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Continental-scale water-level response to a large earthquake

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ABSTRACT

Co-seismic groundwater-level changes induced by earthquakes have been reported for thousands of years. The M8.0 Wenchuan earthquake caused co-seismic groundwater-level responses across the Chinese mainland. Three types of changes were recorded in 197 monitoring wells: co-seismic oscillations ranging in amplitude from 0.004 to 1.1 m, immediate co-seismic step changes ranging from 0.0039 to 9.188 m, and more gradual postseismic changes ranging from 0.014 to 1.087 m. We find that the co-seismic groundwater-level response is complex. There is neither a clear relationship between the response amplitude and the distance from the epicenter, nor a clear relationship between the groundwater response and lithology at the continental scale. Both the sign and amplitude of water-level changes are random at the continental scale, and a poroelastic response to the co-seismic static strain cannot explain most of the co-seismic changes. However, wells located near the edges of tectonically active blocks have larger response amplitudes than those in the middle of these 'stable' blocks. Considered together, these observations indicate that permeability enhancement caused by the earthquake is a significant or dominant mechanism causing water-level changes. These data indicate that large earthquakes can cause the widespread permeability changes in the shallow crust although the magnitude of permeability change is uncertain.

Key words: co-seismic strain, groundwater level, permeability, Wenchuan earthquake

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INTRODUCTION

Co-seismic hydrological responses following earthquakes have been documented for thousands of years (Institute of Geophysics-CAS 1976). These include changes in the water level, temperature, and chemical composition in wells, disappearance or formation of springs, increasing streamflow, and changes in the activity of mud volcanoes and geysers (Roeloffs 1996; Montgomery & Manga 2003; Manga & Wang 2007; Wang & Manga 2010a). Understanding the origin of these hydrological phenomena may have significant impacts on understanding the occurrence of liquefaction (Cox *et al.* 2012), water supply and quality (Gorokhovich & Fleeger 2007), and underground waste storage (Carrigan *et al.* 1991; Wang *et al.* 2013). Furthermore, the hydrological responses may provide unique insight into the interaction between hydrogeologic and tectonic processes at scales in space and time that help us to understand the long term evolution of groundwater flow. Understanding hydrological responses to stresses may also provide a framework to assess proposed hydrological precursors to earthquakes (Wang & Manga 2010b).

In the past decades, a large number of hydrological responses have been documented. Among these, changes in water level have attracted the most attention, and many mechanisms have been put forward to explain these phenomena. These include: (i) the co-seismic groundwater-level response can be explained by the co-seismic static strain and pore pressure change predicted by poroelastic theory (Wakita 1975; Roeloffs 1996; Ge & Stover 2000; Jónsson *et al.* 2003; Shi *et al.* 2013b); (ii) undrained dilatation and consolidation of saturated sediment lead to the step-like changes in water level (Wang 2001; Manga *et al.* 2003; Wang & Chia 2008); (iii) permeability enhancement of the crust in the intermediate- and far-field (Rojstaczer *et al.* 1995; Sato *et al.* 2000; Brodsky *et al.* 2003; Wang *et al.* 2009; Shi *et al.* 2013c; Xue *et al.* 2013); (iv) oscillations caused by the seismic waves in the far-field produced by resonant coupling of flow between the well and the aquifer (Cooper *et al.* 1965; Liu *et al.* 1989; Kano & Yanagidani 2006; Wang *et al.* 2009).

The majority of these investigations focused on the co-seismic response in a small region, or the response of a small set of wells to several earthquakes. Response over large alluvial fans was documented following the 1999 M7.1 Chi-Chi earthquake in Taiwan (Chia *et al.* 2001, 2008; Wang 2001; Wang & Chia 2008) and the 2011 M7.1 Christchurch earthquake, New Zealand (Cox *et al.* 2012; Gulley *et al.* 2013). Here, we consider co-seismic response in consolidated rocks to the great Wenchuan M8.0 earthquake. Many studies have investigated the relationship between water-level changes and the well-epicenter distance, and several have found that the co-seismic response amplitude is correlated with the earthquake magnitude and well-epicenter distance (Roeloffs 1998; Sil & Freymueller 2006; Chia *et al.* 2008). The present data set allows us to re-examine the relationship between the well-epicenter distance and the water-level response amplitude at the continental scale.

THE WENCHUAN EARTHQUAKE AND THE GROUNDWATER-LEVEL MONITORING NETWORK

The Wenchuan earthquake

The 12th May 2008, M8.0 Wenchuan earthquake occurred in the Longmenshan fault zone on the eastern margin of the Tibetan plateau. Three major subparallel faults constitute the northeast trending Longmenshan fault zone: the Pengguan fault to the east along the mountain front fault; the Beichuan fault about 10–15 km to its west; and the Wenchuan–Maowen fault about another 30 km west of the Beichuan fault (Shen *et al.* 2009). The Wenchuan earthquake was the largest earthquake in the mainland of China in the past 60 years. It killed 69 227 people and destroyed many towns and villages (Burchfiel *et al.* 2008). The epicenter is 31.02°N, 103.37°E, with a focal depth of 19 km (USGS, http://comcat.cr.usgs.gov/earthquakes/eventpage/pde20080512062801570_19#summary). Co-seismic fault scarps reveal a complicated pattern of slip, with the Wenchuan earthquake rupturing 240 km of the Beichuan fault and 72 km of the parallel Pengguan fault (Xu *et al.* 2009). InSAR analysis shows that the co-seismic slip on the fault can be divided into two parts with the boundary in Beichuan: thrust fault–slip dominated along the southwest part of the fault while dextral fault–slip dominated along the northeast part of the fault (Hao *et al.* 2009).

