Structural analysis and interpretation of the surface deformation associated with the Ning'er, Yunnan Province, China $M_s6.4$ earthquake of June 3, 2007*

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Abstract

The seismogenic fault and the dynamic mechanism of the Ning'er, Yunnan Province $M_s6.4$ earthquake of June 3, 2007 are studied on the basis of the observation data of the surface fissures, sand blow and water eruption, landslide and collapse associated with the earthquake, incorporating with the data of geologic structures, focal mechanism solutions and aftershock distribution for the earthquake area. The observation of the surface fissures reveals that the Banhai segment of the NW-trending Ning'er fault is dominated by right-lateral strike-slip, while the NNE-trending fault is dominated by left-lateral strike-slip. The seismo-geologic hazards are concentrated mainly within a 330° -extending zone of 13.5 km in length and 4 km in width. The major axis of the isoseismal is also oriented in 330° direction, and the major axis of the seismic intensity VIII area is 13.5 km long. The focal mechanism solutions indicate that the NW-trending nodal plane of the Ning'er $M_s6.4$ earthquake is dominated by right-lateral slip, while the NE-trending nodal plane is dominated by left-lateral slip. The preferred distribution orientation of the aftershocks of $M_s \geq 2$ is 330° , and the focal depths are within the range of 3~12 km, predominantly within 3~10 km. The distribution of the aftershocks is consistent with the distribution zone of the seismo-geologic hazards. All the above-mentioned data indicate that the Banhai segment of the Ning'er fault is the seismogenic fault of this earthquake. Moreover, the driving force of the Ning'er earthquake is discussed in the light of the active block theory. It is believed that the northward pushing of the Indian plate has caused the eastward slipping of the Qinghai-Tibetan Plateau, which has been transformed into the southeastern-southernward squeezing of the southwest Yunnan region. As a result, the NW-trending faults in the vicinity of the Ning'er area are dominated by right-lateral strike-slip, while the NE-trending faults are dominated by left-lateral strike-slip. This tectonic framework might be the main cause of the frequent occurrence of $M_s6.0$ ~ 6.9 earthquakes in the area.

Key words: Ning'er earthquake; surface deformation; seismogenic fault; dynamics

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Introduction

On June 3, 2007, an earthquake of magnitude 6.4 occurred in the Ning'er County, Yunnan Province. The macroseismic epicenter of this earthquake is located at about 3 km to the south of the Ning'er county town, and the magistoseismic area (seismic intensity VIII) involves the Ning'er county town and its surrounding mountainous areas. The event has caused serious damages to the economics and communities of the region. Historically, eight earthquakes of magnitude $6.0 \sim 6\frac{3}{4}$ had occurred in the Ning'er-Simao area, which is thus considered as an area of frequent occurrences of strong earthquakes. According to statistic data, the earthquakes of magnitude equal and above $6\frac{3}{4}$ all over the world might produce surface rupture zone, and sometime a few earthquake of magnitude less than 6.5 may also produce surface ruptures (DENG *et al*, 1992). In general, the direct evidence for the identification of the seismogenic structures by geologic method is the discovery of earthquake surface fault. In this way, the coseismic parameters of fault activity can be determined. One day after the occurrence of the Ning'er earthquake on June 3, we carried out the hazard assessment and scientific observation of the earthquake. A lot of valuable data about the surface fissures, sand blow and water eruption, and the band-like distribution of landslides associated with the earthquake have been obtained. This paper presents the results of the study of the seismogenic fault and its surficial appearance during the shock, as well as the origin of the driving force of the Ning'er earthquake on the basis of the actual observation data incorporating with the data of focal mechanism solutions and aftershock distribution.

