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Slip-Partitioned Surface Breaks for the M_w 7.8 2001 Kokoxili Earthquake, China

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Abstract Slip-partitioned fault breaks have been mapped for a 70-km stretch of the 450-km surface rupture of the 14 November 2001 Kokoxili earthquake. Simultaneous dip-slip and strike-slip motion on parallel faults has been proposed before, but the new observations demonstrate unequivocally that it can occur in a single earthquake and allows the mechanical processes to be scrutinized. Observed normal fault offsets were between 0.5 and 1 m and strike-slip offsets were 3–5 m. The partitioned stretch of faulting has a strike that differs by 2–3° from the pure strike-slip faulting to the east and west. This allows a horizontal opening vector of 0.25 m to be determined for the partitioned region. The distance between the two faults is greatest (~2 km) at the center of the partitioned portion and diminishes toward the ends.

The faulting is modeled to result from strains due to a buried oblique slip-fault dipping at 80° to the south. The depth to the top of the buried fault is shown to vary commensurately with the separation of the surface faults. Clear surface rupture is observed where the predicted model mechanisms are colinear and where substantial faults can develop into a kinematically stable partitioned system. In a few interesting examples fragmentary, oblique surface ruptures occur where the predicted mechanisms are not colinear, but they are not associated with long-term surface faulting.

The proposed mechanism for slip partitioning requires that rupture propagates upward from depth. For the Kokoxili surface breaks this is a consequence of coseismic, dynamic rupture traveling faster at depth than near the surface, leaving the surface deformation to catch up. While the mechanism we propose requires slip weakening and localization to create faults or shear zones, it does not require that faults with different mechanisms have different frictional behavior.

Introduction

On 14 November 2001, a major earthquake (M_w 7.8) occurred in the Kokoxili region of the Kunlun fault along the North side of the Tibetan Plateau (Fig. 1a). The surface breaks extended for more than 400 km making it one of the largest strike-slip events known (Van der Woerd *et al.*, 2002a; Xu *et al.*, 2002; Lin *et al.*, 2002). The desert conditions resulted in clear surface breaks being formed and preserved. Mapping of these breaks has been undertaken by field mapping combined with analysis of Ikonos satellite images (Klinger *et al.*, unpublished manuscript, 2004). The latter have a pixel size of 1 m, which allows even small surface features with sufficient intensity contrast to be seen. In practice, this means that fissures with widths as small as 30 cm can be mapped. At present 100 km of the fault rupture has been mapped in detail. Here we discuss a stretch that shows clear slip partitioning. The major displacement is ~ 5 m of left-lateral strike slip, although at up to 2 km away and parallel to the strike slip are pure normal surface breaks with throws of up to 1 m. Although slip partitioning at this scale has been documented elsewhere (Allen *et al.*, 1984; Armijo *et al.*, 1986, 1989), this is the first time that such faults are known to have moved simultaneously in a single earthquake.

Recently Bowman *et al.* (2003) have shown that a process of upward propagation of deformation from a buried oblique-slip fault can explain fault distribution and mechanisms on the scale of tens of kilometers. In this article we show that the same process can explain the smaller-scale Kokoxili observations and suggest how it relates to the processes of dynamic rupture propagation.

The Origin of Slip Partitioning

The term “slip partitioning” is used to describe oblique motion along a fault system that is accommodated on two or more faults with different mechanisms (Fitch, 1972). Nu-

