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Water-Level Changes in the Wells of Kamchatka at the Time of the M_w 7.6, April 20, 2006 Olyutorskii Earthquake

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Abstract—The seismic waves excited by the M_w 7.6 Olyutorskii earthquake that occurred on April 20, 2006 in the Koryak Upland gave rise to water-level changes in five wells situated in continental areas of Kamchatka at hypocentral distances of 750–1150 km. We describe the effects due to seismic waves, as well as the water-level anomalies for February–April 2006 before the earthquake. We used an original technique for the processing of water-level records based on the study of barometric and tidal water-level responses in order to estimate the volume strain in water-saturated rocks during synchronous level variations at two wells. We discuss possible mechanisms for producing anomalous water-level changes due to elastic deformation of monitored groundwater reservoirs and to crack dilatancy in the water-saturated rocks.

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INTRODUCTION

Water-level observations in piezometric wells involve simultaneous recording of water-level and air-pressure variations; such observations are generally considered as an effective method for monitoring the stress and strain in the upper crust [2, 4, 12]. The special focus on such geophysical observations to be conducted in seismic regions is due to the fact that water-level variations contain several changes caused by the passage of seismic waves, as well as the hydrological precursors of large earthquakes [2–5, 12]. At the same time, the question as to a quantitative estimation of strain in water-saturated rocks based on water-level measurements remains debatable.

A crustal M_w 7.6 earthquake occurred in the Koryak Upland at 23 h 25 min UT, April 20, 2006 (Fig. 1a). The epicenter coordinates are 60.98° N, 167.37° E, and a depth within 1 km. The earthquake caused shaking of intensities as high as VIII–IX on the MSK-64 scale at population centers of the Koryak Autonomous Okrug and was followed by numerous aftershocks, with four of these having magnitudes equal to or greater than 6 [8].

No specialized well observations were conducted in the epicentral area of the Olyutorskii earthquake because no observational network was available north of 56° N. According to the observations of T.K. Pinegina and T.G. Konstantinova who investigated the epicentral area [11] and to reports of local residents, the earthquake was accompanied by mass seismogeological occurrences in the shape of liquefaction (thixotropy) and eruption of water-saturated rocks producing peculiar landforms ("mud volcanoes"). Cracks and collapses formed on the ground surface, which discharged and squeezed out loose water-saturated material. Some mud discharges occupied areas of a few square kilometers. Residents in the village of Talovka, 120 km from the epicenter, reported turbid water coming into the plumbing system from intake wells long after the earthquake. These facts point to a considerable impact of the Olyutorskii earthquake on the upper horizons of the underground hydrosphere in the epicentral area.

We discuss water-level variations in Kamchatka wells (Fig. 1, Table 1) during the Olyutorskii earthquake in order to evaluate its effects on groundwater and to search for possible hydrologic precursors. Some attention is paid to identified anomalous water-level changes and to a quantitative estimation of strain in water-saturated rocks during these changes. To do this we use an original technique based on the study of barometric and tidal responses of the water level in wells [6].

THE WELLS AND THE DATA PROCESSING TECHNIQUE APPLIED TO WATER-LEVEL MEASUREMENTS

The observing wells are situated in continental areas of Kamchatka at distances of R = 748–1150 km from the instrumental hypocenter of the Olyutorskii earthquake. The depths to water-saturated rocks range between 28–40 m (well 1306) and 310–800 m (well YuZ-5) (Fig. 1b).

