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Co-seismic mole track structures produced by the 2001 Ms 8.1 Central Kunlun earthquake, China

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Abstract

Extensive co-seismic mole track structures have been observed along a 400-km-long surface rupture zone associated with the 2001 Ms 8.1 Central Kunlun earthquake, north Tibet. The mole track structures appear in an angular-ridge pattern, which resembles an angular triangle-shaped frame, and in a bulge pattern forming small flat hillocks. The mole tracks are developed within alluvial fans, river channels, and bajada, and form a linked array of structures along the rupture zone. The angular-ridge structures resulted from flexural slip folding and faulting of frozen alluvial deposits and surface ice, whereas bulge-type structures developed by squeezing-up of unconsolidated to weakly consolidated alluvial sediments. The mole tracks generally formed within the co-seismic rupture zone due to contraction in the right-bend and right-stepover areas between sinistral shear faults and are controlled by the pre-existing fault and fold structures along the left-lateral strike-slip Kunlun fault.

Keywords: Central Kunlun earthquake; Co-seismic surface rupture zone; Mole track; Strike-slip Kunlun fault; Push-up structure

1. Introduction

The magnitude (Ms) 8.1 Central Kunlun earthquake occurred on 14 November 2001, in the central Kunlun mountain area, north Tibet (Fig. 1), and produced extensive surface rupturing over a distance of ~400 km along the pre-existing Kunlun fault zone (Fig. 1; Lin et al., 2002, 2003). The co-seismic surface rupture was dominated by strike-slip faulting with a large left-lateral displacement up to 16.3 m (Lin et al., 2002). Both the rupture length and maximum displacement are the largest ever reported among the co-seismic surface rupture zones generated by continental earthquakes. The general deformation characteristics of the co-seismic rupture zone (herein named the Kunlun rupture zone) have been described in Lin et al. (2002, 2003). In this study, we focus our attention on the structural and morphologic characteristics of co-seismic mole track structures produced by the 2001 Central Kunlun earthquake along the strike-slip Kunlun fault zone. The field investigations were carried out during the month immediately after the earthquake. The timely observations provide precise data on the deformation characteristics and geometry of the co-seismic surface ruptures and the mole track structures that are used in this paper.

Koto (1893) first described mole track structures associated with the strike-slip faulting produced by the 1891 Ms 8.0 Mino-Owari earthquake, Japan: "the line of the fault appears on the surface like a rounded ridge of soft earth 30 to 60 cm high and, as I have already stated, resembles very much the pathway of gigantic mole". Other studies (e.g. Ambraseys and Zátopek, 1969; Deng et al., 1986; Bergerat et al., 2003) have described similar structures that are consistent with the modern definition of mole structures as "A small, geologically short-lived ridge, 30–60 cm high, formed by the humping up and cracking of the ground where movement along a large strike-slip fault occurred in heavily alluviated terrain" (Jackson, 1997). The recognition and identification of the mole track structures has the potential to provide new insight into understanding the fault geometry of co-seismic surface rupture zones and seismogenic structures along large strike-slip faults.

This paper presents an unusual example of co-seismic mole track structures found along the 400-km-long Kunlun

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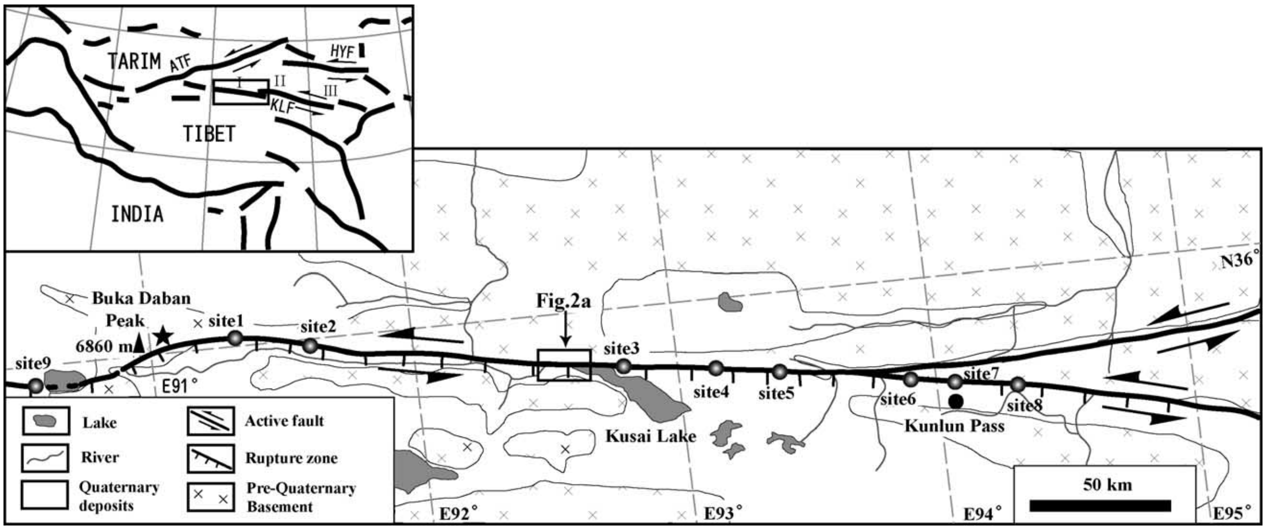

