Waveform inversion of the rupture process of the 2008 Wenchuan earthquake based on the near field strong motions and surface rupture data

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SUMMARY:
We inverted the source rupture process of the 2008 Wenchuan earthquake based on 49 near field 3 components strong motion velocity records and surface offset data by the non-negative least-squares method and the multiple-time widow technique with a flat-lying layers velocity structure model. The result show that the whole rupture process lasted for 90s, and rupture front propagate rapidly in the northeast direction with average velocity of about 3.1km/s than that in the southwest direction. The rupture result in 3 asperities in Beichuan fault and 2 small asperities in the Pengguan fault, with maximum slip of the 8.2m and 5.2m. The slip duration is longer with maximum time of about 60s in the Yinxiu area of the Beichuan fault. The rupture fronts are very irregular, and rupture paused in some area especially in southeast direction. The total seismic moment of the inversion is 0.99×10^{21}Nm.

Keywords: rupture process, Wenchuan earthquake, near field strong motion, mult-itime window

1. INTRUDUCTION

The Wenchuan earthquake (Mw 7.9) caused catastrophic damage and more than 300km surface rupture, which is one of the biggest earthquakes in China. The coseismic surface ruptures, the aftershocks distribution and industry seismic profiles, show that the earthquake rupture involves slip along a variety of fault sections that compose an imbricate thrust belt, and two imbricate structures have ruptured simultaneously. This earthquake, therefore, provides a valuable opportunity to study the large complex earthquake source process. After the Wenchuan earthquake, several research groups carried out the source inversion by using the far-field long-period teleseismic waveform data, assuming a single fault segment or multiple fault segments with fixed dip angles. Most results show that the rupture duration are more than 100 s, and formed 2 large slip areas, the Yingxiu area and the Beichuan area. The rupture mainly propagated in the NE direction, and the Dujiangyan-Wenchuan segment is with dominant slip reverse faulting while the Beichuan-Qingchuan segment with strike-slip faulting.

During the Wenchuan earthquake, the strong-motion network maintained by the China Earthquake Administration recorded 100 three-component accelerograms within a distance of 300 km (Li *et al.* 2008), including 3 records within a distance of 10 km, 10 records within 30 km, and 42 records within 100 km. The closest record was from a site within 2 km of the fault-rupture plane. By now, all studies used the far-field long-period teleseismic waveform data with advantage on the location of fault slip but disadvantage on the detail of the rupture. In this study, we used near field strong motion data and the surface offset of the Wenchuan earthquake to inverse the time-spatial rupture process of the earthquake.

2. DATA AND METHOD

2.1. Fault Rupture Model

By the seismic lines, geologic maps, topography, aftershock and the surface rupture, Xu *et al* (2009) propose a three dimensional model for the Wenchuan earthquake rupture geometry. The structure shows that the Longmenshan foothills in the epicentral zone consists of an imbricate stack of thrust faults, including three major reverse faults, the Wenchuan-Maowen, Beichuan, and Pengguan faults. The Beichuan fault dips steeply, >45°, at the surface, and appears to root into a basal detachment in the mid-crust. The Pengguan fault is a shallowly dipping thrust faults in the footwall. The Wenchuan earthquake initiated close to the base of the Beichuan fault and propagated upward to the Beichuan fault, and part of the rupture entered the Pengguan fault, which merges with the Beichuan fault at depth.

According to the results of Xu *et al* (2009), we constructed the fault model with two major reverse causative faults, the Beichuan and the Pengguan fault, as shown in figure 1. The strike of two faults is 245° and they dipped to the NW direction. We use two rectangle fault to represent the curved Beichuan fault with dip angle 33° and 47° ,respectively, and a rectangle plane fault to represent the Pengguan fault with dip angle 47° . The two faults merged at 10.8 km in depth. We take the fault length as 400km long for Beichuan fault and 100km long for Pengguan fault by the surface rupture and aftershock distribution (the surface rupture zone is 240-km-long along the Beichuan fault and 72-km-long along Pengguan fault (Xu *et al*,2009)). The epicenter is located at 30.986°N, 103.364°E and the focal depth is taken as 19km. For the Beichuan fault, 268 km are north to the epicentre whereas 132km south to the epicenter. We take the Pengguan fault parallel to the Beichuan fault and the distance between them was 6.54 km.

