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INSIGHTS GAINED FROM THE SEISMICITY AROUND THE ZIPINGPU RESERVOIR BEFORE THE WENCHUAN M_S8.0 EARTHQUAKE

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Abstract: The 2008 Wenchuan M_S8.0 earthquake occurred on Longmenshan fault zone (LMSF), which is at the eastern margin of the Tibetan plateau. The epicenter is near the Shuimogou earthquake swarm, which was thought to be triggered by the Zipingpu reservoir after its impounding in 2004. People have speculated that the large earthquake was triggered by the water filling of the reservoir. To figure out the role of the Zipingpu reservoir on the earthquake, the local seismicity recorded by the Zipingpu local seismic network during the period from 31 July 2004 to 11 May 2008 were analyzed in detail. The distribution of hypocenters showed that most earthquakes occurred on Yingxiu-Beichuan fault (YBF) in the reservoir area with hypocenters depth less than 10 km, which is a major source fault of the Wenchuan earthquake. Useful information on fault geometry in the depth was also obtained. The spatial-temporal distribution of hypocenters demonstrated clear migration pattern that indicated pore-pressure diffusion, it also showed a hydraulic diffusivity (D) of 0.7 m^2/s. Previous experiments show the existence of the synergism process of the fault under a meta-instability state before fault sliding. It enhances the stress on the stronger portion of the fault and the synergism degree by reducing strength of the weak portions and by increasing the total length of weak portions. According to this view, the pore pressure diffusion by water filling of Zipingpu reservoir increased the total length of weak portions and enhanced the stress at the focal.

Key words: Wenchuan earthquake, Zipingpu reservoir, diffusivity, meta-instability state.

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АНАЛИЗ СЕЙСМИЧНОСТИ В РАЙОНЕ ВОДОХРАНИЛИЩА ЗИПИНГПУ ПЕРЕД ВЕНЧУАНЬСКИМ ЗЕМЛЕТРЯСЕНИЕМ (M_S 8.0)

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Аннотация: Венчуаньское землетрясение (M_S 8.0) произошло в 2008 г. в разломной зоне Лонгменшан, расположенной на восточной окраине Тибетского плато. Его эпицентр находился рядом с роем землетрясений Шуимогу, возникновение которых связывают с влиянием водохранилища Зипингпу после его заполнения в 2004 г. Считалось, что главной причиной сильного землетрясения было заполнение водохранилища водой. Для выяснения роли водохранилища Зипингпу в инициировании Венчуаньского землетрясения был проведен детальный анализ данных, накопленных местной сетью сейсмических наблюдений в районе Зипингпу в период с 31 июля 2004 г. по 11 мая 2008 г. Судя по распределению гипоцентров, большинство землетрясений произошли на разломе Инксю-Бейчуан в районе водохранилища, при этом глубина гипоцентров не превышала 10 км, и это основной разлом, инициировавший Венчуаньское землетрясение. Кроме того, были получены полезные данные по глубинной геометрии разлома. По пространственно-временному распределению гипоцентров установлен характер миграции с рассеиванием порового давления, а также определен коэффициент гидравлической диффузии (D=0.7 м^2/с). По результатам предыдущих экспериментов установлено наличие синергетического процесса на изучаемом разломе в метастабильном состоянии перед смещением по разлому, что привело к усилению напряжений на прочном участке разлома и синергии при уменьшении прочности ослабленных участков, а также увеличении общей протяженности ослабленных участков разлома. По нашему мнению, рассеивание порового давления при заполнении водой водохранилища Зипингпу привело к увеличению общей длины ослабленных участков разлома и увеличению напряжений в очаговой зоне.

Ключевые слова: Венчуаньское землетрясение, водохранилище Зипингпу, коэффициент гидравлической диффузии, метастабильное состояние.

