RE-EVALUATION OF SURFACE RUPTURE PARAMETERS AND FAULTING SEGMENTATION OF THE 2001 KUNLUNSHAN EARTHQUAKE (MW7.8), NORTHERN TIBETAN PLATEAU, CHINA

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ABSTRACT

The 14th November 2001, Mw=7.8 Kunlunshan earthquake ruptured the westernmost part of the Kunlun Fault, northern Tibetan Plateau. The main segment affected by this event was the Kusaihu segment. Field investigations allowed us to constrain the length, the width and the co-seismic horizontal displacement distribution of the Kunlunshan earthquake rupture zone. The mapped surface rupture zone starts from 90.257°E in the west and ends at 94.795°E in the east with a total length of 426 km. It consists of three main sections, the western strike-slip section, the transtensional section and the eastern strike-slip section. The rupture zone is oriented N100º±10ºE on average. The distribution of the co-seismic horizontal displacements is characterized by multiple peaks departing clearly from a general bell-shape distribution. Reassessment of the maximum co-seismic horizontal left-lateral displacement yields a value of 7.6±0.4m at the site (35.767ºN, 93.323ºE) consistent with independent measurements derived from Insar and seismology. From this site the horizontal displacement decreases unevenly to both the west and east. Co-seismic vertical (reverse) displacement is also noted at the eastern end of the rupture but it remains much smaller than the horizontal component. The width of the rupture zone varies from site to site from several meters to few kilometers. The maximum width measured reaches 8km along the Yuxi Feng subsection where a large number of shaking related cracks were well developed.

INTRODUCTION

At 5:26 PM local time (09:26:GMT) on November 14th, 2001, the Mw7.8 Kunlunshan earthquake ruptured along the western part of the Kunlun fault. This fault had long been recognized as one of the major left-lateral strike-slip faults bounding the Tibetan plateau (Tapponnier and Molnar, 1977; Van der Woerd et al., 2002; Lin, et al., 2002; Xu et al., 2002a; Song, 2003). Surface ruptures of the Kunlunshan earthquake extend over 426 km in total, with azimuth averaging N100º ±10ºE, making these surface ruptures the longest yet observed in the world (Yeats et al., 1997). From west to east, the surface ruptures can be divided in three distinct sections: a strike-slip

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section about 26km long on a secondary strike-slip fault, a transtensional section in a pull-apart basin 50km long and 10km wide, and the eastern strike-slip section on the Kusaihu segment about 350km long (Figure 1).

Earthquake rupture length and maximum co-seismic displacement are valuable parameters to describe earthquake surface rupture pattern. Such parameters could be linked to moment magnitude (Mw) through empirical relationships and later use in seismic hazard assessment for similar segmented long active faults (Wells & Coppersmith, 1994; Yeats et al., 1997). Therefore, despite remoteness and high elevation (~4500m asl), many research teams visited the earthquake rupture area soon after the Kunlunshan earthquake and a large amount of data such as co-seismic displacements, length of individual rupture segment and width of the faulting zone have been collected (Lin et al., 2002; Xu et al., 2002a; Dang et al., 2002; Chen et al., 2003, Klinger et al., 2005; Li et al., 2005). Although these data provide preliminary information to understand the earthquake surface rupture mechanism, some of the rupture parameters, such as the maximum co-seismic horizontal displacement, are still under debate (Xu et al., 2002a; Lin et al., 2002 & 2003; Song R., 2003; Chen et al., 2003). Values proposed for the maximum horizontal displacement range from 16.3m (Lin et al., 2002) to 6.4m (Chen et al., 2003). Better constraint on the maximum slip is however critical to estimate magnitude and maximum co-seismic displacement of future earthquakes along the large strike-slip faults in the northern Tibetan Plateau.

Here we present parameters of the Kunlunshan earthquake surface rupture zone derived from both field measurements and interpretations of high-resolution satellite images (Ikonos satellite, pixel resolution 1m), including a reassessment of the maximum co-seismic horizontal displacement, length and width of the surface rupture zone.