Groundwater monitoring network in China

Groundwater monitoring is an important component of the earthquake prediction research program in China. Many monitoring wells were constructed and some abandoned oil exploration wells have also been utilized (Wang 1985; Roeloffs 1988). Since the 1960s, the groundwater monitoring network has experienced four development stages: (i) creation stage (1966–1978); (ii) development stage (1979–1989); (iii) enhancement stage (1991–2000); and (iv) overall modernization stage (2000–). Today, there are 670 monitoring wells (including springs); among them, more than 400 wells specifically for groundwater-level monitoring (Shi *et al.* 2013a). These wells are maintained at different administrative levels: (i) the basic wells and the regional wells are supported by the State Seismological Bureau and managed by the State Seismological Bureau and provincial seismological bureaus, respectively; (ii) the local wells are supported by the local government and managed by the local government seismological bureaus; (iii) the enterprise wells (springs) are supported and managed by enterprises such as petroleum companies (Huang *et al.* 2004). After two digital upgrades of the monitoring wells, most of the basic and regional monitoring wells sample with periods of 1 h or 1 min, and the accuracy of water-level measurement can reach 1 mm. The data from the basic wells, regional wells, and some local wells are sent to the China Earthquake Network Center (CENC) each day for analysis and prediction (all of the data are raw records, without corrections for barometric pressure or tides). The rest are sent to the local earthquake administration or saved by the specialists who work at the monitoring stations. All of the wells are constructed along faults or points of special tectonic interest in consolidated rock and tap confined aquifers (Huang *et al.* 2004).

CO-SEISMIC GROUNDWATER-LEVEL CHANGES INDUCED BY THE WENCHUAN EARTHQUAKE

The Wenchuan earthquake caused large-scale groundwater-level changes across the Chinese mainland. We collected groundwater-level data from the CENC for a total of 336 monitoring wells. Among these, 76 wells were out of order at the time of the earthquake and 63 wells exhibited no co-seismic response to the earthquake. The other 197 monitoring wells did record a co-seismic response: groundwater level went up in 88 wells, went down in 67 wells, and showed only oscillations in 42 wells (Fig. 1).

Figure 1 shows that almost all the monitoring wells that showed co-seismic responses are located along or near the boundary of active blocks. Active tectonic blocks are defined as geological units separated by active tectonic boundaries across which there are high gradient of differ-

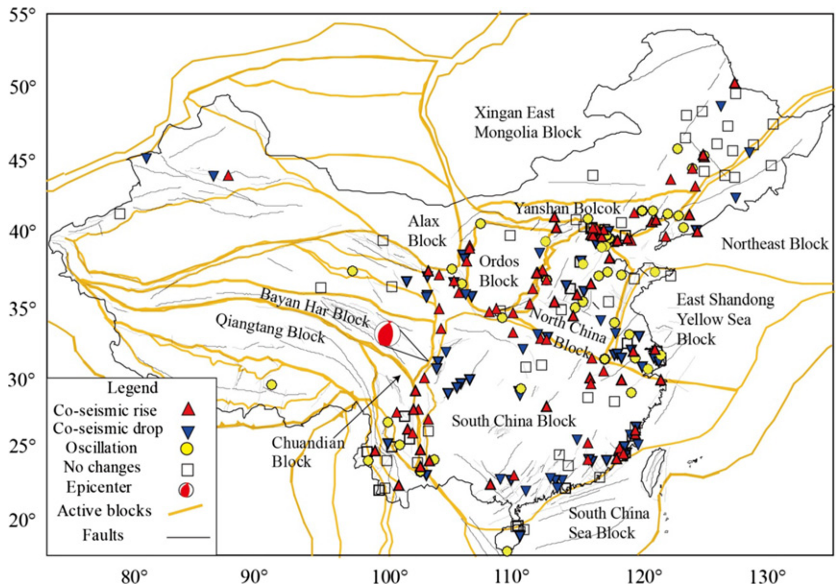

Fig. 1. Co-seismic water-level changes in response to the Wenchuan earthquake.

ential movement. These are zones of late Cenozoic to the present tectonic deformation which likely have a series of fault zones. Almost all earthquakes of magnitude >8 and 80–90% of earthquakes of M > 7 occur along these boundaries (Zhang *et al.* 2003).

Groundwater levels rose in the Chuandian block, north and east of the South China block, and on the junction boundary of the Ordos block and North China block, the Yanshan block and North China block. Water-levels decreased near the epicenter, along the boundary of South China block and South China Sea block, and near the southwest boundary of Shandong Yellow Sea block. We find that most wells exhibiting only groundwater oscillations are located far from the epicenter, with epicenter distance larger than 1000 km, especially in the northeast of the North China block, Northeast Block, and the southwest of the East Shandong Yellow Sea block. Several stations in Chuandian block also show oscillations in groundwater level. The wells which have no response are mostly located in the interior of the blocks and at large distances from the epicenter.

Spatially, the response amplitudes are variable (Fig. 2). The maximum water-level rise occurred near the epicenter (JY well with an epicenter distance of 161 km), but large increases also occurred in the southeast of China. Monitoring wells located within 80 km of the junction of active tectonic blocks (junction of Ordors and North China block, junction of Yanshan and Northeast block) also showed large co-seismic responses. For co-seismic water-level decline, the maximum excursion also occurred near the epicenter; however, near the junction of some of the active blocks there were also large decreases. Wells in Northeast China, at the junction between the North China block and the South China block, showed the largest amplitude of water-level oscillations (as large as 1.1 m at an epicenter distance of 1400 km) despite the large well-epicenter distance.

