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Present-day motion and deformation of the Colorado Plateau

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[1] We analyze data from continuous GPS stations in the southwestern United States and present the first observations of a systematic motion of the Colorado Plateau region. Relative to a North America-fixed reference frame, westward velocities increase rapidly across the Wasatch fault system, which comprises the plateau's northwestern margin, but increase more gradually between the Great Plains and the Mojave Desert province. We detect no significant extension across most of the Rio Grande Rift, but extension could be as high as ~0.5 mm yr^{-1} along its southernmost portion. We suggest that the motion between the plateau and stable continent may partly be accommodated instead across the Jemez Lineament. Only when we consider GPS velocities within the plateau's center, do the data support a rigid body rotation of 0.103° Ma^{-1} around a pole in the northern Rocky Mountains. We conclude that active extension has encroached into the plateau from both the east and west.

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1. Introduction

[2] The Colorado Plateau (CP) has played a distinct role as a long-lived rigid entity in the tectonic evolution of a large part of the western United States. Evidence suggests that the CP has acted as an independent and relatively undeformed crustal block since the Permian [e.g., *Steiner*, 1988]. During the Laramide orogeny the CP rotated clockwise relative to the North American continent around an Euler pole east of the plateau contributing to shortening across the Laramide fold and thrust belt [e.g., *Hamilton*, 1981]. Subsequently, starting in the mid-Tertiary, clockwise rotation of the plateau around a pole farther to the north has been suggested to cause opening of the Rio Grande Rift (RGR) [e.g., *Hamilton*, 1981; *Cordell*, 1982].

[3] Geodetic measurements of CP motion have been sparse to date. Very Long Baseline Interferometry (VLBI) measurements at 3 sites on the CP suggested a possible clockwise rotation around a pole located to the plateau's north, with rates along the southern CP of >3 ± 1 mm yr^{-1} [*Gordon et al.*, 1993; *Argus and Gordon*, 1996]. *Bennett et al.* [2003] inferred from GPS velocities that the westernmost portion of the CP moves (i.e., translates or rotates) at an average of 0.9 ± 0.1 mm yr^{-1} towards the northwest, but could not assess whether this motion applies to the CP as a whole.

[4] Here we present velocities for a large number of continuously measured GPS monuments in an area spanning the southern Basin and Range (BR) in the south, the Wasatch fault zone in the north, the Great Plains in the east and the northern BR and Mojave Desert provinces in the west (Figure 1a). From these velocities we identify zones of significant velocity gradients, assess the spatial extent of the plateau's rigidity, and determine a pole of rotation relative to our realization of the North America plate-fixed reference frame.

2. Tectonic Setting

[5] The CP is bounded to its east by the RGR, a major continental rift zone (Figure 1a). Estimated opening rates of the RGR are on average 0.14 mm/yr between 5 Ma and present [e.g., *Golombek et al.*, 1983]. Classical geodetic measurements near Socorro, New Mexico [*Savage et al.*, 1980] failed to detect any significant extension rates across the RGR, with an upper bound of 1 mm/yr (95% confidence limit).

[6] At an angle with the RGR lies the ~N52°E trending Jemez lineament, a zone characterized by some of the most significant recent volcanism in the western United States that stretches from east-central Arizona to northeastern New Mexico [e.g., *Aldrich and Laughlin*, 1984]. To the west and south, the CP is bound by the northern and southern BR, respectively. The geodetic motion across the Wasatch fault system between the northern CP and northern BR is ~2–3 mm yr^{-1} of extension [e.g., *Hammond and Thatcher*, 2004; *Chang et al.*, 2006]. The Intermountain Seismic Belt (ISB) coincides with the Wasatch fault system, and has an E–W trend in southern Nevada (Figure 1a). The present-day extension rate across the Hurricane and Sevier-Toroweap normal faults, the southward extension of the Wasatch front, is yet unknown, but geologic estimates do not exceed 0.3 mm yr^{-1} [e.g., *Fenton et al.*, 2001; *Amoroso et al.*, 2004; *Karlstrom et al.*, 2007].

