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ARTICLES

GEOPHYSICS

Slip rate along the Lijiang-Ninglang fault zone estimated from repeating microearthquakes

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Seismicity and slip rates along the Lijiang-Ninglang fault zone between 1999 and 2006 were investigated with the waveform data recorded by the Yunnan digital Seismic Network. The relocated seismicity by the double difference method clearly exhibits different features between the northern and southern segments. More than 76% earthquakes occurred in the southern segment of the fault near the Lijiang area. The relocated seismicity appears to reflect the crustal velocity structure of the study area. Using cross-correlation analysis, we identified a total of 92 doublets and 70 multiplets that show high waveform similarity. Most of these sequences are aperiodic with recurrence intervals varying from a few minutes to hundreds of days. Using two sequences that occurred regularly over the study period, we obtained a fault slip rate of approximately 5 mm/a at ~23 km, in good agreement with geologic and surface GPS measurement.

Lijiang-Ninglang fault zone, repeating earthquake, fault slip rate

Fault slip rate is a key parameter for earthquake study. As such, it has been widely investigated in seismology and geology[1,2]. It can also be estimated from surface geodetic observations such as GPS, InSAR (Interferometric Synthetic Aperture Radar)[3,4]. Most of the geologic and geodetic observations are, however, surficial measurements which require an assumed rheology to estimate the slip rate at seismogenic depth. Nadeau et al.[5] found the "characteristic" earthquakes in the Parkfield section of the San Andreas Fault. These "characteristic" earthquakes, also known as repeating earthquakes, occurred very regularly at the same patch of the fault. Their waveforms are very similar when recorded at the same station. Nadeau and McEvilly[6] later proposed a direct estimate of deep slip rate by using seismic moments of the repeating earthquakes and their recurrence intervals. Repeating earthquakes are usually found at plate boundaries where frequent occurrence of earthquakes generates a weak layer that allows continuous creeping for most part of the fault except for a few strong asperities that produce earthquakes. It is still unclear whether the rarely occurring intraplate earthquakes can also create the same faulting system. Using teleseismic waveform data, Schaff and Richards[7] found that ~10% of seismic events in China were repeating earthquakes. Li et al.[8] found that the seismicity along the Tangshan fault consists of as much as ~53% similar events by examining local and regional waveform data. They also identified a few quasi-periodic sequences and used them to constrain the current slip rate of the fault. They further speculated that the fault generating the 1976 deadly earthquake in North China, though being an intraplate fault system, is actually mature enough to develop a weak layer essential for earthquake repeating. To further understand the relationship of faults development

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and earthquake repeating, we investigated another seismically active region in China, Yunnan Province. Especially, we targeted the Lijiang-Ninglang area where several strong earthquakes, such as *M* 7.0 and *M* 6.2 earthquakes, occurred within the last ten years.

Yunnan Province is located at the southeast edge of the highly deformed Tibetan Plateau, which was a result of the continuing collision between India and Asia. It is one of the most tectonically active regions in China. Yunnan is also featured by a complicated terrain that hosts numerous seismically active faults (Figure 1). The Lijiang-Xiaojinhe Fault system is perhaps the most

