Research Article

Latest Quaternary Active Faulting and Paleoearthquakes on the Southern Segment of the Xiaojiang Fault Zone, SE Tibetan Plateau

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The Xiaojiang fault zone (XJFZ) is an important part of the Xianshuihe-Xiaojiang fault system, acting as the eastern boundary of the Chuan-Dian block on the southeastern margin of the Tibetan Plateau and accommodating the lateral extrusion of the block. The faulting activity and paleoseismic history on the southern segment of the XJFZ remain poorly understood. Here, trench excavations and radiocarbon dating revealed that four recent surface-rupturing paleoearthquakes have occurred on the Jianshui fault (JSF) in the southern segment of the XJFZ since ~15370 yr BP. The ages of these events, labeled E4-E1 from oldest to youngest, are limited to the following time ranges: 15360-12755, 10845-6900, 1455-670, and 635-145 yr BP, respectively. The most recent event E1 was most likely the 1606 Jianshui earthquake. These events appear to occur unregularly in time. The time interval between the last two events is \(726 \pm 235\) yr, and the average recurrence interval for all four events is \(4589 \pm 3132\) yr. The deformed strata show that the JSF is characterized kinematically by transtension, which likely respond to the apparent change in the direction of clockwise rotation of the Chuan-Dian block around the eastern Himalayan syntaxis. Combined with the analysis of the neighboring NW-striking faults, our study suggests that the south-southeastward motion of the Chuan-Dian block is likely to be firstly accommodated in part by the right-lateral shear and dip-slip motions of the Qujiang and Shiping faults and continues across the Red River fault zone, then is transmitted southward along the Dien Bien Phu fault. Therefore, the southern segment of the XJFZ plays a dominant role in the tectonic deformation of the southeastern Chuan-Dian block, with a high seismic hazard.

1. Introduction

The Xiaojiang fault zone (XJFZ) constitutes the continuous Xianshuihe-Xiaojiang left-lateral strike-slip fault system, together with the Xianshui fault zone, Anninghe-Zemuhe fault zone, and Daliangshan fault zone, and Daliangshan fault zone and Daliangshan fault zone (Figure 1(a)). The fault system acts as the eastern boundary of the Chuan-Dian block on the southeastern margin of the Tibetan Plateau and plays a key role in accommodating the lateral extrusion of the block and clockwise rotation around the eastern Himalayan syntaxis (e.g., [1–5]). The tectonic deformation and seismicity of the XJFZ have been intense since the late Quaternary, and the fault zone forms a vital part of the north-south seismic belt [6–8]. The XJFZ is approximately 400 km long and can be generally divided into three segments (Figure 1(a), [9–11]). The northern segment is located on the northern side of Dongchuan County and is composed of a single fault (Figure 1(a)). The central segment is divided into eastern and western branches that extend from Dongchuan County to Fuxian Lake. The southern segment is located on the southern side of Fuxian Lake and is composed of multiple fault branches to the north of the Jianshui Basin. There is only one fault branch near and to the south of the Jianshui Basin, which is called the Jianshui fault (JSF; Figure 1(a); [12]).

The southward motion of the western wall of the XJFZ or Chuan-Dian block was generally considered to be absorbed and accommodated by the NW-striking Qujiang and Shiping...
faults in the form of dextral shearing and transverse shortening [5, 9, 13, 14]. The left-lateral shearing of the Xianshui-Xiaojiang fault system might end to the north of the Jianshui Basin. Accordingly, several large earthquakes with magnitudes of ≥7.0 have occurred on the northern and central segments throughout history (Figure 1(a)), including the 1733
M.75 Dongchuan earthquake, 1833 M.8.0 Songming earthquake, 1500 M7 Yiliang earthquake, and 1789 M7 Huaining earthquake [5, 15, 16]. There were minimal activity and no past surface-rupturing earthquakes in the southern segment of the XJFZ abutting the Red River fault zone [9, 11, 17, 18]. The only earthquake to occur on the western side of the JSF is the 1606 M6.75 Jianshui earthquake [15]. However, the GPS velocity field presented by Shen et al. [1] and the kinematic models of the SE Tibetan Plateau proposed by Schoenbohm et al. [19] and Wu et al. [20] show that the crustal material of the Chuan-Dian block does not accelerate significantly in the vicinity of the southern segment of the XJFZ and that clockwise rotation continues across the Red River fault zone. Therefore, studying the late Quaternary faulting activity of the southern segment of the XJFZ will contribute to understanding the tectonic deformation pattern of the Chuan-Dian block and reasonably assessing the seismic risks of the SE Tibetan Plateau.

To better understand the faulting activity of the southern segment of the XJFZ and its role in accommodating the tectonic deformation of the SE Tibetan Plateau, the JSF, abutting the Red River fault zone, was mapped in detail through high-resolution satellite image interpretation, field investigation, and fine-scale measurement of offset landforms. The deformation characteristics and paleoseismic history of the fault were constrained by the trench excavations and radiocarbon dating. Then, we discussed the latest Quaternary faulting behavior and kinematic property of the JSF and compared the tectonic activity of the fault with those of the neighboring faults. Finally, we found that four paleoearthquakes occurred on the JSF during the latest Quaternary and the fault plays a dominant role in the tectonic deformation of the southeastern Chuan-Dian block.

