# Surface Rupture of the 1515 Yongsheng Earthquake in Northwest Yunnan, and Its Seismogeological Implications

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**Abstract: The 1515 M7¾ Yongsheng earthquake is the strongest earthquake historically in northwest Yunnan. However, its time, magnitude and the seismogenic fault have long been a topic of dispute. In order to accurately define those problems, a 1:50000 active tectonic mapping was carried out along the northern segment of the Chenghai–Binchuan fault zone. The result shows that there is an at least 25 km–long surface rupture and a series of seismic landslides distributed along the Jinguan fault and the Chenghai fault. Radiocarbon dating of the $^{14}$C samples indicates that the surface rupture should be a part of the deformation zone caused by the Yongsheng earthquake in the year 1515. The distribution characteristics of this surface rupture indicate that the macroscopic epicenter of the 1515 Yongsheng earthquake may be located near Hongshiya, and the seismogenic fault of this earthquake is the Jinguan–Chenghai fault, the northern part of the Chenghai–Binchuan fault zone. Striations on the surface rupture show that the latest motion of the fault is normal faulting. The maximum co–seismic vertical displacement can be 3.8 m, according to the empirical formula for the fault displacement and moment magnitude relationship, the moment magnitude of the Yongsheng earthquake was Mw 7.3–7.4. Furthermore, combining published age data with the $^{14}$C data in this paper reveals that at least four large earthquakes of similar size to the 1515 Yongsheng earthquake, have taken place across the northern segment of the Chenghai–Binchuan fault zone since 17190±50 yr. BP. The in–situ recurrence interval of Mw 7.3–7.4 characteristic earthquakes in Yongsheng along this fault zone is possibly on the order of 6 ka.**

**Key words: historical earthquake, earthquake surface rupture, normal fault, Chenghai–Binchuan fault zone, Southeastern margin of the Tibetan Plateau**

## 1 Introduction

The northwest Yunnan area located on the northwest end of the Red River fault (Allen et al., 1984; Guo Shunmin et al., 1996), is a very significant extension deformation zone between a series of large–scale strike slip fault systems on the southeastern margin of the Tibetan Plateau (Tapponnier et al., 1986; Allen et al., 1991; Wang and Burchfiel, 1997; Wang et al., 1998; Bac et al., 2016; Xu Zhiqin et al., 2016). Influenced by the clockwise rotation of crustal material in the southeastern margin of the Tibetan Plateau (Wang et al., 1998; Zhang et al., 2004; Shen et al., 2005; Tong Yabo et al., 2017), a series of N–S, NW and NE trending faults developed and formed the diamond–shaped Dali fault system (Fig. 1) (Wang et al., 1998; Fan et al., 2006; Wu Zhonghai et al., 2009; Huang Xiaolong et al., 2016). Affected by main active faults, strong earthquakes occur frequently in this area and the risk of seismogeological disasters are prominent (Geology Institute of China Seismological Bureau and Seismological Bureau of Yunnan province, 1990; Mao Yuping et al., 2003; Zhang Duo et al., 2016; Wu Zhonghai et al., 2016). According to historical and instrument–based records, at least 70 earthquakes of M≥5.0 and 4 earthquakes of M≥7.0 were attributed to movement along the main faults of the Dali fault system, since 780 A.D. Among them, the 1515 M7¾ Yongsheng earthquake is the strongest recorded in history, and has drawn the most attention (Department of earthquake

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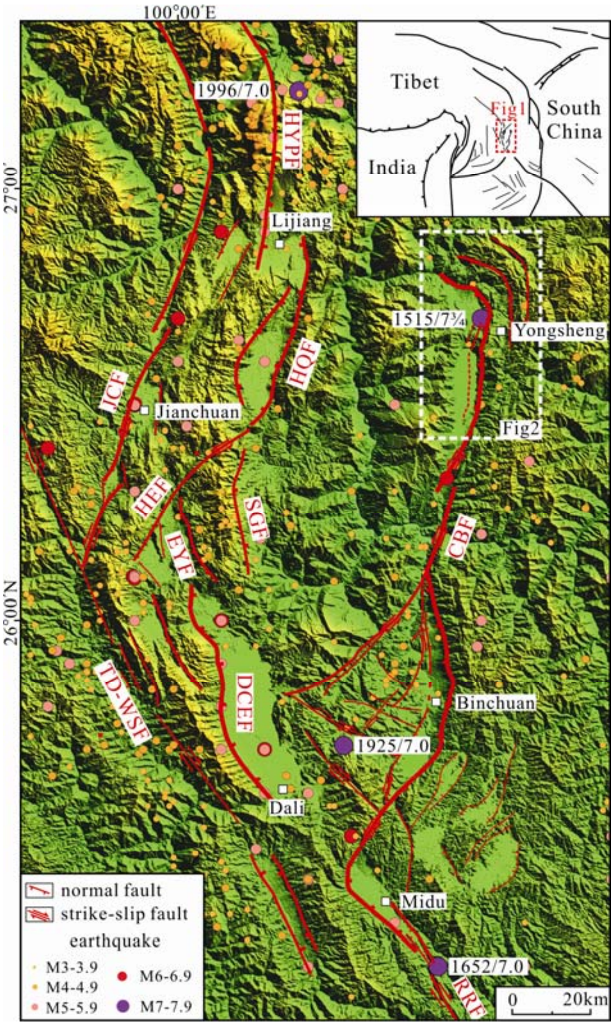


Fig. 1. Major active faults and seismic events in the northwest Yunnan, showing on SRTM 90 m digital elevation model image.

