Crustal strain rates of southeastern Tibetan Plateau derived from GPS measurements and implications to lithospheric deformation of the Shan-Thai terrane

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Abstract: The link between the crustal deformation and mantle kinematics in the Tibetan Plateau has been well known thanks to dense GPS measurements and the relatively detailed anisotropy structure of the lithospheric mantle. However, whether the crust deforms coherently with the upper mantle in the Shan-Thai terrane (also known as the Shan-Thai block) remains unclear. In this study, we investigate the deformation patterns through strain rate tensors in the southeastern Tibetan Plateau derived from the latest GPS measurements and find that in the Shan-Thai terrane the upper crust may be coupled with the lower crust and the upper mantle. The GPS-derived strain rate tensors are in agreement with the slipping patterns and rates of major strike-slip faults in the region. The most prominent shear zone, whose shear strain rates are larger than $100 \times 10^{-9}$ a$^{-1}$, is about 1000-km-long in the west, trending northward along Sagaing fault to the Eastern Himalayan Syntaxis in the north, with maximum rate of compressive strain up to $-240 \times 10^{-9}$ a$^{-1}$. A secondary shear zone along the Anninghe-Xiaojiang Fault in the east shows segmented shear zones near several conjunctions. While the strain rate along RRF is relatively low due to the low slip rate and low seismicity there, in Lijiang and Tengchong several local shear zones are present under an extensional dominated stress regime that is related to normal faulting earthquakes and volcanism, respectively. Furthermore, by comparing GPS-derived strain rate tensors with earthquake focal mechanisms, we find that 75.8% (100 out of 132) of the earthquakes $T$-axes are consistent with the GPS-derived strain rates. Moreover, we find that the Fast Velocity Direction (FVDs) at three depths beneath the Shan-Thai terrane are consistent with extensional strain rate with gradually increasing angular differences, which are likely resulting from the basal shear forces induced by asthenospheric flow associated with the oblique subduction of the India plate beneath the Shan-Thai terrane. Therefore, in this region the upper crust deformation may be coherent with that of the lower crust and the lithospheric mantle.

Keywords: strain rate tensor; GPS measurement; lithospheric deformation; southeastern Tibetan Plateau; Shan-Thai terrane

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1. Introduction

The Tibetan Plateau, the highest in the world, has been created by the ongoing convergence of the India and Eurasia plates since ~50 Ma ago, through deformation processes at all depths from surface to the uppermost mantle (Yin A and Harrison, 2000). The deformation and the growth of the Tibetan Plateau are characterized by coeval crustal thickening to twice normal thickness (~70 km), and north-south shortening across a series of orogenic belts from the Himalayas to the south to Tianshan Mountain to the north, as well as crustal extrusion along large-scale strike-slip faults (e.g., Tapponnier et al., 1982, 2001; Yin A and Harrison, 2000).

The crustal extrusion in the southeast Tibetan Plateau, revealed from present-day GPS velocity field in Eurasia-fixed reference frame, is predominantly clockwise rotation around the eastern Himalayan Syntaxis (EHS) (e.g., Wang Q et al., 2001; Zhang PZ et al., 2004; Gan WJ et al., 2007; Liang SM et al., 2013). Such surface deformation is highly correlated with large-scale lateral strike-slip faults (Tapponnier et al., 2001), topography (Royden et al., 1997) and orientations of maximum shear stress (Huchon et al., 1994) as well as fast polarization directions of upper mantle anisotropy (e.g., Sol et al., 2007; Wang CY et al., 2008; Chang LJ et al., 2015). According to the consistency among these various measurements, many researchers have suggested that, beneath the central Tibetan Plateau and most of southeastern margin, the deformation of the underlying mantle seems to be coupled with the crust and surface (Wang CY et al., 2008; Chang LJ et al., 2015; Sol et al., 2007). Furthermore, the lower crustal flow (e.g., Royden et al., 1997; Bai DH et al., 2010) may be compatible with coupling due to the deformable boundaries along strike-slip faults (Bendick and Flesch, 2007). As a result, lithospheric material may coherently extrude eastward to the north of EHS, southward to the east of it, and southwestward to the further south region across the
the northernmost section of the Indochina block is decoupled due to the large difference in the directions between crustal and mantle observations. Though the seismic anisotropy measurements provide constraints on deep deformation, such discrepancies may be partially due to the lack of constraints on the entire crustal deformation. Recently, based on 3D P-wave tomography images, Wei W et al. (2016) found that the FVDs are dominantly in the NW-SE direction at depths of 60–150 km beneath the West Yunnan and Shan-Thai terranes, providing direct constraints to the deep deformation in this area.

