**). In four cases, simultaneous increases were detected in the concentrations of sulfate ion, calcium, and sodium. Within one month before the earthquake of March 2, 1992, water mineralization increased by 25%, and the hydrogeochemical type of water has changed due to the increase in the concentration of sulfate ion and the decrease in the concentration of bicarbonate ion (Kopylova et al., 1994).

The changes in the concentrations of chloride ion, sulfate ion, bicarbonate ion as well as sodium and calcium were observed in the G-1 well before the earthquakes of January 1, 1996 and December 5, 1997 (**Supplementary Materials Figure S3**C) (Khatkevich and Ryabinin, 2006).

The maximum durations of hydrogeochemical anomalies (T_1) and lead times before earthquakes (T_2) in individual wells are presented in **Supplementary Materials Table S2**. The T_1 and T_2 values coincide for wells GK-1 and G-1. At the same time, the M-1 well is characterized by the appearance of relatively short-term hydrogeochemical anomalies (T_1 = 4 weeks) during 4–21.5 weeks before earthquakes. This feature of the well is associated with a high rate of water exchange in the wellbore due to the high water discharge ($q = 1.5\ dm^3/s$) compared to wells GK-1 and G-1 (q = 0.1 and <0.001 dm^3/s).

Examples of hydrogeological precursors in water-level changes in wells E-1 and YuZ-5 are given in (Kopylova, 2001; Kopylova, 2006; Boldina and Kopylova, 2017; Kopylova and Boldina, 2019; **Supplementary Materials Figures S4–S7**).

According to digital observations 1996–2016 at well E-1, two types of the pre-seismic signals are identified in daily rate of water-level decreases: PS1 developing weeks prior to the earthquakes (**Supplementary Materials Figures S4,S6**) and PS2 with a manifestation time of 5–6 years (**Supplementary Materials Figure S7**). The PS1 signal manifests itself in a more rapid water-level decline with increased daily rate before the earthquakes with $M \geq 5.0$ at epicentral distances $d_e \leq 350$ km. It was found that an expected earthquake can occur within a time of about one month after the end of the PS1 (in 90% of the cases) or during the PS1 development (in 10% of the cases).

According to the manual level measurements in 1987–1994, seven cases of a water-level decreases with amplitudes 4–47.4 cm were revealed during 3–36 weeks before earthquakes with M_w = 5.6–7.5 considered as hydrogeodynamic precursors (Kopylova, 2001).

The PS2 signal appears as a more rapid long-term water-level decline with increased daily rate preceding and accompanying the groups of the Kamchatka strong earthquakes (Kopylova and Boldina, 2019). This type of HGP was observed in 1991–1997 (six 1992–1997 earthquakes with M_w = 6.9–7.8 at epicentral distances up to 300 km) (Kopylova, 2001) and in 2012–2016 (four 2013–2016 earthquakes with magnitudes M_w = 6.6–8.3 (**Supplementary Materials Figure S7**).

In the YuZ-5 well, we have revealed retrospectively two cases of the anomalous changes in the water-level before the earthquakes of December 5, 1997 with M_w = 7.8 and January 30, 2016 with M_w = 7.2 (Kopylova and Boldina, 2019; **Supplementary Materials Figure S5**).

The durations of hydrogeological precursors in different wells prior to individual earthquakes (T_1) ranged from 4 to 39 weeks, i.e., from about 1 to 9 months, and do not show any relationship with earthquake magnitudes (**Supplementary Materials Figure S2A**). For the M-1 well, there is an increase in the lead time of the hydrogeochemical anomaly (T_2) in the range 1–5 months with an increase in the magnitude of subsequent earthquake (**Supplementary Materials Figure S2B**).

The hypothetical mechanisms of the hydrogeochemical and hydrogeodynamic precursors in observation wells of the Kamchatka Peninsula were considered in previous publications and briefly presented in **Supplementary Materials S2**.

The expert councils for earthquake prediction have been working in Kamchatka Krai for many years providing official seismic forecasts based on seismological, geophysical, hydrogeological, and other types of observations (Chebrov et al., 2011; Chebrov et al., 2013). Observation data at the wells of the Petropavlovsk-Kamchatsky test site are also used in the practice of such expert councils. Our collaboration with the Kamchatka branch of the Russian Expert Council for Earthquake Forecasting and Seismic Hazard and Risk Assessment (KB REC) which determines the correspondence between the released forecasts and the occurrence of the actual earthquakes provides the unique possibility to demonstrate practical significance of the some types of HGPs for real-time forecasting of the Kamchatka earthquakes.

Long-term data were obtained on the occurrences of the precursory signal PS1 in water-level changes in the E-1 well. The retrospective forecasting 1996–2012 earthquakes on the base of PS1 according the approach (Gusev, 1974; Kopylova, 2001; Chebrov et al., 2011; Chebrov et al., 2013) is presented in **Supplementary Materials Table S3**.

When PS1 is detected in real time, the forecast is made for 1–2 months (**Supplementary Materials Figure S8**). The observational data and the timing of the forecast are shown in **Supplementary Materials Figure S6**.

In accordance with the KB REC assessments our forecasts made on base of PS1 in 2004–2016 were true in terms of the time, location, and magnitude of the six events with M_w = 5.3–7.2 (**Figure 1A**).

RELATIONSHIP BETWEEN HYDROGEOLOGICAL PRECURSORS AND EARTHQUAKE PARAMETERS

When using HGP in individual well to predict earthquakes, it is necessary to know about the relationship between the HGP in that well and the parameters of subsequent earthquakes (magnitude, epicentral distance), as well as to estimate the expected seismic impact in the observation area.

We have analyzed the relationship between considered HGPs in individual wells and the parameters of the subsequent earthquakes (**Figure 2**). As the parameters characterizing the earthquakes, we considered the ratio between magnitude M_w and epicentral distance to the well (d_e). The value of the specific density of seismic energy in the wave (e) was used as a parameter of the earthquake impact in the area of the observation well. The e value is proportional to the square of the seismic wave velocity and can be applied as a metric for some co- and post-seismic processes such as soil liquefaction and undrained consolidation of sedimentary deposits (Wang and Chia, 2008; Wang and Manga, 2010). The e values were estimated by the formula $\log d_e = 0.48M_w - 0.33\log e - 1.4$ (Wang, 2007; Wang and Chia, 2008) and used to evaluate the range of e variations for the earthquakes preceded by the HGPs in the wells of the Kamchatka Peninsula. Previously in (Wang, 2007; Wang and Chia, 2008; Wang and Manga, 2010; Kopylova and Boldina, 2020), the e values were applied to assess co- and postseismic phenomena in ground- and surface waters. In this work, the e values are used to assess the possible seismic impact of earthquake in the observation area with manifestations of hydrogeological precursors.

The earthquakes with M_w = 6.5–7.8 before which there have been precursory anomalies in the groundwater chemical composition in two to three wells occurred at the epicentral distances d_e = 95–308 km, or 2.1–3.7 maximum linear sizes of earthquake sources according to (Riznichenko, 1976) (**Figure 2A**). During these earthquakes which were accompanied by the ground shaking with intensity I = 4.5–5.5 on MSK-64 scale (**Supplementary Materials Table S2**) the e values were 0.1–0.3 J/m^3. Close values of e were obtained for the two earthquakes, before which a precursor appeared in water-level changes in the YuZ-5 well (**Figure 2B**).

As mentioned above, long-term data were obtained on the occurrences of the precursory signal PS1 in the E-1 well before earthquakes with $M \geq 5.0$, $d_e \leq 350$ km highlighted retrospectively (**Figure 2B**, **Supplementary Materials Table S3**). **Figure 2B** also shows 1996–2012 earthquakes with $M \geq 5.0$, $d_e \leq 350$ km before which PS1 did not appear for the period of retrospective analysis (red crosses). In the range of magnitudes M = 5.0–6.5, the PS1 signal appears in 44% of cases (blue crosses), whereas before earthquakes with M_w = 6.6–7.8, PS1 manifested itself almost always.