Fig. 1. Geological map showing the major strike-slip faults in northern Tibet and the Kunlun rupture zone. KLF: Kunlun fault; I: Kusai Lake segment; II: Xidatan segment; III: Tuosuo Lake segment; ATF: Altyn Tagh fault; HYF: Haiyuan fault. Sites 1–9 indicate the locations where the mole tracks were observed along the Kunlun rupture zone. Star shows the epicenter of the 2001 Ms 8.1 Central Kunlun earthquake determined by Earthquake Research Institute (ERI), University of Tokyo (Lin et al., 2003).

rupture zone of the strike-slip Kunlun fault zone and discusses their deformation mechanisms and the relationship between the mole tracks and the geometric structures of the co-seismic surface rupture zone by using our own field observations and Landsat ETM (Enhanced Thematic Mapper, 30 m resolution), SPOT (Satellite Pour I'Observation de la Terre, 10 m resolution) and IKONOS (1 m resolution) images. By studying the co-seismic mole track structures, we can examine the affects of surface geology on the deformation traits of the co-seismic surface ruptures and the relationship between the geometric structures of the co-seismic surface ruptures and pre-existing fault and fold structures.

2. Outline of the Kunlun fault zone and co-seismic rupture zone

The Kunlun fault zone is located within the Kunlun mountains of north Tibet at an average elevation of >4500 m (Fig. 1). The ~1200-km-long fault zone strikes E–W to WNW–ESE, and is one of the major faults along which strike-slip accommodates the eastward extrusion of Tibet (Molnar et al., 1987; Avouac and Tapponnier, 1993; Meyer et al., 1998; Van der Woerd et al., 1998, 2002; Chen et al., 1999). From studies of satellite images, cosmogenic surface dating (Van der Woerd et al., 1998, 2002), and trenching surveys (Zhao, 1996), the Kunlun fault zone has been inferred to be active in the Holocene with a left-lateral strike-slip rate of 9–12 mm/yr during the past 30–40 ka.

The 400-km-long surface rupture zone associated with the 2001 Ms 8.1 Central Kunlun earthquake is developed mostly along the western segment of the Kunlun fault zone (Fig. 1; Lin et al., 2002). The rupture zone extends from the east of Kunlun Pass, through the northern side of Kusai Lake, and terminates at the west of Buka Daban peak (Fig. 1) as a straight lineament on the Landsat images (Lin et al., 2002; Fig. 2a). Surface ruptures are distributed within a zone ranging in width from 3 to 550 m, but generally from 5 to 50 m, which is composed of distinct shear faults, extensional cracks, and mole tracks (Lin et al., 2002). Along the trace of the surface rupture zone, recent topographic features such as glaciers, moraines, stream channels, gullies, and roads are sinistrally offset by up to 16.3 m, but generally between 4 and 8 m (Lin et al., 2002). Field observations and analysis of the teleseismic waveform reveal that the earthquake had nearly pure strike-slip mechanics and that the temporal and spatial displacement distribution and rupture process are controlled by the pre-existing geological structures of the Kunlun fault zone (Lin et al., 2003).

2.1. Mole track structures

Mole tracks are widely developed upon the alluvial fans, bajada, and frozen stream channels along the 2001 co-seismic surface rupture zone (Fig. 1). Both the co-seismic mole tracks and pre-existing push-up structures can be recognized on the Landsat ETM, SPOT and IKONOS images taken after the 2001 Central Kunlun earthquake (Figs. 2 and 3). The pre-existing push-up structures are generally developed within the south-sloping alluvial fans along the Kunlun fault zone where the displacements are accumulated in the southward flowing rivers and gullies (Fig. 2a; Lin et al., 2003). The axis of the push-up structure strikes N50°W to E–W, generally oblique to the general trend of the Kunlun fault with a clockwise angle of 5–35°. The push-up structures appear like a rounded ridge with a

