Sustained groundwater level changes and permeability variation in a fault zone following the 12 May 2008, M_w 7.9 Wenchuan earthquake

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Abstract:

We analyse the groundwater level changes following the Wenchuan earthquake in three wells – NX, DZ and BBLY – located in the same fault zone, in the near field (distance of ~300 km from the epicentre). Co-seismic falls in the water level and gradual recovery were recorded in these wells but with different recovery periods (from 200 days to more than 1600 days). The response of the groundwater level to Earth tides is used as a proxy to explore the permeability evolution. We found that the permeability increased in response to the Wenchuan earthquake in the three wells but with different post-earthquake recovery processes. Only BBLY recovered to its pre-earthquake value 260 days after the Wenchuan earthquake and remained stable. The permeability in NX returned to its pre-earthquake value over a similar period but then continued to drop. The permeability in DZ returned to its pre-earthquake value much quicker than that in the other two wells and remained stable below the pre-earthquake value 200 days after the earthquake. This suggests that the groundwater level changes in the three wells were mainly caused by permeability changes. In the BBLY well, the unclogging/clogging of the fracture flow path mechanism may explain the permeability evolution, whereas mechanisms such as unclogging/clogging or the opening/closing of the fracture associated with blocking of the narrow fracture apertures appears to be responsible for the permeability evolution in the NX and DZ wells. Copyright © 2014 John Wiley & Sons, Ltd.

KEY WORDS groundwater level; sustained change; tidal response; permeability evolution

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INTRODUCTION

Earthquake-induced hydrological changes, including those in stream flows, reservoir water levels, temperature and chemical composition, have been documented for thousands of years (Matsumoto and Roeloffs, 2003; Manga and Wang, 2007). Co-seismic and post-seismic water level changes in wells are the most widely reported among the earthquake-induced hydrologic phenomena because they can be measured easily and precisely (Wang and Manga, 2007). Water level changes following earthquakes can be classified on the basis of three major patterns: step-like changes, sustained changes and oscillations (Cooper et al., 1965; Roeloffs, 1998; Brodsky et al., 2003; Shi et al., 2013a). Several mechanisms were proposed to explain these changes. Step-like changes in a few source dimensions of earthquake epicentres can often be explained by elastic static strain (Wakita, 1975; Roeloffs, 1998; Ge and Stover, 2000). In some cases, however, the magnitude of the water level changes was not consistent with the calculated volumetric strain changes in some sedimentary aquifers; undrained consolidation and dilatation of the sediments may be responsible for these cases (Wang and Chia, 2008). Sustained changes are mostly observed when the epicentre distance is more than one ruptured fault length; the mechanism is related to the permeability changes of the aquifers (Brodsky et al., 2003; Matsumoto and Roeloffs, 2003; Wang and Chia, 2008). However, other mechanisms similar to ‘liquefaction’ (Roeloffs, 1998), shaking-induced dilatancy (Bower and Heaton, 1978), diffusion of co-seismic, localized pore pressure changes or co-seismic discharge changes (Roeloffs et al., 2003) are also employed to interpret sustained changes in some cases. For water level oscillation in wells, it is thought that surface waves from a distant seismic event can cause aquifers to expand and contract, which may lead to resonant motion in high-transmissivity aquifers with suitable geometry (Cooper et al., 1965; Liu et al., 1989).
Among the mechanisms mentioned earlier, the permeability change induced by seismic waves in aquifers is a favourable mechanism to explain many of these hydrological processes in the intermediate or far field. Because static stress/strain changes beyond the near field are smaller and rarely cause large-amplitude water level changes in wells, only dynamic stress will result in transient or sustained changes in hydrogeologic properties; therefore, hydrological changes can be expected at large distances from the epicentre (Manga et al., 2012). However, there are no direct observations of permeability and water level evolution during and after earthquakes despite a few field and laboratory studies dealing with permeability changes and recovery (Elkhoury et al., 2006, 2011; Faoro et al., 2012; Candela et al., 2014). It is important to study the relationship between permeability and groundwater changes, which may provide insight into the mechanism of post-seismic groundwater and permeability changes in the near field (Manga et al., 2012).

