Fault zone structures of northern and southern portions of the main central fault generated by the 2008 Wenchuan earthquake using fault zone trapped waves*

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Abstract The rupture process of the May 12, 2008 $M_{\text{s}}8.0$ Wenchuan earthquake was very complex. To study the rupture zones generated by this earthquake, four dense temporary seismic arrays across the two surface breaking traces of the main-shock were deployed in July and recorded a great amount of aftershocks. This paper focuses on the data interpretation of two arrays across the central main fault, the northern array line 1 and southern array line 3. The fault zone trapped waves recorded by the two arrays were used to study the structure of the central main fault and the difference between the northern and southern portions. The results show that the widths of the rupture zone are about 170–200 m and 200–230 m for northern and southern portions respectively. And the corresponding dip angles are 80° and 70° . The seismic velocity inside the fracture zone is about one half of the host rock. By comparison, the northern portion of the rupture zone is slightly narrower and steeper than the southern portion. Besides these differences, one more interesting and important difference is the positions of the rupture zone with respect to surface breaking traces. At the northern portion, the rupture zone is centered at the surface breaking trace, while at the southern portion it is not but is shifted to the northwest. This difference reflects the difference of rupture behaviors between two portions of the central main fault. The width of the rupture zone is smaller than that of $M8.1$ Kunlun earthquake though these two earthquakes have almost the same magnitudes. Multiple ruptures may be one factor to cause the narrower rupture zone.

Key words: Wenchuan earthquake, seismic rupture zone, fault zone trapped waves

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1 Introduction

In comparison with other intra-continental earthquakes, the 12 May 2008 Wenchuan earthquake possesses much more complex rupture process. Laterally, this quake ruptured two NW-dipping imbricate reverse faults of the Longmenshan fault zone simultaneously, which are separated about 5–25 km on the surface and converge at depth. One is the high angle central main fault (Yingxiu-Beichuan fault) and the other is the low angle front range fault (Guanxian-Jiangyou fault) (Wang et al, 2008; Ji et al, 2008). Correspondingly, two surface breaking zones were generated with different lengths of

240 km and 72 km respectively as shown in Figure 1 (Zhang et al, 2008a; Xu et al, 2008; Wang et al, 2009b). Along the rupture propagation direction, the rupture behaviors are quite different at different positions of the central main fault. The convergent displacement is significant in the southern portion while the strike-slip displacement is dominant in the northern portion (Chen et al, 2008; Ji et al, 2008; Parsons et al, 2008; Liu et al, 2008; Zhang et al, 2008b; Zhang et al, 2009). To understand such a complex rupture process of Wenchuan earthquake, we need to learn the details of fracture zones, including their geometries, velocity structures of seismic waves, and rheology at different segments.

The method of fault zone trapped waves has been very powerful in revealing the physical properties of seismic fracture zones (Li et al, 1994). The fault zone

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trapped waves are the wave trains that follow the S waves, and usually with large-amplitude and low-frequency (2–5 Hz) (Li and Leary, 1990; Li et al, 1994). Since the trapped waves arise from coherent multiple reflections at two boundaries of the fault, their waveforms and dominating frequencies are strongly dependent on the position, geometry and physical properties of the fault, and thus can be used to determine these parameters.

Shortly after the Wenchuan earthquake, we carried out field experiments in the main-shock region and deployed 128 three-component digital seismographs in July 2008 to record aftershocks (Lai and Li, 2008). As shown in Figure 1, four temporary seismic arrays with dense instruments were deployed. Three arrays cross the central main fault and one crosses the front range fault. This paper focuses on the data interpretation of two arrays across the central main fault, the northern array line 1 and southern array line 3. The fault zone trapped waves recorded by the two arrays were used to study the structure of the central main fault and the difference between the northern and southern portions.

Figure 1 Map showing geological setting, surface breakout, earthquake distribution (by Xu et al, 2008) and positions of the temporary seismic arrays.

