The November 14th, 2001, Mw=7.8 Kokoxili Earthquake in Northern Tibet (Qinghai Province, China)

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INTRODUCTION

On 14 November, 2001, at 5:26 pm local time (9:26:10.3 GMT) a great earthquake (Ms=8.1) struck the Kokoxili region of the northwest part of Qinghai province (China, Figure 1). Although this earthquake was felt in Sichuan province, more than 1000 km away from the epicentral area, it did not attract much media attention because it shook a thinly populated area on the northern margin of the Tibetan Plateau. The preliminary epicenter (US Geolocial Survey-National Earthquake Information Center NEIC) is located near 90.5°E, about 300 km west of the Golmud-Lhasa road (Figures 2 and 3), across which surface rupture has been reported near the Kunlun Pass. As mentioned in several Chinese newspapers, the famous milestone statue at the Kunlun Pass broke and fell because of the earthquake and the construction of the Golmud-Lhasa railroad has been put on hold since the occurrence of this unexpected event.

The 14/11/01 earthquake appears to have ruptured the left-lateral Kunlun Fault (Tapponnier and Molnar, 1977) or Kusai-Dongxi-Maqu Fault (Cui and Jiang, 1979; Jia et al., 1988), which extends roughly east-west for about 1600 km in north Tibet. This event follows, nearly four years later, the 8 November, 1997, Mw=7.6 Manyi earthquake, which broke another segment of the same active fault system farther west (Figure 2).

The centroid (Harvard CMT Catalog), at 35.5°N-92.7°E, lies about 200 km east of the USGS (NEIC) and China Seismological Bureau (CSB) preliminary epicentral locations, and about 35 km south of the fault, consistent with a south-dipping fault-plane (Figure 3). 18 of the 22 aftershocks with magnitude Mb ≥ 3.8 that occurred during the first week are located another 100 km farther east, between 93°E and 94.7°E. The easternmost ones are located east of the Kunlun Pass. Two focal mechanisms, one from the Harvard CMT Catalog, and the other, from the Earthquake Information Center in Tokyo (Earthquake Research Institute ERI, Tokyo), indicate pure left-lateral to normal-left-lateral motion on a N90-96°E striking plane, compatible with the average N95-100°E strike of the Kunlun Fault in the area. The USGS fault plane solution, on the other hand, appears to be radically different, but would not be inconsistent with slip on a steep, N20°E-trending normal fault plane (figure 3).

Shortly after the earthquake, the Chinese Seismological Bureau deployed about 10 temporary stations at the eastern end of the rupture, along the Golmud to Lhasa road. The earthquake was also recorded by a set of 10 temporary stations deployed since June 2001 for a passive seismologic experiment in western Tibet, about 1000 km to the west (IT program, INSU, CNRS France). Unfortunately, these stations had to be moved away 4 days after the main shock.

In this report, after describing the Kunlun Fault and what is known of previous events along it, we discuss the rupture length, the positions of the largest aftershocks and possible triggering scenarios for future earthquake occurrence.

TECTONIC SETTING

Since about 50 Ma, the continued northward convergence of India relative to Siberia has created the largest continental collision zone on the planet. At present, out of the ~5 cm/yr shortening between the two continents, ~2 cm/yr are absorbed by the Himalayan frontal thrust (Lavé and Avouac, 2000; Bilham et al., 1997) resulting in the growth of the world’s highest mountain range. Most of the remaining convergence appears to be absorbed along Tibet’s northern margin, by extrusion of lithospheric blocks along great strike-slip faults combined with oblique thrusting and crustal thickening (Meyer et al., 1998; Tapponnier et al., 2001a). The Altyn Tagh and Haiyuan faults, north of the Qaidam basin, as well as the Karakorum, and the Kunlun and Xian Shui He faults, on the western and eastern side of Tibet, respectively, allow the blocks to move past each other at long-term rates on order of a few cm/yr (Figure 1) (Avouac and Tapponnier, 1993; Lasserre et al., 1999; Mériaux et al., 2000a; Van der Woerd et al., 2000).

The Kunlun Fault is not only one of the faults that takes part in the extrusion of Tibet but also an example of large-scale slip-partitioning in the continental crust (e.g. Meyer et al., 1998; Tapponnier et al., 2001a). Northeastward convergence between Tibet and the Gobi, guided by left-lateral slip on the Altyn Tagh Fault, has led to crustal-shortening of the Qaidam basin and Qilian ranges, apparently above a décollement that roots underneath the Kunlun range, where the lithospheric mantle of the latter regions subducts southwards (Tapponnier et al., 1990; Meyer et al., 1998; Chen et al., 1999). The orientation of the Kunlun fault, which is parallel to the Kunlun range, and the strong E-W shear-wave splitting anisotropy across it

(McNamara et al., 1994; Lavé, 1996; Herquel et al., 1995) suggest that the fault extends deeper in the lithosphere as a shear zone, as does the Altyn Tagh Fault (Wittlinger et al., 1998).

For more than 1000 km, the Kunlun Fault runs south of the Kunlun range along and north of the most recent (12 Ma to present), calcalkaline volcanic belt of Tibet (Turner et al., 1996, Mériaux et al., 2000b; Jolivet et al., 2001). The range, an active margin in the Permo-Triassic, separates the folded turbidites and phyllites of the Songpan Ganze terrane of eastern Tibet (Chang et al., 1986) from the Paleozoic and lower Protoreozoic basement of the Qaidam to the north. The timing of Cenozoic motion along the fault is not well known. It has probably been slipping since at least the Mid-Miocene (12 Ma) coevally with shortening to the north, which started also in the Miocene (e.g. Meyer et al., 1998; Métivier et al., 1998), and with volcanism to the south (Deng, 1991; Arnaud et al., 1992; Turner et al., 1996). However, it may have started to slip earlier, in the late Oligocene, as shortening driven by the collision propagated northeastwards into Asia (Tapponnier et al., 2001a).

