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Hydrogeoseismological Research in Kamchatka: 1977–2017

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Abstract—This paper is concerned with the main stages in the setting-up and technical development of a system specializing in physical and chemical parameters of groundwater at a network of wells and springs in the Petropavlovsk Geodynamic Test Area, Kamchatka. The focus is on a description of hydrogeochemical and hydrogeodynamic precursors to Kamchatka earthquakes (M_w = 6.6–7.8) that occur a few weeks to a few months before a seismic event, manifesting themselves in anomalous changes in chemical composition and groundwater level. The precursors are discussed in application to their use at specialized councils on earthquake prediction. It is shown that the system of automated observation of groundwater parameters at wells as developed at the Kamchatka Branch of the Geophysical Survey of the Russian Academy of Sciences (KB GS RAS) is capable of identifying hydrogeodynamic precursors of water level in near real time and of providing, in some particular cases, quantitative estimates of pre-seismic and coseismic of deformation in water-saturated rocks. This can be useful in geophysical monitoring and intermediate-term prediction of strong earthquakes for the Kamchatka region.

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INTRODUCTION

Hydrogeoseismology began to be developed beginning in the latter half of the 20th century; this is a new line of research at the boundary between hydrogeology and seismology (Kissin et al., 1982). The subject matter of hydrogeoseismology is the issues of how groundwater is affected by seismicity, which is understood as the totality of individual earthquakes and their preparation processes; the search for hydrogeologic precursors of earthquakes and the development of these based on methods of earthquake prediction.

The birth of hydrogeoseismology was related to the implementation of national earthquake prediction programs in several leading countries (the former USSR, the United States, China, and others) where observations of groundwater parameters were included (Rikitake, 1976). The necessity of observation of groundwater parameters in the search for earthquake precursors in seismic regions was also mentioned in several publications of Russian and foreign authors since the pioneering work of Ulomov and Mavashev (1967).

The achievement of the goals set before hydrogeoseismology implies solutions to many technical, methodological, and applied problems (Kissin et al., 1982; Kopylova, 2010), as follows:

the development of networks specializing in hydrogeological observations at well and springs, the acquisition of time series resulting from recording of groundwater physical and chemical parameters; identification and systematization of the hydrogeologic effects due to earthquakes;

the study of patterns observable in the occurrence of seismicity-induced effects and the processes involved in their generation in a variety of geotechnical and hydrogeologic systems, in particular, in the well—water-bearing rock, or groundwater—rock systems, and others;

the development of methods for predicting of strong earthquakes using hydrogeologic observations.

The variation in physical and chemical parameters of groundwater due to earthquakes, or *hydrogeoseismic variations* (Kopylova, 1992) are the chief object of study for hydrogeoseismology. In accordance with the times of occurrence relative to the earthquake time, all hydrogeoseismic variations can be divided into hydrogeologic precursors, coseismic, and postseismic effects (Kissin, 2009; Kopylova, 2010).

The classification of hydrogeoseismic variations based on the pre-2000 knowledge can be found in (Kopylova, 2006a). It was shown in this work that the various types of hydrogeoseismic variation are responses of groundwater to the action of seismicity factors, which include the following:

the earthquakes preparation processes, which can be accompanied by *hydrogeologic (hydrogeodynamic and hydrogeochemical) precursors* in the variations of groundwater parameters due to elastic deformation of the water-bearing rocks, changes in their capacity and permeability, the development of fissure dilatancy, and changes of the groundwater mixing conditions that have different chemical composition (Kissin, 2009);

changes in the static state of stress in water-bearing rocks due to ruptures in the sources of local earthquakes; these changes are followed by *coseismic steps* of either increasing or decreasing groundwater level (pressure);

dynamic deformation of water-bearing rocks and wellbore shaking during the passage of seismic waves excited by strong earthquakes with a variety of accompanying *coseismic and postseismic effects* like oscillations, water level increases and decreases in piezometric wells, changes in discharge and temperature of the water from springs and flowing wells; and variations in the chemical composition of groundwater.

The coseismic and postseismic effects that are caused as affected by seismic waves radiated from the earthquakes sources on the underground water-bearing formations are recorded in the changes of regime parameters at wells and springs some hundreds or thousands of kilometers from the epicenter. There are numerous descriptions of such effects in the literature, see, e.g., (Wang and Manga, 2010).

Changes in the parameters of groundwater and gases that occur during the preparation periods of earthquakes (hydrogeologic precursors) are much less frequently observed. Based on the 1987–1997 data on the occurrence of hydrogeologic precursors at wells in Kamchatka and worldwide (Kopylova, 2006a), it was shown that the areas where these occur are much smaller than the areas of coseismic and postseismic effects. The study referred the dependence of characteristic areas sizes where hydrogeologic precursors occurred at observation wells (d_e is epicentral distance, km) on earthquake magnitude for $M_w \geq 5.0$ events:

$$M_W \geq 3.37 \log d_e - 0.84. \quad (1)$$

A similar relationship for $M_w \geq 4.0$ events was previously cited in (Kopylova, 1992):

$$M_W \geq 3.33 \log d_e - 0.67. \quad (2)$$

Expressions (1) and (2) yield comparable estimates of the maximum areas sizes where hydrogeologic precursors occurred in relation to earthquake magnitude: the maximum value of d_e for $M_w = 5$ events is 50 km at most, being $d_e \leq 100$ km for $M_w = 6$, $d_e \leq 200$ km for $M_w = 7$, and $d_e \leq 400$ km for $M_w = 8$.

Comparison of the estimates of maximum d_e as given by (1)–(2) with the lengths of earthquakes sources along strike L (Riznichenko, 1976) yields the result that the $L/d_e = 2.4$–6 ratio is 4 on average for the $M_w = 5$–8 earthquakes. This shows that the occurrence of hydrogeologic precursors as observed in groundwater behavior is a property of the "near zone" of sources of future earthquakes. Their advance times, that is, the interval of time between the moment of their appearance and the earthquake time is a few days to a few weeks to a few months (Kopylova, 2006a).

The above evidence for the space–time occurrence of hydrogeologic precursors shows that these can be of practical use in earthquake prediction systems for predicting the location and time of future earthquakes that entail catastrophic impact on the population, infrastructure, and environment in seismic regions.

Hydrogeoseismological research has been conducted in the Kamchatka seismic region since 1977. The decisive contribution to this line of research is due to the Kamchatka Branch of the Geophysical Survey of the Russian Academy of Sciences (KB GS RAS) with the participation of the Institute of Volcanology of the RAS Far East Branch, the *OAO Kamchatgeologiya*, Institute of Physics of the Earth (RAS), and other organizations.

This paper is concerned with the main stages in the organization of the observing network and in the organization and technical development of the system of hydrogeoseismological research in Kamchatka for a 40-year period; information is provided bearing on the occurrence of hydrogeologic precursors as reflected in changes in the chemical composition and levels of groundwater at observing wells before strong Kamchatka earthquakes and on their practical use in the earthquake-prediction system.

THE HISTORY OF HYDROGEOSEISMOLOGICAL RESEARCH AND ITS RESULTS

Three stages stand out in the study of seismicity as it affects the behavior of groundwater in Kamchatka (Kopylova, 2017):

the early stage, before 1977;

organizing and conducting the hydrogeochemical observations at flowing wells and springs in the Petropavlovsk Geodynamic Test Area lasting from 1977 until the present time;

creating a system specializing in observation at wells using automatic means of recording for groundwater parameters (the instrumental stage), 1996 until the present time.

