Relocating ruptures of two $M6$ earthquakes in Zhongba, South-central Tibet in 2004 and 2005 with seismological and geodetic methods*

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Abstract To better understand repeatability of strong earthquakes in previously ruptured zones during one seismogenic period, we studied the rupture zones of the doublet of $M6$ earthquakes in Zhongba region of south-central Tibet, China, in 11 July 2004 and 7 April 2005, respectively. We focused on the overlapping degree of two strong quakes' aftershock areas one week after the mainshocks by using the SQH station in China Seismic Network and a 68-stations temporary broadband seismic array, a part of the international HI-CLIMB project. About 115 local earthquakes were recorded in one week after the mainquakes, and we located these earthquakes by master event relative location (MERL) method. We also used this method to relocate 31 other $M3.7^+$ earthquakes from 1 July 2004 to 1 July 2005. Meanwhile, we studied two mainshocks' coseismic ruptures with satellite interferometric synthetic aperture radar (InSAR). Our results show that the ruptured zones of the two earthquakes do not overlap substantially, either from early aftershock data or from InSAR inversions.

Key words: rupture zone overlapping; Zhongba earthquake sequences; earthquake doublets; master event relative location; InSAR

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1 Introduction

Rupture zone generated by a mainshock generally features a linear and limited distribution in releasing stress after brittle fracture of what happened underground (Waldhauser and Ellsworth, 2000). Many parameters used to describe the nature of rupture zone structure such as location, area, rupture length and width, can be observed in the surface sometimes (Xu et al., 2008). However, most damaging normal fault earthquakes are buried deep into the Earth and have little surface rupture. To better understand the fault geometry associated with these earthquakes and assess local seismic hazard as well as gaining a better

understanding of rupture process, some methods have been used, such as simulating rupture process by using finite-fault model simulation (Somerville et al., 1991; Li et al., 2005), determining aftershock zones by using high-precision aftershock location, and defining the fault geometry and slip distribution by using modern InSAR processing (Massonnet et al., 1994; Xu and Li, 2008).

Whether another strong earthquake could take place in previous rupture zones, or two mainshocks' rupture zones could overlap with each other substantially during the same seismogenic time remains a puzzle and has attracted many seismologists' attention. Structural features such as faults, trenches, and ridges, can separate adjacent ruptures, which have been observed in Japan (Mogi, 1969) and Aleutian Islands (Kelleher, 1970; Sykes, 1971). Consequently, it is suggested that barriers caused by fault geometry such as bends, steps, corners (Segall and Pollard, 1980), or crustal inhomogeneity

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geneities inferred from velocity anomalies, delimit two earthquake rupture zones and are regarded as acting as stress concentrators (Aki, 1979).

One method to obtain rupture dimensions and correlations of earthquakes' rupture zones is to analyze aftershocks' distribution and it is discovered that aftershock areas of larger earthquakes tend to fill up a seismic zone without significant overlap (Aki, 1978). Similarly, great ($M_S \geq 7.5$) and shallow earthquakes in the Kamchatka, Kurile and Japan regions rupture and split to discrete fault segments, which were defined as aftershock zones (Fedotov, 1965).

The main purpose of this paper is to obtain the aftershock areas of Zhongba earthquake doublets, which occurred in 11 July 2004 and 7 April 2005, respectively. Combining master event relative location (MERL) and Interferometric Synthetic Aperture Radar (InSAR) technology, we discussed the properties of the aftershock areas and overlapping degree of earthquake doublets'

rupture zones.