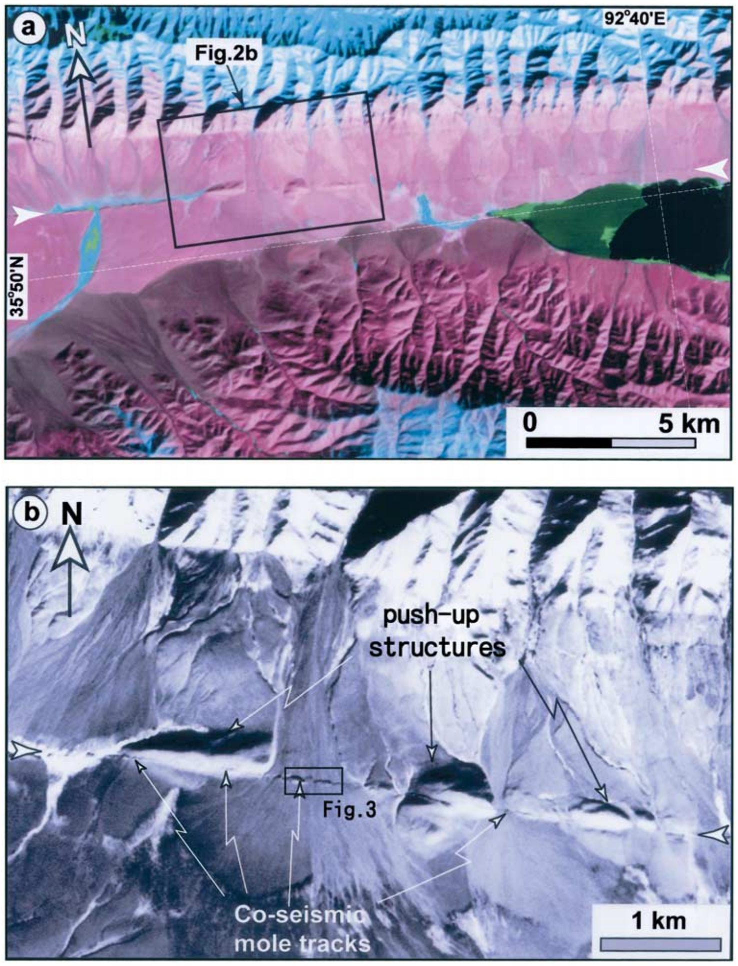

Fig. 2. (a) Landsat ETM and (b) SPOT images, showing the mole tracks along the co-seismic surface rupture zone west of Kusai Lake. (a) Landsat ETM image west Kusai Lake taken in December 2001 after the 2001Central Kunlun earthquake. (b) SPOT image taken in June 2002. Large white arrows indicate the general trends of co-seismic surface rupture zone.

gentle slope on the alluvial fans, which are linked as a hillocky range. Co-seismic ruptures and mole tracks are intermittently distributed along the Kunlun rupture zone and are clearly shown to be partially duplicated on the pre-existing push-up structures on the south-sloping alluvial fans (Fig. 2). The mole tracks are generally duplicated on one side of the pre-existing push-up structures and form an array parallel to these. The pre-existing push-ups vary in size from several metres to one kilometre both in length and width, and up to 50 m in height. In contrast to the pre-existing push-ups, the co-seismic mole tracks are generally <50 m in length and width and <3 m in height, and are widely found on all the south-sloping alluvial fans including the youngest alluvial fans and iced water in the current stream channels (Figs. 2–4). Although the co-seismic mole tracks partially duplicate the pre-existing push-up structures, it is easy to distinguish the co-seismic mole tracks and the pre-existing push-up structures in the field by the pristine occurrences and deformation characteristics of the co-seismic mole tracks as shown in Figs. 4 and 6.

The co-seismic mole tracks are commonly observed along the whole 400-km-long Kunlun rupture zone (Fig. 1). The sites observed in the field that contain mole tracks record between 3 and 8 m of sinistral displacement, with no observable vertical offset. The mole tracks were generally developed in a contraction area where two parallel right-stepping strike-slip faults overlap (Figs. 3–5). As shown in the high resolution IKONOS image (Fig. 3), the mole tracks are observed in the jog area between two main right-stepping co-seismic surface ruptures (Fig. 3b) where co-seismic displacements of 3–4 m were observed (Lin et al., 2002, 2003). The mole track axes are oblique to the strike of main surface ruptures (strike-slip faults) and oblique to the general trend of the co-seismic rupture zone with a clockwise angle of 5–50° (Fig. 3b). This oblique relationship between the mole track axes and main surface ruptures can also be observed in the field (Figs. 4 and 6). A lot of extensional cracks showing an irregular pattern occurred in the hinge area, along which no distinct left-lateral displacement can be observed (Figs. 3 and 4).

The co-seismic mole tracks can be divided into two types by their structural characteristics: angular-ridge pattern and

