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Key Points:
- Permeability enhancement was detected 528 km distant from the epicenter
- Not only dynamic but also static stress contributes to the permeability increase

Supporting Information:
- Figures S1–S5

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Shallow crustal permeability enhancement in central Japan due to the 2011 Tohoku earthquake

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Abstract Pore pressure decreased at the Kamioka mine in central Japan after the Tohoku earthquake (*M*9.0) on 11 March 2011, which can be attributed to a permeability increase. We focus on the Earth's tidal response before and after the earthquake to evaluate rock permeability change through hydraulic diffusivity change. If we assume a constant elastic modulus, hydraulic diffusivity is found to increase from 3.3 to 6.7 m^2/s after the Tohoku earthquake. We also analyzed data before and after the 2007 Noto Hanto (*M*6.9) and 2008 Suruga Bay (*M*6.5) earthquakes, which yield no significant tidal response changes. We examined the amount of dynamic and static stress changes caused by these earthquakes and show that it is difficult to attribute the permeability enhancement solely to dynamic stress, and static stress change may also affect the permeability enhancement.

1. Introduction

Previous studies have investigated the relationship associated with earthquakes between water and rock mass via pore pressure, groundwater, and seawater changes. Earthquake-induced changes in groundwater level have been widely observed [e.g., *Manga et al.*, 2012]. For example, the *M*8.1 Showa-Nankai earthquake of 1946 lowered the groundwater level and dried up wells located on the Pacific coast of Japan from the Kii Peninsula to Shikoku [*Hydrographic Bureau*, 1948]. The 1995 Kobe earthquake (*M*6.9) of Japan changed the discharge rates of springs, water levels in wells, and radon concentrations in the groundwater [*Fujimori et al.*, 1995; *Tokunaga*, 1999; *Igarashi et al.*, 1995]. At 377 monitoring stations of well water in Taiwan, coseismic changes in groundwater level were observed in 276 wells after the 1999 Chi-Chi earthquake (*M*7.6) [*Chia et al.*, 2008]. Almost all of these affected wells were located within 50 km of the thrust fault, suggesting that hypocentral distance was an important control on whether a well was affected by the earthquake. However, well water anomalies were observed in Japan more than 5000 km from the hypocenter of the *M*9.0 Sumatra earthquake [*Kitagawa et al.*, 2006]. As such, both hypocentral distance and earthquake magnitude are controls on potential groundwater changes [*Matsumoto and Roeloffs*, 2003].

Montgomery and Manga [2003] suggested that coseismic changes in groundwater are caused by crustal deformation and ground shaking. Seismic waves are important in this respect as they oscillate the ground and travel long distances. *Brodsky et al.* [2003] hypothesized that seismic waves remove temporary barriers consisting of sediments in cracks which facilitates groundwater flow. Thus, such dynamic deformation can cause changes in groundwater level and affect rock permeability.

Elkhoury et al. [2006] examined the tidal effects on well water levels and suggested that permeability might be enhanced by seismic waves or dynamic stress caused by distant earthquakes. *Xue et al.* [2013] used the tidal effects on water levels in a deep borehole to track permeability for a period of 18 months in the damage zone of the fault that produced the 2008 Wenchuan earthquake (*M*7.9) and noted a sudden permeability increase due to regional earthquakes.

In this study, we show that (1) permeability enhancement occurred at a distant site at the time of the Tohoku earthquake from examination of tidal response of pore pressure and (2) static strain change is one of the causes of the permeability enhancement.

2. Data

Since 2005, we have been continuously monitoring pore pressure in borehole wells and atmospheric pressure with a recording interval of 1 s at the Kamioka mine in Gifu Prefecture of central Japan (Figure 1a).