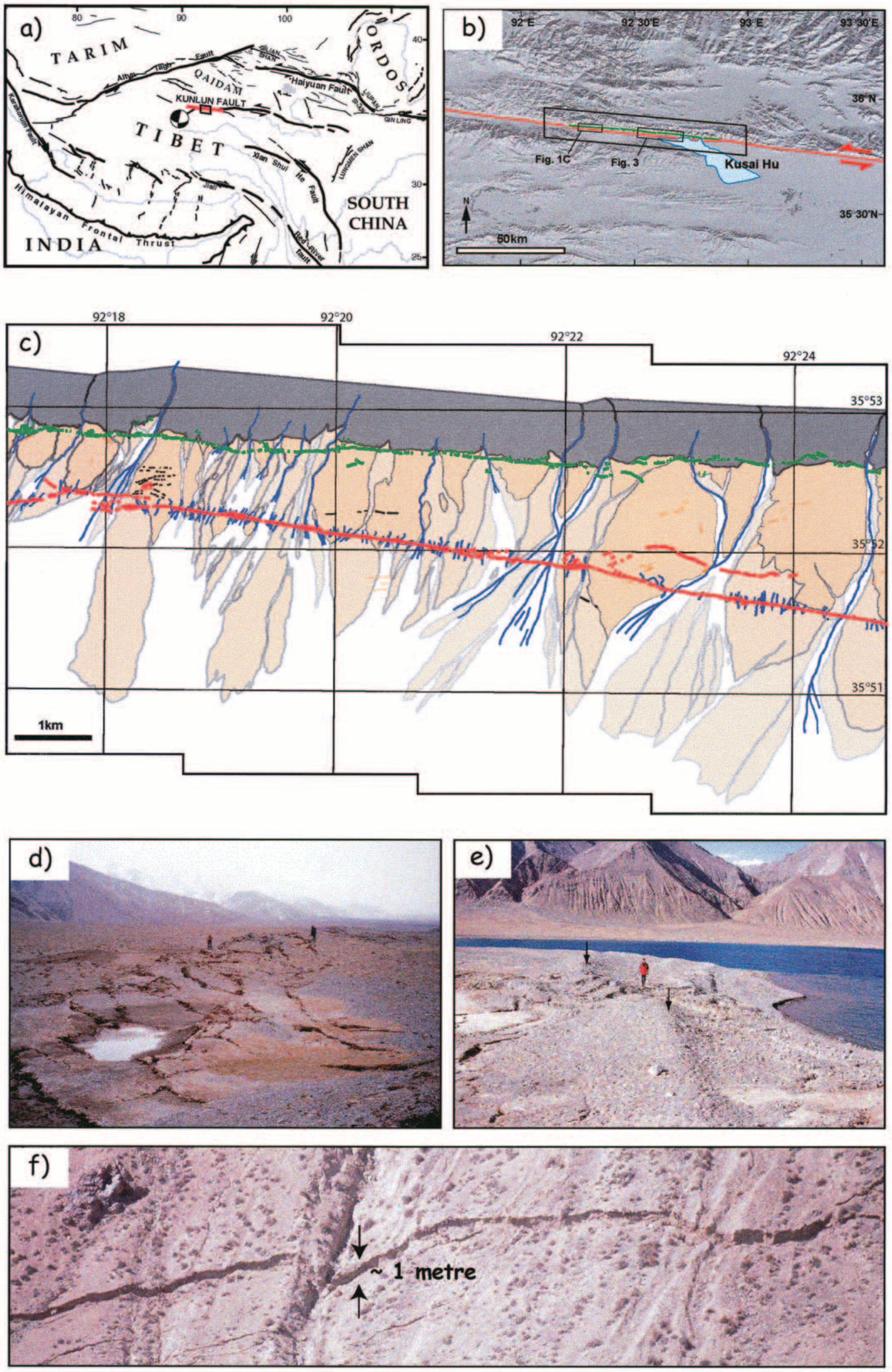
a)
80
90
100
40
30
25
TARIM
Altyn Tagh Fault
QILIAN SHAN
QAIDAM
Haiyuan Fault
ORDOS
LIUPAN SHAN
QIN LING
KUNLUN FAULT
Karakorum fault
TIBET
Xian Shui He Fault
LUNGMEN SHAN
Jiali
Himalayan Frontal Thrust
INDIA
SOUTH CHINA
Red River fault
b)
92°E
92°30'E
93°E
93°30'E
36°N
35°30'N
Fig. 1C
Fig. 3
Kusai Hu
N
50km
c)
92°18
92°20
92°22
92°24
35°53
35°52
35°51
1km
d)
e)
f)
~ 1 metre