In this study, we will investigate with the latest GPS measurements (Liang SM et al., 2013; Wang W et al., 2017) and FVDs (Wei W et al., 2016) whether the upper crust of Shan-Thai terrane is coupled with its lower crust and upper mantle. For this purpose, we first calculate strain rate tensors derived from the GPS-measured velocity field, and then compare them with both earthquake focal mechanisms and FVDs at depths of 60 km, 100 km, and 150 km measured by Wei W et al. (2016). Finally, we discuss whether the spatial pattern of the GPS-derived strain tensor is consistent with both the T-axes of earthquakes in the crust and the FVDs in both the lower crust and the upper mantle.

2. Tectonic Settings

The Shan-Thai Terrane—hereafter the Shan-Thai Block (STB)—is located in the southeastern Tibetan Plateau, adjacent to the South Yunnan Block on its east, and to the Myanmar Block along the Sagaing fault and the Gaoligong shear zone to its west, with the

Red River fault, as shown from GPS measurements (Figure 1b) (e.g., Wang Q et al., 2001; Gan WJ et al., 2007; Liang SM et al., 2013; Wang W et al., 2017).

Despite the coherent lithospheric deformation within the main plateau, numerous studies have revealed that a transition zone from coupling to decoupling modes exists approximately in the region between 26°N and 27°N (e.g., Lev et al., 2006; Sol et al., 2007; Wang CY et al., 2008; Shi YT et al., 2012); south of this region, the fast polarization directions of XKS phase waves resulting from the upper mantle anisotropy change to nearly the EW-direction, inconsistent with the clockwise rotation of the surface velocity and active faults that trend westward to Myanmar and perpendicular to the Sagaing fault to the west. Furthermore, the fast polarization orientations of shear waves in the crust are predominantly in the north-south direction (Shi YT et al., 2012), suggesting different deformation styles and mechanisms between the crust and the upper mantle.

In the region further to the south, such as the Shan-Thai and Indochina terranes, it remains controversial whether the crust deforms coherently with the upper mantle. For example, Bai L et al. (2010) suggested that the crust and upper mantle are coupled in the northern Indochina block because the Fast Polarization Directions (FPDs) are almost parallel to the surface displacement and the absolute plate motion; Chen Y et al. (2013), however, argued that the deformation between the crust and upper mantle within the northernmost section of the Indochina block is decoupled due to the large difference in the directions between crustal and mantle observations. Though the seismic anisotropy measurements provide constraints on deep deformation, such discrepancies may be partially due to the lack of constraints on the entire crustal deformation. Recently, based on 3D P-wave tomography images, Wei W et al. (2016) found that the FVDs are dominantly in the NW-SE direction at depths of 60–150 km beneath the West Yunnan and Shan-Thai terranes, providing direct constraints to the deep deformation in this area.

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Indochina Block along the Dien Bien Phu fault to its southeast (Shi XH et al., 2018; Li SH et al., 2017).

In the early stages of the India-Eurasia post-collision at ~50–23 Ma, the STB and the Indochina block underwent coeval clockwise rotation of 20° and southward extrusion of ~600 km along SF to the west and RRF to the east, slipping left-lateral at this period (Li SH et al., 2017; Tanaka et al., 2008). Thus, the stress pattern was dominated by a nearly north-south compression (Huchon et al., 1994). As the India plate continuously indented beneath EHS in the Miocene-Pliocene, the lower crustal flow within the Tibetan Plateau was initiated, and the WSB and CYB to the north of RRF began to extrude, resulting in the transition of RRF to right-lateral deformation (Tapponnier et al., 1982, 2001). To the west, though the Sagaing fault accommodates most of the right-lateral slip of India past Indochina, the oblique subduction of the India plate would result in basal traction and internal deformation within the Shan block (Vigny et al., 2003; Rangin et al., 2013). Furthermore, the extensional stress owing to the pull of the Sunda trench may also affect the deformation of the Shan block (Simons et al., 2007).