2. Regional Seismotectonic Setting

The Chuan-Dian block is located on the southeastern margin of the Tibetan Plateau, bounding with Sichuan Basin and South China blocks to the east (Figure 1(a)). The block moves south-southeastwards due to the convergence and extrusion of the India plate to the Eurasian plate [4, 19]. Two groups of active faults with different strikes of nearly N-S and NW-NNW are located in the southeastern Chuan-Dian block (Figure 1(a)). The nearly N-S-striking faults are composed mainly of the XJFZ. Many large earthquakes with magnitudes of M ≥ 7 have occurred on the central and northern segments of the XJFZ throughout history. Among them, the 1833 M8.0 Songming earthquake occurred on the western fault branch of the central segment and generated a surface rupture zone with a length of approximately 150 km and a maximum coseismic offset of ~8.4 m [16]. The geologically measured late Quaternary left-lateral slip rates of the central and northern segments are 10-16 mm/yr [10, 11, 23], and geodetic measurements limit the slip rate of the fault segments to be 7-10 mm/yr [1, 5, 24]. Previous trench excavations revealed that several paleoearthquakes have occurred since the late Quaternary, and the time intervals between the events are 2000-4000 yr [11, 25], 2000-2500 yr [10], and 340-480 yr [26].

Compared with the central and northern segments, the southern segment of the XJFZ, including the JSF, is still poorly studied. He et al. [9] and Song et al. [11] believed that the fault did not extend to the Red River valley and terminated near Shanhua village, Jianshui County, 10-15 km from the Red River valley (Figure 1(b)). However, previous proposed kinematic models of the SE Tibetan Plateau have shown that the Xiaojiang fault zone passes through the Red River fault zone southward and connects with NE-striking faults, including the Dien Bien Phu fault on the south side (Figure 1(a)), constituting a continuous eastern boundary of the southeastern margin of the Tibetan Plateau [4, 19, 20]. Han et al. [12] suggested that the JSF extends from the north side of the Jianshui Basin to the Red River valley and estimated the Holocene left-lateral slip rate to be 7.02 ± 0.20 mm/yr based on the offset measurements of the faulted river terraces and radiocarbon dating of its formation age, which is in good agreement with the slip rate constrained by GPS data [1]. The paleoseismology of the fault has not been reported.

The Qujiang, Shiping, and Red River fault zones (QIF, SPF, and RRF) are three important NW-WNW-striking faults in the area (Figure 1(a)). They are distributed at nearly regular intervals from north to south, and these accretion faults are convex to the southwest. Three earthquakes with magnitudes of M ≥ 7 have occurred on the Qujiang fault in recorded history, namely, the 1588 M7.0 Qujiang earthquake, 1913 M7.0 Eshan earthquake, and 1970 M7.7 Tonghai earthquake [15, 27]. Among them, the 1970 M7.7 Tonghai earthquake produced a right-lateral surface rupture zone with a length of 60 km, a maximum right-lateral offset of 2.7 m, and a maximum vertical offset of 0.47 m [28]. The Holocene right-lateral strike-slip rate of the Qujiang fault is 2.8-3.5 mm/yr [29, 30]. Two earthquakes with magnitudes of M7 occurred on the Shiping fault in 1799 and 1887. The Red River fault zone experienced a motion reversal from left-lateral to right-lateral in the Neogene [31]. The right-lateral slip rate of the fault has been estimated to be 2-3 mm/yr [32], 2.0-2.6 mm/yr since the middle Pleistocene [33], and 1.2-1.4 mm/yr since the Pliocene [20]. Shi et al. [2] revealed that the seismic recurrence interval of the fault zone has been 6000 ± 1000 yr over the last 30000 yr and that the late Quaternary slip rate is 1.1 ± 0.4 mm/yr.

3. Methods

The surface traces of the JSF were mapped in detail based on high-resolution (~0.6 m) Google Earth optical image interpretation and field investigations of offset landforms, including fault scarps, fault troughs, and left-laterally offset streams, terraces, and ridges. Three trenches were excavated in sag ponds or small depressions where sediments were relatively continuous and undisturbed, and radiocarbon samples could be collected. We used airborne light detection and ranging (LiDAR) technique to finely measure faulted landforms near the trench excavation sites to obtain high-resolution (0.5 m) digital elevation models (DEMs) after the removal of vegetation [34-36]. Trenches were excavated across the fault subvertically (Figure 1(c)), and trench sections were...
systematically cleaned to expose clear evidence of paleoseismic events. Horizontal level rulers were placed on the walls of trenches TC1 and TC2. The structure from motion (SFM) method was used to photograph the trench walls with an overlap rate between photos of >70%. The SFM mosaic was constructed utilizing Agisoft Photoscan software, and detailed field logging was carried on the printed map; this map was then digitized using vector software [37–39]. For the previously excavated trench TC3, a 1.0 m × 1.0 m grid was built on the walls to take photos, and square grid paper was used as a base map for logging in detail; these logs were then digitized using vector software [40].