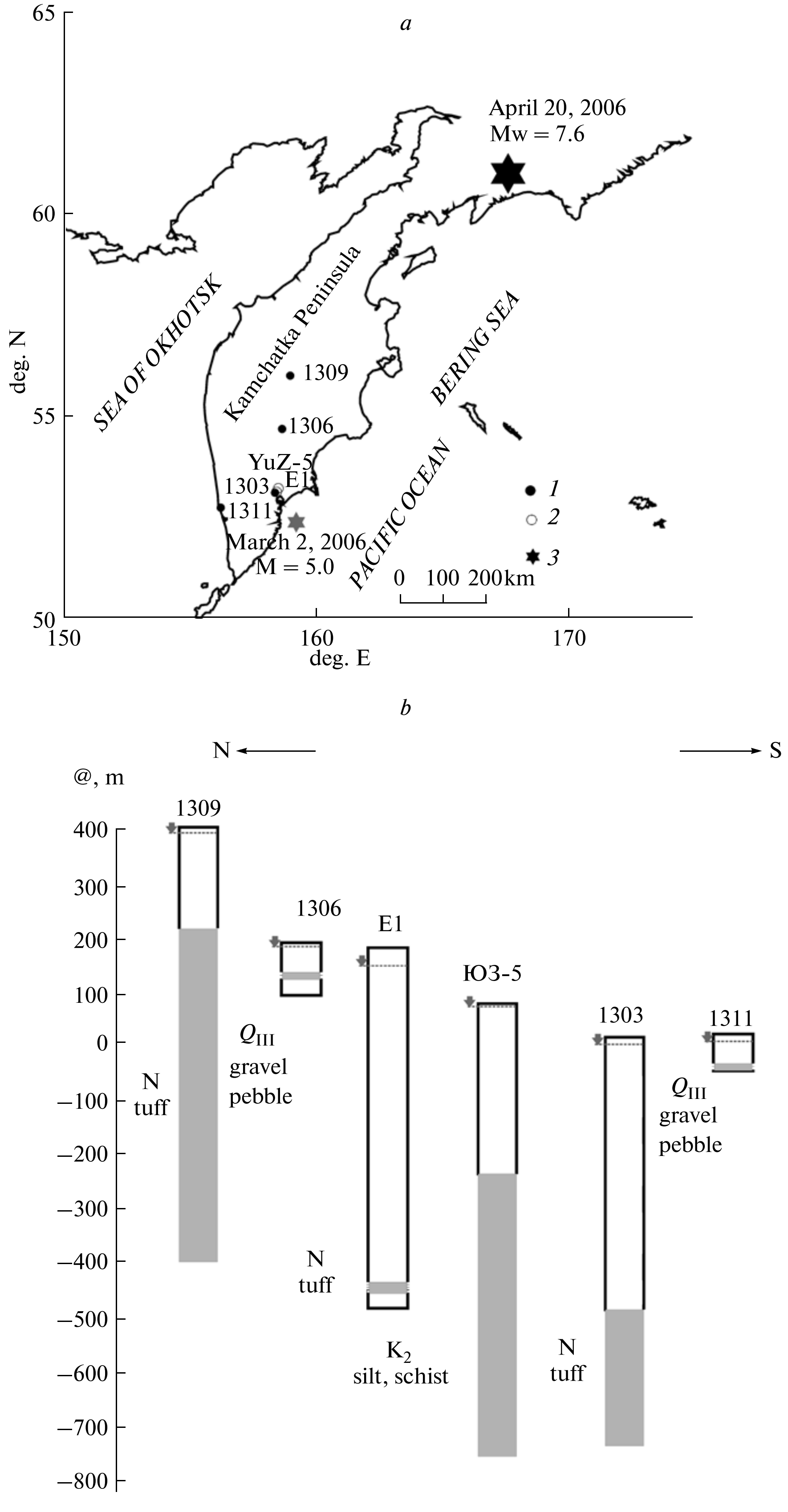

Fig. 1. Positions of observing wells (*a*) and their structures (*b*): (*1*) wells of the OAO Kamchatgeologiya, (*2*) wells of the KB GS RAS, (*3*) earthquake epicenters.

Table 1. Characteristics of observing wells

Well#	Coordinates, deg.		Absolute altitude, m; depth, m; level, m	Depth interval penetrated, m	Aquifer rocks; transmissivity, m^2/day	Fluid parameters			
	N	E				M, g/l	Chemical composition	Ga	T, deg., C
1303	53.15	158.35	31; 717; 25	517–717	$N_2–N_1^2$ tuffstone; 0.32	0.67	$(HCO_3–SO_4)/Na$	none	4.7
1306	54.73	158.63	200; 100; 11	28–41	Q_{IV} gravel–pebble deposits;1451	1.5	$HCO_3/(Ca + Mg)$	@? CO_2	2.0
1309	56.05	158.95	406; 750; 4	223–750	N_{al} tuff; 75	1.5	$SO_4/(Na + Ca)$	none	6.6
1311	52.79	156.20	20; 80; 12	67–69; 70–73	Q_{IV} rubble gravel deposits; 165	0.18	$(HCO_3–Cl)/$ $(Mg–Ca, Na)$	none	4.0
YuZ-5	53.17	158.41	70; 800; 1.5	310–800	$\hat{E}_2$ silt; 7.8	0.4	$(HCO_3–SO_4)/(Na–Ca)$	none	14.0
E1	53.26	158.48	180; 665; 29	625–645	N_2, tuff; 0.005	1.5	$(Cl–HCO_3)/Na$	@ $N_2–CH_4$	10.0

The water-saturated rocks consist of Neogene tuffaceous sedimentary deposits (wells 1303, 1309, and E1), Late Cretaceous terrigenous metamorphic deposits (well YuZð5), and by Quaternary formations (wells 1306 and 1311). The values of hydraulic conductivity in the groundwater reservoirs vary over a wide range (0.005–1451 m^2/day) as found from pumping tests (Table 1). The coupling of wells 1309, 1303, and YuZ-5 to water-saturated rocks is via open parts of the wells and through aperture filters in wells 1306, 1311, and E1.

Water-level observations at these wells are being conducted by the Kamchatgeologiya Company and by the Kamchatka Branch of the Geophysical Service of the Russian Academy of Sciences (KB GS RAS) using Kedr A2 self-contained digital recorders (Polinom Ltd., Khabarovsk) equipped with ultrasonic level sensors and air-pressure sensors. This observational arrangement provides 0.1 cm sensitivity for water-level variations and 0.2 hPa for air-pressure measurements. The sampling interval was 10 min at the KB GS RAS wells, 1 h (well 1306) and 10 min (1303, 1311, 1309) at the Kamchatgeologuya wells. We used records of water-level variation and air pressure obtained in January–April 2006.

The technique used for data processing of water-level measurements was developed at the KB GS RAS and includes the following steps [4, 6]:

Cross-spectral analysis of water-level and air-pressure time series was performed in order to estimate the parameters in the statically confined barometric response of the water level (squared modulus of coherency spectrum, barometric efficiency, the phase difference between water-level and air-pressure variations $\Delta\varphi$) and the range of periods where that response is observed;

A tidal analysis of hourly water-level time series was performed using the ETERNA 3.0 program package [14] for estimating the tidal sensitivity of water level A_v with respect to the theoretical volumetric strain;

Compensation of the barometric variation in water-level measurements based on estimated complex-valued air-pressure-to-water-level transfer function was made [9]; identification of earthquake-related changes in the trend and the high-frequency component of the water-level variation using digital data filtering was performed.

In [1, 4, 6, 12, 13] a statically confined water-level response to barometric and tidal excitations was considered to be an important indicator of the content borne by water-level observations for detecting changes in the stress

Table 2. Results from barometric and tidal analysis of water-level variations based on observations of Kamchatka wells in January–April 2006

Well	Results from cross-spectral analysis of water-level and air-pressure variations			Results from tidal analysis of water-level variations	
	Squared coherence spectral modulus	Barometric efficiency, cm/hPa	Phase difference, $\Delta\varphi$, deg	Identified waves after [10]	Tidal sensitivity of water level A_v, cm/10^{-9}
1303	0.85	0.43	−178	O_1, N_2, M_2, S_2K_2	0.214
1306	0.80	0.20	−162	–	–
1309	0.79	0.45	−166	O_1, N_2, M_2, S_2K_2	0.099
1311	0.14	0.18	−170	O_1, N_2, M_2, S_2K_2	0.300
YuZ-5	0.92	0.39	−179	$Q_1, O_1, 2N_2, N_2, M_2, S_2K_2$	0.158
E1	0.50	0.01	−106	–	–

and strain of the crust. The fact that such a response occurs shows that the well under study has reached a groundwater reservoir in which the hydraulic coupling with unconfined groundwater and with other water-saturated horizons is insignificant compared with pore pressure changes resulting from strain in the reservoir. The range of periods where the response is observed is found from the straight segment of the frequency-dependent coherency function and of the amplitude transfer function, which transforms air-pressure changes into water-level changes [5, 7]. In this range one can neglect water flow in the reservoir and the inertia in the water exchange between the well and the groundwater reservoir; that is, the response of the well-water level to pore-pressure changes in this range is not distorted by water-exchange processes. The statically confined water-level response is related in a linear manner to the strain in the water-saturated rocks and is controlled by the reservoir's elastic parameters [1, 12, 13]. If an area of study has wells with statically confined water-level responses, it becomes possible to quantitatively evaluate the seismotectonic strain based on the amplitudes of hydrodynamic precursors, coseismic level changes, and other geodynamic effects due to quasi-elastic deformation of groundwater reservoirs. The water-level changes observed at wells 1303, YuZ-5, 1306, and 1309 clearly show barometric responses at periods of a few hours to a few tens of days (Table 2). For these wells we hypothesize that statically confined conditions exist in tapped groundwater reservoirs over the range of periods from a few hours to a few days to a few tens of days. These responses are strongly distorted for wells E1 and 1311; for the former this is owing to the presence of free gas in the pore fluid [4] and for the latter it is due to the distinct effect of tidal loading on water-level changes (well 1311 is 1.5 km distant from the coast of the Sea of Okhotsk).

