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SUBJECT AREAS:
GEOPHYSICS
HYDROGEOLOGYReceived
17 July 2014Accepted
13 October 2014Published
4 November 2014Correspondence and
requests for materials
should be addressed toY.O. (orihara@u-
gakugei.ac.jp)

Preseismic Changes of the Level and Temperature of Confined Groundwater related to the 2011 Tohoku Earthquake

Yoshiaki Orihara¹, Masashi Kamogawa¹ & Toshiyasu Nagao²¹Department of Physics, Tokyo Gakugei University, Japan, ²Earthquake Prediction Research Center, Tokai University, Japan.

Anomalous groundwater changes started three months before the 2011 M9.0 Off the Pacific coast of the Tohoku Earthquake (Tohoku EQ), Japan. Groundwater level and temperature decreased almost simultaneously in a 2000-m well at a spa, Goyo-onsen, in Iwate Prefecture, 155 km northwest of the epicenter. Since the source of Goyo-onsen, located above the edge of a coseismic rupture area of the Tohoku EQ fault, is probably confined, the observed anomalies were caused probably by preseismic crustal deformation. Preseismic groundwater anomalies have been observed prior to similar large subduction EQs such as the 1946 M8.1 Nankai EQ. Thus, monitoring confined groundwater may be useful to identify precursors of large subduction EQs.

There are many reports of anomalous changes of groundwater prior to large earthquakes (EQs). Wakita identified many cases of significant changes of groundwater level and muddiness at the 1975 M7.0 Haicheng, 1976 M7.5 Tangshan, and 1976 M7.2 Songpan Pingwu EQs, China¹. Sadovsky et al. reported a rise in the level and temperature of water in a well located 30 km away from the epicenter prior to the main shock of the 1970 M6.7 Przhevalsk EQ, Kyrgyzstan². In Japan, 17 eyewitness reports were made on the changes in the level and muddiness of groundwater in the western and eastern Shikoku 5–7 and 1–2 days before the 1946 M8.1 Nankai EQ, respectively³. Furthermore, a drop of the groundwater level and temperature at 30 km from the epicenter was reported a month and a half before the main shock of the 1978 M7.0 Izu-Oshima-Kinkai EQ⁴. The Sanriku region has suffered with many large EQs with great tsunamis such as the 1896 M8.5 Meiji Sanriku EQ, 1933 M8.1 Sanriku EQ (Figure 1 and Table 1)⁵. Preseismic changes of the level and muddiness of groundwater were reported in a number of wells prior to these EQs⁵. In general, these earthquakes were accompanied by not only preseismic changes but also by large coseismic offsets and post-seismic fluctuations of water level.

Various preseismic anomalies have been reported for the Tohoku EQ⁶. For example, a long-term seismic quiescence around the deeper edge of the coseismic rupture region had started 23.4 years before⁷. Tidally-induced stresses and small EQ occurrences around the epicentral region began up to ten years prior to the main shock, implying that the rupture area gradually approached a critical state⁸. The linear slope of the logarithmic cumulative number of EQs versus their magnitude (i.e., *b*-value of the Gutenberg-Richter relation) around the rupture region started to decrease in around 2005⁹. Two sequences of the migrating seismicity into the region of initial rupture occurred. The first one from one month to two weeks prior, and the second one from two days prior (i.e., after the M7.3 foreshock) to the day of the main shock¹⁰. An episodic slow slip, corresponding to M7.0, on the same sections of the megathrust fault was observed for a period of a month and a half prior to the M7.3 foreshock¹¹.

However, there have not been any reports concerning preseismic groundwater changes for the Tohoku EQ, partly because the public water supply has almost completely replaced household wells in Japan. Therefore, in this study, we focused our attention on commercial spas (onsen or kosen in Japanese) listed in Table 2 in the Sanriku region (Figure 1). Preseismic groundwater changes were observed only in Goyo-onsen (Goyo Spa), Iwate Prefecture (Figure 1), where the groundwater level and temperature had been recorded since October 2007. In this paper, we used these recorded data.

