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Constraints on Jalisco Block Motion and Tectonics of the Guadalajara Triple Junction from 1998–2001 Campaign GPS Data

Michelle M. Selvans,[1] Joann M. Stock,[1] Charles DeMets,[2] Osvaldo Sanchez,[3] and Bertha Marquez-Azua[4]

Abstract—A GPS campaign network in the state of Jalisco was occupied for ~36 h per station most years between 1995 and 2005; we use data from 1998–2001 to investigate tectonic motion and interseismic deformation in the Jalisco area with respect to the North America plate. The twelve stations used in this analysis provide coverage of the Jalisco Block and adjacent North America plate, and show a pattern of motion that implies some contribution to Jalisco Block boundary deformation from both tectonic motion and interseismic deformation due to the offshore 1995 earthquake. The consistent direction and magnitude of station motion on the Jalisco Block with respect to the North America reference frame, ~2 mm/year to the southwest (95% confidence level), perhaps can be attributed to tectonic motion. However, some station velocities within and across the boundaries of the Jalisco Block are also non-zero (95% confidence level), and the overall pattern of station velocities indicates both viscoelastic response to the 1995 earthquake and partial coupling of the subduction interface (together termed "interseismic deformation"). Our results show motion across the northern Colima rift, the eastern boundary of the Jalisco Block, which is likely to be sinistral oblique extension rather than pure extension. We constrain extension across both the Colima rift and the northeastern boundary of the Jalisco Block, the Tepic-Zacoalco rift, to ≤8 mm/year (95% confidence level), slow compared to relative rates of motion at nearby plate boundaries.

Key words: Colima rift, GPS, interseismic, Jalisco Block, Tepic-Zacoalco rift, triple junction.

1. Introduction

Jalisco is an interesting region for geodetic study for two main reasons. First, geologic evidence points to concentrations of tectonic deformation in two bounding rifts inland from the Rivera plate, the Tepic–Zacoalco and Colima rifts (see Fig. 1). Second, following the 9 Oct 1995 ($M_w = 8.0$) Colima-Jalisco earthquake, the hinge of deformation (between subsidence and uplift) quickly moved onshore (Melbourne *et al.*, 2002), providing better Global Positioning System (GPS) coverage of overall deformation than exists for most subduction megathrusts. Neither the deformation due to the earthquake cycle nor the local tectonics is fully understood.

This study seeks to constrain the tectonic motion of the Jalisco Block with respect to North America. We use average velocities during 1998–2001 for a network of twelve GPS stations to investigate rifting rates across the Tepic–Zacoalco and Colima rifts, as well as motion across the Chapala rift. We also investigate the contribution to station motion from earthquake cycle effects. The 1995 $M_w = 8.0$ event offshore from Jalisco may contribute significantly to the velocities of the network stations, so careful consideration of both tectonic and earthquake cycle signatures in the GPS data is necessary.

Constraining the current rate of tectonic motion in the Jalisco area will narrow down the likely scenarios for ongoing deformation in a region of active plate rearrangement (e.g. Luhr *et al.*, 1985; Johnson and Harrison, 1990; Allan *et al.*, 1991; Ferrari, 1995; Rosas-Elguera *et al.*, 1996; DeMets and Traylen, 2000). The Jalisco Block lies onshore from the northernmost section of the Middle America Trench, above the subducting Rivera plate, just south of rifting in the Gulf of California, and has often been cited as an example of continental rifting (e.g. Luhr *et al.*, 1985).

Characterizing the pattern and magnitude of earthquake cycle effects in the dataset is essential to

[1] Seismological Laboratory, California Institute of Technology, Pasadena, CA 91125, USA. E-mail: selvans@gps.caltech.edu
[2] Department of Geoscience, University of Wisconsin-Madison, Madison, WI 53706, USA.
[3] Instituto de Geofisica, Universidad Nacional Autonoma de Mexico, 04510 Mexico D.F, Mexico.
[4] DGOT/SisVoc, Universisdad de Guadalajara, Av. Maestros y Mariano Barcenas, 93106 Guadalajara, Jalisco, Mexico.

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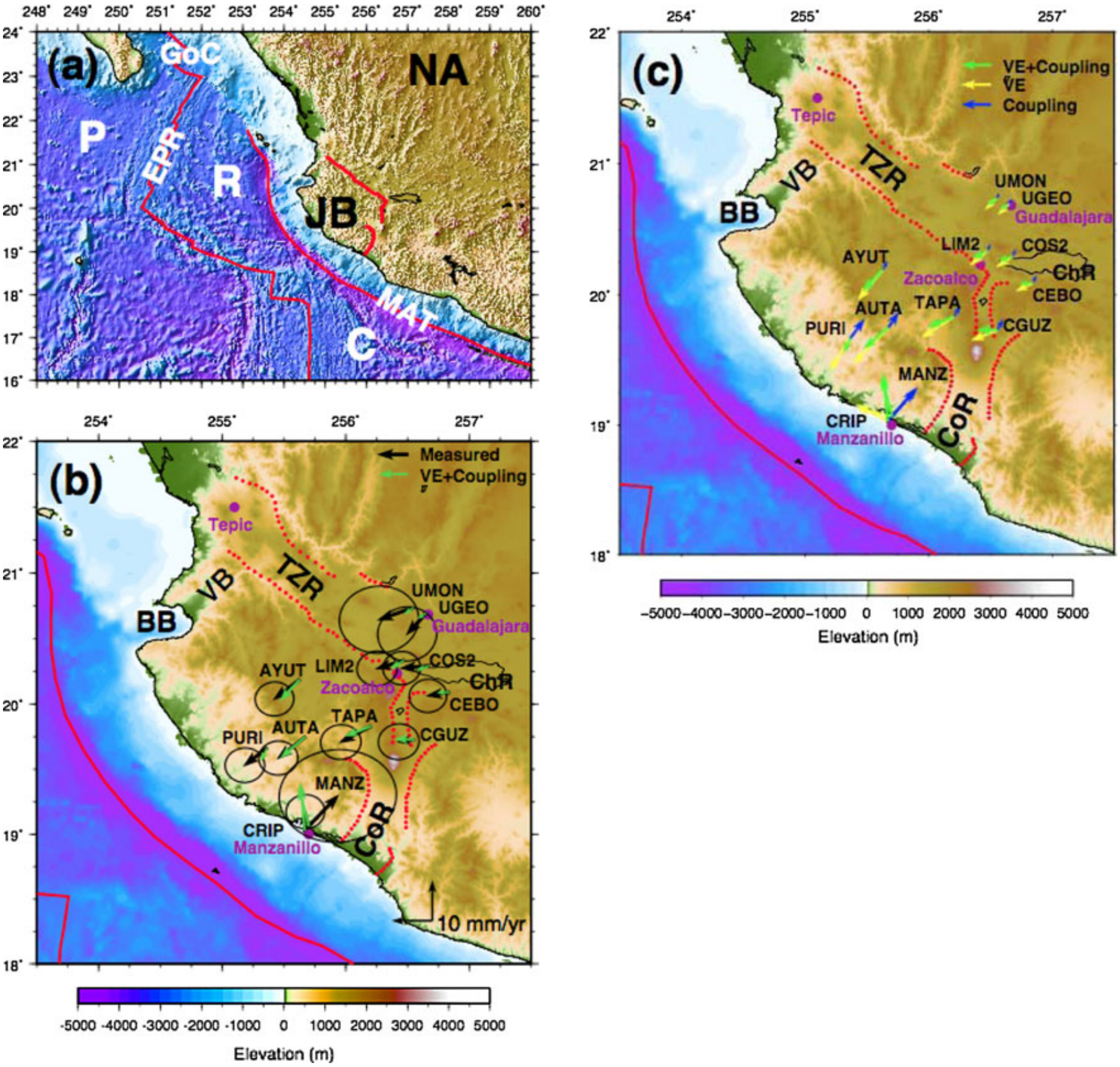