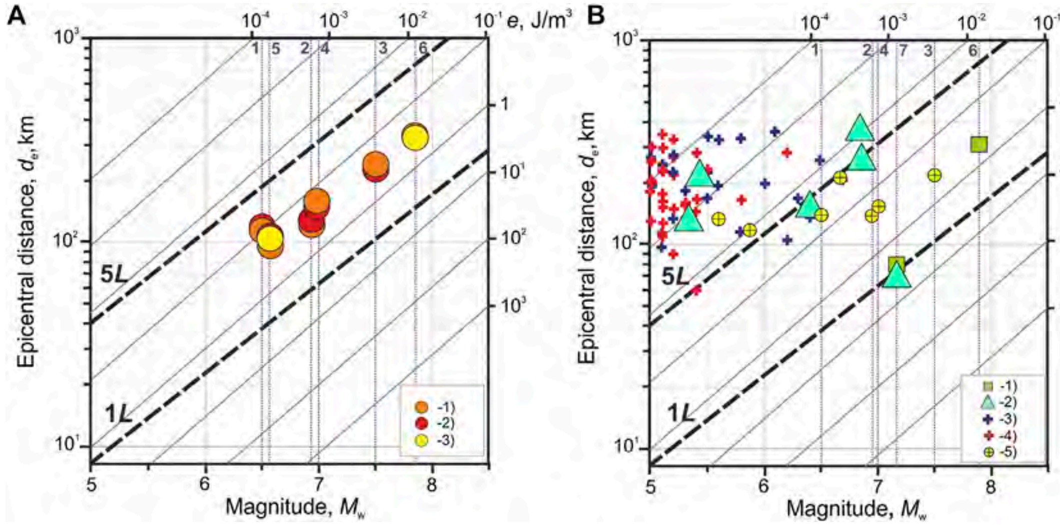

FIGURE 2 | Distribution of earthquake hydrogeological precursors in the observation wells as function of the parameters of the subsequent earthquakes: magnitude M_w, epicentral distance d_e, and specific density of seismic energy e: **(A)** hydrogeological precursors in chemical composition of water in flowing wells (1) GK-1, (2) M-1, (3) G-1 (**Supplementary Materials Table S2**); **(B)** hydrogeological precursors in water-level changes in wells (1) YuZ-5, (2)–(5) E-1: (2) PS1, determined in real time with the issuance of a conclusion on a possible earthquake for KB REC; (3) 1996–2012 earthquakes with $M \geq 5.0$, $d_e \leq 350$ km preceded by retrospectively identified PS1 (**Supplementary Materials Table S3**); (4) 1996–2012 earthquakes with $M \geq 5.0$, $d_e \leq 350$ km not preceded by PS1, and (5) water-level decreases at an increased rate preceded the 1987–1996 earthquakes (Table 3 in Kopylova, 2001). Thin vertical dotted lines on the magnitude scale indicate earthquakes preceded by hydrogeological precursors in two to four wells, the earthquake numbers correspond to the numbers in **Supplementary Materials Table S2**. The lines 1*L*, 5*L* show one and five maximal linear sizes of the source.

Before the six 2004–2016 earthquakes, PS1 was identified in real time and advanced forecasts were issued (**Figures 1A**, **2B**). We believe that with pronounced manifestations of PS2 and PS1 in water-level changes in the E-1 well, as well as other types of considered HGPs, a seismic forecast is possible for the strongest earthquakes in the adjacent segment of the Kamchatka seismic focal zone. Such earthquakes can be characterized by the magnitudes $M_w \geq 6.6$, the d_e/L ratio below 5, and the e value above 0.1 J/m^3 (**Figure 2**).

CONCLUSION

(1) Hydrogeological precursors manifesting themselves in the changes of chemical composition and pressure of groundwater at depths from hundreds of meters to a few first km are demonstrated on the case study from the Kamchatka Peninsula with a low population density and lack of industrial enterprises. The wells where hydrogeological precursors were detected are characterized by the absence of the influence of groundwater development and other anthropogenic factors which can disrupt the natural state of groundwater during the preparation of earthquakes. Unfortunately, in many cases when studying hydrogeological effects before earthquakes, an important aspect of the technogenic impact on the regime of observation wells is not sufficiently taken into account (King, 2018; King and Manga, 2018; Wang et al., 2018). When discussing the relatively long-term manifestations of hydrogeological precursors from urbanized and densely populated countries, it is necessary to consider technogenic factors in more detail, as well as climatic factors and their influence on the processes of groundwater filtration. Otherwise, ideas about the forms of hydrogeological precursors and their connections with the parameters of subsequent earthquakes may be distorted.

(2) A correlation was detected between the manifestations of hydrogeological precursors in considered wells and the parameters of the subsequent earthquakes (**Figure 2**). In the Kamchatka Peninsula, the hydrogeological precursors were mainly observed before the earthquakes with M_w = 6.6–7.8 at the epicentral distances of 80–300 km from the wells. These earthquakes caused ground shaking with intensity four to six on MSK-64 scale; seismic energy density during these events in the regions of the wells ranged from 0.1 to 4.5 J/m^3. The HGPs were mainly observed in the near and intermediate field zones of the earthquake sources (d_e/L = 0.9–3.7). The data obtained on the HGPs manifestations can be useful in the study of the phenomena in the groundwater preceding strong earthquakes of other seismically active regions and other geophysical fields associated with changes in water pressure and physical properties of water-saturated rocks.

(3) In the case of the E-1 well, we revealed the increased sensitivity of fluid pressure during the preparation of the strong earthquakes which manifested itself in the more rapid water-level falls at an increased rate both before separate earthquakes (PS1 precursory signal) and before groups of the

strong earthquakes (PS2 precursory signal). This indicates that during the preparation of strong ($M_w \geq 6.6$) earthquakes, a decrease of water pressure in gas-saturated groundwater occurs over a period of time from weeks to several years. Such a process can occur with an increase in the capacity of water-bearing rocks, as well as due to phase transitions of gas and an increase in the density of groundwater in water-bearing rocks and in the wellbore.

(4) The retrospective analysis of the PS1 manifestations has shown that with the increase in the magnitudes of the predicted earthquakes from $M \geq 5.0$ to $M_w \geq 5.8$, the efficiency of PS1 for the seismic forecast increases from J = 1.4 to J = 2.4 (**Supplementary Materials Table S3**). This indicates that PS1 is a useful precursor of the strong earthquakes which may improve the forecasts of such earthquakes by a factor of 1.4–2.4 compared to random guessing. At the same time, the relatively low statistical estimates of the correlation between the PS1 and the subsequent earthquakes make the PS1 applicable for seismic forecasting only if combined with the other observation data and other precursors. The correlations between the other precursors and the subsequent earthquakes in Kamchatka are also low and not exceeding the values obtained for the PS1 (Serafimova and Kopylova, 2010; Chebrov et al., 2011; Chebrov et al., 2013). This highlights the need for developing new methods for analyzing of the prognostic data for increase the accuracy and reliability of earthquake forecasting. The data on the joint occurrence of different precursors before earthquakes from the archives of the expert councils may help much in providing more objective estimates of the efficiency of the precursors for seismic forecasting.

(5) Since 2001, an experiment has been conducted on the use of the PS1 precursor, and since 2012, together with the PS2 precursor, to predict earthquakes in real time by submitting forecasts to the KB REC. According to the KB REC conclusions, successful predictions of the location, time, and magnitude were made for six 2004–2016 earthquakes with M_w = 5.3–7.2 (**Figures 1A**, **2B**).

We believe that progress in the study of hydrogeological and other types of earthquake precursors for seismic forecasting can be achieved with closer collaboration of specialists observing precursors with expert councils for earthquake prediction.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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SUPPLEMENTARY MATERIALS

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2020.576017/full#supplementary-material