**EARTHQUAKE SURFACE RUPTURE PATTERN**

Field investigation and detailed mapping from post-earthquake Ikonos images (Xu et al., 2002; Chen et al., 2003; Klinger et al., 2005) show that the surface rupture of the Kunlunshan earthquake consists, in first order, of two strike-slip sections, the western section (A) and the eastern section (C), connected by one left-stepping transtensional section (B) (Figure 1). The three sections are described below from west to east.

**Western Section (A)**

The western section is about 26km long. The westernmost surface break is located at 35.959°N, 90.257°E, east of Kushuihuan Lake. From this location, surface breaks extend eastward along the Heituofeng fault to the Taiyang Lake (35.926°N, 90.548°E), where the epicenter was located (USGS National Earthquake Information Center, 2001). The Heituofeng fault is a secondary strike-slip fault, which is part of the horsetail fault system that ends the Kunlun fault westward (Xu et al., 2002a; Van der Woerd et al., 2002).

The western end of the rupture, oriented N240°, is characterized by a series of N35° E-trending en echelon extensional fissures connected by moletracks. The fissures are 5-25 m long and the moletracks are 3-10 m long and 5-20 cm high. Eastward, the rupture strikes N105° for about 7km before it jumps abruptly ~1.4km southward to strike N110°. The eastern end of this rupture, along the western shore of the Taiyang Lake, also displays a succession of long extensional fissures (20m to 50m
long and 5cm to 50cm wide) and low mole tracks (<5m long and 20cm to 30cm high) in between. Those extensional fissures strike ~N50°E. In the field we could not observe any evidence for the rupture entering the lake and the shoreline did not appear to be offset during the earthquake.

The western section cuts terrace risers, young gullies and also car tracks anterior to the earthquake, displaying predominant left-lateral strike-slip motion with some vertical component. In some places, the last rupture clearly overprint a cumulative scarp down to the north by about 1 to 1.5 m. Co-seismic horizontal displacement varies from 1.7 ± 0.2m at the site (35.942°N, 90.311°E) to 4.5m (Klinger et al., 2005). At one site (35.932°N, 90.469°E), using a total station, we could measure 3.9m of horizontal displacement associated to 0.6m of vertical motion from the offset riser. Some of the offset car-tracks, offering excellent piercing lines, were also measured and show a horizontal offset in the range of 3 to 3.5m.

**Transtensional Section (B)**

The transtensional section connects the western to eastern strike-slip sections (Figure 1). Although surface breaks along this section were already noted (Klinger et al., 2005), here for the first time we report quantitative measurements of co-seismic offsets. The ruptures, about 18km long, are located in a 50-km-long extensional pull-apart basin at the southern front of the ice-capped Bukadaban Feng (6800m a.s.l.).

The surface breaks start on the northeastern shore of the Taiyang Lake (35.957°N, 90.716°E), where discontinuous fresh breaks have been identified with vertical down throw of 30 cm to the south and a minor left-lateral component that increases eastward. Right-stepping fissures extend discontinuously eastward across the large alluvial fans that abut the southern front of Bukadaban Feng. Below the main summit of Bukadaban Feng, the surface breaks that strike N65° ± 5°E are well developed. The breaks cross a hydrothermal field about 1.5 km long that was reactivated after the 2001 earthquake, according to locals, although it was already noted on the geological maps. The hydrothermal activity is characterized by vents with surging boiling water and fumes coming out from the freshly opening fissures. Even if the hydrothermal field is highly localized, it is clearly associated to the overall extension that is visible in the pull-apart between the western and eastern strike-slip sections south of Bukadaban Feng.