Figure 1

a Topography and bathymetry of western Mexico shows the plate tectonic context for the Jalisco Block (JB), with plate boundaries and Jalisco Block boundaries in red. The Jalisco Block is just southeast of the Gulf of California (GoC), and may move rigidly with respect to North America (NA). The Pacific (P) and Rivera (R) plates diverge at the East Pacific Rise (EPR). The Rivera and Cocos (C) subduct along the Middle America Trench (MAT). **b** Twelve GPS sites used in this study lie on the Jalisco Block and surround the rift-rift-rift triple junction, where the Tepic–Zacoalco, Colima, and Chapala rifts meet [TZR, CoR, and ChR, respectively; bounding faults for the Tepic–Zacoalco and Colima rifts are shown in red, after Allan (1986) and Ferrari *et al*. (1994)]. Bahía de Banderas (BB) and the Valle de Banderas (VB) are the proposed northwest boundary of the Jalisco Block (*e.g.* Johnson and Harrison, 1990). Rivera plate boundaries are after DeMets and Wilson (1997). Station velocities with respect to North America are plotted in black (see Appendix 2, Table 1), with north and east errors displayed as 2D 95% confidence intervals. For comparison, modeled interseismic velocity vectors are shown in *green*. **c** Modeled vectors include partial coupling along the subduction interface (50% coupling shown in blue) and viscoelastic (VE) deformation of the overriding plate (*yellow*) (Masterlark *et al*., 2001; Marquez-Azua *et al*., 2002). All measured and predicted station velocities are scaled to the reference vectors in the lower right. Shuttle Radar Topography Mission data and estimated seafloor topography are $\sim$1 km resolution (Becker and Sandwell, 2006)

its reliable interpretation. GPS analysis and modeling of the coseismic and postseismic (transient) effects of the 1995 earthquake (Hutton *et al*., 2001; Masterlark *et al*., 2001; Marquez-Azua *et al*., 2002), indicate that some signature of the earthquake cycle is expected during our study period, likely due to viscoelastic deformation of the mantle beneath our study area and partial to full coupling of the subduction interface (together termed "interseismic deformation").

We assess our network velocities with respect to forward-modeling predictions of earthquake cycle phenomena and predictions of multiple hypotheses for tectonic motion of the Jalisco Block. These phenomena predict different station velocity patterns: (1) stations on the Jalisco Block move together to the west or southwest relative to North America, due to rifting of the Jalisco Block from North America, (2) all stations move toward the 1995 rupture zone, due to viscoelastic response of North America to the earthquake, and (3) all stations move away from the 1995 rupture zone, due to partial coupling of the subduction interface. The first prediction has three variants (detailed below), based on alternative hypotheses for the formation and motion of the Jalisco Block and its bounding rifts. We also examine the smaller region around the "Guadalajara triple junction" (where three rifts—the Tepic–Zacoalco, Chapala, and Colima rifts—meet each other). For this region, we assume local tectonic rates dominate over any viscoelastic gradients, permitting us to place constraints on the velocity triangle that includes North America and the Jalisco and Michoacan Blocks, which surround this triple junction (e.g. Johnson and Harrison, 1990).

2. *Tectonic Setting*

2.1. *Regional Tectonics*

Jalisco is a coastal state of western mainland Mexico, located southeast of the Gulf of California (Fig. 1a). The surrounding region is shaped by a series of recent tectonic events, including subduction along the west coast of North America, an eastward jump of the East Pacific Rise to produce rifting in the Gulf of California, and separation of the Rivera and Cocos plates, resulting in the current differential subduction beneath Jalisco and the rest of western Mexico to the southeast. Convergence is slower between the Rivera and North America plates than between the Cocos and North America plates, and is increasingly oblique from south to north along the Rivera-North America trench (e.g. Kostoglodov and Bandy 1995; DeMets and Traylen 2000).