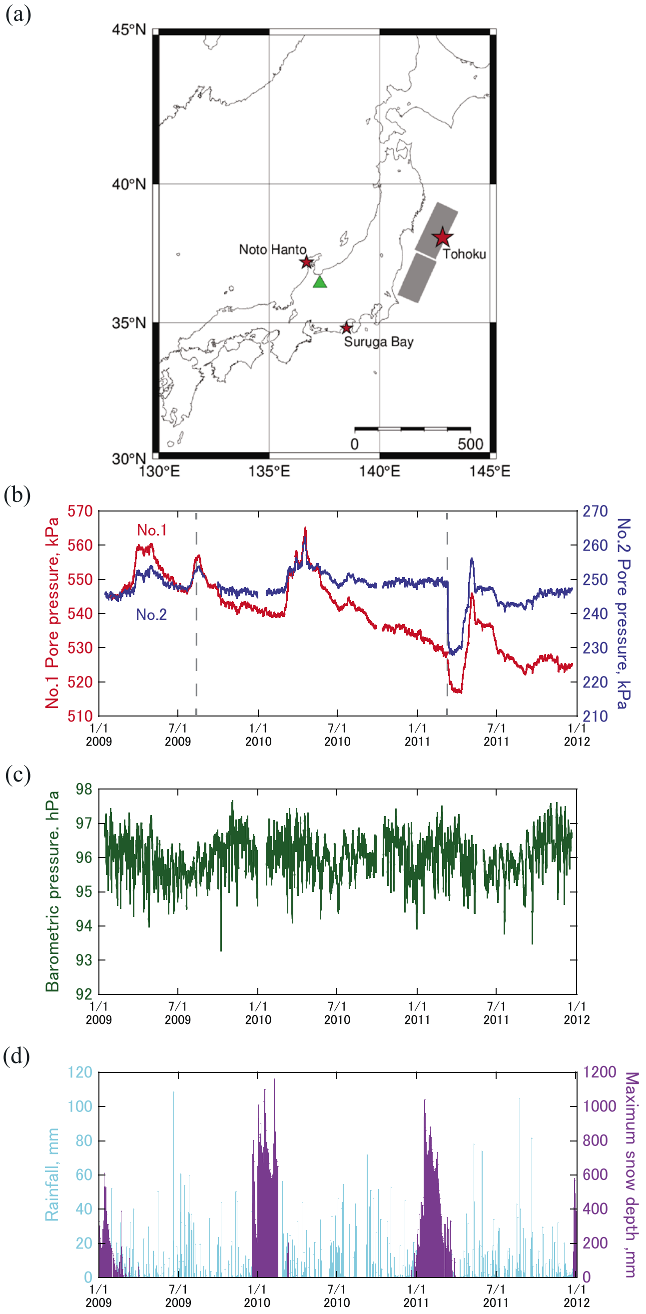

Figure 1. Site map and observational data during the period from April 2009 to December 2011. (a) Map of the observation site (green triangle) and epicenters (red star) of the events used for analysis. The gray rectangle shows the fault model of the Tohoku earthquake used for strain calculation (see text for the detail). (b) Pore pressure of no. 1 is the red line and that of no. 2 is the blue line. The dashed lines mark the times of the 2009 Suruga Bay and 2011 Tohoku earthquakes. (c) Barometric pressure. (d) Rainfall (light blue) and maximum snow depth (purple).

The observation site is located at 36.43°N, 137.29°E, and the depth from the surface is 350 m. We selected two wells (nos. 1 and 2) located about 6 m apart from which water flows out. Horizontal observation boreholes were drilled into the gneiss bedrock with lengths of 350 and 90 m, respectively. The installed pressure transducers were quartz response pressure gauges, which convert resonant frequency to pore pressure. Pore pressure data were transmitted via a RS232C port and recorded on a hard drive. Average absolute values of the pore pressure are approximately 500 and 200 kPa for nos. 1 and 2, respectively, which suggests that they have different aquifers.

In general, pore pressure change is caused by meteorological effects, Earth's tides, and crustal deformation. In addition, there are annual changes in pore pressure caused by rainfall and snow. An increase in pore pressure depends on precipitation and its underground flow. Most rainfall is received in June, and melted snow also affects the observed pore pressure every March–April. The snowmelt effects are more significant than those of rainfall, because our observation site is relatively deep (350 m). Pore pressure peaks lag the snowfall peaks because of the time for the snow to melt and flow into the subsurface (Figure 1).

