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Characterization of spatial coseismic response of groundwater levels in shallow and deep parts of an alluvial plain to different earthquakes

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Abstract

Coseismic changes in groundwater levels have been investigated in many places throughout the world, but most studies have focused on the effects of one large earthquake. Few studies have looked at the spatial patterns of level changes in response to several earthquakes, or at the relationship of the patterns to shallow and deep groundwater in the same area. The aim of this study was to investigate these patterns and to construct a model of hydraulic responses. We selected the Kumamoto City area in southwest Japan, a region with one of the richest groundwater resources in Japan, as our study site. Data from hourly measurements of groundwater levels in 54 wells were used to characterize the coseismic spatial responses to four large earthquakes that occurred in 2000, 2001, 2005, and 2008. Although the distance to the epicenter (12 to 2573 km), and seismic energy ($Mw = 4.8$ to 8.0) of these earthquakes varied, systematic groundwater level changes were observed in the range of 0.01 to 0.67 m. The zones where coseismic rises were observed were generally wider for deep groundwater than for shallow groundwater. We observed general trends in the changes in groundwater levels, and calculated pressure changes, in the deep groundwater, but the coseismic increases or decreases in compressive stress in the shallow groundwater were variable, depending on the distance to the earthquake epicenter. We developed a conceptual model of the mechanism underlying this phenomenon and also investigated the importance of Togawa lava, consisting of porous andesite and forming a main aquifer, in determining the pattern of groundwater level change.

1 Introduction

Groundwater levels are influenced by barometric pressure, precipitation, earth tide, and earthquakes. The effect of earthquakes has been a focus of research because the correlation between groundwater level fluctuations and earthquakes can contribute to a pre-warning system for earthquake disasters (Roeloffs, 1988; Igarashi and Wakita,

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

1991). Groundwater levels tend to change abruptly during an earthquake, particularly in seismically active areas. Moreover, unusual changes in groundwater levels are thought to have potential as signals of fault movement or crustal deformation before earthquakes (King et al., 2000). Groundwater levels respond rapidly to an earthquake and begin to change during ground shaking (coseismic), and continue to change after ground shaking ceases (post-seismic). These immediate and delayed responses are caused by different mechanisms including proximity to the epicenter, geological structure, and hydraulic properties. This study focuses on coseismic changes because they are generally much larger than post-seismic changes.

Coseismic changes in groundwater levels have been studied in many places throughout the world (e.g. Wakita, 1975; Roeloffs, 1988; Kissin and Grinevsky, 1990; Rojstaczer and Wolf, 1992; Ohno et al., 1997; Grecksch et al., 1999; King et al., 1999; Chia et al., 2001). Various mechanisms have been proposed to explain groundwater level changes in wells during earthquakes, including static strain of aquifers, shaking of surface strata, fracturing of bedrock, and permeability change at the site (Montgomery and Manga, 2003; see Fig. 1). Of these mechanisms, redistribution of static stress or the strain field induced by fault displacement, which is probably associated with the generation of persistent coseismic changes in the near field of the epicenter, has been of particular interest to earthquake hydrologists (Roeloffs, 1996). Although the distribution of coseismic static strains can be estimated using simple dislocation models (Okada, 1992; Ge and Stover, 2000), in many cases the magnitude of observed coseismic groundwater level changes was not consistent with that of volumetric strains calculated from the theoretical models (Quilty and Roeloffs, 1997; Grecksch et al., 1999; Matsumoto and Roeloffs, 2003). Further studies on observed earthquake-related groundwater level changes in the vicinity of seismogenic faults are needed to improve understanding of the distribution of coseismic changes, and underlying mechanisms.

High-frequency automated recording systems for well water levels have recently been developed, and have significantly improved the monitoring of responses to earthquake activity. However, observations of the distribution and process of earthquake-related groundwater level changes are often limited by sparsely located monitoring wells. In the study areas where groundwater levels have been intensively monitored, such as the Tokai area of Japan, Parkfield in California, and the Koyna-Warna region in India, large earthquakes seldom occur (King et al., 2000; Chadha et al., 2003).

In this study we investigated the detailed spatial distribution of coseismic groundwater level changes over an unconsolidated sedimentary basin rich in groundwater resources. One new approach of this study was to compare the level changes between shallow and deep groundwater. Another was to construct a conceptual model for the mechanism of groundwater level changes by integrating the coseismic responses to different earthquakes. Being part of the circum-Pacific seismic belt, Japan is one of the most seismically active regions in the world. Therefore, groundwater levels in Japan would be expected to change frequently in response to earthquakes. The Kumamoto City area in central Kyushu, southwest Japan (Fig. 2) is one of the best sites to conduct research on the spatial distribution of groundwater level changes, because all drinking water, and water used for agriculture and industry by the population of 700 000, is sourced from local groundwater. The systematic measurement of groundwater levels has been implemented at many wells to monitor the groundwater resource. We therefore selected the Kumamoto City area as our study site.

2 Physical and mathematical models for coseismic change

2.1 Two types of coseismic change

Two types of coseismic change in groundwater levels, oscillatory and persistent, have been observed at monitoring wells. Oscillatory coseismic changes only appear in high-frequency data because they are the response of the water column in the well, and pore-water pressure in the aquifer, to passing earthquake waves, in particular, Rayleigh waves (Liu et al., 1989; Ohno et al., 1997). As interpreted by Cooper et al. (1965), the magnitude of oscillatory change reflects the amplification of pore pressure in the aquifer as a result of coseismic dilatational strain. This change usually diminishes shortly after earthquake waves pass through, and the well water returns to its pre-earthquake level.

On the other hand, persistent coseismic changes appear as abrupt or step-like rises or falls in groundwater levels, and usually last for a short time after the earthquake. The mechanism underlying persistent coseismic changes is thought to be the short-term response of pore pressure to the redistributed stress accompanying fault displacement (Muir-Wood and King, 1993; Roeloffs, 1996; Wang, 1997). Large stress changes induce large persistent changes, and affect the magnitude of Skempton's coefficient, described in Sect. 2.2. The persistent changes can be interpreted using the poroelastic theory that couples crustal deformation with pore water flow (Biot, 1941). Another possible mechanism is the removal of a temporary barrier in a fracture resulting from the shaking of seismic waves (Brodsky et al., 2003), because persistent changes have also been observed in wells far from the hypocenter (Montgomery and Manga, 2003). Based on the characteristics and possible causes of level changes in the study area, we focused on persistent coseismic changes, interpreted using the poroelastic theory, as described in the next section.

2.2 Poroelastic theory for pressure change

According to the poroelastic theory (Biot, 1941; Roeloffs, 1996), stress, strain, pore pressure, and water content are related to each other. Based on these relationships, Montgomery and Manga (2003) proposed two main causes for earthquake-related groundwater level changes: static volumetric strain changes, and ground shaking, with the later including dynamic volumetric strain changes (see Fig. 1). Hydrologic responses to crustal strain can be described quantitatively using the theory of linear poroelasticity (e.g. Roeloffs, 1996). The constitutive stress–strain relation for a porous elastic material is

$$\Delta\varepsilon_{ij} = \frac{1}{2G_\mathrm{u}}\left[\Delta\sigma_{ij} - \frac{\gamma_\mathrm{u}}{1+\gamma_\mathrm{u}}\Delta\sigma_{kk}\delta_{ij}\right], \quad (1)$$

where $\Delta\varepsilon_{ij}$ is the difference in the strain tensor, G_u is the undrained shear modulus (Pa), σ_{ij} and σ_{kk} are components of the stress tensor (Pa), γ_u is the undrained Poisson's ratio, and δ_{ij} is the Kronecker delta. In this study we used typical values for rocks, 2.3×10^4 MPa for G_u (Jaeger, 1969), and 0.25 for γ_u (Detournay and Cheng, 1993), and simplified the stress tensor as $\sigma_{ij} = \sigma_{kk}$, which allowed consideration of only one component, as a scalar. This simplification was adopted because it was difficult to correctly define the anisotropic behavior of the stress-strain field around an arbitrary study area.

