Significant late Neogene east-west extension in northern Tibet

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ABSTRACT

Field mapping in northern Tibet reveals that the normal slip along late Cenozoic north-south–trending faults is comparable to that estimated for equivalent structures in southern Tibet. The orientation of fault striations in two north-south–trending rifts suggests an east-northeast–west-northwest direction of extension in northern Tibet, which in turn implies that northeast-striking active faults in northern Tibet have significant left-slip components. Initiation of rifting in northern Tibet postdates the early Oligocene, and possibly occurred after 4 Ma. The broad similarities in the magnitude of slip and the direction of extension for normal faults in both northern and southern Tibet imply that the entire plateau has been extending. This precludes significant eastward extrusion of north Tibet relative to south Tibet and requires a regional boundary condition as the cause of east-west extension for the entire Tibet plateau.

INTRODUCTION

In one of the first papers documenting active east-west extension in Tibet, Molnar and Tapponnier (1978) attributed the extension to gravitational spreading of its thick crust. England and Houseman (1989) related extension to rapid uplift of the Tibetan plateau caused by convective removal of the lower mantle lithosphere. Other workers have argued that east-west extension in southern Tibet reflects local boundary conditions such as oblique convergence between India and Asia (McCaffery and Nabelek, 1998), outward expansion of the Himalayan arc (Seeber and Armbruster, 1984; Klootwijk et al., 1985; Molnar and Lyon-Caen, 1989; Ratschbacher et al., 1994; Seeber and Pecher, 1998), and eastward extrusion of north Tibet (Armijo et al., 1986). However, Yin and Kong (1997) proposed that the late Neogene extension in Tibet is part of widespread extension affecting much of east Asia in the past 10 m.y. (e.g., formation of the Shanxi graben and Baikal rift). The ongoing debate about the causes of late Cenozoic east-west extension in Tibet reflects, in part, a lack of information on the timing and magnitude of rifting in northern Tibet.

FIELD OBSERVATIONS

The presence of north-south–trending rifts in northern Tibet has long been recognized by interpretation of Landsat images (Ni and York, 1978; Armijo et al., 1986). However, these structures have never been studied in the field nor documented in any existing geologic maps, although their characteristic rift morphology is evident in various topographic or relief maps of Tibet (e.g., Liao, 1990). Here we present the results of detailed geologic mapping across two active north-south–trending rifts: the Muga-Purou rift near Shuang Hu and the Chagd rift near Gangma Co in north-central Tibet (Fig. 1).

Shuang Hu Area

The east-dipping Shuang Hu normal fault system is along a dramatic topographic front with a relief of ~1.0 km (Figs. 2 and 3A). The fault system offsets alluvial fans and shows prominent fault scarps. Directly below the range-bounding fault are numerous minor east-dipping normal faults, which have offsets of tens of centimeters to a few tens of meters. Striations on these faults indicate a slip direction of N50°–65°E (Fig. 3B), implying that the Shuang Hu fault has a significant left-slip component. The Shuang Hu fault cuts two post-Triassic strike-slip faults and the Early Jurassic Falong detachment fault (Kapp et al., 1997; Yin et al., 1998a). We estimate the normal slip across the Shuang Hu fault to be ~7 km, partitioned between two faults (Fig. 2B), on the basis of matching a Triassic unit (Trd). The buried eastern fault is required by the distribution of the Trd unit and the Triassic stratigraphy.

The Qiagam fault strikes north-northeast in the north, but makes a sharp turn to strike northeast at its southern end. Although this fault does not show clear evidence for Quaternary faulting, it bounds a Quaternary basin, which is suggestive of youthfulness. Correlating the blueschist-bearing metamorphic rocks belonging to the footwall of the Falong detachment suggests a minimum slip of 4 km across this fault (Fig. 2B).