The fault stretches from 86°E to 105°E (about 1600 km), from the borders of Xinjiang, Xizang and Qinghai provinces, accross the dry permafrost plateau (~5000 m. a.s.l.) down to the humid, forested and deeply incised mountainous rim of the Sichuan basin (Figures 1 and 2). From cosmogenic dating (^{14}C, ^{10}Be, ^{26}Al) of offset alluvial terraces along the fault, the long-term slip-rate along much of the Kunlun Fault has been determined to be 11.5±2.0 mm/yr (Van der Woerd et al., 1998; 2000; 2002). East of the Kunlun Pass, coseismic offsets of channels and terraces risers have been interpreted to result from the occurrence of large earthquakes ($7.5 \leq M \leq 8$) with recurrence times of about 900 yrs in the west, and 450 yrs in the east (Van der Woerd et al., 2000; 2002).

THE KUSAI HU SEGMENT OF THE KUNLUN FAULT

The main trace of the Kunlun fault may be divided into 6 principal segments separated by first-order bends, jogs or junctions (Figure 2). The 14 November, 2001 earthquake ruptured the western, Kusai Hu segment of the fault, named from the large lake that it crosses in its central part (Figure 3). This segment, though arguably the most remote and least well known along the main stretch of the fault, is one of its clearest and longest (270 km) (Figures 3 and 4). Between ~91°E and 94°E it strikes N100E, which is close to the average strike of the entire fault system. West of 91°E, the fault splays into an extensional horsetail with several oblique, normal-sinistral strands whose strikes range between N20°E and N120°E (Mériaux et al., 2000b). The fault traces, which are a few ten to a few hundred kilometers long, are well marked across the Quaternary bajadas of the plateau. One of the longest is the Manyi fault, which extends for 270 km between 86.5°E and 89.5°E with a N80°E average strike (Tapponnier and Molnar, 1977; Xu et al., 1999).

Although the Kusai Hu segment of the Kunlun fault is remarkably straight between 91°E and 94°E, a progressive change in strike, from N100°E in the west to N95°E in the east, induces slightly different styles of faulting, from oblique normal-strike-slip, to nearly pure strike-slip and oblique reverse-strike-slip faulting.

Near 91°E, one oblique normal strand appears to be chiefly responsible for the uplift of the Buka Daban Feng, highest peak of the eastern Kunlun range, at 6800 m a.s.l.. This strand bounds the steep, SW-trending southern flank of Buka Daban, at the foot of which large glaciers pond between faceted spurs (Figure 4A). East of 91°E, slip-partitioning occurs between two parallel, normal and pure left-lateral, strands. Normal faulting takes place at the base of south facing triangular facets, along the Kunlun range front, while sinistral slip occurs 1 to 2 km southwards, across the coalescent fans of the piedmont bajadas (Figures 4C and 4D), a geometry often found along oblique strike-slip faults in Tibet and adjacent areas (Armijo et al., 1986; Van der Woerd, 1992; Allen et al., 1984; Replumaz et al., 2001). This partitioning implies that the Kunlun fault dips southwards. At a more detailed level, the bajada trace is divided into three right stepping sub-segments that have lengths of ~30, 75 and 60 km. Some of the most spectacular, clean-cut sinistral offsets of terrace risers and channels incised into post-glacial fans and terraces are visible on SPOT images of the fault trace, west of Kusai Hu (Figure 4C). These offsets typically range between 25 and 60 meters, implying that, given the ~11 mm/yr rate, they postdate the end of the early Holocene climatic optimum (~6000 yr). East of Kusai Hu, the fault follows the range front more closely. Yet farther east, past a left-step at 93.6°E, the fault splays into two distinct strands (Figure 4B). The northern one continues eastwards as the Xidatan-Dongdatan segment of the main fault. The southern one connects with the oblique, sinistral reverse Kunlun Pass Fault (Kidd and Molnar, 1988; Van der Woerd et al., 2002) which bounds the steep southern face of the Burhan Budai range.

HISTORICAL AND RECENT SEISMICITY

The north central Tibetan plateau is such a remote and sparsely inhabited area that information about earthquakes is nonexistent, to our knowledge, before 1900. No paleoseismological evidence has been published yet in the western literature. The long-term seismic behavior of the Kunlun Fault is thus unknown. Since 1900, however, several earthquakes with Ms ≥ 7 have occurred along the fault and related surface structures have been described (Gu et al., 1989).

Far east of Burhan Budai Shan, a large event (35.5°E-97.5°E) with an estimated magnitude M ~ 7.5 ruptured most of the Dongxi Co segment of the fault on 7 January 1937 (Jia et al., 1988). The epicenter is located approximately at the western end of this segment and the rupture clearly extended eastwards. We mapped and measured fresh free faces, large mole tracks, and sinistral offset rills (~4m) east of Dongxi Co that are unambiguously due to this event (Van der Woerd, 1998; 2002). The 1937 rupture, which crosses the Dongxi Co pull-apart is thus at least 150 km long. Our field observations, however, indicate that it did not cross the Qinglong river, east of Xiadawu. The length obtained is in good agreement with the estimated magnitude of 7.5, according to magnitude/rupture length scaling laws (Wells and Coppersmith, 1995). No focal mechanism has been determined for the 1937 event, but it is predominantly sinistral strike-slip in the field (Figure 5).

A second earthquake with a magnitude of about M ~ 7 occurred about 100 km westward of the 1937 event epicenter, on 19 April 1963. It probably ruptured part of the Alag Hu segment of the fault. Fitch (1970) determined the focal mechanism to be left-lateral strike-slip. Molnar and Deng (1984), quoting reported displacements of several meters (Li and Jia, 1981), suggested that the total rupture length for the two events of 1937 and 1963 might have reached about 300 km, but this is likely overestimated. In 1971, a smaller earthquake with magnitude M ~ 6.4 occurred at the junction between the Alag Hu and Dongxi Co segment of the fault. The focal mechanism is nearly pure left-lateral strike-slip.

Prior to 14 November, 2001, no large earthquake had been documented along the Kusai segment of the fault. One significant event, however, was the M ~ 5.8, 6 March, 1980 earthquake north of the western stretch of that segment, apparently on the central Kunlun fault. The focal mechanism of this event shows left-lateral strike-slip with a thrust component (Harvard CMT). Another significant event was the M~5.8, 3 January, 1994 earthquake, located southwest of Buka Daban Feng, hence southwest of the western termination of the Kusai segment. This latter event had a normal fault plane solution with NE-striking nodal planes, consistent with the oblique normal fault strands observed in the area.