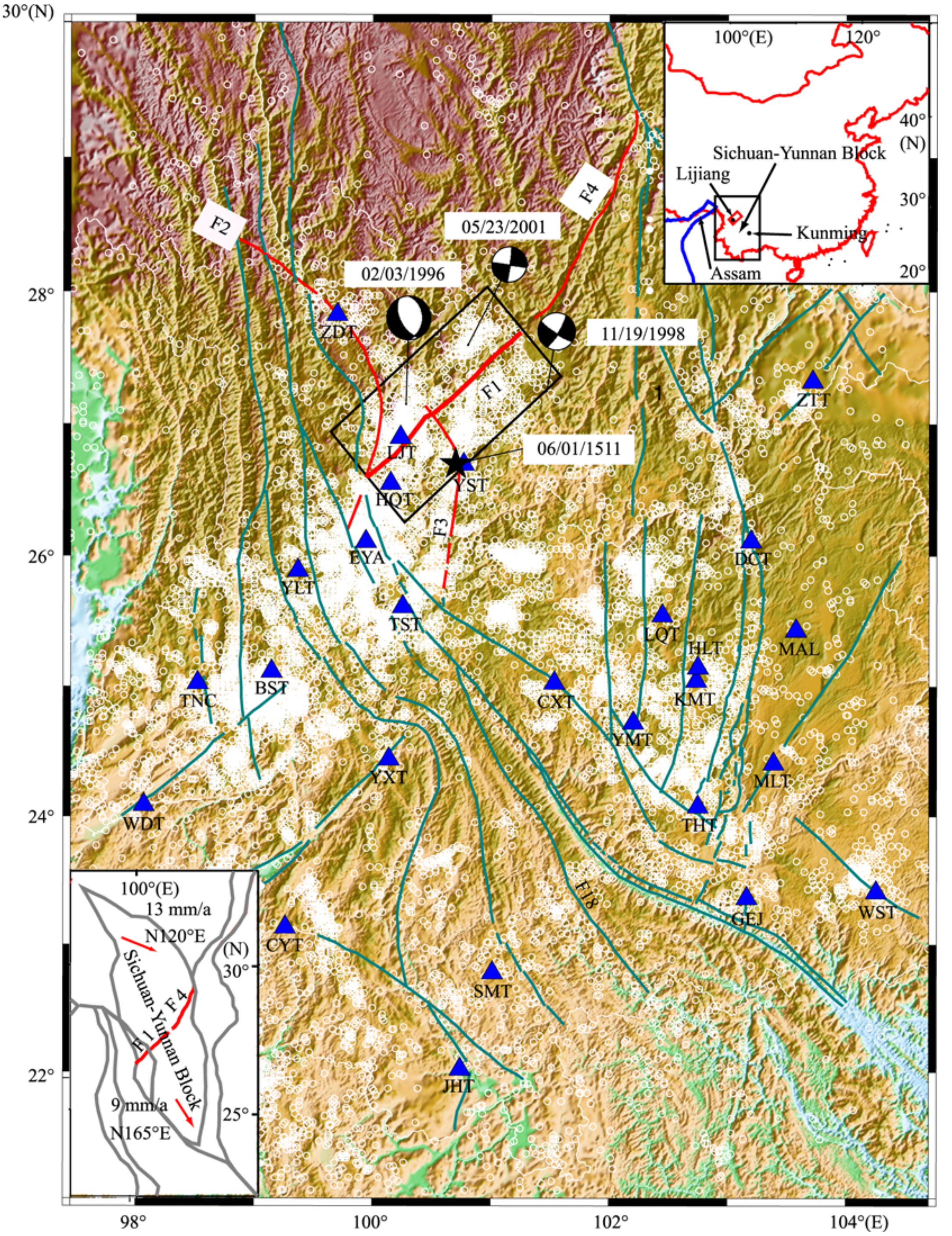

Figure 1 Geographic map showing seismicity (white open circles) in the period of 1999－2006, major faults (colored solid lines), and the Yunnan digital Seismic Network (blue triangles) in the study area. Low insert illustrates Sichuan-Yunnan block that moves toward south-southeastward while rotating clock wisely. Upper right inset shows the geographic location of the study area. The Assam massif is illustrated in blue solid lines. F1, Lijiang-Ninglang Fault (the south segment of Lijiang-Xiaojinhe Fault); F2, Zhongdian Fault; F3, Chenghai Fault; F4, the north segment of Lijiang-Xiaojinhe Fault.

seismically active fault among them. This left strike-slip fault essentially cuts the "Sichuan-Yunnan Rhombic Block" in the middle into two sub-blocks[1,2]. GPS measurements[9] show that the northern sub-block moves toward N120°E with an annual rate of 13 mm/a while the southern sub-blocked directs to N165°E at a rate of 9 mm/a. The southern part of the fault system, which is known as the Lijiang-Ninglang faults, interacts with other two major faults in the region: the northwest oriented Zhongdian Fault and the north-south oriented Chenghai Fault. Interactions among these multiple faults resulted in the occurrence of the 1511 *M* 7.5 earthquake, the 1996 *M* 7.0 earthquake, the 1998 *M* 6.2 earthquake and the 2001 *M* 5.8 earthquake that showed very different focal mechanism (Figure 1). To better monitor the seismic activity in the Yunnan area, the Chinese Earthquake Administration (CEA) installed the Yunnan digital Seismic Network (YSN) in the late 1990s. Currently the network consists of 26 broadband telemeter stations (Figure 1). Since its operation in July of 1999, a large amount of data including waveform data has been collected. The data provide a new opportunity for investigating the spatial and temporal features of the seismicity along the Lijiang-Ninglang fault as well as its slip behavior.

