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Rupture behavior and deformation localization of the Kunlunshan earthquake (M_w7.8) and their tectonic implications

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Earthquake surface rupture is the result of transformation from crustal elastic strain accumulation to permanent tectonic deformation. The surface rupture zone produced by the 2001 Kunlunshan earthquake (M_w7.8) on the Kusaihu segment of the Kunlun fault extends over 426 km. It consists of three relatively independent surface rupture sections: the western strike-slip section, the middle transtensional section and the eastern strike-slip section. Hence this implies that the Kunlunshan earthquake is composed of three earthquake rupturing events, i.e. the M_w=6.8, M_w=6.2 and $M_w \leqslant 7.8$ events, respectively. The $M_w \leqslant 7.8$ earthquake, along the eastern section, is the main shock of the Kunlunshan earthquake, further decomposed into four rupturing subevents. Field measurements indicate that the width of a single surface break on different sections ranges from several meters to 15 m, with a maximum value of less than 30 m. The width of the surface rupture zone that consists of en echelon breaks depends on its geometric structures, especially the stepover width of the secondary surface rupture zones in en echelon, displaying a basic feature of deformation localization. Consistency between the Quaternary geologic slip rate, the GPS-monitored strain rate and the localization of the surface ruptures of the 2001 Kunlunshan earthquake may indicate that the tectonic deformation between the Bayan Har block and Qilian-Qaidam block in the northern Tibetan Plateau is characterized by strike-slip faulting along the limited width of the Kunlun fault, while the blocks themselves on both sides of the Kunlun fault are characterized by block motion. The localization of earthquake surface rupture zone is of great significance to determine the width of the fault-surface-rupture hazard zone, along which direct destruction will be caused by co-seismic surface rupturing along a strike-slip fault, that should be considered before the major engineering project, residental buildings and life line construction.

Tibetan Plateau, Kunlunshan earthquake, earthquake surface rupture zone, deformation localization, rupture behavior

The earthquake surface rupture behavior is the key linkage to understand transformation from elastic strain accumulation to permanent tectonic deformation in the crust. It contains basic information about the deformation pattern, amplitude of motion, movement state and earthquake faulting process in the continental crust[1−3]. Various empirical relationships between parameter of earthquake surface rupture zone in different faulting environments, such as the rupture length, rupture area, or coseismic displacement, and the earthquake moment magnitude, have been derived by many previous researchers on the basis of the basic parameters of earthquake surface rupture zones collected from earthquake rupture observation all over the world, in order to reach an insight into an inherence relation between the surface fault dislocation and earthquake focal rupturing[4−6].

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However, little attention has been paid to the width of the surface rupture zone and its controlling factors. The ignorance of this problem may not only hinder recognition of the entire characteristics of the earthquake surface rupture zone and faulting mechanics of the upper crustal rocks, but also hamper proactive thoughts on the countermeasures of the engineering hazard reduction of active faults, which are the main source of earthquake disasters.

On 14 November, 2001, an exceptionally large earthquake (M_w7.8) occurred on the Kusaihu segment of the Kunlun fault, a northwest trending boundary fault between the Bayan Har and Qilian-Qaidam blocks, northern Tibet Plateau. The earthquake is called the Kunlunshan earthquake or Kusaihu earthquake[7]. Discussions on the distribution of the earthquake surface rupture zone, coseismic displacement, post-seismic creep, and temporal and spatial earthquake faulting process of the earthquake have been made by many researchers[8−18]. Although deformation is concentrated toward in a narrow main break zone have been made in a rock under brittle/brittle-ductile conditions[1,19,20], however, the discussion on the problem about whether deformation localization exists on the earthquake surface rupture zone has rarely been reported in the past[21,22]. Based on field measurements of the surface rupture zone by using Total Station, interpretation of Ikonos high-resolution images, and large-scale mapping of the key sections of the surface rupture zone, in this paper, we discuss the earthquake rupture behavior of the 2001 Kunlunshan earthquake, the width of its surface rupture zone and its controlling factors. This study may not only provide important constraint on the width of the “fault-surface- rupture hazard zone” for anti-faulting project, but also have important scientific significance to analysis of the problem about whether deformation localization exists on large-scale strike-slip fault zone in the Tibet Plateau, as well as the understanding of crustal deformation pattern.

1 Earthquake surface rupturing behavior

1.1 Earthquake parameters

Following the occurrence of the Kunlunshan earthquake at 17:26 Beijing time on 14 November, 2001, the basic parameters for this event, such as epicentral location, focal depth, moment magnitude, total scalar seismic moment release and focal mechanism solution provided by various seismic institutions both in China and abroad, are somewhat different (Table 1 and Figure 1). The instrumental epicenter of the event was located to the northeast of the Bukadaban Peak by the China Seismic Network, on the western shore of the Taiyang Lake to the southwest of the Bukadaban Peak by the National Earthquake Information Center, United States Geological Survey, at the west of the Taiyang Lake by the Earthquake Research Institute of Tokyo University, Japan, and in the vicinity of the Kusai Lake by the Harvard CMT Catalog. The determined focal depth varies from 11 km to 22 km, and the scalar moment released is in the range of (2.2−5.8)×10^{20} Nm. The inconsistency difference in the focal parameters obtained by different institutions reflects the complexity of the rupturing process and characteristics of the earthquake surface rupture zone.

1.2 Basic characteristics of the earthquake surface rupture zone

Field investigations, interpretation of Ikonos images, and the inversion of GPS observation data have shown that the 2001 Kunlunshan earthquake surface rupture zone consists of several basic surface break units, including N45°−50°E trending tensional break, N60°−75°E trending transtensional break, N100°E trending strike-slip break, mole track at right stepover and tensional gash at left stepover, and is a pure left-lateral strike-slip rupture zone with a general strike of N100°±10°E[7,16−18]. The surface rupture zone starts at the eastern shore of the Kushui Lake at 90.257°E in the

Table 1 Focal parameters of the 2001 Kunlunshan earthquake

Time (UTC)	Epicentral location		Focal depth (km)	Seismic moment (×10^{20} Nm)	M_w	Nodal plane I (°)			Nodal plane II (°)			Source[a)]
	Long. (N)	Lat. (E)				Strike	Dip	Slip-angle	Strike	Dip	Slip-angle	
9:27:10.8	35.54°	92.75°	15	5.8	7.8	96	54	–7	190	84	–144	Harvard University, 2001
9:26:10.1	35.95°	90.54°	10	3.5	7.7	32	4	–76	198	86	–91	USGS, 2001
9:26:10.1	36.01°	90.50°	20	3.9	7.7	89	88	–2	179	88	–178	ERI, Tokyo University, 2001
9:26:10.1	36.58°	90.80°	22	2.2	7.5	273	11	–140	144	83	–81	CCDSN, 2001
9:26:10.1	35.97°	90.59°	11	3.2	7.6	113	68	49	0	46	14	IGP, CEA, 2001
9:26:10.1	35.97°	90.59°	11	3.2	7.6	290	85	–10	21	80	–175	[11]

a) USGS, United States Geological Survey; ERI, Earthquake Research Institute; CCDSN, the China Center of Digital Seismic Network; IGP, Institure Geophysics; CEA, China Earthquake Administration.

