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Tidal response variation and recovery following the Wenchuan earthquake from water level data of multiple wells in the nearfield

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ABSTRACT

An important dataset to emerge from the Wenchuan earthquake Fault Scientific Drilling project is direct measurement of the permeability evolution of a fault zone. In order to provide context for this new observation, we examined the evolution of tidal responses in the nearfield region (within ~1.5 fault lengths) at the time of the mainshock. Previous work has shown that seismic waves can increase permeability in the farfield, but their effects in the nearfield are more difficult to discern. Close to an earthquake, hydrogeological responses are generally a combination of static and dynamic stresses. In this work, we examine the well water level data in the region of the large M_w 7.9 Wenchuan earthquake and use the phase shift of tidal responses as a proxy for the permeability variations over time. We then compare the results with the coseismic water level pattern in order to separate out the dynamic and static effects. The coseismic water level pattern for observed steps coincident with the Wenchuan mainshock mainly tracks the expected static stress field. However, most of the wells that have resolvable tidal responses show permeability enhancement after this large earthquake regardless of whether the coseismic response for the well water level is increasing or decreasing, indicating permeability enhancement is a distinct process from static poroelastic strain.

1. Introduction

It has been reported for a long time that large earthquakes can cause various hydrological responses, such as the variations in groundwater level (Akita and Matsumoto, 2001; Chia et al., 2008; Huang et al., 2004; S.H. Lee et al., 2012; T.-P. Lee et al., 2012; Liu et al., 1989; Niwa et al., 2012; Roeloffs, 1996; Sil, 2006), springs and stream discharge (Manga, 2001; Manga and Rowland, 2009; Manga et al., 2003; Mohr et al., 2012; Montgomery and Manga, 2003; Wang et al., 2004). Among them, changes in well water levels are the most commonly reported phenomenon.

Abrupt changes in well water levels in the nearfield (within 1–2 fault lengths) are often explained by the static poroelastic strain of aquifers caused by earthquakes (Akita and Matsumoto, 2004; Matsumoto and Roeloffs, 2003; Roeloffs and Bredehoeft, 1985; Shi et al., 2012; Shibata et al., 2010; Wakita, 1975; Wang and Chia, 2008; Zhang and Huang, 2011). In the intermediate and farfield (many fault lengths), the static poroelastic strains from displacement during earthquakes are small and can fail to explain the sign of the sustained variations in water levels (Manga et al., 2003). Brodsky et al. (2003) proposed a new model for coseismic pore pressure steps in the farfield, in which the temporary barriers from the groundwater flow are removed by more rapid flow caused by seismic waves and thus the permeability is enhanced. This hypothesis was supported by subsequent observations of permeability enhancement in the farfield (Elkhoury et al., 2006; Geballe et al., 2011; Manga et al., 2012; Wang et al., 2009). Xue et al. (2013) found a similar phenomenon in the deep borehole at WFSD-1 (Wenchuan earthquake Fault Scientific Drilling) where post-mainshock healing is interrupted by permeability increases associated with regional and teleseismic earthquakes. The permeability enhancement hypothesis therefore appears to be useful for farfield datasets.

As the datasets of permeability changes increase, a persistent question is the relative importance of the poroelastic and dynamic stresses in controlling the permeability changes in the nearfield where the static and dynamic stress fields are more difficult to disentangle. Here we use the exemplary digital data of the Groundwater Monitoring Network (GMN) of water wells in the region of the Wenchuan earthquake to examine this question.

The great M_w 7.9 Wenchuan earthquake on May 12, 2008 caused widespread water level changes both on the Chinese mainland and in the Taiwan region (e.g. S.H. Lee et al., 2012; T.-P. Lee et al., 2012; Yang et al., 2008). Huang (2008) studied the coseismic water level steps on

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the Chinese mainland in response to this earthquake, and proposed that for confined and consolidated aquifers, water level changes reflect the change in the in-situ borehole strain. Zhang and Huang (2011) found that the poroelastic theory can be used to explain the coseismic water level changes within 1.5 fault lengths. Shi et al. (2012) revisited this problem and concluded that within 500 km, the sign of the coseismic water level changes can match the static stress field predicted from a dislocation model, though the magnitudes may be inconsistent for some wells. In this paper, we examine the underground water level data in the region of this large earthquake, use the phase shift of tidal responses as a proxy for the permeability variations over time for the wells that have resolvable tidal responses, and compare the results to both the predicted static stress field and the coseismic water level step pattern. We attempt to study the permeability variation and recovery time following this large earthquake in the nearfield, which is significant for understanding the physical origin of permeability variation and recovery.

2. Data

The digital transformation of the Groundwater Monitoring Network (GMN) in China was completed by the end of 2007. The water levels in wells are measured by the LN-3 digital recorders, and the sampling interval is 1 min (The Monitoring and Forecasting Department of China Earthquake Administration, 2007). The great M_w 7.9 Wenchuan earthquake happened on May 12, 2008, so we were able to collate data from the GMN of the China Earthquake Networks Center from 2007 to 2009 in the nearfield, which we define as within 1.5 fault lengths of the surface rupture. As shown in Fig. 1, there are 16 wells in all and 15 of them respond to this large earthquake, whereas one well (YY) has no response.

