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Coseismic surface deformation and engineering damage associated with the large strike-slip faulting: Lessons from the 2001 Mw 7.8 Central Kunlun earthquake

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Abstract: We analyzed coseismic surface deformations associated with the 2001 Mw 7.8 Central Kunlun earthquake, which occurred on 14 November 2001 along the west (Kusai Lake) segment of the left-lateral strike-slip Kunlun fault in northern Tibet, China. Field investigations and analyses of satellite remote sensing imagery indicate that a 400-km-long coseismic rupture zone occurred along the pre-existing Kunlun fault zone. The coseismic surface rupture zone is mainly composed of sinistral shear faults, tensional cracks, mole tracks, and pull-apart sag ponds and grabens. Width of the coseismic surface rupture zone ranges from several meters to 1 km. This earthquake caused damage to the highway between Golmud and Lhasa, base of the Qinghai-Tibet railway, and temporary housing for railway construction workers. It also triggered snow and glacier avalanches. The analyses of coseismic surface deformational features and engineering damage provide us useful experience to evaluate possible engineering damage associated with future great earthquakes on strike-slip faults in highly populated and industrialized regions. Furthermore, it also provides us an unusual opportunity to understand the growth of geomorphic features due to repeated large seismic events along an active strike-slip fault.

Keywords: Coseismic surface deformation, strike-slip faulting, permafrost region, engineering damage, Central Kunlun earthquake

1. Introduction

The Mw 7.8 Central Kunlun earthquake occurred along the western part of the Kunlun fault system on 14 November 2001 in northern Tibet, China (Fig. 1). The Kunlun fault system is one of large strike-slip faults in the northern Tibet, which extends for about 1600 km between 87°E and 105°E (e.g., Tapponnier and Molnar, 1977; Van der Woerd *et al*., 2002). There are no reports of casualties or great damage because strong ground motions from the earthquake were concentrated on a sparsely populated region mostly at over 4,500 meters in the Kunlun Mountains, where the northern boundary of permafrost is located (Zhou *et al*., 1991). It caused slight engineering damage to the base of the Qinghai-Tibet railway and temporary housing for railway construction workers. However, it provides us a unique opportunity to analyze the coseismic surface deformational features and possible engineering damage associated with the large continental earthquakes induced by large-scale strike-slip faulting.

The previous studies on the 2001 Central Kunlun earthquake mainly reported strike-slip offsets along the rupture zone and spatial distribution of the coseismic surface rupture zone (Dang and Wang, 2002; Fu and Lin, 2003; Lin *et al*., 2002; Xu *et al*., 2002; Zhao *et al*., 2002). In this study, we describe detailed coseismic surface deformational features along the frozen ground and discuss their potential impact on engineering construction based on the field investigations and analyses of high-resolution satellite imagery.

2. Methods

The 2001 Central Kunlun earthquake occurred on the high mountainous region (up to 6860 m at the Buka Daban Peak, Fig. 1), crowned by glaciers and moraines with an average elevation above 4,500 m (Lin *et al*., 2002). Therefore, in-situ observations and measurements of coseismic surface deformations are difficult to conduct. Fortunately, high spatial resolution space images available now do have a potential to analyze the coseismic surface deformations produced by strong earthquakes (Fu and Lin, 2003; Fu *et al*., 2003). After the Central Kunlun earthquake, satellite remote sensing data along the surface rupture zone were acquired by the French Systeme Probatoire de 1`Observation de 1a Terre (SPOT) High Resolution Visible (HRV) sensor, and Japanese Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). Spatial resolution of SPOT HRV Pan and ASTER Visible and Near Infrared (VNIR) data are 10 m and 15 m, respectively. All the imageries were geometrically corrected. These remote sensing data were processed using the ER-Mapper software. Contrast stretch was used to enhance the deformational features of the surface rupture zone. Meanwhile, we conducted field investigations along the eastern part of coseismic rupture zone in December 2001, September 2002 and March 2003, after the Central Kunlun earthquake, in order to obtain detailed ground truth data on coseismic deformational features and engineering damage.

3. General features of coseismic surface rupture zone

The Kunlun earthquake resulted from the slip of the Kunlun fault, which is one of large left-lateral strike-slip faults in northern Tibet (See index map in Fig. 1a). Coseismic rupture zone can be recognized on the satellite images (Fig. 2). The trace of surface rupture appears as a single lineament or en echelon lineaments as shown in Fig. 2. A number of typical coseismic deformational features occurred along the coseismic surface rupture zone. We here describe these deformational features in detail as follows.

3.1 Sinistral shear faults and tensional cracks

Sinistral shear faults and tensional cracks are most common coseismic surface deformational phenomena along the coseismic surface rupture zone (Fig. 3). Sinistral shear faults extend N 75° -90° W, whereas en echelon or subparallel extensional cracks are oblique to the shear faults with a strike varying from N 50° to 75° E (Fig. 3a). In the field, we can observe the shear faults displaying en-echelon pattern or single strand of distinctive rupture (Fig. 4). Tensional cracks such as sinkhole and tensile cracks occurred along the surface rupture zone (Fig. 5). Fault scarps with a height ranging from 50 cm to 3 m can be observed along the south-facing or north-facing shear faults. Actually, the fault scarps were mostly produced by the left-lateral strike-slip displacement of south-sloping alluvial fans (Fig. 6a). This is a common characteristic of strike-slip faults (Allen *et al*., 1991; Baljinnyam *et al*., 1993), and has been termed scissoring (Yeats *et al*., 1997). Moreover, the shear faults displaced alluvial fans, terraces, stream channels and modern moraines left-laterally by 3 to 8 m (Fig. 6). The maximum total lateral displacement across the shear fault zone reaches 16.3 m (Lin *et al*., 2002).

3.2 Mole tracks and pressure ridges

Mole tracks are typical push-up structures along the strike-slip rupture zone (Aydin and Kalafat, 2002; Deng *et al*., 1986; Koto, 1893). The mole tracks are most characteristic deformational structures formed along the Kunlun surface rupture zone, and most of mole tracks show asymmetrical triangular shape (Fig. 7). They mostly occurred on frozen alluvial fans, terraces, frozen lakes and stream channels (Fig. 7). The size of mole tracks varies from 50 cm to 3.5 m high, 1.5 to 6 m wide and 3 to 15 m long. Most of them developed in the pushing-up location between two overlapped parallel or subparallel right-stepping shear faults or bending part of a single shear fault. The coseismic push-up structures (mole tracks) as well as large pressure ridges (up to 2 km in length and several ten meters in height) can be observed clearly on SPOT image (Fig. 8a). In the field, these pressure ridges appear as linear hills, which are composed of Quaternary alluvial deposits (Fig. 8b). These large-scale pressure ridges most likely resulted from cumulative deformations formed by multiple large seismic events during late Quaternary along the strike-slip fault zone.

3.3 Pull-apart sag ponds and grabens

Sag ponds and half-grabens, several meters wide and several ten meters long, occurred along the Kunlun coseismic rupture zone (Fig. 9a). They are mainly formed in releasing bends where two overlapped parallel or subparallel shear faults form an extensional step over (Fig. 9). As a result of growth of small sag ponds and pull apart grabens, large-scale sag ponds and pull-apart grabens several ten meters wide and several hundred meters long are formed along the strike-slip Kunlun fault zone (Fig. 9b). These large sag ponds and pull-apart grabens can be recognized from satellite imagery. Similarly, we can infer that the Kusai Lake is formed as a result of long-term geomorphic growth along the Kunlun fault from its morphotectonic and geometric features (Fig. 1b).

3.4 Liquefaction

Sand boil is a common phenomenon that occurs along the surface rupture zone as a result of liquefaction at shallow depth. Sand and water boils produced by liquefaction were found near lakes and stream channels along the surface rupture zone (Fig. 10). Ice cones a few centimeters in diameter were formed because of the temperature below the freezing point (Fig. 10b).

4. Engineering damage

The highway between Golmud and Lhasa, the base of Qinghai-Tibet railway and temporary housing for railway construction workers have been displaced or damaged during the 2001 Central Kunlun earthquake (Figs. 11 and 12).