We classified the co-seismic water-level responses into three major types (gradual, step-like, and oscillation) and nine subtypes (Fig. 3): (i) gradual drop; (ii) gradual rise; (iii) gradual-drop oscillation; (iv) gradual-rise oscillation; (v) step drop; (vi) step rise; (vii) step-drop oscillation; (viii) step-rise oscillation; and (ix) oscillation. For the gradual change, we take the maximum amplitude of changes in 24 h as the response amplitude. This classification is similar to that adopted by Cox *et al.* (2012). We use the amplitude of steps as the co-seismic response amplitude for the step-like changes, and we take the maximum oscillation amplitude as the co-seismic change for oscillations. Because the sampling interval for most wells was 1 min (see table in the supplemental material), co-seismic oscillations were recorded. We further divide the locations of wells into two categories: the near-field, within approximately 1.5 rupture fault lengths, and intermediate-field, 1.5–10 rupture fault lengths (Shi *et al.* 2014). Figure 4 summarizes the relationship between co-seismic groundwater-level response, so-defined, and the distance from the epicenter.

The relationship between the co-seismic groundwater-level response and distance to the Wenchuan epicenter is not as strong that reported for the Chi-Chi earthquake (Chia *et al.* 2008). In fact, the amplitude and sign of co-seismic water-level changes show only a weak relationship with distance from the epicenter. The best-fit regression curve to the co-seismic rise h as a function of well-epicenter distance x is $h = -0.27 log(x) + 2.25$ with squared correlation coefficient (R^2) of 0.14, indicating a weak correlation between co-seismic water-level rise and the well-hypocenter distance. For the co-seismic water-level

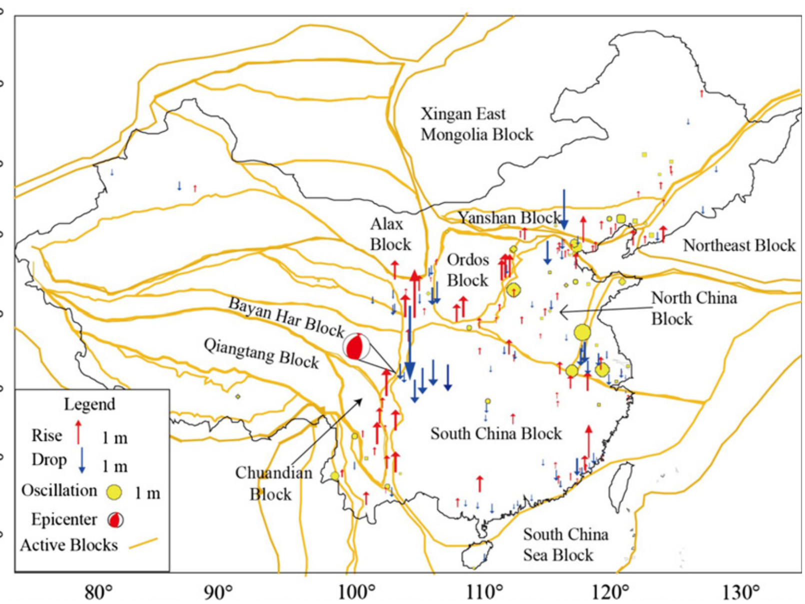

Fig. 2. Distribution of co-seismic response amplitudes induced by the Wenchuan earthquake.