Farther west of Buka Daban Feng, the Manyi fault, and faults west of it, have produced two large earthquakes during the latter part of the 20th century. On 14 July, 1973, two earthquakes of magnitude M ~ 7.3 and M ~ 6.1 (NEIC), at the western end of the Manyi segment, near 35.25°N – 86.5°E, ruptured an oblique, normal sinistral fault striking NE-SW (Tapponnier and Molnar, 1977) (Figure 2). On 8 November, 1997, the Manyi earthquake, of magnitude Mw ~ 7.6, produced a 170 km long surface break with maximum offsets on order of 7 m (Peltzer et al., 1999). Both the Insar results and the focal mechanism (NEIC, Harvard CMT) indicate pure left-lateral strike-slip on a Quaternary fault mapped on Landsat imagery (Tapponnier and Molnar, 1977). The mainshock was followed by a series of aftershocks that roughly lined up with the surface rupture (Velasco et al., 1998; Xu et al., 1999).

14/11/01 MAIN SHOCK AND AFTERSHOCK SEQUENCE

Length of the 14 November, 2001 earthquake rupture

Preliminary locations of the epicenter of the 14 November, 2001 earthquake, of estimated magnitude Ms 7.9 to 8.1 (NEIC; Chinese Seismological Bureau, 2001, Li Haibing, personal com.) place it at 36°N, 90.5°E, near the highest summits of the Eastern Kunlun Range (Buka Daban Feng and Wei Xue Shan, ~6800 m and ~6000 m, respectively) at the western termination of the Kusai Hu segment of the fault. The centroid, on the other hand, is located at 35.5°N and 92.7°E, about 200 km eastwards near lake Kusai. The source duration of the event was ~120 seconds. Following a weak initial pulse in the west the bulk of the energy was dissipated eastwards in about 80 seconds (ERI, Tokyo). It is thus likely that the rupture started in the west, possibly on an oblique normal fault near Buka Daban

Feng and propagated eastwards along much of the length of the Kusai segment (~ 270 km) with most of the seismic energy radiated along the main strike-slip strand of the fault and a maximum left-slip in excess of 5 m (figure 3, inset). Since surface breaks are seen east of the Golmud-Lhasa road near the Kunlun Pass, with probably still meters of sinistral slip (Figure 6) apparently along the Kunlun Pass Fault, the rupture length may have exceeded that of the Kusai Hu segment, unless the westernmost part of that segment was spared by the 4 November, 2001 earthquake. If the rupture length was in excess of 270 - 300 km, then it would rank second only to that of the 1905 Bolnai earthquake in Mongolia (> 350 km) (Khilko et al., 1985), and make the Kokoxili earthquake one of the largest strike-slip event in Asia during the last ~100 yr, ahead of even the 1920 Haiyuan earthquake (230 km) in Gansu province (Deng et al., 1986; Gaudemer et al., 1995), or the 1957 Gobi Altai earthquake (260 km) in Mongolia (Baljinnyam et al., 1993).

Aftershock sequence

Between November 14th and December 8th, 22 aftershocks with magnitude greater than 3.8 occurred, 11 of them in the day (15 hours) following the main shock, and 7 in the next 5 days. Most of the aftershocks occurred east of 93°E, extending as far east as 94.8°E (NEIC), close to the Kunlun Pass splay, in the general area where the rupture likely stopped (Figure 3). Two of the fault plane solutions of the eastern aftershocks have thrust mechanisms, which is consistent with an east propagating rupture stopping near 94°N. The distance from the NEIC epicenter to the easternmost aftershocks reaches 350 km. Even with a maximum uncertainty of 50 km in the longitudinal location of these events, this distance would still be 250 km. This corroborates the inference that the entire Kusai Hu segment ruptured during the 14 November, 2001 mainshock. Preliminary field investigations (Xu Xiwei, personal com.), confirm that the rupture crosses the Kunlun Pass road at 94.05°E, to continue eastward, south of the Burhan Budai Shan. No breaks, on the other hand, have been described so far along the trace of the Kunlun Fault in Xidatan, implying that the next 160 km-long segment of the fault towards the east (Van der Woerd et al., 1998; 2002) was not involved in the recent event.

POSSIBLE TRIGGERING OF FUTURE LARGE EARTHQUAKES

The seismicity in the last 100 years is certainly not representative of the long-term behavior of the Kunlun Fault. However, the fact that since 1937 several segments of the fault system have ruptured with earthquakes of magnitude > 7 implies that the whole fault is in an active period of its seismic cycle. Other segments, along which no large earthquake has occurred in the last 100 yrs, may thus be ready to break in the next future (Xidatan Dongdatan, Alag Hu, or Maqen segment farther east, Figure 2).

Based on the 11.5 mm/yr slip-rate and co-seismic, apparently characteristic, displacements of 8-12 m determined along the Xidatan segment, we deduced a recurrence time for large earthquakes rupturing that segment of about 900 years (Van der Woerd et al., 2000; 2002; Tapponnier et al., 2001b). At one site, the last large earthquake mole tracks on the lowest terrace were clearly washed out by a flood dated (with cosmogenic ^{10}Be and ^{26}Al) to be 278±87 yrs old (Van der Woerd et al., 1998; 2002). Trenching at different sites along the segment (Zhao et al., 1994; Zhao, 1996), further corroborates the inference that no large earthquake ruptured the youngest alluvial terrace and fan surfaces along the Xidatan segment in the last 500 years.

The clustering of aftershocks, some of them with thrust fault plane solutions, at the eastern end of the rupture, near and east of the Kunlun Pass, implies that the occurrence of the 14/11/01 earthquake induced fairly large stress changes in the region encompassing the western end of the Xidatan Dongdatan segment of the fault. This segment has not broken in the last 500 years, and only two large earthquakes have offset, by ~24±3 m, a riser dated at 1788±388 yrs at one site in the middle of Xidatan, near 35.4°N-94.4°E (Van der Woerd et al., 1998, 2002). Such observations are not inconsistent with the inference that we might be close to the end of the average recurrence interval of large earthquakes on that part of the Kunlun fault. If this were the case, then the Coulomb stress concentration induced by the 14 November, 2001 event in the Kunlun Pass area could trigger another large earthquake with magnitude > 7.5 on the Xidatan Dongdatan segment of the Kunlun Fault in the next months or years. Such sequential triggering of earthquakes would not be surprising. It has been observed along other major strike slip-faults, most remarkably the North Anatolian Fault in Turkey. Since 1939, nearly all the principal segments of that fault have ruptured successively from East to West, each M>7 earthquake triggering the next, months or decades later, in cascade mode (e.g. Stein et al., 1997). As a result, the whole length of the North Anatolian Fault between Erzinjan and Izmit (~1200 km) slipped in 60 years.