2.2. *Boundaries of the Jalisco Block*

The Tepic–Zacoalco rift consists of several tectonic depressions bounding the northeastern extent of a topographically high portion of the state of Jalisco (Fig. 1b). Structural mapping of the Tepic–Zacoalco rift indicates some extension and right-lateral motion occurred ~12–8.5 Ma, with extension continuing to the present day, probably related to opening of the Gulf of California (Ferrari, 1995; Frey *et al*., 2007). Recent rates of motion are small, with average minimum deformation rates that decrease from 0.75 mm/year in the late Miocene to 0.1 mm/year in the Quaternary (Ferrari and Rosas-Elguera, 2000). Beginning at 4.7 Ma, alkaline and calc-alkaline volcanic lavas were concentrated within the Tepic–Zacoalco rift, some with compositions commonly found in ocean islands and intraplate rifts (e.g. Allan *et al*., 1991). Furthermore, rhyolitic ignimbrites were embedded in this rift on an order of magnitude greater volume during the interval of 5–3 Ma than is documented for the volcanism of the last ~1 Ma, indicating significant lithospheric extension occurred during that time (Frey *et al*., 2007). Seismicity to a depth of ~35 km within the Tepic–Zacoalco rift also indicates deep crustal faulting between the Jalisco Block and North America (Nuñez-Cornú *et al*., 2002). Additionally, a tomographic study of the crust and upper mantle in Jalisco and adjacent states reveals distinct low velocity lineaments beneath both the Tepic–Zacoalco and Colima rifts (Wang *et al*., 2008); in the upper mantle, these features are associated with tearing of the subducted slab (Yang *et al*., 2009).

The Colima rift bounds the eastern edge of the Jalisco highlands (Fig. 1b). Except for the massive deposition of rhyolitic ignimbrites (Frey *et al*., 2007), volcanism within this Jalisco Block boundary is similar in composition and duration to that of the Tepic–Zacoalco rift (e.g. Allan *et al*., 1991). Since ~5 Ma, rocks of the southern Colima rift have been faulted, both onshore (e.g. Garduño-Monroy *et al*., 1998) and offshore (Bourgois *et al*., 1988; Khutorskoy *et al*., 1994; Bandy *et al*., 2005), and the northern Colima rift has subsided 0.07–0.7 mm/year (Rosas-Elguera *et al*., 1996). Other crustal faults, such as the Tamazula fault to the west of the southern

Colima rift, may now form the southeastern boundary of the Jalisco Block (Garduño-Monroy *et al.*, 1998). These faults have had recent seismic activity (Garduño-Monroy *et al.*, 1998; Pacheco *et al.*, 2003; Andrews *et al.*, in press). Farther north, the eastern edge of the Jalisco block is roughly aligned with a sharp change in slab dip just east of the Colima rift (Pardo and Suarez, 1995), visible in seismic tomography (Grand *et al.*, 2007; Yang *et al.*, 2009).

The Zacoalco half-graben lies at the continental rift-rift-rift triple junction (termed the Guadalajara triple junction) where the Tepic–Zacoalco, Colima, and Chapala rifts come together. A sequence of magnitude 1.5–3.5 earthquakes in 1997 on shallow normal faults (Pacheco *et al.*, 1999) confirms formation of the half-graben as tilt blocks overlying listric faults (Rosas-Elguera *et al.*, 1997); additionally, the composite focal mechanism indicates possible right-lateral slip along a northwest-southeast oriented nodal plane within the Zacoalco graben near the triple junction (Pacheco *et al.*, 1999). Historical records indicate the potential for much larger earthquakes at this triple junction, such as the >7.0 magnitude earthquake of 27 December 1568 (Suarez *et al.*, 1994).

Receiver functions reveal Moho depths of 25–45 km in the continental interior of the Jalisco Block (Suhardja *et al.*, 2007). To fully delineate the inland boundaries of the Jalisco Block, its northwestern corner must be defined. Seismicity and structural mapping suggest Valle de Banderas, trending northeast from Bahía de Banderas to the Tepic–Zacoalco rift, has been the northwestern limit of the Jalisco Block since ~5 Ma (e.g. Johnson and Harrison, 1990; Nuñez-Cornú *et al.*, 2002); these lines of evidence are corroborated by gravity and magnetics data (Arzate *et al.*, 2006). An alternative interpretation of the geologic and magnetic data is that the northwest boundary of the Jalisco Block follows this same trend, but is located just to the northwest of Valle de Banderas (Urrutia-Fucugauchi and Gonzalez-Moran, 2006). While deformation is possible within and along all boundaries of the Jalisco Block, this study focuses on characterizing motion across the two most prominent boundaries between the Jalisco Block and neighboring continental material, the Tepic–Zacoalco and Colima rifts.

3. *Predictions of Current Deformation*

3.1. *Hypotheses for Block Motion*

Three hypothetical scenarios for the formation and motion of the Jalisco Block could explain the current morphologies of the Tepic–Zacoalco and Colima rifts. An early hypothesis for Jalisco Block formation and motion, based on regional tectonics, the clear inland delineation of the Jalisco Block by the Tepic–Zacoalco and Colima rifts, and the composition of volcanism in the rifts, was an imminent eastward jump of the East Pacific Rise to the Colima rift (e.g. Luhr *et al.*, 1985). This hypothesis suggests the eventual attachment of the Jalisco Block to the Pacific plate (i.e. northwestward motion with respect to North America), and predicts opening in the Colima rift and primarily right-lateral strike slip along the Tepic–Zacoalco rift. A variant of this hypothesis, based on similarities between volcanism in the Tepic–Zacoalco rift and that of the Gulf of California 12–6 Ma, is that recent Tepic–Zacoalco volcanism is a precursor to rifting of the Jalisco Block from North America (F*rey* et al*.,* 2007).

Alternatively, the Tepic–Zacoalco and Colima rifts are explained as passive responses of North America to tearing of the subducting slab, which stresses the continental crust (e.g. Ferrari, 1995, 2004). The Colima rift approximately overlies the sharp change in dip between the Rivera and Cocos slabs (P*ardo and* S*uarez,* 1995) and, as with the Tepic–Zacoalco rift, overlies a region of low seismic velocities; respectively, these low velocities may be due to differential motion between the subducting slabs (e.g. Stock, 1993) and a lateral tear in the Rivera slab (e.g. Nixon, 1982). This hypothesis for Jalisco Block motion predicts opening along both the Colima and Tepic–Zacoalco rifts (i.e. southwestward motion with respect to North America), with the possibility of motion being dominantly trenchward (southward) (Ferrari *et al.*, 1994; Rosas-Elguera *et al.*, 1996).