The thumbnail upper right corner shows the outline of active tectonics in southeastern margin of the Tibetan Plateau, and the location of Fig. 1. Major faults (Wang et al., 1998, Wu Zhonghai et al., 2009): CBF=Chenghai–Binchuan Fault Zone, HYPF=Eastern piedmont Fault of the Haba–Yulong Snow Mountain, HQF=Heqing Fault, HEF= Heqing–Eryuan Fault, EYF=Eryuan Fault, SGF=Songgui Fault, DCEF= Eastern piedmont Fault of Diancang Shan (These belong to Lijiang–Dali Fault Zone); JCF=Jianchuan Fault, TD-WSF= Tongdian–Weishan Fault Zone; RRF = Red River Fault. Epicenters and magnitude of earthquakes in northwest Yunnan are compiled from China earthquake information network (http://www.csi.ac.cn/). Dashed box indicates location of Fig. 2.

damage defense of China Earthquake Administration, 1995). It is generally believed that the macroscopic epicenter of this earthquake is located in the area of Hongshiya to Caohu, east of Yongsheng (Office of the Central Seismological Working Group, 1971).

However, due to limited historical literature, the actual time, magnitude and seismogenic fault of this earthquake have long been disputed (Deng Ruisheng, 1980; Han Mukang et al., 1981; Han Yuan, 1983; Zhang Shousheng, 1985; Guo Shunmin et al., 1988). This restricts the correct understanding of the active tectonic patterns in northwest Yunnan and its relationship with strong earthquakes. In the 1:50000 active fault mapping of Yongsheng area, a number of well–preserved earthquake surface ruptures and earthquake landslide–collapse relics were discovered along the northern segment of the Chenghai–Binchuan fault zone. Preliminary age data suggest that the newly discovered earthquake surface rupture may be the product of the 1515 Yongsheng earthquake. A brief outline of these new discoveries and a further discussion on the magnitude of the Yongsheng earthquake and the paleo–earthquake recurrence interval of the seismogenic fault, are provided below.

## 2 Disputes about the 1515 Yongsheng Earthquake

Historical record indicates that the 1515 Yongsheng earthquake led to large–scale destruction of buildings in the Yongsheng–Heqing area, “All houses, official and private, were destroyed”. It also caused many fatalities, especially in Yongsheng, where “thousands of lives were lost and the number of the wounded was several times the number” (Office of the Central Seismological Working Group, 1971). This earthquake also resulted in ground crack–induced water emitting and land subsidence, due to which “hundreds hectares of fields were flooded and formed a lake (Caohu Lake)” and led to “serious collapse of Hongshiya” (Lou Baotang, 1996). Nevertheless, as little confirmatory details are available from historical sources, no consensus has been reached among the earlier researchers over the time, magnitude and seismogenic structure of this earthquake. The occurrence time of this earthquake may be the year 1511 or 1515 (Deng Ruisheng, 1980; Han Yuan, 1983; Zhang Shousheng, 1985). Due to the lack of sufficient evidence, the occurrence time of this earthquake will not be discussed in this article, and the time 1515 recorded in the strong earthquake catalog will be used in this article (Department of earthquake damage defense of China Earthquake Administration, 1995). Another argument is focused on the magnitude of this earthquake. Thorough analysis of historical documents, Deng Ruisheng (1980) suggests that the magnitude of this earthquake was 6.5; Han Yuan (1983) believes that its magnitude was 7.5; Zhang Shousheng (1985) argued its magnitude could be as high as 8.0. In the strong earthquake catalog magnitude of the Yongsheng earthquake was listed as 7¾, the macroscopic epicenter was near Hongshiya in the northwest of Yongsheng County, intensity of the meizoseismal area is up to 10, the long axis of the meizoseismal area is NNE trending and about 30 km long (Fig. 2) (Department of earthquake damage defense of China Earthquake Administration,