1. INTRODUCTION

The Zipingpu reservoir may have hastened the occurrence of the Wenchuan M_S8.0 earthquake, which was pointed out soon after the earthquake occurred [*Lei et al., 2008*]. Study of the changes of Coulomb failure stress (ΔCFS) on Longmenshan fault zone (LMSF) has pervaded discussions based on the above-mentioned viewpoint [*Deng et al., 2010; Gahalaut K., Gahalaut V.K., 2010; Ge et al., 2009; Lei, 2011; Sun et al., 2012*]. However, a key unsolved issue is regarding the factors that should be adopted for modeling to calculate ΔCFS. There are two main factors controlling ΔCFS results: the fault geometry and the hydraulic diffusivity. Using different factors, previous study yielded conflicting results. In this study, these factors of LMSF were evaluated based on pre-earthquake data recorded by a local seismic network firstly. The role of water filling of Zipingpu reservoir on the Wenchuan earthquake is discussed according to viewpoint that fault exists a meta-instability state before sliding [*Ma et al., 2012; Ren et al., 2013; Zhuo et al., 2013*].

2. FAULT GEOMETRY

A digital seismic network was operated in the Zipingpu reservoir region for recording micro earthquakes since July 2004. For making out what had happened on LMSF before the Wenchuan M_S 8.0 earthquake, earthquakes from July 2004 to 11 May 2008 were examined and 1772 earthquakes whose magnitudes were between M_L –0.2 and 4.4 were found. Figure 1a shows the distributions of the epicenters and the characteristic of them. Furthermore, Figure 1b shows the distributions of the events and stations in detail near the reservoir. In Figure 1c, a cross-section A-A’ is used to determine the fault geometry, which is across LMSF.

LMSF lies near the eastern margin of the Tibetan plateau and contains three major thrust faults: Wenchuan-Maoxian fault (WMF), Yingxiu-Beichuan fault (YBF), and Guanxian-Jingyou fault (GJF), which dip toward NW trend [*Zhang et al., 2009*]. Two clusters located around the reservoir are characterized by the occurrence of a large number of events (Figure 1a). One is beyond 200 km, striking NE. The other is about 60 km long toward N55°W trend. This indicates that two existed faults were being active before the Wenchuan M_S8.0 earthquake. The one toward NW trend is the Xiaoyudong-Lixian fault (XLF). Chen reported a similar result obtained from the aftershocks of the Wenchuan M_S8.0 earthquake about XLF [*Chen et al., 2009*], which was confirmed by the rupture of the main earthquake [*Xu et al., 2008*]. Also, the faults geometry underlying was also clear. As shown in Figure 1c, almost all events occurred above 10 km. However, depth of the aftershocks was between 10 and 20 km [*Zhu et al., 2008*; *Chen et al., 2009*], and the dip angle of YBF was found to be high at the surface and becoming lower with depth. Toward the east of YBF, a seismicity band could be noted in 5~15 km depth, which did not reach the surface; this could be the reflection of the buried fault.

3. PORE-PRESSURE DIFFUSION

Limestone distribute widely in this region. Because of limestone erosion processes, many big cracks along the YBF are left [*Wang, 2001*]. That is a geological background for analyzing the pore pressure diffusion of the Zipingpu reservoir.

In order to realize the diffusion process, the spatiotemporal pattern of the seismic activity near the reservoir is shown in Figure 2. In 2004, the seismicity was only near the dam. With the water level rising, the seismicity migrated toward both side in 2005. From 2006 to 2008, the seismicity was mainly at the end of the reservoir, where Shuimogou earthquake swarm was less than 10 km away from the epicenter of Wenchuan earthquake (Figure 2b). Uniting the stream profile and the seismicity, the characteristic can be seen that the distributions of the events spread to the end of the reservoir gradually with the water filling of