At the southwestern piedmont of Bukadaban Feng, west of the recent moraines, three different alluvial fan surfaces, a0, a1 and a2 can be identified. a0 surface is characterized by ground surface covered by gravels at the western front of the moraines further east, a1 surface is characterized by the smooth grassland where one car and a man stood as scales, and a2 surface is the eroded high grassland where gravels outcrop. The 2001 rupture is clearly localized along a pre-existing cumulative fault scarp. Using total station we measured co-seismic deformations and cumulative offsets at a site (35.964°N, 90.888° E). On average, the pre-existing scarp is about 1.5 ± 0.1m high across the oldest part of the alluvial fan (a2), about 0.6 m high across the intermediate part of alluvial fan (a1) and only the 2001 fresh breaks are visible across the youngest part of the fan (a0). The 2001 co-seismic left-lateral horizontal displacement is 1.5m, and the vertical throw is 0.3m down to the north. Thus, the rupture could possibly behave following a vertical characteristic-slip scheme (Sieh, 1996; Klinger et al, 2003; Liu, et al., 2004). In that case it would show evidences
across the different part of the fans for respectively four and one similar surface-rupturing events prior to the 2001 earthquake.

Further east, along the southern piedmont of Bukadanbang Feng, moraines have developed and the 2001 Kunlunshan earthquake surface breaks are unclear. Numerous fresh landslides, however, are aligned along the moraine talus that could have been triggered by the earthquake. Nowhere found unambiguous surface breaks at the base of the large triangular facets that bound Bukadanbang Feng. It is therefore possible that along this section the surface rupture did not reach the surface. Extensional surface breaks are visible again at a site (35.989°N, 91.106° E), west of the easternmost glacial lobe at the southeastern piedmont of Bukadanbang Feng, where they connect with the eastern section. Thus, there is a 20-km-long surface rupture gap between the transtensional section and eastern strike-slip section.

**Eastern Section (C)**

The eastern section forms the main surface rupture associated to the Kunlunshan earthquake. Starting at the southeastern piedmont of Bukadanbang Feng (35.989°N, 91.016° E), the surface breaks extend east-southeast (N100° ± 10°E) for a distance of 350 km to end at the site (35.556°N, 94.795°E) about 70 km east of the Golmud-Lhasa Highway (Xu et al., 2002). This section of the rupture follows the long–time recognized Kusaihu segment of the Kunlun fault. In addition to the 2001 rupture, many evidences for paleo-earthquakes have also been reported along this section of the fault, attesting of its important seismic activity in the past (Earthquake Administration of Qinghai Province, 1999; Van der Woerd et al., 2000; Li et al., 2005).

Based on large-scale geometry and co-seismic slip distribution, the eastern section can be divided into 4 subsections, from west to east, the Hongshuihe (C-1), the Kusaihu (C-2), the Yuxi Feng (C-3) and the Yuzhu Feng (C-4) subsections (Figure1).

**Hongshuihe Subsection (C-1)**

The Hongshuihe subsection is 115km long. To the west, it is connected to the transtensional section. To the east, it ends about 6km east of the outlet of Hongshuihe (35.889°N, 92.283°E), a river that flows north through the Kunlun Range (Figure1).

The western end of the subsection is characterized by two sets of extensional fissures facing each other. These fissures, extending westward to the terminal point (35.989°N, 91.016° E), are oriented ~115° cw relative to the average N100° ± 10°E strike of the Kusaihu segment. They form a small graben about 1000m wide that crosscuts recent moraines from Bukadanbang Feng glacier and alluvial fans. At one site (36.004°N, 91.106° E) we could measure the northern extensional fissure to form a south-facing fault scarp about 1—1.5 m high with 1m to 2m of opening.