The change in volume strain is accompanied by a change in the volume of solid material and a proportional undrained change in fluid pressures. This can be described by the next constitutive relationship, developed by Rice and Cleary (1976) based on the formulations of Biot (1941)

$$\Delta P = C\Delta\varepsilon_{ii}, \quad (2)$$

where P is fluid pressure (Pa) and C is a proportionality coefficient. The C has a relationship with the G_u and γ_u

$$C = -BG_\mathrm{u}\left[\frac{2(1+\gamma_\mathrm{u})}{3(1-2\gamma_\mathrm{u})}\right] = \frac{B}{\alpha}, \quad (3)$$

where B is Skempton's coefficient with a value between 0 and 1, and α is bulk compressibility (Pa^{-1}). The variable B is related to the porosity of solid grains and saturated rock, and to the compressibilities of the pore fluid, and approaches 1 for unconsolidated sediments. In this study, the values B and α were given as 1 assuming an unconsolidated state, and 4×10^{-11} following the typical value of the upper crust as described by Cutillo and Ge (2006).

For modeling the pressure changes in groundwater, we assumed the so-called undrained limit, in which there is no flow of pore fluid, because this condition corresponds to persistent changes occurring within a short time (Hamiel et al., 2005). According to Manga and Wang (2007), the change in pore pressure p caused by a change in mean stress σ_{kk} under the undrained condition can be formulated by

$$p = -\frac{B}{3}\sigma_{kk}, \tag{4}$$

The mean stress σ_{kk} is defined as the algebraic difference between the maximum and minimum stresses in one cycle of fluctuating loading, as measured in a fatigue test. Tensile stress is defined as positive, and compressive stress as negative. The sign convention was chosen so that negative σ_{kk} indicated compression.

Groundwater level displacement in a well measures the head change in the aquifer induced by the strain of seismic waves. Hydraulic head h is defined as

$$h = \frac{p}{\rho g} + z, \tag{5}$$

where ρ is the density of groundwater, g is gravitational acceleration, and z is the elevation of the groundwater level. Pore pressure change caused by an earthquake, Δp, can be calculated from the hydraulic head change Δh as

$$\Delta p = p_\mathrm{a} - p_\mathrm{b} = \rho g \Delta h = \rho g (h_\mathrm{a} - h_\mathrm{b}), \tag{6}$$

where the subscripts “b” and “a” denote the hydraulic head before and after the earthquake, respectively.

We assumed that the groundwater flow system in the study area behaved as a poroelastic medium, and that the matrix deformation caused by the release of elastic strain energy during an earthquake induced a proportional undrained change in the water level.

2.3 Spline for point-data interpolation

Because the Δh and Δp were calculated at individual observation wells, values had to be interpolated using a suitable spatial estimator to identify their spatial characteristics over the study area. Kriging methods, such as ordinary kriging and co-kriging based on geostatistics (e.g. Isaaks and Srivastava, 1989; Kitanidis, 1997), and splines, are the most common estimators, and both have been widely used in GIS. Splines as a geometrical method are more versatile than kriging, because kriging requires stationarity of the sample data, the existence of clear spatial correlation between data pairs, and a sufficient amount of data for quantifying the correlation statistically. The spatial correlations between Δh and Δp were unclear in our data; therefore we used a spline for their interpolation.

A spline estimates values between sample points using a mathematical function that minimizes the overall surface curvature and passes through the data points. The spline function uses the following formula for surface interpolation

$$s(x,y) = T(x,y) + \sum_{j=1}^{N} \lambda_j R(r_j), \tag{7}$$

where $j = 1, 2, ..., N$ (N is the number of points), λ_j are coefficients by solving a system of linear equations, r_j is the distance from a point (x,y) to the jth data point, and $T(x,y)$ and $R(r)$ are defined differently, depending on the selected option. For a regularized spline, $T(x,y)$ and $R(r)$ are expressed as

$$\begin{aligned} &T(x,y) = a_1 + a_2 x + a_3 y \\ &R(r_j) = \frac{1}{2\pi}\left\{\frac{r^2}{4}\left[\ln\left(\frac{r_j}{2\tau}\right) + c - 1\right] + \tau^2\left[K_0\left(\frac{r_j}{\tau}\right) + c + \ln\left(\frac{r_j}{2\pi}\right)\right]\right\}, \end{aligned} \tag{8}$$

where τ^2 is an arbitrary positive parameter, K_0 is the modified Bessel function, c is a constant equal to 0.577215, and a_i are coefficients for defining a plane (Franke, 1982; Mitas and Mitasova, 1988).

3 Study area and data

3.1 Geological setting and observation wells

The Kumamoto City area covers 266.26 km^2 around its center at 32°47′ N latitude and 130°43′ E longitude (Fig. 2). The geology of this area consists mainly of upper Quaternary unconsolidated sediments. In particular, alluvial clay (Ariake clay) deposited during the transgression after the last glacial epoch, pyroclastic flow deposits from the eruption of Mt. Aso, and Togawa lava, which consists of pyroxene andesite, are distributed extensively under the area. The pyroclastic flow deposits consist of four units, Aso-1, -2, -3, and -4. The oldest, Aso-1, and the youngest, Aso-4, are 270 000 yr old and 90 000 yr old, respectively, and the Togawa lava is stratigraphically situated between the Aso-1 and Aso-2 deposits (Watanabe, 1979). The upper and lower parts of the lava are porous, as shown in Fig. 3, while the middle is dense and contains fresh andesite with sparse joints. Togawa lava and pyroclastic flow deposits form excellent aquifers for groundwater resources because of their high permeability (Koike et al., 1996). Pre-Aso volcanic rocks, older than the pyroclastic flow deposits, underlie the deposits and form a hydrogeologic basement.

A groundwater level monitoring system was established at the beginning of 2000 in the Kumamoto City area. This system measures levels on the hour, from 00:00 to 23:00 JST, at the 54 groundwater well sites shown in Fig. 2. To identify the location and depth of the groundwater records, we expressed each data set as a number plus A, B, or C for wells situated within the distribution of Togawa lava, or a number plus a or b for wells outside the Togawa lava. The A, B, and C signify that the groundwater was measured above, within, or below the Togawa lava, respectively. Therefore, the groundwater level deepens from A (shallow groundwater) to C (deep groundwater). The a and b represent shallow and deep groundwater wells, respectively, which generally measure groundwater in the first (shallow) and second (deep) aquifers. Data denoted by B were further separated into shallow and deep depending on the well depth. Data for wells shallower than 70 m were grouped in to shallow groundwater, and deeper wells were grouped in to deep groundwater.

Data from 1 January 2000 to 31 December 2009, measured by the Kumamoto City Waterworks and Sewerage Bureau, were used to investigate the distribution of coseismic level changes during several earthquakes, and to examine the implications of these changes in the underlying mechanism of coseismic responses. Although groundwater levels can be influenced by pumping, rainfall, tide, barometric pressure, and surface water, coseismic changes tend to occur over a short time period and can be separated from the other factors.

3.2 Earthquakes for coseismic analysis

During the 10 yr study period (2000 to 2009), four large earthquakes that had recognizable effects on the groundwater levels at the wells in the Kumamoto City area were identified. Figure 4 shows that the epicenters of three earthquakes were located near Kumamoto City and one was located in southern China, more than 2500 km away. The four earthquakes are referred to as the Kumamoto Earthquake (KME), the Geiyo Earthquake (GYE), the Fukuoka West Offshore Earthquake (FOE), and the Sichuan Earthquake (SCE), and occurred in 2000, 2001, 2005, and 2008, respectively..