In this study we first applied the double difference relocation method[10] to the bulletin and regional waveform data collected by YSN to obtain a better seismicity map of the region. We then investigated the spatial and temporal features of the relocated seismicity. Finally we used a few quasi-periodic similar events to estimate the current slip rates along the Lijiang-Ninglang fault.

1 Data and analysis

A total of 2684 events were detected along the Lijiang-Ninglang fault (rectangle in Figure 1) by the YSN during the period of 1999—2006. Magnitude of these events ranges from 0.1 to 5.8 in Richter magnitude scale. Among the 2684 events, 1819 events have waveform data. Besides the waveform data, we also obtained thousands of picks (from 1798 events) that were reported to the preliminary and formal seismic bulletins issued by YSN. When an event is not recorded by enough stations, focal depth of this event is usually not included in the bulletins. We found that 768 events did not have a reported focal depth.

Catalog locations were routinely determined from picks of P- and S-wave arrival times. Typical location error is in the order of a few kilometers to a few tens of kilometers. To better resolve the seismicity along Lijiang-Ninglang fault, we used the double difference (DD) method[10] to relocate these events. The DD method was designed to determine relative locations with respect to the centroid of the correlated events, which is frequently referred to as a cluster. It used residual between observed and theoretical differential travel time (or double-differences) to avoid uncertainty in origin time. Since it is sensitive only to velocity structure near the cluster, the DD method minimizes errors due to unmodeled velocity structure. Moreover, differential time used in the DD relocation methods is usually measured by waveform cross correlation methods that give much better accuracy than the manual picks. This further improves the location accuracy.

The data preprocessing applied to the raw waveform data includes the following steps: a 1—10 Hz bandpass filter was first applied to the data. The bandpass filtered data, which were digitized by a sampling rate of 50 samples per second, were then interpolated to a higher sampling rate for differential time measurement. Interpolation was performed in the frequency domain by packing additional zeros to the original spectrum. The sampling interval of the interpolated data is 0.3125 ms, which was selected based on the uncertainty in the differential traveltime measurement. The uncertainty is in principle determined by signal-to-noise ratio (SNR) of the waveform data.

We calculated the cross correlation and the differential time in the time domain using a 1.1 s time window (0.1 s and 1.0 s before and after the onset of the P wave, respectively). To ensure the time window is correctly selected, we manually picked 5677 P-wave arrival times from high SNR waveform data. We imposed a threshold in selecting the event pairs. We finally selected 84963 pairs that have a cross-correlation coefficient >0.7. These high quality differential travel time data were added to the bulletin data in the DD relocation analysis.

We used a 1D velocity model modified from the one proposed by Yang et al.[11]. The revised model has a refined top layer constructed from velocity models derived from Depth Seismic Sounding (DSS) profile studies[12,13]. To objectively assign an initial depth to those events without a focal depth report, we first excluded them in the relocation process and obtained 1030 earthquakes for relocation. The pattern of the relocated 706 earthquakes

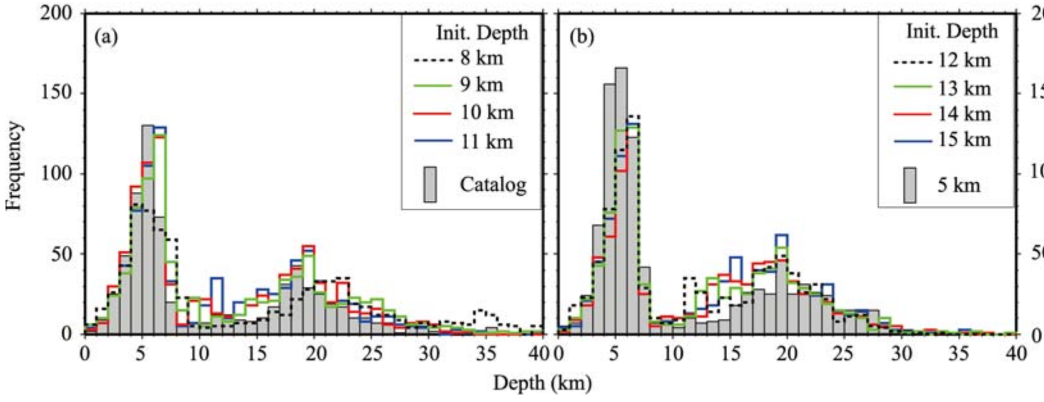

Figure 2 Histogram of relocated focal depths. Gray filling in panel (a) indicates the depth distribution for relocated event that has a reported depth in the bulletin. Gray filling in panel (b) is the focal depth distribution by assigning a 5 km focal depth to those events without focal depth report. Histograms of the focal depth corresponding to different initial values are also shown for comparison. Note the minor difference in the focal depth distribution among cases that different initial values were assigned to those events without focal depth report.

with less than 1 s RMS showed a primary peak at depth around 5 km which took up about 20% of the total relocated seismicity (see the gray histogram in Figure 2(a)). In the next round relocation, we assigned an initial depth of 5 km to those events without focal depth reports.