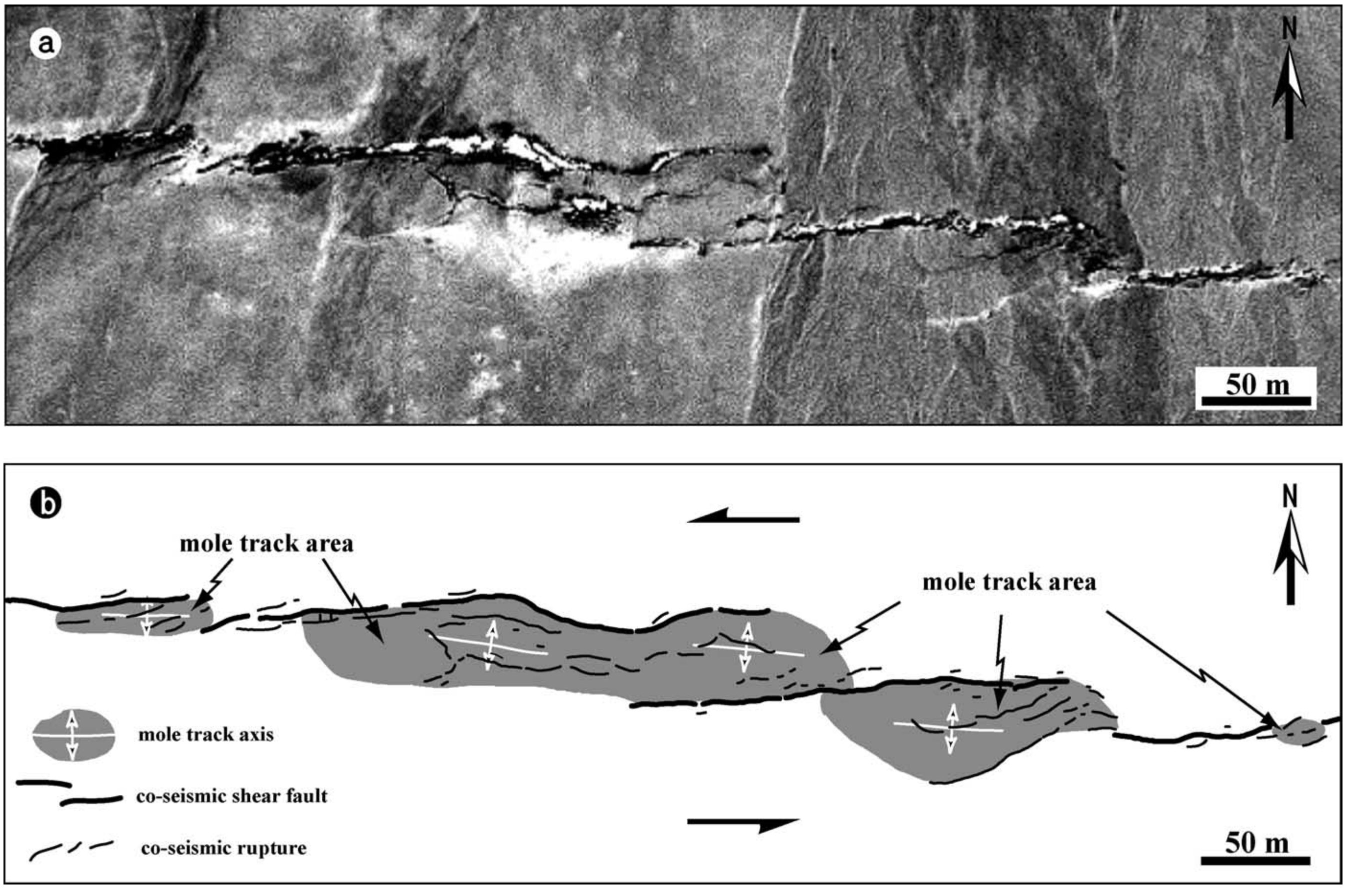

Fig. 3. (a) IKONOS image and (b) corresponding sketch of the area around typical co-seismic mole track structures west of Kusai Lake. The co-seismic mole tracks occurred in the jog area between the right-stepping en échelon shear faults. See Fig. 2b for detailed locality. IKONOS image was taken in March 2002 after the 2001 Central Kunlun earthquake.

bulge pattern, both forming a linked row with the distinct shear faults (Figs. 4 and 6; Table 1). The ridges are typically 50 cm to 1 m in height although locally up to 3 m, 1–10 m in width, and 2–15 m in length. The ratio of the length to width of a single mole track ranges from 1 to 10. The axis of the single mole track is oblique to the general trend of the surface rupture zone by a clockwise angle of 5–25°. The angular-ridge type of mole track resembles an empty angular triangle-shaped frame in cross-section, and consists of opposing ramped-up rigid plates (Fig. 4a–d). Along the axis of the mole track, the top soil layer was separated from the underlying coarse-grained deposits and locally offset by faulting (Fig. 4b–d). This type of mole track was generally developed in alluvial deposits of interbedded clay, fine-grained sand, sandy-gravel and gravel (Fig. 4) and also within active stream channels. A typical stratigraphic section was observed at Site 7 (Fig. 5). The top 50-cm-thick layer consists of clay and fine-grained sand, which was frozen. Under the top soil layer, an 80-cm-thick unfrozen and unconsolidated sandy gravel layer was sandwiched between the top frozen layer and lower permafrost layer. The top soil layer and river water frozen as rigid plates 30–50 cm thick covering the underlying loose (unfrozen) alluvial deposits were ruptured and pushed up if they were bedded rocks (Fig. 4). This type of mole track was also reported in the co-seismic rupture zones associated with the 1978 Ms 7.0 Izu-Oshima Kinkai earthquake (Kano and Murata, 1998) and the 1995 Ms 7.2 Kobe earthquake

Table 1
Deformation characteristics of the co-seismic mole tracks

Mole track type	Deformation characteristics			
	Morphology	Surface geology	Length:width	Angle (°)[a]
Angular-ridge type	Angular triangle shaped frame	Frozen soil and alluvial deposits, iced water in stream channels	1–10	5–25
Bulge-type	Bulge shape like small hillock	Unfrozen soil, coarse-grained alluvial deposits	1–5	10–50

[a] Clockwise oblique angle between the co-seismic mole track axis and general trend of the co-seismic rupture zone.