Figure 1b shows that pore pressure decreased after the 2011 Tohoku earthquake on 11 March. The distance of the Tohoku earthquake is approximately 528 km from the Kamioka mine. We explored the possibility that the permeability changes resulted in the decrease in pore pressure. We focused on the Earth's tidal response before and after the earthquake and extracted tidal amplitude information for the largest constituents, (M_2) and (O_1) from the observed data during the period of April 2009 to December 2011. The amplitude and phase changes were obtained for time windows of 3 months at daily steps.

3. Methods

3.1. Tidal Analyses

We decomposed the tidal signal from the observational data using the tidal analysis program BAYTAP-G [*Tamura et al*., 1991], which can identify four components from pore and barometric pressures. The four components are (1) background noise; (2) trend: slow, long-term seasonal, or interannual variations; (3) barometric response: pore pressure changes due to barometric fluctuations in the aquifer; and (4) Earth's tides: rock deformation that affects the flow of groundwater. Pore and barometric pressures were recorded every second and resampled hourly. We chose a time window boundary to at 14:00 JST on 11 March 2011 when the Tohoku earthquake occurred, in order to examine the pore pressure changes before and after the earthquake. BAYTAP-G selects the amplitude and phase of Earth's tides separately.

3.2. Estimation of Hydraulic Diffusivity

Permeability changes associated with earthquakes have been interpreted from tidal response analysis. *Lai et al.* [2014] looked at the response of ~17 near-field wells before and after the 2008 Wenchuan earthquake and found permeability enhancement. They utilize the poromechanical solution of *Hsieh et al.* [1987] that assumes a confined aquifer.

There is another solution to estimate permeability from the response to solid Earth's tides. *Roeloffs* [1996] proposed that the hydraulic diffusivity can be estimated from water table drainage or degree of confinement for different frequency bands. In general, an aquifer behaves as unconfined under loading at longer periods because there is sufficient time for fluids to flow toward water table during low-frequency deformation. The degree of confinement controls the frequency response of pore pressure to loading, especially in low-frequency bands such as tidal loading.

Roeloffs [1996] presented the relationship between pore pressure and strain changes:

$$\frac{p_0(z)}{\varepsilon_0} = -BK_u\left[1 - \exp\left(-\left[i\omega(z - z_w)^2/c\right]^{\frac{1}{2}}\right)\right] \tag{1}$$

where $p_0(z)$ and ε_0 are the observed pore pressure and strain change caused by the Earth's tides, ω is the angular frequency of the loading, c is the hydraulic diffusivity, and $z - z_w$ is the depth of measurement relative to water table. B is the Skempton's coefficient, which has a value between 0 and 1. This represents the frequency response of pore pressure to tidal loading. Equation (1) includes complex values, where the real part shows the amplitude ratio and the imaginary part shows phase difference between tidal strain and pore pressure. BK_u can be estimated using pore pressure response to seismic waves [*Kano and Yanagidani*, 2006]. The $z - z_w$ is 20 m for the absolute value of pore pressure in the no. 2 borehole. The only unknown is hydraulic diffusivity, c, for which we tested a range of values at intervals of 10^{-2} m^2/s to fit the ratio of amplitudes of extracted tidal components.

The Kamioka site is located in a rock mass of gneiss from the surface of the mountain to the observation site. Aquifers exist as an assembly of cracks and fractures from surface. It is natural to consider that there is no cap rock, and thus, the aquifer is unconfined. The barometric response extracted from tidal analyses is similar to the pore pressure record for the no. 2 borehole, which suggests that the changes in the water table directly balance the barometric pressure and the aquifer is unconfined. We therefore adopted the model proposed by *Roeloffs* [1996].