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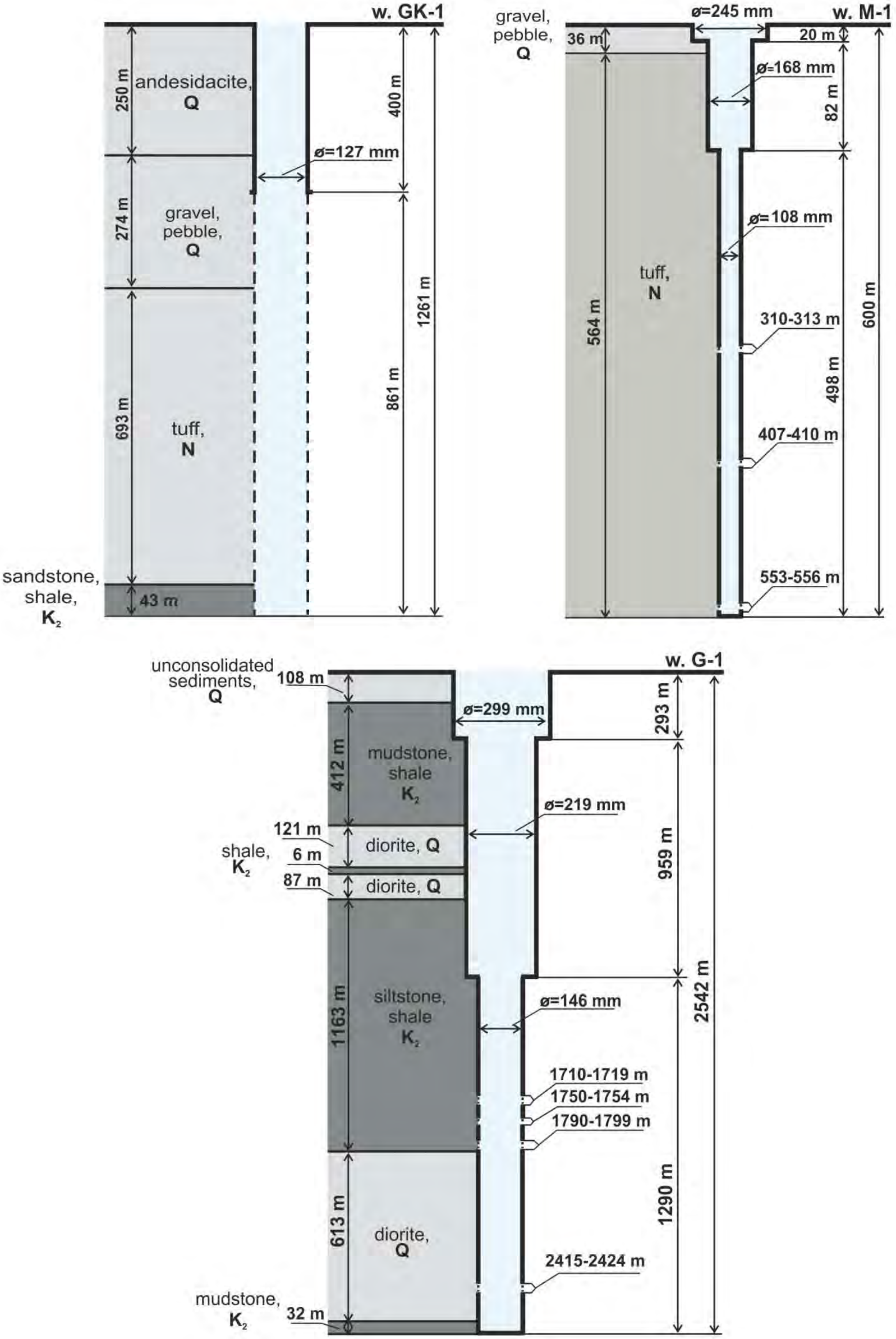
Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Supplementary Materials S1

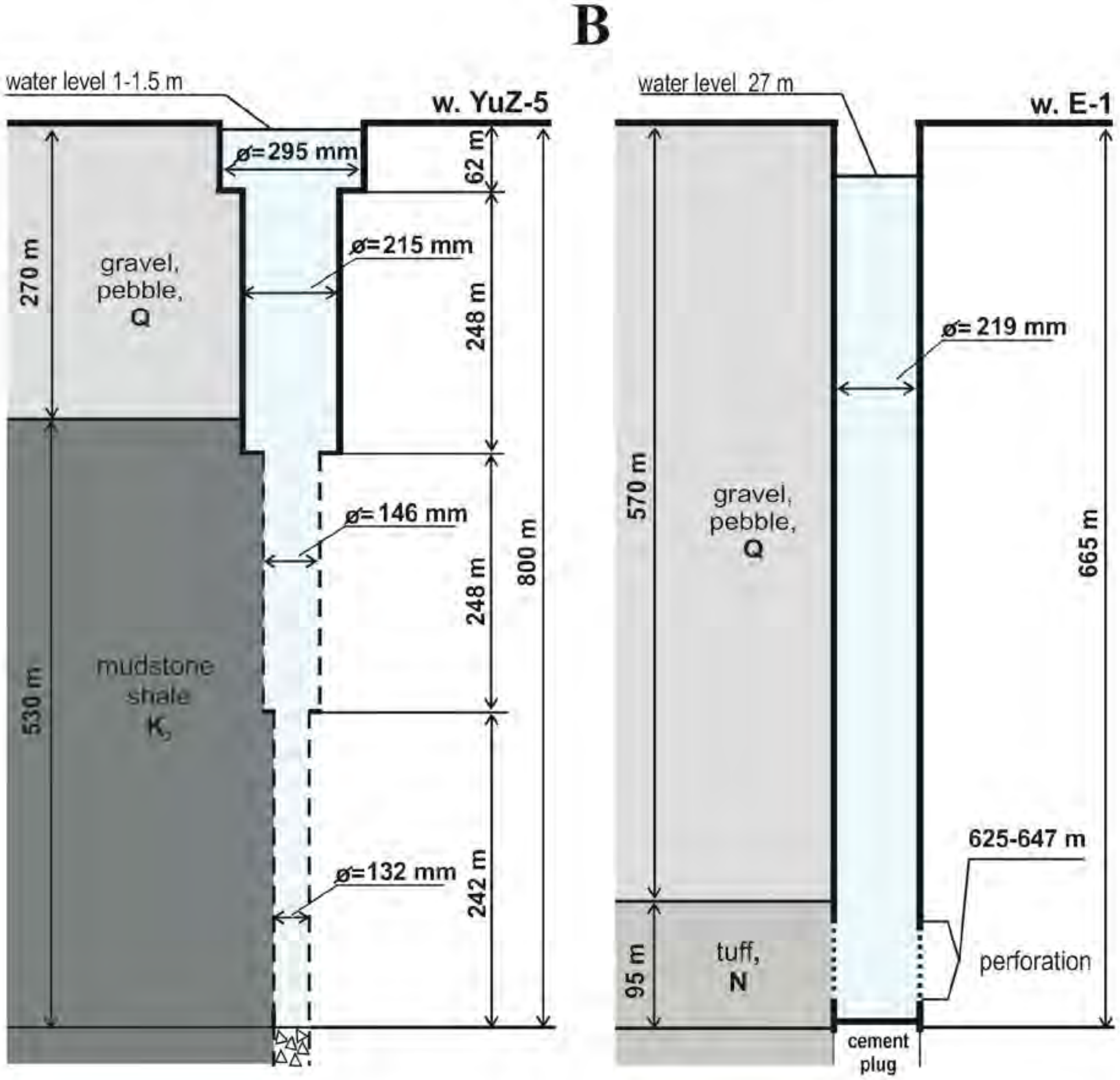
Supplementary Materials Table S1. Observation wells, Kamchatka Peninsula

Well	**Coordinates**	**Depth,** m **Open interval,** m	**Lithology: age, composition**	**Discharge rate,** q, dm^3/s; **Water-level depth,** h, m	**Water temperature,** °C	**Water mineralization,** g/dm^3	**Water type**	**Gas composition**	**Observations: covered period, frequency of measurements**
GK-1	53.28°N 158.40°E	1261 400–1261	Q, N, K_2, tuff, siltstone, shale	flowing, 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, 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, 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: 03.01.1987–08.07.1994, 1 day; 29.01.1996–2016, 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	09.09.1997–2016, 5–10 minutes

A



w. GK-1
andesidacite, Q
250 m
gravel, pebble, Q
274 m
tuff, N
693 m
sandstone, shale, K_2
43 m
ø=127 mm
400 m
861 m
1261 m
w. M-1
gravel, pebble, Q
36 m
ø=245 mm
20 m
ø=168 mm
82 m
ø=108 mm
tuff, N
564 m
310-313 m
407-410 m
553-556 m
498 m
600 m
w. G-1
unconsolidated sediments, Q
108 m
ø=299 mm
293 m
mudstone, shale K_2
412 m
ø=219 mm
121 m
diorite, Q
shale, K_2
6 m
87 m
diorite, Q
959 m
siltstone, shale K_2
1163 m
ø=146 mm
1710-1719 m
1750-1754 m
1790-1799 m
diorite, Q
613 m
2415-2424 m
1290 m
2542 m
mudstone, K_2
32 m