2 Relocated seismicity

We selected event pairs by the following criteria: (1) the two events are located within 10 km in the original catalog; (2) most of the stations are located within 500 km from the events; and (3) the pairs are recorded by at least two common stations. The final dataset consists of 1275 well-connected events that form a few clusters. We started the inversion by applying large weight to the catalog data to establish the large-scale distribution, and then gave more weight to the cross-correlation picks in the late stages to adjust event locations. After a long and tedious refining process, we obtained a better located seismicity that consists of 971 events. The relocated events tend to distribute only in certain regions (Figure 3). Geographically, the relocated seismicity revealed that more than 76% of the earthquakes occurred in the southern segment of the fault (Figure 3) where the Lijiang-Ninglang fault interacts with other two major fault systems. Although the relocated events appeared to be more focused, they however, still were widely distributed in the two sides of the fault. The complicated fault system in the region is probably responsible to the wide distribution of seismic events observed here. Moving to the north, in the Ninglang area, seismicity seems to be even more diffused, except for a cluster near the 2001 *M* 5.8 Ninglang earthquake.

Most of the relocated events tend to occur at two depth ranges, 0—8 km and 15—30 km. There seems to be a nearly aseismic layer at the depths between 8 to 15 km (Figures 2 and 3). Although the seismic stations in study area are sparsely distributed, especially in the north segment of the fault, it is pretty obvious that the lack of seismicity at 8—15 km depths is a true feature. We confirmed that this feature is not caused by the initial values assigned to those events without a focal depth report. In fact, we extensively tested how the assigned initial values (8 to 15 km) affect the final depth distribution. We found that initial value has a little effect on the final results (Figure 2). Besides this noticeable difference in occurrence frequency, there is another significant difference in *b* value of the seismicity among the three depth ranges (Figure 3(e)). The *b* values calculated from the three depth ranges (0—8 km, 8—15 km and 15—30 km) are 0.75±0.01, 0.50±0.02 and 0.85±0.01, respectively. The large contrasts in seismicity and *b* value observed here may suggest that there are significant differences in rock property, stress level and rheology among the three depth levels. Relatively large earthquakes occurred in the shallow crust while small earthquakes frequently occurred at great depths. This feature in the seismicity appears to have some correlation with the crustal velocity structure of the study region.

Geologic study[14] found that the southern segment of the Lijiang-Ninglang fault experienced a long and active history of tectonic deformation. Rocks along the fault are found to belong to the cataclasite series. The cataclastic rocks are generally considered to have formed under a condition of low temperature and high shear

