

# Present-day crustal motion within the Tibetan Plateau inferred from GPS measurements

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[1] Using the measurements of  $\sim$ 726 GPS stations around the Tibetan Plateau, we determine the rigid rotation of the entire plateau in a Eurasia-fixed reference frame which can be best described by an Euler vector of  $(24.38^\circ \pm 0.42^\circ N, 102.37^\circ \pm 0.42^\circ E, 0.7096^\circ \pm$  $0.0206^{\circ}$ /Ma). The rigid rotational component accommodates at least 50% of the northeastward thrust from India and dominates the eastward extrusion of the northern plateau. After removing the rigid rotation to highlight the interior deformation within the plateau, we find that the most remarkable interior deformation of the plateau is a glacier-like flow" zone which starts at somewhere between the middle and western plateau, goes clockwise around the Eastern Himalayan Syntaxis (EHS), and ends at the southeast corner of the plateau with a fan-like front. The deformation feature of the southern plateau, especially the emergence of the flow zone could be attributed to an eastward escape of highly plastic upper crustal material driven by a lower crust viscous channel flow generated by lateral compression and gravitational buoyancy at the later developmental stage of the plateau. The first-order feature of crustal deformation of the northeastern plateau can be well explained by a three-dimensional elastic half-space dislocation model with rates of dislocation segments comparable to the ones from geological observations. In the eastern plateau, although GPS data show no significant convergence between the eastern margin of the plateau and the Sichuan Basin, a small but significant compressional strain rate component of  $\sim 10.5 \pm 2.8$  nstrain/yr exists in a relatively narrow region around the eastern margin. In addition, a large part of the eastern plateau, northeast of the EHS, is not undergoing shortening along the northeastward convergence direction of the EHS but is stretching.

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# 1. Introduction

[2] The collision and continuous convergence of India-Eurasia since the Eocene epoch (~50 Ma ago) have not only uplifted the Tibetan Plateau, a ~2.4 × 10<sup>6</sup> km<sup>2</sup> area of central Asia to become the "roof of the world" with an average elevation of ~4500 m but also induced offsets of dozens to hundreds of kilometers along a series of transverse fault zones in and around the boundaries of the plateau [e.g., *Peltzer et al.*, 1989; *Avouac and Tapponnier*, 1993]. While the crustal thickening, shortening, and eastward movement of the plateau in response to the collision

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are obvious, how the crustal material deforms in detail or what kind of model can best describe the tectonic process and mechanical evolution of the plateau remains subject to debate: Is the horizontal deformation characterized by rigid or slowly deforming block motion in the upper crust with elastic strain accumulated and released on the boundaries of the blocks by slip [e.g., Tapponnier et al., 1982; Peltzer and Tapponnier, 1988; Avouac and Tapponnier, 1993; Peltzer and Saucier, 1996; Replumaz and Tapponnier, 2003; Thatcher, 2007], or continuous throughout the entire lithosphere and dominated by broadly distributed crustal shortening and thickening [e.g., Molnar and Tapponnier, 1975; Houseman and England, 1986, 1993; Vilotte et al., 1986; Holt et al., 2000; Flesch et al., 2001] or by narrowly distributed viscous channel flow in the lower crust [e.g., Royden et al., 1997; Shen et al., 2001]? Does the rapid slip on the major faults within the plateau and on its margins play a dominant role in the accommodation of the India-Eurasia convergence [e.g., Tapponnier et al., 1982; Peltzer et al., 1989], or is it just a byproduct of shortening and thickening [e.g., Vilotte et al., 1986; Houseman and England, 1986, 1993]?

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**Figure 1.** GPS velocity field of crustal motion in central Asia relative to the stable Eurasia. The GPS velocities are from *Niu et al.* [2005] and *Wang et al.* [2001] (blue vectors), *Paul et al.* [2001], and *Banerjee and Burgmann* [2002] (red vectors). The rectangular box surrounding the Tibetan Plateau encloses the area concerned in this study. The yellow solid line in the northern plateau indicates the  $\sim$ 420-km-long surface rupture of the 2001 Kokoxili Ms 8.1 earthquake.

[3] In recent years, Global Positioning System (GPS) measurements carried out around the Tibetan Plateau have produced a relatively dense set of observations for the crustal motion within the plateau and on its margins [e.g., *Wang et al.*, 2001; *Zhang et al.*, 2004; *Niu et al.*, 2005]. This velocity field not only reveals the characteristics of differential tectonic motion of the plateau, but also provides us with important constraints that may allow us to judge the applicability of a catalogue of classic models, or to explore the middle ground among them [e.g., *Chen et al.*, 2004; *Zhang et al.*, 2004; *Shen et al.*, 2005; *England and Molnar*, 2005; *Thatcher*, 2007].

[4] When investigating the crustal motion of the Tibetan Plateau using GPS velocities, most people assume a fixed Eurasia with India "positively" colliding into Asia. Thus we are familiar with the crustal motion image of the Tibetan Plateau relative to the stable Eurasia. For example, *Niu et al.* [2005], using  $\sim$ 1100 GPS stations, produced a dense velocity field for the Chinese Mainland in a Eurasia fixed reference frame (Figure 1); *Zhang et al.* [2004] showed that relative to the stable Eurasia, material within the plateau

interior moves roughly eastward with speeds that increase toward the east, and then flows southward around the eastern end of the Himalayas. However, from a viewpoint of kinematics, the choice of a crustal motion reference frame is arbitrary. For instance, we can also survey the deformation of the Tibetan Plateau from the perspective of a fixed India with Eurasia colliding over it, and produce an apparently different crustal motion image of the collision zone.

[5] In this study, for the purpose of highlighting the interior deformation within the Tibetan Plateau, we are going to remove the rigid rotation of the entire plateau, and thus transform the GPS velocity field around the plateau into a "Tibetan Plateau fixed reference frame" to facilitate the investigation of the horizontal deformation of the plateau.

#### 2. GPS Data

[6] The principal data used for this study are from the Crustal Movement Observation Network of China (CMO-NOC) collected during 1998 and 2004, including 27 con-



**Figure 2.** Map showing the observed GPS velocity field (blue arrows) around the Tibetan Plateau relative to the stable Eurasia and the calculated rigid rotation velocity field (red arrows) with the Euler vector of the plateau. The Euler pole is located near the southeast corner of the plateau with an ellipse of 95% confidence. The thick black solid lines indicate principal active faults.

tinuous stations, 55 annually observed campaign stations with an occupation of  $\sim$ 7 days in each survey, and  $\sim$ 1000 campaign stations observed in 1999, 2001, and 2004, respectively, with an occupation of at least 4 days in each survey.