2 Stations and data

Most data in our study come from the Himalayan Tibetan Continental Lithosphere during Mountain Building experiment (Hi-CLIMB), an international collaborative project to investigate active mountain-building over the entire thickness of the lithospheric structures across the Himalayan-Tibetan zone of continent-continent collision from 2003 to 2005. During the three-year experiment, 115 broadband seismometers were deployed from southern Nepal to the north of the Bang-gong suture in central Tibet (Hetenyi et al., 2008; Nabelek et al., 2009; Wittlinger et al., 2009). The northern section of Hi-CLIMB network consisted of 75 stations, and 68 of these stations were in south-central Tibet (Figure 1). Those stations and the SQH station (a permanent station in China Seismic Network),

Figure 1 Distribution of stations, regional geological tectonics and preliminary determination epicenter from NEIC. The triangles are stations used in the research area indicated by the dashed rectangle; the circles are preliminary determination epicenters located by USGS from 1 July 2004 to 1 January 2005, and the crosses are preliminary determination epicenters from 1 April 2005 to 1 October 2005. Two squares are earthquake doublets' preliminary determination epicenter from NEIC. The solid dots indicate county towns. Two thick dashed lines implicate BNS (Banggong-Nujiang Suture) and YTS (Yarlung-Tsangpo Suture). The thin solid lines indicate local active faults.

were used in our study. The seismic station array with a strike of about N345°W was deployed from June 2004 to September 2005 and can be divided into two sections from Lhasa block's Gyirong-Saga-Cochen-Gerze to Qiangtang Block roughly. Our study region is between YTS (Yarlung-Tsangpo Suture) and BNS (Banggong-Nujiang Suture), situated at the northeast of Himalayan block and the south of Qiangtang block.

Two datasets of seismic waveform were selected for this study. One contains data from earthquakes of magnitude greater than 2 in a week after 11 July 2004 and 7 April 2005, respectively, while the other group comprised earthquakes of magnitude greater than 3.7 from 1 July 2004 to 1 July 2005. The two M_6 mainshock are very close to each other according to NEIC's catalog, and their aftershocks seem to overlap each other (Figure 1) which may suggest that the two mainshocks ruptured overlapped area. But NEIC's location is typically not accurate within 15 km, therefore the seemingly overlapping could be an artifact, and accurate relocation is necessary to illuminate the issue of whether the aftershock zones overlap.

The aftershocks within one week from the mainshock are chosen as early shocks, which are proposed to present rupture zones of the mainshock. Later shocks may migrate well beyond the main rupture zone (Kisslinger, 1996), but the cut-off span of one week could be a little bit arbitrary. Wan et al. (2009) find that the aftershocks in the first two hours are good enough to delineate rupture zones. The data came from various seismometers' observation such as broadband seismometers Streckeisen STS-2, Guralp CMG-3T with a natural period of 120 s, and intermediate-band seismometers Guralp CMG-3ESP with a natural period of 33 s. To compare results from different instruments, seismograms were corrected by removing instrument response with the pole zero files.

3 Methods

Master event relative location (MERL) is a method to determine event position by using a set of P-wave traveltimes differences ($T_{Xj} - T_{Rj}$) recorded at N stations for $j=1, 2, \dots, N$, in which R is a reference event and X is a nearby event (Spence, 1980; Zhou et al., 1999; Yang et al., 2002). Given the reference event R , of latitude φ_R , longitude λ_R , and focal depth h_R , closing to a candidate event X with undetermined epicentral location ($\varphi_X, \lambda_X, h_X$), an equation for the reference event R 's arrival time at a seismic station j is

$$t_{Rj} = t_{0R} + T_j(\varphi_R, \lambda_R, h_R) + s_j. \quad (1)$$

Similarly, the equation for the candidate event X 's arrival time at seismic station j is

$$t_{Xj} = t_{0X} + T_j(\varphi_X, \lambda_X, h_X) + s_j. \quad (2)$$

There are N stations, each of which has been given the coefficient of station correction s_j . The t_j is arrival time of P wave obtained from waveform, and t_0 is the origin time. T_j represents travel time from the epicenter to the seismic station.

