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Spatially varying surface seasonal oscillations and 3-D crustal deformation of the Tibetan Plateau derived from GPS and GRACE data

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A B S T R A C T

Measurements of 189 continuous and 933 campaign-mode Global Positioning System (GPS) stations with 3–16 yr data spans over the Tibetan Plateau reveal contemporary three-dimensional (3-D) crustal deformation during 1999–2016. The Empirical Orthogonal Function method was used to characterize the spatial variations in the surface deformation with distinct seasonal oscillations at the GPS sites in five regions of the Tibetan Plateau. We find that these surface variations are highly correlated with the corresponding mass load signals observed by the Gravity Recovery and Climate Experiment (GRACE) mission. The improved GPS processing strategy used to determine the 3-D velocity field includes maximum likelihood estimation, removal of common mode errors from GPS time series using Principal Component Analysis (PCA), and power law plus white noise stochastic error modeling. We determined the rates of vertical crustal movement by removing GRACE-observed non-tectonic origin load deformation, 2002–2016. The corrected vertical crustal deformation shows that the Himalaya region is uplifting at an average rate of ∼1.7 mm yr^{-1}, and that the northeastern Tibetan Plateau is uplifting at an average rate of ∼1.3 mm yr^{-1}. In addition, the horizontal velocity relative to the stable Eurasian plate and its corresponding dilatation throughout the Tibetan Plateau suggest that tectonic shortening and crustal thickening is occurring at −90 to −80 nanostrain yr^{-1} in the southern Tibetan Plateau and −30 to −20 nanostrain yr^{-1} in the northeastern Tibetan Plateau, which could be related to the geologic shortening and elastic strain accumulation. The interior Tibetan Plateau exhibits crustal thinning and block movement along strike-slip faults. Eastward motion of the crust north of the Xianshuihe-Xiaojiang Fault system relative to crust to its south results in shear strain and reflects eastward escape of plastic crustal material in the southeastern Tibetan Plateau.

1. Introduction

Since the Eocene epoch (∼45–55 Ma), continental collision between the Indian and Eurasian plates has been driving the Cenozoic tectonic evolution of the Tibetan Plateau (Tibetan Plateau) and surrounding regions, consequently causing shortening and thickening of the Tibetan Plateau crust (Molnar and Tapponnier, 1975; Yin and Harrison, 2000; Royden et al., 2008). Substantial underthrusting of the Indian crust beneath Eurasia created a crustal setting of active orogenic belts and the tectonic processes that led to the Tibetan Plateau (Li et al., 2008; Styron et al., 2015). Copley et al. (2011) reported that the Indian crust retains its strength as it under-thrusts the Tibetan Plateau; however, subsequent extension at a high rate and magnitude in southern Tibet reflects thinning of the upper crust in response to thickening of the lower crust as the Indian plate continued to under-thrust (Styron et al., 2015). From a geological viewpoint, the Cenozoic extensional grabens on the Tibetan Plateau are the product of rapid uplift of the plateau caused by a deep dynamic mechanism after an earlier strong crustal shortening (Yin and Harrison, 2000). Active faults and blocks produce strong earthquakes that occur along the plate boundary, stemming directly from plate motions throughout the region, as shown in Fig. 1. Therefore, the Tibetan Plateau is one of the most tectonically active regions on Earth where the geologic history of a mountain belt can be analyzed (Avouac, 2015).

GPS observations on and around the Tibetan Plateau reveal dramatic tectonic movements and the north-eastward crustal flow within the Tibetan Plateau, absorbed by crustal shortening and

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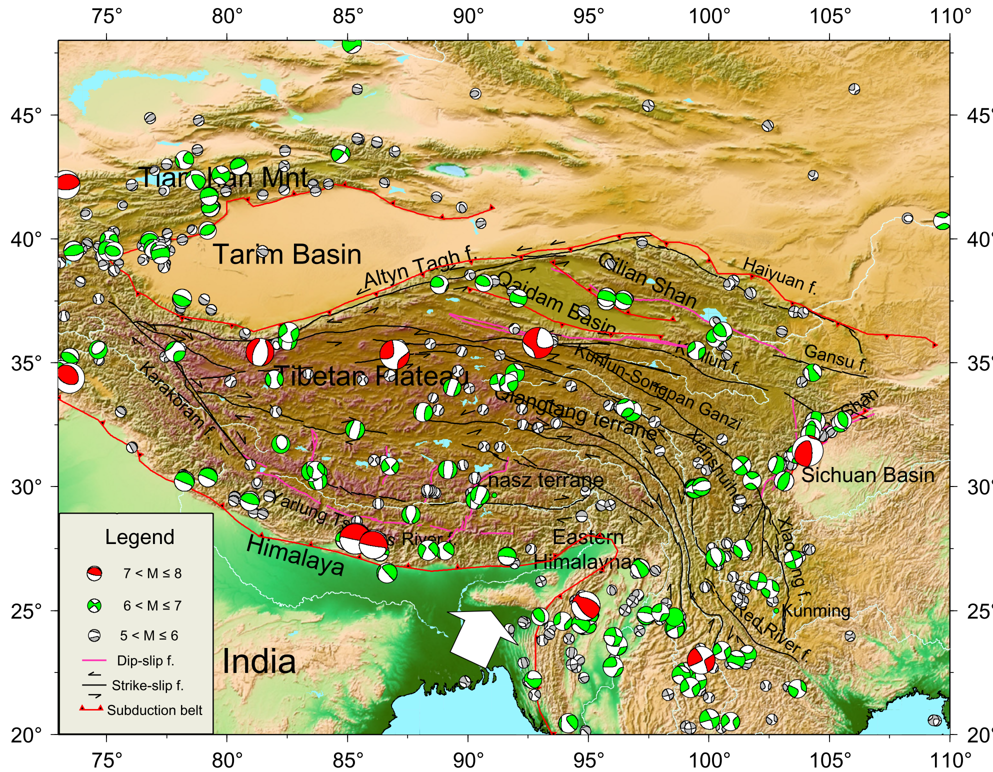