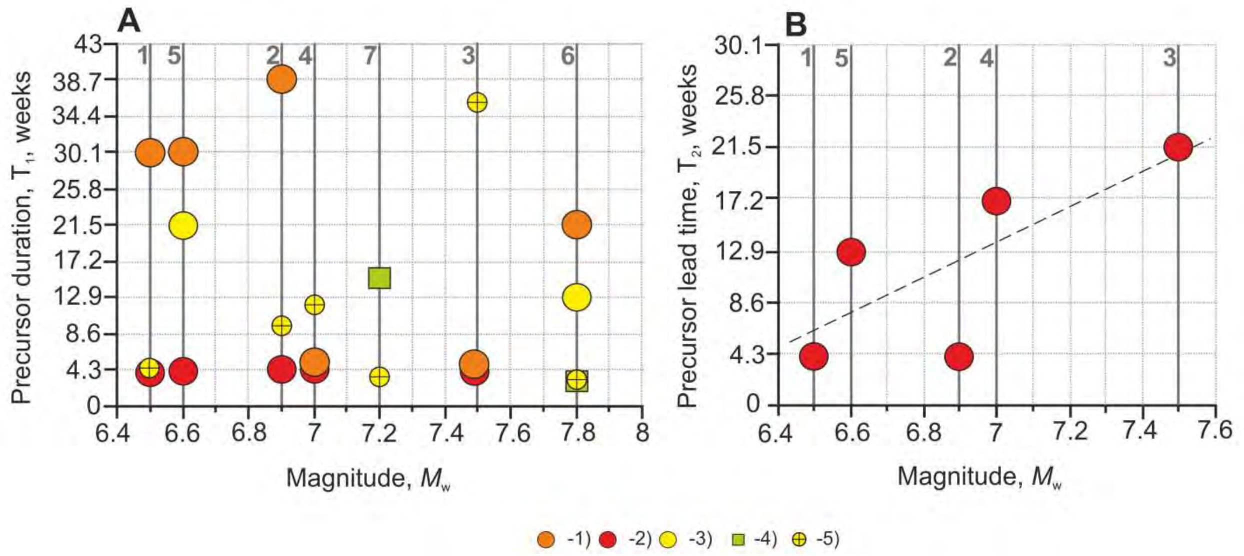


Supplementary Materials Figure S1. Structure of observation wells, Kamchatka Peninsula: **(A)** – flowing wells: GK-1, M-1, G-1; **(B)** – piezometric wells: YuZ-5, E-1.

Supplementary Materials Table S2. Earthquakes (https://earthquake.usgs.gov/earthquakes/, http://sdis.emsd.ru/info/earthquakes/catalogue.php) preceded by hydrogeological precursors in at least two observation wells, Kamchatka Peninsula

No	**Date,** dd.mm.yyyy	**Earthquake epicenter**	**Depth** H, km	**Magnitude** M_w	**Earthquake source length**[(i)] L, km	**Earthquake epicentral distance to wells** d_e, km	d_e/L	**Specific density of seismic energy** e, J/m^3	**Earthquake intensity on the MSK-64 scale**[(ii)]	**Wells (precursor duration, T_1 / precursor lead time T_2**[iiiii]**, weeks)**
1	06.10.1987	52.86ºN 160.23ºE	33	6.5	37	130–134	3.5–3.7	0.1	5	GK-1 (30/30), M-1 (4/4), E-1[(iii)](5/5)
2	02.03.1992	52.76ºN 160.20ºE	20	6.9	56	133–136	2.4	0.2	5–6	GK-1 (39/39), M-1 (4/4), E-1[(iii)](9.5/9.5)
3	08.06.1993	51.20ºN 157.80ºE	40	7.5	103	220–233	2.1–2.3	0.3	5	GK-1 (4/4), M-1 (4/21.5), E-1[(iii)](36/36)
4	13.11.1993	51.79ºN 158.83ºE	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[(iii)](12/12)
5	01.01.1996	53.88ºN 159.44ºE	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	54.64ºN 162.55ºE	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[(iiii)](3/3), YuZ-5[(iiii)](3/3)
7	30.01.2016	53.86ºN 158.73ºE	168	7.2	76	70–80	0.9-1.1	2.7–4.1	4	E-1 (3/3), YuZ-5 (15/15)

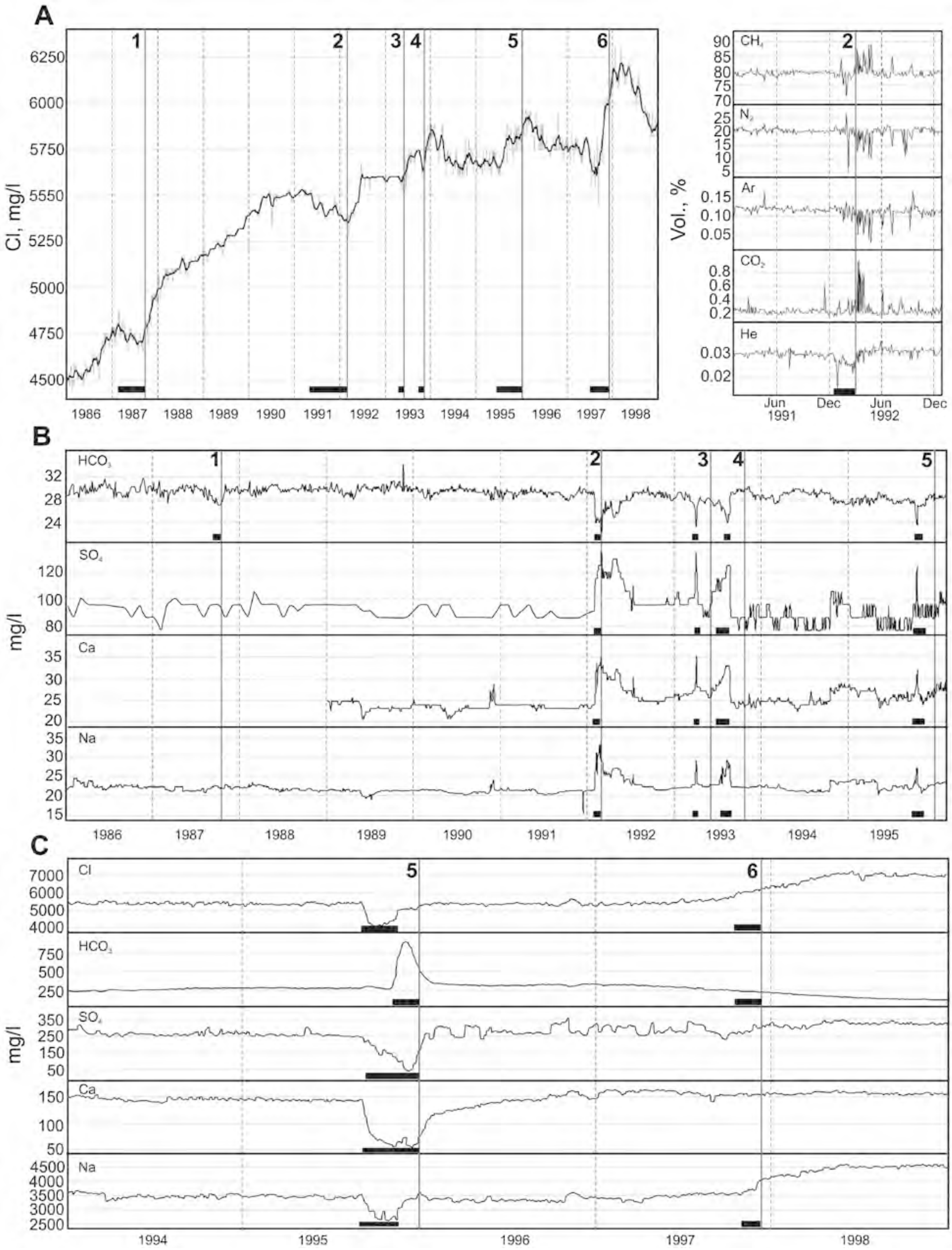
(i) – maximum linear size of the earthquake source according to (Riznichenko, 1976).
(ii) – Medvedev–Sponheuer–Karnik scale, also known as 12-points MSK-64, is a macroseismic intensity scale used for evaluating the shaking of the Earth's surface based on the observed effects in the earthquake area; the values of points are given for Peropavlovsk-Kamchatsky city.
(iii) – lowering of the water-level with amplitudes >3 cm with at an increased rate (see Table 3 in Kopylova, 2001);
(iiii) – the first description of the precursors in water-level changes within three weeks is given in (Kopylova, 2006);
(iiiii) – precursor duration T_1 – maximum duration of abnormal changes in hydrogeological parameters in the well, precursor lead time T_2 – maximum time from the beginning of an anomalous change in the hydrogeological parameters in the well to the earthquake.



Supplementary Materials Figure S2. A – Distribution of the precursor duration (T_1) in 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 **Supplementary Materials Table S2**; earthquakes are shown with gray vertical lines. **B** – Distribution of the lead time (T_2) of hydrogeochemical precursors in the M-1 well (**Supplementary Materials Figure S3B**), depending on the magnitude M_w of earthquakes No. 1–5 (the linear correlation coefficient is 0.74).

