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Accommodation of missing shear strain in the Central Walker Lane, western North America: Constraints from dense GPS measurements

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ABSTRACT

We present 264 new interseismic GPS velocities from the Mobile Array of GPS for Nevada Transtension (MAGNET) and continuous GPS networks that measure Pacific–North American plate boundary deformation in the Central Walker Lane. Relative to a North America-fixed reference frame, northwestward velocities increase smoothly from ∼4 mm/yr in the Basin and Range province to 12.2 mm/yr in the central Sierra Nevada resulting in a Central Walker Lane deformation budget of ∼8 mm/yr. We use an elastic block model to estimate fault slip and block rotation rates and patterns of deformation from the GPS velocities. Right-lateral shear is distributed throughout the Central Walker Lane with strike-slip rates generally <1.5 mm/yr predicted by the block model, but extension rates are highest near north-striking normal faults found along the Sierra Nevada frontal fault system and in a left-stepping, en-echelon series of asymmetric basins that extend from Walker Lake to Lake Tahoe. Neotectonic studies in the western Central Walker Lane find little evidence of strike-slip or oblique faulting in the asymmetric basins, prompting the suggestion that dextral deformation in this region is accommodated through clockwise block rotations. We test this hypothesis and show that a model relying solely on the combination of clockwise block rotations and normal faulting to accommodate dextral transtensional strain accumulation systematically misfits the GPS data in comparison with our preferred model. This suggests that some component of oblique or partitioned right-lateral fault slip is needed to accommodate shear in the asymmetric basins of the western Central Walker Lane. Present-day clockwise vertical axis rotation rates in the Bodie Hills, Carson Domain, and Mina Deflection are between 1–4°/Myr, lower than published paleomagnetic rotation rates, suggesting that block rotation rates have decreased since the Late to Middle Miocene.

1. Introduction

The Walker Lane is a ∼100-km-wide zone of transtensional faulting that lies between the northwest translating Sierra Nevada/Great Valley microplate and the westward extending Basin and Range province (Fig. 1) (Stewart, 1988). Up to 25% of the 50 mm/yr Pacific–North American relative right-lateral plate boundary deformation is accommodated east of the Sierra Nevada in the Walker Lane and Basin and Range (e.g. Bennett et al., 2003; Dixon et al., 2000; Thatcher et al., 1999), with the majority of the remaining motion accommodated on the San Andreas fault system (e.g. Argus and Gordon, 2001; Minster and Jordan, 1987). Deformation in the Walker Lane is considered transtensional because of obliquity between the Sierra Nevada/Great Valley-North American microplate motion and the orientation of faults within the Walker Lane (e.g. Unruh et al., 2003; Kreemer et al., 2009) and the presence of both strike-slip and normal faulting (e.g. Stewart, 1988; Taylor and Dewey, 2009). In this study, we focus on active deformation in the Central Walker Lane, which we define as the set of normal and strike-slip faults that extend from the southern edge of the Mina Deflection north to the Carson Domain on the eastern margin of the Sierra Nevada microplate (Fig. 1).

GPS observations measure the active and ongoing contemporary deformation of the crust that is the prelude to earthquakes on faults that release a portion of the accumulated strain. The Central Walker Lane accommodates 8–10 mm/yr of right-lateral transtensional shear (Hammond and Thatcher, 2004; Oldow et al., 2001), however it remains unclear what percentage of this shear is released on mapped active fault structures and what implications the deformation has for regional seismic hazard (Wesnousky et al., 2012). Paleomagnetic and neotectonic observations identify spatially distinct zones of deformation in the Central Walker Lane

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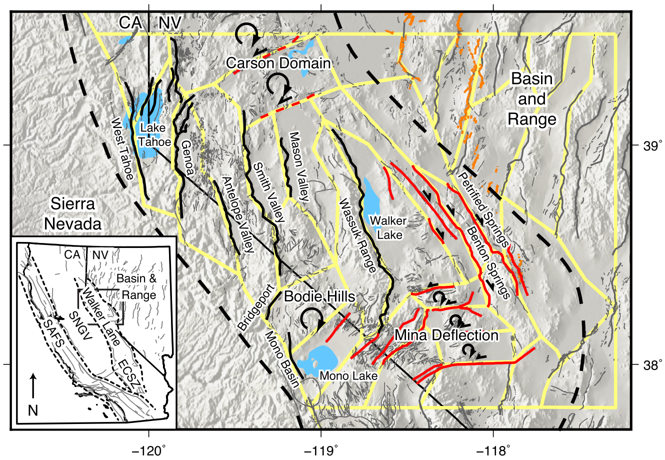

Fig. 1. Regional map showing the block model boundaries (yellow lines) in relation to the topography and faults of the Central Walker Lane. The Central Walker Lane (region within the dashed black lines) lies between the northeast striking normal faults of the Basin and Range and the Sierra Nevada microplate. Black lines delineate major normal faults of the Central Walker Lane, and red lines mark the location of strike slip faults (arrows indicate slip direction). Paleomagnetic observations indicate that crustal blocks in the Carson Domain, Bodie Hills, and Mina Deflection accommodate dextral shear through clockwise vertical axis rotations (Cashman and Fontaine, 2000; Petronis et al., 2009; Rood et al., 2011b; Carlson et al., 2013). Orange lines mark the locations of surface rupture that resulted from historic earthquakes in the Central Nevada Seismic Belt. Faults traces are modified from the USGS Quaternary Fault and Fold database (U.S. Geological Survey, California Geological Survey, Nevada Bureau of Mines and Geology, 2006). Inset map shows the location of the study area in relation to other elements of the Pacific/North America Plate boundary zone. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