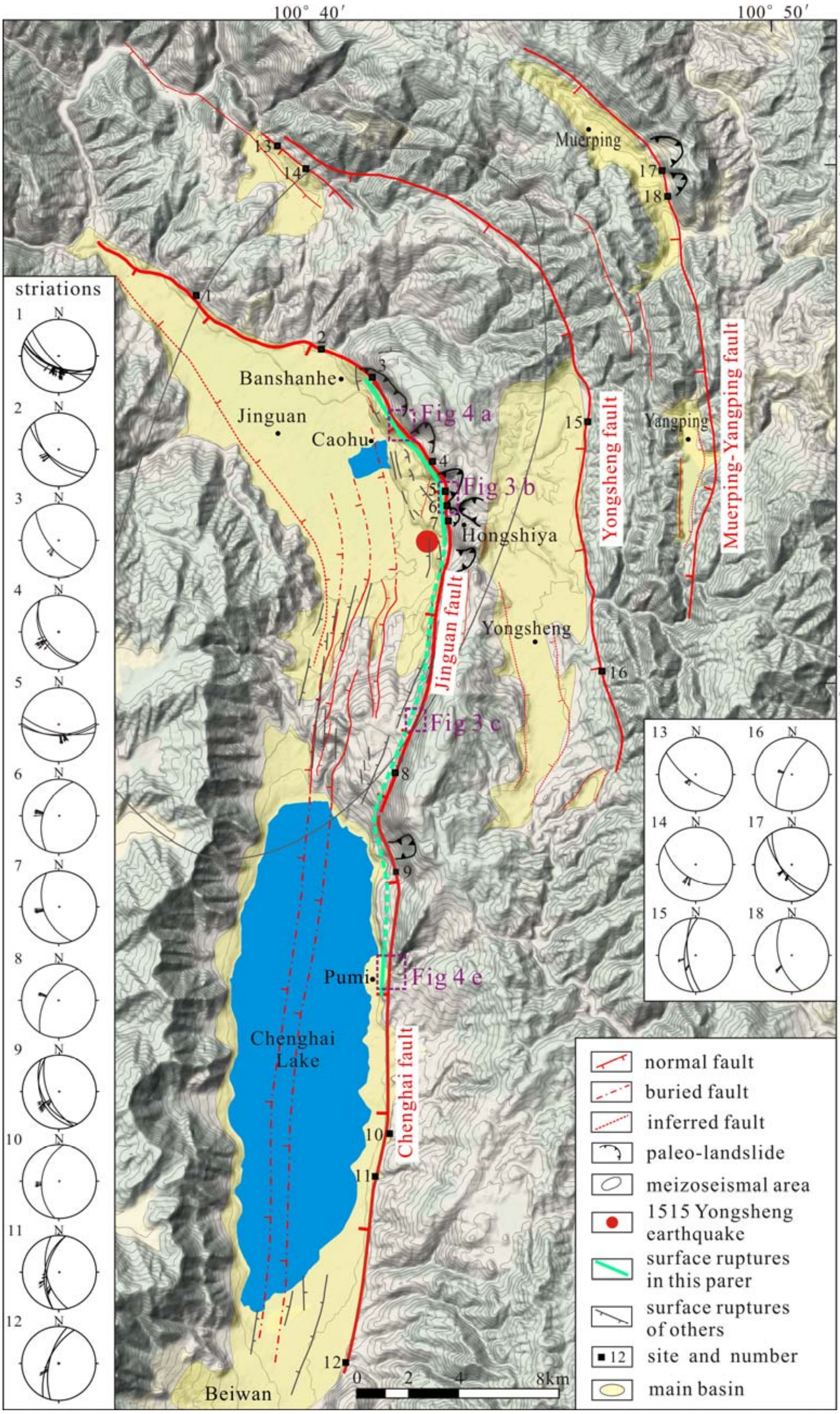


Fig. 2. Major active faults and surface ruptures of the 1515 Yongsheng earthquake area, show on Google topographic map.

Surface ruptures of others refer to Guo Shunmin et al., 1988. Black squares mark the locations we measured fault kinematic markers during our field survey. Striations were analyzed using Stereo 32 and all striations correspondence with the lower–hemisphere equiangular projection.

1995). Through the investigation of ground fissures near Hongshiya, the seismogenic structure of this earthquake was considered to be an E–W trending fault (Han Mukang et al., 1981). However, field surveys show that the deformation zone of this earthquake is about 42 km long, 8 km wide and occurred along the northern segment of the Chenghai–Binchuan fault zone. Accordingly, the magnitude of the Yongsheng earthquake is considered to be M≥7.5 and caused by the activities of the Chenghai–Binchuan fault zone (Guo Shunmin et al., 1988).

Overall, the magnitude and seismogenic fault provided by former researchers are mostly speculation based on historical record, and are greatly influenced by the lack of accuracy and detail of historical records. The earthquake deformation zone is an effective means for paleoearthquake and historical earthquake research (Li Xi et al., 2015; Wu Jiwen et al., 2017). However, historical earthquake such as the Yongsheng Earthquake, which occurred in areas with high weathering and strong human activity, is difficult to accurately obtain the distribution characteristics and scale of the deformation zone, let alone estimating their magnitudes. In order to determine the magnitude and seismogenic structure of the Yongsheng earthquake, new evidence is needed.

## 3 Regional Tectonic Settings

The nearly E–W extensional stress since the Pliocene (Cui Xiaofeng et al., 2006; Qian Xiaodong et al., 2011), has given rise to three groups of faults the NW, NE and N–S trending faults in northwest Yunnan. Among them the N–S trending fault is the most active (Wang et al., 1998; Fan et al., 2006; Wu Zhonghai et al., 2009; Huang Xiaojin et al., 2014; Huang Xiaolong et al., 2016). Faults in the Dali fault system can be divided into four strands from east to west. The N–S trending Chenghai–Binchuan fault zone, a normal fault zone with left–lateral strike–slip component; the Lijiang–Dali fault zone, a Z–shaped fault zone consisting of a series of N–S, NW trending extensional faults from Daju to Dali; the Tongdian–Weishan fault zone, a NW trending fault with right–lateral strike–slip; and the left–lateral Jianchuan fault. Among them, the Lijiang–Dali fault zone and the Chenghai–Binchuan fault zone are generally arc curved at the southern and northern ends, making the whole Dali fault system appear in a Z–shape (Wu Zhonghai et al., 2009; Huang Xiaolong et al., 2016), which is seen as a typical tectonic feature at the end of a transtensional fault (Wu Zhonghai et al., 2009, 2015).