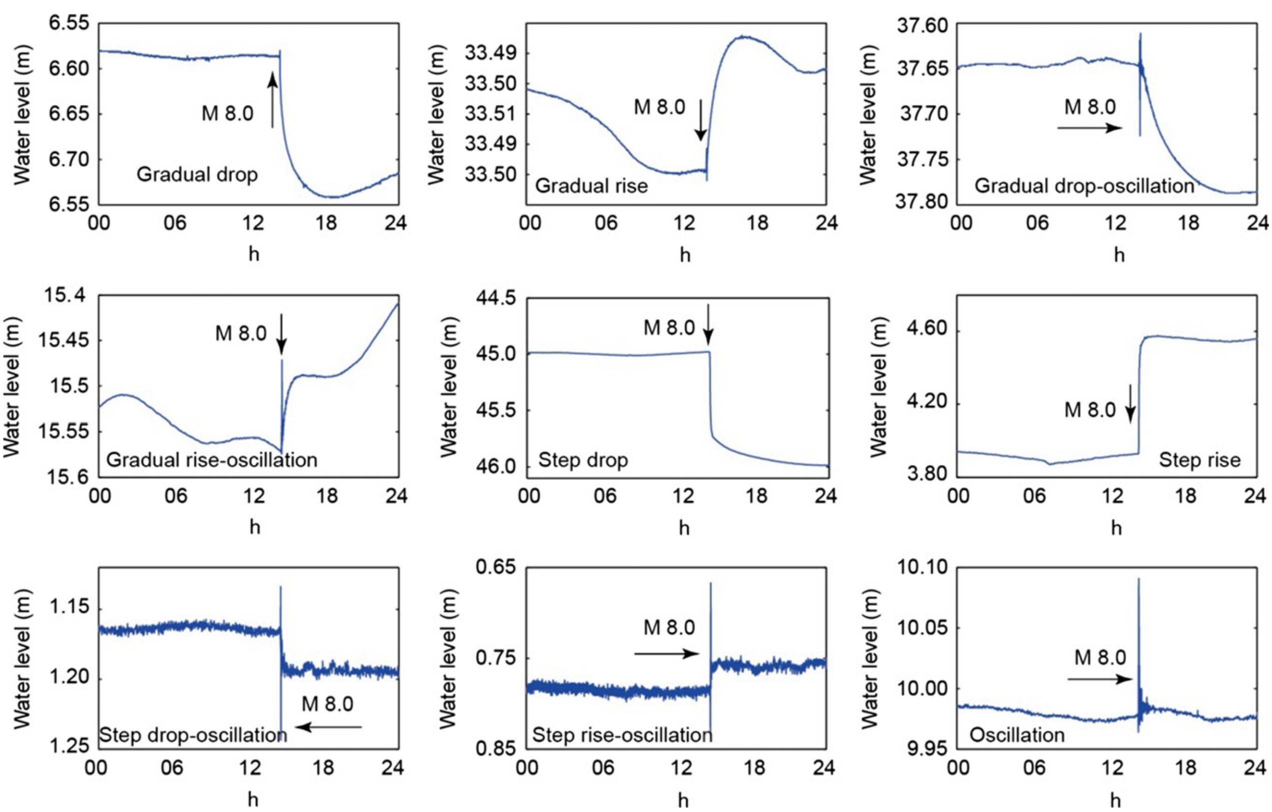

Fig. 3. Nine distinct response patterns of water-level changes induced by the Wenchuan earthquake. All of the examples shown have sampling intervals of 1 min.

drop, the R^2 is only 0.074, an even weaker correlation. This can be largely attributed to the relative heterogeneity of the geological and tectonic settings of the two earthquakes. For the Chi-Chi earthquake, almost all of the wells were installed in an alluvial fan consisting of unconsolidated sand and gravel (Wang 2001); hence, the documented water-level changes reflect the response of these materials to dynamic shaking and the attenuation of seismic stress with distance. The monitoring wells in the present study, however, are located in many different

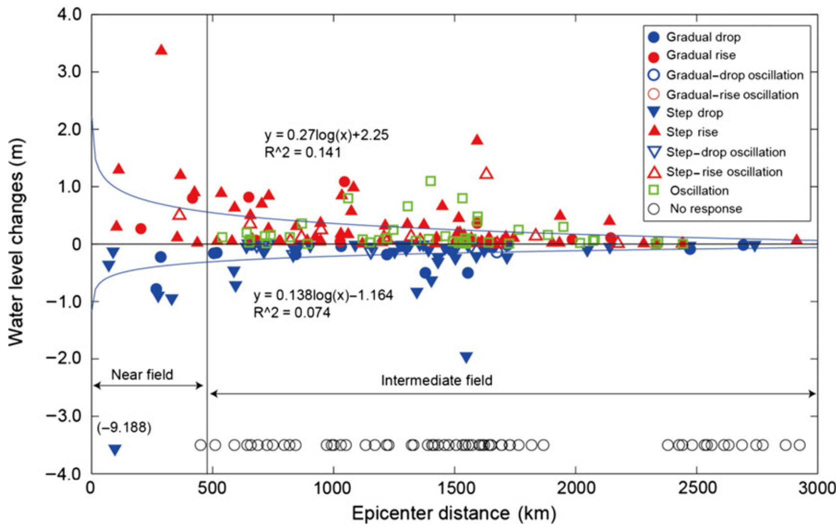

Fig. 4. Co-seismic groundwater-level responses as a function of distance from the epicenter. The black circles indicate the locations of wells that recorded no co-seismic response.

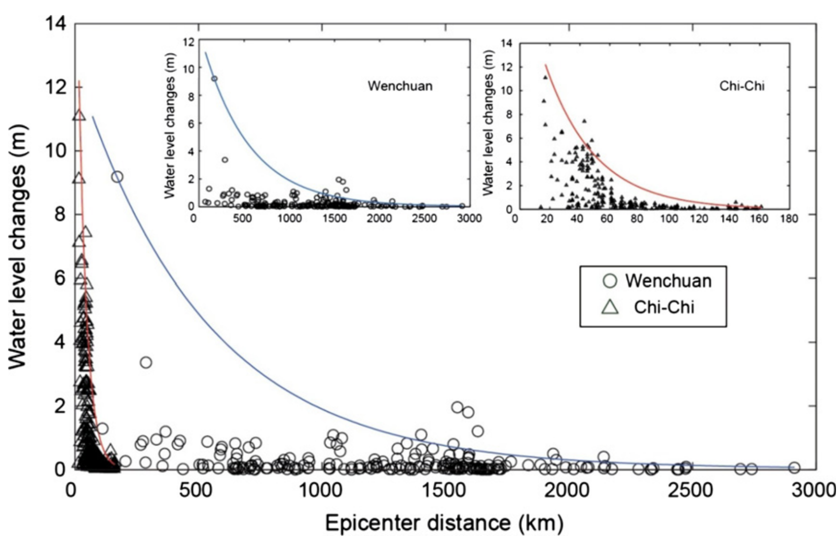

Fig. 5. Envelopes of the responses to the Wenchuan and 1999 Chi-Chi earthquakes. Triangles show the co-seismic response following the 1999 Chi-Chi earthquake and the circles show the co-seismic response following the Wenchuan earthquake. The red curve is the envelope for the Chi-Chi earthquake and the blue curve is the envelope for the Wenchuan earthquake

geological and tectonic settings, and most of them are located in consolidated sedimentary and crystalline rocks. We compared the co-seismic responses to the Wenchuan and Chi-Chi earthquakes in Fig. 5. The co-seismic responses following the Chi-Chi earthquake display a more systematic variation with distance than the responses to the Wenchuan earthquake.