Fig. 1. Map showing the active strike slip faults as black lines and the edges of the thrust faults with red lines. The focal mechanism solutions are given from January 2008 to December 2015, from the Global Centroid-Moment-Tensor (CMT) catalog (Ekström et al., 2012). Red beach balls indicate earthquakes with 7.9 ≥ Mw ≥ 7.0; green beach balls are for earthquakes with 6.9 ≥ Mw ≥ 6, and blue beach balls for 5.9 ≥ Mw ≥ 5. The white arrow shows the continental collision direction of the Indian plate into the Eurasia Plate. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

thickening (Wang et al., 2001; Gan et al., 2007). Liang et al. (2013) investigated the crustal vertical deformation using measurements from 750 GPS stations and revealed that the entire Tibetan Plateau is continuously uplifting relative to the stable neighboring region to the north. However, quantifying the vertical crustal deformation is still challenging because it is not easy to separate the tectonic signals from the non-tectonic or climatic/hydrologic signals in geodetic observations. GPS time series in Himalaya has shown strong seasonal signals and peaks during dry late summer and autumn seasons (Fu and Freymueller, 2012). Hydrologic loading, derived from the Gravity Recovery and Climate Experiment (GRACE) mission data, contributes to the surface vertical deformation of $\sim$1 mm yr^{-1} (Fu and Freymueller, 2012). Here, we assume that tectonic signals are negligible in the GRACE data. To isolate the vertical crustal deformation representing the tectonic signals over the Tibetan Plateau, we remove the GRACE-derived surface loading signals with climatic/hydrologic origins from the vertical velocity derived from the continuous and campaign-mode GPS data.

The new 3-D velocity field inferred from the combined data sets reveals significant horizontal tectonic deformation of the Tibetan Plateau and suggests that crustal thickening and shortening are the main causes driving the Tibetan Plateau crustal uplift. A comparison of the improved GPS vertical velocity field with the strain characteristics illustrates that the crustal deformation is vertically coherent. This paper is organized as follows. In Section 2, the data sources and methodology are introduced, followed by a description and discussion of the results in Sections 3 and 4. Finally, the conclusions are summarized in Section 5.

2. Data and methods

We use continuous and campaign-mode GPS data to analyze the 3-D crustal movements of the Tibetan Plateau. Since GPS data include variations caused by offsets, seasonal loading, tectonic and other effects, the time series data are preprocessed using the QOCA (Quasi-Observation Combination Analysis software package, http://qoca.jpl.nasa.gov/). We also analyze the spatial and temporal properties of this regional GPS network to estimate the common mode errors in the time series using Principal Component Analysis (PCA). To determine the secular change in time series with high accuracy and realistic uncertainty, we filter the common mode errors from the GPS time series, and estimate the secular rate and its corresponding uncertainty using a maximum likelihood estimation (MLE) optimization scheme. The RL05 data product from the CSR (Center of Space Research, University of Texas at Austin) provides the GRACE monthly Stokes coefficients, which represent the variations in Earth's gravity field, and are used to estimate the surface deformation caused by the non-tectonic mass loads. We add back the Atmosphere and Ocean De-Aliasing Level-1B (GAC) to the GRACE spherical harmonics coefficients (GSM). The surface mass deformation obtained from GRACE is used for correcting the GPS vertical rates to determine the vertical velocity due to tectonics. The vertical velocities constrained by GPS and GRACE may provide a new insight into the crustal vertical deformation within and around the Tibetan Plateau.

2.1. GPS data and processing

The continuous and campaign-mode GPS data used for this study are from the Crustal Movement Observation Network of China (CMONOC I and II) and Caltech Tectonics Observatory (CTO). The station details are provided in Supplemental Materials. The CMONOC II continuous stations have recorded observations since 2010, and long-term observation stations from the CMONOC I and CTO have recorded data for more than 15 yr, from 1999 to 2016. All the original GPS time series data used in this paper span more than 2.5 yr. We used the GIPSY6.2 software to process the GPS