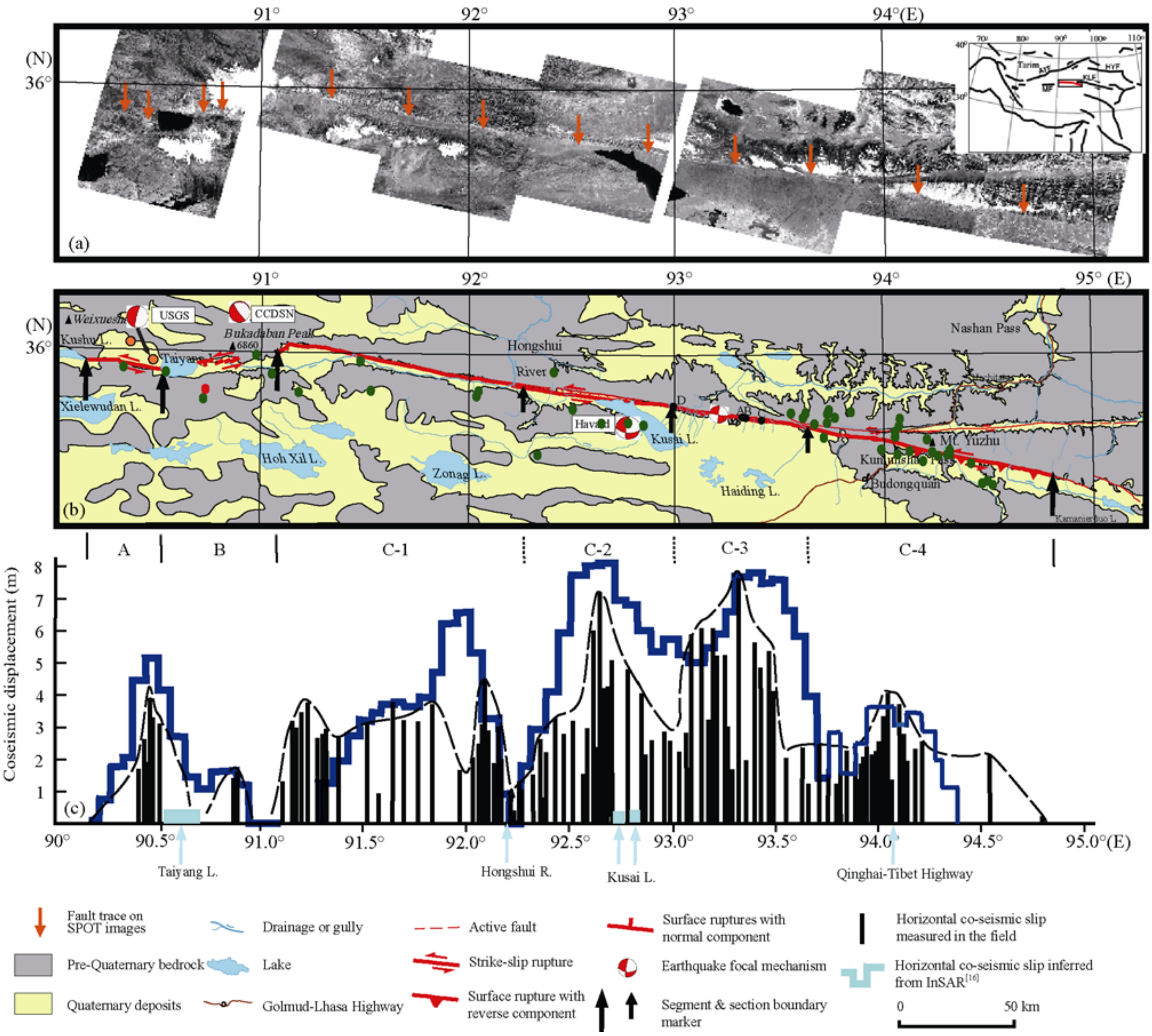

Figure 1 Simplified map of the 2001 Kunlunshan earthquake surface rupture zone (modified from ref. [18]). (a) SPOT mosaic images showing preexisting fault traces; (b) segmentation, focal mechanism solutions, and spatial distribution of aftershocks for the 2001 Kunlunshan earthquake surface rupture zone (A, B and C denote the western, middle and eastern sections of the surface rupture zone, respectively); (c) distribution of the measured coseismic left-lateral displacements.

west, and ends at 94.795°E to the east of the Qinghai-Tibet Highway. Total length is for over 426 km. It can be divided into three relatively independent earthquake surface rupture sections: the western section is about 26 km long (A), the middle section is about 18 km long (B) and the eastern section is about 350 km long (C) (Figure 1). The maximum coseismic left-lateral displacement for these three sections is 4.5, 1.5, and 7.6 m, respectively[18].

The western section is located between the Kushui and Taiyang Lakes (Figure 1). It consists of a series of basic surface break units, including en echelon tensional gashes, tensional breaks, transtensional breaks, and mole tracks. The surface rupture zone displays a predominant strike-slip faulting. Vertical offset is rarely observed even on both sides of the tensional gashes (Figure 2(a) and (b)). Average coseismic left-lateral displacement is measured to be 2 m to ~3 m. It is, therefore, a pure strike-slip faulting section. The middle section starts at the southwest piedmont of the Bukadaban Peak, making a left stepover together with the western section. The stepover is occupied by the Taiyang Lake, which is about 10 km long. The section is dominated mainly by a transtensional faulting, along which the co-seismic