To find a linearization of the equation (2) in the parameter space of the reference event R , a Taylor series expansion is formed at $T_j(\varphi_R, \lambda_R, h_R)$.

$$\begin{aligned} t_{Xj} &= t_{0X} + T_j(\varphi_R + \delta\varphi, \lambda_R + \delta\lambda, h_R + \delta h) + s_j \\ &= t_{0X} + T_j(\varphi_R, \lambda_R, h_R) + \frac{\partial T_j(\varphi_R, \lambda_R, h_R)}{\partial \varphi} \delta\varphi + \\ &\quad \frac{\partial T_j(\varphi_R, \lambda_R, h_R)}{\partial \lambda} \delta\lambda + \frac{\partial T_j(\varphi_R, \lambda_R, h_R)}{\partial h} \delta h + s_j. \end{aligned} \quad (3)$$

Equation (3) minus equation (1), we obtain

$$\begin{aligned} \delta t_j &= \delta t_0 + \frac{\partial T_j(\varphi_R, \lambda_R, h_R)}{\partial \varphi} \delta\varphi + \\ &\quad \frac{\partial T_j(\varphi_R, \lambda_R, h_R)}{\partial \lambda} \delta\lambda + \frac{\partial T_j(\varphi_R, \lambda_R, h_R)}{\partial h} \delta h, \end{aligned} \quad (4)$$

namely,

$$\delta t_j = \delta t_0 + \delta T_j. \quad (5)$$

Arrival time difference δt_j is available. However, origin time difference δt_0 and the travel time difference δT_j is unknown.

As it shown in the Figure 2, equation (5) can be indicated as

$$\delta t_j = \delta t_0 + \frac{\delta x}{v} \sin \alpha + \frac{\delta y}{v} \cos \alpha \quad (6)$$

The v is the mean velocity of P wave in the Earth's crust, and the α is reference event R 's azimuth, which is identified with the undetermined event X as two quakes are so close.

4 Results

The first mainshock on July 11 2004, was relocated with arrival time data from the SQH station and Hi-CLIMB stations, and then chosen to be the master event of MERL to improve the accuracy of absolute position of earthquake sequences.

Figure 2 Sketch map of the master event relative location. The triangle is some station, and the circles are master and undetermined events’ epicenters. The α is event R ’s azimuth, identified with event X ’s azimuth.

4.1 Relocation of master event

The earthquake location program HYPOINVERSE-2000 was adopted to achieve absolute positioning of the master event. In the program, we picked P wave arrival time from seismic station record in the 68 stations of Hi-CLIMB seismic array and SQH station; also one-dimension crustal velocity structure model beneath Lhasa block was introduced. This model came from existing study in the nearby region (Zhao et al., 1991, 2001; Nabelek et al., 2009; Wittlinger et al., 2009) , and we assumed the value of the P to S velocity ratio to be 1.73 (Table 1).

Table 1 One-dimensional velocity structure of the crust used in the study

Layer	Depth/km	$v_P/\text{km}\cdot\text{s}^{-1}$	$v_S/\text{km}\cdot\text{s}^{-1}$
Upper crust	0.0–18.0	5.60	3.24
Middle crust	18.0–33.0	6.00	3.47
Lower crust	33.0–65.0	6.50	3.76
Upper mantle	>65.0	8.00	4.62

Table 2 Location of master event, 11 July 2004

Method	Date a-mo-d	Origin time (UTC)	Lat./°N	Long./°E	Depth/km	M
USGS	2004-07-11	23:08:44.18	30.69	83.67	13	6.2
MERL	2004-07-11	23:08:42.19	30.68	83.73	8	6.15*

Note: The number with * is achieved by the method of cut and paste (CAP).

Table 2 shows the difference between our result and USGS, where location difference is about 6 km, better than the typical NEIC accuracy of 15 km. Of course our location may have some error because the azimuthal gap of the stations is fairly large (about 250°; Figure 1). We also included S wave arrival in locating the mainshock, but the difference is small as compared with location with P wave only. Considering that S onset picking is not very precise, here we only report location from P arrivals. Seismic location of the master event was plotted in the Figure 3.