Gangma Co Area

The Gangma Co area is ~500 km west of Shuang Hu (Figs. 1 and 4), where the west-dipping Chagd fault cuts Quaternary alluvial deposits. An east-dipping normal fault is present in the south-central study area with N50°E trending

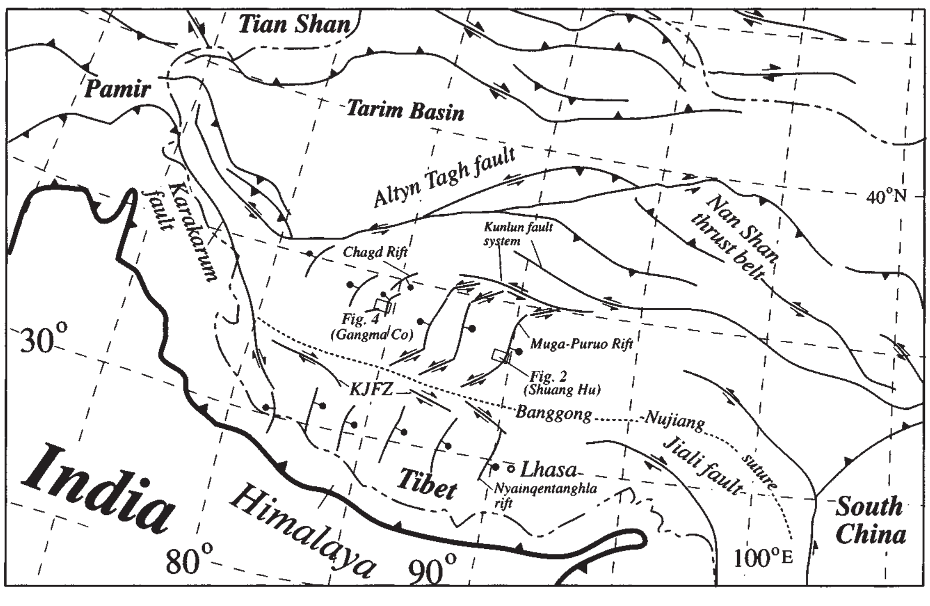

Figure 1. Regional tectonic map of Tibetan plateau and its neighboring regions. Note that Shuang Hu area (see Fig. 2) is located in central part of Muga-Purou rift, whereas Gangma Co area (see Fig. 4) is located in southern part of Chagd rift. KJFZ is Karakorum-Jiali fault zone.

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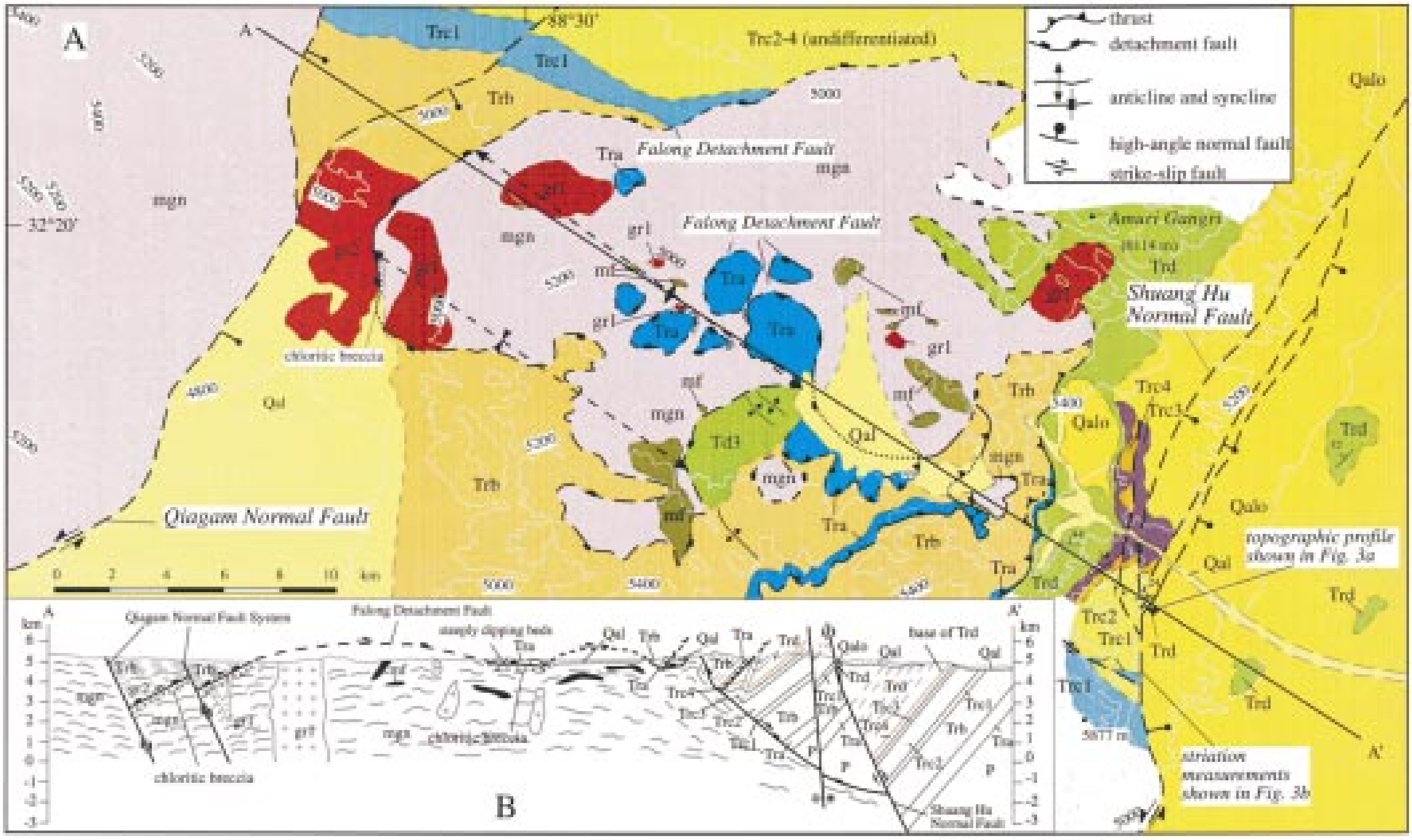