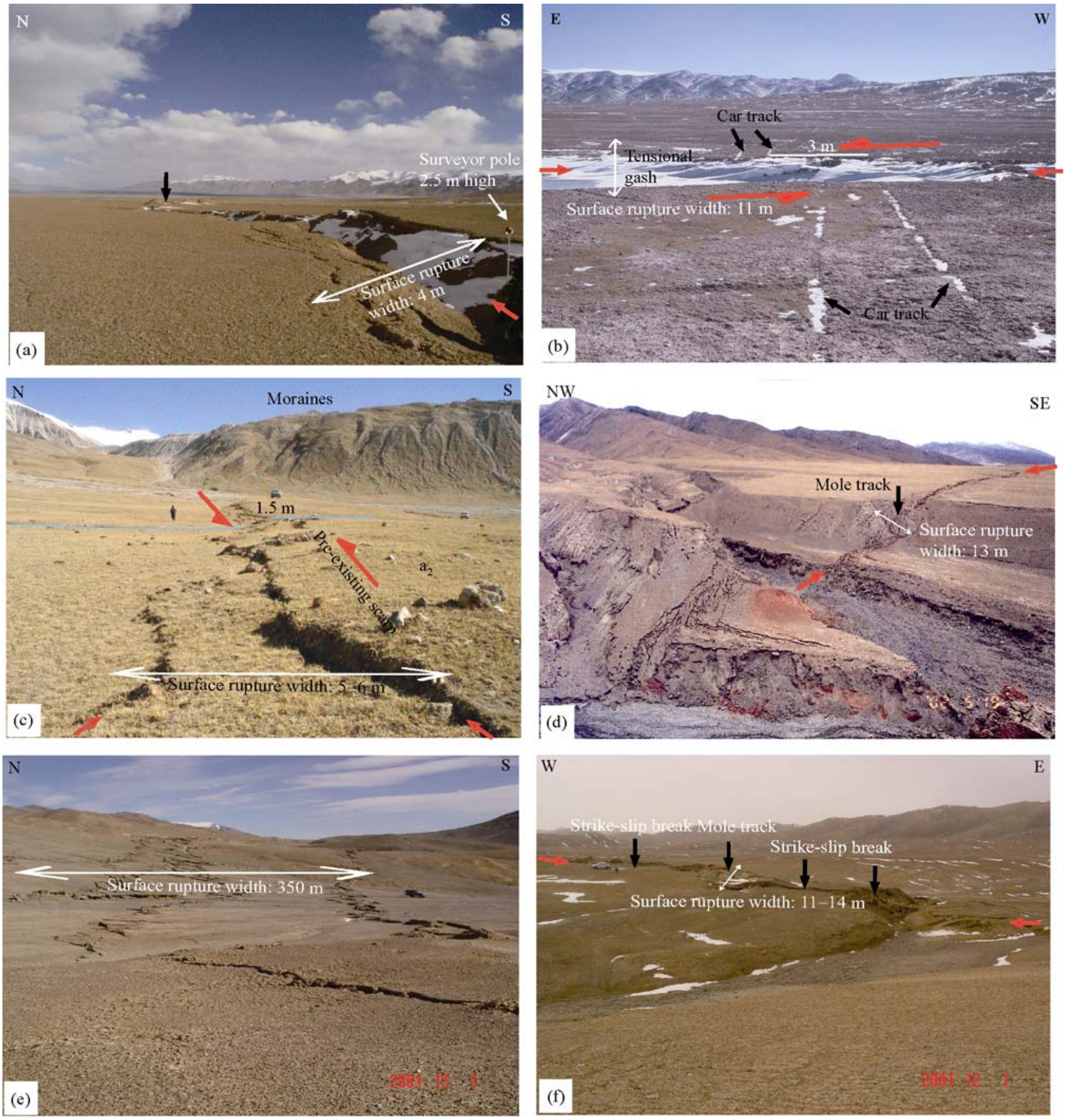

Figure 2 Typical offset geomorphic features on the 2001 Kunlunshan earthquake rupture zone. (a) A 4 m wide tensional gash at the west end of the western section; (b) an 11 m wide tensional gash that sinistrally offset car tracks about 3 m on the middle part of the western section; (c) north dipping transtensional surface breaks on the middle section at the southwestern piedmont of the Bukadaban Peak; (d) offset terraces of various levels that are sinistrally offset on the eastern section for about 6 km to the west of the outlet of the Hongshui River; (e) configuration of the stepover of the 350 m wide secondary strike-slip breaks on the eastern section, to the northeast of the Kusaihu Lake; (f) en echelon strike-slip breaks and mole tracks in the stepover on the eastern section.

left-lateral displacement is about 1.5 m, and the normal vertical offset is 0.2 m to ~0.3 m (Figure 2(c)). Westward, close to the Taiyang Lake, the section is characterized by step-like normal breaks accompanied by the occurrence of hot springs, displaying predominant transtensional faulting. At the southern piedmont of the Bukadaban Peak, a surface rupture gap of about 20 km long exists between the middle and eastern sections (Figure 1). The eastern section includes the main rupture section for the 2001 Kunlushan earthquake. It has a more complex structure than the western and middle sections (Figure 2(d)–(f)). The eastern section consists mainly of en echelon strike-slip breaks and transtensional breaks. Mole tracks and tensional gashes at various scales have developed in the stepovers. Coseismic left-lateral displacement along this section is 4 m to ~5 m on average. This section can be described as a pure strike-slip faulting section.

According to the geometric structures of the earthquake surface rupture zone, the main rupture section or the eastern section can be further divided into 4 subsections (Figure 1). From west to east, they are the Hongshuihe subsection (C-1), Kusaihu subsection (C-2), Yuxifeng subsection (C-3) and Yuzhufeng subsection (C-4), respectively[10,18]. Among them, the Hongshuihe subsection (C-1) initiates from the south of the glacial lobe at the eastern piedmont of the Bukadaban Peak (35.989°N, 92.283°E) in the west, connecting with the NE-trending middle section, and terminates at about 6 km east of the Hongshui River (35.889°N, 92.283°E), forming a right stepover of about 1.4 km wide with the strike-slip faulting strand of the Kusaihu subsection (Figure 3). The subsection has a general strike of 100°±10° and a total length of 115 km, and it can be assigned to a pure strike-slip faulting subsection with a distinct linear breaking feature. It consists of en echelon strike-slip breaks, transtensional breaks and tensional breaks, along which the coseismic displacement reaches 3m to ~5 m on average. The Kusaihu subsection (C-2) starts from the outlet of the Hongshui River (35.872°N, 92.225°E) in the west, extends eastward along 95°±10° direction for about 76 km, and terminates at (35.814°N, 92.950°E) in the east. The subsection consists of two sub-parallel strands, southern and northern strands, with about 2 km apart from each other (Figure 4). The northern strand is a normal faulting strand at the southern piedmont of the Kunlun Mountains, along which the coseismic vertical displacement is 0.5—1 m. The southern strand offsets left-laterally the colluvial and lacustrine sediments on the northern shore of the Kusai Lake, and can be assigned to strike-slip faulting strand. Along the southern strand, the coseismic left-lateral displacement is 4±1 m on average with a maximum value of 7.2 m. The two sub-parallel normal faulting and strike-slip faulting strands show a coseismic rupture partitioning on the Kusaihu subsection due to local extensional component induced by anticlockwise diversion of the subsection strike from N100º±10ºE for about 5º (Figure 4). The