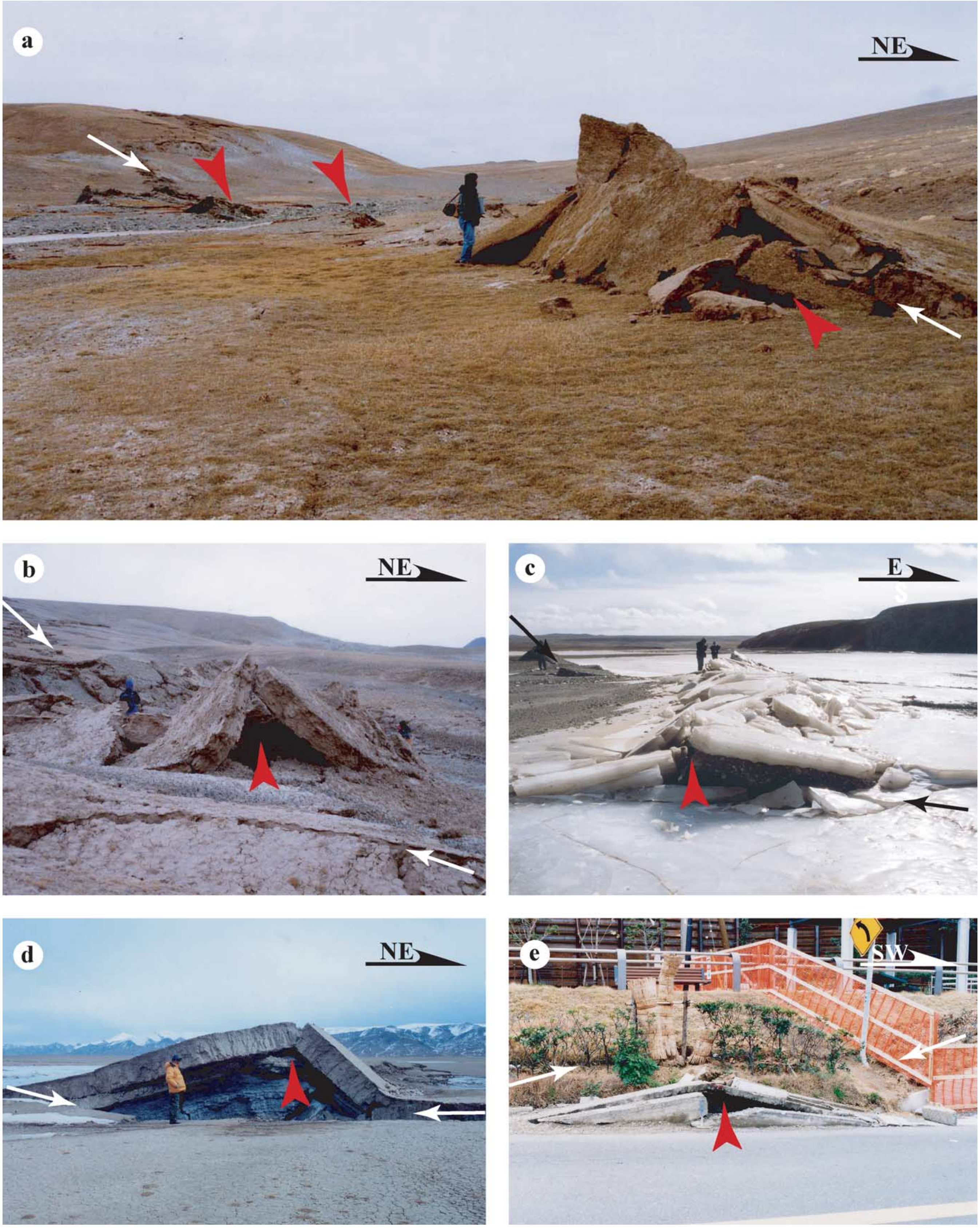

Fig. 4. Typical occurrences of the angular -ridge type mole tracks. (a)–(d) The angular-ridge type mole tracks observed in alluvial fans (a and b, Site 7), frozen stream channel (c, Site 6), and lake (d, Site 9, from Seismological Bureau of Xinjiang Uygur Autonomous Region). (e) The angular-ridge type mole track produced in the Nojima surface rupture associated with the 1995 Ms 7.2 Kobe earthquake. See Fig. 1 for localities of outcrop sites. The long arrows indicate the general trends of shear faults that show a right-stepping en échelon pattern. Red arrows indicate the ridge of mole track structures.

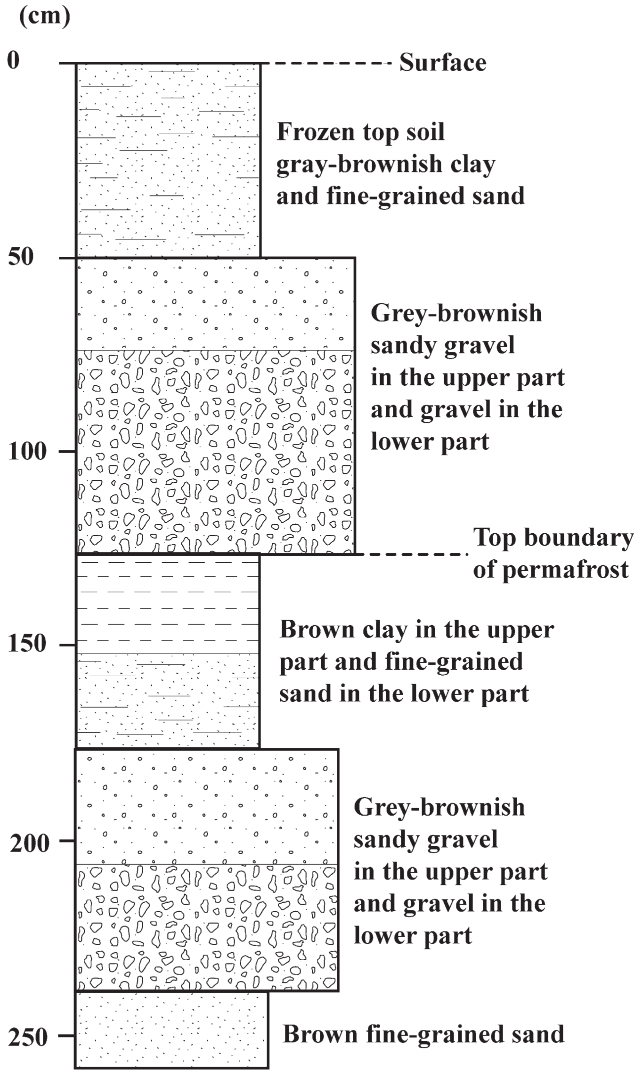

Fig. 5. Stratigraphic section of the alluvial deposits at Site 7. Note that the top soil layer was frozen as a rigid plate. The permafrost was observed below at a depth of 1.3 m.