The rupture zone cut through the Golmud-Lhasa highway near the mile tablet of 2894 km where the highway was damaged by shear faults (Fig. 11b). Two main shear fractures occurred in a 16-m-wide rupture zone and the lateral offset varies from 0.8 to 1.5 m along the highway. East of the mile tablet of 2894 km, the rupture zone displaced the nearly N-S-extending base of the Qinghai-Tibet railway under construction. The total lateral offset is about 3.3 m across a 9.5-m-wide rupture zone (Fig. 11c). Fig. 12a shows a collapsed wall near Xidatan, 10 km north of the coseismic rupture zone, where the wall toppled down toward NNE. 45 km southwest of the Kunlun Pass, the wall of a temporary building fell down toward SSW (Fig. 12b). At the Kunlun Pass, the memorial tablet of Kunlun Pass fell down toward west. Furthermore, this earthquake has also triggered snow and glacier avalanches near the rupture zone (Fig. 13). For example, glacier avalanches occurred in the southern and northern slopes of the Yuzhu Peak as shown on the satellite imagery and observed in the field (Figs. 13c, 13d and 13e). Snow and glacier avalanches also occurred at the Buka Daban Peak in the western part of the rupture zone (Dang and Wang, 2002).

5. Discussion

5.1 Formation mechanism of mole tracks and pressure ridges on the frozen ground

The push-up structures (mole tracks and pressure ridges) associated with the 2001 Central Kunlun earthquake are one of the most characteristic surface deformational features along the coseismic rupture zone as described in section 3.2 (Fig. 7). This kind of deformational feature commonly occurred along the strike-slip rupture zones worldwide (Aydin and Kalafat, 2002; Bergerat et al., 2003; Baljinnyama *et al*., 1993; Deng *et al*., 1986). The previously reported mole tracks formed by a single seismic event are 30 to 80 cm in height, 50 cm to 1.5 m in width, and 2 to 3 m in length. Large-scale mole tracks produced by the 2001 Central Kunlun earthquake are rare phenomena in the world (Fig. 7). The maximum size is 3.5 m in height, 5 m in width, and over 10 m in length (Figs. 7a and 7b). Bergerat *et al*. (2003) reported that the maximum height of mole tracks is 4.35 m, which was measured in the Holocene lava. However, it is uncertain whether it was produced by a single seismic event or original geomorphic effect of lava flow. Hence it is an interesting question to explain the formation mechanism of these large-scale mole tracks produced by the 2001 Central Kunlun earthquake. The formation of large-scale mole tracks is probably related to two factors: large magnitude of this earthquake (Mw 7.8) and physical properties of deformed sediments. The earthquake has produced approximately 400-km-long coseismic surface rupture zone (Lin *et al*., 2002; Fu and Lin, 2003). It is the longest one among coseismic surface rupture zones produced by intraplate earthquakes ever reported (Lin *et al*., 2002). The Kunlun Mountains is the northern limit of permafrost region in the Tibet Plateau (Zhou *et al*., 1991). Field observations indicate that the mole tracks mostly occurred on frozen fluvial fans, moraines and terraces, which consist of fine soils and pebble layers (Fig. 7). The permafrost horizon can be observed at depth of 1.5 to 3 m. Fig. 14 shows the deformation and shortening caused by mole tracks on the frozen ground. The shortening rate associated with mole tracks is 20~30 % within a zone 3 to 5 m wide (Fig. 14). Obviously, this extensive shortening will produce destructive impact on the engineering construction.

Meanwhile, large-scale pressure ridges, several hundred meters to several kilometers long and several to several tens of meters high, are found along the Kunlun fault zone (Fig. 8). Numerous studies have explained mechanical aspects of the growth of pressure ridges along strike-slip faults (Aydin and Nur, 1982; Deng *et al*., 1986; Segall and Pollard, 1980; Wallace, 1990). For example, Bilham and King (1989) indicated that strain fields that reduce area result in uplift along the strike-slip faults. Some scientists (e.g., King *et al*., 1988; Stein *et al*., 1988) have suggested that relatively small deformations associated with individual earthquakes should accumulate over time to create large fault-bounded geological structures. Similarly, recurrent ruptures of strike-slip faults will increase the size of pressure ridges (Aydin and Nur, 1982). Thus, these large-scale pressure ridges are most likely to result from repeated large seismic events during late Quaternary.

In general, these mole tracks and pressure ridges have not only impact on the engineering construction, but also implication for understanding the long-term growth of geomorphic features along the strike-slip faults.

5.2 Implications for earthquake hazard and mitigation of engineering damage

Along the 2001 Kunlun coseismic rupture zone, the lateral offsets generally range from 3 to 8 m (Fig. 6; Dang and Wang, 2002; Xu *et al*., 2002; Zhao *et al*., 2002), and the maximum total displacement is up to16.3 m (Lin *et al*., 2002). The width of the rupture zone varied from several meters to 500 m (Fig. 4a), up to 1 km (Fig. 2b; Fu *et al*., 2003). Lateral offset caused large damage directly on engineering constructions across the coseismic rupture zone. The highway between Golmud and Lhasa, and the base of the Qinghai-Tibet railway under construction were damaged during the 2001 Central Kunlun earthquake (Fig. 11). This kind of engineering damage caused by the lateral offset also observed for the 1999 Izmit earthquake on the North Anatolian fault (Aydin and Kalafat, 2002) as well as the 2002 Denali fault earthquake in Alaska (Phillips *et al*., 2003). Thus, the engineering constructions should be set back from the rupture zone with a width ranging from several tens to several hundreds of meter. Engineering design of the Qinghai-Tibet railway across the rupture zone has been changed after the 2001 Central Kunlun earthquake. The overhead railway took the place of surface railway in order to avoid the potential engineering hazard.

6. Concluding remarks

The 2001 Mw 7.8 Central Kunlun earthquake provides a good example to analyze the coseismic surface deformational features related to large strike-slip faulting in the permafrost region. Sinistral shear faults, tensional cracks, mole tracks, pull-apart sag ponds and grabens were formed during the strike-slip faulting along the 400-km-long surface rupture zone. The surface ruptures of various scales are characterized by en echelon or subparallel pattern. The large-scale mole tracks due to the deformation of frozen ground are rare deformational features, which show an asymmetric triangular shape. The large lateral offsets ranging from 3 to 8 m, as well as coseismic mole tracks and sag ponds, provide us useful experience to evaluate the possible engineering damage associated with future great earthquakes triggered by the strike-slip faulting in the highly populated and industrialized region. Furthermore, the 2001 Central Kunlun earthquake also provides an unusual opportunity for understanding the relationship between coseismic deformational features associated with individual large seismic events and long-term growth of geomorphic features due to repeated large earthquake events along the strike-slip faults.

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（要　旨）

傅　碧宏・粟田泰夫・狩野謙一・林　愛明・佃　栄吉
大規模な横ずれ断層活動による地表変形と構造物被害：2001 年崑崙山中部地震（Mw 7.8）の教訓
2001 年 11 月 4 日，チベット（西蔵）北部で 2001 年崑崙山中部地震（Mw 7.8）が発生した．著者らは，現地調査と衛星画像解析により，この地震に伴って出現した地表地震断層および変形構造を詳しく解析した．その結果，長さ 400km に達する地表地震断層は，既存の左横ずれ断層である崑崙断層の西部（庫賽湖）セグメントに沿って生じたことが確かめられた．地震断層は幅数mから数 100m，最大 1km の帯状地域をなして出現しており，左ずれ断層（剪断面），引張性割れ目，モールトラック，プルアパート状の断層池，グラーベンなどから構成される．この地震はゴルムド（格爾木）ーラサ（拉薩）間の公路（国道），チンハイ（青海）ーチベット（西蔵）鉄道の基礎，同鉄道従業員の仮設住宅などに被害を与え，さらに，雪崩や氷河の崩壊を引き起こした．この地震に伴う地表地震断層と構造物被害の解析は，人口が多く工業化された地域における，横ずれ断層の活動による大地震の被害を予測・評価する上で，極めて有用な経験となった．また，この地震は，数 m に達するような大きな断層変位の繰り返しによって，横ずれ断層沿いに形成される大規模な変形構造（長さ数 100m～数 km のプレッシャーリッジなど）の成長過程を理解する上でも，またとない機会を提供してくれた．

Fig. 1. (a) Landsat ETM/TM mosaic image of the Kusai Lake segment, Kunlun fault system (indicated by red arrows) in northern Tibet. The location of epicenter (indicated by a yellow star) of the 2001 Mw 7.8 Central Kunlun earthquake was determined by U.S. Geological Survey, and the focal mechanism solution was given by the Earthquake Research Institute, University of Tokyo. ATF: Altyn Tagh Fault, HYF: Haiyuan Fault, KLF: Kunlun Fault in index map. (b) Spatial distribution of the surface rupture zone produced by the 2001 Central Kunlun earthquake. Modified from Fu and Lin (2003).