2.2 Synthetic Green's Function, Strong Motion Records and Surface Offsets Constraints

The crust structure and topography is complex for the Longmenshan area, so the accurate Green's function needs a 3 dimensions crust and topography model. In this study, for simplicity, we use approximate simplified 2-d model of this area, the regional velocity structure is shown in table 1.

Table 1. Regional velocity structure

Depth /km	Vp /(km/s)	Vs /(km/s)	Density /(g/cm^3)
0	4.88	2.86	2.40
2.9	5.80	3.40	2.67
8.3	6.04	3.55	2.67
30	6.82	3.98	3.01
43.1	7.61	4.45	3.25
68.5	8.38	4.90	3.50

The Green's functions used to calculate the strong-motion synthetics are computed with the DWFE (Discrete Wavenumber/Finite Element) code of Olson (1982). The rise time of each Green's function is represented by a rectangle with duration of 2 sec.

3 components velocity records of 49 stations are used in this study, and the distribution of these stations are shown in figure 2. The original accelerograms are integrated to velocity then rotate to the direction parallel and normal to the fault strike. The velocity records were band-pass filtered from 0.05 to 0.5 Hz.

The trigger time of the instrument is important for the inversion. For these 49 stations, most of the stations have GPS trigger time, but some have not. The trigger time is estimated by the GPS time and the time traveled from the epicenter to the stations computed by our simplified 2-d velocity structure. Other important parameters to be considered in the inversion problem are the record length to be used. For most of the stations, the strong shaking is in 50 to 70 sec. Considering the time required for the rupture front to propagate down the entire length of the fault plus the time required for the slowest phase of interest to travel to the most distant station used in the inversion, and the strong shaking time, we take the record length as 70s. The surface rupture data are taken form the study of Xu *et al* (2009), as shown in table 2 and 3.

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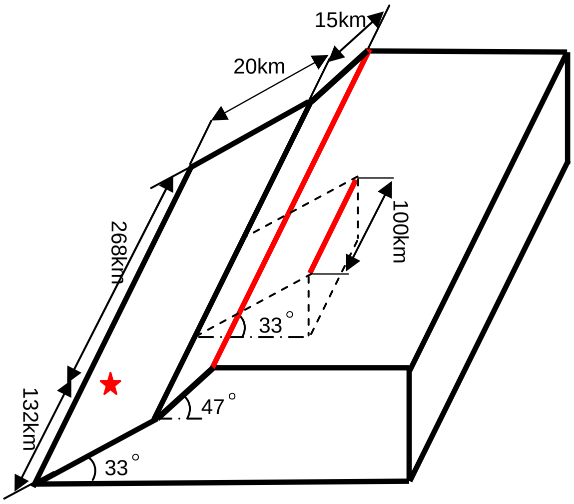