A water-level response to earth tides with 4–6 individual diurnal and semi-diurnal waves identified was found for wells 1303, 1309, and YuZ-5 (Table 2). This shows that the water level in these wells can react to elastic strain of groundwater reservoirs at amplitudes of a few 10^{-9} to a few 10^{-8} at the diurnal and semi-diurnal periods. The tidal sensitivities of water level A_v for these wells were estimated from the water-level amplitudes in the diurnal and semi-diurnal wave groups as dependent on the corresponding theoretical strain to be 0.099–0.214 cm/10^{-9}.

The absence of a tidal water-level response at well E1 is due to increased compressibility of the pore fluid because of free methane–nitrogen gas present in it [3]. For well 1306 we also assume the presence of a gas phase in the pore fluid. The strong distortion of tide-caused water-level variations at well 1311 is due to the influence of tidal excitation on the shaping of the hydrodynamic regime. The oceanic tide contains waves that are similar to solid-earth waves in their periods, but which have different phases [10]. This variable loading due to oceanic tide explains the overestimated tidal sensitivity for well 1311 ($A_v = 0.300$ cm/10^{-9}) derived from our tidal analysis using the ETERNA 3.0 package.

The Seismicity of Eastern Kamchatka in January–April 2006. An analysis of the distribution of $K_s \geq 12.0$ ($M \geq 4.0$) earthquakes in the Benioff zone of Kamchatka in the latitude band 51°–60° N for the period January–April 2006 showed that the nearest earthquake to the observing wells was that of March 2, 2006 ($K_s = 12.4$, $M = 5.0$, epicenter coordinates 52.42° N, 159.19° E, depth 37 km) (Fig. 1a). The epicentral distances to wells YuZ-5, 1303, and E1 were R = 105, 106, and 111 km, respectively. The event caused shaking of intensity II–IV (MSK-64 scale) in the town of Petropavlovsk-Kamchatskii. The other earthquakes (K_s = 12.1–13.2, M = 4.2–6.0) occurred at much greater distances from the wells (318–815 km) and were not accompanied by shaking.

WATER-LEVEL CHANGES IN THE OBSERVING WELLS DURING THE PERIOD OF THE OLYUTORSKII EARTHQUAKE

Figure 2 shows the results from the processing of observations made at the nearest (to the epicenter) well, 1309 (R = 748 km). We consider the time interval April 11–30, which covers the Olyutorskii earthquake. The water-level changes involve barometric and tidal variations, as well as fragments of the seasonal trend. Figure 2 also shows a water-level series with compensated barometric variations using the algorithm form [9] and a low-frequency trend. The trend was identified by filtering the "compensated-level time series, removing the spectral components at periods of 7–13 and 23–30 h using an ideal filter. Below that we present time series of precipitation and air temperature based on observations made at the Pionerskaya weather station of the Kamchatka Agency for Hydrometeorology and Environmental Control.

The variations in the "compensated level" and "trend" time series clearly exhibit a water-level drop of 10 cm amplitude lasting 4 days after the earthquake. The drop was caused by the passage of seismic waves excited by the Olyutorskii earthquake and indicates a temporary lowering of fluid pressure in the groundwater reservoir being monitored. The mechanism responsible for this level lowering might involve a depression of fluid pressure due to a local increase in the permeability of water-saturated rocks near the well during seismic shaking [1]. The level began to recover itself from April 25 with a superimposed increasing seasonal trend due to the incipient spring recharge of groundwater. No anomalous water-level changes were observed before the earthquake.

Figure 3 shows the trends identified in the hourly water-level variations in all the six observing wells. Figure 4 shows water-level variations due to the Olyutorskii earthquake at a sampling rate of 10 min in four wells; these provide a clearer idea of the character of the variations.

The seismic waves excited by the Olyutorskii earthquake are seen to cause clear-cut water-level changes in wells 1309, 1306, and YuZ-5 (Fig. 3). A 2-day water-level lowering of 3 cm amplitude was observed in well 1306. That the level drop was so rapid during the first 4 hours after the earthquake can be explained by a more intensive decrease in the pore pressure near the well and a lesser decrease at some distance from the well. It may be hypothesized that the passage of seismic waves tended to clean the short perforated filter in well 1306 from fine-grained fractions and to improve the hydraulic coupling between the well and the groundwater reservoir. No anomalous preseismic water-level changes have been identified.

A level rise of 1.3 cm amplitude and 2-day duration was observed after the earthquake in well YuZ-5 (Fig. 3); this rise can be explained by a short-lived increase in pore pressure in the groundwater reservoir. It was found from recordings at intervals of 10 min that the highest rate of level rise was observed during the first 30 min after the earthquake (Fig. 4). The April 17–20 water-level trend variation, i.e., during the 4 days before the Olyutorskii earthquake, showed a baylike change of 1 cm amplitude (highlighted by a grey horizontal bar in Fig. 3) which could have been caused by an extension of the water-saturated rocks.

The influence of the Olyutorskii earthquake on water-level variations in wells 1303 and 1311 is not identified in mean hourly data. However, the 10-min observations were found to contain weak effects in water-level variations due to the passage of seismic waves (Fig. 4). It should be noted that the water-level trend behavior in well 1303 was found to contain a lowering of 2 cm amplitude between April 17 and 20 (Fig. 3), which can have been caused by extension of water-saturated rocks (similarly to the area of well YuZ-5).

ANOMALOUS WATER-LEVEL CHANGES IN JANUARY–APRIL 2006 AND THE ESTIMATION OF STRAIN IN WATER-SATURATED ROCKS

Long-term observations in well E1 revealed a "warning indicator," which manifests itself as greater rates of water-level decrease before large earthquakes [3, 7]. The mechanism of such level drops is thought to be due to crack dilatancy developing in water-saturated rocks during the precursory periods of earthquakes, increasing capacity of these rocks, and decreased pore pressure [5].