As a result, conjugate active strike-slip faults of distinct trends formed in the Shan-Thai block, i.e., the NE-trending sinistral-slip faults and the NW-trending dextral-slip faults. These faults straddle neighboring regions of China, Myanmar, Thailand, Laos, and Vietnam. The geological slip rates on these faults are relatively poorly determined due to the large dating uncertainty (Shi XH et al., 2018). Though the dextral-slip faults dominate the areas adjacent to the large-scale Sagaing and Red River faults, they are shorter and narrower than their sinistral counterparts. In contrast, GPS velocity field data (e.g., Liang SM et al., 2013; Wang W et al., 2017) show that the extruding Tibetan crust rotates around the Eastern Himalayan Syntaxis, causing southward to southwestward velocities toward the Shan-Thai block through these sinistral faults.

3. Data and Method
Since the late 1990s, a national GPS network, Crustal Movement Observation Network of China (CMONOC), has been implemented in China in order to quantify crustal deformation and assess seismic risk. The network has extended since 2009 to a total of ~2000 campaign-mode and 260 continuous GPS stations (CMONOC II) covering the Chinese mainland (e.g., Wang Q et al., 2001; Liang SM et al., 2013). Based on the CMONOC network, many researchers have obtained horizontal velocity fields around the Tibetan Plateau (e.g., Shen ZK et al., 2005; Zhang PZ et al., 2004; Gan WJ et al., 2007; Liang SM et al., 2013; Wang W et al., 2017), providing direct description of the deformation field of this plate boundary zone and critical constraints on the long-term crustal deformation and tectonic processes in continents.

Although these previous GPS velocity fields cover most of the southeastern margin of the Tibetan Plateau, the coverage is relatively sparse in regions to the west of Yunnan province, especially in the Shan plateau located to the east of Sagaing fault (Figure 1b). In order to obtain more accurate strain rate tensors in this region, we combine part of the latest velocity field by Wang W et al. (2017) with several previous published GPS measurements in the adjacent tectonic units, including the East Himalaya Syntaxis (Gupta et al., 2015), the Sagaing fault (Vigny et al., 2003; Rangin et al., 2013) and the region near the Red-river fault, Vietnam (Trân et al., 2013; Duong et al., 2013) and Southeast Asia (Simons et al., 2007) by estimating rotation and translation parameters that minimize the differences between velocities at collocated sites. The majority of the horizontal velocity vectors have an uncertainty of 2 mm/a at 95% confidence level.

With these GPS data, we calculate strain rate tensors on a regular 0.5°×0.5° grid (Figure 2) using the method described in Tape et al. (2009) by decomposing an interpolated continuous velocity field into a symmetric part (the strain rate tensor) and an antisymmetric part (the vorticity tensor, which is not shown in this study). In comparison to Tape et al. (2009), we obtain the continuous velocity field through interpolation with a ‘spline in tension’ technique (Wessel and Becker, 2008) with the ‘Tension’ of 0.5, which represents the optimal value to minimize short wavelength noise. Sites with large velocity uncertainties and/or showing inconsistent movements with respect to nearby sites were removed (Figure 1b).

Since the geodetic strain is accommodated mostly by seismic slip on faults in this region (Copley, 2008; Holt et al., 2000), earthquake focal mechanisms give a good indication of the style of strain releasing. We validate the GPS-derived strain rate tensors by comparing the directions of extensional principal strain rates with the T-axes of the focal mechanisms of earthquakes shallower than 30 km (Figure 3).

In the past two decades, many SKS splitting studies have been made to characterize the azimuthal anisotropy beneath the Tibetan Plateau and its adjacent regions. These studies provide important constraints on the structure and dynamics of the India-Eurasia collision zone. Though the pattern of anisotropy in the Tibetan Plateau is so complicated that the FPDs of SKS/PKS/XKS splitting results (available from http://splitting.gm.univ-montp2.fr/DB) in the same site by different researchers differ significantly from one another (Figure 4), the SKS splitting results exhibit approximately E-W to NW-SE FPDs in most of central and eastern plateau, whereas they suddenly change to EW to the southwest of RRF. Recently, based on 3D P-wave tomography images, Wei W et al. (2016) showed that FVDs present a similar pattern between 100 and 200 km depths beneath the Tibetan Plateau and adjacent regions, providing new insight into the subducting Indian plate and mantle dynamics in East Asia. We will compare strain tensors with their FVD measurements at depths of 60 km, 100 km and 150 km (Figure 4).