Figure 1. The fault rupture model

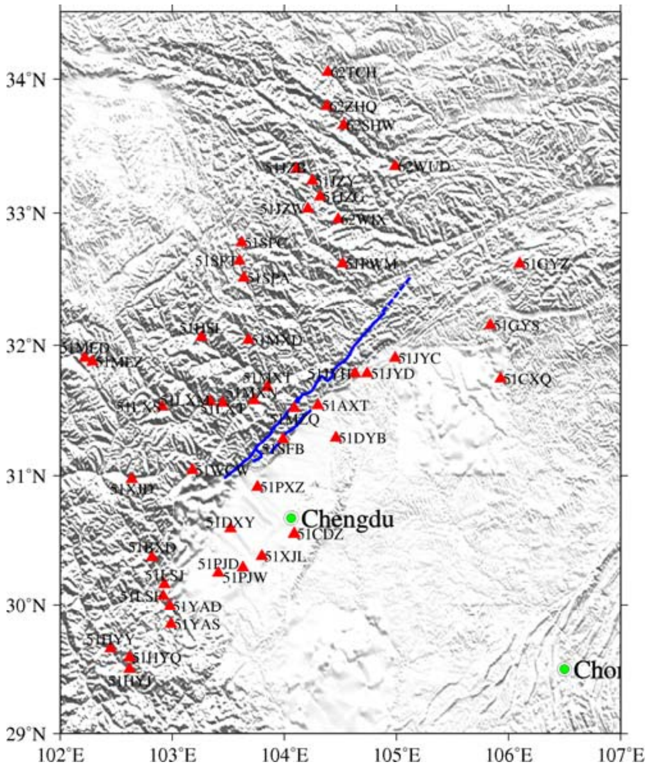

Figure 2. Stations used for inversion, the blue line represent the surface rupture

2.4 Inversion Method

Taking the subfault size as 10 km in the fault strike direction and 5km in the fault down dip direction, we divided the Beichuan and Pengguan faults into subfaults. The Beichuan fault consist of 40×3 subfaults in the upper segment and 40×4 subfaults in the lower segment, while the Pengguan faults consist of 10×4 subfaults. We use linear least-squares inversion method to obtain the subfault dislocation values which give the best fit to the velocity waveforms and surface rupture vectors. The inversion is damped by minimizing the difference in dislocation values between adjacent subfaults, and by minimizing the total amount of slip. It is also constrained by requiring that the slip is everywhere positive. This method and constraints have been previously discussed by Hartzell and Heaton (1983). We also impose an additional constraint that the slip on the shallowest subfaults is equal to the observed surface offsets, which has been used by wald *et al* (1994) in the 1992 Landers earthquake source inversion.

Trying the initial rupture velocity range from 2.5 to 3.2 km/sec, we found that 2.7 km/sec is most suitable. For large earthquakes, the source time functions are varied within the fault, and the slip duration in some subfaults is usually very long relative to the rise time of the Green's function, so a multiple-time window technique is necessary in the inversion, which has been discussed by wald *et al* (1994). In this study, we give each subfault 8 to 39 time widows, which permit each subfault to slip in any one of time windows 2.0s. Each window had an overlap of 0.5 s. By using multiple-time window, we can inverse the source time function and rupture velocity more flexible and resulting in more detail rupture process. The inverse problem and the additional constrains can be posed as an over determined system of linear equation,

$$\begin{bmatrix} A \\ \lambda_1 S \\ \lambda_2 M \\ \lambda_3 F \end{bmatrix} [x] \cong \begin{bmatrix} b \\ 0 \\ 0 \\ d \end{bmatrix} \tag{1}$$

Where A is the matrix of Green's function, x is the solution vector consisting of subfault dislocation, and S is smoothing constraints which minimize the slip difference between adjacent subfaults. The term M is a matrix of minimizing the seismic moment constraints .Matrix F forces the sum of all time windows for a shallowest subfault to equal to he measured surface offsets d. λ_1 λ_2 λ_3 were constrained scalar weights.

3. INVERSION RESULTS

3.1. Spatial Distribution

Figure 3 shows the final inversion result derived from 49 stations. From the isodepth line we can see that most of the slip larger than 3m is located at the shallow part of the fault (<15 km for Beichuan fault and <10km for Pengguan fault), generally in 200km range for Beichuan fault (from 40km southwest to the epicenter to 160km northeast to the epicenter) and 60km for Pengguan fault. The slip below 15 km in depth is less than 2m, except for areas within 80 km northeast to the epicenter. This means that the Wenchuan earthquake was nucleated at basal detachment in the mid-crust with relative flat dip angle then rupture to the steep dip angle and generate large slip. Most energy emitted in this earthquake was from the upper segment of the Beichuan fault.

In the Beichuan fault with distance longer than 50 km southwest to the epicenter, most slip are less than 1m, while in the opposite directions, almost all slip within 260 km is larger than 1.5 m. This means the Wenchuan earthquake is mostly a unilateral rupture which is consist with the results of source inversion by far field data. The slip near the epicenter is about 2 m, which is relatively smaller compared to that in the northeast region. This phenomenon has been observed in similar source studies of damaging earthquakes, such as the 1979 Imperial Valley earthquake (Hartzell and Heaton, 1983); 1992 Landers earthquake (Wald and Heaton, 1994) and the 1999 Chi-Chi earthquake(Lee *et al* 2006).