(Fig. 4e; Lin and Uda, 1996) where the thin concrete layer on the road was ruptured and locally pushed up.

Bulge-type mole tracks were developed within unconsolidated to weakly consolidated and unfrozen coarse-grained alluvial deposits. The bulges are conspicuous as small hillocks in the bajada and are easy to recognize in the field (Fig. 6a–c). In contrast to the angular-ridge type mole tracks, the ridges of bulge-shaped mole tracks are flat topped and vary from 30 cm to 1 m in height, 1–15 m in width, and 2–30 m in length. The bulge-type mole track axis is oblique to the general trend of the surface rupture zone by a clockwise angle of 10–50°. The ratio of the length to width of a single mole track is 1–5. Similar bulge-shaped lines of disturbed earth have also been described associated with the following earthquakes: the 1891 Ms 8.0 Mino-Owari earthquake, Japan (Koto, 1893), the 1967 Ms 7.1 Mudurnu Valley earthquake, west Anatolia, Turkey (Ambraseys and Zátopek, 1969), the 1973 Ms 7.6 Luhuo earthquake, China (Deng et al., 1986), and the 1999 Ms 7.6 Chi-Chi (Taiwan) earthquake (Lin et al., 2001a,b). Such bulge-shaped ridges contain numerous tension cracks within the hinge region of the bulges, and formed within unconsolidated to weakly consolidated deposits that were deformed and flexurally folded.

3. Discussion

Strike-slip fault zones, both observed in the field and developed experimentally, generally consist of several subparallel shear faults and related extensional and contractional structures (e.g. Segall and Pollard, 1980; King, 1986; Yeats et al., 1997). Push-up and mole track structures are one of the typical contraction structures within strike-slip fault zone and surface ruptures where contractional overstepping dominates. Both types of mole tracks described here occurred in the alluvial deposits, which show a flexural-slip folding pattern. In the angular-ridge type of mole tracks, the top layer is composed of clay and fine-grained sand that was frozen as a rigid plate. A typical angular-ridge type mole track was reported in the co-seismic surface rupture zone associated with the 1995 Ms 7.2 Kobe earthquake (Fig. 4e), where the concrete plate of a ditch was pushed up (Lin and Uda, 1996). This shows that the concrete plate was compressed, detached and flexurally slipped along the boundary between the rigid concrete and underlying soft soil. On the basis of the above description and documents, we conclude that the angular-ridge type of mole tracks were generated by flexural-slip folding and faulting of the top rigid layer as illustrated in Fig. 7a. In this type of mole track, the near-surface deformation mainly occurred by slip along the layer between the frozen top layer (rigid plate) and the underlying unfrozen deposits, where no change in thickness of the top layer occurred. In the bulge-type of mole tracks, however, the top layer is composed of unconsolidated to weakly consolidated coarse-grained alluvial deposits. A typical bulge-type mole track was reported in the Chelungpu surface rupture zone associated with the 1999 Ms 7.6 Chi-Chi (Taiwan) earthquake, which formed in a rice field (Fig. 6d) where the surface layer is composed of water-rich clay-mud that was folded (Lin et al., 2001a,b). This indicates that the area where the mole track formed was compressed and shortened. We conclude, therefore, that the bulge-type mole tracks were produced by folding and cracking of layers of loose deposits, as shown in Fig. 7b. The flexural-slip folding and faulting could also occur in the bulge-type mole track structures. The immediate investigations after the earthquake allow us to recognize the difference between the angular-ridge type and bulge-type mole tracks. When we visited there in the summer of 2002, the angular-ridge type mole tracks had collapsed due to dissolution of the top frozen layer.

The geometry and structures of rupture zones provide important constraints on the co-seismic rupturing process