The possibility of similar earthquake triggering along the Kunlun fault, possibly all the way to Alag Hu, makes it particularly urgent to instrument and study the region located east of the Kunlun Pass in detail, with the various techniques that are now commonly used to understand post- and pre-seismic deformation and related phenomena.

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FIGURE CAPTIONS

Figure 1. Map of the active faults of Tibet, after Tapponnier et al. (2001a).

Figure 2. Simplified large-scale map of the Kunlun Fault and of its first-order segmentation (after Van der Woerd, 1998).

Figure 3. Map of Kusai Hu segment of the Kunlun Fault with location of main shock epicenters and centroid, and of aftershocks with magnitude ≥ 4. Fault planes solutions of main shock and of M≥5.5 aftershocks and previous events since 1980 are also shown. Maximum extent of surface rupture is outlined. Inset displays source modelling results redrawn from Kikuchi and Yamanaka (ERI, Tokyo), centered on Harvard CMT. Scale for slip is in meters, maximum slip is 5 meters.

Figure 4. Satellite image views of specific sites along the Kusai Hu segment of the fault.

a) Landsat view of western part of Kusai Hu segment, showing splaying of Kunlun fault west of Buka Daban Feng.

b) SPOT mosaic of eastern part of Kusai Hu segment and of splay between Xidatan segment and Kunlun Pass fault.

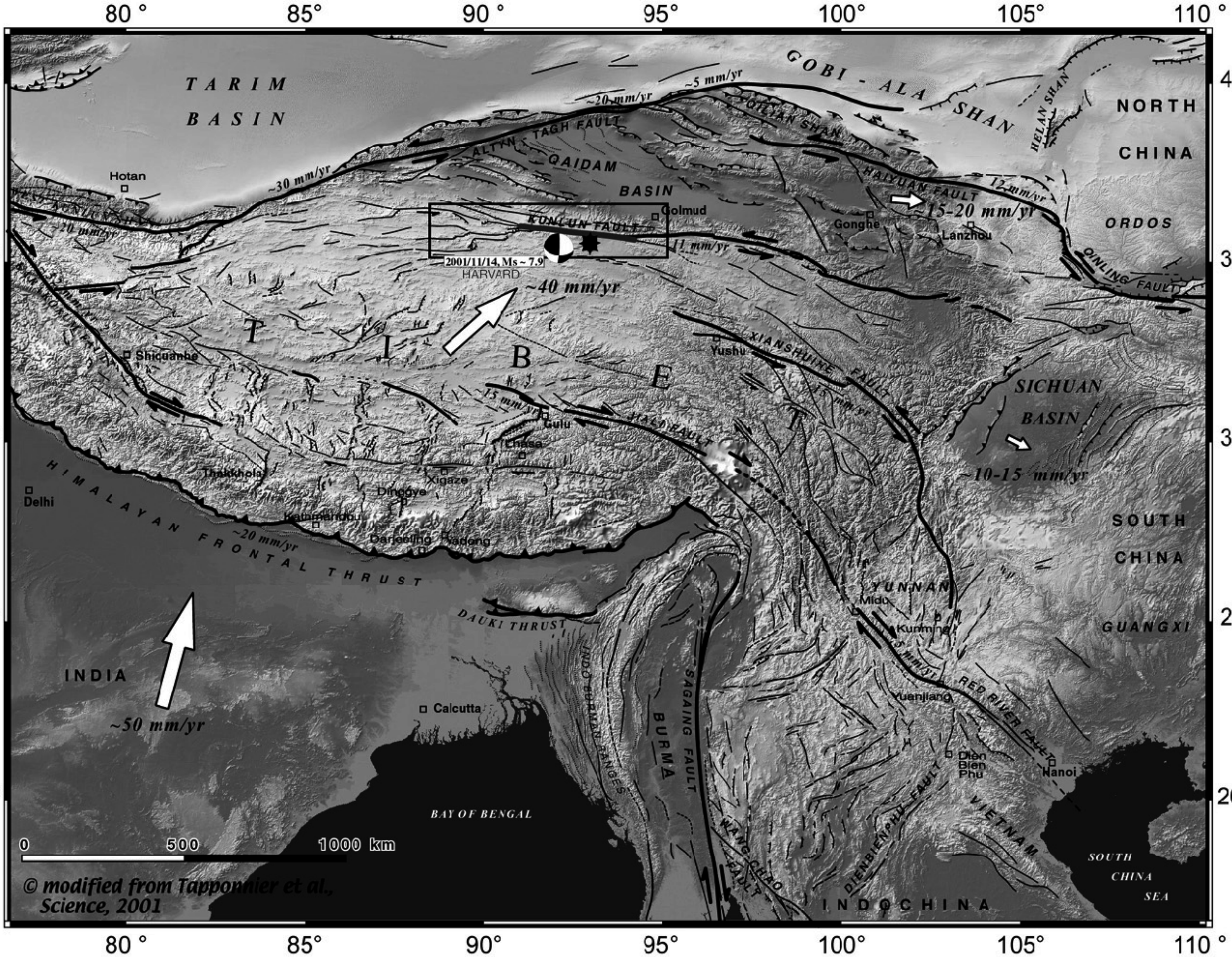
c) SPOT image enlargement of terrace and stream offsets due to cumulative left-lateral displacement along the fault. This is the area shown on August 15, 2000, Geophysical Research Letter cover.

d) SPOT image enlargement of pull-apart and large offset alluvial fan along left-lateral strand of fault, south of normal fault bounding faceted spurs of East Kunlun range. Both faults, only 1-2 km apart, probably merge at depth, testifying to local transtensionnal kinematics on south-dipping, oblique fault in basement beneath sediments.