From the epicenter to the northeast direction, the slip amount and width increase. In the Yingxiu area, the first asperity appeared with a length about 30km and width 8km, and the average slip of this asperity is bigger than 5m, with maximum slip about 8.2m. Passed the first asperity, rupture continues to the northeast direction and encountered the second and the third asperity. The second asperity located in area from 40km to 100km northeast to the epicenter (the area between Wenhcuan and Beichuan), while the third asperity in the area within 50km form Beichuan to the northeast direction. The Maximum slip of these two asperities is about 7m and 6.5m. The second asperity is the largest and widest one with width about 15km, whereas the width of the first and third asperity is less than 10km. In some area under the second asperity, slip is still larger than 3.5m whereas the slip in the adjacent area is smaller. This means in the Wenchuan area, the mid-crust with relative flat dip angle also emitted relative large energies. As the rupture passed the third asperity, slip decrease rapidly form 5m to less than 2m, and wihin 70km, slips maintain about 1.5m. In the northeast end of Beichuan fault (the Qiangchuan area), slips increase a little to about 2.5m. there are two small asperites in the Pengguan fault with size of 10km×5km and 15km×7km. The Maximum slip of these two asperities is about 5.2m and 5m.

The vector in figure 3 shows the final rake angle on the fault plane. The rake angle on each subfault has apparent variations. Most of the fault shows an oblique right lateral thrusting slip. In the shallow part of fault, the ratio of dip slip component to strike slip component is bigger than that in the deeper part, whereas it is smaller in the northeast part.

Figure 4 shows the comparison of the observed and synthetic three-component waveforms for the final inversion result. The red and blue line represents the observational and synthetic waveforms; respectively. The left and middle figure represent the components parallel and normal to the fault strike and the right figure represent the vertical component; respectively. The value in each time history is the peak value of the synthetic record (unit: cm/s). In general, the synthetic waveforms satisfy the observations in amplitude and frequency, whereas some simulated waveforms cannot fit the records well. Note that records with large amplitude such as 51WCW, 51PXZ, 51XZD, 51SFB, 51MXN, 51MXT, 51MZQ, 51AXT, 51DYB, 51JYH, and 51JYD, etc, fit well, whereas records with small amplitude, such as the 62ZHQ, 62TCH, 62WIX, 51ZHY, 51SPA, 51MED, 51MEZ station, etc, fit badly. Since most of the records with large amplitude are in the near fault region which may have more information about the earthquake source, we have not normalized the record. This cause that records with small amplitude has little weight in the linear least-squares inversion, and result in bad fit of them. The simple 2-d velocity structure is also the reason for the bad fit, since it may not give the correct Green's function in the interesting frequency band. Another reason may be the fault model cannot represent the real complex fault. The study of Xu *et al*(2009) indicate that the northeast part of Longmenshan fault may have more steep dip angle, but in this paper we use the same dip angle for the whole Beichuanfault.

