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Evidence that the 2008 M_w 7.9 Wenchuan Earthquake Could Not Have Been Induced by the Zipingpu Reservoir

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Abstract According to the Coulomb failure criterion the variation of either shear stress, normal stress, or pore pressure can affect the occurrence, or not, of earthquakes. Abnormal seismicity increases around reservoirs are often thought to be induced by the water impounded behind the dam, which leads to nearby increases in crustal pore pressure and Coulomb stress, and so may promote the nearby faults to fail. To investigate how much the Zipingpu reservoir, whose dam is just a few hundred meters from the Longmen Shan fault, influenced the 12 May 2008 Wenchuan earthquake M_w 7.9, we calculated the Coulomb stress variation induced by the filling of the Zipingpu reservoir, which began in October 2005. We also analyzed the correlation between local seismicity variations and the induced Coulomb stress variations. Both the calculated Coulomb stress variations and the observed seismicity analysis suggest that the probability that the huge Wenchuan earthquake, M_w 7.9, was induced by the Zipingpu reservoir is very low. The filling of the Zipingpu reservoir could only result in an increase in the rate of shallow earthquakes with hypocenter depth smaller than 5 km near the reservoir region.

Introduction

The 12 May 2008 Wenchuan earthquake, M_w 7.9, was the most destructive earthquake in China in the last 30 years, with 68,712 people killed, hundreds of thousands of people wounded, and 17,921 people missing, all according to the reports of the Chinese government. The huge earthquake was caused by slip on the Longmen Shan fault, which induced extensive landslips, surface ruptures, and crustal deformation along and near the fault zone. Inversions for the earthquake rupture process (Wang *et al.*, 2008; Ji, 2008) show that the earthquake was characterized mainly by thrust motion, but with a component of right lateral strike slip near the northern end. The maximum slip on the fault is over 12 m; the earthquake led to a 300 km long rupture zone along the Longmen Shan fault. The hypocenter depth of this earthquake is reported to be from 14 km to 19 km depending on different research agencies (Ji, 2008; Huang *et al.*, 2008; Chen, Liu, Li *et al.*, 2009).

The earthquake occurred in the western Sichuan region where seismic activity is generally very high, with lots of destructive earthquakes in historic times. This activity is due to the strong eastward tectonic push of Tibet (Fig. 1). However, the slip rate and seismicity rate along the Longmen Shan fault itself are relatively weak compared with other faults in this region, at least in recent years (Zhou, 2008). No strong earthquakes ($M_s \geq 6.0$) have occurred along the Longmen Shan fault since 1976. The epicenter distribution of the regional seismicity (Fig. 1) shows a clear seismicity gap since 2002 along the Longmen Shan fault, which suggests that the fault was tightly locked since then (Chen, Zhao, Wang *et al.*, 2009). We can also find evidence from GPS observations (Li *et al.*, 2009) to support this inference.

Another interesting aspect of this huge earthquake is how the construction and filling of the Zipingpu reservoir, which is about 10 km away from the epicenter, might be involved (Fig. 2). Some articles have publicly said that water impounded behind the Zipingpu dam might trigger the failure of the nearby fault, a failure that went on to rupture almost 300 km and kill several tens of thousands of people (Lei *et al.*, 2008; Klose, 2008; Kerr and Stone, 2009). Conversely, Chen (2009) denied the possibility that the Wenchuan earthquake was a reservoir-induced earthquake based mainly on empirical evidence. However, Chen did not do any quantitative analysis, and his evidence was not strong enough to make his conclusion definite.

Investigating if the Wenchuan earthquake could have been induced by the filling of the Zipingpu reservoir is obviously an important issue both for science and society. The motivation of this article is to address this question by (1) calculating the Coulomb stress changes near the hypocenter of the earthquake that were induced by the water impounded behind the Zipingpu reservoir dam, and (2) considering the correlation between the regional seismicity variations and the relevant induced Coulomb stress variations.