Figure 1. (a) The location and overall focal mechanism (Harvard moment tensor) of the 14 November 2001 (M_w 7.8) earthquake. The section that ruptured is marked in red. (b) 200 km of the mapped faulting near Kusai Hu (Lake). The central sector exhibits strike-slip and normal surface breaks (enclosed in a box). Strike-slip breaks are shown in red and dip-slip in green. There is a difference in strike between the central section and the fault to the east and west of 3–4°. (c) A 12-km part of the detailed fault map. Strike-slip surface breaks are identified in red and dip-slip in green. In many places the November 2001 earthquake broke along features from previous events: Older scarps not reactivated in the recent event are shown in black. Rivers are shown in blue and older terraces in shades of yellow. Bedrock is indicated by dark gray. The locations of Figure 1c and Figure 3 are shown. (d) Strike-slip faulting surface breaks to the east of Kusai Hu. The remains of a sag pond from a previous event can be seen in the foreground. (e) Strike-slip surface breaks cutting the shore of Kusai Hu (Lake) with an offset of ~5 m. Arrows indicate an offset beach strand. The normal fault surface breaks occur near the base of the approximately 500-m-high escarpment in the background. The faceted spurs and wine-glass valleys indicate substantial late Quaternary normal faulting. (f) Normal surface breaks near the base of the escarpment shown in d.

←

merous examples are reviewed by Molnar (1992). The mechanics of slip partitioning has long been controversial because of the complex stress fields implied by the geometry and kinematics of partitioned systems. Michael (1990) and Wesnousky and Jones (1994) have suggested that slip partitioning might represent a minimum energy condition. However, because faults do not form closed thermodynamic systems there is no reason why such a condition should prevail. Another common explanation of partitioning is that major strike-slip faults evolve to have very low friction and thus are able to move in an overall stress field that favors dip-slip faulting. This has also been proposed as a solution to the low-heat-flow paradox along the San Andreas Fault (Henyey and Wasserburg, 1971). However, neither a widely accepted mechanism for producing low friction nor the reliability of the heat-flow measurements has been established (Scholz, 2000).

Jackson and McKenzie (1983) and Molnar (1992) have proposed models where a solid upper crust is deformed by viscous flow in the lower crust and upper mantle. These models might produce features similar to slip partitioning, but specific examples of partitioned faults in the crust have never been modeled in this way. Their view is also compromised by geological evidence (Wallace, 1984; Tapponnier *et al.*, 1990; Leloup *et al.*, 1995; Meyer *et al.*, 1998; Tapponnier *et al.*, 2001; Hubert-Ferrari *et al.*, 2003) and Global Positioning System (GPS) data (Meade *et al.*, 2002; Flerit *et al.*, 2004) showing that the deformation in the lower crust and upper mantle of continents is localized on shear zones. Seismic imaging of Moho offsets and lower crust and upper mantle features are also inconsistent with modeling deformation of the lower crust and upper mantle as a viscous fluid (Wittlinger *et al.*, 1998, 2004; Vergnes *et al.*, 2002).

Simple kinematic models for slip partitioning have been suggested, with a number of authors proposing that many examples of partitioned systems in Asia are an upper crustal response to oblique slip on deep-seated faults or shear zones (Armijo *et al.*, 1986, 1989; Gaudemer *et al.*, 1995; Tapponnier *et al.*, 2001). These models provide kinematic explanations of the observed surface deformation. The kinematic models, however, do not explain the origin and evolution of the stress fields that initiate and maintain partitioned systems, although, as we discuss below, specific kinematic conditions must be satisfied for partitioned faults to become long-lived features.

