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Block-like versus distributed crustal deformation around the northeastern Tibetan plateau

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ABSTRACT

It has been debated for decades whether crustal deformation in and around the Tibetan plateau is distributed or block-like. We model crustal deformation in northeastern Tibet using a deformable-block-motion model, in which kinematic parameters of block motion and internal deformation and the associated boundary slip rates are inverted for using GPS velocity data. The F-test is used to screen out station velocity outliers, justify independence of neighboring blocks, and determine the significance of block internal strains through an iteration process. As a result, fifteen blocks are identified, with their boundary faults slipping at rates of 1–10 mm/a. Blocks located east and north of the plateau have large sizes (>10^4 km^2 in area) in general, with little internal deformation. Six blocks within the plateau, in contrast, are smaller in sizes, with internal strain rates on the order of 1–10 nanostrain/a. Five blocks sitting at the northeast borderland of the plateau have small block sizes but no significant internal deformation. Our results show sinistral slip rates of 4.3 ± 1.6 and 4.6 ± 1.8 mm/a across the western and eastern segments of the Haiyuan fault, and 10.8 ± 2.3, 4.6 ± 2.6, and 3.8 ± 2.1 mm/a across the western, central, and eastern segments of the East Kunlun fault, respectively. The southwestern, central, and northeastern segments of the Longmenshan fault slip right-laterally at rates of 1.7 ± 1.1, 1.1 ± 0.8, and 1.1 ± 0.8 mm/a, with shortening rates of 1.1 ± 1.2, 0.4 ± 0.8, and 0.8 ± 1.1 mm/a, respectively. We also develop a scheme to convert geodetic strain rate into seismic moment accumulation rate within blocks and at block boundaries, and estimate the two rates as $\sim 8.40 \times 10^{18}$ and $\sim 2.06 \times 10^{19}$ N·m/a, respectively. In comparison, the corresponding seismic moment release rates are estimated as $\sim 6.06 \times 10^{18}$ and $\sim 2.44 \times 10^{19}$ N·m/a using an contemporary earthquake catalog of 1920–2015. Such results indicate that the seismic moment accumulation and release rates are comparable for the latest 95 years when the earthquake catalog is complete for strong to large events. Both geodetic and seismic estimates suggest that a major portion (~70–80%) of the total seismic moment is accumulated and released at block boundaries, and a minor but still significant portion (~20–30%) is accumulated and released within blocks.

1. Introduction

Unlike most parts of the continental interiors of the world, the Tibetan plateau and its surrounding region have been undergoing intense tectonic deformation, whose evolution has long been the focus of continental dynamics research. The region has also been frequently hit by strong earthquakes, whose locations and mechanisms were usually controlled by faults in and around the plateau. Quantitative research on the distribution of regional crustal deformation and fault slip not only provides valuable data for seismic risk assessment, but also plays an important role in understanding the dynamics underlying the evolution of the Tibetan plateau.

Two alternative end-member models have been proposed on the deformation kinematics and dynamics of the Tibetan plateau. At one extreme, ignoring the plasto-elastic deformation of the crustal medium, the rigid block motion model suggests that the continental lithosphere is composed of a collage of large-scale rigid blocks, whose boundaries are delineated by a limited number of lithospheric strike-slip dominant faults. The eastward extrusion of the plateau is believed to be accommodated by rapid slip along these faults (Tapponnier and Molnar, 1976; Tapponnier et al., 1982, 2001; Peltzer and Tapponnier, 1988; Avouac and Tapponnier, 1993; Peltzer and Saucier, 1996; Replumaz and Tapponnier, 2003). At the opposite extreme, deformation is claimed to be

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widely distributed throughout the continental interior. Plateau uplift is proposed to be the result of bulk crustal shortening and thickening, while contribution of major fault zones to crustal deformation, is discounted or neglected (Vilotte et al., 1982, 1986; England and McKenzie, 1982; Houseman and England, 1986, 1993; England and Molnar, 1997; Flesch et al., 2001). Thatcher (2007) suggested that the two end-member models converge, that although the surface deformation in first-order is block-like, deformation at depth in the ductile part of lithosphere might well be considerably more continuous than it is at the surface. Chen et al. (2004) interpreted an early set of GPS vectors in the Tibetan plateau with a deformation model that the plateau is cut by a few major, rapidly slipping strike-slip fault zones, with broadly distributed strain between those zones.

Wang et al. (2003a) classified the regions in continental China into three categories, demonstrating block-like, intermediate, and distributed deformation respectively. The northeastern Tibetan plateau was considered as of the second category, while stable cratons such as the Ordos terrane was classified as with block-like deformation (Wang et al., 2003a). Such a contrast prompts us to develop a deformable block motion model, which is similar to the one used by Chen et al. (2004), as an effective description of deformation in northeastern Tibetan plateau, and investigate how the deformation is distributed between different tectonic units in the region (Fig. 1). In such a model both deformations in the block and along block boundaries are measured, and their relative weight defines where the reality is situated between the two end member models.