The early stage is characterized by accidental observations of earthquake-induced effects in the behavior of thermal wells, springs, geysers, and steam–gas fumaroles. Manukhin (1979) reported information concerning changes in discharges and water temperature at the Pinachevo springs and at the GK-1 well (Fig. 1) resulting from the Petropavlovsk earthquake of November 24, 1971, $M_{LH} = 7.3$ with intensity VII on the *MSK-64* scale (Medvedev et al., 1965). The spring discharges became larger, occasionally by as much as six times, after the event, and the water temperature increased by 3°C. The water discharge of the springs took 6 months to return to the background values after the earthquake. Higher temperatures and concentrations of macrocomponents in the chemical composition of the water were recorded for as long as 3 to 10 years. Kopylova (1992) used 1971–1988 observations to estimate the effects of seis-

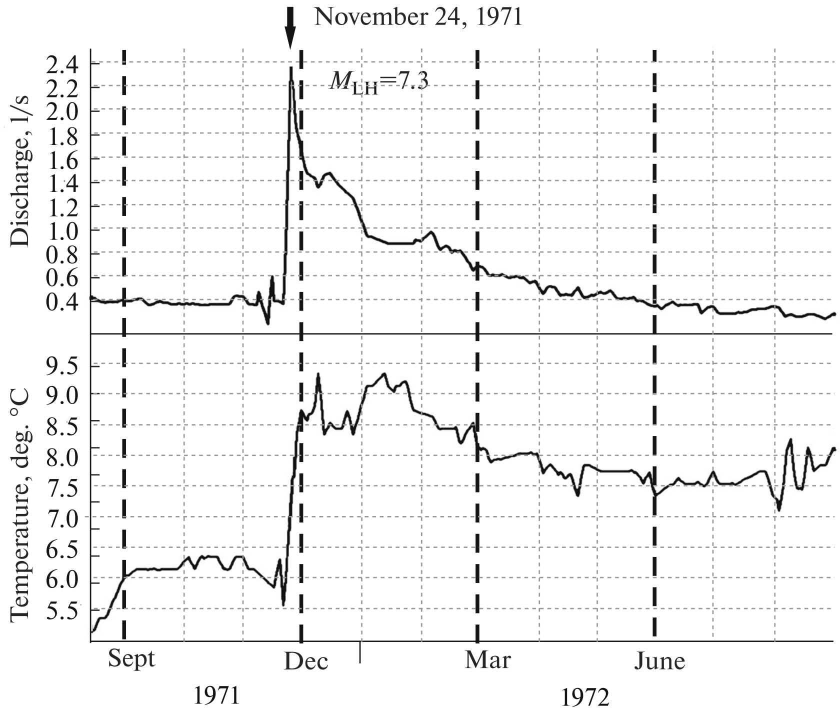

Fig. 1. The variation in the discharge and temperature of water in the Pinachevo spring 1 following the Petropavlovsk earthquake of November 24, 1971, M_{LH} = 7.3 (the zone of intensity VII) based on observations of the *OAO Kamchatgeologiya* between July 1, 1971 and August 1, 1972. The earthquake time is marked by an arrow.

micity on the aqueous, thermal, and mineral discharge of the Pinachevo springs and showed that strong local earthquakes of magnitudes of approximately 7 caused considerable disturbances lasting a few months or a few years in the heat-and-mass transport in the water-bearing system that recharges the springs. The contribution of seismicity as estimated from the differences between the amplitudes of postseismic increases in water discharge and of the outward transport of heat and mineral substances above their background values turned out to be appreciable, viz., regarding the water discharge, 16% of its total value was the postseismic increase in spring discharges; regarding the total amount of heat transported to the surface with groundwater, the value was 14%; lastly, for various mineral components the increase ranged between 8% and 33% (33% for chlorine ion, 28% for sodium and potassium, and 8% for boron).

Stage 2. Regular observations were initiated in 1977 at three springs and at the GK-1 well in the Pinachevo area (the Pinachevo station, Fig. 2b) by V.M. Sugrobov and Yu.M. Khatkevich at the Laboratory of Hydrogeology and Geothermics, Institute of Volcanology, Far East Science Center, USSR Acad. Sci. The workers who conducted observations were transferred in 1979 to the Kamchatka Experimental and Methodical Seismological Department to make a distinct structural unit that was termed a group at first, and afterwards became the Laboratory of Hydroseismology (Head Yu.M. Khatkevich, 1979–2009).

Observations were also organized at three more stations in 1983–1992 (Moroznaya in 1983, Verkhnyaya Paratunka in 1989, and Khlebozavod in 1992) (see Fig. 2b) in the Petropavlovsk Geodynamic Test Area (see Fig. 2a), in addition to the Pinachevo station. The observing network did not experience any substantial changes from 1992 until the present. It includes four low termal (with water temperatures of 6–11°C) springs in the Pinachevo area, seven flowing wells that reach cold groundwater at depths of between 120 m and 2.5 km in the zone of active and impeded water exchange, and thermal waters of nitrogen–methane and nitrogen compositions (Kopylova et al., 2018).

The method of observation has been essentially the same during these 40 years. The wells and springs were visited once in 3 to 6 days to measure discharge by the volumetric technique and water temperature with a thermometer graded at steps of 0.1°C, and to sample water, free and dissolved gas. The samples were analyzed in the laboratory to determine a wide range of chemical components in the compositions of water and gas. Detailed descriptions of the observing network and measuring methods can be found in (Kopylova, 2010; Kopylova et al., 1994, 2018; Khatkevich and Ryabinin, 2004).

These observations yielded homogeneous time series of various groundwater parameters, namely, discharges and water temperatures, and the concentrations of the main components in the chemical compositions of water and gas. In their changes, post-seismic

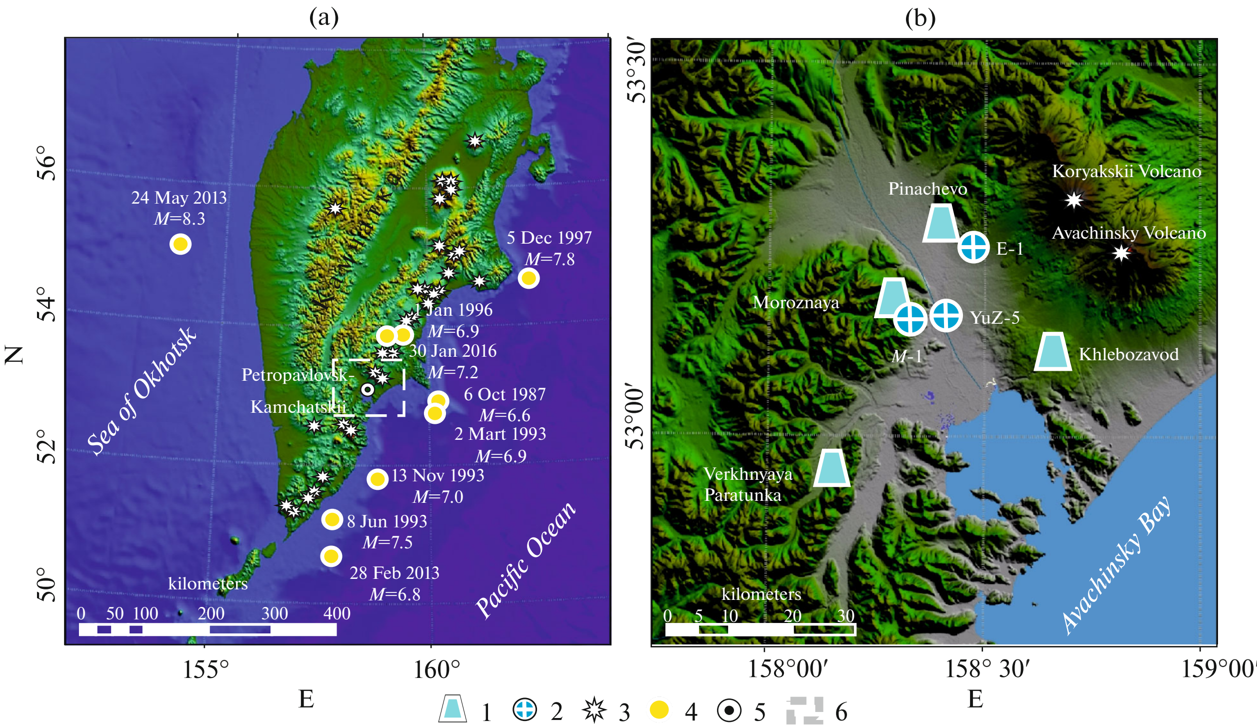

Fig. 2. A map of observing stations and epicenters of strong earthquakes that were accompanied by hydrogeologic precursors based on observations of the KB GS RAS. (a) location map of the Petropavlovsk Geodynamic Test Area (PGTA) and the epicenters; (b) stations for hydrogeochemical and hydrogeodinamic observations in the Petropavlovsk Geodynamic Test Area (PGTA) as of 2017. (1) stations of hydrogeochemical observation (Pinachevo, GK-1 well , depth h = 1261 m and four springs; Moroznaya, Moroznaya 1 well, h = 600 m; Khlebozavod, GK-1 well , h = 2500 m; Verkhnyaya Paratunka, four wells, h = 125–1600 m); (2) wells equipped with automatic systems for recording physical and chemical parameters of groundwater (E-1 is an piezometric well, h = 665 m; YuZ-5 is an piezometric well, h = 800 m; Moroznaya 1 is a flowing well, h = 600 m); (3) active volcanoes; (4) earthquake epicenters (dates of earthquakes are indicated in the format dd.mm.yyyy and magnitude values are shown); (5) Petropavlovsk-Kamchatskii; (6) the PGTA area in Fig. 2a.