A third hypothesis for Jalisco Block formation and motion (which is potentially compatible with the preceding hypothesis) is that its inland boundaries accommodate little to no motion today, in keeping with geologic evidence for slow rates of opening (average minimums of <1 mm/year) across the Tepic–Zacoalco and Colima rifts from the late Miocene through the Quaternary (Rosas-Elguera *et al.*, 1996; Ferrari and Rosas-Elguera, 2000). This hypothesis predicts opening of up to a few millimeters per year across the inland Jalisco Block boundaries.

3.2. Earthquake Cycle Effects

The shallow portion of the slab interface ruptured in a pair of large earthquakes ($M_w = 8.2$ and $M_w = 7.8$) in 1932 (Singh *et al.*, 1985), after which no large subduction-related earthquakes ruptured the Rivera plate subduction interface until 1995 ($M_w = 8.0$) and 2003 ($M_w = 7.2$) (e.g. Melbourne *et al.*, 1997; Pacheco *et al.*, 1997; Yagi *et al.*, 2004). After the 1995 earthquake, GPS stations within 200 km of the rupture zone exhibited rapidly decaying transient deformation attributable to a combination of afterslip focused along areas of the subduction interface downdip from the rupture zone and viscoelastic flow of the upper mantle due to the elevated stresses from the 1995 earthquake (Hutton *et al.*, 2001; Marquez-Azua *et al.*, 2002; Melbourne *et al.*, 2002). Finite element modeling of the expected steady deformation from frictional coupling of the subduction interface and the transient, viscoelastically induced deformation of the overriding North America plate shows that these two processes cannot by themselves match deformation recorded between 1993 and 2001 at a continuous GPS station directly onshore from the 1995 rupture zone (Masterlark *et al.*, 2001; Marquez-Azua *et al.*, 2002), in accord with the aforementioned studies which conclude that fault afterslip contributed significantly to the deformation after the 1995 earthquake. Rapid transient postseismic deformation after the 1995 earthquake concluded by mid-1997, after which station motions were linear or nearly linear until the 22 Jan 2003 Tecoman $M_w = 7.2$ earthquake offshore from the study area triggered additional postseismic deformation consisting in part of aseismic fault afterslip (Schmitt *et al.*, 2007).

By limiting the present analysis to GPS data collected from 1998 to 2001, we exclude the years when coseismic and postseismic signals (i.e. obvious deviations from strictly linear motion) associated with the 1995 and 2003 earthquakes dominated the station velocities (2002 is excluded because no campaign GPS data were collected that year). When interpreting our data, we assume these 4 years are representative of ongoing tectonic motion. However, motion of the Jalisco Block may have varied over the last few million years, and interseismic earthquake cycle effects may still contribute significantly to motion of GPS sites during the time interval of our study.

Viscoelastic response of North America to the 1995 event would cause stations in our study to move southwestward toward the earthquake rupture zone, with the largest velocities closest to the epicenter, and similar directionality but decreasing magnitude at stations further inland (yellow vectors in Fig. 1c). This effect would produce motion in generally the same direction as predicted by the second hypothesis for block motion; although, in that case no strain gradient is expected. Partial coupling of the subduction interface would also result in a strain gradient, again with the largest magnitudes at the coast, but of generally northeastward motion (blue vectors in Fig. 1c).

Differences in predicted strain patterns allow us to assess the relative contributions of viscoelastic response, partial coupling on the subduction interface, and tectonic motion. We do not expect other large-scale contributions to the station motion in the Jalisco area. Because GPS stations farther inland in northern Mexico do not move significantly with respect to North America (Marquez-Azua and DeMets, 2003; 2009), motion related to the Basin and Range region is not expected to influence our study area.

4. Data and Methods

4.1. Data Collection and Processing

We use ten GPS stations from a Jalisco campaign network, occupied for ~36 h per station, with up to four stations simultaneously operating (Hutton *et al.*, 2001), as well as two continuous sites that ran for months at a time (UGEO and MANZ). We select these twelve stations to provide good coverage of the study area, including multiple data points on the Jalisco Block and baselines across the Tepic–Zacoalco and Colima rifts (Fig. 1b), so that we can investigate internal deformation as well as motion concentrated in the Jalisco Block boundaries.

Our analysis includes 62 sessions (days) over the 4-year time span. Fifteen GPS stations in North America (east of the Mojave desert) are used to define the reference frame relative to ITRF2000 (Altamimi *et al.*, 2002). Final orbits from the Jet Propulsion Laboratory are used for satellite positions.

For all sessions, loosely constrained least-squares solutions of position and velocity components and their correlation matrices are obtained for each station using GAMIT (Herring *et al.*, 1990). Using GLOBK (Dong *et al.*, 1998), these quasi-observations for each session are processed with constraints on station position and velocity, reference frame motion, and orbital and Earth orientation parameter values, in order to determine station coordinate time series with respect to North America. Further processing with the Markov process (white noise) in a recursive, time-domain Kalman filter allows us to obtain station velocities for 1998–2001. See Appendix 1 for more detail on the data processing.