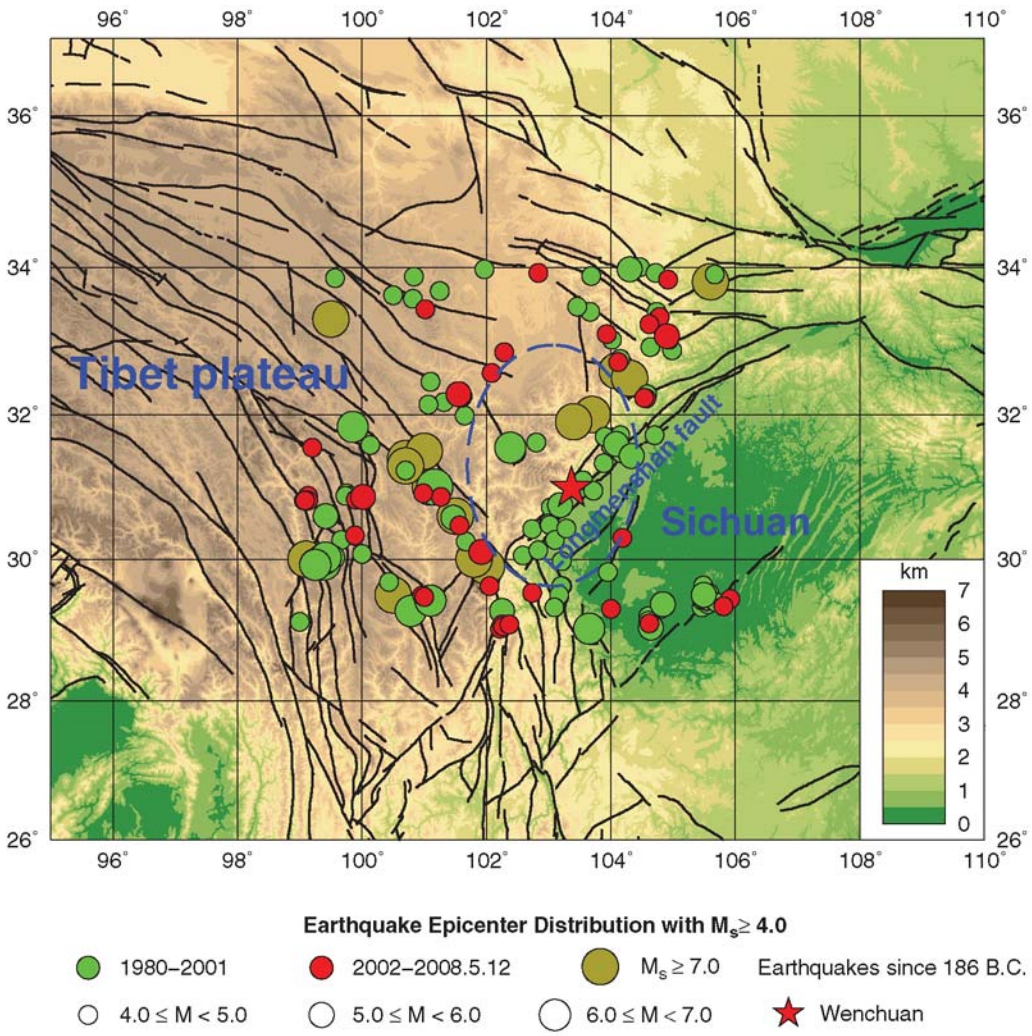

Figure 1. Seismicity in the Longmen Shan and neighboring regions. The dashed blue circle shows that a seismicity gap along the Longmen Shan fault was formed between 2002 to the time of occurrence of the Wenchuan earthquake (Chen, Zhao, Wang *et al.*, 2009). The black lines indicate the active faults.

Calculation of Coulomb Stress Changes Induced by the Zipingpu Reservoir

A possible earthquake triggering mechanism is based on the well-known criterion for earthquake occurrence, the Coulomb failure criterion (Harris, 1998; Steacy *et al.*, 2005):

$$\Delta \mathrm{CFF} = \Delta\tau - \mu(\Delta\sigma_n - \Delta P), \qquad (1)$$

where $\Delta\tau$ is the shear stress change calculated along the slip direction on the assumed fault plane (positive along the slip direction), $\Delta\sigma_n$ is the normal stress change (positive for pressure), ΔP indicates the pore pressure change, and μ indicates the dry friction coefficient on the fault, which usually ranges from 0.6 ~ 0.8 (Robinson *et al.*, 2005). Obviously, a positively induced Coulomb stress change ΔCFF means that a triggering event would promote failure elsewhere.

Equation (1) tells us that the Coulomb stress change induced by a reservoir may have two sources. One is the static loading due to the water impounded behind the reservoir dam that leads to changes in the shear stress and the normal stress on an assumed fault plane. Another is the pore pressure variation due to the diffusion of the reservoir water.

Calculation of the Pore Pressure Variation

As seen in Figure 2, the water impounded behind the Zipingpu reservoir dam just crosses the Longmen Shan fault; its size is quite small compared with the rupture length of the Wenchuan earthquake. It should be reasonable to simplify this problem into a 2D problem as shown in Figure 3a and analyze the pore pressure variation along a simplified Wenchuan earthquake fault plane. We use the parameters in Table 1, which were inferred from inversion results for the rupturing process of the Wenchuan earthquake (Ji, 2008; Wang *et al.*, 2008; Zhang *et al.*, 2009). Figure 3a shows the locations of the Zipingpu reservoir, the hypocenter of the Wenchuan earthquake on the fault, and a computational grid for calculating the pore pressure by the finite element method (FEM) as described in the following paragraphs.

ΔP occurs in two ways: (1) instantly in response to undrained loading, ΔP_u, in which the porous rock is compressed yet the fluid remains confined within it (Skempton, 1954); (2) the diffusion pore pressure ΔP_{diff}, from the reservoir to the hypocentral location (Talwani, 1997; Chen and Talwani, 2001). So we have

$$\Delta P = \Delta P_{\mathrm{diff}} + \Delta P_u, \tag{2}$$

where $\Delta P_u = B\Delta\bar{\sigma}$, $\Delta\bar{\sigma}$ is the average normal stress change and B is the Skempton's coefficient. We set $B = 0.7$ in our modeling, following Chen and Talwani (2001).

According to Darcy's Law, the diffusion of pore pressure on the fault plane due to an intrusion of fluids from a high-pressure source can be described by the diffusion equation

$$\frac{\partial P}{\partial t} = D\nabla^2 P, \tag{3}$$

where D is the hydraulic diffusivity, which is generally expected to be between 0.01 and 10 m^2/s for the crust (Scholz, 2002). Talwani *et al.* (2007) estimated the hydraulic diffusivity from about 100 reservoir-induced seismicity cases and found that it ranges between 0.1 and 10 m^2/s. Also in (3) p indicates ΔP_{diff} of equation (2) for simplification. If we define the