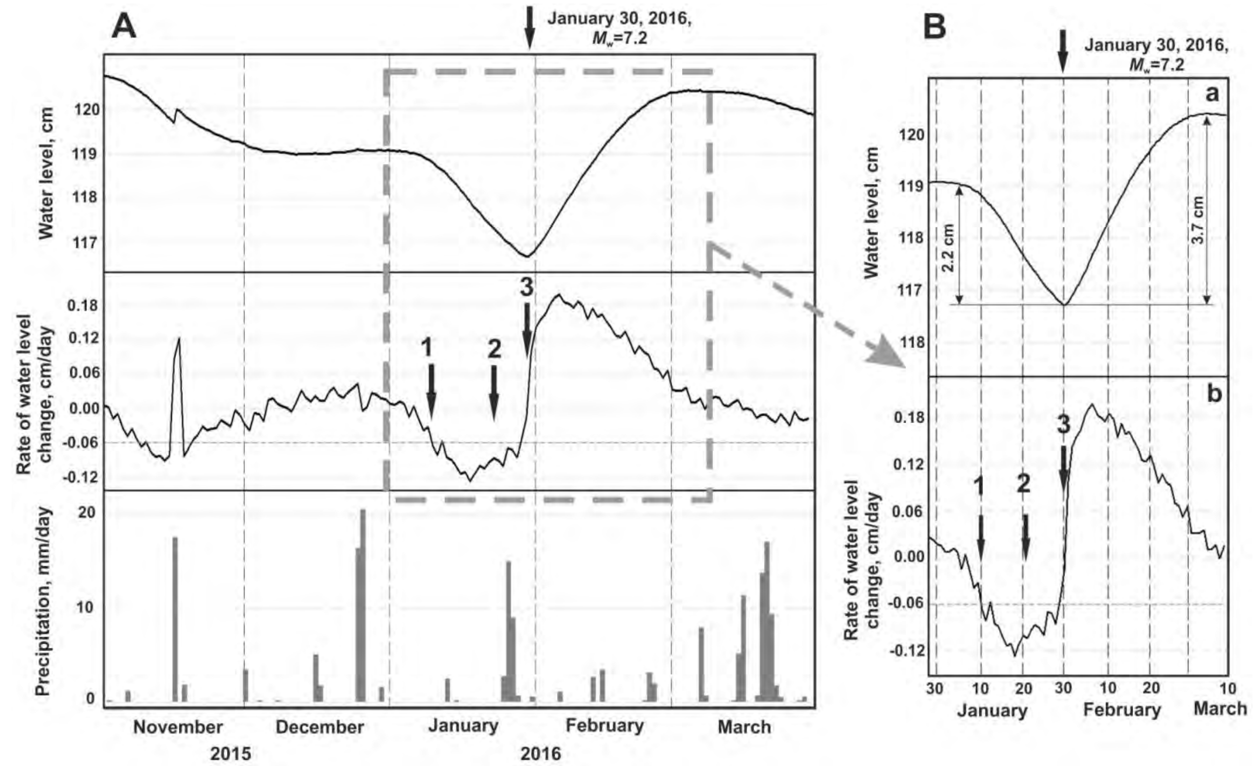
Note 1: Hydrogeological precursors of earthquakes No. 1–6 in wells GK-1, M-1, E-1, G-1 are previously presented in (Kopylova et al., 1994, Figures 3,5,7; Kopylova, 2001, Figures 2,8, Table 3; Khatkevich and Ryabinin, 2004, Figures 5,6,7; Kopylova, 2006, Figure 7; Serafimova and Kopylova, 2010, Figure 2; Kopylova and Boldina, 2019, Figure 4), as well as in **Supplementary Materials Figure S3**. Hydrogeological precursors of earthquake No. 7 in water-level changes in wells E-1 and YuZ-5 are previously presented in (Boldina and Kopylova, 2017, Figures 3,9; Kopylova and Boldina, 2019, Figures 7,8), as well as in **Supplementary Materials Figure S5,6**.

Note 2: We believe that the increased duration of hydrogeodynamic precursors in water-level in the E-1 well before earthquakes No. 3 and No. 4 (**Supplementary Materials Table S2)** caused by the superposition of the precursor signals PS1 and PS2 due to the impossibility of correct separation of two signals according to rare and rough observational data in 1987–1994 (Kopylova, 2001).



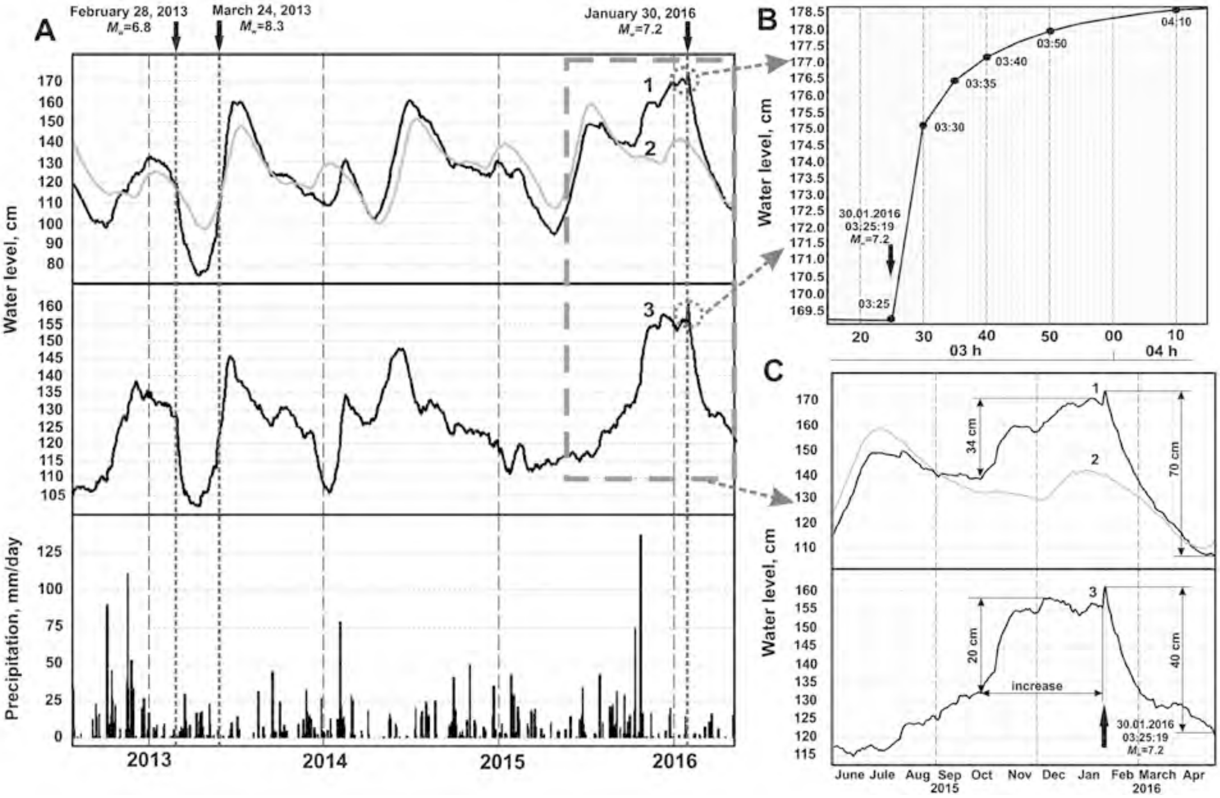
Supplementary Materials Figure S3. Anomalous effects (bold horizontal lines) in the time series of hydrogeochemical parameters of groundwater from flowing wells: **(A)** GK-1, **(B)** M-1, **(C)** G-1. The vertical lines show earthquakes 1987–1997 (**Figure 1A)**, earthquake numbers correspond to the **Supplementary Materials Table S2**.