4.2. *GPS Velocity Estimation*

Seven GPS stations show small amounts of significant motion with respect to North America (AUTA, AYUT, CEBO, COS2, LIM2, PURI, TAPA; see Appendix 2, Table 1), with an overall pattern of southwestward and west-southwestward motion for all ten inland stations (black vectors in Fig. 1b). Sites in the Jalisco Block interior (AUTA, AYUT, PURI, TAPA) move most similarly to each other compared with any other group of stations in this study, at 2–3 mm/year to the southwest with respect to North America (95% confidence level). Stations closest to the Guadalajara triple junction (LIM2, COS2) also move ~2 mm/year with respect to North America (95% confidence level), in a more westward direction than those of the Jalisco Block interior. Since our uncertainties on vertical motion are so large, the contribution to LIM2 and COS2 motion from slip on high-angle normal faults and/or listric normal faults in the area (e.g. Rosas-Elguera *et al.*, 1997) cannot be determined. This is also true for the stations on the Michoacan Block (CGUZ, CEBO), both of which are at the edges of the rifts they bound and so may also move in part due to local normal faulting. Five GPS stations (UMON, UGEO, CGUZ, CRIP, MANZ) do not move with respect to North America (95% confidence level), although we note that the coastal stations (CRIP and MANZ) do uniquely move inland. The direction of motion at stations CRIP and MANZ is likely due to interseismic strain accumulation (Marquez-Azua *et al.*, 2002; Schmitt *et al.*, 2007); the relatively large error ellipse on the MANZ station is due to only having 2 years of data during the 1998–2001 interval, and our analyzing that data only on days when at least one campaign station was active.

5. *Velocity Field Analysis Results*

We use station TAPA as a reference point for station velocities (Appendix 2, Table 2) because it is the station on the Jalisco Block closest to the Guadalajara triple junction. With respect to TAPA, we see no significant motion (lower end of the 95% confidence level) within the Jalisco Block or across the Colima and Tepic–Zacoalco rifts. Directly across the Colima rift from TAPA, the CGUZ station shows at most ~8 mm/year eastward motion and ~7 mm/year northward motion with respect to TAPA (upper end of the 95% confidence level), which provides an upper bound on the opening rate of the northern Colima rift during the years 1998 to 2001. Similarly with respect to TAPA, LIM2 limits the opening rate across the Zacoalco half-graben to a maximum of ~5 mm/year east and ~6 mm/year north.

We can further limit the range of possible motions by considering velocity constraints on the triple junction, using a flat-earth assumption involving only the stations closest to the triple junction (TAPA, CGUZ, CEBO, UMON, UGEO; see Fig. 2). Our velocity diagram has northward velocity on the y axis and eastward velocity on the x axis. This diagram is centered on a velocity of zero, which corresponds to station TAPA, which we use as our local reference frame. The resulting velocities are minimum constraints on block motions.

We fix station TAPA, on the Jalisco Block (Fig. 2a), and plot the best fit velocity vectors and their 95% confidence limits of the other four stations (values from Appendix 2, Table 2 using the

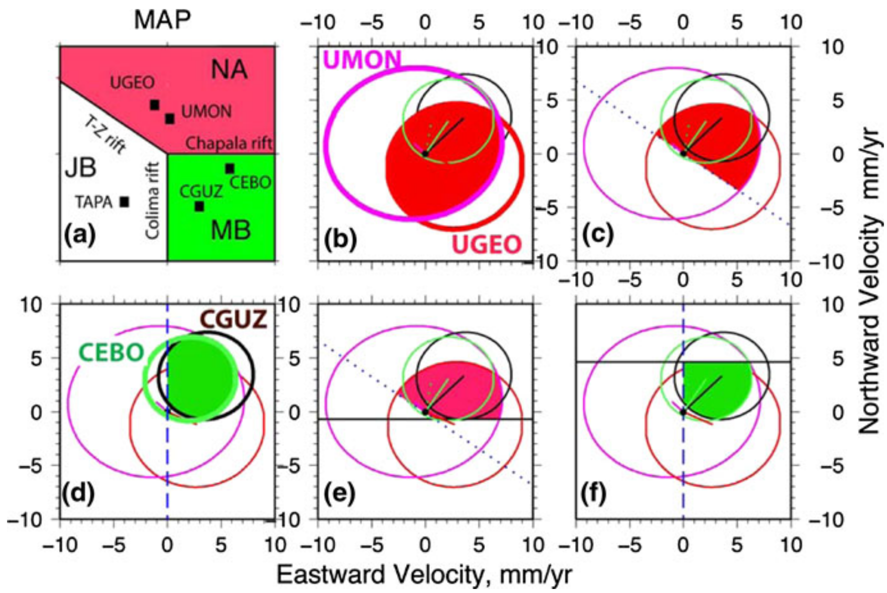

Figure 2

Velocity diagram analysis for a simplified Guadalajara triple junction constrains the sense of motion along the inland boundaries of the Jalisco Block (JB). **a** Schematic map showing the geometry of the triple junction and the location of the five stations. North America (NA) is in *red*; the Michoacan Block (MB) in *green*. Block JB (*white*) is the fixed block. Ellipses in *panels* (**b**) through (**f**) show the 95% confidence limits of station velocities relative to TAPA, whose velocity lies at the center of the diagram (*black dot* at coordinates 0,0). East–west velocity is on the *horizontal axis*; north–south velocity is on the *vertical axis*. *Straight lines* extending from the dot (best visible in *panels* **b** and **c**) indicate the best-fit velocity of each station with respect to TAPA, colored as follows: CEBO *green*, CGUZ *black*, UMON *pink*, UGEO *red*. **b** Intersection of UMON and UGEO ellipses shaded *red* to show allowable velocity values for NA motion relative to the JB. **c** Allowable velocities of NA relative to TAPA if no compression is occurring across the Tepic–Zacoalco (T-Z) rift. **d** Allowable velocities of the MB relative to TAPA if no compression is allowed across the northern Colima rift. **e** and **f** Allowable velocities of NA and the MB relative to TAPA if no compression is allowed across the Chapala rift. See Appendix 3 for a more detailed explanation

mathematical calculations of 2D Gaussian distributions (e.g., Molnar & Stock, 1985)). We then constrain the possibilities for block velocities further using the assumptions detailed in Appendix 3.

For the N–S trending northern Colima rift, this indicates an upper limit on opening of ~8 mm/year, with a significant component of left-lateral strike-slip possible (green shaded velocity field, Fig. 2f); the lower limit of motion rate across the northern Colima rift is nearly 0 mm/year (lower end of the 95% confidence level). These velocity constraints allow for ~5 mm/year of pure extension across the northern Colima rift (i.e. normal to its strike). Within the uncertainties they also permit alternatives, such as up to 6 mm/year of left-lateral motion or oblique sinistral transtension. Across the N56°W trending Tepic–Zacoalco rift, an upper limit of ~8 mm/year opening between the Jalisco Block and North America is possible, with ~6 mm/year of pure extension possible. Some amount of either pure left slip or pure right slip is possible (red shaded velocity field, Fig. 2e).