effects from local tangible earthquakes were detected manifesting in increased discharge, temperature and water salinity, increased or redistributed concentrations of macrocomponents in the chemical composition of groundwater and gas in Pinachevsky springs and at the wells GK-1 (Pinachevo station), Moroznaya 1 (Moroznaya station), G-1 (Khlebozavod station), GK-15 and others (Verkhnyaya Paratunka station).

Changes in the chemical composition of water and gas were recorded before the six strongest seismic events of 1987–1997, viz.: October 6, 1987, M_w = 6.6; March 2, 1992, M_w = 6.9; June 8, 1993, M_w = 7.5; November 13, 1993, M_w = 7.0; January 1, 1996, M_w = 6.9; and December 5, 1997, M_w = 7.8 (see Fig. 2a) that occurred at epicentral distances of 90 to 300 km from the stations, at the wells GK-1, Moroznaya 1, G-1, and GK-15. These changes were recognized to be hydrogeochemical precursors. The time before the occurrence of the respective earthquakes ranged from 1 to 9 months. The most complete description of the hydrogeochemical precursors observed before the 1987–1997 earthquakes can be found in (Kopylova, 2010; Kopylova et al., 1994; Khatkevich and Ryabinin, 1998, 2004).

Figure 3 shows earthquakes of 1977--1997 in the magnitude--epicentral distance coordinates that had various types of associated hydrogeoseismic variations in the regime of flowing wells and springs in the Petropavlovsk Test Area. The dashed line indicates the area of hydrogeochemical precursors that were observed as changes in the water and gas compositions at observing wells before earthquakes of magnitude M_w = 6.6–7.8 at epicentral distances d_e ranging between 90 and 300 km. The intensity of ground shaking in the vicinity of stations due to these events was I = 5–6 intensity units on the *MSK-64* scale (Medvedev et al., 1965). The events were also followed by postseismic variations in discharge and in the chemical composition of water and gas, mostly at the Pinachevo springs. Earthquakes of magnitude M_w = 4–6 at epicentral distances $d_e \geq$ 100–300 km that caused ground shaking with intensity of I = 3–4 in the Petropavlovsk Test Area were also followed by postseismic changes in discharge and chemical composition of the water at the Pinachevo springs.

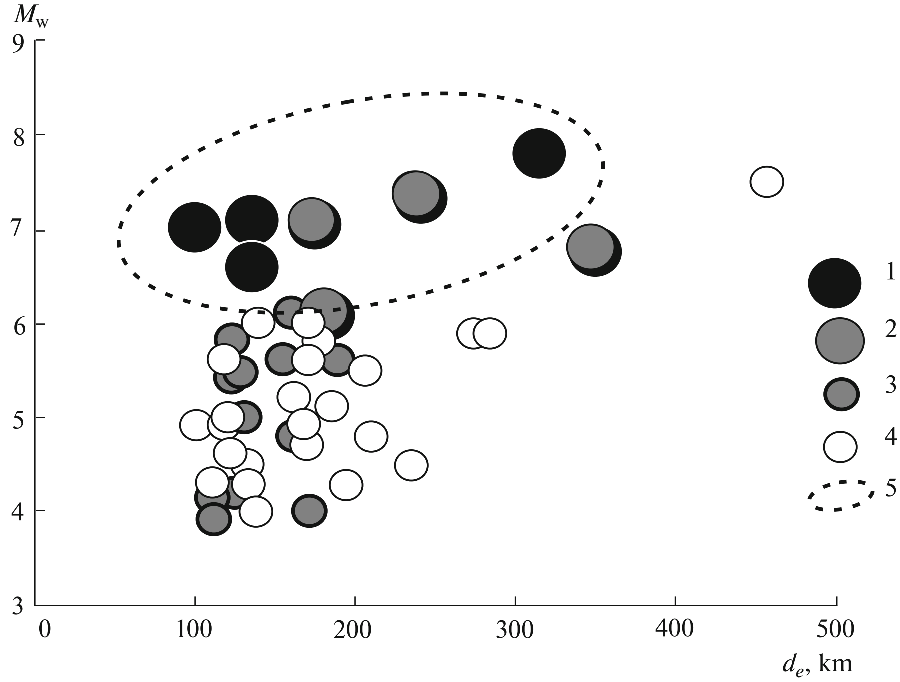

Fig. 3. The occurrence of different types of hydrogeoseismic variations in the behavior of observed springs and wells on the Petropavlovsk Geodynamic Test Area in relation to earthquake parameters: magnitude M_w and epicentral distance d_e, km based on observations of the KB GS RAS in 1977–1997. (1) amplitude hydrogeochemical precursors and postseismic changes in the chemical compositions of water and gas, increases in the discharge of springs and flowing wells; (2) less obvious hydrogeochemical precursors and postseismic changes in discharge and chemical composition of water; (3, 4) postseismic variations: (3) increased discharges and changes in chemical composition of water, (4) increased discharge of springs; (5) domain of the parameters M_w and d_e for those earthquakes preceded by hydrogeochemical precursors.

The patterns that were observable in the occurrence of hydrogeochemical precursors as changes in the chemical composition of water and gas at the wells GK-1 and Moroznaya 1 before the earthquakes of October 6, 1987, $M_w = 6.6$ and March 2, 1992, $M_w = 6.9$ (see Figs. 2a, 2b) were analyzed by G.N. Kopylova, V.M. Sugrobov, and Yu.M. Khatkevich to develop an empirical algorithm for intermediate-term estimation of the times of occurrence for Kamchatka earthquakes that would cause ground shaking at least $I = 5–6$, as follows: *The best-pronounced feature to signal the precursory process of a strong earthquake that can cause ground shaking intensities above V in the area of Petropavlovsk-Kamchatskii consists in a combined occurrence of relative diminution in the concentration of chlorine ion in the water discharged by GK-1 well for times at least 5 months in conjunction with anomalous variations in other parameters in the behavior of observed wells and springs* (Kopylova et al., 1994; Khatkevich, 1994). This algorithm has been used since the late 1990s to develop weekly prediction statements based on hydrogeochemical observations and to transmit these statements for consideration to the Kamchatka Branch of the Russian Expert Council on Earthquake Prediction and the Assessment of Seismic Hazard and Risk (KB REC). The statements are discussed at KB REC sittings and are incorporated in intermediate-term assessments of the hazard of strong earthquakes in Kamchatka based on combined seismic prediction data (Chebrov et al., 2011).

The **second stage** was concerned with a study of the ways the hydrogeochemical precursors are generated, besides the postseismic variations in the chemical composition of groundwater due to seismic waves. Kopylova and Voropaev (2006b) and Kopylova and Boldina (2012b) presented physico-chemical models of the hydrogeoseismic variations in the chemical composition of the water discharged by the Pinachevo springs and at the Moroznya 1 and GK-1 wells. The leading mechanism that is responsible for the formation of hydrogeochemical precursors and postseismic effects as observed in the groundwater coming to the surface was considered to be a change in the mixing conditions in zones of higher permeability and in wellbores for waters of differing compositions that reside in water-bearing systems of observing wells and springs (Wang et al., 2004).