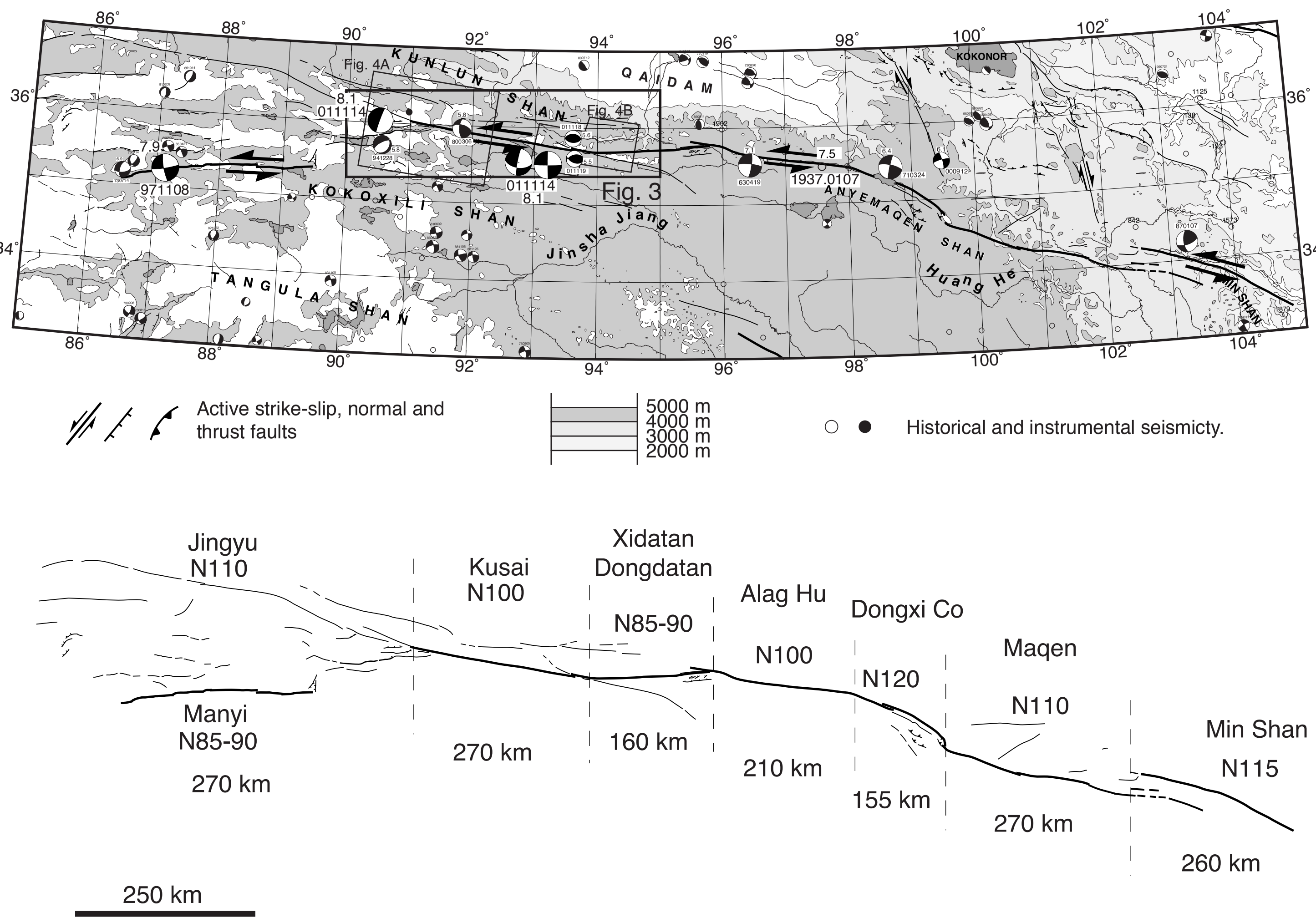
Figure 5. View, looking west, of eroded moles tracks of 1937 earthquake east of Dongxi lake.

Figure 6. View of fresh mole tracks due to November 14th, 2001 Mw=7.8 earthquake near Kunlun Pass, at eastern end of rupture (courtesy of Xinhua press). Several meters of sinistral slip are required to produce the cracks and pressure ridges that tear the frozen ground.

Figure 1



TARIM
BASIN
GOBI - ALA SHAN
HELAN SHAN
NORTH
CHINA
ORDOS
QILIAN SHAN
HAIYUAN FAULT
ALTYN TAGH FAULT
QAIDAM
BASIN
KUNLUN FAULT
QINLING FAULT
~5 mm/yr
~20 mm/yr
~30 mm/yr
12 mm/yr
15-20 mm/yr
11 mm/yr
~40 mm/yr
2001/11/14, Ms ~ 7.9
HARVARD
Hotan
Golmud
Gonghe
Lanzhou
T I B E T
Shiquanhe
Yushu
XIANSHUIHE FAULT
SICHUAN
BASIN
~10-15 mm/yr
15 mm/yr
Gulu
Lhasa
Xigaze
Thakkhola
Dingye
Kathmandu
Darjeeling
Yadong
Delhi
HIMALAYAN FRONTAL THRUST
~20 mm/yr
SOUTH
CHINA
GUANGXI
YUNNAN
Midu
Kunming
Yuanjiang
RED RIVER FAULT
Dien Bien Phu
Hanoi
VIETNAM
DIENBIENPHU FAULT
INDOCHINA
WANG CHAO FAULT
SAGAING FAULT
BURMA
INDO BURMAN RANGES
DAUKI THRUST
INDIA
~50 mm/yr
Calcutta
BAY OF BENGAL
SOUTH CHINA SEA
0
500
1000 km
© modified from Tapponnier et al., Science, 2001
80 °
85°
90 °
95°
100°
105°
110 °
40°
35°
30°
25°
20 °



KUNLUN SHAN
QAIDAM
KOKONOR
Fig. 4A
Fig. 4B
Fig. 3
8.1
011114
7.9
971108
7.5
1937.0107
KOKOXILI SHAN
TANGULA SHAN
Jinsha Jiang
ANYEMAQEN SHAN
Huang He
MIN SHAN
Active strike-slip, normal and thrust faults
5000 m
4000 m
3000 m
2000 m
Historical and instrumental seismicty.
Jingyu
N110
Kusai
N100
Xidatan
Dongdatan
N85-90
Alag Hu
N100
Dongxi Co
N120
Maqen
N110
Min Shan
N115
Manyi
N85-90
270 km
270 km
160 km
210 km
155 km
270 km
260 km
250 km

Figure 2.