Bowman *et al.* (2003) recently proposed that slip partitioning can be explained as a result of upward propagation of oblique shear at depth. If the lower crust and upper mantle are not a viscous fluid then a slip-weakening, elasto-plastic rheology is the best approximation to their behavior (McClintock, 1971; Peltzer and Tapponnier, 1988; Cowie and Scholz, 1992a,b; Lawn and Wilshaw, 1975; Hubert-Ferarri *et al.*, 2003). As discussed by Bowman *et al.* (2003), the upper crust responds to stress from buried shear zones in a process of upward crack propagation that can be modeled with elastic fracture mechanics. Their approach is similar to that used to explain the creation and maintenance of en echelon midocean ridge structures (Abelson and Agnon, 1997; Hubert-Ferarri *et al.*, 2003).

Standard fracture mechanics models describe a zone of permanent deformation that extends around a crack or fault tip. The deformation within this "process or damage zone" can be modeled using an elastic approximation. In the process zone, stress amplitudes are poorly determined and much lower than an elastic model predicts, but strains and the principal axes of strain are more or less correct (Hubert-Ferrari *et al.*, 2003). The form of the strain tensor can consequently be used together with a simple Coulomb-like failure criterion (King and Cocco, 2000) to define the orientations and mechanism of predicted faulting.

In the process zone the material loses strength before being traversed by the propagating fault. Under simple shear conditions a mode II or III crack (Lawn and Wilshaw, 1975) can propagate through the process zone. However, the complex strain boundary conditions associated with an oblique fault beneath the Earth's surface prevent it from extending through the process zone as a single structure. The strain field around the fault tip is not simple, and hence, deformation distributes over several planes with different orientations and slip directions. Nearer to the surface and further from the fault tip the strains over substantial regions are more homogeneous, allowing new faults to form. These faults have mechanisms that are different from each other and from the buried fault, however. This explanation of the origin of slip partitioning (Bowman *et al.*, 2003) and can be used to create simple numerical models of partitioned systems that closely imitate observations.

Field Observations

The 14 November 2001 earthquake ruptured part of the Kunlun fault in northeast Tibet (Fig. 1a). This fault has long been recognized as one of the major strike-slip faults in Tibet, allowing eastward escape of the Tibetan plateau in response to the India/Eurasia collision (Tapponnier *et al.*, 2001). With a slip-rate of ~1 cm/yr (Van der Woerd *et al.*, 1998, 2000, 2002b), the Kunlun fault is known to have hosted several large earthquakes with magnitude > 7 (Tapponnier and Molnar, 1977; Peltzer *et al.*, 1999; Van der Woerd *et al.*, 2002a). The ground rupture associated with the 14 November 2001 events is more than 400 km long and mainly follows the southern flank of the Kunlun range (Lin *et al.*, 2002; Van der Woerd *et al.*, 2002b; Xu *et al.*, 2002) with the exception of the two extremities where the rupture branches onto secondary faults. This study focuses on the central segment of the rupture, the Kusai Hu segment, named after the largest lake in the region (Fig. 1b). This includes a 70-km stretch of slip partitioning with parallel normal and strike-slip surface breaks separated by up to 2 km. These partitioned faults strike at an angle of 3–4° to the pure strike-slip faulting observed to the east and west. The average horizontal slip along the stretch of faulting shown in Figure 1b is about 5 m. This change of strike allows the opening due to partitioning to be estimated to be ~0.25 m.

A part of the mapped fault is shown in Figure 1c with strike-slip surface breaks shown in red and normal slip breaks shown in green. Photographs of the strike-slip fault are shown in Figure 1d and e. In Figure 1e a sag pond formed by a previous earthquake can be seen, and Figure 1d shows where the fault offsets the shore of the Kusai Hu (lake) by about 5 m. Normal faults occur near the base of the escarpment shown in Figure 1e and f. The faceted spurs and wineglass canyons (Fig. 1e) indicate that normal faulting has been taking place for tens of thousands of years.