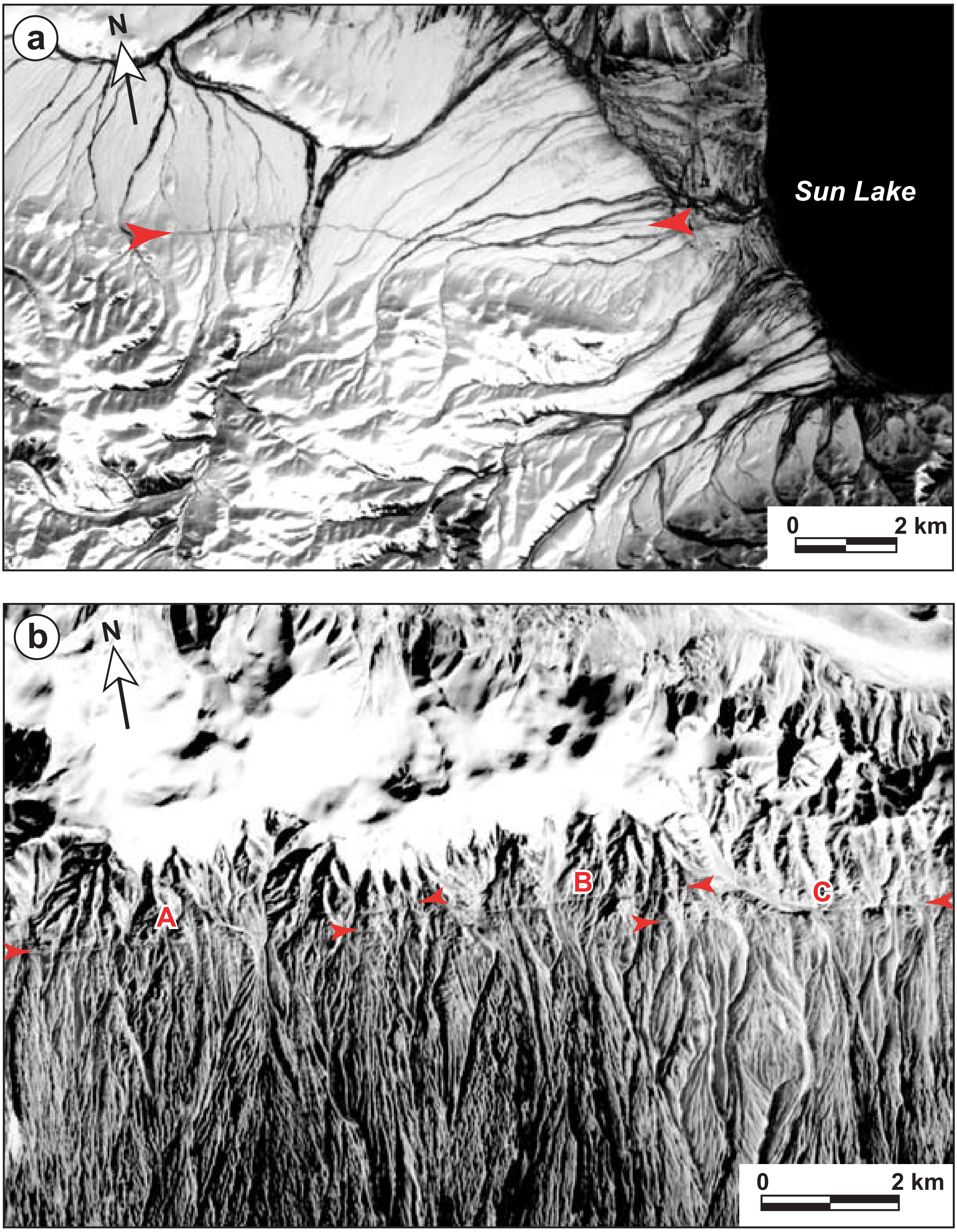

Fig. 2. Satellite images showing the trace of surface rupture zone. (a) Surface rupture zone (indicated by red arrows) appears as a distinctive lineament to the west of the Sun Lake on ASTER image. See Area 1 in Fig. 1b for the location. (b) Coseismic surface ruptures (A, B, and C indicated by red arrows) show a right-stepping en echelon pattern on ASTER image. See Area 3 in Fig. 1b for the location.

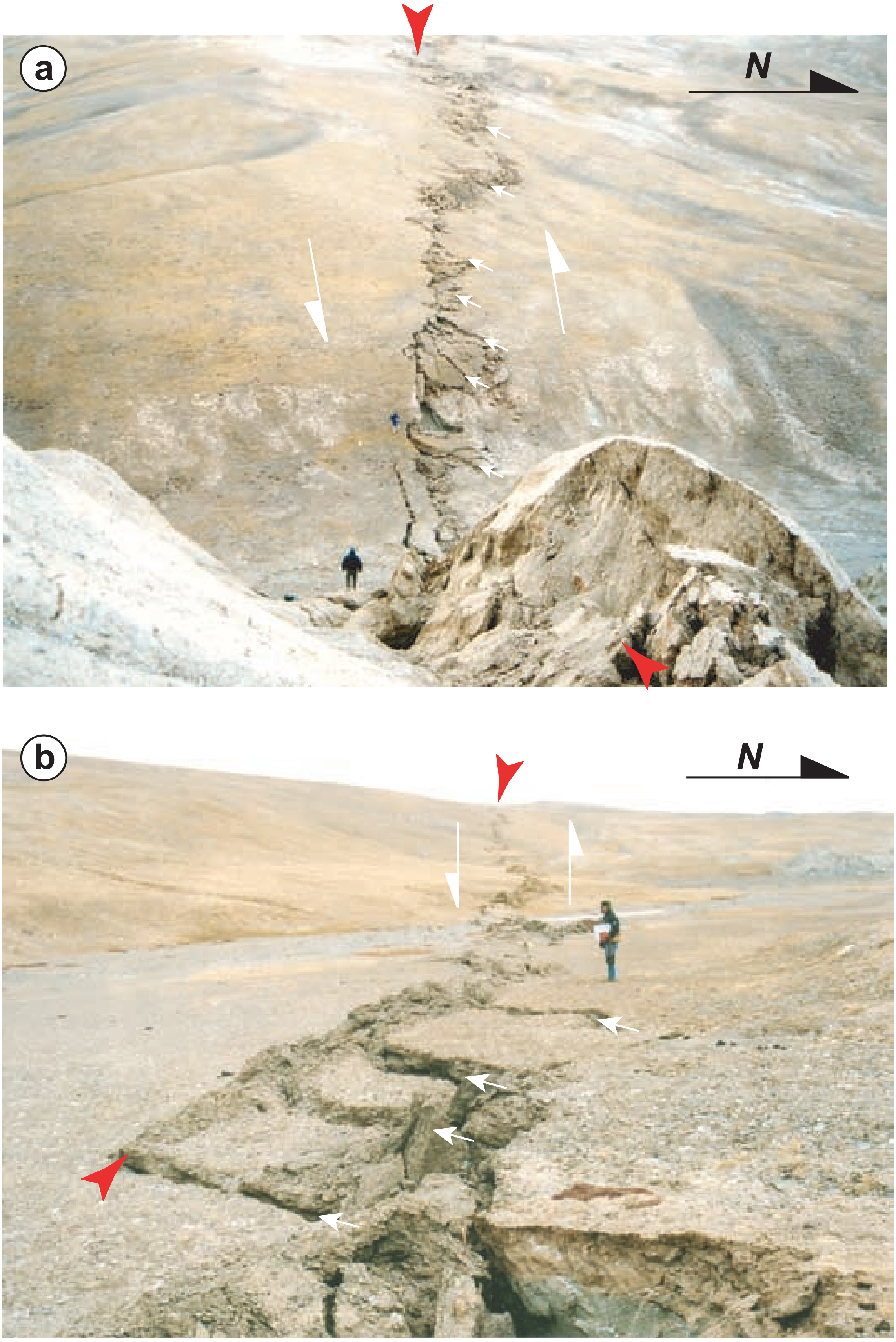

Fig. 3. Typical features of the surface rupture zone. (a) A distinctive shear fault (indicated by red arrows) and oblique tensional cracks (indicated by white arrows) at Site 6. (b) Subparallel tensional cracks (indicated by white arrows) perpendicular to the main shear fault (indicated by red arrows) at Site 7. See Fig. 1b for the locations of Sites 6 and 7.