Water level responses to Earth tides provide a good proxy for studying the permeability evolution of the crust (Hsieh et al., 1987; Elkhoury et al., 2006). Xue et al. (2013) employed this method in the Wenchuan earthquake fault zone to explore permeability evolution and revealed a variable recovery pattern of healing and damage after the large Wenchuan earthquake (Xue et al., 2013). We can gain more insight into the interaction between earthquakes and fault responses in the region by examining whether a similar process occurs in other fault zones nearby. In this paper, we study the relationship between long-term changes of the water level and permeability evolution following the Wenchuan earthquake in three confined wells located in the same fault zone (the Huayingshan fault zone, which lies parallel to the Wenchuan earthquake fault zone). The permeability evolution is inferred from the phase changes through tidal analysis of long-term groundwater level monitoring data. We analyse the water level recovery processes and the permeability and explore the mechanism of permeability changes.

**STUDY AREA AND DATA**

The 12 May 2008, $M_w$ 7.9 great Wenchuan earthquake caused large-scale water level changes in wells in mainland China. Step-like, sustained and oscillation changes in the water level were recorded following this event (Yang et al., 2008; Shi et al., 2013a). In this study, we examine the sustained changes in three monitoring wells, NX, DZ and BBLY, located along a north east–south west line on the Huayingshan fault zone, which is parallel to the Wenchuan earthquake fault (Longmenshan fault) zone and approximately 300 km away from the epicentre of the Wenchuan earthquake (Figure 1 and Table I). The basement of the Huayingshan fault was formed with a right-lateral thrust during the Jinningian period. With a length of about 600 km, it is one of the largest faults in the Sichuan basin. The fault strike is NE 40–45° with a dip angle of 30–70°. Concomitant sub-structures developed on its cap rocks such as a series of en-echelon sub-faults with lengths of several to dozens of kilometres and fault-fold structures.

![Figure 1. Location of the $M_w$ 7.9 Wenchuan earthquake epicentre and the three groundwater monitoring wells. The ‘beach ball’ plot shows the focal mechanism of the earthquake. Black triangles denote the groundwater monitoring wells. Red lines indicate the faults, and yellow circles show the earthquakes that occurred around the Huayingshan fault between September 2007 and April 2013.](image)

<table>
<thead>
<tr>
<th>Well name</th>
<th>Depth (m)</th>
<th>Lithology</th>
<th>Epicentre distance (km)</th>
<th>Co-seismic ground water level changes (m)</th>
<th>Hydraulic conductivity$^a$ (m/day)</th>
<th>Casing interval (m)</th>
<th>Groundwater type</th>
</tr>
</thead>
<tbody>
<tr>
<td>NX</td>
<td>101</td>
<td>Quartz sandstone</td>
<td>266</td>
<td>-1.10</td>
<td>0.41</td>
<td>57.5–101</td>
<td>Fracture groundwater</td>
</tr>
<tr>
<td>DZ</td>
<td>108.7</td>
<td>Mud and sandstone</td>
<td>284</td>
<td>-0.68</td>
<td>0.05</td>
<td>45.5–108</td>
<td>Fracture groundwater</td>
</tr>
<tr>
<td>BBLY</td>
<td>105.4</td>
<td>Mud and sandstone</td>
<td>328</td>
<td>-0.95</td>
<td>—</td>
<td>42.1–105</td>
<td>Fracture groundwater</td>
</tr>
</tbody>
</table>

$^a$ The hydraulic conductivity was obtained from the pump test performed when the wells were constructed.
distributed along the anticline axes. These structures play an important role in controlling the local seismic activity (Wang et al., 2011). There is no historical evidence of earthquakes of M ≥ 5.0 along this fault, but there were many earthquakes with M ≥ 3 along the fault, some of these attributed to water injection at a nearby gas field (Lei et al., 2008). Between September 2007 and April 2013, 93 earthquakes of M > 3 occurred in the area (Figure 1; China Earthquake Data Center).