Results

Time series of groundwater level and temperature in Goyo-onsen and related data are shown in Figure 2. The groundwater level, which is the distance between ground and water surfaces is depicted in Figure 2a and the

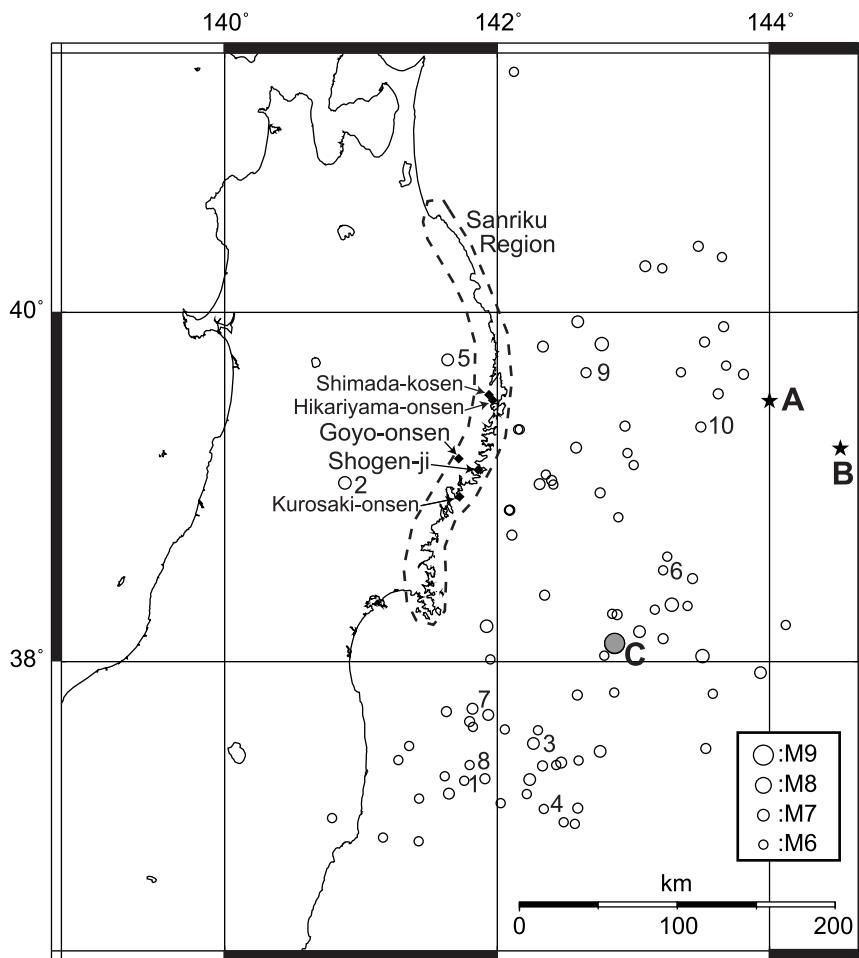


Figure 1 | Open circles denote EQs with a magnitude of more than 6.0 from October 1, 2007 to November 30, 2012. Numbers (1–10), stars (A) and (B), and Gray circle (C) indicate EQs listed in Table 1. The location of spas is shown in Table 2. The area surrounded by the dashed line indicates the Sanriku region. This map was generated by the generic mapping tools (<http://www.soest.hawaii.edu/gmt/>) which is an open source collection.

groundwater temperature in Figure 2b. General behavior of the water level, such as coseismic large offset and post-seismic fluctuation for the Tohoku EQ, can be recognized in Figure 2a. To identify the anomalies, Figure 2a also shows the 10 and 90 percentile ranges of the variation prior to the main shock. The groundwater level gradually decreased from October 2007 to March 2011. To reduce this

trend, the percentile ranges in Figure 2a are represented with the straight-line approximation of the groundwater level data. The shaded areas show more than 90 percentile periods before the main shock. Figure 2b, however, does not show thresholds as the temperature mainly remained constant before the main shock. The periods during which the temperature stayed below 22 degrees before the main shock are marked by gray shade. In addition, the time series of EQ occurrences greater than 6.0 magnitude with epicenter within 250 km of Goyo-onsen is illustrated in Figure 2c. Precipitation and atmospheric pressure recorded by the Japan Meteorological Agency (JMA) at approximately 12 km south of Goyo-onsen are shown in Figures 2d and 2e, respectively. In Figure 2e, a running mean is also presented for the atmospheric pressure data.