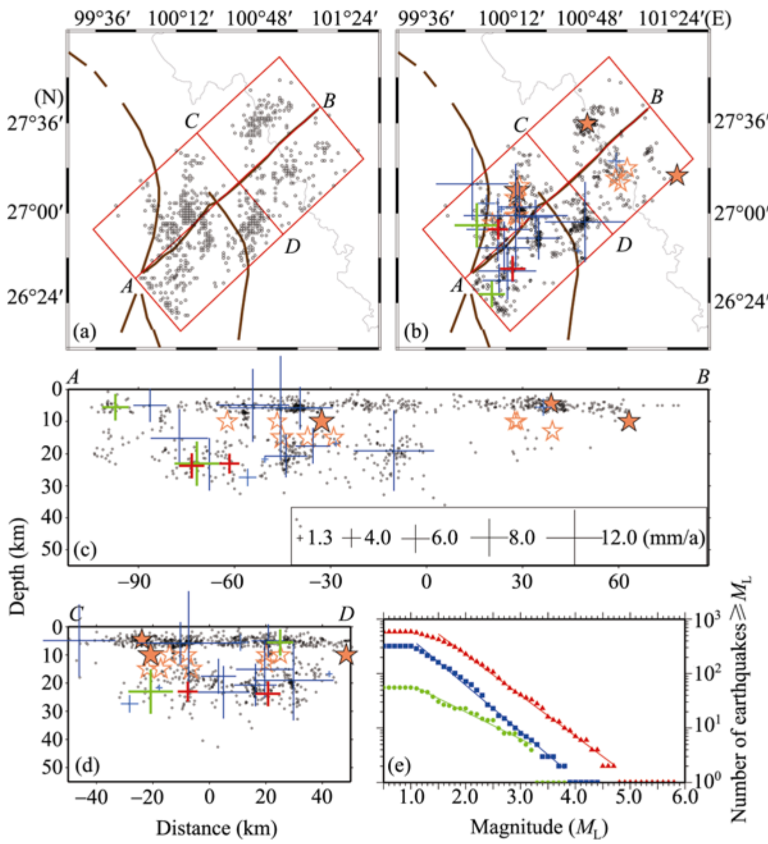

Figure 3 A comparison of YSN catalog locations (a) and the relocated seismicity (b). Relocated seismicity is plotted in depth section *AB* along the fault (c), and a depth section *CD* across the fault (d). Solid stars indicate the major earthquakes mentioned in the text and open stars represent their large aftershocks (M≥5). Size of the crosses is proportional to the slip rates estimated from similar-earthquake (blue) and repeating-earthquake sequences (red and green). The red two are shown in Table 1. (e) Cumulative frequency-magnitude distribution of the seismicity occurring in the three depth ranges. Triangles, circles and squares indicate 0—8 km, 8—15 km and >15 km depth ranges, respectively.

stress level. The presence of cataclasite series thus indicates that major seismic events occurred at a very brittle condition typical of the upper crust. Our result that relatively large events are concentrated in the shallow layer of 0—8 km thus agrees with geologic observations.

Several DSS experiments[12] were conducted in the study area in the 1980s. The active source profiles all showed that the crust consists of three major layers. The middle layer started from ~16—17 km depth to ~37—38 km below the surface. There is a low-velocity zone starting from ~27—29.5 km, which is interpreted the middle layer as the brittle-ductile transition zone. Recent passive-source seismic tomography study by Huang et al.[15] confirmed these active-source results. Our relocated seismicity showed that most earthquakes occurring at depth greater than 15 km are of low magnitude, usually less magnitude 3.8. Thus the relocated seismicity is consistent with the crustal velocity structure. It confirms the laboratory observation that earthquakes occurring in the brittle-ductile transition zone tend to be small.

As far as for the lack of seismicity in the depth range of 8—15 km, there are two possible explanations. Zhu et al.[16] proposed a ductile deformation mechanism to explain the lack of seismicity in the depth range of 15 to 20 km observed beneath the east edge of the Tibetan Plateau in western Sichuan Province. Thus it is likely that the lack of seismicity observed here is also caused by ductile deformation of the granite in the middle crust. Another possibility is that it might be the consequence of the previous seismicity or a quiescence region preparing for the next major events. We noticed that the 1996 M 7.0 Lijiang earthquake, the 1998 M 6.2 Ninglang earthquake and their large aftershocks (stars in Figure 3) all occurred at around 10 to 15 km. The fault could be still in a healing process.

3 Repeating earthquakes identification and slip rate estimate

We noticed that many events have similar waveforms during the cross-correlation calculation. So our next goal is to search potential repeating event clusters from the relocated seismicity dataset. We first began with the search of events that show similar waveforms. We define similar events to be event clusters having cc>0.8 for a time window 1 s before the P wave to 5 s after S wave recorded at least one station. The similar events include both repeating events and similar aftershocks; the difference between the two is defined by their spatial distribution. The principle rupture areas of the repeating events overlap with each other, while those of the similar aftershocks are displaced from each others. After scanning of the whole catalog, we identified a total of 162 similar event sequences (Figure 4), which include 92 doublets consisting of two events and 70 multiplets consisting of at least three events. The total number of earthquakes in the 162 sequence is 736, with magnitude ranging from M_L1.0 to 3.3. Figure 5 shows an example of waveforms from an identified similar event sequence. We found significant variations in the recurrence interval for most of the sequences. The recurrence interval varies from a few minutes to hundreds of days. GPS measurements[9] indicate that the Sichuan-Yunnan block is moving toward SSE at an annual rate of 9—13 mm/a. If we assume this is the tectonic loading rate of the Lijiang-Ninglang fault, then the recurrence interval of a M_L1.0 earthquake is around 30 days. There are 25 multiplets that roughly satisfy this requirement on minimum recurrence interval.