Modeling Slip Partitioning

The mechanics of slip partitioning can be understood by regarding the buried oblique fault to be a dislocation. The resulting strain field and fault mechanisms are calculated with Almond 7.05 software (www.ipgp.jussieu.fr/~king) based on the program developed by Okada (1982) to calculate displacements and strains around a rectangular dislocation in a homogeneous half-space. Figure 2a shows that the strain between the dislocation and the surface exhibits a range of different fault mechanisms (for more examples, see Bowman *et al.*, 2003 supplementary material). Two regions occur that have either predominantly strike-slip or predominantly normal mechanisms. These are outlined in red and green, respectively. Although deformation occurs throughout the zone of high strain, it is only within these regions that coherent and colinear strike-slip or normal faults can form. Where the predicted mechanisms vary spatially, no single simple through-going fault can form, instead incoherent multiple fracturing is to be expected (Bowman *et al.*, 2003).

The mathematical modeling treats the top of the dislocation as an edge dislocation. As discussed earlier, the region is in reality a large damage zone with no such abrupt boundary. Consequently, the term “top of the buried fault” that we use later should be interpreted as the center of the damage zone rather than as an abrupt feature.

The surface breaks in map view are modeled assuming that the strike-slip component of displacement on the buried fault is 5 m and the horizontal component of opening is 0.25 m (Fig. 2b). The depth to the top of the fault and its dip are adjusted to fit the observations (Fig. 2c). The dip-slip component of motion is calculated from the horizontal motion and the chosen dip. There are consequently two variables that can be adjusted to fit the observations, dip and depth. The best fit is found by forward modeling. This is straightforward because of the limited sensitivity to parameters discussed by Bowman *et al.* (2003) (see supplementary material www.sciencemag.org/cgi/content/full/300/5622/1121/DC1) and below. Models can be found that fit the location of the observed faulting over a range of dips from 65° to 85°. The amount of dip-slip motion on the main fault is determined by its dip to give the 0.25 m of horizontal motion. This in turn determines the vertical component. Thus, shallower dips require a smaller vertical component of displacement on the main fault. A dip of 80° on the buried fault requires a dip-slip component of 1.5 m. Resolving this onto a near-surface normal fault with a nominal dip of 45° permits the observed 1-m displacements. Shallower dips predict smaller displacements and consequently seem less likely.

The distance between the zones of normal and strike-slip faulting is relatively insensitive to the dip of the oblique fault. The separation between the normal and strike-slip faulting, however, is sensitive to the depth to the top of the oblique driving fault. The depth to the top of the driving fault that produces the best fit is shown in Figure 2d.

The fit of the model to the main through-going strike-slip and normal surface breaks is very close. These occur where the predicted mechanisms are colinear and thus allow a through-going fault to form for the same reason considered when discussing the cross section. Deformation is mainly localized on two structures; however, some deformation does occur elsewhere as shown in Figure 3. Although the strike-slip surface break forms a narrow feature, normal faulting may consist of many small ruptures oblique to the overall trend of the faulting. This is consistent with the model, which correctly predicts such a distribution of faulting. Unlike faults evolving where colinear faulting is predicted, these scattered oblique surface breaks cannot link to form long-lived features. Many older breaks (black in Fig. 3) that did not move in the last event attest to the transitory nature of this oblique faulting.