Upward fault termination is generally the most effective for identifying the latest event, and later ruptures are likely to occur along preexisting fault planes (e.g., [38, 40, 41]). The most recent event was identified based on the offset strata at the uppermost termination of the fault. The older paleoearthquakes were identified using multiple identifying features, including cross-cutting relationship, colluvial wedges, filled fissures, differential deformation, and angular unconformities between the layers in the trench sections (e.g., [38, 40, 42–46]).

We collected 19 radiocarbon samples from the faulted and unfaulted strata of the three trenches and sent them to the Beta Analytics in the United States and State Key Laboratory of Earthquake Dynamics in China for dating. The ages of the samples are corrected as σ calendar ages (68.2% confidence interval) with the OxCal 4.3 procedure. The timings of the paleoseismic events from each trench were also modeled and limited using the OxCal 4.3 software and the ages of the samples [47, 48]. If the radiocarbon ages with unknown stratigraphic sequence were from the same layer, they were put in a phase in the above modeling program. Then, the progressive constraining method was used to constrain the paleoseismic events and their ages from all the trenches [49–51]. Finally, the average recurrence interval and time intervals between the events were also estimated.

4. Paleoseismic Investigation

4.1. Fangmaping Trench (TC1)

4.1.1. Site Location and Offset Landforms. Several streams along the slope flow from west to east at the Fangmaping site, and flat alluvial terraces are developed on both banks of the streams (Figures 2(a) and 2(b)). The linear features of the fault striking N22°E can be identified on the DEM-derived
hillshade map without vegetation (Figure 2(b)), and fault scarps in local areas are well preserved (Figure 2(c)). Both streams and terraces are left-laterally displaced by the fault. The offset of stream S1 is well preserved and measured to 5.6 ± 0.4 m. Although streams S2 and S5 have been artificially modified, offsets can still be identified (Figure 2(d)). There is no left-lateral offset in stream S3a. However, beheaded stream S3b is developed downstream of the fault on the
eastern side of stream S3a (Figure 2(b)) and is interpreted as a result of the left-lateral offset of stream S3a. Two alluvial terraces can be identified on both banks of stream S5 and are also offset left-laterally along the fault.

4.1.2. Stratigraphy. Trench T1 represents excavation of the outcrop section of the terrace and has a length of 6.0 m and a depth of 2.0-2.2 m (Figure 3). The strata consist mainly of a weathered bedrock crust, clay layers on both sides, and clay layers in a small graben bounded by two groups of faults in the middle. We divided these strata into ten layers that were numbered in ascending order from bottom to top. The description of the strata is shown in Table 1.

4.1.3. Evidence for Events. Based on the oriented gravel clasts in the gravelly clay layers and the deformation and lithological differences in the strata, two groups of faults can be identified, which dip opposite each other to form a small graben. Based on the analysis of deformed strata and paleoseismic markers, three paleoearthquakes were identified, named EF1, EF2, and EF3, from the youngest to the oldest.

(1) Event EF3. Faults F1 and F2-3 offset the weathered crust of limestone U-① and greenish-yellow clay layer U-② (Figures 3(a)–3(c)). A wedge-shaped deposit, gray-yellow gravelly clay layer U1-1, formed on the eastern side of fault F1 and is interpreted as a scarp-derived colluvial wedge deposited following an earthquake. The top contact of the gray-black silt layer U1-2 on top of fault F2-3 is relatively stable and exhibits no obvious deformation. Additionally, layer U1-2 forms a clear unconformity with the underlying strata U1-1, U-①, and U-②, reflecting differential deformation. Therefore, event EF3 occurred before the sedimentation of U1-1.

(2) Event EF2. The gray-brown sandy clay layer U1-3 is faulted by faults F1-2 and F2-2. The gray-black clayey silt layer U2-1 on top of F1-2 and F2-2 is continuous and undisturbed (Figures 3(b) and 3(c)). A filled wedge or wedge-shaped deformation zone formed between faults F2-1 and F2-2. The thickness of layer U2-1 thins eastward, and this unit is interpreted as a scarp-derived wedge-shaped sediment following an earthquake. Layer U1-3 along fault F2-1 has a larger displacement than the overlying layer U2-1, indicating different amounts of deformation between layers U1-3 and U2-1. Therefore, the above evidence suggests that event EF2 occurred after deposition of U1-3 and before deposition of U2-1.

(3) Event EF1. Faults F1-1 and F2-1 offset layers U2-2, U2-3, U2-4, and U3-1 and almost extend to the ground surface (Figures 3(b) and 3(d)). The most recent event occurred after the sedimentation of layer U3-1. The well-preserved fault scarps are interpreted to have been caused by event EF1.

4.1.4. Radiocarbon Dating of Events. Five radiocarbon samples were collected and tested from the trench section (Table 2). The ages of these samples are in a normal sequence (Figure 3(b)); that is, the age of the lower stratum is older than that of the upper stratum. Samples of the same age in the same stratum were placed in a phase, and the ages of the paleoearthquake events were simulated using the OxCal 4.3 program. The modeling results show that events EF3, EF2, and EF1 occurred before 1640, 1475-675, and after 625-495 yr BP, respectively (Figure 4).