3.3. Decrease in Pore Pressure

A step-like and transient change of pore pressure is observed at the time of the Tohoku earthquake. In general, a step-like change of pore pressure at the time of an earthquake may be explained by a coseismic strain step caused by the dislocation of earthquake [*Roeloffs*, 1996]. A coseismic strain step is an instantaneous change, and pore pressure should respond to the strain change in an undrained manner. The relationship between coseismic strain change, ε_{kk}, and pore pressure, p, can be expressed as

$$p = -BK_u\varepsilon_{kk} \tag{2}$$

The step change in pore pressure is likely related to a static stress change from the Tohoku earthquake that caused dilation within the surrounding rocks. This is also represented by equation (1) in the high-frequency limit.

Table 1. Results for the Three Earthquakes

							Hydraulic Diffusivity Change (m^2/s)	
Date	Magnitude	Epicentral Distance (km)	PGV (Borehole) (cm/s)	PGA (Borehole) (gal)	Dynamic Strain (10^{-6})[a]	Volumetric Strain (10^{-9})	Before	After
Noto Hanto (25 Mar 2007)	6.9	112	1.92	17.41	7.76	25	0.71	0.88
Suruga Bay (11 Aug 2009)	6.5	214	0.22	1.29	0.14	1.1	2.25	2.49
Tohoku (11 Mar 2011)	9.0	528	2.82	4.11	12.19	340	3.30	6.70

[a] Dynamic strain is calculated from equation (1). We calculated BK_u following *Kano and Yanagidani* [2006], and Δp was picked from original pore pressure data with sampling rate of 1 s.

The observed pore pressure decrease in a day was 12.8 kPa, but if BK_u is constant and the volumetric strain is 340×10^{-9} calculated from *Okada* [1992], the theoretical pore pressure change from equation (2) is only 6.0 kPa, which is smaller than observed. Moreover, a transient or continuous pore pressure decrease with time was observed during the few days after the Tohoku earthquake, indicating that the pore pressure cannot be fully explained by simple poroelastic response (Table 1). Another possible cause of the pore pressure decrease might be a change of permeability in the aquifer. Here we assume that the fluid flow in the aquifer is controlled by Darcy's law:

$$Q = \frac{k}{p_0 - p} \frac{A}{d} \tag{3}$$

where Q is the fluid flux, k is the permeability, A is the area of aquifer, and p_0 and p are the pore pressures for the far field and at the borehole, respectively. The distance d is measured between far-field reference point and borehole. If we assume that the fluid flux is constant, a decrease of p requires an increase in k.

Lai et al. [2014] found that permeability increases regardless of whether the step change in water level went up or down and independent of the location within either dilatational or compressive quadrants.

Permeability can be related to hydraulic diffusivity by assuming the viscosity of the pore fluid. There is the relationship between hydraulic diffusivity (c), permeability (k), fluid viscosity (μ), and specific storage (S) [*Wang*, 2000].

$$c = k/\mu S \tag{4}$$

Xue et al. [2013] shows that specific storage remains almost unchanged following some earthquakes and the sensitivity of specific storage to diffusivity is weaker than that for permeability. We cannot determine specific coefficient in our models and assume that it is constant before and after the earthquakes. After all, the fluctuation of hydraulic diffusivity is considered to be equivalent to permeability change.

4. Results

Figures 2a and 2b show the amplitude fluctuations of the M_2 and O_1 tidal constituents versus the time for no. 2 borehole during the period of January 2009 to December 2011. The dashed lines show the times of the 2009 Suruga Bay earthquake ($M6.5$), which occurred in Shizuoka Prefecture on 11 August 2009 and the 2011 Tohoku event. The amplitude changes of the M_2 and O_1 constituents correlate with pore pressure fluctuations. The results for borehole no. 1 are shown in the supporting information.