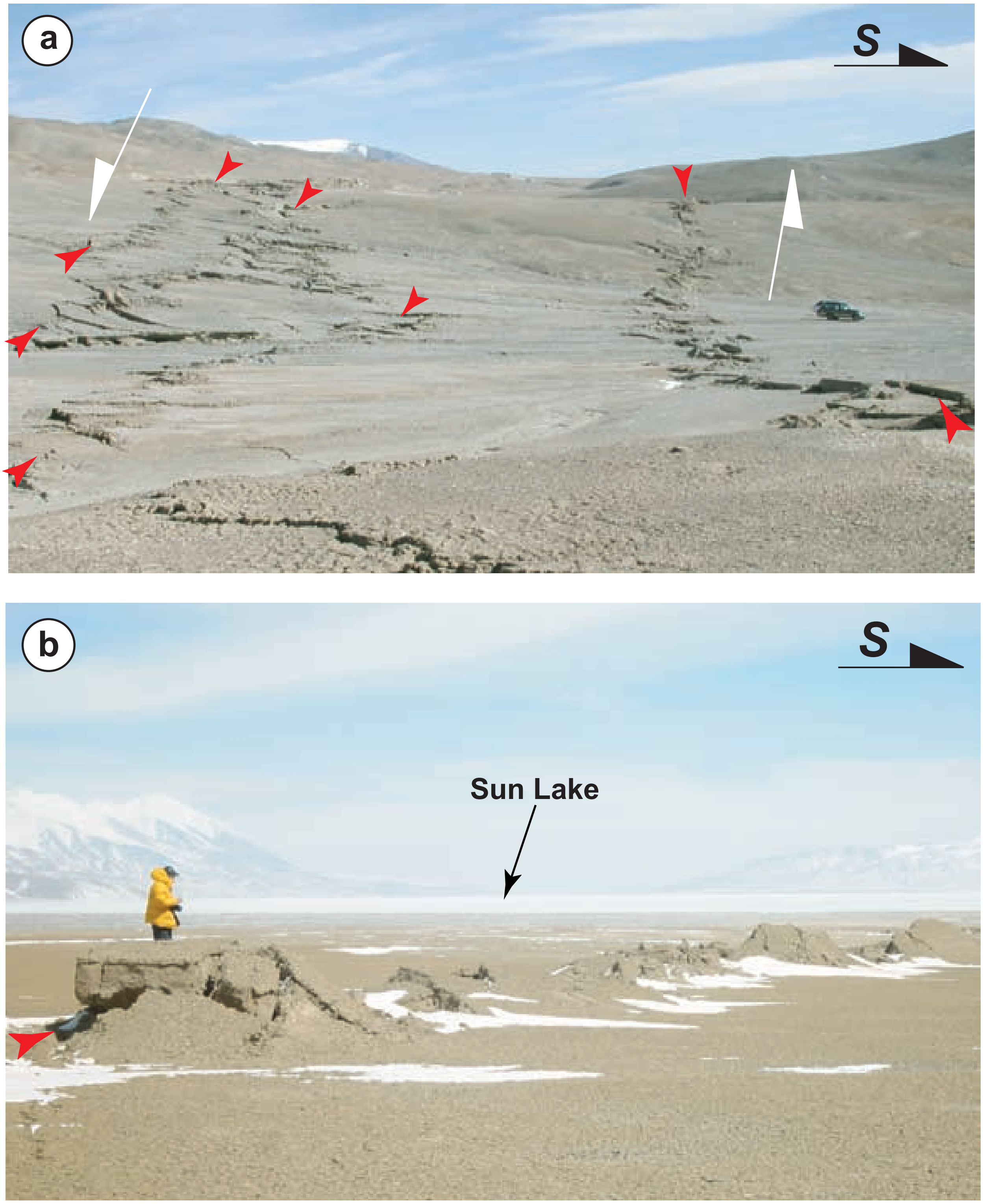

Fig. 4. (a) An 80-m-wide rupture zone composed of four strands of subparallel shear fault at Site 5. (b) A single strand of shear fault at Site 3, west of Sun Lake. Locations of Sites 3 and 5 are shown in Fig. 1b.

Fig. 5. Tensional structures found along the rupture zone. (a) Opening cracks produced by the lateral displacement near Site 8. See the person for the scale. (b) A tensional crack about 50 cm wide on the frozen surface of Kushuiwan Lake, at the westernmost end (Site1) of the coseismic rupture zone. See Fig. 1b for the locations of Sites 1 and 8.