A water-level lowering at an increased rate ($\leq$–0.1 cm/day) was observed during 14 days, from February 16 to Match 2, 2006. This period of time was terminated by an earthquake (March 2, 2006, M = 5.0) at a hypocentral distance of 111 km from well E1 (Figs. 1a, 5).

Synchronous water-level changes were also identified in closely spaced wells, 1303 and YuZ-5, from February 1 to March 2 (Fig. 1a). Figure 6 presents mean hourly variations in water level with compensated air pressure, as well as spectral components of level variation in both wells at periods of 2–45 days (48–1080 h). Bandpass filtering in a window of 1/48–1/1080 h^{-1} has removed tidal variations and (partly) the seasonal trend from the water-level time series.

Synchronous water-level changes were observed in both wells from February 1 to March 2: a lowering of amplitude H_1 = –5 cm and –4.8 cm during February

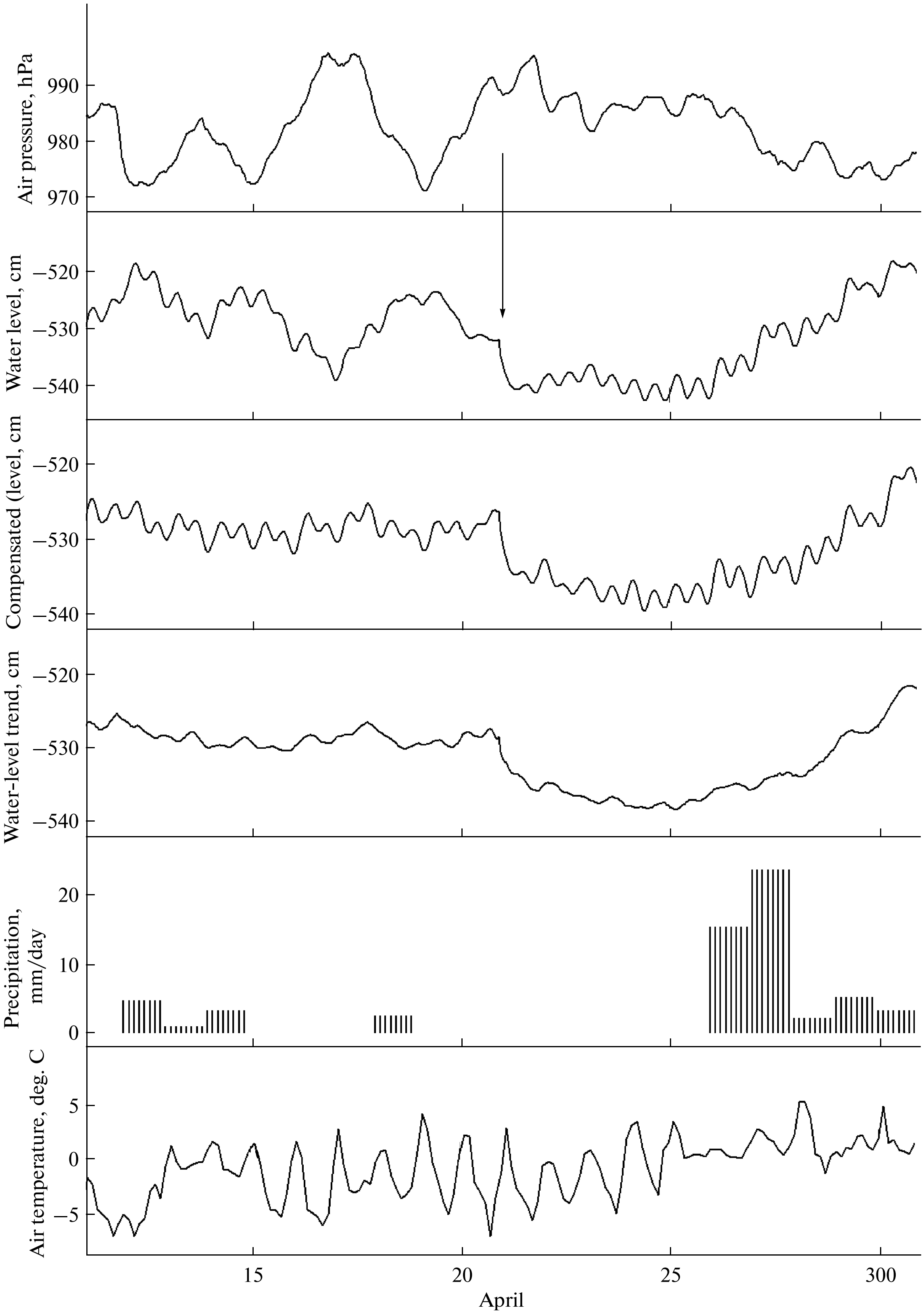

Fig. 2. Water-level changes in well 1309 in April 11–30, 2006 compared with meteorological observations. Arrow marks the occurrence time of the Olyutorskii earthquake.