The Chenghai–Binchuan fault zone extends about 200 km from Jinguan to the southern end of the Midu basin, and strikes roughly N–S in a Z–shape. The activity of the Chenghai–Binchuan fault zone was strong during the Mesozoic, resulting in a significant loss of Jurassic to Paleogene strata in the Dali area compared to the Chuxiong basin east of it (Bureau of Geology and Mineral Resources of Yunnan Province, 1990; Wang et al., 1998). The fault was reactivated during early Cenozoic and its main activity was low–angle west to east thrusting (Li Guangrong and Jin, 1990). Since the late Miocene, the regional tectonic stress field was redirected due to the onset of the right–lateral strike–slip of the Red River fault (Lacassin et al., 1998; Leloup et al., 1993). The movement type of the Chenghai–Binchuan fault zone changed from transpressional deformation to the present transtensional deformation (Li Guangrong and Jin, 1990; Wang et al., 1998; Fan et al., 2006; Luo Ruijie et al., 2015). Most of the major faults are normal or left–lateral strike–slip faults, or oblique slip fault with both normal and left strike–slip components (Wang et al., 1998; Huang Xiaolong et al., 2016).

Yongsheng lies in the northern segment of the Chenghai–Binchuan fault zone, where the Chenghai–Binchuan fault zone scatters into an arc fault bundle made up of many west dipping faults (Fig. 2). Controlled by the extensional faulting of the normal faults in the area, three faulted basins with declining altitude from the east to the west have formed, suggesting a significant vertical displacement under the control of a series of normal faults. Active fault mapping revealed 14 Quaternary faults in this area (Huang Xiaolong et al., 2016). Among them the Jinguan, Yongsheng and Muerping–Yangping faults are larger in size, generally 25–30 km in length and have had strong activity since the late Quaternary.

As the main boundary fault of the Jinguan basin, a series of prominent triangular facets and steep fault scarps appear along the Jinguan fault. The phrase mentioned in historical record "hundreds of hectares of fields were flooded and became a lake (Caohu Lake), Hongshiya has cracked and collapsed" refer to areas in the proximity of this fault. Therefore, this fault is considered to be the main seismogenic fault of the 1515 Yongsheng earthquake (Guo Shunmin et al., 1988). Tectonic geomorphologic, field survey and fault striation statistics indicate that this fault was a typically normal fault, with accumulated vertical displacement up to 1000–1300 m and average dip–slip rate of 0.2–0.3 mm/a (Fig. 2)(Huang Xiaolong et al., 2016). Southwards, it is connected with the Chenghai fault on the eastern boundary of the Chenghai basin. The Chenghai fault strikes N–S, extends about 20 km, and has been dominated by normal faulting since the Quaternary like the Jinguan fault. Furthermore, on the western side of the Jinguan fault, a number of secondary normal faults may have extended into the Chenghai Basin and are buried beneath the Chenghai Lake. All those faults constitute the active fault framework of the1515 Yongsheng earthquake area.

## 4 Newly Discovered Earthquake Surface Ruptures

Field survey revealed a variety of paleoearthquake relics along the Jinguan and Chenghai faults, especially the area within 10 km of the south and the north of Hongshiya (Huang Xiaolong et al., 2016). Landform in this section is characterized by a straight, steep, 700–800m high fault scarp (Fig. 3a). Collapses and landslides at different periods are covered on the fault scarp, and at least 6 large ancient landslides that may be associated with seismic events are visible coming off of these fault scarps (Fig. 2). Continuous normal faulting has displaced multiple giant paleo–landslides on this fault scarp. This caused numerous landslide deposits in the hanging wall of the fault to be displaced to the piedmont in the margin of the basin and slide beds to be raised to the mountainside, with a 100–200 m high, straight, continuous and stably distributed fault scarp appearing between them (Fig. 3a).

Field survey along the eastern margin of the Jinguan basin discovered a fresh earthquake surface rupture of about 8 km long between Hongshiya and Banshanhe. It distributes at the bottom of the above fault scarp, strikes N–S, dips west, with a vertical dislocation of 2–3m. According to the difference of outcropping, it can be divided into two categories (Fig. 3b). One type is directly exposed on the bedrock and is characterized by a fresh fault plane, which is generally considered to be a typical coseismic surface rupture (Papanikolaou et al., 2005, Rao et al., 2011). The other type is mainly exposed on the eluvium–deluvial at the bottom of the fault scarp is characterized by a 2–3m high fault scarp. In addition, fault scarp formed in landslide deposits also exist in local areas.