4. Results and Discussion
Figure 2 shows that the maximum shear strain rates are concentrated along several strike-slip faults, including the SF in the west and ANF-XJF in the east. In the west part, there are three conspicuous zones with shear strain rates larger than 200×10⁻⁹ a⁻¹. The northernmost one is located in area to the southwest of Chayu, where the India plate indented beneath Eastern Himalayan Syntaxis (EHS). In the northwest of this area, the compressive principal strain rate, parallel to the indenting direction while perpendicular to the fault, is dominated by the principal compressive
strain rate up to $-240 \times 10^{-9}$ a$^{-1}$. At the corner of EHS near Motuo, both principal strain rates are compressive, suggesting the convergence between India and the Tibetan Plateau. In contrast, to the south of Chayu, the compressive strain rate decreases significantly, and the extensive strain rate in the SE-direction becomes dominant. Further south, both principal axes are compressive, and the maximum axes change to the SE direction. This transition is consistent with strain rate results by Copley (2008) and is consistent with the reverse faulting earthquakes that have occurred in this area, as shown in Figure 1a. The other two are located further south in areas to the northwest of Tengchong and to the south of Mandalay, respectively. The most remarkable feature is that these two shear zones are connected along the Sagaing fault, as shown from the contour of isoline of $100 \times 10^{-9}$ a$^{-1}$ for the maximum shear strain rate.

![Figure 2](image_url)

Figure 2. The maximum shear strain rate and principal strain rate tensors derived from GPS horizontal velocity fields in Figure 1b on the southeastern margin of the Tibetan Plateau. The pink and blue arrows denote compressive and extensional strain rates, respectively; arrow lengths denote the magnitudes. Thin black lines show the isovalue of $100 \times 10^{-9}$ a$^{-1}$ for the maximum shear strain rate.

In the east, a secondary shear zone forms from ANF in the north to XJF in the south. The isovalue of $100 \times 10^{-9}$ a$^{-1}$ seems present in the conjuncts between fault segments, consistent with the segmental seismicity along this boundary, as shown in Figure 1. It is notable that, in the area north of Kunming, the isovale of $100 \times 10^{-9}$ a$^{-1}$ extends eastward and westward from the NS-trending fault, forming a ‘shear zone’ perpendicular to the major fault. Because only strike-slip faulting earthquakes occurred in this area...
local stress would account for such anomalous variation.

In the central area, the shear strain rate is relatively low along RRF, consistent with the low slip rate and low seismicity there. In contrast, the other two local shear zones, bounded by the isovalue $100 \times 10^{-9}$, are located to the north and south of Lijiang, respectively, consistent with results of Copley (2008). Since several normal faulting earthquakes occurred there (Figure 1a), the extensive principal strain rate dominated there; it is perpendicular to the faults, probably resulting from the local stress regime (Figure 2).

In order to further validate our GPS-derived strain rate tensors, we compare them with earthquake focal mechanisms (Figure 3), which are available from the Global CMT (Centroid Moment Tensor) catalogue from 1 January 1976 to 31 December 2017. Both extensional axes and $T$-axes are projected to horizontal surface without scaling to the magnitudes. Figure 3a shows that the principal extensional axes of GPS-derived strain rate tensors are in agreement with the $T$-axes of focal mechanisms of earthquakes, with an average misfit of 9.5° (or 23.8° when using the absolute angular difference) (Figure 3b). We found that most large misfits result from reverse faulting and normal faulting earthquakes. Figure 3c shows that the percentage for misfit less than 20° increases from 61.3% to 75.8%, while the average misfit decreases to 7.9° (or 15.6° for absolute value) when a total of 31 out of 47 normal faulting and reverse faulting earthquakes with misfit larger than 20° are omitted in the comparison. In addition, because the angular differences between $P$- and $T$-axes for ~86% (114 out of 132) of the remaining earthquakes are larger than 80°, the $P$-axes are nearly perpendicular to $T$-axes and the comparison with compressional strain rate will not be shown here. The GPS measurements may be much more vulnerable and sensitive to local stress perturbations in regions where deformation is associated with dip-slip faulting due to the vertical movement.

The region near Tengchong is a second region showing extensional dominated principal strain rates, which are probably associated with the mantle upwelling (Li C et al., 2008; Lei JS et al., 2009; Wei W et al., 2012), that resulted in the normal faulting earthquakes there (Figure 1a, Figure 3a). More remarkably, the extensional axes seem to change from NW near Tengchong to EW, NW along CLC belt, and finally NNW in the region to the south of Simao; to the east of Simao, the extensional axes in that region change to EW, and NE across RRF, roughly consistent with SKS FPs (Figure 4), most of which are located in the region north of CLC belt.