We did not use the doublets to constrain slip rate as the variations are probably too large to give any meaningful results. Our estimates of slip rates are thus based on the selected 25 multiplets. We first adopted the assumption proposed by Nadeau et al.[6] that the slip rate is the division between the coseismic slip and the recurrence interval.

To calculate the coseismic slip, we first used the moment-magnitude relationship of Hanks and Kanamori[17]:

$$\log(M_0) = 16.1 + 1.5M, \qquad (1)$$

to convert the local magnitude, M_L, to the seismic moment, M_0. We also assumed a circular rupture model and estimated the rupture radius, r, from M_0 using the scaling rule introduced by Kanamori and Anderson[18]:

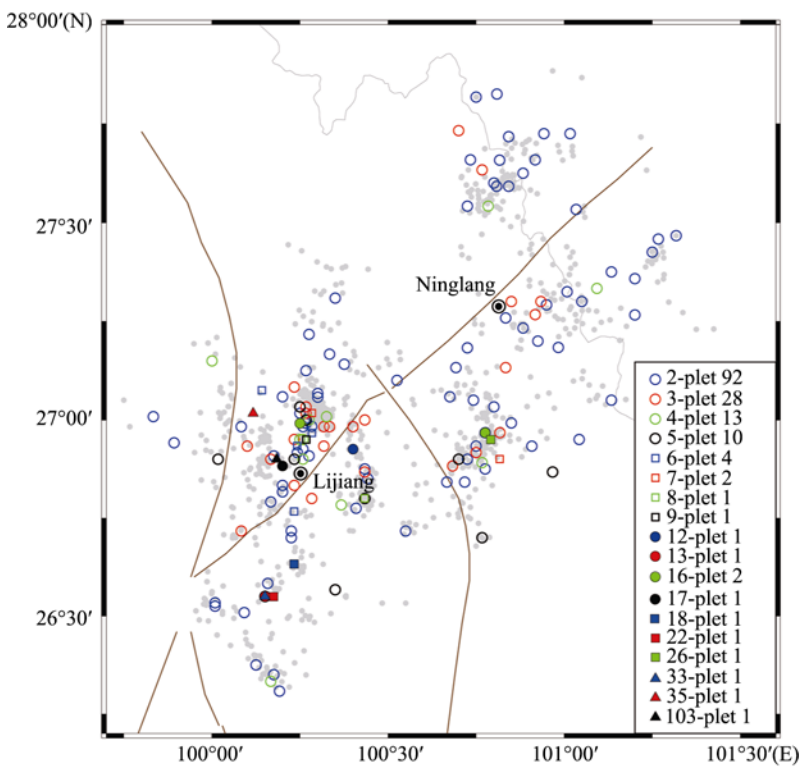

Figure 4 Map view of the locations of the identified similar events clusters. Grey circles represent the background seismicity after relocation. These sequences are shown in different color symbols, with their corresponding doublets/multiplets shown in the legend.