Comparison of the water-level responses during the two events may thus highlight the effect of geological settings on the co-seismic response. Various co-seismic response types occurred in the near- and far-field, and differ from those reported in previous studies. As summarized by many previous studies, step-like changes are usually observed in the near-field (Chia *et al.* 2001; Wang 2001; Jónsson *et al.* 2003), gradual changes in intermediate-field (Roeloffs 1998; Brodsky *et al.* 2003), and oscillations in the far-field (Cooper *et al.* 1965; Liu *et al.* 1989; Kano & Yanagidani 2006). In the near-field of the Wenchuan earthquake, most of the wells show step-like changes, but four of them show gradual changes. In the intermediate-field, step-like changes and oscillations are observed, in addition to gradual changes (Fig. 4). The step-like changes have larger response amplitudes than the gradual changes and oscillations.

MECHANISMS OF THE CO-SEISMIC WATER-LEVEL CHANGE

Relationship between volumetric strain and water-level change

Several studies have suggested that co-seismic water-level changes are due to the co-seismic volumetric strain caused by slip on the ruptured fault (Roeloffs 1996; Ge & Stover

2000; Jónsson *et al.* 2003). For wells installed in unconsolidated sedimentary aquifers, however, the changes in water level have often shown the opposite sign to those predicted by the co-seismic static strain change (Wang 2001; Koizumi *et al.* 2004). As noted earlier, water-level changes after the Wenchuan earthquake were complicated by the geological and hydrological settings. Nevertheless, it may still be informative to assess the relationship between the co-seismic water-level changes and the volumetric strains. Here, we calculate the static strain change induced by an earthquake assuming a fault dislocation in a uniform half space with the analytical expression of Okada (Okada 1992; Lin & Stein 2004; Toda *et al.* 2005). We use 31.100°N, 103.300°E as the location of the Wenchuan epicenter and the finite fault model obtained from the USGS, which consists of 168 subfaults, each with a length of 15 km and a width of 5 km. Details of the fault model are available at http://www.geol.ucsb.edu/faculty/ji/big_earthquakes/home.html. The computed co-seismic static volumetric strain is shown in Fig. 6.

The sign of the groundwater-level response is generally consistent with the static strain changes when the strain is larger than 5×10^{-8} (Fig. 7). The well-hypocenter distance that results in strains larger than 10^{-8} is approximately 1000 km for the Wenchuan earthquake, consistent with the result derived from Dobrovolsky *et al.* (1979). The volumetric strain ε_{kk} can be related to pore-pressure change p in a well by $p = -(2GB/3)[(1 + \nu_u)/(1 - 2\nu_u)]\varepsilon_{kk}$, where G is the shear modulus of the material, B is Skempton's coefficient, and ν_u is the 'undrained' Poisson ratio. Typical values of the coefficient $((2GB/3)[(1 + \nu_u)/(1 - 2\nu_u)])$ on the right side are 5 to 50 GPa (assuming G of 5 Gpa to 30 Gpa, B of 0.5 to 0.8, $\nu_u = 0.3$ (Detournay & Cheng 1993)). If the coefficient equals 10 GPa, volumetric strain of 10^{-6} can produce a water-level change of 1 m, whereas a strain of 10^{-8} would produce a 1 cm change (Roeloffs 1996; Montgomery & Manga 2003). Thus, for the co-seismic water-level changes for the Wenchuan earthquake, most amplitudes are larger than predicted from this scaling. There are 71 wells that show response amplitudes larger than 0.1 m in areas with $<10^{-8}$ static strain, and many wells show co-seismic responses despite static strain $<10^{-9}$ (Fig. 7). Thus, the co-seismic static strain may only explain a small fraction of the water-level changes. For most of the water-level changes, the amplitude dose not simply scale with the static strain, and the relationship between response amplitude and static strain is random for many wells. Especially when the static strain is $<10^{-8}$, the direction of many water-level changes is opposite that predicted from the static strain field, implying that static strain is not responsible for most co-seismic responses. Other factors such as dynamic stress, geological, and hydrogeological conditions must play important or dominant roles.

Relationship between ground motion and co-seismic water-level change

Dynamic strain, induced by the passage of seismic waves, can also cause groundwater-level changes (Montgomery & Manga 2003; Itaba *et al.* 2008). Several studies have investigated the relationship between co-seismic water-level changes and ground shaking in Taiwan and Japan (Wang *et al.* 2003; Lai *et al.* 2004; Wong & Wang 2007; Itaba *et al.* 2008). As the peak ground velocity (*PGV*) is proportional to the dynamic strain (Brodsky *et al.* 2003; Jiang *et al.* 2010; Wang & Manga 2010a), we plot *PGV* versus groundwater-level change at 21 locations where the seismic stations are <25 km from our groundwater monitoring wells (although only 21 data points were selected, they are

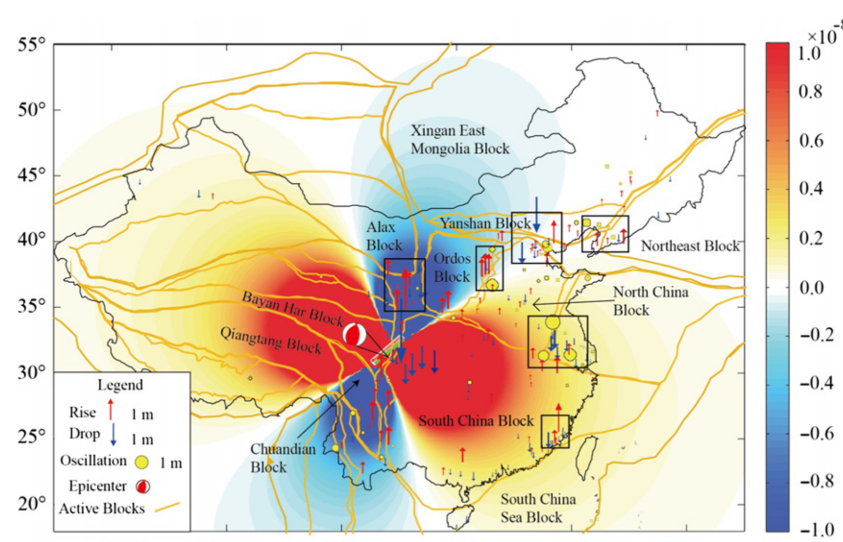

Fig. 6. Co-seismic groundwater-level changes as a function of volumetric strain calculated from the dislocation model. Red colors indicate dilatation, blue colors indicate contraction. The black rectangles highlight sensitive monitoring sites which have large co-seismic responses to the earthquake.