4.2. Dongcun Trench (TC2)

4.2.1. Site Location and Offset Landforms. Trench TC2 is located at the Dongcun site to the southeast of Jianshui County. The geomorphology of the area is dominated by low hills and valleys. The fault cuts through the hillside (Figure 5(a)). Field photos and the DEM-derived hillshade map without vegetation show that linear features are obvious along the fault and that offset landforms are clear (Figure 5). The fault shows seismic surface rupture zones, including a fault scarp and a sag pond. Three small streams along the slope were synchronously left-laterally offset (Figure 5(c)). The back-slipped measurements of the high-resolution hillshade map show that streams S1, S2, and S3 have similar amounts of left-lateral displacement of 6.8 m (Figure 5(d)). The sag pond is developed on the eastern side of stream S2, where the terrain is relatively gentle (Figure 5(d)). The sag pond was chosen to be excavated for TC2. A landslide was observed along the fault at the western end of the study area (Figure 5(a)), but it destroyed the continuity of the surface ruptures; this landslide may have been caused by the most recent event.

4.2.2. Stratigraphy. Trench TC2 is approximately 14.0 m long, 2.0 m wide, and 2.8-3.5 m deep. The strata consist mainly of weathered limestone crust and fault rocks on both sides of the south wall and several sets of gravelly clay layers in the middle part (Figures 6 and 7). The distribution of the clay layers is controlled by the fault zones, and they form an extensional graben-shaped structure. The fault rocks can be roughly divided into 3 sets of rocks with different degrees of faulting. Five sets of layers, named in ascending order from

| Table 1: Unit description of TC1 at the Fangmapiing site. |
|-----------------|-----------------|
| Unit no. | Description |
| U3-1 | Gray-black modern soil layer. |
| U2-4 | Brown clay layer. |
| U2-3 | Gray-black silt layer. |
| U2-2 | Gray-brown clay layer. |
| U2-1 | Gray-black silt layer mixed with clay. There is a trend of thinning eastward. |
| U1-3 | Gray-brown sandy clay layer. |
| U1-2 | Gray-black silt layer. |
| U1-1 | Yellow-brown wedge-shaped clay layer mixed with pebbles. |
| U1-① | Limestone and weathered crust. |
| U1-① | Greenish-yellow clay layer mixed with multicolored bands. |
Table 2: Radiocarbon samples and dating results from the three trenches along the Jianshui fault.

| Lab code  | Sample no. | Radiocarbon age (a BP) | Calibration years (cal BP) | Analyzed material | Lab | Trench no. |
|-----------|------------|------------------------|---------------------------|-------------------|-----|------------|
| Beta-482197 | FMP-C-2 | 630 ± 30               | 606 ± 34                  | Organic sediment  |     | TC1        |
| Beta-482199 | FMP-C-6 | 720 ± 30               | 668 ± 26                  | Organic sediment  |     | TC1        |
| Beta-482200 | FMP-C-9 | 680 ± 30               | 629 ± 41                  | Organic sediment  |     | TC1        |
| Beta-482201 | FMP-C-12 | 1750 ± 30             | 1658 ± 43                 | Charcoal          |     | TC1        |
| Beta-482202 | FMP-C-14 | 1610 ± 30             | 1487 ± 47                 | Organic sediment  |     | TC1        |
| Beta-493806 | DC-C-1  | 9620 ± 30              | 10964 ± 110               | Organic sediment  | BETA| TC2        |
| Beta-493807 | DC-C-2  | 10810 ± 30             | 12715 ± 17                | Organic sediment  |     | TC2        |
| Beta-493805 | DC-C-5  | 12940 ± 40             | 15463 ± 106               | Organic sediment  |     | TC2        |
| Beta-493804 | DC-C-6  | 9920 ± 30              | 11311 ± 52                | Organic sediment  |     | TC2        |
| Beta-493808 | DC-C-7  | 10320 ± 30             | 12139 ± 104               | Organic sediment  |     | TC2        |
| Beta-493814 | DC-C-25 | 6010 ± 30              | 6849 ± 44                 | Organic sediment  |     | TC3        |
| Beta-493813 | DC-C-28 | 210 ± 30               | 182 ± 94                  | Organic sediment  |     | TC3        |
| Beta-493813 | DC-C-27 | 1780 ± 30              | 1696 ± 54                 | Organic sediment  |     | TC3        |
| Beta-493813 | DC-C-23 | 15780 ± 50             | 19029 ± 79                | Organic sediment  |     | TC3        |
| Beta-493803 | DC-C-22 | 13490 ± 40             | 16239 ± 91                | Organic sediment  |     | TC3        |

Note: 1The age is in radiocarbon years using the Libby half-life of 5568 years, and the uncertainties are reported as 1σ. 2The calendar dates were calculated using the OxCal v4.3 program ([47]; [48]). 3BETA: Beta Analytic Inc., Miami, Florida 33155, USA; SKLED: State Key Laboratory of Earthquake Dynamics (SKLED), A-1, Huayanli, Beijing 100029, China.