Before conducting the coseismic analysis, we checked the meteorological data and confirmed that there was no rainfall or marked changes in atmospheric pressure at the times the earthquakes occurred. No pumping effect was observed, and earth tide loadings did not change significantly during the study periods. Therefore, we assumed that the groundwater level changes observed around the times of the earthquakes had been caused by those earthquakes. Details of the four earthquakes, including occurrence time, hypocenter location (latitude, longitude, and depth), magnitude (moment magnitude, Mw), distance range between the hypocenter and groundwater wells, and the range of groundwater level changes observed over one hour around the time of the earthquake, are summarized in Table 1. For example, if an earthquake occurred at

09:30, groundwater levels at 09:00 and 10:00 were recorded to determine if there had been a sudden drop or rise.

Although the KME was the smallest in seismic energy (Mw = 4.8), a strong effect was observed on the groundwater level. The changes observed ranged from −0.2 m (a 0.2 m coseismic drop in the level) to +0.67 m (a 0.67 m coseismic rise) among the 54 wells. This large effect can be attributed to the short distance of the hypocenter from the study area. The effect of the GYE on levels was smaller because of the greater distance to the hypocenter, while the FOE had the second strongest effect on groundwater levels because it was centered at the second shortest distance from the study area. A small effect was detected for the SCE, one of the most destructive earthquakes in recent time, even though it was centered more than 2500 km from the study area.

4 Results

4.1 Variation of coseismic changes with different depths

Theoretically, groundwater levels in confined aquifers rise stepwise in areas of coseismic contraction, and fall in areas of extension as a result of decreasing compressive stress. Most groundwater levels at the observation wells showed persistent coseismic responses to the four earthquakes. To investigate how the responses varied with location and the presence or absence of the Togawa lava, data from two sites for each earthquake were selected. These sites consisted of two or three wells in a similar location but with different depths, ranging from 10 to 206 m, as shown in Fig. 5 and Table 2. These wells were selected because their data were representative of temporal trends in different sections of the study area. We selected wells located in the recharge area in the middle of the study area (sites 28a, 29b, 31a, and 32b), in the lowlands facing Ariake Bay (sites 35a, 36b, 37a, and 38b), and in the southeast study area, covered by Togawa lava and dotted with many springs (sites 13A, 14B, 15C, 16A, 17C, 18A, and

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

19C). Using data from these representative sites we examined the differences in water level changes between shallow and deep groundwater wells in the study area.

During the KME, the groundwater level changes observed at the two sites with two wells each were coseismic rises (Fig. 6a and b). The magnitude of the rise was similar in wells 13A and 14B (0.13 m and 0.14 m, respectively) and the rise patterns were also similar although the well depths differed by 35 m. This similarity may have been caused by a hydraulic connection between two permeable layers with similar pore compressibility. The same mechanism could explain the similar behaviors observed in wells 18A and 19C; with both showing 0.03 m rises despite a large difference in depth (155 m). During the GYE however, the responses differed with depth as shown in Fig. 6c and d. A 0.05 m rise was recorded in the deepest well, 15C, a small rise of 0.01 m in well 14B, and no change in the shallowest well, 13A. Near the middle of the Togawa lava, there was no level change in well 16A, but a 0.04 m rise was measured in the deeper well, 17C.

During the FOE, both coseismic rises and falls were observed at different depths. A 0.01 m rise was recorded in wells 13A and 14B, while a 0.05 m rise occurred in the deep well, 15C (Fig. 6e). Just before the earthquake, the groundwater level at well 15C declined suddenly, and then increased again after the earthquake. Therefore, the direction of the coseismic change differed between the shallow and deep parts of a similar location, depending on an increase or decrease in pore pressure. At another site outside the distribution of Togawa lava, coseismic rises occurred in two wells with a depth difference of 80 m. The levels rose by 0.01 m in the shallow well, 31a, and by 0.11 m in the deep well, 32b (Fig. 6f). Therefore, the level in the deep well changed more than the level in the shallow well.

Groundwater levels can be affected by distant earthquakes via seismic waves that interact with aquifers and cause sustained changes in pore pressure (Rexin et al., 1962; Bower and Heaton, 1978; Roeloffs, 1998; King et al., 1999). This phenomenon was observed in our study area for the SCE, as shown by the level changes at two sites over three days, including measurements made before, during, and after the earthquake

(Fig. 7). A feature of note is that the groundwater levels fluctuated more after the SCE than before it in well 15C where the coseismic rise was 0.01 m (Fig. 7a). No groundwater level changes were observed in the shallower wells 13A and 14B. Near the middle of the Togawa lava, in wells 18A and 19C, levels peaked just after the SCE. The coseismic rises were 0.04 m in well 18A and 0.01 m in well 19C.

From the above results, we concluded that coseismic groundwater level changes vary with location, depth, and the magnitude and distance of earthquakes. Based on the poroelastic theory, such variability is caused by differences in aquifer properties or local stress change (Chia et al., 2009). Previously, obvious coseismic changes have not been observed in shallow unconfined aquifers (Chia et al., 2008). In our study area, however, obvious changes were identified in partially confined aquifers, as sampled at well 14B, during all four earthquakes. Changes were also observed in unconfined aquifers, sampled at well 13A, during the KME and the FOE, at well 18A during the SCE, and at well 31a during the FOE. Changes were also measured in confined aquifers, sampled at well 15C during the GYE, the FOE, and the SCE, at well 17C during the SCE, and at well 32b during the FOE. Therefore, all aquifers in our study area underwent coseismic level changes in response to earthquakes of relatively large seismic energy.

4.2 Variation in the shape of coseismic change patterns

There are four types of pattern used to describe coseismic groundwater level changes over time: up-down, up-up, down-up, and down-down, as described by Wang et al. (2004). Following a coseismic rise, an exponential decline in groundwater level occurs in the up-down type, but in the up-up type the level increase is maintained. Following a coseismic drop, an exponential rise in groundwater level occurs in the down-up type, while the decline in level continues in the down-down type. Representative patterns for each type are shown in Fig. 8.

The typical “up-down” pattern fitted with the level changes observed in well 13A for the KME, and well 18A for the SCE. The levels rose abruptly by 0.13 m within one hour after the KME in well 13A, and slowly by 0.04 m within one hour after the SCE in well 18A. This type of response is typically found in unconsolidated sediments, and the rise is stopped by coseismic consolidation of the sediments (Wang et al., 2004; Manga et al., 2003). After a peak in the coseismic rise, the groundwater level tends to decrease gradually following an exponential function with time or a more complex function when the groundwater moves vertically between adjacent aquifers (Jang et al., 2008). The "up-up" pattern type was seen in wells 32b for the KME and 12C for the GYE. Levels rose gradually by 0.04 m in well 32b and by 0.02 m in well 12C, within one hour of each earthquake. After an hour, the levels remained constant (32b) or rose further (12C) before declining. This pattern of change is also most commonly associated with unconsolidated sediments.

The remaining two pattern types are associated with coseismic falls in groundwater levels. The level change pattern in well 47b for the SCE was defined as the "down-up" type, because after a 0.03 m fall, the level gradually recovered. In the "down-down" type, the levels continue to decline, as seen in well 21C for the FOE and well 42a for the GYE. The coseismic falls in these wells were 0.06 m and 0.02 m, respectively.

In summary, the "up" pattern types were seen following the two closest earthquakes, the KME and the FOE (32b), while the "down" pattern types were observed following the distant earthquakes, the GYE (42a) and the SCE (47b). In the deep groundwater wells coseismic changes continued slightly longer than in the shallow groundwater wells. Another finding of note was the groundwater levels in the Togawa lava area tended to change more in magnitude, and more quickly, with shorter recovery times (as seen in wells 13A and 18A), than levels outside the lava (Fig. 8).