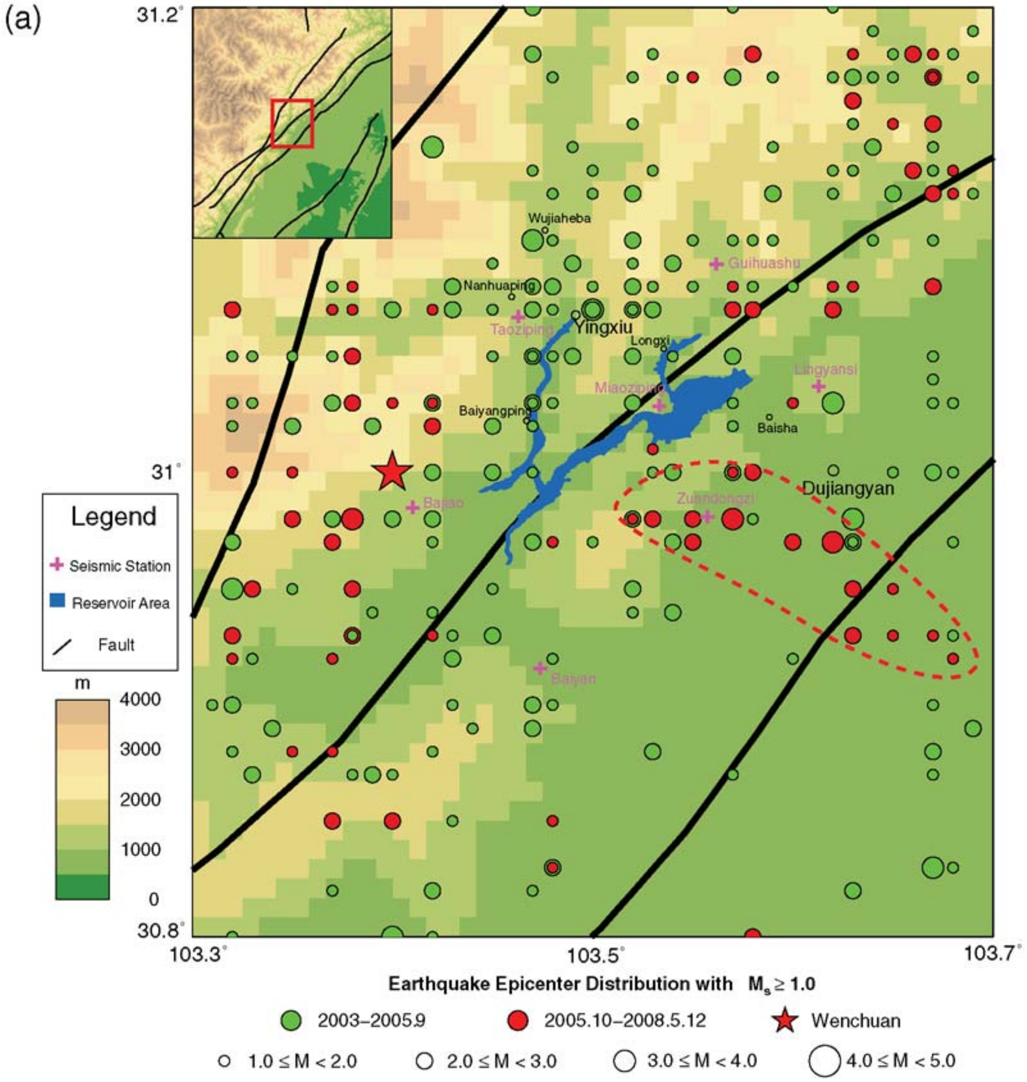

Figure 2. The earthquake epicentral and temporal distributions before impoundment are given in green in (a) and (b); those after impoundment are shown in red in (a) and in blue in (b). (a) Epicenter distribution in the reservoir region within the same time windows before and after the impounding time of Zipingpu reservoir on 1 October 2005. All of the three main faults shown on the figure contributed to the huge Wenchuan earthquake; the central one is the initial rupturing fault (Wang *et al.*, 2008). The seven seismograph stations (marked by crosses) have been operating since 2004. The area circled by the dashed line is the location of the earthquake swarm in February 2008. (b) Magnitude–time plot before and after the impounding time (red dash line) of Zipingpu reservoir on 1 October 2005 for events with magnitude $M_L \geq 1.0$ in the reservoir region shown in (a). Each circle represents an event. The reservoir water filling curve is shown in Figure 3b. (*Continued*)

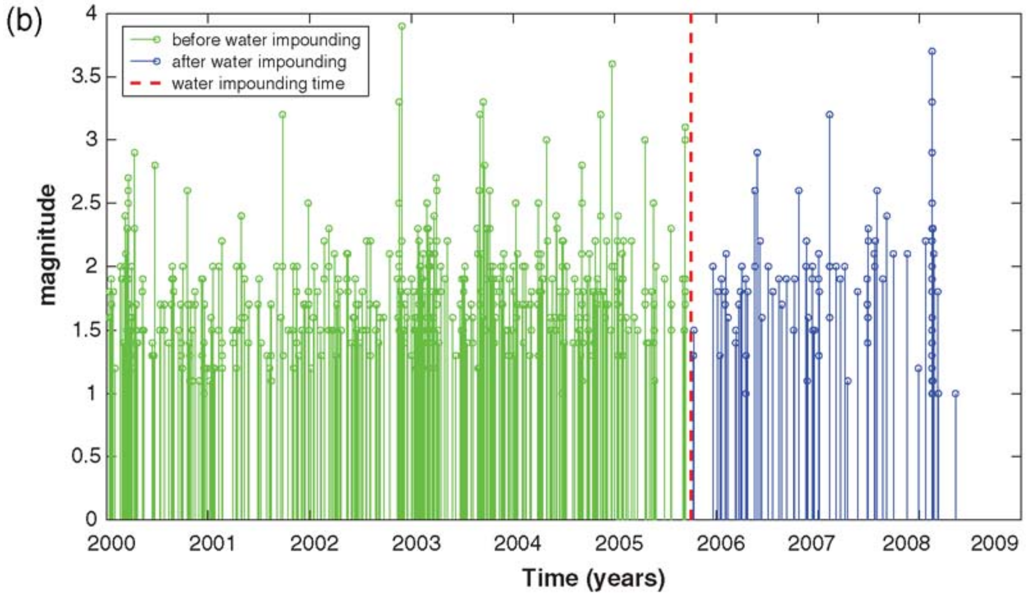

Figure 2. Continued.

coordinate system such that the x axis is along the strike of Longmen Shan fault and the z axis is downward, the boundary condition equation for our model is given by

$$P(x, z = 0, t) = \begin{cases} \rho_w g h(t), & \text{when } |x| \le 2.5 \text{ km} \\ 0, & \text{when } |x| > 2.5 \text{ km} \end{cases}, \qquad (4)$$

where ρ_w is the water density, and $h(t)$ is the height of the water impounded behind the Zipingpu reservoir dam at time t, which is from Lei *et al.* (2008) and illustrated in Figure 3b.

The pore pressure diffusion evolution is simulated by finite element method (FEM). Figure 3b shows the calculated diffusive pore pressure variations with time for different diffusivity values at different locations. We can see that although the simulations vary somewhat for different diffusivity values, the overall characteristics are almost independent of the parameter settings. Pore pressure at shallow depths near the intrusive source (not further than 5 km away) will increase to about 5 bars after a long enough time. However, the pore pressure at greater depths or far away from the intrusive source increases very slowly. The pore pressure at the initial rupture point of the Wenchuan earthquake cannot reach more than 0.4 bars, even when setting the diffusivity to be 10.0 $\mathrm{m^2/s}$, an unreasonably big value. Moreover, the pore pressure at the initial rupture point of the Wenchuan earthquake can only reach to 0.001 bars if setting the diffusivity to be 0.3 $\mathrm{m^2/s}$, a reasonable value used by Hainzl and Ogata (2005) and Lei *et al.* (2008).