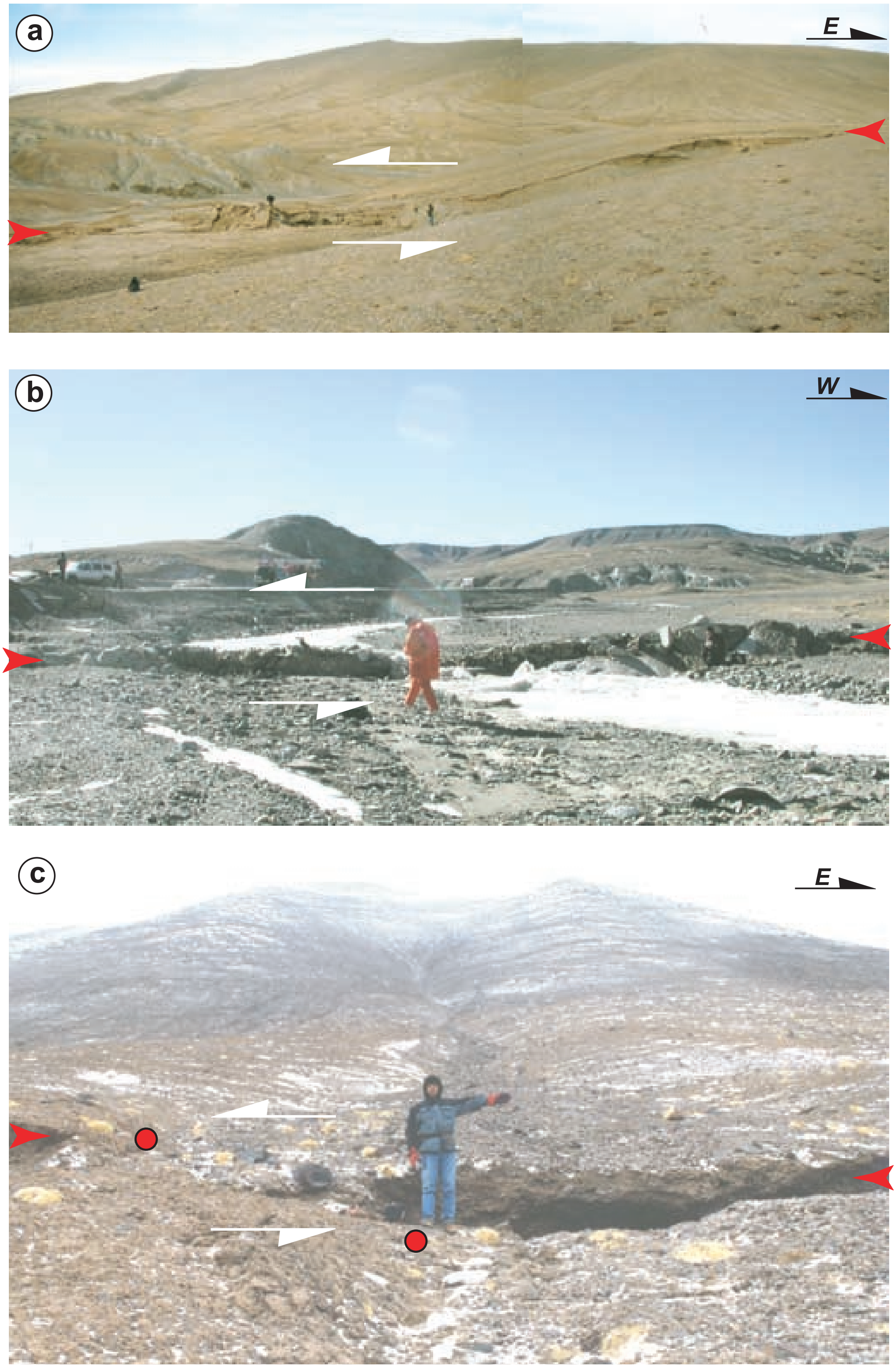

Fig. 6. Left-lateral strike-slip offset of alluvial fans, terraces and stream channels along the coseismic rupture zone. (a) South-facing fault scarp 1-3 m high between Sites 7 and 8. The fault scarp displays a typical scissoring structure, which was formed by a left-lateral strike-slip displacement of the south-sloping alluvial fan. (b) Left-lateral strike-slip offset of a river channel at Site 9, west of the mile tablet of 2894 km. Lateral displacement of the river bed is about 4.3 m. (c) Displaced terrace edge at Site 10. Red circles indicate the terrace edge, which was displaced 4.2 m laterally. See Fig. 1b for locations of Sites 7-10.

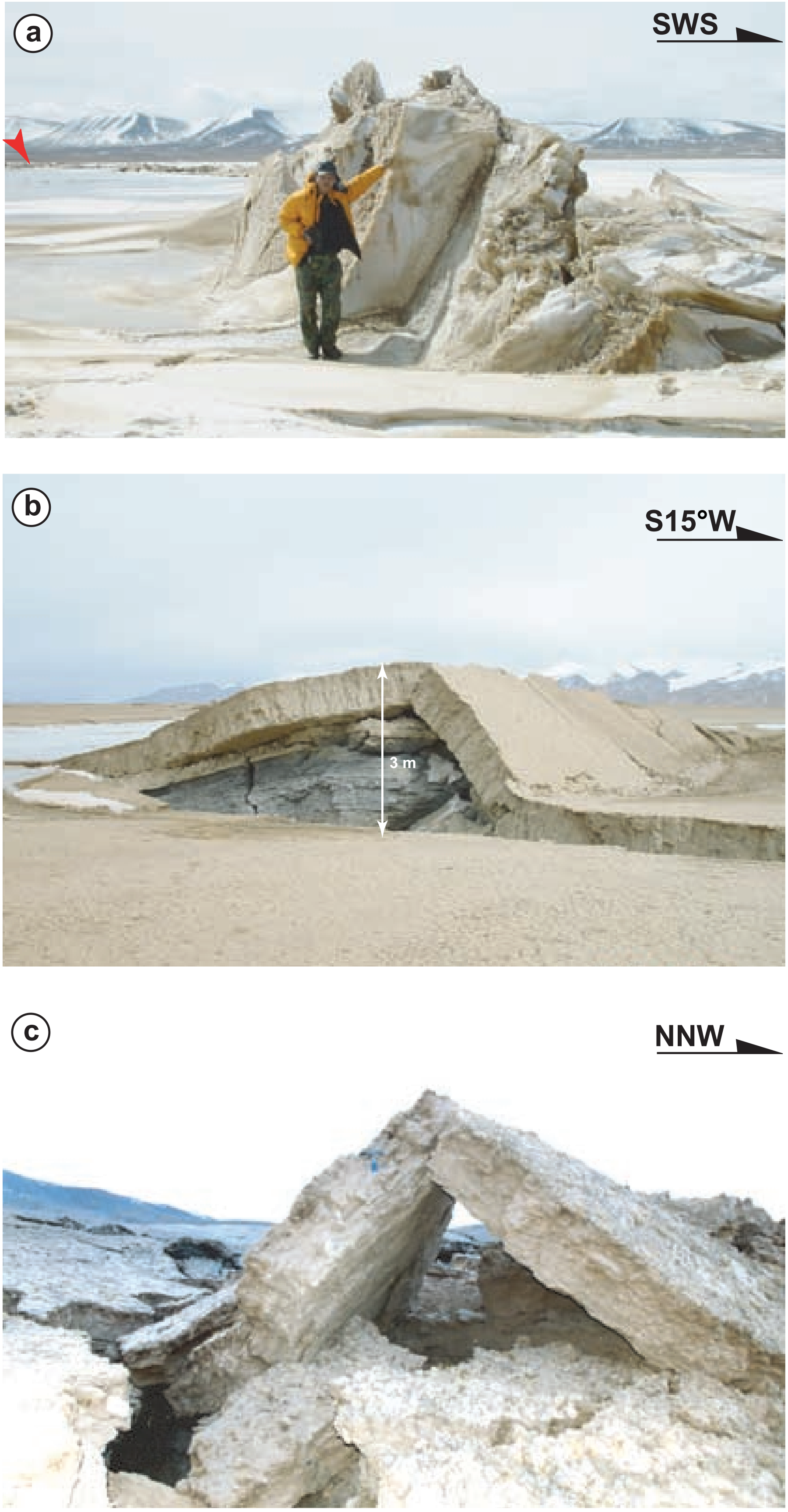

Fig. 7. Typical mole tracks (push-ups) along the Kunlun rupture zone. (a) Push-up structure (maximum height is 3.5 m) on the frozen surface of Kushuiwan Lake at Site 1. (b) Mole track (maximum height is 3.0 m) at Site 2, west of Sun Lake. (c) Mole track (maximum height is1.8 m) at Site 7. Locations of Sites 1, 2 and 7 are shown in Fig. 1b.