4.3 Spatial distribution of coseismic changes

To investigate the spatial distribution of coseismic groundwater level changes over the Kumamoto City area, the changes were classified into coseismic rise, coseismic fall or no response at every observation well, and mapped for the four earthquakes (Fig. 9).

Two maps were prepared for each earthquake showing the changes in shallow and deep groundwater levels.

During the earthquake closest to the study site (the KME), levels changed in 32 out of 54 wells. Among them, coseismic rises were observed in 13 shallow groundwater wells and 9 deep groundwater wells. For both shallow and deep groundwater wells, coseismic rises were mainly concentrated in the southeast part of the study area that overlapped with the area of the Togawa lava. The number of wells showing coseismic level falls was smaller, and the 8 wells where falls were observed were deep groundwater wells, located mainly in the low land.

Because the GYE was centered further from the study site than the KME, most shallow groundwater levels showed no significant change despite the greater magnitude of the GYE. Coseismic rises and falls were observed in 11 wells each and most occurred in the deep groundwater wells. During the second closest earthquake (the FOE), coseismic responses were observed in 30 wells, 12 in the shallow groundwater and 18 in deep groundwater. Rises occurred in 19 wells and falls in 11 wells. Despite the distance of the SCE from the study area, rises and falls were observed in 9 and 19 wells, respectively, therefore level changes were observed in more than half of the wells (28 out of 54). In the shallow groundwater wells, the rises occurred in the Togawa lava area, while the falls occurred outside this area. The number of wells showing a response in the deep groundwater in the Togawa lava area was small, but both rises and falls were observed.

From the results for the four earthquakes two general characteristics were evident for the Kumamoto City area: the groundwater levels in the Togawa lava area were more sensitive to the earthquakes than other parts of the study area, and the deep groundwater levels changed more than the shallow groundwater levels. To examine the spatial distribution of the changes in shallow and deep groundwater levels in detail, the level changes were interpolated using a spline. The resultant maps (Fig. 10) reveal four general and important properties. First, the zones where coseismic rises were observed were generally wider in the deep groundwater than the shallow groundwater.

For all four earthquakes, rises were predominant in the deep groundwater wells in the part of the Togawa lava distribution with a thickness of 30 m or more.

The arrows in the figure roughly represent the directions of seismic waves arriving for each earthquake. Although the direction of seismic waves differed for each earthquake, the anisotropic behavior of the level changes did not, and similar level changes tended to be distributed in a N–S to NW–SE direction. This second property may be attributable to a strong anisotropy of the hydraulic structure that has continuity along this direction, and in particular, the propagation of pressure changes. The third property is the similarity and dissimilarity of the level changes between shallow and deep groundwater. As evident in the KME map, in the same areas where falls where marked in the shallow groundwater, rises occurred in the deep water wells. This dissimilarity is also evident in the FOE map. In the GYE and SCE maps however, the direction of level changes was similar for the shallow and deep groundwater wells. Therefore, our results suggest that nearby earthquakes cause an opposite level change in the shallow and deep groundwater, whereas distant earthquakes cause level changes in the same direction. The possible mechanism underlying this observation is discussed in Sect. 4.6.

Finally, the fourth property is the existence of a clear boundary between the areas where rises and falls were observed in the northwest part of the study area. On the side of the study area near Mt. Kinpo, which is composed of pyroxene andesite, large falls were observed during the four earthquakes. This mountain may therefore act as an impermeable boundary for the level changes.

4.4 Spatial characteristics of pressure changes

Using Eq. (2), the coseismic groundwater level changes measured in the shallow and deep wells were converted to pressure changes. Figure 11 shows maps of the pressure changes caused by the four earthquakes. Based on the definition of the sign of stress in Eq. (4), negative pressure change means an increase in compressive stress accompanying the earthquake, while positive change means a decrease in compressive stress that causes a stress release, tensile condition. The lower limit of level change detected was 0.01 m for all four earthquakes, equivalent to a pressure change of 0.12 kPa. The closest earthquake, the KME, induced the largest pressure changes over the study area. For the second closest earthquake, the FOE, the magnitude and pattern of the pressure changes, shown in the shallow and deep maps were similar to those for the KME. Also of note, the changes caused by the most distant earthquake, the SCE, showed similar spatial characteristics and magnitude in the shallow and deep groundwater as the GYE, despite the large difference in the hypocenter distance. Furthermore, the similarities observed between the changes caused by the KME and the FOE, and the SCE and the GYE, occurred despite differences in the arrival direction of seismic waves. The findings illustrated in the pressure change maps show that the parts of the Togawa lava distribution with a thickness greater than 30 m underwent smaller increases in compressive stress for all earthquakes.

Although the magnitude and spatial pattern of pressure changes differed slightly among the earthquakes, general trends in the deep groundwater changes were seen. The western and eastern parts of the Kumamoto City area underwent coseismic increases and decreases in compressive stress, respectively. The pressure changes in the shallow groundwater in the western part of the area tended to occur in an opposite direction compared with the deep groundwater. For the closest earthquakes, the KME and the FOE, the zone where relatively large decreases in compressive stress were observed in the shallow groundwater, colored red on the maps, and increases in compressive stress were observed in the deep groundwater. Therefore, coseismic increases or decreases in compressive stress in the shallow groundwater are variable depending on the distance of the earthquake from the study site.

4.5 Effect of Togawa lava

The maximum groundwater level changes during the four earthquakes were 0.67 m (the KME), 0.11 m (the GYE), 0.24 m (the FOE), and 0.10 m (the SCE), equivalent to pressure changes of 8.6 kPa, 1.4 kPa, 3 kPa, and 1.3 kPa, respectively. The magnitude and spatial pattern of these changes may be partly related to the configuration of the Togawa lava, because there was no clear correlation between the pressure changes and the distance to the earthquake hypocenter. To investigate this further, the pressure changes in each well were correlated with the lava thickness at the well location, as shown in Fig. 12. Except for the SCE, there was no significant correlation between pressure change and lava thickness. For the SCE, although the data were scattered around the regression line, compressive stress increased with an increase in the lava thickness (coefficient of determination $R^2 = 0.63$). Therefore, correlation between lava thickness and an increase in compressive stress was seen only for the distant earthquake and is an interesting phenomenon identified by this analysis. A possible cause of this phenomenon is that impact of the slow load of the seismic force with a long wavelength on the lava may have brought out its elastic property.

4.6 Conceptual model for level change mechanism

As one interpretation of the level and pressure changes shown in Figs. 10 and 11, a conceptual model for the mechanism of groundwater level changes resulting from close and distant earthquakes is shown in Fig. 13. In this model, we assume that the shallow and deep aquifers are partly connected by fractures, or the absence of aquicludes between the aquifers, as described by Parvin et al. (2011). Mt. Kinpo is used as an impermeable boundary. For close earthquakes, the deep groundwater is strongly compressed because of the large seismic force, which causes relatively large rises in groundwater level. Because of the propagation of the strong pressure toward the shallow aquifer, or the large seismic force at shallow depths, new fractures or fissures may be generated around the shallow aquifer. This is an important factor contributing to groundwater level change, as shown in Fig. 1. New fractures or fissures result in a release of pressure, and consequently the levels of shallow groundwater fall, as seen for the KME and the FOE, and illustrated in Fig. 10.

On the other hand, for distant earthquakes, the seismic forces may be uniform over the depth range, leading to increases in compressive stress in both the shallow and deep aquifers. However, if the forces are not strong enough to generate fractures or fissures, the level changes will be small. As a result, rises in groundwater levels and increases in compressive stress would occur most frequently in the zones in which the stresses are concentrated in the shallow and deep aquifers.