On the eastern side of Banshanhe, the surface rupture is best exposed and preserved. The fault plane is flat and fresh, have light black coloring as a result of long exposure to lichen and moss growth (Figs. 4a, 4b). Thin–layered sedimentary type secondary calcareous crust (caliche) of 3–5 mm thickness can be seen in local places. These calcareous crusts are generally attributed to surface accretionary processes (Li and Jones, 2014), and may have been deposited from surface water leach when the fault was fault was buried in the early stage, and have been elevated above the ground by subsequent fault activity. Field measured by laser rangefinder indicates that this fresh fault plane is 3.0±0.2 m high, its attitude is 230°∠62°. Striations from the most recent activity are preserved at the bottom of the fault plane, the attitude of which is 220°∠60°, suggesting that the most recent activity is normal faulting (Fig. 4c). On the west side of the fault plane is a fault collapse wedge made up of sand and brecciform limestone gravel. The accelerator mass spectrometry (AMS) $^{14}C$ age of peat samples collected from the collapse wedge of this fault is 530±30 yr. BP, which approximately represents the formation time of this fresh fault plane (Fig. 4d). As it is so close to the time of the 1515 Yongsheng earthquake, and historically there have been no other large earthquakes in the area, it can be deduced that this fresh fault plane is a relic of the surface rupture of the 1515 Yongsheng earthquake. Furthermore, the AMS $^{14}C$ age of secondary calcareous crust collected from this fresh fault plane is 17190±50 yr. BP, which possibly represents the time when the calcareous crust formed after the fault was elevated to the shallow subsurface and exposed to surface water leach, under the action of earlier paleoearthquake activity.

South of Hongshiya, multi–level fault scarps with a height of several meters to tens of meters are found in limestone along the Jinguan fault (Fig. 3c), which were considered to be part of the deformation zone of the 1515 Yongsheng earthquake (Guo Shunmin et al., 1988). Multi–level fault scarps and heights of several meters to several tens of meters all indicate that they are the result of multiple seismic cumulative activities. It is difficult to determine which of them were associated with the Yongsheng earthquake. Tracking southwards along the Chenghai fault, on the eastern side of Pumi, an alluvial fan with about 10 m high above the river，was vertically displaced by the fault and the displacement is about 3.8±0.3m (Fig. 4e). The AMS $^{14}C$ ages of two peat samples collected from the soil layer at both sides of the fault are dated as 1010±30 yr. BP and 1000±30 yr. BP (Fig. 4f, Table 1), which indicate the pedogenesis age of this alluvial fan surface. As this alluvial fan has a vertical throw similar to the fresh fault plane in the Jinguan fault, and no obvious multistage displacements have been found since the formation of the fan top, the fault scarp at the top of this fan surface must also be the result of the 1515 Yongsheng earthquake. If this is the truth, it can be deemed that the surface rupture of the 1515 Yongsheng earthquake can extend from Banshanhe to Pumi, at least 25 km long, and that the co–seismic vertical displacement can be 3.0–3.8 m.

## 5 Epicenter, Magnitude and Seismogenic Structure of the Yongsheng Earthquake

According to field survey, the surface ruptures of the 1515 Yongsheng earthquake was roughly centered on Hongshiya and extended north and south. It was also the region with the richest relics of ancient earthquakes. Therefore, the macroscopic epicenter of the 1515

Yongsheng earthquake may be located near Hongshiya in the west of Yongsheng, which is basically consistent with the speculation by early researchers based on historical records (Office of the Central Seismological Working Group, 1971; Department of earthquake damage defense of China Earthquake Administration, 1995). Furthermore, rich ancient earthquake relics indicate that it may also be the epicenter of a series of ancient earthquakes in the Yongsheng area.

The deformation zone of the 1515 Yongsheng earthquake is considered to originate from the eastern side of Jinguan, run southwards past Hongshiya and Chenghai, terminate near Beiwan, and is about 42 km long and 8 km wide (Guo Shunmin et al., 1988). However, the current survey discovered that the surface rupture is only 25 km long, which is much shorter than 42 km and may be shorter than the true coseismic rupture. It can be seen that using the length of surface rupture to estimate the magnitude of historical or paleo earthquake is likely to produce serious deviations in areas of high erosion and strong human activity where the surface rupture is difficult to preserve. Coseismic displacement, another important parameter for inferring the magnitude of a paleoearthquake, can possibly reflect the magnitude of the earthquake to the furthest extent, if it is well exposed and preserved. As the two deformations of earthquake described in this paper are well preserved, we believe that they can best represent the magnitude of the paleoearthquake.

The coseismic displacement, the length of the seismic deformation zone and the moment magnitude formula obtained from the seismic statistics (Wells and Coppersmith, 1994):

$M_W$ =6.93+0.82´log (D) ($M_W$ =Moment magnitude, D= Coseismic displacement) (1)