Calculation of the $\Delta\tau$ and $\Delta\sigma_n$ Induced by the Static Loading

We set the xy plane on the ground with the x axis along the strike of the fault and the z axis pointing down. The induced stress tensor $\mathbf{S}(x, y, z)$ induced by the surface static loading $F(x, y)$ in a half-space elastic media can be expressed as

$$\mathbf{S}(x, y, z) = \iint_A \mathbf{G}(x - \xi, y - \eta, z) \times F(\xi, \eta) d\xi d\eta, \qquad (5)$$

where A is the area of the surface loading. $\mathbf{G}(x, y, z)$ is called the Green's function tensor, which is the induced stress tensor by a unit vertical point force located at the coordinate origin. The six elements of the $\mathbf{G}(x, y, z)$ tensor can be calculated from (Timoshenko and Goodier, 1970):

$$\begin{aligned} S_{xx}(x, y, z) &= S_\rho \cos^2\varphi + S_\varphi \sin^2\varphi, \\ S_{yy}(x, y, z) &= S_\rho \sin^2\varphi + S_\varphi \cos^2\varphi, \\ S_{zz}(x, y, z) &= -\frac{3z^3}{2\pi R^5}, \\ S_{xy}(x, y, z) &= (S_\rho - S_\varphi) \sin\varphi \cos\varphi, \\ S_{yz}(x, y, z) &= -\frac{3\rho z^2}{2\pi R^5} \sin\varphi, \\ S_{zx}(x, y, z) &= -\frac{3\rho z^2}{2\pi R^5} \cos\varphi, \end{aligned} \qquad (6)$$

where,

$$\rho = \sqrt{x^2 + y^2}, \qquad R = \sqrt{x^2 + y^2 + z^2},$$
$$\varphi = \arcsin(y/\rho), \qquad S_\rho = \frac{1}{2\pi R^2}\left[\frac{(1 - 2\nu)R}{R + z} - \frac{3\rho^2 z}{R^3}\right],$$
$$S_\varphi = \frac{(1 - 2\nu)}{2\pi R^2}\left(\frac{z}{R} - \frac{R}{R + z}\right), \qquad (7)$$

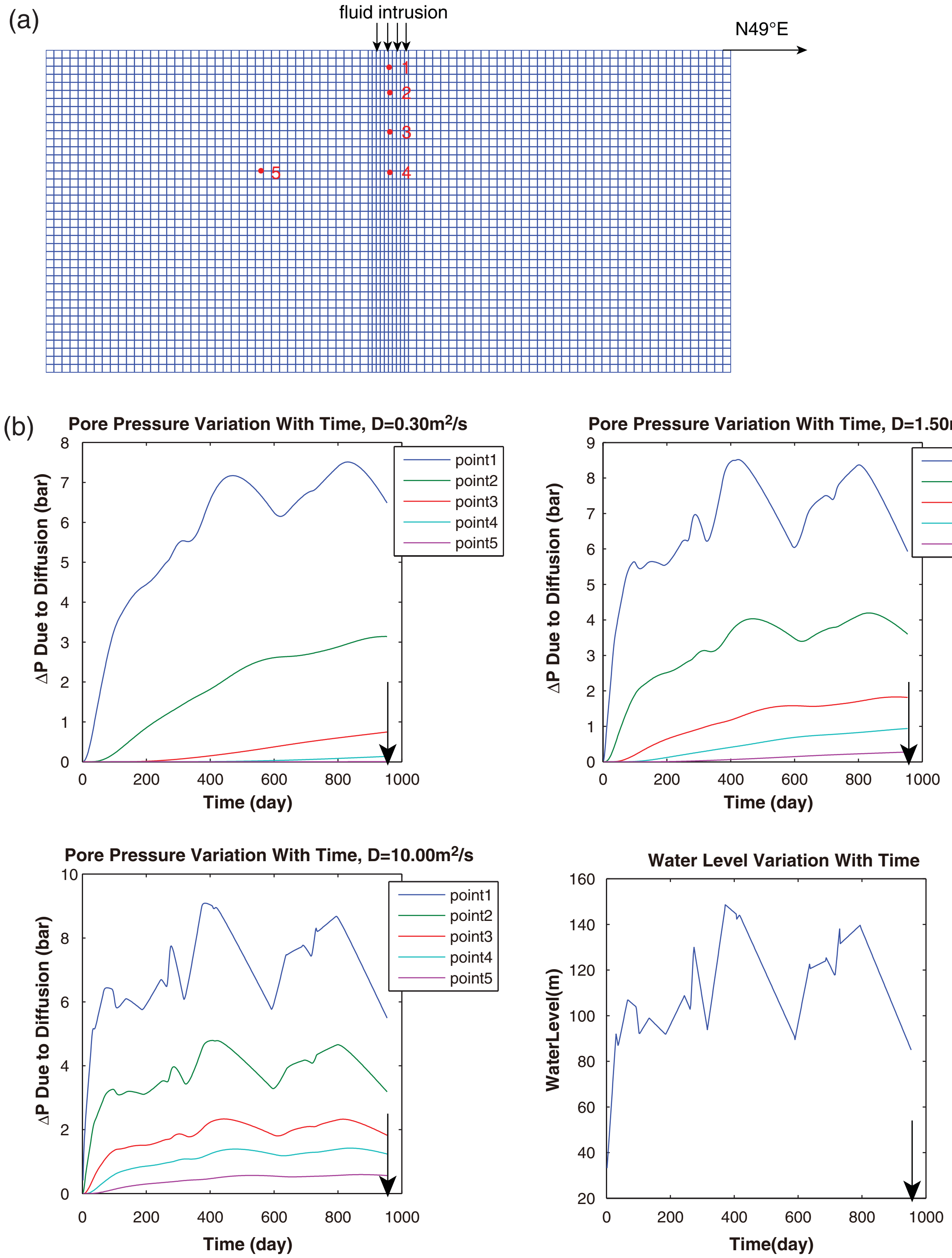

Figure 3. (a) Illustration of the model configuration. The grid size is 1 km × 1 km; the width of the reservoir water intrusion is 5 km. Red circles 1, 2 , 3, and 4 are at 2, 5, 10, and 15 km below the reservoir, respectively. Red circle 5 is the location of the initial rupturing point of the Wenchuan earthquake, which is 15 km below and 10 km west from the reservoir. The *x* axis is along the fault strike direction and the *z* axis is vertical down on the plot. (b) The calculated diffusive pore pressure variations with time for different diffusivity values at different locations and water level variation of the Zipingpu reservoir. The date of time zero is 1 October 2005, the impounding time of the Zipingpu reservoir. The black arrow indicates the time of the Wenchuan earthquake.