1 Geologic setting of the Ning'er earthquake area

The convergence between the Indian and Eurasian plates beginning at about 50 Ma B.P. had caused the closure of the Tethys Sea and the rapid uplift of the Qinghai-Tibetan Plateau, greatly affecting the geologic-geomorphic evolution of the eastern margin of the plateau. On the one hand, the east-directed compressive napping action was formed owing to the northward and eastward pushing force associated with the northward motion of the east Himalayan syntaxis. As has been recently confirmed, the eastward napping of the Lanping nappe in Yunnan Province and the Chiang Mai nappe in Thailand reaches up to 80~100 km (Bureau of Geology and Mineral Resources of Yunnan Province, 1990; XU *et al*, 1992). On the other hand, under the action of gravity potential associated with the rapid uplift of the Qinghai-Tibetan Plateau the plastic flow of the deep crust materials has produced horizontal pushing force (ZHOU and HUANG, 1980). Under the combining actions of the two forces, the western Yunnan region has become a NNW-trending Meso-Cenozoic fold-thrust belt, and at the same time a large scale strike-slip fault system was formed in the western Yunnan and western Sichuan regions (ZHONG *et al*, 1998) (Figure 1).

The Ning'er area is located on the southeastern margin of the Qinghai-Tibetan Plateau, where the outcropped oldest strata are the Upper Carboniferous Mapping formation limestone and the Permian Longtan formation sandstone. During Mesozoic era, a large number of sandstone, mudstone and conglomerate were deposited in the area, while during Cenozoic era only a small amount of sandy gravel and coal-bearing series were deposited. The Quaternary strata occur limitedly within the small basins such as the Ning'er and Simao basins in the area. In addition, basaltic eruption occurred during the Himalayan orogeny on the northern side and at the bottom of the Ning'er basin^{①②}. In the Ning'er area there exist mainly the NNW-trending reverse faults and fold

^① Geological Bureau of Yunnan Province. 1976. *Regional Geologic Map of the Pu'er Sheet (1:200,000) and the Observation Report*.

^② Geological Bureau of Yunnan Province. 1983. *Regional Geologic Map of the Simao Sheet (1:200,000) and the Observation Report*.

structures involving the Mesozoic strata. Moreover, the NW-trending faults are associated with right-lateral strike-slip, while the ENE-trending faults with left-lateral strike-slip (GUO *et al*, 1999; DENG *et al*, 2007). The major faults in the vicinity of the Ning'er area are WSW- or ENE-dipping and NNW- or NW-striking, while the Carboniferous and Permian strata are thrust eastward or westward over the Cretaceous mudstone and sandstone (Figure 1).

Figure 1 Seismotectonic sketch map of the Ning'er area

1. Quaternary; 2. Neogene; 3. Paleogene; 4. Cretaceous; 5. Jurassic; 6. Triassic; 7. Pre-Mesozoic; 8. Basalt of Himalayan epoch; 9. Reverse fault; 10. Strike-slip fault; 11. Normal fault; 12. M6.0~6.9 earthquakes

2 Surface fissures, sand blow and water eruption, landslide and collapse associated with the Ning'er earthquake

After the occurrence of the Ning'er earthquake, a series of regularly distributed surface fissures, sand blow and water eruption, landslides and collapses occurred in the epicentral area.

2.1 Earthquake surface fissures, sand blow and water eruption

After the occurrence of the Ning'er earthquake on June 3, 2007, a series of earthquake surface fissures independent to slope effects were produced in the area of seismic intensity VIII.

Among them, one set of fissures is $320^{\circ}\sim 330^{\circ}$ -striking, and the other set is $70^{\circ}\sim 80^{\circ}$ -striking (Figure 2). The surficial distribution and displacement direction of these two sets of fissures are described as follows.

2.1.1 NNW-trending surface fissures, sand blow and water eruption

Field observations discover that the WNW-trending surface fissure zones are well developed at three sites. They are the Kanchaihe, Longdong and Liyuantou, respectively (Figure 2).

2.1.1.1 Earthquake surface fissures, sand blow and water eruption at Kanchaihe

The NW-trending surface fissures at Kanchaihe are about 70 m long, having a general strike of 305° . They consist of five fissures of variable length and 1.0~1.5 m spacing, forming a fissure zone of 5~8 m in width. The fissure zone is developed at the bottom of a 330° -extending gully, which had become flat cultivated land. The individual fissure is 10~20 m long and 5~12 cm wide, having a visible depth of 0.5 m. Figure 3a shows the segment of one set of the fissures. It can be seen from the figure that the fissures are characterized by tracing distribution. Among them, the nearly N-S-trending fissures are opened relatively widely, having a width of about 8~12 cm, while the 320° -trending ones are relatively closed, having a width of less than 5 cm. No vertical offset is observed on both sides of the fissures. It can be postulated, however, that the fissures have a right-lateral offset of about 4~5 cm on both sides, as evidenced by the variable closures of the fissures of various strikes and the marker points on both sides of the fissures.