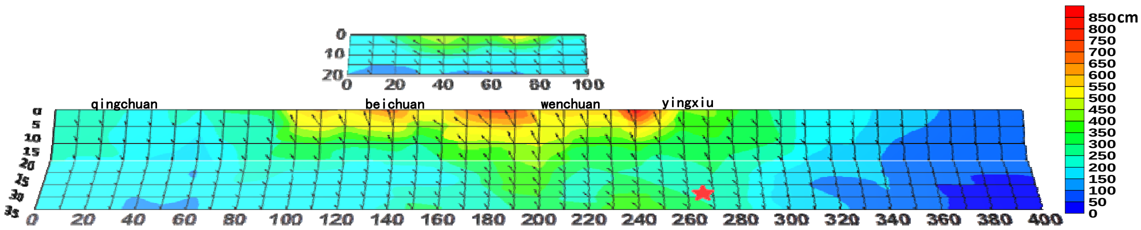

Figure 3. The final dislocation distribution

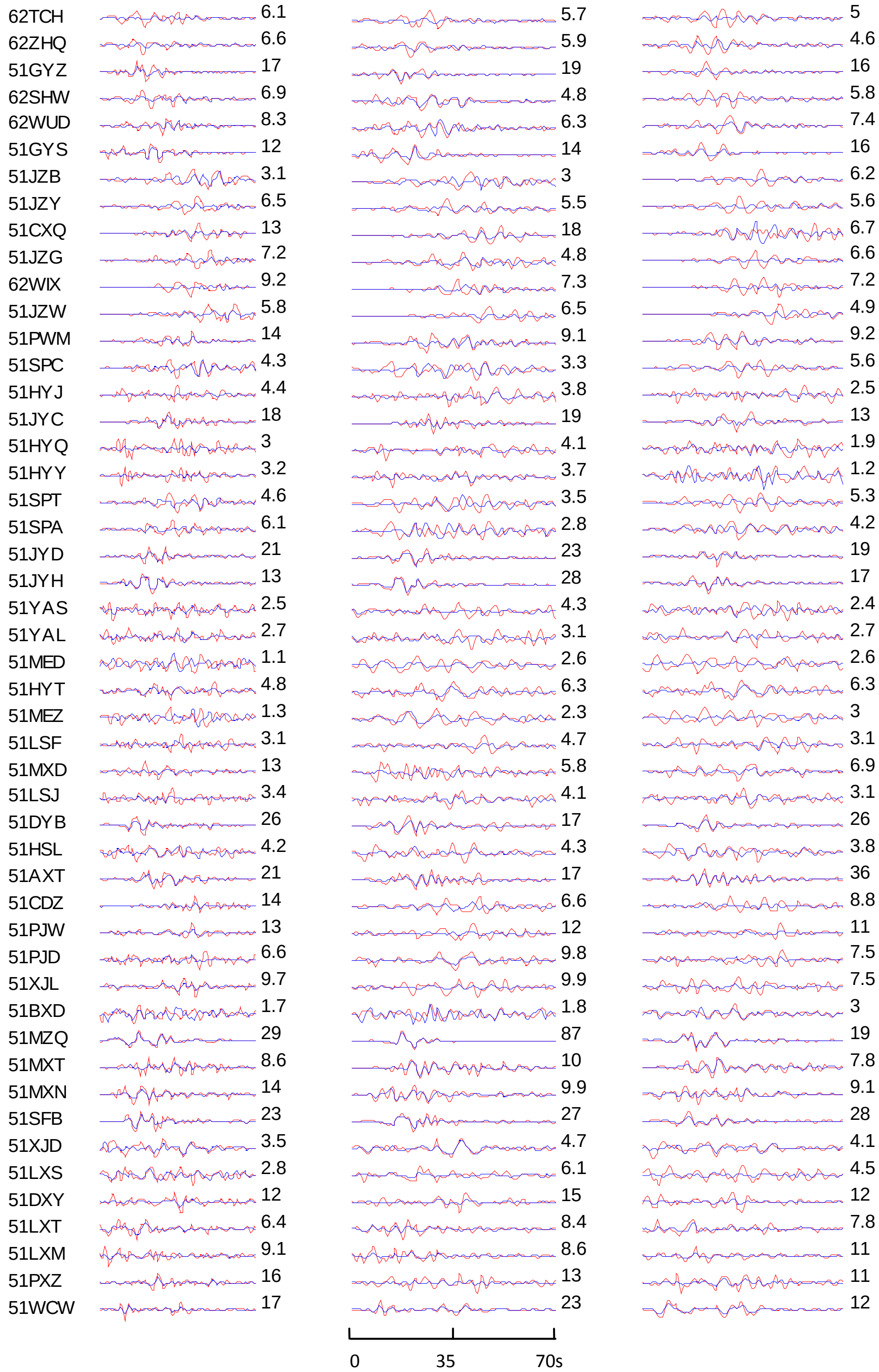

Figure 4. Comparisons of the synthetics (blue lines) and observations (red lines) for the 49 stations