5 Conclusions

The aim of this study was to characterize the detailed spatial distribution of coseismic changes in shallow and deep groundwater over a sedimentary basin during four earthquakes. We also attempted to identify the mechanisms underlying the level changes by integrating the coseismic responses. The Kumamoto City area, with one of the richest groundwater resources in Japan, was chosen for this study, and data from hourly groundwater level measurements at 54 wells from 2000 to 2009 were used for the analyses. The main findings are summarized below.

1. Although the epicenter distances (12 to 2573 km) and seismic energy (Mw = 4.8 to 8.0) of the four earthquakes varied considerably, systematic groundwater level changes were observed in the range of 0.01 to 0.67 m. The effect of earthquakes on groundwater levels became stronger with shorter epicenter distances, regardless of the seismic energy, but a small effect from the Sichuan Earthquake was detected despite the distance to the epicenter being more than 2500 km.

2. The importance of the Togawa lava, a porous andesite, for groundwater level change was identified, because levels in the Togawa lava area tended to change more in magnitude, and more quickly, with a shorter recovery time, than levels measured in the area outside the lava.

3. The coseismic level change maps showed that zones where coseismic rises were observed were generally wider in the deep groundwater than the shallow groundwater. Rises were more likely to be recorded where the Togawa lava was more

than 30 m thick, and were more likely in the deep groundwater for all four earthquakes, probably as a result of an increase in compressive stress.

4. Despite the difference in the arrival directions of seismic waves, general trends in the level and pressure changes in the deep groundwater were observed over the study area. However, the coseismic increase or decrease in compressive stress in the shallow groundwater varied with the distance to the earthquake epicenter.

5. We developed a conceptual model for the mechanism underlying level and pressure changes as follows. During earthquakes close to the study site, deep groundwater is strongly compressed, resulting in a relatively large rise in groundwater level. Because of the propagation of strong pressure from the deep to shallow aquifers, or large seismic forces at shallow depths, new fractures or fissures may be generated around the shallow aquifer, causing falls in shallow groundwater levels. On the other hand, during distant earthquakes, the seismic forces may be uniform over the depth range, but not strong enough to generate fractures or fissures and consequently, the rise in groundwater levels and the increase of compressive stress occurs in both the shallow and deep aquifers.

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Table 1. Details of the four earthquakes and the range of coseismic changes in groundwater levels.

Name of the Earthquake	Occurrence time	Analysis time	Location of the hypocenter		Depth of the hypocenter (km)	Moment Magnitude (Mw)	Hypocenter distance (km)	Range of GWL change (m)
			Latitude	Longitude				
KME	8 June 2000 09:32:46 JST	09:00 and 10:00	32°47′18″ N	130°45′8″ E	10	4.8	12–25	0.01–0.67
GYE	24 March 2001 15:27:55 JST	15:00 and 16:00	34°04′59″ N	132°31′34″ E	51	6.7	232–246	0.01–0.05
FOE	21 March 2005 10:53:40 JST	10:00 and 11:00	33°44′18″ N	130°10′30″ E	9	7.0	106–123	0.01–0.15
SCE	12 May 2008 15:28:01 JST	15:00 and 16:00	31°01′16″ N	130°22′01″ E	19	8.0	2551–2573	0.01–0.04

Table 2. Bottom depths of the wells selected for measuring coseismic groundwater level changes shown in Figs. 6 and 7. See Fig. 5 for their locations.

Wells	Latitude	Longitude	Depth (m)
13A 14B 15C	32°45′54″ N	130°46′48″ E	25.3 70.45 201
16A 17C	32°46′14″ N	130°47′16″ E	31 202
18A 19C	32°46′20″ N	130°45′48″ E	40 195
31a 32b	32°50′05″ N	130°43′18″ E	17.2 97.9

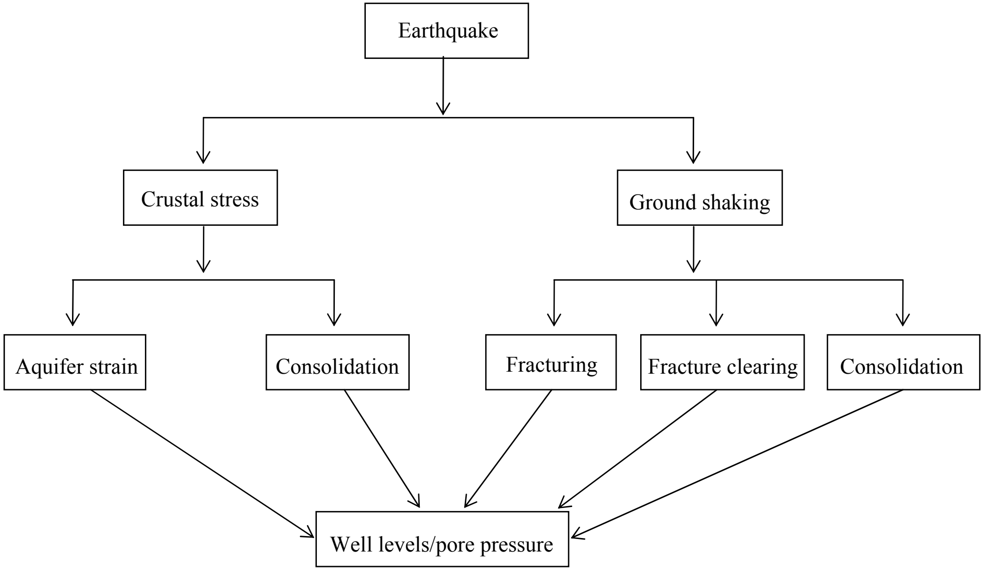

Fig. 1. Interactions between earthquakes and hydrological processes according to Montgomery and Manga (2003).

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| | |▶
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

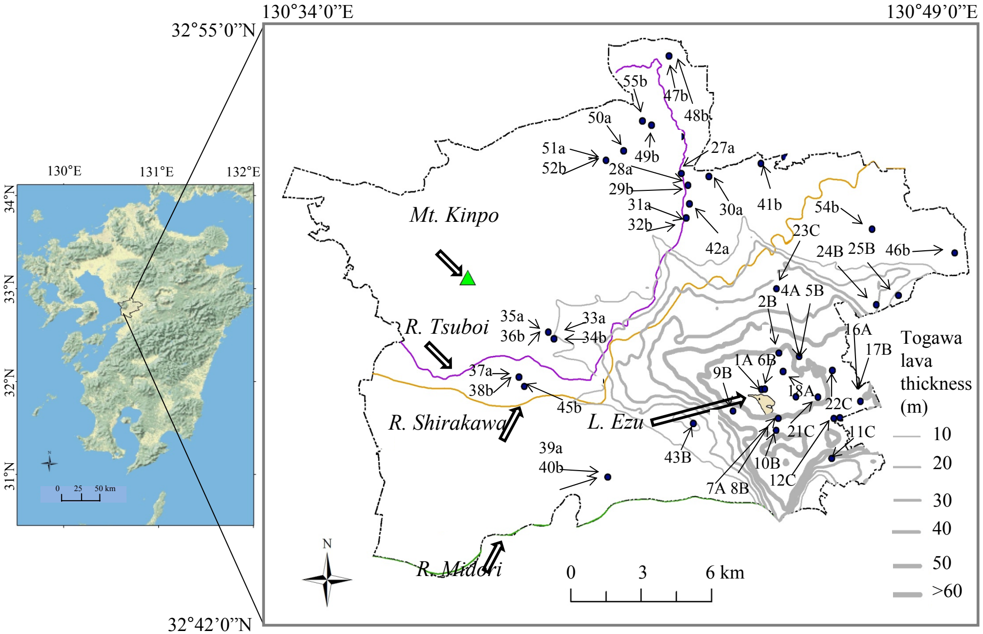

Fig. 2. Location of the study area and distribution of 54 wells used to monitor groundwater levels. The thickness of the Togawa lava is overlapped with the distribution on the basis of three-dimensional geological modeling of the study area by Koike and Matsuda (2005).