$M_W$ =5.08+1.16´log (L) ($M_W$ =Moment magnitude, L=

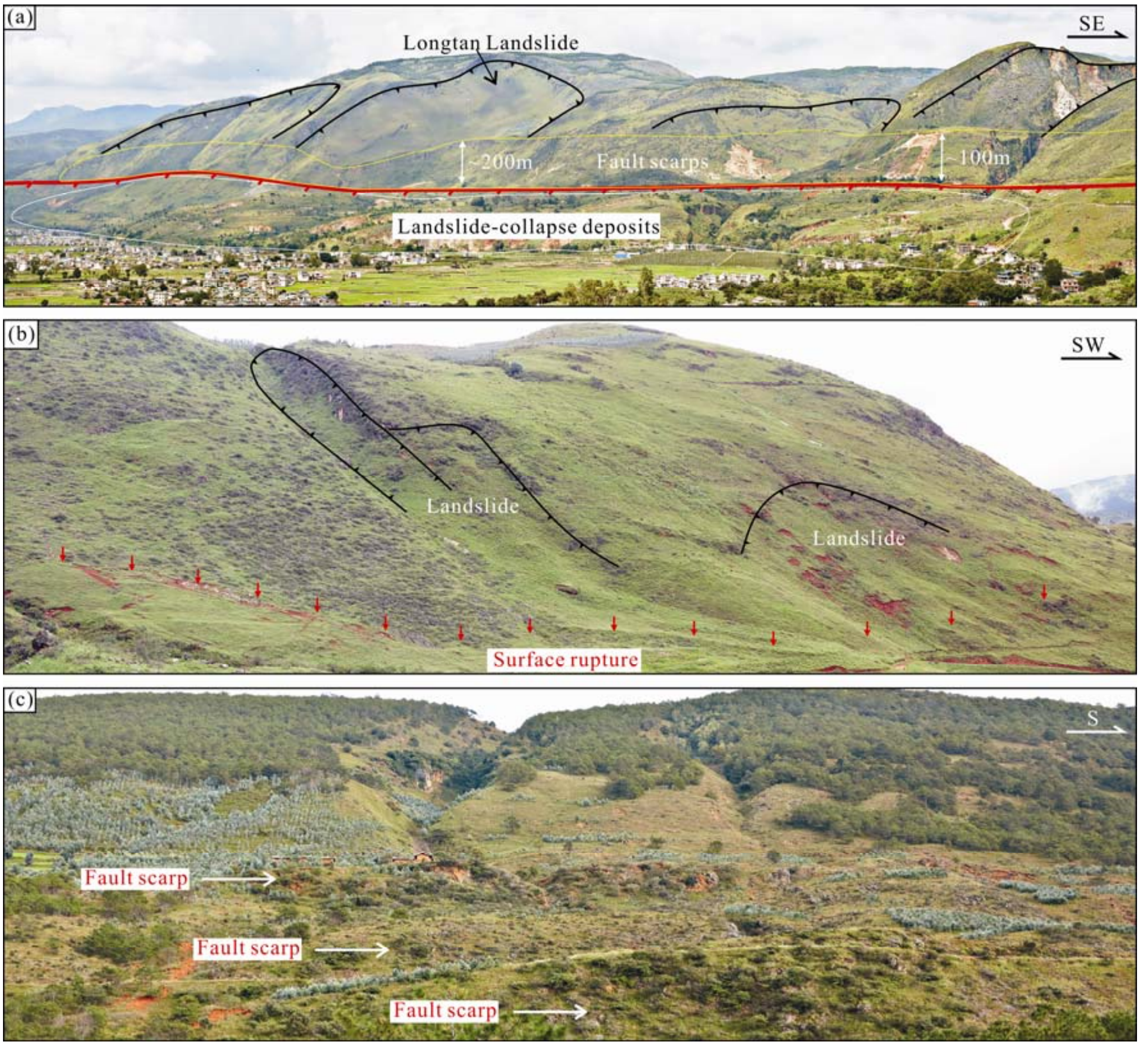


Fig. 3 Field photos of the Jinguan fault and surface ruptures of the 1515 Yongsheng earthquake.
(a), Paleoearthquake landslide relics and fault scarps along the Jinguan fault, yellow line marks the location of the fault scarps; (b), surface rupture of the 1515 Yongsheng earthquake, red arrows indicate location of the surface rupture; (c), multi–level fault scarps along the Jinguan fault.

Length of surface rupture) (2)

According to formula (1), the moment magnitude of the 1515 Yongsheng earthquake can be 7.3–7.4. If formula (2) is used, the moment magnitude of this earthquake is only 6.7; even if the length of the deformation zone is 42 km, the moment magnitude is no more than 7.0. Obviously, the surface rupture of the 1515 Yongsheng earthquake should be even longer than that found. Given the intense surface weathering and significant vegetation modification and surface water erosion, the relics preserved on the surface may only be part of the surface rupture at that time.

Surface rupture is an extension of the seismogenic fault to the surface, and its distribution characteristics are an important indicator to determine the seismogenic fault. The surface ruptures of the Yongsheng Earthquake in 1515 are mainly distributed along the Jinguan and Chenghai faults in the northern segment of the Chenghai–Binchuan fault zone. It can be considered that the seismogenic fault of this earthquake is the Jinguan–Chenghai fault in the northern segment of the Chenghai–Binchuan fault zone. The latest motion of the fault is normal faulting which triggered the Yongsheng earthquake.