These constraints on opening rates across the Tepic–Zacoalco and Colima rifts (in the vicinity of the Guadalajara triple junction) permit more movement of the Jalisco Block with respect to North America than is observed geologically (average minimum values of ~0.1 mm/year since 5 Ma (Rosas-Elguera *et al.*, 1996; Ferrari and Rosas-Elguera, 2000; Frey *et al.*, 2007), and yet are consistent with the geology within the 95% confidence level of the velocity estimates.

Although the above analyses are based on holding station TAPA fixed, it is important to note that all four of our stations on the Jalisco highlands (TAPA, PURI, AUTA, AYUT) have similar velocities with respect to North America. The significant and coherent motion of these four stations, ~2 mm/year to the southwest with respect to North America, may be representative of the Jalisco Block rifting with respect to North America, with the caveat that viscoelastic deformation in response to the 1995 earthquake and partial coupling of the subduction interface may also contribute to the motions of these sites.

To understand the potential contributions from viscoelastic deformation, partial coupling of the subduction interface, and tectonic motion, we look qualitatively at the pattern of station velocities. Within the uncertainties, a distinct strain gradient is absent in the four stations on the Jalisco highlands (in contrast to predictions of both partial plate coupling and viscoelastic deformation), suggesting some contribution from Jalisco Block tectonic motion to the overall station velocities for 1998–2001. However, the overall pattern of estimated station velocities compares favorably with the modeled combination of viscoelastic response to the 1995 earthquake and 50% coupling along the subduction interface of previous researchers (yellow and blue arrows, respectively, in Fig. 1c) (Masterlark *et al.*, 2001; Marquez-Azua *et al.*, 2002).

The strain caused by coupling on the subduction interface consists of shortening, normal to the offshore subduction trench, counter to any extension across the Tepic–Zacoalco and Colima rifts. In contrast, the viscoelastic strain-rate gradient is extensional toward the rupture area of the 1995 earthquake, nearly opposite the sense of the gradient due to coupling, and so adds (temporarily) to any ongoing extension across the Tepic–Zacoalco or Colima rifts. The modeled and observed velocity vectors agree within the 2σ uncertainty ellipses, particularly with respect to the overall pattern of station motion (compare green and black vectors in Fig. 1b). While this similarity is suggestive, the relative role of off-fault and fault rheologies is still an open question (Wang, 2007), and the closest station to the 1995 rupture zone (PURI) does not fit well into the pattern of station motion predicted by the model of interseismic deformation.

6. Discussion

Although no previous analyses of GPS data have focused on motion across the Tepic–Zacoalco and Colima rifts, it is encouraging that similar earthquake cycle studies agree with our station velocity results. We find that GPS stations moved only $\sim$2 mm/year with respect to the North America plate reference frame, when considered at the 95% confidence level (Fig. 1b). Hutton *et al.* (2001) analyze campaign and continuous GPS data in the area for 1995–1999, and report varying amounts of postseismic motion for 1998–1999 with respect to NA: from 0 mm/year at CRIP, to $\sim$10 mm/year at TAPA and CEBO, and to $\sim$20 mm/year at AUTA, AYUT, PURI, and UMON, all to the southeast or southwest. Of these stations, they find that only the last four have significant motion with respect to North America ($\sim$10 mm/year at the 2σ level), and then only for the north component. Since this transient postseismic motion is well explained with a rate-and-state friction law model of the 1995 earthquake (Hutton *et al.*, 2001), it is an upper bound on annual velocity at these stations, and so is consistent with the significant motion of $\sim$2 mm/year with respect to North America that we find at stations on the Jalisco highlands for 1998–2001 (at the 95% confidence level).

Schmitt *et al.* (2007) analyze 1996–2003 GPS data in the Jalisco area to model interseismic and postseismic deformation due to the 2003 earthquake. They find that for the 1998–2001 time period, CRIP moved northeast with respect to the North America reference frame, and that TAPA, AUTA, AYUT, CGUZ, CEBO, and LIM2 moved southwest, all by $\sim$20 mm or less over the study period, or >7 mm/year (in agreement with our velocity estimates, within 2σ error ellipses). Schmitt et al. (2007) do not report position component errors for each year, but do report them for coseismic offsets, so we use the latter for comparison. The 1σ error on coseismic position estimates for TAPA, PURI, LIM2, and UGEO is 2–10 times larger than the measurement itself, and similarly the 2σ error for CGUZ, AYUT, and CEBO is larger than the measurements (Schmitt *et al.*, 2007). These relatively large errors suggest unresolved, although seemingly systematic, geodetic motion for 1998–2001 in the Jalisco area, as observed in our analysis of the data as well.

In both of the above analyses of Jalisco GPS data (Schmitt *et al.*, 2007; Hutton *et al.*, 2001), the intention was to model effects of the earthquake cycle on geodetic measurements in the area, and so neither focused on putting a robust constraint on the contribution from tectonic motion. We present a focused analysis of GPS data on and near the Jalisco Block that only covers the interseismic portion of the earthquake cycle, and obtain hard upper limits of 8 mm/year for opening along both the Tepic–Zacoalco and Colima rifts (5 and 6 mm/year of pure extension, respectively, near the Guadalajara triple junction). Interestingly, for the northern Colima rift there also may be significant left-lateral strike-slip motion (up to 5 mm/year of pure left-lateral strike-slip) and, in fact, some left-lateral strike-slip motion is required for the minimum allowed velocity based on our velocity diagram analysis (Fig. 2). These constraints may include Jalisco Block motion with respect to North America, as well as partial coupling of the subduction zone and viscoelastic response of the overriding North America plate (i.e. interseismic deformation).