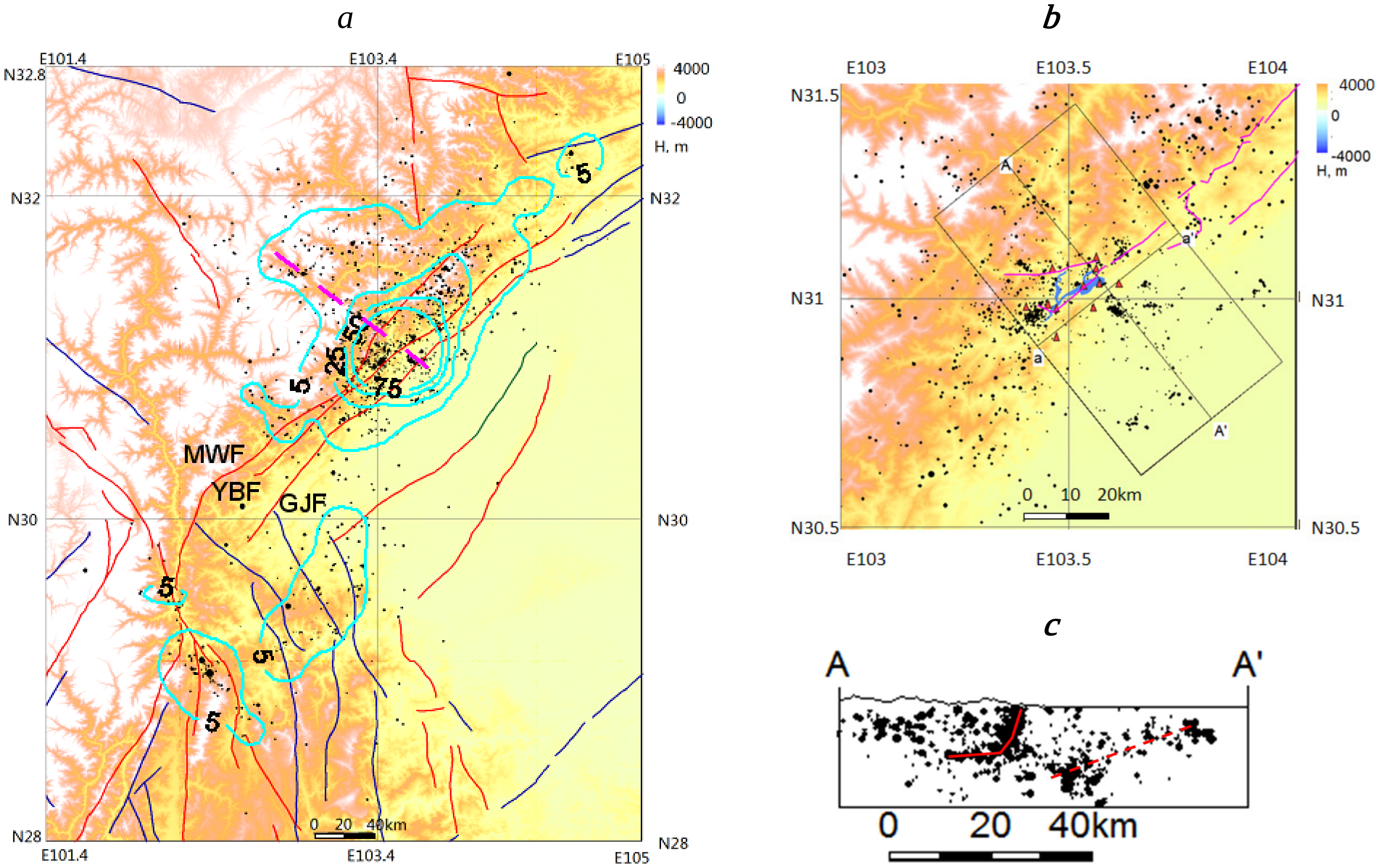

Fig. 1. *a* – active faults (red, blue, and green line [*Deng et al., 2007*]) and epicenters of earthquakes (31 July 2004 – 11 May 2008) on Longmenshan thrusts and surrounding regions observed by the Zipingpu local seismic network. Black circles indicate earthquakes. MWF, YBF, and GJF indicate Maoxian-Wenchuan fault, Yingxiu-Beichuan fault, and Guanxian-Jiangyou fault. Cyan lines are the contours of the epicenters distributions with the step size of 0.2 degree. Dash line is the buried fault; *b* – map view of Wenchuan earthquake surface ruptures (red lines) of M_S 8.0, the Zipingpu reservoir (blue region), and the Zipingpu local seismic network (red triangle); *c* – cross-section of the details shown in (*b*).