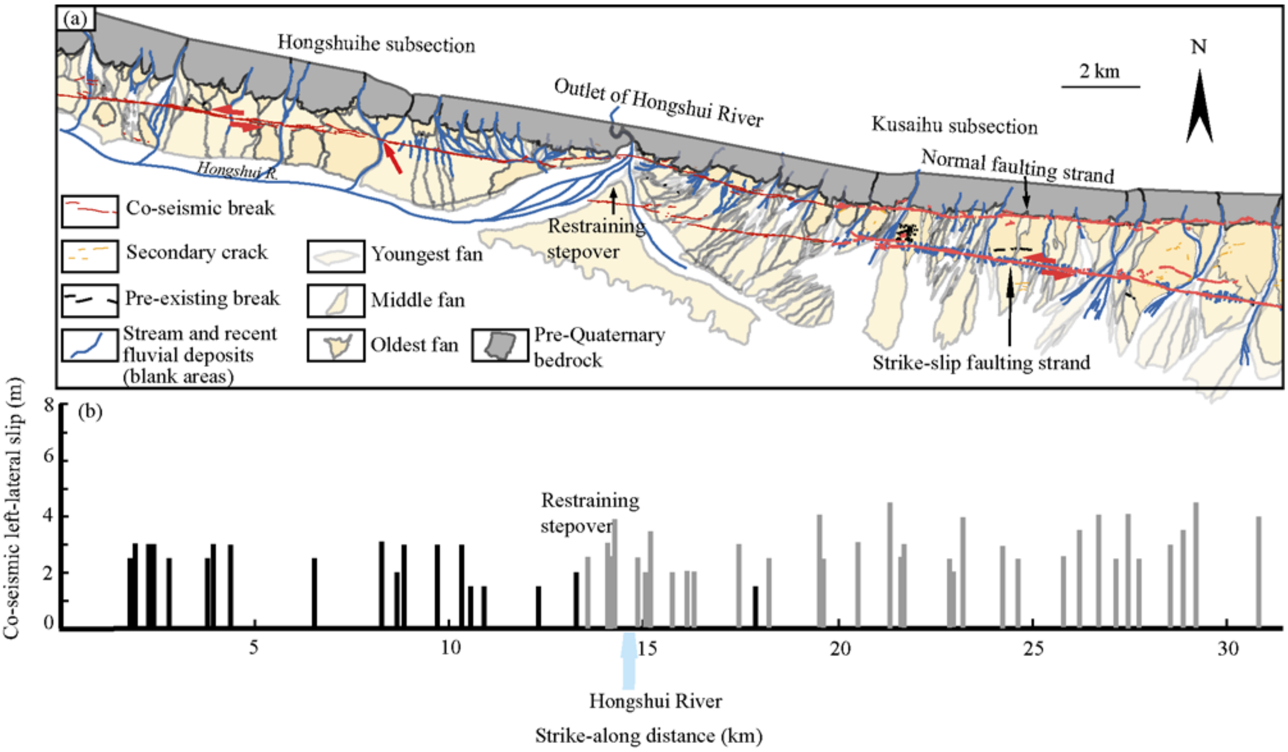

Figure 3 (a) Structure of the restraining stepover between the Hongshuihe and Kusaihu subsections on the eastern section of the Kunlunshan earthquake surface rupture zone at the outlet of the Hongshui River interpreted from Ikonos images; (b) strike-along distribution of the coseismic left-lateral displacement (black lines on the Hongshuihe subsection and grey lines on the Kusaihu subsection).

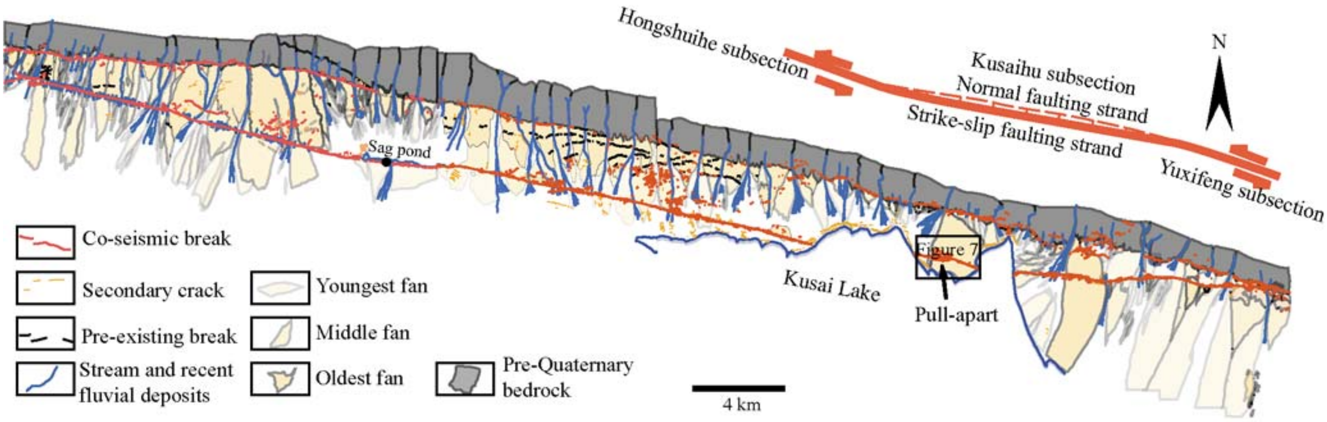

Figure 4 Detailed strip map of the surface breaks to the north of the Kusai Lake and surface rupture partitioning (the northern strand is a normal faulting rupture with coseismic vertical offset of about 1 m while the southern strand is a pure strike-slip faulting with coseismic left-lateral displacement of about 5—6 m; Inset map on right upper corner shows the interpretation of rupture partitioning pattern during the earthquake.

Yuxifeng subsection (C-3) starts in the west from the junction of the southern and northern strands of the Kusaihu subsection (35.814°N, 92.950°E), and ends in the east at Dahonggou (35.848°N, 93.513°E). The subsection has a general strike of 100º±10º with a length of about 60 km, and consists of a series of en echelon strike-slip breaks. Stepovers are well developed between the en echelon strike-slip breaks, with 2 km overlapping. Besides, the reverse faulting breaks also exist locally. Maximum coseismic horizontal displacement along this subsection reaches up to 7—8 m, which is the largest offset ever measured along the 2001 Kunlunshan earthquake surface rupture zone. The Yuzhufeng subsection (C-4) is located at the easternmost end of the eastern section of the Kunlunshan earthquake surface rupture zone. The subsection starts from Dahong Gully in the west, extends eastward for about 112 km, and ends at (35.550°N, 94.800°E) in the east. It has a general strike of 106°±5°, diverging southward for about 6° from the general strike of the Yuxifeng subsection. This subsection can be described to a strike-slip faulting with reverse component, along which the coseismic horizontal displacement is about 2.5 m on average with a maximum value of about 4 m.

It should be pointed out that although the Hongshuihe (C-1), Kusaihu (C-2), Yuxifeng (C-3) and Yuzhufeng (C-4) subsections on the eastern section of the 2001 Kunlunshan earthquake rupture zone are longer than the middle and western sections (Figure 1), the size of the section boundary structures for the western, middle and eastern sections are significantly larger than those for the subsections. For example, the discontinuous stepover between the western and middle sections is about 2.7 km wide and 6.7 km long, and that between the middle and eastern sections is about 5 km wide and 21.5 km long. Moreover, the adjacent sections are quite different in strike and mechanical property: the western section is a NWW-trending pure strike-slip faulting section, the middle one can be tectonically assigned to an NE-trending transtensional faulting section developed in the pull-apart basin in the left stepover between the eastern and western sections, while the eastern section is a NWW-trending pure strike-slip faulting section again. The size of stepovers between the sections are close to the minimum width of about 4 km which is enough for stopping the strike-slip rupturing propagation[23−28].