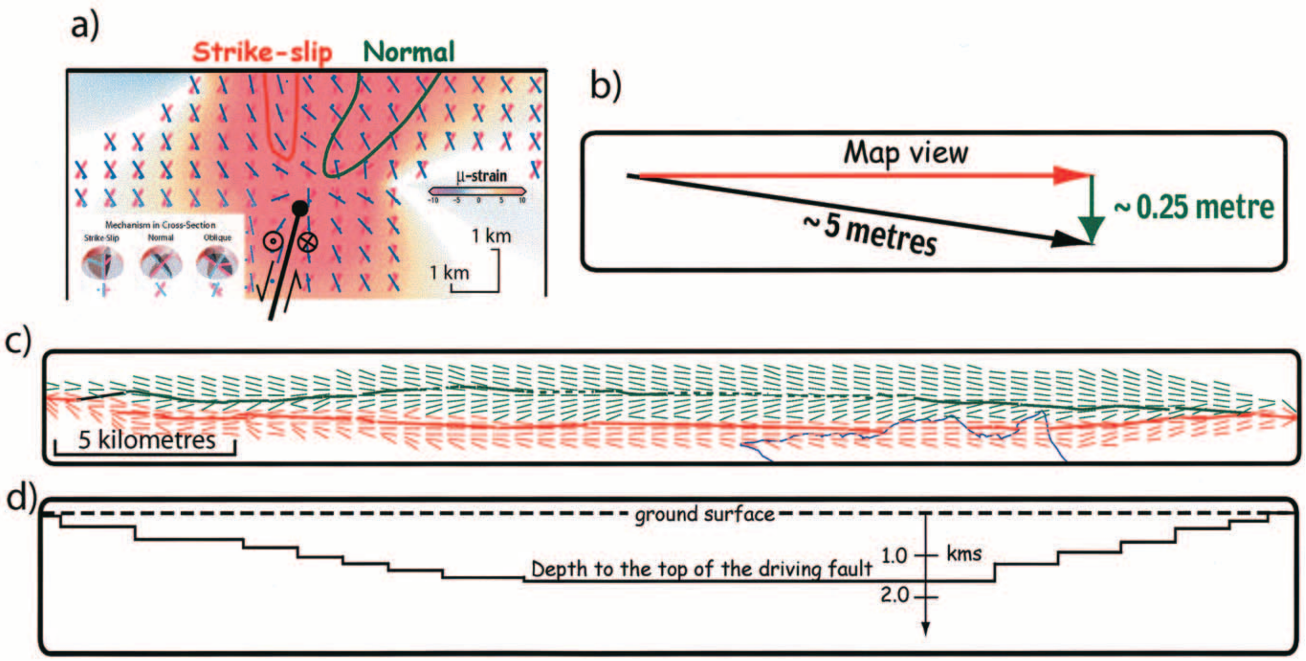

Figure 2. (a) Cross section of the distribution of strain resulting from a dipping buried strike-slip, normal-slip fault. The mechanism of faults that can relieve the strain is indicated by lines and dots. (See the inset for interpretation and Bowman *et al.*, 2003.) Two areas are identified where strike-slip and dip-slip mechanisms predominate. The separation between these zones at the surface is slightly less than the depth to the top of the dislocation. (b) The faulting to the east and west of the partitioned section is pure strike slip with and average offset of 5 m. The 3–4° strike difference suggests that the opening component is about 0.25 m. (c) A simplified surface break map of the region shown in the box in Figure 1b. Strike-slip surface breaks are shown in red and normal fault in green. Predicted fault strikes using the same color code are shown by short lines. The predicted slip directions are calculated for an 80° dipping fault with 5 m of strike-slip motion and 1.5 m of dip-slip motion (corresponding to 0.25 m of opening). The continuous strike-slip and normal breaks occur where the model predicts colinear faulting. (d) A cross section showing the depth to the top of the dislocation that produces the model shown in c.