Рис. 1. а – активные раломы (красные, голубые и зеленые линии) по [*Deng et al., 2007*] и эпицентры землетрясений в период с 31 июля 2004 г. по 11 мая 2008 г. на надвигах Лонгменшан и вблизи них по данным местной сети сейсмических наблюдений в районе Зипингпу. Землетрясения показаны как залитые кружки. Разломы: MWF – Маоксиан-Венчуаньский, YBF – Инксю-Бейчуаньский, GJF – Гуаньксиан-Янгуйский. Голубыми линиями оконтурены районы распределения эпицентров (шаг 0.2 градуса). Пунктиром показан погребенный разлом; *b* – карта изучаемого района; поверхностные разрывы после Венчуаньского землетрясения (M_S 8.0) показаны линиями красного цвета; водохранилище Зипингпу показано синим цветом; красные треугольники – сейсмостанции в районе Зипингпу; *c* – разрез к рис. (*b*).

reservoir. It can be observed that the distance of seismic migration toward NE trend is short, but is long toward SW trend. The reasons for this might be the terrain and shape of the Zipingpu reservoir. A point worth emphasizing is that the impoundment of the Zipingpu reservoir at September in 2005 could be responsible for the abrupt increase in the speed of seismic migration.

For evaluating hydraulic diffusivity (D) of the crust, the method developed by Shapiro to describe pore-pressure perturbations caused by fluid injections into a borehole was used [*Parotidis et al., 2003, 2004; Shapiro et al., 1997, 2002, 2005, 2006*]. In the isotropic medium, the pore pressure diffusion can be described as Biot's equation, the equation has the form

$$\frac{\partial P}{\partial t} = D\nabla^2 P, \tag{1}$$

where D is hydraulic diffusivity, P is pressure produced by waterhead increment, t is time. If a time-harmonic perturbation $P_0 exp(-iwt)$ of pore pressure perturbatoin is given on a small spherical surface of radius α with the center at an injection point, the solution of equation takes the forms

$$P(r,t) = P_0 e^{-iwt}\frac{\alpha}{r}exp\left[(i-1)(r-\alpha)\sqrt{\frac{\omega}{2D}}\right], \tag{2}$$