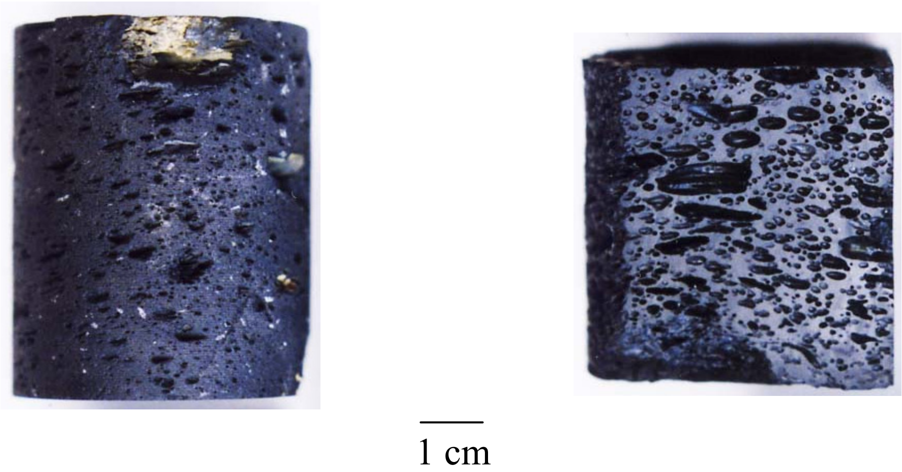

Fig. 3. Photographs of porous sections of Togawa lava (Pleistocene pyroxene andesite).

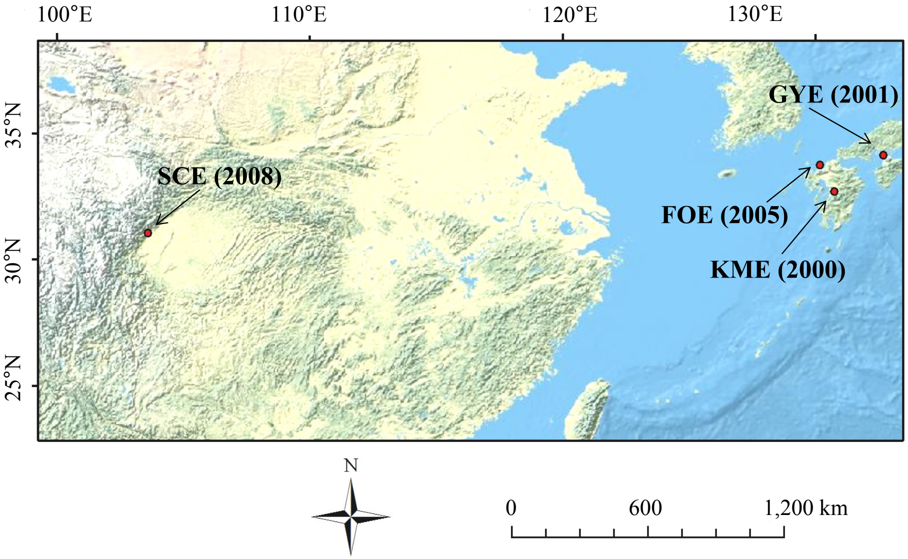

Fig. 4. Locations of the epicenters of four earthquakes that affected the groundwater levels in the Kumamoto City area. The Kumamoto Earthquake in 2000 (KME), the Geiyo Earthquake in 2001 (GYE), the Fukuoka West Offshore Earthquake in 2005 (FOE), and the Sichuan Earthquake in 2008 (SCE).

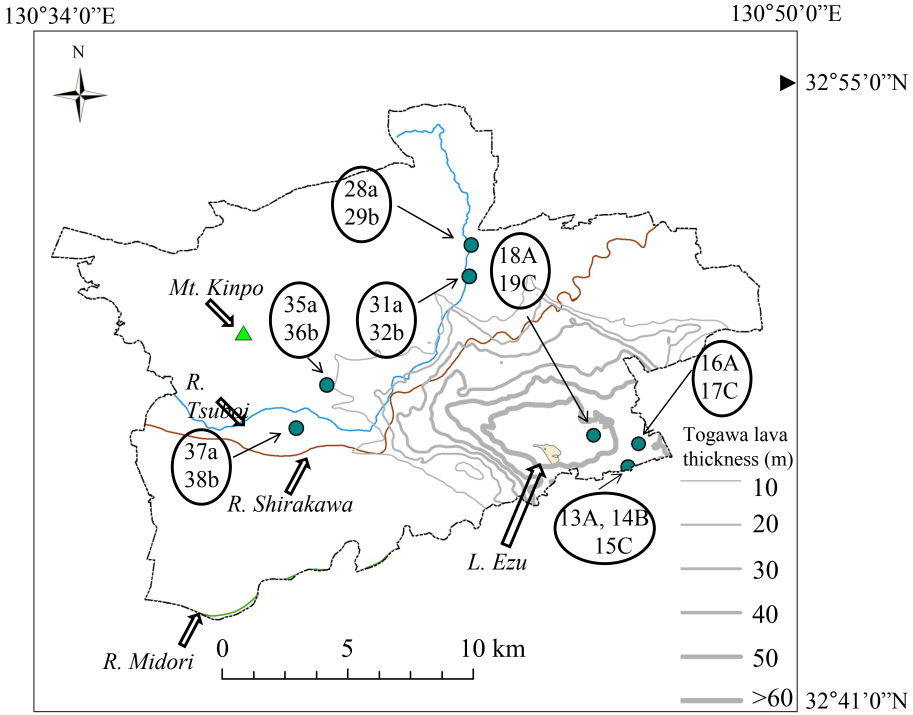

Fig. 5. Locations of representative wells selected for investigating coseismic changes during the four earthquakes in Fig. 6. The two or three wells circled together were closely located, but with different bottom depths to sample the shallow and deep groundwater as shown in Table 2.

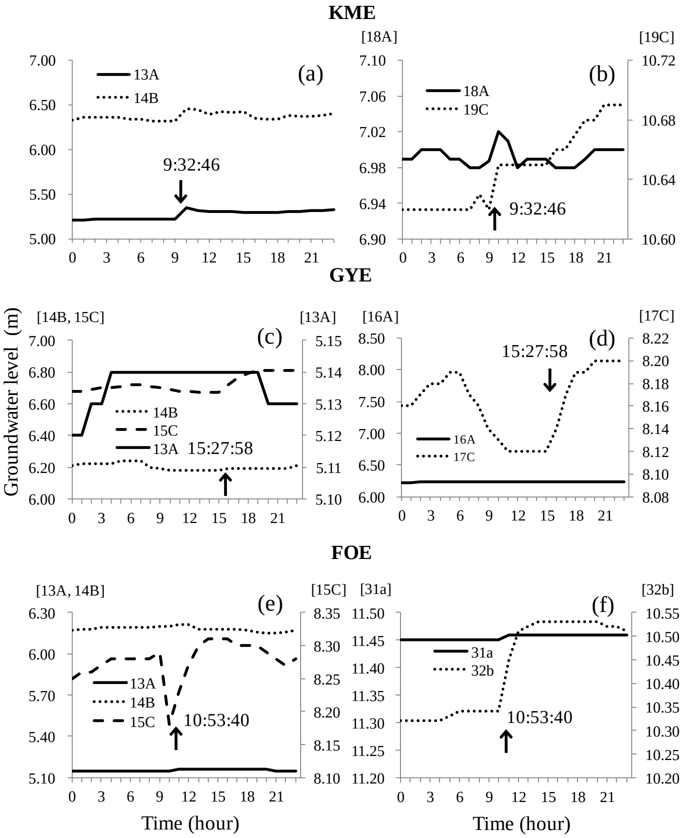

Fig. 6. Groundwater level changes recorded during the three earthquakes centered in Japan. Graphs show changes measured during the day of earthquake occurrence in two or three wells with similar locations, but different bottom depths as shown in Table 2. The arrows indicate the occurrence time of the earthquake.