The three monitoring wells, NX, DZ and BBLY, were constructed as part of the subsurface fluid monitoring network in the Huayingshan fault, specifically for monitoring fluid pressure and crustal deformation changes associated with a possible earthquake precursor. The NX well, located in the north-western part of the Qingshanling anticline and the fault zone, penetrated a confined sandstone aquifer, which had three small fractures with a dip angle of 5–60°. The well is 101.5 m deep and screened along the depth interval of 57.5–101 m where it penetrates the quartz sandstone aquifer (Table 1). The casing radius is 10.5 cm, and the well radius is 8 cm with a water temperature of about 20.54 °C. The DZ well is located in the western part of the west mountain anticline in the western Huayingshan fault zone. The well is 108.7 m deep and penetrates a confined fractured aquifer. It was screened at depths of 45.5–108 m in the middle Jurassic sandstone aquifer. The well has a casing radius of 7.5 cm and a well radius of 6.4 cm. The water level sensor is located 11.3 m below the ground surface, where the water temperature is around 19.94 °C. Weathering fractures developed near the ground surface around the well, and the aquosity of the rock decreased with depth. The well has a hydraulic conductivity of 0.05 m/day (Chen et al., 2012). The BBLY well is located in the western part of the Guanyinxia anticline, at the hanging wall of the Huayingshan fault. A sub-fault named Baizimiao exists near the well. The well is 105.4 m deep and penetrates a confined fractured aquifer. The water level sensor is located 6.5 m below the ground surface, where the water temperature is around 20.79 °C.

The water levels in the three monitoring wells, NX, DZ and BBLY, were recorded by an LN-3 digital instrument developed by the Institute of Earthquake Science, China Earthquake Administration at a sampling rate of 1 min and accuracy of 1 mm. The monitoring system in the wells was upgraded to a digital system in late 2007; therefore, we selected the water level data from September 2007 to April 2013 for our analysis. Additionally, rainfall and barometric pressure data were collected from a station near the DZ well. To better evaluate the water level changes associated with the earthquakes, we removed the barometric pressure and tidal signals from the raw water level time series using the Baytap-G program (Tamura et al., 1991; Tamura and Agnew, 2008). Comparison between the original and corrected water levels (Figure 2) shows slight differences, indicating that the barometric pressure and tidal signals have some effect on the water levels. The rainfall, especially the peak rainfall activity, may also correlate with water level changes in some periods (such as at DZ during 2010–2011). Generally, however, the main water level trends are not significantly affected by these meteorological factors, and the co-seismic and post-seismic changes caused by the earthquakes can be clearly identified (Figure 2).

METHODS

The water level response to Earth tides in a confined aquifer tapped by wells can be used to investigate crustal permeability, thus providing a method to monitor long-term, continuous permeability evolution (Elkhoury et al., 2006; Xue et al., 2013). For a single, laterally extensive, homogeneous and isotropic confined aquifer, a phase lag (or time lag) exists between the tidal dilatation of the aquifer and the water level response of the well. The phase lag is related to the aquifer transmissivity. The permeability is also proportional to the transmissivity (Hsieh et al., 1987). Small phase lags correspond to high transmissivity of the aquifers, whereas large phase lags correspond to low transmissivity. Thus, we can infer the permeability changes from the variation in phase lags.

To obtain the phase lags in the aquifer, we use the tidal analysis data. For tidal analysis, we compare the observed tidal oscillations with the theoretical Earth tides. Several open programs can be used for the tidal analysis, such as VAV, ETERNA, Baytap-G and PIASD. The analysis in this study was carried out using Baytap-G, which uses Akaike’s Bayesian information criterion. It assumes that a time series can be divided into the following parts (Tamura et al., 1991; Doan et al., 2006; Tamura and Agnew, 2008):

\[ y_i = \sum_{m=1}^{M} (\alpha_mC_{mi} + \beta_mS_{mi}) + \sum_{k=0}^{K} b_kx_{i-k} + d_i + e_i \quad (1) \]

The first term on the right-hand side is the tidal component: \( C_{mi} \) and \( S_{mi} \) are theoretically calculated values for the \( m \)th group of tidal constituents, and \( \alpha_m \) and \( \beta_m \) are the tidal response constants to be determined in the statistical model. The barometric response component is expressed as \( \sum_{k=0}^{K} b_kx_{i-k} \), where \( x_{i-k} \) is the
observed barometric pressure and $b_k$ is a response coefficient, $d_l$ is the long-term trend and $e_l$ is the noise. This program incorporates a Bayesian inversion process that allows the parameters $\alpha_m$ and $\beta_m$ to be calculated and then evaluated by minimizing the Akaike Bayesian information criterion that is formulated from Equation (1). The result of the Baytap-G analysis provides the amplitude and phase for each tide group (Burbey, 2010).