The work carried out during the **second stage** involved the development of methods to be applied to the processing of the available hydrogeochemical data using various modifications of one-variate and multivariate time series analysis in order to identify signals of earthquake precursory processes. The methods were due to A.A. Lyubushin, G.N. Kopylova, G.V. Ryabinin, F. Bella, P.F. Biagi, S. Kingsley, and others. The results obtained by using these statistical methods in application to detection of seismicity effects turned out to be in good agreement with the observations described previously (Kopylova et al., 1994; Khatkevich, 1994, among others) regarding hydrogeochemical precursors and postseismic effects in the changes observed in the composition of groundwater during the preparation periods and occurrence of strong earthquakes in Kamchatka (see, e.g., Kopylova and Taranova (2013); Bella et al., 1998; Biagi et al., 2000a, 2000b, 2000c, 2001; Kingsley et al., 2001)).

The most important results obtained during the **second stage** of hydrogeoseismological research in Kamchatka in the area of earthquake prediction include the following:

the detection of hydrogeochemical precursors in the changes of the macrocomponent composition of groundwater and gases with advance times between 1 and 9 months before the occurrence of strong local earthquakes (M_w = 6.6–7.8, d_e = 90–300 km, $M_w/\log d_e \geq 3.1$, and the intensity of ground shaking at least I = 4–6 intensity units, see Fig. 3);

practical use, for the earthquake prediction system for Kamchatka, of the space–time patterns as identified in the occurrence of hydrogeochemical precursors in order to achieve intermediate-term (with advance times between a few weeks to a few months) estimation of times of occurrence for strong earthquakes in the Kamchatka seismic zone at distances as large as a few hundred kilometers from the observing stations.

Stage 3: instrumental. During the instrumental stage (1996 until the present), G.N. Kopylova, D-r Sci. (Geol.–Mineral.) initiated and headed work by colleagues at the Laboratory of Geophysical Studies, KB GS RAS to equip three wells (E-1 in 1996, YuZ-5 in 1997, and Moroznaya 1 in 2013) (see Fig. 2b) with digital recording systems for groundwater parameters (level, temperature, and electrical conductivity) and for meteorological parameters (air temperature and pressure). All these measurements were conducted at intervals of 10–15 minutes.

The equipment was modernized three times during 1996–2013. The pressure was measured in 1996–2000 using DU and DA pressure sensors designed at the Design Bureau of the Institute of Physics of the Earth RAS (Bagmet et al., 1989). In 2001–2010, hydrogeologic and meteorological parameters were measured with instruments of the Kedr A2 series (manufactured by OOO Polinom, Khabarovsk), with removable data drives. The data were retrieved and processed once every 2 weeks. From 2010 onward, we used instruments of the Kedr DM series with data transmitted via cellular communication channels (Kopylova et al., 2016, 2017). Similar equipment sets were also installed by the *OAO Kamchatgeologiya* at five other wells in Kamchatka Krai for hydrogeodynamic monitoring purposes using the methodology developed at the All-Russian Research Institute of Hydrogeology and Engineering Geology (Kopylova and Smolina, 2009; Kopylova et al., 2007).

The **third stage** saw the development of methodology to deal with water level observations in order to identify hydrogeoseismic variations in water level (2004–2010, G.N. Kopylova and S.V. Boldina); the software of the POLYGON Information System (2003, G.N. Kopylova, E.R. Latypov, and E.A. Pantyukhin), which is used to update the database residing at the Information Processing Center of the KB GS RAS, and to perform fast processing and analysis of water level data in near real time.

Water level was recorded at the E-1 and YuZ-5 observation wells and at wells by the *OAO Kamchatgeologiya* using very sensitive ultrasound sensors at a resolution of ±0.1 cm that were designed by Cand-Sci. (Eng.) G.A. Kalinov, Mining Institute, FEB RAS, Khabarovsk. Unique records have been acquired using these sensors during the strong Kamchatka and great worldwide earthquakes of 1997–2017 (Boldina and Kopylova, 2017; Kopylova, 2006b, 2010; Kopylova and Boldina, 2012b; Kopylova et al., 2012, 2016, among others).

Below, we provide a description of hydrogeoseismic variations in water level at the YuZ-5 and E-1 wells, which were recorded during the strongest Kamchatka earthquakes of 1997–2017.

The Kronotsky earthquake of December 5, 1997, M_w = 7.8 (abbr. KE below) (see Fig. 2a). The observing wells were at an epicentral distance of d_e = 300 km (see Fig. 2a) in a V–VI intensity zone (Levina et al., 2003). Judging from the 1-day aftershock area, the KE rupture zone 220 km in extent was southwest of the instrumental epicenter, with the center of the source area being 200 km distant from the wells.

On the occasion of this earthquake, successive occurrences of hydrogeoseismic variations of water level were recorded for the first time at the YuZ-5 and E-1 wells; the variations were due to the main factors of seismic excitation acting on water-bearing rocks, viz., the processes of earthquake preparation, the static rearrangement of stress state of the medium after the rupture in the earthquake source, and the dynamic effects of seismic waves (Fig. 4) (Kopylova, 2006b, 2010; Kopylova and Boldina, 2012b, among others).

The water levels in both of these wells were observed to have been decreasing during 3 weeks before the KE occurred; the decrease was identified as a hydrogeodynamic precursor of the event (Kopylova, 2006b) (see Figs. 4a, 4b). The amplitude of level change at the YuZ-5 well was Δh = –11 cm and that at E-1 was Δh = –1 cm. The hydrogeodynamic precursor occurred simultaneously with horizontal movements of the GPS stations in the Kamchatka network (KAMNET) at distances of a few hundreds of kilometers from the earthquake. These movements were identified as a deformation precursor of the event by Gordeev et al. (2001). Kopylova and Boldina (2012b) used water level data, strainmeter, and seismological observations to show that the hydrogeodynamic precursor was due to volumetric expansion of the water-bearing rocks with amplitude $D_t = 7 \times 10^{-8}$ near the