Figure 2. A: Simplified geologic map of Shuang Hu region. Locations of both fault scarp profile and kinematic measurements (Fig. 3, A and B) are indicated. Units: mgn, mylonitic gneisses and schists; mf, mafic intrusives; gr1, granitoids below Falong detachment fault; gr2, granitoid above Falong detachment fault; Qalo, old Quaternary alluvial deposits; Qal, young alluvial deposits. Triassic strata are divided into four units, Tra, Trb, Trc, and Trd; Trc is divided into four lithologic subunits. Lithologies and approximate thickness estimates of Triassic units: Tra (>350 m thick), dolostone; Trb (~1600 m thick), volcanic sequence consisting of andesite interbedded with shale and siltstone; Trc1 (150–200 m thick), gray limestone; Trc2 (800–1000 m), conglomerate interbedded with sandstone; Trc3 (400–500 m), fluvial sandstone interbedded with minor conglomerate; Trc4 (200–400 m), conglomerate; Trd (>600 m), red sandstone interbedded with mudstone. KJFZ, Karakorum-Jiali fault zone. B: Geologic cross section of Shuang Hu region.

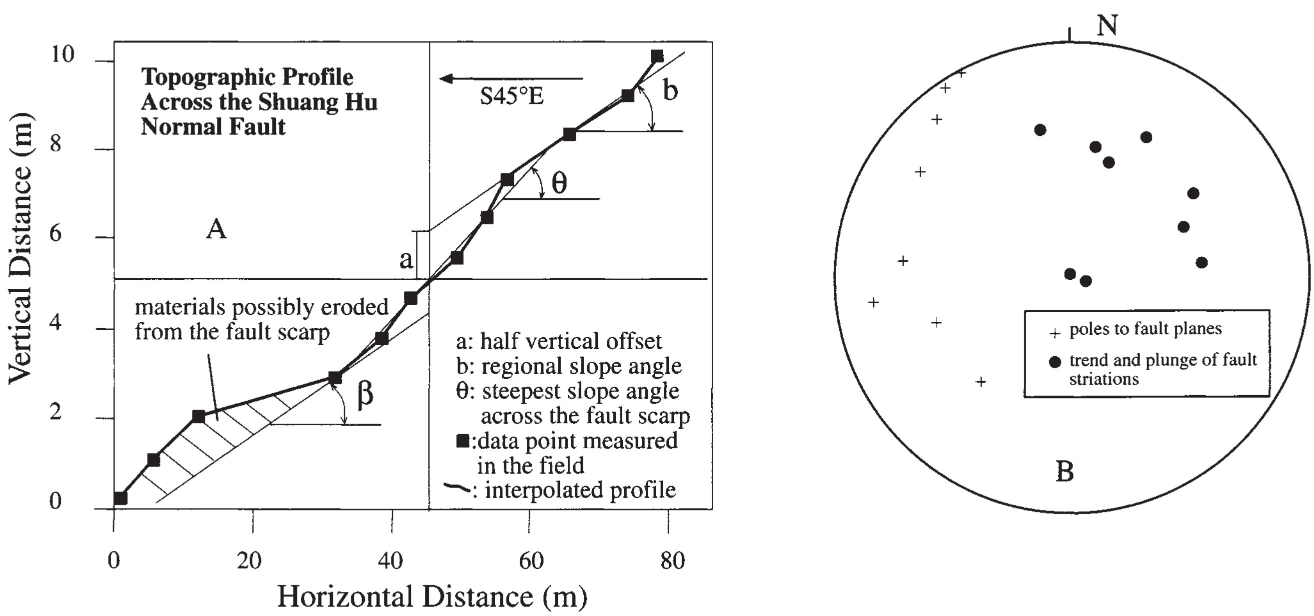

Figure 3. A: Topographic profile across active strand of Shuang Hu fault system: *a* = 1.2 ± 0.3 m, *b* = tan10°, and θ = 25° (see text). Note that lower regional slope below fault scarp is significantly lower than upper regional slope, possibly due to accumulation of materials eroded from fault scarp. B: Poles of minor east-dipping normal faults and trend and plunge of fault striations measured from Shuang Hu fault zone.

striations in the fault zone (Fig. 2). This fault offsets the Cenozoic Gangma Gangri thrust system (Yin et al., 1998b; Kapp et al., 1998), which juxtaposes a blueschist-bearing melange complex over the early Neogene Kangtuo Formation of Cheng and Xu (1986). Exhumation of the blueschists was related to motion along the Late Triassic–Early Jurassic Gangma Co detachment fault (Yin et al., 1998a; Manning et al., 1998).