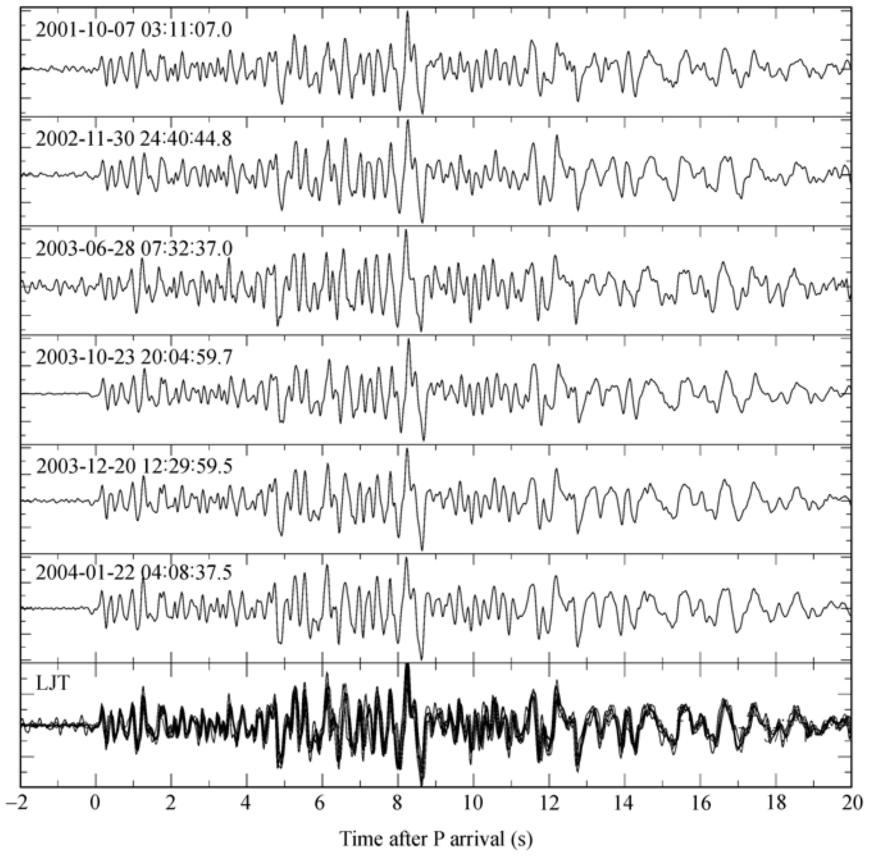

Figure 5 Examples of seismograms from one similar event sequence recorded at the broadband station LJT. The lowest is overlapped waveform.

$$r = \left(\frac{7M_o}{16\Delta\sigma}\right)^{1/3}. \quad (2)$$

We used a coseismic stress drop ($\Delta\sigma$) of 3 MPa in our calculation. The coseismic slip is then calculated from the estimated M_0 and r:

$$d = M_o / \mu\pi r^2 , \quad (3)$$

where the shear modulus μ is taken to be 3×10^{10} N/m^2.

We obtained a wide range of slip rates, from 1.3 to 22.1 mm/a, with a mean and median of 7.9 mm/a, and 7.2 mm/a, respectively. The relocated catalog showed that 7 of the 25 selected similar event sequences are poorly located, we thus excluded them in the slip-rate estimates. The estimated slip along the entire section of the fault is shown in Figure 3. It appears that the northern segment has a relatively low slip rate in comparing with the southern segment. The lowest slip rate is found near the 1996 M 7.0 Lijiang earthquake.

The large variations in the estimated slip rate are probably related to our assumption that the multiplets are repeating events. In principle, this assumption must be tested through careful relocation analysis[19,20]. Most of YSN stations are located in northwestern side of the Lijiang-Ninglang fault, resulting in a one-side distribution to the earthquakes occurred in study area. With this station distribution, it is impossible to accurately determine the relative locations of earthquakes in each sequence. We thus seek a rather empirical way to determine the candidacy of a repeating event sequence.

We applied the following criteria to select multiplets: (1) average cc>0.9; (2) internal inconsistence in travel time picking <0.5 ms[19]; and (3) average recurrence interval >100 days. We consider the multiplets that satisfy the above requirements as potential candidates of repeating earthquake sequences. Only 4 multiplets belong to this category (Figure 3). Among which, 2 of them have only 3 events.

The 2 sequences with more than 5 events are listed in Table 1. We obtained an annual slip rate of 5.4±0.4 mm/a and 4.3±0.9 mm/a using a linear regression of the cumulative slip shown in Figure 6. Geologic estimate of the average slip rate since late Pleistocene along the Lijiang-Ninglang fault is ~3.8 mm/a[2], and the average slip rate along Zhongdian fault is 5.0±1.0 mm/a[21]. Re-

Table 1 The result from 2 repeating earthquakes

Seq. ID[a)]	Evt. ID	Date	Time (hh:mm:ss.ss)	Mag. (M_L)	Radius (m)	Slip (mm)
1	1	2001-03-23	16:41:32.40	1.3	25.4	1.8
1	2	2002-06-01	12:31:28.30	1.1	20.2	1.5
1	3	2003-11-23	14:07:51.70	1.2	22.6	1.6
1	4	2004-02-19	14:27:25.40	1.4	28.5	2.1
1	5	2004-06-27	13:37:30.80	1.2	22.6	1.6
1	6	2004-11-09	14:57:28.90	1.3	25.4	1.8
1	7	2004-11-24	11:28:04.70	1.0	18.0	1.3
1	8	2004-12-14	11:07:13.30	1.0	18.0	1.3
1	9	2005-01-25	16:21:24.50	1.3	25.4	1.8
1	10	2005-06-10	11:27:40.00	1.0	18.0	1.3
1	11	2005-07-03	07:03:57.10	1.2	22.6	1.6
1	12	2006-03-18	11:45:03.10	1.3	25.4	1.8
1	13	2006-06-30	20:49:24.30	1.2	22.6	1.6
1	14	2006-07-06	14:12:57.10	1.3	25.4	1.8
1	15	2006-12-16	12:15:26.00	1.0	18.0	1.3
2	1	2003-11-26	23:25:48.70	1.7	40.2	2.9
2	2	2004-09-26	08:49:18.60	1.9	50.7	3.7
2	3	2005-03-01	10:51:02.50	2.0	56.8	4.1
2	4	2005-05-30	10:41:04.80	1.5	32.0	2.3
2	5	2006-05-02	12:23:50.30	1.3	25.4	1.8
2	6	2006-10-16	18:46:36.70	1.2	22.6	1.6