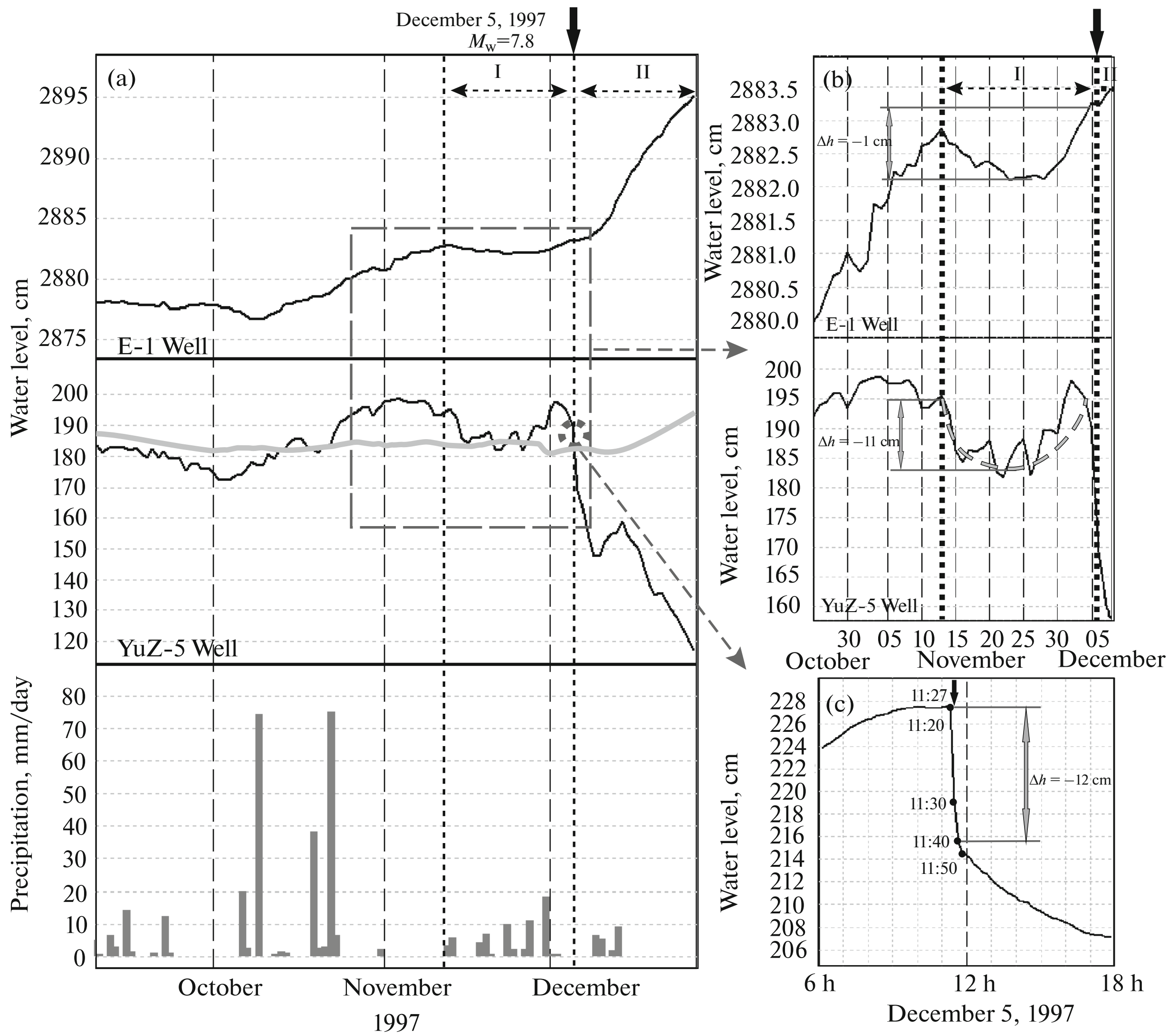

Fig. 4. The water level changes in the E-1 and YuZ-5 wells during the Kronotsky earthquake of December 5, 1997, $M_w = 7.8$. (a) water level changes in the wells between September 9 and December 31, 1997 compared with daily precipitation based on data of the meteorological station Pionerskaya: numerals I and II and two-sided horizontal arrows mark time intervals: (I) manifestation of the hydrogeodynamic precursor before the KE (see inset (b): two-sided vertical arrows with numerals mark the amplitudes of water level lowering); (II) manifestation of the coseismic step of lowering and postseismic variations in water level changes in the YuZ-5 well (see inset (c): 11:27 is the time of seismic wave arrival based on the records of the PET seismic station) and postseismic variations in water level.

wells owing to aseismic movements in the area of future KE source.

A water level drop with amplitude ($\Delta h = -12$ cm) was recorded at the YuZ-5 well during approximately 12 min after the formation of rupture in KE source (see Fig. 4c); this was a response of groundwater pressure to the volume coseismic deformation in water-bearing rocks (Kopylova, 2006b). The expansion deformation of the water-bearing rocks was $D_t = 8 \times 10^{-8}$ as inferred from water level data, and was in good agreement with the estimate of coseismic deformation in the area of the well using model an extended dislocation source with the CMT source parameters. The method used to obtain point estimates of volume coseismic deformation in water-bearing rocks from water-level measurements at the YuZ-5 well, is described in Kopylova et al. (2010).

The dynamic effect of seismic waves on the state of the water-bearing rocks and shaking of wellbores was accompanied by amplitude changes in water level at both of these wells during a long period of time (see Fig. 4a). The disturbed state of the well–water-bearing rock system at the YuZ-5 well due to the KE occurrence lasted approximately 2.5 years and was seen as a 1-m lowering of water level during 3 months and a subsequent recovery lasting 2 years. The water level at the E-1 well after the KE was rising during 3 months and had an amplitude of 30 cm (Kopylova, 2006b).

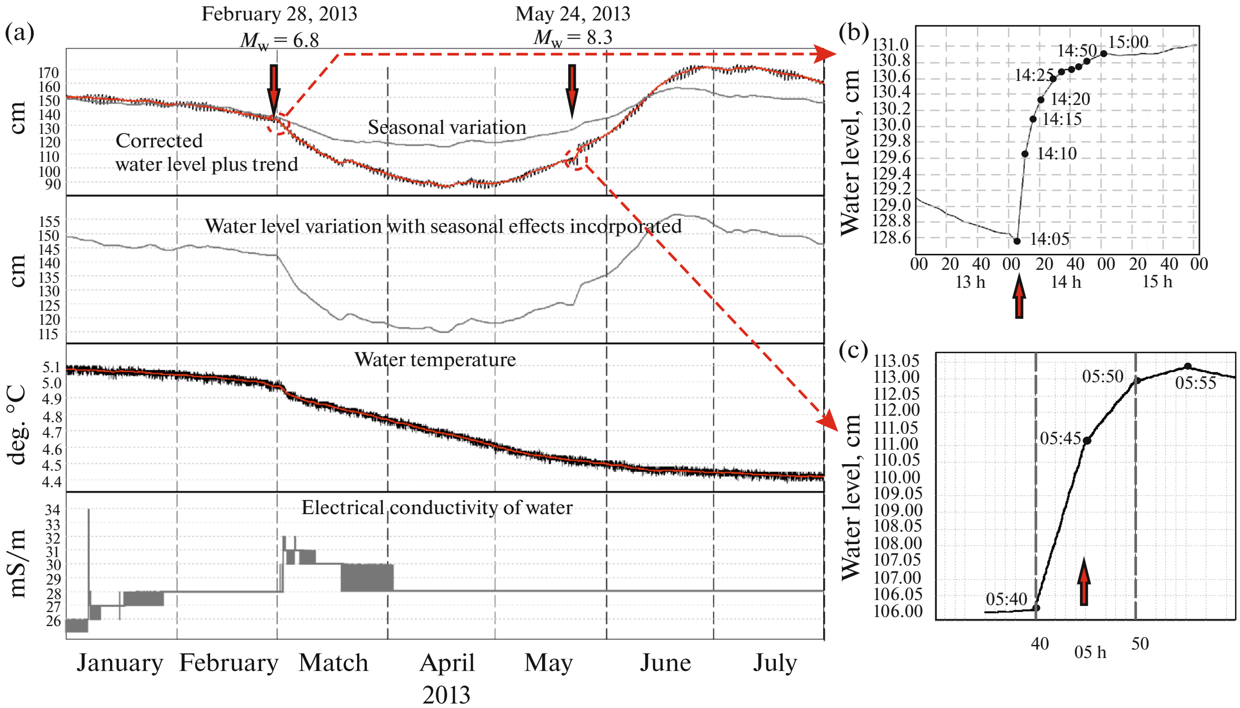

Fig. 5. The variations in the physical and chemical parameters of groundwater at the YuZ-5 well in January–July 2013. (a) changes in water level, temperature, and electrical conductivity, including the coseismic and postseismic variations due to the earthquakes of February 28 and May 24, 2013 (marked by arrows). The insets show the coseismic rise in water level following wave arrivals due to the February 28, 2013 earthquake (b) and to the Sea-of-Okhotsk earthquake of May 24, 2013 (c) based on 5-min observations.

The strong earthquakes of 2013. A sequence of strong earthquakes occurred in the south part of the Kamchatka focal zone (*Sil'nye ...,* 2014). The maximum magnitudes of these seismic events reached $M_w = 6.8$ (February 28, 2013) and $M_w = 8.3$ (the Sea-of-Okhotsk earthquake of May 24, 2013 in the mantle) (see Fig. 2a). These earthquakes, as well as the other seismic events of 2013 with magnitudes $M_w \geq 6.0$, were accompanied by sharp coseismic steps of water level at the YuZ-5 well with amplitudes between 0.2 and 7 cm (Kopylova et al., 2016, 2017) (Figs. 5b, 5c), which were in agreement with estimates of the amplitudes and the character of the volume coseismic deformation in the area of the well according to model of extended dislocation source (Okada, 1985) with the source parameters from the International earthquake tensor moment catalog, Global CMT (http://www.globalcmt.org/) (Boldina and Kopylova, 2016). The amplitudes of coseismic water level changes were used to derive quantitative estimates of volume coseismic deformation in the area of the YuZ-5 well during rupture formation in earthquakes sources (D_t between a few 10^{-9} and $\approx 1 \times 10^{-7}$). The deformation character was determined from the directions of water level changes, with a rise indicating a volume deformation of compression, while a lowering indicated a volume deformation of expansion of water-bearing rocks.