When encountering missing data during the analysis, if less than 24 h of data were missing, we used linear interpolation to complement the gap. If the data gap was more than 24 h, we ignored that period in the analysis. We set a data window of 30 days with an overlap of 15 days. The tidal waves are grouped into five major constituents, $O_1$, $K_1$, $M_2$, $S_2$ and $M_3$, which have different and distinct frequencies. In this study, we used the $M_2$ wave results for further analysis because this wave component is more stable and less influenced by barometric pressure (Doan et al., 2006; Shi and Wang, 2013). After calculating the tidal analysis, we obtained the phase and amplitude changes from 2007 to 2013 (Figure 3).

RESULTS AND DISCUSSION

Co-seismic water level changes in the three wells

As shown in Figure 2, the original data of the water level in the three wells exhibit a large fall in amplitude following the Wenchuan earthquake, which did not recover even after a few months. The water level decreased 1.1 m in NX, 0.68 m in DZ and 0.95 m in BBLY (Table I). The water level in the three wells also responded to large remote earthquakes. After the 2011 Tohoku $M_w$ 9.0 earthquake, the water level showed a 0.18-m step decrease in NX and then recovered to the pre-earthquake water level. The water level at BBLY increased 0.1 m after the earthquake and then continued increasing progressively. The water level in DZ showed a 0.04-m decrease after the 2011 earthquake and then started to increase. The 2012 Sumatra $M_w$ 8.6 and $M_w$ 8.2 earthquakes (which occurred on the same day) caused a 0.06-m rise in NX, 0.08-m rise in BBLY and 0.02-m decrease in DZ.

Tidal response changes with times

As shown in Figure 3, all three wells had a large phase increase when the Wenchuan $M_w$ 7.9 earthquake occurred. However, the phase changes after the Wenchuan earthquake differed (Table II). At NX, the phase gradually declined after the initial increase. The phase was $5.3^\circ$ higher than the pre-earthquake level, returning to the pre-earthquake value about 300 days after the earthquake. It then continued to decline, dropping to $-6^\circ$ in April 2013 at a decline rate of about $-0.006^\circ$ per day. The phases at DZ remained low after an initial increase of $8.5^\circ$.

Figure 2. Groundwater level variations in the NX, DZ and BBLY wells during 2007–2013. The dashed lines represent the times of the earthquake events. The black curve in the top three panels is the original groundwater level, and the red curve is the groundwater level with the barometric pressure and Earth tide removed.
and finally recovered to a low steady value about 200 days after the earthquake. The estimated decline rate is $-0.042^\circ$ per day. For the BBLY well, an $11.2^\circ$ increase in phase occurred during the earthquake; the phase returned to the pre-earthquake value about 260 days after the earthquake, which is a recovery rate of about $0.043^\circ$.
The phases in the NX and DZ wells are negative most of the time, although a positive phase appeared for a short time following the Wenchuan earthquake and then decreased to the pre-earthquake value; it then remained stable with small fluctuations. The amplitude in DZ increased by 0.14 cm following the Wenchuan earthquake and then continually decreased. In April 2013, the amplitude was 0.21 cm higher than it was before the Wenchuan earthquake. At BBLY, a 0.2-cm drop in amplitude occurred during the Wenchuan earthquake, and then the amplitude increased continuously until April 2013. The amplitude was about 0.1 cm higher compared with the pre-earthquake value. Here, the amplitude represents the groundwater level that was induced by the M2 tide. Thus, the amplitude changes may signify the ability of the aquifer to respond to Earth tides in the well; i.e. the evolution of the tidal amplitude may also indicate changes in the aquifer properties.