Along the bank of a pond about 30 m to the northwest of the surface fissure zone at Kanchaihe, sand blow and water eruption occurred at 5 sites during the earthquake (Figure 4a). According to the local residents, the height of the water fountain reached up to 2 m during the shock.

2.1.1.2 Earthquake surface fissures, sand blow and water eruption at Longdong

On flat cultivated land in the northwest of the Longdong village, a NW-trending surface fissure zone of about 150 m in length and 15 m in width is well developed with a general strike of 320° . The length of the single fissure within the zone is usually 20~30 m. The surface fissure zone is characterized also by tracing distribution (Figure 3b), in which the nearly N-S-trending fissure sections are about 3 cm in width, while the $315^{\circ}\sim 320^{\circ}$ -trending ones are 1.5~2.0 cm in width, displaying right-lateral slipping.

The surface fissures are accompanied by sand blow and water eruption during the earthquake. According to primary statistics, there are about 30 sites of sand blow and water eruption, which are distributed along the northwest direction within the range of about 180 m long and 30 m wide.

2.1.1.3 Surface fissures in Jurassic sandstone at Liyuantou

The strata outcropped in the vicinity of the Liyuantou village are mainly Jurassic fine-grained sandstone. Along the ridge of hills, where the bedrocks are outcropped, a 330° -trending surface

Figure 2 Distribution of surface fissures, landslides, collapses, sand blow and water eruption associated with the Ning'er earthquake

Figure 3 The NW-trending surface fissures associated with the Ning'er earthquake
 (a) Surface fissures at Kanchaihe; (b) Surface fissures at Manlian-Longdong; (c) Surface fissures at Liyuantou;
 (d) Surface fissures developed in Jurassic sandstone at Liyuantou. Red arrow indicates the location of surface fissures, blue arrow shows localized extensional structure

fissure zone of 150 m length was formed during the earthquake, consisting of 4 sub-parallel surface fissures of variable lengths. At the sites, where the surface fissures were developed, Jurassic sandstone used to be widely exposed, but had been covered partly with 10~30 m thick sandy soil when a road was built passing the sites. The surface fissures developed in the sandstone are generally 330° -striking, while a part of faults at this site are nearly N-S-trending (Figure 3d). It is observed that a sandstone block in this place is dissected by the fault into two sections, with a

right-lateral offset of 3 cm between each other.

At the sites covered with sandy soil, surface fissures are also developed in the sandy soil itself, having a general strike of 330° . The 330° -trending fissure sections are generally 1~2 cm wide, while the 300° -trending ones are less than 1 cm wide, or tightly closed (Figure 3c).

2.1.2 ENE-trending surface fissures, sand blow and water eruption

At Xinping and Kun'e villages, which are within the range of the magistoseismic area, 70° ~ 80° -trending surface fissure zones of 100~150 m length were discovered (Figure 2). The two surface fissure zones are developed on flat cultivated land, and no slope topography is observed in surroundings.

2.1.2.1 Surface fissures, sand blow and water eruption at Xinping

The surface fissure zone at Xinping village has a general strike of 70° ~ 71° , a width of about 15 m, and a length of about 120 m, consisting of 12 parallel fissures of variable lengths. Figure 5a shows a typical segment of the surface fissure zone at the Xinping village. It can be seen from the figure that the 70° -trending section of the fissures is 2.0~2.5 cm wide, while the 55° ~ 60° -trending one is 4.0~5.0 cm wide. It can be postulated from the geometry of the fissures and the marker points on both sides that the surface fissure zone at Xinping village is characterized by right-lateral strike-slip, having an offset amount of 2~3 cm.

Moreover, 30 sites of sand blow and water eruption were observed within the surface fissure zone at Xinping village. Figure 4b shows a vent of sand blow and water eruption, and the diameter of the preserved silt-fine sand cone reaches 50~60 cm. According to the local residents, who saw the process of sand blow during the earthquake, a large number of water fountains occurred in the corn field, and the fountains were higher than the stems of the corn. The height of the corn stems is usually 1.70~1.80 m, and thus the height of the fountains can be postulated to be about 2 m.