The fact that our estimates of volume coseismic deformation based on YuZ-5 observations (the amplitudes and character of the water level changes incorporated) were consistent with the theoretical estimates according to the model of Okada (1985) corroborated good strain-measuring properties of the well in the range D_t = a few 10^{-9} to a few 10^{-7}. Nevertheless, no hydrogeodynamic precursors as expressed in water level changes at the well before the earthquakes of February 28 and May 24, as well as before the other strong earthquakes of 2013, have been detected.

Postseismic water level variations at the YuZ-5 well were recorded in relation to the events of February 28 (a water level lowering during 1.5 months with amplitude $\Delta h = -35$ cm) and that of May 24 (a water level rise during 1 month with amplitude $\Delta h = 24$ cm) (see Fig. 5a). The February 28 earthquake was also followed by a decrease in water temperature with amplitude 0.6°C and a rise in electrical conductivity by 4 mS/m. Changes in groundwater physical and chemical parameters such as those above can also be classified as postseismic variations in the behavior of that well. A rise in electrical conductivity of water with amplitude 6 mS/m was recorded on January 7, 2013, approximately 8 weeks before the February 28 earthquake (see Fig. 5a). The possible significance of the effect for earthquake prediction can be assessed from subsequent observations.

The changes of water level resulting from 30-year observations at the E-1 well (from 1987 until the pres-

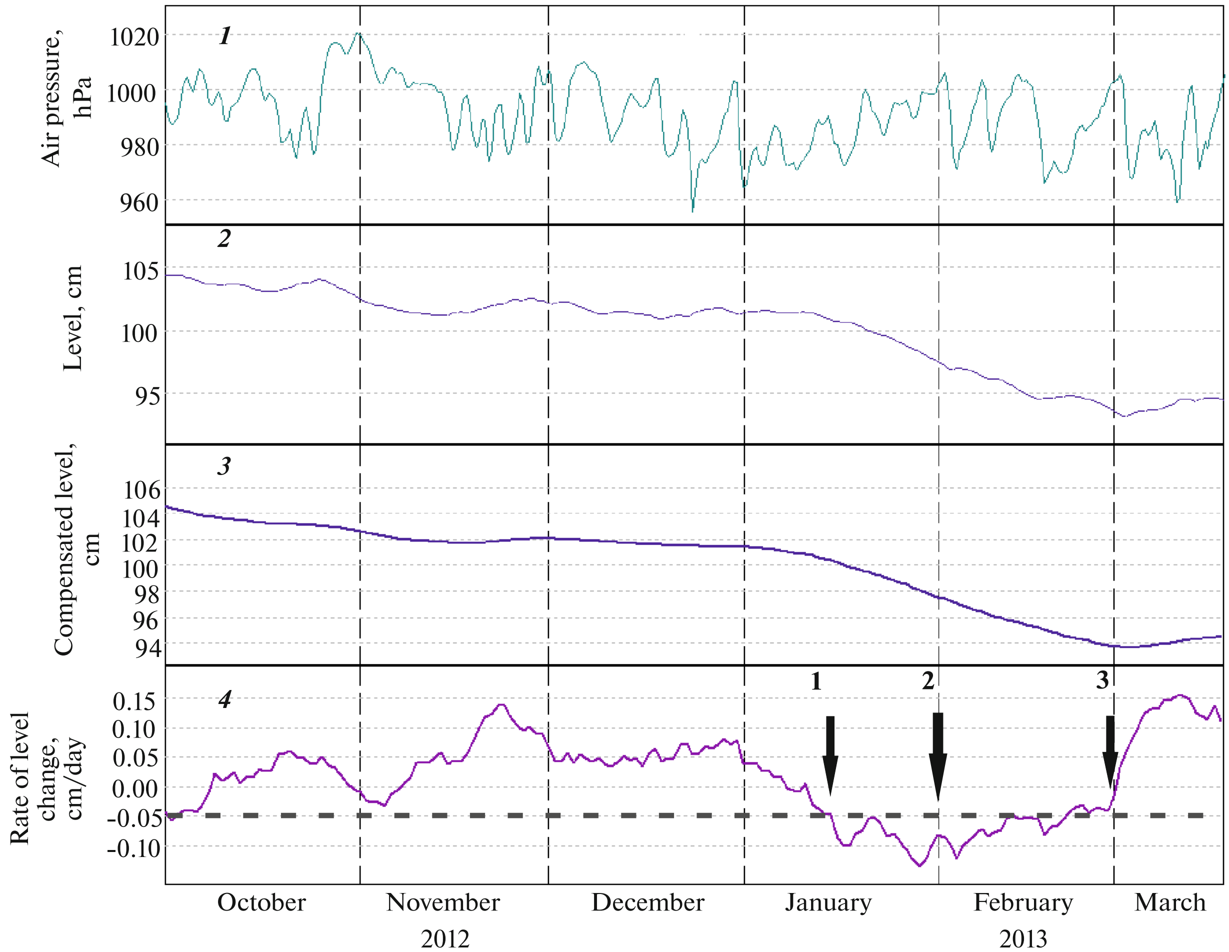

Fig. 6. The changes in water level in the E-1 well from October 2012 to March 18, 2013, including the manifestation of a hydrogeodinamic precursor HP_I and the postseismic increase related to the earthquake of February 28, 2013, $M_w = 6.9$. (***1***, ***2***) 5-min records of air pressure and water level, (***3***) mean daily changes of water level with compensated barometric variations, (***4***) daily rate of water level change with due account of the rate of a descending trend. The arrows in plot (***4***) show: (**1**) January 16, 2013, start of the hydrogeodynamic precursor GP_I; (**2**) February 1, 2014, the date the forecast statement was submitted to the KB REC; (**3**) February 28, 2013, the date of the earthquake. The horizontal dashed line represents the threshold value of daily rate in water level variation.

ent) were found to contain two types of hydrogeodynamic precursors:

a precursor GP_I whose advance time varied between a few days and a few tens of days (Kopylova, 2001, 2013; Kopylova and Boldina, 2012a]);

a precursor GP_II whose advance time was as long as to reach a few years (Kopylova, 2001; Firstov et al., 2016).

The hydrogeodynamic precursor GP_I occurred in the form of water level lowerings at an elevated rate during some days to 1 month before $M_w \geq 5.0$ earthquakes at epicentral distances of $d_e \leq 350$ km. Kopylova (2001, 2013) gives a parametric description of the GP_I. The regular occurrence of the GP_I before $M_w \geq 5.0$ earthquakes (over 70% of the cases), as well as an enhanced statistical relationship between it and subsequent earthquakes of greater magnitudes, permit the use of the GP_I for intermediate-term estimation of times of local earthquakes with magnitudes $M_w \geq 5.5 \pm 0.5$, providing advance times of a few days to a few weeks (Kopylova, 2001; Kopylova and Boldina, 2012a; Kopylova and Sizova, 2012; Kopylova et al., 2012). Since the early 2000s, the GP_I has been in use for developing and transmitting, to the expert councils on earthquake prediction, statements as to the likelihood of strong earthquakes in the Kamchatka region with advance times no longer than one month (*Sil'nye* ..., 2014; Chebrov et al., 2011, 2016; Firstov et al., 2016).