Except at its western end, the Hongshuihe subsection is characterized by localized left-lateral strike-slip faulting with only minor vertical motion. This subsection displays typical strike-slip rupture morphology as a series of linear segments connected by mole tracks or tension gashes, depending on the geometry of the relay zone. In many places, streams, alluvial fans and terrace risers are offset sharply, allowing accurate measurements of co-seismic horizontal displacements. Typical co-seismic horizontal displacements along this subsection are in the range of 3m to 5m (Klinger et al., 2005). At one site (35.893°N, 92.159°E) about 6 km west of
the outlet of Hongshuihe River, where two south-flowing gullies join, several terrace
risers and gullies incising into those terraces allowed us to measure the 2001
earthquake horizontal displacements and also cumulative offsets. The most recent
displacement is measured as 3m from the offset young riser and a cumulative
horizontal offset about 6m from the offset old riser. Such repeated observations along
the Hongshuihe subsection strongly suggest that this subsection has a slip-
characteristic behavior for occurrence of surface rupturing earthquakes (Klinger et al.,

**Kusaihu Subsection (C-2)**

The Kusaihu subsection starts at the outlet of Hongshuihe River (35.872ºN,
92.225ºE) and extends for about 76 km eastward, striking on average N95º ±
5ºE (Figure 1). It ends at 35.814ºN, 92.950ºE. The beginning of this section in the west is
characterized by an ill-defined surface rupture that splits in two sub-parallel segments
eastward (Klinger et al., 2005). These two fault traces coexist for about 60km before
they join in a single strand again. The southern strand that cuts through bajadas and
fan surfaces exhibits almost pure strike-slip motion with typical associated
morphology. The northern strand is located at the base of the Kunlun range front,
about 2km north from the southern strand, and exhibits mainly normal faulting with
vertical motion in the range of 0.5m to 1m. This peculiar geometry has been
interpreted as due to slip-partitioning between the horizontal and vertical slip
components when the rupture reaches to the surface (King et al., 2005).

The normal faulting strand, segmented and discontinuous, is located at the base
of large triangular facets several hundred meters high. Short normal scarps are also
visible between the normal and the strike-slip faulting strands. From the Ikonos
images, however, it is clear that only some of those scarps were reactivated during the
2001 earthquake. These scarps are oblique to the strike-slip strand and curve to align
with the normal strand to the north. They correspond to zones where none of the two
regimes dominates enough to allow formation of long-term active features (King, et
al., 2005; Klinger et al., 2005).

The strike-slip faulting strand shows almost no evidence of significant vertical
motion that could affect south-flowing drainages from the southern Kunlun Range. However, at one site (35.851 ºN, 92.479 ºE) vertical slip is noticeable. There, a north-facing cumulative fault scarp has clearly developed that blocks southward-flowing drainages to form a large sag pond. Two co-seismic left-lateral offsets of 2.7m and 2.8m respectively have been measured from two offset gullies incising into the scarp. Although the cumulative vertical scarp is 6.5m in height, the co-seismic vertical motion is only 0.4m. Besides, the surface breaks sinistrally cut several risers at its western end near the outlet of Hongshuihe River. There the earthquake fault dips
toward the north and cuts the Neogene and Quaternary, showing its northern wall up
with a reverse component.

A large cumulative pull-apart basin (about 600m long, 120m wide and 20m deep)
has developed along the Kusaihu subsection (N35.82 ºN, E92.77 ºE). Both normal and
strike-slip ruptures could be observed in the basin due the Kunlunshan earthquake. In
the field, we could measure 1.9m of vertical throw on the southern normal bounding
fault and about 1m on the northern flank. Strike-slip motion is localized in the center
of the basin, along its longest diagonal. In addition, a large number of distributed
tensile cracks sub-parallel to the northern shoreline of the Kusaihu Lake have been
observed that step down to the south, where the strike-slip faulting strand enters the
lake. These are probably secondary ruptures created by local strong shaking.

From the eastern shoreline of the lake to the junction of the strike-slip strand to the normal strand (35.806ºN, 92.950ºE), about 12km eastward from the lake, the strike-slip strand remains rather simple. The junction between the two strands is characterized by a bend of the fault and could be considered as segment boundary (Figure 1).