For the tidal analysis, we limit the dataset to high quality water well records with well-resolved tides (Table 1). (Note: Because the surface rupture extends 300 km, the epicentral distances in Fig. 1 for some northern wells exceeds 1.5 fault lengths for well, e.g., PL and JY). We only study the eight wells with large amplitude responses to tides (responses >0.45 mm per nanostrain) to ensure that the tidal signal is well-separated from the noise level (Fig. 2). Because the digital upgrade of the network was carried out over a long period, the beginning of the water level records and the continuity of the data are different at each well. As a result, there is no uniform time period with high quality data for all of the wells. For seven wells, the reported water level is the distance between the wellhead and the water surface inside the well; for the one artesian well (ZZ), because the hydraulic head is higher than the ground, it is measured with a pressure transducer sampling inside a tube above the ground surface. We also check the timing of each well and make clock corrections as necessary based on the initial response time of the water level to the Wenchuan earthquake (Table 1).

3. Comparison of water level steps and static stress changes

Zhang and Huang (2011) and Shi et al. (2012) previously measured the coseismic water level changes, and used them to estimate the static poroelastic strain caused by the Wenchuan earthquake. By comparing the calculated strain to the theoretical strain from the Okada dislocation model, they concluded that within 500 km, the sign of the coseismic water level changes can effectively match the dislocation model, although the magnitudes may be hard to predict for some wells. The predicted values based on the Okada model are for homogeneous and isotropic media. However, the actual complex geology as well as the confinement of the aquifer can affect the magnitude to a large extent. Zhang and Huang (2011) attributed the magnitude difference to different Skempton's coefficients which are defined under undrained conditions.

Shi et al. (2012) studied seventeen nearfield wells with one-minute sampling interval data for eleven wells and hourly sampling for the remaining six wells. We do not have the hourly sampling data, but do have additional five wells from Gansu and Shaanxi Province with one-minute sampling. These new data fill in a gap in the previous dataset to the northeast of the mainshock rupture. As shown in Fig. 1b, the coseismic water level change pattern of twelve wells matches the overall pattern previously reported. The area to the East identified as extensional, has decreasing water levels whereas the regions identified as compressional along strike have increasing water levels. The water

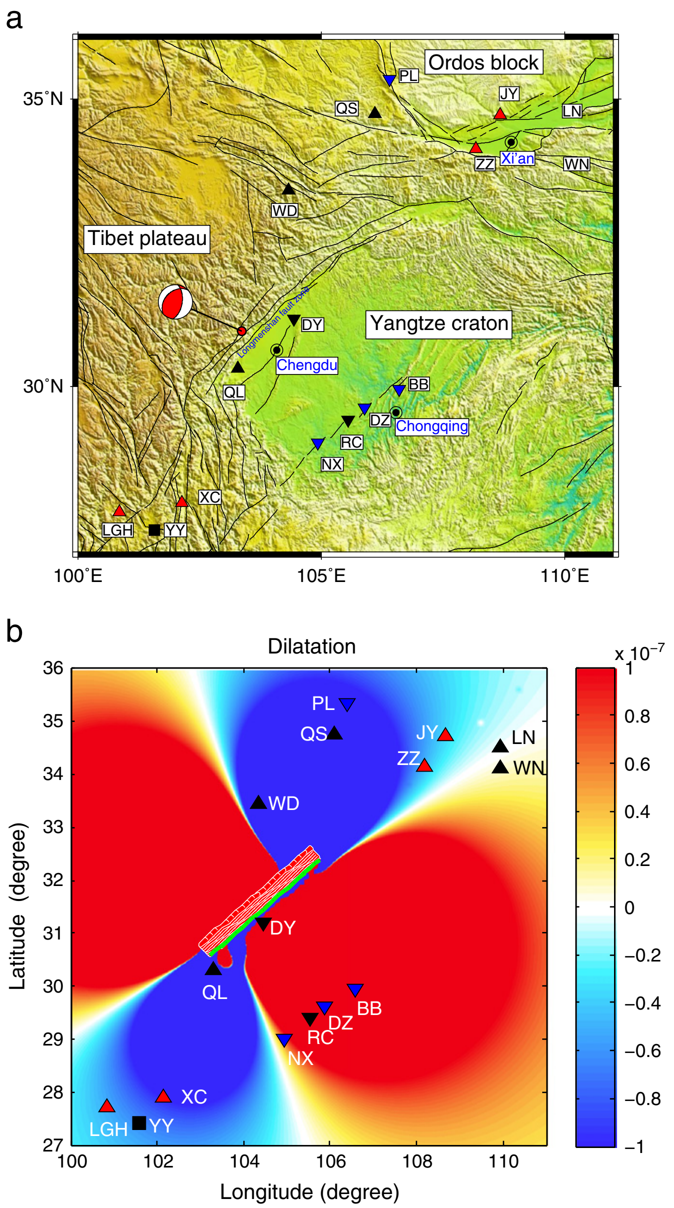

Fig. 1. (a) The epicenter location (red filled circle) of the M_W 7.9 Wenchuan earthquake on May 12, 2008 and the groundwater level observation wells within ~1.5 fault lengths. "Beach ball" shows the lower hemisphere projection of focal mechanism (strike 225°/dip 39°/rake 120°) of the earthquake (Zhang et al., 2009). Triangles imply coseismic water level rise and inverted triangles imply coseismic water level fall. The black square indicates no observed coseismic change in the well YY. The red triangles and blue inverted triangles indicate the wells we used for tidal analysis in this work. All capital letters (such as the WD, DY ect.) represent different well names. Black lines indicate the location of faults (Deng et al., 2004). The main cities (black circles), geological units and faults are shown in the map. (b) The calculated coseismic poroelastic strain (Lin and Stein, 2004; Toda et al., 2005) based on the finite fault model of Chen Ji (http://www.geol.ucsb.edu/faculty/ji/big_earthquakes/2008/05/12/ShiChuan.html), positive for dilatation, as well as the coseismic water level change pattern for the 16 wells. The meanings of the triangles, inverted triangles, square and capital letters are the same to (a).