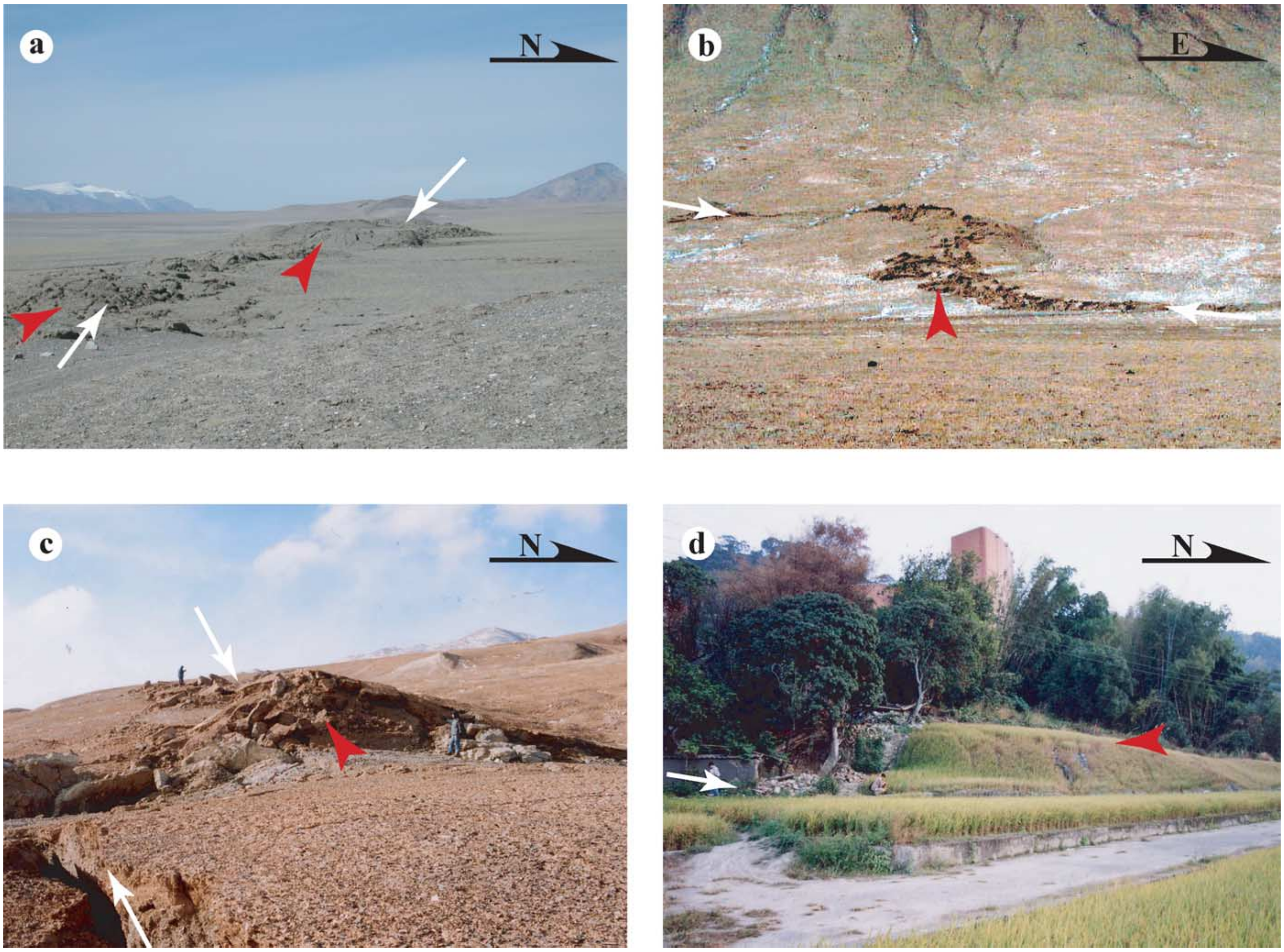

Fig. 6. Typical occurrences of the bulge-type mole tracks. (a)–(c) The bulge-type mole tracks observed in the bajada where the deposits were unconsolidated to weakly consolidated and unfrozen (a: Site 3, b and c: Site 4). (d) The bulge-type mole track produced in a rice field within the Chelungpu surface rupture zone associated with the 2001 Ms 7.6 Chi-Chi (Taiwan) earthquake (Lin et al., 2001a). The long arrows indicate the general trends of shear faults that show a right-stepping en échelon pattern. Red arrows indicate the general trend of the mole track structures.

and kinematics of the seismic source fault (Lin et al., 2001a, b, 2003) and the relationship between the co-seismic ruptures and the pre-existing fault structures (e.g. Johnson et al., 1994; Lin and Uda, 1996; Lin et al., 2001). The geometry of strike-slip faults is dependent on the arrangement (pinnate or en-échelon), on step sense (left-step or right-step), and on the rank (small faults within larger faults) of the subparallel faults (Deng et al., 1986). Strike-slip faults generally include bends and stepovers (Twiss and Moores, 1992). Bends are curved parts of a continuous fault trace that connect two noncoplanar segments of faults. Stepovers are regions where one fault ends and another en échelon fault of the same orientation begins. Field observations and focal mechanism solutions show that the earthquake had a nearly pure strike-slip mechanism along the Kunlun fault zone (Lin et al., 2002, 2003). Based on the morphological characteristics, geological structures, displacement distributions and inversion results of the teleseismic waveform, the Kunlun rupture zone is divided into four distinctive segments having lengths from 70 to 130 km, which are bounded by stepovers including push-up and pull-apart structures (Lin et al., 2003). Push-up structures are also widely developed in the bend and stepover regions within the pre-existing strike-slip Kunlun fault (Van der Woerd et al., 2002). The stepovers of push-up structures between the tens- to 100-km-long segments impede rupture, and are where small co-seismic displacements were observed (Lin et al., 2003). It is well known that there is a close relation between the morphologic characteristics of surface ruptures and the rupture process (e.g. King and Nabelek, 1985; Lin, 1997; Lin et al., 2003). Rupture in individual earthquakes apparently is limited to regions between jogs in faults (King, 1986). Field observations and inversion results show that the deformational characteristics, co-seismic displacement distributions and the rupture process of the Central Kunlun earthquake were controlled by the pre-existing geological structures along the Kunlun zone (Lin et al., 2003). The pre-existing push-up structures developed