Permeability and water level evolution following the Wenchuan earthquake

The phases in the NX and DZ wells are negative most of the time, although a positive phase appeared for a short time following the Wenchuan earthquake. The phase in BBLY is positive during the entire monitoring period. According to Hsieh et al. (1987), for a single, homogeneous, isotropic, laterally extensive, confined aquifer, the phase shifts between the Earth tides and the water level are assumed to be caused by the time required for water to flow into and out of the well. The water table drainage effect in this case is negligible, and the phase shifts should be negative; hence, a phase shift increase implies an increase in transmissivity or permeability (Hsieh et al., 1987; Elkhoury et al., 2006). A positive phase shift may be observed if the aquifer is not completely confined because then the drain at the water table cannot be ignored. Roeloffs (1996) presented a model in which vertical drainage of the water table can cause positive phase shifts. In this model, a phase increase (such as from 5° to 10°) indicated an increase in the hydraulic diffusivity of the aquifer, which can be regarded as an increase in the permeability (Rojstaczer and Riley, 1990; Roeloffs, 1996). Thus, a phase increase (either positive or negative) implies an increase in permeability (Lai et al., 2014). Here, we only estimate the changes in the hydraulic conductivity of DZ before and after the Wenchuan earthquake and the hydraulic conductivity of NX before and after the Wenchuan earthquake and when it reached the stable state in 2013 (both points have a negative phase shift). The estimated hydraulic conductivity of DZ using the Hsieh model (Hsieh et al., 1987) was around 0.028 m/day before the Wenchuan earthquake and increased to 0.057 m/day after the Wenchuan earthquake. The hydraulic conductivity of NX was around 0.4 m/day before the Wenchuan earthquake and stabilized at around 0.08 m/day in 2013. The hydraulic conductivity estimated from the tidal response in DZ and NX was close to the results of the pump tests (Table I), which indicates that we can use the phase of the tidal response as a proxy of the permeability. An increase in phase implies an increase in permeability.

On the basis of the preceding analysis, the permeability in all three wells increased following the Wenchuan earthquake; this is consistent with other studies showing a rise in permeability during the earthquakes (Rojstaczer et al., 1995; Brodsky et al., 2003; Elkhoury et al., 2006; Wang et al., 2009; Manga et al., 2012; Shi et al., 2013b). However, the post-earthquake evolution of the permeability in the three wells is quite different. Only BBLY recovered to its pre-earthquake value and remained stable 260 days after the Wenchuan earthquake. The permeability in NX returned to its pre-earthquake value over a similar period but then continued to drop. The permeability in DZ returned to its pre-earthquake levels much quicker than that in the other two wells and remained stable below the pre-earthquake levels 200 days after the earthquake. In previous studies, the rise in permeability was followed by a process of recovery to the pre-earthquake value (Manga et al., 2012), but the subsequent drop after the recovery has not been previously reported. As shown in Figure 2, the post-earthquake water levels in the three wells also have different responses (Table II). The water level in NX had not returned to its pre-earthquake value by the end of the monitoring period (although the water level fell after the

<table>
<thead>
<tr>
<th>Well name</th>
<th>Co-seismic tidal amp change (mm)</th>
<th>Co-seismic phase change (°)</th>
<th>Co-seismic static strain $a$</th>
<th>Estimated WL by static strain $a$ (m)</th>
<th>WL recovery time (day)</th>
<th>Phase recovery time (day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NX</td>
<td>0.6</td>
<td>5.3</td>
<td>$4.9 \times 10^{-8}$</td>
<td>$-0.02$</td>
<td>&gt;1600</td>
<td>300</td>
</tr>
<tr>
<td>DZ</td>
<td>1.4</td>
<td>8.5</td>
<td>$2.1 \times 10^{-7}$</td>
<td>$-0.16$</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>BB</td>
<td>2.0</td>
<td>11.2</td>
<td>$2.3 \times 10^{-7}$</td>
<td>$-0.15$</td>
<td>1000</td>
<td>260</td>
</tr>
</tbody>
</table>

$a$ The static strain and estimated water level changes are according to Shi et al. (2014).
other earthquakes, the drop in amplitude was much smaller. The water level in DZ recovered about 200 days after the Wenchuan earthquake, about the same time it took the permeability to stabilize. However, the water level still shows large fluctuations after that, indicating that the hydraulic gradient of the aquifer did not recover to its pre-earthquake state. At BBLY, the water level recovered gradually and returned to its pre-earthquake state approximately 1000 days after the Wenchuan earthquake. This indicates that the co-seismic water level changes are closely related to the permeability changes, but the recovery of the water level requires much more time than the recovery of the permeability. Although other factors, such as rainfall and barometric pressure, may cause some small phase shift fluctuations in some periods, the general trends are not significantly affected by the meteorological factors. Seismic activity after the Wenchuan earthquake also shows no obvious impact on the permeability recovery of the three wells. Thus, the evolution of the phase shifts should represent the changes in permeability associated with the Wenchuan earthquake.

Note that the study of Xue et al. (2013) on the permeability evolution in the Wenchuan earthquake fault zone shows a long-term decrease in permeability, which indicates the process of fault healing after the damage caused by the Wenchuan earthquake. In our study, we found that the permeability in the Huayingshan fault also changed after the Wenchuan earthquake. Although the mechanism behind the permeability evolution in the three wells in this study may be different, both results indicate that the permeability in the fault zone is affected by a dynamic process and will respond to seismic activity.