**Yuxi Feng Subsection (C-3)**

From the junction between the two strands of the Kusaihu subsection, the Yuxi Feng subsection extends eastward to Dahong River (35.848ºN, 93.513ºE), striking on average N100º ±5ºE. The length of this subsection is ~60km (Figure 1). At the outlet of Dahong River, the rupture bends ~6º southward. It is also at the outlet of Dahong River that the Xidatan-Dongdatan segment of the Kunlun fault branches out from the Kunlunshan earthquake fault. It is noticeable that even the Xidatan-Dongdatan segment is the main continuation of the Kunlun fault eastward; no co-seismic displacement was triggered on this segment.

The surface ruptures along this subsection consist of multiple sub-parallel fault strands tens to several hundred of meters apart that form a surface rupture zone as wide as 550m at the southern piedmont of Kunlunshan Range (Xu et al., 2002). Most of the strands are strike-slip that could overlap for more than 2km. Locally, a little thrusting component has been observed with a south facing scarp ~0.5m high. In addition, a large number of shaking-related cracks distributed in the range of 3—4 km have been observed to the south of the surface rupture zone. Thus, in total the width of the co-seismic ruptures and the shaking-related cracks together may reach 8 km along this subsection. One possible explanation for such a large width might be the conjunction of the large co-seismic slip and the presence of permafrost (Lin et al., 2004). Hence, the frozen ground hampered any folding or plastic deformation and made all the deformation fragile. It is clear, from the different teams involved in the Kunlunshan earthquake study (Lin, et al., 2002, Xu, et al., 2002; Dang et al., 2002; Chen et al., 2003; Klinger et al., 2005; Lasserre et al., 2005), that this subsection bears the maximum co-seismic slip, even if the exact amount of horizontal displacement is still under debate (see discussion below).

**Yuzhu Feng Subsection (C-4)**

This section starts east of Dahong River and extends for about 112km to the east, and ends at the site (35.55ºN, 94.800ºE) about 70km east of the Kunlun pass (Figure 1). The average azimuth is N106º ±5ºE. The surface ruptures are well localized along a pre-existing fault, being no more than 20m wide in most cases. The rupture is characterized by short strike-slip segments with some thrusting and tensile breaks displaying typical en echelon pattern. Field measurement of an offset channel yields a co-seismic horizontal displacement of 3.4 ±0.2m in left-lateral sense, while a cumulative horizontal offset of the riser is about 6.8m at site A-1 (35.668ºN, 94.070ºE). A similar cumulative offset from a gully on an alluvial fan is also measured to be 7.1m at site A-2 (35.668ºN, 94.069ºE). Such repeated observations along the Yuzhu Feng subsection also strongly suggest that this subsection has a slip-characteristic behavior (Klinger et al., 2005; Li et al., 2005; Liu, et al. 2004; Sieh, 1996). Some WNW-trending short thrusting breaks are also observed in the field. Topographic profile across the surface rupture zone at site A-3 (35.668ºN, 94.0727ºE) shows that the co-seismic vertical (reverse) displacement reaches 0.4 m (southern wall
up) with pressure-ridges about 1.0 ± 0.4m high that accommodate a local reverse component. East of 94.80ºE, 35.556ºN, the surface ruptures bend from N106º ± 5º to N75ºE and they consist of en echelon N60º E-trending saw-like tensile cracks and low mole tracks that mark the eastern end of the rupture zone.