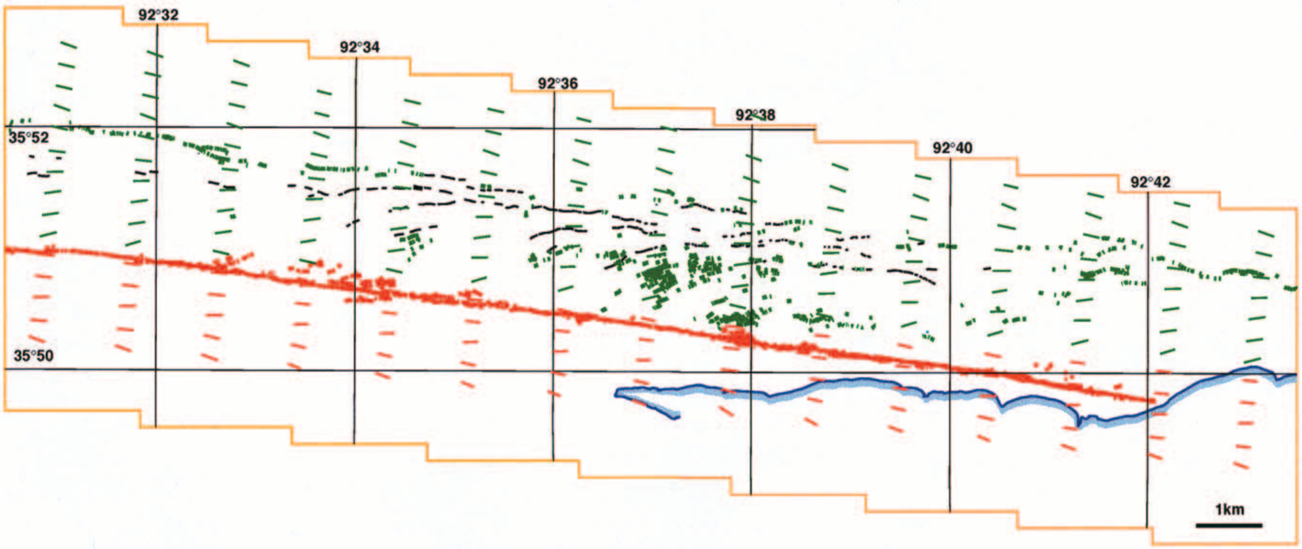

Figure 3. In some places the normal faulting does not form a continuous trace. Both old and new breaks correspond to predicted directions that are not colinear.

Discussion

Slip partitioning is a consequence of propagation of rupture. Should all parts of a fault move together, partitioning would not occur. It is consequently appropriate to ask why some parts of a fault should move before other parts. This problem is analogous to the question of how edge dislocations can be repeatedly created within the body of a crystal. This was solved by the recognition of the Frank-Reid source from which dislocations are born and spread along crystal planes (Nabarro, 1967).

No such single explanation seems available for faults. For the crustal scale examples discussed by Bowman *et al.* (2003) it was noted that faults or shear zones in lower crust or mantle must slip prior to those in the upper crust. King and Bowman (2003) discuss why stable sliding at depth should drive slip in the seismogenic upper crust and why slip at seismogenic depths lags slip at greater depth, catching up only at the time of an earthquake. Although this provides a possible explanation, their models for the Transverse Ranges and North Tibet require that the top of the driving fault is at 40–50 km (Bowman *et al.*, 2003). This is too deep to correlate with the stick-slip/stable sliding transition. For the even larger-scale slip partitioning associated with subduction systems (Fitch, 1972) no unequivocal explanation seems to be immediately available.

Unlike the larger-scale examples, the small-scale partitioning associated with the Kokoxili earthquake can be explained in terms of dynamic propagation. The rupture in the November 2001 earthquake propagated from west to east (Xu *et al.*, 2002; Antolik *et al.*, 2004; Bouchon and Vallée, 2003). Figure 4 indicates the generalized form of the rupture front. Seismic velocities almost invariably increase with depth. Thus, the rupture advances faster at depth than near to the surface and, consequently, the top kilometer or two experience nearly upward propagation.

The reduction of seismic velocity near to the surface can be due to several effects. Surface, poorly consolidated sediments exhibit low velocities and low velocity also appears in basement rocks as a result of cracks and fissures that remain open under the low confining pressures (Scholz, 2002). A further effect is the relaxation of stress over a similar depth range due to stress corrosion cracking (Scholz, 2002). This latter process has been discussed by King and Vita-Finzi (1981) and Vita-Finzi and King (1985) in the context of surface folding, a process that also involves upward propagation.

For the Kokoxili earthquake partitioning, the top of the driving oblique fault could coincide with the bottom of surface sediments with the low seismic velocity in the sediments being largely responsible for upward propagation as proposed by Armijo *et al.* (1986, 1989). For the Kokoxili earthquake slip partitioning is only observed where the strike-slip fault cuts sediment; elsewhere, the strike-slip fault appears at the base of the mountain front. This is consistent with the partitioning being a result of the surface sediments. However, because of the differences of strike, only the partitioned Kusai segment is associated with opening. Thus no normal faulting is expected elsewhere. The sediments can also be the consequence rather than the cause of slip partitioning. Sediments deposited on the hanging wall of normal faults will, over time, cover the strike-slip fault, causing the system to evolve toward that observed.