**Mechanism of permeability evolution**

Previous studies have suggested that the permeability increase following an earthquake can be explained by several mechanisms, such as the clogging/unclogging of fracture flow paths, formation of new microfracturing, mobilization of drops and bubbles and particle mobilizing (such as colloidal deposits) (Elkhoury et al., 2011; Manga et al., 2012; Candela et al., 2014). The recovery of permeability may be related to the poroelastic processes, i.e. permeability recovery is caused by fracture despressurization (Faoro et al., 2012) or controlled by geochemical processes that can slowly clog the flow path (Manga et al., 2012; Candela et al., 2014). In our case, an increase in permeability occurred after the Wenchuan earthquake, and the levels recovered through different processes. The permeability evolution in BBLY agrees well with the mechanism of unblocking/clogging of the flow path of the fracture. For the NX and DZ wells, the permeability was lower than its pre-earthquake level. If the permeability rise is caused only by the removal of the temporary barrier in the fracture by the seismic wave, the permeability should recover to its pre-earthquake level rather than attain a lower level; thus, a process that decreased the permeability of the two wells may have occurred during the earthquake. Considering that the NX and DZ wells are within one rupture length of the Wenchuan earthquake, the static strain caused by the fault slipping cannot be ignored (the static strains in the NX, DZ and BBLY wells are about $4.9 \times 10^{-8}$, $2.1 \times 10^{-7}$ and $2.3 \times 10^{-7}$, corresponding to calculated water level changes of $-0.02$, $-0.16$ and $-0.15$ m, respectively; Table II; Shi et al., 2014). Dilatational strain may also cause the opening of the fracture aperture (Faoro et al., 2012) or produce new fractures, both of which will produce a new flow path and lead to an increase in the permeability. Thus, for these two wells, the mechanism of unclogging of the barrier and/or the mechanism of dilation strain may play an important role in raising the permeability (the strain amplitude required to cause the permeability changes observed in the field is as small as $10^{-6} - 10^{-7}$; Manga et al., 2012; Candela et al., 2014). In such cases, the unclogging or open fracture aperture will lead to a rise in the permeability immediately after the earthquake, whereas shaking-induced transport of particles (barriers) may block the narrow fracture apertures (Liu and Manga, 2009). After the earthquake, the new flow path produced by the unblocking of the barriers or the dilation of the fracture aperture will be clogged or closed again; this will lead to the return of permeability to its pre-earthquake level. However, the process of blocking the pre-existing fracture aperture will reduce the permeability, resulting in permeability levels that are lower than the pre-earthquake ones. This may explain the lower permeability levels in the DZ and NX wells. Another possibility is that the natural ‘ageing’ of the well may clog the filter/well over a few years, leading to a reduction in permeability. However, the natural ageing of the wells should be much slower than the processes caused by natural forces such as an earthquake. Thus, the different periods of permeability evolution in NX and DZ are most likely associated with the earthquake and may reflect the different hydrogeological properties of the two aquifers.

**CONCLUSIONS**

Long-term changes in groundwater level following the great Wenchuan earthquake were observed by three monitoring wells in the Huayingshan fault zone. The water levels dropped in all three wells but with different post-earthquake recovery processes. The groundwater levels in the DZ and BBLY wells recovered to their pre-earthquake values, but the level in the NX well remained...
below its pre-earthquake value. The response of the groundwater level to Earth tides was used as a proxy to explore the mechanism affecting the behaviour of the water level and permeability. The permeability increased in response to the Wenchuan earthquake in all three wells but with different post-recovery processes. Only the BBLY water level regained its pre-earthquake value. The permeability in DZ reached a lower value than its pre-earthquake level and has remained steady since. The NX well shows a sustained slow decrease in permeability. The earthquake level and has remained steady since. The NX well shows a sustained slow decrease in permeability. The groundwater level changes in the three wells are caused mainly by the permeability changes. The process of unclogging/clogging of the fracture flow path may explain the permeability evolution in BBLY, whereas a mechanism such as the unclogging/clogging or opening/closing of the fracture associated with blocking the narrow fracture apertures appears to be responsible for the permeability evolution in the NX and DZ wells.

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