Figure 4: Timings of paleoseismic events recorded in TC1 constrained with OxCal modeling.
4.2.3. Evidence for Events. The trench sections show that the fault zone comprises a series of faults and fault rocks between the faults (Figures 6 and 7). The faults form a negative flower structure, controlling the distribution of deposits. Based on the analysis of deformed strata and paleoseismic markers, three paleoseismic events were recognized, named ED1, ED2, and ED3, from youngest to oldest.

(1) Event ED3. Faults F6, F7, F8, and F9 offset the black organic-containing silt layer U1 and the brownish sandy and gravelly clay layer U2 (Figures 6 and 7). The overlying brownish clay layer U3 mixed with peat at the top of these four faults is relatively stable and exhibits no visible deformation. Layers U1 and U2 have more deformation and a more limited distribution than layer U3. Layer U3 features an unconformity with the underlying layers U1, U2, and fault rocks, reflecting differential deformation. The above deposition and deformation features indicate that event ED3 occurred before deposition of U3 and after deposition of U2.

(2) Event ED2. Fault F3 offsets the gray-brown clay layer U3 (Figure 6). No deformation is found in the overlying brown silty clay layer U4 at the top of fault F3, showing that F3 offset layer U3 but did not offset layer U4. Additionally, layer U3 contains a large amount of peat, which is interpreted to have been the paleo ground surface. Therefore, these observations show that event ED2 occurred between the sedimentation of layers U3 and U4.

(3) Event ED1. Faults F2, F5, and F10 offset brown silty clay layer U4, and F11 ruptures upward to the ground surface (Figure 6). No faulting deformation is observed in the bottom to top, can be recognized from the trench section. The description of strata is shown in Table 3.
overlying layer U5-1 (Figure 7). Additionally, a well-preserved surface rupture zone is observed at this site (Figure 5). The deposition and geomorphology features indicate that the most recent event was likely to occur after the deposition of layer U4 and might almost have ruptured upward to the ground surface.

4.2.4. Radiocarbon Dating of Events. Ten radiocarbon samples were collected and tested from the trench section (Table 2). The ages of most samples are in a normal sequence (Figures 6(b) and 7(b)). However, the age of sample DC-C-23 (19029 ± 79 yr BP) in layer U3 in the north wall is much older than that of other samples (~11000-13000 yr BP) in U3 in the
both banks of the streams also show left-lateral offset of the fault (Figure 9(b)). The alluvial fans and small ridges on the front of the fault scarp and fault trough (Figures 9(b) and 9(c)). Three streams are left-laterally offset. Satellite images and field investigations reveal that the age of sample DC-C-23 might be an outlier, and the sample was excluded when limiting the timings of paleoseismic events. Samples of the same age in the same stratum were placed in a phase, and the age of paleoseismic events. Samples were collected and tested from the trench section (Table 2). The ages of the samples are in a normal sequence (Figure 10). The modeling results show that events EL2 and EL1 occurred between the sedimentation of layers U4 and U6.

4.3.3. Evidence for Events. According to the aligned gravel clasts in the gravel layer and the deformation and lithological differences among the strata, two groups of faults with opposite dips were identified. Based on the deformed strata and paleoseismic markers, two paleoseismic events were recognized, named EL1 and EL2, from the youngest to the oldest.

4.3.1. Site Location and Offset Landforms. The Luoshuidong site is located in the northern part of the fault. Streams and alluvial fans are developed along the slope (Figures 9(a) and 9(b)). Satellite images and field investigations reveal that the fault shows a linear fault scarp and fault trough (Figures 9(b) and 9(c)). Three streams are left-laterally offset when crossing the fault (Figure 9(b)). The alluvial fans and small ridges on both banks of the streams also show left-lateral offsets. The back-slip measurements of the satellite image show that these three-stream channels have similar amounts of left-lateral offset of ~4.2 m (Figure 9(d)). A small depression is developed at the front of the fault scarp and which is conducive to deposition. Thus, trench T3 was excavated in the small depression across the fault scarp with a height of 2.5-3.7 m (Figure 9(c)).

4.3.2. Stratigraphy. Trench TC3 is approximately 15.0 m long, 2.0 m wide, and 2.0-2.7 m deep. The strata of the trench exhibit a graben-like structure, with fault zones on both sides of the section and clay and gravel layers in the middle. Six sets of layers, named in ascending order from bottom to top, can be recognized from the trench section (Figures 10(a)–10(c)). The description of strata is shown in Table 4.

4.3.3. Evidence for Events. According to the aligned gravel clasts in the gravel layer and the deformation and lithological differences among the strata, two groups of faults with opposite dips were identified. Based on the deformed strata and paleoseismic markers, two paleoseismic events were recognized, named EL1 and EL2, from the youngest to the oldest.