[7] A persistent zone of normal-slip earthquakes along N–S to NW–SE trending fault planes is observed east of the Sevier-Toroweap fault system, called the northern Arizona seismic belt (NASB) [*Brumbaugh*, 1987]. The NASB connects the ISB with the seismically less active CP-southern BR transition zone [*Menges and Pearthree*, 1989]. Recognized Quaternary fault displacements in the transition zone are smaller than those of the Hurricane and Sevier-Toroweap fault zones. The density of known fault scarps is very low in central Arizona, but increases in southeastern Arizona, where a prominent fault scarp indicates an earthquake of probable magnitude ≥ M7 [e.g., *Pearthree and Calvo*, 1987; *Johnson and Loy*, 1992]. The largest historic earthquake in the Intermountain West occurred in northernmost Mexico (i.e.,

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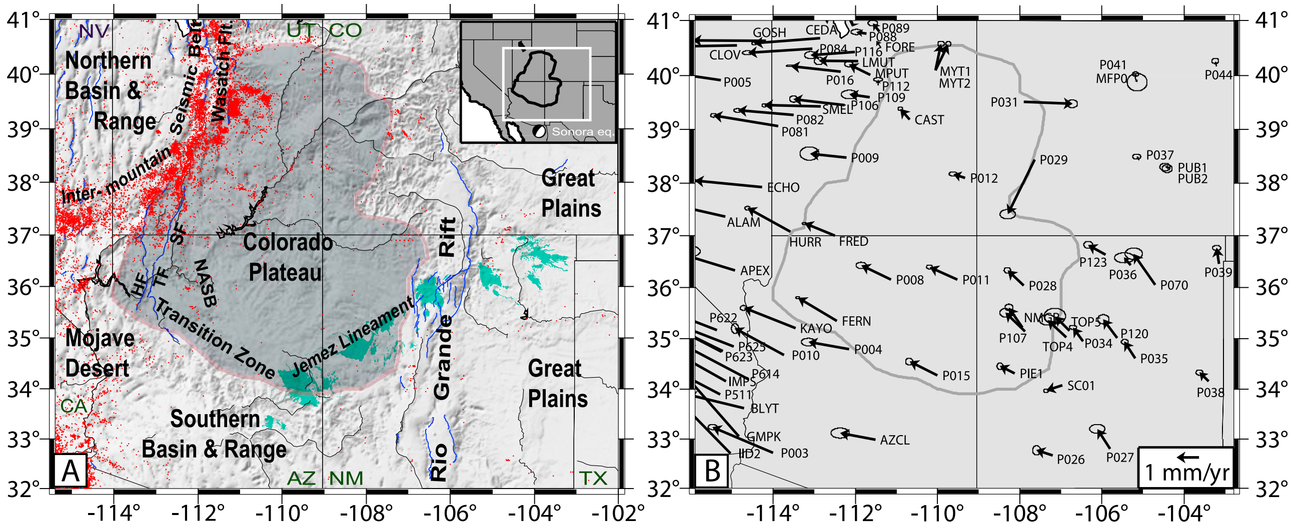

Figure 1. (a) Tectonic setting of Colorado Plateau region. Physiographic extent of plateau is in grey. Red dots are epicenters of events between 1964–2003 in the Advanced National Seismic System (ANSS) catalog. Blue lines are faults from the U.S.G.S. Fault and Fold Data Base with known Quaternary slip rates. Outlines of volcanic centers of the Jemez Lineament are shown in green (after *West et al.* [2004]). Focal mechanism of 1887 Sonora earthquake in inset is from *Natali and Sbar* [1982]. NASB, northern Arizona seismic belt; HF, Hurricane fault; SF, Sevier fault; TF, Toroweap fault. (b) GPS velocities relative to a North America fixed reference frame. Error ellipses show 1-σ uncertainties. Some velocities west of the CP are removed for clarity.

the 1887 M7.5 Sonora earthquake [e.g., *Natali and Sbar*, 1982], see inset Figure 1a), just to the south of this large southeastern Arizona scarp.