These data show that three months prior to the Tohoku EQ, the water dropped beyond the 90 percentile range and the temperature decreased by 1 degree or 2 degrees. Earlier, similar drops of groundwater level only occurred on Aug. 15, 2008 (Figure 2a), while the water temperature decreased to 21°C on Feb. 9, Feb. 15, Feb. 21 and Mar. 1, 2008 (Figure 2b). In other words, simultaneous anomalies of groundwater level and temperature occurred only once in the 3.5 year records, i. e., only in about three months before the Tohoku EQ main shock. Thus, the relation between the observed water changes and the Tohoku EQs may have been real (see case 1 in Methods section).

During the 3.5 year period, the M7.2 Iwate-Miyagi Nairiku EQ on June 14 of 2008 occurred 75 km away from Goyo-onsen (Figure 1 and Table 1). An obvious decrease in groundwater level over 10

Table 1 | Earthquake catalogue. (1–10) Large earthquakes with a magnitude greater than 6.0 during the 3.5-year period prior to the Tohoku EQ, within 250 km from Goyo-onsen and (A–C) EQs with great tsunamis near Sanriku region

No.	Day (Local Time)	Magnitude	Depth (km)
1	Nov. 26, 2007	6.0	44.1
2	June 14, 2008	7.2	7.7
3	July 19, 2008	6.9	31.5
4	July 21, 2008	6.1	27.3
5	July 24, 2008	6.8	108.0
6	Dec. 4, 2008	6.1	24.0
7	Mar. 14, 2010	6.7	39.7
8	June 13, 2010	6.2	40.3
9	July 5, 2010	6.4	34.4
10	Aug. 10, 2010	6.3	30.0
A	June 15, 1896	8.5	-
B	Mar. 3, 1933	8.4 (Mw)	-
C	Mar. 11, 2011	9.0 (Mw)	24.0



Table 2 | List of onsen, kosen (spas), and wells

Site	Longitude	Latitude	Altitude [m]	Depth [m]
Goyo-onsen	141.7175°E	39.1686°N	430	2000
Kurosaki-onsen	141.7227°E	38.9525°N	22	500
Shogen-ji	141.8596°E	39.1062°N	28	Around 2
Shimada-kosen	141.9389°E	39.5339°N	58	Upwelling
Hikariyama-onsen	141.9677°E	39.5021°N	137	Upwelling

percentile was observed from Apr. 25 to May 23, 2008, which recovered one day before the main shock. No change, however, was recorded for the water temperature. Thus, we did not identify this

anomaly as a precursor. The Tohoku EQ is the only earthquake that was preceded by anomalous changes both in water level and temperature.