Because the Chagd fault is poorly exposed, its kinematics cannot be directly determined. However, several mesoscopic, east-dipping normal faults are present in its hanging wall near the central segment of the Chagd fault. The trend of the striations on these faults is N50°–65°E. Because the main east-dipping normal fault cuts the early Neogene strata and is parallel to the Chagd fault, we infer that the two faults were formed as a conjugate set and therefore share the same east-northeast–west-northwest extensional direction (Fig. 4).

In the hanging wall of the Chagd normal fault, a thrust juxtaposes a Carboniferous carbonate sequence over Tertiary redbeds. It may be correlated with the Gangma Gangri thrust in its hanging wall because the lithology of the Tertiary redbeds is similar to that in the footwall of both thrusts, and both thrusts consist of a similar Carboniferous carbonate sequence in their hanging walls (Fig. 4). If this correlation is correct, it implies that the Chagd fault has a normal slip of ~11 km (Fig. 4B). We consider that the 11 km of normal slip across the Chagd fault is a maximum estimate, and favor a smaller displacement, because (1) the Tertiary basin in the hanging wall of the Chagd normal fault appears to be shallow, as suggested by the isolated Carboniferous outcrops in the hanging-wall basin close to the main fault (Fig. 4A), and (2) Cretaceous tuffs, dated between 91.9 ± 1.4 Ma and 132 ± 8.2 Ma by $^{40}Ar/^{39}Ar$ on single sanidines crystal (samples from Kv3 in Fig. 4A), are preserved in the footwall of the Chagd normal fault, suggesting that its footwall denudation by faulting and erosion has been negligible since the mid-Cretaceous. To reconcile these geologic observations, we interpret that the offset thrust by the Chagd fault has a listric geometry, making the inferred normal offset along the Chagd fault 5–7 km.

AGE AND SLIP RATE OF THE NORMAL FAULTS

The ages of Cenozoic normal faults in northern Tibet are highly uncertain. In the Gangma Co area, normal faults cut the Miocene Kangtuo Formation of Cheng and Xu (1986), the lower age of which is defined by the underlying Nadin Formation. The Nadin Formation, exposed ~100–150 km south of the study area, consists of ~650-m-thick andesitic flows that yield a K-Ar age of 31 Ma (Cheng and Xu, 1986).