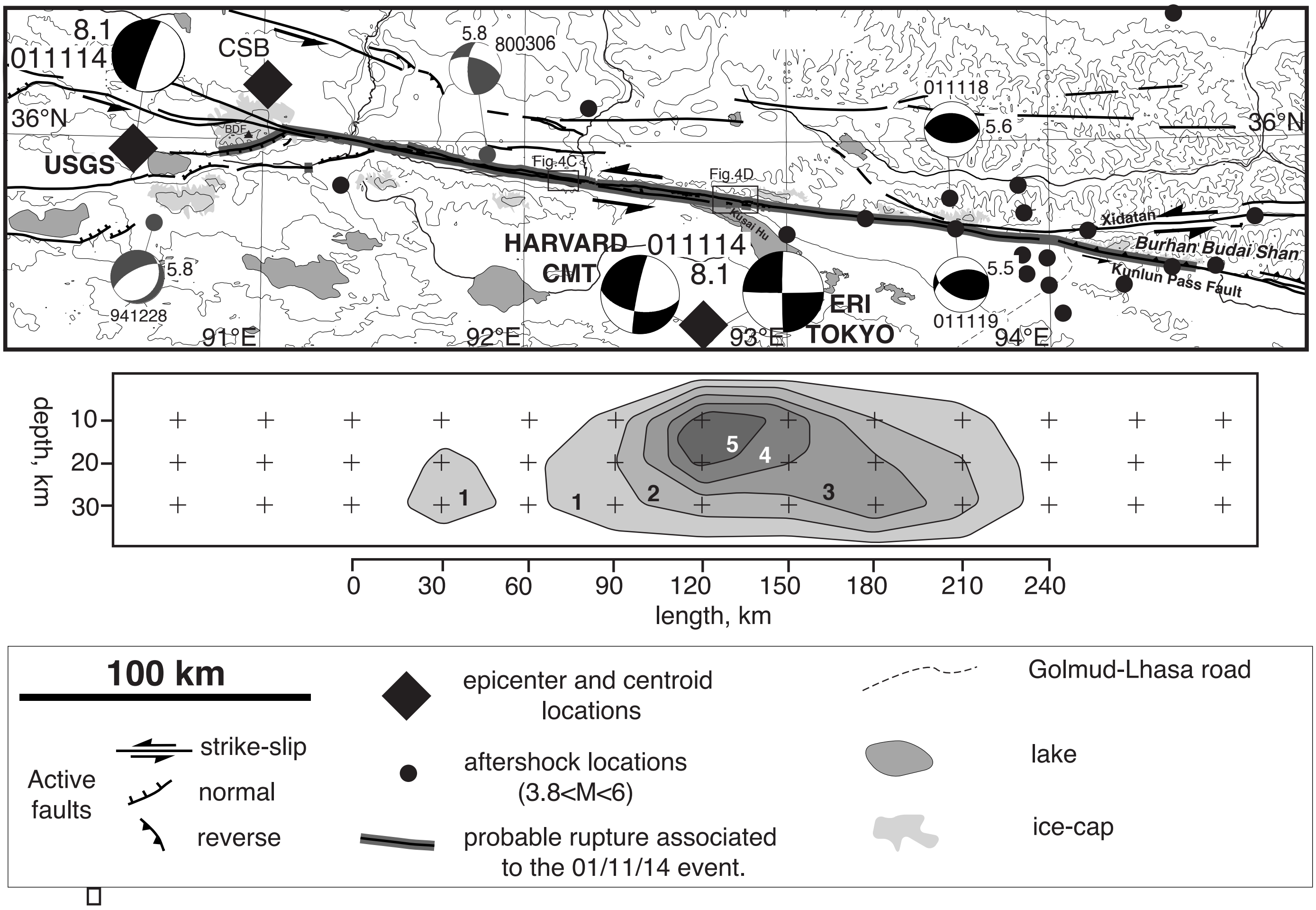
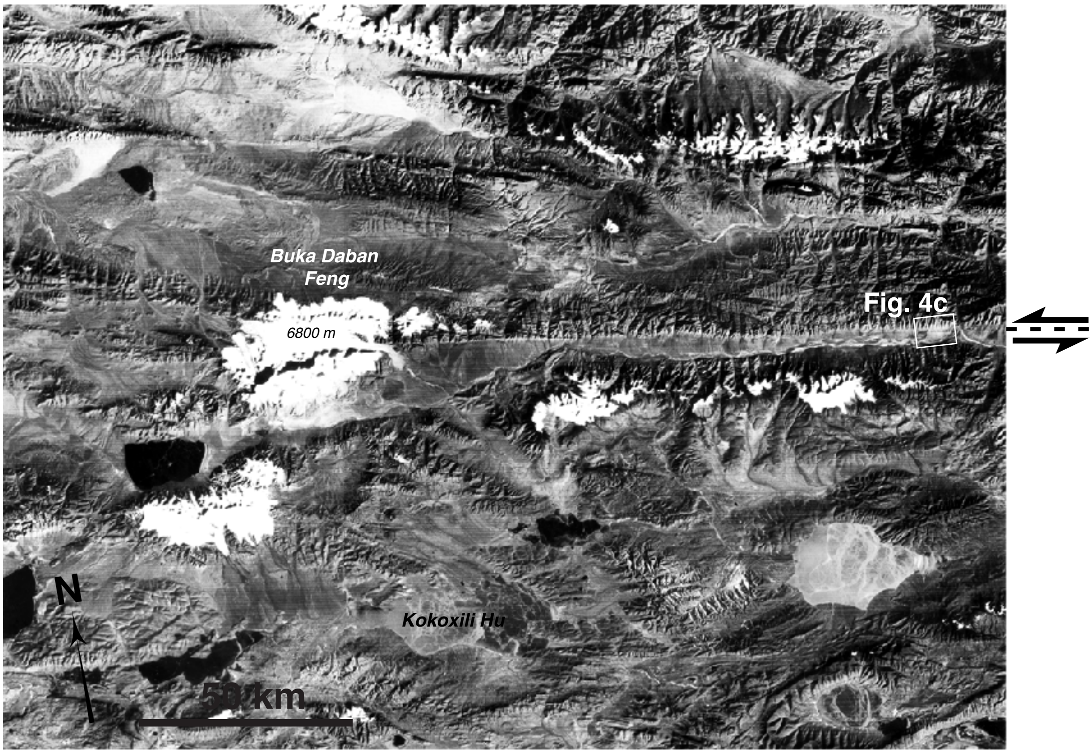

8.1
011114
CSB
5.8
800306
36°N
BDF
USGS
Fig.4C
Fig.4D
Kusai Hu
011118
5.6
HARVARD
CMT
011114
8.1
ERI
TOKYO
5.8
941228
5.5
011119
Xidatan
Burhan Budai Shan
Kunlun Pass Fault
91°E
92°E
93°E
94°E
depth, km
10
20
30
1
1
2
3
4
5
0
30
60
90
120
150
180
210
240
length, km
100 km
Active faults
strike-slip
normal
reverse
epicenter and centroid locations
aftershock locations (3.8<M<6)
probable rupture associated to the 01/11/14 event.
Golmud-Lhasa road
lake
ice-cap

Figure 3.