The Zhupanovsky earthquake of January 30, 2016, M_w=7.2
(No. 7 in **Supplementary Materials Table S2**), E-1 well



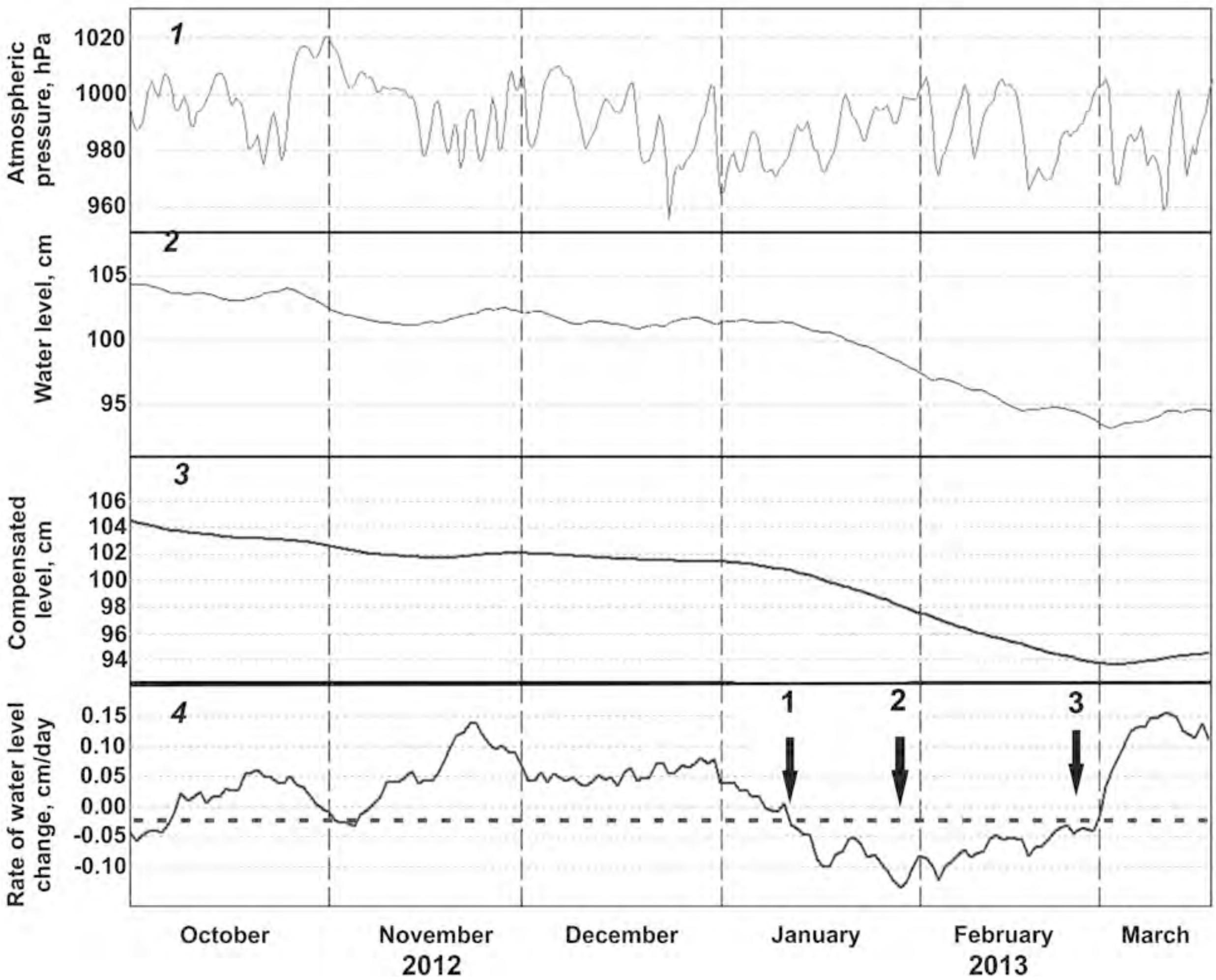
Supplementary Materials Figure S4. Water-level changes in E-1 well:
(A) time series of water-level changes and their average daily rate as compared to time behavior of precipitation, November 2015 to March 2016; the Zhupanovsky earthquake of January 30, 2016, M_w=7.2 is indicated by arrow. Figures on the graph of daily rate of water-level changes: **1,** January 10, the beginning of PS1; **2,** January 21, the date of submission of the prognostic conclusions as to the possibility of strong earthquake to KB REC; **3,** January 30, the Zhupanovsky earthquake. The thin dashed line shows the threshold value of the rate of water-level decrease – -0.06 cm/day. The thick dashed line delineates the fragment of water-level variations shown in Figure **(B)**: (**a)** water-level changes from December 30, 2015 to March 10, 2016 including the manifestation of PS1 and post-seismic increase; (**b)** the change in the average daily rate of water-level variations as compared to the threshold value – -0.06 cm/day (Boldina and Kopylova, 2017).

The Zhupanovsky earthquake of January 30, 2016, M_w=7.2
(No. 7 in **Supplementary Materials Table S2**), YuZ-5 well



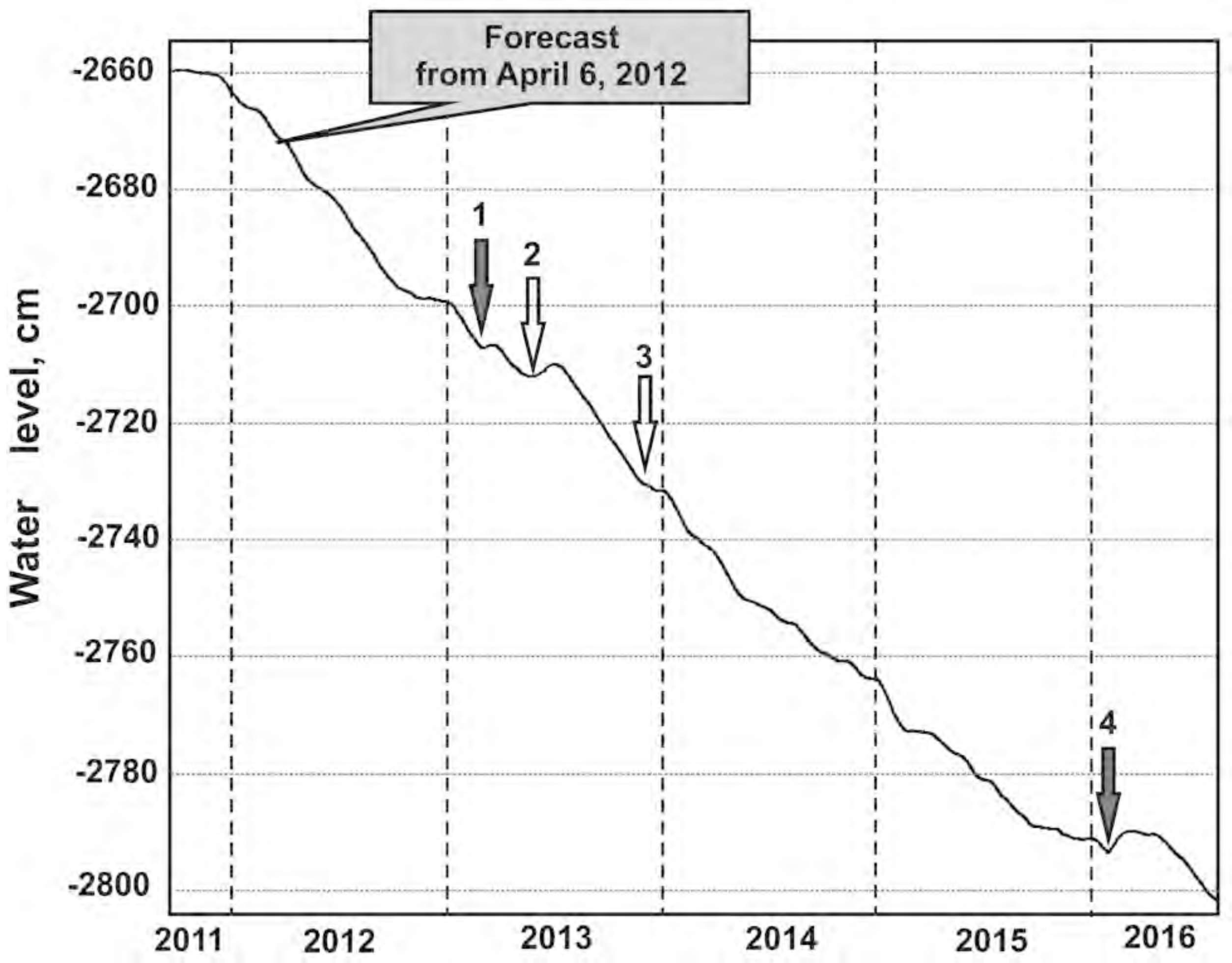
Supplementary Materials Figure S5. Water-level changes in YuZ-5 well:
(A) water-level changes in July 2012 to May 2016 as compared to the time behavior of precipitation and occurrence of earthquakes with M_w≥6.8 (shown by arrows): 1, average hourly observation data with corrected for baric variations (black line); 2, annual seasonal variations in water-level (gray line); 3, residuals in water-level changes after correction for annual seasonality and trend: bold dashed line indicates a fragment of graphs during the Zhupanovsky earthquake; **(B)** coseismic step in the water-level behavior after the arrival of seismic waves (03:25 UT); **(C)** pre-seismic rise and post-seismic fall in the water-level (Boldina and Kopylova, 2017).