The size of the subsection boundary structures along the eastern section is relatively small. For example, the discontinuous stepover between the Hongshuihe and Kusaihu subsections is only 1.2 km wide, while the boundary structures between the subsections appear to a local variation in the combined features and mechanical properties of the surface ruptures due to the slight diversion of their general strike. Therefore, the division of the 2001 Kunlunshan earthquake surface rupture zone into the western, middle and eastern sections based on the significant differences in the strike and mechanical properties of the surface rupture zone as well as size of the section boundary structures corresponds to the first order segmentation of the earthquake surface rupture zone. This may imply that the 2001 Kunlunshan earthquake is composed of three relatively independent seismic rupturing events, in good agreement with results based on teleseismic body wave inversion by using multi-branched fault model[29,30]. Initial rupture occurred on the western section, characterized by pure strike-slip-faulting focal mechanism and then propagated bilaterally on the western section while the rupture propagated in the pull-apart basin for about 20 s, beginning with a focal mechanism of normal-faulting mechanism. Later the rupture continued to expand along the eastern section alone in about 30 s, characterized by strike-slip-faulting focal mechanism. According to the empirical relationship between the earthquake magnitude (M_w) and the length of the strike-slip surface rupture zone (L): M_w=5.02+1.19log L[31], it can be inferred that the western, middle and eastern sections might correspond to M_w=6.8, M_w=6.2 and M_w=8.0 rupturing events, respectively. Among them, the rupturing event M_w=8.0 occurring on the eastern section is the main shock of the Kunlunshan earthquake, and its magnitude (M_w) calculated from the length of the surface rupture zone seems to be overestimated. In fact, it should be less than M_w7.8. Moreover, the subdivision of the eastern section indicates that the main shock of the Kunlunshan earthquake is further composed of at least four subevents: from west to east, the magnitudes of those subevents are M_w=7.5, M_w=7.2, M_w=7.1 and M_w=7.4, respectively, inferred from their surface rupture lengths.

2 Width of a single surface break and its controlling factors

Field investigations and measurements of the earthquake surface ruptures by using a Total Station along the transtensional section (middle section) and along the pure strike-slip section (western and eastern sections), show that the width of an individual surface break, such as tensional break, transtensional break, strike-slip break, tensional gash or pull-apart basin and mole track, is limited. This may indicate that the earthquake surface rupture is characterized by deformation localization.

2.1 Strike-slip break

Strike-slip breaks are the main rupture unit of the Kunlunshan earthquake surface rupture zone, usually in left-stepping or right-stepping en echelon to form surface rupture strands. Tensional gashes or pull-aparts are usually developed in the left stepovers of the en echelon strands, while mole tracks in the right stepovers of the en echelon strands (Figure 2). The structure of the strike-slip break itself, in fact, is rather simple, and its width is very narrow.

At the 2894 km milestone of the Qinghai-Tibet Highway and along its western side extent, the earthquake surface rupture zone consists of a series of nearly east-west trending right-stepping strike-slip breaks. Mole tracks of 1—1.5 m high have developed in the right stepovers. Here the coseismic left-lateral displacement is 3.5—4 m, and the width of a single strike-slip break is only several meters, but becomes 8—15 m if the mole tracks in the stepover are included. At the site where the surface rupture crosscuts the Qinghai-Tibet Highway, the surface rupture splits in several secondary breaks, and its width reaches 32.5 m[7]. Similarly, the widths of the strike-slip breaks at other sites are also very limited, ranging from 11 m to 14 m (Figure 2(d) and (f)). Besides, along the eastern bank of the Hongshui River, the Kunlun fault is observed to cut all the terrace risers, among which the T_2/T_1 riser is left-laterally offset by about 6 m, T_3/T_2 riser by about 30±2 m, and the T_4/T_3 rise about 63±2 m (Figure 5(a)). The maximum cumulative displacement of the drainage system flowing on the T_4 terrace is larger than 100 m (Figure 5(a)). Moreover, detailed strip mapping indicates that the coseismic left-lateral displacement on the T_4 terrace is 3—3.5 m, while the width of the surface rupture zone here ranges from ten more meters to 23 m (Figure 5(b) and (c)). The extreme example is observed at a site on the western section (35.942°N, 90.411°E), where the surface ruptures are very simple, consisting of right-stepping NWW-trending secondary strike-slip breaks. The coseismic left-lateral displacement here is 1.7 m, and the widths of the secondary breaks are only 1—2 m, and about 4—5 m if taking the width of the adjacent stepover between the en echelon strands into account[18].

2.2 Transtensional break

Transtensional break refers to a strike-slip break with normal component, and is commonly observed along the Kunlunshan earthquake surface rupture zone. The middle section of the earthquake surface rupture zone to the southwestern piedmont of the Bukadaban Peak is a typical transtensional break zone. Here the surface rupture is superimposed on a preexisting north-facing fault scarp. On the basis of field measurements, the coseismic left-lateral displacement along this section is determined to be 1.5 m while the coseismic vertical offset to be 0.3 m, and the maximum width of the surface rupture is

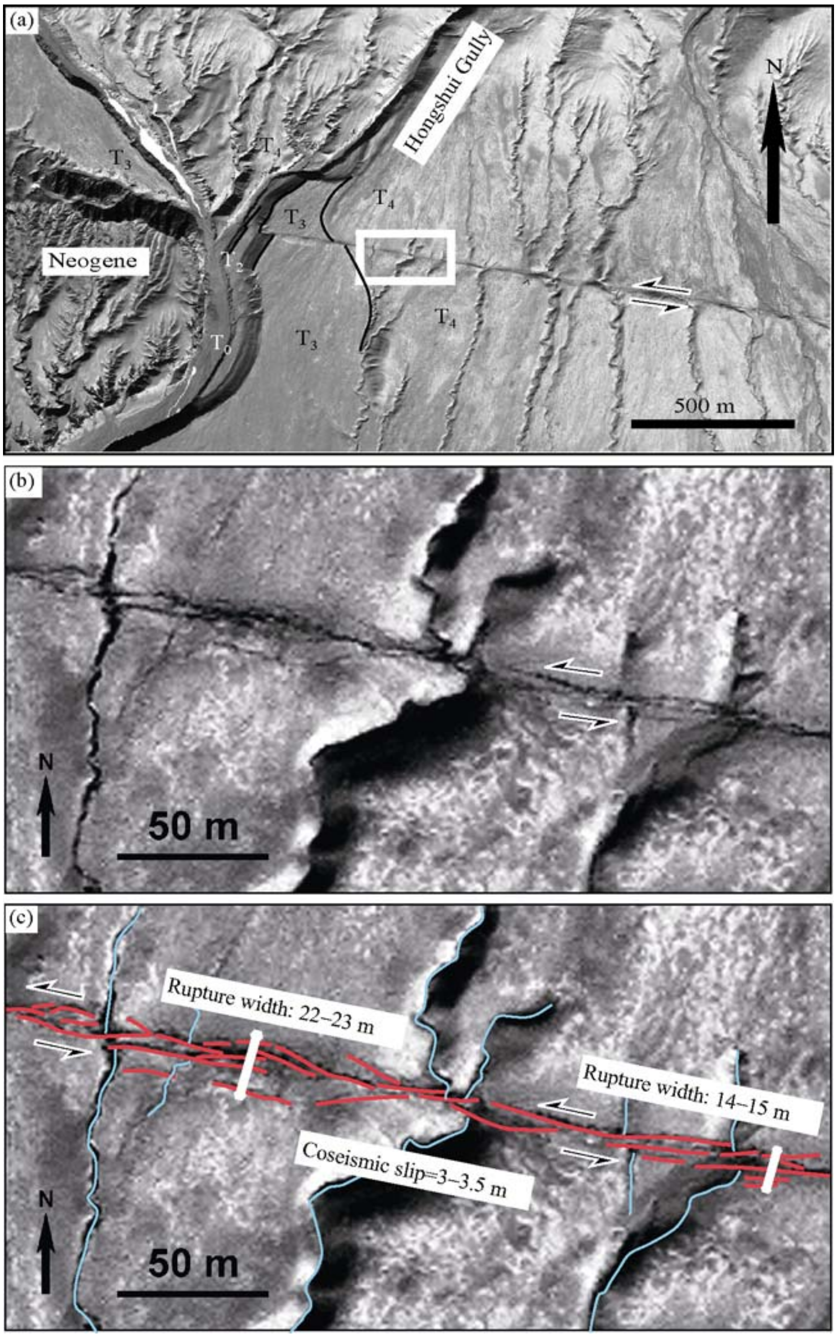

Figure 5 Localization of pure strike-slip surface rupture of the Kunlunshan earthquake nearby Hongshui Gully. (a) Offset geomorphic features along the Kunlun fault from Ikonos images; (b) local satellite images showing the deformation localization of the surface rupture; (c) detailed interpretation map of the deformation localization of the surface ruptures.