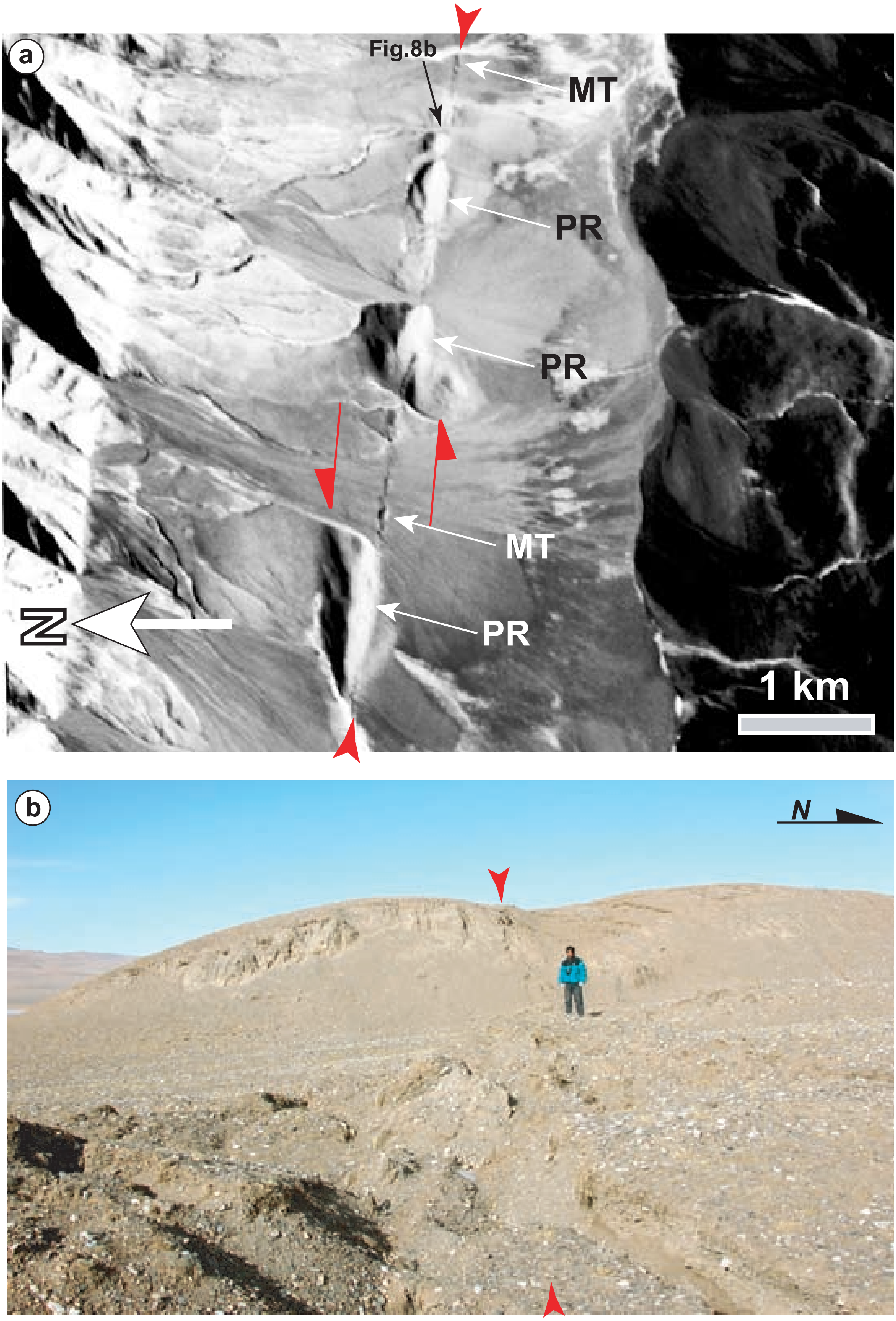

Fig. 8. Large-scale pressure ridges along the Kunlun fault zone. (a) 3D perspective SPOT image shows coseismic mole tracks (MT) and large-scale pressure ridges (PR) to the west of Kusai Lake. See Area 2 in Fig. 1b for the location. (b) A pressure ridge appears as a small hill. Note a coseismic surface rupture indicated by red arrows. See the person for the scale. Location is given in Fig. 8a.

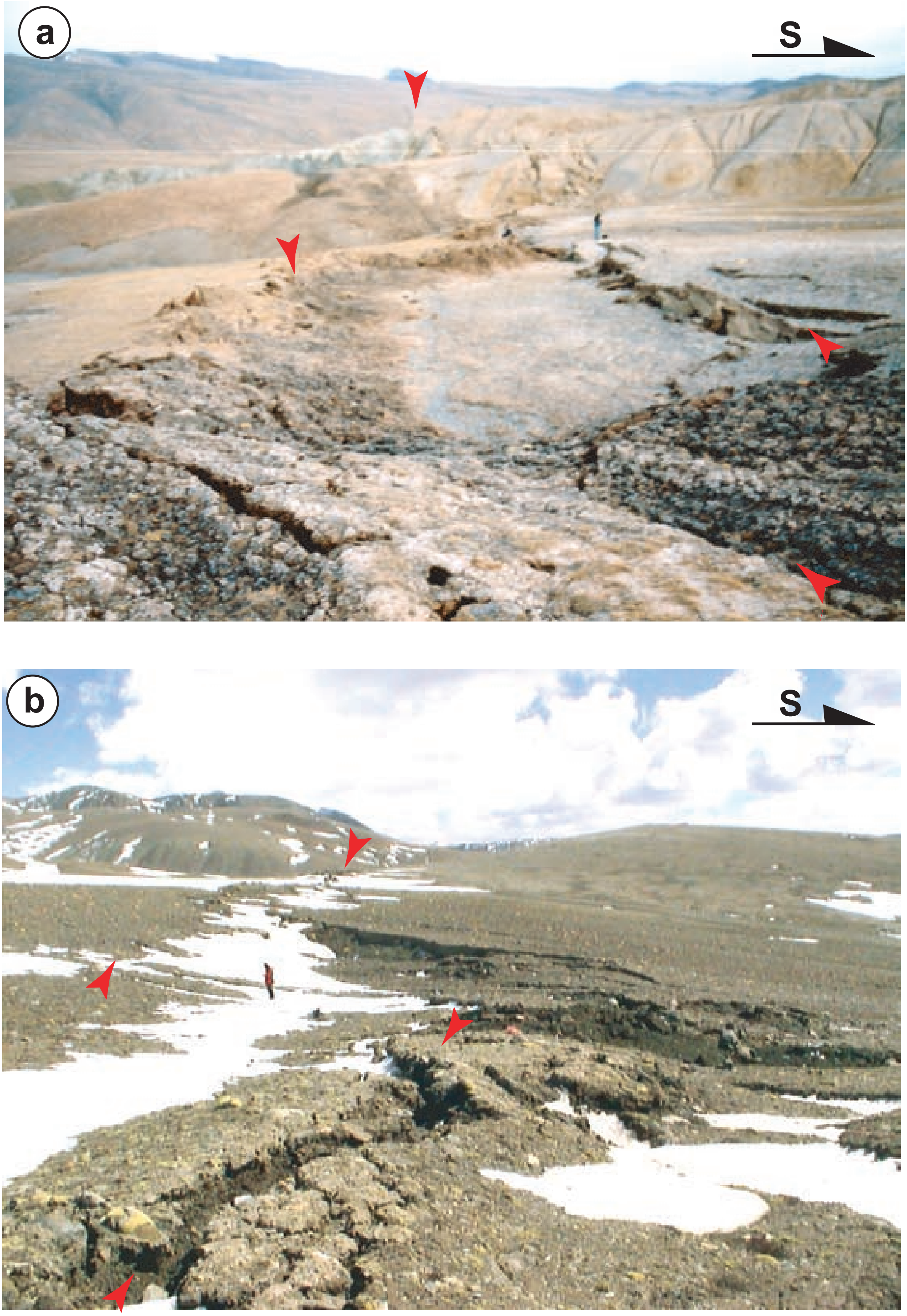

Fig. 9. Pull-apart sag pond and graben along the Kunun fault zone. (a) Pull-apart sag pond near Site 6. The size of the sag pond is about 10 m long and 3.5 m wide. (b) Pull-apart graben near Site 10. The graben is 95 m long and 40 m wide. Note that the graben is formed in a step-over between two subparallel ruptures. Push-up structures (mole tracks) and extensional cracks are also developed. For locations of Sites 6 and 10 see Fig. 1b.

Fig. 10. Ice cones produced by liquefaction on the northern bank of Kusai Lake. (a) Ice cones observed at Site 4. See Fig. 1b for the location. (b) Close-up of ice cones several centimeters in diameter. For the scale see the magic pen.