To the southwest of the CLC belt, the extensional axes of principal strain rates are generally consistent with FVDs at all three
depths with subtle angular differences. Nevertheless, these angular differences differ from each other from one region to the other, and thus may give new insight into the deformation from upper crust to upper mantle. For example, in the region to the near east of Sagaing fault, the NNW extension is consistent with FVDs with angular differences less than 20° (Figure 4), suggesting that the shear across the Sagaing fault plays a dominant role in controlling the lithospheric deformation of nearby regions. To the east of this SF shear zone, and to the west of CLC belt, the FVDs in deep depths are in directions rotating clockwise with respect to the shallower ones (Figure 4). Though depth-dependent rheological variations may not be ruled out (Royden et al., 2008), the clockwise rotation of FVDs from the lithospheric mantle to the upper crust would be more probably associated with shearing forces due to the oblique subduction of the India plate beneath the Shan-Thai block (Li C et al., 2008; Rangin et al., 2013; Wei W et al., 2016).

Based on 3D P-wave velocity tomographic images, Li C et al. (2008) revealed differential along-strike slab structures extending far beyond regional seismicity into the upper mantle beneath the Indo-Burma ranges. In the west, the Shan-Thai block dips almost sub-vertically in the upper mantle and spreads over a large area in the transition zone between the Burmese arc and the Red River fault. Because the fast structure in the upper mantle parallels both the shallow seismicity zone as well as the geological structures at the surface, the asthenospheric flow due to kinematics may contribute to the surface strain. Recently, Shi XH et al. (2018) found that the motion of the Shan block, revealed by GPS velocities in Sunda-fixed reference frame, shows a tongue-like kinematic pattern, suggesting the combination of crustal shearing forces that relates to the India indentation into Eurasia plates, and gravitational spreading to the north, and the deep traction due to asthenospheric flow. In contrast, beneath the region to the west of Tengchong, the subducting slab dips eastward with an angle ~60° to a depth of 300 km. As a result, the observed EW-direction of FVDs of SKS splitting beneath the region to the southwest of RRF agree well with the absolute plate motion direction (Huang ZC et al., 2011, Lev et al., 2006), suggesting a deformation transition from simple shear in the Tibetan Plateau to pure shear (E-W extension) between the RRF and CLC belt (Wang CY et al., 2008; Huang ZC et al., 2011). The deformation transition further indicates the significant role of the shearing force along the dextral-slip Sagaing and Red River faults (Li SH et al., 2017; Leloup et al., 1995; Taponnier et al., 2001). More recently, according to 3D numerical geodynamic modelling of the collision-subduction system, Sternai et al. (2016) suggested that the asthenospheric flow associated with the oblique subduction of India beneath Shan Thai block has played a primary role in driving southeast Asia extrusion tectonics and uplift of the terrains around the eastern Himalayan syntaxis. As such, the tectonics and topographic growth of the southeast Tibetan Plateau are controlled not only by crustal and lithospheric deformation but also by asthenospheric dynamics (Li C et al., 2008; Sternai et al., 2016). The coherent deformation in the Shan Thai block may suggest that the lower crust is strong enough to transmit the stress arising from the mantle dynamics to upper crustal levels.

5. Conclusions

In this study, we investigate the deformation patterns of the Southeastern Tibetan Plateau through GPS-derived strain rate...
tensors, which are in agreement with both the slipping patterns and the rates of the major strike-slip faults in the region. There are several shear zones showing shear strain rates larger than $100 \times 10^{-9}$ a$^{-1}$. The most prominent one is about 1000-km-long in the west, trending from Mandalay in the south along the right-lateral Sagaing fault, to the Eastern Himalayan Syntaxis in the north; a secondary shear zone is along the left-lateral Anninghe-Xiaojiang fault in the east, which shows segmented shear near several conjunctions. Nevertheless, the shear strain rate is relatively low along RRF, mostly due to the low slip rate and low seismicity there. In addition, several local shear zones are present in areas under extensional stress regimes such as Lijiang and Tengchong; they are related to normal faulting earthquakes and volcanism, respectively.

Furthermore, the GPS-derived strain rates are consistent with the T-axes of 75.8% (100 out of 132) shallow earthquakes, except for those exhibiting dip-slip faulting due to local stress perturbations. Moreover, the extensional axes of strain rate tensors are consistent with the P-wave FVDs beneath the Shan-Thai block, and show gradually increasing angular differences, which are likely associated with basal shear from the upper mantle, indicating that the upper crust may be coupled with the lower crust, and with the lithospheric mantle beneath the Shan-Thai block.

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