2 Observation and data acquisition

From the beginning of July, 2008, the field observation lasted for one month. Because our observation was conducted at the time just less than two months after the main-shock, aftershocks in this region were still very frequent, and the surface ruptures generated by the main shock were still obvious. In order to get high resolution to the fault zones, all the seismic observational lines were deployed with very dense receivers and

crossed through the surface break traces of the main shock. Since the faults are usually along very narrow valleys and there are very steep cliffs at both sides, our observational lines could not be long. The observational lines are 500–700 m long with receiver space 25–50 m, and are all approximately centered at the surface rupture traces. Figure 2 shows the station positions of the northern array, line 1 and the southern arrays line 3.

Figure 2 Position map of the temporal stations along line 1 and line 3.

The instruments used are PDS-1 24-bit seismographs with three-component sensors. In this observation, all the instruments were set in continuous recording mode with a sampling rate of 100 per second. The free-running frequency of sensors is 2.5 Hz. Each geophone has one vertical component and two horizontal components. In this experiment, one horizontal component was set to be parallel to the strike of the fault and the other was perpendicular to the strike.

Since the instruments were set in continuous recording mode, we need to pre-process the data following two steps. Firstly, the continuous records of each instrument were played back, and a search program was used to pick out seismic records of aftershocks according to the pre-set threshold. This process is similar to setting the instruments in trigger mode during field observation. However, searching the continuous records is more secure for data acquirement and more flexible for threshold selection. Secondly, the separated seismic data from all the instruments of the same array were put together and those aftershocks were chosen which were recorded simultaneously by at least 90% stations of that

array. After these processes, 3 600 seismic records from 230 aftershocks were obtained.

3 Data analyses

3.1 Southern array

To analyze fault zone trapped waves, for each array we selected aftershocks located in or near rupture zones with hypocentral distance smaller than 40 km from its stations. Figure 3 shows three typical record sections of the southern array, line 3 across the central main fault. These are records of aftershocks 1, 2 and 3, the epicenters of which are shown in Figure 1. Considering that the fault dips to the northwest, from Figure 1 we can find that the sources of these events are located within or very close to the rupture zone. Besides the original seismic record sections (left), we also present the filtered record sections by 4-order Butterworth filter with 0.5–3 band pass (middle), and corresponding S wave-normalized amplitude spectra (right) for comparison and analyses. Station numbers are shown at the left side and are the same as those in Figure 2. It should be noticed that the station numbers in some record sections are not continuous for lack of records from some stations.

As shown in the seismic record sections, fault zone trapped waves after filtering are clearly observed after S waves at all three events between station 6 and station 13 (Encircled with ellipses). Compared with direct P and S waves, the dominant frequencies of these trapped waves are lower. And they usually have multiple envelopes with long duration. Since the fault zone trapped waves arise from coherent multiple reflections at two boundaries of the fault, they can be observed at stations located within or very close to the fault zone (Li and Leary, 1990; Li et al, 1994). However, it is difficult to observe these waves at the stations far away from fault zone. Thus we can estimate the position and width of the rupture zone according to the extent of the trapped waves in the record section. From Figure 3, we infer that the rupture zone generated by Wenchuan earthquake is about 200–230 m wide and locates between station 6 and station 13. Considering station 6 is near a fault scarp observed at Honglou (arrow in Figure 3) (Xu et al, 2008), the seismic rupture zone is estimated from surface breaking zone to the northwest. That is, the rupture zone is not centered at the surface rupture trace but is shifted to the northwest.

In Figure 3 we used a two-second time window starting from the arrivals of trapped waves to get the

amplitude spectra of trapped waves. These spectra were normalized by S waves to eliminate instrument and receiver site effects on spectra. Figure 3 shows that an obvious peak appears at about 3 Hz on the spectral curves recorded at stations with strong trapped waves.