only 5—6 m (Figure 2(c)). At a site (35.932°N, 90.469°E) on the western section, where a maximum coseismic left-lateral displacement of about 4.5 m is observed, the transtensional rupture zone strikes NW and consists of several transtensional breaks facing each other to form a pull-apart furrow of 1.5 m in depth. Here the maximum width of the surface rupture zone is only 7 m (Figure 6(a)).

2.3 Tensional break and tensional gash

The combination of tensional breaks usually make up a tensional gash (Figure 2(a) and (b)), including pull-aparts developing in the left stepovers between en echelon strands. Commonly, the width of a tensional break or tensional gash is from several meters to 30 m wide. For example, at one site (35.925°N, 90.510°E) on the western section, there exists an open tensional gash,

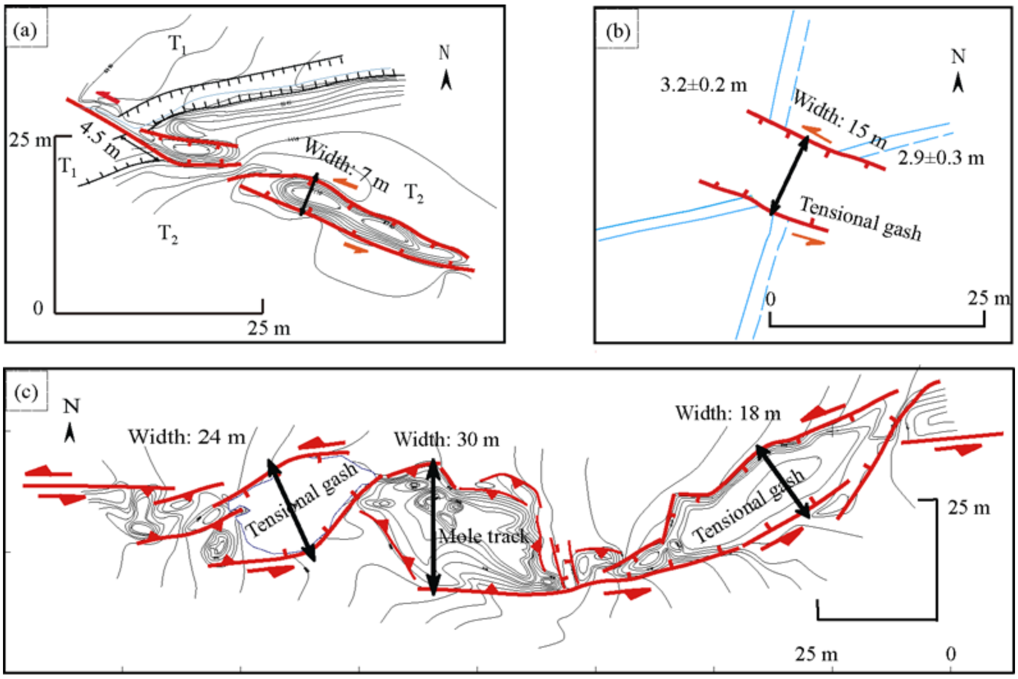

Figure 6 Measured topographic map showing surface rupture pattern and its width. (a) Transtensional breaks at site (35.932°N, 90.469°E); (b) tensional gash at site (35.925°N, 90.510°E); (c) composite surface breaks at site (35.925°N, 90.522°E).

offsetting two crossing car tracks by about 2.9—3.2 m in left-lateral sense. Its width is about 15 m (Figure 6(b)). Nearby this site, the surface rupture zone consists of a series of en echelon strike-slip breaks, tensional breaks, tensional gashes or pull-aparts and mole tracks and the widths of two tensional gashes are also limited, and measured to be 18 m and 24 m, respectively (Figure 6(c)).

It should be pointed out here that the width of the tensional gash, and especially the width of the pull-apart depends strongly on the width of the stepover itself. For example, nearby the epicenter a left stepover between two en echelon strike-slip breaks reaches to about 350 m wide. Tensional or transtensional breaks are well developed within the stepover, while outside the stepover, few similar breaks exist (Figure 2(e)). On the southern pure left-lateral strike-slip faulting strand of the Kusaihu section north of the Kusai Lake, there exists a 600 m-long, 250 m-wide and 20 m-deep pull-apart basin (92.767°E, 35.817°N). At this site, the surface breaks are strictly controlled by the geometric structures of the seismogenic fault, while tensional breaks and transtensional breaks are localized mainly in the pull-apart basin and its adjacent areas (Figure 7). Moreover, the earthquake surface rupturing pattern here displays *in-situ* recurrence behavior for surface-rupturing earthquakes, resulting in accumulation of various left-lateral strike-slip displacement on alluvial fans or terraces formed in different periods. For example, the cumulative left-lateral displacements of the T_2/T_1, T_3/T_2, and T_4/T_3 risers on both sides of the pull-apart basin, including the coseismic horizontal displacement produced by the 2001 Kunlunshan surface ruptures, are 96±10, 195±20, and 340±20 m, respectively. In addition, along the shore of the Kusai Lake to the east of the pull-apart basin, the 2001 Kunlunshan earthquake ruptures left-laterally offset the lake terrace T^{l}_{1} by about 4.6 m, while at the same site, the cumulative left-lateral displacement of the eastern edge of T_4 alluvial fan reaches up to 92±10 m. All these phenomena indicate that the earthquake surface rupture zone displays a basic characteristic of deformation localization.

2.4 Mole track or pressure ridge

Mole track or pressure ridge is a discontinuous tectonic unit to link en echelon strike-slip breaks, which is commonly observed along the earthquake surface rupture zone. It refers to various tectonic uplifts developed in a restraining stepover between en echelon strike-slip faults. The scale (length, width and height) of the mole track is closely related to the size of the stepover (width and overlap length) and the horizontal displacement along the en echelon strike-slip faults controlling the stepover.