[8] Sparse focal mechanisms and other stress indicators along the CP-southern BR transition zone indicate NE–SW oriented extension [e.g., *Zoback and Zoback*, 1980; *Brumbaugh*, 2008], consistent with focal mechanisms of small earthquakes within the plateau [e.g., *Wong and Humphrey*, 1989]. *Menges and Pearthree* [1989] infer a belt of long-wavelength uplift across the transition zone based on regional topographic anomalies and dissection patterns. Southwest of the transition zone in the southern BR, there is a dearth of seismicity and Quaternary faults.

3. GPS Results and Interpretation

[9] We use data from continuous GPS stations in the southwestern United States, and present results for stations between 115.4°W–103°W and 32°N–41°N. Considering the low deformation rates in this region, we only present results from sites with the most stable monuments: i.e., either metal/concrete pillar monuments or those that are deep or shallow braced.

[10] We use the GIPSY-OASIS II software to obtain daily coordinates for all available data early 2010 [*Zumberge et al.*, 1997]. We use reprocessed orbits from the Jet Propulsion Laboratory's IGS Analysis Center, and the most recent absolute phase center models. Carrier phase ambiguities are successfully resolved across the entire network using our Ambizap software [*Blewitt*, 2008]. We use 10 sites (away from glacial isostatic rebound signal) to constrain North America rotation and an additional 36 sites on and around North America to reduce continental-scale common-mode noise through a daily 7-parameter transformation (see *Kreemer et al.* [2010] for details). For all sites with >2.5 years of data, we estimate velocities from the resulting position time-series with the CATS software package [*Williams*, 2003] and account for annual and semi-annual constituents. The same software was used to estimate rate uncertainties assuming an error model that consists of white plus flicker noise. GPS velocities are shown in Figure 1b and tabulated in the Supplemental Material.[1]

[11] We exclude from our analysis the velocities of P029 and P031 in western Colorado that show large anomalous velocities (Figure 1b) and time-variable deformation. We see more anomalous motions for other monuments in that region (not presented here) and speculate that GPS motions there are affected by the reported wide-spread subsurface evaporate dissolution [e.g., *Kirkham and Scott*, 2002].

[12] The first-order characteristic of the GPS velocity field is an east-to-west increase in the westward velocities. A velocity increase from zero to 2 mm yr^{-1} occurs rapidly across <100 km at the Wasatch fault system (Figure 2a). A similar increase in rate occurs, however, over >600 km (between eastern New Mexico and the Mojave Desert) at the latitudes of the southern CP and southern BR. Most of the normal faulting earthquakes in the region occur within this southward-broadening extensional zone (Figure 2a).

[13] Except for the southernmost RGR, where extension across the rift could be ~0.5 mm yr^{-1}, no significant deformation across the RGR can be detected. Instead, present-day extension appears to occur west of the RGR. Sites in northwestern New Mexico show mostly northwestward motion and a consistent pattern of westward motions becomes only evident well west of the Jemez Lineament.

[14] Despite this evidence for a diffuse extensional zone across the area, we also attempted to model the motion of

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[1] Auxiliary materials are available on the ftp site. ftp://ftp.agu.org/apend/gl/2010gl043374/.