EQ of February 28, 2013, 50.83° N, 157.93° E, M_w=6.8, H=45 km, d_e=270 km **(Figure 1A),**
E-1 well



Supplementary Materials Figure S6. Water-level changes in well E-1, October 1, 2012 to March 18, 2013: ***1, 2,*** atmospheric pressure and water-level time series with a sampling interval of 5 min; ***3,*** daily average water-level changes with corrected for baric variations; ***4,*** daily rate of water-level variations: arrows on the graph indicate (**1**) January 16, 2013, the beginning of PS1; (**2**) February 1, 2013, the prognostic conclusions were sent to KB REC (**Supplementary Materials Figure S7**); (**3**) February 28, 2013, the date of the earthquake. Horizontal dashed line shows the threshold value for the daily rate of water-level variations (Kopylova et al., 2017).

PS1 and PS2 manifestations in water-level changes in E-1 well,
November 2011 to September 2016



Supplementary Materials Figure S7. The fall in the water-level at increased rate in December 2011 to March 2012, exceeding the maximum duration of PS1, and a similar water-level decrease in 1991–1997 preceding and accompanying the group of strong earthquakes in 1992–1997 (M_{max}=7.8) (Kopylova, 2001) served as the basis for submitting the prognostic conclusion on April 6, 2012 to KB REC. In the conclusion, it was reported that one or more earthquakes with $M_w \geq 6.0$ are probable within a radius of up to first hundreds of kilometers from the well during the months to the first years. This predictive conclusion was based on PS2.

During 2013–2016, more than 20 events with $M_w \geq 6$ took place within a radius of 350 km from the well, most of which were aftershocks of the four major earthquakes with magnitudes M_w=6.6–8.3 (shown by arrows) (Sil'nye.., 2014; Chebrov et al., 2016).

During the development of the long-term water-level lowering, two successful predictions of the main events based on PS1 were made (shown by dark arrows): **1,** February 28, 2013, M_w=6.8 (**Supplementary Materials Figure S6,8**), **4,** January 30, 2016, M_w=7.2 **Supplementary Materials Figure S4).** Open arrows indicate major earthquakes for which no predictions based on PS1 have been issued: **2**, May 24, 2013, M_w=8.3; **3**, November 12, 2013, M_w=6.6. We believe that the lack of forecasts of these two events is associated with a weak manifestation of PS1 against the background of a long-term water-level lowering and post-seismic water-level variations after the earthquake of February 28, 2013 (**1**) (Firstov et al., 2016; Kopylova et al., 2018).

Supplementary Materials Table S3. Retrospective parametric description of the precursor signal PS1 in water-level changes in the E-1 well (Kopylova, Sizova, 2012; Kopylova et al., 2019)

Data for analysis	Water-level observation data from well E-1 (53.26°N, 158.48°E), February1996 to October 2012, total observation time **T**=4042 days (10.4 years)
Earthquake monitoring area	A region within a radius of 350 km from the E-1 well
Studied parameter	Daily rate of water-level changes with corrected for baric variations and trend
Precursor signal PS1	The increase in the daily rate of water-level decline to 0.05–0.07 cm/day for at least 5 days
Retrospective analysis of PS1 for forecasting the earthquakes with M≥5.0	
Total number of earthquakes, **n**	59
Total number of PS1 manifestations before earthquakes (successful forecasts), **m**	27
Probability of correlation between PS1 manifestations and earthquakes, **P=m/n**	**P=27/59=0.46**
Probability of missing a target, $\mathbf{P_{mt}}$**=(n–m)/n**	$\mathbf{P_{mt}}$**=(59–27)/59=0.54**
Total number of PS1 manifestations, **m′**	32
Total number of cases when no earthquake occurred after PS1 manifestations (false alarms)	6
Probability of a successful forecasts for PS1 manifestations, **P′=m/m′**	**P′=27/32=0.84**
Probability of false alarm, $\mathbf{P_{fa}}$**=(m′–m)/ m′**	$\mathbf{P_{fa}}$**=(32–27)/32=0.16**
Total alarm time, **τ**	1316 days
Ratio of total alarm time to total observation time, **τ/T**	1316/4042 = 0.33
Efficiency of PS1 for forecasting the earthquakes with magnitude M ≥5.0, **J=P/(τ/T)**	**J=0.46/0.33=1.4**
Retrospective analysis of PS1 for forecasting earthquakes with M_w≥5.8	
Total number of earthquakes, **n**	14
Total number of PS1 manifestations before earthquakes (successful forecasts), **m**	11
Probability of correlation between PS1 manifestations and earthquakes, **P=m/n**	**P=11/14=0.79**
Probability of missing a target, $\mathbf{P_{mt}}$**=(n–m)/n**	$\mathbf{P_{mt}}$**=(14–11)/14=0.21**
Probability of a successful forecast for PS1 manifestations, **P′=m/m′**	**P′=11/32=0.34**
Probability of false alarm, $\mathbf{P_{fa}}$**=(m′–m)/m′**	$\mathbf{P_{fa}}$**=(32–11)/32=0.66**
Efficiency of PS1 for forecasting the earthquakes with magnitude M_w≥5.8, **J=P/(τ/T)**	**J=0.79/0.33=2.4**

Explanation to **Supplementary Materials Table S3.**

A retrospective parametric description of the PS1 precursor signal includes an assessment of five statistical quantities characterizing the features of the relation between the forecasts based on this kind of precursor and subsequent earthquakes of a given energy range and from a given spatial area:

1 **–** probability of a connection between successful forecasts of earthquakes according to PS1 and earthquakes, equal to the ratio of successful forecasts to the total number of earthquakes that have occurred (**P**)**;**

2 **–** probability of missing a target, equal to the ratio of the number of not predicted earthquakes to the total number of earthquakes that occurred (**P_{mt}**);

3 **–** probability of a successful forecasts of earthquakes during occurrence of PS1, equal to the ratio of the number of PS manifestations before earthquakes to the total number of PS1 manifestations (**P′**);

4 **–** probability of false alarm, equal to the ratio of the number of PS1 manifestations, after which no earthquake occurred, to the total number of PS1 manifestations (**P_{fa}**);

5 **–** retrospective efficiency of earthquake forecasts on base of PS1 (**J**).

We used the approach (Gusev, 1974) to assess the retrospective efficiency of earthquake forecasts on base of PS1. If the forecast according to the specified technique is given for the same spatial area (within a radius of up to 350 km from well E-1) and for the same energy range of earthquakes ($M \geq 5.0$ and $M_w \geq 5.8$), then the efficiency of this technique **J** can be estimate by the formula

$$\mathbf{J=(m/n)/(\tau/T)=P/(\tau/T)},$$

where **m** is the number of “predicted” earthquakes, that is, those that correspond to successful forecasts; **n** is the total number of earthquakes that occurred with parameters (location–energy) that correspond to the forecast, that is, earthquakes that could be predicted; **τ** is total alarm time, that is, the total duration of all successful and unsuccessful forecasts, including the time of all cases of PS1 manifestation up to the moment of the earthquake minus 5 days in each case of PS1 manifestation or, in the case of "false alarms", the durations of PS1 minus 5 days and plus 30 days corresponding to the waiting time of the earthquake after the end of the PS1 manifestation; and **T** is the total time of monitoring the seismic situation by the technique that is being assessed.

Accordingly, the efficiency **J** is the ratio between the number of predicted earthquakes according to PS1 and the number of those events that could occur accidentally during an alarm time, assessed by the ratio of **τ/T**. Obviously, the random guess method would make **J** equal to 1. If the value **J**>1, then this technique is useful for predicting earthquakes.

When drawing up forecast conclusions for the Expert Council on Earthquake Forecasting (**Supplementary Materials Figure S8**), we include information on retrospective statistical assessments of the relationship between the PS1 precursor and subsequent earthquakes, so that the experts of Council have objective data on the significance of the precursor we are using.