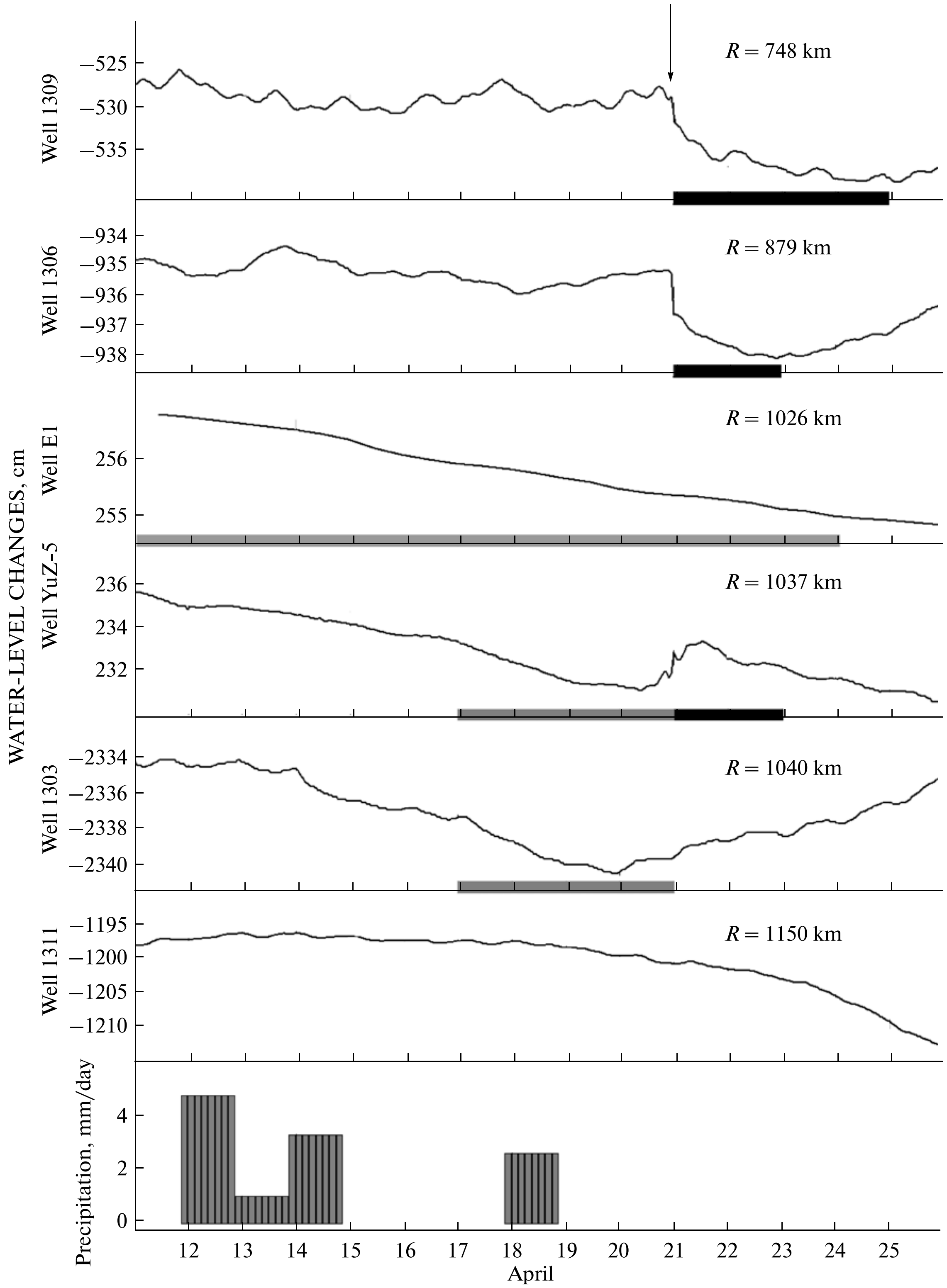

Fig. 3. Water-level variations in observing wells during the period of the Olyutorskii earthquake of April 20, 2006 ($M_w = 7.6$) (marked by an arrow). Black horizontal bars mark the time intervals of postseismic water-level changes, grey horizontal bars mark the water-level variations before the Olyutorskii earthquake. *R* is hypocentral distance to a well.

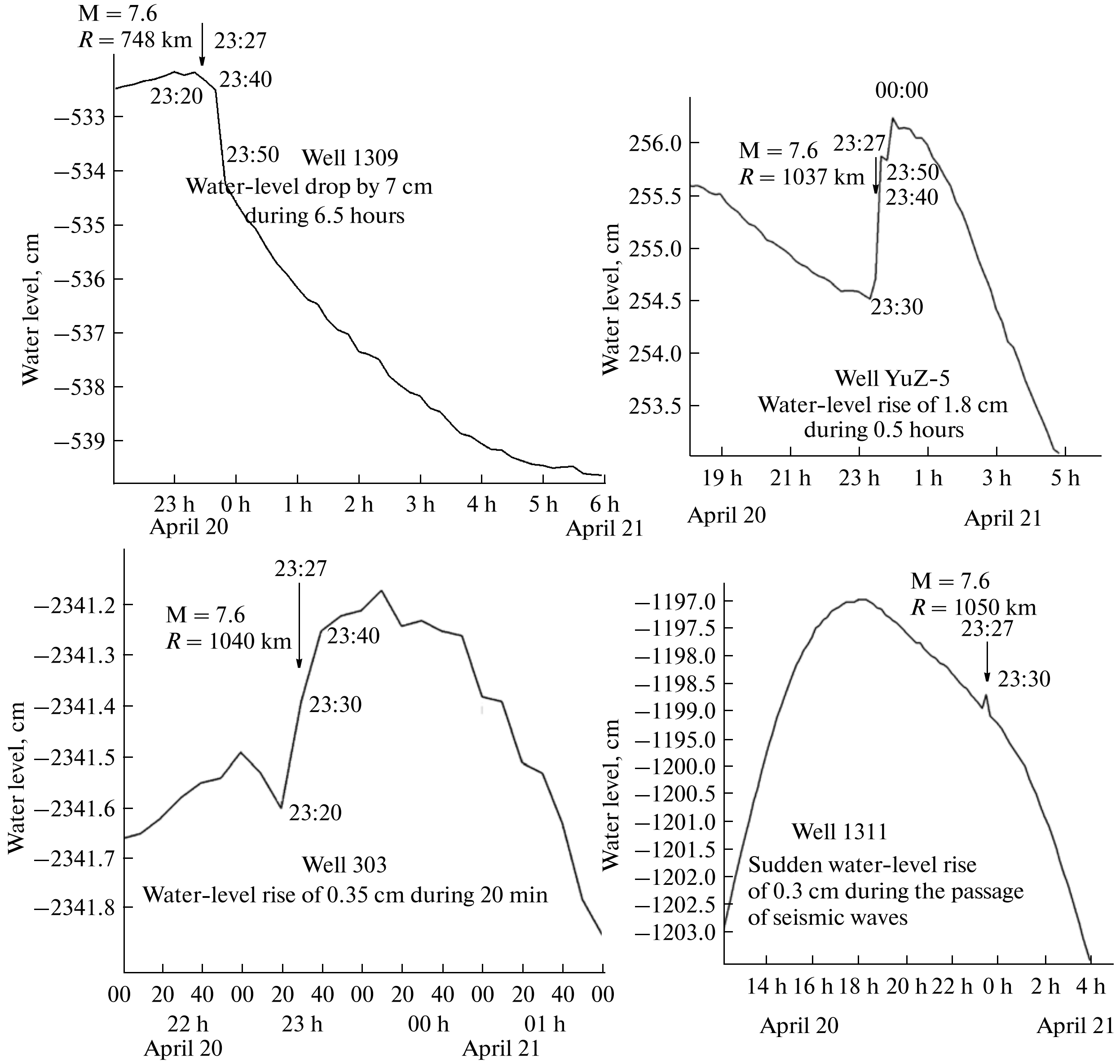

Fig. 4. Water-level changes in wells 1309, YuZ-5, 1303, and 1311 due to the passage of seismic waves excited by the Olyutorskii earthquake based on data sampled at 10-min intervals. *R* is hypocentral distance to a well.