In terms of the hypotheses for Jalisco Block motion, the data do not support an eastward jump of the East Pacific Rise, because we do not find the motion across the Tepic–Zacoalco rift to be dominantly right-lateral strike-slip. However, although only 1 mm/year of pure right-lateral strike-slip is allowed in our velocity diagram analysis (Fig. 2), the Tepic–Zacoalco rift is comprised of many faults with a range of orientations (N56°W being the overall orientation of the rift), the more E–W oriented of which may have slightly more pure right-lateral strike-slip motion. The second and third hypotheses for Jalisco Block motion, either some opening at both rifts due to tearing of the subducted slab or no current Jalisco Block motion with respect to North America, are both consistent with our upper limit of 8 mm/year opening across the Tepic–Zacoalco and Colima rifts, and the lower limit of only very slow motion across these boundaries (within the 95% confidence interval). These constraints confirm that relative motion between the Jalisco Block and North America (if present) is small compared to relative rates of motion at nearby plate boundaries (e.g. Bandy and Pardo, 1994), and is consistent with Quaternary geology.

With respect to earthquake cycle behavior of subduction megathrusts, we see station velocities following the 1995 earthquake that are largely consistent with modeled interseismic station velocities, suggesting homogenous response of the overriding North America plate and rapid resumption of coupling on the subduction interface. This indication of homogeneous earthquake cycle deformation onshore from the Rivera plate is in contrast to the heterogeneous response to earthquakes beneath Oaxaca to the south (Correa-Mora *et al.*, 2008), and suggests the Jalisco area as a promising location for better understanding earthquake cycle behavior.

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Appendix 1: Methods

Data are processed using the software packages GAMIT and GLOBK, developed at the Massachusetts Institute of Technology by T. A. Herring and D. Dong (Herring *et al.*, 1990; Feigl *et al.*, 1993; Zumberge *et al.*, 1997; Dong *et al.*, 1998). Inputs into GAMIT are the data files, session specifications (year and day, receiver and antenna types, and antenna heights), and good initial station coordinates. Outputs are the loosely constrained solution files, which are passed to GLOBK for multi-session processing. A least-squares analysis is used to obtain the GAMIT solution files, and a combination of well-defined reference frame and Kalman filter with white noise are used in GLOBK to obtain the station coordinate time series and velocities.

The recursive, time-domain Kalman filter (run eight times) estimates the state of a dynamic system from a series of incomplete and noisy measurements, such as campaign GPS data (Mao *et al.*, 1999); only the previous time step and the current measurement are needed to estimate the current state, with a linear relation used in the calculation, making it computationally efficient (Herring *et al.*, 1990). The Kalman filter uses a multivariate normal distribution for the process noise, which is independent of past process noise for every time step (i.e. the Markov process). In the simplest case, the Markov process allows separate noise levels for the north, east, and vertical components of position (we use 2 mm/year in the horizontal directions, 5 mm/year in the vertical direction).

The same a priori position and velocity constraints for each station are used in GAMIT and GLOBK, and are obtained from standard ITRF2000 files for the North America reference stations, and from the online Scripps Coordinate Update Tool for the campaign stations. Rotation and translation of three components of position and their rates are permitted when determining the reference frame in GLOBK. We iterate the reference frame solution eight times in order to stabilize the coordinate system, with 75% weighting on the coordinate sigmas of the previous iteration, and a 4-sigma cutoff for sites that are discordant with a priori values. Height residuals allowed in the stabilization are limited to 5 mm between the best and median for position (and 5 mm/year for the related rate), and 3 mm for the rms position (and 3 mm/year for the related rate).

Earth orientation parameters are tightly constrained in GLOBK by Markov process values of 0.25 mas/day in orientation and 0.1 mas/day in its rate of change. Since final orbits are used, a priori GPS satellite orbital parameters are also tightly constrained, with correspondingly tightly constrained random walk variation allowed while processing multiple sessions. Changes to orbital parameters due to random noise are constrained to 10 cm/day in XYZ, 0.01 mm/s/day for the XYZ time derivatives, 1%/day in direct and y-bias non-gravitational parameters, 0.1%/day in *b* axis bias and once-per-rev parameters, and 1 cm/day for SV antenna offsets.

Appendix 2: Results

See Tables 1 and 2.

Table 1

*Global [North America (NA)] and campaign GPS sites, their velocity components and 1σ errors (relative to North America, as defined by the stations with a *), and the cross-correlation (ρ) between north (N) and east (E) rates*

Long. (deg)	Lat. (deg)	E rate (mm/year)	N rate (mm/year)	Eσ	Nσ	ρ	H rate (mm/year)	Hσ	Site
284.912	38.777	0.06	0.44	1.29	1.14	0.028	−3.48	1.79	CHL1*
284.476	39.160	−0.07	0.61	1.97	1.80	0.042	1.05	4.13	DNRC*
284.430	39.561	−0.12	0.79	1.58	1.43	0.055	−1.17	2.27	RED1*
284.430	39.562	−2.99	−1.41	3.55	3.49	0.004	−3.57	10.83	RED2*
280.157	32.758	−0.04	0.75	1.19	1.14	−0.024	0.32	1.40	CHA1*
278.347	24.582	−0.69	0.59	1.15	1.18	0.031	3.96	1.48	KYW1*
273.910	36.358	1.59	−1.15	1.72	1.68	0.005	−0.25	2.50	HTV1*
265.183	35.367	1.28	−1.71	1.17	1.12	0.012	0.49	1.35	SAL1*
264.598	39.126	−0.02	−0.08	1.18	1.13	−0.005	−1.47	1.46	KAN1*
264.089	41.778	1.66	−1.02	1.62	1.57	−0.012	4.54	2.68	OMH1*
262.244	30.312	−0.24	0.75	1.22	1.16	0.070	−4.07	1.65	AUS5*
257.685	31.874	−0.88	0.09	1.25	1.12	0.098	−1.62	1.72	ODS5*
256.839	20.090	−5.30	−0.85	1.89	1.67	0.023	−2.09	4.02	CEBO
256.675	20.293	−6.79	−0.57	1.89	1.67	0.018	2.71	3.88	COS2
256.650	20.694	−4.66	−5.11	2.97	2.73	0.017	2.52	7.87	UGEO
256.554	19.730	−3.83	−0.57	2.05	1.80	0.031	0.87	4.68	CGUZ
256.547	20.737	−8.48	−2.98	3.99	3.39	0.027	4.38	12.83	UMON
256.472	20.335	−6.67	−2.03	2.02	1.75	0.030	3.99	5.09	LIM2
256.203	19.831	−7.42	−3.91	2.03	1.75	0.030	−4.29	4.50	TAPA
255.985	30.681	−1.94	0.13	1.43	1.37	0.006	0.97	1.73	MDO1
255.702	19.064	7.10	7.43	5.90	4.67	0.030	−8.17	15.94	MANZ
255.671	19.748	−6.62	−5.18	1.97	1.72	0.018	2.05	4.04	AUTA
255.667	19.031	0.19	4.60	1.95	1.71	0.017	62.74	3.67	CRIP
255.626	20.188	−6.19	−4.78	1.94	1.71	0.015	17.50	3.93	AYUT
255.363	19.665	−5.50	−4.28	1.98	1.74	0.016	12.42	4.09	PURI
251.881	34.302	−1.35	−2.36	1.45	1.43	0.019	0.01	1.91	PIE1
249.028	32.224	−1.51	0.48	2.49	2.01	0.162	3.42	4.48	COT1*