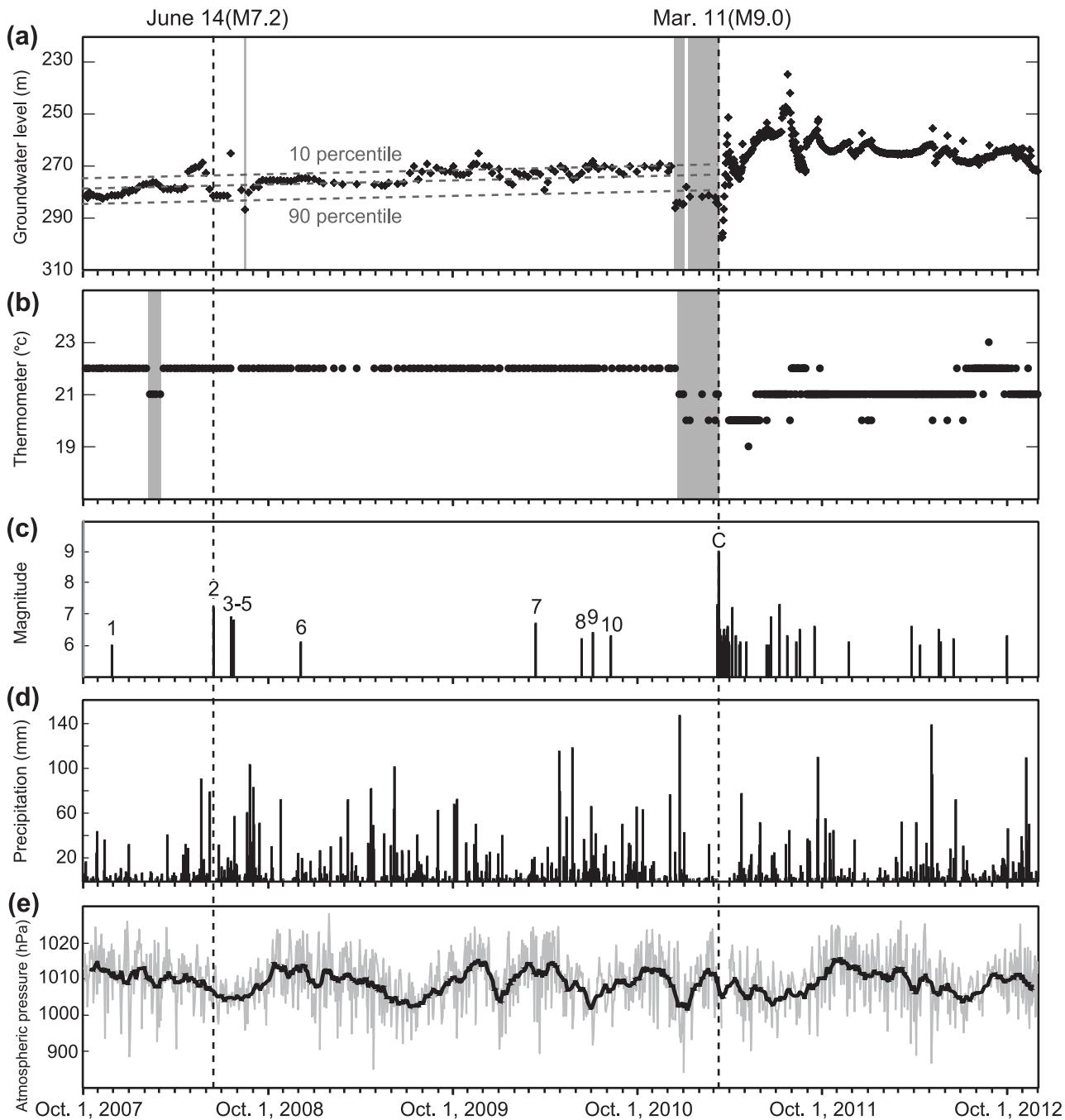


Figure 2 | Time series of (A) groundwater level, (B) groundwater temperature, (C) EQs ($M \geq 6$), (D) precipitation, and (E) atmospheric pressure (Solid line: ± 14 -day running mean and gray line: one day data). Horizontal dashed lines denote thresholds of the interquartile range of the groundwater variation before the main shock. Vertical dashed lines indicate the 2008 M7.2 Iwate-Miyagi Nairiku and Tohoku EQs.

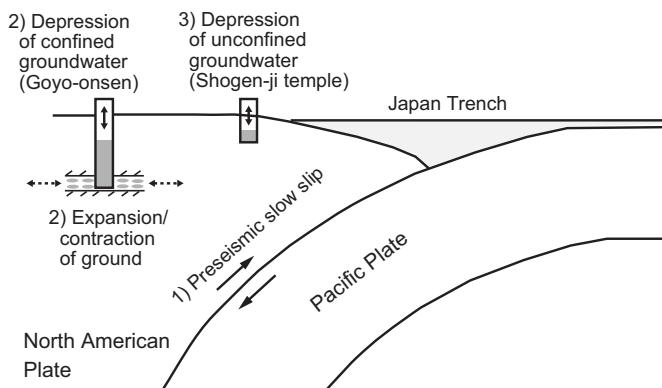


Figure 3 | A schematic of the proposed physical mechanism modified from Koizumi (2013). The events 1–3 are thought to have occurred in order before the Tohoku EQs.