Figure 3 Location of earthquake sequences, including earthquake doublets and their aftershocks within one week after the mainshocks. The solid square is the master event, the first mainshock, relocated by HYPOINVERSE-2000, also located and cataloged by USGS, demonstrating by open square. The circles are the aftershock sequences within a week after the first mainshock, 11 July 2004. And the crosses are the aftershock sequences within a week after the second mainshock, 7 April 2005. The thin lines indicate local active faults.

4.2 Accurate location of undetermined event

The accuracy of absolute epicentral location is limited by the knowledge of the crustal structure and one-dimensional velocity model is not sufficient to obtain very accurate absolute location. However, errors in structure can be effectively minimized by using relative location methods, such as MERL (Spence, 1980).

Considering that aftershock zones may expand both horizontally and vertically, aftershock zones within a week after the mainquake are more suited to represent the range of co-seismic rupture zone than that within several months (Henry and Das, 2001; Kisslinger, 1996). In our study region, 115 local earthquake sequences of magnitude greater than 2, including the two mainshock and earthquake doublets' aftershocks recorded within one week after the mainquakes, were located via MERL using data from 68 stations of Hi-CLIMB seismic array. The onset of the seismic data was picked from P waveforms. As shown in Figure 3, the epicenter of earthquake doublets sequences are divided into two parts and presents a linear and limited distribution

with 60 km long in SN direction. The length of north aftershock zone is about 27 km, and the width is about 22 km. However, the length of south aftershock zone is about 39 km, and the width is about 14 km. The second co-seismic rupture zone is slenderer than the first one, the master event's rupture area. We also note that three events, happened in 12 July 2004, of the first earthquake sequence have shocked inside the second rupture zone, and are much close to the second mainshock. As these three events occurred on the second day after the first mainshock and next to the second mainshock, we supposed that they may have had a role in triggering the second mainshock. Of course, this supposition needs further research to prove to be true.

However, seismological methods usually do not provide ground truth location for earthquakes. In contrast, InSAR data can provide very accurate ground truth locations (Saikia et al., 2003). Therefore, we also modeled these two mainshocks with INSAR data. The co-seismic deformation field in the line of sight (LOS) associated with these two mainshocks was obtained

Figure 4 Earthquake doublets co-seismic deformation fields using InSAR technique. The blue open squares were earthquake doublets located by USGS, the black solid squares are located via MERL, and red dots are the centroid location from InSAR inversion.

from SAR images recorded by the European Space Agency's (ESA) C-Band ENVISAT. We have used the interferometric pair 20040317 and 20040908 to obtain the co-seismic deformation of 11th July, 2004 main event. Correspondingly, the deformation of 7th April, 2005 mainshock has been resolved using acquisitions from the pair 20050109 and 20050529. We utilized a sensitivity-based iterative method (Wang et al., 2008) to derive the slip distribution from the InSAR data. The fault dimension of the 11th July, 2004 is 16 km×16 km, in the along-strike and down-dip directions, respectively, while the fault dimension of 7th April, 2005 extends 27 km along-strike and 18 km in the down-dip direction. To solve the slip distribution that best describing the observed deformation, we have used a preliminary geometry of each fault derived from cut and paste (CAP) method as the constrained fault mechanism in the inversion process. To contradistinguish seismic results and geodetic results, the slip distribution was superimposed on the orthographic projection plane of faults at the horizontal surface (Figure 4). The two red solid circles represent the centroid points of the slip distributions. It seems that the earthquake doublets' rupture zones separate from each other and non-overlapping exist, which is similar to the result of aftershock zones. From InSAR inversion, we found that the 2004 mainshock is about 15 km in length and 15 km in width, and the 2005 event is about 25 km in length and 15 km in width. And these two events' ruptures do not overlap though they are very close to each other.