We have no constraint on the age of the Shuang Hu fault. However, its minimum slip rate may be determined from a topographic profile across a fault scarp (Fig. 3A). The continuous extent of the fault scarp in map view is about 7 km. The measured profile was selected where the terrace offset is maximum. On the basis of its simple morphological characteristics and the lack of minor branches of terrace offsets, we interpret that the scarp was generated by a single earthquake event. The oldest age for the fault scarp may be estimated by using a linear diffusion model (e.g., Avouac, 1993):

$$\tan\theta = \frac{a}{\sqrt{\pi\tau}} + b, \qquad (1)$$

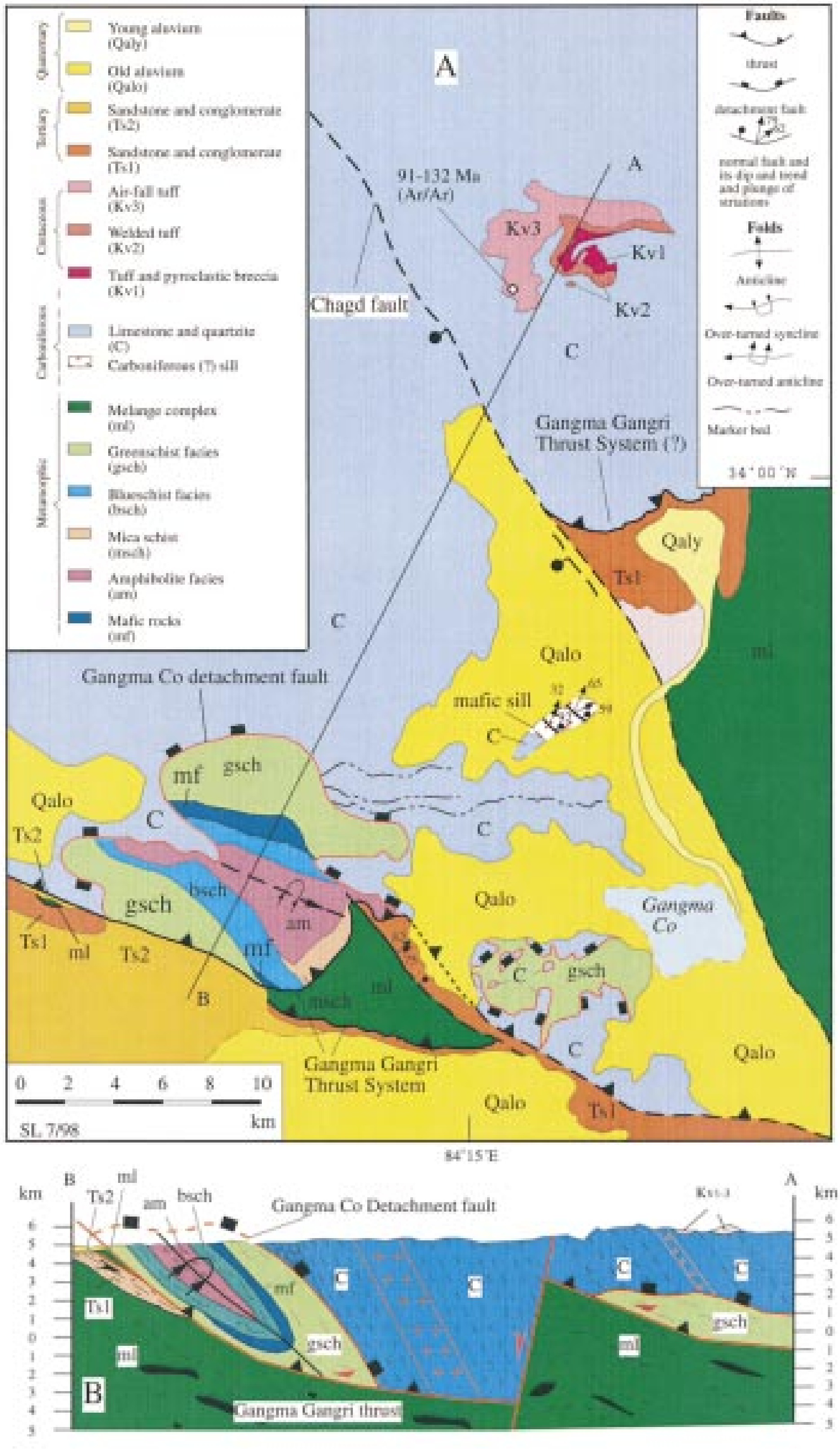

Figure 4. A: Geologic map of Gangma Co area. B: Geologic cross section of Gangma Co area.