CO-SEISMIC SLIP DISTRIBUTION

Maximum Horizontal Displacement

The maximum co-seismic horizontal displacement we could measure in the field is 7.6m. This maximum value is measured at site A (35.767ºN, 93.323ºE) along the Yuxi Feng subsection (Figure 3). There the ENE-trending en echelon rupture crosses a south-flowing gully and adjacent alluvial fans. At this site we measured a left-lateral offset of 7.1m along the western riser of the gully and a 8m offset along the eastern riser of the gully, yielding an average co-seismic horizontal displacement of 7.6m. From this site the horizontal displacement decreases unevenly both eastward and westward. At site B (35.767ºN, 93.325ºE) about 200m east of the site A, we could measure another offset gully. At this site the rupture displays two main strands, a northern strike-slip strand and a southern thrust strand. The northern strand, 35m wide, is formed by six en echelon transtensional breaks with a general strike of N85ºE. The total horizontal displacement measured from the offset youngest riser (T1/T0, from the active stream channel T0 to the youngest abandoned terrace T1) is 6.3m. As the measurement was done during the winter of year 2001, just after the earthquake, when freezing reduces water flow almost to zero, the chances that the terrace riser has been already partially eroded are very low. Therefore, we do not consider that we underestimate the actual co-seismic displacement significantly. At this site we could also measure a cumulative horizontal displacement from the offset riser T2/T1, which is 13.2 ± 0.2m. In this case we argue it is only a minimal value due to possible partial erosion of the riser located south of the rupture caused by water flowing at the T1 surface, before T1 got incised to form the current stream bed T0. Across the southern thrusting strand we measured a vertical displacement of ~0.45m. Measurements at site C (35.762ºN, 93.398ºE), where ruptures are formed by two strands, yields a total horizontal displacement of 5.9 ± 0.5m. Finally, a similar horizontal displacement of about 5.4m is obtained at site D (35.814ºN, 92.955ºE).

Those measurements, incorporated with other co-seismic displacement data we collected in the field and from satellite images, are displayed in Figure 2 & 3. It shows that the maximum horizontal co-seismic displacement due to the 2001 Kunlunshan earthquake is 7.6m with an average horizontal one of 4m to 5m. This maximum co-seismic horizontal displacement is quite different from the value reported earlier by Lin et al. (2002) who have proposed that the maximum displacement was 16.3m measured across a large gully located at a site 35.762ºN, 93.365ºE. We argue that this site is not suitable for measuring the co-seismic horizontal displacement, owing to a complicated surface rupture pattern that makes any field measurement difficult (Figure 4). From Ikonos satellite images we could map this site in detail. There the rupture consists mainly of three sub-parallel strands (F1, F2 & F3). The southernmost one (F1) has the most complicated geometry. Measurements of several offset piercing lines across this fault yield the co-seismic horizontal displacements from 2m to 3m. Similarly, the co-seismic horizontal displacements measured from the offset linear
geomorphic markers are only ~2.5m for the middle (F2) and northern (F3) strands. Thus, the total horizontal displacement at this site should be in the range of 5~6m identified from the high-resolution image. Here, it should be noted that the horizontal displacement measured from the satellite images is usually larger than that measured in the field (Klinger et al., 2005), probably due to the difficulty of measuring off-fault displacement in the field (Rockwell, et al., 2002), bringing our measurement as an upper bound for the actual co-seismic horizontal displacement at this site. However, the value of 5-6m is in agreement with our field measurements at sites A, B and C, all located nearby and with a field measurement of 5.7m reported by Wang et al (2004) for the same location. Most probably the 16.3m offset corresponds to a cumulative displacement, which was not always decipherable in the field due to the harsh field conditions that prevail along the 2001 Kunlunshan earthquake ruptures. Based on the same reasoning, we argue the 13.5m offset reported by the same team few km east of the alleged 16.3m offset suffers the same kind of misinterpretation. In this case again, all independent measurements (field, InSAR, optic correlation, seismology) are coherent in showing a limited co-seismic horizontal displacement about 8m. We feel quite confident in our interpretation as we did also measure several offsets larger than 12m in the same areas that we demonstrated to be clearly associated to the cumulative offsets. In this area the rupture is composed of sub-parallel or en echelon strands and offsets many landforms, including drainage networks and terrace risers. Those offset drainage networks and terrace risers provide good geomorphic piercing lines to measure co-seismic horizontal displacements. Most of the co-seismic horizontal displacements we measured from offset young geomorphic markers range from 1m to 6m on single surface breaks, and this yields an average sum of the horizontal displacement of 6~7m. We also measured several larger offsets ranging from 12m to 21m (Figure 2), but they should be the cumulative values. For instance, at the site E (35.760°N, 93.400°E), the surface rupture consists of two sub-parallel strands about 300m wide. The northern strand offset small gullies on the young fans about 4m in left-lateral sense. At this site we could measure a cumulative horizontal offset of ~12m from the T4/T1 riser (Xu et al., 2002). Similarly, at site F the last surface rupture offsets the young T1/T0 risers and small gullies only 4m~6m, while about 15m or even up to 21m for the adjacent older risers (T2/T1) and large gullies.