2) Surface fissure zone at Kun'e

The surface fissure zone is developed in vegetable farm and cornfield to the north of the Kun'e village. The vegetable farm is located on the eastern side, and the cornfield is located on a platform of 1.5 m height to the west of the vegetable farm. The surface fissure zone there has a general strike of 70° ~ 80° , a length of 150 m, and a width of about 10 m. The individual fissure within the zone is not a single continuous fissure, but rather a right-stepping arranged fissure set consisting of several fissures of variable lengths. Figure 5d shows one of the fissure set consisting of two right-stepping arranged fissures. Among them, the western one dissects a water well, and offsets left-laterally the well head about 2.5 cm (Figure 5c). The eastern one is developed on a small path between the farms, having distinct surficial traces. The nearly N-S-trending section of the fissures is 2.5~3.0 cm wide, while the 70° ~ 80° -trending section is relatively closed, having a width of only 1.0 cm or less (Figure 5b). According to the geometry and width of the fissures, as well as the marker points on both sides, it can be postulated that the fissure zone had produced left-lateral offset during the earthquake.

2.2 Earthquake landslide and collapse

The Ning'er $M_s6.4$ earthquake occurred in mountainous areas of the southwest Yunnan Province. The landforms of the earthquake area are characterized by high mountains and gorges, where the outcropped strata are mainly Mesozoic sandstone and Paleozoic limestone. Investigation of seismo-geologic hazards after the shock revealed that landslide, collapse and the cracks of the road are distributed along 330° direction within the range of 13.5 km long in north-south direction and 4 km wide in east-west direction (Figure 2).

Figure 4 Sand blow and water eruption associated with the Ning'er earthquake
(a) Vent of sand blow and water eruption at Kanchaihe; (b) Vent of sand blow and water eruption at Xinping; (c) Vents of sand blow and water eruption at Longdong

Figure 5 The ENE-trending surface fissures associated with the Ning'er earthquake
(a) Surface fissures at Xinping; (b), (c) and (d) Surface fissures at Kun'e

3 Focal mechanism solutions, aftershock distribution and isoseismals of the Ning'er earthquake

3.1 Focal mechanism solutions of the Ning'er earthquake

After the occurrence of the Ning'er earthquake, US Geological Survey and China Earthquake Network Center have provided the focal mechanism solution of this earthquake, respectively, on the basis of their obtained data.

The tensor solutions for the earthquake provided by the US Geological Survey are as follows: The nodal plane 1 is 138°-striking, having a dip angle of 57° and an inclination of 140°; the nodal plane 2 is 252°-striking, having a dip angle of 58° and an inclination of 40° (Table 1). The NW-SE-trending fault plane is dominated by right-lateral displacement, while the NE-SW-trending fault plane is dominated by left-lateral displacement (Figure 1). The magnitude of the earthquake is $M_W 6.1$, and

the focal depth is 5 km. China Earthquake Network Center has determined the M_S magnitude of the Ning'er earthquake of June 3, 2007 to be 6.4.

During the period of 1970~1993, four M_S 6.2~6.8 earthquakes had occurred in the vicinity of Ning'er. The focal depth of these four earthquakes is in the range of 10~24 km. Except for the M_S 6.3 earthquake in 1973, which is characterized by normal faulting, the other three events are characterized by right-lateral displacement along the NW-trending nodal plane and the left-lateral displacement along the NE-trending nodal plane with the principal stress axis oriented nearly in north-south direction (LONG *et al*, 2007) (Table 1).

Table 1 Focal mechanism solutions for the earthquakes of $M>6$ in the vicinity of Ning'er