Figure 6 shows water level changes for the E-1 well during the occurrence of the February 28, 2013 earthquake as related to the start times of the GP_I (arrow **1** in the bottom plot), the time of the earthquake (**3**), and the date the prediction statement was submitted to the KB REC (**2**). The statement of February 1, 2013 pointed out that *there is an increased likelihood of an* $M_w \geq$ *5.0 earthquake at distances within 350 km of the*

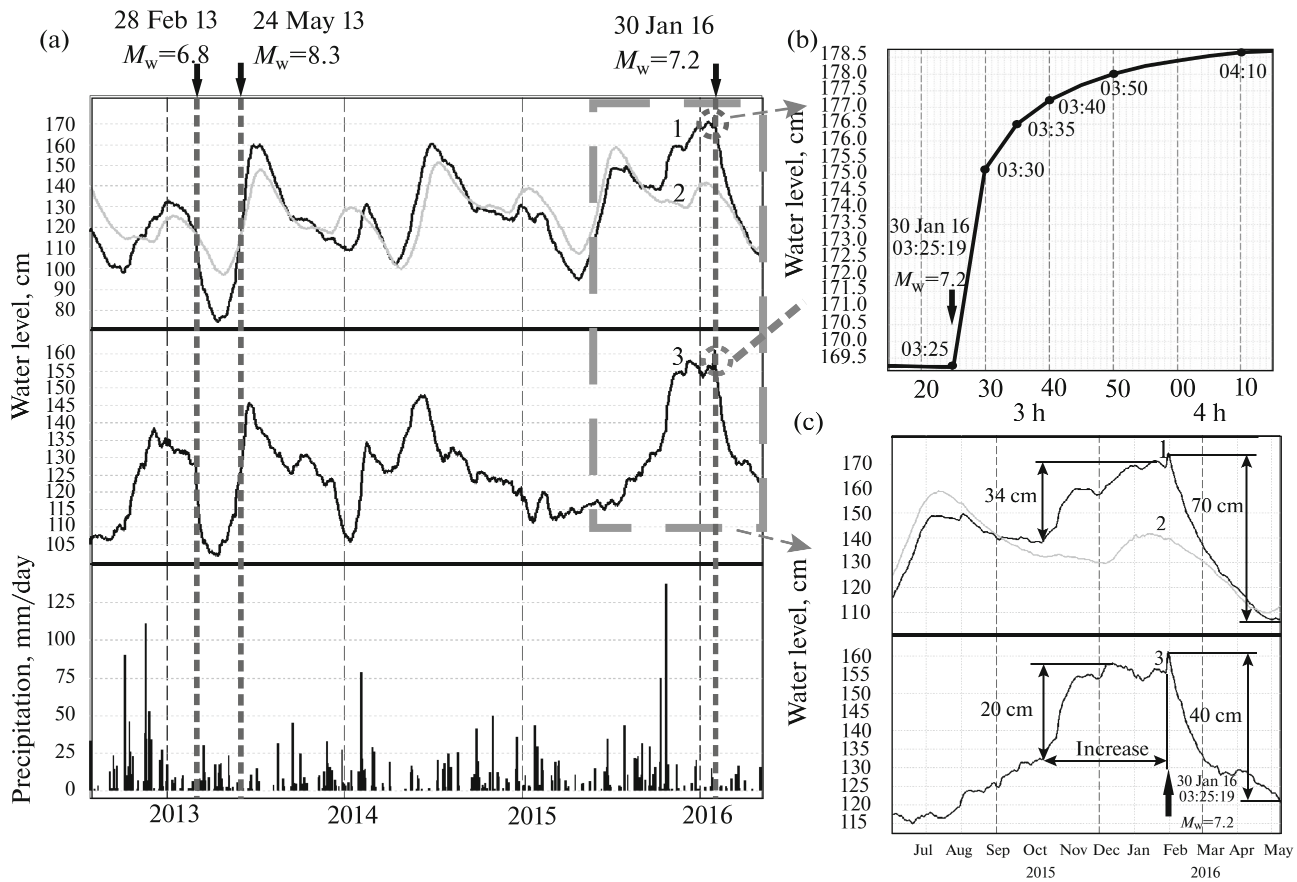

Fig. 7. The hydrogeoseismic variations in water level changes in the YuZ-5 well due to the Zhupanovo earthquake of January 30, 2016, $M_w = 7.2$ (see Fig. 2). (a) water level changes in July 2012 to May 2016 compared with precipitation and strongest earthquakes (marked by arrows, and see Fig. 2): (1) mean hourly observations with air pressure variations compensated, (2) seasonal water level variations with the linear trend retained, (3) residuals of water level variations after compensating for annual seasonal changes and subtracting the trend: the heavy dashed line shows the fragment of the plots during the preparation period and occurrence of the Zhupanovo earthquake (see Fig. 7c); (b) coseismic water level rise after the arrival of seismic waves (03:25); (c) hydrogeodynamic precursor and postseismic water level changes.

well during 1 to 2 months. As well, the statement provided estimates for the reliability of the present earthquake forecast for earthquakes with different magnitudes based on a retrospective analysis of the occurrences of the GP_I for a period of many years (Kopylova and Sizova, 2012]: *the probability of an* $M_w \geq 5.0$ *event is* $p = 0.45$, ... *the probability of an* $M_w \geq 5.9$ *event is* $p = 0.73$. The earthquake of February 28, 2013 was consistent with the February 1 forecast with regard to magnitude, time, and location, and the forecast was recognized as a success at the KB REC (*Sil'nye ...,* 2014, p. 152). The water level changes at E-1 during the occurrence of the February 28 earthquake include the following: a lowering at a higher rate during 44 days before the earthquake and a rise with an amplitude of 2 cm after the earthquake (see Fig. 6, plots ***3*** and ***4***). This is a typical combination of water-level events during the occurrence of strong ($M_w \geq 6.6$) local earthquakes within 300 km (Kopylova, 2001).

The other type of prediction signal in water level variations at the E-1 well (GP_II) was first identified in 2001 (Kopylova, 2001) and corroborated in 2016 (Firstov et al., 2016). The GP_II occurred in the form of long-continued (up to 6 years) lowerings of water level at higher rates that preceded and accompanied the occurrence of strong earthquake sequences in Kamchatka. Such lowerings were observed in 1991–1997 (six M = 6.9–7.8 earthquakes in 1992–1997 at epicentral distances within 300 km) and in 2012–2017 (a sequence of strong earthquakes of 2013–2016 whose maximum magnitudes were M_w = 6.8–8.3). We believe that such long-continued lowerings of water level at the E-1 well reflect geodynamic situations that involve the precursory periods and occurrence of magnitude 7 or greater earthquakes in the segment of the Kamchatka seismic focal zone adjacent to the Petropavlovsk Geodynamic Test Area. The lowerings are thought to be caused by increased capacity of the water-bearing rocks as fissure dilatancy in the rocks and phase changes in the water–gas system are developing.