Discussion

Groundwater level is affected by solid-earth tides, atmospheric pressure, and precipitation¹². The preseismic groundwater level changes must be discriminated from the changes due to these. We did not recognize solid-earth tides effects due to irregular sampling and long interval of sampling. As shown in Figure 2, the groundwater level at Goyo-onsen was not affected by atmospheric pressure and precipitation although the reason is unclear. From the aforementioned reasons, the observed anomalies may be considered as a precursor.

As mentioned earlier, macroscopic anomalies, namely eyewitnessed preseismic anomalies, such as mudying and dropping of groundwater, associated with disastrous EQs with tsunami, have previously been reported in more than ten wells in the Sanriku region for the 1933 Sanriku EQ⁵. Although most of the wells were for residential use and are no longer in operation, one well in the Shogen-ji temple (Figure 1) containing unconfined groundwater is still in use. We investigated those in charge of this well to see if there were groundwater anomalies associated with the Tohoku EQ. Groundwater at the Shogen-ji temple well could not be pumped one month before the Tohoku EQ, implying that a groundwater drop occurred. The groundwater in the Shogen-ji temple was reported to have become muddy prior to the 1933 Sanriku EQ. Since the groundwater could not be pumped up from the well before the Tohoku EQ, it is not known if the water was muddy at that time.

Here we speculate on the physical mechanism of the phenomena. For the periodic and disastrous Nankai EQs, a drop in the confined groundwater and water inflow were recorded in Dogo-onsen (132.79°E , 33.85°N) located in northern Shikoku, north of the epicenters¹³. Linde and Sacks¹⁴ proposed a slow slip of the plate in a deep region of Nankai trench, namely a thrust-type slow pre-slip, to qualitatively explain the unconfined groundwater drop in the wide area, including the Pacific side of Shikoku, associated with the 1946 Nankai EQ. This explanation also implies that a slow slip occurred not only in the Pacific coast region but also in the northern region of Shikoku including Dogo-onsen. Furthermore, to explain the time delay of the drop, Koizumi¹² speculated that unconfined groundwater drop occurred as a result of movement to the confined ground