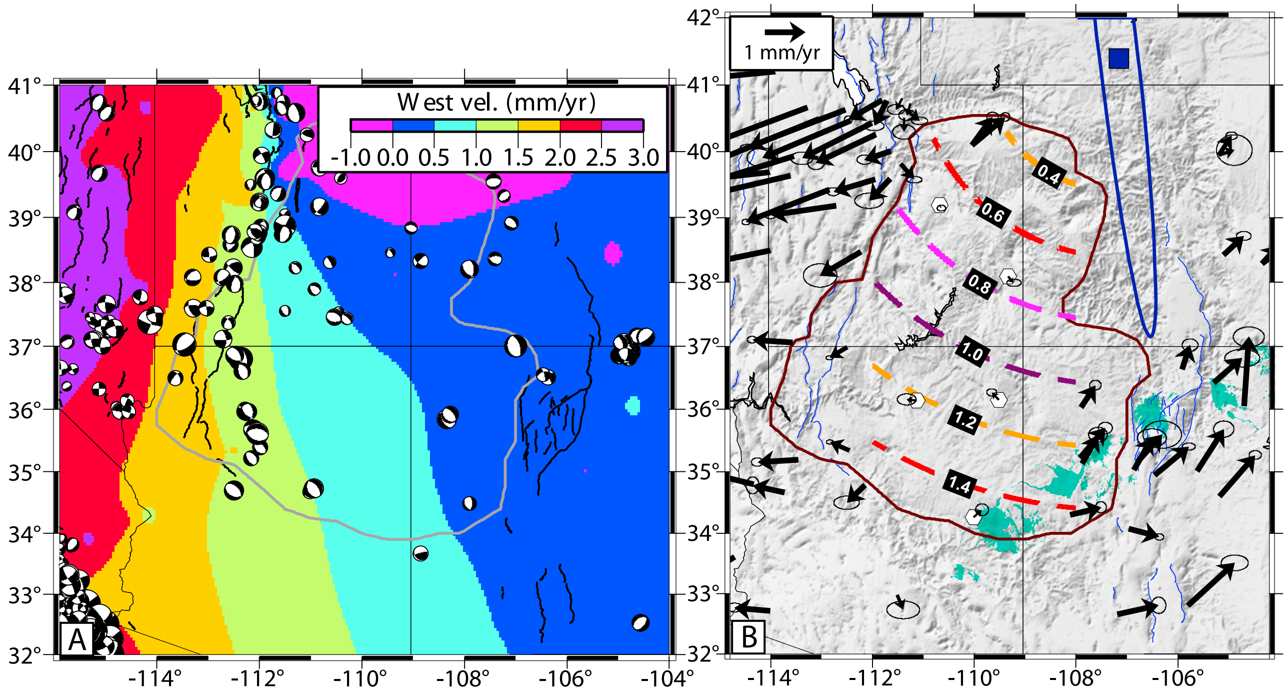

Figure 2. (a) Contour plot of westward velocities (minus P029 and P031). Focal mechanism are those for all single events with M > 2 (see *Kreemer et al.* [2010] for references). (b) Selection of residual velocities after a rotation of the central CP has been removed. Rotation is determined by five sites on plateau (white hexagons). Blue square and ellipse are Euler pole and 1-σ error ellipse, respectively. Dashed lines are small circles around pole, and numbers are in mm yr^{-1}. Active faults are thin blue lines and Jemez Lineament is in green.

the CP as a rigid body rotation. While we find a poor fit to the data when we consider all sites on the plateau (χ^2 per-degree-of-freedom statistic is 12.3), a rigid body rotation fits the data considerably better when we take the velocities of five sites along the spine of the plateau (CAST, P008, P011, P012, P015). For this case $\chi^2 = 2.3$, roughly equal to what we find for fitting a rotation to the velocities of stations on stable North America ($\chi^2 = 2.4$). We estimate a clockwise rotation at a rate of $0.103 \pm 0.017°$ Ma^{-1} around a pole located at 41.4°N and 107.2°W (Figure 2b). The southwestern CP (i.e., FRED and FERN) departs from the apparently rigid central portion of the CP, moving westward at a rate of 0.5 ± 0.1 mm yr^{-1} (Figure 2b). This motion is consistent with diffuse extension across the transition zone and NASB. Northwestern New Mexico also appears to be kinematically distinct from the rigid central portion of the CP, but the cause of its NNE motion of up to 1 mm yr^{-1} is less clear.

4. Discussion and Conclusions

[15] We find an average motion of ~1.0 mm/yr of the CP's western portion. While this result is consistent with the 0.9 ± 0.1 mm/yr inferred by *Bennett et al.* [2003], we find significant north-to-south variation (e.g., CAST vs. FRED). Sites on the southwestern plateau thus do not represent rigid CP motion. The inferred rigid-body rotation predicts 1.4 ± 0.1 mm yr^{-1} along the plateau's southern margin relative to stable North America, faster than the rate of 0.6 ± 0.4 mm yr^{-1} that corresponds to the Euler vector inferred by *Cordell* [1982]. Our rotation rate estimate is much slower than found by the VLBI studies, which probably suffered from poor reference frame control.