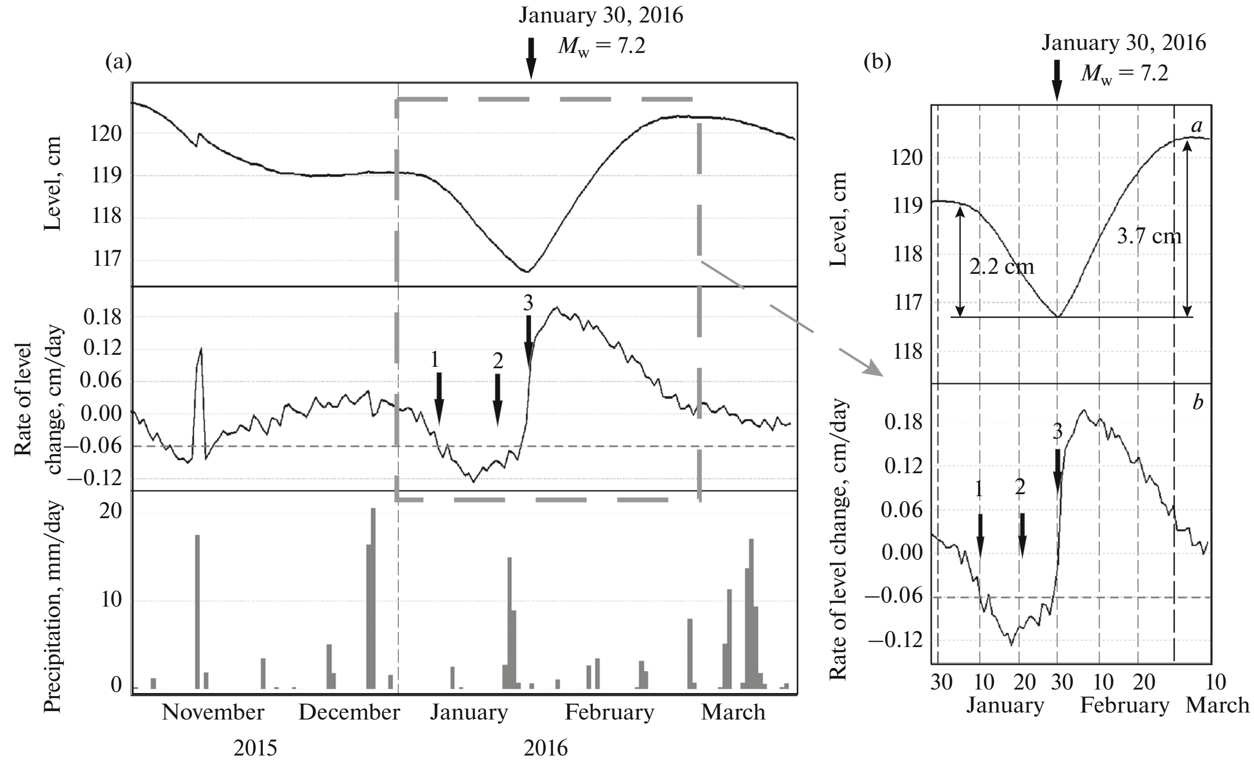

Fig. 8. Water level variations in the E-1 well during the Zhupanovo earthquake of January 30, 2016, M_w = 7.2. (a) Water level variations and its mean daily rate of change between November 2015 and March 2016 compared with precipitation. The plot of mean daily rate of change, the numerals: (1) January 10 is the start of the hydrogeodynamic precursor GP_I, (2) January 21 is the date of prediction statement submission of a high likelihood of a strong earthquake to the KB REC, (3) January 30 is the date of the Zhupanovo earthquake; the dashed line shows the threshold value of the rate of water level lowering, –0.06 cm/day; the bold dashed line encloses that fragment of water level variations during the Zhupanovo earthquake shown in Fig. 8b: *a* water level changes from December 30, 2015 to March 10, 2016 that contain the hydrogeodynamic precursor and the postseismic rise, *b* the change in the mean daily rate of water level variation compared with its threshold value, –0.06 cm/day.

Zhupanovo earthquake of January 30, 2016, M_w = 7.2, intensity $I = 5$, $d_e = 90$ km, hypocenter distance 200 km (ZhE) was accompanied by coseismic and postseismic variations in the water level changes at the YuZ-5 and E-1 wells, and also hydrogeodynamic precursors (Figs. 7c, 8) were registered before the ZhE , (see Fig. 2a).

An anomalous rise of water level by at least 20 cm was observed at the YuZ-5 well during 3.5 months before the ZhE. This was a serious disturbance to the annual seasonal behavior. This water level rise was identified as a hydrogeodynamic precursor to the ZhE (see Fig. 7c) (Boldina and Kopylova, 2017).

The arrival of seismic waves due to the ZhE was followed by water level rising during 45 minutes with amplitude $\Delta h = 9.4$ cm (see Fig. 7b) due to superposition of a coseismic rise of groundwater head and a corresponding step in water level at the well combined with an impulsive rise of pressure near the wellbore during seismic shaking. The estimated amplitude of the coseismic rise of water level ($\Delta h = 7.3$ cm) and of the corresponding compression in water-bearing rocks $D_1 = -4.5 \times 10^{-8}$ as inferred from water level observations were consistent with the estimated volume coseismic deformation in the area of the well according to the model of a dislocation source in a homogeneous elastic half-space with the parameters of ZhE source mechanism ($D_2 = -4.6 \times 10^{-8}$).

After the ZhE, the water level was subsiding during 3 months with amplitude Δh = ~40 cm (see Fig. 7c) due to a head drop in the aquifer caused by improved filtration properties of the water-bearing rocks due to seismic shaking.

The occurrences at the E-1 well were a hydrogeodynamic precursor GP_I during 21 days before the ZhE and a water level rise of amplitude 3.7 cm during 1 month after the earthquake (see Fig. 8). The water level lowering had amplitude $\Delta h = -2.2$ cm during all that time at a mean daily rate of –0.06 to –0.12 cm/day (see Figs. 8a and 8b, part b).

The precursor GP_I that was detected in real time was used to develop and transmit to the KB REC a forecast of a high likelihood of a strong earthquake within 350 km of the E-1 well to be expected during 1 month. The ZhE was consistent with the forecast as regards its magnitude, time of occurrence, and location (Chebrov et al., 2016).

The **third stage** also involved doing some research work, viz., developing models of the formation of various types of hydrogeoseismic water level variations in wells-hydrogeodynamic precursors, coseismic and postseismic variations (taking the YuZ-5 well as an example); the evaluating the informativity of observation wells for detection of hydrogeodynamic precursors of earthquakes and quantitative estimation of water-bearing rocks deformation (G.N. Kopylova and S.V. Boldina).

The results from all technical and research effort during the third stage of our hydrogeoseismological studies constitute the scientific methodological base for a new method of monitoring the modern geodynamic processes and for earthquake prediction in the Kamchatka seismic region using hydrogeological data.

CONCLUSIONS

The most valuable results from multiyear continuous observations at the network of observation wells installed in the Petropavlovsk Geodynamic Test Area consist in the acquisition of reliable data concerning hydrogeologic precursors in the form of changes in groundwater physical and chemical parameters that occur before strong (M = 6.6–7.8) earthquakes in Kamchatka. The totality of these data constitutes a scientific feasibility study for the use of the hydrogeologic method in geophysical monitoring and earthquake prediction in the Kamchatka seismic region.

The emerging connection between the occurrences of hydrogeochemical and hydrogeodynamic precursors on the one hand and the earthquake parameters on the other was used to propose methods for intermediate-term estimation of the times of strong Kamchatka earthquakes (with magnitudes greater than 7) based on current observations. These methods are employed in practical work at the councils on earthquake prediction that are currently active in Kamchatka Krai.

The observations at the E-1 well were used to develop forecasts for several strong earthquakes of 2004–2016, including the February 28, 2013 earthquake and the Zhupanovo earthquake of January 30, 2016, with advance times between a few days to 1 month.

The observations at the YuZ-5 well were used to estimate volume coseismic deformation in water-bearing rocks in the range between a few 10^{-9} and 1×10^{-7}.

In addition, we obtained important scientific results that provide a basis for further development of hydrogeoseismological research in Kamchatka. These results are as follows:

the development of a system specializing in hydrogeologic observations at wells conducted by the KB GS RAS in near real time and aiming at fast detection of hydrogeoseismic changes in the variations of groundwater physical and chemical parameters, including hydrogeologic (hydrogeochemical and hydrogeodynamic) precursors to strong local earthquakes;

the development of information resources for hydrogeoseismological research in Kamchatka as part of a continually updated data base accumulating observations at the network of wells and springs in the Petropavlovsk Geodynamic Test Area for the observation period from 1971 until the present; data on observation wells and published texts that contain systematic descriptions of hydrogeologic effects that occurred during earthquakes (see http://www.emsd.ru/lgi/result).

The databases, which contain specialized hydrogeologic observations in Kamchatka for a 40-year period and the data on variations in groundwater physical and chemical parameters that occurred during past earthquakes, including data on hydrogeologic precursors, are unique. They can be used to pose new scientific and applied problems in an in-depth study of seismicity as it affects groundwater, and to develop new methods of earthquake prediction using hydrogeologic data.

The success of hydrogeoseismological research in Kamchatka depends on continuing acquisition of reliable data on various responses of groundwater to seismic excitations, on hydrogeologic precursors in the first place, on the patterns that govern their occurrence, and on their relationships to the parameters of strong earthquakes.

The other important lines of research include:

the study of the processes that generate hydrogeologic precursors and other seismicity-induced effects in various natural and combined manmade–natural systems such as well–water-bearing rock, the system where water, rock, and gas interact etc. using simulation techniques;

further technical development of the system specializing in hydrogeologic observations in Kamchatka.

It should also be noted that the data acquired during the 40-year period of observation at wells and springs in Kamchatka are widely required. They formed the basis for dozens of publications in leading reviewed journals in Russia and abroad and for four Cand-Sci. dissertations (G.N. Kopylova, G.V. Ryabinin, E.A. Zapreeva, and S.V. Boldina), two D-r Sci. dissertations (A.A. Lyubushin in 1996 and G.N. Kopylova in 2010). Diploma theses have been prepared by graduates from the Vitus Bering Kamchatka State University, Kamchatka State Technical University, Moscow University, Tomsk Polytechnical University, etc.

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