## 6 Discussions

### 6.1 In–situ recurrence interval of characteristic strong earthquakes in Yongsheng

In addition to the surface ruptures formed by recent

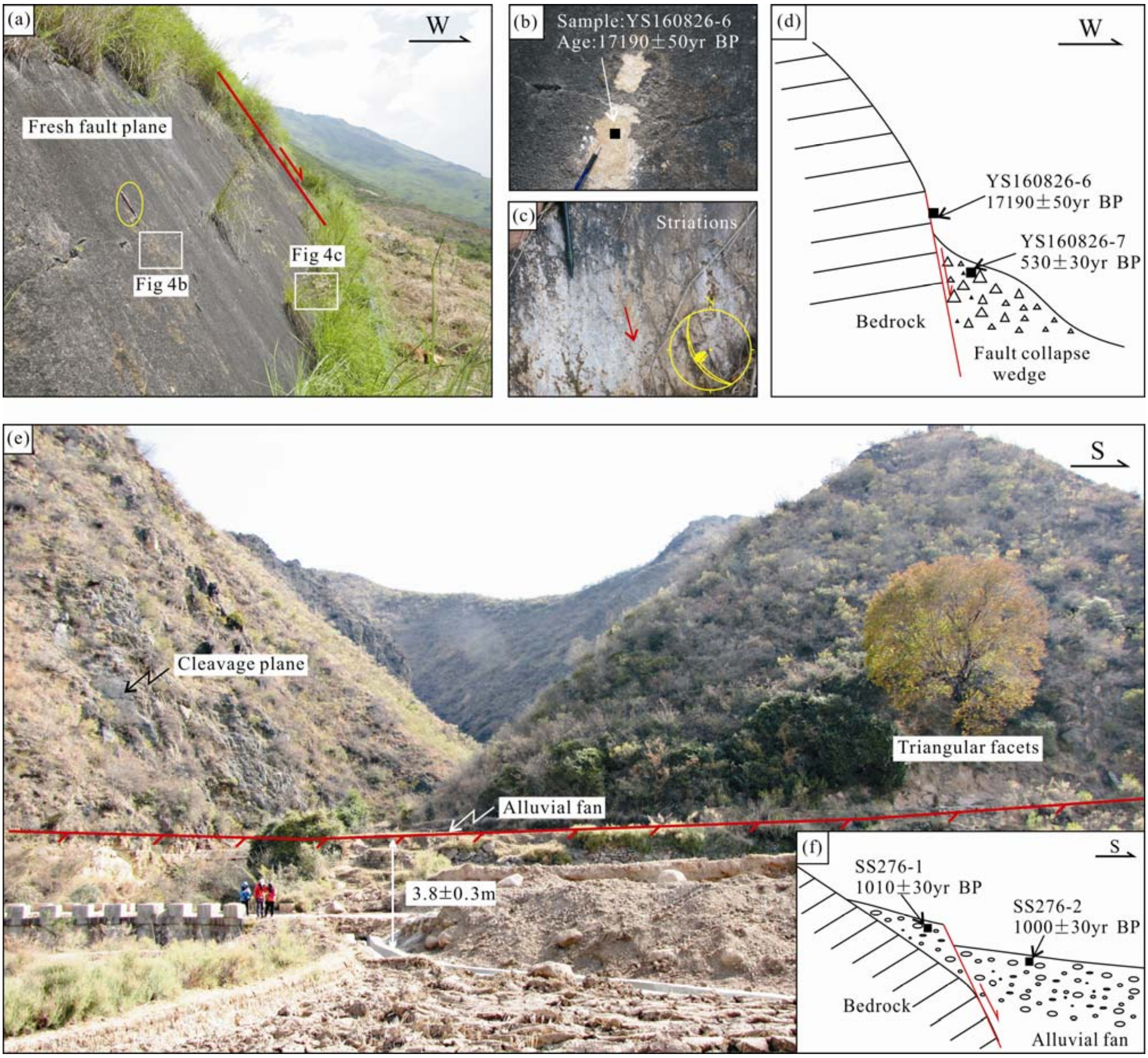


Fig. 4. Field photos of the 1515 Yongsheng earthquake surface ruptures and sketch diagram of the sampling location.
(a), Fresh fault plane outcropping from the limestone strata; (b), sedimentary type secondary calcareous crust exposed in local places of the fresh fault plane and the location of sample YS160826-6; (c), close–up of the fault plane with striations; the red arrow and a stereonet projection show the motion of the fault; (d), schematic cross section diagram across the fresh fault plane, with the location sample YS160826-6/7; (e), alluvial fan that was vertically offset by the surface ruptures of the 1515 Yongsheng earthquake; (f), schematic cross section diagram of the offset alluvial fan, show the location of sample SS276-1/2.

earthquakes, there are also many obvious paleoearthquake relics along the northern segment of the Chenghai–Binchuan fault zone, such as multi–level fault scarps with varying heights. Their formation is the accumulation of multiple paleoearthquake events. Field mapping also reveals many large to giant ancient bedrock landslide along the northern segment of the Chenghai–Binchuan fault zone, their formation may be also related to paleoearthquake events. On the east side of Jinguan, the Longtan landslide which may have formed during the mid–Pleistocene was vertically offset and formed a ca. 200 m high fault scarp (Huang Xiaolong et al., 2016). Calculations using the displacement of the Yongsheng earthquake, the formation of this fault scarp should have taken at least 50 to 60 earthquakes similar to the Yongsheng earthquake. Therefore it is clear that paleoearthquake in the Yongsheng area not only exists but also has a very large number.