3.2 Northern array

Figure 4 shows three record sections of the northern array, line 1 corresponding to aftershocks 4, 5 and 6 respectively. Like line 3, line 1 also crosses through the central main fault, therefore through comparison of these record sections with those from line 3 we can study the differences between northern and southern portions of the rupture zone. Epicenters of these events are shown in Figure 1. After filtering, fault zone trapped waves are also observed after S waves at all three events from station 5 to station 11 (Encircled with ellipses). Similarly, these trapped waves have low dominant frequencies, long durations and multiple envelopes. Thus we can estimate the width of the rupture zone to be 170–200 m. By comparison, the rupture zone here is slightly narrower than that at the southern portion as obtained from line 3.

Similar to Figure 3, the right row is the S wave-normalized amplitude spectra. The peak appears at about 3–3.5 Hz on the spectral curves recorded at stations with strong trapped waves. That means the dominant frequency of the trapped waves is slightly higher than that from line 3. Since the trapped waves arise from coherent multi-reflections, the dominant frequency is related to the width of the fault and velocities inside it. The wider the fault zone or the lower the velocity, the lower the dominant frequency of observed trapped waves. Thus from another aspect we can deduce that the northern portion of the rupture zone is slightly narrower than the southern portion.

In general, the dominant frequencies from two lines are less than that observed in Hector Mine earthquake region, California (Li et al, 2002), but larger than that in Kunlun earthquake region (Li et al, 2005; Wang et al, 2004; Lou et al, 2006; Yao et al, 2007; Wang et al, 2009a). The dominant frequencies from Hector Mine and Kunlun earthquake regions are 4–7 Hz and 1.5–1.8 Hz, respectively. Accordingly, the width of rupture zone caused by the Wenchuan earthquake is larger than that by the $M_s7.1$ Hector Mine earthquake and smaller than that by the $M_s8.1$ Kunlun earthquake. According to the results from Li et al (2002), Li et al (2005), Wang et al (2004), Lou et al (2006), Yao et al (2007), Wang et al (2009a), the widths of the rupture zones caused by the

M_S 7.1 Hector Mine and the M_S 8.1 Kunlun earthquakes are about 100 m and 300 m, respectively. These two values can be regarded as the lower and upper limita-

tions for the width of rupture zone generated by the Wenchuan earthquake.

Figure 3 The original seismic record sections (left), filtered record sections by 4-order Butterworth filter with 0.5–3 Hz band pass (middle), and corresponding S wave-normalized amplitude spectra (right) of line 3 from aftershocks 1, 2 and 3.

Figure 4 The original seismic record sections (left), filtered record sections by 4-order Butterworth filter with 0.5-3 Hz band pass (middle), and corresponding S wave-normalized amplitude spectra (right) of line 1 from aftershocks 4, 5 and 6.

From Figure 4 we can see that the trapped waves exist at both sides of the surface breaking zone. It indicates that in the northern portion, the rupture zone is

approximately centered at the surface breaking trace. In this regard, the northern and southern portions of rupture zone show quite different behaviors which may be re-

lated to the different rupture modes of two portions.

3.3 Synthetic seismograms

To verify the above estimation, we calculated the synthetic seismograms for different fault zone models and compare them with the observed data. The synthetic seismograms were calculated using a 3D finite difference method (Graves, 1996). Through try and error, we found the width of the rupture zone at line 3 and line 1 are 200–230 m and 170–200 m, respectively, and the dip angles are about 70° and 80° , respectively. The velocity inside the rupture zone is about one half of velocity outside. The results indicate that the northern portion of the rupture zone is slightly narrower and steeper than the southern portion.