Table 1
Parameters of the Simplified Fault Plane for Modeling

						The Initial Rupturing Point of the Wenchuan Earthquake		
Length (km)	Width (km)	Strike	Dip	Rake	Top (km)	Latitude	Longitude	Depth
320	40	229°	35°	120°	0	30.986°	103.364°	15 km

and ν is Poisson ratio of the media, which is set to be 0.25 in our calculations.

From (6), the formula to calculate $\Delta\tau$ and $\Delta\sigma_n$ in equation (1) can be inferred as

$$\begin{aligned}\Delta\sigma_n &= -[(S_{yy}\sin^2\delta + S_{zz}\cos^2\delta) - S_{yz}\sin 2\delta],\\ \Delta\tau &= (S_{xy}\sin\delta - S_{xz}\cos\delta)\cos\lambda - [0.5\sin 2\delta(S_{yy} - S_{zz})\\ &\quad + S_{yz}(\sin^2\delta - \cos^2\delta)]\sin\lambda, \qquad (8)\end{aligned}$$

where δ and λ are the dip and rake angles, which are listed in Table 1.

Coulomb Stress Variations on the Fault due to Load of the Reservoir

Figure 4a shows the Coulomb stress change on the fault induced by the reservoir before the occurrence of the earthquake. We can see that Coulomb stress change induced by the reservoir is big enough to impact the seismicity just within an area that is not farther than 10 km from the reservoir and not deeper than 5 km. The Coulomb stress change induced by the reservoir at the nucleation area of the Wenchuan earthquake is only on the order of 10^{-4} bars, which is less than that induced by the Earth tide (Tanaka *et al.*, 2002). So the link between the filling of the Zipingpu reservoir and the occurrence of the Wenchuan earthquake is rather weak, judging from the small induced Coulomb stress change.

Detecting Indications of Triggering from the Seismicity Data

It is expected from Figure 4a that the seismicity in the area near the reservoir should increase during the filling of the Zipingpu reservoir. However, a plot of the seismicity near the reservoir, with different time periods shown with different colors (Fig. 2), seems to deny that expectation. There is no obvious seismicity increase except for a shallow earthquake swarm that occurred in February 2008. To quantitatively investigate the seismicity variations, we made a plot to illustrate the trend of the cumulative number of earthquakes with $M_L \geq 1.0$ since 2000 (Fig. 5). This shows a small increase in shallow seismicity (depth ≤ 5 km) occurring in November 2006, and a larger, sharp increase of the shallow seismicity occurring in February 2008, about 400 and 850 days after the impounding time of the Zipingpu reservoir, respectively. For deeper earthquakes (depth > 5 km), no similar features are seen. Comparing Figures 4 and 5, we find that is very reasonable. First, the filling of the Zipingpu reservoir could make the Coulomb stress increase in the region close to the reservoir by about 4 bars at a depth of 2 km, and by 1 bar at a depth of 5 km, which is probably big enough to make the regional seismicity show an abnormal increase. However, the amplitudes of the Coulomb stress increases are only on the order of 10^{-2} and 10^{-3} bars at the depths of 10 and 15 km, which are smaller than the stress change induced by the Earth tide (Tanaka *et al.*, 2002), so their triggering ability is weak. Also, the behavior of the reservoir-induced seismicity depends on the rate of increase of pore pressure and the rate of the fluid flow (Talwani *et al.*, 2007). Figures 3 and 4 show that the biggest increase in rates of both the pore pressure and the Coulomb stress occurred within about 400 days after the impounding time of the Zipingpu reservoir, which is the time when the small shallow seismicity increase occurred. The sharp increase of the shallow seismicity occurring in February 2008 was delayed 850 days after the reservoir water impounding time, which is just the time that the Coulomb stress at a depth of 5 km increased to a value big enough to trigger earthquake swarms. The activity could also be the result of the fluids entering a rock, which had up until that time not been seismic. Chen and Talwani (2001) presented a similar example in their study of the seismicity following the impoundment of the Monticello reservoir.

Discussion

Because the nucleation area of the Wenchuan earthquake is so deep (14 km–19 km), the induced Coulomb stress there due to the filling of the Zipingpu reservoir is small enough to be ignored. Thus, the probability that this huge earthquake was induced by the Zipingpu reservoir is very low. Observed seismicity data in the region also supports the conclusion that the Zipingpu reservoir is not big enough to trigger earthquakes at depths > 5 km. Another question is whether the Coulomb stress changes induced by the Zipingpu reservoir would increase enough to trigger earthquakes such as the Wenchuan earthquake if the water intrusion time was long enough. The answer is negative if we examine Figure 3b carefully. We set the hydraulic diffusivity to be 10 m^2/s in a model to investigate the long time effect of the smaller diffusivity model. The pore pressure keeps almost a constant value of 1 bar and 0.5 bar at the depths of 10 and 15 km, after a long-term increase. Because the Coulomb stress variation with time induced by water intrusion mainly originates from the water diffusion process, the reservoir water induced Coulomb stress change would also keep constant after a long-term increase. In other words,