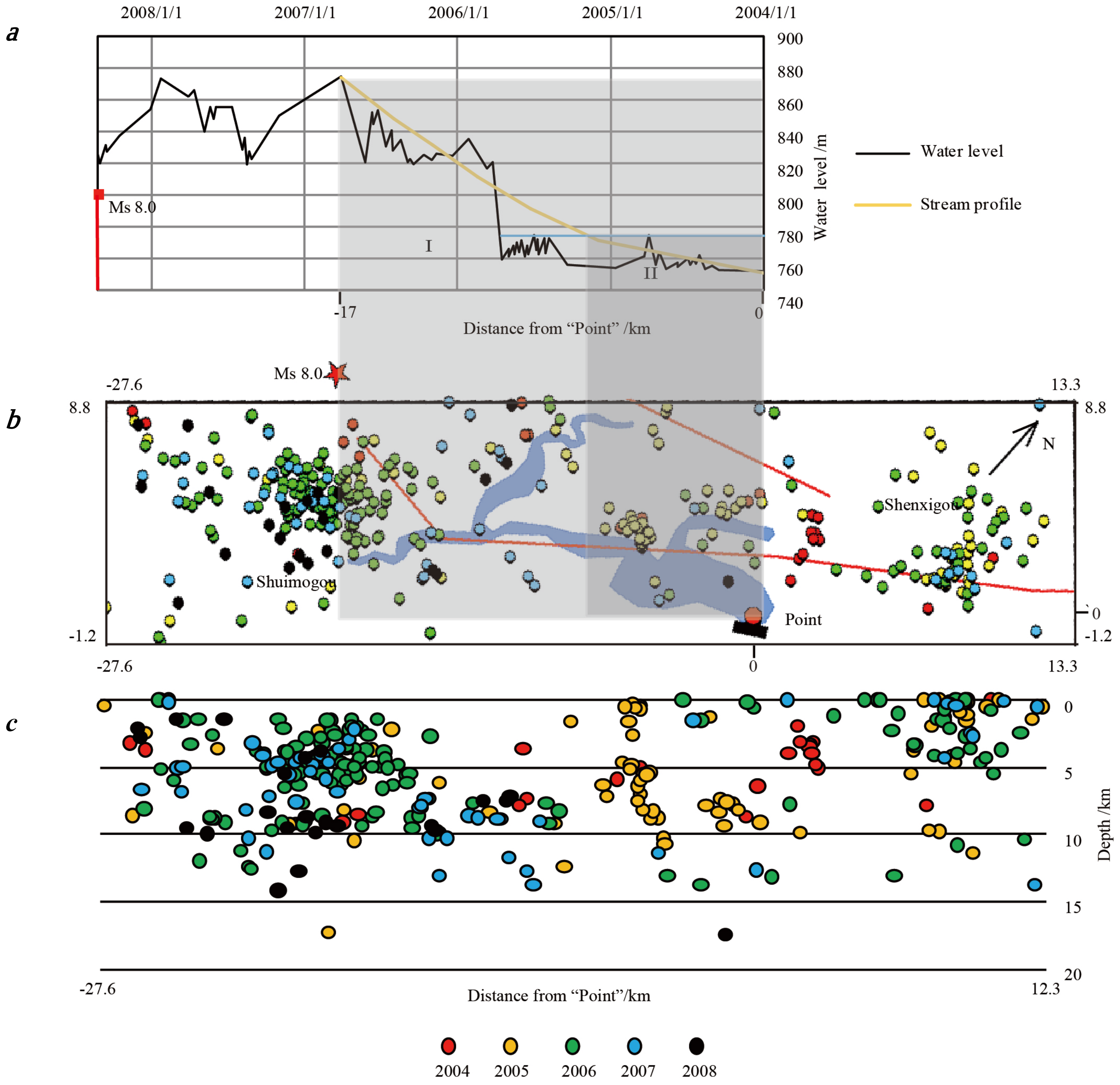

Fig. 2. *a* – water level and stream profile; *b* – epicenters of earthquakes (2004/8/1 – 2008/05/11) and Wenchuan earthquake surface ruptures of M_S8.0 along the Zipingpu reservoir. Red bigger circles are the filling points. The point symbols of red, orange, green, blue, and black are the locations of the earthquakes of 2004, 2005, 2006, 2007, and 2008, respectively; *c* – cross-section of the details shown in (*b*).

Рис. 2. *a* – уровень воды и профиль водоема; *b* – эпицентры землетрясений с 01 августа 2004 г. по 11 мая 2008 г. и поверхностные разрывы после Венчуаньского землетрясения (M_S 8.0) у водохранилища Зипингпу. Крупные красные точки – места, откуда велось заполнение водой. Точки красного, оранжевого, зеленого, голубого и черного цвета показывают местоположение землетрясений, произошедших в 2004, 2005, 2006, 2007 и 2008 гг., соответственно; с – разрез к рис. (*b*).

where ω is the angular frequency and γ is the distance from the injection point to the point where the solution is looking for. When the medium is homogeneous and isotropic, the slowness of slow wave can be used to estimate the size of spactial domain. The pore-pressure perturbation at the injection point can be looked as a step function $p(t)=p_0$ if $t\geq0$ and $p(t)=0$ if $t<0$, then the dominant part of the power spectrum is located in the frequency range below $2\pi/t_0$. Thus, the probability that seismic even at time t_0 was triggered by signal components from the frequency range $\omega\leq2\pi/t_0$ is high. Then, the equation employed can be given as follows:

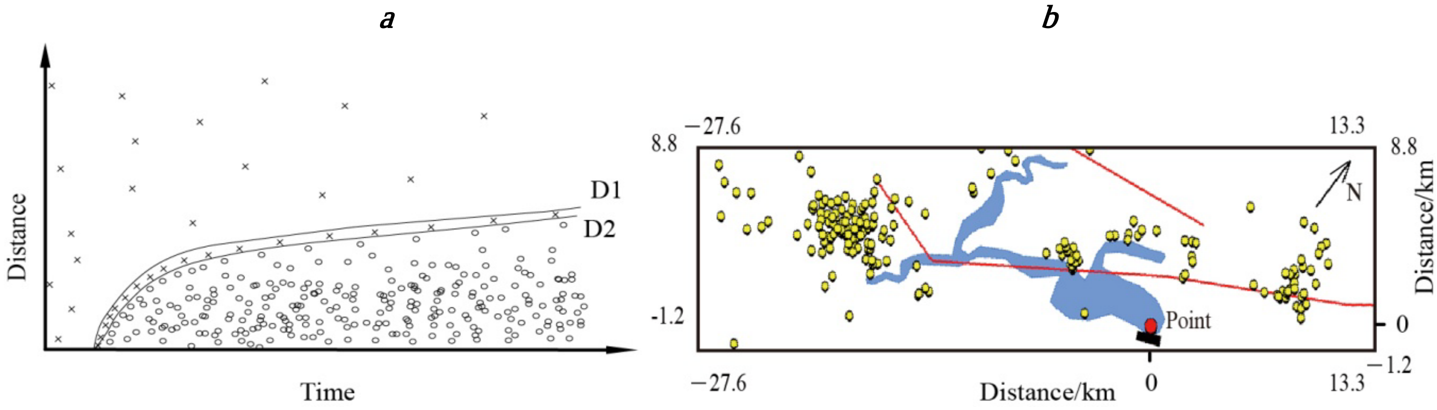

Fig. 3. *a* – model for evaluating hydraulic diffusivity in a reservoir region with background seismicity. Crosses indicate the possible expected background seismicity by active faults. Circles indicate the earthquakes triggered by reservoir; *b* – the obtained events after rejecting the background earthquakes value.

Рис. 3. *а* – модель для оценки коэффициента гидравлической диффузии для района водохранилища с учетом фоновой сейсмичности. Крестики – возможная ожидаемая фоновая сейсмичность активных раломов. Кружочки – землетрясения, спровоцированные водохранилищем. *b* – полученные события без величины фоновой сейсмичности.

$$\gamma = \sqrt{4\pi Dt}. \qquad (3)$$

However, shocks had occurred before the Zipingpu reservoir was built on LMSF. It meant that the earthquakes, which were not connected with the water filling of reservoir, could also occur after the reservoir was built. These events would make some disturbance to the evaluation of the hydraulic diffusivity and should be deleted. The principle of rejecting data is shown in Figure 3a. First, a typical region far away from the reservoir was selected. The frequency of shocks in this region was then evaluated. Second, the events near the reservoir area were scanned. The earlier events in every cell, which were with the same frequency of the studied region, should be deleted. In Figure 3a, the data with cross would interfere with the evaluation of the D, then being rejected. Maybe some useful data was deleted in this progress, such as the events between curve of D_1 and D_2. However, the data left would be better for us to catch the characteristics of pore-pressure diffusion. The events, which were possibly triggered by the Zipingpu reservoir, were obtained in this way (Figure 3b).

Taking Point as the injection point source, the D of the crust in the Zipingpu reservoir area was evaluated using the data in Figure 2b and Figure 3b. When the data in Figure 2b was used, we could hardly see the diffusion because of the background seismicity by LMSF (Figure 4a). However, the pore-pressure diffusion is clear in Figure 4b after the background seismicity being rejected. The value of $5 m^2/s$ is obvious too big. However, the D of $0.5 m^2/s$ is a little small and not all the events are in the curve. The best fitted value of D was $0.7 m^2/s$.

Two types of seismic response after the filling of large reservoir were given by simpson: one is the rapid response type; the other is the delayed response type [*Simpson et al., 1988*]. Considering the fact that lots of events appeared in Shuimogou region with the rising water level after September 2005 (Figure 2b), most earthquakes, which occurred far away from Point as soon as the reservoir filling, could be the rapid response type.

4. Discussion and Conclusions

Similar to the analyses by Lei et al. [*2008*], Ge et al. [*2009*], Deng et al. [*2010*], Gahalaut et al. [*2010*], and Lei et al. [*2011*], we examined the local seismicity before the occurrence of Wenchuan M_S 8.0 earthquake. However, unlike the earlier researches, we focused on the faults geometry and pore-pressure diffusion, but not ΔCFS. These factors were noted to be significant for modeling to calculate ΔCFS.

Our results showed that the dip angle of YBF was low at 8 km depth and close to zero at 10 km depth. This finding is not in agreement with that of Zhu et al. [*2008*] and Chen et al. [*2009*] based on aftershocks, which were deeper than our results. The reasons for this might be that YBF has more complex structure. The obtained result is confirmed by seismic interpretation profiles [*Zhou et al., 2010*]. Hence, we infer that the fault in shallow was actived by the reservoir.