A



B

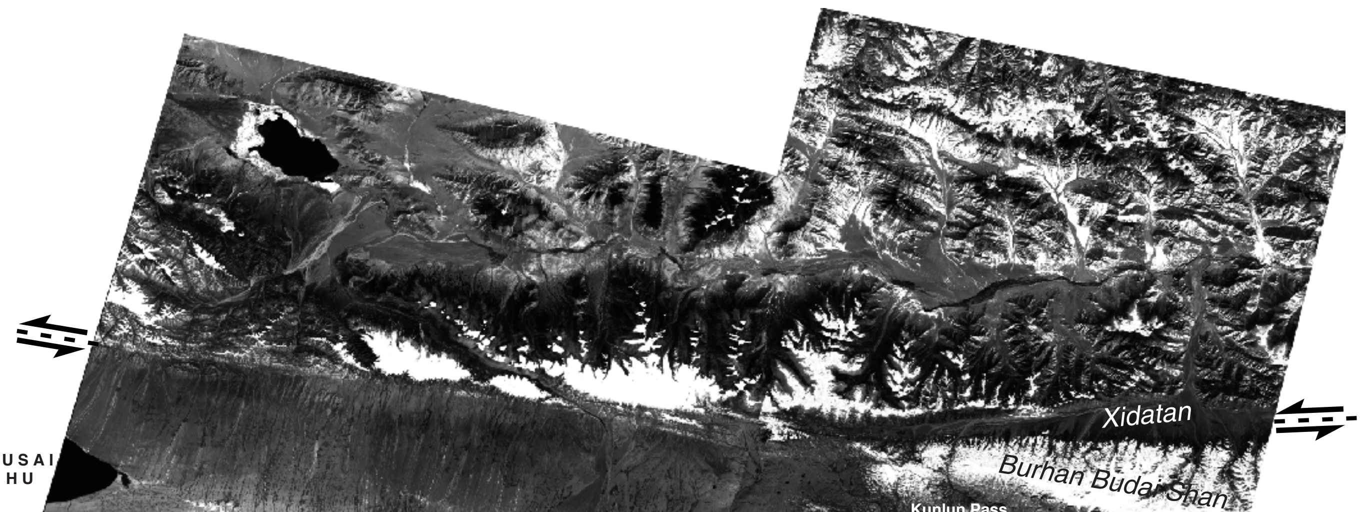
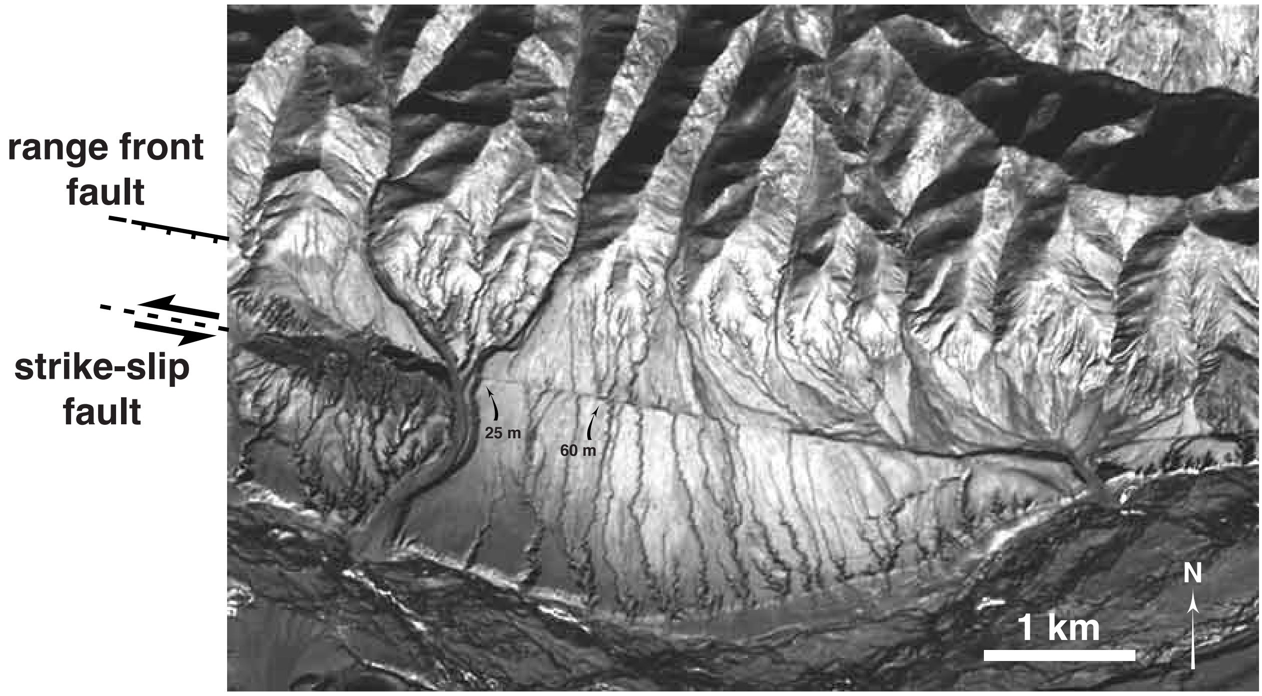
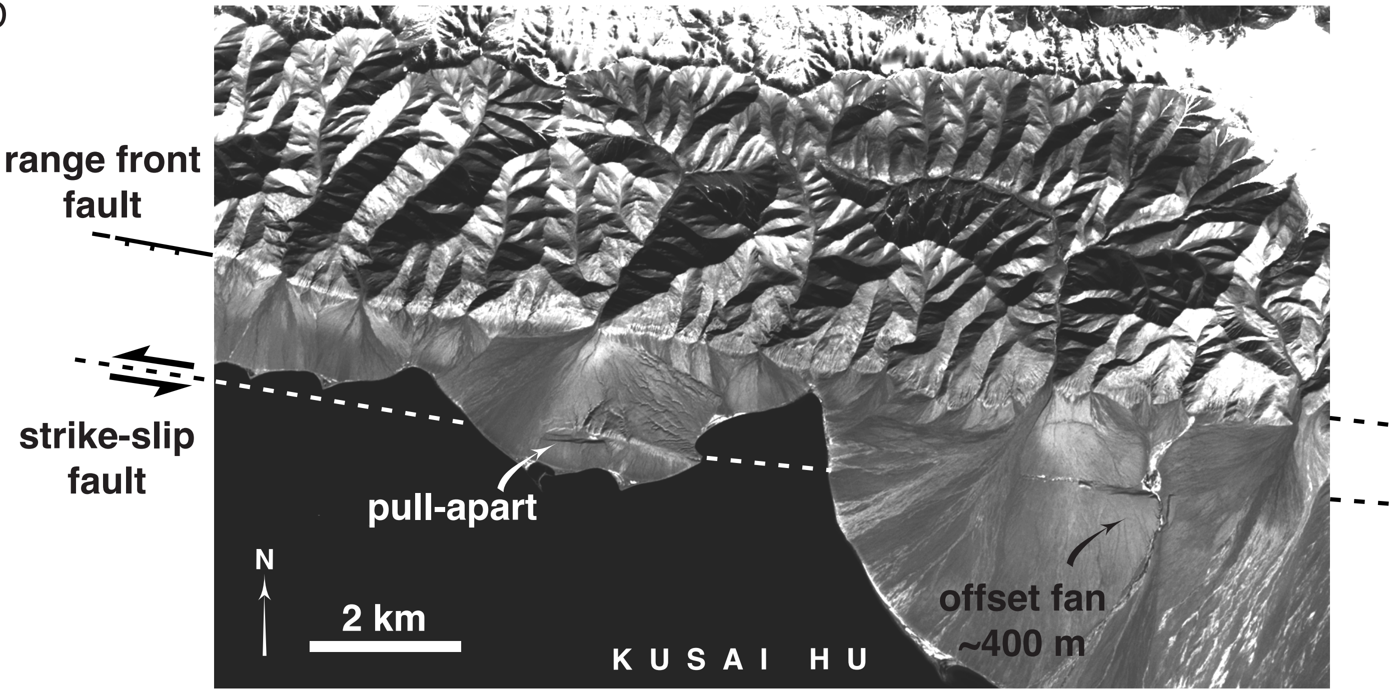