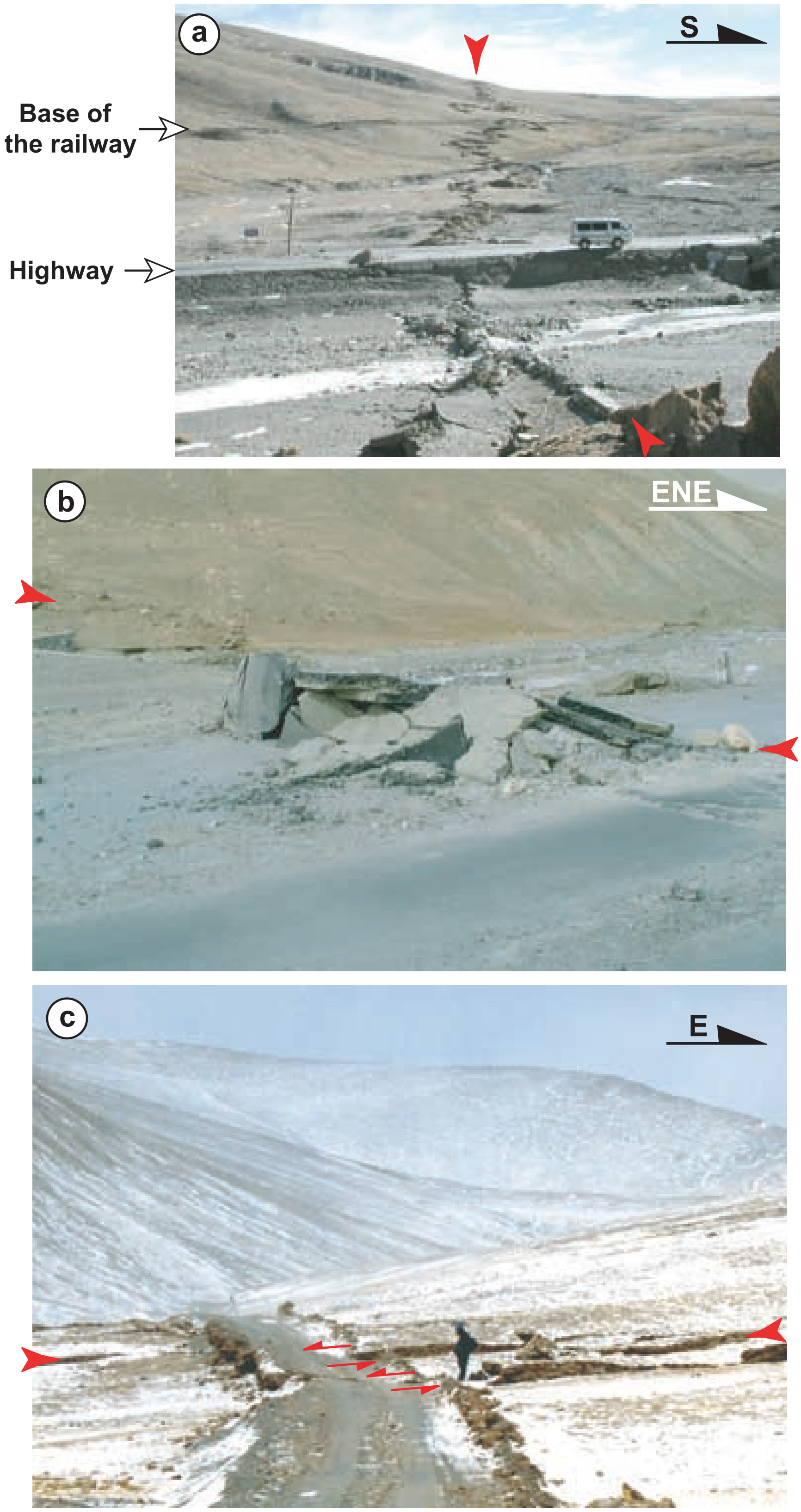

Fig. 11. Engineering damage of the highway and the base of Qinghai-Tibet railway across the rupture zone near the mile tablet of 2894 km. (a) Rupture zone passing through the highway and base of the railway. (b) Close-up of the displaced highway near the mile tablet of 2894 km. (c) Laterally displaced railway base under construction. Note the bookshelf effect of the blocks. Total lateral offset is about 3.3 m.

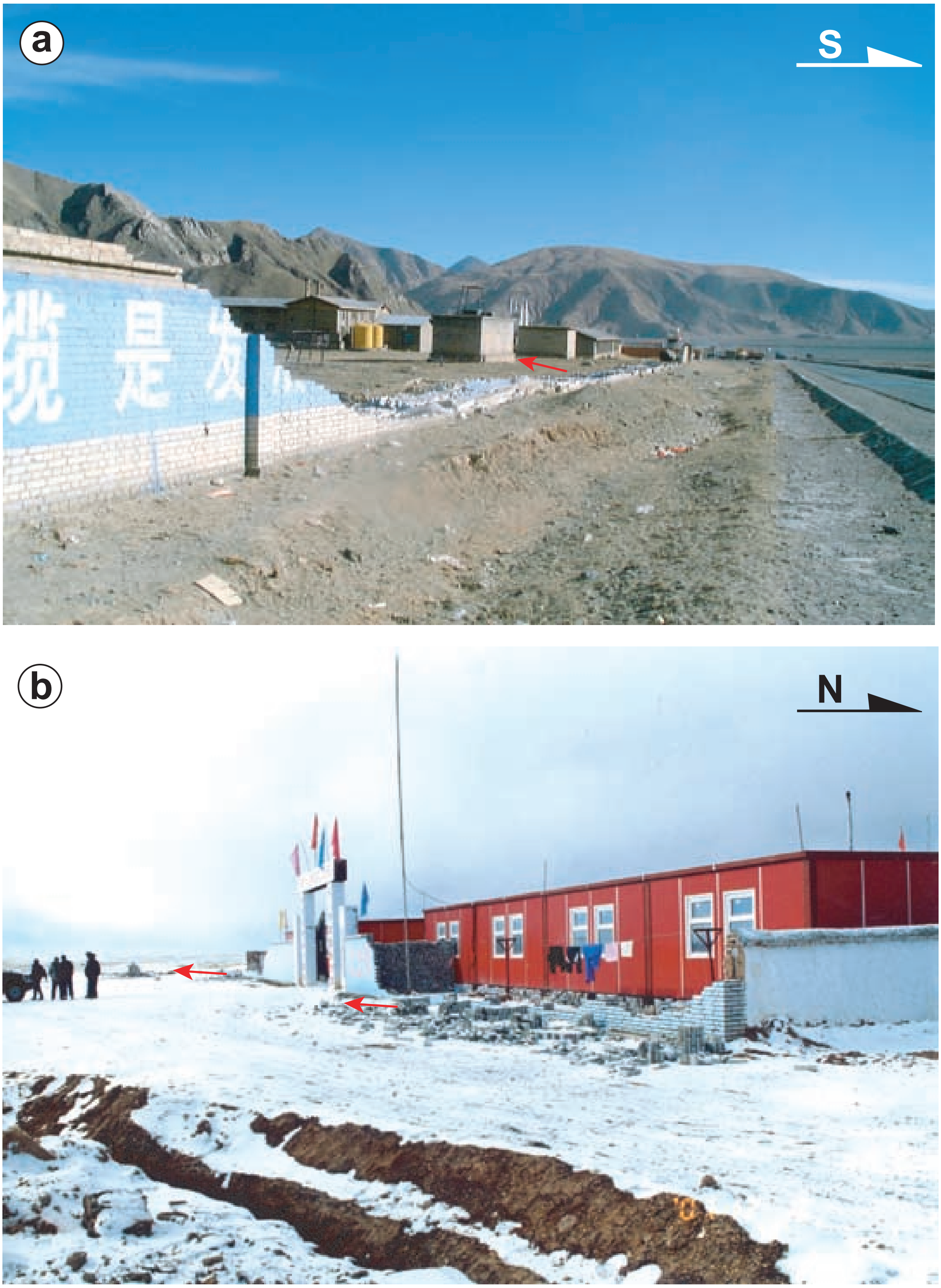

Fig. 12. Walls collapsed during the 2001 Central Kunlun earthquake. (a) A wall fell down toward NNE. Near Xidatan. (b) A wall toppled down toward SSW. 45 km southwest of the Kunlun Pass. Red arrows indicate the direction of collapse.