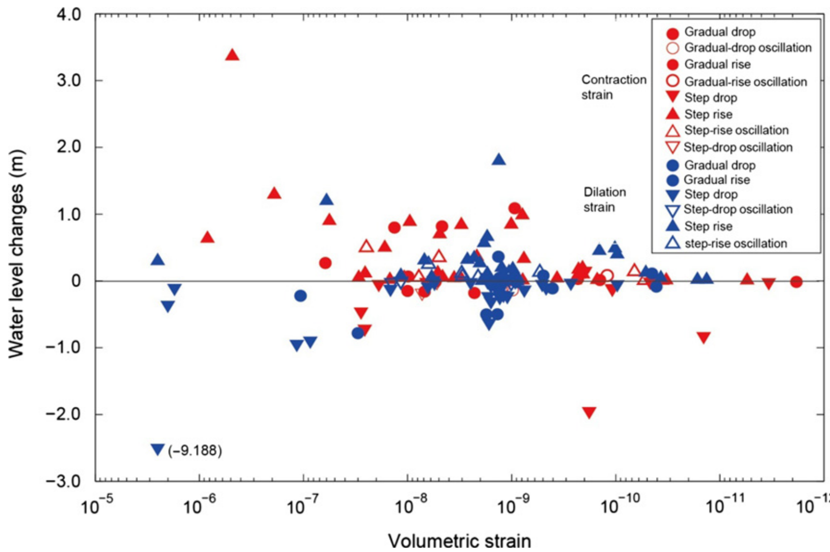

Fig. 7. Relationship between volumetric strain and the water-level response.

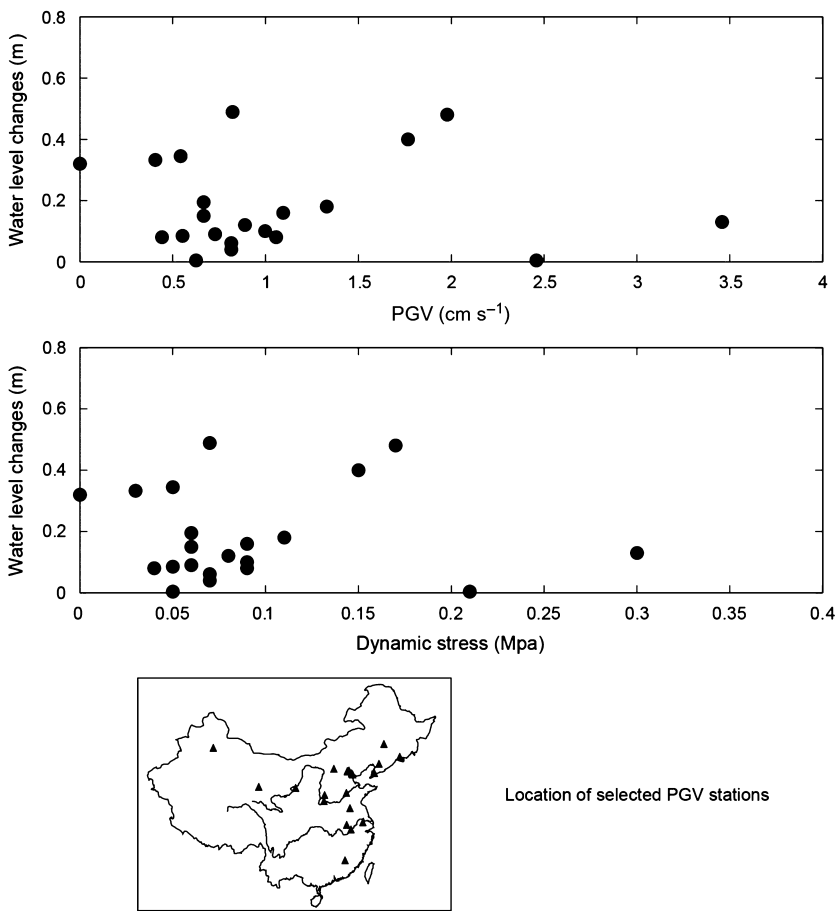

Fig. 8. Relationship between co-seismic water-level changes and PGV (dynamic stress); 21 PGV stations were selected from 271 stations of Chinese Digital Seismic Network (CDSN). The selected seismic stations are <25 km from groundwater monitoring wells (PGV data obtained from Jiang *et al.* 2010).

distributed throughout the Chinese mainland) (Fig. 8). The plot shows no clear relationship between water-level changes and PGV, similar to the result reported by Lai *et al.* (2004), indicating that the local geological or tectonic factors may have a more important effect on the magnitude of co-seismic water-level changes.