1–12 and a rise of amplitude H_2 = 9 cm and 8.8 cm between February 13 and March 2 (Fig. 6, Table 3). This level change can be explained by an ongoing extension of the water-saturated rocks that was later replaced by compression. The strain values D_v as estimated from the amplitudes of water-level variation H_1 and H_2 (Fig. 6) normalized to tidal sensitivity A_v by the formula $D_v = -H/A_v$ were 3.2×10^{-8} and -5.7×10^{-8} in the YuZ-5 area and 2.2×10^{-8} and -4.1×10^{-8} in the well 1303 area (Table 3).

Immediately before the Olyutorskii earthquake (April 17–20) a synchronous lowering of water level was observed in wells 1303 and YuZ-5 upon the background of a downward trend with amplitudes H = –2 cm and –1 cm, respectively. These level drops are highlighted by horizontal grey bars in Fig. 3. The extensional volume strain D_v is 0.9×10^{-8} for well 1303 and 0.6×10^{-8} for YuZ-5 (Table 3). A “warning indicator” appeared in well E1 between April 4 and 24 (21 days); this was a water-level drop at an increased rate (Figs. 3, 5).

The great distances between the Olyutorskii earthquake and the wells (*R* = 1026–1040 km) make it unlikely that there was a relationship between the observed “warning indicator” in well E1 and the baylike level drops in wells 1303 and YuZ-5 and the precursory process of the earthquake, which were seen as aseismic movements in

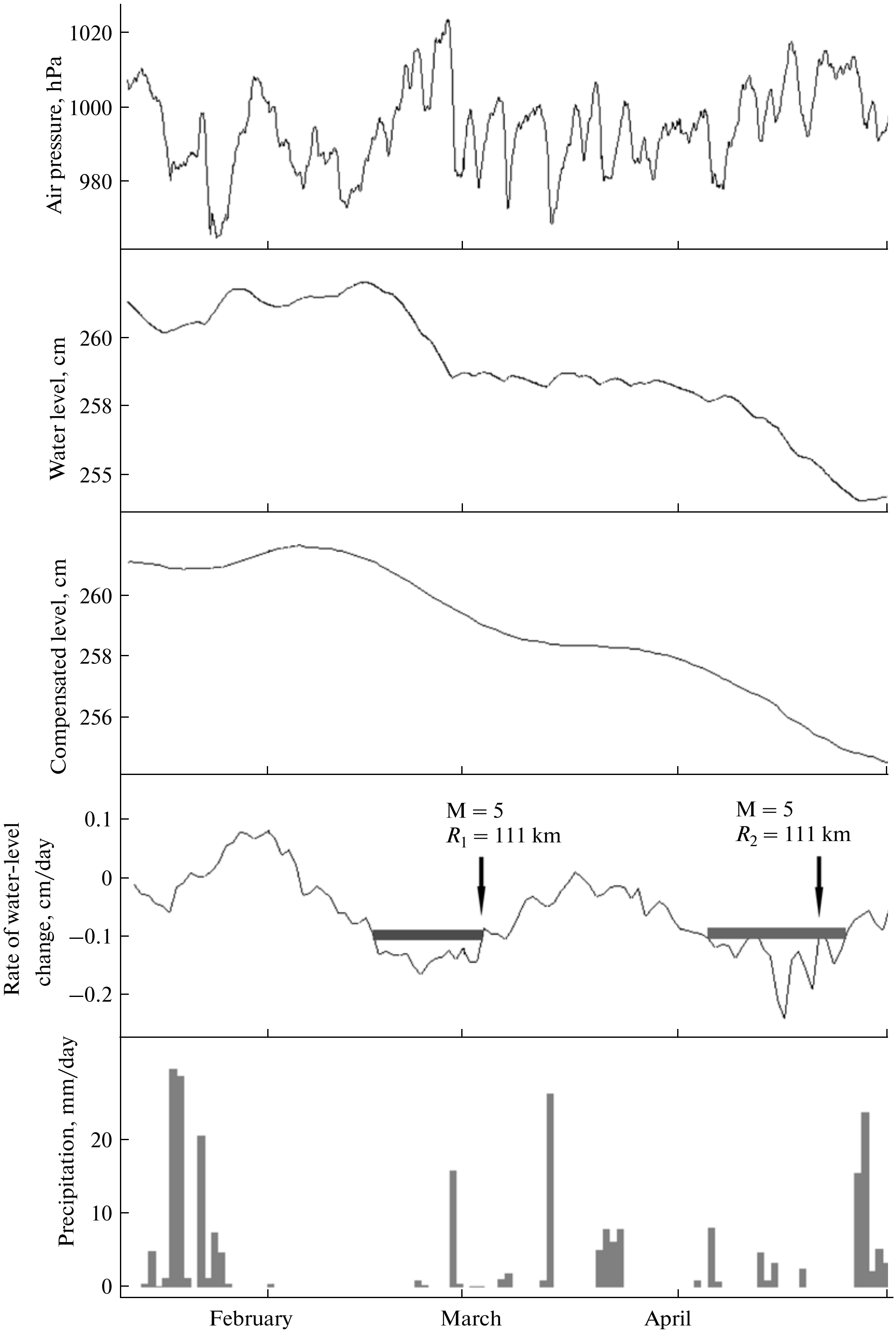

Fig. 5. Water-level changes in well E1 in January–April 2006. The time intervals of the "warning indicator" are marked by black horizontal bars. R_1 is hypocentral distance to the hypocenter of the March 2, 2006 earthquake, R_2 is same for the Olyutorskii earthquake.

Table 3. Anomalous water-level changes in wells YuZ-5, 1303, and E1 in January–April 2006 and estimated volume strain for aquifers

Well	Tidal sensitivity of water level to theoretical volume strain $A_{v,}$ cm/10^{-9}	Time interval of anomalous water-level change	Amplitude of level change, *H*, cm	Volume strain, D_v, 10^{-8}
YuZ-5	0.158	February 2–1	−5	3.2
		February 12–March 2	9	−5.7
		April 17–20	−1	0.6
1303	0.214	February 1–12	−4.8	2.2
		February 13–March 1	8.8	−4.1
		April 17–20	−2	0.9
E1	–	February 16–March 2 April 4–24	Manifestation of "warning indicator": increased rate of water-level lowering £0.1 cm/day	

the future rupture zone. It is quite probable, however, that such water-level changes in three wells in April 2006 could be caused by changes in the stress and strain of the groundwater reservoirs being monitored.

