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Present-day crustal deformation characteristics of the southeastern Tibetan Plateau and surrounding areas by using GPS analysis

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ABSTRACT

The southeastern Tibetan Plateau and surrounding areas comprise a typical tectonic belt in mainland China, characterized by a complex geological background and intense tectonic activity. We study present-day crustal deformation characteristics of this region based on GPS data for the periods 1999–2007 and 2009–2011. We first analyze the variations in crustal motion and strain rate, and then discuss the 3D crustal motion and local sub-block activities, as well as the correlation between the intensity of crustal activity and the strain rate distribution. Finally, we explain the present-day geodynamic characteristics of the region. Our results indicate that the entire region shows overall clockwise motion with respect to the stable Eurasian Plate. The tectonic boundary belts between this region and the South China Block display significant compressional strain, accompanied by associated extensional strain. Relatively high maximum shear strain and the transition zones of the significant plane strain gradients are also mainly concentrated along the Ganzi–Yushu–Xianshuihe, Anninghe–Zemuhe–Xiaojiang, Lijiang–Xiaojinhe, and Red River faults, as well as the western and southern Yunnan Province. 3D crustal velocities further reflect significant differences in tectonic activity between different structural belts. We conclude that the regions showing higher shear strain and the transition zones of the significant plane strain gradients correspond to the areas with frequent earthquakes. According to the crustal deformation and strain characteristics, we infer that the present-day geodynamic setting of the region is related to the ongoing India–Eurasia collision and the associated resistance of the stable Alashan, Ordos, and South China blocks, resulting in the extrusion of the southeastern Tibetan Plateau crustal material with an overall clockwise flow around the Eastern Himalayas and significant compressional strain along the tectonic boundary belts. Furthermore, notable compressional strain and enhanced sub-block motions occurred around the Longmenshan fault area following the Wenchuan earthquake.

1. Introduction

The southeastern Tibetan Plateau (SETP) is an important passageway for the materials of the Tibetan Plateau moving toward the southeast, and as a result, this region comprises an intense tectonic belt in mainland China (Fig. 1, Chen et al., 2013a; Royden et al., 2008; Zhu et al., 2017; Li et al., 2016a; Wang et al., 2017). In recent years, many studies have revealed various important characteristics of the SETP and surrounding areas. The continental dynamic setting and stress evolution was simulated using numerical simulation models (Liu et al., 2007; Yang and Liu, 2009; Bai et al., 2010; He et al., 2011; White and Lister, 2012; Chen et al., 2013b; Liu et al., 2015; Liu et al., 2016). The tectonics of faults and earthquakes were described by field investigations and focal mechanism data (Lin et al., 2014; Shi et al., 2016; Zhang and Wang, 2007; Shao et al., 2016; Fu et al., 2011; Lin et al., 2011). The velocities of the active faults were investigated using GPS, InSAR and leveling observations (Chen et al., 2015; Jiang et al., 2014; Shen et al., 2009; Zou et al., 2015; Liu et al., 2011; Wang et al., 2011; Gan et al., 2007; Liang et al., 2013; Wu et al., 2015a; Xu and Stamps, 2016; Zhang et al., 2013a,b; Chang et al., 2017; Hao et al., 2014). The deep structure of the crust was also explored by seismic wave velocity and Bouguer gravity data (Robert et al., 2010; Jiang et al., 2012; Chen et al., 2013a; Cai et al., 2016; Li et al., 2016b).

These aspects of the continental dynamic setting, fault slip rates, seismic activities, stress evolution, deep structures, and crustal activities are of great importance for better understanding of the geodynamics of the SETP. Among the above-mentioned methods, GPS technology has great advantages in providing crustal motion data with

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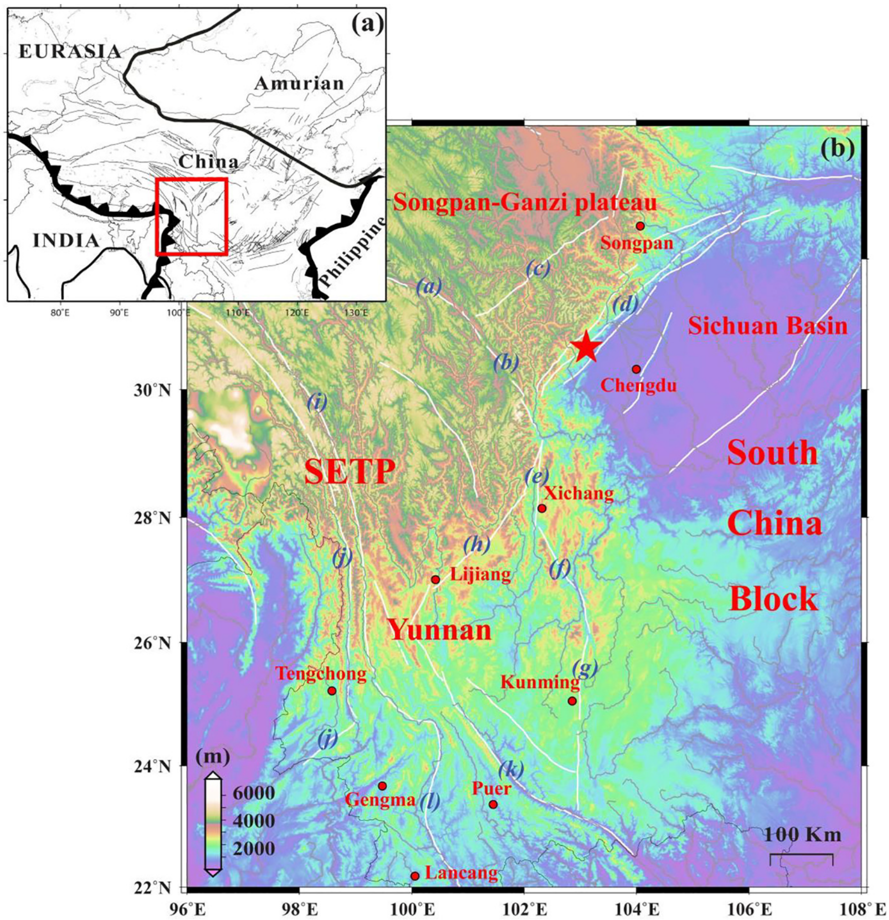