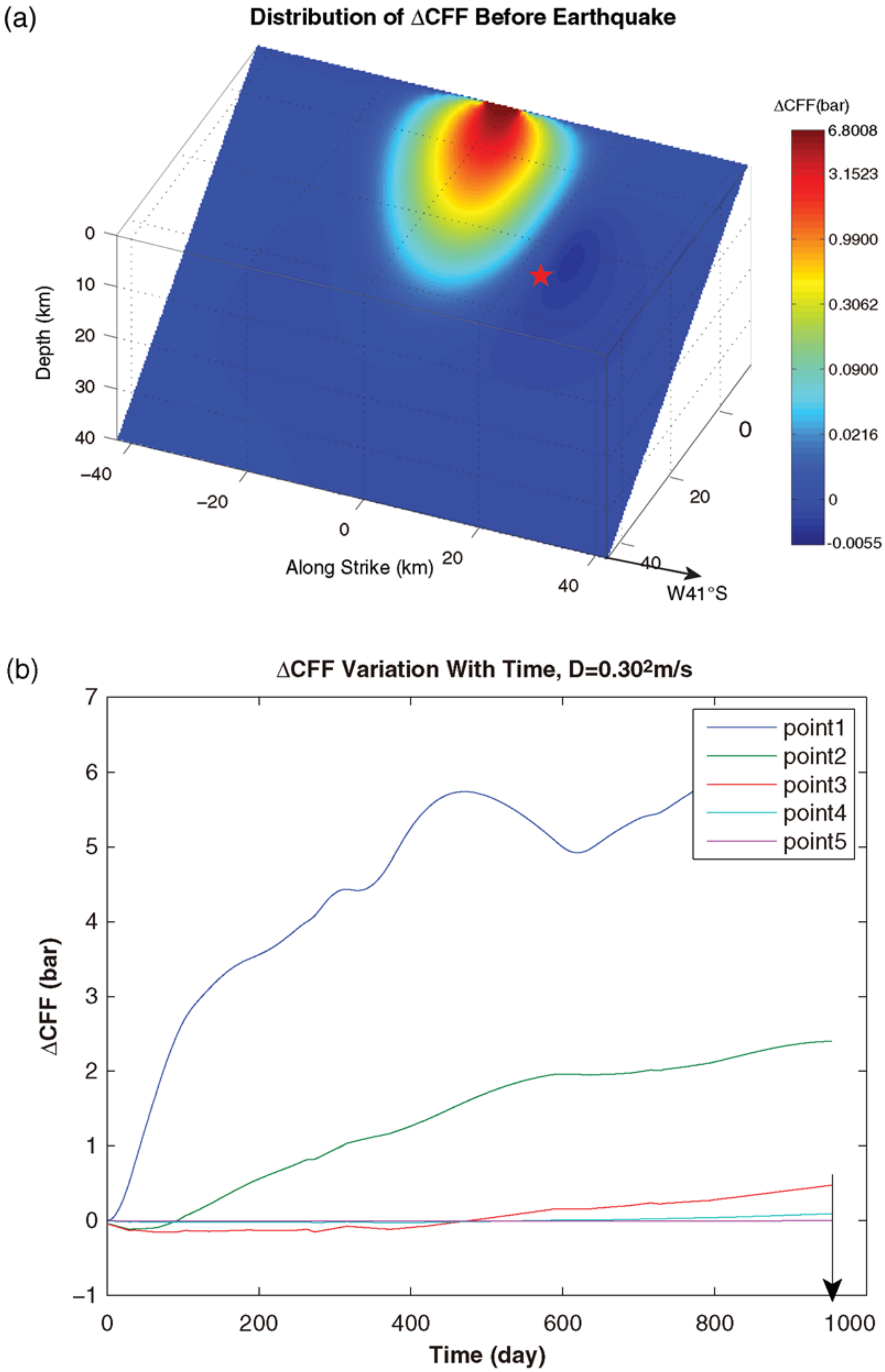

Figure 4. (a) Induced Coulomb stress change on the fault on the day before the Wenchuan earthquake. (b) Coulomb stress variations with time at different points. The time zero is the same as that described in Figure 3b. The black arrow indicates the time of the Wenchuan earthquake.

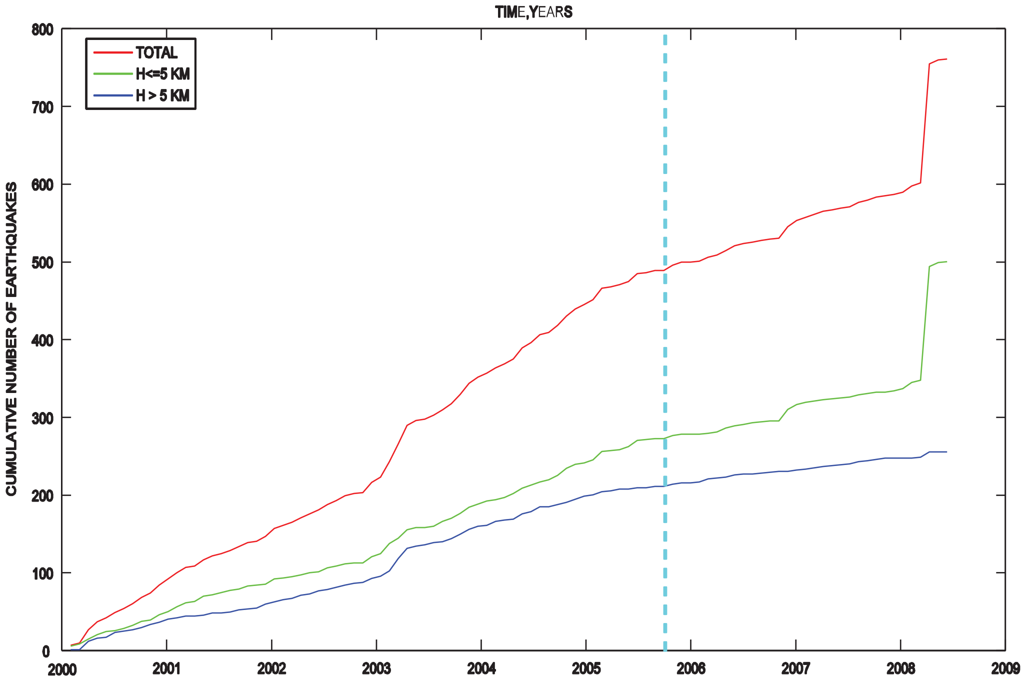

Figure 5. Cumulative earthquake frequency plot for earthquakes with magnitude $M_L \geq 1.0$ from 2000 to 11 May 2008 (the day before the Wenchuan earthquake) in the reservoir region as shown in Figure 2a. The vertical dashed line marks the Zipingpu reservoir impounding time, shown in Figure 2b. The red curve represents the cumulative number of earthquakes for events of all depths. The blue curve represents the cumulative number of events with depth > 5 km. The green curve represents the cumulative number of earthquakes for events with depth ≤ 5 km; it shows that a sharp increase in very shallow seismicity occurred in February 2008.

the induced Coulomb stress in the deep area would not increase to as high as that in the shallow area, which is why the reservoir-induced earthquakes are close to the reservoir, mostly within 5 km depth. Their focal depths are mostly shallower than 5 km and very few are deeper than 10 km (Chen 2009; Valoroso *et al.*, 2009).