**Along-Strike Variation of Co-seismic Displacements**

The field measurements collected along the different sections of the rupture zone show large variation of the co-seismic horizontal displacements associated with the 2001 Kunlunshan earthquake. Although the displacement is larger in the middle section on each section, the displacement-curve is not bell-shaped, but it is rather characterized by several peaks of high displacements separated by low displacements.

In summary, horizontal displacement along the western section is as large as 4.5m and decreases to less than 1m close to the Taiyang Lake. Along the transtensional section, although the observed surface rupture is very limited in length, the horizontal displacement is ~1.5m. Along the eastern section, the displacement-curve generally corresponds to the segmentation that was derived from the geometric characteristics of the rupture. Along the Hongshuihe subsection the horizontal displacement is rather constant with an average displacement of ~3.5m. The maximum displacement reported along this section is 5.7m (Dang & Wang, 2002), but this value is almost two times larger than those nearby. So, we prefer a maximum
horizontal displacement about 4.5–5m that we measured at a site (35.899°N, 92.096°E) for the Hongshuihe subsection. Along the Kusaihu subsection, a first large peak is observed with a maximum horizontal displacement of ~7.2m. This subsection is characterized by the double fault-strands resulting from the slip-partitioning (King et al., 2005). Along the northern strand, the normal faults exhibit vertical displacement in the order of 0.5m to 1m. Along the Yuxi Feng subsection, the horizontal displacement bursts with the maximum one of 7.6±0.4m, the largest value measured along the entire rupture zone. Nowhere could we find evidence for the 4m vertical displacement reported by Chen et al. (2003). This large displacement could correspond to misinterpretation of apparent vertical motion related to large horizontal offset (Lin et al, 2004). The eastern subsection (Yuzhu Feng) shows displacement up to 4m decreasing gradually eastward. A clear thrust component has been identified along this subsection with a vertical reverse motion as large as 0.7m (Xu et al., 2002).

Thus, the co-seismic horizontal displacement-curve associated with the 2001 Kunlunshan earthquake is characterized by six peaks corresponding to the different subsections. This displacement distribution is clearly consistent with other displacement-distributions derived from InSAR by Lasserre et al. (2005) and from optical correlation by Klinger et al. (2005).

**FAULTING SEGMENTATION AND SUB-EARTHQUAKES**

Description of fault segmentation originates in the common observation that large faults usually do not rupture along their entire length in a single earthquake (Schwartz & Coppersmith, 1984; Zhang et al., 1991). Geometric discontinuities along faults have long been considered as barrier that can delimitate individual fault segments and possibly stop the rupture propagation (Aki, 1979; King and Nabelek, 1985; Depolo et al., 1991). Based on field survey and satellite-image interpretation the surface rupture zone of the Kunlunshan earthquake can be divided in 3 main segments, the western strike-slip segment, the transtensional segment and eastern strike-slip segment. The eastern strike-slip segment itself can also be split in 4 sub-segments as shown by the slip-distribution.

In the case of the Kunlunshan earthquake, the connection between the different segments is always associated to some obvious geometric asperity. The Taiyang Lake that separates the western strike-slip segment from the transtensional segment is clearly located in a pull-apart basin that makes the transition between the two strike-slip segments (Klinger et al., 2005). Such a pull-apart basin could possibly stop a propagating rupture (Harris and Day, 1993 & 1999) although in the case of the Kunlunshan earthquake the pull-apart basin was rather the starting point of the rupture. The connection between the transtensional segment and the eastern segment is marked by a bend of the rupture of ~20°, which could also be considered as a major geometric asperity.