The effect of lithology to the co-seismic water-level response

Both Figs 4 and 7 show that some groundwater-level changes have large amplitude in the intermediate-field despite small static strains ($<10^{-8}$). We selected 20 wells with response amplitude larger than 0.3 m, epicenter distances larger than 1000 km, and static strains $<10^{-8}$ (Table 1). Of these wells, 15 are located in sedimentary rocks (i.e., sandstone, limestone), and the others are in igneous rocks. Thus, lithology also seems to have little impact on the co-seismic groundwater changes. The static stresses caused by the Wenchuan earthquake are too small to cause these large changes. Thus, the dynamic stresses from the passage of seismic waves must be responsible for the changes or there must be some additional mechanism that allows small static stress changes to cause large responses. One common explanation is that the dynamic or static stresses cause an increase in permeability that leads to changes in water level as hydraulic heads adjust to the permeability changes (Brodsky *et al.* 2003; Elkhoury *et al.* 2006; Wang & Chia 2008; Manga *et al.* 2012).

In order to assess the overall influence of lithology on the co-seismic response, we divide well-aquifer systems into three types: sandstone aquifers (105 wells), limestone aquifers (42 wells), and igneous rock (including granite) aquifers (47 wells), and plot the response amplitude and epicenter distance for each lithology (Fig. 9). Step-like changes are the most common in all of the three kinds of lithology. Only three wells in igneous rock show oscillations, compared with 18 in limestone and 21 in sandstone. The relationship between co-seismic response amplitude and epicenter distance are all weak for all of the three types of rocks: for igneous rocks, the square correlation coefficient (R^2) between water level and epicenter distance is 0.11 for co-seismic rise and 0.10 for co-seismic drop; for the limestones, it is 0.35 for the co-seismic rise and 0.10 for co-seismic drop; for the sandstones, it is 0.15 for co-seismic rise and 0.07 for co-seismic drop. The poor correlation indicates that the co-seismic groundwater-level responses are not dominated by lithology.

Table 1 Monitoring wells with larger response amplitude

Well name	Amplitude (m)	Epicenter distance (m)	Strain	Lithology
XY	0.845	1034	−1.01E-09	Sandstone
JX	1.087	1045	−9.34E-10	Sandstone
GP	0.57	1073	1.84E-09	Sandstone
QX	0.984	1082	−7.90E-10	Pyroclastic
HUS	0.32	1213	2.66E-09	Sandstone
AQ	0.345	1305	2.29E-09	Sandstone
SZ	−0.829	1344	−1.43E-11	Limestone
ZC	0.333	1373	−7.63E-10	Basalt
CH	−0.502	1379	1.75E-09	Sandstone
HS	−0.63	1404	1.65E-09	Sandstone
WH	−0.307	1431	1.58E-09	Limestone
WX	0.66	1449	1.72E-09	Gravel
HY	0.453	1517	1.44E-10	Limestone
ZJZ	−1.952	1548	−1.80E-10	Limestone
ZZNJ	−0.5	1555	1.37E-09	Granite
YC	1.8	1593	1.33E-09	Granite
AX	0.363	1593	1.34E-09	Rhyolite
TSCS	1.2125	1631	8.29E-12	Limestone
LF	0.489	1936	1.02E-10	Sandstone
DDB	0.4	2140	9.69E-11	Pegmatite

Effect of tectonic setting

Finally, we test whether the tectonic setting affects the co-seismic response. To reduce the effect of static strain caused by the slip in the near field, we choose the wells beyond the near field to plot the relationship between co-seismic water-level response (absolute value of water-level change) versus distance to active block boundary (Fig. 10). We find that most of the wells which had large co-seismic response (larger than 0.5 m) are located <80 km from a boundary. We thus infer that tectonic setting may have an important effect on co-seismic water-level responses.

Furthermore, in Fig. 6, we identify six areas that show large amplitudes of co-seismic response at large epicenter distances. One common feature is that they are all located near the junction of two or three active blocks. Discontinuous deformation due to repeated accumulation and release of tectonic stress near the junctions of these blocks may have damaged and weakened the rocks that make up these aquifers (Zhang *et al.* 2003). Those wells that showed large response at great distances may be located at sites that are sensitive to seismic shaking (King *et al.* 1999) or at sites where seismic waves or shaking focuses.

Previous studies indicate that the fault permeability structure is complex and variable by increasing and/or decreasing permeability (Chester *et al.* 1993; Evans *et al.* 1997). Faults can be hydraulically permeable (conduit faults) or hydraulically permeable parallel to the fault and less permeable normal to the fault (conduit-barrier fault), which Bense *et al.* (2013) suggest are the most common. As active faults form the boundaries of active blocks, the junctions of active blocks are expected to have higher permeability, and the larger amplitude of water-level changes may reflect this higher permeability (Manga & Wang 2007; Shi *et al.* 2013c). Other possibilities are that the wave-guide effect of active fault zones (Li *et al.* 1997) may focus seismic energy, enhancing shaking near the junction of active blocks, thus enhancing response amplitudes. Alternatively, fault zone material along active faults zones may be more elastic than the surrounding material, and wells located in such zones would exhibit larger pressure changes in response to stress changes. More observational data are needed to test these hypotheses.