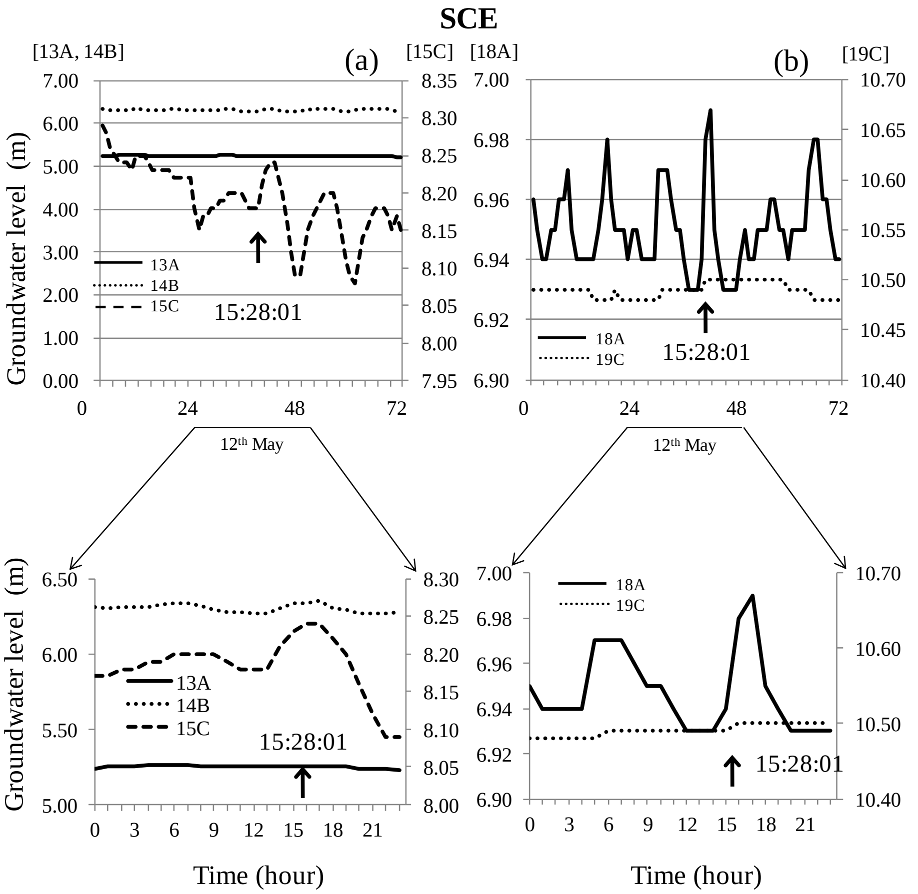

Fig. 7. Groundwater level changes over three days around the time of the SCE, the most distant earthquake, in two or three wells with the same location in the distribution of Togawa lava, but with different bottom depths (Table 2). The bottom graphs are enlargements of the day of the earthquake.

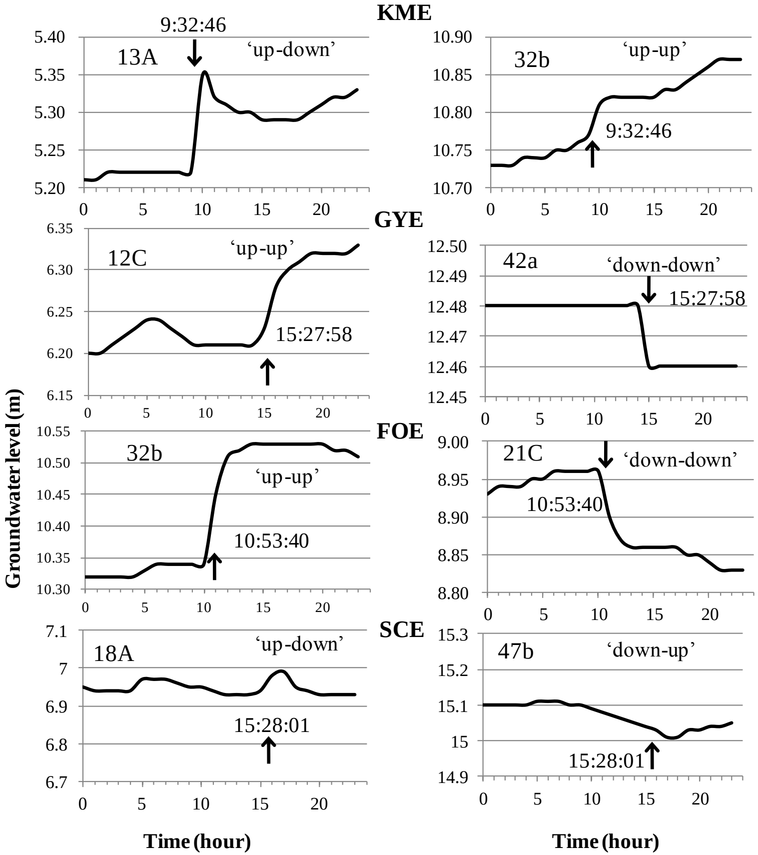

Fig. 8. Representative coseismic change patterns for groundwater levels classified in to four types, "up-down", "up-up", "down-up", and "down-down".

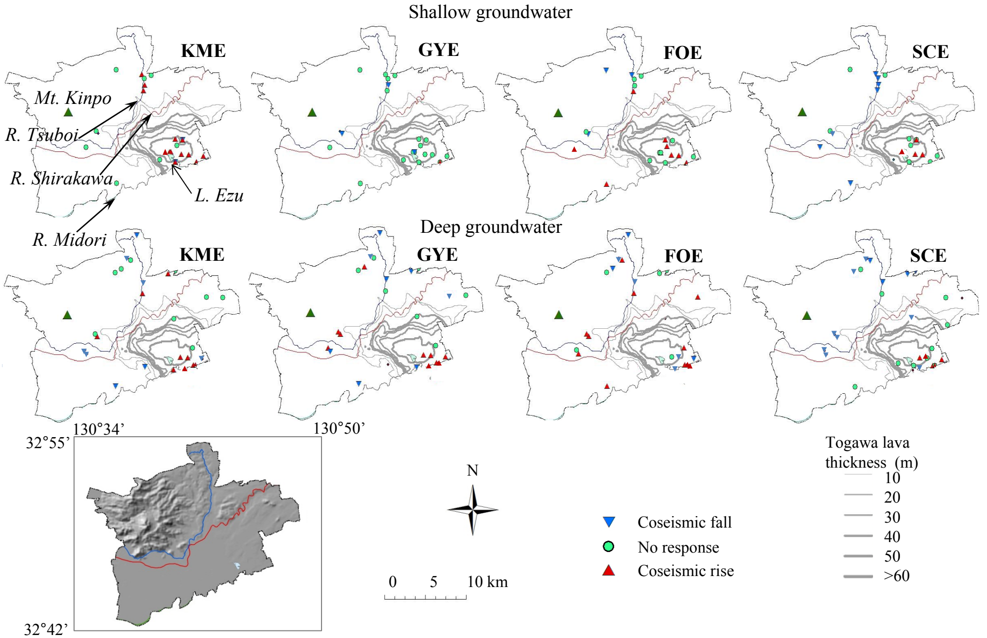

Fig. 9. Spatial distribution of coseismic level changes in the shallow and deep groundwater during the four earthquakes, classified as coseismic rise, coseismic fall, and no response.