Figure 5 shows the effects of the dip angle of the rupture zone on the waveforms of trapped waves. For different dip angles of the fault zone, we calculated the corresponding seismograms generated by an earthquake inside the fault zone. From the left to right, the dip an-

gles are 60° , 70° and 80° , respectively, and the widths of the fault zone in three examples are all 200 m. Twenty stations are supposed to be deployed in an array with equal station space of 25 m. The stations are numbered from northwest to southeast. In all the models, the fracture zone is supposed to dip to the northwest and be centered at the middle point of the array, i.e., at the middle point between station 10 and station 11. It can be found that the waveforms of trapped waves are very sensitive to the dip angles. For dip angles of 60° and 70° , trapped waves mainly appear at the northwestern half of the profile. However, for dip angles of 80° , trapped waves are basically concentrated at the middle part of the profile with a symmetric pattern. Comparing Figure 5 with observed data, it can be found that 70° is a reasonable value for the dip angle at line 3, while 80° is suitable for line 1.

Figure 5 Synthetic seismograms with different dip angles of rupture zone.

4 Discussion and conclusions

According to the joint analysis of receiver functions and gravity data, the central main fault is a boundary fault of Tibetan plateau and Yangtze block (Lou et al, 2008). It plays an important role for the generation of the Wenchuan earthquake. There are two rupture zones generated by this earthquake. By comparison, the rupture zone of central main fault is much longer than the other and released most of the strain energy. To study the geometry and structure of this rupture zone, and their difference between northern and southern portion, we have used trapped waves recorded from northern and southern seismic arrays.

The results from these two arrays are very close.

The widths of the rupture zone are about 200–230 m and 170–200 m for southern and northern portions respectively. And the corresponding dip angles are 70° and 80° . The seismic velocity inside the fracture zone is about one half of the host rock.

By comparison, the northern portion of the rupture zone is slightly narrower and steeper than the southern portion. Besides these differences, one more interesting and important difference is the positions with respect to surface breaking traces. At the northern portion, the rupture zone is centered at the surface breaking trace, while at the southern portion it is not but is shifted to the northwest.

According to studies on the source process of the $M_s 8.0$ Wenchuan earthquake, the convergent displace-

ment is significant in the southern portion while the strike-slip displacement is dominant in the northern portion (Chen et al, 2008; Ji et al, 2008; Parsons et al, 2008; Zhang et al, 2008b; Zhang et al, 2009). For thrust fault, under the compression of the stress field, the upper wall is active and its substances near the fault plane are usually weaker than those at lower wall. Thus strong deformation and displacement are usually concentrated within the upper wall as shown in line 3. On the contrary, line 1 locates at the northern portion of the rupture zone where the strike-slip is dominant. In this case, both stress field and structure are symmetrical. So the deformation and displacement are also symmetrical and are centered at the interface of the two walls. The maximum displacement usually occurs at the center of the rupture zone. And so does the surface breaking trace.

The width of the rupture zone is about 200 m. It is larger than that by the $M_S7.1$ Hector Mine earthquake and smaller than that by the $M_S8.1$ Kunlun earthquake. As compared with Hector Mine earthquake, it is easy to understand. Because the magnitude of Hector Mine earthquake is smaller than Wenchuan Earthquake, its rupture zone is shorter and narrower. However, magnitudes of the Wenchuan and Kunlun earthquakes are almost same. Why their widths of rupture zones are so different? We think one important factor is the mode of the rupture zones: single or multiple fracture zones? For the $M_S8.1$ Kunlun earthquake, there is only one rupture zone. While for $M_S8.0$ Wenchuan earthquake, there are two imbricate rupture zones. Since the strain energy of Wenchuan earthquake was released through two rupture zones rather than through a single one, the width of each rupture zone should be smaller than that of Kunlun earthquake although the total energies released by these two earthquakes are almost equal.

The results presented in this paper are just from the arrays of line 1 and line 3 in the rupture zone of central main fault. To study variations of parameters along the whole rupture zone of central main fault, we also need results from the middle array, line 2. Furthermore, we need results from the array line 4, which crosses through another rupture zone, rupture zone of the front range fault. Only with its results, can we make a comparison between the two rupture zones generated by $M_S8.0$ Wenchuan earthquake. The data of the other two arrays are in processing and the results will be obtained later.

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