In addition to the retrospective statistical assessments, constantly updated empirical data on the duration and lead time of the precursor signal PS1 before earthquakes, as well as estimates of the spatial area of earthquakes, before which PS1 appears, are important in drawing up forecast conclusions. Such empirical evidences are also taken into account in determining the formulation of forecasting conclusions. In particular, for the preparation of forecast statements, the following empirical data on PS1 (average value (range of variations)) are taken into account:

– epicentral distances of earthquakes ($M \geq 5$), which were preceded by the PS1: (80–360) km;

– time of PS1 manifestation: 43 (8–70) days;

– time from the beginning of PS1 to earthquakes with $M \geq 5.0$: 65 (45–105) days.

Директору КФ ГС РАН,
Председателю КФ РЭС
Чеброву В.Н.
от зав. лабораторией геофизических исследований
Копыловой Г.Н.

Служебная записка

1. Довожу до Вашего сведения информацию по изменениям уровня воды в скважине Е-1:
- с 16 по 31 января 2013 г. наблюдается понижение уровня воды с повышенной скоростью; продолжительность развития «тревожного признака» составляет Тп=15 суток.

Заключение: в течение времени 1-2 месяца повышена вероятность возникновения землетрясения с M≥5.0 на расстоянии до 350 км от скважины.

Оценки надежности прогноза по ретроспективным данным:
- вероятность события с **M≥5.0** p=0.45, прогнозная эффективность предвестника I=1.4;
- вероятность события с **M≥5.9** p=0.73, прогнозная эффективность предвестника I=2.2.

2. По данным наблюдений на скв. ЮЗ-5 аномальные изменения уровня воды не обнаружены.

1.02.2013 г. Копылова Г.Н.

Supplementary Materials Figure S8. An example of a forecast report dated February 1, 2013, submitted to the Kamchatka branch of the Russian Expert Council for Earthquake Forecast, Seismic Hazard and Risk Assessment (KB REC). The **Supplementary Materials Figure S6** presents the observation data from E-1 well**.** In the **Supplementary Materials Table S3,** retrospective estimates of the precursor PS1 efficiency for forecasting earthquakes with M≥5.0 and M_w≥5.8 are presented.

Translation

To Director of KB GS RAS,
Head of the KB REC
Chebrov V.N.
From Head of laboratory of geophysical research
Kopylova G.N.

1. Bring to your attention information on water-level changes in E-1 well:

– from January 16 to January 31, 2013, water-level decreases at higher rate; the duration of the “warning signal” is T=15 days.

Conclusions: over a period of 1–2 months, there is an increased probability of an earthquake with M≥5.0 to occur at a distance up to 350 km from the well.

The forecast reliability estimates based on the retrospective data are following:

– probability of the event with M≥5.0 is P=0.45, the prognostic efficiency of the precursor is J=1.4;

– probability of the event with M≥5.9 is P=0.73, the prognostic efficiency of the precursor is J=2.2.

2. In the observations at YuZ-5 well, anomalous water-level changes are not detected.

February 1, 2013 Kopylova G.N.

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Supplementary Materials S2

Conceptual models of hydrogeological earthquake precursors in observation wells of the Kamchatka Peninsula

Long-term research of the HGPs in the wells of Kamchatka Peninsula have detected that for each observation well there are features in the manifestation of precursor anomalies both in the chemical composition of groundwater and in the water-level variations. This indicates the uniqueness of each observation well as a natural and technical object for monitoring processes in the well – water-bearing rock system at the preparation of strong earthquakes. Therefore, there is a need to develop and consistently refine the conceptual models of the hydrogeological precursor's formation for each individual well.

The water-level changes before earthquakes can be caused by a change in groundwater pressure due to quasi-elastic deformation or inelastic variations in the volume of the fractured-pore space of water-bearing rocks. It should be noted that an independent verification of such assumptions regarding the leading mechanisms of HGPs in water-level is impossible without special experiments and additional data. At the same time, we admit the indirect evidences of the predominant mechanism of the hydrogeodynamic precursors on the basis of a data combination on tidal, barometric and other geodynamic responses of water-level in the well. This approach has been implemented for the wells E-1 and YuZ-5 in (Kopylova, 2009).

We assumed that the quasi-elastic mechanism could be applied for water-level variations in the YuZ-5 well before the Kronotsky earthquake on December 5, 1997 (Figure 7 in Kopylova, 2006) and before the Zhupanovsky earthquake on January 30, 2016 (Boldina and Kopylova, 2017; **Supplementary 1. Figure 5**). The YuZ-5 well exhibits distinct tidal responses in the range of diurnal and semidiurnal waves, the barometric efficiency of water-level 0.4 cm/hPa for periods of ≥6 hours and coseismic steps of water pressure during the formation of ruptures in the sources of strong earthquakes (Kopylova, 2006). Based on the behavior of the amplitude-frequency function of the water-level barometric response, the range of statically confined conditions in the well – water-bearing rock system was estimated from 6 hours to the tens of days. For this range of periods, the values of the Skempton coefficient B=0.67, the porosity of the water-bearing rocks (0.11) and the tidal sensitivity of the water-level A_v=0.161 cm×10^{-9} were obtained (Table 2 in Kopylova and Boldina, 2012). Quantitative estimates of elastic properties of water-bearing rocks obtained for the YuZ-5 well make it possible to estimate the volumetric deformation of the water-bearing rocks D at the stage of the earthquake preparation by the amplitude of the water-level change Δh (cm) and the value of the tidal sensitivity A_v: $D=\Delta h/A_v$. In the case of the precursor of the Kronotsky earthquake, an estimate was obtained for the volumetric deformation of the water-bearing rocks D=0.7·10^{-7} (expansion), and in the case of the precursor of the Zhupanovsky earthquake D=1.2 10^{-7} (compression).

Increases in the pore-fracture capacity of low-porosity water-bearing rocks and density of groundwater due to phase changes in gas were considered as possible mechanisms of precursors PS1 and PS2 in the lowering of the water-level in the E-1 well. The proof of the hypotheses put forward for explanation the PS1 and PS2 mechanisms is in development.

The elastic mechanism is incompatible with the manifestations of PS1 and PS 2 in the form of monotonic decreases in the water-level with an increased rate. The quasi-elastic mechanism was considered also as secondary due to the absence of coseismic steps, tidal effects and low barometric response of water-level as well as low Skempton coefficient (B=0.044–0.17) and increased compressibility of underground water due to gas in the groundwater. The low value of the strain sensitivity of water-level A_v=0.015 cm×10^{-9} also shows that the E-1 well reacts weakly to quasi-elastic deformation of water-bearing rocks (Kopylova, 2009; Kopylova and Boldina, 2012).

Variations in the chemical composition of underground water from the flowing wells GK-1, M-1 and G-1 before earthquakes can occur as a result of changes in the mixing of waters of different compositions. Such variations in the chemical composition of groundwater can occur when the hydrodynamic conditions change in the aquifer or when the water-bearing rock fracture-pore capacity changes. It is also possible to change the conditions of interaction in the water-rock system during the earthquake preparation. In previous publications (Kopylova and Boldina, 2012; Kopylova et al., 2018; Kopylova and Boldina, 2019) we considered both of these probable mechanisms of hydrogeochemical precursors.

Note that experimental and theoretical verification of assumptions put forward on t he mechanisms of hydrogeochemical precursors is not yet possible, primarily due to technical difficulty of providing the necessary complex of physicochemical parameters of underground water. In order to build adequate models of hydrogeochemical precursors in flowing wells, it is necessary to observe all macrocomponents in the chemical composition of water (anions and cations), gas composition, pH, temperature, and hydrodynamic parameters of groundwater (pressure and discharge rate). In the absence of the indicated complex of observed parameters, there are significant uncertainties in the hydrogeochemical system behavior during the preparation of earthquake.

Given the above, we believe that the study of hydrogeological precursors in Kamchatka Peninsula is at the initial stage of the accumulation of reliable facts about hydrogeological precursors. Despite decades of scientific interest in the topic of hydrogeological precursors, too little data is available to build adequate conceptual models and discuss them meaningfully with conclusions for seismic forecasting and the observation system improvement.

In our review, we consider at piezometric and flowing wells in undisturbed conditions. This circumstance removes questions about the influence of anthropogenic hydrodynamic effects on the precursor manifestations. It is shown that all five considered wells are informative for the search for earthquake precursors and the data obtained can be used for seismic forecasting while ensuring natural regime of observation wells. In our review, we refrain from discussing conceptual models of hydrogeological precursors, paying attention to the more important issues of presenting comprehensive information about observation wells, manifestations of precursors, their relationship with the parameters of subsequent earthquakes and their use in seismic forecasting.

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