Origin time	Epicentral location			M_S	Nodal plane A			Nodal plane B			P axis		T axis		B axis		Fault type
	$\varphi_N/^\circ$	$\lambda_E/^\circ$	Site		Strike/ $^\circ$	Dip/ $^\circ$	Rake/ $^\circ$	Strike/ $^\circ$	Dip/ $^\circ$	Rake/ $^\circ$	Az/ $^\circ$	Pl/ $^\circ$	Az/ $^\circ$	Pl/ $^\circ$	Az/ $^\circ$	Pl/ $^\circ$	
1970-02-07	22.9	100.8	Pu'er	6.2	129	78	160	223	70	13	177	5	85	23	279	66	Strike-slip
1973-08-16	23.1	100.9	Pu'er	6.3	150	45	-90	330	45	-90	0	90	240	0	330	0	Normal
1979-03-15	23.1	101.1	Pu'er	6.8	132	89	164	222	73	1	178	11	85	12	309	74	Strike-slip
1993-01-27	22.93	101.1	Pu'er	6.3	329	88	-159	238	69	-2	196	16	102	13	335	69	Strike-slip
2007-06-03	23.04	101.02	Ning'er	6.4*	138	57	140	252	58	40	15	0	105	50	285	40	Strike-slip

Note: Since April 18, 2007 the Pu'er County has been renamed as Ning'er County, and the Simao City has been renamed as Pu'er City.

* Focal mechanism solutions are from the US Geological Survey, and the other data from LONG *et al* (2007).

3.2 Spatial distribution of aftershocks

After the occurrence of the Ning'er earthquake on June 3, 2007, temporary seismic observation network consisting of six mobile seismic stations was set up in the Ning'er area by the Earthquake Administration of Yunnan Province (Figure 6a). Since 20:5:45.3 of June 3 to 09:29:40.2 of June 10, 155 earthquakes of $M_S>2.0$ had been recorded. All these earthquakes have been located by using Hypo 81 earthquake locating program from the US Geological Survey. The residual error for the location of about 90% of the aftershocks occurred in Ning'er area is 0.1, among which the relative error of epicenter location is 1.0 km, and that of focal depth location is less than 1.5 km^①. Plotting all these earthquakes on planimetric map, one may find that the aftershocks of this earthquake are distributed within a narrow 330°-trending zone (Figure 6a). Plotting the main shock and aftershocks into 3-dimensional space and on the NE-trending profile (Figure 6b and 6c), one may find that the concentration zone of aftershocks is dipping northeast, and the depth is 3~12 km. The focal depth of about 40% of the earthquakes is 3~10 km, and that of about 20% of the earthquakes is 3~8 km.

3.3 Distribution of isoseism

The microseismic epicenter of this event is located in the area from the Banhai to Qianjin villages. The seismic intensity of the meizoseismic area is VIII, and the area is about 167 km². Damage phenomena indicative of seismic intensity IX occurred in individual villages of the area. The isoseismal is elliptical in shape, the major axis of which is 330°-striking and about 17 km long (MIAO *et al*, 2007). The isoseismals of the intensity VII and VI are also elliptical in shape, and the major axes of the isoseismals are also NNW-trending. In general, the major axis of the isoseismal of the meizoseismic area indicates the strike of the seismogenic fault, and the length of the major axis is consistent with that of the seismogenic fault. Therefore, it is determined that the seismogenic fault of the Ning'er earthquake is NNW-striking, having a length of about 17 km.

^① CHEN Hui, YE Jian-qing, LIU Xue-jun, *et al*. 2007. Monitoring and study of the Ning'er M_S 6.4 earthquake.

Figure 6 Distribution of the mainshock and aftershocks of the Ning'er earthquake and the isoseismals (a) Distribution of the mainshock and aftershocks ($M \geq 2.0$); (b) Spatial distribution of earthquakes; (c) Distribution of earthquakes in NNE-trending cross-section; (d) Isoseismals. Figures 6a~6c are plotted from the data of mobile seismic network, Yunnan Province; black triangle in Figure 6a represents the mobile seismic station; Figure 6d is modified from MIAO *et al.*, 2007

4 Identification of the seismogenic fault and discussion on its dynamics

Comparing the seismotectonic map of the Ning'er area, one may find that a 330° -trending fault is developed about 3 km on the western side of Ning'er. The geologic hazards including surface fissure, sand blow and water eruption, landslide and collapse are concentrated within a 330° -striking zone of 13.5 km length and 4 km width. The zone is consistent well with the spatial extension of the Ning'er fault. Moreover, the 330° -trending surface fissures display right-lateral displacement, while the $70^\circ \sim 80^\circ$ ones show left-lateral displacement. Focal mechanism solutions indicate that the NW-trending nodal plane of the earthquake is dominated by right-lateral thrust slip, while the NE-trending one is dominated by left-lateral strike-slip. In addition, aftershock distribution reveals also that the seismogenic fault is NW (330°)-striking and dipping steeply toward northeast, and that the focal depth of this event is 3~12 km. It is proposed, therefore, that the seismogenic fault of the Ning'er $M_s 6.4$ earthquake of 2007 is the NW-trending strike-slip fault, *i.e.* the Banhai segment of the Ning'er fault, along which right-lateral displacement occurred during the earthquake. The focal depth is determined to be less than 10 km. Seismological study