[16] Our results suggest that rotation can not be assumed for the entire physiographic plateau. The deviation from a rigid-body rotation in the (south-)western and eastern CP are too large to be explained by elastic strain accumulation from motion on single faults along the plateau's boundary. Our results partly rely on the high precision with which velocities from (continuous) GPS stations can now be achieved. Other geodetic studies may find that other assumed rigid crustal blocks may deform internally as well. Such insight would need to be considered in the ongoing debate on whether the continental lithosphere deforms block-like or as a continuum [e.g., *Thatcher*, 2009].

[17] We see no clear relationship between CP rotation and RGR opening, because GPS sites in western New Mexico do not show the rotation. Motion between the CP and North America appears to be diffuse within the zone between the RGR and the New Mexico-Arizona border. This inference is consistent with seismic and gravimetric studies that find a rift signature in the mantle west of the RGR and centered underneath the Jemez Lineament [e.g., *Spence and Gross*, 1990; *West et al.*, 2004; *Roy et al.*, 2005]. The NW-directed GPS velocities in northwestern New Mexico (Figure 1b) would be consistent with observed normal-oblique slip on NNE trending Pliocene-Quaternary faults and the presence of NNE-trending dikes along the Jemez Lineament [*Aldrich and Laughlin*, 1984].

[18] Encroachment of extension into the western plateau is implied by the diffuse deformation within the transition zone along the southwestern margin of the plateau. To the extent that the plateau's interior may be considered rigid, extension penetrates the plateau as far eastward as between ~112.5°W (longitude of sites FERN and FRED) and 111°W

(longitude of P008). This extension coincides with the transition between thick CP lithosphere to the east and thin southern BR lithosphere to the west, inferred from seismic tomography [*Sine et al.*, 2008]. *Karlstrom et al.* [2008] speculated that this transition has migrated eastward (coeval with an eastward migration of magmatism [e.g. *Best and Hamblin*, 1978; *Nelson and Jones*, 1987; *Wenrich et al.*, 1995]) and that it is related to mantle upwelling due to edge-driven convection. This mantle upwelling may be responsible for the extension, and it should be noted that extensional seismicity in the NASB occurs right above this transition. Mantle upwelling may also provide a mechanism for the regional uplift inferred by *Menges and Pearthree* [1989]. More geodetic data is needed to constrain the spatial extent of the encroachment. In any case, the deviation from block-like behavior in (south-)western and eastern CP, right where there is a shallow mantle signature, suggest a mantle control on surface deformation, possibly through thermal and/or magmatic softening.

[19] Our results can not currently constrain whether extension in the western CP is localized or not, but we propose that extension is distributed from ~111°W westward into the Mojave Desert province. Distributed extension from the Mojave Desert into the western CP would be consistent with an EW trending sinistral shear zone in southern Nevada that *Kreemer et al.* [2010] proposed based on geodetic and seismologic data. This Pahranagat Shear Zone, which follows the ISB, marks the boundary between a rigid northern BR and an extending Mojave province.

[20] The strain rate field implied by the GPS velocities is characterized by east-west extension, but the extensional stress field implied by earthquake moment tensors and other indicators is on average directed more NE–SW [*Flesch and Kreemer*, 2010]. The observed stress field is aligned with that predicted from the high gravitational potential energy (GPE) in the area [*Flesch and Kreemer*, 2010]. The discrepancy between stress and strain orientations may suggest that the GPE variations are not (or at least not solely) responsible for the extension observed by the geodetic data, and that plate boundary forces or active drag due to the complex mantle flow contribute to the westward motion.

[21] We show 2.6 ± 0.2 mm yr^{-1} motion between southwestern Arizona and stable North America. Some (i.e., ~0.5 mm yr^{-1}) of that motion may be accommodated across the southern RGR. Although we currently have limited geodetic constraints, we speculate that the remaining 2.1 mm yr^{-1} is likely distributed diffusely within a broad, southward-widening zone that includes the CP-southern BR transition zone. A very diffuse and low-rate extensional zone would explain the dearth in seismicity and Quaternary faults, yet provides enough strain to cause rare large (i.e., characteristic) earthquakes consistent with observations.

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