a) Seq. 1: median location 26.628°N, 100.248°E, 23.7 km; Seq. 2: median location 26.889°N, 100.141°E, 23.0 km.

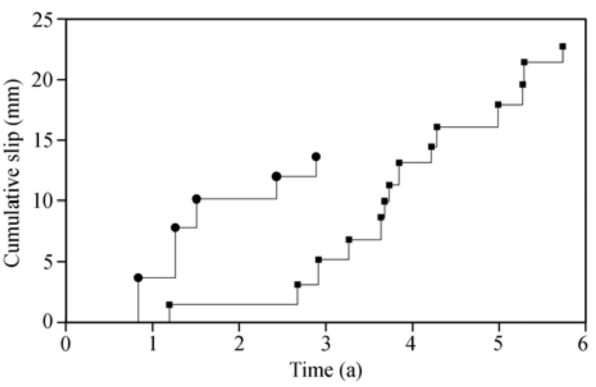

Figure 6 Cumulative slip from 2 repeating earthquakes consisting of 6 events shown in circles and 15 events in rectangles. Event 1 occurred at time zero and is not shown here.

cent GPS measurements showed that the relative motion between the two sides of the Lijiang-Ningliang fault is ~3 mm/a between 1999 an 2004[22]. We want to notice here that our estimates should be considered as an upper boundary of the actual stress build up along the fault, since it is based on the assumption that the two sequences are repeated slips of the same asperities. If the rupture areas of the earthquakes in each sequence overlap only partially with each others, it could take longer than the recurrence interval to build up the strain energy released in each event. We also noticed that the recurrence intervals could be still under the influence of the 1996 *M* 7.0 Lijiang earthquake and the 1998 *M* 6.2 Ninglang earthquake. We also found that both of the 2 repeating earthquake clusters occurred in the brittle-ductile transition zone. This again indicates that the presence of relatively weak regions is crucial for generating repeating earthquakes.

The given slip rates may be an actual creep of the tectonic loading at depth. For the estimated values from similar events, the 2 large values of 17.1 and 22.1 mm/a are likely to be associated with frequent occurrences of earthquakes near similar events (Figure 3). Except those two values, other estimated rates consist with tectonic loading rate from GPS observations, which controls the movement of the study area.

4 Conclusions

We have investigated seismicity between 1999 and 2006 in Lijiang-Ninglang area, and here is what we have found:

(1) The relocated seismicity clearly exhibits a significant difference between the northern and the southern segment of the fault. More than 76% of the earthquakes during the study period occurred in the southern segment near Lijiang area, which is likely due to the interactions of multiple fault systems;

(2) The relocated focal depth distribution is consistent with the crustal velocity structure of the study region. High seismicity are found at two depth ranges, 0—8 km and 15—30 km, which correspond, respectively, to the brittle upper crust and the ductile-brittle transition zones in the lower curst. The lack of seismicity at 8—15 km depths may indicate the existence of a ductile middle crust in the study region, but it could also be attributed to the quiescence region either as the consequence of previous seismic events or the cause of future strong earthquakes;

(3) Using cross-correlation analysis of waveform, approximately 40% of the earthquakes show very similar waveforms, suggesting that a significant portion of the seismicity is related to spatial clustering. Slip rates estimated from similar earthquakes roughly agree with the tectonic loading rate derived from geologic and geodetic data;

(4) Based on 2 clusters that exhibit some "characteristic" features of a repeating event sequence, we obtained a fault slip rate of ~5 mm/a at ~23 km. Depth of the 2 sequences coincides with the brittle-ductile transi-

tion zone, indicating that creeping of weak materials in the surrounding areas is essential for generating repeating earthquakes.

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