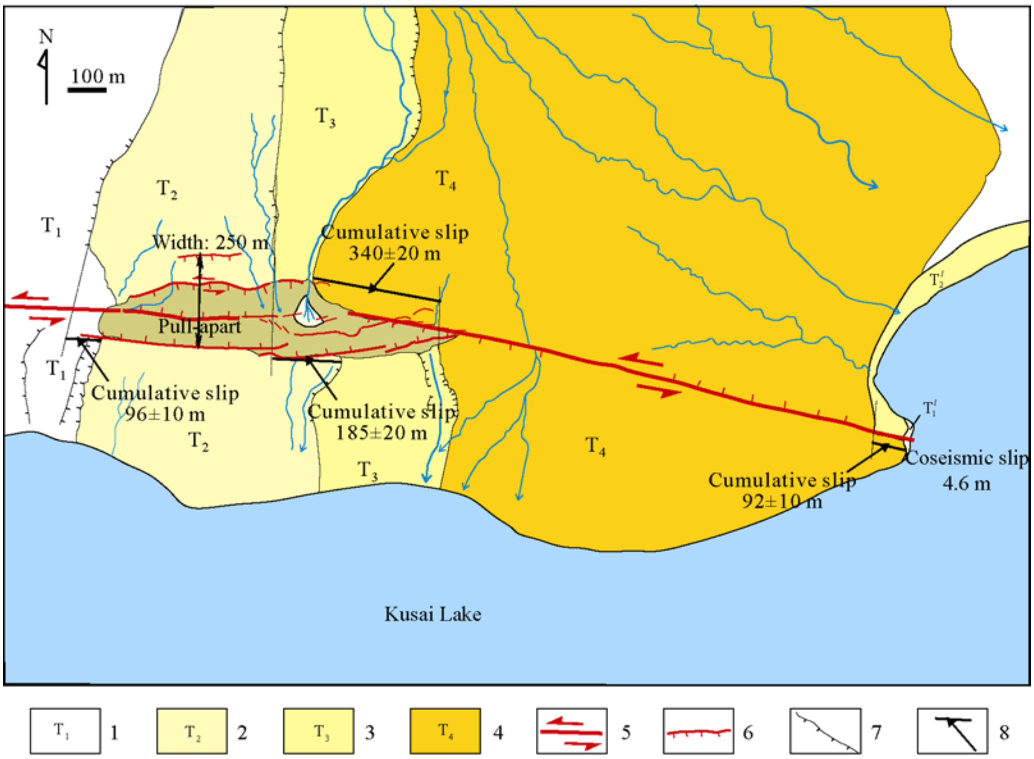

Figure 7 Simplified map showing the *in-situ* recurrence behavior of the surface-rupturing earthquakes and cumulative displacement on the southern strike-slip faulting strand around a pull-apart basin, northern shore of the Kusai Lake (location is marked in Figure 4). 1, Flood plain/T_1 terrace; 2, T_2 terrace; 3, T_3 terrace; 4, T_4 terrace; 5, strike-slip fault; 6, normal fault; 7, terrace riser; 8, left-lateral displacement.

Usually a mole track is several meters to dozens of meters wide, and dozens of centimeters to 1—2 m high (Figure 2(d) and (f)). A mole track on the western section was measured to be about 30 m in width with coseismic uplift of about 1.5m (Figure 6(c)). Mole track group may be developed in many stepovers, but both sides of the stepover still display strike-slip offset and may dissect sinistrally the drainage systems and terrace risers in various orders (Figure 8). When the size of the stepover is relatively large, with a width of several hundred meters or up to 1 km, the coseismic uplift produced by a single earthquake is rather small (Figure 3). However, a local tectonic uplift could be formed after occurrence of many surface-rupturing earthquakes, displaying a cumulative effect of the tectonic uplift.

The above measurements show that the structure of a single break or two en echelon strike-slip breaks is relatively simple, and its width normal to the strike of the breaks is relatively narrow, being only several meters or less than 30 m in general. This result is consistent with that reported before[7]. The widths of the tensional gash, pull-apart and mole track in the stepover are mainly controlled by the size of the stepover itself, and should be equal to the stepover width plus 15 m on both sides.

3 Width of surface rupture zone and its controlling factors

Field investigation and interpretation of Ikonos images show that surface rupture-and-slip partitioning exists on the Kusaihu subsection of the 2001 Kunlunshan earthquake surface rupture zone at the north of the Kusai Lake. Here the surface rupture zone splits into two 2-km-apart strands (Figure 4): a pure strike-slip faulting strand in the south and a normal faulting strand in the north. The southern pure strike-slip faulting strand consists of a series of en echelon basic surface break units, and the width of a single break is only several meters to ten-odd meters. In the stepovers between en-echelon strike-slip or transtensional breaks, the width of the surface rupture zone depends on the width of the stepover itself. The large left stepover or pull-apart along the southern strand can be taken as an example (Figure 7). The northern normal faulting strand is located along the piedmont of the Kunlun Mountains. Coseismic vertical offset is ~1 m, and its continuity is worse than that of the

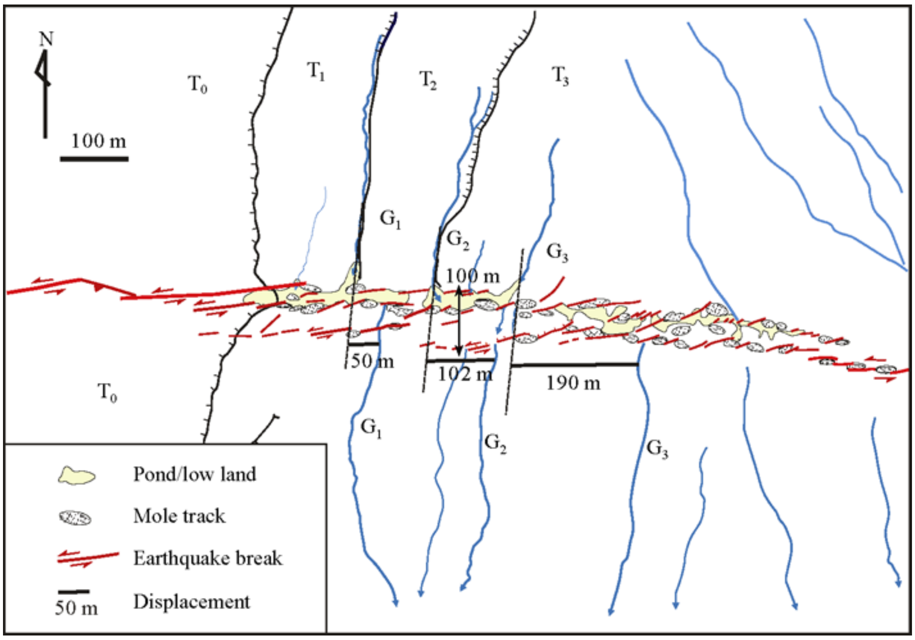

Figure 8 Mole track group in the overlapped stepover on the Yuzhufeng section of the Kunlunshan earthquake surface rupture zone. G_1, G_2 and G_3 are numbered gullies, and T_1, T_2 and T_3 the numbered terraces from young to old.

southern pure strike-slip faulting strand (Figure 4). Moreover, many secondary short normal fault scarps are developed in the area between the southern and northern strands. The strike of these short normal fault scarps obliquely crosscuts the strike of the southern strand, but is consistent with the strike of the northern strand. On the basis of field investigation and interpretation of Ikonos images, we conclude that only some of the short normal fault scarps were reactivated during the 2001 Kunlunshan earthquake as indicated by red line in Figure 4, when the most of them were not reactivated as indicated by black line in Figure 4. This may show that these short surface normal fault scarps are secondary surface breaks, reflecting relatively strong deformation of the block seized by the normal faulting strand and the pure strike-slip faulting strand on both sides. Therefore, excluding these small and short secondary breaks, we may show that the surface ruptures along the northern shore of the Kusai Lake are localized on both the southern pure strike-slip faulting strand and the northern normal faulting strand. This phenomenon may reflect near-surface rupture-and-slip partitioning of the transtensional faulting of several kilometers deep under a local tensional condition in a releasing jog between the Hongshuihe and Yuxifeng subsections (inset map at right upper corner of Figure 4).