No shallow focal mechanism data are available to support the field observations of slip partitioning near Kusai Hu because no local stations exist in the region. However, the mechanisms of small earthquakes along the central Denali Fault, Alaska, after the 2002 earthquake (Ratchkovski, 2003) could be explained by the propagation processes that we invoke.

Conclusions

Coseismic slip partitioning between pure strike-slip and pure normal faulting is observed along the Kusai Hu segment of the Kunlun fault. Both the strike-slip and the normal faulting have been active through the Quaternary and both rebroke during the 14 November 2001 Kokoxili earthquake. By combining field studies with analysis of Ikonos high-resolution satellite images, the faulting has been mapped in

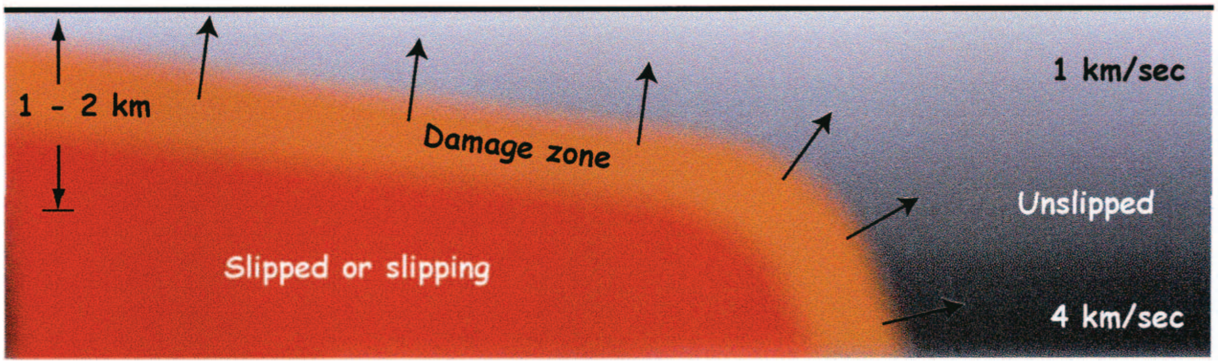

Figure 4. Seismic velocity increases with depth. Thus, deep rupture propagates faster than rupture near to the surface, resulting in upward rupture propagation.

detail. Following earlier work by Bowman *et al.* (2003), we have modeled the surface ruptures on the assumption that they result from upward propagation from a dipping oblique-slip fault at depth. We follow their assumption that a plastic (or damage zone) develops ahead of the propagating fault and that distinct faults form where the strain is coherent over a sufficient distance to be relieved by a fault of significant dimensions.

The modeling has only two adjustable parameters—the dip of the buried fault and its depth—and is consequently robust. The model that most closely fits the observations has a dip of 80° and a maximum depth to the top of the buried fault of 2 km. Through-going rupture occurs only where the model mechanisms are colinear, allowing coherent faults to form. The resulting geometry is similar to that described kinematically by Armijo *et al.* (1986, 1989). It is unlikely, however, that the faults join at a simple triple junction at depth. It is more likely to be a region of a complex of small faults with a range of mechanisms as predicted by the modeling. In a few places scattered oblique faults occur at the surface in places where the predicted mechanisms are not colinear. These include both new rupture and features from previous events that were not reactivated. The foregoing adds further support to the view proposed by Bowman *et al.* (2003) that significant faults can only evolve where the strain field is homogeneous over a significant distance.

The mechanism for slip partitioning that we adopt requires that rupture propagates upward from depth. For the Kokoxili surface breaks this is a consequence of coseismic, dynamic rupture traveling faster at depth than near the surface, leaving the surface deformation to catch up. Although the mechanism we propose requires slip weakening and localization to create faults or shear zones, it does not require different values of friction for faults with different mechanisms.

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