Slip rates and seismic moment deficits on major active faults in mainland China

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[1] The Chinese mainland features widespread active faults and intensive seismic activity; both can be described in terms of slip rates on these faults. Previous studies of fault slip rates in mainland China have focused on individual faults or fault segments, and large discrepancies exist among results derived from different methods. Here we derive a self-consistent estimate of the slip rates on all major faults in mainland China using the recently updated GPS data and an elastic block model. The predicted slip rates are high in western and low in eastern China, ranging from 25.1 ± 2.0 mm/yr in the Himalayan Thrust System to less than 1.0 mm/yr in north China. Using these slip rates, we estimated the rates of moment accumulation on the major fault zones and compared them with the seismic moment released on each fault zone using the Chinese historical earthquake catalog that extends for more than 2000 years in many regions. The results show nine seismic zones with large moment deficits (unreleased moment). Future refinement of GPS measurements and earthquake history will allow better estimates of slip rates on individual faults and better assessment of earthquake hazard on these faults in mainland China.


1. Introduction

[2] China is a country of active tectonics with high seismic hazard (Figure 1). Devastating earthquakes include the 1556 Huaxian earthquake (M 8.0), the deadliest earthquake in human history with 830,000 people perished [Division of Earthquake Monitoring and Prediction, State Seismological Bureau, 1995], and the 1976 Tangshan earthquake (M 7.8) that destroyed the industrial city of Tangshan and killed ~250,000 people. In 2008, the great Wenchuan earthquake (Mw 7.9) killed more than 80,000 people and injured thousands, and 2 years later, on 14 April 2010, an Mw 6.9 earthquake in the Tibetan Plateau took nearly 3000 people’s lives and collapsed more than 15,000 houses.

[3] Assessing earthquake hazard in China is particularly challenging, because most of these earthquakes occur on a complex network of faults in the interior of the Eurasian plate (Figure 1). In the past decade extensive GPS measurements have been conducted in mainland China (Figure 2). The GPS results help to identify fast moving faults and deforming regions, but these results do not directly relate to seismic hazard. The 2008 Wenchuan earthquake, for example, occurred on the Longmen Shan fault zone where the slip rate is <3 mm/yr [Gan et al., 2007; Shen et al., 2005; Zhang et al., 2004].

[4] Nonetheless, slip rates are a basic indicator of the rates of strain energy accumulation on faults. When compared with moment release by previous earthquakes, the deficit (unreleased moment) or surplus (over-released moment) can provide some useful insight into the potential earthquake hazard on a given fault [Meade and Hager, 2005a]. Doing so requires a long and, ideally, a complete record of previous earthquakes, which is unavailable in most places. In China the problem is less because of its long historic record of earthquakes that extends for more than 2000 years in many regions [Division of Earthquake Monitoring and Prediction, State Seismological Bureau, 1995].

[5] Although slip rates have been studied for many faults in mainland China, results from different methods often give large discrepancies [Cowgill, 2007; Cowgill et al., 2009; Meade, 2007; Meiraux et al., 2005, 2004; Tapponnier et al., 1990; Zhang et al., 2007]. Most studies have also focused on individual faults or fault segments. In this study we derive self-consistent slip rates on all major faults in mainland China using the recently updated GPS data [Zhang and Gan, 2008] in a continental-scale elastic block model. We then use these slip rates to estimate the rates of moment accumulation on these faults and compare them with seismic moment release.

2. Active Faults in Mainland China

[6] The active fault systems in western China are predominantly E-W oriented strike-slip and thrust faults (Figure 3), reflecting the long history of terrane accretion to the southern margin of the Eurasian plate [Yin and Harrison, 2000] and the continued collision between the Indian and
Asian continents in the past 50–70 Ma [Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1977; Tapponnier et al., 1982, 2001; Yin and Harrison, 2000]. From the Himalayan Thrust System northward, the major faults in the Tibetan Plateau include the Karakorum-Jiali fault, the Xianshuihe fault, the Kunlun fault, the Altyn Tagh fault, and the Qilian Shan-Haiyuan fault; the last two bound the northern margin of the Tibetan Plateau. The compressive faulting goes all the way to the Tian Shan and the Altai mountains, showing the far-field impact of the Indo-Asian collision [Tapponnier and Molnar, 1979; Yin et al., 1998].

The eastern margin of the Tibetan Plateau is bounded by the Longmen Shan fault and the Anninghe-Xiaojiang fault. Together with the faults bounding the western side of the Ordos block (Figure 3), these faults form the so-called south-north seismic belt in Chinese literature. This belt, roughly following the 105°E longitude, also separates the collision-controlled western China from eastern China. The latter consists of the south China and the north China blocks, which are two cratons that collided since early Mesozoic along the Qinling-Dabie fault belt [Kusky et al., 2007; Yin and Nie, 1996]. Active faults in eastern China reflect both the influence from this collision and the effect of late Mesozoic to early Cenozoic convergence between the Eurasian and Pacific plates, as witnessed by the system of NE-SW oriented faults (Figure 3).

3. The Elastic Block Model and GPS Constraints

Fault slip rate is a primary indicator of active tectonics and seismic activity. In this section we briefly describe the elastic model and the GPS data we used to derive a self-consistent estimate of fault slip rates on all major active faults in mainland China.

3.1. The Elastic Block Model

The GPS data (Figure 2) can be used to derive fault slip rate on the major faults. Most GPS site velocities, measured over a period of a few years, reflect mainly the interseismic crustal strain rate. Although faults are locked...
between ruptures, the slip rate on the fault can be estimated from the GPS velocities across the fault. For a single fault, this can be done using a one-dimensional elastic dislocation model [Savage and Burford, 1973]. For an infinitely long strike-slip fault, the station velocity, $v$, along a profile perpendicular to the fault is related to the slip rate ($b$), fault locking depth ($D$) and distance from the fault ($x$):

$$v = \frac{b}{C^2} \arctan\left(\frac{x}{D}\right) \left(1 - \frac{1}{x^2}ight)$$

For a network of faults, Meade et al. [2002] and Meade and Hager [2005b] have developed a three-dimensional elastic block model to derive self-consistent slip rates on all faults. The slip rates so derived are the total slip rates, which include both the interseismic and coseismic slips. In the model, the interseismic velocity ($V_I$) is assumed to be the difference between block velocity (the total slip rate, $V_B$) and the yearly coseismic slip deficit velocity ($V_{CSD}$):

$$V_I = V_B - V_{CSD}$$

where $\tilde{v}_{B}(\tilde{x}_S)$ represents the fault geometry. The block velocity is established using the rotation about an Euler pole $\Omega$:

$$\tilde{v}_B(\tilde{x}_S) = \Omega \times \tilde{x}_S$$

The yearly coseismic slip deficit velocity ($V_{CSD}$) is calculated using the elastic dislocation model [Okada, 1992]. The predicted interseismic velocity at a point is equal to the sum of the block rotation rate and the integrated effects of elastic strain accumulation from all faults. The predicted slip rates meet the condition of internal consistency that any closed path integral of velocity sums to zero [Meade et al., 2002].

[11] We use this approach to construct a block model for mainland China (Figure 4), using the code from Meade and Hager [2005b]. The division of the blocks follows that of previous studies, which were based on neotectonics and geodetic results of crustal motion in mainland China [Chen et al., 2004; Deng et al., 2002; Gan et al., 2007; Han et al., 2003; Meade, 2007; Shen et al., 2005; Thatcher, 2007; Zhang and Gan, 2008; Zhang et al., 2003]. We delineated the block boundaries based on traces of the major faults, simplifying complex fault zones as linear boundaries. In north China where the traces of some major active fault are not clear, the boundaries are based on geophysical data and earthquake activity [Han et al., 2003]. These blocks are listed in Table 1.

[12] All faults are assumed to be vertical except the Himalayan Thrust System, which dips $\sim 10^\circ$ northward [Meade, 2007]. This simplification has two reasons. One reason is the uncertainty of the geometry of most faults at depth. The other is that most GPS sites are far from the faults, hence the predicted velocities at these sites are not sensitive to the detailed fault geometry at depth. Similar simplification has been used in previous studies [McCaffrey, 2005; Meade, 2007; Meade and Hager, 2005b]. With fault planes simplified to be vertical, the dip-slip motion (compressive or extensional) on such a fault is represented by
Figure 3. Topography, major active faults, and tectonic units in mainland China. Dashed lines indicate hidden faults from the interpretation of satellite images. Data of faults are from Deng et al. [2002].

Figure 4. The block model for mainland China. Names of the blocks are listed in Table 1. The thin lines are active faults described in Figure 3. Barbed lines are plate boundaries.
horizontal convergence toward, or divergence from, the block boundaries, respectively.

[13] Because Okada’s solutions [Okada, 1992] are for surface deformation in a homogeneous elastic half-space, to use this approach in our large-scale model we need to project the fault geometry and station position from spherical to planar geometry. We use a locally tangent oblique Mercator projection to flatten the spherical geometry. In such a way, the trace of a fault segment is approximated as a great circle path between its two endpoints. The spatial distortion due to the projection is < 2%, and the far-field velocities produced by the fault dislocation are insignificant [Meade and Hager, 2005b]

3.2. The GPS Constraints

[14] The GPS data used in our study are from a recently updated compilation by Zhang and Gan [2008], which is mainly based on results from the Crustal Motion Observation Network of China (CMONC). CMONC consists of 25 continuous stations, 56 annually surveyed stations, and nearly one thousand survey mode stations. The data were collected between 1998 and 2004; measurements at each site were for at least 72 h. In addition, Zhang and Gan [2008] combined other data sets to increase the coverage and spatial density in Mongolia, India, Himalayan, and central Tibet.

[15] The GPS data include some outliers of various non-tectonic sources. These outliers are usually of large measurement errors and not coherent with other nearby observations. In our block model, we used both the complete GPS data set and a reduced data set with the outliers removed. We removed the outliers using the $F$ test. First, we use all the GPS site velocities in the block model to calculate site velocities, and evaluate the RMS $\chi^2_n$ ($\chi^2_n = r^T C^{-1} r$), where $n$ is the number of GPS sites in the model, $r$ is the vector of residual velocities and $C$ is the data covariance matrix. Next, we remove the site with the largest RMS residual, and use the rest of the GPS data to predict the site velocities again and then evaluate the RMS $\chi^2_{n-1}$. Finally, we use the $F$ test to evaluate the significance of the outlier. The $F$ value is defined as

$$F = F(\chi^2_n, 2n - 3; \chi^2_{n-1}, 2n - 5) = \frac{\chi^2_n}{2n - 3} / \frac{\chi^2_{n-1}}{2n - 5}$$

Then the probability $P(F)$ is evaluated. The site is removed if the $F$ test exceeds 90% confidence, and the procedure repeats until the $F$ test yields <90% confidence. The reduced GPS data set has 1162 GPS site (91.8% of total sites) velocities. The mean uncertainties of this reduced GPS data set are 1.67 mm/yr in the east-west direction and 1.63 mm/yr in the north-south direction, respectively (Figure 2). The results in section 4 are from this reduced data set, and the impact of removing the outliers is discussed in section 6.2.

4. Model Results

4.1. Locking Depths of Major Faults and the Site Velocities

[16] The depth to which the faults stay locked between ruptures affects the distribution of strain rates on the surface, as shown in equation (1). A deeper locking depth would cause broader strain distribution, and vice versa. The locking depths can be constrained in the block model by fitting to the GPS data. Figure 5 shows how the fits vary with the locking depth in various regions. The optimal locking depth is obtained at the minimum of RMS $\chi^2$. First, we determine a uniform locking depth for all faults and use it as the initial
value in our block model (Figure 5a). The best fit is about 19 km. Using this initial value, we then determined the optimal locking depth of faults in the Tibetan Plateau (21 km), the Xinjiang region (9 km), and north China (>40 km). In north China, the variation of $c^2$ for a range of locking depths (0–40 km) is less than 2% (Figure 5d), indicating that the GPS data cannot well constrain the locking depths. The reason is that many GPS site velocities in north China have errors larger than their velocity components (Figure 2).

[17] Additional constraints of fault locking depth are provided by earthquake focal depths. Zhang et al. [2002] have shown that the mean earthquake focal depth is 16 ± 7 km in Chinese continent. The focal depths of most events (90% of all events) are 5–24 km in eastern China and are 5–34 km in western China. The mean earthquake focal depth is 13 ± 6 km in eastern China, and 18 ± 8 km in western China. Relocation of major earthquakes in the Tibetan Plateau indicates the focal depths of most events to be shallower than 25 km [Yang et al., 2005]. Hence, the locking depths indicated by focal depths are generally consistent with those estimated from the block model except in north China. We use 10 km as the locking depth of faults in north China, according to the focal depths of major earthquakes and the estimated depths of the seismogenic layer in this region [Zhu et al., 2005].

[18] Using the optimal locking depths for the major faults, we predicted site velocities using the block model. The results are in good agreement with the GPS velocities (Figure 6). The mean residual velocity is 0.91 mm/yr, less than the mean uncertainty of the GPS data with 90% confidence. About 69% of the residual velocity components are smaller than 1.0 mm/yr. The large misfits are mainly found around southern and western Tibet, where the GPS sites are sparse and the observational errors are relative large (Figure 2).

4.2. Block Rotation

[19] Figure 7 shows the predicted rotation of crustal blocks in the Chinese mainland; their Euler poles and rotation rates are listed in Table 1. The largest rotation occurs around the Tibetan Plateau. In general, more rotation is found in western China than in eastern China.

![Figure 5. Optimal fault locking depths for mainland China and its various regions. The red lines show the percent increase in velocity misfit relative to the best fitting model. Black lines show the rate of moment accumulation for each region as a function of the locking depths of faults. The gray shaded bands show the uncertainties due to errors of slip rates. The light red bands indicate the range of locking depth where change in $\chi^2$ is significant to 90%. (a) Mainland China; (b) Tibetan Plateau; (c) Xinjiang region; (d) north China.](image-url)
Figure 6. Residual velocities (the difference between the predicted and the GPS site velocities). The mean RMS is 0.91 mm/yr. Inset is the histogram of residuals that shows good agreement between the predicted and the GPS velocities.

Figure 7. Predicted rigid rotation of the blocks. The fans in gray show predicted block rotations of each block; the small fans show $2\sigma$ uncertainties.
The Tarim, the Ordos, and the South China blocks are relatively rigid blocks, so we compare their rotations from our model with those from previous regional-scale studies. For the Tarim block, our predicted Euler pole (98.3° ± 0.7°E and 37.8° ± 0.3°N) is similar to that found by Shen et al. [2001] (96.2° ± 0.8°E and 37.5° ± 0.4°N), who used a subset (28 GPS site velocities) of the data set used in our study. These locations are also similar to that found by Li et al. [2003] (100.5° ± 1.0°E, 37.1° ± 0.3°N). The Ordos block is shown to rotate around an Euler pole located at 121.7° ± 3.1°E and 48.2° ± 2.0°N in our model, similar to the location of 133.2° ± 11.3°E and 54.2° ± 4.8°N found by Li et al. [2003]. The counterclockwise rotation of the Ordos block is consistent with the eastward crustal extrusion driven by the Indo-Asian collision [Xu et al., 1993]. The South China block rotates clockwise around an Euler pole at 41.4° ± 14.9°E and 56.9° ± 5.4°S, similar to that found by Zhang and Gan [2008].

The southeastern Tibet in our model consists of 4 blocks (blocks 1, 4, 9, and 10 in Figure 4). These blocks rotate at similar rates, with their Euler poles clustered within 93°–96°E and 22°–25°N. These results are consistent with the clockwise rotation around the eastern Himalayan syntax in the southeastern Tibet [Allmendinger et al., 2007].

4.3. Slip Rates on Major Faults

The main results from our block model are a self-consistent estimate of the slip rates on all major faults in mainland China (Figure 8). The details are listed in Table 2, together with previous estimates based on geological or geodetic data. Our predicted slip rates show sharp contrast between western China (high) and eastern China (low), roughly separated along 105°E longitude, or the south-north seismic belt. We briefly describe the results in three tectonic regions where the slip rates are the highest: the Tibetan Plateau, the Xinjiang region, and north China.

4.3.1. Slip Rates in the Tibetan Plateau and Its Vicinity

The highest slip rates are found in the faults within and around the Tibetan Plateau. From east to west along the Himalaya Thrust System, the predicted mean contraction rate changes from 22.0 ± 1.8 mm/yr to 18.3 ± 1.3 mm/yr, similar with those found by Meade [2007] but higher than the rates by others [Shen et al., 2000; Wang et al., 2001; Zhang et al., 2004]. In the eastern part of the Tibetan Plateau, the Indo-Eurasian plate boundary is mainly a system of right-lateral strike-slip faults. Our model predicts more than 40 mm/yr right-lateral strike-slip motion and 14.6 ± 1.1 mm/yr convergence on this part of the plate boundary. These results are higher than previous estimates [Bertrand et al., 1998; Maurin et al., 2010; Vigny et al., 2003].

Within the Tibetan Plateau, the dextral Karakorum fault has a strike-slip rate of 11.6 ± 3.7 mm/yr and a convergence rate up to 4.3 ± 1.6 mm/yr, similar to those estimated from InSAR data [Wright et al., 2004] but smaller than geological results [Brown et al., 2002; Chevallier et al., 2005; Valli et al., 2007]. The dextral Red River fault has a slip rate about 2.4 ± 1.0 mm/yr. The sinistral Xianshuixia-Xiaojiang fault has high slip rates ranging from 18.2 ± 0.8 to 10.4 ± 0.4 mm/yr on its various segments. The sinistral east Kunlun fault has a mean slip rate of 10 mm/yr. Bounding the Tibetan Plateau to the north is the sinistral Altyn Tagh-Haiyuan fault zone. The mean slip rate on the Altyn Tagh fault is 6.9 ± 0.9 mm/yr, generally decreasing eastward. These rates are generally consistent with those from other GPS measurements [Shen et al., 2001; Zhang et al., 2004, 2007], but is lower than the 17.8 ± 3.6 mm/yr geological estimates [Meriaux et al., 2004] (Table 2). The predicted mean slip rate on the Haiyuan fault is 8.7 ± 0.9 mm/yr. Bounding the eastern margin of the Tibetan Plateau is the Longmen Shan fault, where the predicted convergence rate is 3.2 ± 0.6 mm/yr, and the dextral slip rate is 1.2 ± 0.5 mm/yr. These low slip rates are similar to previous estimates [Gan et al., 2007; Shen et al., 2005; Wang et al., 2010; Zhang et al., 2004].

Consistent with the formation of north trending grabens within the Tibetan Plateau [Blisniuk et al., 2001; Kapp et al., 2008; Liu and Yang, 2003; Yin, 2000], the model results show the south-north trending faults in Tibet to be extensional, with the extension rates up to 10.7 ± 2.5 mm/yr (Figure 8b).

Figure 8. Predicted fault slip rates along major active faults. (a) Strike-slip rates. (b) Dip-slip rates shown as contraction/extension rates because most faults are simplified as being vertical. Thickness of lines is proportional to the rates (scales are shown in the inset).
Predicted Fault Slip Rates on Major Faults

<table>
<thead>
<tr>
<th>Fault</th>
<th>Strike-Slip Ratea (mm/yr)</th>
<th>Contraction/ Extension Rateb (mm/yr)</th>
<th>Previous Resultsc (mm/yr)</th>
<th>Geological</th>
</tr>
</thead>
<tbody>
<tr>
<td>Himalaya Thrust System</td>
<td>~4.0 ± 2.0</td>
<td>~22.0 ± 1.8 to ~18.3 ± 1.3d</td>
<td>~16 to ~24 (1); ~22 ± 2.0 (2); ~16 (3); 15–20 (4)</td>
<td>~21 ± 5.0 (5)</td>
</tr>
<tr>
<td>Sagaing</td>
<td>~45.6 ± 1.2</td>
<td>~14.6 ± 1.1</td>
<td>~20 (1); ~20 (6); ~18 (7)</td>
<td>~10 to ~23 (8)</td>
</tr>
<tr>
<td>Karakorum</td>
<td>~11.6 ± 3.7</td>
<td>~4.3 ± 1.6</td>
<td>~4 to ~2 (1); about ~7 (9)</td>
<td>~9 to ~17 (10); ~1 to ~3 (11); ~10 (12)</td>
</tr>
<tr>
<td>Red River</td>
<td>~2.4 ± 1.0</td>
<td>~3.1 ± 0.8</td>
<td>~10 (1); 0.6 (13); 2 (14)</td>
<td>~1 to ~3 (15)</td>
</tr>
<tr>
<td>Xianshuie</td>
<td>18.2 ± 0.8</td>
<td>3.5 ± 1.0</td>
<td>10–12 (14); ~14.4 (16)</td>
<td>15 ± 5 (18)</td>
</tr>
<tr>
<td>Xiaojiang</td>
<td>10.4 ± 0.4</td>
<td>3.2 ± 0.6</td>
<td>9.4 (13); 7 (14)</td>
<td>12–28 (15)</td>
</tr>
<tr>
<td>Longmen Shan</td>
<td>~1.2 ± 0.5</td>
<td>~3.2 ± 0.6</td>
<td>~3 (1); ~4.0 ± 2.0 (4); ~1.1 (13); ~4.1 (16); ~1.2 to ~3.3 (19)</td>
<td>&lt;~3 (20)</td>
</tr>
<tr>
<td>West Kunlun</td>
<td>0.5 ± 2.0</td>
<td>~3.0 ± 2.0</td>
<td>10 (1); 12–14 (3); 7.1 (13); 10–12 (14); 13.7 (16)</td>
<td>11.5 ± 2 (22); 10 to &lt;2 (22)</td>
</tr>
<tr>
<td>East Kunlun</td>
<td>10.1 ± 1.2</td>
<td>~3.0 ± 1.1</td>
<td>2.3 ± 1.3; 7.2 ± 0.6 (1); 5.0 ± 2.0–6.5 ± 1.6 (4); 7–10 (9); 1.6–15.9 (16); 0 ± 2–10 ± 2 (23)</td>
<td>17.8 ± 3.6 (24); 20–34 (25); 14–9 (26)</td>
</tr>
<tr>
<td>Altyn Tagh</td>
<td>6.9 ± 0.9</td>
<td>~1.5 ± 1.3</td>
<td>~2 (16); ~5.5 ± 1.8 (4)</td>
<td>~0.4 to ~1.9 (27)</td>
</tr>
<tr>
<td>Qilian</td>
<td>~1.3 ± 1.1</td>
<td>~6.0 ± 1.1</td>
<td>8.6 (16)</td>
<td>4.5 ± 1.0 (27); 5–10 (29); 10 ± 2 (30); 12 ± 4 (31)</td>
</tr>
<tr>
<td>Haiyuan</td>
<td>8.7 ± 0.9</td>
<td>~2.7 ± 0.5</td>
<td>~10 to ~13 (32)</td>
<td>&lt;~2 (33)</td>
</tr>
<tr>
<td>South Tian Shan</td>
<td>2.8 ± 0.6</td>
<td>~6.8 ± 0.8 to ~2.9 ± 1.0</td>
<td>~2 to ~12 (32)</td>
<td>~3 (34)</td>
</tr>
<tr>
<td>North Tian Shan</td>
<td>1.1 ± 0.8</td>
<td>~6.3 ± 1.1</td>
<td>~2.6 ± 1.0 to ~1.2 (35)</td>
<td>~1 to ~3.2 (39)</td>
</tr>
<tr>
<td>Altau</td>
<td>~4.9 ± 0.5 to ~7.9 ± 0.7</td>
<td>~5.4 ± 0.6</td>
<td>~3 (36)</td>
<td>5(37); 7 ± 2 (38)</td>
</tr>
<tr>
<td>Qingling-Dabie</td>
<td>0.9 ± 0.4</td>
<td>0.8 ± 0.4</td>
<td>~4.6 ± 0.4</td>
<td>~1.1 to ~3.2 (39)</td>
</tr>
<tr>
<td>Southeast China coastal zone</td>
<td>~1.8 ± 0.5</td>
<td>~4.6 ± 0.4</td>
<td>~4 ± 2 (2); ~0.4 (38); 2 (40)</td>
<td></td>
</tr>
<tr>
<td>Shanxi rift</td>
<td>~0.6 ± 0.5</td>
<td>~0.8 ± 0.3</td>
<td>0.5 ± 0.5</td>
<td>~1 (35); 1.6 (38)</td>
</tr>
<tr>
<td>Weihai rift</td>
<td>1.4 ± 0.4</td>
<td>0.5 ± 0.3</td>
<td>~3 (2)</td>
<td>2 to ~39 (41)</td>
</tr>
<tr>
<td>Tantu</td>
<td>~0.7 ± 0.6</td>
<td>0.5 ± 0.5</td>
<td>~4 ± 2 (2); ~0.4 (38); 2 to ~39 (41)</td>
<td></td>
</tr>
<tr>
<td>Hetao</td>
<td>0.6 ± 0.4</td>
<td>0.5 ± 0.5</td>
<td>~2.3 ± 0.8 (38)</td>
<td>2.2–6.47 (40)</td>
</tr>
<tr>
<td>Yinchuan rift</td>
<td>~2.6 ± 0.5</td>
<td>1.0 ± 0.5</td>
<td>~3.1 (38); 1.6 (39)</td>
<td>2.6–4.7 (40)</td>
</tr>
<tr>
<td>Zhangjiakou-Bohai</td>
<td>1.9 ± 0.4</td>
<td>0.5 ± 0.5</td>
<td>1.8 ± 1.0 (2)</td>
<td>~</td>
</tr>
</tbody>
</table>

4Positive for sinistral motion, and negative for dextral motion.

5Positive for extension (normal fault) and negative for contraction (reverse fault). Most faults are assumed to be vertical; for them the positive and negative values represent horizontal motion toward or away from the faults, respectively. In all cases, the slip rate is the mean value of all segments of a fault.


[26] On the Sagaing fault, the predicted slip rates (~40 mm/yr) is much higher than the ~18 mm/yr strike-slip rate based on geological data [Bertrand et al., 1998; Maurin et al., 2010; Vigny et al., 2003]. This may be partially due to the lack of GPS sites near the fault in our model.

4.3.2. Slip Rates in the Xinjiang Region

The northwestern China, or the Xinjiang region, stretches from the southern Tarim basin to the Altai Mountains (Figure 3) and includes blocks 17–19 in Figure 4. Major faults here include those bounding the northern and southern sides of the Tian Shan and Altai Mountain ranges. They are mainly reverse faults with strike-slip components. The active compressive deformation in this region witnesses the far-field impact of the Indo-Asian collision [Molnar and Tapponnier, 1975; Yin et al., 1998].

[27] On the south Tian Shan fault, the mean convergence rate is 6.8 ± 0.8 mm/yr on the western segments and 2.9 ± 1.0 mm/yr on the eastern segments. Similar trends are found
for the north Tian Shan fault. The total rate of crustal shortening across the Tian Shan main ranges is nearly 50% of the convergence rate between the Indian and Eurasian plates, consistent with the results of previous results [Abdrakhmatov et al., 1996; Molnar and Ghose, 2000; Thompson et al., 2002; Wang et al., 2000; Yang et al., 2009].

The predicted slip rate on the right-lateral Altai fault is about 4.9–7.9 mm/yr, similar to the results of Calais et al. [2003]. Our model also predicts 4.4–6.4 mm/yr convergence on the Altai fault, confirming that the Indo-Asian collision affected at least this far north [Molnar and Tapponnier, 1975].

4.3.3. Slip Rates in North China

The North China block has many large historic earthquakes and some damaging earthquakes in the past century (Figure 1), including the 1976 Tangshan earthquake (M = 7.8). It is bounded by the Zhangjiakou–Bohai fault zone to the north and the Qinling–Dabie fault system to the south (Figure 3). From west to east, the North China block consists of the relatively rigid Ordos Plateau, the North China Plain, and the coastal regions. The Ordos Plateau is bounded by rift zones, and the North China Plain has a system of ENE and WNW oriented faults (Figure 3). The predicted slip rates on the faults in north China are generally less than 3.0 mm/yr (Figure 8). For example, the Shanxi rift is shown to have a right-lateral strike-slip rate of 0.6 ± 0.5 mm/yr and extension rate of 0.8 ± 0.3 mm/yr. These results are comparable with previous geodetic estimates but lower than the 2–4 mm/yr extension rates from geological estimates (Table 2). Some of this discrepancy may be due to the timescale-dependent fault behavior [He et al., 2003]. The relatively low fault slip rates are consistent with the lower seismicity in north China in comparison with that in western China.

5. Moment Balance

[31] The predicted slip rates on major active faults provide useful insight into active tectonics in mainland China; when combined with earthquake history on the faults, they may also contribute to a better understanding of earthquake hazard. Here we use the predicted slip rates to estimate the rate of moment accumulation on the major active faults in mainland China, and compare the results with seismic moment release to identify faults of large moment deficit (unreleased moment).

5.1. Rates of Moment Accumulation

[32] The rates of scalar moments ($M_o$) accumulation on a given fault segment can be estimated as $M_o = \sum |s|s|A|$, where $|s|$ is the magnitude of the total slip rate, which includes both strike-slip and dip-slip (contraction/extension for vertical faults) rates on the fault segment, $A$ is the area of locked fault plane, and $\mu$ is the shear modulus. Assuming $\mu = 30$ GPa and using the optimal locking depths (Figure 5), we found that the rate of moment accumulation is $185 \pm 34 \times 10^{18}$ N m/yr for the entire Chinese mainland (the uncertainties are based on those of the predicted fault slip rate). It is equivalent to the moment release by an $M_w$ 7.4 earthquake per year.

[33] Moment accumulation is the fastest in the Tibetan Plateau (Figure 9), consistent with the intense seismicity there (Figure 1). The total moment accumulation in the
The numbering of the seismic belt is the same as in Figure 10.

The slip rates are mean values for the seismic belts.

Only moment deficits are shown. Number in parentheses indicates the equivalent moment magnitude if all the moment deficits are released by one earthquake.

<table>
<thead>
<tr>
<th>No.</th>
<th>Seismic Belt</th>
<th>Rate of Moment Accumulation</th>
<th>Released Seismic Moment (10^20 N m)</th>
<th>Moment Deficits (10^20 N m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mw Rate (10^18 N m/yr)</td>
<td>Starting Year</td>
<td>Accumulated Mw (10^20 N m)</td>
</tr>
<tr>
<td>1</td>
<td>Himalayan</td>
<td>15.6 ± 3.3</td>
<td>25.20 ± 5.20</td>
<td>1800</td>
</tr>
<tr>
<td>2</td>
<td>Karakorum-Jiali</td>
<td>12.9 ± 3.3</td>
<td>13.90 ± 3.10</td>
<td>1900</td>
</tr>
<tr>
<td>3</td>
<td>East Kunlun</td>
<td>11.2 ± 1.8</td>
<td>14.60 ± 2.50</td>
<td>1890</td>
</tr>
<tr>
<td>4</td>
<td>West Qinling-Delingha</td>
<td>3.7 ± 1.8</td>
<td>1.92 ± 0.97</td>
<td>1600</td>
</tr>
<tr>
<td>5</td>
<td>Haiyuan-Qilian</td>
<td>8.2 ± 1.3</td>
<td>6.50 ± 1.09</td>
<td>1800</td>
</tr>
<tr>
<td>6</td>
<td>West Kunlun</td>
<td>9.7 ± 2.1</td>
<td>3.49 ± 0.77</td>
<td>1880</td>
</tr>
<tr>
<td>7</td>
<td>Altyng Tagh</td>
<td>8.3 ± 1.7</td>
<td>6.47 ± 1.32</td>
<td>1900</td>
</tr>
<tr>
<td>8</td>
<td>South Tian Shan</td>
<td>5.3 ± 1.1</td>
<td>2.76 ± 0.54</td>
<td>1850</td>
</tr>
<tr>
<td>9</td>
<td>North Tian Shan</td>
<td>2.9 ± 1.3</td>
<td>0.95 ± 0.32</td>
<td>1750</td>
</tr>
<tr>
<td>10</td>
<td>Altai</td>
<td>8.0 ± 1.1</td>
<td>2.20 ± 0.30</td>
<td>1850</td>
</tr>
<tr>
<td>11</td>
<td>Lancang River</td>
<td>10.0 ± 1.8</td>
<td>5.41 ± 0.95</td>
<td>1850</td>
</tr>
<tr>
<td>12</td>
<td>Red River</td>
<td>8.2 ± 1.3</td>
<td>3.14 ± 0.50</td>
<td>1900</td>
</tr>
<tr>
<td>13</td>
<td>Sanjiang</td>
<td>1.6 ± 1.7</td>
<td>0.59 ± 0.21</td>
<td>1850</td>
</tr>
<tr>
<td>14</td>
<td>Xianshuihe</td>
<td>18.1 ± 13</td>
<td>4.10 ± 0.30</td>
<td>1850</td>
</tr>
<tr>
<td>15</td>
<td>Anninghe-Xiaojia</td>
<td>12.7 ± 0.9</td>
<td>5.64 ± 0.39</td>
<td>1700</td>
</tr>
<tr>
<td>16</td>
<td>MinShan-Longmen Shan</td>
<td>2.8 ± 0.8</td>
<td>1.45 ± 0.36</td>
<td>1600</td>
</tr>
<tr>
<td>17</td>
<td>Yinchuan Graben</td>
<td>3.0 ± 0.7</td>
<td>0.57 ± 0.13</td>
<td>1500</td>
</tr>
<tr>
<td>18</td>
<td>Southeast China coastal zone</td>
<td>4.9 ± 0.6</td>
<td>1.64 ± 0.21</td>
<td>1400</td>
</tr>
<tr>
<td>19</td>
<td>Qinling-Dabies</td>
<td>1.5 ± 0.6</td>
<td>0.33 ± 0.14</td>
<td>1400</td>
</tr>
<tr>
<td>20</td>
<td>Fenhe-Weihe</td>
<td>1.2 ± 0.6</td>
<td>0.16 ± 0.07</td>
<td>1000</td>
</tr>
<tr>
<td>21</td>
<td>Hebei Plain</td>
<td>0.5 ± 0.7</td>
<td>0.18 ± 0.10</td>
<td>1400</td>
</tr>
<tr>
<td>22</td>
<td>Anyang-Heze-Linyi</td>
<td>0.4 ± 0.9</td>
<td>0.46 ± 0.21</td>
<td>1400</td>
</tr>
<tr>
<td>23</td>
<td>Tanlu</td>
<td>0.9 ± 0.8</td>
<td>0.48 ± 0.27</td>
<td>1500</td>
</tr>
<tr>
<td>24</td>
<td>Yin Shan</td>
<td>0.9 ± 0.7</td>
<td>0.41 ± 0.80</td>
<td>1900</td>
</tr>
<tr>
<td>25</td>
<td>Yan Shan-Bohai</td>
<td>1.5 ± 0.7</td>
<td>0.38 ± 0.13</td>
<td>1400</td>
</tr>
</tbody>
</table>

The Tibetan Plateau is 163 ± 30 × 10^18 N m/yr, about 88% of that in the entire Chinese mainland. The predicted rates of moment accumulation for major fault systems are listed in Table 3. The highest rates are found on the Himalayan Thrust System plate boundaries (25.2 ± 5.2 × 10^18 N m/yr). Other faults with high moment accumulation rate in this region include the Karakorum-Jiali fault (13.9 ± 3.1 × 10^18 N m/yr), the Xianshuihe-Xiaojia fault (9.74 ± 0.69 × 10^18 N m/yr), the Kunlun fault (18.1 ± 3.3 × 10^18 N m/yr), the Haiyuan-Qilian fault (6.50 ± 1.09 × 10^18 N m/yr), and the Altyng Tagh fault (6.47 ± 1.32 × 10^18 N m/yr). The Xinjiang region has the second highest moment accumulation rate in mainland China (Figure 9), consistent with the relatively intense seismicity there (Figure 1).

Because of the low fault slip rates in eastern China, moment accumulation rate there is considerably lower: 5 ± 2 × 10^18 N m/yr for the entire north China, and 4 ± 1 × 10^18 N m/yr for south China.

### 5.2. Seismic Moment Release

Seismic moment (Mw, in Newton meters) released by an earthquake can be estimated from its moment magnitude (Mw):

\[ M_w = (2/3) \log M_o - 6.03 \]  \hspace{1cm} (5)

However, most earthquakes in the Chinese catalog are given in surface wave magnitude (Mw). Because the difference between the Mw and M0 is usually small, we treated all magnitudes in the catalog as Mw in our estimation of seismic moment release. The error of magnitude in the Chinese earthquake catalog is estimated to be ±0.2 [Liu et al., 2006].

Using equation (5), we estimate the total scalar seismic moment released in mainland China during 1920–2007 to be 170.45 ± 127.33 × 10^20 N m, much lower than the predicted 197.95 ± 36.38 × 10^20 N m that would have accumulated during this period. The difference is the moment deficit, which is equivalent to the moment released by an Mw 8.2 earthquake. While this moment deficit provides some sense of the seismic potential in mainland China, earthquakes occur by rupturing individual faults. Hence we need to examine moment deficits on each fault or fault segment, which is not feasible for the scale of this study. Instead, we would discuss the moment deficit for each of the seismic belts, which are the simplified fault systems.

#### 5.3. Moment Deficit on Seismic Belts

We define 25 major seismic belts in mainland China based on seismicity and active faults (Figure 10), all of them are the boundary faults of our block model (Figure 3). The simplification is reasonable because all known M ≥ 8.0 earthquakes occurred on these block boundary faults, so are more than 80% of M = 7.0−7.9 events [Zhang et al., 2005] (Figure 10).

To balance the moment on each seismic belt, we need to consider a period as long as possible that spans one or more seismic cycles and have complete record of large earthquakes. Although the earliest earthquake recorded in the Chinese mainland was a M 7.0 event in 23rd century B.C. [Division of Earthquake Monitoring and Prediction, State Seismological Bureau, 1995], the record is incomplete, espe-
cially for the early centuries. Furthermore, the situation varies greatly from region to region. In western China, the earthquake record is short, often available only for the past century. The seismic belts with long historical record are regions with long history of human habitation, such as near the north Tian Shan belt, the Xianshuihe belt, the Anninghe-Xiaojiang belt, and the Longmen Shan-Min Shan belt. The relatively long earthquake records (likely complete for $M > 6.0$ since 1851) and high slip rates on the Xianshuihe and the Anninghe-Xiaojiang seismic belts means that the records likely covered at least one earthquake cycle [Wen et al., 2008]. In eastern China, the historical earthquake record is nearly 3000 years long because of the long history of human habitation [Division of Earthquake Monitoring and Prediction, State Seismological Bureau, 1995], but the recurrence intervals are also long because of the low slip rates. In north China the catalog for $M \geq 6.0$ events is likely complete since 1300 [Huang et al., 1994].

In Figure 11a we show the seismic moment released on each seismic belt in the most recent period. The starting year for this period varies for each belt, depending on the time span for which we likely have a complete record for $M \geq 6.0$ events for the belt (Table 3). The highest moment release is found in the Himalayan seismic belt. Other seismic belts of high moment release include the Haiyuan-Qilian belt, the south and north Tian Shan belts, the Anninghe-Xiaojiang belts, the Fenhe-Weihe belt, and the Tanlu belt, all with $M \geq 8.0$ events in the period considered. Figure 11b shows the predicted moment accumulation for each seismic belt during the same periods as considered in Figure 11a.

Comparing Figure 11a with Figure 11b, we identify nine seismic belts with significant moment deficit (i.e., more accumulation than release) (Figure 12). Of particular concern are the seismic belts with large moment deficit in north China because of the high density of human populations there.

### 6. Discussion

The elastic block models assume that crustal deformation is concentrated along fault zones bounding rigid crustal blocks. This is a reasonable approximation for crustal deformation over the timescales (less than $10^3$ years) considered here. Many studies have shown that in such short timescales, crustal strain is mainly elastic [Meade and Hager, 2005b; Pollitz, 2003; Yang and Liu, 2010]. On the other hand, some authors have argued that crustal deformation in Chinese continent is continuous [England and Houseman, 1986; England and Molnar, 2005; Royden et al., 1997; Royden et al., 2008; Vergnolle et al., 2007; Zhang et al., 2004]. The difference between the rigid block models and those of continuous deformation depends on the scales of blocks. Thatcher [2007] has suggested that the block models and the continuum models converge as the number of faults increase and the block size decreases. Zhang and Gan [2008] have presented a model combining rigid block motion with continuous deformation to describe
the present-day crustal deformation within continental China. Vergnolle et al. [2007] show that crustal kinematics of a large part of Asia is apparently consistent with block- or plate-like motions, and continuous internal strain is mostly limited to the Tibetan Plateau. 

[42] One major result of this study is the self-consistent slip rates on all major faults in mainland China (Table 2 and Figure 8). Although slip rates on many of these faults have been determined in previous GPS studies [Calais et al., 2006, 2003; Chen et al., 2004; Deng et al., 2002; Gan et al., 2007; He et al., 2003; King et al., 1997; Li et al., 2009; Meade, 2007; Shen et al., 2005, 2001; Thatcher, 2007; Wang et al., 2001, 2008; Yang et al., 2009; Zhang et al., 2004, 2007], most of these studies are focused on individual faults or on certain region of continental China, and earthquake cycle on faults are often not considered.

Figure 11. (a) Estimated seismic moment released by earthquakes in major seismic belts during the most recent period (the starting year differs for each belt depends on the completeness of the earthquake catalog, see text for details). (b) Predicted moment accumulation during the same period as for moment release in Figure 11a. Numbers are in $10^{20}$ N m/yr.

Figure 12. Predicted moment deficit (red) and surplus (blue) for major seismic belts in mainland China. Values are in $10^{20}$ N m/yr. The numbers in parentheses indicate the equivalent moment magnitude of an earthquake if it releases all the moment deficits in the seismic belt.
Geological estimates, on the other hands, are limited in numbers and often show large discrepancies for the same fault, such as for the Altyn Tagh fault and the Haiyuan fault (Table 2). Hence the predicted total slip rates on all major faults in this study provide a useful framework for understanding active tectonics and associated earthquake hazard in mainland China. Interpreting the results presented here, however, requires understanding the limitations and uncertainties of the model and data, which are briefly discussed in this section.

6.1. Stability of the Block Model

The results of the elastic block model can be affected by the geometry of the blocks, which is necessarily a simplification of nature’s complex fault systems. Our block model is based on previous studies of geological structures, fault activity, crustal motion, and seismicity [Chen et al., 2004; Deng et al., 2002; Gan et al., 2007; Han et al., 2003; Meade, 2007; Shen et al., 2005; Thatcher, 2007; Zhang and Gan, 2008; Zhang et al., 2003]. To see whether or not reasonable variations of the block geometry significantly alter our results, we tested a number of block configurations. For example, we adjusted the block geometry in the southeastern and northeastern parts of the Tibetan Plateau and changed the boundary between the Qiangtang block and the Songpan–Ganze block. The results are close to those of our preferred model. The mean residual velocity between the preferred model and our various test models is less than 0.05 mm/yr. Other elastic block models have been applied in the Tibetan Plateau region [Meade, 2007; Shen et al., 2005; Thatcher, 2007; Wang et al., 2008, 2010] with different block geometry and GPS data sets; such differences did not lead to significantly different slip rates on the major faults. Hence our results are not sensitive to reasonable choices of block geometries.

6.2. Uncertainties of the GPS Data

The GPS data used in this work are a compilation of the results from the Chinese GPS network and many other groups [Zhang and Gan, 2008]. As such they include some site velocities with large errors (Figure 2). We removed some of these outliers using the F test. Including these outliers in our model does not significantly change our results but would worsen the fit between the data and the model results. The mean residual velocity is 1.49 mm/yr, contrasting to 0.91 mm/yr in our preferred model with the outliers removed. Most of the outliers are located outside of our block model domain, hence their influence is mainly on the external boundary faults of our model. Within the model domain the GPS sites are relatively dense, so the influence of outliers is limited.

When using GPS data to constrain the block model, one assumes that the GPS data measure interseismic deformation [Meade and Hager, 2005b]. It is possible that some of the GPS data are tainted by postseismic strain. Wallace et al. [2004] found the occurrences of the 1997 Mw 7.6 Manyi earthquake and the 2001 Mw 7.8 Kokoxili earthquake may have reduced the slip rates on the Altyn Tagh fault. However, the influence of postseismic deformation is likely minor for the continental-scale model presented here. Furthermore, the sites strongly tainted by postseismic strain likely appear as outliers that fail our F test and are removed in our model. These include a few site velocities near the epicenter of the 2001 Mw 7.8 Kokoxili earthquake. On the other hand, the GPS site velocities around Tangshan may include postseismic deformation, contributing to the misfit there (Figure 6). Another region of noticeable misfit is in central and southern Tibetan Plateau due to the lack of GPS data there. Overall, the GPS data are consistent with the predicted interseismic crustal motion. The mean residual between the predicted and the GPS velocities has the normal distribution with the residual velocity at most sites close to zero (Figure 6).

6.3. Limitation of Seismic Moment Balance

We have attempted to determine the seismic belts with large moment deficits, but the results need to be interpreted with caution. The major problem comes from the short and incomplete earthquake records. The long earthquake records exist mainly for eastern China, but the low fault slip rates there imply long recurrence intervals. So the period of complete record of large earthquakes in the catalog is not long enough to cover a complete earthquake cycle, making it difficult to balance the moment. This problem is compounded by the clustering of earthquakes and long and irregular recurrence intervals that are common for intracontinental earthquakes [Stein et al., 2009]. The impact of such problems is illustrated by the 2008 Wenchuan earthquake (Mw 7.9) that occurred on the Longmen Shan fault, which has a low slip rate and only moderate seismicity in the past few centuries. Balancing moment accumulation and release on the Longmen Shan fault over the past 400 years would yield a small moment deficit incapable of producing a large earthquake [Wang et al., 2010]. However, the recurrence interval for large earthquakes on the Longmen Shan is estimated to be more than 1000 years [Burchfiel et al., 2008; Densmore et al., 2007; Shen et al., 2009; Zhang et al., 2010]. Because there is no evidence of large earthquakes on the Longmen Shan fault in the past millennium before the 2008 Wenchuan earthquake [Densmore et al., 2007], balancing moment over the past millennium would yield an alarmingly large moment deficit (1.15 × 10^{21} N m) that is sufficient to explain the 2008 Wenchuan earthquake [Wang et al., 2010].

Problems may also arise from the simplification of the seismic zones in our model. For example, the Qinling–Dabie fault belt is a Mesozoic suture zone that separates the north China and the south China cratons. The fault belt itself is not seismically active, so the predicted moment deficit along this belt may be better interpreted as indicating strain energy distributed over the transition zone between the North China and South China blocks, rather than the potential for a large earthquake on this belt. Furthermore, the external boundaries of the model domain are not well constrained, so the predicted moment deficit along the southeast China costal zone may not be reliable. Finally, the predicted moment deficit is a lumped sum for large fault systems or regions, whereas earthquakes occur on individual fault segments. With all the limitations, our estimate of moment deficit on major seismic belts in mainland China provides some guidance for future studies. Further GPS measurements across individual active faults will allow refined block models to estimate slip rates on these faults or fault segments, which, with more complete earthquake his-
tory from paleoseismic studies, will lead to better assessment of earthquake hazards.

7. Conclusions

[as] We have determined the self-consistent slip rates on all major active faults in mainland China using a three-dimensional elastic block model and the recently updated GPS data. The slip rates show a sharp contrast between western China (high) and eastern China (low), roughly separated along the 105°E longitude, or the south-north seismic belt. The highest slip rates (>10 mm/yr) are mostly found on faults bounding and within the Tibetan Plateau, reflecting the impact of the ongoing Indo-Asian collision. The faults in northwestern China (the Xinjiang region) have the second highest slip rates (~3–5 mm/yr). The Altai faults show up to 5.4 mm/yr contraction, indicating the far-field effect of the Indo-Asian collision. In contrast, slip rates in eastern China are much lower (<3 mm/yr). The South China block moves as a generally coherent block, and slip rates on major faults in north China vary between 0.5 and 3.0 mm/yr. The spatial pattern of active tectonics delineated by the fault slip rates is generally consistent with the intensity of seismic activity in mainland China.

[as] Using the predicted slip rates and locking depths, we estimated the rates of moment accumulation on major active faults and compared them with seismic moment release on these faults based on the Chinese earthquake catalog. The results show nine major seismic belts with significant moment deficits, including the Altyn Tagh fault, the west Kunlun fault, the Yin Shan fault, and the fault zones in the southern part of the North China block. These predicted moment deficits are only suggestive because of the incomplete earthquake history. Further studies in these regions, especially faults with high moment deficit in north China, are particularly needed because of the large human populations around these fault zones.

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