where θ is the maximum slope angle of the scarp, a is the half scarp offset, and b is the regional slope angle. For a fault dip angle of δ that we take to be 60°, the total slip is $S = 2a/\sin \delta$. Parameter τ is the characteristic time for diffusion, which is defined as $\tau = kt$ (k is the coefficient of mass diffusivity, and t is the age of the fault scarp). The coefficient k is estimated to be $3.3 \pm 1.7\ m^2\ k.y.^{-1}$ in southern Tarim north of Tibet (Avouac and Peltzer, 1993; Fig. 1). A higher value for k is expected in north-central Tibet, because it has a higher precipitation rate (~200 mm yr^{-1} in Tibet vs. <90 mm yr^{-1} in Tarim; see Derbyshire and Goudie, 1997) and is located in a high-altitude permafrost setting (Liao, 1990). We thus use the k value from southern Tarim as the lower bound for that in northern Tibet. This yields about 2 ka for the oldest age of the fault scarp and ~2 mm yr^{-1} for its minimum slip rate. Because we estimate the total amount of normal slip across the Shuang Hu fault to be ~7 km, the initiation age of the fault may be inferred to be no older than 4 Ma.

DISCUSSION AND CONCLUSIONS

Armijo et al. (1986) estimated the magnitude of slip across major late Cenozoic normal faults in southern Tibet to be on the order of several kilometers with slip rates of 1–4 mm yr^{-1}. An exception to this range of slip magnitude is that for the Nyainqentanghla rift (>20 km; Harrison et al., 1995; Cogen et al., 1998). Armijo et al.'s estimates are roughly comparable to ours for northern Tibet, implying that the east-west extension is distributed rather uniformly across the entire plateau. This precludes explanations such as oblique convergence, spreading of the Himalayan arc, and eastward extrusion of rigid north Tibet relative to deforming south Tibet as primary causes for initiation and subsequent development of Tibetan rifts. It suggests, however, that the extension in Tibet has been either a result of the dynamic condition of the entire plateau (Molnar and Tapponnier, 1978; England and Houseman, 1989) or part of widespread extension in east Asia in the past 10 m.y. (Yin and Kong, 1997).

Our mapping shows that major active faults in north-central Tibet change their strikes abruptly, from a north-south to east-west and northeast strikes (Fig. 2). The kinematic data collected by this study are preliminary, especially when compared with the large data set available for rifts in southern Tibet (Mercier et al., 1987; Ratschbacher et al., 1994). Nevertheless, if the east-northeast slip direction obtained by this study is regionally significant, it requires that active east-west– and northeast-striking faults in northern Tibet have significant left-slip components. This inference is consistent with the result of a more detailed kinematic study conducted on normal faults in the central Muga-Purou rift, 40 km south of our Shuang Hu study area (Blisniuk et al., 1998).

Although fault-plane solutions of earthquakes in north-central Tibet suggest that conjugate strike-slip faulting may be important (Molnar and Lyon-Caen, 1989), the lack of recognizable right-slip faults during our field investigation and interpretation of Landsat images (Armijo et al., 1989) suggest that left-slip faults may be the only geologically significant strike-slip structures in the region. We note that several major rift systems in northern Tibet merge with the left-slip Kunlun fault system to the north. These rifts also make an abrupt turn from a general north-south trend to a northeast trend at their southern end toward the Banggong-Nujiang suture. As implied by our kinematic data, the northeast-trending faults in the south would be left slip. This fault pattern for northern Tibet is in a mirror image to that in southern Tibet, where northwest-trending right-slip faults are either linked with or terminate the north-south–trending rifts (Fig. 1). This overall kinematic pattern suggests that the Tibetan plateau has undergone constrictional deformation (Rothery and Drury, 1984; Mercier et al., 1987).

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