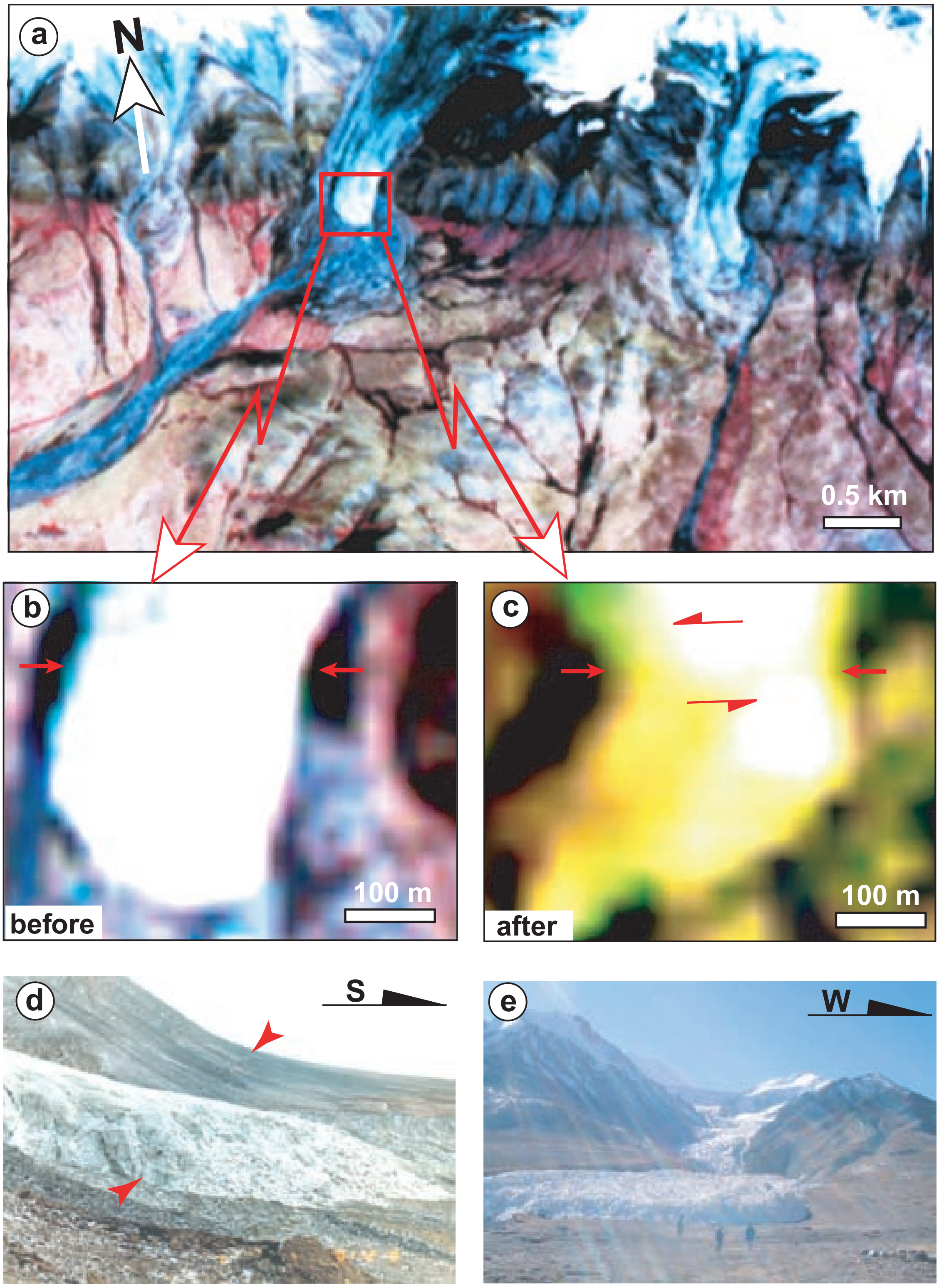

Fig. 13. (a) ASTER image shows tongue-like glaciers on the south slope of the Yuzhu Peak. See Area 4 in Fig. 1b for the location. (b) Enlarged ASTER image of a glacier before the 2001 earthquake. (c) Enlarged ASTER image shows the glacier displaced by the 2001 earthquake. (d) and (e) Snow and glacier avalanches triggered by the 2001 earthquake, on the south and north slopes of the Yuzhu Peak, respectively. Locations are given in Fig. 1b.

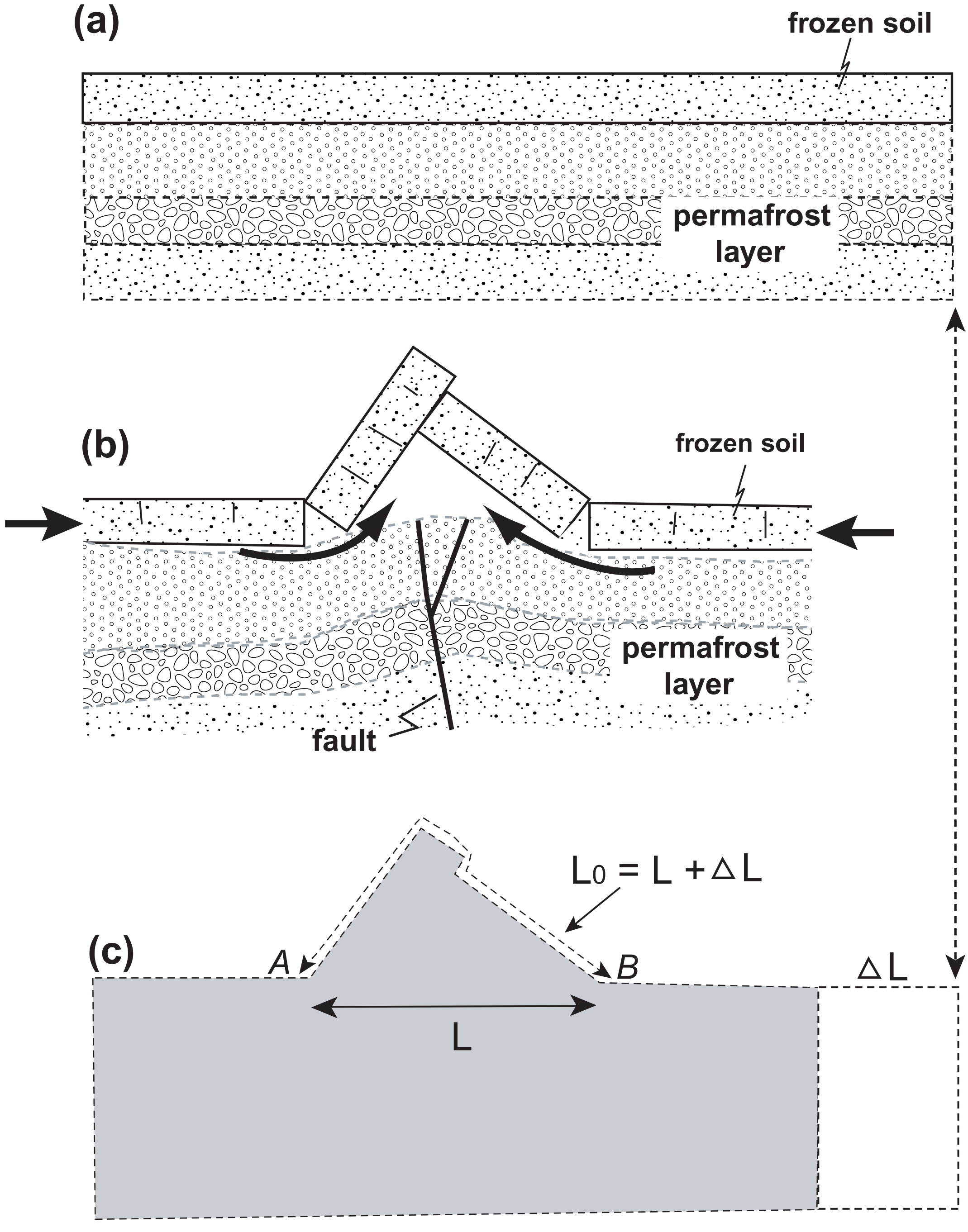

Fig. 14. (a) Frozen soil and permafrost layers before the formation of a push-up. (b) Near surface deformation of frozen soil and permafrost layers caused by the push-up. (c) Shortening rate, $\Delta L / L_0 = (L_0 - L) / L_0$, is measured in the direction perpendicular to the push-up axis. L_0 is the original (pre-seismic) horizontal distance between the two points (A and B) on the opposite sides of the push up, and L is the post-seismic horizontal distance between the two points. L_0 can be calculated based on detailed measurement and restoration of deformed frozen soil and permafrost layers.