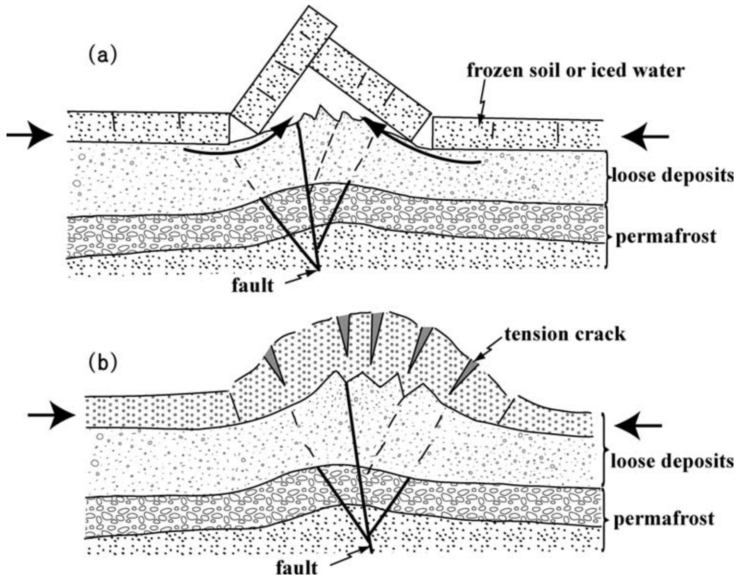

Fig. 7. Sketches showing the sections of (a) angular-ridge type and (b) bulge-type mole tracks. Both types of mole tracks were produced by horizontal compression (indicated by short arrows). The angular-ridge type mole track was produced by flexural slip folding and faulting of the top rigid layer. The bulge-type mole track formed mainly by folding and shortening of the unconsolidated to weakly consolidated alluvial deposits.

within the alluvial fans, which are inferred to have formed in the period between the last glacial and the Holocene (20–10 ka; Van der Woerd et al., 2002) along the Kunlun fault zone, show that pushing-up deformations have accumulated during the last 20 ka. It is estimated that large earthquakes (Ms ~ 8) recurred the Kunlun fault zone with characteristic left-lateral strike-slip of 9–12 m every 800–1000 years, and that the slip-rate in the last 30–40 ka is 10–12 mm/yr (Zhao, 1996; Van der Woerd et al., 1998, 2002). The co-seismic mole tracks formed during the 2001 Ms 8.1 earthquake are generally <50 m in length and width. The pre-existing push-up structures up to 1 km in size within the alluvial fans, therefore, can be inferred to be developed by more than 20 Ms ~ 8 earthquakes during the last 20 ka, and the recurrence interval of Ms ~ 8 seismic events are <1 ka. This is not in contradiction to that inferred from the recent activity of the Kunlun fault zone. Based on the deformation characteristics of push-up structures, the maximum displacement and the magnitude were inferred for historical earthquakes along the strike-slip Leirubakki fault zone in Iceland (Bergerat et al., 2003).

The Kunlun rupture zone also consists of en-échelon ruptures and steps between subparallel faults on a metre- to kilometre-scale (Lin et al., 2002, 2003). The mole tracks generally formed in the right-bend and right-stepover areas between the left-lateral strike-slip faults along the Kunlun rupture zone (Figs. 3, 4c and 6b and c). Because of a synthetic movement of faults on both sides of bend and overstep, a contractional environment forms around the bend and overstep areas (Figs. 3 and 8). Compressive structures such as folds, thrusts and uplifts commonly appear in such an area. The mole track is typical of such compressive structures (Figs. 3 and 8). The Kunlun rupture zone, therefore, provides an exceptional opportunity to study the geometry of co-seismic rupture structures along a large strike-slip fault for further understanding the relationship between the fault geometry and rupturing process.

4. Conclusions

Field observations reveal that the co-seismic mole track structures are widely developed along a 400-km-long surface rupture zone of the strike-slip Kunlun fault zone associated with the 2001 Ms 8.1 Central Kunlun earthquake, north Tibet. The mole track structures can be divided into two types by their geometric patterns: angular-ridge pattern,

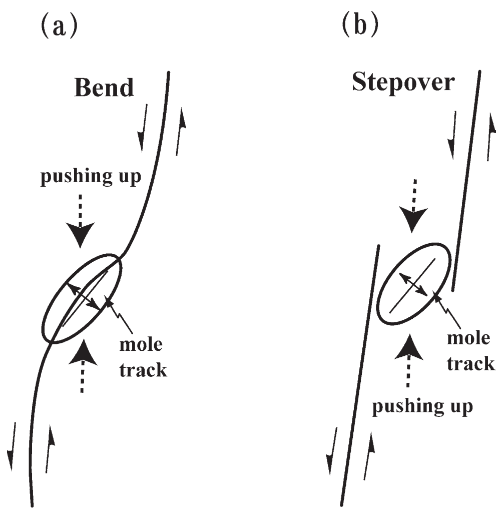

Fig. 8. Formation mechanism of mole tracks at (a) a contractional bend and (b) a stepover along strike-slip faults. Long arrows indicate the dominant shear sense of the strike-slip fault. Pairs of dashed arrows indicate the contraction across the bend and overstep. Long line within the oval indicates the hinge line of mole track.

which resembles a angular triangle-shaped frame, and bulge-type pattern, which develops as a small hillock. The angular-ridge type mole tracks formed by flexural slip folding and faulting of frozen alluvial deposits and surface iced water, whereas the bulge-type mole tracks are developed by squeezing-up of unconsolidated alluvial deposits within the co-seismic Kunlun rupture zone due to contraction in the right-bend and right-stepover areas between left-lateral faults. Both the co-seismic mole tracks and the pre-existing push-up structures are developed within the alluvial fans formed during the last glacial to Holocene time and are controlled by the pre-existing fault structures.

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