Thanks to the rapid developments of geodetic technology (especially GPS), significant advancements have been made to measure crustal deformation and understand its mechanisms (e.g. Feigl et al., 1993; Reilinger et al., 1997; Bilham et al., 1997; Holt et al., 2000; McCaffrey et al., 2000, 2007; Wang et al., 2001, 2009; Zhang et al., 2004; Wallace et al., 2004; d' Alessio et al., 2005; Meade and Hager, 2005; Loveless and Meade, 2011). When one attempts to use a block motion model to characterize crustal deformation, it is inevitable to address the issue how to qualify a region as a block. As Bird (2003) pointed out, the cumulative number and area of blocks, in a global scale, roughly obey a power law relationship, implying a fractal structure of the crust. Identification of smaller blocks, however, can be challenging, since as the size of a block reduces, it becomes less clear to distinguish deformations within and along the boundaries of the block.

In recent years an approach of cluster analysis has gained momentum to be used for crustal block motion analysis (e.g. Simpson et al., 2012). It has been applied for deformation studies in the Tibetan plateau region (Loveless and Meade, 2011; Zhang and Wei, 2011). We take a different approach to this problem, starting from dividing the studied region into candidate blocks as small as possible, and introducing statistical tests to combine them into larger ones until the kinematic independence between any couple of neighboring blocks exceeds a statistical threshold. The method and result will be compared with the ones using the cluster analysis approach (Loveless and Meade, 2011; Zhang and Wei, 2011). Relative motion rates across block boundaries (i.e. fault slip rates) and mean strain rates within blocks are also estimated, and the results are converted to seismic moment accumulation rates for comparison with earthquake catalog derived seismic moment release rates. The results are further compared with that of a similar study of Wang et al. (2009).

2. GPS data and processing

GPS data used in this study are mainly from the Crustal Motion Observation Network of China (CMONC) project observed in 1999, 2001, 2004, and 2007 in the region of northeastern Tibetan plateau (Wang et al., 2003a; Zhang et al., 2004; Niu et al., 2005; Gan et al., 2007). We also include data from the National Basic Research Project (Wang, 2009), the postseismic survey of the 2001 Mw 7.8 Kokoxili earthquake (Ren and Wang, 2005), and the 1998 Sino-US joint survey in the Altyn Tagh region (Shen et al., 2001).

The GPS data were analyzed using the GAMIT/GLOBK (Herring et al., 2010) and QOCA (http://gipsy.jpl.nasa.gov/qoca/) software (Wang et al., 2003a; Shen et al., 2011). During this process, the GPS data carrier phase data were first processed to obtain loosely constrained daily solutions for station positions and satellite orbits using the GAMIT software. The regional daily solutions were then combined with global solutions produced by the Scripps Orbital and Permanent Array Center (http://sopac.ucsd.edu) using the GLOBK software. In the last step the station positions and velocities were estimated using the QOCA software and referenced to the stable Eurasia plate using a group of IGS sites located in northern Europe and Siberia, and the velocity solution in the studied region is shown in Fig. 2. Most GPS stations spanning the range of 94–106°E, 32–42°N show east-northeastward motion with respect to the Eurasia plate, with their velocities decreasing from ~20 mm/a in southwest to ~5 mm/a in northeast. The velocity field in the studied region also presents a clockwise rotation, which is consistent with previous observations (Wang et al., 2001, 2003a; Zhang et al., 2004; Gan et al., 2007).

3. GPS data inspection and block model parameterization

The results of block models can be very sensitive to the assumed block geometry, and decisions about block boundaries are sometimes made subjectively. We applied a multi-step process to define the block model geometry that is designed to minimize subjective decisions or assumptions. We first select 24 velocity profiles to investigate deformation across faults of potential interest and invert for their slip rates. The region is then divided into 20 initial blocks based on previous geological and geophysical studies and examination of the GPS velocity profiles, with the block boundaries including both faults of known geological significance and faults with significant slip rates inferred from the GPS data. All blocks must have closed boundaries, so these are assumed when the set of active faults is not sufficient by itself to produce a full set of closed blocks. Adjacent blocks are then combined if they are not statistically independent according to the F-test, resulting in the final block model geometry. The detailed procedure is described below.

3.1. Velocity profiles

In order to define the block geometry, we first investigate differential motions across faults determined from previous geological and geophysical studies (e.g. Deng et al., 2003; Guo et al., 2000). In addition, localized velocity gradient zones are identified as block boundaries in the initial model. GPS velocity profiles are used for close examination and fault slip rates are estimated accordingly. To better visualize the differential motion across a fault, we choose one side of the fault as reference where the station velocities show more consistent motion than the other side of the fault. A best-fit Euler vector is determined by using all the GPS observations within the reference block, and the corresponding velocity field with respect to the block is obtained by removing the rigid body rotation component from all the GPS stations. Velocities of involved GPS stations are decomposed into strike-parallel and strike-normal components respectively.

For an infinitely-long strike-slip fault locked above and creeping below the locking depth, the associated surface velocity field along