Three paleoearthquake wedges similar to the 1515 Yongsheng earthquake have been discovered through the coseismic surface rupture survey of the Yongsheng earthquake (Guo Shunmin et al., 1988). The $^{14}C$ dating of these events being 18300 yr. BP, 12500 yr. BP, and 6600 yr. BP. The date of the earliest earthquake basically agrees with the time of secondary calcareous crust on the fresh fault plane. Therefore, the time for these earthquakes to occur is 17190±50 yr. BP (18300 yr. BP), 12500 yr. BP, 6600 yr. BP, and 530±30 yr. BP. If these earthquakes did exist, it can be deemed that the in–situ recurrence interval of M7.0 or larger earthquakes along the Chenghai–Binchuan fault zone in Yongsheng area is approximately 6000 years. If the displacement of each large earthquakes is similar to that of the 1515 Yongsheng earthquake, i.e. around 3.0–3.8 m, the average vertical slip rate of this fault during the Holocene must have been 0.5–0.6 mm/a, which is obviously higher than the long–term average slip rate since the Pliocene (ca. 0.2–0.3 mm/a) (Huang Xiaolong et al., 2016). This obvious increase in the Holocene fault slip rate possibly implies that the northern segment of the Chenghai–Binchuan fault zone was in a seismic cluster period during the Holocene.

Based on this fault vertical slip rate, combined with the estimated late Quaternary vertical slip rate of the eastern piedmont fault of the Haba–Yulong Snow Mountain (Wu Zhonghai et al., 2009), it can be seen that the vertical slip rate of the regional main normal faults is on the order of 0.2–1.4 mm/a. Even taking into account the branching faults, the average vertical slip rate of faults across the entire Dali fault system in northwest Yunnan would not exceed 2–3 mm/a, which is obviously smaller than the amount needed for the end extension of the Red River fault zone. This may suggests that the approximately 5 mm/a left–lateral strike–slip rate deemed by some researchers is obviously overestimated (Replumaz et al., 2001; Schoenbohm et al., 2006), or that the Quaternary activity of the northwest Yunnan fault depression zone itself is not the result of the end extension of the Red River fault zone.

### 6.2 Regional earthquake distribution and its kinematic implications

In northwest of Yunnan, medium and large magnitude earthquakes are mostly distributed along major faults in the region. The frequency and intensity of earthquakes are closely related to the activity intensity of the faults. Along the Chenghai–Binchuan fault zone and the Lijiang–Dali fault zone, which are relatively active, there are not only a large number of earthquakes but also earthquakes of M≥7.0. Furthermore, the most concentrated part of the earthquake appears in the end of the arc curve of faults, the only four M≥7.0 earthquakes in this area all took place on the end of the arc curve of faults (Fig. 1). Among them the 1996 Lijiang M7.0 earthquake took place on the north end of the Lijiang–Dali fault zone, along the eastern piedmont fault of the Haba–Yulong Snow Mountain (Wu Zhonghai et al., 2009); the 1925 Dali M7.0 earthquake took place on the south end of the Lijiang–Dali fault system along the east margin fault of the Diancang Mountain (Mao Yuping et al., 2003); the 1515 Yongsheng earthquake and the 1652 Midu earthquake, took place at the end of the ends of the Z–shaped Chenghai–Binchuan fault zone. Like the arc bending of the fault at the end, the intense seismic activity at the end of the fault may also indicate that there is a rotational–shear deformation in the northwestern Yunnan. And the rotational–shear deformation may be related to the clockwise rotational of the Dali block.

## 7 Conclusions

(1) The newly discovered surface rupture of the 1515 Yongsheng earthquake extends about 25 km from

**Table 1 AMS $^{14}C$ age of the samples along the surface rupture of 1515 Yongsheng earthquake**

| Sample No. | Laboratory No. | MRA* | $^{13}C/^{12}C$ (‰) | CRA* | 2 Sigma Calibration (95%) Cal BP |
|---|---|---|---|---|---|
| SS276-1 | Beta-323606 | 1010±30 BP | −27.1 | 980±30 BP | 940-900/870-820/820-800 |
| SS276-2 | Beta-323607 | 1000±30 BP | −25.2 | 1000±30 BP | 960-910/850-830/810-800 |
| YS160826-6 | Beta-458524 | 17190±50 BP | −3.7 | 17540±50 BP | 21350-21030 |
| YS160826-7 | Beta-458525 | 530±30 BP | −16.3 | 670±30 BP | 675-635/595-560 |

MRA*=Measured Radiocarbon Age. CRA*= Conventional Radiocarbon Age. The test is completed by Beta Analytic Radiocarbon Dating Laboratory.

Banshanhe to Pumi, and the vertical displacement is up to 3.8 m. The distribution characteristics of this surface rupture indicate that the macroscopic epicenter of the 1515 Yongsheng earthquake may be located near Hongshiya, and the seismogenic fault of this earthquake is the Jinguan –Chenghai fault, in the northern part of the Chenghai–Binchuan fault zone.

(2) The magnitude of the earthquake calculated using empirical formula for displacement–moment magnitude relationship yielded a magnitude of 7.3–7.4. Paleoearthquake have been frequent along the Jinguan–Chenghai area. Given the height of the fault scarp that has resulted from the Longtan landslide, there have been at least 50 to 60 characteristic earthquake events similar to the Yongsheng earthquake.

(3) The ages published by the earlier researcher and the $^{14}C$ ages in this paper jointly revealed four most recent paleoearthquakes in 17190±50 yr. BP (18300 yr. BP), 12500 yr. BP, 6600 yr. BP, and 530±30 yr. BP. The results indicate that the in–situ recurrence interval of M7.0 or larger earthquakes in Yongsheng area along the Chenghai–Binchuan fault zone is approximately 6000 years.

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