The issue was very significant that whether the earthquakes before the Wenchuan M_S8.0 earthquake were connected with the pore-pressure diffusion. Because of the background seismicity by LMSF, it could hardly see the diffusion of pore-pressure. However, when the data disturbing our evaluation was rejected, we can see the diffusion clearly. The D of the crust was estimated to be $0.7 m^2/s$. In the earlier researches, the D of the crust was estimated to be in a range between 10^{-4} and $10 m^2/s$ [*Lei,*

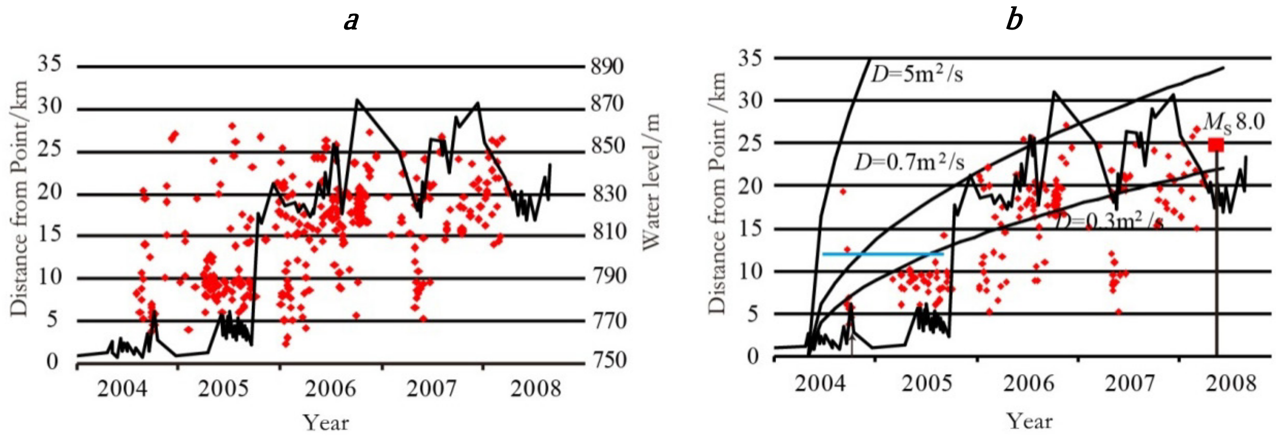

Fig. 4. The distance from Point to earthquakes with time, containing the background seismicity (*a*); the distance from Point to earthquakes with time, rejecting the background earthquakes (*b*).

Рис. 4. Расстояние от точки наблюдения до землетрясений с учетом времени, включая фоновую сейсмичность (*a*); расстояние от точки наблюдения до землетрясений с учетом времени без фоновой сейсмичности (*b*).

2011; Scholz, 2002; Talwani et al., 2007]. Our results also suggest that there were two types earthquakes near the reservoir. Some earthquakes were the background seismicity by LMSF with a similar shock frequency to areas far away from the Zipingpu reservoir. Other earthquakes were the rapid response type, which appeared immediately far away from the injection sources as soon as the reservoir filling. Because limestone and big cracks distribute widely in this region, the pore pressure diffusing in big cracks is in charge of these rapid response type earthquakes.

Previous experiments show the existence of the synergism process of the fault under a meta-instability state before fault sliding [*Ma et al., 2012; Ren et al., 2013; Zhuo et al., 2013*]. It enhances the stress on the stronger portion of the fault and the synergism degree by reducing strength of the weak portions and by increasing the total length of weak portions. To LMSF, an obvious locked segment of 60 km long came into being after 2004, which include the fault near the reservoir [*Ma et al., 2013*]. According to the points above, it can be sure that the pore pressure diffusion due to the water filling of reservoir played a key role on reducing the strength of fault of 20 km long near the reservoir. As a result, the strength of locked segment was reduced and the stress increased at the main shock location.

There is no doubt that the tectonic stresses on the LMSF result from the movement of eastward mass flow of the Tibetan Plateau, against the strong and stable crust block underlying the Sichuan Basin and southeastern China. However, the Zipingpu reservoir impoundment had possibly helped the occurrence of Wenchuan earthquake.

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