We can estimate the minimum magnitude of the completeness of the catalog in this region from a magnitude-

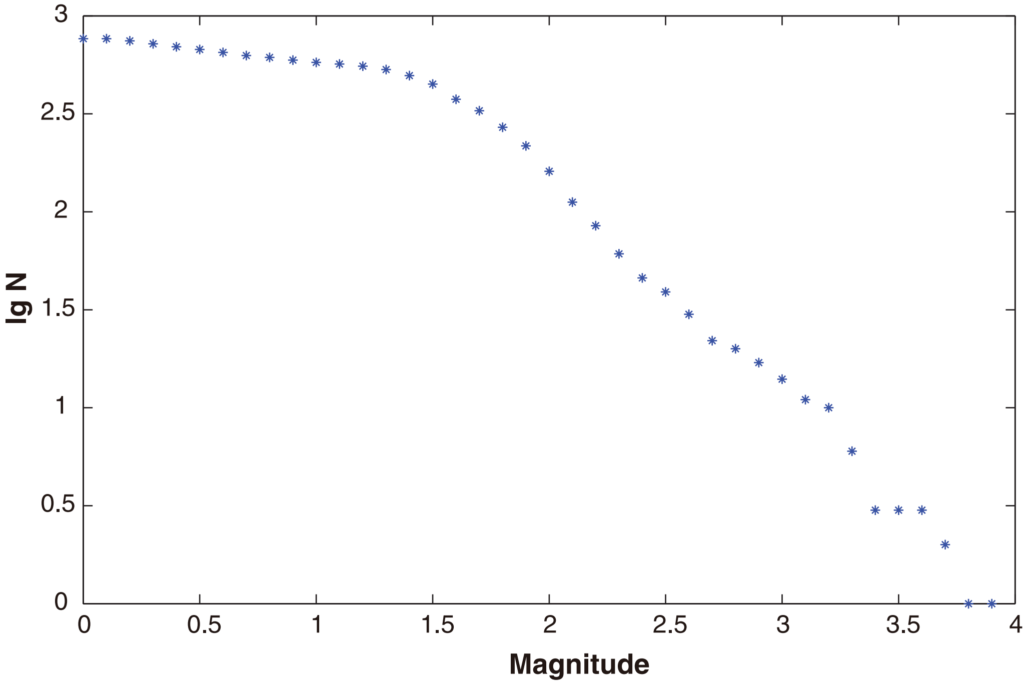

Figure 6. A cumulative plot of the number of events versus magnitude for the observed seismicity from January 2000 to April 2008 in the reservoir area, which indicates that the minimum magnitude of completeness for the catalog in this region is probably near 1.5.

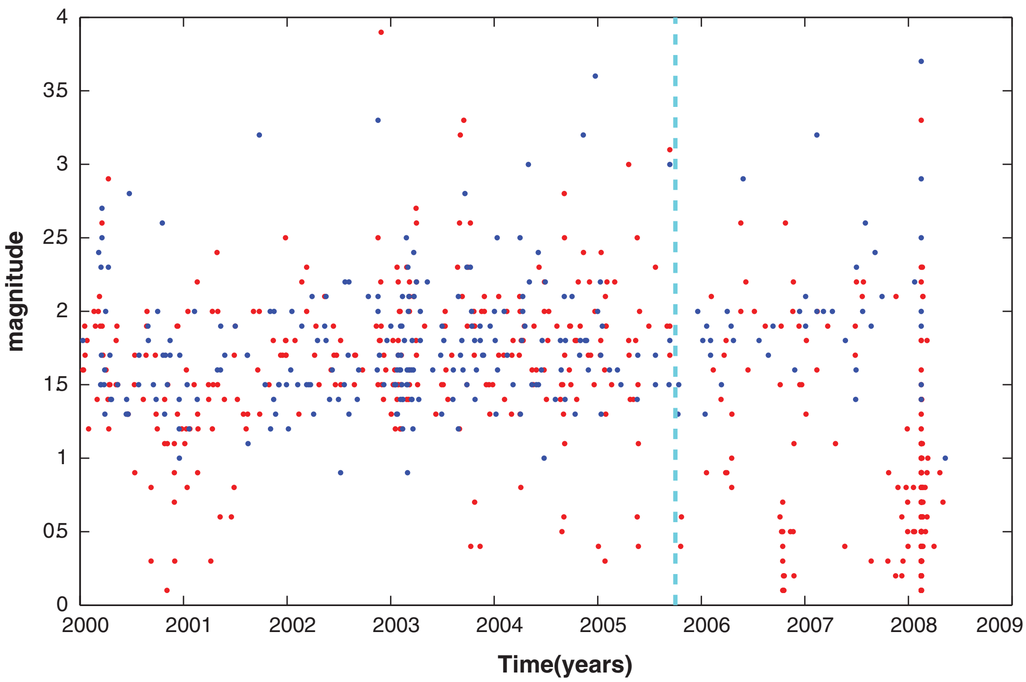

Figure 7. The temporal evolution of the seismicity in the reservoir area from 2000. The shallow (≤ 5 km) and deep (> 5 km) events are respectively indicated by red and blue dots. The vertical dashed line is the time of reservoir impoundment.

frequency plot (Fig. 6). A limit of 1.5 seems appropriate. However, considering that the magnitudes of most of the events in the swarm that occurred in February 2008 are smaller than 1.5, we chose a full catalog to search for the possible reservoir-induced seismicity in this paper. Figure 7 shows the temporal evolution of the seismicity in the reservoir area from 2000. It illustrates that the shallow low magnitude seismicity increased very obviously after the impoundment although the number of events at larger magnitudes did not change much. At least, we can conclude from Figures 2, 5, or 7 that the reservoir water impoundment did not lead to an increase in local, deep seismicity, although the number of small and shallow events obviously increased after the impoundment.