3.2. Fault rupture process

Figure 4 shows the time and spatial fault rupture process of the two faults At the first 5 sec after the earthquake occurred, the slip is very small and rupture propagate very slowly. After 5s, slips increased gradually and at about 10s to 1.5m in the epicenter area, while the rupture continues to propagate upward penetrating the ground surface. Then the rupture front mainly propagates to the northeast direction. At about 20s, rupture front passed the Yinxiu area and entered the Penguan fault. Then after 10s the rupture front gets over a barrier and propagates to the southwest direction rapidly. At about 35s, the rupture front reached the Wenchuan area, while slips in Yingxiu area increase to about 5 m. The rupture front continue to propagate to the northeast direction; at about 45s, it passed through the Wenchuan area going to Beichuan area, and the second asperity appeared.

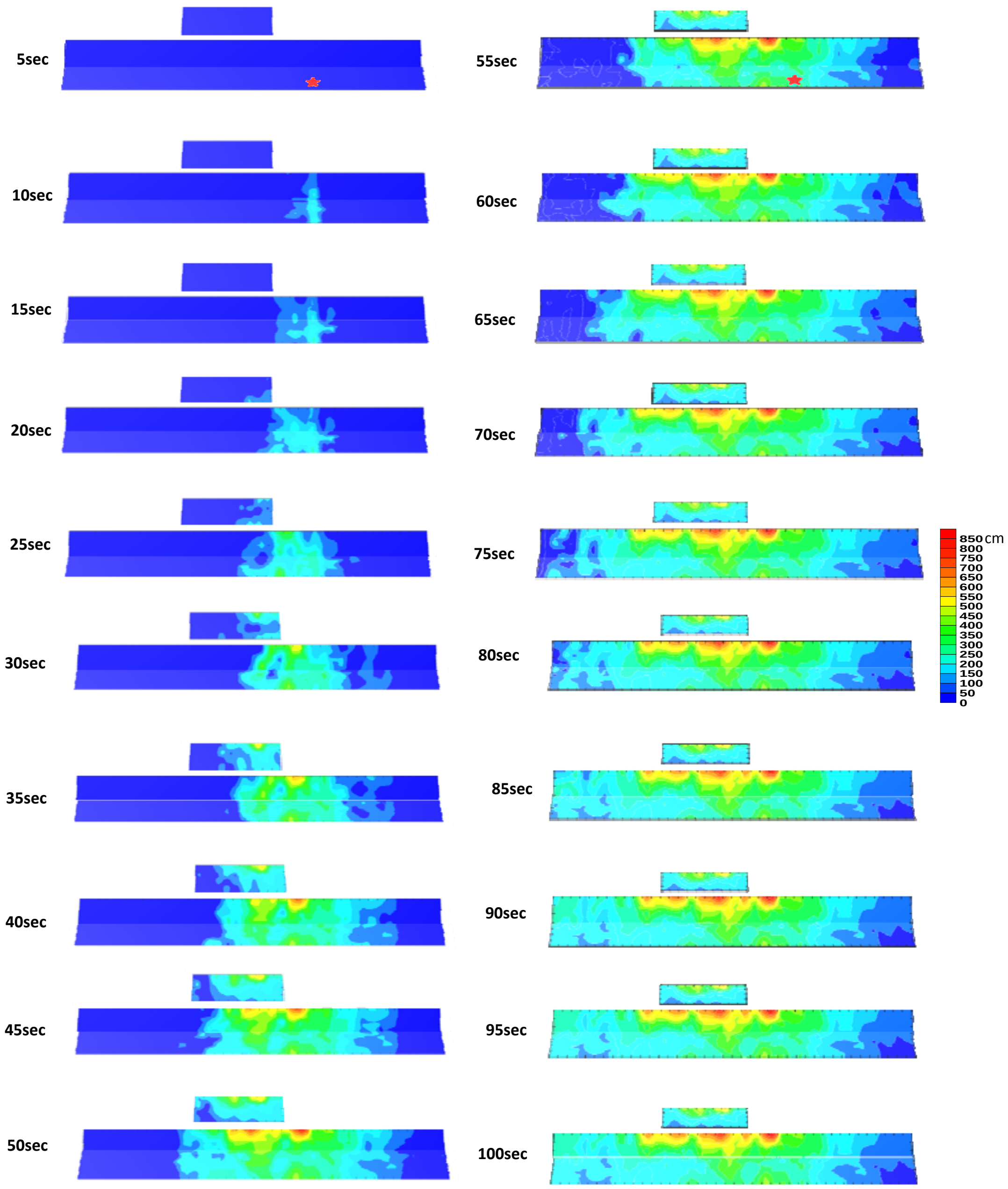

Figure 5. The rupture process of the Beichuan and Pengguan fault at intervals of 5 sec.