We compared the data for the 3 month period before and after the earthquake and identified that the M_2 and O_1 amplitudes decreased after the Tohoku earthquake. The time window after earthquake starts from 12 March because the uncertainties just after the event are large (supporting information). The M_2 and O_1 amplitudes were 22.2 and 10.4 Pa before the earthquake and decreased to 16.1 and 7.1 Pa after the earthquake, respectively. Figures 2c and 2d show the phase changes of the M_2 and O_1 constituents with time during the period of April 2009 to December 2011. The M_2 and O_1 phases were $-132°$ and $-137°$ before the earthquake and changed to $-135°$ and $-124°$ after the earthquake, respectively. If ε_0, BK_u, and $z - z_w$ in equation (1) are constant, the tidal amplitude decreases, and phase lead indicates permeability enhancement (refer to Methods section). If hydraulic parameters change, tidal amplitude and phase should change in the same direction, but for these data, a significant phase change was not seen. A small phase lead of the O_1 constituent was detected, but the M_2 constituent changed in the opposite sense, which we still do not understand. This study focuses on only tidal amplitudes, and future work must investigate the effect of permeability changes on the phase changes.

To evaluate the cause of the change in tidal response, it is necessary to examine strain changes along with pore pressure changes. Observational strain data are available but only for 2010. Thus, we used the theoretical strain determined from GOTIC2 [*Matsumoto et al.*, 2001], which calculates the Earth and oceanic tides by assuming an Earth structure model. The calculated strain was verified by comparisons with the observed strain data in 2010. The M_2 and O_1 amplitudes were obtained by the same method as used for the pore pressure analyses. The M_2 and O_1 amplitudes for pore pressure and calculated theoretical strain were then compared. Figure 3 shows $\Delta p/\Delta\varepsilon$ plotted versus frequency (cycles/day) and indicates an increase in diffusivity from 3.30 to 6.70 m^2/s at the time of the earthquake. The increase in hydraulic diffusivity is consistent with the pore pressure reduction.

Estimated hydraulic diffusivity increased after the Tohoku earthquake over 3 months and then gradually decreased. The recovery is continuing but has not yet reached the value before the earthquake (supporting information).