Our analysis based on an incomplete catalog does not affect the conclusion that the reservoir water impoundment did not trigger a deep (> 5 km) seismicity increase, although the conclusion on the shallow seismicity increase was induced by the impoundment cannot be confirmed fully. The reason is that a special seismic array with seven stations within the region from 30.6° to 31.4° N latitude and from 103.1° to 103.9° E longitude (refer to Fig. 2) was installed and started to work in 2004, a year earlier than the time of the Zipingpu reservoir impoundment. Seven stations added into the local network would increase the monitoring capability and locate more small events. So the fact that the deep seismicity did not increase after the impoundment is true. The conclusions on the induced shallow seismicity inferred from the incomplete catalog might not be very strong. However, no obvious change in the observed seismicity rate in year 2004, when seven stations were included into the local network, could be evidence to argue the incompleteness of the catalog with $Ml \geq 1.0$ is not too important.

Figure 5 also shows a seismicity increase around January 2003. Comparing it with the two cases (2006 and 2008) of the seismicity increase that occurred after the impoundment, we can find from Figure 5 or 7 that the seismicity increase in 2003 included an increase in both the shallow and deep seismicity. This suggests that the cause is some unknown tectonic change, whereas the swarm of small, shallow events in 2006 and 2008 are likely due to the water impoundment.

Data and Resources

The earthquake catalog used in this paper is from the Center of Seismic Network Data Management of China (http://www.csndmc.ac.cn/newweb/data.htm).

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References

Chen, L., and P. Talwani (2001). Mechanism of initial seismicity following impoundment of the Monticello Reservoir, South Carolina, *Bull. Seismol. Soc. Am.* **91,** 1582–1594.

Chen, J., Q. Liu, S. Li, B. Guo, Y. Li, J. Wang, and S. Qi (2009). Seismic tectonic study by relocation of the Wenchuan M_s 8.0 earthquake sequence, *Chinese J. Geophys.* **52,** 390–397 (in Chinese).

Chen, Yong (2009). Did the reservoir impoundment trigger the Wenchuan earthquake? *Science China (D)* **52,** 431–433.

Chen, Z., C. Zhao, Q. Wang, W. Hua, L. Zhou, H. Shi, and H. Chen (2009). A study on the occurrence background and process of Wenchuan M_s 8.0 earthquake, *Chinese J. Geophys.* **52,** 455–463 (in Chinese).

Hainzl, Y., and Y. Ogata (2005). Detecting fluid signals in seismicity data through statistical earthquake modeling, *J. Geophys. Res.* **110,** B05S07, doi 10.1029/2004JB003247.

Harris, R. (1998). Introduction to special section: Stress trigger, stress shadows, and implications for seismic hazard, *J. Geophys. Res.* **103,** 24,347–24,358.

Huang, Y., J. Wu, T. Zhang, and D. Zhang (2008). Relocations of the M_s 8.0 Wenchuan earthquake and its aftershock sequence, *Science China (D)* **51,** 1703–1711.

Ji, C. (2008). Preliminary result of the May 12, 2008 M_w 7.9 eastern Sichuan, China earthquake, May 12, 2008, http://www.geol.ucsb.edu/faculty/ji/big_earthquakes/2008/05/12/ShiChuan.html (last accessed 8 June 2008).

Kerr, R., and R. Stone (2009). A human trigger for the great quake of Sichuan?, *Science* Jan. 16, **323,** 322, doi 10.1126/science.323.5912.322.

Klose, C. D. (2008). The 2008 *M* 7.9 Wenchuan earthquake—Result of local and abnormal mass imbalances?, *Eos Trans. AGU* **89,** no. 53, Fall Meet. Suppl., AbstractU21C-08.

Lei, X., S. Ma, X. Wen, J. Su, and F. Du (2008). Integrated analysis of stress and regional seismicity by surface loading—A case study of Zipingpu reservoir, *Seismology and Geology* **30,** 1046–1064 (in Chinese).

Li, Y., J. Zhang, W. Zhou, X. Hu, L. Guo, and Z. Zhang (2009). The mechanism and dynamics of the generation and occurrence for Wenchuan M_s 8.0 earthquake, *Chinese J. Geophys.* **52,** 519–530 (in Chinese).

Robinson, R., S. Zhou, S. Johnson, and D. Vere-Jones (2005). Precursory accelerating seismic moment release (AMR) in a synthetic seismicity catalogue: A preliminary study, *Geophys. Res. Letter* **32,** L07309.

Scholz, C. (2002). *The Mechanics of Earthquakes and Faulting*, Cambridge Univ. Press, New York.

Skempton, A. W. (1954). The pore pressure coefficients A and B, *Geotechnique* **4,** 143–147.

Steacy, S., and J. Gomberg (2005). Introduction to special section: Stress transfer, earthquake triggering, and time-dependent seismic hazard, *J. Geophys. Res.* **110,** B05S01, doi 10.1029/2005JB003692.

Talwani, P. (1997). On the nature of reservoir-induced seismicity, *Pure and Applied Geophys.* **150,** 473–492.

Talwani, P., L. Chen, and K. Gahalaut (2007). Seismogenic permeability, k_s, *J. Geophys. Res.* **112,** B07309, doi 10.1029/2006JB004665.

Tanaka, S., M. Ohtake, and H. Sato (2002). Evidence for tidal triggering of earthquakes as revealed from statistical analysis of global data, *J. Geophys. Res.* **107,** no. B10, 2211, doi 10.1029/2001JB001577.

Timoshenko, S. P., and J. N. Goodier (1970). *Theory of Elasticity*, McGraw-Hill, New York.

Valoroso, L., L. Improta, L. Chiaraluce, R. Di Stefano, L. Ferranti, A. Govoni, and C. Chiarabba (2009). Active faults and induced seismicity in Val D'Agri area (Southern Apennines, Italy), *Geophy. J. Inter.* **178,** 488–502.

Wang, W., L. Zhao, J. Li, and Z. Yao (2008). Rupture process of the M_s 8.0 Wenchuan earthquake of Sichuan, China, *Chinese J. Geophys.* **51,** 1403–1410 (in Chinese).

Zhang, Y., L. Xu, and Y. T. Chen (2009). Spatio-temporal variation of the source mechanism of the 2008 great Wenchuan earthquake, *Chinese J. Geophys.* **52,** 379–389 (in Chinese).

Zhou, S. (2008). Seismicity simulation and analysis of the fault interactions in Western Shichuan of China, *Chinese J. Geophys.* **51,** 165–174 (in Chinese).

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