(1) Event EL2. Fault F1 offset dark brown subangular clayey gravel layer U2, resulting in faulted contact between U1 and U2 (Figures 10(a) and 10(b)). Above F1, no deformation is found in the overlying brown gravel layer U3. Layer U3 features an unconformity with the underlying layer U2 and the limestone tectonic zone, reflecting differential deformation. The above features indicate that a seismic event occurred after sedimentation of U2 but before that of U3.

(2) Event EL1. Faults F2 and F3 faulted layers U3 and U4, and the overlying layer U6 is relatively stable without visible deformation (Figure 10(b)), indicating that the contact between the U6 and underlying strata is a sedimentary contact and that only a single event happened between the sedimentation of U3 and U6. Layer U5 is a wedge-shaped mixed deposit and is interpreted as a scarp-derived colluvial wedge deposited following an earthquake. The fault zones of F2 and F3 are wider than those of the other faults (Figures 10(b)–10(e)), reflecting differential deformation. Thus, the above evidence shows that event EL1 occurred between the sedimentation of layers U4 and U6.

4.3.4. Radiocarbon Dating of Events. Four radiocarbon samples were collected and tested from the trench section (Table 2). The ages of the samples are in a normal sequence (Figure 10). The modeling results show that events EL2 and EL1 occurred at 12940-5655 and 3845-505 yr BP, respectively (Figure 8).

5. Discussion

5.1. Paleoseismic Sequence of the JSF. The progressive constraining method was used to constrain the paleoseismic events and ages in the three trenches (Figure 12). The trenches of TC1 and TC2 showed that faults have cut the layer with a formation age of ~625 yr BP but have not cut the layer with a formation age of ~185 yr BP (Figures 3 and 7). Although trench TC3 did not reveal evidence of faulting of the modern soil layer (Figure 10), fresh earthquake surface rupture zones were observed at all three trench sites. Thus, the most recent events EF1 and ED1 identified in the two trenches were interpreted to be the same event (E1 of the fault). Based on the analysis of the geomorphic, geologic, and historical data, the most recent event E1 of the fault is most likely the 1606 Jianshui earthquake.

Layer U1-3 in TC1 is offset along faults F1-2 and F2-2, and overlying layer U2-1 is not deformed (Figure 3). Layer U2-1 is a scarp-derived wedge-shaped deposit deposited following an earthquake. A filled wedge is developed between faults F2-1 and F2-2. The displacement of layer U1-3 along fault F2-1 is larger than that of the overlying layer U2-1. Therefore, the evidence of the penultimate event EF2 is strong in TC1 (Figure 3). In addition, the age of paleoseismic event EL1 in TC3 overlaps with event EF2 in TC1 (Figure 12). Therefore, EF2 and EL1 in trenches TC1 and TC3 were interpreted as seismic event E2 of the fault.

Evidence for event EL2 in trench TC3 at the Luoshuidong site is weak (Figure 10), but the age range of the event

| Table 3: Unit description of trench TC2 at the Dongcun site. |
|------------------|---------------------------------|
| Unit no. | Description |
| U5-1 | Gray-black organic-rich, gravelly clay layer. |
| U5-2 | Brown-reddish clay layer. |
| U4 | Brownish silty clay layer. |
| U3 | Brownish clay layer mixed with peats. |
| U2 | Brownish clay layer mixed with gravels and sands. |
| U1 | Black organic-rich silt layer. |
| Ub | Highly weathered limestone. |
| Z1 | Fine-grained cataclastic zone. |
| Z2 | Coarse-grained cataclastic zone. |
| Z3 | Clayified fault zone. |
overlaps with the age range of event ED2 in trench TC2 (Figure 12). Layers U3 and U4 in TC2 have differential deformation (Figures 6 and 7), and layer U3 is interpreted to have been the paleo ground surface. Considering the evidence of the event from these two trenches, this event was interpreted as paleoseismic event E3 of the fault.

Event ED3 was the oldest event in trench TC2 and was not observed in the other two trenches (Figure 12). Layers U1 and U2 in TC2 have more deformation and a more limited distribution than layer U3 (Figures 6 and 7). Layer U3 features a distinct unconformity with the underlying layers U1, U2, and fault rocks, reflecting differential deformation. The strong evidence permits us to interpret this event as paleoseismic event E4 of the fault.

Therefore, four paleoearthquakes occurring since 15370 yr BP were constrained from these three trenches (Figure 12). The ages of events E4, E3, E2, and E1, from the oldest to the youngest, are 15360-12755, 10845-6900, 1455-670, and 635-145 yr BP, respectively, and the most recent event might correspond to the 1606 Jianshui earthquake.

5.2. Seismic Recurrence Characteristics of the JSF. We used the OxCal model to calculate intervals with a variability of 5199 ± 1429, 7840 ± 1214, and 726 ± 235 yr between events E4, E3, E2, and E1, respectively. This indicates an average recurrence interval of 4589 ± 3132 yr. The time intervals between the three old events E4, E3, and E2 are much longer than the time interval between the two young events E2 and E1. There are two possible explanations for this trend: (1) the fault features irregular earthquake recurrence; (2) some events may be missing.