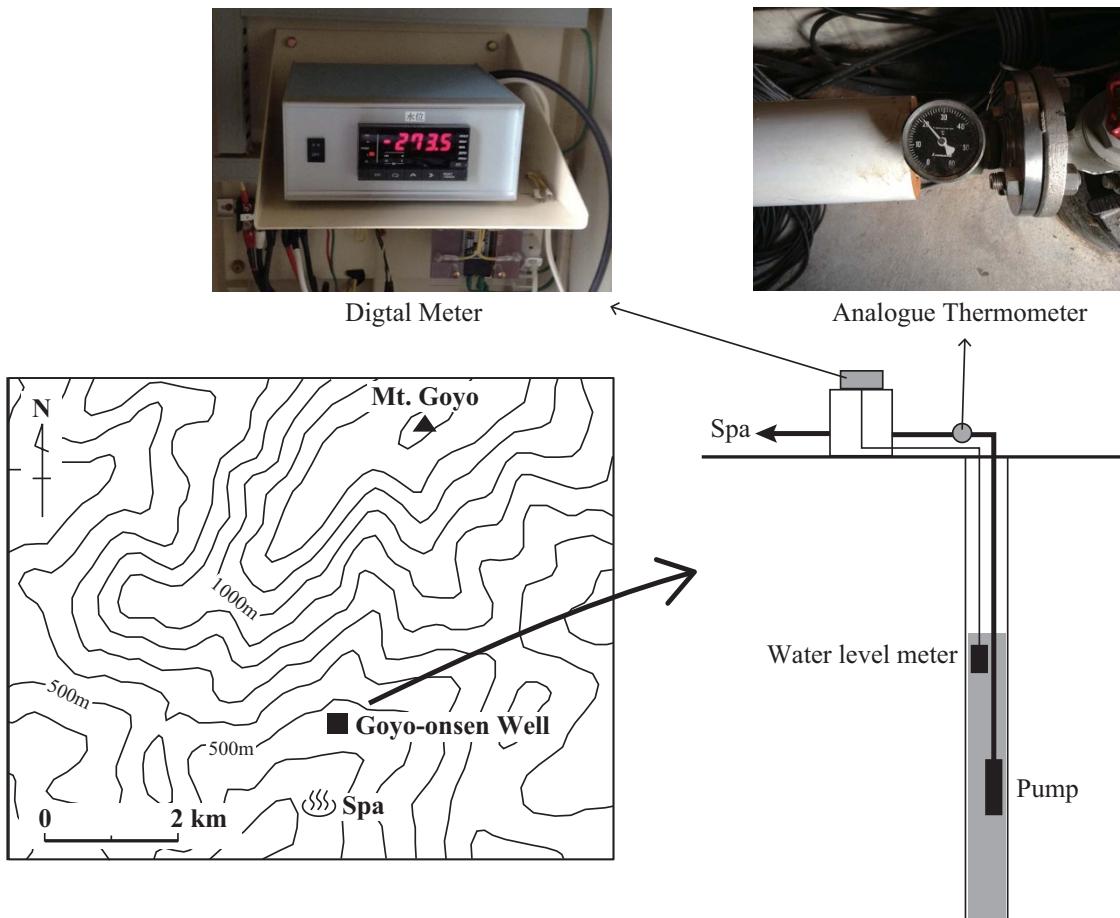


Figure 4 | A map around Goyo-onsen and a schematic diagram of instrumentation. This map was generated by the generic mapping tools (<http://www.soest.hawaii.edu/gmt/>) and was modified by using Adobe Illustrator (<http://www.adobe.com/>).



water. We note that Koizumi assume the groundwater drop in Dogo-onsen before the 1946 Nankai EQ, although the detailed description of time of drop was not recorded in the document¹⁵. Similar events could be expected in the Tohoku EQ (Figure 3). First, the preseismic slow slip occurred around the plate boundary. Second, the volumetric expansion of the North American plate and the confined groundwater drop (and temperature decrease) in Goyo-onsen occurred three months before the main Tohoku EQ shock, potentially associated with the slow slip. We presume that the expansion around the confined groundwater region produced a new path of water, which caused the groundwater temperature decrease due to inflow of colder water from other aquifer. Finally, a decrease in the unconfined groundwater in the Shogen-ji temple occurred a month before the main shock. The speculation requires a pre-slip event. In fact, the pre-slip event was observed a month and a half before the Tohoku EQ in the epicentral area by the ocean bottom pressure sensor¹¹. In addition, radon concentration in the groundwater in Izu peninsula gradually increased three month before the Tohoku EQ¹⁶. The distance between the observation point and the epicenter was about 500 km. However, the pre-seismic increase of the radon concentration occurred only this time during 35-year observation. The volumetric strain change could be a plausible explanation for this radon emission anomaly.

In the study of EQ prediction, continuous scientific measurements are vital to determine correlations between plausible precursors and EQ occurrence. Large EQs occur infrequently in limited regions covered by scientific monitoring. Since the number of installed devices for adequate scientific measurement is limited, continuous records of monitoring for non-scientific purposes are often invaluable for the study of EQ prediction as this study shows.

Methods

Procedure. Various EQ precursors have been identified, such as geochemical, hydrological, geodetic, seismic, and electromagnetic phenomena¹⁷. Time series data with anomalies prior to the main shock can be classified as follows:

Case 1) The anomaly monotonically increases until the main shock^{18–20}. If enough events are not obtained (e.g., one or a few), the following criteria should be satisfied to strengthen the claim of the relation between the anomaly and EQ: a) anomaly was observed only before the main shock for a long-period observation, and b) the intensity of the anomaly before the main shock was significantly larger than the variations during the aseismic period (e.g., beyond two times the standard deviation of variations and interquartile range).