Uncertainties on vertical rates (H) are too large to constrain that component of motion. Stations are ordered by longitude

Table 2

GPS sites in the Jalisco region, their velocity components and 1σ errors (calculated relative to North America, as defined in Table 1, and presented relative to TAPA, a campaign site on the Jalisco Block), and the cross-correlation (ρ) between N and E rates

Long. (deg)	Lat. (deg)	E rate (mm/year)	N rate (mm/year)	Eσ	Nσ	ρ	H rate (mm/year)	Hσ	Site
256.203	19.831	0	0	0	0	0	0	0	TAPA
256.839	20.090	2.12	3.06	2.13	1.95	0.028	2.20	5.21	CEBO
256.675	20.293	0.63	3.34	2.13	1.96	0.026	7.00	5.10	COS2
256.650	20.694	2.75	−1.20	3.14	2.92	0.018	6.81	8.56	UGEO
256.554	19.730	3.58	3.35	2.21	2.03	0.031	5.17	5.38	CGUZ
256.547	20.737	−1.06	0.94	4.11	3.53	0.032	8.67	13.18	UMON
256.472	20.335	0.74	1.89	2.23	2.02	0.034	8.28	6.04	LIM2
255.702	19.064	14.52	11.35	5.96	4.76	0.030	−3.87	16.33	MANZ
255.671	19.748	0.80	−1.27	2.16	1.98	0.028	6.34	5.15	AUTA
255.667	19.031	7.61	8.52	2.11	1.95	0.025	67.03	4.78	CRIP
255.626	20.188	1.23	−0.87	2.14	1.97	0.025	21.79	5.05	AYUT
255.363	19.665	1.92	−0.37	2.16	1.99	0.027	16.71	5.18	PURI

Uncertainties on vertical rates (H) are too large to constrain that component of motion. UGEO, CRIP, and MANZ are continuous sites, while all other stations are part of the campaign. Stations are ordered by longitude

Appendix 3: Assumptions used in triple junction constraints

We assume a simplified geometry: three blocks (the Jalisco Block (JB), North America (NA), and the Michoacan Block (MB) (e.g. Johnson and Harrison, 1990) meet at a continental triple junction formed by the Tepic–Zacoalco rift, the northern Colima rift, and the Chapala rift. GPS sites UGEO and UMON are on NA; GPS sites CEBO and CGUZ are on the MB; and GPS site TAPA is on JB. We assume a flat-earth geometry because of the close spacing of these stations (<100 km separation). We use the results from Appendix 2, Table 2 to constrain the velocity of NA and the MB relative to the JB, assuming no compression across any of the boundaries, as follows.

1. UGEO and UMON lie on NA, and should move together with respect to TAPA. Thus, the velocity of NA must lie within the intersection of the 95% confidence limits of the UMON and UGEO velocities relative to TAPA (red region in velocity diagram in Fig. 2b). Similarly, the velocity of the MB must lie within the intersection of the 95% confidence regions of the CEBO and CGUZ velocities.
2. We assume no compression across the Tepic–Zacoalco rift, which trends N56°W. Therefore, the velocity of NA with respect to TAPA must lie northeast of a line with an azimuth of N56°W. This confines the allowable velocities for NA to points within the region shown in red in Fig. 2c.
3. We assume no compression in the northern Colima rift, which trends N–S. Thus, the velocities of stations on the MB (CEBO and CGUZ) must lie east of a line trending N–S from the origin. This requires their velocities to lie within the green region shown in Fig. 2d.
4. We assume no compression across the east–west trending Chapala rift. This eliminates velocities of NA from Fig. 2c that lie south of the southernmost point in the green velocity field in Fig. 2d, yielding the possible velocities of NA relative to block JB, shown in red in Fig. 2e. Similarly, we eliminate velocities of stations CGUZ and CEBO from Fig. 2d that lie north of an E-W line that passes through the northernmost point of the allowed velocity field for NA in Fig. 2e. The velocity for the MB then is restricted to the green field of Fig. 2f.

This yields the following constraints on the velocity triangle at the Guadalajara triple junction. At 95% confidence, the velocity of NA relative to the JB can lie anywhere in the red shaded region of Fig. 2e. The velocity of the MB relative to the JB can lie anywhere in the green-shaded region on Fig. 2f. However, the combination of velocities (one point from the red field and one point from the green field) must further satisfy two additional constraints. First, the red point cannot lie south of the green one (otherwise there would be compression across the Chapala rift). Second, the points on the velocity triangle must have the same topology as the blocks in map view (i.e. the JB, NA, and the MB must be encountered in clockwise order going around the triangle). A velocity triangle with the JB, NA, and the MB in counterclockwise order would imply that at least one of the boundaries is compressional.

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