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Relative motion across the eastern Tibetan plateau: Contributions from faulting, internal strain and rotation rates

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ABSTRACT

A kinematic model comprising 14 rotating, elastic–plastic blocks is used to represent the modern deformation of eastern Tibet and neighboring regions. Block rotations, fault slip rates and permanent strain rates within the blocks are constrained by inverting GPS velocities, slip vector azimuths derived from earthquakes, and fault slip rates derived from geology. The calculated internal strain rates of blocks in eastern Tibet amounts to 10 to 30×10^{-9}/yr, in contrast to relatively low rates ($<5\times10^{-9}$/yr) in adjacent blocks including the south China, Alxa and Thailand blocks. F-test statistics show that neither the internal strain rates nor the spins of the blocks can be neglected in describing the surface deformation of eastern Tibet. Furthermore, slip on the main faults verifies that the use of deformable blocks can also predict strain localization and strike-parallel variations in slip rates. In terms of east–southeast motion of the eastern Tibetan plateau relative to the Eurasian plate, the net relative velocity contributed by internal strain rates in the blocks amounts to ~10 mm/yr, about half of that due to the faulting. In terms of N–S shortening of plateau, however, the internal strain rises to a first order factor west of 95°E, contributing approximately 10 mm/yr, nearly two times larger than that from faulting. The kinematics in eastern Tibet shows that different types of deformation, i.e., NW–SE shear and N–S compression, are taken up by faulting on major faults and distributed contraction, respectively.

1. Introduction

Among the key questions in the debate on the mechanism of the Tibetan plateau tectonics is whether the deformation is distributed broadly or localized on a few major faults (England and Molnar, 2005; Loveless and Meade, 2011; Molnar and Dayem, 2010; Tapponnier et al., 2001; Thatcher, 2007, 2009). Kinematic analysis may provide clues though large diversity exists in the descriptions of kinematics based on the same data. Analogous to the rigid plate hypothesis for plate tectonics, the principle that the deformation of continents can be represented by interactions among elastic blocks has been successfully applied in some regions (e.g., McCaffrey, 2005; Meade and Hager, 2005). As to the Tibetan plateau, however, although the GPS velocity field has been explained by rotations of a small number of rigid blocks (e.g., Meade, 2007; Thatcher, 2007, 2009), it can also be described by continuum deformation suggesting pervasively distributed strain (e.g., England and Molnar, 2005; Zhang et al., 2004).

In terms of distribution of crustal strain rates, the distinction between the block models and continuous deformation is not entirely clear. Earlier block models indicated that the internal strain rates in the blocks on the Tibetan plateau are negligible (e.g. Thatcher, 2007). Loveless and Meade (2011) find that small internal strain rates within the Tibetan blocks are needed to fit the residual velocities relative to a rigid block model but they suggest that the internal strain rates are not significantly greater than the level of observational noise. These block models predict fast and uniform slip on major west–east strike-slip faults, indicating strong strain localization. Though continuum models could also allow strain localization along main faults on the plateau, Molnar and Dayem (2010) interpret the localization as concentrations of strain along boundaries of strong medium rather than relative motion between adjacent blocks. These divergent views can be addressed by allowing internal deformation in the blocks and testing whether or not the internal deformation improves the fit to the data and adds significantly to the deformation.

Eastern Tibet undergoes N–S contraction and eastward crustal extrusion relative to the Eurasian plate (Tapponnier et al., 2001). Deformation is composed of zones of strain localization (Molnar and Dayem, 2010) on northeast-to-east-striking strike-slip faults with some amount of strike-parallel variation in rates (Kirby et al., 2007; Zhang et al., 2007) and flow-like crustal motion in the broad area of southeast Tibet (Gan et al., 2007). We use F-test statistics to test the importance of the internal strain rates of eastern Tibet under the framework of block kinematics constrained by multiple types of

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data (McCaffrey, 2005). The importance of strain rates is also compared with that of the major faults by estimating how much each contributes to the relative velocities between the eastern Tibetan plateau and the northern margin.

2. Block modeling

2.1. Model settings

In this paper, the surface deformation of eastern Tibet is assumed to consist of a finite number of regions (blocks) whose velocities are due to a combination of internal, horizontal strain rates, rigid rotations on the sphere and interseismic elastic strain accumulation near their bounding faults. The parameters that describe the models are estimated simultaneously by least-squares fitting of geodetic, earthquake and geologic data (McCaffrey, 1996, 2005). The study area includes the extensive plate boundary between India and Eurasia, ranging from Burma–Thailand in the south to Alxa in the north and from the interior of Tibet in the west to South China in the east (Fig. 1a, b and c). Being focused on block kinematics rather than frontal collision, the study avoids the highly deformed Himalayan thrust.