At time between 35 and 45s, rupture front almost stop to propagate to southwest direction about 10 minute, which means it may encounter a big barrier. Then about 50s, rupture front continue to propagate to southwest direction. Meanwhile, in the northeast direction, the first and second asperities reach their maximum slip, and the rupture front passed the Beichuan area and the whole Pengguan fault. The third asperity appeared at about 60s, and its slip increased to the maximum value at about 80s. At about 90s, the rupture front passed the whole Beichuan fault, and all the rupture stopped, the final dislocation on the fault accomplished. The average rupture velocity in the northeast direction is relative fast, about 3.1km/s, whereas it is slow in the southwest direction, about 2.4km/s. Note that in the whole rupture process, when the rupture front propagates, slips on the areas which has ruptured still increase, and some areas of the fault re-ruptured.

3.2. Slip Duration Time

Figure 6 shows the slip duration time of the Beichuan and Pengguan fault. We can see that the slip duration are about 40 to 60s in the upper segment of Beichuan fault in the area of the first and second asperity, while in the lower segment it decreases to about 30 to 40s. This means the rupture process are long and complex in the asperity area and most of re-rupture occurred in this area. The largest slip duration is occurred in the Yinxiu area with time of about 60s. In the Beichuan area (the third asperity), the slip duration time is also more than 30s.

In the areas outside Beichuan in the northeast direction, most of the slip duration time decrease to less than 15 s except for some area in the shallow part of the fault, which means rupture process of these areas are relatively simple. In contrast, the slip time duration is still more than 30s at most shallow part in area southwest to the epicenter. The slip time duration in the Pengguan fault is relative small(less than 15s), except for the asperity area (more than 20s).

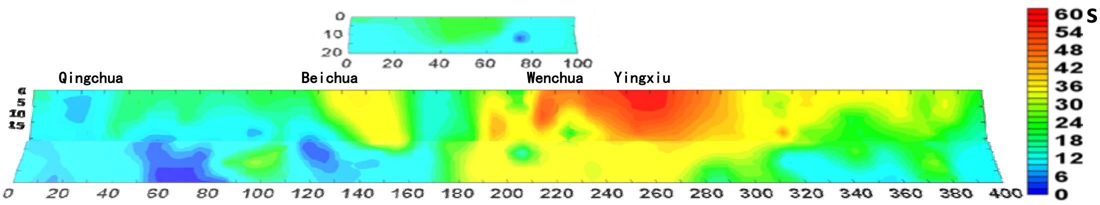

Figure 6. The Slip Duration Time of two faults

4 CONSLUSION

The time and spatial rupture process of the 2008 Wenchuan earthquake are inverted based on 49 near field 3 components strong motion velocity records and surface offset data by the non-negative least-squares method and the multiple-time widow technique. The result show that the whole rupture process lasted for 90s, and rupture front propagate rapidly in the northeast direction with average velocity of about 3.1km/s than that in the southwest direction of about 2.4km/s. During the rupture process, the rupture fronts are very irregular, and rupture paused in some area especially with 10s pause in southeast direction. Most of re-rupture occurred in area with in 150 km from the epicenter to the northeast direction. The rupture result in 3 asperities in Beichuan fault and 2 small asperities in the Pengguan fault, with maximum slip of the 8.2m and 5.2m for these two causative faults. The slip duration is long with maximum time of about 60s in the Yinxiu area of the Beichuan fault.

Some synthetic waveforms cannot satisfy the observations well which maybe contribute to the simple 2-d velocity structure and the relative simple fault model. So the complex 3-d velocity structure and more really complex fault model need to be considered in the further study.

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