Case 2) Transient anomalies occur before the main shock^{21–23}. In this case, statistical method is required to reveal a significant correlation between anomalies and EQs. A statistical method determines the anomaly appearance rate (AAR) and EQ occurrence rate (EOR). AAR is defined by the number of EQs that occur in a prescribed lead-time interval after the anomaly divided by the total number of EQs, while EOR reflects the number of anomalies preceding EQs in the same lead-time interval divided by the total number of anomalies. Alternatively, a statistical Phi correlation between the anomaly and EQ can be used. In this study, the relation between groundwater changes and the Tohoku EQs does not exactly correspond to case 1, because the anomalies did not monotonically change until the main shock. Although the anomalies started three months before with the constant intensity until the Tohoku EQ, we applied case 1 for the evaluation.

Data. Goyo-onsen is located at the altitude of 430 m in the southern foot of Mt. Goyo, above the edge of coseismic rupture area of the fault of the Tohoku EQ²⁴. The main body of Mt. Goyo and the region around the well comprises acid plutonic rocks and granodiorite-tonalite, respectively²⁵. Drilling work to locate hot springs terminated in February 1997. The initial flow rate of the hot springs was 222 m³ per day with a temperature of 39.5°C²⁶. The alkaline hot springs came out from the 2000-m well. Three years later, in 2000, a commercial spa opened. Pumped-up rate is controlled to be constant. The Goyo-onsen office monitors the groundwater levels and temperature, as well as the weather. After the Tohoku EQ, the office recorded these data daily until October 15, 2011 and every two days after that. Before the Tohoku EQ, however, the office recorded these data only intermittently and irregularly. The average interval between each record was 8 days, with the maximum period of 34 days with no data. The sampling hour of the day was not fixed. The groundwater level and temperature were read from a digital meter and an analogue meter, respectively (Figure 4). The groundwater level indicates the distance between the ground and water surfaces, a larger number indicating lower water level. Since this value fluctuates slightly during the recording, in the order of 0.1 m, the average value is a rough estimate. Water temperature, on the other hand, was measured at the ground surface after pumping using an analogue thermometer with a 1°C resolution. Sometimes the

temperature was recorded with a 0.1°C resolution, but most of records prior to the Tohoku EQ had the 1°C resolution. Therefore, we adopted the 1°C resolution. In this study, we use data from Oct. 1, 2007 to Dec. 30, 2012.

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Acknowledgments

We thank Mr. Yoshiro Konno of Goyo-onsen for the data provided and Dr. Naoji Koizumi for his knowledge of groundwater. The study was partially supported by the Ministry of Education, Science, Sports and Culture, Grant-in-Aid for Scientific Research (C), No. 23510218, 2011 (MK), and Encouragement of Scientists, No. 23906010, 2011 (YO),



Observation and Research Program for Prediction of Earthquakes and Volcanic Eruptions, 2009–2013 (YO, MK, and TN), the Joint Research Program of Earthquake Research Institute, the University and Tokyo, and by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan, under its Earthquake and Volcano Hazards Observation and Research Program, 2014–2016 (YO) and Tokyo Marine Kagami Memorial Foundation (MK and TN). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Author contributions

Y.O. and M.K. designed the study; Y.O. contributed to collecting data; Y.O. and T.N. analyzed the data; Y.O. and M.K. wrote the manuscript; All authors reviewed the manuscript.

Additional information

Competing financial interests: The authors declare no competing financial interests.

How to cite this article: Orihara, Y., Kamogawa, M. & Nagao, T. Preseismic Changes of the Level and Temperature of Confined Groundwater related to the 2011 Tohoku Earthquake. *Sci. Rep.* 4, 6907; DOI:10.1038/srep06907 (2014).



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