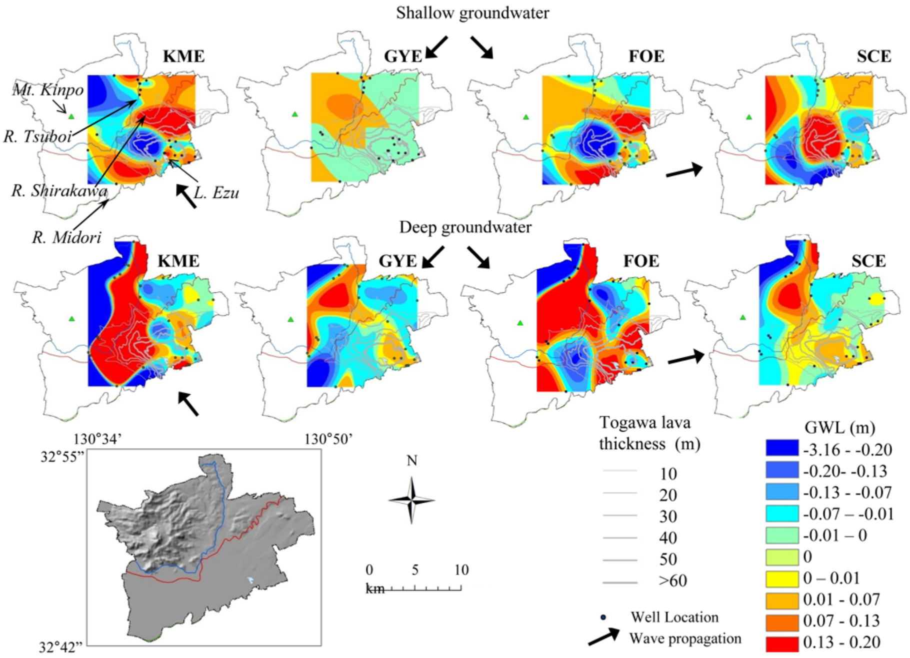

Fig. 10. Coseismic level change maps for the shallow and deep groundwater, produced by spline interpolation of the well data in Fig. 9, in which positive and negative values mean rise and fall of water levels, respectively.

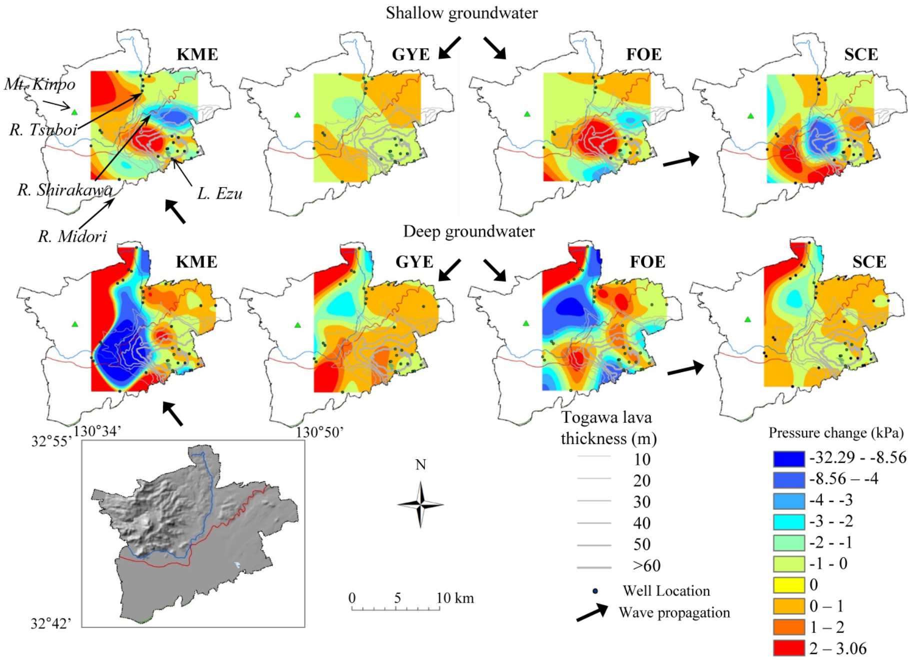

Fig. 11. Coseismic pressure change maps for the shallow and deep groundwater, calculated from Fig. 10 and using Eq. (2), in which positive and negative values mean coseismic decrease and increase of compressive stresses, respectively.

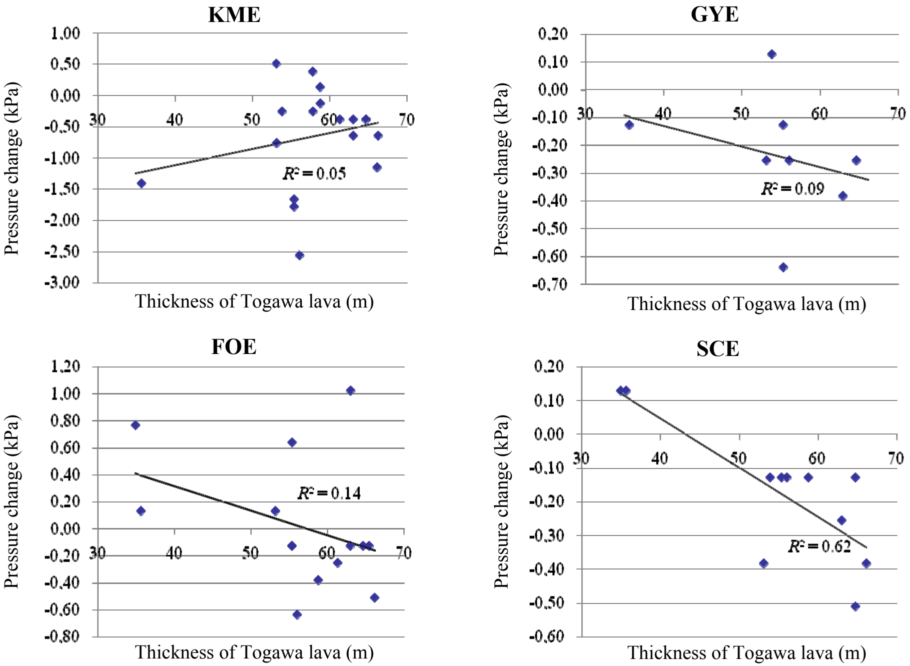

Fig. 12. Correlation between the groundwater pressure changes and the thickness of Togawa lava during the four earthquakes.

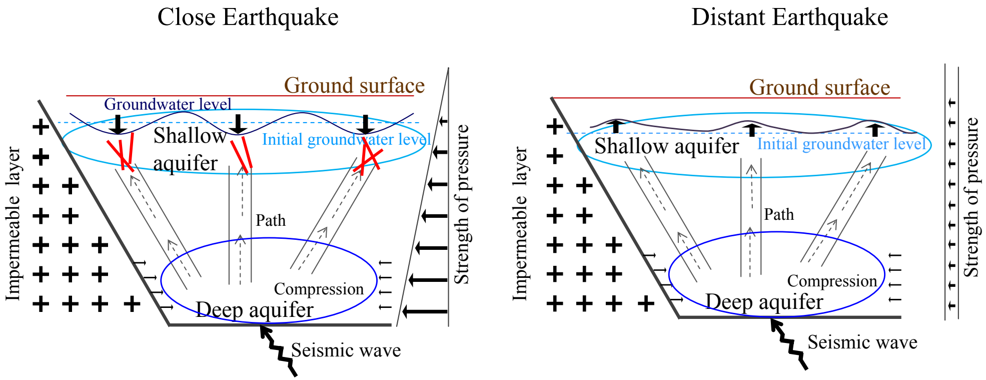

Fig. 13. A conceptual model for the mechanism of groundwater level changes caused by close and distant earthquakes, in which the shallow and deep aquifers are assumed to be connected partly by fractures, or the absence of aquicludes between the aquifers.

HESSD

9, 5317–5354, 2012

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀◀
▶▶
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion