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Special Section:

100-year Anniversary of the Great 1920 Haiyuan Earthquake: What have We Learnt on Large Continental Earthquakes and Faults?

Key Points:

- The inclusion of secondary active faults in block modeling affords a closer examination of strain partitioning
- The senses of motion and slip rates of active faults predicted by our model are generally in agreement with geologic observations
- Deformation of North Eastern Tibet and its surroundings can be interpreted as the result of relative motions between blocks and block rotations

Supporting Information:

Supporting Information may be found in the online version of this article.

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Tectonic Deformation of the Northeastern Tibetan Plateau and Its Surroundings Revealed With GPS Block Modeling

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Abstract The northeastern Tibetan Plateau and its surroundings are a tectonically complex region resulting from the continuing collision of India with Eurasia. We studied the tectonic deformation of this region using a GPS block model, which was produced using the most recently published, dense, precise, and complete GPS velocities available combined with a detailed fault geometry. The comparison between our preferred model with numerous faults and a model with fewer faults demonstrates the need for inclusion of lesser active faults affords a closer examination of strain partitioning. The predicted senses of motion and slip rates of active faults in our preferred model are consistent with the geological estimates, supporting the assumption that the decadal GPS slip rates are representative of millennial-scale geologic slip rates. The observed fault kinematics in the northeastern Tibetan Plateau and its surroundings can be interpreted as the consequence of relative motions between different blocks and block rotations.

1. Introduction

The northeastern Tibetan Plateau is tectonically complex, resulting from the ongoing India-Eurasia collision and bordered by the rigid Alashan and Ordos blocks in the north and northeast, respectively (e.g., Tapponnier et al., 2001; Zhang et al., 2003; Figure 1). The deformation of the northeastern Tibetan Plateau and its surroundings are characterized by a variety of tectonic settings including strike-slip (e.g., the East Kunlun and Haiyuan faults), contraction (e.g., the Qilian and Liupan Mountains), and extension (e.g., the Yinchuan and Weihe Basins; Figure 1). A great effort has been made in previous studies using the GPS block model to characterize the crustal deformation of the northeastern Tibetan Plateau and its surroundings. Some researchers (e.g., Meade, 2007; Loveless & Meade, 2011; Wang et al., 2011; Zhang et al., 2013; W. Wang et al., 2017; Y.Z. Wang et al., 2017; Y. Li et al., 2018) claim that tectonic deformation in this region is focused primarily on a limited number of major faults, with some deformation absorbed by intra-block strain. These models distribute strain among a small number of fault-bounded blocks. Although there is agreement regarding the geodetically estimated slip rates of major active faults (e.g., the East Kunlun and Haiyuan faults), the kinematics and partitioning of deformation within this region remain poorly understood. For example, how does the northeastward expansion of the Tibetan Plateau affect the kinematics of active faults in and around the northeastern Tibetan Plateau? Is crustal deformation concentrated on a finite number of lithospheric strike-slip faults, or diffusely distributed within the northeastern Tibetan Plateau and its surroundings? What role does the counterclockwise rotation of the Ordos block play in affecting the kinematics of its peripheral active faults? Accurate descriptions of the senses of motion and slip rates of active faults, and modern block rotations are critical for a complete understanding of the tectonic deformation patterns in this region.

In this paper, we present two comparative GPS block models that clarify the importance of the including secondary active faults in the kinematic framework of the northeastern Tibetan Plateau and its surroundings. In our preferred model, the region is divided into 42 blocks separated by 57 active faults (represented by 121 fault segments) using the latest dense and accurate GPS data processed by Wang and Shen (2020) combined with an updated active fault map of China from the Seismic Active Fault Survey Data Center

Figure 1. Fault geometry and kinematics of active faults in the northeastern Tibetan Plateau and its surroundings. Sections of block, basin, mountain, and fault discussed in the text are labeled in alphabetical order: AWCF = Awancang fault; AYF = Ayouqi fault; BNF = Bayannuorigong fault; BSF = Beishan fault; BYB = Bayankhar block; BYF = Bayanwulashan fault; EKLF = East Kunlun fault; ELSF = Elashan fault; GDF = Guangaishan-Dieshan fault; GHB = Gonghe basin; HCB = Hexi Corridor basin; HLF = Huanghe-Lingwu fault; HLSF = Helishan fault; HTB = Hetao basin; HYF = Haiyuan fault; JTSF = Jintananshan fault; JXB = Jiuxi basin; KGF = Kouzhen-Guanshan fault; LJF = Liangdang-Jiangluo fault; LLF = Lixian-Luojiaobao fault; LPF = Liupanshan fault; LPM = Liupanshan mountain; LRBF = Longriba fault; LSPF = Langshan Piedmont fault; LSF = Luoshan fault; LSSF = Longshoushan fault; LTF = Lintan-Tanchang fault; LXB = Linxia basin; LZB = Longzhong basin; MXSF = Maxianshan fault; NQF = North Qinling faults; NQLF = North Qilianshan fault; NSF = Niushoushan fault; QHB = Qinghai basin; QLB = Qinling block; QLM = Qilianshan mountain; QMF = Qishan-Mazhao fault; RYSF = Riyueshan fault; SLF = Shuangquan-Linqi fault; SLPF = South Liupanshan fault; STF = Seertengshan fault; TJSF = Tianjingshan fault; TLSF = Tuolainanshan fault; WHB = Weihe basin; WHF = Weihe fault; WHLF = West Helanshan fault; WHSF = Weinan-Huashan fault; WLSF = Wulashan fault; WQLF = West Qinling fault; WTF = Wuwei-Tianzhu fault; XHB = Xunhua basin; XNB = Xining basin; XRB = Xingren Basin; YBF = Yabrai fault; YCB = Yinchuan basin; YMSF = Yumushan fault; YSB = Yinshan block; ZLHF = Zhuanglanghe fault; and ZZSF = Zhuozishan fault. Blue dots indicate historical earthquakes from Gu et al. (1983) before 1970; Red dots indicates instrumental earthquakes from the National Earthquake Data Center (<http://data.earthquake.cn/index.html>) from 1970 to 2019. Active fault data are from the Seismic Active Fault Survey Data Center (<http://www.activefault-datacenter.cn/>).

(accessed December 2020, <http://www.activefault-datacenter.cn/>). In the other model, the same region consists of 14 blocks bound by 22 active faults (represented by 44 fault segments). First, we estimate the senses of motion, slip rates of active faults, and rotations of active blocks. Based on these results, we compare the discrepancies between these two models and discuss the importance of secondary active faults in block modeling. We then compare the geodetic and geologic slip rates and discuss the utility of our model for estimating fault slip rate. Finally, we characterize the deformation patterns of the northeastern Tibetan Plateau and its surroundings.

2. Tectonic Setting

The northeastern Tibetan Plateau is defined here as the region north of the East Kunlun fault, south of the Alashan block, and west of the Ordos block (Figure 1). The northeastern Tibetan Plateau is cut by a complex system of faults, including the west-northwest-striking East Kunlun, Haiyuan, and West Qinling faults, and the northwest-north-striking Elashan, Riyueshan, and Zhuanglanghe faults. These active faults divide the northeastern Tibetan Plateau into numerous basins, such as the Qinghai, Gonghe, Xining, Xunhua, Linxia, and Longzhong basins (Figure 1). To the north of the Haiyuan fault, a series of sub-parallel, several hundred-kilometer-long, northwest-striking thrust faults have produced a series of tens-of-km-wide intra-mountain basins in the Qilianshan mountains (Wang et al., 2016). To the north of these thrust faults, the continuing northeastward expansion of the Tibetan Plateau has produced the Jiuxi and Hexi corridor basins bounded by the northern Qilianshan fault to the south and the Helishan and Longshoushan faults to the north (Zheng et al., 2013, Figure 1). To the east, the Xingren basin lies between the Haiyuan and Tianjingshan faults. Tectonic deformation primarily occurs on the basin-bounding faults, as evidenced by the along-fault distributions of medium to large ($\geq M_s 5$) earthquakes (Figure 1). Additionally, to the south of the East Kunlun fault is the rigid Bayankhar block with numerous large earthquakes around its margins (e.g., 2001 Kunlun M_s 8.1, 2008 Wenchuan M_s 8.0, and 2010 Yushu M_s 7.1 earthquakes; Deng et al., 2014, Figure 5 therein).

The rigid Alashan blocks are composed of a basement of Precambrian metamorphic rocks (Bureau of Geology and Mineral Resources of Gansu Province, 1989). A series of northwest-striking faults (e.g., the Helishan, Longshoushan, Wuwei-Tianzhu faults) combined with the nearly east-west-striking Tianjingshan fault forms the southern boundary of the Alashan block. To the east, the western Helanshan, Bayanwulashan, and Langshan faults constitute the eastern boundary of the Alashan block. In our model, the Alashan area is divided into two blocks (i.e., the North and South Alashan blocks) by the northeast-striking Ayoubi-Yaburay-Bayinnuorigong fault system (Yu et al., 2016, Figure 1). Most moderate to large earthquakes have occurred along the block-bounding faults, and only a few have happened within the South Alashan block.

The Ordos block forms the western part of the North China Craton with a lithosphere as thick as ~ 200 km (Chen et al., 2009). The rigid block is a seismically quiescent region with little internal deformation (Zhang and Gan, 2008) and tectonic activity mainly occurs along its margins. The Ordos block is surrounded by a series of Cenozoic extensional basins: the Yinchuan basin along its western margin, the Hetao basin along its north margin, and the Weihe basin along its southern margin (Figure 1). In contrast, the southwestern margin of the Ordos block hosts the contractional Liupanshan Mountain. To the north of the Ordos block is the Yinshan block, consisting of late Archean metamorphic rocks (Lu et al., 2008). To the south of the Ordos block is the Qinling orogenic belt, which resulted from the Palaeozoic collision between the North and South China Cratons (Mattauer et al., 1985). The Qinling orogenic belt has been a part of the tectonically stable South China Block since the early Cenozoic, and today, it behaves as a rigid block (Dong et al., 2011; Zhang et al., 2003).

3. Data and Methods

3.1. GPS Data

The GPS velocities used in this study come from multiple sources, including the Crustal Monitoring Observation Network of China collected from 1999 to 2016, and the Second Monitoring Center, China Earthquake Administration collected from 1999 to 2011. The data collection, time series processing, and secular velocity estimation methodologies are described in detail by Wang and Shen (2020). Here, we use a subset of their velocity field including a total of 389 continuous and campaign GPS stations spanning the region from 97.73° – 110.13° E and 33.27° – 41.57° N, which is listed in Table S1 in the supporting information. Considering the impacts of coseismic and postseismic displacements caused by large earthquakes on the GPS sites, Wang and Shen (2020) modeled the coseismic and postseismic deformation using a rigorous data processing algorithm. Details of the processing of the coseismic and postseismic displacements of large earthquakes are described in Section 2.3 of Wang and Shen (2020). Figure 2a displays the GPS velocity field for the northeastern Tibetan Plateau and its surroundings with respect to the fixed Eurasia plate. The error ellipses represent 70% confidence. Overall, the GPS velocity vectors show northeastward motion of stations in

Figure 2. GPS velocity field and regional map showing block model boundaries in relation to the topography of the northeastern Tibetan Plateau and its surroundings. (a) GPS velocity field in the northeastern Tibetan Plateau and its surroundings. The velocity field is relative to stable Eurasia, and the error ellipse indicates 70% confidence. (b) Details of block boundaries defined by active faults (black solid line) and “invented faults” (black dashed lines). Small black number indicates the fault number. Large white number indicates the block number.

the loop (Figure 2). The block models nearly always have some block boundaries that do not align with mapped known traces of active faults. This is because the observed faults are often not visibly connected up into neat and complete block-surrounding structures, they instead often terminate or become difficult to observe through geologic, seismic, geodetic or any other known means. We are left with the problem of designing a model that obeys the basic rules of kinematic consistency while minimally violating the geologic data, and minimally inventing faults to join blocks into contiguous structures that adequately represent the geologic framework. This leads to models where some block boundaries do not explicitly represent named, observed faults, but could still represent zones of accommodation of the crustal deformation.

The quality of the modeling results is also related to the GPS data coverage. In our model, the GPS data cover most blocks in the region (Figure 2a). Only 3 out of 42 blocks (Blocks 10, 11, and 23) lack GPS data. The reason for retaining these three blocks is that their boundaries are well defined by major active faults, and omitting them from the model would result in an overestimation of the slip rate on neighboring faults. The motion of such blocks in the model are estimated through minimization of the slip rates along the boundary of the blocks, resulting in motion that is roughly an average of the surrounding blocks. As we included

the northeastern Tibetan Plateau (in the western part of the study area) and an east-southeastward rotation in the eastern part of the study area. The magnitudes of the velocity vectors gradually decrease from ~20 mm/yr in the southwest to ~3 mm/yr in the eastern part of the study area.

3.2. Block Modeling

Elastic block modeling is a commonly used technique that relates block motions and fault slip rates to interseismic geodetic measurements in a kinematically consistent manner (e.g., Bennett et al., 1996; Bormann et al., 2016; Evans et al., 2015; Hammond et al., 2011; Hammond & Thatcher, 2007; McCaffrey, 2002; McCaffrey et al., 2007; Meade & Hager, 2005; Meade & Loveless, 2009; Prawirodirdjo et al., 1997). In this method, the study region is divided into a mosaic of contiguous, elastic, fault-bounded blocks based on the mapped traces of active faults. The GPS velocities on each block are used to determine an Euler rotation vector that describes the individual block motion, while accounting for the effects of elastic strain accumulation on GPS velocities near the block bounding faults. Block models are kinematically consistent because the slip rate on each fault is determined by projecting the relative motion between neighboring blocks on to the fault plane. Where block boundaries change orientation, fault slip rates, and slip styles change according to the relative block motion. In this study, we construct our block model using the same elastic block-modeling approach as Hammond et al. (2011) and Bormann et al. (2016).

3.3. Block Geometries and Regularization Parameters

The choice of block geometry has a tremendous impact on the estimate of block rotations and fault slip rates. Here, the block boundaries are plotted based on the simplified surface traces of active faults in China from the Seismic Active Fault Survey Data Center (<http://www.activefault-datacenter.cn/>). To better illustrate the fine details of some areas (e.g., the Yinchuan, Hetao, and Weihe basins), we include more active faults than that of previous studies in the northeastern Tibetan Plateau and its surroundings (e.g., Loveless & Meade, 2011; Meade, 2007; Thatcher, 2007; Y. Z. Wang et al., 2017). In the model, we divide the region into 42 blocks that are separated by 121 fault segments (Figure 2b). The fault segments are defined by changes in orientation along the generalized fault surface traces. Some “invented” faults indicated by dashed lines are used to close

Table 1
Model Assumptions and Regularization Parameters

Type	Value
Strike-slip fault dip	60°
Normal fault dip	65°
Thrust fault dip	45°
Lock depth (L)	16 km
Poisson's ratio (ν)	0.25
Shear modulus (μ)	3×10^{10} Pas
Slip rate consistency (α)	1×10^{-4} m/yr
Block centroid vertical axis rotation damping (β)	10×10^{-9} rad/yr
Slip rate damping (γ)	3.2×10^{-3} m/yr

almost all of the known active faults in the northeastern Tibetan Plateau and its surroundings in our preferred model, we do not consider diffuse faulting (i.e., internal strain) in our divided blocks. Also, it is reasonable to assume that the smaller blocks in the interior of the Tibetan Plateau in our block model are rigid. To illustrate that by dividing the northeastern Tibetan Plateau and its surroundings into 42 rigid micro-blocks, the GPS velocities could be reasonably modeled, a comparative block model with fewer blocks (14 blocks bounded by 44 fault segments) was developed roughly following that of Y.Z. Wang et al. (2017), which divided the same region into many blocks when compared to other previous works.

Apart from the aforementioned block geometry and GPS data coverage, the model is also constrained by a series of parameters (Table 1). Here, all the faults are assumed to have the same locking depth, and an optimal uniform locking depth of 16 km is found based on the trade-off of fault locking depth as a function of root mean square (RMS) error (Figure 3a).

The estimated locking depth is generally consistent with the average focal depth of 16 ± 7 km and 18 ± 8 km of earthquakes ($M_L \geq 2$) in mainland and western China, respectively (Zhang et al., 2002). The resulting optimal locking depth in our model is also in agreement with those determined from previous block models (16 km, Loveless & Meade, 2011; 15 km, W. Wang et al., 2017). Based on the analysis of dips of different types of faults versus RMS, we calculated the optimal dip angle to be 60°, 65°, and 45° for strike-slip, normal, and thrust faults, respectively (Figure 3b). Increasing the dip angle of normal faults, as in Figure 3b, does not significantly change the RMS compared to strike-slip and

Figure 3. Optimal fault locking depth, dip angles, and regularization parameters in block modeling. (a) Velocity misfit RMS as a function of depth. (b) Velocity misfit RMS as a function of dip angle for strike-slip, normal, and thrust faults. (c) Value of model misfit (left vertical axis) and value of model spin rate norm (right vertical axis) as a function of vertical axis damping parameter β . (d) Value of model misfit (left vertical axis) and value of model slip rate norm (right vertical axis) as a function of slip rate damping parameter γ . RMS, root mean square.

thrust faults, consistent with the predominance of shear and compressional strain in this region (Wang and Shen, 2020).

In our block model, we regularize the weighted least squares inversion by introducing three types of parameters to simultaneously solve for the long-term block motion and the strike-slip and dip-slip components of fault slip using the methodology of Hammond et al. (2011). The first regularization constraint (α) enforces the consistency between relative block motions and fault slip rates. This condition is strictly enforced in all models, with an a priori uncertainty of 10^{-4} m/yr. The second and third types of regularization constraints minimize the block centroid vertical axis rotations (spin rates) and fault slip rates, forcing deformation patterns within the model to vary smoothly. The two stochastic damping parameters β and γ represent the prior uncertainties in the condition that minimizes the block spin rate and the fault slip rate, respectively. When β and γ values are very small, the block spin and fault slip rates are forced to be zero, causing a large misfit to the GPS data. When these conditions are relaxed by using slightly larger values of β and γ , the block spin and fault slip rates are minimized, while still allowing the GPS data to be fit. We select preferred values β and γ through a grid search approach that finds a balance between a low model misfit to the data and minimum slip rate and spin rate norms (Hammond et al. 2011). The optimal values of β and γ are listed in Table 1 and shown in Figures 3c and 3d.

4. Results

4.1. Fault Slip Rates

The senses of motion and slip rates of active faults in the northeastern Tibetan Plateau and its surroundings predicted by our preferred GPS block model (Table 2 and Table S2 in the supporting information; Figure 4a) are generally consistent with the previous geological observations. As shown in Figure 4a, our results suggest that most of the left-lateral shear strain is concentrated along the west-northwest-striking East Kunlun and Haiyuan faults. The modeled slip rates of the East Kunlun fault are 9.3 ± 1.0 , 8.0 ± 0.5 , and 4.3 ± 0.8 mm/yr along the Tuosu Lake, Maqin, and Maqu segments, respectively, which agree with the geological slip rates 8.9–10.9, 7.4 ± 0.8 , 4.5 ± 0.5 mm/yr (Kirby et al., 2007; Li et al., 2011; Van der Woerd et al., 2002). The modeled slip rate along the primary segments of the Haiyuan fault is 5.4 ± 0.4 mm/yr, consistent with the geologic slip rates of 4.5 ± 1.0 mm/yr (Li et al., 2009). To the north of the Haiyuan fault, the model predicts 1.5 ± 0.4 mm/yr of left-lateral slip on the Tianjingshan fault, in agreement with the geological constraint of 1.1 ± 0.2 mm/yr (Li, Li, et al., 2019). The modeled left-lateral slip rate on the West Qinling fault is 2.5 ± 0.3 mm/yr, decreasing to 1.1 ± 0.4 mm/yr to the east, consistent with geologic rates decreasing eastward from 2.3 ± 0.2 to 1.2 ± 0.2 mm/yr (Wu, 2016).

The northwest-north-striking Elashan and Riyueshan faults slip right-laterally at modeled rates of 1.7 ± 0.8 and 2.5 ± 0.5 mm/yr, respectively (Figure 4a), which are comparable to the geological slip rates of 1.1 ± 0.3 and 1.2 ± 0.4 mm/yr for the Elashan and Riyueshan faults (Yuan et al., 2011). To the north of the Haiyuan fault, contractional rates are modeled across the North Qilianshan (1.5 ± 0.7 mm/yr), Yumushan (1.6 ± 0.7 mm/yr), Wuwei-Tianzhu (2.6 ± 0.4 mm/yr), Jintananshan (0.9 ± 0.5 mm/yr), and Helishan (0.4 ± 0.4 mm/yr) faults, which are comparable with the geologic contractional rates (Champagnac et al., 2010; Liu et al., 2017; Palumbo et al., 2009; Wen et al., 2015; Zheng et al., 2013; Table 2).

The predicted left-lateral slip rate on the Yabrai fault within the Alashan block is 1.5 ± 0.3 mm/yr, almost consistent with the geologic slip rate of 0.2–0.8 mm/yr (Yu et al., 2016). Left-lateral and contractional rates on the Bayannuorigong fault are estimated at 1.4 ± 0.3 and 1.0 ± 0.3 mm/yr, respectively.

To the west of the Ordos block, right-lateral and extensional rates are predicted on the Langshan Piedmont (0.2 ± 0.4 and 0.3 ± 0.4 mm/yr), Zhuozishan (0.9 ± 0.3 and 0.7 ± 0.3 mm/yr), East Helanshan (0.3 ± 1.3 and 0.2 ± 0.7 mm/yr), Huanghe-Lingwu (1.0 ± 0.5 and 0.4 ± 0.8 mm/yr), and Luoshan (2.5 ± 0.7 and 0.5 ± 0.8 mm/yr) faults, consistent with the geological estimates (Lei et al., 2016; Liang et al., 2019; Middleton et al., 2016; Min et al., 2003; Rao et al., 2018). At the northern margin of the Ordos block, the right-lateral and extensional rates (0.4 ± 0.5 and 0.1 ± 0.3 mm/yr) are determined for the North Ordos fault. At the south margin of the Ordos block, the right-lateral and extensional rates are estimated on the basin-bounding Beishan (0.4 ± 0.4 and 0.4 ± 0.5 mm/yr), Kouzhen-Guanshan (0.2 ± 0.4 and 0.6 ± 0.3 mm/yr), and Shuangquan-Linqi (0.4 ± 0.4 and 0.6 ± 0.4 mm/yr) faults, which are generally in agreement with

Figure 4. Senses of motion, slip rates, block rotations, and residuals estimated from our preferred model with more faults and the comparative model with fewer faults. (a)–(a') Predicted senses of motion and slip rates of active faults. Thickness of red (black) line indicates left-lateral (right-lateral) slip rate. Length of fault-normal cyan (blue) line indicates contractional (extensional) rate. (b)–(b') Rigid block rotation and motion exaggerated by a factor of 10^7 representing 10 million years of deformation. Color of the block indicates the vertical axis rotation rate. (c)–(c') Residual GPS velocities (black arrows) after subtracting the model predictions. The colored surface represents an interpolation of the residual magnitude, with cold colors indicating the regions of smallest misfit.

the long-term geologic slip rates (Lin et al., 2015; Rao et al., 2014; Seismological Bureau of Shaanxi Province, 1996; Xu et al., 1988). In contrast, the Seertengshan and North Qinling faults that are located to the north and south of the Ordos block slip left-laterally with normal components at rates of $(1.1 \pm 0.4$ and 0.5 ± 0.4 mm/yr) and $(0.5 \pm 0.8$ and 1.3 ± 0.7 mm/yr), consistent with the geologic estimates (Seismological Bureau of Shanxi Province, 1996; Yang et al., 2002).

4.2. Block Motions and Rotations

Block motions (Euler pole rotations) and vertical-axis, or block spin rotations predicted by our block model (Figure 4b) show that (1) blocks in the northeastern Tibetan Plateau and its surroundings move eastward overall, with rates decreasing from south to north with respect to the stable Eurasian plate, (2) blocks in the eastern part of the northeastern Tibetan Plateau rotate clockwise about a vertical axis, in contrast to the counterclockwise rotations of some blocks in the western part of the northeastern Tibetan Plateau, (3) the

Table 2
Comparison of GPS Slip Rates With Geologic Slip Rates

Fault code	Fault segment number	Fault name	Abbr.	GPS rate		Geologic rate		Reference ^c
				Strike-slip ^a	Contractional ^b	Strike-slip	Contractional	
1-1	1	East Kunlun Fault	EKLF	9.3 ± 0.6		8.9–10.9		Van der Woerd et al., 2002
1-2	3			8.0 ± 0.5		7.4 ± 0.8		Li, Xu, et al., 2011
1-3	4			4.3 ± 0.8		4.5 ± 0.5		Kirby et al., 2007
2	8	Guanggaishan-Dieshan Fault	GDF		0.5 ± 0.9		0.3–0.8	Yu et al., 2012 ^c
3	23	West Qinling Fault	WQLF	2.5 ± 0.3		2.2 ± 0.2		Wu., 2016
4	45	Haiyuan Fault	HYF	5.4 ± 0.4		4.5 ± 1.0		Li et al., 2009
5	48	South Liupanshan Fault	SLPF	1.1 ± 0.2		1.5 ± 0.3		Li, Feng, et al., 2019
6	50	Tianjingshan Fault	TJSF	1.5 ± 0.3		1.1 ± 0.2		Li, Li, et al., 2019
7	57	Elashan Fault	ELSF	−1.7 ± 0.8		−1.1 ± 0.3		Yuan et al., 2011
8	60	Riyueshan Fault	RYSF	−2.5 ± 0.5		−1.2 ± 0.4		Yuan et al., 2011
9	70	North Qilianshan Fault	NQLF		1.5 ± 0.7		1.3 ± 0.3	Liu et al., 2017
10	75	Wuwei-Tianzhu Fault	WTF		2.6 ± 0.4		2.5 ± 0.8	Champagnac et al., 2010
11	76	Yumushan Fault	YMSF		1.6 ± 0.7		0.5–0.8	Palumbo et al., 2009 ^c
12	79	Jintananshan Fault	JTSF		0.9 ± 0.5		0.6–0.8	Wen et al., 2015
13	80	Helishan Fault	HLSF		0.4 ± 0.4		0.2–0.5	Zheng et al., 2013
14	81	Ayouqi Fault	AYQF	0.7 ± 0.6		0.1–0.9		Yu et al., 2017
15	83	Yabrai Fault	YBF	1.5 ± 0.3		0.2–0.8		Yu et al., 2016
16	90	Zhuozishan Fault	ZZSF		−0.7 ± 0.3		−(0.4–0.8)	Liang et al., 2019 ^c
17	94	Seertengshan Fault	STF		−0.5 ± 0.3		−(0.4–0.7)	Yang et al., 2002 ^c
18	95	Langshan Piedmont Fault	LSPF		−0.3 ± 0.4		−(0.4–0.7)	Rao et al., 2018
19	98	West Helanshan Fault	WHLF	−2.2 ± 1.2		−1.4 ± 0.1		J. H. Lei, 2015
20	99	East Helanshan Fault	EHLF		−0.2 ± 0.7		−0.7 ± 0.1	Middleton et al., 2016
21	102	Huanghe-Lingwu Fault	HLF		−0.4 ± 0.8		−(0.2–0.3)	Liao et al., 2000 ^c
22	103	Luoshan Fault	LSF	−2.5 ± 0.7		−2.2 ± 0.2		Min et al., 2003
23	105	Niushoushan Fault	NSSF	−1.1 ± 1.0		−0.4 ± 0.1		Lei et al., 2016
24	108	Qishan-Mazhao Fault	QMF	0.2 ± 0.5		0.5–1.0		X. Li et al., 2018
25	111	Beishan Fault	BSF		−0.4 ± 0.5		−(0.2–0.4)	Lin et al., 2015 ^c
26	112	Kouzhen-Guanshan Fault	KGF		−0.6 ± 0.3		−(0.1–0.3)	Xu et al., 1988 ^c
27	113	Shuangquan-Linyi Fault	SLF		−0.6 ± 0.4		−(0.3–0.5)	Xu et al., 1988 ^c
28	116	Weinan-Huashan Fault	WHPF		−0.5 ± 0.5		−(1.0–1.2)	Rao et al., 2015 ^c
29	119	North Qinling Fault	NQF		−1.3 ± 0.7		−(0.7–1.1)	SBSP, 1996 ^c

^aPostive value indicates left-lateral slip rate. ^bPostive value indicates contractional rate. ^cContractional or extensional rate corrected based on vertical slip rate combined with fault dip.

South Alashan block shows no apparent rotation relative to the stable Eurasian plate, but the North Alashan block rotates clockwise at $0.22 \pm 0.02^\circ/\text{Myr}$ with an Euler pole located at (78.1°E , 32.3°N), and (4) the Ordos block has a counterclockwise rotation at a rate of $0.25 \pm 0.01^\circ/\text{Myr}$ with a Euler pole located at (116.0°E , 48.2°N). The vertical-axis rotation rates of blocks in the northeastern Tibetan Plateau and its surroundings are listed in Table S3 in the supporting information.

Figure 5. Histograms of residuals and normalized residuals for east and north component, respectively. (a)–(c) Histograms of residuals and normalized residuals for east and north component of our optimal block model with numerous faults. (a')–(c') Histograms of residuals and normalized residuals for east and north component of the comparative block model with fewer faults.

4.3. GPS Data Misfit

Overall, our block model yields a fit to the GPS data with a small residual root mean square misfit in east (north) velocity of 0.62 (0.49) mm/yr. The normalized residual root mean square (NRMS) misfit is 1.84 (1.40) mm/yr in the east (north) component (Figure 5). The value of χ^2 per degree of freedom is determined to be 3.2, which is associated with the number of blocks. The larger the number of blocks included in the model, the number of model parameters increases and the χ^2 per degree of freedom decreases. The residual GPS velocities of our preferred model are randomly oriented as shown in Figure 4c. Most of the residual GPS velocities are less than 1 mm/yr only except for a few that located in the southwestern part of the region.

5. Discussion

5.1. Importance of Inclusion of Secondary Active Faults in Block Modeling

We compare our preferred block model having numerous faults to a model with fewer faults as shown in Figure 4a'–4c' and Figure 5a'–5d'. A significant discrepancy between these two models is that the left-lateral

Figure 6. Comparison of predicted GPS slip rates with geologic slip rates. See Table 2 for references to numbers and see text for detail. Black line indicates the linear fit depicting the relationship between the GPS and geologic slip rates. The confidence bands and prediction bands represent the uncertainties in the regression analysis.

slip rate on the East Kunlun fault is constant at a rate of 7.3 ± 0.8 mm/yr estimated from the comparative model with fewer faults (Figure 4a). It differs from the pattern of eastward decrease in slip rate as shown in our preferred model with more faults as well as that observed by previous studies (Kirby et al., 2007; Li et al., 2011; Van der Woerd et al., 2002). The reason of the discrepancy is that the secondary active faults (i.e., Awancang and Longriba faults) partitioning the left-lateral slip of the East Kunlun fault are not included in the comparative model with fewer faults. Additionally, right-lateral slip along the inner ring of the Ordos block cannot be seen in the second model, which is important for understanding the kinematic deformation pattern around the perimeter of the Ordos block.

The velocity residuals for the comparative model with fewer faults are generally larger than that of the preferred model with numerous faults (Figure 3c–3c'). The warm color located at the eastern termination of the East Kunlun fault in the model with fewer faults indicates great misfit between the model prediction and observed data, probably due to the lack of secondary active faults on both sides of the East Kunlun fault. The region of the Yinchuan Basin to the west of the Ordos block in the model with fewer faults also misfits the GPS data in comparison with our preferred model with more faults. The reason for this misfit may be related to the diffuse faulting at the margin of the redivided so-called rigid Ordos block, actually contains many secondary active faults. Besides, the RMS misfit in east (north) velocity of 0.77 (0.61) mm/yr and the normalized

RMS misfit east (north) velocity of 2.31 (1.87) calculated in the comparative model with fewer faults are apparently larger than those estimated from our preferred model with more faults (Figure 5). Therefore, we conclude that by including more blocks in the model, GPS velocities could be reasonably modeled. Besides, the advantage of more blocks in the model is to discuss the strain partitioning among numerous secondary active faults in the northeastern Tibetan Plateau and its surroundings.

5.2. GPS Versus Geological Slip Rates

Overall, the predicted slip rates of active faults in our block model are consistent with the geologically recorded fault slip rates as listed in Table 2 and shown in Figure 6. A linear regression through all the available data points (i.e., 31 GPS/geologic slip rate pairs) yields a Pearson correlation coefficient (Pearson's r value) of 0.98 and a coefficient of determination (R^2 value) of 0.97, suggesting a near-perfect positive relationship between the GPS and geologic slip rates. Therefore, the consistency between GPS and geologic slip rates in our preferred model supports the assumption that the decadal GPS slip rates are representative of the late Quaternary slip rates at time scales of thousands of years (Mohadjer et al., 2017). Potential reasons for the agreement between the GPS and geologic slip rates may include, but may not be limited to, (1) fault slip rates have remained constant since the late Quaternary (e.g., Chevalier et al., 2018; Hetzel et al., 2019; Li, Li, et al., 2019), (2) deformation is mainly concentrated on the block-bounding faults with negligible strain within the blocks (Xu et al., 2008), (3) postseismic deformation has little or no impact on the geodetically estimated fault slip rates as no large earthquakes ($M_s > 6.7$) occurred in this region during the past 25 years of GPS observations (National Earthquake Data Center, <http://data.earthquake.cn/index.html>).

Though generally the GPS and geologic slip rates match well, GPS slip rates of individual faults are not always as representative of those estimated by Quaternary methods. For example, the GPS slip rate 2.5 ± 0.5 mm/yr of the Riyueshan fault (fault code 8) is a factor of ~ 2 larger than the geologic slip rate 1.2 ± 0.4 mm/yr. In contrast, the geologic slip rate 0.5–1.0 mm/yr of the Qishan-Mazhao fault (fault code 24) is ~ 2 –5 times the GPS rate 0.2 ± 0.5 mm/yr. One reason for the mismatches is that the slip rates are small enough that a slight variation (~ 0.2 mm/yr) may cause a significant difference between the GPS and geologic slip rates. If considering the errors, the GPS and geologic slip rates are actually of the same order and are comparable with each other. Many other important factors also contribute to the discrepancies of

slip rates for individual faults. First, the GPS results are sensitive to the fault geometry, number of blocks, and GPS station density within each block in the block model, which may highly influence the correlation between GPS and geologic slip rates (Thatcher et al., 2009). Second, the GPS-measured present-day strain includes transient (elastic and some viscous) and permanent (plastic) components, whereas only permanent strain is kept in geological records, so the present-day strain rates can differ from those from geological observations (Meade & Hager, 2005). Third, the geologic slip rate largely depends on the reliability of offset measurements and geochronological data, as well as the choice of an upper or lower terrace reconstruction (Cowgill, 2007). Fourth, sometimes only vertical slip rates were determined by previous geological studies, which cannot be directly compared with the contractional/extensional rates derived by the GPS methods. The conversion from vertical slip rates to contractional/extensional rates relies on an assumption of fault dip, uncertainty of which may result in the discrepancy between the GPS and geologic slip rates. In sum, though a variety of uncertainties may influence the correlation between the GPS and geologic slip rates, a general agreement between the GPS and geologic slip rates supports the utility of our preferred model for estimating fault slip rate.

5.3. Tectonic Deformation Pattern

The predicted senses of motion and slip rates of active faults, and block motion and rotations in our preferred block model provide constraints on understanding the deformation pattern in the northeastern Tibetan Plateau and its surroundings. The left-lateral motion on the East Kunlun and Haiyuan faults is a result of the relative eastward motion between different blocks (Figure 4b). The observed eastward decrease in slip rate on the East Kunlun fault is a result of the partitioning of slip by the Awancang and Longriba faults, branches of the East Kunlun fault (Li et al., 2016; Figure 4a). The west-northwest-striking active faults (i.e., the Lintan-Tanchang and Guanggaishan-Dieshan faults) located between the East Kunlun and West Qinling faults also accommodate left-lateral slip, likely a result of a combination of the relative motions between different blocks and systematic clockwise vertical-axis block rotations (Figures 7a–7c). The right-lateral slip on the Elashan and Riyueshan faults is mainly due to the northward motion of the western blocks relative to the eastern blocks, and is partially a result of the systematic counterclockwise vertical-axis rotations in this region (Figure 7d). To the east of the Riyueshan fault, the northwest-north-striking Zhuanglanghe fault also slips right-laterally, due to the difference in rates of northward motion between blocks on either side of the fault.

The predicted senses of along- and normal-strike partitioning of motion on active faults within the Alashan block agree with the geological observations (Yu et al., 2016, Figure 7e). In particular, the Yabrai fault is dominated by left-lateral slip with a normal component in the central segment of the range front, but with thrust faulting on its westerly fault segment (Figure 3a). The relative northeastward motion of the South Alashan block relative to the North Alashan block contributes to the left-lateral slip along the Yabrai and Bayannuorigong faults (Figures 4f and 4g). Additionally, the releasing stepover along the Yabrai fault accommodates normal slip as a result of the relative motion between the South and North Alashan blocks. Clockwise rotation ($0.22 \pm 0.02^\circ/\text{Myr}$) of the North Alashan block with a Euler pole located at (78.1°E , 32.3°N) also contributes to the contractional deformation across the Bayannuorigong fault. Similarly, the northeastward motion of the South Alashan block relative to the Helanshan Mountain to the east (Figure 7h) results in right-lateral slip on the West Helanshan fault, which is the eastern margin of the Alashan block.

Most of the active faults around the Ordos block are characterized by right-lateral and normal slip (Figure 3a), which may be related to the counterclockwise rotation of the Ordos block (Figure 7k). In contrast to the right-lateral slip on most active faults along the inner ring of the Ordos block, the Seertengshan and North Qinling faults slip left-laterally, which are located to the north and south of the Ordos block, respectively (Figure 7i). The reason for left-lateral slip on the Seertengshan fault is that the Ordos block moves eastward relative to the Yinshan block to the north. Similarly, the left-lateral slip on the north Qinling fault is due to eastward motion of the Qinling block with respect to the Ordos block (Figures 7j and 7k). At the southwest margin of the Ordos block, the Liupanshan fault is characterized by not only contraction but also by left-lateral slip (Figure 7i). The predicted senses of motion of the South Liupanshan and Qishan-Mazhao faults are consistent with the deformation pattern proposed by X. Li et al. (2018), where

Figure 7. Fault geometry, kinematics, and simplified models showing the accommodation of tectonic deformation in the northeastern Tibetan Plateau and its surroundings. (a) Geometry and kinematics of active faults in the northeastern Tibetan Plateau. Black arrow indicates the regional principal stress direction. EKLK = East Kunlun fault; HYF = Haiyuan fault; ELSF = Elashan fault; RYSF = Riyueshan fault; ZLHF = Zhanglanghe fault; WQLF = West Qinling fault; LTF = Lintan-Tanchang fault; GDF = Guangaishan-Dieshan fault. (b) Block rotations (see Figure 2 for the sense of rotation) and (c)–(d) conceptualized sketch showing how left-lateral slip on west-northwest striking faults and right-lateral slip on northwest-north striking faults accommodate the deformation resulting from relative motion between different blocks and block rotations. (e) Fault geometry and kinematics of the Alashan block and its surroundings. AYBF = Ayouqi-Yabrai-Bayannuorigong fault system; WHLF = Western Helanshan fault. (f) Block rotations and (g)–(h) simplified sketches showing how block-bounding faults accommodate deformation resulting from the relative motion between different blocks and block rotations. HLSB = Helanshan block. (i) Fault geometry and kinematics of faults around the Ordos block. LPF = Liupanshan fault; NQF = North Qinling fault; QMF = Qishan-Mazhao fault; STF = Seertengshan fault; TJSF = Tianjingshan fault. (j) Block rotations and (k) simplified sketches showing how sinistral shear to the north and south of the Ordos block and the push on its southwest margin from the Tibetan Plateau result in the counterclockwise rotation of the Ordos block. QLB = Qinling block; YSB = Yinshan block.

most of the left-lateral slip of the Haiyuan fault is accommodated by contraction across the Liupanshan Mountains, and the remaining part is transferred through the South Liupanshan fault to the subparallel Qishan-Mazhao fault. In sum, we speculate that the observed kinematic deformation pattern around the Ordos block is a result of a combination of the sinistral shear to the south and north of the Ordos block and the push on its southwest margin from the Tibetan Plateau (Middleton et al., 2016; Xu & Ma, 1992; Zhang et al., 1998).

6. Conclusions

We determine the fault slip rates, block rotations, and kinematic deformation pattern in the northeastern Tibetan Plateau and its surroundings using an elastic block model with numerous blocks and faults. In comparison with a model with fewer faults, our preferred model with more faults better predicts the senses of motion and slip rates of active faults. Thus, we suggest that by including more blocks in the model, GPS velocities could be reasonably modeled. Besides, the advantage of more blocks in the model is to afford a closer examination of strain partitioning. The predicted slip rates of active faults from our preferred model are generally in agreement with geologic observations, supporting the assumption that slip rates estimated using decadal scale GPS velocities are representative of the late Quaternary slip rates estimated geologically.

Our model demonstrates that the observed fault kinematics can be attributed to the relative motions between different blocks and block rotations. The eastward decrease in slip rate on the East Kunlun fault is a result of the partitioning of slip by the Awancang and Longriba faults being branches of the East Kunlun fault. In the northeastern Tibetan Plateau, differences in rates of eastward motion between blocks results in left-lateral slip on the west-northwest-striking faults. Similarly, differences in rates of northward motion of blocks contributes to the right-lateral slip on the northwest-north-striking faults. The relative northeastward motion of the South Alashan block relative to the North Alashan block contributes to the left-lateral slip along the Yabrai and Bayannurong faults. Fault kinematics around the Ordos block suggest that the counterclockwise rotation of the Ordos block may be a result of a combination of the sinistral shear on its north and south margins and the push on its southwest margin from the Tibetan Plateau.

Data Availability Statement

No new data are used in this work. The GPS data displayed in Figure 2a are available through Wang and Shen (2020) and are listed in Table S1 of the supporting information.

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