The length of each segment is quite different. The western strike-slip segment is about 26 km long, the transtensional segment is about 18 km long and the eastern strike-slip segment is about 350 km long. Using the relation between the moment magnitude (Mw) and the surface rupture length (L), \( M_w = 5.02 + 1.19 \log L \) (Wells & Coppersmith, 1994), the magnitudes associated to the western segment, the transtensional segment and the eastern segment are respectively Mw6.8, Mw6.2 and Mw8.0.
CONCLUSIONS

The 2001 Kunlunshan earthquake surface rupture zone has a complicated surface rupture pattern, involving primary and secondary breaks. The width of the rupture zone varies from few tens of meters to several kilometers. The main rupturing process is strike-slip, accounting for ~350km of surface rupture, although one subsection displays a fair amount of normal motion. We have shown that the maximum coseismic horizontal displacement is ~7.6m with an average slip of 4—5m. Larger displacement data very probably correspond to measurement of cumulative offset. This interpretation is clearly consistent with other displacement-distribution available for the Kunlunshan earthquake (Lasserre et al., 2005; Klinger et al., 2005). Interestingly, the ratio between average horizontal displacement and the rupture length is rather low compared to similar size earthquake as the Denali earthquake (Mw~7.9; 03/11/02) whose rupture length is only 340 km, including a 48km-long pure thrust rupture (Haeussler et al., 2004). This might be interpreted as the seismogenic crust being less thick in the Kunlunshan and therefore needing a longer rupture to achieve similar magnitude.

These data are useful for reduction of earthquake hazard directly generated by surface faulting.

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Figure 1 Simplified map of the 2001 Kunlunshan earthquake surface rupture zone on the pre-existing fault traces of the westernmost segments of the Kunlun Fault. (a) SPOT mosaic images showing pre-existing fault traces of the Kusaihu segment of the Kunlun fault (indicated by red arrows), and inset map at the right upper corner showing locations of the Kusaihu segment (red line) of the Kunlun Fault (KLF), Mani Fault (MF), Altyn Tagh Fault (ATF) and Haiyuan Fault (HYF). (b) Distribution of the 2001 Kunlunshan earthquake surface rupture zone (A: western strike-slip section; B: transtensional section; C: eastern strike-slip section; C-1: Hongshuihe subsection; C-2: Kusaihu subsection; C-3: Yuxi Feng subsection; C-4: Yuzhu Feng subsection).
Figure 2 (a) Detailed strip map of the Yuxi Feng section of the Kunlunshan earthquake surface rupture zone northeast of Kusaihu Lake from 93.2500°E to 93.4667°E derived from IKONOS satellite images, showing a complicated structure of multiple sub-parallel strike-slip faulting strands with a reverse faulting strand on the south to form as wide as 550 m surface rupture zone produced directly by faulting (Blank areas north of the surface rupture zone are pre-Quaternary bedrocks of Kunlun Range and black square is the location for Figures 15 & 16); (b) Co-seismic left-lateral displacements identified from linear geomorphic markers on the IKONOS images and also field measurements. Yellow triangle or mauve square represents co-seismic displacement on the single strand and blue rhombus the sum of the co-seismic displacements on the different strands at the same site. Black cross represents the cumulative offset value.

Figure 3 Distribution of the measured horizontal co-seismic horizontal displacements along the strike of the surface rupture zone. Blue lines represent the co-seismic horizontal displacements inferred from INSAR data (Lasserre et al., 2003). Other legends are the same as in Figure 1. Horizontal displacements are collected from Xu et al., 2002; Dang & Wang, 2002; Chen et al., 2003 and also measurements in the field).
Figure 4 (a) IKONOS image created on 06 January, 2003, around the site 93.365°E where Lin and their colleagues (2002) gave a maximum co-seismic horizontal displacement of 16.3m; (b) Detailed strip map showing the surface rupture pattern of the Kunlunshan earthquake and co-seismic horizontal displacements on different rupture strands (Blank areas are the pre-Quaternary of Kunlun Range.)