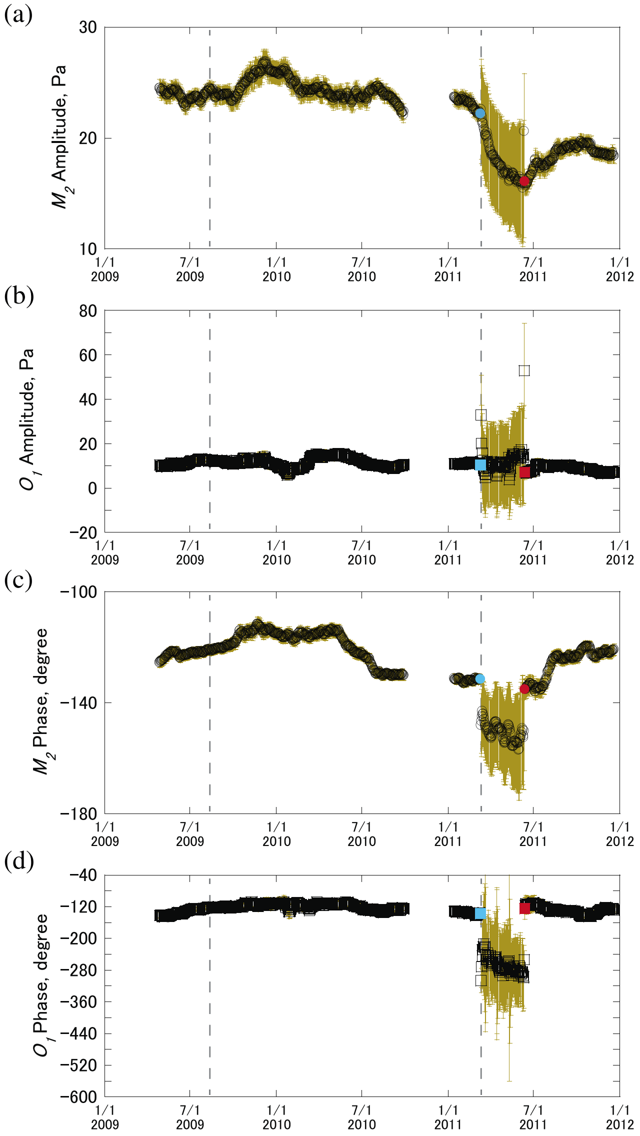

Figure 2. No. 2 borehole results (no. 1 results are shown in supporting information). Fluctuations in the (a and b) amplitudes and (c and d) phases of the M_2 and O_1 constituents with time during the period from April 2009 to December 2011. Amplitudes of the M_2 (Figure 2a) and O_1 (Figure 2b) constituents. Phases of M_2 (Figure 2c) and O_1 (Figure 2d) constituents. The dashed lines mark the times of the 2009 Suruga Bay and 2011 Tohoku earthquakes. The error bars are large during March to July 2011 following the Tohoku earthquake because it is difficult to estimate the tidal response due to the large seismic waves. The blue circle and square symbols are calculated from the 3 month preseismic data, and the red symbols are calculated from the 3 month postseismic data.

5. Discussion

The causes of the permeability change can be related to stress changes, which can be classified into dynamic and static stresses. *Brodsky et al.* [2003] and *Elkhoury et al.* [2006] showed that permeability is enhanced by seismic wave or dynamic stress. *Miyazawa* [2011] showed that the main cause of distant triggered (beyond 1000 km) events for the Tohoku earthquake was dynamic stress because it was 2 orders larger than static stress beyond 1000 km. But in the area closer to epicenter, not only dynamic stress changes but also static stress changes are significant. If static stress changes cause permeability enhancement, its effect may persist.

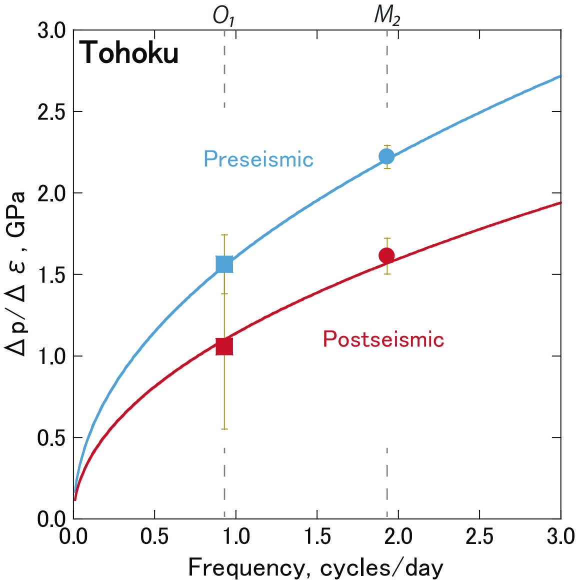

Figure 3. Ratio of pore pressure to strain change plotted versus frequency in cycles/day. The blue line, circle, and square symbols are preseismic, and the red are postseismic, respectively. The curved line is from equation (1), where the slope depends on hydraulic diffusivity. The blue and red lines show 3.30 and 6.70 m^2/s of hydraulic diffusivity which increased after the Tohoku earthquake.

To understand the mechanism of diffusivity change, we also analyzed other earthquakes with the same procedure. We compared the results from the 2011 Tohoku earthquake with the results from the 2007 Noto Hanto (*M*6.9) and the 2009 Suruga Bay (*M*6.5) earthquakes. The epicentral distances of these two earthquakes from our observation site were about 112 and 214 km, whereas the Tohoku earthquake was $>$500 km (Figure 1a). Hydraulic diffusivity after each earthquake were 0.17, 0.24, and 3.40 m^2/s for the Noto Hanto, Suruga, Bay and Tohoku earthquakes, respectively (Table 1). Only the Tohoku earthquake showed a change following the seismic event. The diffusivity changes for the Tohoku and Suruga Bay earthquakes were obtained from the data of no. 2, but Noto Hanto results are from no. 1 because the observations of no. 2 borehole started in 2009. Moreover, we do not have barometric pressure in 2007, but we verified that there is no significant difference between the results with and without barometric pressure in the BAYTAP-G [*Tamura et al.*, 1991] analysis from 2009 to 2011.