DISCUSSION

After collecting data recorded at 260 groundwater monitoring wells which were operational on May 12, 2008, we identified 197 wells with co-seismic responses. The tectonic setting of the wells seems to control the co-seismic response. The signs of groundwater-level changes are

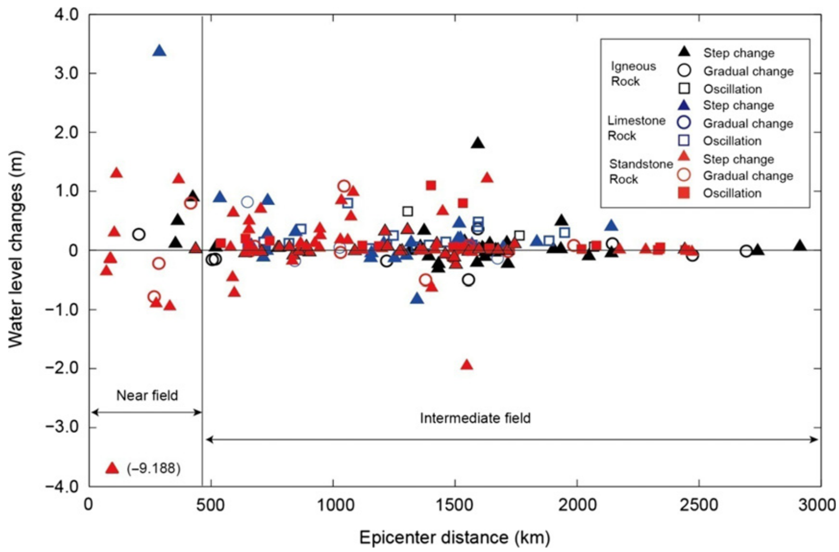

Fig. 9. Relationship between co-seismic groundwater-level changes and lithology.

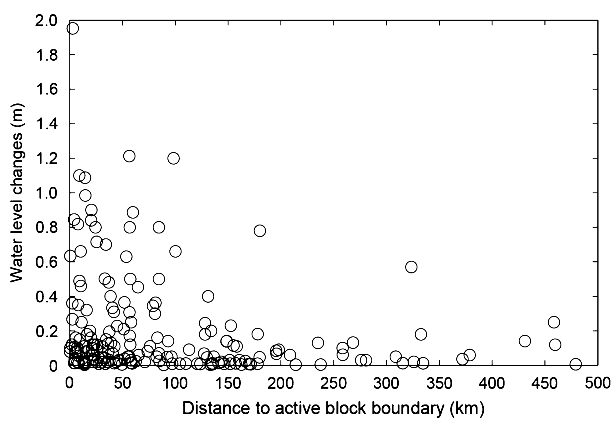

Fig. 10. Relationship between the co-seismic water-level response and tectonic blocks. The distance to block boundaries is the minimum distance from the well to the nearest active block boundary.

roughly consistent with the co-seismic static strain field when the wells are located within 1000 km of the epicenter and static strains are $>10^{-8}$. However, the relationship between the response amplitude and epicenter distance or static strain is not consistent with a poroelastic response in most wells (Shi *et al.* 2014). In the near field, hydrogeological responses are generally caused by a combination of static and dynamic stresses (Lai *et al.* 2014). Because both the static and dynamic stresses (strains) caused by the earthquake are significant (Manga & Brodsky 2006), both may have effects on the water level that are not easily distinguished. Indeed, some wells that located within an epicentral distance <300 km showed static strain effects after the Wenchuan earthquake (Shi *et al.* 2013b). Overall, however, even in the near-field (about 500 km for the Wenchuan earthquake), the co-seismic water-level response is not consistent with the static strain, especially the predicted magnitude of water-level changes (Shi *et al.* 2014). It should be noted, however, there are only several wells located very near to the epicenter, and the tidal signals in these wells are not clear, which impedes further work to distinguish the effect of static and dynamic strains. More observations are needed to carefully deal with 2015.

Our conclusion that static strains have only a small effect on water-level change is quite different from those of some previous studies that found a good relationship between well-hypocenter distance and co-seismic response amplitude (Roeloffs 1998; Chia *et al.* 2008). In these studies, the wells were mostly located in unconsolidated sediments and similar tectonic settings, so the co-seismic responses are largely controlled by sediment consolidation (Wang 2001) and the attenuation of seismic energy. However, because of the heterogeneity of geological and tectonic settings at the continental–scale, co-seismic response amplitudes are highly variable. Many of the responses that we document are likely responses to changes in permeability, which can lead to either positive or negative changes in the water level because enhanced permeability can occur either up-gradient or down-gradient of a well. If the enhanced permeability is located up-gradient of the well, then the water level in the well will exhibit a co-seismic rise. If the enhanced permeability occurs down-gradient of the well, then a co-seismic fall in water level would be expected. At the continental-scale, permeability enhancement may occur either in up-gradient or down-gradient of wells. If a sufficiently large number of observations are available, the model of enhanced permeability would predict a statistically random occurrence in the sign of the water level change as a function of distance from the epicenter (Wang & Chia 2008), and this is the case in the intermediate-field after the Wenchuan earthquake.

CONCLUSIONS

In this paper, we report the co-seismic continental–scale groundwater-level changes following the Wenchuan earthquake. Three types of changes were recorded in 197 monitoring wells, with co-seismic oscillations ranging in amplitude from 0.004 to 1.1 m, immediate co-seismic step changes ranging from 0.0039 to 9.188 m, and more gradual postseismic changes ranging from 0.014 to 1.087 m. The co-seismic water-level changes on the continental–scale are rather complex, and there is great variability in the relationship between water-level changes, epicentral distance, and static strain. Hydrogeological and tectonic settings are dominant factors in determining the co-seismic response. Wells located near the edges of active blocks can have large co-seismic responses even when the epicenter distance is large. Both the sign and amplitude of water-level changes are random at the continental scale. Poroelastic response to the co-seismic static strain cannot explain most of the co-seismic changes. Permeability changes caused by stress changes (either static or dynamic) may explain the large variability of the co-seismic response amplitude. These results also suggest that earthquakes can cause the widespread permeability changes in the shallow crust.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table S1. Well information for 197 groundwater wells which show co-seismic response to the 2008 M8.0 Wenchuan earthquake.

GEOFLUIDS

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