DISCUSSION OF RESULTS

The Olyutorskii earthquake excited seismic waves which caused water-level changes in wells 1306, YuZ-5, 1309, and 1311 (Figs. 3, 4). The corresponding time intervals are marked by black horizontal bars in Fig. 3. The changes were recorded both in the mean hourly variations and in the 10-min data for wells 1309, 1306, and YuZ-5; and in 10-min data only for wells 1303 and 1311. The wells that were nearest to the epicenter (1309 and 1306) showed water-level drops, while short-lived rises of water level were observed at the more distant wells (YuZ-5 and 1303).

Such water-level changes can be explained by changes in pore pressure due to the deformation of water-saturated rocks during the passage of seismic waves. The most likely mechanism responsible for this pore pressure change is a local change in the permeability of the water-saturated rocks and possibly in the percolation connections inside the well–reservoir system or inside the groundwater reservoirs being monitored. The character of the water-level changes (rise or drop) may have been due to the character of seismic signals coming to the wells (their amplitude–frequency content). The changes in the hydrodynamic behavior of the wells lasted from 2–4 days to a few hours or minutes. The amplitudes of water-level changes did not exceed 10 cm.

Taken on the whole, the Olyutorskii earthquake did not exert any considerable influence on the behavior of the Kamchatka wells. At the same time, the presence of such variations in water level caused by the passage of seismic waves excited by a large distant earthquake indicates that these variations should be taken into account when interpreting water-level observations during the search for precursors of Kamchatka earthquakes.

The grey horizontal bars in Fig. 3 mark the water-level changes in wells YuZ-5, 1303, and E1 before the Olyutorskii earthquake. Well E1 showed a water-level drop, which occurred at an increased rate during April 4–24, while baylike water-level drops were observed in wells YuZ-5 and 1303 during the period April 17–20. We do not believe that these changes were related to preseismic movements in the Olyutorskii earthquake rupture zone because of the great epicentral distances (R = 1026–1040 km), but they might have been caused by local strain and stress changes in the groundwater reservoirs being monitored.

Some anomalous changes were also observed in the water-level variations at three closely spaced wells (YuZ-5, 1303, and E1) during the period from February 1 to March 2 (Figs. 5, 6). These might be related to the development of aseismic movements in the adjacent part of the Benioff zone of Kamchatka. A magnitude 5 earthquake occurred at the end of the anomalous period (March 2). In that case the water-level variations in the three wells can be considered as a water-level precursor of the earthquake.

The amplitudes H_1 and H_2 (Fig. 6) and the values of water-level tidal sensitivity in wells YuZ-5 and 1303 (A_v) were used to estimate the volume strain of the water-saturated rocks D_v (Table 3). The estimated extension and compression in the YuZ-5 area are systematically greater than the respective values for the area of well 1303. This may be related to the greater distance between well 1303 and the stress concentration volume that caused the extension–compression succession. From this it follows that the stress concentrator was situated east of wells 1303 and YuZ-5, that is, in the adjacent part of the Benioff zone.

Unambiguous statement of a relationship (or the absence of such a relationship) between the above water-level anomalies in wells YuZ-5, 1303, and E1 in February–April 2006 and the precursory process of the Oly-

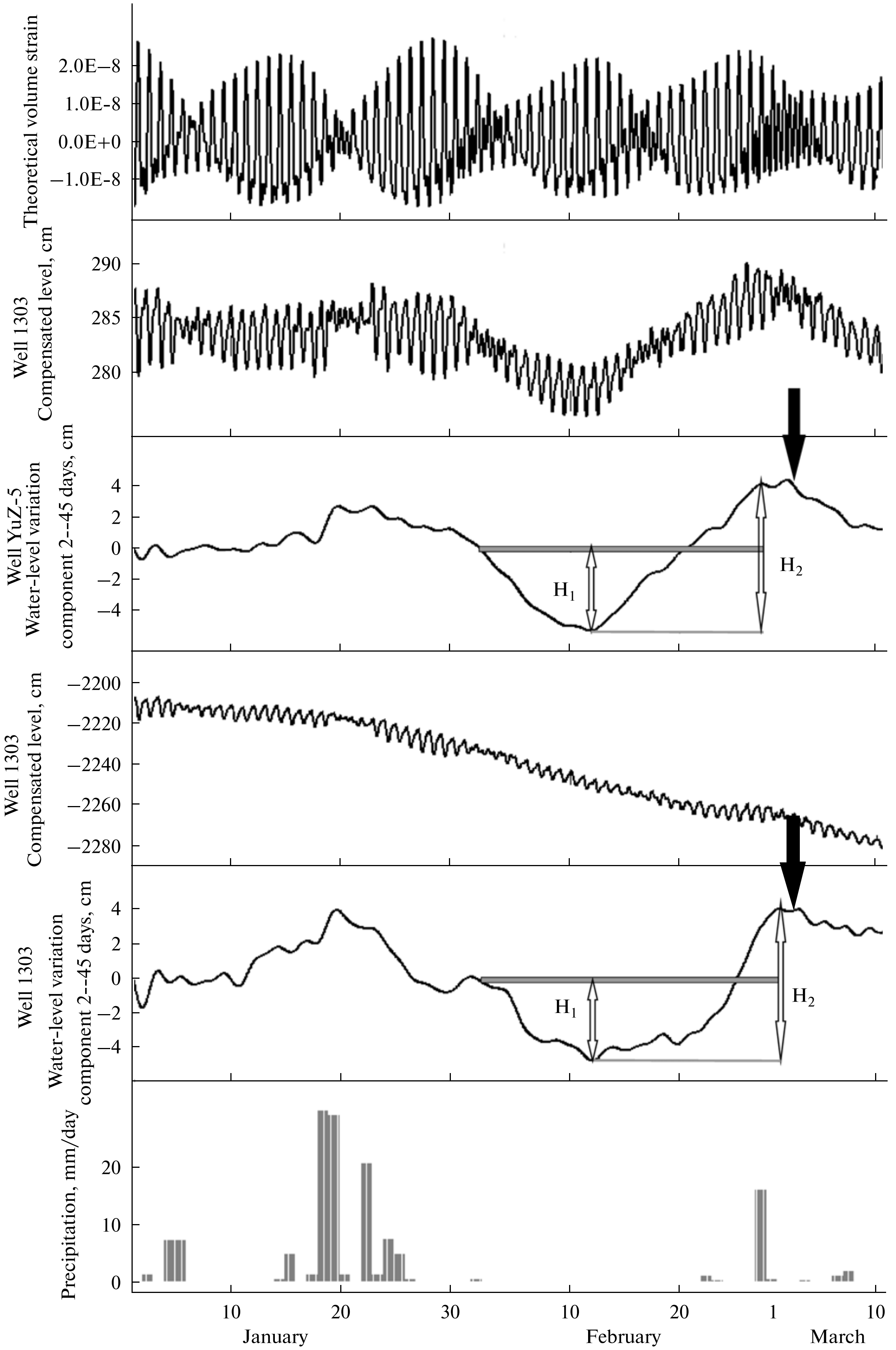
Theoretical volume strain
2.0E−8
1.0E-8
0.0E+0
−1.0E-8
Well 1303
Compensated level, cm
290
285
280
Well YuZ-5
Water-level variation
component 2–45 days, cm
4
2
0
−2
−4
H_1
H_2
Well 1303
Compensated level, cm
−2200
−2220
−2240
−2260
−2280
Well 1303
Water-level variation
component 2–45 days, cm
4
2
0
−2
−4
H_1
H_2
Precipitation, mm/day
20
10
0
10
20
30
10
20
1
10
January
February
March