Trenches TC1 and TC2 are only ~1.5 km apart (Figure 1(c)), and the surface trace of the fault is continuous between these sites. The two locations should have suffered from the same number of seismic events. Trench TC1 is located on a gentle alluvial terrace. Multiple sets of thin clay layers have been deposited since ~1658 ± 43 yr BP and are distributed in a small graben. Therefore, the strata in trench TC1 are most likely continuous, and the paleoseismic events recorded should be complete. Although trench TC2 is located on a flat area on a mountain slope, few layers of sediment have been deposited since ~6849 ± 44 yr BP, and events E1
and E2 were not separated in TC2. Trench TC3 was excavated in a small depression, and the morphology of the depression was well preserved. However, the age ranges of the oldest two events constrained from TC2 and TC3 are relatively large. Additionally, the erosion from precipitation is strong in the study area, and the sedimentary strata might be discontinuous. We cannot rule out the possibility of missing events in the obtained paleoseismic sequence. However, the time interval between events E2 and E1 is 726 ± 235 yr, which is quite different from the time intervals between events E4, E3, and E2. We are more inclined to believe that the fault is featured by irregular earthquake recurrence. Therefore, the time interval of 726 ± 235 yr between the last two events is more representative of the recent activity of the fault than the earthquake recurrence interval of 4589 ± 3132 yr averaging from four events.

The central segment of the XJFZ and the Anninghe-Zemuhe fault zone also show irregular seismic recurrence intervals. Li et al. [26] revealed that six paleoearthquakes occurred at irregular intervals on the west branch of the central segment of the XJFZ over 40000 yr through trench excavations and concluded that the three youngest events were continuous and gave an average earthquake recurrence interval of 370-480 yr. Wang et al. [29] found that five paleoearthquakes that occurred on the Zemuhe fault since 8000 yr appeared to be unevenly spaced in time and estimated the average seismic recurrence interval to be ~2300 yr. Similarly, Wang et al. [52] revealed that the time intervals between five paleoearthquakes on the southern segment of the Anninghe fault since 3400 yr vary widely and range from ~130 to 2200 yr. These events are unevenly spaced in time, with an average seismic recurrence interval of approximately 600-800 yr. The similar seismic recurrence behaviors of these faults indicate that the JSF appears to positively respond to uneven tectonic movement of the central and northern segments of the Xiaojiang fault, Anninghe fault, and Zemuhe fault.

An irregular earthquake recurrence of a fault may be related to the interaction among faults in a fault system [26, 29, 53, 54]. The geometric structure of the southern segment of the XJFZ is more complex than that of the central and northern segments. Multiple fault branches are developed in the southern segment, and the interaction among the faults may be obvious. In addition, the eastern terminations of the NW-striking Qujiang and Shiping faults are located near the southern segment of the XJFZ (Figure 1(a)). Both faults show right-lateral strike-slip motion during the Holocene (Han et al., 1993; [29]). Therefore, the fault systems around the JSF are complex, and the earthquake recurrence of the JSF may be affected by the interaction both among the internal fault branches of the nearly NS-striking XJFZ and with the NW-trending strike-slip faults.

5.3. Kinematic Property of the JSF. The XJFZ exhibits an arcuate shape that is convex eastward (Figure 1(a)). The strike of the fault zone changes from NNW in the northern segment to nearly N-S in the central segment to NNE in the southern segment. Li et al. [26] suggested that the northern part of the central segment has experienced long-term compression and shearing driven by thrusting and folding of strata in a trench. The three trenches in this study reveal that the fault branches of the JSF present a normal dip-slip component and create graben or negative flower structures. In terms of large landform expression, it can be observed from the DEM, satellite image, and field investigations that some late Quaternary basins are distributed along the JSF (Figures 1(b) and 1(c)), such as the Baiyun Basin, Xinzhai Basin, and Goujie Basin. In addition, the calculated focal mechanism of small earthquakes located near the southern
segment of the XJFZ shows that the normal strike-slip motion dominated along the fault zone (Hu et al., 2013). The transtension is also observed along the Dien Bien Phu fault on the southern side of the JSF, which strikes NNE and shows as a left-lateral strike-slip motion with a normal component [55, 56]. Therefore, the above observations and analysis permit us to believe the JSF is characterized kinematically by extension and shearing as a whole.

The change in the strike of the XJFZ is accompanied by a change in the kinematic properties, indicating that the interaction between the Chuan-Dian and South China blocks transforms from transpression to transtension. These changes are likely caused by the apparent change in the direction of clockwise rotation of the Chuan-Dian block around the eastern Himalayan syntaxis. It also suggests that the SE Tibetan Plateau turns to move south-southwestwards at the south of the central segment of the XJFZ and might have not expanded eastwards further. So the lateral extrusion of the SE Tibetan Plateau does not make an obvious impact on the South China block.