The block boundaries coincide with the major active faults (Deng, 2007) except that the boundary between the north- and south-Qiangtang blocks is inferred from geologic terrane divisions (Pan and Ding, 2004) and the boundary between the Qingchuan and Qilian blocks is added to separate two distinct patterns of GPS velocities. The strike-slip faults in Tibet (e.g., Tapponnier et al., 2001) are assumed to be steeply dipping. Moderate dips are assigned to the Longmenshan fault and the Minjiang fault, on the east edge of Tibet (Chen et al., 1994; Zhang et al., 2010). Some block boundaries for this region are modified from previous studies (e.g., Meade, 2007; Shen et al., 2005; Thatcher, 2007). Above 10–15 km depth, faults are assumed to be fully locked with a linear transition in locking down to 20–25 km and freely-slipping below 25 km.

2.2. Significance test of model components

The data misfit is calculated in the form of the reduced Chi-square statistic, χ_n^2, the weighted residual variance divided by the degrees of freedom (DOF = number of data minus number of free parameters). Using more free parameters to match same number of observations in general will result in better fit to the data in the sense of lowering the weighted residual variance but, if the resulting change of χ_n^2 is small due to the increase in DOF, the new parameters may not be deemed necessary to fit the data. By contrast, if the added parameters have great influence on the model fit, the inclusion of those parameters can cause a significant reduction of residuals and subsequently a decrease of χ_n^2. The confidence that the variance change is not by chance

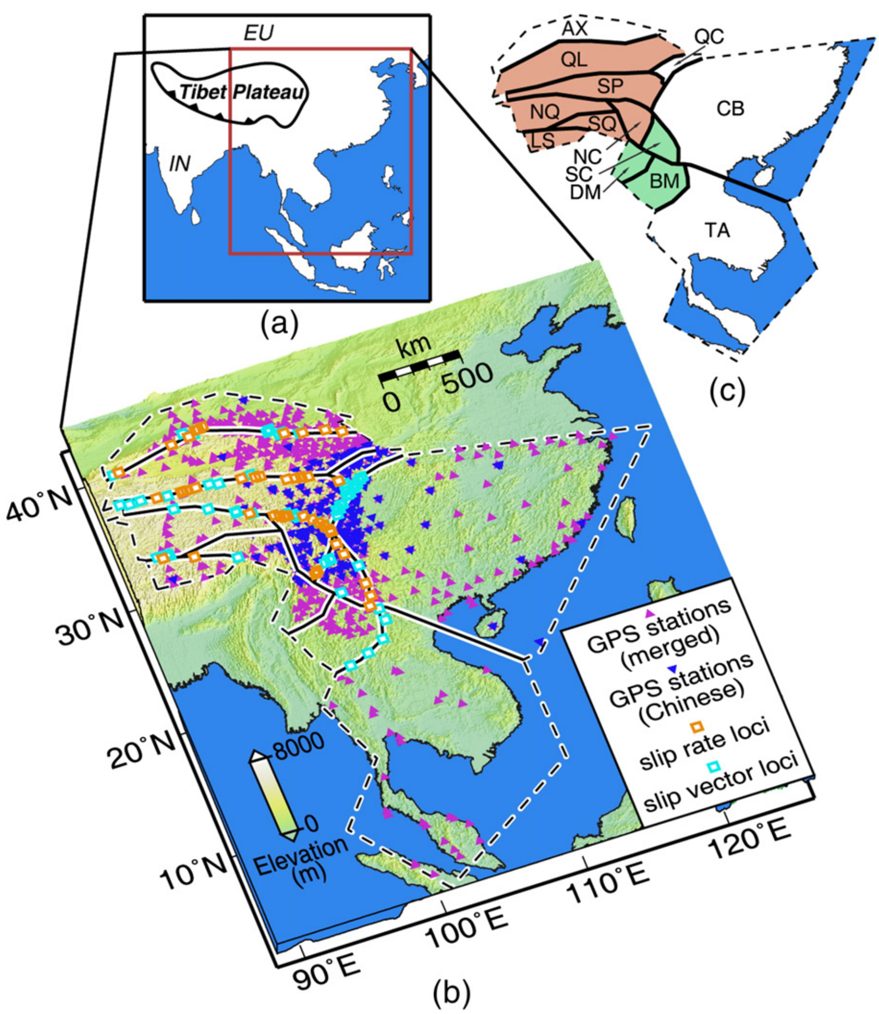

Fig. 1. (a) Study region enclosed by red box. EU and IN are Eurasia plate and India plate, respectively. (b) Map of study region. Solid lines represent block boundaries and dashed line is outer boundary of model domain. (c) Block geometry: block codes are: AX, Alxa; QL, Qilian; SP, Songpan; QC, Qingchuan; NQ, North Qiangtang; SQ, South Qiangtang; LS, Lhasa; NC, North Chuandian; SC, South Chuandian; DM, Dian-Burma; BM, Burma; TA, Thailand; and CB, South China. The blocks on the plateau and those adjacent to the eastern Himalayan syntaxis are highlighted with light red and light green, respectively.