with three different mechanisms of active strain release: (1) left-lateral faulting and clockwise block rotations in the Mina Deflection, Bodie Hills, and Carson Domain (e.g. Carlson et al., 2013; Cashman and Fontaine, 2000; Nagorsen-Rinke et al., 2013; Petronis et al., 2009; Rood et al., 2011b; Wesnousky, 2005a), (2) right-lateral slip on northwest trending strike slip faults in the eastern half of the Central Walker Lane (e.g. Wesnousky, 2005a), and (3) extension (e.g. Unruh et al., 2003; Wesnousky et al., 2012) and possible clockwise block rotations (Wesnousky et al., 2012) across a left-stepping series of en-echelon normal fault-bounded basins that stretch from Walker Lake to Lake Tahoe (Fig. 1). Previous geodetic studies generally conclude that transtensional deformation is distributed throughout the Central Walker Lane, however interpretations of the deformation partitioning are conflicting. Oldow (2003) and Hammond and Thatcher (2004) find a zone of shear-dominated transtension across the northwest trending strike-slip faults in the eastern Central Walker Lane and a zone of extension-dominated transtension across the normal fault-bounded basins in the western Central Walker Lane. Surpless (2008) suggests that dextral shear is concentrated only in the region that coincides with the northwest trending strike-slip faults and that deformation in the western Central Walker Lane is almost purely extensional. Unruh et al. (2003), Kreemer et al. (2009), and Hammond et al. (2011) find transtensional deformation throughout the Central Walker Lane, with a zone of both increased extension and shear along the eastern margin of the Sierra Nevada. With the exception of the Hammond et al. (2011) Northern Walker Lane study (which overlaps with our Central Walker Lane study between 38.5–39.5° latitude), none of the geodetic studies directly address how the observed transtensional strain is released through slip on active faults and block rotations.

In this study, we present a new interseismic velocity solution that combines observations from the semi-continuous Mobile Array of GPS for Nevada Transtension (MAGNET) network (Blewitt et al., 2009) with data from the EarthScope Plate Boundary Observatory (PBO) and other continuous GPS networks that measure present-day deformation in the Central Walker Lane. Our velocity solution has dense station spacing (∼20 km) with mean velocity uncertainties of less than 0.3 mm/yr, representing a significant improvement in resolution and coverage over previously published Central Walker Lane velocity solutions (Hammond and Thatcher, 2004; Oldow et al., 2001; Oldow, 2003; Surpless, 2008). We use these velocities and the mapped traces of Central Walker Lane faults to estimate kinematically consistent fault slip and block rotation rates through an elastic block-modeling approach. Our preferred block model predicts patterns of deformation that are generally consistent with geological observations with the exception of the normal fault-bounded basins in the western portion of the Central Walker Lane. Here, the GPS data predicts oblique slip on many of the basin-bounding faults and minor clockwise rotation of the fault-bounded blocks, whereas neotectonic studies of the basin bounding faults document purely normal slip (Wesnousky et al., 2012 and references therein). We use our block model to test the hypothesis that shear deformation across these basins is accommodated through a combination of purely normal faulting and clockwise block rotations (Wesnousky et al., 2012). We demonstrate that a model that does not allow oblique slip on the basin-bounding faults systematically misfits the GPS data in comparison with our preferred model. This suggests that some component of strike-slip motion is needed to accommodate the geodetically observed shear strain in the western Central Walker Lane.

2. Central Walker Lane GPS velocities

We present horizontal velocities for 264 continuous and semi-continuous GPS stations on the Sierra Nevada/Great Valley microplate and across the Walker Lane/Basin and Range transition between 37°N–40°N and 117°W–122°W (Fig. 2 and Supplemental Table S1). Of the 264 velocities, 86 represent the motion of continuous GPS stations, and the other 178 represent the motion of semi-continuous MAGNET stations (Blewitt et al., 2009).

The GPS velocities we present in this study are calculated from daily coordinate time series derived as part of a global GPS network analysis that includes data from over 13,000 stations. We use the GIPSY-OASIS II software package (Zumberge et al., 1997) to estimate daily station position coordinates using the precise point positioning method for all GPS data available between 1996 and August 2014. The processing uses reanalyzed fiducial-free GPS satellite orbit and clock parameters provided by the Jet Propulsion Laboratory's IGS Analysis Center with antenna calibration models for station receivers and satellite transmitters. The observation model includes solid earth tides and oceanic tidal loading (Scherneck, 1991). The Global Mapping Function was applied to model tropospheric refractivity (Boehm et al., 2006), and the tropospheric wet delay was modeled as a random walk zenith parameter with two random walk horizontal gradient parameters (Bar Sever et al., 1998). The carrier phase ambiguities are resolved using the WLPB method (Bertiger et al., 2010).

We align the daily position solutions with a custom North America-fixed, spatially filtered reference frame, NA12 (Blewitt et al., 2013). NA12 has an origin and scale that is consistent with the International Terrestrial Reference Frame, ITRF2008. The seven-parameter daily coordinate transformations from the JPL fiducial-free frame to NA12 are publicly available for GIPSY-OASIS II users at ftp://gneiss.nbmg.unr.edu/x-files, and the daily position time series data are available and plotted at http://geodesy.unr.edu. We correct the daily coordinate time series to remove the effects of transient deformation resulting from postseismic viscoelastic relaxation following historic surface rupturing earthquakes in the Central Nevada Seismic Belt (Gourmelen and Amelung, 2005; Hammond et al., 2009) using the method of Hammond et al. (2010)