on the Qinghai-Tibetan Plateau (ZHENG and GAO, 2001) indicates that the focal depth of most of the earthquakes occurred in the plateau and its surrounding areas is less than 20 km, except for a few earthquakes which have a focal depth of greater than 20 km. The crustal thickness in this region is 40~70 km in average. Therefore, it is considered that most of the earthquakes in the Qinghai-Tibetan Plateau occurred within the shallow part of the crust or upper crust, and thus the mid-crust and lower crust in this region can be considered as aseismic layers.

The northward pushing of the Indian plate has provided the driving force for the motion and deformation of the blocks within the Qinghai-Tibetan Plateau and its surrounding areas. The Indian Plate is moving northward at a rate of 50 mm/a (Minster and Jordan, 1978), giving rise to crustal shortening and uplift of the Qinghai-Tibetan Plateau. At the same time, it has caused the right-lateral slipping along the Honghe Fault and the NW-trending faults on its western side, as well as the left-lateral slipping along the NE-trending faults. DING and LU (1989) proposed that under the action of north-directing movement of the Indian Plate, a series of NW-trending left-lateral strike-slip active faults were formed within the plateau. Among them, the Xianshuihe and Kunlun faults have divided the Qinghai-Tibetan Plateau into western and eastern parts, resulting in a fan-shaped fault block movement pattern spreading northward and southeastward from the Qinghai-Tibetan Plateau as a center (ZHANG *et al*, 2002, 2005; Shen *et al*, 2005).

Owing to the eastern-northeastward squeezing of the Indian plate, the Myanmar thrust belt and the Shijie, Longling-Lancangjiang and Honghe right-lateral strike-slip faults were formed on the plate margin (GUO *et al*, 2001) (Figure 7). The Ning'er fault is located at the Simao micro-block between the Longling-Lancangjiang and Honghe faults, being a right-lateral strike-slip fault with a general strike of north-northwest (ZHONG *et al*, 1998; DENG *et al*, 2002). It is just because of the northward pushing of the Indian plate, that the Qinghai-Tibetan Plateau has been squeezing eastward, which has been transformed into SSE-directing pushing force in southwest

Figure 7 Seismogenic model for the Ning'er $M_s6.4$ earthquake

F_1 , Longling-Lancangjiang fault; F_2 , Ruili fault; F_3 , Nandinghe fault; F_4 , Ning'er fault; F_5 , Chenghai fault; F_6 , Jianchuan fault; F_7 , Honghe fault; F_8 , Qujing fault; F_9 , Anninghe fault; F_{10} , Xianshuihe fault

Yunnan region (XU *et al*, 2003; Shen *et al*, 2005). This has caused the right-lateral displacement along the NNW-trending Ning'er fault, and left-lateral displacement along the NE-trending faults. The Ning'er $M_s6.4$ earthquake of 2007 just occurred at the convergence between the two sets of faults. Both the NNW-trending and NE-trending faults in the Ning'er area can be assigned to late Pleistocene-Holocene active faults, which make up a net-like active fault system (DENG *et al*, 2002, 2007). Owing to the crosscutting of the faults each other, the length of the individual fault section is usually less than 20 km. According to the empirical relation between the seismic mag-

nitude and the length of the active fault segment (DENG *et al.*, 1992), the magnitude of the potential earthquake in the Ning'er area is calculated to be less than 7.0. This estimation coincides well with the magnitude of earthquakes that have occurred in this area so far. In other words, the broken crustal structures of the Ning'er area might be the main cause of the frequent occurrence of M_s 6.2~6.8 earthquakes in the area, and that is why the area has no tectonic condition for the occurrence of much larger earthquake.

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