Moreover, at the northeast corner of the Kusai Lake (35.767ºN, 93.323ºE) on the Yuxifeng subsection, the coseismic horizontal displacement reaches up to 7.6 m. At this site, the structure of the earthquake surface rupture zone is rather complicated, and its width ranges from dozens of meters to several hundred meters, significantly wider than the other subsections. This can be attributed to the fact that the en echelon sub-parallel secondary strike-slip or transtensional rupture zones are mostly right-stepping. Overlapping length and width of the stepover are relatively large. All these factors have caused the surface rupture zone wider than a single break[18].

Therefore, the width of the earthquake surface rupture zone depends mainly on the geometric structures and kinematics of the seismogenic fault at different depths. Among them, the partitioning of strike-slip ruptures and dip-slip ruptures may occur along the strike-slip fault with normal or reverse component, resulting in the widening of the surface rupture zone. Along the Kusaihu subsection of the 2001 Kunlunshan earthquake surface rupture zone, there exists normal faulting and pure strike-slip faulting strands, and hence the width of the surface rupture zone may reach up to ~2 km. Although many secondary surface breaks were developed in between those two strands resolved from the main ruptures, the slip is mostly concentrated along the normal faulting strand and on the pure strike-slip faulting strands, each being 30 m or less in width The surface rupture zone displaying rupture-and-slip partitioning is still characterized by deformation localization.

4 Discussion and conclusion

The above mentioned data show that the 2001 Kunlunshan earthquake occurring on the Kusaihu segment of the Kunlun fault, northern Tibet Plateau, has a complicated rupturing pattern. The earthquake surface rupture zone can be divided into three relatively independent surface rupture sections: the 26 km-long western strike-slip section, the 16 km-long middle transtensional section, and the eastern strike-slip section. They correspond to M_w=6.8, M_w=6.2 and $M_w\leqslant$7.8 rupturing events, respectively. Among them, the $M_w\leqslant$7.8 event on the eastern section, is the main shock of the Kunlunshan earthquake, could be subdivided into four subevents. The analysis of the structures and width of the individual breaks and the surface rupture zones shows that the width of either a single break or their assemblage is limited: the width of a single break ranges commonly from several meters to 15 m, with a maximum value not more than 30 m, while the width of the surface rupture zone depends mainly on its geometric structures, and especially on the width of stepover between the secondary en echelon surface rupture zones. Rupture-and-slip partitioning usually occurs along a surface rupture zone with vertical component, resulting in sub-parallel pure strike-slip faulting surface rupture zone and normal or reverse faulting surface rupture zone. Width of these two individual zones displays a characteristic similar to that displayed by the width of a single surface rupture or its simple assemblage. Secondary surface breaks may occur between the two zones, but are much fainter than the surface rupture zone itself. It is known from the exploration of the trapped wave into the Kunlun fault being 20 km to the west of the Kunlun Pass, that the width of the subsurface rupture zone as defined by low-velocity and low-quality Q factor is only 250－300 m[32,33]. Therefore, it can be concluded that the surface rupture zone generated by the 2001 Kunlunshan earthquake occurring on the Kusaihu segment of the Kunlun fault displays a hoghly localized deformation. Moreover, the surface rupture zones produced by the 1937 Huashixia earthquake (M7.5) occurring on the Anyemaqen segment, the 1963 Tosonhu earthquake (M7.0) on the Alghu segment and the 1997 Mani earthquake (M7.7) on the Margaichaka segment of the Kunlun fault are all characterized by the localized rupture[34－36].

The earthquake surface rupture zone is the instantaneous main manifestation of permanent tectonic deformation transformed from GPS- and InSAR-monitored present-day crustal elastic strain, when the latter has been accumulated to a certain degree. Observations of offset geomorphic features and geologic investigation reveal that the late Quaternary left-lateral slip rate of the Kunlun fault, which has experienced many surface rupturing earthquakes, reaches 11.5±2.0 mm/a[37]. The left-lateral shear strain rate across the Kunlun fault determined from GPS measurements in the range of about 400-km-wide on both sides of the fault is 10－12 mm/a[38,39]. Despite existence of other late Quaternary active faults, such as the Fenghuoshan fault, Erdaogou fault, Wudaoliang fault, and the central Kunlunshan fault within the range of about 400 km on both sides of the Kunlun fault[40,41], no significant east-west trending slip rate on these faults is observed from the GPS velocity profile across those active faults. The elastic strain accumulation seems to be only concentrated on the Kunlun fault[39]. Moreover, GPS observation has shown that the 2001 kunlunshan earthquake deformation is distributed mainly along the surface rupture zone, and is dominated by left-lateral strike-slip with additional normal or reverse motion, according to local variations of azimuth of the fault. In addition, the amplitudes of post-seismic eastward creeping motion of the block south to the surface rupture zone near or away from the fault and their attenuation with time as well as the eastward motion of the block north to the surface rupture zone are very similar[42]. This similarity are indicative of a rigid block model, may show a block creeping model, especially for the southern block of the Kunlun fault. Hence, the Quaternary geologic slip rate is consistent well with the GPS-monitored slip rate. These results incorporated with the above mentioned deformation localization of the earthquake surface rupture zone may indicate that the tectonic deformation in between the Bayan Har and Qilian-Qaidam blocks is concentrated mainly on the Kunlun fault, appearing to be strike-slip faulting along a limited width, while the blocks themselves display a block motion. Moreover, this may indicate that the upper crust of both the southern and northern blocks of the Kunlun fault in the northern Tibetan Plateau does not experience continuous internal deformation, but appears to be a localized left-lateral strike-slip faulting along the Kunlun fault. The earthquake surface rupture zone is about 30 m wide, and the width of the surface rupture zone composed of various break units depends mainly on the width of its geometric structure itself.

In addition, as for the outcropped strike-slip fault with a potential for generating earthquakes, if we can correctly locate the fault traces, using trenching technique across the fault, and determine the maximum width of its near-surface geologic deformation zone, then the width of the fault-surface-rupture hazard zone that needs to keep away from major project, residential and lifeline constructions can be determined as the maximum width of the near-surface geologic deformation zone plus 15 m on both sides[43], as suggested by the "Alquist-Priolo Earthquake Fault Zoninig Act", formulated by the State Government of California, USA in 1994. This would help to prevent the direct destruction caused by large coseismic surface ruptures along the strike-slip faults. The width of the near-surface geologic deformation zone for buried active fault depends not only on the geometric structure of the fault itself, but also on the thickness of the overlaying Quaternary sediments and on the amplitude of the coseismic displacements during the earthquake[44]. This problem comes down to a rather complicated prediction of upward rupturing propagation on the buried fault, which would deserve further investigation.

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