4.3 Focal depth determination

It is difficult to determine focal depth precisely by using traditional methods. It's known that most stations are set up in the surface and we can easily constrain horizontal parameters such as epicenter. However, the observation of these stations has little vertical information about earthquake, so we cannot easily determine focal depth. Meanwhile, focal depth and seismic travel time has stronger dependency on the position equation and traditional location methods have difficulty to decouple them. Thus, in our research, we choose cut and paste (CAP) to determine focal depth. CAP as a full waveform inversion method, is an effective tool to locate focal depth. The 31 events of magnitude greater than 3.7, which have been located and cataloged by USGS from 1 July 2004 to 1 July 2005, were relocated. We obtained epicenter via MERL and we gained focal depth by CAP.

As is described in the Figure 5, earthquake doublets sequences present a linear and limited distribution,

they are independent of each other and do not have any overlap as an entity, neither horizontally nor vertically.

Figure 5 Location of earthquake sequences from 1 July 2004 to 1 July 2005. (a) Horizontal distribution via MERL; (b) Depth distribution via CAP from south to north of study area. Black solid squares are the master event, the first mainshock relocated by HYPOINVERSE-2000; The open square is the second mainshock's location, 7 April 2005. Circles are the aftershock sequences of magnitude 3.7 or greater from 1 July 2004 to 6 April 2005. And Crosses are the aftershock sequences of magnitude 3.7 or greater from 7 April 2005 to 1 July 2005.

5 Discussion and conclusions

In this study the MERL technique has been applied to studying aftershocks of earthquake doublets, July 11 2004 and April 7 2005, in south-central Tibet from 30°N to 31°N and 83°E to 84°E, to obtain clearer views of aftershock zones and seismicity distribution then study characteristic of two rupture zones. It is demonstrated that the relative location method presented in this study indicates a significant improvement in location precision in the existing preliminary locations determined by the routine earthquake location method and listed in the NEIC's catalog due to the reduction of errors in structure. Meanwhile, we also modeled two mainshocks with INSAR data and studied earthquake doublets' co-seismic rupture zones.

The two M_6 mainshocks are very close to each other according to NEIC's catalog, and their aftershocks

look like to overlap each other, which may suggest that the earthquake doublets ruptured and produced an overlapped area, however, this study find that epicenters of aftershocks for the earthquake doublets can be distinguished from each other, which means that rup-

ture zones of the two mainquakes were not overlapping basically. Earthquake doublets' co-seismic deformation fields have been obtained by InSAR technique, which also confirms that these two co-seismic ruptures are not overlapping (Figure 6).

Figure 6 Superposition of earthquake doublets' rupture zones through two methods. Two blue solid squares are mainshocks relocated by HYPOINVERSE-2000. The red open stars are the aftershock sequences within a week after the first mainshock, 11 July 2004. And the black open stars are the aftershock sequences within a week after the second mainshock, 7 April 2005. The red solid circles are the centroid location from InSAR inversion.

It has been discovered that widely distributed NS trending rifts or rift-depressions and NE and NW trending strike-slip faults have been developed in southern Tibet. And in this area, the north-south trending normal faults, north-east and north-west trending strike-slip faults are the major active tectonics (Wang et al., 2000). In this study, the epicenters of earthquake dou-

blets are mainly located at the intersections of north-south and north-west fracture, and two rupture zones from seismological and InSAR methods present nearly NS-trending distribution, which is parallel to the NS-trending rifts' direction. It can be conjectured that the earthquake doublets maybe influenced by north-south fracture zones.

The expansion of the aftershock area with time has been noted for many earthquakes, and it is considered that if a short time period after the main earthquake is selected, the aftershock area gives a good estimate of the co-seismic rupture zone of the mainshock (Henry and Das, 2001; Bao et al., submitted for publication). Furthermore, structural features of fault zones might be related to the sizes and locations of early aftershock zones, which could be the result of stress rearrangement after mainshocks and mainly distributed along the rupture zones (Mendoza and Hartzell, 1988). In addition, some aftershock, happening in some distance from the mainshock possibly, might be triggered by the mainshock statically. In this study, the rupture zones of the earthquake doublets, described as early aftershock zones, were accommodated by discrete segments rather than overlap for reasonable short periods, just within a seismogenic period.

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