To evaluate dynamic stress changes, we examined the relationship between the peak ground velocity (PGV), peak ground acceleration (PGA), and the permeability changes associated with earthquakes (Table 1). The records of 14 KiK-net three-component borehole strong motion seismographs near Kamioka were used to obtain the PGV and PGA. The records were band-pass filtered between 0.05 and 10 Hz, and velocity was calculated by integrating acceleration data. Average PGA and PGV values for each earthquake are shown in Table 1.

The amplitude of dynamic strain is comparable between the Tohoku and Noto Hanto earthquakes (Table 1), although the Noto Hanto event did not show a tidal response change. PGV and PGA are also shown in Table 1 as an indicator of dynamic strain effects. Table 1 suggests that the magnitude of static strain may also have an effect for diffusivity changes. The PGV for the Tohoku event is the largest, which may affect the hydraulic changes along with the frequency content and duration of shaking. The dominant frequency was much lower for the Tohoku earthquake, which may have caused the permeability change in the crust.

Brodsky et al. [2003] observed persistent groundwater level changes caused by distant earthquakes and proposed the mechanism that the shaking caused by seismic waves removed sediment in crack and groundwater flowed easily. The Oaxaca earthquake ($M_w = 7.4$), hypocentral distance 3850 km, is one of the events investigated by *Brodsky et al.* [2003]. When this event occurred, water level decreased 11 cm, which corresponds to static stress change of 10^3 Pa. But static stress change of this earthquake estimated from the size of earthquake was less than 0.2 Pa. So *Brodsky et al.* [2003] considered that dynamic stress and resulting sediment removal were the main cause of groundwater level change.

In the case of our observation of Tohoku earthquake, however, magnitude is larger, and hypocenter is much closer, which produces relatively large static strain change at the site. The static strain as well as dynamic strain may contribute to permeability change. Indeed, volumetric strain of our observation site for Tohoku earthquake is equivalent to pore pressure changes of 10 kPa. It is possible to change permeability of aquifer.

To evaluate the effect of static stress, we calculated the coseismic strain change using the method of *Okada* [1992] (Table 1). We obtained coseismic strain by assuming a simple fault model that consists of two rectangular faults [*Imakiire and Kobayashi*, 2011] for the 2011 Tohoku earthquake (Figure 1a). For the Noto

Hanto and Suruga Bay events, we assumed a fault geometry and slip amount based on the centroid moment tensor solution provided by F-net National Research Institute for Earth Science and Disaster Prevention, Japan. The volumetric strain change at Kamioka caused by the Tohoku earthquake is 1 or 2 orders of magnitude larger than that caused by the other earthquakes, which suggests that the difference in amount of static stress can be a major factor in permeability enhancement. *Miyazawa* [2011] discussed the cause of triggered earthquakes focusing on static and dynamic stresses and suggested that the static stress change is comparable with dynamic stress change around the Hida region, where our observation site is located and that it is difficult to distinguish static and dynamic triggering at the area. This may also be the case for permeability enhancement.

From another point of view, the permeability change caused by static stress changes has been constrained in laboratory experiments that show that an increase in differential stress on the order of 100 MPa is necessary to double the permeability [*Zoback and Byerlee*, 1975; *Kiyama et al*., 1996]. The static stress change at Kamioka at the time of the Tohoku earthquake was 10 kPa, which is much smaller than the stress change from laboratory experiments. But it is possible that the structure of the fault zone, such as fractures concentrated on the fault, or preexisting stress makes the setting more sensitive to stress changes than solid rock samples studied during laboratory experiments.

Permeability changes associated with static changes of this order have never been observed before. This observation is an important clue for understanding the crustal response by static strain. Static strain, in particular, is considered to be large in the area closer to the hypocenter, which may cause much larger effects of permeability enhancement. The permeability enhancement is discussed in context of triggering of earthquakes [e.g., *Brodsky et al*., 2003]. If permeability enhancement is caused by static strain changes, this may control the triggering of earthquakes in the close vicinity of the hypocenter such as aftershocks. Also, this raises the question whether the crustal permeability is affected by deformation with longer periods, such as tidal loading. It is difficult to discriminate between static and dynamic strains for permeability changes, so future work should explore the effects of static strain changes on permeability enhancement.

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