Fig. 1. Location of the SETP and its surroundings in China, as well as the major plate boundaries in and near mainland China (Fig. 1a). The red dashed box indicates the SETP and its adjacent tectonic belts (Fig. 1b). The white solid lines represent the major active faults (Zhang et al., 2005). The small red circles represent major cities. The red star indicates the epicenter of the Wenchuan earthquakes. The italic alphabet characters represent the major faults of the SETP, such as Ganzi-Yushu (a), Xianshuihe (b), Longriba (c), Longmenshan (d), Anninghe (e), Zemuhe (f), Xiaojinghe (g), Lijiang–Xiaojinhe (h), Jinshajiang (i), Nujiang (j), Red River (k), Lancangjiang (l).

higher spatial resolution and more flexible timescales, and can also effectively reflect the present-day dynamic processes. However, although GPS data have been used to describe the general characteristics of crustal activity of the SETP within a certain time period, the detailed variations in crustal deformation and strain fields before and after a large tectonic event (e.g., the May 2008 Wenchuan earthquake) need to be further studied. Variations in the GPS velocity field, particularly the crustal strain field, can not only better describe the evolution of tectonic activity, but also characterize the present-day internal geodynamic mechanism of the region. Moreover, combining the overall motion with the local sub-block motion and the 3D crustal motion can more comprehensively reflect the regional dynamic environment.

In this study, we first use GPS horizontal velocities for different periods to investigate the variations of present-day crustal deformation of study region before and after the 2008 Wenchuan earthquake. Instead of using GPS horizontal velocity only to describe the general characteristics of crustal activity of the SETP within a certain time period, we also integrate the vertical velocity from leveling data and the horizontal velocity from GPS to analyze the three-dimensional (3D) differential crustal movement and sub-block activities. Second, considering that the crustal strain field could better reflect the response of the internal mechanism(s) of crustal deformation and reveal local strain accumulation rates and their possible correlation to seismicity, we further establish a sound strain model based on the least-squares collocation (LSC) technique, to overcome the observation errors in GPS data as well as sparseness and poor geometric distribution of the GPS data. Finally, based on our results and the regional crustal geodynamic, we discuss the correlation between the intensity of crustal activity and the strain rate distribution and the implication for the present-day geodynamic characteristics of the SETP.

2. Study area

The SETP is located in the transitional zone between the Tibetan Plateau and the SCB (Chen et al., 2013a), which is characterized by a steep topographic gradient and the South–North Seismic Zone of China (Xu et al., 2013) (Fig. 1). The region is tectonically active and shows strong crustal deformation, as well as markedly differential tectonic deformation patterns (Hao et al., 2014).

The SETP comprises a series of active faults, including the left-lateral Ganzi–Yushu–Xianshuihe and Anninghe–Zemuhe–Xiaojiang faults in the north and east, and the right-lateral Nujiang, Lijiang–Xiaojinhe, Lancangjiang, and Red River faults in the west and south (Hao et al., 2014; Ma et al., 1989) (Fig. 1). The strike-slip rates of these major faults have been studied through geological observations. The left-lateral strike slip rates of the Ganzi-Yushu, Xianshuihe, Anninghe, Zemuhe and Xiaojing faults are 12 ± 2.0 mm/yr, 14 ± 2.0 mm/yr, 6.5 ± 1.0 mm/yr, 6.4 ± 0.6 mm/yr, 10 ± 2.0 mm/yr, respectively (Song et al., 1998; Xu et al., 2003a,b). The right-lateral strike slip rates of the Lijiang–Xiaojinhe, Red River, Lancangjiang, Jinshajiang , Longriba and Longmenshan faults are 3.8 ± 0.7 mm/yr, 3.5 ± 1.5 mm/yr, 5.3 ± 1.1 mm/yr, 6.0 ~ 7.0 mm/yr, 5.4 ± 2.0 mm/yr, 1.5 ~ 2.0 mm/yr, respectively. (Ma et al., 2005; Zhou et al., 2006; Xu et al., 2003a,b, 2008, 2017). The occurrence of frequent earthquakes is also typically associated with these active faults. Historical earthquake records and paleoseismic data reveal that at least four strong earthquakes (M > 7) have occurred along the Ganzi–Yushu fault zone over the past ~700 years (Zhou et al., 1997a,b); approximately 20 earthquakes (M > 6) have occurred along the Xianshuihe fault since 1700 (Wen, 2000; Wen et al., 2008a); and almost 20 earthquakes (M > 6) have occurred along the Xiaojiang fault zone over the past 500 years (Shen et al., 2003; Song et al., 1998; Wen et al., 2008b; Xie and Cai, 1987). In