Figure 4AB

C


range front fault
strike-slip fault
25 m
60 m
N
1 km

D


range front fault
strike-slip fault
pull-apart
N
2 km
K U S A I H U
offset fan ~400 m

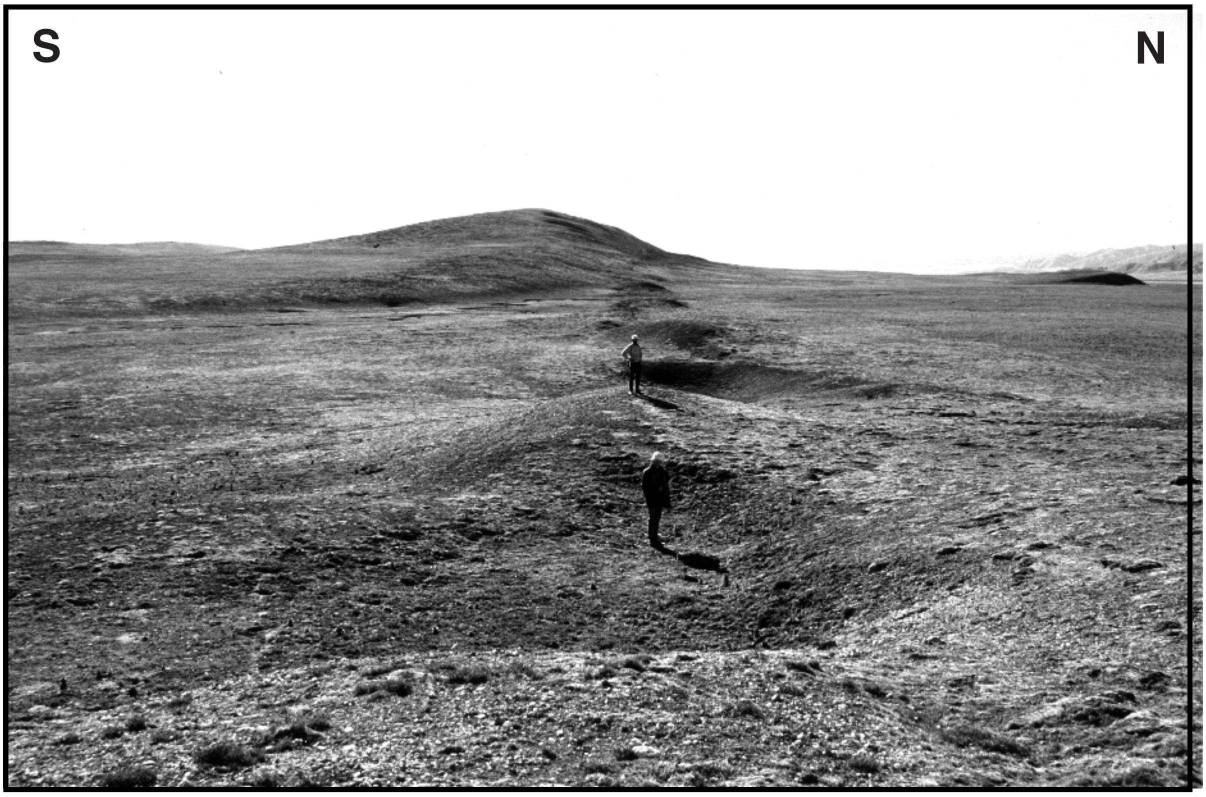


Figure 5

Figure 6.