[7] The data were processed in four steps [Z.-K. Shen et al., 2001]: (1) All the observation data for a given day were combined to solve for the daily loosely constrained station coordinates and satellite orbits using the GAMIT software [King and Bock, 1995]; (2) using the GLOBK software [Herring, 1998], the daily solution for local stations was combined with the loosely constrained global solutions of  $\sim 80$  IGS core tracking stations produced at the Scripps Orbital and Position Analysis Center (SOPAC, http://sopac. ucsd.edu/); (3) station positions and velocities were estimated in the ITRF2000 reference frame using the QOCA software [Dong et al., 1998]. The QOCA modeling of the data was done through sequential Kalman filtering, allowing adjustment for global translation and rotation of each daily solution; and (4) the velocity solution was transformed into a Eurasiafixed reference frame using the Euler vector of Eurasia with respect to the ITRF2000 deduced from 11 IGS stations (NYAL, ONSA, HERS, WSRT, KOSG, WTZR, VILL, GLSV, IRKT, TIXI) in the stable Eurasia. Considering that

the 2001 Kokoxili Ms 8.1 earthquake happened in the northern Tibetan Plateau (Figure 1) during our GPS observation periods, we used the strategy of *Niu et al.* [2005] to remove or reduce the impact of this earthquake to the velocity field: First, the coseismic displacement of each GPS station and its corresponding uncertainty were estimated with a coseismic dislocation model. Then, for the stations whose coseismic displacement estimates are equal or greater than 3 mm, we added 3 coseismic displacement parameters when solving the velocity field. As the impact from the postseismic displacements was relatively small, it was not considered in the data processing.

[8] Besides the CMONOC data set, we collected three additional velocity data sets from *Paul et al.* [2001], *Wang et al.* [2001], and *Banerjee and Burgmann* [2002] to increase the coverage and station density of the India, Himalayas, and central Tibet. The data set of *Paul et al.* [2001] contains 13 stations in India and the Himalayas; that of *Wang et al.* [2001] contains 41 stations distributed in India, the Himalayas, and central Tibet; and that of *Banerjee and Burgmann* [2002] contains 24 stations in the western Himalayas. While all the three are namely in their Eurasia-fixed reference frames, the frames differ slightly from each other and also differ from our Eurasia-fixed reference frames



**Figure 3.** GPS velocity field of the Tibetan Plateau in a Tibetan Plateau fixed reference frame, in which the rigid rotation of the whole plateau was taken out and only the interior deformation remains. The thick black solid lines indicate principal active faults. The gray dashed lines indicate boundaries of tectonic blocks. The light gray ellipse at the tip of each velocity vector is 95% confidence.

for the CMONOC data set. As each of the additional velocity data sets shared some stations with the CMONOC data set, we transformed them into our Eurasia-fixed reference frame using a seven-parameter Helmert transformation. After that, the maximum differences of north and east components of the velocities for the same stations in different data sets are  $\sim 2.6$  and  $\sim 1.7$  mm/yr, respectively. Although these values are within 2 standard deviations of the velocity components, it should be mentioned that such a level of error could have the potential to bias strain rate estimates on the boundaries between networks if these errors have a systematic component. The final velocities of the common stations are the weighted average of the values from all the above data sets in the same Eurasia-fixed reference frame. Notice that the method we used to combine these four sets of velocity data is not quite strict mathematically, but the approximation is good enough for the purpose of investigating the characteristics of crustal deformation.

[9] In Figure 1, the combined velocities of  $\sim$ 1300 GPS stations in a Eurasia-fixed reference frame clearly demonstrate the first-order characteristics of motion and deformation of different tectonic units in central Asia under the interactions of the surrounding plates, especially the re-

markable motion within the Tibetan Plateau. On the whole, the following tectonic features can be seen: (1) While most of the northeast thrust from India was accommodated by the shortening, eastward extrusion as well as southeastward flow of the Tibetan Plateau, a large amount of the rest was accommodated by the northeastward motion of the Tarim Basin and Tianshan area; (2) in the middle to western part of the Tibetan Plateau, the velocities decrease sharply from south to north without much change in orientation, which implies that the shortening of the plateau accommodates a large amount of the northeastward advancement of the India; (3) the most remarkable crustal motion is the clockwise rotation of southeastern Tibet around the eastern end of the Himalayas; (4) the South China Block and North China Block in eastern China move east-southeastward relative to the stable Eurasia. The velocities increase toward the south, which seems that the two blocks are rotating counterclockwise as one rigid block around an Euler pole located somewhere in the eastern Siberia [Calais et al., 2003].

[10] In this study, we focus on the area outlined by the rectangle in Figure 1 to discuss the interior deformation of



**Figure 4.** Strain rate field of the Tibetan Plateau deduced from GPS velocities. Each strain rate tensor is calculated with nine interpolated velocities on  $0.5^{\circ} \times 0.5^{\circ}$  grids in a  $1^{\circ} \times 1^{\circ}$  (longitude and latitude) area. The thick black solid lines indicate principal active faults. The dashed lines indicate the boundaries of tectonic blocks.

the Tibetan Plateau using the  $\sim$ 726 GPS velocities around the plateau. The data are listed in auxiliary material.<sup>1</sup>

# 3. Rigid Rotation and Differential Motion Field

[11] Relative to the stable Eurasia, the velocity field of the Tibetan Plateau includes a rigid rotational component and an interior deformation component. Although the rigid rotation mixed in the velocity field does not affect the deformation calculation, it blurs or submerges the differential motions within the concerned area. In order to take out the rigid rotation so as to highlight the interior deformation of the plateau, we solved for the Euler vector that minimized the RMS velocity of all the 313 GPS stations within the plateau. The resulting Euler pole has a location and magnitude of  $(24.38^{\circ} \pm 0.42^{\circ} \text{ N}, 102.37^{\circ} \pm 0.42^{\circ} \text{ E}, 0.7096^{\circ} \pm$  $0.0206^{\circ}$ /Ma). Figure 2 shows the rotation pole, the calculated rotation velocities with the Euler vector, and the observed velocities in the Eurasia fixed reference frame. The rotation pole is near the southeast corner of the plateau and roughly coincident with the Eastern Himalayan Syntaxis (EHS). Figure 3 is the new velocity field after taking out the rigid rotation of the whole plateau. It clearly highlights the differential motions within the plateau, such as a remarkable glacier-like flow zone around the EHS, apparent dislocations across a series of active faults, and abrupt shortening in the mid to southern area of the plateau. While appreciating the advantage of the new velocity field, we should make it clear that this velocity field, mathematically, has an "invisible" but exclusive reference frame, in which the "whole" Tibetan Plateau has no more net rigid rotation. In other words, this is a velocity field in a Tibetan Plateau fixed reference frame. Although this frame has no obvious geologic significance because the Tibetan Plateau deforms internally, this fact does not reduce its utility in studying parts of the signal contained in the velocity field.

[12] From Figure 2 it can be seen that the rigid rotation velocity field is a first-order approximation to the GPS velocity field, except for the southeastern plateau where rapid clockwise flow around the EHS dominates the crustal deformation. For the northern plateau, especially the northeastern plateau, more than 80% of the crustal motion, including magnitude and orientation, can be well modeled by the rigid rotation. For the southwestern plateau, about 40-60% of the northeastward thrust from India is accom-

<sup>&</sup>lt;sup>1</sup>Auxiliary materials are available at ftp://ftp.agu.org/apend/jb/ 2005jb004120.



**Figure 5.** Rotation rate field of the Tibetan Plateau deduced from GPS velocities. Each rotation rate tensor is calculated with nine interpolated velocities on  $0.5^{\circ} \times 0.5^{\circ}$  grids in a  $1^{\circ} \times 1^{\circ}$  (longitude and latitude) area. The fan-shaped symbols denote rotation rates referenced to zero azimuth. The thick black solid lines indicate principal active faults. The dashed lines indicate the boundaries of tectonic blocks.

modated by the rigid rotation. In fact, the velocity field in the Tibetan Plateau fixed reference frame (Figure 3) is also a residual velocity field of the rigid rotation. Comparing Figure 3 with Figure 2, it can be concluded that the rotational component of the Tibetan Plateau generally accommodates at least 50% of the northeastward thrust from India, and the rigid rotation dominates the eastward extrusion of the northern plateau.

#### 4. Interior Deformation Features

[13] After removing the rotational component of the entire plateau, the interior deformation within the plateau manifests quite different style in its southern region and northern region bounded by the Manyi-Yushu-Xianshuihe fault, rather than the Karakorum-Jiali fault, which was suggested by *Armijo et al.* [1989] as a throughgoing right-lateral shear zone to separate rapidly extending southern Tibet from relatively undeformed northern Tibet.

[14] In Figure 3, the following deformation features are clearly visible: For the whole plateau, the most remarkable interior deformation is the glacier-like flow zone that goes clockwise around the EHS, and ends at the southeast corner of the plateau with a fan-like front. The flow zone has a clear north boundary, the Manyi-Yushu-Xianshuihe fault, but its south boundary becomes indistinct at the west side of the syntaxis, although the Karakorum-Jiali fault zone has the potential to be the boundary. As the GPS velocity field does not show a significant gradient change in the southern plateau, it seems more likely that the Karakorum-Jiali fault zone is widely distributed in the viscously deformed crust. On the basis of the scanty GPS stations in the mid to western region of the plateau, we cannot determine the exact starting position of the flow zone, but can infer that the starting position is located somewhere between the mid and western plateau; For the area around the eastern margin of the plateau, northwest of the Sichuan basin, the GPS velocity does not show significant eastward extrusion relative to the whole plateau, which also means that the motion of this area relative to the stable Eurasia can be well modeled by the rigid rotation of the entire plateau.

#### 5. Strain Rate Field

# 5.1. Strain Rate Calculation

[15] In order to get a continuous strain rate map of the plateau, we use a "spline in tension" technique [*Wessel and Bercovici*, 1998] with the tension parameter  $\tau = 0.95$  to



**Figure 6.** Map showing N-S striking normal fault zones in the southern plateau and GPS velocities observed (blue vectors) and predicted (red vectors) by the dislocation model. The velocities are in the Tibetan Plateau fixed reference frame, and the ellipse at the tip of each blue velocity vector shows 95% confidence. The thick gray dashed lines represent the fault segments used in the dislocation model. The sinuous yellow solid lines represent active faults in Holocene. The sinuous thin gray solid lines represent active faults in Guaternary. (F1, Nielamu fault zone; F2, Dingjie-Shenza fault zone; F3, Yadong-Gulu rift; F4, Cuona fault zone, YZS, Yarlung-Zangbo suture zone).

interpolate the GPS velocities on  $0.5^{\circ} \times 0.5^{\circ}$  (longitude and latitude) grids, and then calculate the strain rate tensor in every  $1^{\circ} \times 1^{\circ}$  area with the nine interpolated velocities on the grids. This method produces a reliable strain result, especially for the area where the distribution of observed velocities is dense.

[16] The tension parameter  $\tau$  ( $0 \le \tau < 1$ ) in the spline in tension algorithm represents the portion of the strain energy resulting from tension relative to total strain energy [Wessel and Bercovici, 1998]. Notice that the strain energy here refers to strain within the spline, not strain in the Earth. When  $\tau = 0$ , the algorithm corresponds to a minimum curvature biharmonic spline. As the tension parameter increases, the squared curvature integrated over the entire surface becomes larger, and, as  $\tau \rightarrow 1$ , the algorithm approaches a whole data based linear interpolation. So, as a general two-dimensional (2-D) interpolation algorithm, the spline in tension is an effective method of obtaining a continuous velocity field based on sparsely distributed GPS velocities [Gan and Prescott, 2001]. The strain rate and rotation rate fields of the Tibetan Plateau deduced from the interpolated GPS velocity field are shown in Figures 4 and 5, respectively.

[17] There are some previous studies calculating the strain rates within the Tibetan Plateau or Asia incorporating Quaternary fault slip rate and GPS data [e.g., *Holt et al.*, 2000; *England and Molnar*, 2005]. Comparing with *England and Molnar*'s [2005] result, we find out that although our method and data set are quite different from *England and Molnar*'s [2005], in which they calculated the strain rate for each triangular mesh averaged over horizontal distances of  $\sim$ 300 km from estimates of

Quaternary fault slip rates and GPS baseline change rates, the results are generally consistent with each other in all the concerned areas within the plateau. Comparatively, our results provide more detailed information about spatial variation of the strain rate field.

#### 5.2. State of Strain in the Southern Plateau

[18] Figure 4 shows that in the southern plateau, the Himalaya arc block accommodates the most extensive compression and shortening in the direction of India-Eurasia convergence. The typical compression rate is  $\sim$ 30-60 nstrain/yr, with some values as high as  $\sim$ 70 nstrain/yr. Whereas, in the Lhasa block, the compression rate along the convergence direction decreases remarkably to a level of  $\sim$ 15-20 nstrain/yr for most of the places.

[19] In the mid to eastern part of the southern plateau between the longitudes of 86°E and 92°E, transverse extension is significant with typical values as large as  $\sim$ 15–25 nstrain/yr. The rotation rates at the west and east sides of the region also show opposite signs (Figure 5). The transverse extension of this region may be explained by existence of a series of N-S striking normal faults [Armijo et al., 1986; Chen et al., 2004a, 2004b] (Figure 6). Among these normal faults, the Yadong-Gulu rift is the most prominent one. Chen et al. [2004a] estimated the opening rate of the Yadong-Gulu rift as  $5.9 \pm 0.7$  mm/yr in the N69°W direction, much higher than the value of 1.4  $\pm$ 0.8 mm/yr estimated by Armijo et al. [1986]. As many more GPS observations are available in our data set to cover the Yadong-Gulu rift (F3) as well as another three N-S striking normal faults (Figure 6), i.e., the Nielamu fault (F1), Dingjie fault (F2), and Cuona fault (F4), we determined the opening

 Table 1. Dislocation Rates of Principal Faults in Southern Tibet

 Estimated by Dislocation Model<sup>a</sup>

| Fault Name         | Lateral-Slip Rate,<br>mm/yr | Opening Rate,<br>mm/yr | Dip-Slip Rate,<br>mm/yr |
|--------------------|-----------------------------|------------------------|-------------------------|
| Nielamu fault (F1) | $3.6 \pm 1.3$ (LL)          | $2.3 \pm 1.0$ (O)      | NA                      |
| Dingjie fault (F2) | $2.3 \pm 1.1$ (LL)          | $3.3 \pm 0.8$ (O)      | NA                      |
| Yadong-Gulu (F3)   | $0.7 \pm 1.1$ (LL)          | $2.0 \pm 0.6$ (O)      | NA                      |
| Cuona fault (F4)   | $0.6 \pm 1.3$ (RL)          | $0.3 \pm 0.9$ (C)      | NA                      |
| Yarlung-Zangbo     | $2.5 \pm 1.1$ (RL)          | NA                     | $4.1 \pm 1.2$ (TS)      |
| suture (YZS)       | · · · · ·                   |                        | · · · · ·               |

<sup>a</sup>LL, left-lateral slip; RL, right-lateral slip; O, opening; C, closing; TS, thrust slip; NA, not available in the model.

(rather than dip slip) and strike-slip rates for each of the faults using a 3-D elastic half-space dislocation model [Okada, 1992] to best fit the observed two horizontal components of GPS velocity at each site around the area. Considering that the E-W striking Yarlung-Zangbo suture zone (YZS) is across the four normal faults, and may have nonnegligible right-lateral and thrust slip components [Chen et al., 2004b], we also included the YZS in our dislocation model to estimate its slip rate together with that of the normal faults. In this model, all the fault zones were represented by simple dislocation segments in an elastic half-space as shown in Figure 6. For each of the normal fault segment, a 45° dip angle (dipping to the west) and zero-locking depth were tentatively assigned. For the YZS, a 45° dip angle (dipping to the south) and 20 km locking depth were assigned. Notice that in the model (1) the slip on each of the faults was constrained to be constant along the entire length of the fault (e.g., all the three simple dislocation segments of the Yadong-Gulu rift shared the same strike-slip and opening rates); (2) the GPS velocity is in the Tibetan Plateau fixed reference frame, and a net translation was included when fitting; and (3) the affection of strain from the curving Himalayan arc was not explicitly considered. The best fit results are listed in Table 1.

[20] From Figure 6 it can be seen that the GPS velocities are well predicted by the model. The results indicate that among the four N-S striking normal faults, the Nielamu fault (F1), Dingjie fault (F2) and Yadong-Gulu rift (F3) have comparable opening rates of 2.3  $\pm$  1.0 mm/yr, 3.3  $\pm$ 0.8 mm/yr and 2.0  $\pm$  0.6 mm/yr, respectively, whereas the Cuona fault (F4) has no significant opening at present-day. Our results also indicate that the Nielamu fault (F1) and Dingjie fault (F2) have statistically significant left-lateral slip rates of 3.6  $\pm$  1.3 mm/yr and 2.3  $\pm$  1.1 mm/yr, respectively. For the Yadong-Gulu rift, our estimate of its opening rate is more consistent with that of Armijo et al. [1986] but much smaller than that of Chen et al. [2004a]. As for the Yarlung-Zangbo suture zone, we obtain a rightlateral slip rate of  $3.3 \pm 0.8$  mm/yr and a thrust slip rate as large as  $4.4 \pm 0.8$  mm/yr. The right-lateral slip rate is comparable with the value of  $2.6 \pm 0.7$  mm/yr estimated by Chen et al. [2004b]. However, the significant slip of the suture zone from our model may just reflect the accumulated strain of a broad region around the suture zone, rather than a fast slip concentrated on the suture zone itself, because these two cases cannot be effectively identified in our model.

# 5.3. State of Strain Within the Flow Zone

[21] As shown in Figures 4 and 5, the strain within the flow zone around the EHS varies from place to place. In order to have a better understanding to the general feature of the strain within the flow zone, we divided the flow zone into three sections shown in Figure 7, and calculated the uniform strain rate in each of the sections using GPS data. The results are listed in Table 2. After resolving the uniform strain rate in each section into a coordinate system with the axes along and across the flow zone, respectively (Figure 7), we found that the NW section (roughly between  $90^{\circ}E - 96^{\circ}E$ ) is undergoing an axial extension of  $\sim 7.1 \pm 3.0$  nstrain/yr along the flow zone, lateral compression of  $\sim 9.8 \pm$ 4.1 nstrain/yr, and left-lateral shear of  $\sim$ 4.3 ± 2.4 nstrain/yr. In the central section, northeast of EHS, the left-lateral shear increased to  $\sim 9.9 \pm 1.3$  nstrain/yr. However, the axial strain rate changed from extension to compression of  $\sim$ 7.6 ± 2.0 nstrain/yr, and the transverse strain rate from compression to extension of  $\sim 13.6 \pm 2.0$  nstrain/yr, respectively. The strain rate status of this section indicates that although the EHS is strongly thrusting northeastward into the Tibetan Plateau, the top layer of the crust above the thrusting tongue is not compressed but extended along the thrusting direction. In fact, we can also see from Figures 4 and 7 that the area with extensional strain component along the convergence direction of the EHS is not limited in the central section of the flow zone, but goes further northeast and reaches somewhere around the eastern Kunlun fault at latitude of  $\sim$ 34°N. In the SE section of the flow zone, the uniform strain rate is characterized as strong lateral extension of  $\sim 22.7 \pm$ 1.4 nstrain/yr, significant axial compression of  $\sim$ 14.2  $\pm$ 1.2 nstrain/yr, and negligible shear along the flow zone. Notice that in the above strain calculation, rotation rate was estimated along with strain rate, so the strain rate estimate cannot be biased by unmodeled rotations. The strain feature within the flow zone implies it is likely a viscous flow zone and the gravitational buoyancy plays an important role in its deformation.

#### 5.4. State of Strain in the Northern Plateau

[22] In the mid to northwest part of the plateau, our result shows that both the strain rate and rotation rate are generally uniform, with a typical strain rate of  $\sim 20$  nstrain/yr and a rotation rate of  $\sim 15$  nrad/yr (Figure 4). However, the feature of uniformity in this area calls in question because there is no observation data in or near this area, and all the results are actually from the interpolation of observed velocities far away from the area. We will leave out the strain rate of this area for further discussion.

[23] Chen et al. [2004a], on the basis of GPS data from 45 stations across the Tibetan Plateau, presented a deforming block model for the interior of the northern plateau and estimated that the strain rate for regions between the major faults was to first-order constant from block to block with a value of  $-19.2 \pm 0.7$  nstrain/yr (N32.6° E  $\pm 1.3$ °) and 8.6  $\pm 1.3$  nstrain/yr (N57.4° W  $\pm 1.3$ °) for maximum contraction and extension, respectively. As many more GPS stations are available for us to detect small-scale concentrations of strain in some area, we reestimated the uniform strain rates of each major block as well as the entire northern plateau. The results are listed in Table 3.



**Figure 7.** Map showing uniform strain rates in different sections of the flow zone around the EHS and in the areas northeast of the Sichuan Basin. Each concerned area is bounded by gray dashed lines. The uniform strain rate in each area was calculated using all the GPS data within the area. The velocity vectors are relative to the Tibetan Plateau fixed reference frame, and the ellipse at the tip of each blue velocity vector shows 95% confidence.

[24] Our results indicate that the strain rate in the northern plateau is far from uniform from block to block bounded by major faults. The nonuniform distribution of strain rate in the northern plateau is clearly visible in our interpolated strain rate field (Figures 4 and 5), especially for some regions along major active faults, where the strain rates are several times higher than the average of the whole area. Even within the principal blocks, the strain rate is also different from subblock to subblock. For example, within the Qaidam block, although the strain is generally characterized as NE-SW compression and NW-SE extension in the mid to eastern part, typical values of the compression and extension rates vary from  $\sim 5$  to  $\sim 20$  nstrain/yr from place

 Table 2.
 Uniform Strain Rates in Different Sections of the Flow

 Zone Around EHS and in the Subregions Around the Northwest of
 Sichuan Basin

| Region                          | Number of<br>Velocities Used | $\dot{\varepsilon}_{1}$ , <sup>a</sup><br>nstrain/yr | $\dot{\varepsilon}_{2}$ , <sup>a</sup><br>nstrain/yr | Azimuth, <sup>b</sup><br>deg |
|---------------------------------|------------------------------|--|--|------------------------------|
| NW section<br>of flow zone      | 15                           | $8.14\pm2.9$   | $-10.8\pm3.9$  | $34.6\pm7.2$                 |
| Central section<br>of flow zone | 40                           | $17.5 \pm 1.6$                                       | $-11.4 \pm 2.2$                                      | $-77.5 \pm 2.7$              |
| SE section<br>of flow zone      | 112                          | 22.7 ± 1.4   | $-14.3 \pm 1.2$                                      | $-12.4 \pm 1.5$              |
| Around Arba                     | 12                           | $16.5 \pm 3.2$                                       | $-19.2 \pm 3.2$                                      | $-89.6 \pm 3.7$              |
| Around                          | 28                           | $7.5\pm 2.2$   | $-11.9\pm2.8$  | $-71.7\pm5.2$                |
| Longmen Shan                    |                              |  |  |                              |

<sup>a</sup>The parameters  $\dot{\varepsilon}_1$  and  $\dot{\varepsilon}_2$  are maximum extension rate and contraction rate, respectively.

<sup>b</sup>Azimuth is measured clockwise from north to the contraction rate axis.

Table 3. Strain Rate in the Northern Tibetan Plateau

| Region/Subregion                          | Number of<br>Sites | $\dot{\varepsilon}_1$ , <sup>a</sup><br>nstrain/yr | $\dot{arepsilon}_{2,}^{\mathrm{a}}$ nstrain/yr | Azimuth, <sup>b</sup><br>deg |
|---|--------------------|--|--|------------------------------|
| Qilianshan Block                          | 50                 | $7.4 \pm 1.2$                                      | $-23.3 \pm 2.6$                                | $42.3 \pm 2.7$               |
| Qaidam Block                              | 85                 | $5.6 \pm 0.6$                                      | $-5.6 \pm 2.0$                                 | $39.2 \pm 4.5$               |
| Kunlun Block                              | 32                 | $15.3\pm3.4$                                       | $-13.6\pm2.0$                                  | $89.1 \pm 3.9$               |
| North of Manyi-Yushu-<br>Xianshuihe fault | 200                | 9.4 ± 0.5  | $-6.6 \pm 0.5$                                 | 58.9 ± 1.6                   |
| North of Karakorum-<br>Jiali fault        | 259                | 13.8 ± 0.6   | $-8.7\pm0.6$                                   | 62.8 ± 1.1                   |

<sup>a</sup>The parameters  $\dot{\varepsilon}_1$  and  $\dot{\varepsilon}_2$  are maximum extension rate and contraction rate, respectively.

<sup>b</sup>Azimuth is measured clockwise from north to the contraction rate axis.

to place. The direction of principal compression also changes gradually from NNE in the mid part to NEE in the eastern part. Within the Kunlun block, the strain is generally characterized as approximately N-S extension and E-W compression in the mid to eastern part, the typical values of compression rate and extension rate are varying from ~10 to ~25 nstrain/yr from place to place. The rotation rate field shows that western part of the northeastern plateau has a remarkable counterclockwise rotation with a typical value as large as 30–40 nrad/yr, whereas the eastern part has insignificant rotation.

# 6. Discussion

#### 6.1. Existing Tectonic Models of Tibetan Plateau

[25] Since early 1980s, various tectonic models have been proposed to simulate the process of the India-Eurasia collision zone and explain the mechanical evolution of the Tibetan Plateau. The most prominent ones can usually be categorized into two end-member models, one in which eastward extrusion of a limited number of rigid or slowly deforming blocks via large strike-slip faults accommodates most of the India-Eurasia convergence (hereafter called "block motion" model [e.g., Tapponnier et al., 1982; Peltzer and Tapponnier, 1988; Avouac and Tapponnier, 1993; Replumaz and Tapponnier, 2003]), and the other in which the crust was treated as a thin viscous sheet, whose deformation and eastward extrusion are dominated by broadly distributed shortening and crustal thickening (hereafter called "thin viscous sheet" model [e.g., England and Molnar, 1997; Flesch et al., 2001]). There has been a long debate over whether the crustal thickening or eastward block-like extrusion has been more significant in accommodating the India-Eurasia collision. In recent years, as additional evidence, especially that from the GPS observations, has accumulated, it becomes clear that the eastward extrusion of the plateau is accompanied with a rather complicated deformation process. Each end-member model can explain some observed features, but neither is completely satisfactory. Thus more recent works have explored the middle ground between these extremes. For example, *Chen et al.* [2004a] argued that the crustal in Tibet is far from a rigid or slowly deforming block assumed by Armijo et al. [1986, 1989] in their block motion model. Instead, it is strongly deformed as proposed by Rothery and Drury [1984], and the rates of deformation in the regions between major faults are comparable to the slip rates across the major faults. They suggested that the block motion model must be modified to account for the significant internal deformation of the plateau. Recently, Thatcher [2007] suggested that the present-day Tibetan deformation can be simply described by the relative motions of 11 quasi-rigid blocks and fault slip across block boundaries. Although he preferred block motion model rather than continuum model for the description of the kinematics and dynamics of continental deformation, his block motion model differs significantly from the classic one, as the classic block motion model, at least potentially, emphasizes the roles played by a limited number of large rigid blocks bounded by major strike-slip faults rather than a series of medium-sized blocks bounded by all kinds of active faults, to explain the first-order feature of the Tibetan Plateau deformation. As another example, Shen et

al. [2001] proposed a 3-D Newtonian viscous crust model to modify the classic thin viscous sheet model. In their model, a layered viscous lithosphere was considered, whose viscosity varied progressively during the growth of the plateau, and viscous channel flow in the lower crust was developed at its later stage (hereafter called "channel flow" model). This model suggests that the plateau has gone through a two-stage development, first the India-Eurasia convergence produced the present-day elevation of Tibet, and subsequently the plateau has grown to the north and east without significant increase in height, and thus the eastwest stretching and eastward plateau growth dominate the present tectonics of the Tibetan Plateau. This developmental sequence of the model differs from the results of classic thin viscous sheet model [e.g., Houseman and England, 1986], where the region of crustal thickening is always distributed, even at the beginning of the crustal thickening process. The recent works of P. Tapponnier and his research group [e.g., Tapponnier et al., 2001; Replumaz and Tapponnier, 2003], also suggested that the plateau formed by the initial uplift and thickening of what is now southern Tibet, followed by successive stepwise growth of the plateau to the north and east, and in the multiphase tectonic history, extrusion and crustal thickening have each dominated at different times.

[26] Despite of completely different mechanical assumptions and interpretation of certain features, the plateau growth histories predicted by Tapponnier et al. [2001] and Shen et al. [2001] contain surprising similarities. If the twostage development of the Tibetan Plateau is true, the block motion model, thin viscous sheet model, and channel flow model could come together to explain the entire collision process and mechanical evolution of different developmental stages and different regions of the plateau: the block motion models may have a better explanation to the early stage of India-Eurasia collision process because at that time the Tibetan crust might not have been thickened enough to allow viscous channel flow to be developed in the lower crust, and lateral extrusion perhaps played a greater role in accommodating India indentation into the Asian continent [Shen et al., 2005]. However, in the later stage the effect of viscous flow in the lower crust of Tibet might have played an important role in crustal deformation of the region.

#### 6.2. Rigid Rotation of the Entire Plateau

[27] Our study indicates that crustal motion of the Tibetan Plateau relative to stable Eurasia can be broken down into two components: clockwise rigid rotation of the entire plateau around an Euler pole near the southeast corner of the plateau, and interior deformation within the plateau. As mentioned in the foregoing part, the rotational component accommodates at least 50% of the northeastward thrust from India and dominates the eastward extrusion of the northern plateau. In particular, the eastward extrusion of the northeastern plateau can be well explained by the rotational component.

[28] The eastward extrusion of the Tibetan Plateau along a series of strike-slip faults was first noticed in the 1980s and is regarded as an important piece of evidence for the development of the kinematic model of "continent escape" or block motion [*Tapponnier et al.*, 1982; *Peltzer and Tapponnier*, 1988; *Armijo et al.*, 1989]. In the model, it was considered that a wide area of the plateau between the



**Figure 8.** Map showing the first-order feature of GPS velocity field in the northeastern plateau well explained by the elastic half-space dislocation model. The velocity field is relative to the stable Eurasia, and the ellipse at the tip of each black velocity vector shows 95% confidence. AT-F, Altyn Tagh Fault; CDM-F, Northern Qaidam Fault; QNS-F, Qinghai Nanshan Fault; QL-F, Qingling Fault; DNS-F, Danghe Nanshan Fault; CM-F, Changma Fault; YMS-F, Yumushan Fault; XT-F, Xiangshan-Tianjinshan Fault; LPS-F, Liupanshan Fault; RYS-F, Riyueshan Fault; KL-F, KunLun Fault; HY-F, Haiyuan Fault; MY-XSH-F, Manyi-Yushu-Xianshuihe Fault; LMS-F, Longmenshan Fault.

Altyn Tagh fault and Karakorum-Jiali fault is escaping eastward as a rigid block, and the strike-slip rates along the Altyn Tagh fault and Jiali fault were predicated as large as 20–30 mm/yr [*Armijo et al.*, 1989; *Peltzer and Saucier*, 1996; *Tapponnier et al.*, 2001]. Comparing the block motion model with our rigid rotation component (Figure 2), it seems that we can lend partial support to the block motion model in the northern plateau. However, the rigid rotation component of the Tibetan Plateau has nothing to do with the Karakorum-Jiali fault, although the fault is as important as the Altyn Tagh fault in the block motion model.

#### 6.3. Interior Deformation of the Northern Plateau

[29] Using a finite element model that minimized deformation within fault-bounded blocks and constrained by geologic fault slip rates, *Peltzer and Saucier* [1996] concluded that 80% of the observed deformation is accommodated by major faults in central and eastern Asia. However, *Chen et al.* [2004a] presented a deforming block model for the interior of the northeastern plateau and argued that the deformation rates within blocks were large and comparable to the slip rates on the block boundaries. As mentioned earlier, *Thatcher* [2007] has recently suggested that the present-day Tibetan deformation can be simply described by the relative motions of 11 quasi-rigid blocks and fault slip across block boundaries. In his model, the most convincing part is that the relatively dense GPS velocity field of the northeastern plateau, bounded by the Manyi-Yushu-Xianshuihe fault, is concisely described by the relative motions of 5 medium-sized blocks with minor misfit residuals, and the blocks are well bounded by the most explicit and active fault zones in the region.

[30] As a tentative experiment, we assume that the crustal deformation of the northeastern plateau is dominated by deep slip of a series of major active faults which are approximated as simple dislocation segments locked 20 km to the surface and slipping below to an infinite depth in an elastic half-space [Okada, 1992] (Figure 8). We then determine the slip rate for each dislocation by minimizing the RMS velocity of all the GPS stations around the area [Gan et al., 2000]. When taking the above determined slip rates as reference to "constrain" the slip rates of all the major faults within a "reasonable" range comparable to the ones from geological observations (Figure 9), we find out that the model can well describe the first-order feature of the GPS velocity filed (Figure 8). This tentative experiment, together with the result from Thatcher [2007], seems to call in question about the continuous deformation models. However, it can be argued that despite of their fundamental differences, both continuum and block motion models acknowledge that the brittle upper crust likely deforms by



**Figure 9.** Map showing the fault parameters (fault segments and slip rates) used in the elastic halfspace dislocation model for the northeastern plateau. The star indicates the location of the 2001 Kokoxili Ms 8.1 earthquake. The dark thick dashed line is the Kokoxili segment, which is coincident with the ~420-km-long surface rupture of the 2001 Kokoxili Ms 8.1 earthquake. GPS measurements across the Kokoxili segment indicate a remarkable lateral slip rate of ~21.6 mm/yr at present, and we think the value is acceptable, considering the postseismic relaxation following the 2001 Kokoxili Ms 8.1 earthquake. AT-F, Altyn Tagh Fault; CDM-F, Northern Qaidam Fault; QNS-F, Qinghai Nanshan Fault; QL-F, Qingling Fault; DNS-F, Danghe Nanshan Fault; CM-F, Changma Fault; YMS-F, Yumushan Fault; XT-F, Xiangshan-Tianjinshan Fault; LPS-F, Liupanshan Fault; RYS-F, Riyueshan Fault; KL-F, KunLun Fault; HY-F, Haiyuan Fault; MY-XSH-F, Manyi-Yushu-Xianshuihe Fault; LMS-F, Longmenshan Fault.

discrete faulting below locking depth, and the distinction between the continuum and block motion models becomes blurred when block dimensions decrease and slip rates on bounding faults become comparable. As the block dimensions in our dislocation model are relatively small and the slip rates on bounding faults are roughly comparable (Figure 9), it becomes difficult for us to judge if block motion models are really better than continuum models to describe the crustal deformation of the plateau. Nevertheless, we agree with the viewpoint of *Thatcher* [2007] that even if the continuum models are true, block models would continue to be important in quantifying local tectonics, because continuum models have a shortage to inevitably smear out the discrete slip occurring across major faults.

#### 6.4. Interior Deformation of the Southern Plateau

[31] In the southern Tibetan Plateau, the flow zone around the EHS has a clear north boundary, the Manyi-Yushu-Xianshuihe fault, but its southern boundary is less clear on the west side of the syntaxis. Although the Karakorum-Jiali fault was suggested as the most important south boundary fault in the block motion model to accommodate a rightlateral slip of  $\sim 20$  mm/yr [*Armijo et al.*, 1989], our GPS velocity does not show any sharp velocity gradient across the fault. It is at best a subboundary of the flow zone. Most likely, the Karakorum-Jiali fault is a widely distributed shear zone embedded in viscously deformed material of the southern plateau, and the whole southern plateau is being pushed northeastward by India, blocked by relatively slow deformed material north of the Manyi-Yushu-Xianshuihe fault, and forced to turn southeastward to join in the flow zone around the EHS.

[32] On the basis of the overall strain features of the clockwise flow zone (Figure 7), together with its GPS velocity image which shows that the rotation of material around the EHS differs fundamentally from a rigid block rotation, where rates increase away from the rotation axis but remain constant along small circles around the axis of rotation (Figures 3 and 7), we ignore the block motion model because of its inability to reproduce the glacier-like flow zone, and focus on the existing continuum models to verify which of them is more effective for describing the state of the crustal deformation around the southeastern plateau. Among the various published continuum models for the deformation and topography of the Tibetan Plateau [e.g., *Molnar and Tapponnier*, 1975; *England and Molnar*,

1997; Houseman and England, 1986, 1993; Vilotte et al., 1986; Royden et al., 1997; Holt et al., 2000; Flesch et al., 2001; Shen et al., 2001], the well known ones can be roughly categorized into two types: the 2-D thin viscous sheet model and 3-D viscous channel flow model. The earlier 2-D thin viscous sheet models, represented by Houseman and England [1993], suggested that extrusion is a minor factor in accommodating the convergence between India and Eurasia, and thus failed to predict the magnitude of the extrusion-like velocity field of eastern Tibet revealed by our GPS data. The more recent 2-D thin viscous sheet model, represented by Flesch et al. [2001], reasonably predicted the eastward extrusion of the southeastern plateau, and involved a clear clockwise rotation around the EHS. However, the crustal motion predicted by the model for the southeast corner of the plateau is quite uniformly southeastward directed, rather than southward directed shown by the GPS velocities. In contrast, the 3-D viscous channel flow model, represented by Shen et al. [2001], can well explain the general features of the observed GPS velocity field of the southeastern plateau, including the abrupt change of movement direction around the EHS from eastward to southeastward, and to southward. It also reasonably explains the lack of significant shortening between the eastern margin of the plateau and the Sichuan basin, a remarkable feature demonstrated by the GPS observations. So we preferred the model of Shen et al. [2001] that the flow zone around the EHS is most likely attributed to a viscous channel flow in the lower crust of the Tibetan Plateau driven by lateral compression and gravitational spreading from the high plateau to the south and east.

# 6.5. Deformation Around the Eastern Margin of Tibetan Plateau

[33] According to our GPS velocity field in the Tibetan Plateau fixed reference frame, the area around the eastern margin of the plateau, i.e., the area northwest of the Sichuan basin, shows neither significant eastward extrusion relative to the whole plateau, nor significant eastward compression relative to the Sichuan basin (Figure 3). This is consistent with the viewpoints of some previous researchers [e.g., Burchfiel et al., 1997; King et al., 1997; Chen et al., 2000; Shen et al., 2005] that there is no significant convergence between the Tibetan Plateau and the Sichuan basin. Nevertheless, our strain calculation results indicate that there is a small but significant compressional strain rate component of  $\sim 10.5 \pm 2.8$  nstrain/yr in a relatively narrow region around the Longmen Shan, a region of significant topography (Figure 7). The resolved uniform strains around this region also show that the eastern margin of the plateau around the Longmen Shan block is not undergoing shortening along the northeastward convergence direction of the EHS but is stretching.

## 7. Summary

[34] On the basis of the measurements of ~726 GPS stations around the Tibetan Plateau, we revealed that the crustal motion of the plateau relative to the stable Eurasia can be broken down into two components: clockwise rigid rotation of the entire plateau with an Euler vector of  $(24.38^{\circ} \pm 0.42^{\circ} \text{ N}, 102.37^{\circ} \pm 0.42^{\circ} \text{ E}, 0.7096^{\circ} \pm 0.0206^{\circ}/\text{Ma})$  near

the southeast corner of the plateau, and interior deformation within the plateau which demonstrates quite different features in northern and southern plateau bounded by the Manyi-Yushu-Xianshuihe fault.

[35] The rigid rotational component of the plateau accommodates at least 50% of the northeastward thrust from India, and dominates the eastward extrusion of the northern plateau, especially the northeast plateau, where more than 80% of the crustal motion, including magnitude and orientation, can be well explained by the rigid rotational component.

[36] The most remarkable interior deformation within the plateau is a glacier-like flow zone which starts at somewhere between mid and western plateau, goes clockwise around the EHS, and ends at the southeast corner of the plateau with a fan-like front. The flow zone has a clear northern boundary, the Manyi-Yushu-Xianshuihe fault, but its southern boundary becomes indistinct at the west side of the syntaxis. The deformation features of the southern plateau, especially the emergence of the glacier-like flow zone, may imply an eastward escape of highly plastic upper crustal material driven by a lower crust viscous channel flow generated by lateral compression and gravitational buoyancy at the later developmental stage of the plateau [*Shen et al.*, 2001].

[37] The strain rate of the northern plateau is far from uniform from block to block. Even within the principal blocks, the strain rate is also different from subblock to subblock. Our tentative experiment shows that the firstorder feature of the GPS velocity field of the northeastern plateau can be well explained by a 3-D dislocation model, in which a series of major faults were represented by simple dislocation segments locked  $\sim 20$  km to the surface and slipping below in an elastic half-space with rates comparable to the ones from geological observations. However, this is not a powerful evidence to judge if the deformation of the northeastern plateau is continuously distributed or block like, because both the continuum and block motion models acknowledge that the brittle upper crust likely deforms by discrete faulting and the distinction between continuum and block motion models becomes blurred in our case where the block dimensions are relatively small and the slip rates on bounding faults are roughly comparable.

[38] Although GPS velocity field does not show significant convergence between the eastern margin of the plateau and the Sichuan basin, there is a small but significant compressional strain rate of  $\sim 10.5 \pm 2.8$  nstrain/yr in a relatively narrow region around the eastern margin of the plateau. A large part of the eastern plateau area, northeast of the EHS and south of the eastern Kunlun fault, is not undergoing shortening along the northeastward convergence direction of the EHS but is stretching.

[39] There has been a long debate over whether the crustal thickening or eastward block-like extrusion has been more significant in accommodating the collision of India-Eurasia. If the two-stage development of the Tibetan Plateau is true, the block motion model, thin viscous sheet model, and channel flow model could come together to explain the entire collision process and mechanical evolution of different developmental stages and different regions of the plateau. [40] Acknowledgments. We thank all of our Chinese colleagues who have worked in the field to collect the GPS data used in this study. Thanks also go to J. Paul, P. Banerjee, and R. Burgmann for making their GPS velocity data available for us. We are grateful to J. C. Savage and W. H. Prescott for their helpful previews of this manuscript. We are particularly indebted to J. T. Freymueller and one anonymous reviewer for their thorough reviews and thoughtful comments which resulted in considerable improvement of this manuscript. This work was supported by the National Science Foundation of China (40674055) and Ministry of Science and Technology of China (2003CCB00600 and 2004CB418403).

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