Fig. 6. Synchronous water-level changes in wells YuZ-5 and 1303 during the period from February 1 to March 2 (marked by grey horizontal bars0 compared with the variation of theoretical volume strain and precipitation. H_1 and H_2 are the amplitudes of water-level drop and rise, respectively. The occurrence time of the magnitude 5.0 March 2, 2006 earthquake is marked by an arrow.

utorskii earthquake seems premature, in the first place, because the rupture zone was so far away. Nevertheless, there are observations [3, 14] that show that water-level precursors may appear at great distances from an earthquake. The great distances of water-level precursors can be explained by increased strain sensitivity of some wells to earthquake precursory processes [2, 5, 12]. Such wells are commonly situated in zones with closely spaced aquifers that have different pore pressure values. If crack dilatancy develops in the intervening impermeable layers before an earthquake, the consequence is that the percolation connection between the aquifers is improved and the pore pressures equalize. That process may be accompanied by amplitude variations of water level in wells.

Testing of wells YuZ-5, 1303, and E1 combined with long-term routine observations does not qualify these wells as unique ones that show increased strain sensitivity. As to well YuZ-5, the only case of a water-level precursor being recorded was a baylike water-level drop of 11 cm amplitude during 3 weeks before the Kronotskii earthquake (December 5, 1997, $M_w = 7.8$, $R = 320$ km) [4]. The precursor can be explained by extension in aquifers with amplitude $\approx 0.75 \times 10^{-7}$ as intensive preseismic movements were developing in the rupture zone of the Kronotskii earthquake. The water-level variation in well E1 was a “warning indicator” prior to earthquakes at hypocentral distances within 320 km [3, 7]. These data demonstrate that the sensitivity of wells YuZ-5 and E1 to the precursory process of a large earthquake (M ~ 7–8) is restricted to a few hundreds of kilometers.

It should be noted that the appearance of anomalous water-level changes in three wells in February 2006 (Figs. 5, 6, Table 3) and the fact that these were simultaneous with the magnitude 5 earthquake of March 2 is unique. Earthquakes of this energy class occur frequently in that area and have not been preceded by anomalous water-level changes in wells YuZ-5 and 1303. This shows that the anomalous water-level changes in the three wells and, possibly, the earthquake of March 2, 2006 are manifestations of geodynamic processes that were activated in the adjacent part of the Benioff zone of Kamchatka. The temporal relationship between this activation and the precursory process of the Olyutorskii earthquake in the Koryak Upland may have been due to a worldwide process and requires verification by more extensive experimental data.

CONCLUSIONS

(1) The propagation of seismic waves excited by the Olyutorskii earthquake of April 20, 2006 ($M_w = 7.6$) caused postseismic water-level changes at five wells situated in continental areas of the Kamchatka Peninsula at hypocentral distances of 748–1050 km. The water level decreased at wells 1309 and 1306 (the nearest ones to the epicenter) during 4 and 2 days by 10 and 3 cm, respectively. At more distant wells (YuZ-5, 1303, and 1311) the water level rose during a few tens of minutes by 0.3–1.8 cm. Overall, the Olyutorskii earthquake did not exert any significant influence on the behavior of observing wells operated by the OAO Kamchatgeologiya and by the KB GS RAS.

(2) Special data processing methods were applied to these water-level observations, including the compensation of air pressure variations in water-level changes and the filtering of the time series with the air pressure variations eliminated; the result was the identification of anomalous water-level changes in wells YuZ-5, 1303, and E1, which were observed during periods before the Olyutorskii earthquake, viz., February 1 to March 2 and April 17 to 20, 2006.

This barometric and tidal analysis of water-level variations revealed the fact that wells YuZ-5 and 1303 are characterized by statically confined conditions from a several hours to several tens of days. This allows one to measure the amplitudes of the identified water-level variations in the range of periods indicated to estimate the strain of the aquifers. We quantitatively estimated the strain values from the identified water-level amplitudes and its tidal sensitivity with respect to theoretical volume strain (Table 3). The character of strain in the aquifers was estimated from the direction of water-level change.

In order to estimate the accuracy attainable with the method of local estimation of aquifer strain based on water-level observations it is necessary to carry out simultaneous recording of water level and the three strain components directly in the area of these wells. It is known from the literature that the accuracy attainable with this method of strain estimation in aquifers is of the order of 50% [12, 13].

(3) The possible relationship of the anomalous water-level variations in wells E1, YuZ-5, and 1303 in February–April 2006 to the precursory process of the Olyutorskii earthquake and of the magnitude 5 earthquake of March 2, 2006 may have been due to activated, mostly aseismic, geodynamic processes within the Benioff zone of Kamchatka. Feasible mechanisms for the anomalous water-level variations include the development of crack dilatancy in aquifers (well E1) and quasi-elastic extension and compression of the aquifers (wells 1303 and YuZ-5).

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