### Table 4: Unit description of trench TC3 at the Luoshuidong site.

| Unit no. | Description |
|----------|-------------|
| U7       | Gray-brown soil layer. |
| U6       | Gray-brown wedge-shaped mixed deposits composed of gravel and sandy soil. |
| U5       | Yellow-brown wedge-shaped clayey gravel layer. |
| U4       | Reddish-brown sandy clay layer. |
| U3       | Brown subangular clayey gravel layer. |
| U2       | Dark brown subangular clayey gravel layer. |
| U1       | Gray-white limestone tectonic zone. |

5.4. Role of the JSF in Accommodating Regional Tectonic Deformation. The nearly N-S-striking XJFZ and NW-
striking Qujiang, Shiping, and Red River faults are the main faults in the southeastern Chuan-Dian block. These three NW-striking faults are mainly manifested as right-lateral strike-slip motion. The Qujiang and Shiping faults are located on the western side of the southern segment of the XJFZ and on the northern side of the JSF (Figure 1(a)). The western segments of the two faults strike NW, and the eastern segments strike from WNW to nearly E-W, forming a curved shape that is convex to the south-southwest. The Red River fault zone is located on the southern side of the JSF.

The XJFZ mainly shows a left-lateral strike-slip motion. Our results suggest that the average earthquake recurrence interval of the JSF since \( \sim 15000 \) yr is \( 4589 \pm 3132 \) yr, which is longer than 2000-2500 yr of the central and northern segments of the XJZ [10], but shorter than 6000 \( \pm 1000 \) yr of the Red River fault zone [2]. The interval of 726 \( \pm 235 \) yr between the most two recent earthquakes of the JSF is also longer than 370-480 yr of the central and northern segments of the XJFZ [26]. Furthermore, the geological left-lateral slip rate of the JSF are \( \sim 7 \) mm/yr [12], which is also slightly lower than 10-16 mm/yr of the central and northern segments of the XJFZ, but much higher than 2.8-3.5 mm/yr, 3-3.6 mm/yr, and 1-3 mm/yr of the Qujiang, Shiping, and Red River fault zones. GPS slip rates also show a similar variation trend. The slip rate constrained by the GPS velocity profile across Qujiang, Shiping, and Red River fault zones with a width of 70 km is \( \sim 4.5 \) mm/yr [5]. GPS slip rate of the JSF was estimated to be \( \sim 7 \) mm/yr [1], which is slightly lower than 7-10 mm/yr of the central and northern segments of the XJFZ and higher than that of the three NW-striking faults. Therefore, the above faulting activity parameters indicate that the late Quaternary activity of the southern segment of the Xiaojiang fault zone may be slightly weaker than that of the central and northern segments but stronger than that of the NW-striking Qujiang, Shiping, and Red River fault zones.
Considering the fault scale, tectonic location, and faulting activity, the XJFZ is an important part of the eastern boundary of the Chuan-Dian block and accommodates the southward movement of the block. The Qujiang and Shiping faults are interpreted as second-order tectonic features accommodating deformation inside the block, which may be caused by bookshelf faulting generated by regional differential crustal shear. The Dien Bien Phu fault on the southern side of the XJFZ has been an active left-lateral strike-slip fault zone in the Quaternary with a probable average slip rate of 2.5 mm/yr [55], sharing the spatial alignment of the Xianshuihe-Xiaojiang fault system. So in the regional kinematic mode, the SSE-directed motion of the southeastern Chuan-Dian block is likely to be firstly accommodated in part by right-lateral shear and dip-slip motion on the Qujiang and Shiping faults and continues across the Red River fault, then is transmitted southward along the Dien Bien Phu fault. Therefore, the southern segment of the XJFZ plays a dominant role in the tectonic deformation of the southeastern Chuan-Dian block on the SE Tibetan Plateau, with a high seismic hazard.

6. Conclusion

Trench excavations and radiocarbon dating revealed that the four most recent surface-rupturing paleoearthquakes on the JSF have occurred since approximately 15370 yr BP. The ages of these events, labeled E4-E1 from oldest to youngest, are limited to the following time ranges: 15360-12755, 10845-6900, 1455-670, and 635-145 yr BP, respectively. The most recent event E1 was most likely the 1606 Jiansui earthquake. These events appear to occur unregularly in time. The time interval of 726 ± 235 yr between the last two continuous events may be more representative of the recent activity of the fault than the average recurrence interval of 4589 ± 3132 yr for all four events.

The deformed strata in the trenches show that the fault branches of the JSF have a normal dip-slip component and display a graben or negative imbricate structural style, indicating that the fault is characterized kinematically by transtension. Based on this work and that of previous studies, the strike of the XJFZ changes from NNW to NNE, and the kinematic properties change from transpression to transtension. These changes likely respond to the apparent change in the direction of clockwise rotation of the Chuan-Dian block around the eastern Himalayan syntaxis.

Combined with the comprehensive analysis of the XJFZ and neighboring NW-striking faults, the late Quaternary activity of the southern segment of the XJFZ is slightly weaker than that of the central and northern segments but stronger than that of the Qujiang, Shiping, and Red River fault zones. Our study suggests that the south-southeastward motion of the Chuan-Dian block is likely to be firstly accommodated in part by the right-lateral shear and dip-slip motions of the Qujiang and Shiping faults and continues across the Red River fault zone, then is transmitted southward along the Dien Bien Phu fault.

Data Availability

All chronological data are shown in the tables, and satellite imageries are accessible in Google Earth.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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